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Interesting Aspects of the STAR Detector and Physics Program*

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The Solenoidal Tracker At RHIC (STAR) is a large acceptance collider detector scheduled to begin operation at the Relativistic Heavy Ion Collider (RHIC) in the fall of 1999. Simply stated, the physics goals of STAR are,

- to study the behavior of strongly interacting matter at high energy density
- to search for signatures of a deconfined partonic phase of matter, and
- to study the importance of spin as a fundamental property of QCD interactions and measure the spin-dependent parton distributions (gluon, valence quark, sea quark) of the proton.

With regard to the search for a deconfined phase of matter, STAR[1] is designed to search for signatures of QGP formation through the measurement and correlation of global observables on an event-by-event basis and the use of hard scattering of partons to probe the properties of high density matter.

The baseline STAR detector (Fig. 1) utilizes a time projection chamber (TPC) in a solenoidal magnetic field of 0.5T covering approximately 4 units of the central rapidity. An additional element of the detector is a silicon vertex tracker (SVT) to locate the position of the primary vertex to high accuracy, and to locate secondary vertices to an accuracy of 20 μm. A *Pb*-scintillator sampling electromagnetic calorimeter will be used to trigger on transverse energy and measure jets, direct photons and leading π^0 production. A portion of the acceptance will be instrumented with a highly segmented TOF array, extending the maximum momentum for π/K separation from 0.6 to 1.5 GeV/c and the corresponding limit for K/p separation from 1–2.4 GeV/c. Forward TPCs (FTPC) located in the region $2 < |\eta| \leq 4.5$ will be used to study the transfer of energy from projectile rapidity to midrapidity by following the fate of the incident baryons rescattered in the collision.

An important measure of recent progress in the construction of STAR is the initiation of the first phase of the STAR "system test". In this effort, all of the key elements of the STAR data taking chain (TPC, front end electronics, DAQ, trigger, and slow controls) are physically interfaced and made to work together for the first time. Progress in this area is

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evident in Fig. 2, in which the first cosmic ray data detected in a STAR TPC pad plane are shown. Further work using both cosmic rays and lasers will test the channel to channel uniformity, the position resolution for a single track, and the two-track resolution.

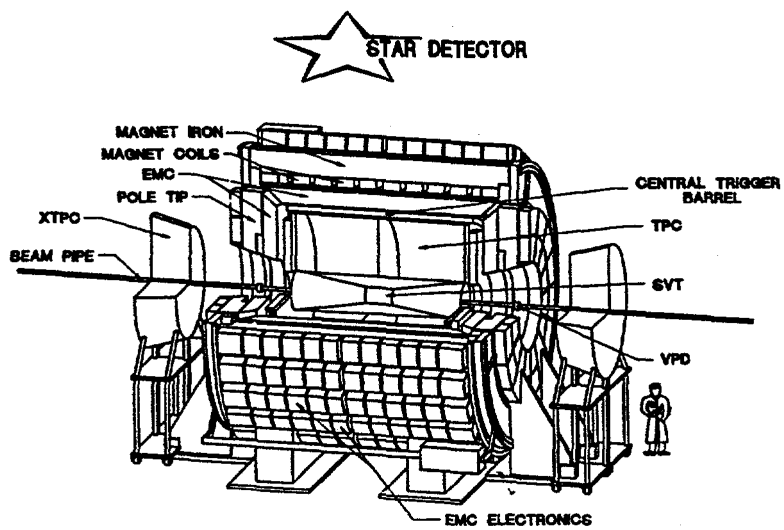

Figure 1: Schematic layout of the STAR detector.

