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VNI

– Version 4.1 –

Simulation of high-energy particle collisions in QCD:

Space-time evolution of $e^+e^- \ldots A+B$ collisions with
– parton-cascades –
– cluster-hadronization –
– final-state hadron cascades –

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Abstract

VNI is a general-purpose Monte-Carlo event-generator, which includes the simulation of lepton-lepton, lepton-hadron, lepton-nucleus, hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions. It uses the real-time evolution of parton cascades in conjunction with a self-consistent hadronization scheme, as well as the development of hadron cascades after hadronization. The causal evolution from a specific initial state (determined by the colliding beam particles) is followed by the time-development of the phase-space densities of partons, pre-hadronic parton clusters, and final-state hadrons, in position-space, momentum-space and color-space. The parton-evolution is described in terms of a space-time generalization of the familiar momentum-space description of multiple (semi)hard interactions in QCD, involving $2 \to 2$ parton collisions, $2 \to 1$ parton fusion processes, and $1 \to 2$ radiation processes. The formation of color-singlet pre-hadronic clusters and their decays into hadrons, on the other hand, is treated by using a spatial criterion motivated by confinement and a non-perturbative model for hadronization. Finally, the cascading of produced pre-hadronic clusters and of hadrons is includes a multitude of $2 \to n$ processes, and is modeled in paralell to the parton cascade description. This paper gives a brief review of the physics underlying *VNI*, as well as a detailed description of the program itself. The latter program description emphasizes easy-to-use pragmatism and explains how to use the program (including simple examples), annotates input and control parameters, and discusses output data provided by it.

Program obtainable from: http://rhic.phys.columbia.edu/rhic/vni
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1 PROGRAM SUMMARY

Title of program: VNI

Computer fo which the program has been designed and others on which it has been tested: IBM RS-6000, Sun Sparc, Hewlett Packard UX A-9000

Operating systems: IBM-AIX, Sun-OS, and any other UNIX operating systems, as well as LINUX.

Programming language used: Fortran 77

Memory required to execute with typical data: 2000 kwords

No. of bits in a word: 64

No. of lines in distributed program: $\approx$ 47000 lines of the package *vni.f* as a whole.

Keywords: Monte Carlo simulation, event generator, QCD kinetic theory, parton cascades, parton coalescence, hadronic final states.

Nature of physical problem:
In high-energy particle collisions certain phase-space regions can be populated by a large number of quanta, such that statistical correlations among them (e.g., in space, momentum, or color) become of essential importance. Examples are deep-inelastic lepton-hadron scattering and hadron-hadron collisions in the region of very small Bjorken-x, or, collisions involving heavy nuclei in the central rapidity region. In these cases the produced particles evolve in a complicated non-equilibrium environment created by the presence of neighboring ones. The 'deterministic' quantum evolution of particle states due to self-interactions (depending only on the particle itself), receives a new 'statistical' kinetic contribution due to mutual interactions (depending crucially on the local density). The theoretical basis for addressing the solution for the dynamics of such particle systems is a quantum-kinetic formulation of the QCD equations of motion, an approximation that combines field-theoretical aspects associated with the renormalization group (including well-known resummation techniques) with aspects of transport theory associated with non-equilibrium multi-particle dynamics (including important quantum effects beyond the classical level).

Method of solution:
The solution of the underlying quantum-kinetic equations of motion for non-equilibrium multi-particle QCD by Monte-Carlo simulation of collisions allowing for a variety of combinations of beam and target particles. To simulate the real-time evolution of the collision system in position space and momentum space on the basis of the equations of motions, the procedure is four-fold: i) the construction of the initial state including the decomposition of the beam and target particles into their partonic substructure, (ii) the evolution of parton cascades including multiple scatterings, emission- and fusion-processes, (iii) the self-generated conversion of partons into hadrons using a phenomenological model for parton-coalescence into pre-hadronic clusters and subsequent decay into final-state particles, and (iv) the final-state interactions among produced clusters and hadrons including scattering, absorption, resonance production.

Restriction on the complexity of the problem:
For very high collision energy ($\sqrt{s} \gg 10$ TeV in hadronic collisions, and $\sqrt{s} \gg 5$ TeV/nucleon in nuclear collisions) numerical inaccuracies due to repeated Lorentz boosts, etc., may accumulate to cause problems, although the program uses double precision throughout.

Typical running time:
The CPU time for a typical simulation is strongly dependent on the type of beam and target, the magnitude of collision energy, as well as on the time interval Δt chosen to follow an event in its real-time evolution. Examples are (for $\Delta t = 35\ fm$): a) $e^+ + e^-$ at $\sqrt{s} = 100$ GeV: 10000 events/hour; b) $p + \bar{p}$ at $\sqrt{s} = 200$ GeV: 5000 events/hour; c) $p + Au$ at $\sqrt{s} = 200$ GeV/nucleon: 100 events/hour; d) $Au + Au$ at $\sqrt{s} = 200$ GeV/nucleon: 1 event/hour; All of the above quotes are approximate, and refer to a typical 133 Mhz or 166 Mhz processor on a modern Power-Workstation or Power-PC.

2 LONG WRITE-UP

2.1 Introduction

VNI [1] is the Monte Carlo implementation of a relativistic quantum-kinetic approach [1, 2] to the dynamics of high-energy particle collisions, inspired by the QCD parton picture of hadronic interactions [3, 4, 5]. It is a product of several years of development in both the improving physics understanding of high-energy multiparticle dynamics in QCD, as well as the technical implementation in the form of a computer simulation program. The most relevant references for the following are Refs. [6, 7, 8, 9, 10, 11], where details of the main issues, discussed below, can be found. The purpose of VNI is to provide a comprehensive description of particle collisions involving beams of leptons, hadrons, or nuclei, in terms of the space-time evolution of parton cascades and parton-hadron conversion. The program VNI is concepted as a useful *tool* (and nothing more) to study the causal development of the collision dynamics in real time from a specified initial state of beam and target particles, all the way to the final yield of hadrons and other observable particles. The collision dynamics is traced in detail on the microscopic level of quark and gluon interactions in the framework of perturbative QCD, supplemented by a phenomenological treatment of the non-perturbative dynamics, including soft parton-collisions and parton-hadronization. The generic structure of the simulation concept is illustrated in Fig. 1.

The main strength of VNI lies in addressing the physics of high-density QCD, which becomes an increasingly popular object of research, both from the experimental, phenomenological interest, and from the theoretical, fundamental point of view. Presently, and in the near future, the collider facilities HERA (ep, eA?), Tevatron ($p\bar{p}$, pA), RHIC and LHC ($p\bar{p}$, AA) are able to probe new regimes of dense quark-gluon matter at very small Bjorken-x or/and at large A, with rather different dynamical properties. The common feature of high-density QCD matter that can be produced in these experiments, is an expected novel exhibition of the interplay between the high-momentum (short-distance) perturbative regime and the low-momentum (long-wavelength) non-perturbative physics. For example, with HERA and Tevatron experiments, one hopes to gain insight into problems concerning the saturation of the strong rise of the proton structure functions at small Bjorken-x, possibly due to color-screening effects that are associated with the overlappping of a large number of small-x partons. Another example is the anticipated formation of a quark-gluon plasma in RHIC and LHC heavy ion collisions, where multiple parton rescattering and cascading generates a high-density environment, in which the collective motion of the quanta imust be taken into consideration. In this context the most advantageous and novel feature of VNI is the space-time cascade picture that provides a potentially powerful tool to study high-density particle systems in QCD, where accounting for the dynamically evolving space-time structure of the collisions is most important. The *necessity of including space-time variables* in addition to energy-momentum variables for high-density systems may be common knowledge in the field of heavy-ion physics, where the space-time aspect of many-body transport theory is essential ingredient to describe nucleus-nucleus collisions, but it is new to many high-energy particle physicists which only recently began to acknowleged the necessity to include time and space on top of the commonly used, pure momentum space description of, e.g., lepton and hadron collisions.

Where does VNI fit into the diverse family of modern event generators for physics simulation of particle collisions (where 'particle' stands for any beam/target particle from an electron to a heavy nucleus)?

The Monte Carlo models for high-energy particle collisions that are on the market, may be crudely divided into two classes:

(i) The first class embodies event generators that restrict to "clean" reactions involving lepton or proton beams only, and which aim at a high-precision description of experimental tests of QCD's first principles. Popular examples are PYTHIA [44], HERWIG [45], ARIADNE [46], LEPTO [47], and ISAJET [48]. The common feature of these event generators is a combination of well understood perturbative QCD parton-shower description and a non-perturbative hadronization prescription to convert the partonic final state into hadrons.

[1] The three letters VNI do not mean anything profound. VNI is pronounced "Vinnie", short for "Vincent Le CuCurullo Con GiGinello", the little guy who likes to hang out with his pals, the quarks (*cucu*rullos) and gluons (*gigi*nellos). That is QCD in Wonderland, and that is the whole, true story.

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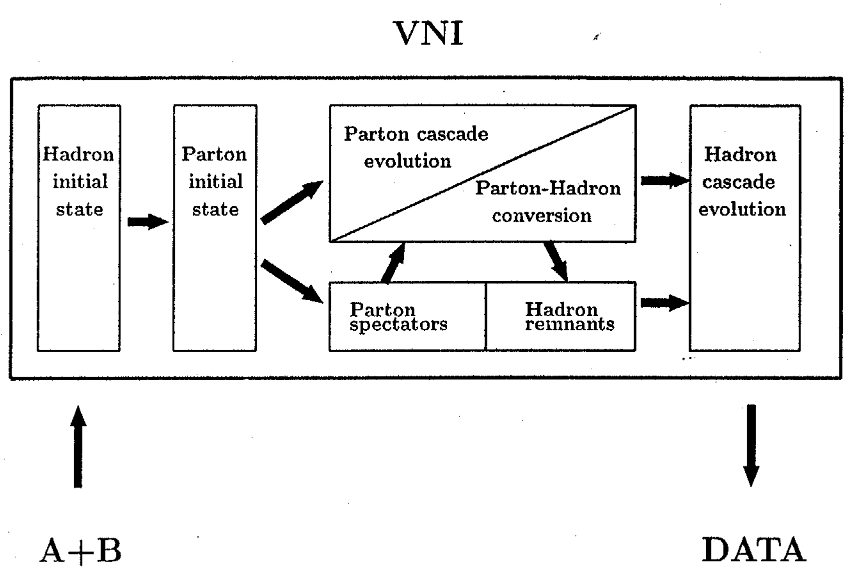

Figure 1: Generic flow-chart of the simulation concept of VNI: It starts with the initial beam target particles A and B, decomposing them (except for leptonic A and/or B) in their hadronic constituents with partonic substructure, then proceeds through the parallely evolving stages of parton-cascade, parton-hadron conversion, fragmentation of beam/target remnants, final-state hadron-cascade, and finishes up with the final particle yield that reflects observables in a detector.

(ii) The second class are event generators that aim to describe "dirty" reactions involving nuclei, much less based on first-principle knowledge, but instead rely on phenomenological models to mimic the unknown details of the underlying physics. Here the widely used concept is to visualize a nuclear collision in terms of nucleon-nucleon collisions on the basis of a constituent valence-quark picture plus string-excitation and -fragmentation. Examples for these models are FRITIOF [49], DPM [50], VENUS [51], RQMD [52], and HIJET [53]. Distinct from these is HIJING [54], which also incorporates a perturbative QCD approach to multiple minijet production, however it does not incorporate a space-time description.

With the exception of HERWIG, all of the above Monte Carlo generators utilize some form of *string fragmentation phenomenology* to model the non-perturbative hadronization and final-state particle production. Most commonly used is the Lund string model [39]. HERWIG on the other hand is built on a very different *parton-cluster formation/fragmentation approach*, which forms the basis of the hadronization scheme developed in VNI.

What are the shortcomings of the above-mentioned Monte Carlo models with respect to the particle dynamics in finite-density regions created by high-energy collisions?

The high-energy particle physics generators of the first class lack the inclusion space-time variables in the dynamics description in both the perturbative QCD parton evolution and the non-perturbative process of parton-hadron transition. These models therefore cannot account for statistical interactions due to the presence of a finite density of particles close-by in space, such as rescattering, absorption of recombination processes. Hence, although these models to large extent use QCD's fundamental quark-gluon degrees of freedom, important aspects of parton dynamics and interactions at finite density are left out, because the particles are assumed to propagate unscathed in free space.

The event generators of the second class, on the other hand, mostly do utilize a space-time description, however on the level of hadronic degrees of freedom (strings, baryons, mesons and resonances) rather than partonic degrees of freedom. For ultra-relativistic nucleus-nucleus collisions the parton approach appears to be more realistic than the hadronic or string picture, as it has been realized that short-range parton interactions play a major role for heavy ion collisions at collider energies of $\sqrt{s} \gtrsim 100$ GeV, at least during the early and most dissipative stage of the first few fm. Here copiously produced quark-gluon mini-jets cannot be considered as isolated rare events, but must be embedded in complicated multiple cascade-type processes. Thus, the short range character of these interactions implies that perturbative QCD can and must be used, and that the picture of comparably large distance excitations of strings or hadronic resonances does not apply in this kinematic regime.

In view of this discussion, the program VNI can be viewed in between the above two classes of Monte Carlo models: It provides a kinetic space-time description of parton evolution by utilizing well-developed techniques for perturbative QCD simulations at zero density or free space, as the event generators of the first class. On the other hand, it applies this concept also to the physics of finite-density particle systems, e.g., in collisions involving nuclei, as the event generators of the second class. Comparing VNI with the above-mentioned Monte Carlo models, the essential differences and partly new aspects are the following:

a) the aspects of the space-time evolution of the particle distributions in addition to the evolution in momentum space [8], and the concepts of quantum kinetic theory and statistical physics [1, 2].

b) the self-consistent interplay of coherent (angular ordered) perturbative parton evolution according to the DGLAP [31] equations, with the fully dynamical cluster-hadronization according to the phenomenological model of Ref. [9].

c) the microscopic tracing of color degrees of freedom and the effect of color-correlations by using explicit color-labels for each parton, which allows to investigate final state interactions in the process of hadron formation [10].

d) the diverse advantages of a stochastic simulation technique with which the various particle interaction processes are determined by the dynamics itself, through the local density of particles as they evolve causally in time.

e) the statistical many-particle description for general non-equilibrium systems, which allows to study thermodynamic behaviour of the bulk matter [55], such as the evolution of macroscopic energy density, pressure, etc., or the dynamical development of the sytem to thermal/chemical equilibrium in heavy ion reactions.

In summary, the improvement to be expected from VNI for the physics simulation of high-energy particle collisions lies clearly in the 'dirty' high-density parton regime, where the space-time aspects are most important, and which currently and in the future is of central interest in experiments at, e.g., HERA, RHIC and LHC. On the other hand, VNI may also be perceived as a valuable alternative to high-energy event generators for the study of 'clean', zero-density collisions as e^+e^- annihilation or $p\bar{p}$ collisions, where the space-time aspects can provide useful additional insight in the collision dynamics for experiments at, e.g., LEP or the Tevatron. Recent applications to e^+e^- and ep collisions may be found in Refs. [9, 10, 11], and to heavy-ion collisions in Refs. [12, 13, 14].

2.2 General concept

The central element in the physics description implemented in VNI is the use of QCD transport theory [8] and quantum field kinetics [1] to follow the evolution of a generally mixed multi-particle system of partons and hadrons in 7-dimensional phase-space d^3rd^3kdE. Included are both the parton-cascade development [4, 5, 15, 16] which embodies the renormalization-group improved evolution of multiple parton collisions including inelastic (radiative) processes, and the phenomenological parton-hadron conversion model of Refs. [9, 10, 11], in which the hadronization mechanism is described in terms of dynamical parton-cluster formation as a local, statistical process that depends on the spatial separation and color of nearest-neighbor partons, followed by the decay of clusters into hadrons.

In contrast to the commonly-used momentum-space description, the microscopic history of the dynamically-evolving particle system is traced in space-time *and* momentum space, so that the correlations of partons in space, time, and color can be taken into account for both the cascade evolution and the hadronization mechanism. It is to be emphasized, that the interplay between perturbative and non-perturbative regimes is controlled locally by the space-time evolution of the mixed parton-hadron system itself (i.e., the time-dependent local parton density), rather than by an arbitrary global division between parton and hadron degrees of freedom (i.e., a parametric energy/momentum cut-off). In particular the parallel evolution of the mixed system of partons, pre-hadronic clusters, and hadrons, with the relative proportions determined by the dynamics itself, is a novel feature that is only possible by keeping track of both space-time and energy-momentum variables.

Probably the greatest strength of this approach lies in its application to the collision dynamics of complicated multi-particle systems, as for example in collisions involving nuclei (eA, pA and AB), for which a causal time evolution in position space and momentum space is essential: Here statistical, non-deterministic particle interactions are most important, which can only be accounted for by following the time-evolution of the particle densities in space *and* energy-momentum. This approach allows to study the time evolution of an initially prepared beam/target collision system in complete phase-space from the instant of collisional contact, through the QCD-evolution of parton distributions, up to the formation of final hadronic states. It provides a self-consistent scheme to solve the underlying equations of motion for the particle densities as determined by the microscopic dynamics.

The model as a whole consists of four major building-blocks, which are illustrated schematically in Fig. 2:

1. The *initial state* associated with the incoming nuclei involves their decomposition into nucleons and of the nucleons into partons on the basis of the experimentally measured nucleon structure functions and elastic form-factors. This procedure translates the initial nucleus-nucleus system into two colliding clouds of *virtual* partons according to the well-established parton decpomposition of the nuclear wavefunctions at high energy [5].
2. The *parton cascade development* starts from the initial interpenetrating parton clouds, and involving the space-time development with mutual- and self-interactions of the system of quarks and gluons. Included are multiple elastic and inelastic interaction processes, described as sequences of elementary $2 \to 2$ scatterings, $1 \to 2$ emissions and $2 \to 1$ fusions. Moreover, correlations are accounted for between primary virtual partons, emerging as unscathed remainders from the initial state, and secondary real partons, materialized or produced through the partonic interactions.

3. The *hadronization dynamics* of the evolving system in terms of parton-coalescence to color-neutral clusters is described as a local, statistical process that depends on the spatial separation and color of nearest-neighbor partons. Each pre-hadronic parton-cluster fragments through isotropic two-body decay into primary hadrons, according to the density of states, followed by the decay of the latter into final stable hadrons.
4. The *'afterburner' hadron cascade* describes the evolution of produced pre-hadronic clusters and hadrons, emerging both from the hadronization of cascading partons, as well as from primary remnant partons which represent the fraction of unscathed initial state nucleons. Pre-hadronic clusters can mutually rescatter, or scatter off close-by hadrons, before they decay into stable final-state hadrons. Similarly, already formed hadrons may deflected by elestic collisions with other hadrons and clusters, or may be excited by inelastic collisions and resonance formation/decay.

Such a pragmatical division, which assumes complex interference between the different physics regimes to be negligible, is possible if the respective dynamical scales are such that the short-range (semi)hard parton interactions (scattering, radiation, fusion) of perturbative nature, and the non-perturbative mechanism of hadron formation (parton-coalescence and cluster-decay), occur on well-separated space-time scales (or momentum scales, by virtue of the uncertainty principle). Loosely speaking, the typical momentum scale associated with parton collisions, radiative emissions, or parton fusion, has to be larger than the inverse 'confinement length scale' $\sim 1\,fm$ which separates perturbative and non-perturbative domains. Further discussion of this condition of validity can be found in, e.g., [8, 17].

2.3 Equations of motion from quantum kinetics for multi-particle dynamics

A firm theoretical basis for the above space-time cascade description of a multiparticle system in high-energy collisions can be derived systematically from *quantum-kinetic theory* on the basis of QCD's first principles in a stepwise approximation scheme (see e.g., Refs. [1, 2] and references therein). This framework allows to cast the time evolution of the mixed system of individual partons, composite parton-clusters, and physical hadrons in terms of a closed set of integro-differential equations for the phase-space densities of the different particle excitations. The definition of these phase-space densities, denoted by F_α, where $\alpha \equiv p, c, h$ labels the species of partons, pre-hadronic clusters, or hadrons, respectively, is:

$$F_\alpha(r,k) \;\equiv\; F_\alpha(t,\vec{r};E,\vec{k}) \;=\; \frac{dN_\alpha}{d^3r d^3k dE}\,, \tag{1}$$

where $r \equiv r^\mu = (t, \vec{r})$, $k \equiv k^\mu = (E, \vec{k})$, and $k^2 = E^2 - \vec{k}^2$ can be off-shell (space-like $k^2 < m^2$, time-like $k^2 > m^2$) or on-shell ($k^2 = m^2$). The densities (1) measure the number of particles of type α at time t with position in $\vec{r} + d\vec{r}$, momentum in $\vec{k} + d\vec{k}$, and energy in $E + dE$ (or equivalently invariant mass in $k^2 + dk^2$). The F_α are the quantum analogues of the classical phase-space distributions, including both off-shell and on-shell particles, and hence contain the essential microscopic information required for a statistical description of the time evolution of a many-particle system in complete 7-dimensional phase-space d^3rd^3kdE, thereby providing the basis for calculating macroscopic observables.

The phase-space densities (1) are determined by the self-consistent solutions of a set of *transport equations* (in space-time) coupled with renormalization-group type *evolution equations* (in momentum space). Referring to Refs. [9, 1] for details, these equations can be generically expressed as convolutions of the densities F_α of particle species α, interacting with specific cross sections $\hat{I}_j$ for the processes j. The resulting coupled equations for the space-time development of the densities of partons F_p, clusters F_c and hadrons F_h is a self-consistent set in which the change of the densities F_α is governed by the balance of the various possible interaction processes among the particles. Fig. 3 represents these equations pictorially. For the densities of *partons*, the *transport equation* (governing the space-time change with r^μ) and the *evolution equation* (controlling the change with momentum scale k^μ), read, respectively,

$$\begin{aligned} k_\mu \frac{\partial}{\partial r^\mu} F_p(r,k) \;=\;& F_{p''}F_{p'''} \circ \left[\hat{I}(p''p''' \to pp') \,+\, \hat{I}(p''p''' \to p) \right] \,-\, F_pF_{p'} \circ \left[\hat{I}(pp' \to p''p''') \,+\, \hat{I}(pp' \to p'') \right] \\ &-\, F_pF_{p'} \circ \left[\hat{I}(p'p'' \to p) \,-\, \hat{I}(pp' \to p'') \right] \,-\, F_p F_{p'} \circ \hat{I}(pp' \to c) \end{aligned} \tag{2}$$

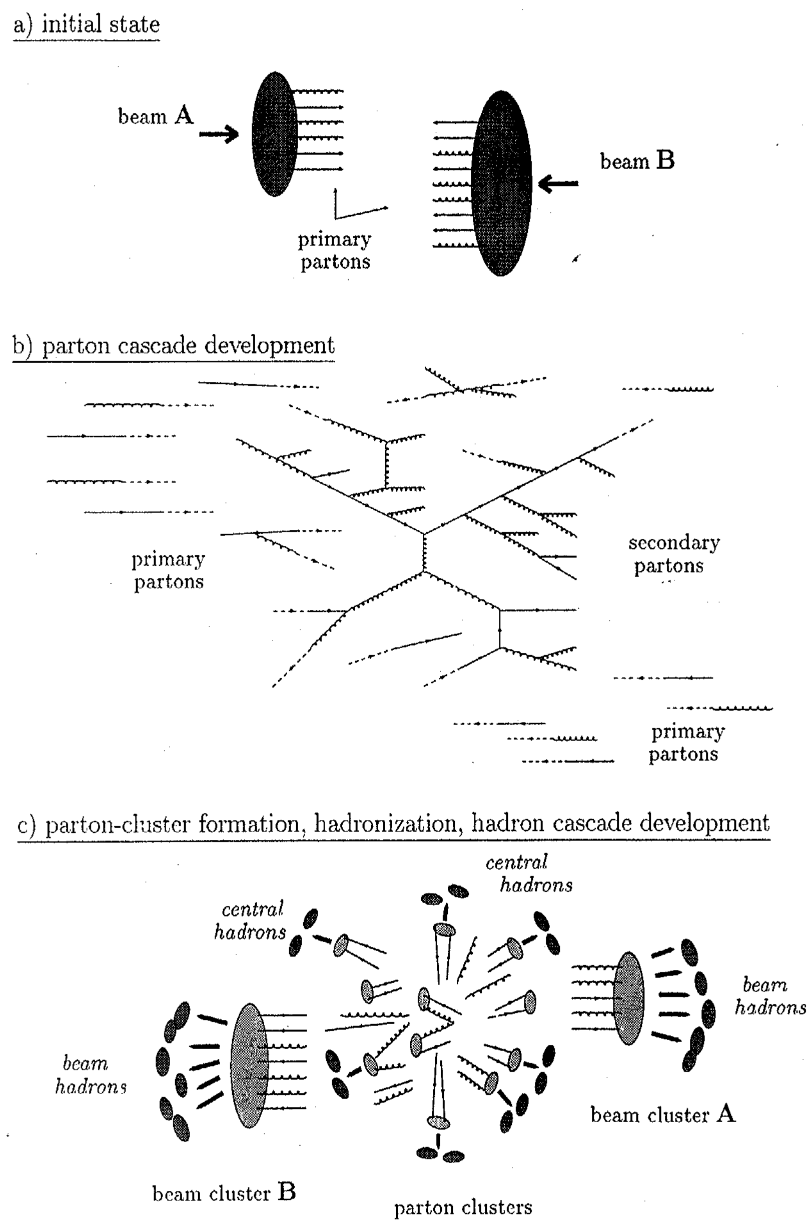

Figure 2: The four components of the model: a) the initial state constructed in terms of the parton distribution of the incoming nuclei; b) the time-evolution of parton cascades in 7-dimensional phase-space c) the formation of color neutral clusters from secondary partons emerging from cascading, as well of the remnant primary partons from the initial state, followed by the fragmentation of the clusters into final hadrons. d) the final-state hadron-cascade evolution 8f produced clusters and hadrons.

$$k^2 \frac{\partial}{\partial k^2} F_p(r,k) \;=\; F_{p'} \circ \hat{I}(p' \to pp'') \;-\; F_p \circ \hat{I}(p \to p'p'') \,. \tag{3}$$

For the densities of *pre-hadronic clusters* and *hadrons*, the evolution equations are homogeneous to good approximation, so that one is left with non-trivial transport equations only, [2] [3]. Hence, for the evolution of the cluster densities F_c, one has

$$\begin{aligned} k_\mu \frac{\partial}{\partial r^\mu} F_c(r,k) \;&=\; F_p F_{p'} \circ \hat{I}(pp' \to c) \;-\; F_c \circ \hat{I}(c \to h) \;+\; F_{c''} F_{c'''} \circ \hat{I}(c''c''' \to cc') \;-\; F_c F_{c'} \circ \hat{I}(cc' \to c''c''') \quad (4)\\ &\quad + F_{c'} F_{h'} \circ \hat{I}(c'h' \to ch) \;-\; F_c F_h \circ \hat{I}(ch \to c'h') \;+\; \ldots\ldots \\ k^2 \frac{\partial}{\partial k^2} F_c(r,k) \;&=\; 0\,, \end{aligned} \tag{5}$$

and similarly, for the evolution of the hadron densities F_h, the equations read (Fig. 3)

$$\begin{aligned} k_\mu \frac{\partial}{\partial r^\mu} F_h(r,k) \;&=\; F_c \circ \hat{I}(c \to h) \;+\; \left[F_{h'} \circ \hat{I}(h' \to h) \;-\; F_h \circ \hat{I}(h \to h') \right] \;+\; F_{h''} F_{h'''} \circ \hat{I}(h''h''' \to hh') \quad (6)\\ &\quad - F_h F_{h'} \circ \hat{I}(hh' \to h''h''') \;+\; F_{c'} F_{h'} \circ \hat{I}(c'h' \to ch) \;-\; F_c F_h \circ \hat{I}(ch \to c'h') \;+\; \ldots\ldots \\ k^2 \frac{\partial}{\partial k^2} F_h(r,k) \;&=\; 0\,. \end{aligned} \tag{7}$$

In (2)-(6), each convolution $F \circ \hat{I}$ of the density of particles F entering a particular vertex $\hat{I}$ includes a sum over contributing subprocesses, and a phase-space integration weighted with the associated subprocess probability distribution of the squared amplitude. Explicit expressions are given in Refs. [8, 9]. In (2)-

(6), each convolution $F \circ \hat{I}$ of the density of particles F entering a particular vertex $\hat{I}$ includes a sum over contributing subprocesses, and a phase-space integration weighted with the associated subprocess probability distribution of the squared amplitude. Explicit expressions are given in Refs. [8, 9].

As mentioned before, the equations (2)-(6) reflect a *probabilistic interpretation* of the multi-particle evolution in space-time and momentum space in terms of sequentially-ordered interaction processes j, in which the rate of change of the particle distributions F_α ($\alpha = p, c, h$) in a phase-space element $d^3r d^4k$ is governed by the balance of gain (+) and loss (−) terms. The left-hand side describes free propagation of a quantum of species α, whereas on the right-hand side the interaction kernels $\hat{I}$ are integral operators that incorporate the effects of the particles' self- and mutual interactions. This probabilistic character is essentially an effect of time dilation, because in any frame where the particles move close to the speed of light, the associated wave-packets are highly localized to short space-time extent, so that comparatively long-distance quantum interference effects are generally very small.

The terms on the right-hand side of the transport- and evolution-equations (2)-(6) correspond to one of the following categories (c.f. Fig. 3):

- parton scattering and parton fusion through 2-body collisions,
- parton multiplication through radiative emission processes on the perturbative level,
- colorless cluster formation through parton coalescence depending on the local color and spatial configuration,
- hadron formation by decay of the cluster excitations into final-state hadrons.

[2] It is worth noting that eq. (3) embodies the momentum space (k^2) evolution of partons through the renormalization of the phase-space densities F_p, determined by their change $k^2\partial F_p(r,k)/\partial k^2$ with respect to a variation of the mass (virtuality) scale k^2 in the usual QCD evolution framework [4, 15, 16]. On the other hand, for pre-hadronic clusters and hadrons, renormalization effects are comparatively small, so that their mass fluctuations $\Delta k^2/k^2$ can be ignored to first approximation, implying $k^2\partial F_c(r,k)/\partial k^2 = k^2\partial F_h(r,k)/\partial k^2 = 0$.

[3] It is worth noting that eq. (3) embodies the momentum space (k^2) evolution of partons through the renormalization of the phase-space densities F_p, determined by their change $k^2\partial F_p(r,k)/\partial k^2$ with respect to a variation of the mass (virtuality) scale k^2 in the usual QCD evolution framework [4, 15, 16]. approximation, implying $k^2\partial F_c(r,k)/\partial k^2 = k^2\partial F_h(r,k)/\partial k^2 = 0$.

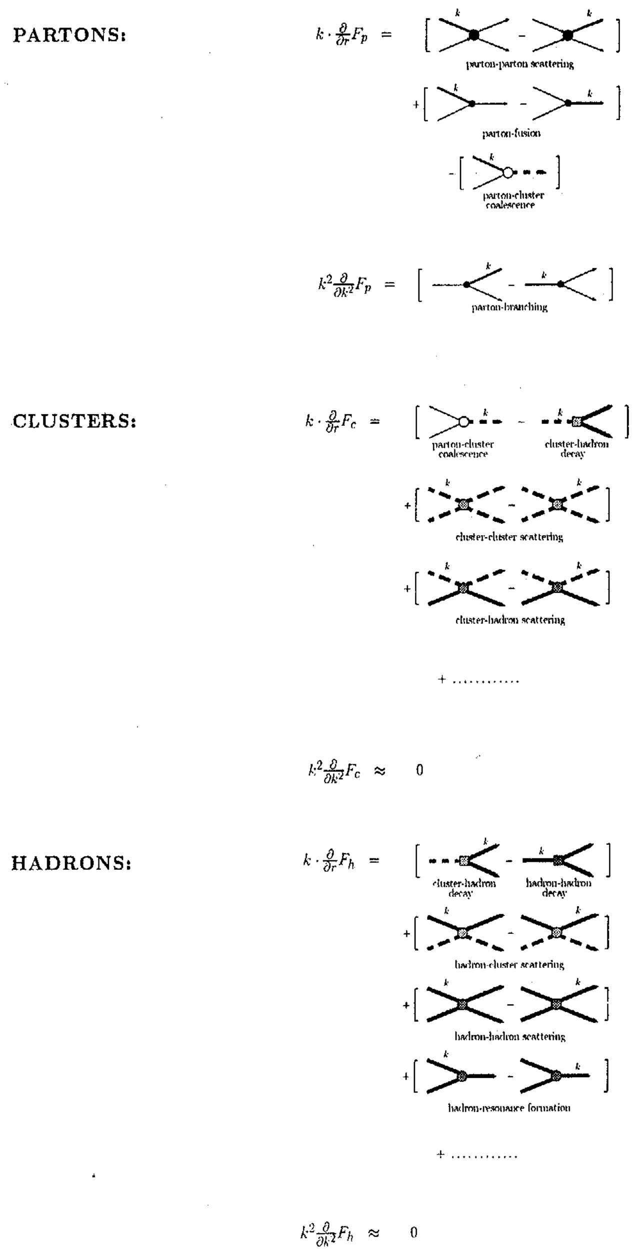

FIG. 3. Graphical representation of the equations (2)-(5) for the particle phase-space densities F_p of partons, F_c of pre-hadronic clusters, and F_h of hadrons. The 'dots' represent further processes not explicitely shown, such as cluster-hadron absorption, as well as inelastic collisions among clusters and hadrons.

- scattering of pre-hadronic clusters or already formed hadrons with other clusters or hadrons. Note: this includes also (as indicated by the 'dots') cluster-cluster fusion, cluster-hadron absorption, as well as inelastic collisions among clusters and hadrons, in which energy-momentum is transferred into excitation.

The equations (2)-(6) reflect a *probabilistic interpretation* of the multi-particle evolution in space-time and momentum space in terms of sequentially-ordered interaction processes j, in which the rate of change of the particle distributions F_α ($\alpha = p, c, h$) in a phase-space element $d^3r d^4k$ is governed by the balance of gain (+) and loss (−) terms. The left-hand side describes free propagation of a quantum of species α, whereas on the right-hand side the interaction kernels $\hat{I}$ are integral operators that incorporate the effects of the particles' self- and mutual interactions. This probabilistic character is essentially an effect of time dilation, because in any frame where the particles move close to the speed of light, the associated wave-packets are highly localized to short space-time extent, so that comparatively long-distance quantum interference effects are generally small for these short-distance interactions (however it does not mean they are unimportant for global particle dynamics such as collective behavior).

It is worth emphasizing that the model goes *beyond a purely classical cascade*! It incorporates a number of quantum mechanical features in the particle dynamics and production, for example:

- the inclusion of off-shell particles, which treats space-like or time-like particles as energy fluctuations with finite life-time given by the dedgee of virtuality $\propto 1/\sqrt{|k^2|}$;
- the feature of coherence in parton scatterings which relates momentum transfer and impact parameter of 2-body scatterings and restricts the possible momentum exchange to be consistent with the uncertainty relation;
- the concept of (angular ordered) coherent parton evolution including important gluon interference effects is used, which is well known to be an important non-classical property of soft (small-x) partons,
- particle scatterings and decays (both partonic and hadronic) are treated consistent with the uncertainty principle, by requiring a scattering/formation time before particles appear as incoherent quanta in the system;
- particles are produced *not* at a sharply localized point in space and momentum space (as it would be classically, but impossible quantum mechanically); rather their position and momentum at the production vertex is smeared with $\exp[-r^2/\sigma^2 - \sigma^2 p^2]$ (with $\sigma = 0.5 fm$ as inferred from Bose-Einstein data from e^+e^- collisions), a prescription which imposes again the uncertainty principle and guarantees $\Delta r \Delta p \gg \hbar$.

Therefore the particle's densities $F_a(r, k)$ are not just the classical phase-space densities (although they are just the number of countable particles per unit phase-space), but incorporate all the above *quantum mechanical features* implicitely. The space-time and energy integrated F_a are in fact observable quantities because after all what is seen in a detector are a particle distributions.

2.4 Scheme of solution in global Lorentz-frame of reference

In the above kinetic approach to the multi-particle dynamics, the probabilistic character of the transport- and evolution equations (2)-(6) allows one to solve for the phase-space densities $F_\alpha(r, k)$ by simulating the dynamical development as a Markovian process causally in time. Because it is an 'initial-value problem', one must specify some physically appropriate initial condition $F_\alpha(t_0, \vec{r}, k)$ at starting time t_0, such that all the dynamics prior to this point is effectively embodied in this initial form of F_α. The set of equations (2)-(6) can then be solved in terms of the evolution of the phase-space densities F_α for $t > t_0$ using Monte Carlo methods to simulate the time development of the mixed system of partons, clusters, and hadrons in position and momentum space [9, 8].

With the initial state specified as discussed below, the phase-space distribution of particles at $t = t_0 \equiv 0$ can be constructed and then evolved in small time steps $\Delta t = O(10^{-3}\ fm)$ forward throughout the parallely evolving stages of parton cascade, parton-cluster formation, and cluster-hadron decays, until stable final-state hadrons and other particles (photons, leptons, etc.) are left as freely-streaming particles. The partons propagate along classical trajectories until they interact, i.e., collide (scattering or fusion process), decay (emission process) or recombine to pre-hadronic composite states (cluster formation). Similarly, the so-formed pre-hadronic parton-clusters travel along classical paths until they convert into primary hadrons (cluster decay), followed by the hadronic decays into stable final state particles. The corresponding probabilities and time scales of interactions are sampled stochastically from the relevant probability distributions in the kernels $\hat{I}$ of eq. (2)-(6).

It is important to realize, that the spatial density and the momentum distribution of the particles are intimately connected: The momentum distribution continously changes through the interactions and determines how the quanta propagate in coordinate space. In turn, the probability for subsequent interactions depends on the resulting local particle density. Consequently, the development of the phase-space densities is a complex interplay, which - at a given point of time - contains implicitely the complete preceeding history of the system.

It is clear that the description of particle evolution is Lorentz-frame dependent, and a suitable reference frame (henceforth called *global frame*) must be chosen (not necessarily the laboratory frame of an experiment). When computing Lorentz-invariant quantities, such as cross sections or final-state hadron spectra, the particular choice is irrelevant, whereas for non-invariant observables, such as energy distibutions or space-time-dependent quantities, one must at the end transform from the arbitrarily-chosen frame of theoretical description to the actual frame of measurement.

For calculational convenience, it is most suitable to choose the *global center-of-mass (cm) frame of the colliding beam particles*, with the collision axis in the z-direction. In this global cm-frame, the incoming particles A, B (= lepton, hadron, or nucleus) have four-momenta,

$$
\begin{aligned}
P^\mu_{A,B} &= (E_{A,B}, 0, 0, \pm P_{cm}) \\
E_{A,B} &= \frac{1}{2\sqrt{s}}\left(s + M_A^2 \pm M_B^2\right) \qquad s = E_{cm}^2 = (P^\mu_A + P^\mu_B)^2 \\
P_{cm} &= \frac{1}{2\sqrt{s}}\sqrt{[s-(M_A+M_B)^2]\,[s-(M_A-M_B)^2]}\,,
\end{aligned}
\tag{8}
$$

where $M_{A,B}$ are the masses of A and B, and so incoming particles then carry well-defined fractions of P_{cm}, having only a non-vanishing longitudinal momentum along the z-axis. Particularly in the case of nuclei A, the daughter nucleons $N_i = 1, \ldots A$, have momenta, $\vec{P}_{N_i} = (0, 0, \pm P_{cm}/A)$.

In the following, the global cm-frame of A and B is assumed to be the reference frame, with the initial energy-momentum of the collision system given by (8). Furtermore the terms 'hadron', respectively 'nucleon', are used to distinguish initial states $A + B$ with A and/or B being a single hadron, respectively a nucleus with A (B) nucleons.

2.5 Initial state

If one or both beam particles A, B are leptons, they are considered as point-like objects which carry the full beam energy, meaning that any QED or QCD substructure of the leptons, as well as initial-state photon radiation by the leptons, is neglected. For *lepton-lepton annihilation*, it is assumed that the colliding leptons produce a time-like γ or Z^0 boson of invariant mass $Q^2 \equiv +q^2$ at time $t = -Q^{-1}$, so that $t = 0$ characterizes the point when the γ (Z^0) decays into a quark-antiquark pair. Similarly, for *lepton-hadron (nucleus) collisions*, the lepton is emitting a space-like virtual γ of invariant mass $Q^2 \equiv -q^2$ at time $t = -Q^{-1}$, and hence $t = 0$ is the point when the γ hits the hadron (nucleus).

In the general case of *collisions involving hadrons and/or nuclei*, the incoming particles A and B are decomposed into their parton substructure by phenomenological construction of the momentum and spatial distributions of their daughter partons on the basis of the known hadron (nucleon) structure functions and elastic hadron (nucleon) form-factors. In the cm-frame, where the two incoming particles A, B (= hadron, nucleus), are moving close to the speed of light, the parton picture is applicable and the parton substructure of the hadrons or nucleons can be resolved with reference to some *initial resolution scale* Q_0. This resolution scale generally varies with beam-energy and mass number A, B, in that it depends on the typical momentum and spatial density of partons as well as on their interaction probability. To be specific, it may be identified with the statistically estimated expectation value for the interaction scale Q^2 of all *primary* parton-parton collisions (that are those in which at least one initial state parton is involved) [18]:

$$
Q_0^2 \;\equiv\; Q_0^2(x, P, A) \;=\; A^\alpha \left(\frac{1}{\langle p_\perp^2 \rangle_{prim}} + \frac{\langle p_\perp^2 \rangle_{prim} R_0^2}{2xP} \right)^{-1}, \tag{9}
$$

where $\langle p_\perp^2 \rangle_{prim}$ is the average relative transverse momentum squared generated by primary parton-parton collisions. and $R_0 = 1GeV^{-1}$. The pre-factor A^α ($0 \leq \alpha \leq 4/3$ a parameter) accounts for the nuclear dependence for $A, B > 1$, and x is the parton's momentum fraction of the mother hadron or nucleon which carries momentum P ($= P_{cm}$ for single hadron, or $= P_{cm}/A$ for a nucleon in a nucleus A). The scale Q_0 defines the initial point in momentum space above which the system of partons is treated as an ensemble of incoherent quanta. The dynamics prior to this point is contained in the initial parton-structure function of the mother hadron (nucleon). Clearly, the convention (9) yields only an average value dominated by the most probable (semi)hard parton collisions with relatively small momentum transfers of a few GeV. However, primary parton collisions with a momentum scale $Q^2 \gg Q_0^2$, which correspond to relatively rare fluctuations, are taken into account individually by the Q^2-evolution of the hadron (nucleon) structure functions through space-like and time-like radiation processes, discussed later.