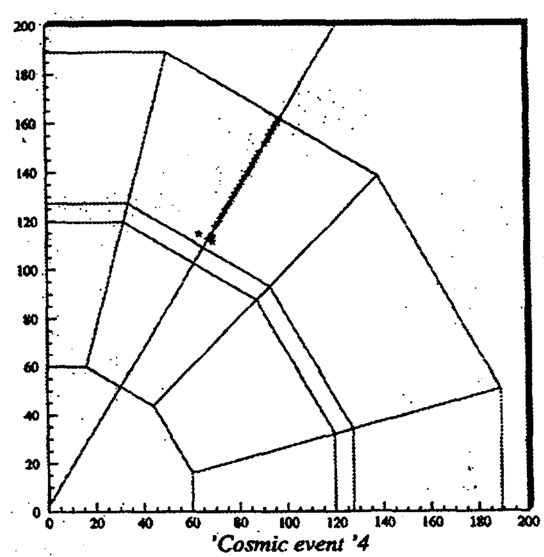

Figure 2: The first cosmic ray data recorded in a STAR TPC pad plane as part of the STAR system test.

One important aspect of the STAR program will be to search for special events in which the measurement and correlation of event-by-event observables (e.g. dn_π/dy, T_π, K/π, $p_{t\pi}$, dn/dy) indicates the transition to a deconfined phase may have occurred. An event in this category might be characterized, for example, by an unusually high inverse slope parameter for the pion spectrum or large non-statistical fluctuations in the dn/dy spectra. A second

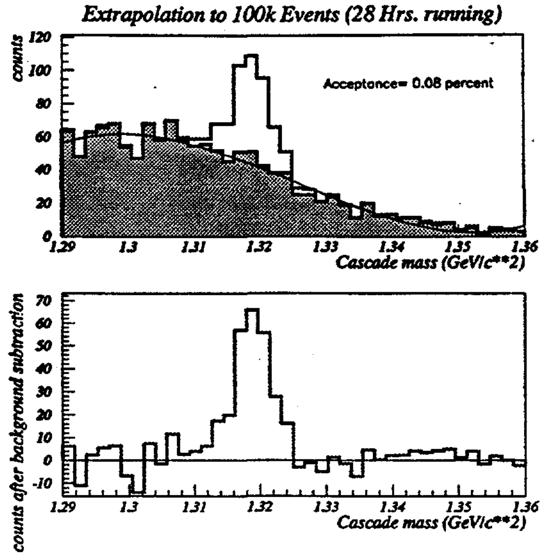

Figure 3: Simulated invariant mass distribution for the Ξ^- using the STAR SVT.

goal will be to measure the thermodynamic observables (T, μ_B, μ_s) for an ensemble of events to establish whether a state of thermal and chemical equilibrium has been reached. This state of matter is predicted to occur in the evolution of the system from deconfinement to hadronization, and its observation would be strong evidence that a phase transition to a QGP had taken place. The design of the detector allows for the precise measurement, for example, of particle ratios ($p/\bar{p}$, $\bar{\Lambda}/\Lambda$, K/π) to determine the strange chemical and baryo-chemical potentials, inverse slope parameters and p_t to determine the energy density (temperature), and dn/dy distributions to investigate entropy production. These observables will be measured and correlated to determine if a state in which chemical and thermal equilibrium has been reached can be identified.

Determination of the strangeness density and strangeness "saturation" in relativistic heavy ion collisions have long been recognized[2] as important probes of plasma production primarily because a rapid increase in $s\bar{s}$ production through gluon-gluon interactions in a QGP would allow saturation of the strangeness degrees of freedom much more quickly than could be achieved in multiple hadronic interactions. The measurement of strange baryons at RHIC however is complicated due to the short lifetime and low mean p_t which characterize the production. As a consequence, combinatorics pose a significant background, and an inner tracking system capable of accurate determination of secondary vertices is essential.

In STAR, this is accomplished with a new type of detector developed at Brookhaven National Laboratory (BNL) through RHIC R&D – the silicon drift detector (SDD). With careful shaping of the electrostatic potentials, the ionization deposited by a charged particle traversing a fully depleted silicon wafer can be made to drift at a constant velocity the entire length of the wafer. Knowing the time of the drift and determining the position in the anode direction by charge sharing, the position of the charged particle can be determined with great precision. Extensive bench tests at BNL and elsewhere have shown that space point resolutions on the order of a few tens of microns are achievable. The STAR silicon vertex tracker (SVT) is constructed of ladders of SDDs arranged in three concentric cylinders at mean radii of 6.5, 10.5, and 14.5 cm.