The actual form of the phase-space distribution of partons, eq. (1) is initially to be specified at the reference point Q_0. It is constructed as the following superposition of the parton distributions in the individual hadrons at Q_0 and at time $t = t_0 \equiv 0$, the point of collision of A and B:

$$
F_a(r, k)\big|_{r^0 = t_0} \;=\; \sum_{i=1}^{N_h} P_a^{N_i}(k, \vec{P}; Q_0^2) \cdot R_a^{N_i}(k, \vec{r}, \vec{R})\,\Big|_{r^0 = t_0} . \tag{10}
$$

The right hand side is a sum over all $1 \leq N_i \leq N_h$ hadrons or nucleons contained in the collision system $A+B$. Each term in the sum is a parton phase-space density given by a convolution of an initial momentum distribution $P_a^{N_i}$ and a spatial distribution $R_a^{N_i}$. The subscript $a = g, q_j, \bar{q}_j$ ($j = 1, \ldots, n_f$) labels the species of partons, and N_i refers to the type of the i-th hadron (for nuclei this is just proton or neutron). The four-vectors $k \equiv k^\mu = (E, \vec{k})$ and $r \equiv r^\mu = (t, \vec{r})$ refer to the partons. The 3-momenta and initial positions of the hadrons or nucleons are denoted $\vec{P}$, respectively $\vec{R}$. All vectors are understood with respect to the global cm-frame, at time $t = t_0 = 0$. The partons' energies $E \equiv E_a(\vec{k}^2, q^2) = \sqrt{\vec{k}^2 + m_a^2 + q^2}$ take into account their initial space-like virtualities $q^2 < 0$ which are distributed around $\langle |q^2| \rangle = -Q_0^2/4$, under the constraint that for each hadron in the initial state, the total invariant mass of the daughter partons must equal the mother hadron mass. This mimics the fact that the initial partons are confined inside their parent hadrons or nucleons and cannot be treated as free particles, i.e. they have not enough energy to be on mass shell, but are off mass shell by a space-like virtuality q^2 (eq. (16) below).

As suggestively illustrated in Fig. 2 and discussed in more detail now, the initial state $A + B$ involving hadrons and/or nuclei, appears in the global cm-frame as two approaching 'tidal waves' of large-x partons (mainly valence quarks), where each 'tidal wave' has an extended tail of low$-x$ partons (mostly gluons and sea-quarks).

2.5.1 Initial momentum distribution

For each hadron or nucleon the number of partons, the distribution of the flavors, their momenta and associated initial space-like virtualities, are obtained from the function $P_a^{N_i}$ in (10). Denoting $P \equiv P_{cm}/N_h$, with N_h the total number of hadrons (nucleons) in $A + B$, it is represented in the form

$$
P_a^{N_i}(k, \vec{P}; Q_0^2) \;=\; \left(\frac{x}{\bar{x}}\right) F_a^{N_i}(x, Q_0^2)\; \rho_a^A(x)\; g(\vec{k}_\perp)\; \delta(P_z - P)\; \delta^2\left(\vec{P}_\perp\right) \tag{11}
$$

with the momentum and energy fractions $x = k_z/P$, $\tilde{x} = E/P = \sqrt{x^2 + (k_\perp^2 + m_a^2 + q^2)/P^2}$ and the normalizations

$$\sum_a \int_0^1 dx\, x F_a^{N_i}(x, Q_0^2) \;=\; 1\,, \qquad \int_0^\infty d^2k_\perp\, g(\vec{k}_\perp) \;=\; 1 \tag{12}$$

$$\sum_a \int \frac{dk^2\, d^3k}{(2\pi)^3 2E}\; E\, P_a^{N_i}(k^2, \vec{k}, \vec{P}; Q_0^2) \;=\; n^{N_i}(Q_0^2, \vec{P})\;. \tag{13}$$

The physics behind the ansatz (11) is the following:

(i) The functions $F_a^{N_i}(x, Q_0^2)$ are the scale-dependent measured hadron (nucleon) structure functions with x being the fraction of the parent hadron's or nucleon's longitudinal momentum P carried by the parton. The transverse momentum distribution $g(k_\perp)$ is specified below. The factor $x/\tilde{x}$ in (12) is included to form the invariant momentum integral $\int d^3k/[(2\pi)^3 2E]$ out of the distribution $P_a^{N_i}$ [19]. In (13) the quantity n^{N_i} is the total number of partons in a given nucleon with momentum $P = |\vec{P}|$ at Q_0^2.

(ii) The function $\rho_a^A(x)$ in (11) takes into account nuclear shadowing effects affecting mainly soft (small x) partons in a nucleus [4]. These shadowing effects are evident in the observations of the European Muon Collaboration [20] as a depletion of the nuclear structure functions at small x relative to those of a free nucleon. Several mechanisms have been proposed to explain this nuclear shadowing effect on the basis of the parton model [21, 22, 23]. However, here instead the phenomenological approach of Wang and Gyulassy [24] is adopted which is based on the following parametrization [23] for the A dependence of the shadowing for both quarks and gluons:

$$\rho_a^A(x) \;\equiv\; \frac{F_a^{A,N_i}(x, Q_0^2)}{A\, F_a^{N_i}(x, Q_0^2)} \;=\; 1 + 1.19\left(\ln A\right)^{1/6}\left[x^3 - 1.5(x_0 + x_L)x^2 + 3x_0 x_L x\right] \tag{14}$$
$$- \left[\beta_A(R_\perp) - \frac{1.08\,(A^{1/3} - 1)}{\ln(A+1)}\sqrt{x}\right] \exp(-x^2/x_0^2)\;.$$

where $F_a^{A,N}$ and F_a^N represent the structure function of a nucleus A, respectively those of a free nucleon, and $x_0 = 0.1$, $x_L = 0.7$. The function $\beta_A(r) = 0.1\left(A^{1/3} - 1\right)\frac{4}{3}\sqrt{1 - \frac{R_\perp^2}{R_A^2}}$ takes into account the impact parameter dependence, with $R_\perp$ labeling the transverse distance of a nucleon from its nucleus center and R_A the radius of the nucleus.

(iii) The distribution $g(k_\perp)$ specifies the primordial transverse momenta of partons according to a normalized Gaussian

$$g(\vec{k}_\perp) \;=\; \frac{1}{2\pi k_0^2} \exp\left[-\frac{|\vec{k}_\perp|^2}{k_0^2}\right]\,, \tag{15}$$

independent of the type of parton or hadron (nucleon). It takes into account the uncertainty of momentum (Fermi motion) due to the fact that the initial partons are confined within the nucleons. This intrinsic $k_\perp$ can be observed in Drell-Yan experiments where it is found that the distribution is roughly independent of s and Q^2 [25]. As inferred from these analyses, the width in (15) is $k_0 = 0.42$ GeV, *corresponding to a mean* $\langle k_\perp \rangle \approx 0.38$ GeV.

The scheme (i)-(iii) to sample the flavor and momentum distribution is carried out independently for each nucleon subject to the requirement

$$\left(\sum_i E_i\right)^2 - \left(\sum_i k_{x_i}\right) - \left(\sum_i k_{y_i}\right)^2 - \left(\sum_i k_{z_i}\right)^2 \;=\; M_h^2 \tag{16}$$

where the summation runs over all partons belonging to the same nucleon as determined by (12) and (13), and M_h is the mother hadron (nucleon) mass. With the partons' 4-momenta distributed as outlined above, the constraint (16) determines the distribution in the variable $q^2 = k^2 - m_a^2 = E^2 - \vec{k}^2 - m_a^2 < 0$, the partons' initial space-like virtualities. The resulting distribution in q^2 is a strongly peaked Gaussian with a mean value of $\approx Q_0^2/4$.

[4] This feature is optional in the simulation, by default it is switched off.

2.5.2 Initial spatial distribution

The initial spatial distribution of the partons, $R_a^{N_i}$, appearing in eq. (10), depends on the magnitude of their momenta, the positions of their parent hadrons (nucleons), as well as on the spatial substructure of the latter. It is represented as

$$R_a^{N_i}(\vec{p}, \vec{r}, \vec{R}) \;=\; \delta^3\left(\vec{R} - \vec{R}_{AB}\right)\left[h_a^{N_i}(\vec{r})\; H_{N_i}(\vec{R})\right]_{boosted}\,, \tag{17}$$

where the momentum dependence is here purely due to boosting the distributions to the global *cm*-frame. The components of the ansatz (17) have the following meaning:

(i) The incoming beam particles (a single hadron, or a nucleus) are assumed to have initial *cm*-positions $\vec{R}_{AB} = (\pm\Delta Z_{AB}/2, \vec{B}_{AB})$, corresponding to a chosen impact parameter $\vec{B}_{AB} = (B_x, B_y)$ and a minimum longitudinal separation ΔZ_{AB}. In the case where A and/or B is not a single hadron, but a nucleus, the individual nucleons are assigned positions around the centers of the parent nucleus in its rest-frame, according to a Fermi distribution for nuclei with mass number $A \geq 12$ and a Gaussian distribution for nuclei $A < 12$,

$$H_{N_i}(\vec{R}) \;=\; \begin{cases} \frac{1}{4\pi}\left(1 + \exp\left[(R - c)/a\right]\right)^{-1} & (A \geq 12) \\ \frac{1}{4\pi}\frac{2}{\sqrt{\pi b}}\exp\left[-R^2/b^2\right] & (A < 12) \end{cases}\;. \tag{18}$$

The parameters are $c = r_0 A^{1/3}$, $r_0 = 1.14\ fm$, $a = 0.545\ fm$ and $b = \sqrt{2/3}\, R_A^{ms}$, where R_A^{ms} is the mean square radius of the nucleus.

(ii) Next, the partons are distributed around the centers of their mother hadrons or nucleons, still in the rest frame of the A, respectively B, with an exponential distribution

$$h_a^{N_i}(\vec{r}) \;=\; \frac{1}{4\pi}\frac{\nu^3}{8\pi}\exp\left[-\nu r\right]\,, \tag{19}$$

where $\nu = 0.84$ GeV corresponds to the measured elastic formfactor of the mother hadron or nucleon, with a mean square radius of $R_h^{ms} \equiv \sqrt{12/\nu} = 0.81\ fm$.

(iii) Finally, as indicated by the subscript *boosted* in eq. (17), the positions of the hadrons or nucleons and their associated valence quarks are boosted into the global *cm*-frame of the colliding beam particles A and B. The valence quarks then occupy the Lorentz contracted region $(\Delta z)_v \approx 2R_A\, M_h/P$, whereas the sea quarks and gluons are smeared out in the longitudinal direction by an amount $(\Delta z)_{g,s} \approx 1/k_z < 2R_A$ ($R_A = r_0 A^{1/3}$) *behind* the valence quarks. This is an important feature of the partons when boosting a hadron or nucleus to high rapidities [26, 27, 28]. As a consequence, the parton positions are correlated in longitudinal direction with their momenta, as required by the uncertainty principle. *This leads to an enhancement of the densities of gluons and sea quarks with* $x < 1/(2R_h M_h)$ proportional to $A^{1/3}$, because such partons from different nucleons overlap spatially when the nucleons are at the same impact parameter.

2.6 Parton cascade development

With the above construction of the initial state, the incoming beam particles A and B are decomposed in *their associated parton content at the initial resolution scale* Q_0^2 at time $t = t_0 \equiv 0$, and the subsequent dynamical development of the system for $t > t_0$ can now be traced according to the kinetic equations (2)-(6). In the kinetic approach, the space-time evolution of parton densities may be described in terms of

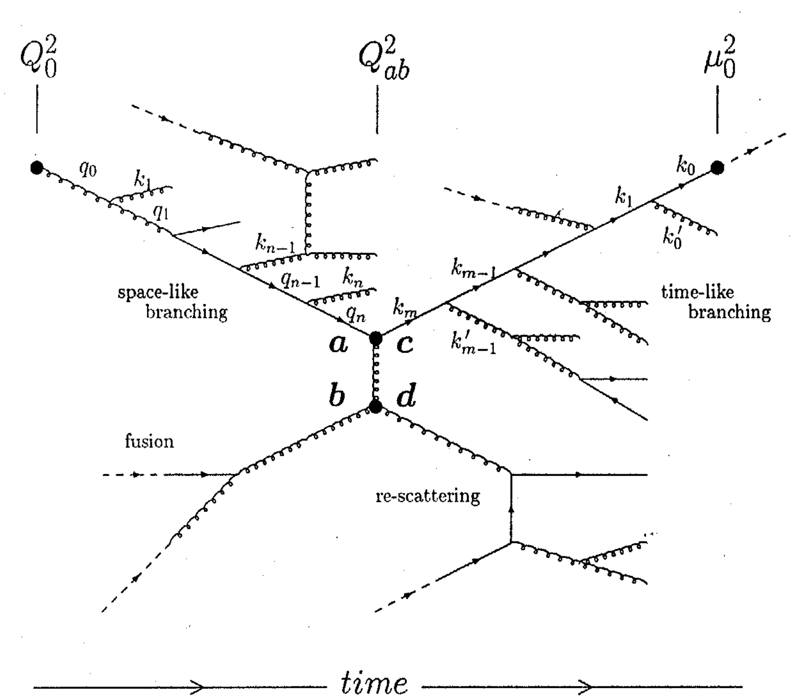

Figure 3: Schematical illustration of a typical parton cascade development initiated by a collision of two partons a and b. The incoming primary parton a evolves through a space-like cascade from the initial resolution scale Q_0^2 up to the scale Q_{ab}^2 at which it collides with parton b. The outgoing partons c and d both initiate time-like cascades which are described as a combination of multiple branchings (or emissions), fusions (or absorptions), or secondary scatterings (or rescatterings). A particular branch in a cascade tree terminates (locally in space-time), when the partons in that branch recombine with neighboring ones to pre-hadronic clusters and their subsequent decay into hadrons.

parton cascades. Fig. 4 illustrates a typical parton cascade sequence. It is important to realize that, in general, there can be many such cascade sequences, being internetted and simultanously evolving (typical for hadron-nucleus or nucleus-nucleus collisions).

Each cascade can be subdivided into elementary $2 \to 2$ scatterings, $1 \to 2$ branchings (emissions), and $2 \to 1$ fusions (absorptions). In Fig. 4, a primary parton a that originates from one of the incident nuclei, collides with another parton b with some momentum transfer characterized by the scale Q_{ab}^2 at the collision vertex. The parton a has evolved from the initial scale Q_0^2, at which it was resolved in its parent hadron or nucleus, up to Q_{ab}^2 by successive space-like branchings. From the scattering of a and b the partons c and d emerge, both of which can initiate sequences of time-like branchings. These newly produced partons can themselves branch, rescatter, or undergo fusion with other partons.

In practice the dynamical interplay of $2 \to 2$, $2 \to 1$ and $1 \to 2$ processes can be simulated as follows: Since the time evolution of the parton system is described in small discrete time steps $\Delta t = O(10^{-3} fm)$, the time scale of an interaction process is compared with Δt to decide whether the interaction occurs within this time interval. A virtual parton e^* with momentum k^μ, $k^2 \neq 0$, that is produced via $a + b \to e^*$, has a short life-time $\tau_{e^*} \propto 1/\sqrt{|k^2|}$, if its invariant mass $|k^2|$ is large and it is likely to decay within $\gamma\tau_{e^*} < \Delta t$ (the full formulae are derived in [29]). Therefore, the $2 \to 2$ process $a + b \to e^* \to c + d$ preferably occurs. On the other hand, if $|k^2|$ is small, corresponding to a long τ_{e^*}, parton e^* is likely not to decay within the time step Δt and the fusion process $a + b \to e^*$ rather happens. In this case, e^* propagates as a quasi-stable particle until in the following time step it has an increased decay probability [29]. This may then result in the $1 \to 2$ decay $e^* \to c + d$. Alternatively, e^* might collide with another parton before its decay or may propagate freely until the following time step, and so on. In this manner the elementary $2 \to 2$, $2 \to 1$, and $1 \to 2$ processes are treated on equal footing and double counting is prevented: either a $2 \to 2$, or a $2 \to 1$, and possibly a subsequent $1 \to 2$ process can occur, but not both. The relative probability is determined by the uncertainty principle, i.e. by relating the momentum scale of the process to the time scale as explained.

For the collisional processes $2 \to 2$ and $2 \to 1$, the statistical occurence is determined by the 2-body cross-section in Born apprpoximation, with higher-order inelastic corrections effectively included in the parton evolution before and after each collision. This parton-evolution is calculated using the well-known jet calculus [15, 16] based on the 'modified leading logarithmic approximation' (MLLA) to the QCD evolution of hard processes [17, 30]. Each individual parton-collision factorizes then in an elementary 2-body collision, in which the in- and out-going partons undergo an ordered sequence of elementary branchings $a \to b + c$, accounting for higher-order radiative corrections to the lowest-order Born approximation. These branchingss can be described stochastically as a Markov cascade in position and momentum space. One distinguishes initial-state, *space-like* branchings of the two partons entering a collision vertex, and final-state, *time-like* radiation off the collided partons after the collision.

The specific feature of the present approach is that, in addition to the definite virtuality and momentum, each elementary vertex has a certain space and time position which is obtained by assuming that the partons in the cascade propagate on straight-line trajectories in between their interactions. In the MLLA framework, the basic properties of both space-like and time-like showers are determined by the DGLAP equations [31], but with essential differences in time ordering, kinematics and the treatment of infrared singularities associated with soft gluon emission.

2.6.1 Elementary parton-parton collisions

For the elementary parton scatterings $a + b \to c + d$, and fusion processes $a + b \to c^*$, two distinct classes of processes are considered:

(i) truly perturbative QCD *hard* parton collisions with a sufficiently large momentum transfer $p_\perp^2$ or invariant mass $\hat{s}$;

(ii) phenomenological treatment of *soft* parton collisions [5] with low momentum transfer $p_\perp^2$ or invariant mass $\hat{s}$.

The motivation for this differentiation of parton-parton collisions is to regulate the singular behavior of the collision integrals in (2) which results from the divergence of the associated Born-amplitudes squared

[5] The inclusion of soft parton collisions is optional in the program, and by default is switched off.

for small momentum transfers Q^2 (except for $\hat{s}$ channel processes such as $q\bar{q}$ annihilation). To render the parton-parton cross-sections finite, an invariant *hard-soft division scale* p_0^2 is introduced such that collisions occurring at a momentum scale $Q^2 \geq p_0^2$ are treated as perturbative (semi)hard collisions, whereas for those with $Q^2 < p_0^2$ a soft, non-perturbative interaction is assumed to occur. That is, the total parton-parton cross-section for a collision between two partons a and b is represented as

$$\hat{\sigma}_{ab}(\hat{s}) = \sum_{c,(d)} \left\{ \int_0^{p_0^2} dQ^2 \left(\frac{d\hat{\sigma}^{soft}_{ab\to c(d)}}{dQ^2} \right) + \int_{p_0^2}^{\hat{s}} dQ^2 \left(\frac{d\hat{\sigma}^{hard}_{ab\to c(d)}}{dQ^2} \right) \right\} , \tag{20}$$

where

$$Q^2 \equiv Q^2(\hat{s},\hat{t},\hat{u}) = \begin{cases} p_\perp^2 \simeq -\hat{t}(-\hat{u}) & \text{for } \hat{t}(\hat{u}) \text{ channel} \\ m^2 = \hat{s} & \text{for } \hat{s} \text{ channel} \end{cases} \tag{21}$$

$$\hat{s} = (p_a + p_b)^2 \quad , \quad \hat{t} = (p_a - p_c)^2 , \quad \hat{u} = (p_a - p_d)^2 \tag{22}$$

That is, the scale Q^2 of the collision is set by $p_\perp^2$ for scatterings $a+b \to a+b$, or by $\hat{s}$ for annihilation processes and $a+b \to c+d$ and fusion processes $a+b \to c$. The sum over c, (d) corresponds to summing over all possible reaction channels (processes). The specific value of p_0 is generally dependent on beam energy $E_{cm} = (P_A + P_B)^2$ of colliding hadrons (nuclei) $A+B$, as well as on the mass numbers A and B. It is treated as a parameter that is determined by existing experimental data. A suitable form is

$$p_0 \equiv p_0(E_{cm}, A, B) = \frac{a}{4} \left(\frac{2E_{cm}/\text{GeV}}{A+B} \right)^b \qquad (a = 2.0 \text{ GeV}, \quad b = 0.27) . \tag{23}$$

The complementation of both hard and soft contributions renders the parton cross-section finite and well defined for *all* Q^2. It must be emphasized that the effect of soft parton collisions on the global dynamics is not essential for collisions involving only leptons and/or hadrons, but plays an important role in hadron-nucleus, or nucleus-nucleus collions. The soft parton collisions naturally involve comparably small momentum transfer, so that their contribution to transverse energy production is small, but the effect on soft particle production is significant.

In accord with the two-component structure of the cross-section (20), these parton collisions are distinguished depending on the momentum transfer:

(i) **Hard collisions above p_0:**

For the *perturbative (semi)hard collisions* above p_0, the momentum scale Q^2 is determined by the corresponding differential cross-sections

$$\frac{d\hat{\sigma}^{hard}_{ab\to cd}}{dQ^2} = \frac{1}{16\pi\hat{s}^2} \left| \overline{M}_{ab\to cd} \right|^2 (\hat{s}, Q^2) \propto \frac{\pi\alpha_s^2(Q^2)}{Q^2} , \tag{24}$$

where $|\overline{M}|^2$ is the process-dependent spin- and color-averaged squared matrix element in Born approximation, published in the literature (see e.g. Refs. [32] and for massive quarks Refs. [33]).

(ii) **Soft collisions below p_0:**

In the case of a non-perturbative soft collision between two partons it is assumed that a very low energy double gluon exchange occurs. This provides a natural continuation to the harder collisions above p_0 where the dominant one gluon exchange processes $gg \to gg$, $gq \to gq$ and $qq \to qq$ have the same overall structure [34]. A simple, and physically plausible, form for the soft cross-section that continues the hard cross-section for Q^2 below p_0 down to $Q^2 = 0$, may be modelled by introducing a screening mass-term μ^2 in the nominator of (24),

$$\frac{d\hat{\sigma}^{soft}_{ab\to cd}}{dQ^2} \propto \frac{2\pi\alpha_s^2(p_0^2)}{Q^2 + \mu^2} \tag{25}$$

where μ is a phenomenological parameter that governs the overall magnitude of the integrated $\sigma^{soft} \propto \ln[(p_0^2 + \mu^2)/\mu^2]$. The value of μ is not known precisely, but it can be estimated to be in the range 0.3 - 1 GeV.

Notice that both hard and soft scatterings are treated in this approach on completely equal footing. That is, with the four momenta of the incoming partons known, the momentum transfer and scattering angle are sampled from the respective differential cross-sections $d\hat{\sigma}/d\hat{t}$ (24) and (25), assuming azimuthal symmetry of the scattering geometry.

2.6.2 Space-like parton evolution

Space-like parton cascades are associated with QCD radiative corrections due to brems-strahlung emitted by primary space-like partons, which are contained in the initial state hadrons (nuclei), and which encounter their very first collision. Thereby such a primary, virtual parton is struck out of the coherent hadron (nucleus) wavefunction to materialize to a real excitation. A typical space-like cascade is illustrated in the left part of Fig. 4, where the parton a_0, originating from the initial hadron (nucleus) state, undergoes successive space-like branchings $a_0 \to a_1 a_1'$, $a_1 \to a_2 a_2'$, ..., $a_{n-1} \to a_n a_n'$ to become the parton $a \equiv a_n$ which then actually collides with another parton b. The branching chain proceeds by increasing the virtualities $|q_i^2|$ of the partons a_i in the cascade, starting from a_0 with $|q_0^2| \simeq Q_0^2/4$ up to $|q^2| \simeq Q^2$ the space-like virtuality of the scattering parton a, where $Q^2 \equiv Q^2_{ab}$ sets the scale of the collision between partons a and b, and hence for the evolution from Q_0^2 to Q^2. The emitted partons a_i' on the side branches with momenta k_i on the other hand have, due to energy-momentum conservation at the branching vertices, time-like virtualities and each of them can initiate a time-like cascade, discussed afterwards.

The proper inclusion of both collinear, hard and coherent, soft branchings is achieved by describing the space-like cascade in both space-time *and* momentum space by using a so-called *angular-ordered* evolution variable $\tilde{q}_j^2$ (rather than the virtualities $|q_j^2|$) [35]

$$\tilde{q}_j^2 \equiv E_j^2 \, \zeta_{j+1} , \qquad \zeta_{j+1} = \frac{q_0 \cdot k_{j+1}}{\omega_0 \, E_{j+1}} \simeq 1 - \cos\theta_{0,\,j+1} \qquad (0 \leq j \leq n) , \tag{26}$$

where $q_j = (\omega_j, \vec{q}_j)$ and $k_{j+1} = (E_{j+1}, \vec{k}_{j+1})$ refer to the j^{th} branching $a_j \to a_{j+1} a_{j+1}'$ with momentum assignment $q_j \to q_{j+1} k_{j+1}$ (see Fig. 4). The space-like cascade is then strictly ordered in the variable $\tilde{q}_{j+1}^2 > \tilde{q}_j^2$, which is equivalent to the ordering of emission angles, $\omega_j \theta_{0,\,j+1'} < \omega_{j+1} \theta_{0,\,j+2'}$.

The space-like cascade terminates with parton $a_n \equiv a$ entering the vertex of collision with parton b, that is, Q^2_{ab} in Fig. 4. The history of parton a is however not known until after it has collided with parton b, because it is this very collision that causes the cascade evolution of parton a. Therefore one must reconstruct the cascade *backwards* in time starting from the time of the collisions at the vertex Q^2_{ab} and trace the history of the struck parton a back to the initial state at time $t_0 = 0$ at which it was originally resolved with Q_0^2 in its hadron (nucleon) mother. The method used here is a space-time generalization of the 'backward evolution scheme' [36]. To sketch the procedure, consider the space-like branching $q_{n-1} \to q_n k_n$ which is closest to the collision vertex Q^2_{ab} in Fig. 4. The virtualities satisfy [16] $|q_n^2| > |q_{n-1}^2|$, and $q_n^2, q_{n-1}^2 < 0$ (space-like) but $k_n^2 > 0$ (time-like). The relative probability for a branching to occur between $\tilde{q}^2$ and $\tilde{q}^2 + d\tilde{q}^2$ is given by

$$d\mathcal{P}^{(S)}_{n-1,n}(x_{n-1}, x_n, \tilde{q}^2; \Delta t) = \frac{d\tilde{q}^2}{\tilde{q}^2} \frac{dz}{z} \frac{\alpha_s((1-z)\tilde{q}^2)}{2\pi} \gamma_{n-1\to nn'}(z) \left(\frac{F(r_{n-1}; x_{n-1}, \tilde{q}^2)}{F(r_n; x_n, \tilde{q}^2)} \right) \mathcal{T}^{(S)}(\Delta t) , \tag{27}$$

where $x_j = (q_j)_z / P_z$ $(j = n, n-1)$ are the fractions of longitudinal momentum P_z of the initial mother hadron (nucleon), with $F(r_j; x_j, \tilde{q}^2) \equiv F(r_j, q_j)$ the corresponding parton distributions defined by (1), and the variables

$$z = \frac{E_n}{E_{n-1}} \simeq \frac{x_n}{x_{n-1}} , \qquad 1 - z = \frac{E_n'}{E_{n-1}} \simeq \frac{x_{n-1} - x_n}{x_{n-1}} \tag{28}$$

specify the fractional energy or longitudinal momentum of parton n and n', respectively, taken away from $n-1$. The function $\alpha_s/(2\pi)\,\gamma(z)$ is the usual DGLAP branching probability [4, 17], with $\gamma(z)$ giving the energy distribution in the variable z. The last factor $\mathcal{T}^{(S)}(\Delta t)$ in (27) determines the time interval in the global *cm*-frame, $\Delta t = t_n - t_{n-1}$, that is associated with the branching process $a_{n-1} \to a_n a_n'$. It accounts for the formation time of a_n from a_{n-1} on the basis of the uncertainty principle: $\Delta t = \Delta\omega / |q_n^2|$, $\Delta\omega \simeq (x_n - x_{n-1}) P_z$. A very simple form is taken here,

$$\mathcal{T}^{(S)}(\Delta t) = \delta\left(\frac{x_n - x_{n-1}}{|q_n^2|} P_z - \Delta t \right) . \tag{29}$$

The backwards evolution of the space-like branching $q_{n-1} \to q_n + k_n$ is expressed in terms of the probability that parton a_{n-1} did *not* branch between the lower bound $\tilde{q}_0^2$, given by the initial resolution scale Q_0^2, and $\tilde{q}_n^2 \equiv \tilde{q}^2 \simeq Q_{ab}^2$. In that case, parton n can *not* originate from this branching, but must have been produced otherwise or already been present in the initial parton distributions. This non-branching probability is given by the *Sudakov form-factor for space-like branchings*:

$$S_n(x_n, \tilde{q}^2, \tilde{q}_0^2; \Delta t) \;=\; \exp\left\{ - \sum_a \int_{\tilde{q}_0^2}^{\tilde{q}^2} \int_{z_-(\tilde{q}')}^{z_+(\tilde{q}')} d\mathcal{P}^{(S)}_{n,n-1}(x_n, z, \tilde{q}'^2; \Delta t) \right\} , \tag{30}$$

where the sum runs over the possible species $a = g, q, \bar{q}$ of parton a_{n-1}. The upper limit of the $\tilde{p}^2$-integration is set by $\tilde{q}^2 \lesssim Q_{ab}^2$, associated with the collision vertex with parton b. The limits $z_\pm$ are determined by kinematics [35]: $z_-(\tilde{q}) = Q_0/\tilde{q}$ and $z_+(\tilde{q}) = 1 - Q_0/\tilde{q}$.

The knowledge of the space-like formfactor $S_n(x_n, \tilde{q}^2, \tilde{q}_0^2; \Delta t)$ is enough to trace the evolution of the branching closest to the hard vertex backwards from q_n^2 at $t = t_n$, the time of collision in the global *cm*-frame, q_{n-1}^2 at $t_{n-1} = t_n - x_n/|q_n^2| P_z$. The next preceding branchings $q_{n-2} \to q_{n-1}k_{n-1}$, etc., are then reconstructed in exactly the same manner with the replacements $t_n \to t_{n-1}$, $x_n \to x_{n-1}$, $q_n^2 \to q_{n-1}^2$, and so forth, until the initial point q_0^2 at $t_0 = 0$ is reached.

2.6.3 Time-like parton evolution

Time-like parton cascades are initiated by secondary partons that emerge either from the side-branches of a preceding space-like or time-like cascade, or directly from a scattering or fusion process. Consider the time-like cascade initiated by the parton c in the right part of Fig. 4, with momentum $k = k_n$. This parton has been produced in the collision $a + b \to c + d$ with a time-like off-shellness $k_n^2 \simeq Q_{ab}^2$.

Again an *angular-ordered* (rather than virtuality-ordered) evolution in space-time *and* momentum-space of the cascade is employed to incorporate interference effects of soft gluons emitted along the time-like cascade tree of Fig. 4, $c \equiv c_m \to c_{m-1}c'_{m-1}$, ..., $c_1 \to c_0c'_0$. In contrast to (26), the time-like version of the angular evolution variable is [37]

$$\tilde{k}_j^2 \;\equiv E_j^2 \,\xi_{j-1} \;, \qquad \xi_{j-1} \;=\; \frac{k_{j-1} \cdot k'_{j-1}}{E_{j-1}E'_{j-1}} \;\simeq\; 1 - \cos\theta_{(j-1),(j-1)'} \qquad (m \geq j \geq 1)\;. \tag{31}$$

so that the time-like cascade can be described by a $\tilde{k}^2$-ordered (rather than k^2-ordered) evolution, which corresponds to an angular ordering with decreasing emission angles $\theta_{j,j'} > \theta_{(j-1),(j-1)'}$.

Proceeding analogously to the space-like case (c.f. (27)), the probability $d\mathcal{P}^{(T)}_{m,m-1}$ for the first branching after the γq vertex, $k_m \to k_{m-1}k'_{m-1}$ with k_{m-1}^2, k'^2_{m-1}, is given by the space-time extension [1, 8] of the usual DGLAP probability distribution [4, 17],

$$d\mathcal{P}^{(T)}_{m,m-1}(z, \tilde{k}^2; \Delta t) \;=\; \frac{d\tilde{k}^2}{\tilde{k}^2}\, dz\; \frac{\alpha_s(\kappa^2)}{2\pi}\, \gamma_{m\to(m-1),(m-1)'}(z)\;\; \mathcal{T}^{(T)}(\Delta t)\;, \tag{32}$$

where $\mathcal{T}^{(T)}(\Delta t)$ is the probabilty that parton m with virtuality k_m^2 and corresponding proper lifetime $\tau_m \propto 1/\sqrt{k_m^2}$ decays within a time interval Δt,

$$\mathcal{T}^{(T)}(\Delta t) \;=\; 1 \;-\; \exp\left(- \frac{\Delta t}{t_m(k)} \right)\;. \tag{33}$$

The actual lifetime of the decaying parton m in the global *cm*-frame is then $t_m(k) = \gamma/\tau_m(k)$, where $t_q(k) \approx 3E/(2\alpha_s k^2)$ for quarks and $t_g(k) \approx E/(2\alpha_s k^2)$ for gluons [7]. As before, F_j denotes the local density of parton species $j = m, m-1$, and $\alpha_s/(2\pi)\gamma(z)$ is the DGLAP branching kernel with energy distribution $\gamma(z)$. The probability (32) is formulated in terms of the energy fractions carried by the daughter partons,

$$z \;=\; \frac{E_{m-1}}{E_m} \quad , \qquad 1 - z \;=\; \frac{E'_{m-1}}{E_m} \quad , \tag{34}$$

with the virtuality k_m of the parton m related to z and ξ through $k_m^2 = k_{m_1}^2 + k'^2_{m-1} + 2E_m^2 z(1-z)\xi$, and the argument κ^2 in the running coupling α_s in (32) is [35] $\kappa^2 = 2z^2(1-z)^2E_m^2\xi \simeq k_\perp^2$.

The branching probability (32) determines the distribution of emitted partons in both coordinate and momentum space, because the knowledge of four-momentum and lifetime (or Δt between successive branchings) give the spatial positions of the partons, if they are assumed to propagate on straight paths between the vertices. The probability that parton m does *not* branch between $\tilde{k}^2$ and a minimum value $\tilde{k}_0^2 \equiv \mu_0^2$ is given by the exponentiation of (32), yielding the *Sudakov form-factor for time-like branchings:*

$$T_m(\tilde{k}^2, \tilde{k}_0^2; \Delta t) \;=\; \exp\left\{ - \int_{\tilde{k}_0^2}^{\tilde{k}^2} \sum_a \int_{z_-(\tilde{k}')}^{z_+(\tilde{k}')} d\mathcal{P}^{(T)}_{m,m-1}(z, \tilde{k}'^2; \Delta t) \right\} , \tag{35}$$

which is summed over the species $a = g, q, \bar{q}$ of parton $m-1$. The integration limits $\tilde{k}_0^2$ and $z_\pm$ are determined by the requirement that the branching must terminate when the partons enter the non-perturbative regime and begin to hadronize. This condition can be parametrized by the confinement length scale $L_c = O(1\,fm)$ with $\tilde{k}_0^{\;2} \gtrsim L_c^{-2} \equiv \mu_0^2$, and $z_+(\tilde{k}_m) = 1 - z_-(\tilde{k}_m) = \mu_0/\sqrt{4\tilde{k}_m^2}$, so that for $z_+(\tilde{k}_0^2) = z_-(\tilde{k}_0^2) = 1/2$ the phase space for the branching vanishes.

The time-like form factor $T_m(\tilde{k}^2, \tilde{k}_0^2; \Delta t)$ determines the four-momenta and positions of the partons of a particular emission vertex as sketched above for the first branching from k_m^2 at $t = t_m$, the time of production of parton c in the global *cm*-frame, to k_{m-1}^2 at $t_{m-1} = t_m + E_m/|k_m^2|$. Subsequent branchings are described completely analogously by replacing $t_m \to t_{m-1}$, $k_m^2 \to k_{m-1}^2$, etc.. Hence $T(\tilde{k}^2, \tilde{k}_0^2; \Delta t)$ generates a time-like cascade as sequential branchings starting from $t = 0$ at the hard vertex forward in time, until the partons eventually hadronize as discussed below.

2.7 Cluster formation and hadronization

In view of lack of knowledge about the details of confinement dynamics and the non-perturbative hadronization mechanism, one must rely at present on model-building. In the present approach, the cluster-hadronization scheme of Ref. [9, 10, 11] is employed. This phenomenological scheme is inspired by the Marchesini-Webber model [38], however it works in space-time plus color-space. On the other hand it is very different from commonly used string-fragmentation models such as the Lund-model [39].

In VNI, both the cluster-formation from the collection of quarks and gluons at the end of the perturbative phase and the subsequent cluster-decay into final hadrons consist of two components:

1. The recombination of the *secondary time-like partons*, their conversion into colorless *parton clusters* and the subsequent decay into secondary hadrons.

2. The recombination of the *primary space-like partons* that remained spectators throughout the collision development into *beam clusters* and the fragmentation of these clusters.

The important assumption here is that the process of hadron formation depends only on the local space-, time-, and color-structure of the parton system, so that the hadronization mechanism can be modelled as the formation of color-singlet clusters of partons as independent entities (pre-hadrons), which subsequently decay into hadrons. This concept is reminiscent of the 'pre-confinement' property [40] of parton evolution, which is the tendency of the produced partons to arrange themselves in color-singlet clusters with limited extension in both position and momentum space, so that it is suggestive to suppose that these clusters are the basic units out of which hadrons form.

2.7.1 Cluster formation

(i) Parton clusters:

Parton clusters are formed from secondary partons, i.e. those that have been produced by the hard interaction and the parton shower development. The coalescence of these secondary partons to color-neutral clusters has been discussed in detail in Refs. [9, 10]. Throughout the dynamically-evolving parton cascade development, every parton and its nearest spatial neighbour are considered as as potential candidates for a 2-parton cluster, which, if *color neutral*, plays the role of a 'pre-confined' excitation in the process of hadronization. Within each single time step, the probability for parton-cluster conversion is determined for each nearest-neighbor pair by the requirement that the total color charge of the two partons must give a composite color-singlet state (if necessary by accompanying gluon emission), and the condition that their *relative spatial distance* L exceeds the critical *confinement length scale* L_c. The scale L is defined as the Lorentz-invariant distance L_{ij} between parton i and its nearest neighbor j:

$$L \;\equiv\; L_{ij} \;=\; \min(\Delta_{i1}, \ldots, \Delta_{ij}, \ldots, \Delta_{in}) \;, \tag{36}$$

where $\Delta_{ij} = \sqrt{(r_{ij})_0^2 + (r_{ij})_x^2 + (r_{ij})_y^2 + (r_{ij})_z^2}$, with $r_{ij}^\mu = r_i^\mu - r_j^\mu$, and the probability for the coalescence of the two partons i, j to form a cluster is modelled by a distribution of the form

$$\Pi_{ij\to c} \;\propto\; \Big(1 - \exp\left(-\Delta F\, L_{ij}\right)\Big) \;\simeq\; 1 - \exp\left(\frac{L_0 - L_{ij}}{L_c - L_{ij}}\right) \qquad \text{if } L_0 \;<\; L_{ij} \;\leq\; L_c \;, \tag{37}$$

and $\Pi_{ij\to c} = 0\ (1)$ if $L_{ij} < L_0$ $(L_{ij} > L_c)$. Here ΔF is the local change in the free energy of the system that is associated with the conversion of the partons to clusters, and the second expression on the right side is a parametrization in terms of $L_0 = 0.6\ fm$ and $L_c = 0.8\ fm$ that define the transition regime. As studied in Ref. [10], the aforementioned color constraint, that only colorless 2-parton configurations may produce a cluster, can be incorporated by allowing coalescence for any pair of color charges, as determined by the space-time separation L_{ij} and the probability (37), however, accompanied by the additional emission of a gluon or quark that carries away any unbalanced net color in the case that the two coalescing partons are not in a colorless configuration.

(ii) Beam clusters:

If one or both of the colliding beam/target particles A and B were a hadron or a nucleus, the one, respectively two beam clusters are formed from the spectator partons that represent the receding beam/target remnants of the original particles A and B. More precisely, the remaining fraction of the longitudinal momentum and energy that has not materialized or been redirected and harnessed during the course of the collision, is carried by those primary partons of the initial-state hadrons or nuclei, which remained spectators throughout. In the present approach these partons maintain their originally assigned momenta and their space-like virtualities. Representing the beam remnants of A and/or B, they may be pictured as the coherent relics of the original hadron (or nucleus) wavefunctions. Therefore the primary virtual partons must be treated differently than the secondary partons which are real excitations that contribute incoherently to the hadron yield. In the global *cm*-frame, the primary partons are grouped together to form a massive beam cluster with its four-momentum given by the sum of the parton momenta and its position given by the 3-vector mean of the partons' positions.

2.7.2 Hadronization of clusters

(i) Parton clusters:

For the decay of each parton cluster into final-state hadrons, the scheme presented in detail in Refs. [9] is employed: If a cluster is too light to decay into a pair of hadrons, it is taken to represent the lightest single meson that corresponds to its partonic constituents. Otherwise, the cluster decays isotropically in its rest frame into a pair of hadrons, either mesons or baryons, whose combined quantum numbers correspond to its partonic constituents. The corresponding decay probability is chosen to be

$$\Pi_{c\to h} \;=\; \mathcal{T}_c(E_c, m_c^2)\;\; \mathcal{N} \int_{m_h}^{m_c} \frac{dm}{m^3}\, \exp\left(-\frac{m}{m_0}\right) \;, \tag{38}$$

where $\mathcal{N}$ is a normalization factor, and the integrand is a Hagedorn spectrum [41] that parametrizes quite well the density of accessible hadronic states below m_c which are listed in the particle data tables, and $m_0 = m_\pi$. In analogy to (33), $\mathcal{T}_c$ is a life-time factor giving the probability that a cluster of mass m_c^2 decays within a time interval Δt in the global *cm*-frame,

$$\mathcal{T}_c(E_c, m_c^2) \;=\; 1 \;-\; \exp\left(-\frac{\Delta t}{t_c(E_c, m_c^2)}\right) \;, \tag{39}$$

with the Lorentz-boosted life time $t_c = \gamma_c \tau_c \simeq E_c/m_c^2$. In this scheme, a particular cluster decay mode is obtained from (38) by summing over all possible decay channels, weighted with the appropriate spin, flavour, and phase-space factors, and then choosing the actual decay mode acording to the relative probabilities of the channels.

(ii) Beam clusters:

The fragmentation of the beam clusters containing the spectator partons mimics in the present model what is commonly termed the 'soft underlying event', namely, the emergence of those final-state hadrons that are associated with the non-perturbative physics which underlies the perturbatively-accessible dynamics of the hard interaction with parton shower fragmentation.

In the spirit of the Marchesini-Webber model [35], a version (suitably modified for the present purposes) of the soft hadron production model of the UA5 collaboration [42], which is based on a parametrization of the CERN $p\bar{p}$ collider data for minimum-bias hadronic collisions. The parameters involved in this model are set to give a good agreement with those data.

Soft hadron production is known to be a universal mechanism [43] that is common to all high-energy collisions that involve beam hadrons in the initial state, and that depends essentially on the total energy-momentum of the fragmenting final-state beam remnant. Accordingly, one may assume that the fragmentation of the final-state beam cluster depends solely on its invariant mass M, and that it produces a charged-particle multiplicity with a binomial distribution [42],

$$P(n) \;=\; \frac{\Gamma(n+k)}{n!\,\Gamma(k)}\; \frac{(\overline{n}/k)^n}{(1+\overline{n}/k)^{n+k}} \;, \tag{40}$$

where the mean charged multiplicity $\overline{n} \equiv \overline{n}(M^2)$ and the parameter $k \equiv k(M^2)$ depends on the invariant cluster mass [6] according to the following particle data parametrization [42],

$$\overline{n}(M^2) \;=\; 10.68\ (M^2)^{0.115} \;-\; 9.5 \qquad k(M^2) \;=\; 0.029\ \ln(M^2) \;-\; 0.064 \;. \tag{41}$$

Adopting the scheme of Marchesini and Webber [35], the fragmentation of a beam cluster of mass M proceeds then as follows: First, a particle multiplicity n is chosen from (40), and the actual charged particle multiplicity is taken to be n plus the modulus of the beam cluster charge. Next, the beam cluster is split into sub-clusters $(q_1\bar{q}_2), (q_2\bar{q}_3), \ldots$ $(q_i = u, d)$, which are subsequently hadronized in the beam cluster rest frame, in the same way as the parton clusters described above. To determine the sub-cluster momenta, the following mass distribution is assumed,

$$P(M) \;=\; c\,(M-1)\, \exp\left[-a(M-1)\right] \;, \tag{42}$$

with c a normalization constant and $a = 2\ \mathrm{GeV}^{-1}$, resulting in an average value of $\langle M\rangle \approx 1.5$ GeV. The transverse momenta are taken from the distibution

$$P(p_\perp) \;=\; c'\, p_\perp\, \exp\left[-b\sqrt{p_\perp^2 + M^2}\right] \;, \tag{43}$$

with normalization c' and slope parameter $b = 3\ \mathrm{GeV}^{-1}$, and the rapidities y are drawn from a simple flat distribution $P(y) \propto$ *const.* with an extent of 0.6 units and Gaussian tails with 1 unit standard deviation at the ends. Finally, all hadronization products of the sub-clusters are boosted from the rest frame of the original beam cluster back into the global *cm*-frame.

[6] Notice that in this model M fluctuates statistically, as a result of fluctuations of the initial-state parton configuration in the incoming hadrons (or nuclei), as well as due to the fluctuating number of remnant partons during the space-time evolution. Hence the distribution (40) and the mean multiplicity (41) vary from event to event. This is in contrast to the original UA5 model, in which the fixed beam energy $\sqrt{s}/2$ controls the energy dependence of soft hadron production.

2.8 Cluster/hadron cascade development

The 'afterburner' hadron cascade development is concepted in in close analogy with the parton cascade evolution. For a description of the physics ingredients and the technical details, the interested reader is referred to Ref. [53]. There are two sources for producing primary hadrons, namely, first, the pre-hadronic parton-clusters (those emerging from coalescence of materialized, interacted partons), and second, the beam/target fragmentation clusters (those resulting from reassembling of the spectator partons that have not interacted at all). Both these classes of clusters and hadrons participate in the hadron cascading. The clusters or hadrons propagate along classical paths until they either scatter off or absorb other clusters or hadrons, or form resonant states with subsequent decays. At each step the newly produced particles can reinteract themselves. The collisions among clusters and hadrons are treated on equal footing, and the corresponding interaction probabilities are calculated from the 'additive quark model' [56] within which one can associate a specific cross-section for any pair of colliding hadrons according to their valence quark content. Cluster-cluster and cluster-hadron collisions are straightforward to include in this approach, since each cluster that emerges from parton coalescence has a definite quark content, depending on the flavor of the mother partons. Again, each newly produced hadron becomes a 'real' particle only after a characteristic formation time $\Delta t_h = \gamma/M_h$ depending on their invariant mass M_h and their energy through $\gamma = E/M_h$. Before that time has passed, a hadron must be considered as a still virtual object that cannot interact incoherently until it has formed according to the uncertainty principle.

3 PROGRAM DESCRIPTION

3.1 The package VNI

The program package VNI is a completely new written code, using only fragments of its predecessors VNI-1.0 (Ref. [6]) and VNI-2.0 (Ref. [7]). The current program is a first release of a long term project that aims at unifying the simulation of a wide class of high energy QCD processes, ranging from elementary particle physics processes, e.g., e^+e^--fragmentation, deep inelastic ep-scattering, via hadronic collisions such as pp ($p\bar{p}$), to reactions involving (heavy) nuclei, e.g. deep inelastic eA scattering, pA, or AA (AB) collisions. The types of collision processes that are available and are discussed in more detail in Section 3.4 below, include collisions involving $e^\pm, \mu^\pm$ for leptons, $p, n, \pi, \Lambda, \Sigma \ldots$ for hadrons, and $\mathrm{De}, \mathrm{He}, \mathrm{O}, \ldots, \mathrm{Au}, \mathrm{Pb}, \mathrm{U}$ for nuclei. Some of these collision processes have of course been investigated before; here they are revisited within the space-time picture of parton cascades and cluster dynamics in order to provide an alternative method for Monte Carlo simulation and also to check the consistency with the wide literature on both experimental measurements and theoretical predictions.

3.2 Overall structure of the program

The program package VNI is written entirely in Fortran 77, and should run on any machine with such a compiler. The program VNI adopts the common block structure, particle identification codes, etc., from the Monte Carlos of the Lund family, e.g., the PYTHIA program [44]. In addition, various program elements of the latter are used in the sense of a library, however modified to incorporate the additional aspects of the space-time and color label information. VNI also employs certain (significantly modified) parts of the HERWIG Monte Carlo [45], used for the final decays of clusters into hadronic resonances and stable particles. It is important to stress that the correspondence of VNI with PYTHIA and HERWIG is rather loose and should not lead to naive identification, in particular since VNI is taylored for a larger set of degrees of freedom that is necessary to describe the space-time dynamics and the information on color correlations. Nevertheless, by truncating the additional information of the particle record of VNI, a direct interface to the particle records of the Lund Monte Carlo PYTHIA, and to the program HERWIG, is actually straightforward. Instructions are given below in Section 3.10.

The package VNI consists of the following files:

(1) the documentation **vni.ps** (this one)

(2) the program VNI: **vni.f**

(3) three include files **vni1.inc, vni2.inc, vni3.inc**

Further useful, but supplementary software (see http://rhic.phys.columbia.edu/rhic/vni):

(4) various example programs for applications of VNI.

(5) a simple, portable histogram package **vnibook.f** .

(5) a program to insert 2-particle probes into VNI, **vniprob.f** .

(5) a program to study Bose-Einstein physics and HBT, **vnihbt.f** .

(6) *the PYTHIA program* **pythia.f**, *to serve as interface with VNI if desired*

The program *vni.f* is the Fortran source code that contains all the subroutines, functions, and block data, as categorized above. All default settings and particle data are automatically loaded by including the three include files *vni1.inc - vni3.inc*. The example programs, as well as the histogram package *vnibook.f*, the programs *vniprob.f*, *vnihbt.f*, and *pythia.f*, are not integral part of the program, i.e. are distributed supplementary as useful guiding tools.

The program source code *vni.f* is organized in 9 parts, in which subroutines and functions that are related in their performance duties, are grouped together (a summary list of all components with a brief description of their purpose is given in Appendix E):

part 1: Main steering routines VNIXRIN (initialization), VNIXRUN (event generation), and VNIXFIN (finalization), plus other general-duty subroutines. VNIXRIN and VNIXFIN are only to be called once, while VNIXRUN is to be called anew for each event, in which the particle system is evolved in discrete time steps and 7-dimensional phase-space.

part 2: Initialization routines. They include, e.g. the process dependent event-by-event initialization of the chosen type of collision process, and various other slave routines associated with the initial set up of an event.

part 3: Package for parton distributions (structure functions). A portable and self-contained collection of routines with a number of structure function parametrizations, plus a possible interface to the CERN PDFLIB, plus various slave routines.

part 4: Evolution routines for the parton cascade / cluster-hadronization simulation, including both (process-dependent) particle evolution routines and (process-independent) universal routines for space-like and time-like shower evolution, for parton scatterings, parton recombination to clusters, and cluster decays to hadrons and other final state particles.

part 5: Diverse utility routines and functions performing the slave-work for the part of perturbative parton evolution.

part 6: Diverse utility routines and functions performing the slave-work for the part of cluster fragmentation to hadrons.

part 7: Evolution routines for the 'afterburner' hadron cascade as a self-contained integrated package. This part was developed by R. Longacre, the *Wizard of Poquott.*

part 8: Event study and analysis routines for accumulating, analysing and printing out statistics on observables.

part 9: Dummy routines and system dependent utilities.

3.3 Special features and machine dependence

Important to remark are the following special features, being not strictly common in standard Fortran 77:

1. The program uses of a *machine-dependent timing routine*, called $VNICLOC$, which measures the elapsed CPU time [7]. Two alternatives are provided: a) the $TIMEX$ routine of the CERN library, in which case the latter must be linked with the program, or, b) the $MCLOCK$ routine which is specific to IBM-AIX compilers. If neither of these options are desired, or does not work in the users local environment, the lines involving calls for $TIMEX$ ($MCLOCK$) calls can easily commented out. [8].

2. All common block variables and dimensions are defined globally within the *include files vni1.inc, vni2.inc, vni3.inc.* This greatly simplifies for instance possible modifications (e.g., enlarging or decreasing) of global common block arrays. Consequently, all subroutines contain INCLUDE statements for these include files, and therefore when compiling and linking the program, the files *vni1.inc, vni2.inc*, and *vni3.inc* must be properly accessible.

3. *Double precision* is assumed throughout since version 4.0. For applications at extremely high energies, single precision for any real variable starts to become a problem. The main source of numerical precision-loss arises from multiple Lorentz boosts of particles throughout the simulation. Therefore the code has been converted now to full double precision.

4. *Implicit variable-type assignment* is assumed, such that variables or functions beginning with letters I - M are of *integer*8* type, and variables or functions with first letters A - H and O - Z are of type *real*8* (double precision).

5. *SAVE statements* have been included in accordance with the Fortran standard. Since most ordinary machines take SAVE for granted, this part is not particularly well tried out, however. Users on machines without automatic SAVE are therefore warned to be on the lookout for any variables which may have been missed.

3.4 The main subroutines

There is a minimum of three routines that a user must know:

1. VNIXRIN for the overall initialization of a sample of collision events,

2. VNIXRUN for the subsequent actual generation of each event,

3. VNIXFIN for finishing up simulation.

These three routines, which are briefly descibed below, are to be called in that order by a user's program as is exemplified by the example program in Section 3.10.

`SUBROUTINE VNIXRIN(NEVT,TFIN,FRAME,BEAM,TARGET,WIN)`

Purpose: to initialize the overall simulation procedure.

$NEVT$: integer specifying the number of collision events to be simulated for a selected physics process.

$TFIN$: final time (in fm) in the global Lorentz frame up to which each collision event is followed.

[7]The usage of the time measurement is not necessary for the performance of the program as-a-whole, although it is a nice convenience.

[8]The subroutine $VNICLOC$ is listed at the very end in *vni.f*.

$FRAME$: a character variable used to specify the global Lorentz frame of the experiment. Uppercase and lowercase letters may be freely mixed.
= 'CMS' : colliding beam experiment in CM frame, with beam momentum in $+z$ direction and target momentum in $-z$ direction.
= 'FIXT': fixed target experiment, with beam particle momentum pointing in $+z$ direction.
= 'USER' : full freedom to specify frame by giving beam momentum in PSYS(1,1), PSYS(1,2) and PSYS(1,3) and target momentum in PSYS(2,1), PSYS(2,2) and PSYS(2,3) in commonblocks VNIREC1 and VNIREC2. Particles are assumed on the mass shell, and energies are calculated accordingly.
= 'FOUR' : as 'USER', except also energies should be specified, in PSYS(1,4) and PSYS(2,4), respectively. The particles need not be on the mass shell; effective masses are calculated from energy and momentum. (But note that numerical precision may suffer; if you know the masses the option 'FIVE' below is preferrable.)
= 'FIVE' : as 'USER', except also energies and masses should be specified, i.e the full momentum information in PSYS(1,1) - PSYS(1,5) and PSYS(2,1) - PSYS(2,5) should be given for beam and target, respectively. Particles need not be on the mass shell. Space-like virtualities should be stored as $-\sqrt{-m^2}$. Four-momentum and mass information must match (see Appendix C for details).

$BEAM$, $TARGET$: character variables to specify beam and target particles. Uppercase and lowercase letters may be freely mixed. An antiparticle may be denoted either by "~" (tilde) or "¯" (bar) at the end of the name. It is also possible to leave out the charge for neutron and proton.
= 'e–' : electron e^-.
= 'e+' : positron e^+.
= 'mu–' : muon μ^-.
= 'mu+' : antimuon μ^+.
= 'gamma': real photon γ (not yet implemented).
= 'pi+' : positive pion π^+.
= 'pi–' : negative pion Π^-.
= 'pi0' : neutral pion π^0.
= 'n0' : neutron n.
= 'n̄0' : antineutron $\overline{n}$.
= 'p+' : proton p.
= 'p̄–' : antiproton $\overline{p}$.
= 'Lambda0': Λ baryon.
= 'Sigma+' : Σ^+ baryon.
= 'Sigma–' : Σ^- baryon.
= 'Sigma0' : Σ^0 baryon.
= 'Xi–' : Ξ^- baryon.
= 'Xi0' : Ξ^0 baryon.
= 'Omega–': Ω^- baryon.
= 'De' : $^{2}_{1}De$ (Deuterium) nucleus.
= 'He' : $^{4}_{2}He$ (Helium) nucleus.
= 'Ox' : $^{16}_{8}O$ (Oxygen) nucleus.
= 'Al' : $^{27}_{13}Al$ (Aluminium) nucleus.
= 'Su' : $^{32}_{16}S$ (Sulfur) nucleus.
= 'Ca' : $^{40}_{20}Ca$ (Calcium) nucleus.
= 'Cu' : $^{64}_{29}Cu$ (Copper) nucleus.
= 'Kr' : $^{84}_{36}Kr$ (Krypton) nucleus.
= 'Ag' : $^{108}_{47}Ag$ (Silver) nucleus.
= 'Ba' : $^{137}_{56}Ba$ (Barium) nucleus.
= 'Wt' : $^{184}_{74}W$ (Tungsten) nucleus.
= 'Pt' : $^{195}_{78}Pt$ (Platinium) nucleus.
= 'Au' : $^{197}_{79}Au$ (Gold) nucleus.
= 'Pb' : $^{208}_{82}Pb$ (Lead) nucleus.

= 'Ur' : $^{238}_{92}$U (Uranium) nucleus.

WIN : related to energy of system (in GeV). Exact meaning depends on FRAME, i.e. for FRAME='CMS' it is the total energy $\sqrt{s}$ of system, and for FRAME='FIXT' it is the absolute 3-momentum $P = \sqrt{\vec{P}^2}$ of beam particle.

SUBROUTINE VNIXRUN(IEVT,TRUN)

Purpose: to generate one event of the type specified by the VNIXRIN. This is the main routine, which administers the overall run of the event generation and calls a number of other routines for specific tasks.

$IEVT$: integer labeling the current event number.

$TRUN$: time (in fm) $TRUN \leq TFIN$ in the global Lorentz frame up to which the space time evolution of the current event $IEVT$ is carried out. If $TRUN < TFIN$, then the particle record contains the history up to this time, and repeated calls resume from $TRUN$ of the previous call (c.f. Section 3.10).

SUBROUTINE VNIXFIN()

Purpose: to finish up overall simulation procedure, to write data analysis results to files, evaluate CPU time, close files, etc.. This routine must be called after the last event has been finished (c.f. Section 3.10).

For a deeper understanding of the physics routines and their connecting structure, I refer to Appendix A for a brief description. Generally, for each of the included collision processes, there is an initialization routine that sets up the initial state, and an evolution routine that carries out the time evolution of the particle distributions in phase-space, starting from the initial state. Within the evolution routines, a number of universal slave routines (i.e. independent of the process under consideration) perform the perturbative parton evolution in terms of space-like branchings, time-like branchings, and parton collisions, as well as the cluster hadronization.

Finally, the program provides some useful pre-programmed event-analysis routines which collect, analyze and print out information on the result of a simulation, and give the user immediate access to calculated particle data, spectra, and other observables. A more detailed description of their duties, and how to call them can be found in Appendix B.

Table 1: Available collision processes.

IPRO	type of collision process
1	$l^+l^- \to \gamma/Z_0 \to 2-jets \to hadrons$
2	$l^+l^- \to Z_0 \to W^+W^- \to 4-jets \to hadrons$
3	$\gamma + h \to jets \to hadrons$
4	$\gamma + A \to jets \to hadrons$
5	$l + h \to l + jets + X \to hadrons$
6	$l + A \to l + jets + X \to hadrons$
7	$h + l \to l + jets + X \to hadrons$
8	$h + h' \to jets + X \to hadrons$
9	$h + A \to jets + X \to hadrons$
10	$A + l \to l + jets + X \to hadrons$
11	$A + h \to jets + X \to hadrons$
12	$A + A' \to jets + X \to hadrons$

3.5 The physics processes

The program is structured to incorporate different classes of particle collision processes in a modular manner. The general classes that are part of the program are summarized in Table 1. All of the generic collision processes in Table 1 allow a further specification of beam and/or target particle, .e.g., $l = e, \mu$ for leptons, $h = p, n, \pi, \ldots$ for hadrons, or $A = De, He, O, \ldots$ for nuclei. They are summarized in Table 2.

As explained before, the actual evolution of any beam/target-particle collision is simulated on microscopic level of the system of partons, clusters and hadrons, and their interactions. For the parton interaction processes, a selection of elementary hard/soft $2 \to 2$ scatterings and $2 \to 1$ fusions are included in VNI, and future extensions are planned. In addition there are the standard space-like and time-like $1 \to 2$

Table 2: Available beam and target particles.

leptons l	hadrons h	nuclei A
$e^\pm$	$\pi^\pm, \pi^0$	$^{2}_{1}$De
$\mu^\pm$	$n, \overline{n}$	$^{4}_{2}$He
	$p, \overline{p}$	$^{16}_{8}$O
	Λ^0	$^{32}_{16}$S
	$\Sigma^\pm, \Sigma^0$	$^{40}_{20}$Ca
	Ξ^-, Ξ^0	$^{64}_{29}$Cu
	Ω^-	$^{84}_{36}$Kr
		$^{108}_{47}$Ag
		$^{137}_{56}$Ba
		$^{184}_{74}$Wt
		$^{195}_{78}$Pt
		$^{197}_{79}$Au
		$^{208}_{82}$Pb
		$^{238}_{92}$U

Table 3: Elementary partonic subprocesses.

Class	ISUB	type of subprocess
a) 2 –>> 2 :	1	$q_i q_j \to q_i q_j$
	2	$q_i \bar{q}_i \to q_k \bar{q}_k$
	3	$q_i \bar{q}_i \to gg$
	4	$q_i \bar{q}_i \to g\gamma$
	5	$q_i \bar{q}_i \to \gamma\gamma$
	6	$q_i g \to q_i g$
	7	$q_i g \to q_i \gamma$
	8	$gg \to q_k \bar{q}_k$
	9	$gg \to gg$
	10	soft scattering
b) 2 → 1 :	11	$q_i \bar{q}_i \to g^*$
	12	$q_i g \to q_i^*$
	13	$gg \to g^*$
c) 1 → 2 (space-like) :	21	$g^* \to q_i q_i$
	22	$q_i^* \to q_i g$
	23	$g^* \to gg$
	24	$q_i^* \to q_i \gamma$
d) 1 → 2 (time-like) :	31	$g^* \to q_i \bar{q}_i$
	32	$q_i^* \to q_i g$
	33	$g^* \to gg$
	34	$q_i^* \to q_i \gamma$

branching processes, which, when combined with the elementary tree processes, provide the usual parton cascade method of including higher order, real and virtual, corrections to the elementary tree processes. The parton-cluster formation and hadronization scheme includes a number of 2-parton recombination processes and the decay of the formed clusters into final state hadron.

It is possible to select a combination of partonic subprocesses to simulate. For this purpose, all subprocesses are numbered according to an $ISUB$ code. The list of allowed codes is given below. In the following g denotes a gluon, q_i represents a quark of flavour $i = 1, \ldots, n_f$, i.e. for $n_f = 6$ this translates to d, u, s, c, b, t. A corresponding antiquark is denoted $\bar{q}_i$. The notation γ is for a real photon, i.e. on shell. An asterix $*$ denotes an off-shell parton.

3.6 The particle record

Each new event generated is in its entity stored in the commonblocks VNIREC1 and VNIREC2, which thus forms the event record. Here each particle that appears at some stage of the time evolution of the system, will occupy one line in the matrices. The different components of this line will tell which particle it is, from where it originates, its present status (fragmented/decayed or not), its momentum, energy and mass, and the space-time position of its production vertex. The structure of the particle record VNIREC1/VNIREC2 follows closely the one of the Lund Monte carlos [44, 46, 47], employing the same overall particle classification of particle identification, status code, etc., however with important differences concerning color- and space-time degrees of freedom..

Note: When in the following reference is made to certain switches and parameters MSTV or PARV, these are described in Sec. 3.7 below.


```
PARAMETER (NV=100000)
COMMON/VNIREC1/N,K(NV,5),L(NV,2)
COMMON/VNIREC2/P(NV,5),R(NV,5),V(NV,5)
```

Purpose: Contains the event record, i.e. the complete list of all partons and particles in the current event.

N : number of lines in the K, L, P, R, and V arrays occupied by the current event. N is continuously updated as the definition of the original configuration and the treatment of parton cascading, cluster fragmentation and hadron production proceed. In the following, the individual parton/particle number, running between 1 and N, is called I. The maximum N is limited by the dimension NV of the arrays.

$K(I,1)$: status code (KS), which gives the current status of the parton/particle stored in the line. The ground rule is that codes 1 - 10 correspond to currently existing partons/particles, while larger codes contain partons/particles which no longer exist.
= **0** : empty line.
= **1** : an undecayed particle or an unfragmented parton.
= **2** : an unfragmented parton, which is followed by more partons in the same color-singlet parton subsystem.
= **3** : an unfragmented parton with special color-flow information stored in $K(I,4)$ and $K(I,5)$, such that color connected partons need not follow after each other in the event record.
= **4** : an unfragmented parton 1, associated with an externally injected 2-particle probe, i.e. $q\bar{q}$, gg, $q\gamma$ (only in conjunction with the package VNIEVPR).
= **5** : an unfragmented parton 2, associated with an externally injected 2-particle probe, i.e. $q\bar{q}$, gg, $q\gamma$ (only in conjunction with the package VNIEVPR).
= **6** : a final state hadron resulting from decay of clusters that have formed from materialized (interacted) partons.
= **7** : a final state hadron resulting from soft cluster decay of beam/target remnants that have formed from left-over (non-interacted) initial state partons.
= **8** : a final state hadron resulting from bound-state formation of $q\bar{q}$ pairs as externally inserted probes (only in conjunction with the package VNIEVPR).
= **9** : a final state hadron resulting from jet fragmentation of q, $\bar{q}$, or g as externally inserted probes (only in conjunction with the package VNIEVPR).
= **10** : a prehadronic cluster that has been reassembled from its original hadronic decay products if those have not passed through their formation time yet; or, in collisions with nuclei, an 'unwounded' nucleon that has been reassembled from its original parton daughters.
= **11** : a decayed particle or a fragmented parton, c.f. = 1.
= **12** : a fragmented jet, which is followed by more partons in the same color-singlet parton subsystem, c.f. = 2.
= **13** : a parton which has been removed when special color-flow has been used to rearrange a parton subsystem, cf. = 3.
= **14** : as = 4, but decayed or fragmented.
= **15** : as = 5, but decayed or fragmented.
= **16** : an unstable and removed hadron resulting from decay of clusters that formed from materialized (interacted) partons, c.f. = 6.
= **17** : an unstable and removed hadron resulting from soft cluster decay of beam/target remnants formed from left-over (non-interacted) initial state partons, c.f. = 7.
= **18** : as = 8, but decayed or fragmented.
= **19** : as = 9, but decayed or fragmented.
= **20** : as = 10, but decayed or fragmented.
< **0** : Particle entries with negative status codes (e.g. -1, -6, -7) parallel in their meaning those from above, but refer to particles which are only virtually present and become active only after a certain formation time, upon which their status code is set to the appropriate positive value.

$K(I,2)$: Flavor code (KF) for partons, hadrons and electromagnetic particles included in the current version of VNI. The particle code is summarized in Tables 3 – 9. It is based on the flavor and spin classification of particles, following the 1988 Particle Data Group numbering conventions. Nuclei are attributed a non-standard code that is internal to VNI, given by $KF = 1000000 + 1000 \cdot N_{neutrons} + N_{protons}$. A negative KF code, where existing, always corresponds to the antiparticle of the one listed in the Tables 3 - 9.

$K(I,3)$: line number of parent particle or jet, where known, else 0. Note that the assignment of a particle to a given jet of a jet system is unphysical, and what is given there is only related to the way the event was generated.

$K(I,4)$: Special color-flow information (for internal use only) of the form $K(I,4)$ = MSTV(2)$\cdot ICFR + ICTO$, where $ICFR$ and $ICTO$ give the line numbers of the partons *from* which the color comes and *to* where it goes, respectively.

$K(I,5)$: Special color-flow information (for internal use only) of the form $K(I,5)$ = MSTV(2)$\cdot JCFR + JCTO$, where $JCFR$ and $JCTO$ give the line numbers of the partons *from* which the anticolor comes and *to* where it goes, respectively.

$L(I,1)$: color label ($L = 1, \ldots, NC$) of a parton, where NC is number of colors specified by the parameter MSTV(5). Is = 0 for antiquarks and all non-colored particles.

$L(I,2)$: anticolor label ($L = 1, \ldots, NC$) of a parton. Is = 0 for quarks and all non-colored particles.

$P(I,1)$: p_x, momentum in the x direction in GeV.

$P(I,2)$: p_y, momentum in the y direction in GeV.

$P(I,3)$: p_z, momentum in the z direction in GeV.

$P(I,4)$: E, energy, in GeV.

$P(I,5)$: $m = p^2$, mass in GeV. For partons with space-like virtualities, i.e. where $Q^2 = -m^2 > 0$, its value is $P(I,5) = -\sqrt{|m^2|} = -Q$.

$R(I,1)$: current x position in frame of reference in 1/GeV.

$R(I,2)$: current y position in frame of reference in 1/GeV.

$R(I,3)$: current z position in frame of reference in 1/GeV.

$R(I,4)$: time (in 1/GeV) of active presence in the system, i.e. $t_{pres} = t - t_{prod}$. Is set equal to PARW(2) at time of production t_{prod} of the particle and then increased by PARW(2) in each timestep until the particle fragments or decays. If $\langle$ 0, giving the remaining formation time for virtually produced, but not yet real particles.

$R(I,5)$: number and type of interactions of a particle, and is equal to MSTV(3)$^2 \cdot NCO$+ MSTV(3)$\cdot NSB + NTB$, where - for partons - NCO is the number of 2-body collisions, NSB of space-like branchings, and NTB of time-like branchings, undergone up to current time. For clusters, hadrons and unstable particles, NSB is zero and NTB counts the number of 2-body decays.

$V(I,1)$: x position of production vertex, in 1/GeV.

$V(I,2)$: y position of production vertex, in 1/GeV.

$V(I,3)$: z position of production vertex, in 1/GeV.

$V(I,4)$: time t of production, in 1/GeV.

$V(I,5)$: encodes origin of production as 10$\cdot$MSTV(4)$\cdot IMO + 10 \cdot ITM + OR$, where IMO is the direct mother, ITM the time of production, and OR the generation of particle IP in a cascade tree, i.e. the genetical origin with respect to the production vertex of its original 'Ur'-mother. (This keeps track of the production history even if the decayed mother has been removed and allows to follow the genealogy of the system.)

Special cases:

For the simulation of collisions involving hadrons or nuclei in the initial state, additional initial state information on the status and specific variables of "primary partons" of the incoming hadron (nucleus) are stored as follows. Note however, that after the first interaction of a "primary parton", this initial state information is lost and the assignments for the components of the arrays K, R, V are the same as above.

$K(I,4)$: KF flavour code of hadron (nucleon), which is mother of the primary parton.

$K(I,5)$: KF flavour code of nucleus from which a primary parton originates. (For hadrons $K(I,4)$ and $K(I,5)$ are equal).

$R(I,5)$: Is equal to $-|x|$, where x is the longitudinal momentum fraction of primary parton that it carries off its mother hadron.

$V(I,4)$: encodes location IB in the particle record of a primary sea-quark's brother, i.e. the sea-antiquark belonging to the same vacuum polarization loop, as MSTV(4)$^2 \cdot IB$+MSTV(4)$\cdot ITM + OR$, analogous to $V(I,5)$ above. For primary valence quarks and gluons it is 0.

Additional remark: The arrays $K(I,3) - K(I,5)$ and the arrays P, R, and V may temporarily take special meaning other than the above, for some specific internal use.

In Section 3.10 below, a typical event listing of the particle record is printed, which serves as an example for the organization of the particle record, exhibiting the information for *momentum space:* It lists the particles contained in VNIREC1/VNIREC2 at a certain point during the evolution of an event, where KS and KF give status and flavor codes, C and A the color and anticolor index, P the energy-momentum-mass in GeV for each particle that appeared at some point in the event history. An analogous listing for the *position space* particle record (not printed here) contains the spatial coordinates and time of active presence for each particle, as well as the particle's rapidity and transverse momentum with respect to the z-axis (jet-axis, or beam-axis). Note: both listings can be obtained at any point by calling the routine VNILIST, described in Appendix B.

Table 4: Quark, lepton and gauge boson codes.

KF	Name	Printed	KF	Name	Printed	KF	Name	Printed
1	d	d	11	e^-	e-	21	g	g
2	u	u	12	ν_e	nu_e	22	γ	gamma
3	s	s	13	μ^-	mu-	23	Z^0	Z0
4	c	c	14	ν_μ	nu_mu	24	W^+	W+
5	b	b	15	τ^-	tau-	25	H^0	H0
6	t	t	16	ν_τ	nu_tau	26		
7			17			27		
8			18			28		
9			19			29		
10			20			30		

3.7 The general input and control parameters

The VNIDA0 common block contains the status code and parameters that regulate the performance of the program. All of them are provided with sensible default values, so that a novice user can neglect them, and only gradually explore the full range of possibilities.

```
COMMON/VNIDAO/MSTV(200),PARV(200),MSTW(200),PARW(200)
```

Purpose: to give access to status code and parameters that regulate the performance of the program. If the default values, denoted below by (D=...), are not satisfactory, they must in general be changed before the VNIXRIN call. Exceptions, i.e. variables that can be changed for each new event, are denoted by (C).

MSTV(200), PARV(200): control switches and physics parameters

1. General:

MSTV(1) : (D=100000) number of lines available in the commonblock VNIREC1/VNIREC2. Should always be changed if the dimensions of the K, P, R, V arrays are changed.

MSTV(2) : (D=25000) is used to trace internal color flow information in the array K.

MSTV(3) : (D=10000) is used to store number and type of interactions of a particle in the array R of VNIREC1/VNIREC2.

MSTV(4) : (D=1000) is used to trace origin of a particle's production in the array V of VNIREC1/VNIREC2.

MSTV(5) : (D=3) number of colors N_c included in the simulation.

MSTV(6) : (D=6) number of quark flavors N_f included.

Table 5: Special codes.

KF	Printed	Meaning
90	CMsoft	Center-of-mass of beam/target remnant system before soft fragmentation
91	cluster	Cluster from coalescence of secondary partons
92	Beam-REM	Cluster from remnant primary partons of beam particle
93	Targ-REM	Cluster from remnant primary partons of target particle
94	CMshower	Four-momentum of time-like showering system
95	SPHEaxis	Event axis found with VNISPHE
96	THRUaxis	Event axis found with VNITHRU
97	CLUSjet	Jet (cluster) found with VNICLUS
98	CELLjet	Jet (cluster) found with VNICELL
99		
100		

Table 6: Meson codes, part 1.

KF	Name	Printed	KF	Name	Printed
211	π^+	pi+	213	ρ^+	rho+
311	K^0	K0	313	K^{*0}	K*0
321	K^+	K+	323	K^{*+}	K*+
411	D^+	D+	413	D^{*+}	D*+
421	D^0	D0	423	D^{*0}	D*0
431	D_s^+	D_s+	433	D_s^{*+}	D*_s+
511	B^0	B0	513	B^{*0}	B*0
521	B^+	B+	523	B^{*+}	B*+
531	B_s^0	B_s0	533	B_s^{*0}	B*_s0
541	B_c^+	B_c+	543	B_c^{*+}	B*_c+
111	π^0	pi0	113	ρ^0	rho0
221	η	eta	223	ω	omega
331	η'	eta'	333	ϕ	phi
441	η_c	eta_c	443	J/ψ	J/psi
551	η_b	eta_b	553	Υ	Upsilon
661	η_t	eta_t	663	Θ	Theta
130	K_L^0	K_L0			
310	K_S^0	K_S0			

MSTV(7) : (D=1) energy and momentum conservation options. Since both the initial generation of initial hadronic or nuclear parton system and the final cluster-hadron decay scheme require occasional reshuffling of 4-momentum, an energy and/or momentum imbalance can occur. This can be corrected, if desired, by renormalizing particle energies and momenta.
= **0** : no explicit conservation of any kind.
= **1** : energy conservation is enforced at the end of each event (i.e. once only per event): particles share energy imbalance compensation according to their energy (roughly equivalent to boosting event to CM frame).
= **2** : as =1, but now energy conservation is enforced at the end of each time step in each event (i.e. continously throughout an event).
= **3** : as =1, but in addition also 3-momentum conservation the end of each event (i.e. once only per event), however at the cost of some particles shifted off-mass shell.
= **4** : as =3, but in addition also 3-momentum conservation the end of each timestep in each event (i.e. continously throughout an event).

MSTV(8) : (D=0) type of particles to be included in energy and momentum conservation options under MSTV(7).
= **0** : all living particles are included.
= **1** : only partons.
= **2** : only hadrons.

MSTV(9) : - not used -

MSTV(10) : (D=111111) initial seed for random number generation.

MSTV(11) : (D=5000000) maximum number of collision events $A + B$, after which program is forcibly terminated.

MSTV(12) : (D=2500) maximum number of time steps per collision event, after which a new collision event is generated. When increased, the dimension of the arrays in commonblock $VNITIM$ need to be altered accordingly.

Table 7: Meson codes, part 2.

KF	Name	Printed	KF	Name	Printed
10213	b_1	b_1+	10211	a_0^+	a_0+
10313	K_1^0	K_10	10311	K_0^{*0}	K*_00
10323	K_1^+	K_1+	10321	K_0^{*+}	K*_0+
10413	D_1^+	D_1+	10411	D_0^{*+}	D*_0+
10423	D_1^0	D_10	10421	D_0^{*0}	D*_00
10433	D_{1s}^+	D_1s+	10431	D_{0s}^{*+}	D*_0s+
10113	b_1^0	b_10	10111	a_0^0	a_00
10223	h_1^0	h_10	10221	f_0^0	f_00
10333	$h_1'^0$	h'_10	10331	$f_0'^0$	f'_00
10443	h_{1c}^0	h_1c0	10441	χ_{0c}^0	chi_0c0
20213	a_1^+	a_1+	215	a_2^+	a_2+
20313	K_1^{*0}	K*_10	315	K_2^{*0}	K*_20
20323	K_1^{*+}	K*_1+	325	K_2^{*+}	K*_2+
20413	D_1^{*+}	D*_1+	415	D_2^{*+}	D*_2+
20423	D_1^{*0}	D*_10	425	D_2^{*0}	D*_20
20433	D_{1s}^{*+}	D*_1s+	435	D_{2s}^{*+}	D*_2s+
20113	a_1^0	a_10	115	a_2^0	a_20
20223	f_1^0	f_10	225	f_2^0	f_20
20333	$f_1'^0$	f'_10	335	$f_2'^0$	f'_20
20443	χ_{1c}^0	chi_1c0	445	χ_{2c}^0	chi_2c0
30443	ψ'	psi'			
30553	Υ'	Upsilon'			

MSTV(13) : (D=0) choice of time grid $TIME(I)$ and time increase $TINC(I)$. Generically, $t(i) = t(i-1) + [f(i) - f(i-1)]$, with $i = 0, \ldots, MSTV(12)$, and $t(0) = t_0$ =PARV(12), t_f =PARV(13).
= 0 : power law increase $f(i) = a \cdot (i)^b$, where a =PARV(14) and b =PARV(15).
= 1 : logarithmic increase $f(i) = a \cdot \ln(i)^b$, where a =PARV(14), b =PARV(15).

MSTV(14) : (D=0) Option to select or switch on/off certain physics processes $ISUB$ in the simulation, by specifying the array $MSUB$ (c.f. Sec. 3.8 below), where $MSUB(ISUB)$ = 0 (1) switches a subprocess off (on).
= 0 : the relevant processes are initialized automatically.
= 1 : user selection of included processes is required.

MSTV(15) : (D=0) Option to smear out classical (sharply localized) positions and three-momenta of particles at their production vertex, according to Gaussian distribution $exp[-r^2/a^2 - p^2/b^2]$, where the widths are a = PARV(16) in fm, and b = PARV(17) in GeV.
= 0 : switched off, i.e. no smearing.
= 1 : smearing of particle *position* according to Gaussian with width PARV(16).
= 2 : as = 1, plus smearing of particle *momentum* according to Gaussian with width PARV(17).

MSTV(16) : (D=0) Option to use PYTHIA for generating the initial state particle system rather than VNI. Presently this applies only to l^+l^- collisions, i.e., IPRO =1 or 2 in Table 1. NOTE: The subroutine package *vnipythia.f* must be linked in order to use this option. Also, in this case, one must comment out the dummy routines PYINIT and PYEVNT at the very end of *vni.f*.
= 0 : switched off.
= 1 : switched on.

Table 8: Baryon codes.

KF	Name	Printed	KF	Name	Printed
			1114	Δ^-	Delta-
2112	n	n0	2114	Δ^0	Delta0
2212	p	p+	2214	Δ^+	Delta+
			2224	Δ^{++}	Delta++
3112	Σ^-	Sigma-	3114	Σ^{*-}	Sigma*-
3122	Λ^0	Lambda0			
3212	Σ^0	Sigma0	3214	Σ^{*0}	Sigma*0
3222	Σ^+	Sigma+	3224	Σ^{*+}	Sigma*+
3312	Ξ^-	Xi-	3314	Ξ^{*-}	Xi*-
3322	Ξ^0	Xi0	3324	Ξ^{*0}	Xi*0
			3334	Ω^-	Omega-
4112	Σ_c^0	Sigma_c0	4114	Σ_c^{*0}	Sigma*_c0
4122	Λ_c^+	Lambda_c+			
4212	Σ_c^+	Sigma_c+	4214	Σ_c^{*+}	Sigma*_c+
4222	Σ_c^{++}	Sigma_c++	4224	Σ_c^{*++}	Sigma*_c++
4132	Ξ_c^0	Xi_c0			
4312	$\Xi_c'^0$	Xi'_c0	4314	Ξ_c^{*0}	Xi*_c0
4232	Ξ_c^+	Xi_c+			
4322	$\Xi_c'^+$	Xi'_c+	4324	Ξ_c^{*+}	Xi*_c+
4332	Ω_c^0	Omega_c0	4334	Ω_c^{*0}	Omega*_c0
5112	Σ_b^-	Sigma_b-	5114	Σ_b^{*-}	Sigma*_b-
5122	Λ_b^0	Lambda_b0			
5212	Σ_b^0	Sigma_b0	5214	Σ_b^{*0}	Sigma*_b0
5222	Σ_b^+	Sigma_b+	5224	Σ_b^{*+}	Sigma*_b+

Table 9: Nucleus codes.

KF	Name	Printed	KF	Name	Printed
1001001	$^2_1$De	de	1061047	$^{108}_{47}$Ag	ag
1002002	$^4_2$He	he	1110074	$^{110}_{74}$W	wt
1008008	$^{16}_8$O	ox	1117078	$^{195}_{78}$Pt	pt
1014013	$^{27}_{13}$Al	al	118079	$^{197}_{79}$Au	au
1016016	$^{32}_{16}$S	su	1126082	$^{208}_{82}$Pb	pb
1020020	$^{40}_{20}$Ca	ca	1146092	$^{238}_{92}$U	ur
1035029	$^{64}_{29}$Cu	cu			

PARV(1) - PARV(11) : - not used -

PARV(12) : (D=0. fm) choice of initial point of time t_i = PARV(12) when evolution of collision event begins.

PARV(13) : (D=0. fm) choice of final point of time t_f = PARV(13). If = 0., then it is set automatically to $TIME$(MSTW(2)), where MSTW(2) is the selected number of time steps. Otherwise, if > 0., it specifies t_f such that the minimum $\min(t_f, t_{max})$ is taken as the point when the evolution of a collision event stops, where $t_{max} = TIME$(MSTV(12)).

PARV(14) : (D=0.05) prefactor a of the time-increment function f, see MSTV(13).

PARV(15) : (D=1.1) exponent b of the time-increment function f, see MSTV(13). For longer collision time scales as in hadron-nucleus or nucleus nucleus collisions, it is automatically scaled by PARV(15) to 1.5 × PARV(15) to extend the time range.

PARV(16) : (D=0.1 fm) For MSTV(15) = 1, width parameter a=PARV(16) of Gaussian $exp[-r^2/a^2]$ for smearing out classical (sharply localized) positions of particles at their production vertex. (Reasonable values are $a = 0.1 - 1$ fm, c.f. Zhang et. al, nuc-th/9704041).

PARV(17) : (D=0.1 GeV) For MSTV(15) = 2, width parameter b=PARV(17) of Gaussian $exp[-p^2/b^2]$ for smearing out classical (sharply localized) momenta of particles at their production vertex. (Note, uncertainty relation requires PARV(17) $\simeq$ 1/PARV(16) GeV/fm).

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2. Initial state of collision system:

MSTV(20) : (D=0) choice of model for initial parton distributions.
= **0** : standard structure functions are used.
= **1** : other parametrization, e.g. a la McLerran *et al.* (not implemented yet).

MSTV(21) : (D=1) choice of nucleon structure-function set (c.f. MSTV(22)).
= **1** : GRV94LO (Lowest order fit).
= **2** : GRV94HO (Higher order: MSbar fit).
= **3** : GRV94DI (Higher order: DIS fit).
= **4** : - not used -
= **5** : CTEQ2M (best higher order MSbar fit).
= **6** : CTEQ2MS (singular at small x).
= **7** : CTEQ2MF (flat at small x).
= **8** : CTEQ2ML (large Λ).
= **9** : CTEQ2L (best lowest order fit).
= **10** : CTEQ2D (best higher DIS order fit).