The utility of the STAR SVT is demonstrated in Fig. 3. Using the characteristic resolutions demonstrated through R&D for this device, the Ξ^- yield and signal to noise ratio for approximately 2-3 days of *AuAu* running are shown to be quite good. This detector is nearing the beginning of its construction phase, and completion is projected for the end of calendar year 1999.

Two specific aspects of the STAR program which merit a somewhat more detailed discussion are measurement of the gluon distribution in the nucleus, and the detection and interpretation of multiple non-statistical correlations possibly indicative of new physics.

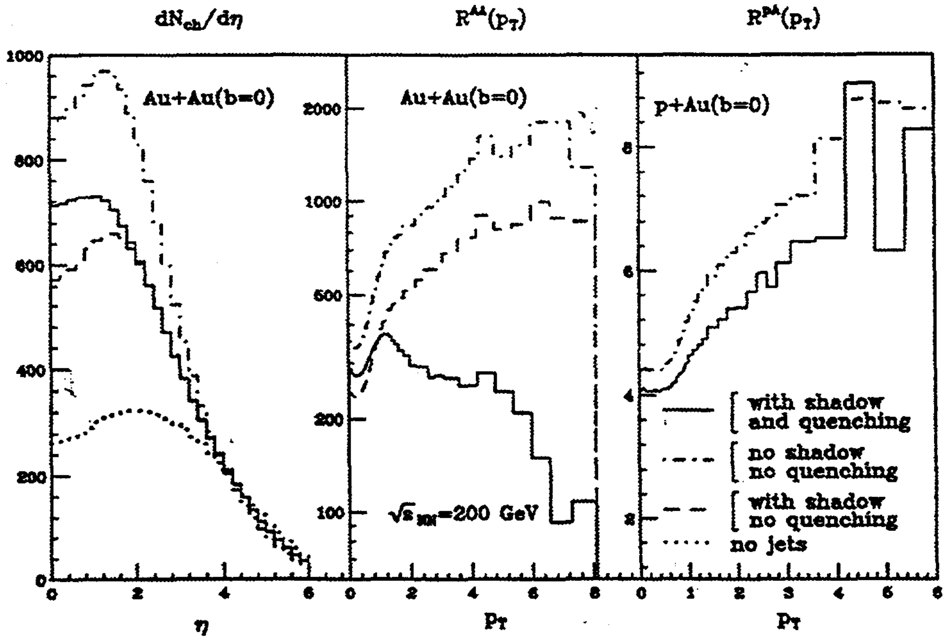

Figure 4: Results from HIJING calculations on the dependence of the inclusive charged hadron spectra in central *AuAu* and *pAu* collisions on mini-jet production (dash-dotted), gluon shadowing (dashed) and jet quenching (solid) assuming that gluon shadowing is identical to that of quarks. $R^{AB}(p_t)$ is the ratio of th inclusive p_t spectrum of charged hadrons in $A+B$ collisions to that of pp [3].

An important element in the ion studies at RHIC and LHC will be the determination of the initial conditions – the parton distributions in the nucleus. RHIC will be the first heavy ion accelerator in which a large part (50%) of the energy transferred into particle production comes directly from partonic processes which are calculable in pQCD. Theoretical guidance as to the evolution of the early stages of the collision is therefore possible if the initial distribution of partons in the nucleus is known. Presently it is expected that gluon-gluon scattering will dominate at early times with chemical equilibration of the quark degrees of freedom proceeding much more slowly. Determination of the gluon distribution in the nucleus in pA interactions, which is not provided by deep inelastic scattering studies, is therefore of particular interest. One would like to know the distribution down to the smallest values of x_{BJ} of relevance for particle production in the ion studies. At RHIC this value is $x_{BJ} \sim .01$. At LHC it is an order of magnitude lower, and this study may be problematic due to the two-in-one magnet design of the accelerator.