MSTV(22) : (D=1) choice of nucleon structure-function library.
= **1** : the internal one with parton distributions chosen according to MSTV(21).
= **2** : the PDFLIB one with MSTV(21)=1000 $\cdot NGROUP + NSET$ (requires PDFLIB to be linked).

MSTV(23) : (D=1) choice of pion structure-function set (c.f. MSTV(24)).
= **1** : Owens set 1.
= **2** : Owens set 2.

MSTV(24) : (D=1) choice of pion structure-function library.
= **1** : the internal one with parton distributions chosen according to MSTV(23).
= **2** : the PDFLIB one with $MSTV(23) = 1000 \cdot NGROUP + NSET$ (requires PDFLIB to be linked).

MSTV(25) : (D=2) choice of minimum Q-value Q_0 used in parton distributions of initial hadronic or nuclear state.
= **0** : fixed at Q_0 =PARV(23).
= **1** : determined by the average momentum tranfer of primary parton collisions $Q_0 = \langle Q_{prim} \rangle$, with initial value Q_0 =PARV(23) before the first event.
= **2** : as =1, but in addition varying with total energy $\sqrt{s}$ of the overall collision system, with $\tilde{Q}_0 = \max[Q_0, \frac{a}{4} \cdot (E_h/GeV)^b]$, where Q_0 =PARV(23), a =PARV(24), b =PARV(25), and $E_h = \sqrt{s}$/hadron the average energy per hadron (nucleon).

MSTV(26) : (D=1) option to choose x-dependent Q_{in} in parton densities.
= **0** : switched off, Q_0 according to selection of MSTV(25) is used.
= **1** : varying with Bjorken-x of struck initial state partons, as well as with total energy $\sqrt{s}$ of collision system, with $Q_0 = Q(x)$ where $1/Q^2(x) = 1/Q_0^2 + Q_0^2/(xE_{had})^2$, and $E_h = \sqrt{s}$/hadron the average energy per hadron (nucleon).

MSTV(30) : (D=0) sub-selection of initial state for the following collision processes $A + B$, where specification of beam/target particles A, B is not unambigous, because collision may proceed via alternative channels (c.f. Table 1):

a) $l^+l^- \to X \to hadrons$:
= **0** : $e^+e^- \to \gamma/Z^0 \to q\bar{q}$
= **1** : $e^+e^- \to W^+W^- \to q\bar{q}'\, l\,\nu$
= **2** : $e^+e^- \to W^+W^- \to q\bar{q}'\, q'\bar{q}$

MSTV(31) : (D=0) initial separation along the collision (z-)axis of beam and target particle in the overall CM frame.
= **0** : fixed at Δz =PARV(31).
> **0** : shifted towards minimal separation, such that beam and target particles almost touch with Δz =MSTV(31)·PARV(31).

MSTV(32) : (D=2) selection of impact parameter b transverse to the collision (z-) axis of beam and target particle.
= **0** : fixed at b = Max[PARV(32),PARV(33)].
= **1** : randomly sampled in between $b_{min} \le b \le b_{max}$, with b_{min} =PARV(32) and b_{max} =PARV(33).
= **2** : as 1, but with b_{min} = PARV(32)$\cdot\sqrt{\sigma_{nd}/\pi}$, and b_{max} = PARV(33)$\cdot\sqrt{\sigma_{nd}/\pi}$, where σ_{nd} is the non-diffractive crossection for given beam/target and beam energy.

MSTV(33) : (D=2) Choice of nuclear matter distribution for collisions involving one or two nuclei, i.e. of nucleons' positions within nucleus.
= **0** : uniform distribution with 'sharp edge'.
= **1** : Gaussian distribution for light nuclei $A \le 12$, and 'smeared edge' distribution for intermediate and heavy nuclei $A > 12$ (c.f. PARV(27)).
= **2** : Gaussian distribution for $A \le 12$, and Fermi distribution for $A > 12$ (c.f. PARV(28)).

MSTV(34) : (D=1) spatial distribution of initial partons within their parent hadrons of beam and target particles, in the hadron restframe within a sphere of the hadron radius.
= **0** : uniform distribution.
= **1** : exponential distribution with width given by PARV(34).
= **2** : Gaussian distribution with width given by PARV(35).

MSTV(35) : (D=2) Lorentz-boosted spatial distribution of initial partons.
= **0** : spatial positions of all partons (valence, sea, glue) inside parent hadron are Lorentz-boosted with the parent hadron's (nucleon's) γ-factor.
= **1** : only valence quarks are boosted with the parent hadron's (nucleon's) γ-factor; seaquarks and gluons are smeared out symmetrically(!) in hadron (nucleon) direction of motion around the valence quark disc.
= **2** : as = 1, but now seaquarks and gluons are distributed all behind(!) the valence quark disc.

MSTV(36) : (D=1) choice of primordial $k_\perp$-distribution of initial partons.
= **0** : no primordial $k_\perp$.
= **1** : exponential $k_\perp$-distribution with width specified by PARV(37).
= **2** : Gaussian $k_\perp$-distribution with width specified by PARV(38).

MSTV(37) : (D=1) choice of masses of initial partons.
= **0** : on mass shell with quark current masses.
= **1** : off mass shell with space-like virtuality as determined by the excess of the partons' momentum over their energies.

MSTV(38) : (D=0) switch for including effects of parton shadowing in nuclear parton structure functions by multiplication with effective shadowing factor $R_A(x) = f_A(x)/f_N(x)$ as a simple parametrization of EMC data, where f_A and f_N are the measured nuclear and nucleon structure functions, respectively.
= **0** : parton shadowing switched off.
= **1** : switched on.

MSTV(39) : (D=0) option for asymmetric (in mass) collision systems involving nuclei, $h + A$ with $h = \pi, p, n, \ldots$, or $A + B$ with $A \neq B$, to choose instead of global c.m. frame or fixed target frame, the frame of equal (hadron)nucleon-nucleon velocity, that is the frame in which hadron (nucleons) from beam side have equal but opposite directed momentum than those from target side.
= **0** : switched off.
= **1** : switched on.

PARV(21) : (D=1. GeV^{-1}) the minimum resolvable partonic Bjorken-x, denoted x_c, is set by the 'confinement radius' R_c =PARV(21), which defines the maximum possible longitudinal spread of a confined parton within $\Delta z = 1/xP < 1/(x_c P) \equiv R_c$, where P is the longitudinal momentum of the mother hadron.

PARV(22) : (D=0.95) the minimum summed x-value $(\sum_i x_i)_{min}$, when 'filling' a hadron with partons of energy(momentum) fractions x_i of the hadron. The value depends, slightly on the value of Q_0 (c.f. PARV(23)-PARV(25)), or if cuts on x are made. It should be adjusted such that when adding one more parton, the average $\langle \sum_i x_i \rangle$ should be = 1. If the sum is smaller than PARV(22), another parton is added to the hadron, i.e. PARV(22) = $1 - \langle \sum_i x_i \rangle$.

PARV(23) : (D=1. GeV) minimum value Q_0 that is used in initial parton distributions (structure functions or alternative distributions). I.e., if $Q < Q_0$, then the value PARV(23) is used.

PARV(24) , **PARV(25)** : (D=2.50,0.25) possibility of using effective, energy-dependent Q_{in} value in structure functions if MSTV(25)=2, according to the function $\tilde{Q}_0 = \max[Q_0, \frac{a}{4} \cdot (E_h/GeV)^b]$, where Q_0 =PARV(23), a =PARV(24), b = PARV(25), and $E_h = \sqrt{s}$/hadron the average energy per hadron (nucleon).

PARV(26) : (D=1.18 fm) nuclear radius parameter r_0, with $R(A) = r_0 A^1/3$.

PARV(27) : (D=3.0 fm) parameter R_d in 'smeared-edge' distribution of nucleons' positions in nucleus with $A > 12$ (for MSTV(33) = 1).

PARV(28) : (D=0.545 fm) parameter R_a in Fermi distribution of nucleons' positions in nucleus with $A > 12$ (for MSTV(33) = 2).

PARV(31) : (D=0.25 fm) initial separation along the collision (z-)axis of beam and target particle in the overall CM frame for MSTV(31)$\geq$ 1.

PARV(32) : (D=0. fm) determines value of *minimum* impact parameter b_{min}, transverse to the collision (z-)axis, such that b_{min} =PARV(32) for MSTV(32) = 0 or 1, or b_{min} =PARV(32)$\cdot\sqrt{\sigma_{nd}/\pi}$ for MSTV(32)=2.

PARV(33) : (D=1. fm) determines value of *maximum* impact parameter b_{max}, transverse to the collision (z-)axis, such that b_{max} =PARV(33) for MSTV(32) = 0 or 1, or b_{max} =PARV(33)$\cdot\sqrt{\sigma_{nd}/\pi}$ for MSTV(32)=2.

PARV(34) : (D=1.19 GeV^{-1}) width w in exponential distribution $\exp[-r/w]$ of partons' positions around its parent-hadron center-of-mass (c.f. MSTV(33)). (Note: $w = 1/\nu$, where $\nu = 0.84$ GeV is the measured nucleon form factor.)

PARV(35) : (D=2.38 GeV^{-1}) sigma s in Gaussian distribution $\exp[-r^2/(2\,s^2)]$ of partons' positions around its parent-hadron center-of-mass (c.f. MSTV(33)). (Note: $s = 2/\nu$, where $\nu = 0.84$ GeV is measured nucleon form factor.)

PARV(36) : (D=2.) cut-off for sampling initial partons' spatial distributions from exponential or Gaussian above, such that $r < a\,R_h$, where a =PARV(36) and R_h is the radius of the mother hadron.

PARV(37) : (D=0.44 GeV) width w in exponential distribution $\exp[-k_\perp/w]$ of primordial $k_\perp$ distribution of initial partons (c.f. MSTV(36)).

PARV(38) : (D=0.44 GeV) sigma s in Gaussian distribution $\exp(-k_\perp^2/(2\,s^2)]$ of primordial $k_\perp$ distribution of initial partons (c.f. MSTV(36)).

PARV(39) : (D=2. GeV) upper cut-off for sampling primordial $k_\perp$ from above exponential or Gaussian distribution.

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3. Parton scatterings:

MSTV(40) : (D=3) master switch for parton collisions.
= **0** : generally switched off.
= **1** : only primary-primary collisions, i.e. those involving 2 partons that both have not interacted before.
= **2** : as = 1 plus primary-secondary collisions, i.e. those involving 2 partons, of which one has had already at least one previous interaction.
= **3** : as = 2 plus secondary-secondary interactions, i.e. all multiple collisions included.

MSTV(41) : (D=1) choice of (semi)hard QCD collision cross-sections.
= **1** : standard $O(\alpha_s^2)$ perturbative cross-sections for $2 \to 2$ and $2 \to 1$ processes.
= **2** : alternative of $2 \to n$ cross-sections (not implemented yet!).

MSTV(42) : (D=1) choice of p_0 to separate ***hard*** and ***soft*** parton collisions, and to act as a regulator for the parton cross-sections $d\hat{\sigma}/dQ^2$, that are divergent for vanishing momentum transfer (or invariant mass) Q.
= **0** : fixed at $p_0 = \max[PARV(42), \max(VKIN(3), VKIN(5)]$.
= **1** : energy and mass dependent, with $p_0 = p_0(s, A)$, according to the parametrization given by PARV(42), PARV(43).
= **2** : initially, before the first event, set to $p_0(s, A)$, c.f. =1, but in subsequent events set equal to the average momentum transfer of primary parton-parton collisions $p_0 := \langle Q_{prim} \rangle$ accumulated by statistics.

MSTV(43) : (D=2) Q^2-definition in $2 \to 2$ parton collision processes; for $\hat{s}$-channel or fusion processes, Q^2 is always chosen to be $m^2 = \hat{s}$. Note that the parton-parton collisions invariants are denoted as $\hat{s} = (p_1 + p_2)^2$, $\hat{t} = (p_1 - p_1')^2$, $\hat{u} = (p_1 - p_2')^2$.
= **1** : $Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$.
= **2** : $Q^2 = 0.5\,(m_{\perp\,1}^2 + m_{\perp\,2}^2)$.
= **3** : $Q^2 = \min(-\hat{t}, -\hat{u})$.
= **4** : $Q^2 = \hat{s}$.

MSTV(44) : (D=2) choice of scheme for parton collision-time estimate.

= **0** : zero collision-time, i.e. instantaneous process.

= **1** : finite collision-time sampled from an exponential distribution $\exp(-x)$, where $x = t/\tau$, t the time in the lab, and τ the mean life-time of the parton in the lab, see PARV(44).

= **2** : finite collision-time sampled from Gyulassy-Wang distribution $(2/\tau)\ x/(1+x^2)^2$, where $x = t/\tau$, t the time in the lab, and τ the mean life-time of the parton in the lab, see PARV(44).

MSTV(45) : (D=1) selection of maximum allowed distance between two partons in their *cm*-frame in order to be able to collide (used for ruling out widely separated pairs to speed up simulation).

= **0** : fixed at a value given by $r_{12\,max}$ = PARV(45).

= **1** : variable at a value $r_{12\,max}$ = PARV(45)/$(\sqrt{\hat{s}}/GeV)$.

MSTV(46) : (D=0) choice of probability distribution W(x) from which collision probability of 2 partons is sampled, where $x = r_{12}^{(sep)}/r_{12}^{(\hat{\sigma})}$, with $r_{12}^{(sep)}$ the transverse 2-parton separation at closest approach and $r_{12}^{(\hat{\sigma})}$ the transverse radius of interaction as given by the parton-parton cross-section $\hat{\sigma}$.

= **0** : flat distribution, $W(x) = \theta(a-x)$, with a = PARV(46).

= **1** : exponential distribution, $W(x) = \exp(-x/a)$, a = PARV(46).

MSTV(47) : (D=2) special treatment of 'flavor excitation' by parton collisions involving one or two primary hadronic or nuclear (anti)quarks by requiring a minimum momentum transfer of the resolving parton with the heavy quark.

= **0** : no special treatment of heavy quarks over light quarks.

= **1** : requirement of minimum momentum transfer for liberation of heavy quark out of initial parton distribution by scattering, where the minimum required momentum trasnfer is given by PARV(47) times the mass of the heavy quark.

= **2** : as = 1, but now both the struck heavy quark as well as its initial antiquark sibling are liberated (i.e. get on mass shell).

MSTV(48) : (D=0) switch for including soft parton collisions according to a phenomenological cross-section $d\hat{\sigma}/dQ^2 \propto \alpha_s^2(p_0^2)/(Q^2+\mu^2)$ for soft parton collisions (c.f. eq. (25)), where p_0 = PARV(42), μ = PARV(48), and $Q^2 = p_\perp^2$ for $\hat{t},\hat{u}$ channel and $Q^2 = \hat{s}$ for $\hat{s}$ channel.

= **0** : switched off.

= **1** : soft collisions are treated complementary to hard collisions, i.e. occur only if $Q < p_0$.

= **2** : soft collisions are treated supplementary to hard collisions, i.e. compete with the latter, whichever cross-section dominates.

MSTV(49) : (D=1) switch to allow for $2 \to 1$ parton fusion processes $a + b \to c^*$ in competition with $2 \to 2$ scattering processes $a + b \to c^* \to d + e$, such that for a given pair a,b either of those processes is selected according to the relative probability given by the respective cross-sections and depending on the 'life-time' of the particle c^*.

= **0** : fusion processes switched off.

= **1** : switched on, with relative weight determined by PARV(49).

PARV(41) : (D=0.25 GeV) nominal Λ-value used in running α_s for parton-parton collisions.

PARV(42) : (D=0.0 GeV) cut-off for perturbative QCD cross-sections that are divergent when the momentum transfer $Q \to 0$. Here the 2-body collsion scale Q is taken equal to $p_\perp$, the transverse momentum exchanged in a parton scattering, or equal to $\hat{s}$ for annihilation or fusion processes. For MSTV(42)=0, the value $p_0 = a$ with a = PARV(42) defines *hard* ($Q > p_0$) and *soft* ($Q < p_0$) collisions. For MSTV(42)=1, see PARV(43). *Note:* If PARV(42) ≤ 0, then it is set automatically upon initialization to = 2.0.

PARV(43) : (D=0.0) parameter for effective p_0 value, if MSTV(42)=1, instead of $p_0 = const$ for MSTV(42)=0. The effective p_0 assumes a dependence on the total collision energy $\sqrt{s}$ and the mass of the (nuclear) collision system. It is parametrized as $p_0(\sqrt{s}, A, B) = \frac{a}{4} \cdot (E_h/GeV)^b$, where a = PARV(42), b = PARV(43), and $E_h = 2\sqrt{s}/(A+B)$ with A (B) the mass number of beam (target) particle, if it is a hadron or nucleus. *Note:* If PARV(43) ≤ 0, then it is set automatically upon initialization to = 0.27 - 0.29.

PARV(44) : (D=0.1) if MSTV(44)=1 or MSTV(44)=2, the proportionality between mean collision time τ of a 2-parton collision process, and the associated transverse momentum generated (for $\hat{s}$-channel processes, the invariant mass of the pair). It is parametrized as $\tau = c(1/Q)$, with c = PARV(45) and $Q = p_\perp$ or $\hat{s}$.

PARV(45) : (D=5. GeV^{-1}) maximum separation of two partons to be able to interact through a 2-body collision. For MSTV(45)=0, it is fixed at r_{12} = PARV(45), whereas for MSTV(45)=1, it is taken s-dependent as r_{12} = PARV(45)/$(\sqrt{\hat{s}}/GeV)$.

PARV(46) : (D=1.0) parameter in the collision-probability distribution $W(x) = \theta(a-x)$ (for MSTV(46)=0) and $W(x) = \exp(-x/a)$ for MSTV(46)=1, with $x = r_{12}^{(sep)}/r_{12}^{(\hat{\sigma})}$, $r_{12}^{(sep)}$ the relative transverse parton separation of closest approach and $r_{12}^{(\hat{\sigma})}$ the transverse radius of interaction as given by the parton-parton cross-section $\hat{\sigma}$.

PARV(47) : (D=1.0) for 'flavor excitation' processes where a primary hadronic or nuclear (anti)quark is struck out by a collision, an effective minimum resolution scale is required, depending on the flavor, such that the momentum transfer $Q^2 > a \cdot m_f$, with a = PARV(47) and m_f the flavor-dependent quark mass. This parameter acts in addition to the constraint set by PARV(42) above.

PARV(48) : (D=0.5 GeV) parameter in the phenomenological cross-section $d\hat{\sigma}/dQ^2 \propto \alpha_s^2(p_0^2)/(Q^2+\mu^2)$ for soft parton collisions, where μ = PARV(48), p_0 is given by PARV(42), and $Q^2 = p_\perp^2$ for $\hat{t},\hat{u}$ channel and $Q^2 = \hat{s}$ for $\hat{s}$ channel.

PARV(49) : (D=10.) parametric strength of $2 \to 1$ parton fusion processes $a + b \to c$ competing with $2 \to 2$ scattering processes $a + b \to c + d$. It is given by the ratio of the two processes which is proportional to $1/(R^2\hat{s})$, where $1/R^2$ =PARV(49).

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4. Space-like parton branchings:

MSTV(50) : (D=1) master switch for space-like branchings.

= **0** : switched off

= **1** : on.

MSTV(51) : (D=3) level of coherence imposed on the space-like parton shower evolution.

= **1** : none, i.e. neither k^2 values nor angles need be ordered.

= **2** : k^2 values at branches are strictly ordered, increasing towards the hard interaction.

= **3** : k^2 values and opening angles of emitted (on-mass-shell or time-like) partons are both strictly ordered, increasing towards the hard interaction.

MSTV(52) : (D=2) structure of associated time-like parton evolution, i.e. showers initiated by emission off the incoming space-like partons.

= **0** : no associated showers are allowed, i.e. emitted partons are put on mass-shell.

= **1** : a shower may evolve, with maximum allowed time-like virtuality set by the phase space only.

= **2** : a shower may evolve, with maximum allowed time-like virtuality set by phase space or by the scale Q^2, the virtuality of the space-like parton created at the same vertex, whichever is the stronger constraint.

PARV(51) : (D=0.25 GeV) Λ-value used in α_s and in structure functions for space-like parton evolution.

PARV(52) : (D=1.0 GeV) invariant mass cutoff q_0 of space-like parton showers, below which parton branchings re not evolved. For consistency it is taken as $q_0 = \max(Q_0, \mathrm{PARV}(52))$ where Q_0 =PARV(23) is the initial resolution scale in the hadron structure functions.

PARV(53) : (D=4.) Q^2-scale of the hard scattering is multiplied by PARV(53) to define the maximum parton virtuality allowed in space-like branchings associated with the hard interaction. This does not apply to $\hat{s}$-channel resonances, where the maximum virtuality is set by $m^2 = \hat{s}$.

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5. Time-like parton branchings:

MSTV(60) : (D=2) master switch for time-like branchings.
= **0** : no branchings at all, i.e. switched off.
= **1** : QCD type branchings of quarks and gluons.
= **2** : also emission of photons off quarks; the photons are assumed on mass-shell.

MSTV(61) : (D=2) branching mode for time-like parton evolution.
= **1** : conventional branching, i.e. without angular ordering.
= **2** : coherent branching, i.e. with angular ordering.

MSTV(62) : not used.

MSTV(63) : (D=1) choice of formation-time scheme for parton emission.
= **0** : no formation time, i.e. instantanous emission.
= **1** : finite formation time sampled from an exponential distribution $\exp(-x)$, where $x = t/\tau$, t the *time in the lab, and τ the mean life-time of the parton in the lab, see* PARV(63).
= **2** : finite formation time sampled from Gyulassy-Wang distribution $(2/\tau)\ x/(1+x^2)^2$, where $x = t/\tau$, t the time in the lab, and τ the mean life-time of the parton in the lab, see PARV(63).

MSTV(64) : not used.

MSTV(65) : (D=0) selection of kinematics reconstruction for branchings initiated by a single off-shell parton.
= **0** : conservation of energy and jet direction, but longitudinal momentum is not conserved.
= **1** : with full energy-momentum conservation at each branching, but the jet direction is not conserved due to recoil.

PARV(61) : (D=0.29 GeV) Λ-value used in running α_s for time-like parton showers.

PARV(62) : (D=1.0 GeV) invariant mass cutoff μ_0 of time-like parton evolution, below which partons are not assumed to radiate. Exception: for the case MSTV(84)=3, for reasons of consistency, the value is automatically scaled to 1.5 × PARV(62).

PARV(63) : (D=0.01) if MSTV(63)=1 or MSTV(63)=2, the proportionality between mean-life time τ of an off-shell parton and its virtuality k^2, is parametrized as $\tau = c(1/\sqrt{k^2})$, with c = PARV(63). (Is inversely related to PARV(65)).

PARV(64) : (D=4.) Q^2-scale of the hard scattering is multiplied by PARV(64) to define the maximum parton virtuality allowed in time-like branchings associated with the hard interaction. This does not apply to $\hat{s}$-channel resonances, where the maximum virtuality is set by $m^2 = \hat{s}$.

PARV(65) : (D=4.) invariant virtuality k^2 of off-shell partons is multiplied PARV(65) to define the maximum parton virtuality allowed in time-like branchings of single parton decays. (Is inversely related to PARV(63)).

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6. Parton-cluster formation and cluster-hadron decay:

MSTV(80) : (D=1) master switch for hadronization of parton clusters.
= **0** : off.
= **1** : on.

MSTV(81) : (D=1) choice of definition of 2-parton spatial separation $r_{12} = r_1 - r_2$ between two partons 1, 2, for measuring probability of pre-hadronic cluster formation of the two partons.
= **0** : distance r_12 measured in the global frame of the collision event.
= **1** : distance r_12 measured in the center-of-mass frame of 1 and 2.
= **2** : distance r_12 measured in the rest-frame of parton 1.

MSTV(82) : (D=4) choice of definition of 2-parton momentum separation p_{12} of two partons 1, 2, for pre-hadronic cluster search.
= **1** : three-momentum, i.e. $p_{12} = \sqrt{p_{x\,12}^2 + p_{y\,12}^2 + p_{z\,12}^2}$.
= **2** : transverse momentum, i.e. $p_{12} = \sqrt{p_{x\,12}^2 + p_{y\,12}^2}$.
= **3** : 'pseudo-mass', i.e. $p_{12} = \sqrt{2\,E_1E_2\,(1 - p_1p_2)/(m_1m_2)}$.
= **4** : invariant mass', i.e. $p_{12} = \sqrt{E_{12}^2 - p_{x\,12}^2 + p_{y\,12}^2 + p_{z\,12}^2}$.

MSTV(83) : (D=1) choice of probability distribution from which cluster formation of 2 partons is sampled. Simulates the conversion process as a 'tunneling' of the partons through a potential barrier set by PARV(81) and PARV(82), separating perturbative and non-perturbative regimes.
= **0** : flat distribution, i.e. θ-function.
= **1** : exponential distribution.

MSTV(84) : (D=3) level of including color correlations among pairs of partons in the process of cluster formation.
= **0** : none, except that *clustering of two partons originating from the same mother is vetoed.*
= **1** : probability of two cluster candidates being in a color singlet state is sampled uniformly with factors $C_{gg} = 1/9$, $C_{q\bar{q}} = 1/3$, $C_{gq} = 1/3$.
= **2** : exact matching of colors and anticolors of two partons is required to give color singlet(s).
= **3** : general case, where arbitrary color configuration of two partons is allowed, and color singlet formation is balanced by additional gluon emission(s) to conserve color locally at each vertex.

MSTV(85) : (D=0) option allowing for diquark clustering, i.e. sequential clustering of two (anti)quarks plus a third (anti)quark (not yet working properly!).
= **0** : off.
= **1** : on.

MSTV(87) : (D=0) choice of effective invariant masses of partons to ensure that kinematical thresholds for cluster-hadron decay can be satisfied.
= **0** : 'curent' masses are used, i.e. m_f = (0.05, 0.01, 0.01, 0.2, 1.5, 5.0, 150) GeV for $f = g, d, u, s, c, b, t$, respectively.
= **1** : 'constituent' masses are used, i.e. m_f = (0.5, 0.32, 0.32, 0.5, 1.8, 5.2, 150) GeV for $f = g, d, u, s, c, b, t$, respectively.

MSTV(88) : (D=0) choice of measure for rough distinction between 'slow' and 'fast' clusters in statistics accumulation of exogamous cluster production with numerical value of boundary given by PARV(88).
= **0** : energy E_{cl}.
= **1** : 3-momentum P_{cl}
= **2** : cluster velocity $\beta = P_{cl}/E_{cl}$.
= **3** : Lorentz factor $\gamma = E_{cl}/M_{cl}$.

MSTV(89) : (D=1) smearing of cluster rapidities within an interval $|y| \le y_c$, where y_c is determined by PARV(89).

MSTV(90) : (D=1) master switch for hadronization of beam/target remnants.
= **0** : off.
= **1** : on.

MSTV(91) : (D=1) switch for the decay of unstable hadrons, emerging either directly from cluster-decays, or from previous unstable hadron decays,
= **0** : off.
$\geq$ **1** : the decay chain is iterated MSTV(91) times, but at most 5 times.

MSTV(92) : (D=1) switch for simulating *stopping effect* in nucleus-nucleus collisions of initial-state nucleons by redistributing them in transverse momentum $p_\perp$ according to a $1/(1+bp_\perp^2)^4$ distribution (approximately an exponential for $p_\perp \leq 2$ GeV), and in longitudinal momentum p_z (or rapidity) according to a Gaussian distribution $\exp[-P_{beam}^2/(2c^2)]$. The parameters b and c are given by PARV(97) and PARV(98), respectively. Option MSTV(92) is inactive for collisions without nuclei.
= **0** : off, i.e. beam nucleon distributions shaped analogous to proton-proton collisions.
= **1** : beam protons and neutrons are redistributed.
= **2** : as = 1, plus Δ's associated with beam nucleon interactions are included.
= **3** : as = 2, plus π's and K's from beam nucleon interactions are accounted.

MSTV(93) : (D=2) option to distingiush - in beam fragmentation of colisions with nuclei - into 'unwounded' and 'wounded' beam nucleons. Former are those whose initial parton content has not altered throughout a collisions, latter are those who have been struck at least once in a hard parton collision. Option MSTV(93) is inactive for collisions without nuclei.
= **0** : off, i.e. spectator partons are not reassembled to their initial mother nucleons, but all those non-interacted spectator partons that belong to an 'unwoundsed' nucleon, are lumped together with the spectator partons from 'wounded' nucleons and hadronize as usual via the beam-fragmentation scheme.
= **1** : on, i.e. for all those nucleons that have not lost a daughter parton through parton collisions, their initial parton content is recollected, and these 'unwounded' nucleons appear in the final state with their initial energy-momentum, modulo some aquired Fermi motion. In this case, only the partons from 'wounded' nucleons participate in the beam-fragmentation, specifically, only a fraction of all initial-state nucleons which is set by PARV(99) (see below).
= **2** : as = 1, but now the reassembled nucleons undergo subsequent fragmentation and are broken up.

MSTV(94) : (D=1) Switch to allow to cluster together excess pions from low-mass parton recombinations, if their density gets above a critical value, and to convert them either into energy transferred to the environment, or to convert then into particle production (see MSTV(95) and MSTV(96)). Specifically, close-by pions lumped together in clusters of mass $\geq 1-5$ GeV and the energy-momentum of these clusters is then transferred to the remaining particle system, or, alternatively, the energy-momentum of π clusters with mass $\geq 1-5$ GeV is converted into pair production of $\pi^\pm, \rho, \omega$.
= **0** : off, i.e. no action taken.
= **1** : on.

MSTV(95) : (D=0) For MSTV(94) > 0, the critical density above which pions may percolate to clusters is set by MSTV(95). IF MSTV(95) ≤ 0, its value is set automatically upon initialization.

MSTV(96) : (D=0) For MSTV(94) > 0, the maximum mass of clusters of pions that can be percolated is set by MSTV(96). IF MSTV(96) ≤ 0, its value is set automatically upon initialization.

MSTV(97) : (D=0) Switch to select shape of $p_\perp$ spectrum of final-state hadrons emerging from fragmentation of beam/target clusters in collisions involving nuclei.
= **0** : exponential distribution $\propto \exp(-bm_\perp]$, $m_\perp = \sqrt{p_\perp^2 + m^2}$.
= **1** : power-law distribution $\propto 1/(m_\perp^2)^b$, $m_\perp = \sqrt{p_\perp^2 + m^2}$.

MSTV(98) : (D=0) Switch to select shape of y spectrum of final-state hadrons emerging from fragmentation of beam/target clusters in collisions involving nuclei. (Notice that in case MSTV(40) > 0, the camel-like option is selected by default, in order to compensate the spectra of hadrons from partonic clusters and those from soft beam/target clusters.)
= **0** : flat-top distribution, i.e. a central plateau with Gaussian tails.
= **1** : camel-like distribution, i.e. a central dip with Gaussian on either side.

MSTV(99) : (D=0) Switch to adjust left-right imbalance of beam/target hadron fragments, if there is such occurrence.
= **0** : off.
= **1** : on.

PARV(81) : (D=3.6 GeV^{-1}) minimum separation of 2 partons, below which a cluster cannot be formed (denoted R_χ in Ref. [9]).

PARV(82) : (D=4. GeV^{-1}) critical separation of 2 partons that sets the space-time scale for cluster formation (denoted R_{crt} in Ref. [9]). Is related to the average cluster size and typically about 10 % above R_χ.

PARV(83) : (D=1.0) 'slope' of the exponential probability distribution $W(R) = \theta(R - R_\chi)\exp(-\text{PARV}(83)R/R_{crt})$ for MSTV(83)> 0, describing the probability of 2 partons to form a pre-hadronic cluster by tunneling through the 'potential barrier' marked by R_χ and R_{crt}, with average cluster size $R_{cl} = 2R_{crt}/\text{PARV}(83)$.

PARV(84) : (D=0.3 GeV) minimum invariant mass of 2 partons required to form a cluster being necessarily above threshold for hadron decay.

PARV(85) : (D=1000. GeV) maximum allowed invariant mass of 2 partons to form a cluster with mass M_{cl}, in order to provide option to suppress production of heavy clusters - in addition to the requirement of PARV(81),PARV(82). Note: default corresponds to no suppression.

PARV(86) : (D=5. GeV^{-1}) maximum allowed separation of 2 partons that are unambigous cluster candidates. Cluster formation is enforced above this value, in order to avoid unphysical separation. In this case the requirement $M_{cl} <$ PARV(85) is overridden.

PARV(87) : (D=1.) 'slope' of exponential Hagedorn-type distribution for sampling the masses of clusters in their 2-body decays, given by $\exp(-a \cdot M_{cl}/M_0)$, where a = PARV(87), M_{cl} is the cluster mass and $M_0 = 0.2$ GeV is the 'Hagedorn temperature' (see Ref. [9]).

PARV(88) : (D=1. GeV) boundary for distinguishing 'slow' and 'fast' clusters in statistics accumulation of exogamous cluster production (c.f. MSTV(88)).

PARV(89) : (D=0.2) determines value of y_c = PARV(89) y_{beam} for smearing of parton cluster rapidities within an interval $|y| \leq y_c$, if MSTV(89) > 0.

PARV(90) : (D=0.0) determines value of y_c = PARV(90) y_{beam} for smearing of beam cluster rapidities within an interval $|y| \leq y_c$. If PARV(90) < 0, it is ste automatically to pre-fitted value, otherwise, PARV(90) > 0 as user input takes this as fixed value.

PARV(91) : (D=0.0) Parametric factor for charged multiplicity from soft fragmentation of beam/target remnants that governs the magnitude of $N_{ch}(\sqrt{s})$ of hadrons emerging from spectator partons. If PARV(91) ≤ 0, then the value of PARV(91) is set automatically to pre-fitted value, otherwise, PARV(91) > 0 as user input takes this as fixed value. (Note: applies only if if MSTV(90) = 1).

PARV(92) : (D=0.0) Factor multiplying the energy of the remnant beam/target clusters that are formed from the spectator partons, and that are fragmented with the total energy E=PARV(92)$\cdot(E_{beam} + E_{target})$. If PARV(92) ≤ 0, then it is set automatically upon initialization.

PARV(93) : (D=1.0) Nuclear dependence in eA, hA or AB collisions of the charged multiplicity N_{ch}, resulting from soft fragmentation of nuclear beam or/and target remnants of the original nuclei with mass number A (B) (case of hadron h corresponds to $A = 1$ or $B = 1$). It is parametrized as: $N_{ch}^{(AB)}(\sqrt{s}, A, B) = [(A+B)/2]^{\beta}\ N_{ch}^{(p\bar{p})}(\sqrt{s})$, where β = PARV(93).

PARV(94) : (D=15.GeV^{-1}) Time in the global collision frame when soft fragmentation starts to become gradually active (default corresponds to 35 fm.)

PARV(95) : (D=1000.GeV^{-1}) The positions of particles produced in fragmentation of both parton clusters and beam/target clusters, are assigned such they become active only after an effective formation time $\Delta t = PARV(95) \times \min(E/M^2$,PARV(95)) (default value corresponds $\Delta t \leq 200$ fm).

PARV(96) : (D=40.) proportionality factor in the uncertainty relation $\Delta t = PARV(96) \times E/M^2$, which determines the mean formation time of particles produced in soft beam/target fragmentation (c.f. PARV(95)).

PARV(97) : (D=0.35 GeV) parameter b in $1/(1 + bp_\perp^2)^4$ distribution for simulating *stopping effect* in nucleus-nucleus collisions of protons and neutrons (and optionally associated Δ's) by redistributing them in transverse momentum $p_\perp$ (c.f. MSTV(92)).

PARV(98) : (D=0.14 GeV) parameter c in Gaussian distribution $\exp[-P_{beam}^2/(2c^2)]$ for simulating *stopping effect* in nucleus-nucleus collisions of protons and neutrons (and associated Δ's) by redistributing them in longitudinal momentum p_z (c.f. MSTV(92)).

PARV(99) : (D=0.) Of all initial-state nucleons which have not lost a daughter parton through parton collisions (those that remained 'unwounded' nucleons) and appear in the final state with their initial energy-momentum, a fraction $0 \leq$PARV(93)≤ 1 is fragmented via the usual beam/target fragmentation scheme, whereas the fraction 1$-$PARV(99) appears as original nucleons in the final state. Is inactive for MSTV(93) = 0.

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7. 'Afterburner' Hadron cascade:

MSTV(100) : (D=3) switch to select various levels of final-state hadron cascading in terms of scattering and resonance production with decay of direction of primary hadrons emerging from both, the parton cluster formation and the beam/target fragmentation. (See additional control switches MSTV(101)-MSTV(103)).
= **0** : switched off completely, i.e., no final-state hadron cascade.
= **1** : switched on, but including *only* hadron cascading of hadrons from parton cluster decays and excluding re-interactions among hadrons from the beam/target fragmentation.
= **2** : switched on, but in contrast to = 1, now *only* hadron cascading of hadrons from beam/target fragmentation are allowed ans re-interactions among hadrons from the parton cluster decays are excluded.
= **3** : switched on in full, i.e., any hadron can re-interact irrespective to its origin.

MSTV(101) : (D=1) Additional selection option in addition to MSTV(100) that allows to include/exclude hadrons that have not become 'real', i.e., that have not passed through their formation time.
= **0** : only on-shell hadrons can interact, that is, those which have passed their formation time.
= **1** : both on-shell hadrons and off-shell hadrons which have *not* passed their formation time yet, can take part in the hadron cascading.

MSTV(102) : (D=3) switch to include/exclude interactions in which pre-hadronic clusters (not yet formed hadrons) are involved (note: applies only if MSTV(101) = 1).
= **0** : no pre-hadronic clusters can interact.
= **1** : only pre-hadronic clusters from parton cluster formation may participate in the hadron cacade.
= **2** : in contrast to = 1, now only clusters from beam/target fragmentation are included in the hadron cacade.
= **3** : any pre-hadronic cluster can interact with other hadrons or clusters, irrespective of the origin.

MSTV(103) : (D=2) Sets (for MSTV(102) $\geq$ 1) the maximum number of preformed hadrons for which is searched for in the event record in order to reconstruct the original cluster from whose decay the hadrons emerged.

MSTV(105) : – not used –

PARV(100) - PARV(104) : – not used –

PARV(105) : (D=5. GeV^{-1}) maximum separation of two hadronic particles to be able to interact through a 2-body collision. For MSTV(105)=0, it is fixed at r_{12} = PARV(105), whereas for MSTV(105)=1, it is taken s-dependent as r_{12} = PARV(105)/$(\sqrt{s}/GeV)$.

PARV(106) : (D=1.0) parameter in the collision-probability distribution $W(x) = \theta(a-x)$ (for MSTV(106)=0) and $W(x) = \exp(-x/a)$ for MSTV(106)=1, with $x = r_{12}^{(sep)}/r_{12}^{(\sigma)}$, $r_{12}^{(sep)}$ the relative transverse hadron separation of closest approach and $r_{12}^{(\hat{\sigma})}$ the transverse radius of interaction as given by the hadron-hadron cross-section σ.

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8. Other settings:

- *Handling of input/output:*

MSTV(110) : (D=1) direction of program output.
= **0** : all output is directed to standard output unit 6.
= **1** : output is directed to units MSTV(111)-MSTV(113).

MSTV(111) : (D=10) unit number to which general output is directed.

MSTV(112) : (D=6) unit number for writing 'on-line' information.

MSTV(113) : (D=20) unit number for listing warnings and error messages.

MSTV(114) : (D=0) switch for general information on unit MSTV(111), which is directed automatically to file VNIRUN.DAT. Allows to select the amount of output provided on the global performance of a simulation consisting of of a sample of collision events:
= **0** : only minimal output concerning selected process and main parameters is written out, as well as final summary of results.
= **1** : as =0, plus a listing the 1st event in momentum and position space.
= **2** : as =1, plus listing of number and properties of elementary subprocesses that occurred during the simulation, written to files VNICOL.DAT, VNISBR.DAT and VNITBR.DAT for collisions, space-like and time-like branchings, respectively.
= **3** : as =2, plus detailed event listing of particle record at the end of each single event, written to VNIRUN.DAT. NOTE: for large particle systems, this slows down the program substantially, and moreover requires a lot of disc space if a large number of events are printed).

MSTV(115) : (D=2) switch for 'on-line' information on unit MSTV(112). i.e. writing of initialization and termination info, and initial and final entries for each event as the simulation goes on.
= **0** : no 'online output'.
= **1** : only initialization and finalization info is printed.
= **2** : 1-line info at beginning and at the end of each event to keep control of the program performance,

= **3** : as = 2, plus listing of entries in particle record after each single time-step in an event (useful for AB collisions).
= **4** : as = 3, plus writing 'standardized' output to file VNIOSC.DAT, according to the OSCAR (Open Standard Codes At RHIC) conventions established at RIKEN-BNL, June 1997.
= **5** : as = 3, plus an "on-screen" display of a sctech of the collision in space-time.

- *Miscellanous control switches for subroutines:*

MSTV(120) : (D=0) flag to indicate initialization of certain HERWIG common blocks and default values that are necessary for using parts of the HERWIG program for the hadronization of clusters. Is set equal to 1 after first intitialization call.

MSTV(121) : (D=0) if MSTV(121) is set to 1 before a VNIROBO call, the V vectors are reset (in the particle range to be rotated/boosted), i.e., they are set to 0 before the rotation/boost. If MSTV(121) is equal to zero, the V vectors are not reset. MSTV(121) is inactive during a VNIROBO call and is set back to 0 upon return.

MSTV(122) : (D=0) specifies in a VNIROBO call the type of rotation of the P, R, and V vectors. The rotation is clockwise (active rotation) for MSTV(122)=0 and anticlockwise (passive rotation) otherwise. The value of MSTV(122) is set back to 0 upon return.

MSTV(123) : (D=0) specifies in a VNIROBO call for performing a boost, whether the vectors R are boosted (MSTV(123)=0) or not (MSTV(123)=1). The vectors P are always boosted. The value of MSTV(123) is set back to 0 upon return.

MSTV(124) : (D=1) pointer to lowest entry in particle record VNIREC1/VNIREC2 to be included in data analysis routines VNIANA1-VNIANA4.

MSTV(125) : (D=100000) pointer to highest entry in particle record VNIREC1/VNIREC2 to be included in data analysis routines VNIANA1-VNIANA4.

MSTV(126) : (D=20) number of lines in the beginning of the particle record that are reserved for internal event history information. The value should not be reduced, but can be increased if necessary.

MSTV(127) : (D=1) in listing of the current state of the particle record by calling the subroutine VNILIST, it can be chosen between listing either color/anticolor C A and the space time origin of a particle I according to the information contained $V(I,5)$ explained above, ($= 0$), or, alternatively the mother KMO and color flow information contained in $K(I,3) - K(I,5)$, ($= 1$). All other listed quantities are the same for either option.

MSTV(128) : (D=0) specifies in calls to VNIEDIT and VNIROBO the classes of particles to be included. The default = 0 *ex*cludes all inactive or decayed particles with $K(I,1) \leq 0$ or $K(I,1) > 10$, whereas the setting = 1 *in*cludes any entry listed in the particle record. MSTV(128) is set back to 0 upon return.