The fact that the quark (valence plus sea) structure function of a nucleon in a nucleus is modified with respect to that for a free nucleon is well known from deep inelastic scattering. It has also been pointed out for some time[3] that one also expects a similar modification of the gluon structure function. Inspecting the middle panel of Fig. 4, for example, the ratio of single particle inclusive production in AA to that in pp varies by a factor of approximately two depending on whether or not such a modification–"gluon shadowing" –is assumed. To reduce this uncertainty in the interpretation of the measured spectra, it would be of great value to have independent knowledge of the gluon structure function in the nucleus.

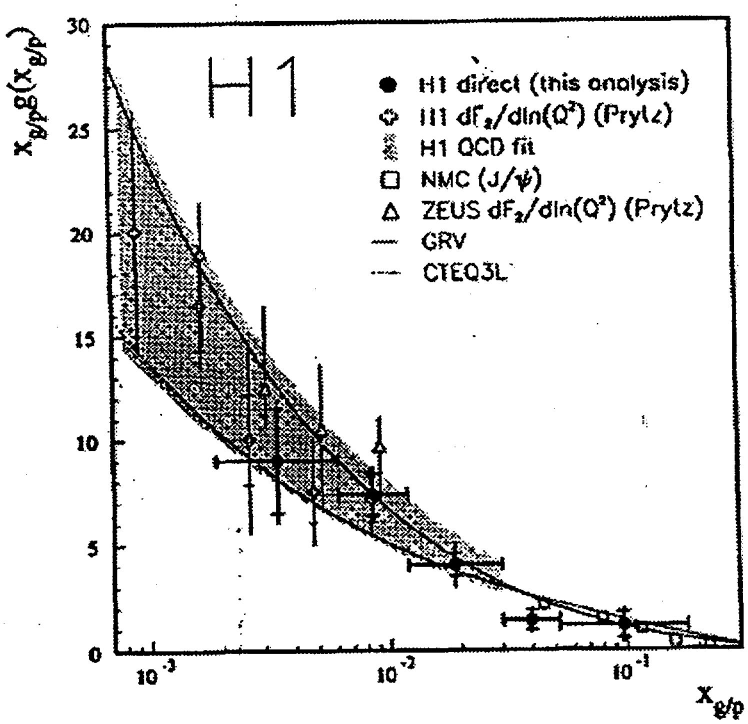

Figure 5: The measured gluon density at an average Q^2 of 30 GeV^2 as a function of the fractional gluon momentum compared with indirect determinations by $H1$ and ZEUS at $Q^2 = 20$ GeV^2 as well as with a determination from J/Ψ production by NMC evolved to $Q^2 = 30$ GeV^2 [4].

Experimental effort thus far has focused on measurement of the gluon distribution in the proton with the consequence that significant data on $xg(x)$ are now available at low x_{BJ} from H1 and Zeus, with complementary data closer to the valence region available from NMC and BCDMS. The data at low x_{BJ} come both from direct measurement of photon-gluon fusion, and from examining the scaling violation of the F_2 structure function at low x_{BJ}, the latter presumably resulting from the production of sea quark pairs in gluon-gluon interactions. A compilation of the available data on $xg(x)$ normalized at a Q^2 of 30 GeV^2 is shown in Fig. 5[4].

It is interesting to note that even at the lowest x_{BJ} measured, the value of $xg(x)$ is considerably less than the value one would naively expect if gluons completely filled the transverse size of the proton. In principle, saturation of the gluon density in the proton at low x_{BJ} could yield important information about the modification of the gluon distribution at higher x_{BJ} in the nucleus, since both effects result from the same basic gluon recombination processes. What is not obvious thus far in the data of Fig. 5 is the extent to which saturation of the parton distribution may already be present in the data, or indeed how to extract this information. A further technical difficulty is that it is precisely at the point where saturation of the parton density occurs that the assumption of factorization may break down.