MSTV(129) : (D=0) specifies in calls to the 'color-linking' routine VNIJCOL the way of encoding the color connections between partons in the components $J = 4,5$ of the array $K(I,J)$. For very large number of entries ($\geq$ 35000) in the record VNIREC, MSTV(129) is set automatically to = 1 in the hadronization process, in order to save memory space. It is reset to = 0 afterwards.

- *Handling of errors and warnings:*

MSTV(130) : (D=2) check on possible errors during program execution.
= **0** : errors do not cause any immediate action.
= **1** : possible errors are checked and in case of problem, it is excited from the subprogram, but the simulation is continued from there on. For the first MSTV(101) errors a message is printed; after that no messages appear.
= **2** : possible errors are checked and in case of problem, the the simulation is forcibly terminated. For the first MSTV(101) errors a message is printed; after that no messages appear.

MSTV(131) : (D=10) max number of errors that are printed.

MSTV(132) : (D=1) printing of warning messages.
= **0** : no warnings are written.
= **1** : first MSTV(103) warnings are printed, thereafter no warnings appear.

MSTV(133) : (D=10) max number of warnings that are printed.

- *Version, date of last change:*

MSTV(140) : (D=1) Print-out of VNI logo on first occasion; MSTV(140) is reset to 0 afterwards.

MSTV(141) : VNI version number.

MSTV(142) : VNI subversion number.

MSTV(143) : year of last change of VNI version

MSTV(144) : month of last change of VNI version.

MSTV(145) : day of last change of VNI version.

9. Statistics, event study and data analysis:

- *Particle record* VNIREC1/VNIREC2: *Choosing event history information.*

MSTV(150) : (D=0) specifies whether the complete particle history with all particles produced at any time during an event, is kept throughout the simulation (rather inefficient for large systems) or whether it is compressed at the end of each time step (thereby loosing information on parent/child genealogy etc.).
= **0** : particle record is greatly compressed after each time step, all 'dead' particles are removed and genealogical history is lost.
= **1:** particle record is partly compressed, keeping some of the genelogical history.
= **2:** full particle history is kept throughout.

- *Subroutine* VNIANA1: *General event statistics.*

MSTV(151) : (D=0) Statistics on initial parton state.

MSTV(152) : (D=0) Number and momenta of produced particles.

MSTV(153) : (D=0) Factorial moments.

MSTV(154) : (D=0) Energy-energy correlations.

MSTV(155) : (D=0) Decay channels.

- *Subroutine* VNIANA2: *Statistics on hadronic observables.*

MSTV(161) : (D=0) time-evolution of flavor, energy and momentum composition.

MSTV(162) : (D=0) Distributions of particles in $y = \ln(1/x)$.

MSTV(163) : (D=0) Bose-Einstein correlation analysis.

- *Subroutine* VNIANA3: *Statistics on pre-hadronic clusters.*

MSTV(171) : (D=0) Rapidity spectra of clusters dN/dy.

MSTV(172) : (D=0) Longitudinal space-time spectra dN/dz.

MSTV(173) : (D=0) Transverse momentum spectra $(1/p_\perp)\ dN/dp_\perp$

MSTV(174) : (D=0) Transverse space-time spectra $(1/r_\perp)\ dN/dr_\perp$.

MSTV(175) : (D=0) Distributions of cluster sizes and masses.

MSTV(176) : (D=0) Polarization profile of cluster density.

- *Subroutine* VNIANA4: *Statistics on partons and produced hadrons.*

MSTV(181) : (D=0) Rapidity spectra of partons and hadrons dN/dy.

MSTV(182) : (D=0) Longitudinal space-time spectra dN/dz.

MSTV(183) : (D=0) Transverse momentum spectra $(1/p_\perp)\ dN/dp_\perp$.

MSTV(184) : (D=0) Transverse space-time spectra $(1/r_\perp)\ dN/dr_\perp$.

MSTW(200), PARW(200): generated quantities and statistics

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1. General:

MSTW(1) : total number of collision events to be generated.

MSTW(2) : total number of time steps per collision event.

MSTW(3) : physics process $A + B$ that is simulated. The current available beam (A) and target (B) particles and the collision processes are the ones listed before in Table 1, with MSTW(3)=IPRO (see also selection switch MSTV(30)).

MSTW(4) : Overall Lorentz frame of reference for event siumulation.
= 1 : center-of-momentum frame (CMS) of beam and target particle.
= 2 : fixed-target frame (FIXT) with target particle at rest.
= 3 : user-defined frame (USER) with given *3-momentum* of beam and target. Particles are assumed on the mass shell.
= 4 : user-defined frame (FOUR) with given *4-momentum* (i.e., 3-momentum and energy) of beam and target particle. The particles need not to be on the mass shell.
= 5 : user-defined frame (FIVE) with given *5-momentum* (i.e., 3-momentum, energy and mass) of beam and target particle. The particles need not to be on the mass shell, but 4-momentum and mass information must(!) match.

MSTW(5) : KF flavour code for beam particle A.

MSTW(6) : KF flavour code for target particle B.

MSTW(7) : type of incoming beam particle A: 1 for lepton, 2 for hadron, and 3 for nucleus.

MSTW(8) : type of incoming target particle B: 1 for lepton, 2 for hadron, and 3 for nucleus.

MSTW(9) : combination of incoming beam and target particles.
= **1** : lepton on lepton
= **2** : lepton on hadron
= **3** : lepton on nucleus
= **4** : hadron on lepton
= **5** : hadron on hadron
= **6** : hadron on nucleus
= **7** : nucleus on lepton
= **8** : nucleus on hadron
= **9** : nucleus on nucleus

MSTW(10) : performance flag for current event. Is =0 at beginning, and set =1 if during the evolution the event turns out to be rejectable, either due to unphysical kinematics, particle combinations, etc., or due to numerical errors.

MSTW(11) : current collision event.

MSTW(12) : current time step in this collision event.

MSTW(13) : current number of successful collision events, i.e. those that completed gracefully with MSTW(10)=0.

MSTW(14) : counter for "non-diffractive" collisions events, i.e. those that involved at least one parton collision (in hadron or nucleus collisions).

MSTW(15) : Status of Lorentz transformation between different global Lorentz frames in which the collision event is simulated (which may be different from the initially specified frame, c.f. MSTW(4)). The value of MSTW(15) saves the last performed transformation:
= **1** : from global *cm*-frame to fixed-target or user-specified frame;
= **2** : from global *cm*-frame to hadronic center-of-mass in DIS (photon-hadron *cm*-frame);
= **-1** : from fixed-target or user-specified frame to global *cm*-frame;
= **-2** : from hadronic center-of-mass in DIS (photon-hadron *cm*-frame) to global *cm*-frame.

PARW(1) : time increment $TINC(I)$ in current time step I.

PARW(2) : time $TIME(I)$ in current time step I.

PARW(3) : local machine time (in CPU) passed when simulation started.

PARW(4) : local machine time (in CPU) when simulation ended.

PARW(5) : conversion factor CPU $\rightarrow$ seconds (machine-dependent: for most processors, it is equal to 0.01, i.e. 1 sec = 100 CPU.

PARW(11) : Total invariant $\sqrt{s} = E_{CM}$, i.e. the total CM energy of the collision system.

PARW(12) : Invariant $s = E_{CM}^2$ mass-square of complete system.

PARW(13) : CM energy per nucleon $E_{CM}/(A+B)$ (where A (B) is the mass number of beam (target), and $A + B$ is the total number of nucleons in the system) in collisions involving nuclei. Is equal to E_{CM} for elementary particle- and hadronic collisions.

PARW(14) : Invariant $s_{eff} = E_{CM}^2/(A+B)$ mass-square per nucleon in collisions involving nuclei. Is equal to s for elementary particle- and hadronic collisions.

PARW(15) : mass M_A of beam particle.

PARW(16) : mass M_B of target particle.

PARW(17) : longitudinal momentum P_{zA} of beam particle in specified global frame.

PARW(18) : longitudinal momentum P_{zB} of target particle in specified global frame.

PARW(19) : angle θ of rotation from CM frame to user-defined frame (also, in e^+e^- via W^+W^-, the rotation of the W-pair along the z-axis).

PARW(20) : azimuthal angle ϕ of rotation from CM frame to user-defined frame, corresponding to PARW(18).

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2. Initial state of collision system:

MSTW(21) : number of neutrons of beam particle A.

MSTW(22) : number of neutrons of target particle B.

MSTW(23) : number of protons of beam particle A.

MSTW(24) : number of protons of target particle B.

MSTW(25) : number of d-valence quarks of beam particle A.

MSTW(26) : number of d-valence quarks of target particle B.

MSTW(27) : number of u-valence quarks of beam particle A.

MSTW(28) : number of u-valence quarks of target particle B.

MSTW(29) : number of s-valence quarks of beam particle A.

MSTW(30) : number of s-valence quarks of target particle B.

MSTW(31) : total number of initial state partons in collisions involving one or more hadron or nucleus.

MSTW(32) : number of initial gluons.

MSTW(33) : $10^5\times$ number of d quarks + number of $\bar{d}$ antiquarks.

MSTW(34) : $10^5\times$ number of u quarks + number of $\bar{u}$ antiquarks.

MSTW(35) : $10^5\times$ number of s quarks + number of $\bar{s}$ antiquarks.

MSTW(36) : $10^5\times$ number of c quarks + number of $\bar{c}$ antiquarks.

MSTW(37) : $10^5\times$ number of b quarks + number of $\bar{b}$ antiquarks.

MSTW(38) : $10^5\times$ number of t quarks + number of $\bar{t}$ antiquarks.

PARW(21) : absolute value of velocity $\vec{\beta}_A$ of beam particle A.

PARW(22) : absolute value of velocity $\vec{\beta}_B$ of target particle$B$.

PARW(23) : Lorentz factor γ_A of beam particle A.

PARW(24) : Lorentz factor γ_B of target particle B.

PARW(25) : rapidity Y_A of beam particle A.

PARW(26) : rapidity Y_B of target particle B.

PARW(27) : radius R_A (in 1/GeV) of beam particle in its restframe.

PARW(28) : radius R_B (in 1/GeV) of target particle in its restframe.

PARW(29) : radius R_n (in 1/GeV) of neutron within in nucleus.

PARW(30) : radius R_p (in 1/GeV) of proton within in nucleus.

PARW(31) : accumulated average Q_0 of initial hadron (nucleus) parton distributions (equals the average momentum scale of primary parton collisions $\langle Q_{prim}\rangle$).

PARW(32) : accumulated average momentum fraction x_A of beam-side initial hadron (nucleus) parton distributions.

PARW(33) : accumulated average momentum fraction x_B of target-side initial hadron (nucleus) parton distributions.

PARW(34) : 3 times the total charge of beam-side particle.

PARW(35) : 3 times the total charge of target-side particle.

PARW(36) : ratio b/b_{max} of actual impact parameter $b_{min} \le b \le b_{max}$ to maximum allowed impact parameter of beam and target particles, if variable impact parameter is chosen (c.f. MSTV(32) and PARV(32), PARV(33)).

PARW(37) : azimuthal angle of colliding beam and target particles around the beam axis, if variable impact parameter is chosen.

PARW(38) : sign of r_x-coordinate of beam-particle A in global frame for variable impact parameter selection (= $-$ sign of target-particle B).

PARW(39) : sign of r_y-coordinate of beam-particle A in global frame for variable impact parameter selection (= $-$ sign of target-particle B).

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3. Parton scatterings:

MSTW(40) : Total number of 2-parton collisions $a + b \to N$ $(N = 1, 2)$.

MSTW(41) : Number of hard $2 \to 2$ collisions of $q + q, q + \bar{q}, \bar{q} + \bar{q}$.

MSTW(42) : Number of hard $2 \to 2$ collisions of $q + g, \bar{q} + g$.

MSTW(43) : Number of hard $2 \to 2$ collisions of $g + g$.

MSTW(44) : Number of soft $2 \to 2$ collisions of $q + q, q + \bar{q}, \bar{q} + \bar{q}$.

MSTW(45) : Number of soft $2 \to 2$ collisions of $q + g, \bar{q} + g$.

MSTW(46) : Number of soft $2 \to 2$ collisions of $g + g$.

MSTW(47) : Number of $2 \to 1$ fusions of $q + \bar{q}$.

MSTW(48) : Number of $2 \to 1$ fusions of $q + g, \bar{q} + g$.

MSTW(49) : Number of $2 \to 1$ fusions of $g + g$.

PARW(40) : total number of 'primary' (i.e., first) collisions among primary partons.

PARW(41) : accumulated average Q^2 of the 'primary' collisions.

PARW(42) : accumulated average $\sqrt{\hat{s}}$ of hard $2 \to 2$ collisions.

PARW(43) : accumulated average rapidity $y^* = y_1^* - y_2^*$ of hard $2 \to 2$ collisions.

PARW(44) : accumulated average $p_\perp$ of hard $2 \to 2$ collisions.

PARW(45) : accumulated average $\sqrt{\hat{s}}$ of soft $2 \to 2$ collisions.

PARW(46) : accumulated average rapidity $y^* = y_1^* - y_2^*$ of soft $2 \to 2$ collisions.

PARW(47) : accumulated average $p_\perp$ of soft $2 \to 2$ collisions.

PARW(48) : accumulated average $\sqrt{\hat{s}}$ of hard $2 \to 1$ collisions.

PARW(49) : accumulated average rapidity $y^* = y_1^* - y_2^*$ of hard $2 \to 1$ collisions.

PARW(50) : integrated 2-parton cross-section $\hat{\sigma}(\hat{s}) = \int dp_\perp^2 (d\hat{\sigma}(\hat{s}, p_\perp^2)/dp_\perp^2)$.

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4. Space-like parton branchings:

MSTW(50) : Total number of space-like branchings $a \to b + c$.

MSTW(51) : Number of space-like processes $CM shower \to b + c$.

MSTW(52) : Number of space-like processes $q(\bar{q}) \to q(\bar{q}) + g$.

MSTW(53) : Number of space-like processes $g \to g + g$.

MSTW(54) : Number of space-like processes $g \to q + \bar{q}$.

MSTW(58) : Number of space-like processes $q/q \to q(\bar{q}) + \gamma$.

PARW(50) : average $\sqrt{Q^2}$ of starting scale for space-like branching evolution.

PARW(51) : average $\sqrt{-q^2}$ of virtuality of branching particle.

PARW(52) : average value of x in $x \to x'x''$ branching.

PARW(53) : average fraction $z = x'/x$ of space-like branchings.

PARW(54) : average relative transverse momentum $q_\perp$ of space-like branchings.

PARW(55) : average longitudinal momentum q_z of branching particle.

PARW(56) : average energy of q^0 branching particle.

PARW(57) : average invariant mass $\sqrt{|q^2|}$ of branching particle.

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5. Time-like parton branchings:

MSTW(60) : Total number of time-like branchings $a \to b + c$.

MSTW(61) : Number of time-like processes $CM shower \to b + c$.

MSTW(62) : Number of time-like processes $q(\bar{q}) \to q(\bar{q}) + g$.

MSTW(63) : Number of time-like processes $g \to g + g$.

MSTW(64) : Number of time-like processes $g \to q + \bar{q}$.

MSTW(68) : Number of time-like processes $q(\bar{q}) \to q(\bar{q}) + \gamma$.

PARW(60) : average $\sqrt{Q^2}$ of starting scale for time-like branching evolution.

PARW(61) : average $\sqrt{k^2}$ of virtuality of branching particle.

PARW(62) : average value of x in $x \to x'x''$ branching.

PARW(63) : average energy fraction $z = x'/x$ of time-like branchings.

PARW(64) : average relative transverse momentum $k_\perp$ of time-like branchings.

PARW(65) : average longitudinal momentum k_z of branching particle.

PARW(66) : average energy of branching particle.

PARW(67) : average invariant mass $\sqrt{m^2}$ of branching particle.

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6. Parton-cluster formation and cluster-hadron decay:

MSTW(80) : Total number of 2-parton cluster formations.

MSTW(81) : Total number of gg clusterings, $gg \to CC + X$, where X is either 'nothing', or g, or gg.

MSTW(82) : Number of processes, $gg \to CC + g$.

MSTW(83) : Number of processes, $gg \to CC + gg$.

MSTW(84) : Total number of $q\bar{q}$ clusterings, $q\bar{q} \to CC + X$, where X is either 'nothing', or g, or gg.

MSTW(85) : Number of processes, $q\bar{q} \to CC + g$.

MSTW(86) : Number of processes, $q\bar{q} \to CC + gg$.

MSTW(87) : Total number of gq ($g\bar{q}$) clusterings, $gq \to C + X$, where X is either q or gq.

MSTW(88) : Number of processes, $gq \to CC + gq$.

MSTW(89) : Total number of $(qq)q \to CC$, $(\bar{q}\bar{q})\bar{q} \to CC$ clusterings.

MSTW(90) - MSTW(99) : Same as MSTW(80) - MSTW(89), but now for the corresponding numbers of 'exogamously' produced clusters, with 'exogamy index' $e_{cl} = (e_i + e_j)/2$ unequal to 0 or 1 (see Ref. [10]).

MSTW(100) : Total number of 'fast' clusters, classified according to the choices of MSTV(88)] and PARV(88).

MSTW(101) : Total number of 'slow' clusters, the fraction complimentary to the 'fast' one.

MSTW(110) : Total number of primary "neutral" particles per event, produced directly by cluster-hadron decays.

MSTW(111) : Number of primary leptons and gauge bosons.

MSTW(112) : Number of primary light mesons.

MSTW(113) : Number of primary strange mesons.

MSTW(114) : Number of primary charm and bottom mesons.

MSTW(115) : Number of primary tensor mesons.

MSTW(116) : Number of primary light baryons.

MSTW(117) : Number of primary strange baryons.

MSTW(118) : Number of primary charm and bottom baryons.

MSTW(119) : Number of other particles.

MSTW(120) - MSTW(129) : Same as MSTW(110) - MSTW(119), but now for charged particles only.

MSTW(130) - MSTW(139) : Same as MSTW(110) - MSTW(119), but now for the numbers of secondary neutral particles per event (i.e. those produced by decays of unstable particles).

MSTW(140) - MSTW(149) : Same as MSTW(130) - MSTW(139), but now for charged particles only.

PARW(81) : accumulated average space-time separation of clustered partons.

PARW(82) : accumulated average energy-momentum separation of clustered partons.

PARW(83) : minimum encountered separation of any two clustered partons with respect to chosen space-time measure (c.f. MSTV(81)).

PARW(84) : maximum encountered separation of any two clustered partons with respect to chosen space-time measure (c.f. MSTV(81)).

PARW(85) : minimum encountered separation of any two clustered partons with respect to chosen energy-momentum measure (c.f. MSTV(82)).

PARW(86) : maximum encountered separation of any two clustered partons with respect to chosen energy-momentum measure (c.f. MSTV(82)).

PARW(91) - PARW(99) : Gives the 'exo(endo)-gamy distribution' (see Ref. [10]) of clusters formed from partons with 'exogamy' index e_i, e_j, such that $e_{cl} = (e_i + e_j)/2$. Inital beam/target particles have $e = 0(1)$, so that e_{cl} lies in the interval [0,1], which is binned as $0, 0.05, 0.2, 0.3, 0.45, 0.55, 0.7, 0.8, 0.95, 1$, with PARW(90)-PARW(99) giving the numbers of clusters in the bins. Note: only those clusters are counted that are classified as 'fast' (c.f. MSTW(88)).

PARW(101) - PARW(109) : Same as PARW(91)-PARW(99), but for 'slow' clusters only. The sums PARW(91)+PARW(101), etc., hence give the total numbers.

PARW(110) - PARW(149) : not used.

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7. 'Afterburner' Hadron cascade:

MSTW(150) : Total number of hadronic collisions involving clusters and/or hadrons.

MSTW(151) : Number of collisions between two clusters $C + C$, where only *light* quark flavors are involved.

MSTW(152) : Number of $C + C$ collisions where *strange* quark flavor is involved.

MSTW(153) : Number of $C + C$ collisions where *charm* quark flavor is involved.

MSTW(154) : Number of $C + C$ collisions where *bottom* quark flavors is involved.

MSTW(155) : – not used –

MSTW(156) - MSTW(160) : Same as MSTW(151)-MSTW(155), but for cluster-meson collisions $C + M1$, where $M1$ are light mesons only.

MSTW(161) - MSTW(165) : Same as MSTW(156)-MSTW(160), but for cluster-meson collisions $C + M2$, where $M2$ are heavy or excited mesons.

MSTW(166) - MSTW(170) : Same as MSTW(161)-MSTW(165), but for cluster-baryon collisions $C + B$, where B is any type of baryon.

MSTW(171) - MSTW(175) : Same as MSTW(166)-MSTW(170), but for meson-meson collisions $M1 + M1$, where $M1$ *and* $M2$ are light mesons.

MSTW(176) - MSTW(180) : Same as MSTW(171)-MSTW(175), but for meson-meson collisions $M1 + M2$, where $M1$ is a light meson and $M2$ an excited or heavy meson.

MSTW(181) - MSTW(185) : Same as MSTW(176)-MSTW(180), but for meson-baryon collisions $M1 + B$, where $M1$ is a light meson and B any type of baryon.

MSTW(186) - MSTW(190) : Same as MSTW(181)-MSTW(185), but for baryon-baryon collisions $B + B$, where both B can be any type of baryon.

MSTW(191) - MSTW(195) : Same as MSTW(186)-MSTW(190), but for baryon-meson collisions $B + M2$, where B is any type of baryon and $M2$ an excited or heavy meson.

MSTW(196) - MSTW(200) : Same as MSTW(191)-MSTW(195), but for meson-meson collisions $M2 + M2$, where both $M2$ are excited or heavy mesons.

PARW(150) : $\langle \sqrt{s} \rangle$ of *all* cluster/hadron collisions.

PARW(151) : $\langle \sqrt{s} \rangle$ of cluster/hadron collisions involving only *light* flavors.

PARW(152) : $\langle \sqrt{s} \rangle$ of cluster/hadron collisions involving *strange* flavor.

PARW(153) : $\langle \sqrt{-t} \rangle$ of cluster/hadron collisions involving *charm* flavor.

PARW(154) : $\langle \sqrt{-t} \rangle$ of cluster/hadron collisions involving *bottom* flavor.

PARW(155) - PARW(159) : – not used –

PARW(160) - PARW(164) : $\langle \sqrt{-t} \rangle$ of cluster/ hadron collisions in paralell to

PARW(165) - PARW(169) : – not used –

PARW(170) - PARW(174) : $\langle\sqrt{-\hat{u}}\rangle$ of cluster/ hadron collisions in paralell to PARW(150)-PARW(154).

PARW(175) - PARW(179) : – not used –

PARW(180) - PARW(184) : $\langle n_{prod}\rangle$ of particles produced in cluster/ hadron collisions in paralell to PARW(150)-PARW(154).

PARW(185) - PARW(190) : – not used –

PARW(191) : Total number of 'unwounded' nucleons at the end of *current event* of collision with nuclei.

PARW(192) : Number of 'unwounded' nucleons at the end of *current event* which are *within* the transverse area of nuclear overlap.

PARW(193) : Number of 'unwounded' nucleons at the end of *current event* which are *outside* the transverse area of nuclear overlap.

PARW(194) - PARW(196 : Numbers of 'unwounded' nucleons *accumulated over all events* in collisions with nuclei, in paralell to PARV(191) - PARV(193).

PARW(197) : Number of determined pairs of 'unwounded' nucleons that are to be fragmented in current event (if they are within nuclear overlap area).

PARW(198) : Number of actually fragmented pairs of 'unwounded' nucleons in current event (ususally equals PARW(197)).

PARW(199) : Accumulated number of actually fragmented pairs of 'unwounded' nucleons, summed over all events.

PARW(200) : – not used –

3.8 Kinematics cuts and selection of subprocesses

The commonblock VNIKIN contains the arrays VKIN and MSUB, which may be used to impose specific kinematics cuts and to switch on/off certain subprocesses, respectively. The notation used in the following is that 'hat' denotes internal variables in a partonic interaction, while '*' is for variables in the global CM frame of the system as-a-whole. All dimensionful quantities are in units of GeV or GeV^{-1}.

Kinematics cuts can be set by the user before the VNIXRUN call. Most of the cuts are directly related to the kinematical variables used in the evolution of the system in each event, and in the event data analysis. Except for the entries VKIN(7) - VKIN(12), the assignments follow the convention of PYTHIA, in order to allow an easy interfacing.

Note, that in the current version of VNI, only the values VKIN(7)-VKIN(12) are actively used. All other quantities are related to parton collision processes involving one or more partons, which are only of relevance in reactions with hadrons (nuclei) in the initial state. As stated before, the latter are presently worked out, but not yet included in the package.

```
COMMON/VNIKIN/VKIN(200),MSUB(200),ISET(200)
```

Purpose: To impose kinematics cuts on the particles' interactions and their space-time evolution. Also, to allow the user to run the program with a desired subset of processes.

VKIN(1), VKIN(2) : (D=2.,-1. GeV) range of allowed $\hat{m} = \sqrt{\hat{s}}$ values. If VKIN(2) < 0, the upper limit is inactive.

VKIN(3), VKIN(4) : (D=2.,-1. GeV) range of allowed (D=0.,-1.) range of allowed $\hat{p}_\perp$ values for parton collisions, with transverse momentum $\hat{p}_\perp$ is defined in the rest-frame of the 2-body interaction. If VKIN(4) < 0, the upper limit is inactive. For processes which are singular in the limit $\hat{p}_\perp \to 0$ (see VKIN(6)), VKIN(5) provides an additional constraint. The VKIN(3) and VKIN(4) limits can also be used in $2 \to 1 \to 2$ processes. Here, however, the product masses are not known and hence assumed vanishing in the event selection. The actual $\hat{p}_\perp$ range for massive products is thus shifted downwards with respect to the nominal one.

VKIN(5) : (D=0.5 GeV) lower cutoff on $\hat{p}_\perp$ values, in addition to the VKIN(3) cut above, for processes which are singular in the limit $\hat{p}_\perp \to 0$ (see VKIN(6)).

VKIN(6) : (D=1. GeV) 2-body parton collision processes, which do not proceed only via an intermediate resonance (i.e. are $2 \to 1 \to 2$ processes), are classified as singular in the limit $\hat{p}_\perp \to 0$, if either or both of the two final state products has a mass $m <$ VKIN(6).

VKIN(7), VKIN(8) : (D=-100.,100.) range of allowed particle rapidities y^* in the CM frame of the overall system.

VKIN(9), VKIN(10) : (D=0.,1000.) range (in GeV) of allowed particle transverse momenta $k_\perp^*$ perpendicular to the z-axis in the global CM frame of the event.

VKIN(11), VKIN(12) : (D=-1000.,1000) range (in GeV^{-1}) of allowed longitudinal positions z^* of particles from the CM of the global collision system.

VKIN(13), VKIN(14) : (D=0.,1000.) range (in GeV^{-1}) of allowed transverse distances $r_\perp^*$ perpendicular to the z-axis in the CM frame of the global collision system.

VKIN(21), VKIN(22) : (D=0.,1.) range of allowed x_A (Bjorken-x) values for the parton of beam-side A that enters a parton collision.

VKIN(23), VKIN(24) : (D=0.,1.) range of allowed x_B (Bjorken-x) values for the parton of target-side B that enters a parton collision.

VKIN(25), VKIN(26) : (D=-1.,1.) range of allowed Feynman x_F values, where $x_F = x_A - x_B$.

VKIN(27), VKIN(28) : (D=-1.,1.) range of allowed $\cos(\hat{\theta})$ values in a $2 \to 2$ parton collision, where $\hat{\theta}$ is the scattering angle in the rest-frame of the 2-body collision.

VKIN(31), VKIN(32) : (D=2.,-1.) range of allowed $\hat{m}'$ values, where $\hat{m}'$ is the mass of the complete three- or four-body final state in $2 \to 3$ or $2 \to 4$ processes (while $\hat{m}$ (without a prime), constrained in VKIN(1) and VKIN(2), here corresponds to the one- or two-body central system). If VKIN(32) $<$ 0, the upper limit is inactive.

VKIN(35), VKIN(36) : (D=0.,-1.) range of allowed $\mathrm{abs}(\hat{t}) = -\hat{t}$ values in $2 \to 2$ processes. Note that for deep inelastic scattering this is nothing but the Q^2 scale of the photon vertex, in the limit that initial and final state radiation is neglected. If VKIN(36) < 0, the upper limit is inactive.

VKIN(37), VKIN(38) : (D=0.,-1.) range of allowed $\mathrm{abs}(\hat{u}) = -\hat{u}$ values in $2 \to 2$ processes. If VKIN(38) < 0, the upper limit is inactive.

VKIN(39) - VKIN(100) : currently not used.

VKIN(101) - VKIN(200) : reserved for internal use of storing kinematical variables of an event.

MSUB(ISUB) : array to be filled when MSTV(14) = 1 (for MSTV(14) = 0, the array MSUB is initialized in VNIXRIN automatically) to choose which subset of subprocesses to include in the generation. The ordering follows the ISUB code given before in Table 3.
= 0 : the subprocess ISUB is *excluded*.
= 1 : the subprocess ISUB is *included*.

ISET(ISUB) : gives the type of kinematical variable selection scheme used for subprocess ISUB.
= 1 : $2 \to 1$ processes (parton fusion processes).
= 2 : $2 \to 2$ processes (hard and soft parton scattering processes).
= 3 : $1 \to 2$ processes (parton branching processes).
= -1 : process is not yet implemented, but space is reserved.
= -2 : process is not defined.

3.9 Instructions on how to use the program

There are a variety of example programs available from the website http://rhic.phys.columbia.edu/rhic/vni. Below described is a very simple example, *vnixple.f*, disguised as a generic skeleton program that calls the steering routines VNIXRIN, VNIXRUN and VNIXFIN (c.f. Sec. 3.4) on a black-box-level. This example generates 1000 $p\bar{p}$ events at $\sqrt{s} = 546$ GeV. Each event is evolved for a time range of 0 - 30 fm in the $p\bar{p}$ center-of-mass frame (the global CM frame).

```
      PROGRAM VNIXPLE

C...Purpose: example for p+p~ collisions at CERN collider with 546 GeV.
      INCLUDE 'vni1.inc'
      CHARACTER*(8) FRAME,BEAM,TARGET


C...Required user input:
C.....number of events and final time (in fm).
      NEVT  = 1000
      TFIN  =   30.
C.....colliding particles, global Lorentz frame, and total energy.
      BEAM  = 'p+      '
      TARGET= 'p-      '
      FRAME = 'cms '
      WIN   = 546.

C.....Specify your change of default parameters here:
C     .........


C...Initialize simulation procedure.
      CALL VNIXRIN(NEVT,TFIN,FRAME,BEAM,TARGET,WIN)


C...Begin loop over of events.
      DO 500 IEVT=1,NEVT
```



```
C.....Generate collision event.
      CALL VNIXRUN(IEVT,TFIN)

C.....Analysis of event as-a whole.
C     .........

C...End loop over events.
  500 CONTINUE


C...Finish up simulation procedure.
      CALL VNIXFIN()


      END
```

This example is rather self-explanatory, and will become further clear with the following subsections. The "..." indicate where one can interface on a black-box-level with the program as-a-whole without needing to dig deeper into its subroutine structure. In particular, one can insert here histograming (either using the included portable package "vnibook.f", or any other package such as the HBOOK or PAW of the CERN library). Note also the pre-programmed histogram options discussed in Sec. 3.7 (switches MSTV(150)-MSTV(200)) and Appendix B (subroutines VNIANA1-VNIANA4).

In the above example only the final state at the end of each event is collected. If the user is interested in the actual space-time development of the collision events, he/she can access this by inserting in the loop over events the following extension:

```
C...Generate collision event; analyze evolution every 5 fm.
      TSTEP=5.
      NTIM=20

C.....Begin loop over time intervals.
      DO 400 ITIM=1,NTIM
      TRUN=ITIM*TSTEP
      IF(TRUN.GT.TFIN.OR.ITIM.EQ.NTIM) TRUN=TFIN
      CALL VNIXRUN(IEVT,TRUN)

C.....Analysis of time development.
C     .........

C.....End loop over time intervals.
  400 IF(TRUN.EQ.TFIN) GOTO 450
  450 CONTINUE
```

Remarks:

(i) In case one desires to interface with the PYTHIA program, one should write a little program with common block

```
COMMON/LUJETS/N,K(4000,5),P(4000,5),V(4000,5)
```

and which copies the variables N, K, P, and V of the particle record VNIREC1/VNIREC2 directly. Be aware however, that VNIREC1/VNIREC2 is dimensioned for 100000 entries, whereas LUJETS has space for only 4000 entries.

(ii) In case one desires to interface with the HERWIG program, one should write a little program with common block

```
      PARAMETER (NMXHEP=2000)
      COMMON/HEPEVT/NEVHEP,NHEP,ISTHEP(NMXHEP),IDHEP(NMXHEP),
     &JMOHEP(2,NMXHEP),JDAHEP(2,NMXHEP),PHEP(5,NMXHEP),VHEP(4,NMXHEP)
```

and which calls the routine HWHEPC($MCONV, IP, NP$) with $MCONV = 1$, $IP = 1$,and $NP = N$. Again, watch the dimensions, 100000 versus 2000.

3.10 Example for a typical collision event

As a result of running the above example program *vnixple.f*, a number of files are created in the directory, all of which are called VNI???.DAT, where "???" are either 3 letters, or 3 digits. The latter are data files that contain event statistics and other information on the performance of a run. (see Sec. 3.7, switches MSTV(150)-MSTV(200) and Appendix B for further options). By default only a few files are created:

VNIRUN.DAT containing the main summary of a simulation with print-out of results,

VNICOL.DAT containing a detailed summary of all parton collisions that occurred,

VNITIM.DAT containing the generated time-step grid and its real-time translation,

VNIRLU.DAT containing the status of the random number generator,

VNIERR.DAT containing error messages in case problems occur.

Most important is the file VNIRUN.DAT, which gives a summary of what occurred during a simulation on the parton cascade level, the cluster formation level and the hadron decay level. One can obtain a listing of an event by simply calling VNILIST(1) at the end or during an event, which gives a first impression (for a complete listing see Appendix D):

(i) The event record begins with the beam/target particles, here p and $\bar{p}$, which are then transformed to the center-of-mass frame (here it coincides with the global frame of reference).

(ii) Then follow the three valence quarks of p, and after that its intrinsic gluons and seaquark-pairs. After that the initial-sate valence quarks and gluons and seaquarks of $\bar{p}$ are listed.

(iii) Then comes the history of the cascade evolution, including hard scatterings with shower (bremsstrahlung), subsequent cluster-formation of the materialized partons and hadron decay of these parton clusters.

(iv) Finally, all non-materialized (non-interacted) partons are recombined to a beam- and a target cluster that undergo a soft fragmentation, again via cluster-hadron decay.

(v) At the very end the sum of charge, three-momentum, energy, and the total invariant mass of the collision system is printed.

Example of the particle record for a $p\bar{p}$ collision event at $\sqrt{s} = 546$ GeV.


```
                       Particle listing (summary: momentum space P in GeV)
                       event no.     1  time step  200   at time  34.75 fm

   I particle       KS      KF  C A     P_x       P_y       P_z         E          M

   1 (p+)           15    2212  0 0     .000      .000   272.998   273.000       .938
   2 (p~-)          15   -2212  0 0     .000      .000  -272.998   273.000       .938
=====================================================================================
   3 (p+)           15    2212  0 0     .000      .000   272.998   273.000       .938
=====================================================================================
   4 (p~-)          15   -2212  0 0     .000      .000  -272.998   273.000       .938
=====================================================================================
   5 (u)            13       2  1 0     .650      .048     1.786     2.319       .006
   6 (d)            13       1  1 0    -.593     -.165     2.092     2.587       .010
   7 (d~)           13      -1  0 3    -.135     -.452     6.724     6.886      -.490
   8 (d)            13       1  3 0     .413     -.211      .408      .935      -.484
   9 (g)            14      21  1 1    1.751      .556     2.232     3.398      -.682
     .
     .
=====================================================================================
  48 (d~)           13      -1  0 2     .526     -.150   -16.659    15.157       .010
  49 (u~)           13      -2  0 3    -.121     -.114    -4.941     4.106      -.174
  50 (u)            13       2  3 0    -.252     -.044    -1.576      .935      -.249
  51 (g)            13      21  3 2    -.110      .229   -12.733    11.449      -.234
     .
     .
=====================================================================================
     .
     .
  83 (g)            14      21  2 1    2.052     2.858     1.999     1.045     -3.909
  84 (d)            14       1  1 0     .000      .000    -8.008     8.008       .000
  85 (d)            14       1  2 0     .000      .000     8.008     8.008       .000
  86 (CMshower)     11      94  0 0    2.661     3.728    -3.710     8.110      5.571
  87 (d)            14       1  2 0    1.128      .073    -1.364     3.504      3.023
  88 (cluster)      11      91  0 0    1.116     1.615    -2.687     3.412       .750
  89 (cluster)      11      91  0 0    -.450     -.605     -.228     1.213       .922
  90 (cluster)      11      91  0 0   -1.528     -.662     1.381     2.181       .280
  91 (cluster)      11      91  0 0    1.252      .689    -1.272     3.136      2.484
  92 (cluster)      11      91  0 0     .110     -.650     5.219     5.796      2.433
  93 pi0             6     111  0 0     .660      .523     -.880     1.171       .135
  94 pi0             6     111  0 0     .461     1.090    -2.094     2.377       .135
  95 rho-            6    -213  0 0    -.334     -.562     -.332     1.068       .769
  96 pi0             6     111  0 0    -.110     -.046     -.182      .186       .135
  97 pi-             6    -211  0 0    -.678     -.312      .548     1.066       .140
  98 pi+             6     211  0 0    -.845     -.352      .547     1.203       .140
     .
     .
=====================================================================================
 109 (Beam-REM)     11      92  0 0    -.315      .737   274.428   281.871     70.164
 110 (Targ-REM)     11      93  0 0    -.907    -1.587  -276.508   247.044   -116.181
 111 (CMF)          15     100  0 0   -1.222     -.850    -2.080   528.915    528.909
=====================================================================================
 112 (cluster)      11      91  0 0    -.315      .737   274.428   281.871     70.164
 113 (cluster)      11      91  0 0    -.907    -1.587  -276.508   247.044   -116.181
```

```
 114 (Beam-REM)    11      92  0 0      .411     .648  127.485  127.543     3.762
 115 (a_1-)        17  -20213  0 0      .493     .228   19.200   19.250     1.275
 116 (Delta+)      17    2214  0 0     -.081     .420  108.286  108.293     1.232
 117 pi0            7     111  0 0      .490     .124    4.473    4.831      .135
 118 (rho-)        17    -213  0 0      .005     .102   14.584   14.605      .769
 119 pi0            7     111  0 0     -.160     .015   35.475   37.042      .135
 120 p+             7    2212  0 0      .085     .402   72.525   75.579      .938
 121 pi0            7     111  0 0     -.122    -.268    8.519    9.014      .135
 122 pi-            7    -211  0 0      .133     .367    5.779    6.174      .140
 123 (Targ-REM)    11      93  0 0    -1.252    -.510  -63.766   63.825     2.384
 124 (Delta~-)     17   -2214  0 0     -.779    -.303  -21.201   21.253     1.232
 125 (eta)         17     221  0 0     -.473    -.208  -42.565   42.572      .549
 126 pi0            7     111  0 0     -.072    -.254   -3.205    3.199      .135
 127 p~-            7   -2212  0 0     -.701    -.052  -18.281   18.903      .938
 128 pi0            7     111  0 0     -.179     .069  -12.277   12.622      .135
 129 pi0            7     111  0 0     -.060    -.060  -12.901   13.269      .135
 130 pi0            7     111  0 0     -.225    -.220  -17.816   18.363      .135
   .
   .
   .
 336 (rho+)        17     213  0 0     -.263     .404   -5.474    5.549      .769
 337 (omega)       17     223  0 0      .067    -.237  -31.485   31.496      .783
 338 pi0            7     111  0 0     -.342     .522   -5.018    5.113      .135
 339 pi+            7     211  0 0      .085    -.120    -.742     .657      .140
 340 pi0            7     111  0 0     -.309     .029  -10.513   10.790      .135
==================================================================================
                sum:     .00            .000     .000     .000  546.000   546.000
```

More information on pre-programmed print-out of results concerning for particle distributions, time evolution, observables, etc., can be switched on with switches MSTW(151) - MSTW(200), as explained in the previous Sec. 3.7.

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A Further physics routines

Aside from the three main routines VNIXRIN, VNIXRUN, and VNIXFIN, the physics routines described below form the heart of the program. In general, for each of the included collision processes of Table 1, there is an initialization routine VNI??IN that sets up the initial state, and an evolution routine VNIEV?? that carries out the time evolution of the particle distributions in phase-space, starting from the initial state. The routines VNICOLL, VNISBRA, VNITBRA, etc., therein perform the perturbative parton evolution in terms of parton collisions, space-like branchings, and time-like branchings, respectively. The routines VNICHAD, VNIBHAD, etc., deal with the cluster hadronization. These routines are universal and independent of the process under consideration.

`SUBROUTINE VNICOL2(NCOL)`

Purpose: to test for all possible pairings of 'alive' partons, whether a collision is allowed, and, if it is allowed, to evaluate the quantities characterizing the 2-body collision at the parton level according to the cross-section and to choose one of the possible subprocesses (channels).

$NCOL$: total number of found collisions.

`SUBROUTINE VNICOLL(ISUB,Q2,IP1,IP2,IP3,IP4)`

Purpose: to perform a 2-body parton collision, find outgoing flavors and colors and calculate kinematics and parton-parton collision.

$ISUB$: Subprocess of 2-body collision (c.f. Table 3).

$Q2$: Momentum transfer scale of subprocess (c.f. MSTV(43), Sec. 3.7).

$IP1$, $IP2$: Line numbers of paerons entering the interaction vertex.

$IP3$, $IP4$: Line numbers of particles emerging from the interaction vertex. For $2 \to 1$ processes $IP4$ is equal to zero.

`SUBROUTINE VNISBRA(IP1,IP2,QMAX)`

Purpose: to generate space-like parton evolution, by backward tracing of branching processes down to some initial resolution scale associated with a non-perturbative cut-off. The performance is regulated by the switches MSTV(50)-MSTV(52) and parameters PARV(51)-PARV(53) (c.f. Sec. 3.7).

$IP1$, $IP2$: partons in lines $IP1$ and $IP2$ in the commonblocks VNIREC1/VNIREC2, are evolved by space-like parton branchings from initial mass scale QMAX. If one of the particles is a non-radiating one, then only one branch is evolved, and the spectator particle role is then only to take up recoil due to emitted particles by the radiating one.

$QMAX$: initial mass scale, from which the two particles are evolved from $Q = QMAX$ backwards to lower $Q < QMAX$ until the cut-off $Q = q_0 \equiv$PARV(52) is reached.