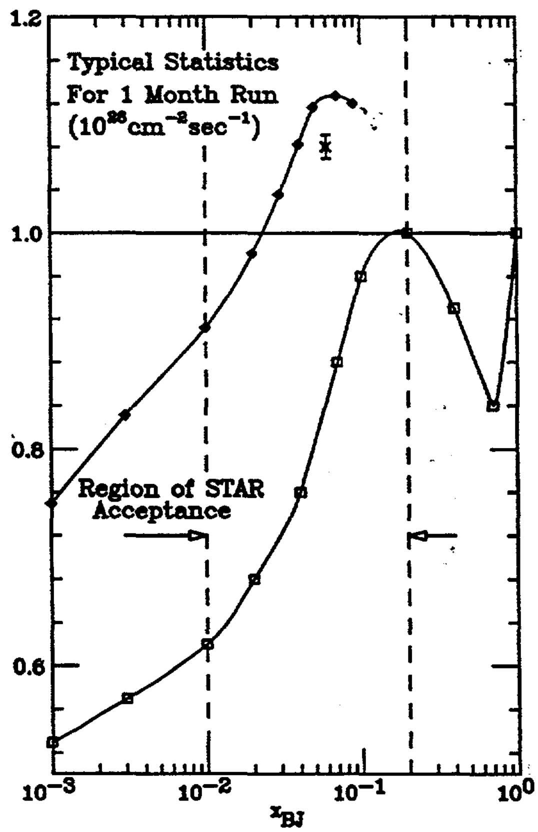

Figure 6: The range of x_{BJ} for which the gluon distribution in the nucleus will be investigated in STAR using direct photon + jet coincidences. The statistical accuracy expected for 1 month of running for pAu interactions at the design luminosity is indicated. The top curve shows a theoretical estimate of gluon shadowing in the nucleus[5]. The quark shadowing in the nucleus expected for pAu interactions is shown for reference (bottom curve).

In STAR, the intent is to measure the gluon distribution in the nucleus directly in order to determine the initial conditions before the collision. This will be probed using the QCD Compton diagram, detecting the final state jet and direct photon coincidence in the STAR

TPC and electromagnetic calorimeter. The contribution to this channel from $q\bar{q}$ annihilation should be small (of order 10%) at these energies. The region of the STAR acceptance (in x_{BJ}) for this measurement as well as the projected sensitivity for a pAu run of 1 month at the design luminosity are indicated in Fig. 6. Work is ongoing within STAR both to refine the design of the EMC to address the measurement of jets and direct photons in AA interactions (in pp and pAu this capability has already been demonstrated) as well as to perform realistic simulations focused on identifying and understanding potential sources of systematic error in this measurement.

A second effort that has recently become the focus of increased effort and interest is to develop techniques from information theory on how, beyond simple two dimensional correlation techniques (e.g. scatterplots), to detect and measure non-statistical multi-dimensional correlations[6].

The basic idea underlying this analysis is that there is a unique physical scale associated with correlations of a particular type. This is to some extent familiar from common experience. If viewed from many miles away, the correlation information contained within a city skyline might be hard to distinguish from the surrounding horizon by the naked eye. From several miles away, however, the skyline of the city would be unmistakable and one would be able to make a fairly precise estimation, for example, of the size and outline of the city. If standing then between two tall skyscrapers within the city which subtended most of the field of view, it would be again hard to determine much about the overall dimensions or outline of the city, although it might be much easier to detect a different correlation,–for example, an unusually high probability of finding a delicatessen in the neighborhood. The essence of this technique then is to determine the correlation information content within a given central AuAu interaction by examining the "topological" or "Renyi entropy"–the amount of information available–at a number of different physical scales which relate to the physical size of various elements of the STAR detector system. The goal is to select events based on the level of their information content, rather than on the extent to which they resemble or differ from criteria developed from event generators of unknown reality.

Practically, to make this determination, each event is first examined to determine the "Renyi entropy" at a given scale. In practice this can be as simple, as counting the number of particles or the transverse energy (normalized for convenience) entering a set of bins (scintillator counters, calorimeter towers, etc.) of a given size and determining the logarithm of the moments of the distribution. This procedure is then repeated with a slightly different binning at the same scale, to insure the results are independent of the choice of binning. The results of several trials determine the average "scaled entropy" for that event. The scaled entropy for a given event may then be compared to the scaled entropy for an ensemble of reference events generated either from an event generator, or some a priori notion concerning the nature of the fluctuations for a given type of distribution.

The difference between the average scaled entropy for an event of interest and the reference ensemble is termed the "scaled information" for that event. Having determined the scaled information at a given scale, the process is repeated to determine the scaled information for each event of interest for a range of different physical scales (usually 50-100). Finally the "dimension lowering" –the derivative of the scaled information with respect to scale size–is determined, for example, at 3 different scales, and the result plotted in a Cartesian space to determine if events belonging to distinctly different populations in this space can be identified.

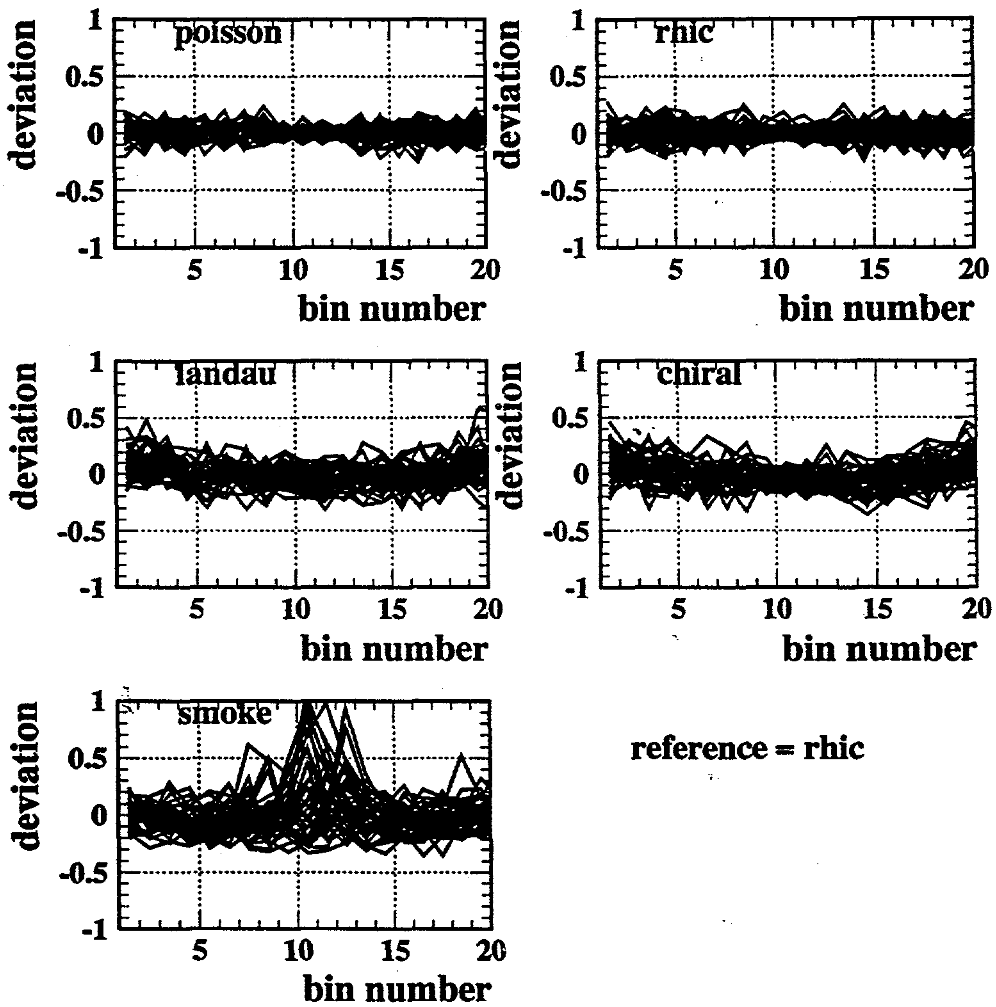

Figure 7: The relative deviation, as a function of pseudorapidity (bin number) of the charged-particle multiplicity for several hypothetical event samples from the event ensemble average of a standard RHIC event class (except for the POISSON events, which are shown relative to a uniform distribution).