`SUBROUTINE VNITBRA(IP1,IP2,QMAX)`

Purpose: to generate time-like parton evolution, by coherent branching processes within a finite time interval, $q \to qg$, $q \to \gamma$, $g \to gg$, $g \to q\bar{q}$. The performance is regulated by the switches MSTV(61)-MSTV(65) and parameters PARV(61)-PARV(65) (c.f. Sec. 3.7).

$IP1 > 0$ $IP2 = 0$: generate a time-like parton branching for the parton in line $IP1$ in commonblocks VNIREC1/VNIREC2, with maximum allowed mass $QMAX$.

$IP1 > 0$ $IP2 > 0$: generate time-like parton branchings for the two partons in lines $IP1$ and $IP2$ in the commonblocks VNIREC1/VNIREC2, with maximum allowed mass for each parton $QMAX$.

$QMAX$: the maximum allowed mass of a radiating parton, i.e. the starting value for the subsequent evolution. (In addition, the mass of a single parton may not exceed its energy, the mass of a parton in a system may not exceed the invariant mass of the system.)

`SUBROUTINE VNICHAD(I1,I2)`

Purpose: to search at a given point of time the particle record for possible clustering of materialized partons, which are those which have been struck out from the initial state or have been produced as secondaries by parton collisions or radiative processes. It consists of checking for each possible pair of two partons, the invariant space-time distance between them, their flavor and origin, the matching of color and anticolor, their common invariant mass, etc.. If a pair satisfies all necessary conditions for the formation of one or two color singlet clusters, then they are combined and converted into a composite cluster with internal flavor content and invariant mass determined by the partons, which then decays either into a pair of color singlet clusters, or into a singlet cluster plus an additional gluon or quark.

$I1$, $I2$: first and last entry of particle record VNIREC1/VNIREC2 in between the cluster formation is carried out by looping over all particles I with $I1 \leq I \leq I2$.

`SUBROUTINE VNICFRA(I1,I2)`

Purpose: to fragment color singlet clusters with given $q\bar{q}$ substructure into final state hadrons. For each cluster its invariant mass and flavor content are checked, and it is determined whether it decays isotropically into a pair of hadrons, or converts directly into a single hadron of corresponding flavor. The hadron decay is described by a phase-space model, in which the probability for forming a certain hadron state is given by the density of hadronic states with mass below the cluster mass. Once a hadron state is chosen, it either propagates on undisturbed if it is a stable particle, or it decays further according to the particle data tables, if it is a resonance.

$I1 > 0$: entry of particle record VNIREC1/VNIREC2 from which analysis starts.

$I2 > I2$: entry of particle record up to which analysis extends.

`SUBROUTINE VNIBHAD(I1,I2)`

Purpose: to perform beam cluster formation and hadronization. The remnant partons of beam/target particles, those that originate from the partonic coherent initial state in collisions involving hadrons or nuclei and have not interacted with decohereing effect. These primary partons are reassembled to clusters along the beam axis, which are then fragmented based on the minimum bias model of the UA5 collaboration, such that color, flavor and energy-momentum of the collision system as-a-whole are conserved.

$I1$, $I2$: first and last entry of particle record VNIREC1/VNIREC2 in between the soft beam/target fragmentation is carried out by looping over all particles I with $I1 \leq I \leq I2$.

`SUBROUTINE VNIBFRA(I1,I2)`

Purpose: to hadronize beam/target clusters consisting of remnant beam partons, using parts of the HERWIG 5.7 program. Beam remnants are those that emerge from the coherent partonic initial state without having undergone any decohering interaction, and carry the remaining energy, flavor and color of the system. The beam remnants are lumped to beam clusters which are fragmented similarly as the clusters arising from the parton cascade evolution.

$I1 > 0$: entry of particle record VNIREC1/VNIREC2 from which analysis starts.

$I2 > I1$: entry of particle record up to which analysis extends.

`SUBROUTINE VNIPADC(I1,I2,NUST)`

Purpose: to decay unstable particles resulting from cluster decays to hadrons. Out of these primary hadrons, those that are unstable resonances are decayed according to the Particle Data, which gives lower mass hadrons plus possibly gauge bosons and leptons. These secondary decay products may decay further.

$I1 > 0$: entry of particle record VNIREC1/VNIREC2 from which analysis starts.

$I2 > I1$: entry of particle record up to which analysis extends.

$NUST$: returns number of decay products that are still unstable.

B E ent analysis routines

The following routines collect, analyze and print out information on the result of a simulation, and give the user immediate access to calculated particle data, spectra, and other observables.

- The routine VNILIST provides a useful tool to obtain a quick overall view of the state of the particle record at any time during the simulation of one or many events, and (in parts) the space-time history of the system.
- The routine VNIEDIT allows to edit the particle record, e.g. to compress, or to exclude certain particle species from the record. It is used frequently during the simulation procedure to clean up used but further on unecessary particle information.
- Via the functions KVNI and PVNI, values of some frequently appearing variables may be obtained more easily.
- The routines VNIANAL and VNIANA1 - VNIANA4 carry out various data accumulation duties, and print out tables at the end of the simulation, which are automatically directed to files named VNI???.DAT where ??? is a 3-digit number, specified below.
- Finally, the six routines VNISPHE, VNITHRU, VNICLUS, VNICELL, VNIJMAS and VNIFOWO allow the possibility to find some global event shape properties as discussed in detail in the PYTHIA documentation [44].
- The common block VNIANA allows to access the bin sizes, and bin ranges of histograms in the routines VNIANA1 - VNIANA4.

```
COMMON/VNIANA/MANA(50),PANA(50)
```

Purpose: to provide data for variable ranges, bin sizes, etc., for histograms and tables created by analysis routines VNIANA1 - VNIANA4.

MANA(1) - MANA(10) : (D=1,21,41,61,91,121,151,181,221,301) Sequential numbers of time steps, at which a snapshot analysis during the space-time evolution of the collision system may be performed in routines VNIANA4 - VNIANA4.

MANA(11) : (D=40) Number of bins for energy distribution in $\ln(1/x)$ (where x is the energy fraction) in routine VNIANA2.

MANA(12) : not used.

MANA(13) : (D=40) Number of bins for pair mass distribution of Bose-Einstein correlations in routine VNIANA2.

MANA(14)-MANA(20) : not used.

MANA(21) : (D=20) Number of bins for cluster y-distribution in routine VNIANA3.

MANA(22) : not used.

MANA(23) : (D=20) Number of bins for cluster r_z-distribution in routine VNIANA3.

MANA(24) : not used.

MANA(25) : (D=20) Number of bins for cluster $p_\perp$-distribution in routine VNIANA3.

MANA(26) : not used.

MANA(27) : (D=20) Number of bins for cluster $r_\perp$-distribution in routine VNIANA3.

MANA(28) -MANA(30) : not used.

MANA(31) : (D=20) Number of bins for parton/hadron y-distribution in routine VNIANA4.

MANA(32) : not used.

MANA(33) : (D=20) Number of bins for parton/hadron r_z-distribution in routine VNIANA4.

MANA(34) : not used.

MANA(35) : (D=20) Number of bins for parton/hadron $p_\perp$-distribution in routine VNIANA4.

MANA(36) : not used.

MANA(37) : (D=20) Number of bins for parton/hadron $r_\perp$-distribution in routine VNIANA4.

MANA(38) - MANA(50) : not used.

PANA(1) - PANA(10) : not used.

PANA(1) ,PANA(12) : (D=0.,6.) Lower and upper bound for energy distribution in $\ln(1/x)$ (where x is the energy fraction of particles), in routine VNIANA2.

PANA(13) ,PANA(14) : (D=0.,3. GeV) Lower and upper bound for pair mass distribution of Bose-Einstein correlations in routine VNIANA2.

PANA(15) - PANA(20) : not used.

PANA(21) ,PANA(22) : (D=-8.,8.) Lower and upper bound for cluster y-distribution in routine VNIANA3.

PANA(23) ,PANA(24) : (D=-40.,40. GeV^{-1}) Lower and upper bound for cluster r_z-distribution in routine VNIANA3.

PANA(25) ,PANA(26) : (D=0.,10. GeV) Lower and upper bound for cluster $p_\perp$-distribution in routine VNIANA3.

PANA(27) ,PANA(28) : (D=0.,40. GeV^{-1}) Lower and upper bound for cluster $r_\perp$-distribution in routine VNIANA3.

PANA(29) - PANA(30) : not used.

PANA(31) ,PANA(32) : (D=-8.,8.) Lower and upper bound for parton/hadron y-distribution in routine VNIANA4.

PANA(33) ,PANA(34) : (D=-100.,100. GeV^{-1}) Lower and upper bound for parton/hadron r_z-distribution in routine VNIANA4.

PANA(35) ,PANA(36) : (D=0.,10. GeV) Lower and upper bound for parton/hadron $p_\perp$-distribution in routine VNIANA4.

PANA(37) ,PANA(38) : (D=0.,100. GeV^{-1}) Lower and upper bound for parton/hadron $r_\perp$-distribution in routine VNIANA4.

PANA(39) - PANA(50) : not used.

```
SUBROUTINE VNILIST(MSEL)
```

Purpose: to list the current state of the particle record during the evolution of an event, or certain specified excerpts of it. Also, to list parton or particle data, or current parameter values.

$MSEL$: determines what is to be listed.

= 0 : writes a logo with program version number and last date of change; is mostly for internal use.

= 1 : gives a simple list of current event record, in an 80 column format suitable for viewing directly on the computer terminal. For each entry, the following information is given: the entry number I, the parton/particle name, the status code KS (K(I,1)), the flavour code KF (K(I,2)), the color and anticolor, C (L(I,1)), and A (L(I,2)), and the three-momentum, energy and mass (P(I,1)-P(I,5)). A final line contains information on total charge, momentum, energy and invariant mass.

= 2 : gives a more extensive list of the current event record, in a 132 column format, suitable for printers or workstations. For each entry, the following information is given: the entry number I, the parton/particle name (with padding as described for $MSEL = 1$), the status code KS (K(I,1)), the flavour code KF (K(I,2)), the color and anticolor, C (L(I,1)) and A (L(I,2)), the origin of the particle in a 3 digit $N1N2N3$, where $N1$ is the event and $N2$ the time step in this event, when the particle

was first produced, and $N3$ is the number of the entry in the particle record that the particle occupied when it first appeared. This labeling allows a unique specification of its 'historical' origin. Finally, it follows the three-momentum, energy and mass (P(I,1) - P(I,5)). A final line contains information on total charge, momentum, energy and invariant mass.
= **3** : gives the same basic listing as = 2, but with an additional line for each entry containing information on production vertex position and time (V(I,1) - V(I,4)).
= **-1** : gives the format of listing as = 1, but instead of momentum, energy and mass, it lists now the particle's position in the overall reference frame, (R(I,1) - R(I,3)), its momentum-rapidity (Y(P)) and its transverse momentum (PT) with respect to the z-axis, which is usually the jet-axis, or beam axis.
= **-2** : gives the format of listing as = 2, but as for = -1, instead of momentum, energy and mass, now the particle's positions, rapidities and transverse momenta in the overall Lorentz frame are listed. As for = 2, additional information on the 'historical' origin of the particle is listed.
= **-3** : gives the format of listing as = 3, again, instead of momentum, energy and mass, now the particle's positions, rapidities and transverse momenta are listed.
= **11** : provides a simple list of all parton/particle codes defined in the program, with KF code and corresponding particle name. The list is grouped by particle kind, and only within each group in ascending order.
= **12** : provides a list of all parton/particle and decay data used in the program. Each parton/particle code is represented by one line containing KF flavour code, KC compressed code, particle name, antiparticle name (where appropriate), electrical and color charge, mass, resonance width and maximum broadening, average invariant lifetime and whether the particle is considered stable or not.
= **13** : gives a list of current parameter values for MSTV, PARV, and for MSTW and PARW. This is useful to keep check of which default values were changed in a given run.
= **14** : gives a list of time grid and size of time slizes used in the current run.

`SUBROUTINE VNIEDIT(MEDIT)`

Purpose: to exclude unstable or undetectable partons/particles from the event record. One may also use VNIEDIT to store spare copies of events (specifically initial parton configuration) that can be recalled to allow e.g. different fragmentation schemes to be run through with one and the same parton configuration. Finally, an event which has been analysed with VNISPHE, VNITHRU or VNICLUS (see below) may be rotated to align the event axis with the z-direction.

$MEDIT$: tells which action is to be taken.
= 0 : empty (KS = 0) and documentation ($KS > 20$) lines are removed. The partons/particles remaining are compressed in the beginning of the VNIREC1 and VNIREC2 commonblocks and the N value is updated accordingly. The event history is lost, so that information stored in K(I,3), K(I,4) and K(I,5) is no longer relevant.
= 1 : as = 0, but in addition all partons/particles that have fragmented/decayed ($KS > 10$) are removed.
= 2 : as = 1, but also all neutrinos and unknown particles (i.e. compressed code KC = 0) are removed.
= 3 : as = 2, but also all uncharged, color neutral particles are removed, leaving only charged, stable particles (and unfragmented partons, if fragmentation has not been performed).
= 5 : as = 0, but also all partons which have branched or been rearranged in a parton shower and all particles which have decayed are removed, leaving only the fragmenting parton configuration and the final state particles.
= 11 : remove lines with K(I,1) < 0. Update event history information (in K(I,3) - K(I,5)) to refer to remaining entries.
= 12 : remove lines with K(I,1) = 0. Update event history information (in K(I,3) - K(I,5)) to refer to remaining entries.
= 13 : remove lines with K(I,1) = 11, 12 or 15, except for any line with K(I,2) = 94. Update event history information (in K(I,3) - K(I,5)) to refer to remaining entries. In particular, try to trace origin of daughters, for which the mother is decayed, back to entries not deleted.
= 14 : remove lines with K(I,1) = 13 or 14, and also any line with K(I,2) = 94. Update event history information (in K(I,3) - K(I,5)) to refer to remaining entries. In particular, try to trace origin of rearranged partons back through the parton shower history to the shower initiator.
= **15** : remove lines with K(I,1) > 20. Update event history information (in K(I,3) - K(I,5)) to refer to remaining entries.
= **21** : all partons/particles in current event record are stored (as a spare copy) in bottom of commonblocks VNIREC1/VNIREC2.
= **22** : partons/particles stored in bottom of event record with = 21 are placed in beginning of record again, overwriting previous information there (so that e.g., a different fragmentation scheme can be used on the same partons). Since the copy at bottom is unaffected, repeated calls with = 22 can be made.
= **23** : primary partons/particles in the beginning of event record are marked as not fragmented or decayed, and number of entries N is updated accordingly. Is simple substitute for = 21 plus = 22 when no fragmentation/decay products precede any of the original partons/particles.
= **31** : rotate largest axis, determined by VNISPHE, VNITHRU or VNICLUS, to sit along the z-direction, and the second largest axis into the xz plane. For VNICLUS it can be further specified to $+z$ axis and xz plane with $x > 0$, respectively. Requires that one of these routines has been called before.
= **32** : mainly intended for VNISPHE and VNITHRU, this gives a further alignment of the event, in addition to the one implied by = 31. The "slim" jet, defined as the side ($z > 0$ or $z < 0$) with the smallest summed $p_\perp$ over square root of number of particles, is rotated into the $+z$ hemisphere. In the opposite hemisphere (now $z < 0$), the side of $x > 0$ and $x < 0$ which has the largest summed p_x absolute is rotated into the $z < 0$, $x > 0$ quadrant. Requires that VNISPHE or VNITHRU has been called before.

`FUNCTION KVNI(I,J)`

Purpose: to provide various integer-valued event data. Note that many of the options available (in particular $I > 0, J \geq 14$) which refer to event history will not work after a VNIEDIT call.

$I = 0, J =$: properties referring to the complete event.
= **1** : N, total number of lines in event record.
= **2** : total number of partons/particles remaining after fragmentation and decay.
= **6** : three times the total charge of remaining (stable) partons and particles.

$I > 0, J =$: properties referring to the entry in line no. I of the event record.
= **1 - 5** : K(I,1) - K(I,5), i.e. parton/particle status KS, flavour code KF and origin/decay product/color-flow information.
= **6** : three times parton/particle charge.
= **7** : 1 for a remaining entry, 0 for a decayed/fragmented/ documentation entry.
= **8** : KF code (K(I,2)) for a remaining entry, 0 for a decayed/fragmented/documentation entry.
= **9** : KF code (K(I,2)) for a parton (i.e. not color-neutral entry), 0 for a particle.
= **10** : KF code (K(I,2)) for a particle (i.e. color-neutral entry), 0 for a parton.
= **11** : compressed flavour code KC.
= **12** : color information code, i.e. 0 for color neutral, 1 for color triplet, -1 for antitriplet and 2 for octet.
= **13** : flavour of "heaviest" quark or antiquark (i.e. with largest code) in hadron or diquark (including sign for antiquark), 0 else.
= **14** : generation number. Beam particles or virtual exchange particles are generation 0, original partons/particles generation 1 and then 1 is added for each step in the fragmentation/decay chain.
= **15** : line number of ancestor, i.e. predecessor in first generation (generation 0 entries are disregarded).
= **16** : rank of a hadron in a jet system it belongs to. Rank denotes the ordering in flavour space, with hadrons containing the original flavour of the jet having rank 1, increasing by 1 for each step away in flavour ordering. All decay products inherit the rank of their parent. Whereas the meaning of a

first-rank hadron in a quark jet is always well-defined, the definition of higher ranks is only meaningful for independently fragmenting quark jets. In other cases, rank refers to the ordering in the actual simulation, which may be of little interest.
= **17** : generation number after a collapse of a jet system into one particle, with 0 for an entry not coming from a collapse, and -1 for entry with unknown history. A particle formed in a collapse is generation 1, and then one is added in each decay step.
= **18** : number of decay/fragmentation products (only defined in a collective sense for fragmentation).
= **19** : origin of color for showering parton, 0 else.
= **20** : origin of anticolor for showering parton, 0 else.
= **21** : position of color daughter for showering parton, 0 else.
= **22** : position of anticolor daughter for showering parton, 0 else.
= **23** : number of 2-body collisions of parton/particle.
= **24** : number of space-like decays of parton/particle.
= **25** : number of time-like decays of parton/particle.
= **27** : entry of direct mother of parton/particle.
= **28** : timestep of production of parton/particle.
= **29** : index of generation in the cascade tree of parton/particle.

`FUNCTION PVNI(I,J)`

Purpose: to provide various real-valued event data. Note that some of the options available ($I > 0, J = 20 - 25$) are primarily intended for studies of systems in their respective CM frame.

$I = 0, J =$: properties referring to the complete event.
= **1 - 4** : sum of p_x, p_y, p_z and E, respectively, for the stable remaining entries.
= **5** : invariant mass of the stable remaining entries.
= **6** : sum of electric charge of the stable remaining entries.

$I > 0, J =$: properties referring to the entry in line no. I of the event record.
= **1 - 5** : P(I,1) - P(I,5), i.e. normally p_x, p_y, p_z, E and m for parton/particle.
= **6** : electric charge q.
= **7** : momentum squared $\vec{p}^2 = p_x^2 + p_y^2 + p_z^2$.
= **8** : momentum $p = \sqrt{\vec{p}^2}$.
= **9** : transverse momentum squared $p_\perp^2 = p_x^2 + p_y^2$.
= **10** : transverse momentum $p_\perp$.
= **11** : transverse mass squared $m_\perp^2 = m^2 + p_x^2 + p_y^2$.
= **12** : transverse mass $m_\perp$.
= **13 - 14** : polar angle θ in radians (between 0 and π) or degrees, respectively.
= **15 - 16** : azimuthal angle ϕ in radians (between $-\pi$ and π) or degrees, respectively.
= **17** : true rapidity $y = \frac{1}{2}\ln((E+p_z)/(E-p_z))$.
= **18** : rapidity y_π obtained by assuming that the particle is a pion when calculating the energy E, to be used in the formula above, from the (assumed known) momentum p.
= **19** : pseudorapidity $\eta = \frac{1}{2}\ln((p+p_z)/(p-p_z))$.
= **20** : momentum fraction $x_p = 2p/W$, where W is the total energy of initial parton/particle configuration.
= **21** : $x_F = 2p_z/W$ (Feynman-x if system is studied in CM frame).
= **22** : $x_\perp = 2p_\perp/W$.
= **23** : $x_E = 2E/W$.
= **24** : $z_+ = (E+p_z)/W$.
= **25** : $z_- = (E-p_z)/W$.

`SUBROUTINE VNIANAL(MSEL)`

Purpose: to administrate in each event, which of the available analysis duties (described below) are carried out, and when during the time evolution of the particle system data samples are taken and accumula- ted to perform a statistical analysis at the end. It calls the routines VNIANA1 - VNIANA4 to do this job, for the options that are switched on by default or by the user. The switches and their effect are described in Sec. 3.7. After the last event of a run, the results are automatically printed out in tabular form to files called VNI???.DAT, with numbers ???, corresponding to the selected analysis options.

MSEL : gives the type of action to be taken.
= **0** : all arrays for data analysis in VNIANA1 - VNIANA4 are reset.
= **1** : data samples are accumulated, stored and analyzed in VNIANA1 - VNIANA4.
= **10** : final results are written to output files called VNI.???.DAT, where '???' is a 3-digit number specified in the descriptions below.

`SUBROUTINE VNIANA1(MSEL)`

Purpose: to provide a number of global analyses referring to time- independent quantities of events as-a-whole, as e.g. total charged multiplicities, etc.. Is adopted from PYTHIA and only slightly altered. Accumulated statistics is written out at the end of a run. When errors are quoted, these refer to the uncertainty in the average value for the event sample as a whole, rather than to the spread of the individual events, i.e. errors decrease like one over the square root of the number of events analyzed.

MSEL : determines which action is to be taken. Generally, a last digit equal to 0 indicates that the statistics counters for this option is to be reset. Last digit 1 leads to an analysis of current event with respect to the desired properties. The statistics accumulated is output in tabular form with last digit 2, and written to disc.

= **10** : statistics on parton multiplicity is reset.
= **11** : the parton content of the current event is analyzed, classified according to the flavour content of the hard interaction and the total number of partons.
= **12** : gives a table on parton multiplicity distribution, written to file VNI110.DAT.

= **20** : statistics on particle content is reset.
= **21** : the particle/parton content of the current event is analyzed, also for particles which have subsequently decayed and partons which have fragmented. Particles are subdivided into primary and secondary ones, the main principle being that primary particles are those produced directly, while secondary come from decay of other particles.
= **22** : gives a table of particle content in events, written to file VNI120.DAT.

= **30** : statistics on factorial moments is reset.
= **31** : analyzes the factorial moments of the multiplicity distribution in different bins of rapidity and azimuth.
= **32** : prints a table of the first four factorial moments for various bins of pseudorapidity and azimuth, written to file VNI130.DAT. The moments are properly normalized so that they would be unity (up to statistical fluctuations) for uniform and uncorrelated particle production according to Poissonian statistics, but increasing for decreasing bin size in case of "intermittent" behaviour.

= **40** : statistics on energy-energy correlation is reset.
= **41** : the energy-energy correlation (EEC) of the current event is analyzed. Events are assumed given in their CM frame. The weight assigned to a pair i and j is $2E_iE_j/W^2$, where W is the sum of energies of all analyzed particles in the event. Energies are determined from the momenta of particles and masses. Statistics is accumulated for the relative angle θ_{ij}, ranging between 0 and 180 degrees, subdivided into 50 bins.
= **42** : prints a table of the energy-energy correlation (EEC) and its asymmetry (EECA), with errors, written to file VNI140.DAT. The definition of errors is not unique. Each event is viewed as one observation, i.e. an EEC and EECA distribution is obtained by summing over all particle pairs of an

event, and then the average and spread of this event-distribution is calculated in the standard fashion, with the quoted error containing a factor of $1/\sqrt{\text{no. events}}$.

$= 50$: statistics on complete final states is reset.
$= 51$: analyzes the particle content of the final state of the current event record. During the course of the run, statistics is thus accumulated on how often different final states appear. Only final states with up to 8 particles are analyzed, and there is only reserved space for up to 200 different final states. Most high energy events have multiplicities far above 8, so the main use for this tool is to study the effective branching ratios obtained with a given decay model for e.g. charm or bottom hadrons.
$= 52$: gives a list of the (at most 200) channels with up to 8 particles in the final state, with their relative branching ratio, written to file VNI150.DAT. The ordering is according to multiplicity, and within each multiplicity according to an ascending order of KF codes. The KF codes of the particles belonging to a given channel are given in descending order.

`SUBROUTINE VNIANA2(MSEL)`

Purpose: to analyze the time evolution of particles yields, energy ad momentum composition. Also, to analyze final state hadron spectra in the energy variable $\ln(1/x)$ and to model Bose-Einstein correlations.

$MSEL$: determines which action is to be taken, with the convention noted before.

$= 10$: statistics on time evolution of particle numbers, energy partitions, longitudinal momentum fractions and average transverse momentum is reset.
$= 11$: the particle content is analyzed in each single time step during an event, for the different particle species individually.
$= 12$: gives a table on the obtained time evolution profiles, written to file VNI210.DAT.

$= 20$: statistics on $y = ln(1/x)$ distribution of final hadrons is reset, where $x = 2E/\sqrt{s}$ is the energy fraction of a particle.
$= 21$: hadron content at the end of each event is binned in $y = \ln(1/x)$ individually for all, and for charged, hadrons. Covered range in y is given by PARW(161) and PARW(162).
$= 22$: gives a table of the obtained $y = ln(1/x)$ spectra, written to file VNI220.DAT.

$= 30$: statistics on Bose-Einstein correlations of final state pions and kaons is reset.
$= 31$: Bose-Einstein effects are simulated according to a simple parametrization, with an algorithm adopted from PYTHIA. The distribution of pair masses is stored for both cases, without and with Bose-Einstein correlations taken into account. Covered range in pair mass is given by PARW(163) and PARW(164).
$= 32$: gives a table of the obtained pair mass spectrum of 'like-sign' pions and kaons, without and with Bose-Einstein effects, written to file VNI230.DAT.

`SUBROUTINE VNIANA3(MSEL)`

Purpose: to analyze the dynamics of pre-hadronic clusters formed from partons during the parton-hadron conversion stage of the system. The cluster size- and mass-distributions, and momentum and spatial spectra are accumulated at various time steps during the time evolution of the system, so that the time change of the spectra gives a history of the cluster formation processes, locally in phase-space.

$MSEL$: determines which action is to be taken, with the convention noted before. The statistics accumulated is output in tabular form with bins, ideally covering the range of momenta and coordinates of relevant particles. Depending on the kinematics, however, the limits of this range may require an adjustment, and/or a finer resolution of bins may be necessary.

$= 10$: statistics on cluster sizes and their invariant mass spectrum is reset.
$= 11$: the cluster content of the system is analyzed each single time step during an an event, and cluster sizes and masses are stored in bins. Covered range of analysis is $0 \leq R \leq 1.5$ fm, and $0 \leq M \leq 7$ GeV.
$= 12$: gives a table on the obtained cluster size- and mass-spectra, written to file VNI310.DAT.

$= 20$: statistics on rapidity (y) spectra of clusters is reset.
$= 21$: the cluster content at certain pre-selected time steps during an an event is analyzed. Covered range in y is given by PARW(171) and PARW(172).
$= 22$: gives a table on the obtained y-spectra, written to file VNI320.DAT.

$= 30$: statistics on longitudinal (r_z) spatial distribitions of clusters is reset.
$= 31$: the cluster positions at certain pre-selected time steps during an event are analyzed, with respect to the overall CM frame and to the z-axis, usually the jet-axis, or beam-axis. Covered range in r_z is given by PARW(173) and PARW(174).
$= 32$: gives a table on the obtained r_z-spectra, written to file VNI330.DAT.

$= 40$: statistics on transverse momentum ($p_\perp$) distribitions of clusters is reset.
$= 41$: the cluster momenta $p_\perp$ at certain pre-selected time steps during an an event are analyzed, transverse with respect to the z-axis. Covered range in $p_\perp$ is given by PARW(175) and PARW(176).
$= 42$: gives a table on the obtained $p_\perp$-spectra, written to file VNI340.DAT.

$= 50$: statistics on transverse ($r_\perp$) spatial distribitions of clusters is reset.
$= 51$: the cluster content at certain pre-selected time steps during an an event is analyzed, with respect to the distance transverse to the z-axis. Covered range in $r_\perp$ is given by PARW(177) and PARW(178).
$= 52$: gives a table on the obtained $r_\perp$-spectra, written to file VNI350.DAT.

`SUBROUTINE VNIANA4(MSEL)`

Purpose: to analyze momentum and spatial distributions of partons and hadrons at various time steps during the time evolution of the system, so that the time change of the spectra gives a history of the dynamics from the initial state all the way to the final state of hadrons.

$MSEL$: determines which action is to be taken, with the convention noted before. The statistics accumulated is output in tabular form with bins, ideally covering the range of momenta and coordinates of relevant particles. Depending on the kinematics, however, the limits of this range may require an extension.

$= 10$: statistics on rapidity (y) spectra of partons and hadrons is reset.
$= 11$: the particle content at certain pre-selected time steps during an an event is analyzed, for gluons, quarks, mesons and baryons seperately. Covered range in y is given by PARW(181) and PARW(182).
$= 12$: gives a table on the obtained y-spectra, written to file VNI410.DAT.

$= 20$: statistics on longitudinal (r_z) spatial distribitions of partons and hadrons is reset.
$= 21$: the particle positions at certain pre-selected time steps during an event are analyzed, with respect to the overall CM frame and to the z-axis, usually the jet-axis, or beam-axis. Covered range in r_z is given by PARW(183) and PARW(184).
$= 22$: gives a table on the obtained r_z-spectra, written to file VNI420.DAT.

$= 30$: statistics on transverse momentum ($p_\perp$) distribitions of partons and hadrons is reset.
$= 31$: the particle momenta $p_\perp$ at certain pre-selected time steps during an an event are analyzed, transverse with respect to the z-axis. Covered range in $p_\perp$ is given by PARW(185) and PARW(186).
$= 32$: gives a table on the obtained pT-spectra, written to file VNI430.DAT.

= **40** : statistics on transverse ($r_\perp$) spatial distribibitions of partons and hadrons is reset.
= **41** : the particle content at certain pre-selected time steps during an an event is analyzed, with respect to the distance transverse to the z-axis. Covered range in $r_\perp$ is given by PARW(187) and PARW(188).
= **42** : gives a table on the obtained $r_\perp$-spectra, written to file VNI440.DAT.

`SUBROUTINE VNISPHE(SPH,APL)`

Purpose: to diagonalize the momentum tensor, i.e. find the eigenvalues $\lambda_1 > \lambda_2 > \lambda_3$, with sum unity, and the corresponding eigenvectors. Momentum power dependence is given by PARU(41); default corresponds to sphericity, PARU(41)=1. gives measures linear in momenta. Which particles (or partons) are used in the analysis is determined by the MSTU(41) value.

SPH : $3(\lambda_2+\lambda_3)/2$, i.e. sphericity (for PARU(41)=2.). Is returned = -1, if analysis not performed because event contained less than two particles (or two exactly back-to-back particles, in which case the two transverse directions would be undefined).

APL : $?/2\lambda_3$, i.e. aplanarity (for PARU(41)=2.). Is returned = -1, as $SPH = -1$

Remark: the lines $N+1$ through $N+3$ ($N-2$ through N for MSTU(43) = 2) in VNIREC1/VNIREC2 will, after a call, contain the following information:
K$(N+i,1) = 31$;
K$(N+i,2) = 95$;
K$(N+i,3)$: i, the axis number, $i = 1,2,3$;
K$(N+i,4)$, K$(N+i,5) = 0$;
P$(N+i,1)$ - P$(N+i,3)$: the i-th eigenvector, x, y and z components;
P$(N+i,4)$: λ_i, the i-th eigenvalue;
P$(N+i,5) = 0$;
V$(N+i,1)$ - V$(N+i,5) = 0$.
Also, the number of particles used in the analysis is given in MSTU(62).

`SUBROUTINE VNITHRU(THR,OBL)`

Purpose: to find the thrust, major and minor axes and corresponding projected momentum quantities, in particular thrust and oblateness. The performance of the program is affected by MSTU(44), MSTU(45), PARU(42) and PARU(48). In particular, PARU(42) gives the momentum dependence, with the default value 1. corresponding to linear dependence. Which particles (or partons) are used in the analysis is determined by the MSTU(41) value.

THR : thrust (for PARU(42)=1.). Is returned = -1, if analysis cannot be not performed, because event contained less than two particles. Is returned = -2, if remaining space in VNIREC1/VNIREC2 (partly used as working area) is not large enough to allow analysis.

OBL : oblateness (for PARU(42)=1.). Is returned = -1, respectively = -2, as for THR.

Remark: the lines $N+1$ through $N+3$ ($N-2$ through N for MSTU(43) = 2) in VNIREC1/VNIREC2 will, after a call, contain the following information:
K$(N+i,1) = 31$;
K$(N+i,2) = 96$;
K$(N+i,3)$: i, the axis number, $i = 1,2,3$;
K$(N+i,4)$, K$(N+i,5) = 0$;
P$(N+i,1)$ - P$(N+i,3)$: the thrust, major and minor axis, respectively, for i = 1, 2 and 3;
P$(N+i,4)$: corresponding thrust, major and minor value;
P$(N+i,5) = 0$;
V$(N+i,1)$ - V$(N+i,5) = 0$.
Also, the number of particles used in the analysis is given in MSTU(62).

`SUBROUTINE VNICLUS(NJET)`

Purpose: to reconstruct an arbitrary number of jets using a cluster analysis method based on particle momenta. Two different distance measures are available, the traditional one roughly corresponding to relative transverse momentum, and one based on the JADE method, which roughly corresponds to invariant mass (in both cases with some important modifications). The choice is controlled by MSTU(46). The distance scale d_{join}, above which two clusters may not be joined, is normally given by PARU(44). In general, d_{join} may be varied to describe different "jet resolution powers". With the mass distance, PARU(44) can be used to set the absolute maximum cluster mass, or PARU(45) to set the scaled one, i.e. in $y = m^2/W^2$, where W^2 is the total invariant mass-squared of the particles being considered. It is possible to continue the cluster search from the configuration already found, with a new higher d_{join} scale, by selecting MSTU(48) properly. In MSTU(47) one can also require a minimum number of jets to be reconstructed; combined with an artificially large d_{join} this can be used to reconstruct a predetermined number of jets. Which particles (or partons) are used in the analysis is determined by the MSTU(41) value, whereas assumptions about particle masses are given by MSTU(42). The parameters PARU(43) and PARU(48) regulate more technical details (for events at high energies and large multiplicities, however, the choice of a larger PARU(43) may be necessary to obtain reasonable reconstruction times).

$NJET$: the number of clusters reconstructed. Is returned = -1, if analysis cannot performed, because event contained less than MSTU(47) (normally 1) particles, or analysis failed to reconstruct the requested number of jets. Is returned = -2, if remaining space in VNIREC1/VNIREC2 (partly used as working area) is not large enough to allow analysis.

Remark: if the analysis does not fail, further information is found in MSTU(61) - MSTU(63) and PARU(61) - PARU(63). In particular, PARU(61) contains the invariant mass for the system analyzed, i.e. the number used in determining the denominator of $y = m^2/W^2$. PARU(62) gives the generalized thrust, i.e. the sum of (absolute values of) cluster momenta divided by the sum of particle momenta (roughly the same as multicity). PARU(63) gives the minimum distance d (in $p_\perp$ or m) between two clusters in the final cluster configuration, 0 in case of only one cluster. Further, the lines $N+1$ through $N+NJET$ ($N-NJET+1$ through N for MSTU(43) = 2) in VNIREC1/VNIREC2 will, after a call, contain the following information:
K$(N+i,1) = 31$;
K$(N+i,2) = 97$;
K$(N+i,3)$: i, the jet number, with the jets arranged in falling order of absolute momentum;
K$(N+i,4)$: the number of particles assigned to jet i;
K$(N+i,5) = 0$;
P$(N+i,1)$ - P$(N+i,5)$: momentum, energy and invariant mass of jet i;
V$(N+i,1)$ - V$(N+i,5) = 0$.
Also, for a particle which was used in the analysis, K$(I,4) = i$, where I is the particle number and i the number of the jet it has ben assigned to. Undecayed particles not used then have K$(I,4) = 0$. An exception is made for lines with K$(I,1) = 3$ (which anyhow are not normally interesting for cluster search), where the color flow information stored in K$(I,4)$ is left intact.

`SUBROUTINE VNICELL(NJET)`

Purpose: to provide a simpler cluster routine more in line with what is currently used in the study of high-$p_\perp$ collider events. A detector is assumed to stretch in pseudorapidity between -PARU(51) and +PARU(51) and be segmented in MSTU(51) equally large η (pseudorapidity) bins and MSTU(52) ϕ (azimuthal) bins. Transverse energy $E_\perp$ for undecayed entries are summed up in each bin. For MSTU(53) nonzero, the energy is smeared by calorimetric resolution effects, cell by cell. This is done according to a Gaussian distribution; if MSTU(53) = 1 the standard deviation for the $E_\perp$ is PARU(55)$\sqrt{E_\perp}$, if MSTU(53) = 2 the standard deviation for the E is PARU(55)$\sqrt{E}$, $E_\perp$ and E expressed in GeV. The Gaussian is cut off at 0 and at a factor PARU(56) times the correct $E_\perp$ or E. All bins with $E_\perp$ >PARU(52) are taken to be possible initiators of jets, and are tried in falling $E_\perp$ sequence to check whether the total $E_\perp$ summed over cells no more distant than PARU(54) in $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ exceeds PARU(53). If so, these cells define one jet, and are removed from further consideration. Contrary to VNICLUS, not all particles need be assigned to jets. *Which particles (or partons) are used in the analysis is determined by the MSTU(41) value.*

NJET : the number of jets reconstructed (may be 0). Is returned = -2, if remaining space in VNIREC1/VNIREC2 (partly used as working area) is not large enough to allow analysis.

Remark: the lines $N+1$ through $N+NJET$ ($N-NJET+1$ through N for MSTU(43) = 2) in VNIREC1/VNIREC2 will, after a call, contain the following information:
K$(N+i,1) = 31$;
K$(N+i,2) = 98$;
K$(N+i,3)$: i, the jet number, with the jets arranged in falling order in $E_\perp$;
K$(N+i,4)$: the number of particles assigned to jet i;
K$(N+i,5) = 0$;
V$(N+i,1)$ - V$(N+i,5) = 0$;

Further, for MSTU(54) = 1:
P$(N+i,1)$, P$(N+i,2)$ = position in η and ϕ of the center of the jet initiator cell, i.e. geometrical center of jet;
P$(N+i,3)$, P(N+i,4) = position in η and ϕ of the $E_\perp$-weighted center of the jet, i.e. the center of gravity of the jet;
P$(N+i,5) = \sum E_\perp$ of the jet;

while for MSTU(54) = 2:
P$(N+i,1)$ - P$(N+i,5)$: the jet momentum vector, constructed from the summed $E_\perp$ and the η and ϕ of the $E_\perp$-weighted center of the jet as $(p_x, p_y, p_z, E, m) = E_\perp(\cos\phi, \sin\phi, \sinh\eta, \cosh\eta, 0)$;

and for MSTU(54) = 3:
P$(N+i,1)$ - P$(N+i,5)$: the jet momentum vector, constructed by adding vectorially the momentum of each cell assigned to the jet, assuming that all the $E_\perp$ was deposited at the center of the cell, and with the jet mass in P$(N+i,5)$ calculated from the summed E and p as $m^2 = E^2 - p_x^2 - p_y^2 - p_z^2$.

Also, the number of particles used in the analysis is given in MSTU(62), and the number of cells hit in MSTU(63).

```
SUBROUTINE VNIJMAS(PMH,PML)
```

Purpose: to reconstruct high and low jet mass of an event, by dividing the collision event into two hemispheres, transversely to the sphericity axis. Then one particle at a time is reassigned to the other hemisphere if that reduces the sum of the two jet masses- squared $m_H^2 + m_L^2$. The procedure is stopped when no further significant change (see PARU(48)) is obtained. Often, the original assignment is retained as it is. Which particles (or partons) are used in the analysis is determined by the MSTU(41) value, whereas assumptions about particle masses are given by MSTU(42).

PMH : heavy jet mass (in GeV). Is returned = -2m, if remaining space in VNIREC1/VNIREC2 (partly used as working area) is not large enough to allow analysis.

PML : light jet mass (in GeV). Is returned = -2, if remaining space in VNIREC1/VNIREC2 (partly used as working area) is not large enough to allow analysis.

Remark: light jet mass (in GeV). After a successful call, MSTU(62) contains the number of particles used in the analysis, and PARU(61) the invariant mass of the system analyzed. The latter number is helpful in constructing scaled jet masses.

```
SUBROUTINE VNIFOWO(H10,H20,H30,H40)
```


Purpose: to do an event analysis in terms of the Fox-Wolfram moments The moments H_i are normalized to the lowest one, H_0. Which particles (or partons) are used in the analysis is determined by the MSTU(41) value.

H10 : H_1/H_0. Is = 0 if momentum is balanced.

H20 : H_2/H_0.

H30 : H_3/H_0.

H40 : H_4/H_0.

Remark: the number of particles used in the analysis is given in MSTU(62).

C Further commonblocks

The subroutines and commonblocks that one normally comes in direct contact with have already been described. For the sake of completeness, some further commonblocks are here described, which might be of interest to a user that desires a more detailed insight.

The common block VNISYS contains information concerning the type and status of the collision system $A + B$ defined by the beam and target particles, c.f Sec. 3.4.

```
COMMON/VNISYS/NSYS(2,5),KSYS(2,5),PSYS(2,5),RSYS(2,5),AB(500,0:10)
```

Purpose: to store information and data concerning beam and target particles. It is in particular of interest if one desires to use the user-specified frames USER, FOUR or FIVE, in which case the user has to give the initial momenta PSYS and coordinates RSYS of the colliding particles by assigning values before the initialization. Furthermore, for collisions involving nuclei, the array AB provides information on how many initial-state nucleons have been 'wounded' and how often they have been struck. For collisions without nuclei, the array AB is empty!

NSYS(I,1) : number of neutrons in beam/target particle $I = 1, 2$.

NSYS(I,2) : number of protons.

NSYS(I,3) : number of d valence quarks.

NSYS(I,4) : number of u valence quarks.

NSYS(I,5) : number of s valence quarks.

KSYS(I,1)- KSYS(I,5) : status code, particle id, origin of beam/target particle $I = 1, 2$, in analogy to the array K in the particle record VNIREC1/VNIREC2.

PSYS(I,1)- PSYS(I,5) : initial momentum, energy, mass of beam/target particle, in analogy to the array P in the particle record VNIREC1/VNIREC2.

RSYS(I,1)- RSYS(I,5) : initial x, y, z position before collision of of beam/target particle, in analogy to the array R in the particle record VNIREC1/VNIREC2. (RSYS(I,4) and RSYS(I,5) are currently not used).

AB(IH,0) : number of collisions of nucleon IH, that is, the number of times an initial-state parton belonging to that nucleon gets struck and liberated from its mother nucleon. Here $1 \leq IH \leq N_{nuc}(A) + N_{nuc}(B)$, with A and/or B being the initial beam and/or target nucleus. AB(IH,0) = 0 initially for all IH, and at the end allows to discriminate 'wounded' (≥ 1)and 'unwounded'($= 0$) nucleons.

AB(IH,1) : *initial* number of partons in nucleon IH, before collision.

AB(IH,2) : *current* number of partons in nucleon IH, during time evolution. For 'unwounded' nucleons AB(IH,2)=AB(IH,1).

AB(IH,3) : KF particle id of nucleon IH (either proton or neutron).

AB(IH,4) : KF particle id of mother nucleus to which nucleon IH belongs.

AB(IH,5) : *initial* $P_\perp$ of nucleon IH (before collision) with respect to collision axis of beam/target.

AB(IH,6) : *initial* P_z of nucleon IH with respect to collision axis.

AB(IH,7) : *initial* E of nucleon IH with respect to chosen Lorentz frame.

AB(IH,8) : *current* $P_\perp$ of nucleon IH (during time evolution of collision) with respect to collision axis of beam/target.

AB(IH,9) : *current* P_z of nucleon IH with respect to collision axis.

AB(IH,10): *current* E of nucleon IH with respect to chosen Lorentz frame.

The common block VNINIA contains detailed information on the number of parton interactions for each of the included sub-process channels.

```
COMMON/VNINIA/NIA(5,0:10)
```

Purpose: to store accumulated statistics on type and number of parton interactions.

NIA(1,0) : total number of hard parton collisions $a + b \to c + d$.

- NIA(1,1) : number of hard $q + q \to q + q$.
- NIA(1,2) : number of hard $q + \bar{q} \to q + \bar{q}$.
- NIA(1,3) : number of hard $q + \bar{q} \to g + g$.
- NIA(1,4) : number of hard $q + \bar{q} \to g + \gamma$.
- NIA(1,5) : number of hard $q + \bar{q} \to \gamma + \gamma$.
- NIA(1,6) : number of hard $q + g \to q + g$.
- NIA(1,7) : number of hard $q + g \to q + \gamma$.
- NIA(1,8) : number of hard $g + g \to q + \bar{q}$.
- NIA(1,9) : number of hard $g + g \to g + g$.

NIA(2,0) : total number of soft parton collisions $a + b \to c + d$.

- NIA(2,1) : number of soft $q + q \to q + q$.
- NIA(2,2) : number of soft $q + \bar{q} \to q + \bar{q}$.
- NIA(2,3) : number of soft $q + \bar{q} \to g + g$.
- NIA(2,4) : number of soft $q + \bar{q} \to g + \gamma$.
- NIA(2,5) : number of soft $q + \bar{q} \to \gamma + \gamma$.
- NIA(2,6) : number of soft $q + g \to q + g$.
- NIA(2,7) : number of soft $q + g \to q + \gamma$.
- NIA(2,8) : number of soft $g + g \to q + \bar{q}$.
- NIA(2,9) : number of soft $g + g \to g + g$.

NIA(3,0) : total number of parton fusions $a + b \to c^*$.

- NIA(3,1) : number of $q + \bar{q} \to g^*$.
- NIA(3,2) : number of $q + g \to q^*$.
- NIA(3,3) : number of $g + g \to g^*$.

NIA(4,0) : total number of space-like branchings $a \to b + c$.

- NIA(4,1) : number of $q \to q + g$.
- NIA(4,2) : number of $g \to g + g$.
- NIA(4,3) : number of $g \to q + \bar{q}$.

NIA(4,4) : number of $q \to q + \gamma$.

NIA(5,0) : total number of time-like branchings $a \to b + c$.

NIA(5,1) : number of $q \to q + g$.

NIA(5,2) : number of $g \to g + g$.

NIA(5,3) : number of $g \to q + \bar{q}$.

NIA(5,4) : number of $q \to q + \gamma$.

The common block VNITIM contains the (upon initialization) pretabulated time increments and time slizes used for following the time-evolution of an collision event.

```
COMMON/VNITIM/TINC(0:2500),TIME(0:2500)
```

Purpose: to store time increments TINC and time steps TIME (in 1/GeV).

TINC(I) : i-th time increment between time steps $i-1$ and i, where i = MSTW(12) and $1 \le i \le$ MSTW(2). PARW(1) is assigned that increment value at a each time step during a collision event.

TIME(I) : i-th time step TIME(i) = TIME($i-1$) + TINC(i), where i = MSTW(12) and $1 \le i \le$ MSTW(2). PARW(2) is assigned that time value at a each time step during a collision event.

The common block VNIINT serves as a temporary storage of quantities during the simulation of a specific parton collision plus its associated branching evolution. It is very similar to a corresponding array in the PYTHIA program.

```
COMMON/VNIINT/MINT(400),VINT(400)
```

Purpose: to provide an intermediate storage for integer and real valued variables as work area, used in the program to carry out the evolution of a single partonic subsystem at a time, consisting of a parton collision and its associated space-like (initial state) and time-like (final state) branchings. These variables must not be changed by the user.

MINT(1) : specifies the general type of partonic subprocess that has occured, according to the ISUB code given in Table 3.

MINT(2) : whenever MINT(1) (together with MINT(15) and MINT(16)) are not enough to specify the type of a $2 \to 2$ parton collision uniquely, MINT(2) provides an ordering of the different possibilities, related to different color-flow topologies. The different possibilities are discussed in Refs. [57]. With i = MINT(15), j = MINT(16) and k = MINT(2), they are:

ISUB = 1, $i = j, q_i q_i \to q_i q_i$;
$k = 1$: color configuration A.
$k = 2$: color configuration B.

ISUB = 1, $i = j, q_i q_j \to q_i q_j$;
$k = 1$: only possibility.

ISUB = 2, $q_i \bar{q}_i \to q_l \bar{q}_l$;
$k = 1$: only possibility.

ISUB = 3, $q_i \bar{q}_i \to gg$;
$k = 1$: color configuration A.
$k = 2$: color configuration B.

ISUB = 6, $q_i g \to q_i g$;
$k = 1$: color configuration A.
$k = 2$: color configuration B.

ISUB = 8, $gg \to q_l \bar{q}_l$;
$k = 1$: color configuration A.
$k = 2$: color configuration B.

ISUB = 9, $gg \to gg$;
$k = 1$: color configuration A.
$k = 2$: colour configuration B.
$k = 3$: color configuration C.

MINT(3) : number of partons produced in the hard interactions, i.e. the number n of the $2 \to n$ matrix elements used, where currently only $n = 1$ or $n = 2$ processes are included.

MINT(4) : number of documentation lines in commonblocks VNIREC1/VNIREC2 that are reserved and used as work space for simulating a parton collision.

MINT(5) : not used.

MINT(6) : current frame of event as initialized, cf. MSTW(4).

MINT(7) : line number for documentation of outgoing particle 1 from a parton collision $2 \to 2$ or $2 \to 1$.

MINT(8) : line number for documentation of outgoing particle 2 from a parton collision $2 \to 2$. Is 0 for $2 \to 1$.

MINT(9) : not used.

MINT(10) : not used.

MINT(11) : KF flavour code of initial beam (side 1) particle (c.f. MSTW(5)).

MINT(12) : KF flavour code of initial target (side 1) particle (c.f. MSTW(6)).

MINT(13) : KF flavour code of side 1 parton that initiates a space-like cascade (only for primary partons, is 0 else).

MINT(14) : KF flavour code of side 2 parton that initiates a space-like cascade (only for primary partons, is 0 else).

MINT(15) : KF flavour code for side 1 incoming parton to collision subprocess.

MINT(16) : KF flavour code for side 2 incoming parton to collision subprocess.

MINT(17) - MINT(20) : not used.

MINT(21) : KF flavour code for parton 3 outgoing from a parton collision.

MINT(22) : KF flavour code for parton 4 outgoing from a parton collision (is 0 for $2 \to 1$ processes).

MINT(23) : KF flavour code for parton 5 outgoing from a parton collision - not used currently (relevant only for $2 \to 3, 2 \to 4$ processes).

MINT(24) : KF flavour code for parton 6 outgoing from a parton collision - not used currently (relevant only for $2 \to 4$ processes).

MINT(25) - MINT(30) : not used.

MINT(31) - MINT(40) : not used.

MINT(41) : type of initial beam particle; 1 for lepton and 2 for hadron and 3 for nucleus (c.f. MSTW(7)).

MINT(42) : type of initial target particle; 1 for lepton and 2 for hadron and 3 for nucleus (c.f. MSTW(8)).

MINT(43) : combination of incoming beam and target particles (c.f. MSTW(9)).

MINT(44) : as MINT(43), but a photon counts as a lepton.

MINT(45), MINT(46) : structure of incoming beam and target particles.
= **1** : no internal structure, i.e. lepton carries full beam energy.
= **2** : defined with structure functions, i.e. hadrons and nuclei.

MINT(47) : combination of incoming beam and target particle structure function types.
= **1** : no structure function either for beam or target.
= **2** : structure functions for target but not for beam.
= **3** : structure functions for beam but not for target.
= **4** : structure functions both for beam and target.

MINT(48) : total number of subprocesses switched on.

MINT(49), MINT(50) : not used.

MINT(51) : internal flag that the simulation of a 2-parton collision system, including space-like initial state and time-like final state cascades, has failed cuts.
= **0** : no problem.
= **1** : failed and to be skipped.

MINT(52) - MINT(60) : not used.

MINT(61) - MINT(70) : not used.

MINT(81), MINT(82) : not used.

MINT(83) : number of lines in the event record already filled by previously considered pileup events.

MINT(84) : MINT(83) + MSTP(126), i.e. number of lines already filled by previously considered events plus number of lines to be kept free for event documentation.

VINT(1) : E_{CM}, CM energy.

VINT(2) : $s = E_{CM}^2$, mass-square of complete system.

VINT(3) : mass of beam particle.

VINT(4) : mass of target particle.

VINT(5) : momentum of beam (and target) particle in CM frame.

VINT(6) : angle Θ for rotation from CM frame to fixed target frame.

VINT(7) : angle Φ for rotation from CM frame to fixed target frame.

VINT(8) : β_x velocity for boost from CM frame to fixed target frame.

VINT(9) : β_y velocity for boost from CM frame to fixed target frame.

VINT(10) : β_z velocity for boost from CM frame to fixed target frame.

VINT(11) : $\hat{\beta}_x$ velocity for boost from overall CM frame to 'microscopic' cm frame of a parton-parton collision subsystem.

VINT(12) : $\hat{\beta}_y$ velocity for boost from overall CM frame to parton-parton cm frame.

VINT(13) : $\hat{\beta}_z$ velocity for boost from overall CM frame to parton-parton cm frame.

VINT(14) : angle $\hat{\theta}$ for rotation from overall CM frame to 'microscopic' cm frame of a parton-parton collision subsystem.

VINT(15) : angle $\hat{\phi}$ for rotation from overall CM frame to parton-parton cm frame.

VINT(16) : Lorentz boost factor γ to parton-parton collision cm frame.

VINT(17) : Rapidity $\hat{y}_{cm}$ of 2-parton cm sytem with respect to global CM frame.

VINT(18) : Transverse momentum $\hat{p}_{\perp\, cm}$ of 2-parton cm sytem in global CM frame.

VINT(19) : Longitudinal separation $\Delta\hat{r}_z$ of 2 partons in their c.m. frame of collision, at the point of 'closest approach'.

VINT(20) : Transverse separation $\Delta\hat{r}_\perp$ of 2 partons in their c.m. frame of collision, at the point of 'closest approach'.

VINT(21) : $\tau = x_1 x_2 s$ with $x_{1,2}$ the longitudinal momentum fractions (Bjorken-x) of 2 colliding partons.

VINT(22) : $\hat{y}^* = 1/2\ln(x_1/x_2)$, the 'relative' rapidity of 2 colliding partons.

VINT(23) : $\cos(\hat{\theta})$) (scattering angle) in $2 \to 2$ parton collision.

VINT(24) : $\hat{\phi}$ (azimuthal angle) in in $2 \to 2$ parton collision.

VINT(25) - VINT(30) : not used.

VINT(31) : $\hat{t}_l$, lower value of kinematic limit on $\hat{t}$ in parton collision.

VINT(32) : $\hat{t}_u$, upper value of kinematic limit on $\hat{t}$ in parton collision.

VINT(33) : $|\hat{t}|_1$, upper absolute value of limit of integration over $d\hat{t}$ of 2-parton cross-section.

VINT(34) : $|\hat{t}|_2$, lower absolute value of limit of integration over $d\hat{t}$ of 2-parton cross-section.

VINT(35) : $\cos(\hat{\theta})_{max}$ for $\hat{\theta} \leq 0$.

VINT(36) : $\cos(\hat{\theta})_{max}$ for $\hat{\theta} \geq 0$.

VINT(37) : integrated 2-parton cross-section $\hat{\sigma}(\hat{s}) = \int d\hat{p}_\perp^2 (d\hat{\sigma}(\hat{s}, \hat{p}_\perp^2)/d\hat{p}_\perp^2$.

VINT(38) : differential 2-parton cross-section $d\hat{\sigma}(\hat{s}, \hat{p}_\perp^2)/d\hat{p}_\perp^2$.

VINT(39) : characteristic proper collision time $\tau_c ol(p_\perp^2) \propto 1/p_\perp$ in the 2-body $c.m.$-frame.

VINT(40), not used.

VINT(41) : the momentum fraction x_1 taken by parton 1 at the 2-parton vertex.

VINT(42) : the momentum fraction x_2 taken by parton 2 at the 2-parton vertex.

VINT(43) : $\hat{m} = \sqrt{\hat{s}}$, mass of 2-parton collision subsystem.

VINT(44) : $\hat{s}$ of the collision subprocess $(2 \to 2, 2 \to 1)$.

VINT(45) : $\hat{t}$ of the collision subprocess $(2 \to 2, 2 \to 1)$.

VINT(46) : $\hat{u}$ of the collision subprocess $(2 \to 2, 2 \to 1)$.

VINT(47) : $\hat{p}_\perp$ of the collision subprocess, i.e., transverse momentum evaluated in the rest frame of the collision.

VINT(48) : $\hat{p}_\perp^2$ of the collision subprocess; see VINT(47).

VINT(49) : $\hat{p}_{\perp min}$ of process, i.e. PARV(42), or max(VKIN(3),VKIN(5)), depending on which is larger, and whether the process is singular in $\hat{p}_\perp \to 0$, or not.

VINT(50) : not used.

VINT(51) : Q of the hard subprocess. The precise definition is process-dependent, see MSTV(43).

VINT(52) : Q^2 of the hard subprocess; see VINT(51).

VINT(53) : Q of the outer hard-scattering subprocess. Agrees with VINT(51) for a $2 \to 1$ or $2 \to 2$ process.

VINT(54) : Q^2 of the outer hard-scattering subprocess; see VINT(53).

VINT(55) : Q scale used as maximum virtuality in parton showers. *Is equal to* VINT(53), *except for* deep-inelastic-scattering processes.

VINT(56) : Q^2 scale in parton showers; see VINT(55).

VINT(57) : α_{em} value of hard process.

VINT(58) : α_s value of hard process.

VINT(59) : $\sin\hat{\theta}$ (cf. VINT(23)); used for improved numerical precision in elastic and diffractive scattering.

VINT(61), VINT(62) : nominal m^2 values, i.e. without initial-state radiation effects, for the two partons entering the hard interaction.

VINT(63), VINT(64) : nominal m^2 values, i.e. without final-state radiation effects, for the two (or one) partons/particles leaving the hard interaction.

VINT(65) : $\hat{p}_{init}$, i.e. common nominal absolute momentum of the two partons entering the hard interaction, in their rest frame.

VINT(66) : $\hat{p}_{fin}$, i.e. common nominal absolute momentum of the two partons leaving the hard interaction, in their rest frame.

VINT(67) - VINT(100) : not used.

VINT(101) - VINT(105) : θ, φ and β for rotation and boost from c.m. frame to hadronic c.m. frame of a lepton-hadron or lepton-nucleus event.

VINT(106) - VINT(110) : θ, φ and β for rotation and boost from c.m. frame to frame of equal nucleon-nucleon velocity in the case of a hadron-nucleus or an asymmetric nucleus-nucleus event with $A \neq B$.

The common block VNICOL contains accumulated data on parton collisions during a beam/target event.

```
COMMON/VNICOL/MCOL(1000,0:10),VCOL(1000,0:10)
```

Purpose: to provide an intermediate storage for a minimal set of integer and real valued variables for all detected parton collisions that occur during a single timestep during an event. The first index I in the arrays MCOL and VCOL labels the sequence number of a collision and the second index J is a pointer to interface with the above MINT and VINT arrays wherein the calculated quantities are written to.

MCOL(I,1) : line number in VNIREC1/VNIREC2 of parton 1 entering the collision subprocess.

MCOL(I,2) : line number in VNIREC1/VNIREC2 of parton 2 entering the collision subprocess.

MCOL(I,3) : = MINT(1)

MCOL(I,4) : = MINT(2)

MCOL(I,5) : = MINT(3)

MCOL(I,6) : = MINT(15)

MCOL(I,7) : = MINT(16)

MCOL(I,8) : = MINT(21)

MCOL(I,9) : = MINT(22)

MCOL(I,10): not used.

VCOL(I,1) : = VINT(23)

VCOL(I,2) : = VINT(24)

VCOL(I,3) : = VINT(26)

VCOL(I,4) : = VINT(41)

VCOL(I,5) : = VINT(42)

VCOL(I,6) : = VINT(44)

VCOL(I,7) : = VINT(45)

VCOL(I,8) : = VINT(46)

VCOL(I,9) : = VINT(48)

VCOL(I,10): = VINT(52)

D Sample output

1. General information on the simulation as-a-whole

The following output stems simulating 500 $p\bar{p}$ collisions at CERN collider energy $\sqrt{s} = 900$ GeV. Unless switched of by setting $MSTV(114) = 0$, this type of output information is provided automatically and written to the file VNIRUN.DAT at the end of a simulation. The output includes a summary of the initialization overall collision system, the gluon and quark content of the initial state, the type and number of occured interaction processes during the parton-cascade development, the number and type of produced pre-hadronic clusters from partons, and the numbers of resulting final-state hadrons.

```
**********************************************************************************
**********************************************************************************
**                                                                              **
**                                                                              **
**                                                                              **
**        **                 x              V       V  NN    N   IIIIII         **
**                         x=x               V     V   N N   N     II           **
**            **   **     x===x               V   V    N  N  N     II           **
**              /  **  x=====x                 V V     N   N N     II           **
**               | /     x=====x                V      N    NN   IIIIII         **
**      x --- *-*-**----- x=====x                                               **
**     x=x ----*--**---*-- x===x               This is VNI version 4. 10        **
**    x===x -*--**---*----- x=x                                                 **
**    x===x -- /--|- ------ x               Last date of change: 30 Jun 1998    **
**     x=x     **  |  *--*                                                      **
**      x           **                                                          **
**               /      **                                                      **
**              /                           Warning: this program is a Monte    **
**            **                            Carlo program! So when you play     **
**                      ----->              roulette, dont do it the Russian    **
**      <-----              B               way - avoid fatal results!          **
**         A                                -- Copyright KayKayGee (1998) --    **
**                                                                              **
**                                                                              **
**          Depository of program versions and documentation:                   **
**               http://rhic.phys.columbia.edu/rhic/vni                         **
**                                                                              **
**                         Official reference:                                  **
**        K. Geiger, Computer Physics Communications 104 (1997) 70.             **
**           (Further relevant references may be found therein)                 **
**                                                                              **
**                             The Crew:                                        **
**                                                                              **
**      KLAUS KINDER-GEIGER    RON LONGACRE    DINESH K. SRIVASTAVA             **
**                                                                              **
**                         Mailing address:                                     **
** Physics Dept., Brookhaven National Laboratory, Upton, N.Y. 11973, U.S.A.     **
**                                                                              **
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**          klaus@bnl.gov               /  USA + (516) 344-3791                 **
**          longacre@bnl.gov            /  USA + (516) 344-3713                 **
**          dks@vecdec.veccal.ernet.in  /  India + (33) 337-1231                **
**                                                                              **
```



```
**                                                                              **
**********************************************************************************
**********************************************************************************

****************** VNIXRIN: initialization of VNI routines *****************

============================================================================
I                                                                          I
I                    VNI will be initialized for a                         I
I                                                                          I
I                          p+ on p- collider                               I
I                                                                          I
I            at     900.00 GeV center-of-mass energy                       I
I                                                                          I
I     corresponding to     900.00 GeV sqrt(s)/hadron(nucleon)              I
I                                                                          I
I                 h + h  ->  jets + X  ->  hadrons                         I
I                                                                          I
I              Number of collision events:       500                       I
I              Number of time steps per event:   200                       I
I                                                                          I
I     Initial time:     .00 1/GeV =       .00 fm  =  0.00D+00 sec          I
I     Final time:    176.10 1/GeV =     34.75 fm  =  0.23D-22 sec          I
I                                                                          I
I                                                                          I
I            Initial parton distributions from VNI:                        I
I            nucleon structure functions GRV set  1                        I
I               pion structure functions  DO set  1                        I
I                                                                          I
I     Minimum initial resolution scale Q_0:           3.42 GeV             I
I     Minimum sqrt(s) in parton collisions:           2.00 GeV             I
I     Minimum pT_0 in parton collisions:              3.60 GeV             I
I     Minimum q_0 in space-like branchings:           3.42 GeV             I
I     Minimum mu_0 in time-like branchings:           1.48 GeV             I
I                                                                          I
I                                                                          I
I          Initial Collision System (in global CM frame):                  I
I                                                                          I
I                                     Beam           Target                I
I     Particle:                       p+             p-                    I
I                                                                          I
I     Number of neutrons:                 0              0                 I
I     Number of protons:                  1             -1                 I
I     Number of d_v quarks:               1             -1                 I
I     Number of u_v quarks:               2             -2                 I
I     Number of s_v quarks:               0              0                 I
I     Radius R_ms (fm):                .810           .810                 I
I                                                                          I
I     Velocity:                     .999998        .999998                 I
I     Gamma factor:                 479.591        479.591                 I
I     Rapidity:                       6.866         -6.866                 I
I                                                                          I
I     p_x (GeV):                       .000           .000                 I
I     p_y (GeV):                       .000           .000                 I
I     p_z (GeV):                    449.999       -449.999                 I
```

```
I        E (GeV):                        450.000         450.000          I
I        M (GeV):                           .938            .938          I
I                                                                         I
I        charge   px_tot    py_tot    pz_tot     E_tot     M_tot          I
I          .0       0.        0.        0.       900.      900.           I
I                                                                         I
I        Initial separation parallel to beam:  Delta Z =   .25 fm         I
I        Min/max impact transverse to beam:     .00 < B <  1.19 fm        I
I                                                                         I
I                                                                         I
===========================================================================

********************** VNIXRIN: initialization completed *********************

******************************************************************************

          Welcome on board! Hope you survive this flight with VNI

******************************************************************************

*********************** VNIXFIN: run finished normally **********************

===========================================================================
I                                                                         I
I        Total CPU time needed:    0 hours   21 minutes   11 seconds      I
I                                                                         I
===========================================================================


===========================================================================
        INITIAL STATE
===========================================================================


   -  Internal parton structure functions selected:

      set  1 ( 1) for nucleons (pions) at initial Q0 =     5.939 GeV


   -  Minimum resolvable x-value resulting from spread of confined
      partons with 1/xP < R_conf =  .20 fm:

       Beam    p+    :        x_min = 0.222D-02
      Target   p~-   :        x_min = 0.222D-02


   -  Average sum of momentum fractions per hadron (nucleon):

       Beam    p+    :       <sum x> =    .9853
      Target   p~-   :       <sum x> =    .9908


   -  Average number of initial state partons:

           gluons :    51.8160
```



```
          u+u~+d+d~:    49.4000
          u-u~+d-d~:      .0000
               s+s~ :    6.7800
               c+c~ :    1.0520
               b+b~ :     .0320
               t+t~ :     .0000

              total :   109.0800


===========================================================================
        PARTON CASCADE EVOLUTION
===========================================================================

        Total number of events N_evt:       500
        Total number of time steps N_tim:   200
        Initial/final time:    .0 fm  /  34.7 fm
        Analysis based on     500 event samples

        All numbers per non-diff. event N_nd  --  N_nd/N_evt =   0.8880D+00

        Actual minimum momentum transfer for hard collisions:    3.6000 GeV

        hard 2 -> 2 collisions:          switched  on
        soft 2 -> 2 collisions:          switched off
        fusions 2 -> 1:                  switched  on
        space-like branchings 1 - > 2: switched  on
        time-like branchings  1 - > 2: switched  on


   -  Average number of hard parton collisions a + b -> c + d :

             q+q  ->  q+q      :      .0000
             q+q~ ->  q+q~     :      .0000
             q+q~ ->  g+g      :      .0000
             q+q~ -> g+gamma   :      .0000
             q+q~ -> 2 gamma   :      .0000
             q+g  ->  q+g      :      .0135
             q+g  -> q+gamma   :      .0000
             g+g  ->  q+q~     :      .0045
             g+g  ->  g+g      :      .2095
        total hard a+b -> c+d  :      .2275


   -  Average number of soft parton collisions a + b -> c + d :

             q+q  ->  q+q      :      .0000
             q+q~ ->  q+q~     :      .0000
             q+q~ ->  g+g      :      .0000
             q+q~ -> g+gamma   :      .0000
             q+q~ -> 2 gamma   :      .0000
             q+g  ->  q+g      :      .0000
             q+g  -> q+gamma   :      .0000
             g+g  ->  q+q~     :      .0000
```

```
     g+g  ->  g+g     :     .0000
total soft a+b -> c+d :     .0000


- Average number of parton fusions a + b -> c :

      q+q~ ->  g*     :     .0000
      q+g  ->  q*     :     .0000
      g+g  ->  g*     :     .0135
total fusion a+b -> c :     .0135


- Average number of space-like branchings a -> b + c:

   ( CMshower -> b+c  :     .1464 )
       q   ->   q+g   :     .0045
       g   ->   g+g   :     .0045
       g   ->   q+q~  :     .0000
       q   -> q+gamma :     .0000
total sp-like a -> b+c :    .0090


- Average number of time-like branchings a -> b + c:

   ( CMshower -> b+c  :     .8829 )
       q   ->   q+g   :     .0608
       g   ->   g+g   :     .7050
       g   ->   q+q~  :     .0586
       q   -> q+gamma :     .0000
total tm-like a -> b+c :    .8243


=========================================================================
     PARTON CLUSTER FORMATION
=========================================================================

     NOTE: numbers refer to clusters from interacted partons only;
           beam/target remnant clusters (if present) are not included.

     Total number of events N_evt:       500
     Total number of time steps N_tim:   200
     Initial/final time:    .0 fm  /  34.7 fm
     Analysis based on     500 event samples

     All numbers per non-diff. event N_nd  --  N_nd/N_tot =   0.8880D+00


- Total numbers of produced clusters:
  all:           1.6171
  fast:          1.3131 ( >  PARV(88)=    1.000   MSTV(88)=  0 )
  slow:           .3041 ( <  PARV(88)=    1.000   MSTV(88)=  0 )
  exogamous:      .0068

- Number of elementary cluster formation processes
```



```
          type                         total   exogamous
     g + g     -> C + C                .1712     .0000
     g + g     -> C + g                .4234     .0000
     g + g     -> C + g + g            .7275     .0000
     q + q~    -> C + C                .0270     .0000
     q + q~    -> C + g                .0428     .0023
     q + q~    -> C + g + g            .0000     .0000
     g + q     -> C + q                .0811     .0045
     g + q     -> C + q + g            .1441     .0000
     qq + q    -> C + C                .0000     .0000
     sum:                             1.6171     .0068

- Distribution of exogamous cluster processes:
     origin              all        fast        slow
   0.00 - 0.05          .2658       .2072       .0586
   0.05 - 0.20          .0000       .0000       .0000
   0.20 - 0.30          .0000       .0000       .0000
   0.30 - 0.45          .0000       .0000       .0000
   0.45 - 0.55          .0023       .0000       .0023
   0.55 - 0.70          .0000       .0000       .0000
   0.70 - 0.80          .0023       .0000       .0023
   0.80 - 0.95          .0023       .0023       .0000
   0.95 - 1.00         1.3446      1.1036       .2410


=========================================================================
     CLUSTER HADRONIZATION AND UNSTABLE PARTICLE DECAYS
=========================================================================

     NOTE: numbers refer to both, clusters from interacted partons
           as well as beam/target remnant clusters (if present)DO

     Total number of events:       500
     Total number of time steps:   200
     Initial/final time:    .0 fm  /  34.7 fm
     Analysis based on     500 event samples

     parton-cluster fragmentation:        switched  on
     beam/target-cluster fragmentation:   switched  on


- Average number of primary particles from cluster decays:

                    type          charged + neutral   charged only

        leptons, gauge bosons:          .0000             .0000
                light mesons:         18.2700            8.8700
              strange mesons:          3.8100            1.7880
       charm, bottom mesons:            .0440             .0140
               tensor mesons:          2.2340            1.1220
               light baryons:          3.0220            2.0860
             strange baryons:          1.4140             .6960
      charm, bottom baryons:            .0000             .0000
                       other:           .0040             .0040
```

total:	49.2540	14.5800

- Average number of secondary particles from unstable particle decays:

type	charged + neutral	charged only
leptons, gauge bosons:	1.9660	.0060
light mesons:	51.1120	32.4320
strange mesons:	5.5240	2.8480
charm, bottom mesons:	.0200	.0080
tensor mesons:	.0060	.0040
light baryons:	5.1600	2.5200
strange baryons:	1.2200	.0060
charm, bottom baryons:	.0000	.0000
other:	.0000	.0000
total:	65.0040	37.8220

==

HADRON CASCADE EVOLUTION

==

Total number of events: 500
Total number of time steps: 200
Initial/final time: .0 fm / 34.7 fm
Analysis based on 500 event samples

All numbers per non-diff. event N_nd -- N_nd/N_tot = 0.8880D+00

- Average number of cluster/hadron collisions a + b -> n (n >= 1):

C = prehadronic cluster
M1 = low lying pseudoscalar & vector mesons
M2 = excited & tensor mesons
B = baryons

channel	all	light	strange	charm	bottom
C + C -> n :	0.0000	0.0000	0.0000	0.0000	0.0000
C + M1 -> n :	0.0000	0.0000	0.0000	0.0000	0.0000
C + M2 -> n :	0.0000	0.0000	0.0000	0.0000	0.0000
C + B -> n :	0.0000	0.0000	0.0000	0.0000	0.0000
M1 + M1 -> n :	0.0000	0.0000	0.0000	0.0000	0.0000
M1 + M2 -> n :	0.0000	0.0000	0.0000	0.0000	0.0000
M1 + B -> n :	0.0000	0.0000	0.0000	0.0000	0.0000
B + B -> n :	0.0000	0.0000	0.0000	0.0000	0.0000
B + M2 -> n :	0.0000	0.0000	0.0000	0.0000	0.0000
M2 + M2 -> n :	0.0000	0.0000	0.0000	0.0000	0.0000
other unidentified :	0.0000	---	---	---	---
sum :	0.0000	0.0000	0.0000	0.0000	0.0000

- Average kinematical quantities and average number of particles per cluster / hadron collision:

	sqrt(s) (GeV)	sqrt(-t) (GeV)	sqrt(-u) (GeV)	# prod. part.
light :	0.0000	0.0000	0.0000	0.0000
strange :	0.0000	0.0000	0.0000	0.0000
charm :	0.0000	0.0000	0.0000	0.0000
bottom :	0.0000	0.0000	0.0000	0.0000
all :	0.0000	0.0000	0.0000	0.0000

==

****

Thanxxxxxxxxx 4 flying with VNI
('We do know that you have the choice')

****

2. A typical event listing

The event listing below is part of the standard output obtained for 500 $p\bar{p}$ collisions at CERN collider energy $\sqrt{s}$ = 900 GeV. The listing, which is is written to the file VNIRUN.DAT, embodies the complete history of the first event from the initial beam particles p and $\bar{p}$, their original gluon and quark content, the newly produced partons by hard scattering and radiation during the parton-cascade development, the formed pre-hadronic clusters and resulting final state particles. The latter emerge from both the parton clusters that result from parton-cascade products, and the beam/target clusters that consist of the remnant initial partons which have not participated in the parton cascades. As explained in Sec. 3.6, each entry contains name, status, flavor, and origin of a particle, as well as it's three-momentum, energy and mass. Particles in brackets are inactive, decayed or fragmented particles. The final line of the listing shows the total charge, three-momentum, anargy and invariant mass of the particle system, given by the sums over all active, stable particles.

```
Particle listing (summary: momentum space P in GeV)
event no.    1  time step   200   at time   34.75 fm
```

I particle	KS	KF	KMO	P_x	P_y	P_z	E	M
1 (p+)	15	2212	0	.000	.000	449.999	450.000	.938
2 (p~-)	15	-2212	0	.000	.000	-449.999	450.000	.938
3 (p+)	15	2212	1	.000	.000	449.999	450.000	.938
4 (p~-)	15	-2212	2	.000	.000	-449.999	450.000	.938
5 (u)	13	2	3	6.468	-.283	67.618	67.928	.006
6 (d)	13	1	3	-2.033	7.351	87.053	87.387	.010
7 (g)	13	21	3	.135	-.110	6.530	6.530	-.175
8 (g)	13	21	3	.410	.205	2.324	2.324	-.459
9 (g)	13	21	3	-.009	.066	3.136	3.136	-.067
10 (g)	13	21	3	-.098	.153	14.160	14.160	-.184
11 (g)	13	21	3	-.094	.012	2.851	2.851	-.095
12 (g)	13	21	3	-.159	-.130	4.587	4.587	-.205
13 (g)	13	21	3	.745	-.058	5.911	5.910	-.747
14 (g)	13	21	3	.015	.208	1.636	1.636	-.208
15 (g)	13	21	3	-.002	.082	1.964	1.964	-.082
16 (g)	13	21	3	-.133	-.088	1.742	1.742	-.159
17 (g)	13	21	3	-.067	-.580	4.587	4.587	-.584
18 (g)	13	21	3	-.343	.022	1.636	1.636	-.344
19 (u~)	13	-2	3	-.355	-.198	.988	.988	-.406
20 (u)	13	2	3	.132	.153	.988	.988	-.202
21 (g)	13	21	3	.007	.003	2.992	2.992	-.010
22 (g)	13	21	3	-.154	.440	3.746	3.746	-.466
23 (g)	13	21	3	-.038	.415	17.137	17.137	-.418
24 (g)	13	21	3	.054	-.036	2.714	2.714	-.065
25 (g)	13	21	3	.054	.037	1.338	1.338	-.065
26 (u~)	13	-2	3	-.406	.103	49.084	49.083	-.431
27 (u)	13	2	3	-.268	.098	1.245	1.245	-.285
28 (g)	13	21	3	-.009	-.030	1.742	1.742	-.031
29 (s~)	13	-3	3	.082	.062	9.842	9.842	-.225
30 (s)	13	3	3	.314	.241	1.070	1.070	-.443
31 (s~)	13	-3	3	-.008	-.001	7.634	7.634	-.200
32 (s)	13	3	3	.016	-.105	.988	.988	-.226
33 (d)	13	1	3	-.029	.227	1.851	1.851	-.229
34 (d~)	13	-1	3	-.030	-.025	.988	.988	-.040
35 (g)	13	21	3	-.015	.008	1.636	1.636	-.017
36 (g)	13	21	3	.218	-.061	6.744	6.744	-.227
37 (g)	13	21	3	.147	-.042	2.581	2.581	-.153
38 (g)	13	21	3	.100	-.031	2.450	2.450	-.105
39 (s~)	13	-3	3	-.080	.236	1.245	1.245	-.319
40 (s)	13	3	3	-.057	.207	.988	.988	-.292

41 (g)	13	21	3	-.044	-.095	2.992	2.992	-.105
42 (u)	13	2	3	-.343	-.011	1.433	1.433	-.343
43 (u~)	13	-2	3	.058	.067	.988	.988	-.089
44 (g)	13	21	3	.084	-.195	1.245	1.245	-.212
45 (g)	13	21	3	.048	.017	1.533	1.533	-.051
46 (g)	13	21	3	-.008	.022	2.200	2.200	-.024
47 (g)	13	21	3	-.019	.610	4.765	4.765	-.611
48 (g)	13	21	3	.032	-.050	2.081	2.081	-.060
49 (u~)	13	-2	3	-.119	-.036	1.636	1.636	-.125
50 (u)	13	2	3	-.144	-.129	.988	.988	-.193
51 (d)	13	1	3	-.225	-.119	2.581	2.581	-.255
52 (d~)	13	-1	3	.209	-.049	.988	.988	-.215
53 (g)	13	21	3	.017	.334	50.278	50.278	-.351
54 (d~)	13	-1	3	-.127	.001	1.156	1.156	-.127
55 (d)	13	1	3	.182	.007	.988	.988	-.182
56 (g)	13	21	3	-.026	-.076	18.553	18.553	-.089
57 (g)	13	21	3	.095	.035	3.746	3.746	-.101
58 (g)	13	21	3	-.248	-.167	4.240	4.240	-.299
59 (g)	13	21	3	.035	.128	1.338	1.338	-.133
60 (g)	13	21	3	-.170	.029	6.320	6.320	-.173
61 (g)	13	21	3	.552	.019	14.477	14.477	-.553
62 (g)	13	21	3	-.178	-.282	2.324	2.324	-.334
63 (d~)	13	-1	3	-.210	.044	2.200	2.200	-.214
64 (d)	13	1	3	.012	-.049	.988	.988	-.051
65 (u~)	13	-2	3	-.056	-.557	2.714	2.714	-.560
66 (u)	13	2	3	-.137	-.062	.988	.988	-.151
67 (g)	13	21	3	.067	-.147	2.851	2.851	-.161
68 (g)	13	21	3	-.409	-.114	10.915	10.915	-.425
69 (g)	13	21	3	.157	-.266	6.961	6.961	-.310
70 (g)	13	21	3	-.363	-.114	5.133	5.133	-.380
71 (g)	13	21	3	.110	.285	8.338	8.338	-.306
72 (u)	13	2	3	.093	.272	6.320	6.320	-.288
73 (u~)	13	-2	3	-.561	.058	.988	.988	-.564
74 (s)	13	3	3	-.252	-.121	7.406	7.406	-.344
75 (s~)	13	-3	3	-.078	.016	.988	.988	-.214
76 (d)	13	1	3	-.095	.011	4.072	4.072	-.097
77 (d~)	13	-1	3	.013	.005	.988	.988	-.017
78 (g)	13	21	3	-.315	.023	5.711	5.711	-.317
79 (u~)	13	-2	3	.376	-.047	1.245	1.245	-.379
80 (u)	13	2	3	-.339	.142	.988	.988	-.368
81 (g)	13	21	3	.009	.110	1.964	1.964	-.111
82 (g)	13	21	3	-.143	-.143	12.337	12.337	-.203
83 (d~)	13	-1	3	.279	.015	2.200	2.200	-.280
84 (d)	13	1	3	-.093	-.020	.988	.988	-.096
85 (g)	13	21	3	-.118	.159	4.587	4.587	-.199
86 (u~)	13	-2	3	-.005	-.196	1.245	1.245	-.196
87 (u)	13	2	3	-.012	-.449	.988	.988	-.449
88 (u)	13	2	3	.203	.190	4.947	4.947	-.278
89 (u~)	13	-2	3	-.086	-.351	.988	.988	-.361
90 (g)	13	21	3	-.041	-.083	4.240	4.240	-.093
91 (g)	13	21	3	-.038	.260	3.434	3.434	-.262
92 (g)	14	21	206	-.149	.025	5.467	5.467	-.147
93 (g)	13	21	3	.001	-.168	7.406	7.406	-.169
94 (d~)	13	-1	3	.095	.010	1.636	1.636	-.096
95 (d)	13	1	3	.029	.014	.988	.988	-.033
96 (u~)	13	-2	4	.538	6.772	-468.861	468.910	.006
97 (d~)	13	-1	4	.239	.502	-143.968	143.969	.010
98 (u~)	13	-2	4	.050	.087	-1.742	1.742	-.101
99 (u)	13	2	4	.149	-.244	-.988	.988	-.286
100 (g)	13	21	4	-.204	.198	-2.324	2.324	-.284
101 (g)	13	21	4	.021	.084	-1.433	1.433	-.087
102 (g)	13	21	4	-.078	-.026	-2.324	2.324	-.082

103 (g)	13	21	4	.001	.009	-4.412	4.412	-.013
104 (u)	13	2	4	.080	.216	-4.240	4.240	-.230
105 (u~)	13	-2	4	.126	.018	-.988	.988	-.127
106 (u)	13	2	4	-.178	-.106	-1.156	1.156	-.208
107 (u~)	13	-2	4	-.008	.354	-.988	.988	-.354
108 (g)	13	21	4	.243	.021	-4.072	4.072	-.244
109 (g)	13	21	4	-.186	-.081	-1.433	1.433	-.203
110 (g)	13	21	4	-.140	-.036	-7.634	7.634	-.145
111 (g)	13	21	4	-.242	-.221	-3.588	3.588	-.328
112 (d)	13	1	4	.129	.089	-4.072	4.072	-.157
113 (d~)	13	-1	4	-.060	.039	-.988	.988	-.072
114 (u)	13	2	4	-.080	0.000	-4.947	4.947	-.081
115 (u~)	13	-2	4	-.029	-.118	-.988	.988	-.122
116 (g)	13	21	4	-.225	.015	-51.488	51.488	-.249
117 (g)	13	21	4	.274	-.045	-1.851	1.851	-.278
118 (g)	13	21	4	.064	-.019	-6.530	6.530	-.068
119 (g)	13	21	4	.304	-.007	-5.322	5.322	-.305
120 (g)	13	21	4	0.000	.433	-2.200	2.200	-.433
121 (g)	13	21	4	-.009	-.028	-10.105	10.105	-.036
122 (u~)	13	-2	4	.044	-.575	-8.100	8.100	-.577
123 (u)	13	2	4	-.047	.452	-.988	.988	-.454
124 (g)	13	21	4	.064	.004	-2.081	2.081	-.065
125 (g)	13	21	4	-.119	.074	-4.240	4.240	-.140
126 (g)	13	21	4	.001	-.027	-2.324	2.324	-.027
127 (g)	13	21	4	.035	-.102	-9.582	9.582	-.110
128 (u~)	13	-2	4	.204	-.155	-2.200	2.200	-.256
129 (u)	13	2	4	.128	-.267	-.988	.988	-.296
130 (s~)	13	-3	4	-.010	-.039	-23.146	23.146	-.209
131 (s)	13	3	4	-.383	-.083	-1.156	1.156	-.439
132 (g)	13	21	4	-.041	.164	-4.765	4.765	-.169
133 (d)	13	1	4	.090	-.176	-.988	.988	-.198
134 (d~)	13	-1	4	.091	-.003	-.988	.988	-.092
135 (s)	13	3	4	.162	.150	-3.434	3.434	-.297
136 (s~)	13	-3	4	-.025	.084	-.988	.988	-.218
137 (d)	13	1	4	.018	.090	-11.758	11.758	-.096
138 (d~)	13	-1	4	.033	-.095	-.988	.988	-.101
139 (g)	14	21	207	.149	-.025	-5.468	5.470	-.065
140 (g)	13	21	4	-.197	.040	-1.636	1.636	-.201
141 (u)	13	2	4	.105	.015	-1.338	1.338	-.106
142 (u~)	13	-2	4	.091	.232	-.988	.988	-.249
143 (g)	13	21	4	-.023	-.024	-4.765	4.765	-.035
144 (g)	13	21	4	-.101	-.226	-7.865	7.865	-.248
145 (d~)	13	-1	4	.001	.029	-.988	.988	-.031
146 (d)	13	1	4	-.368	.013	-.988	.988	-.369
147 (u)	13	2	4	-.037	-.162	-14.477	14.477	-.169
148 (u~)	13	-2	4	-.036	.378	-.988	.988	-.380
149 (g)	13	21	4	-.255	-.163	-1.070	1.070	-.303
150 (u)	13	2	4	.178	-.143	-1.533	1.533	-.229
151 (u~)	13	-2	4	.010	.247	-.988	.988	-.247
152 (g)	13	21	4	-.169	-.036	-33.894	33.894	-.187
153 (g)	13	21	4	-.070	-.382	-15.448	15.448	-.389
154 (g)	13	21	4	-.005	.047	-1.851	1.851	-.048
155 (g)	13	21	4	-.299	.012	-1.636	1.636	-.299
156 (d~)	13	-1	4	-.013	.200	-1.245	1.245	-.201
157 (d)	13	1	4	.078	.115	-.988	.988	-.139
158 (g)	13	21	4	.161	.004	-1.533	1.533	-.161
159 (g)	13	21	4	.055	-.005	-1.742	1.742	-.055
160 (g)	13	21	4	.001	-.032	-1.338	1.338	-.032
161 (u)	13	2	4	.170	-.191	-11.192	11.192	-.257
162 (u)	13	-2	4	-.263	-.035	-.988	.988	-.266
163 (g)	13	21	4	.065	-.013	-2.581	2.581	-.067
164 (g)	13	21	4	-.086	-.321	-6.530	6.530	-.332
165 (d)	13	1	4	.029	-.140	-1.245	1.245	-.143

166 (d~)	13	-1	4	-.162	-.100	-.988	.988	-.191
167 (g)	13	21	4	-.039	-.325	-2.081	2.081	-.328
168 (d~)	13	-1	4	-.091	.017	-1.338	1.338	-.093
169 (d)	13	1	4	-.042	-.771	-.988	.988	-.772
170 (g)	13	21	4	.206	.254	-1.533	1.533	-.328
171 (g)	13	21	4	-.061	.332	-2.200	2.200	-.337
172 (d)	13	1	4	.074	.105	-6.961	6.961	-.130
173 (d~)	13	-1	4	.050	-.015	-.988	.988	-.053
174 (s~)	13	-3	4	-.012	-.001	-1.583	1.533	-.199
175 (s)	13	3	4	-.105	.060	-.988	.988	-.233
176 (g)	13	21	4	-.470	-.003	-2.200	2.200	-.470
177 (g)	13	21	4	.081	-.082	-1.338	1.338	-.115
178 (u~)	13	-2	4	.053	-.060	-2.324	2.324	-.080
179 (u)	13	2	4	.043	.004	-.988	.988	-.044
180 (u)	13	2	4	.008	.105	-5.711	5.711	-.107
181 (u~)	13	-2	4	-.027	.029	-.988	.988	-.040
182 (g)	13	21	4	.105	.007	-1.245	1.245	-.105
183 (g)	13	21	4	-.029	.063	-4.412	4.412	-.070
184 (g)	13	21	4	-.044	-.104	-2.992	2.992	-.113
185 (g)	13	21	4	-.005	.003	-1.338	1.338	-.007
186 (d~)	13	-1	4	.003	.128	-1.964	1.964	-.129
187 (d)	13	1	4	-.271	.071	-.988	.988	-.281
188 (d~)	13	-1	4	.045	.236	-1.338	1.338	-.240
189 (d)	13	1	4	-.009	-.141	-.988	.988	-.142
190 (g)	13	21	4	-.148	-.079	-1.742	1.742	-.168
191 (g)	13	21	4	.066	-.088	-6.320	6.320	-.111
192 (g)	13	21	4	-.093	.334	-4.765	4.765	-.347
193 (g)	13	21	4	.259	.034	-3.434	3.434	-.262
194 (u)	13	2	4	.025	.168	-21.558	21.558	-.176
195 (u~)	13	-2	4	-.037	.036	-.988	.988	-.052
196 (g)	14	21	92	.141	.040	3.588	3.588	-.147
197 (g)	14	21	139	.062	.001	-8.338	8.338	-.065

198 !g!	21	21	200	.141	.040	3.588	3.588	-.147
199 !g!	21	21	201	.062	.001	-8.338	8.338	-.065
200 !g!	21	21	0	-5.188	.107	-3.853	6.463	.000
201 !g!	21	21	0	5.392	-.066	-.897	5.466	.000
202 (g)	14	21	0	.141	.040	3.588	3.588	-.147
203 (g)	14	21	0	.062	.001	-8.338	8.338	-.065
204 (g)	14	21	200	-5.188	.107	-3.853	6.463	.000
205 (g)	14	21	201	5.392	-.066	-.897	5.466	.000
206 (g)	14	21	0	.000	.000	5.470	5.470	-.000
207 (g)	14	21	0	.000	.000	-5.470	5.470	-.000
208 (CMshower)	11	94	204	.204	.041	-4.750	11.929	10.941
209 (g)	14	21	208	3.659	-.030	-2.183	7.624	6.322
210 (cluster)	11	91	209	-2.497	1.963	-4.249	5.660	1.973
211 (cluster)	11	91	209	-.843	.635	-1.481	2.437	1.623
212 pi+	6	211	210	.627	.196	.847	1.081	.140
213 (K*_10)	16	20313	210	-.463	.736	-1.950	2.646	1.563
214 (phi)	16	333	211	-.743	.632	-.926	1.688	1.020
215 K-	6	-321	211	0.000	0.000	.565	.751	.494
216 (K*0)	16	313	215	0.000	0.000	-1.227	1.536	.924
217 pi0	6	111	215	-.237	-.351	.038	.446	.135
218 K-	6	-321	218	-.001	0.000	.373	.619	.494
219 K+	6	321	218	0.000	0.000	.098	.503	.494
220 K0	6	311	218	0.000	0.000	.093	.506	.498
221 pi0	6	111	218	-.142	.010	.243	.312	.135
222 (g)	13	21	209	2.096	-1.634	1.690	3.150	.010
223 (Beam-REM)	11	92	209	7.456	2.673	668.286	671.476	498.322
224 (Targ-REM)	11	93	209	-1.241	7.624	-1060.622	1060.682	960.492
225 (CMF)	15	100	223	6.215	10.297	-392.336	1732.158	1687.097

226 (cluster)	11	91	223	7.456	2.673	668.286	671.476	498.322

```
227 (cluster)     11     91   224   -1.241    7.624-1060.622 1060.682  960.492
228 (Beam-REM)    11     92   226    3.106    1.329  413.755  413.777    2.559
229 (K*0)         17    313   228    2.034     .486  173.846  173.861     .892
230 (Sigma0)      17   3212   228    1.071     .843  239.909  239.916    1.192
231 pi0            7    111     0     .672     .201  220.546  220.547     .135
232 K0             7    311     0    -.801    -.560 -295.110  295.112     .498
233 ((gamma))     -7     22   234    0.000     .045    6.088    6.089     .000
234 Lambda0        7   3122     0    -.317    -.704   93.191   93.200    1.116
235 (Targ-REM)    11     93   226   -1.050    5.146 -773.796  773.817    2.117
236 (Delta~-)     17  -2214   235    -.580    2.264 -368.320  368.329    1.232
237 (rho+)        17    213   235    -.470    2.883 -405.476  405.487     .769
238 pi0            7    111     0    -.021     .284   20.497   20.500     .135
239 p~-            7  -2212     0     .229     .387   59.692   59.701     .938
240 pi0            7    111     0    -.101     .147    6.308    6.312     .135
241 pi+            7    211     0    -.298    -.690   11.165   11.191     .140
242 (Beam-REM)    11     92   226    3.084     .532  228.653  228.682    1.886
243 (rho+)        17    213   242     .631     .097   81.099   81.105     .769
244 (rho-)        17   -213   242    2.453     .435  147.554  147.577     .769
245 pi0            7    111     0    1.086    -.372   13.180   13.231     .135
246 pi+            7    211     0     .670     .010    6.556    6.592     .140
247 pi0            7    111     0    -.310     .098    1.379    1.423     .135
248 pi-            7   -211     0     .317    -.273    1.674    1.731     .140
249 (Beam-REM)    11     92   226     .350    1.923   41.821   41.947    2.589
250 pi0            7    111     0     .338    -.061     .993    1.059     .135
251 (f_2)         17    225   249     .251    2.340   38.840   38.932    1.273
252 pi-            7   -211     0     .173     .234     .476     .575     .140
253 pi+            7    211     0    -.126     .040     .015     .193     .140
254 (Beam-REM)    11     92   226     .848     .209    2.363    2.994    1.619
255 (rho+)        17    213   254     .405     .603     .830    1.345     .769
256 pi-            7   -211     0     .311     .020     .030     .343     .140
257 pi0            7    111     0    -.133     .085     .042     .212     .135
258 pi+            7    211     0    -.142     .273     .267     .431     .140
259 (Targ-REM)    11     93   226    -.645     .059   -4.906    6.079    3.532
260 (a_20)        17    115   259    -.785    -.697   -3.994    4.335    1.318
261 (f_2)         17    225   259     .140     .756    -.912    1.744    1.273
262 pi+            7    211     0     .159    -.214     .257     .395     .140
263 (rho-)        17   -213   260   -1.001    -.566   -3.481    3.746     .769
264 pi-            7   -211     0    -.222     .216     .622     .709     .140
265 pi+            7    211     0     .508    -.089    1.136    1.256     .140
266 (pi0)         17    111   263    -.206     .103   -1.282    1.309     .135
267 pi-            7   -211     0    -.131    -.273     .880     .941     .140
268 (Targ-REM)    11     93   226     .334    -.009  -13.547   13.730    2.207
269 (K*+)         17    323   268     .543    -.031  -10.390   10.442     .892
270 (K*~0)        17   -313   268    -.209     .022   -3.157    3.288     .892
271 pi+            7    211     0    -.937     .548   -3.593    3.756     .140
272 K0             7    311     0    -.641     .364   -6.401    6.463     .498
273 pi+            7    211     0     .032    -.219   -2.566    2.580     .140
274 K-             7   -321     0     .135     .027   -5.088    5.113     .494
275 (Targ-REM)    11     93   226     .342    -.955  -20.126   20.346    2.810
276 pi-            7   -211     0     .063     .297   -4.395    4.407     .140
277 (f_2)         17    225   275     .518    -.135  -18.057   18.110    1.273
278 pi-            7   -211     0    -.897     .386  -16.770   16.799     .140
279 pi+            7    211     0     .078     .064   -6.170    6.172     .140
280 (Targ-REM)    11     93   226     .011    2.337 -277.032  277.048    1.826
281 (omega)       17    223   280    -.282    1.678 -154.896  154.908     .783
282 (rho0)        17    113   280     .293     .659 -122.136  122.141     .769
283 ((gamma))     -7     22   285    -.076     .029  -16.715   16.715     .000
284 pi0            7    111     0     .272     .281  -27.169   27.172     .135
285 pi-            7   -211     0    -.065    -.210  -17.101   17.103     .140
286 pi+            7    211     0    -.015    -.300  -48.046   48.047     .140
==============================================================================
             sum:   .00             .000     .000    0.000  900.000  900.000
```


E Summary list of subroutines

```
C***********************************************************************
C                                                                      *
C                                                                      *
C  List of subprograms grouped according to general program structure  *
C                                                                      *
C          (S = subroutine, F = function, B = block data)              *
C                                                                      *
C                                                                      *
C      PART 1: Main steering routines and general utilities            *
C                                                                      *
C  B   VNIDATA   to give default values to particle and decay data     *
C  S   VNIXRIN   to initialize the overall run and simulation procedure *
C  S   VNIXRUN   to steer the simulation of a single collision event   *
C  S   VNIXFIN   to finish up the overall run and simulation procedure *
C  S   VNICBIN   to interface parameters sets between commonblocks     *
C  S   VNILOGO   to write program header                               *
C  S   VNILIST   to list event record, particle, or parameter values   *
C  S   VNIEDIT   to perform global manipulations on the event record.  *
C  S   VNICOPY   to save/restore copy of commonblocks & particle record *
C  F   KVNI      to provide integer-valued event information           *
C  F   PVNI      to provide real-valued event information              *
C  F   RLU       to provide a random number generator                  *
C  S   RLUGET    to save the state of the random number generator      *
C  S   RLUSET    to set the state of the random number generator       *
C  S   VNIERRM   to write error messages and abort faulty run          *
C  S   VNIFILE   to open and close output files                        *
C  S   VNIDUMP   to dump(read) state of all commonblocks to(from) file *
C                                                                      *
C                                                                      *
C  PART 2: Initialization routines (global and process dependent)      *
C                                                                      *
C  S   VNICSIN   to initialize collision system and kinematics         *
C  S   VNIABXS   to give parametrized cross-sections for beam/target   *
C  S   VNITMIN   to initialize time slizes and form of time increment  *
C  S   VNI2JIN   to set up an initial 2-jet in l+l- -> gamma/Z0 -> qq~ *
C  S   VNI2JFL   to select flavour for initially produced qq~ 2-jet    *
C  S   VNI2JPY   to get energy-momentum of initial 2-jet using PYTHIA  *
C  S   VNI4JIN   to set up an initial 4-jet in l+l- -> W+W- -> qq~ q'q'~*
C  S   VNI4JFL   to initialize W+ and W- decay vertices and the 4 jets *
C  S   VNI4JPY   to get energy-momentum of W+W- and 4 jets using PYTHIA *
C  S   VNILHIN   to set up initial system for l- + h -> l- + jet(s) + X *
C  S   VNILAIN   to set up initial system for l- + A -> l- + jet(s) + X *
C  S   VNIXDIS   to generate the variables of DIS photon-hadron(nucleus)*
C  F   VNIGAQX   to give elementary photon-quark cross-sections        *
C  S   VNIGAQQ   to give qq~ fluctuation of photon from VDM            *
C  S   VNIHHIN   to set up initial system for h  + h'->  jets + X      *
C  S   VNIHAIN   to set up initial system for h  + A ->  jets + X      *
C  S   VNIABIN   to set up initial system for A  + A'->  jets + X      *
C  S   VNIBTIN   to set up initial state of hadronic or nuclear beams  *
C  S   VNINPDT   to tabulate nuclear neutron/proton distribution       *
C  S   VNIRPIN   to initialize single hadrons, or nucleons in nucleus  *
C  S   VNIQGDT   to tabulate distributions in x and flavor of partons  *
C  F   VNIEFFQ   to give parametrization of eff. parton resolution Q(x) *
C  F   VNIQGSH   to give simple parametrization of parton shadowing   *
C  S   VNIVQKF   to extract the valence quark content of a hadron      *
C  S   VNIQGXF   to initialize x and flavor of partons in parent hadron *
C  S   VNIQGCS   to arrange a set of partons as color singlet hadron   *
C  S   VNIQGIN   to distribute initialized partons inside parent hadron *
C  S   VNIPRKT   to give primordial kT to initial partons              *
```

```
C  S   VNIXTIN  to find spatial extension of initial particle system   *
C                                                                       *
C                                                                       *
C           PART 3: Particle structure function package                *
C                                                                       *
C - portable, self-contained program unit with interface to PDFLIB -    *
C                                                                       *
C  S   VNISTFU  calls structure functions: photon, pi+, n, p, hyperon  *
C  S   VNISTGA  gives photon structure function                        *
C  S   VNISTAG  gives anomalous part of photon structure function      *
C  S   VNISTGS  parametrized parton distributions in a virtual photon  *
C  S   VNISTPI  gives pi+ structure function                           *
C  S   VNISTFL  gives proton structure function at small x and/or Q^2  *
C  S   VNISTPR  gives proton structure function                        *
C  S   VNIFCTQ  CTEQ2'94 parametrization of parton distributions       *
C  S   VNIFGRV  GRV'94 parametrizations of parton distributions        *
C  F   FV       Function for GRV parametrizations                      *
C  F   FW       Function for GRV parametrizations                      *
C  F   FWS      Function for GRV parametrizations                      *
C  F   FHS      Function for GRV parametrizations                      *
C  F   VNIHFTH  gives threshold factor for heavy flavour production    *
C  F   VNIDILN  gives Dilogarithm function                             *
C  F   VNIGAMM  gives ordinary Gamma function                          *
C                                                                       *
C                                                                       *
C     PART 4: Main routines for cascade evolution and hadronization    *
C                                                                       *
C  S   VNIEVND  to administer general duties at the end of an event    *
C  S   VNIEVOK  to decide whether event is o.k. (accept or regenerate) *
C  S   VNIEV2J  to perform evolution for l+ + l- -> 2 jets -> hadrons  *
C  S   VNIEV4J  to perform evolution for l+ + l- -> 4 jets -> hadrons  *
C  S   VNIEVLH  to perform evolution for l- + h  ->  jets -> hadrons   *
C  S   VNIEVLA  to perform evolution for l- + A  ->  jets -> hadrons   *
C  S   VNIEVAB  to perform evolution for A  + B ->   jets -> hadrons   *
C  S   VNICOLP  to find 2-parton collisions and their kinematics       *
C  S   VNICOLX  to give cross-sections for 2 -> 2 and 2 -> 1 collisions*
C  S   VNICOLI  to set up a found 2-parton collision subsystem         *
C  S   VNICOLL  to find outgoing flavors and type of parton collision  *
C  S   VNISBRA  to generate space-like parton branchings               *
C  S   VNITBRA  to generate time-like parton branchings                *
C  S   VNICHAD  to organize parton cluster formation and hadronization *
C  S   VNICFOR  to form one or two cluster(s) from a pair of partons   *
C  S   VNICREC  to reconnect cluster-partons according to color flow   *
C  S   VNICFRA  to fragment found parton clusters into hadrons         *
C  S   VNIBHAD  to do beam remnant cluster formation and hadronization *
C  S   VNIBFRA  to fragment beam/target remnant clusters into hadrons  *
C  S   VNIBMPS  to give phase-space dist. of hadrons from cluster decay*
C  S   VNIBMMO  to balance beam/target side momentum of hadrons        *
C  S   VNIPADC  to decay unstable particles according to particle data *
C  S   VNIPAKF  to give a hadronic particle from a flavor pair         *
C  S   VNINSPE  to recollect/fragment partons of spectator nucleons    *
C  S   VNISTPG  to simulate baryon stopping in nuclear A+B collisions  *
C  S   VNIPICL  to cluster pions together if above critical density    *
C  S   VNICOLH  to find & perform 2-body collisions of clusters/hadrons*
C  S   VNIHACL  to reconstruct cluster from its hadronic decay products*
C                                                                       *
C                                                                       *
C                 PART 5: Auxiliary routines I:                         *
C                                                                       *
C         - parton cascades & cluster formation -                       *
C                                                                       *
C  F   VNIALEM  to give the alpha_electromagnetic value                 *
C  F   VNIALPS  to give the alpha_strong value                          *
```



```
C  F   VNIANGL  to give the angle from known x and y components        *
C  F   INVCHGE  to give three times the electric charge                *
C  F   INVCOMP  to compress standard KF flavour code to internal KC    *
C  S   VNICOLB  to boost/rotate 2-body collision subsystem along p_z   *
C  S   VNIDEC2  to generate 2-body decay                               *
C  S   VNIFLAV  to give flavor composition & baryon number of system   *
C  S   VNIFRAM  to perform boosts between different frames             *
C  S   VNIKLIM  to find kinematic limits in 2-parton collsions         *
C  S   VNICCOL  to connect color indices in 2-parton collisions        *
C  S   VNIJCOL  to connect  partons with color flow indices            *
C  S   VNILCOL  to label color indices according to color flow tracing *
C  F   VNIMASS  to give the mass of a particle or parton               *
C  F   VNIMTHR  to give 'current' or 'constituent' masses for partons  *
C  S   VNINAME  to give the name of a particle or parton               *
C  F   VNIGORI  to give the origin of a particle in space-time history *
C  F   VNISORI  to sey the origin of a particle in space-time history  *
C  S   VNIONSH  to put final-state off-shell hadrons on mass-shell     *
C  S   VNIPROP  to propagate a given number of particles               *
C  S   VNIPSEA  to generate  a hadron pair from the Dirac 'sea'        *
C  S   VNIQSEA  to generate a q or q~, or a qq~-pair from the 'sea'    *
C  S   VNIROBO  to rotate and/or boost a given number of particles     *
C  S   VNIRSCL  to rescale particle momenta for numerical precision    *
C  F   VNIRCAM  to generate random number from a 'camel' distribution  *
C  F   VNIRMTP  to generate random number from a power-law distribution*
C  F   VNIRMTX  to generate random number from 2-dim exp. distribution *
C  F   VNIRPLT  to generate random number from flat-top distribution   *
C  F   VNIRGAU  to generate random number from Gaussian distribution   *
C  S   VNISMRP  to smear out classical particle positions and momenta  *
C  S   VNISORT  to count and sort particles                            *
C  S   VNIWIDT  to calculate width of particle resonances              *
C                                                                       *
C                                                                       *
C                 PART 6: Auxiliary routines II:                        *
C                                                                       *
C     - cluster-hadron decay and beam/target fragmentation -            *
C                                                                       *
C  S   HWHEPC  to convert VNI event record to or from standard HEP      *
C  S   HWLIST  to list event record in HEP format                       *
C  S   HWIGIN  to set parameters of HERWIG                              *
C  S   HWUINC  to compute constants and lookup tables                   *
C  S   HWUINE  to perform re-initialization of a new event              *
C  S   HWURES  to load common blocks with particle data                 *
C  S   HWUIDT  to translate particle identifiers                        *
C  S   HWCCUT  to cut up heavy cluster into two clusters                *
C  S   HWCFLA  to to set up flavors for cluster decay                   *
C  S   HWCHAD  to hadronize prepared beam/target clusters               *
C  S   HWDHAD  to decay unstable hadrons from beam/target remnants      *
C  S   HWDTWO  to generate two-body decay 0->1+2                        *
C  S   HWDTHR  to generate three-body decay 0->1+2+3                    *
C  F   HWDPWT  to give matrix element squared for phase-space decay     *
C  F   HWDWWT  to give matrix element squared for V_A weak decay        *
C  F   HWMNBI  to compute negative binomial probability                 *
C  S   HWMLPS  to generate cylindrical phase-space                      *
C  S   HWMULT  to pick charged multiplicity of beam/target diffraction  *
C  F   HWUPCM  to compute c.m. momentum for masses in 2-body decay      *
C  S   HWULOB  to transform momenta from rest frame into lab frame      *
C  S   HWULOF  to transform momenta from lab frame into rest frame      *
C  S   HWUMAS  to put mass in 5th component of momentum vector          *
C  S   HWUROB  to rotate vectors by inverse of rotation matrix R        *
C  S   HWUROT  to perform rotation with rotation matrix R               *
C  S   HWUSOR  to sort n-tupel A(N) into ascending order                *
C  F   HWUSQR  to give square root with sign retention                  *
C  S   HWUSTA  to make a particle type stable                           *
```

```
C  S   HWVDIF   to give vector difference                              *
C  F   HWVDOT   to give vector dot product                             *
C  S   HWVEQU   to give vector equality                                *
C  S   HWVSCA   to give product of vector times scalar                 *
C  S   HWVSUM   to give vector sum                                     *
C  S   HWVZRO   to give zero vector                                    *
C  F   HWRGEN   to provide random number generator                     *
C  S   HWRAZM   to randomly rotate 2-vector pT                         *
C  F   HWREXP   random number from 1-dim. exponential distribution     *
C  F   HWREXT   random number from 2-dim. exponential distribution     *
C  F   HWRGAU   random number from 2-dim Gaussian distribution         *
C  F   HWRINT   random integer in finite interval                      *
C  F   HWRLOG   random logical                                         *
C  S   HWRPOW   random number from power-law distribution              *
C  F   HWRPOT   random number from 2-dim power-law distribution        *
C  F   HWRCAM   random number from 'camel' distribution                *
C  F   HWRUNG   random number from flat-top distribution               *
C  F   HWRUNI   uniform random in finite interval                      *
C  S   HWUTIM   dummy routine                                          *
C  S   HWWARN   dummy routine                                          *
C  B   HWUDAT   to provide HERWIG common blocks with data              *
C                                                                      *
C                                                                      *
C                PART 7: Integrated package WIZ                        *
C                                                                      *
C                 - hadron / cluster cascade -                         *
C                                                                      *
C        All components of WIZ were developed and put together by the  *
C                 "Wizard of Poquott"    Ron Longacre                  *
C                                                                      *
C                                                                      *
C  S   WIZDATA  to give default values to switches & parameters of WIZ *
C  S   WIZCOLL  to perform cluster / hadron collisions in a time step  *
C  S   WIZADQM  to get cross section using the additive quark model    *
C  S   WIZSIGM  to get cross section using the parametrized exp. data  *
C  S   WIZMMXS  to evaluate total meson-meson interaction cross-section*
C  S   WIZNNXS  to evaluate total nucleon-nucleon cross-section        *
C  S   WIZCNQU  to determine baryon, strange, charm and bottom number  *
C  S   WIZCHCK  to check energy-momentum, charge, flavor conservation  *
C  S   WIZXSEC  to set up collsion of two (pre)hadronic particles      *
C  S   WIZYSEC  to perform collision of two (pre-)hadronic particles   *
C                                                                      *
C                                                                      *
C  S   ANNIL    to annihilate a baryon and antibaryon to a meson pair  *
C  S   MAKBBAR  to make (create) a baryon-antibaryon from a meson pair *
C  S   TNICES   to generate outgoing particles of (pre-)hadronic coll. *
C  S   ROTIT    to rotate coordinate system for boosts                 *
C  S   RBIAS    to generate minimum bias event or beam jets            *
C  S   FXQUOD   to determine strangeness number in HEP id code         *
C  S   FXCSBY   to determine charm number in HEP id code               *
C  S   CHNGID   to perform isospin rotation for minimum bias events    *
C                                                                      *
C  S   SCATS    to do low-energy coll.'s - meson-nucleon, Delta-N      *
C  S   SCATKN   to do low-energy coll.'s - K-N                         *
C  S   SKATH    to do low-energy coll.'s - K-Lambda, K-Sigma           *
C  S   SWAVE    to rotate colliding particle momenta creating a S-wave *
C  F   BARPRO   to get probability for Delta-Pi or Rho-N channels      *
C  F   BCHPRO   to get probability for 3-body decay out of collision   *
C  S   DELKST   to determine K* or Delta modes in K-N collision        *
C  F   ETAPRO   to get probability for eta production                  *
C  F   KNPRO    to get probability for K-N production                  *
C  F   KSTPRO   to get probability for K* production                   *
C  F   LAMPRO   to get probability for Lambda production               *
```



```
C  F   LPIPRO   to get probability for Lambda-Pi production in K-N     *
C  F   PKNPRO   to get probability for pi K-N production               *
C  F   RHOSC    to determine if F.F. for rho-N is called               *
C  F   SCPPRO   determines if F.F. is called for non-MM scattering     *
C  F   SCPRO    determines if elastic scattering for non-MM channels   *
C  F   DELPR    determine the probability for Delta N -> N N           *
C                                                                      *
C  F   SIGBR    get branching ratio for Sigma-Pi charge states         *
C  F   SIGLAM   get branching to K-Lambda from Pi-N                    *
C  F   SIGPRO   determine if Sigma is produced in low energy M B coll. *
C  S   SIGRHO   to determine Sigma* or Rho modes in K-N collision      *
C  F   SPIPRO   determine Sigma pi for low energy K-N collision        *
C  F   SRHPRO   determine Sigma pi pi for low energy K-N collision     *
C  F   SWAPRO   determine three modes from low energy K-N collision    *
C  S   RECPRO   to determine Delta or Rho modes in Pi-N collision      *
C  F   BCHKH    determines if three body in Pi-Hyperon interaction     *
C  F   LAMKH    determine if Lambda is produced in K-Hyperon scattering*
C  F   SIGKH    determine if Sigma is produced in K-Hyperon scattering *
C                                                                      *
C  S   MMSCAT   to collide 2 mesons and generate outgoing particles    *
C  S   SCAM     to do low-energy coll.'s M M scattering                *
C  F   SCPPI    determines if F.F. is called M M scattering            *
C  F   SCPI     determines if elastic scattering for M M               *
C  F   XEHC     determine charge exchange for K* system                *
C  F   CHEX     determine charge exchange low energy Pi Pi K Pi scatt. *
C  F   ETAETA   determine if eta eta is produced from M M scattering   *
C  F   KKBAR    determine if K Kbar is produced from M M scattering    *
C  F   PIPI     determine if pi pi is produced from M M scattering     *
C  F   ETPI     determine if eta pi is produced from M M scattering    *
C  F   PIK      determine if K pi is produced from M M scattering      *
C  F   BCHTB    determines if three body in M M interaction            *
C  S   RECP     determine delta or rho isobars in M N collision        *
C  S   ISOSCAT  collide isobar states N* Y* A1 ect. with isobar or reg.*
C                                                                      *
C  F   SCPA1    determines if F.F. is called A1 meson scattering       *
C  S   SCA1T    to do low-energy coll.'s - Pi-A1                       *
C  F   PIA1     determines if Pi-A1 is produced                        *
C  F   RA1PI    determines the charge mode for Pi-A1                   *
C  F   CHEXPI   determines the correct charge for the outgoing Pi Pi   *
C  F   KKB4PI   determines if K Kbar should be produced from Pi-A1     *
C  S   MAKISO   makes isobars out of 2 particles                       *
C  S   A1PRB    to determine probability for A1 formed from 2 particles*
C                                                                      *
C  S   PUTPNT   reuse array position that stores isobar decay products *
C  S   GETPNT   gets a reused position to store isobar decay products  *
C  F   CHARJ    returns charge of particle and works for isobars       *
C  F   A1MASS   returns mass of particle and works for isobars         *
C  F   PBARGT   determines energy dep. for diquarks at Ecm in F.F.     *
C  S   ANMESID  B Bar annihilation into mesons the meson id's are made.*
C  F   PANNIL   determines the B Bar annihilation probability.         *
C  S   BBARID   to decompose baryon id into flavor/spin of a baryon    *
C  F   YSTPRO   determines Y* production.                              *
C                                                                      *
C  S   PHIEXT   determines phi production in non M M scattering.       *
C  S   PHIEXTM  determines phi production in M M scattering.           *
C  F   PHIPI    determines if a phi pi state is produced in M M scatter*
C  F   PHIK     determines if a phi K state is produced in M M scatter *
C  F   PHIKST   determines if a phi K* state is produced in M M scatter*
C  F   PHIETA   determines if a phi eta state is produced in M M scatt.*
C  F   PHIPHI   determines if a phi phi state is produced in M M scatt.*
C  F   PHIPIA1  determines if a phi pi state decays from the rho prime.*
C  S   CHAGID   Puts in the correct OZI suppression for phi B scatters.*
C                                                                      *
```

```
C  F   IDISA    to convert particle id's from HEP to WIZ codes           *
C  F   IDHEP    to convert particle id's from WIZ to HEP codes           *
C  F   HEPMASS  to provide particle masses according to HEP standard     *
C  F   RANF     to provide internal random number generator for WIZ      *
C                                                                        *
C  S   MBSET    Set parameters for generating minbias or beam jets.      *
C  S   MOVLEV   Moves one array into an other array.                     *
C  S   DECAY    The WIZ decay of particles not used outside of WIZ.      *
C  S   FLAVOR   The flavor decode of WIZ id's.                           *
C  F   LABEL    Returns character*8 string for WIZ id's.                 *
C  F   AMASS    Mass of particles with WIZ id's.                         *
C  F   CHARGE   Charge of particles with WIZ id's                        *
C  F   DBLPCM   Calculate com momentum for A->B+C with double precision*
C  F   GETPT    generates pt for quark pairs for the F.F. chain.         *
C  S   IDGEN    Does nothing.                                            *
C  S   LOREN4   Does a general Lorentz transformation.                   *
C  S   PRTEVT   Prints the event stored in the ISAJET part of WIZ.       *
C  S   READIN   Setup parameters for the ISAJET part of WIZ.             *
C  S   RESCAL   Rescales momentum of particles to the total energy.      *
C  S   RESET    Resets all user defined variables for ISAJET part of WIZ
C  S   SETCON   Sets the constants for the ISAJET part of WIZ.           *
C  S   SETDKY   Sets the decay table that is used inside WIZ.            *
C  S   SETTYP   Sets jetype flags in ISAJET.                             *
C                                                                        *
C                                                                        *
C          PART 8: Event study and data analysis routines                *
C                                                                        *
C  S   VNIANAL  to steer pre-programmed event analysis                   *
C  S   VNIANA1  statistics on global particle properties & observables *
C  S   VNIANA2  statistics on time evol., ln(1/x) spectra, BE effect     *
C  S   VNIANA3  statistics on pre-hadronic clusters                      *
C  S   VNIANA4  statistics on partons and produced hadrons               *
C  S   VNISPHE  to perform sphericity analysis                           *
C  S   VNITHRU  to perform thrust analysis                               *
C  S   VNICLUS  to perform three-dimensional jet cluster analysis        *
C  S   VNICELL  to perform jet cluster analysis in (eta, phi, E_T)       *
C  S   VNIJMAS  to give high and low jet mass of event                   *
C  S   VNIFOWO  to give Fox-Wolfram jet moments                          *
C                                                                        *
C                                                                        *
C          PART 9: Dummy routines and system dependent utilities         *
C                                                                        *
C  S   VNIPRIN  dummy routine: remove when linking 'vniprob.f'           *
C  S   VNIEVPR  dummy routine: remove when linking 'vniprob.f'           *
C  S   VNIPRND  dummy routine: remove when linking 'vniprob.f'           *
C  S   VNIPRIN  dummy routine: remove when linking 'vniprob.f'           *
C  S   PYINIT   dummy routine: remove when linking 'vnipythia.f'         *
C  S   PYEVNT   dummy routine: remove when linking 'vnipythia.f'         *
C  S   PDFSET   dummy routine: remove when linking PDFLIB                *
C  S   STRUCTM  dummy routine: remove when linking PDFLIB                *
C  S   VNICLOC  to measure and return the CPU time used  (sys. dep.)     *
C  S   VNIDATE  to give current date and time  (sys. dep.)               *
C                                                                        *
C                                                                        *
C************************************************************************
```


F Bibiliography

References

[1] K. Geiger, Phys. Rev. **D54**, 949 (1996).

[2] K. Geiger, Phys. Rev. **D56**, 2665 (1997).

[3] J. Kogut and L. Susskind, Phys. Rep. **8**, 75 (1973).

[4] Yu. L. Dokshitzer, D. I. Dyakonov, and S. I. Troyan, Phys. Rep. **58**, 269 (1980).

[5] L. V. Gribov, E. M. Levin, and M. G. Ryskin, Phys. Rep. **100**, 1 (1983).

[6] K. Geiger and B. Müller, Nucl. Phys. **B369**, 600 (1992)

[7] K. Geiger, Phys. Rev. **D47**, 133 (1993).

[8] K. Geiger, Phys. Rep. **258**, 238 (1995). Phys. Rev. **D54**, 5443 (1996).

[9] J. Ellis and K. Geiger, Phys. Rev. **D54**, 949 (1996),

[10] J. Ellis and K. Geiger, Phys. Rev. **D54**, 1755 (1996).

[11] J. Ellis, K. Geiger, and H. Kowalski,

[12] K. Geiger and D. K. Srivastava, Phys. Rev. **C56**, 2718 (1997); D. K. Srivastava and K. Geiger, Phys. Lett. **B422**, 39 (1998); K. Geiger, ⟨ nucl-th/9801007 ⟩, to appear in Nucl. Phys. **A**.

[13] D. K. Srivastava and K. Geiger, ⟨ nucl-th/9802034 ⟩, submitted to Phys. Rev. **C**.

[14] K. Geiger and R. Longrace, ⟨ nucl-th/9705041 ⟩.

[15] K. Konishi, A. Ukawa, and G. Veneziano, Nucl. Phys. **B157**, 45 (1979).

[16] A. Bassetto, M. Ciafaloni and G. Marchesini, Phys. Rep. **100**, 203 (1983).

[17] *Basics of Perturbative QCD*, Advanced Series on Directions in High Energy Physics, Vol. 5 (Editions Frontieres, Gif-sur-Yvette Cedex, France, 1991).

[18] M. Gyulassy, *private communication.*

[19] R. P. Feynman and R. D. Field, Phys. Rev. **D15**, 2590 (1977); Nucl. Phys. **B136**, 1 (1978).

[20] European Muon Collaboration: J. Ashman *et al.*, Phys. Lett. **B202** 603 (1988); M. Arneodo *et al.*, Phys. Lett. **B211**, 493 (1988).

[21] L. L. Frankfurt and M. I. Strikman, Phys. Rep. **160**, 235 (1988).

[22] A. H. Mueller and J. Qui, Nucl. Phys. **B268**, 427 (1986); J. Qui, Nucl. Phys. **B291**, 746 (1987), **746**;

[23] F. E. Close, J. Qiu and R. G. Roberts, Phys. Rev. **D 40**, 2820 (1989); A. H. Mueller, Nucl. Phys. **B335**, 115 (1990).

[24] X. N. Wang and M. Gyulassy, Phys. Rev. **D44**, 3501 (1991).

[25] V. M. Belyaev and B. L. Ioffe, Nucl. Phys. **B313**, 647 (1989); D. Antreasyan *et al.*, Phys. Rev. Lett. 48, 302 (1983).

[26] J. D. Bjorken in *Current Induced Reactions, Proceedings of the International Summer Institute on Theoretical Particle Physics*, Hamburg, 1975, edited by J. Körner et al. (Lecture Notes in Physics, Vol. 56, Springer, New York 1976).

[27] R. C. Hwa and K. Kajantie, Phys. Rev. Lett. **56**, 696 (1986)

[28] A. H. Mueller, Nucl. Phys. **A498**, 41c (1989).

[29] K. Geiger, Phys. Rev. **D46**, 4965 (1992).

[30] Yu. L. Dokshitzer, V. A. Khoze, A. H. Mueller, and S. I. Troyan, Rev. Mod. Phys. **60**, 373 (1988).

[31] L. N. Lipatov, Sov. J. Nucl. Phys. **20**, 94 (1975); Yu. L. Dokshitzer, Sov. Phys. JETP **46**, 641 (1977); G. Altarelli and G. Parisi, Nucl. Phys. **B126**, 298 (1977).

[32] R. Cutler and D. Sivers, Phys. Rev. **D17**, 196 (1978); B. L. Combridge, J. Kripfganz and J. Ranft, Phys. Lett. **70B**, 234 (1977).

[33] B. L. Combridge, Nucl. Phys. **B151**, 429 (1979); P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. **B303**, 607 (1988); **B327**, 49(1989); **B335**, 260 (1990).

[34] G. Gustafson, Z. Phys. **C15**, 155 (1982).

[35] G. Marchesini and B. R. Webber, Nucl. Phys. **310**, 461 (1988); Nucl. Phys. **B349**, 617 (1991).

[36] T. D. Gottschalk, Nucl. Phys. **B277**, 100 (1986); M. Bengtsson, T. Sjöstrand and M. van Zijl, Z. Phys. **C32**, 67 (1986); M. Bengtsson and T. Sjöstrand, Z. Phys. **C37**, 465 (1988).

[37] G. Marchesini and B. R. Webber, Nucl. Phys. **B238**, 1 (1984); B. R. Webber, Ann. Rev. Nucl. Part. Sci. **36**, 253 (1986).

[38] G. Marchesini and B. R. Webber, Nucl. Phys. **B238**, 1 (1984); B. R. Webber, Nucl. Phys. **B238**, 492 (1984).

[39] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, Phys. Rep. **97**, 33 (1983); B. Andersson, G. Gustafson and B. Söderberg, Nucl. Phys. **B264**, 29 (1986).

[40] D. Amati, A. Bassetto, M. Ciafaloni, G. Marchesini, and G. Veneziano, Nucl. Phys. **B173**, 429 (1980); G. Marchesini, L. Trentadue and G. Veneziano, Nucl. Phys. **B181**, 335 (1981).

[41] R. Hagedorn, *Thermodynamics of Strong Interactions*, Cargèse Lectures in Physics, Vol. 6 (1973).

[42] UA5 Collaboration, G. J. Alner *et al.*, Nucl. Phys. **B291**, 445 (1987); Phys. Rep. **154**, 247 (1987).

[43] K. Goulianos, Phys. Rep. **101**, 169 (1983).

[44] T. Sjöstrand, Comp. Phys. Com. **82**, 74 (1994).

[45] G. Marchesini, B. R. Webber, G. Abbiendi, I. G. Knowles, M. H. Seymor and L. Stanco, Comp. Phys. Com. **67**, 465 (1992).

[46] L. Lönnblad, Comp. Phys. Com. **71**, 15 (1992).

[47] G. Ingelman, A. Edin, and J. Rathsman, preprint DESY-96-057 (1996), hep-ph/9605286.

[48] F. Paige and S. Protopopescu, in *Supercollider Physics*, edited by D. Soper (World Scientific, 1986); H. Baer, F. Paige, S. Protopopescu and X. Tata, in *Proceedings of the Workshop on Physics at Current Accelerators and Supercolliders*, edited by J. Hewett, A. White and D. Zeppenfeld (Argonne National Laboratory 1993).

[49] B. Andersson, G. Gustafson and B. Nilsson-Almquist, Nucl. Phys. **B281**, 289 (1987); B. Nilsson-Almquist and E. Stenlund, Computer Phys. Comm. **43** (1987), 387; B. Lörstad, Int. J. Mod. Phys. **A12**, 2861 (1989).

[50] A. Capella, U. Sukhatme, C.-I. Tan, and J. Tran Tranh Van, Phys. Rep. **236**, 225 (1994)

[51] K. Werner, Z. Phys. **C42**, 85 (1989); Phys. Rep. **232**, 87 (1993).

[52] H. Sorge, H. Stöcker, and W. Greiner, Nucl. Phys. **A498**, 567c (1989); Ann. Phys. **192**, 266 (1989).

[53] A. Shor and R. Longacre, Phys. Lett. **B218**, 100 (1989).

[54] X. N. Wang and M. Gyulassy, Phys. Rev. **D44**, 3501 (1991); Comp. Phys. Com. **83**, 307 (1994).

[55] K. Geiger, Phys. Rev. **D46**, 4986 (1992).

[56] See e.g.: F. Wagner, in the proceedings of *11th Rencontre de Moriond*, Flaine, France, published in Moriond Conf.1976:217 (QCD161:R34:19 76:V.1)

[57] H. U. Bengtsson, Comp. Phys. Com. **31**, 323 (1984).