In principle one can generalize this technique to examine events in an n-dimensional space to search for unique non-statistical n-dimensional correlations. Further, this analysis technique may be used either at the trigger level, or in off-line analysis. The power of this technique is illustrated in Figs. 7 and 8, in which several event types which differ in the nature of the energy deposition in the interaction region have been used. What is noted is

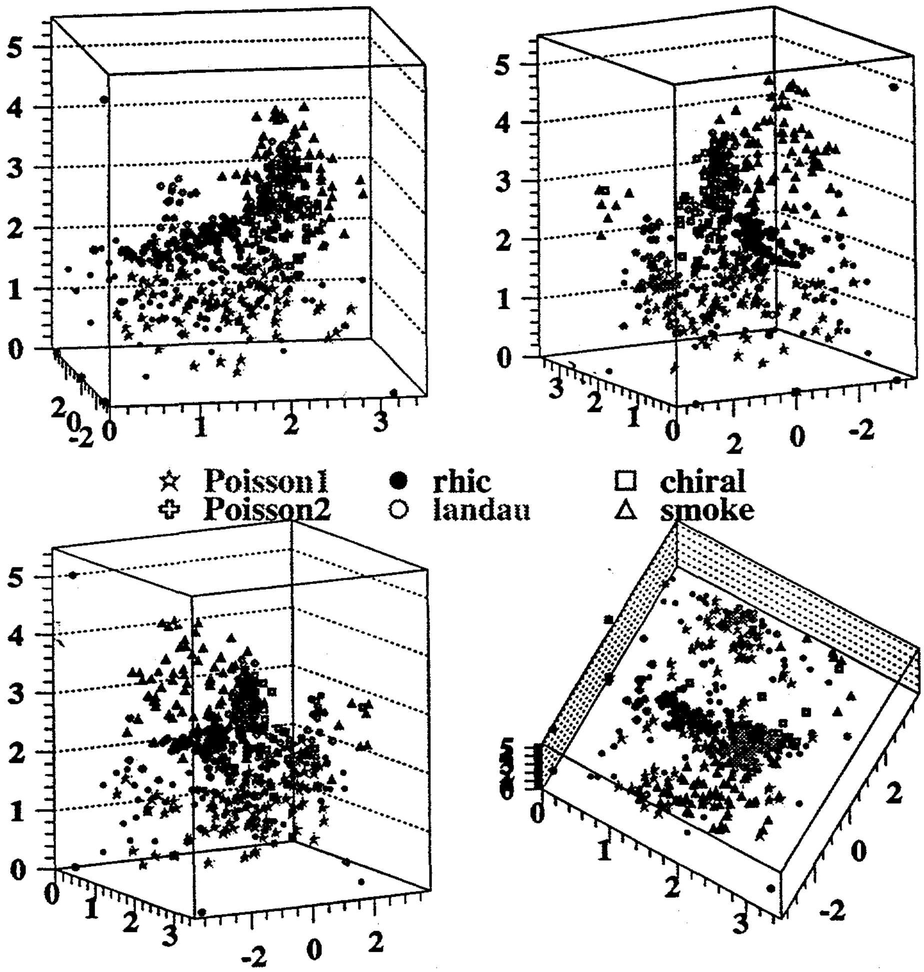

Figure 8: The distribution in a polar coordinate space, for the same event samples plotted in Fig. 7, of the dimension lowering at three different physical scales. (Each axis locates for a given event the dimension lowering at one physical scale). Close inspection (made easier by the use of color plots not shown here) indicates that, plotted in this manner, the event samples shown in Fig. 7 populate different regions in this space corresponding to differing assumptions regarding the deposition of energy and subsequent hadronization in the interaction.

that essentially all event types exhibit very similar multiplicity distributions (Fig. 7) which do not distinguish one type of event from another. When the dimension lowering for each event at 3 different scales is plotted in a Cartersian space however (Fig. 8), the event types are quite distinct and the events contained in one particular population can be separated out for further analysis with appropriate cuts.

This technique appears to be quite promising, and it would be of significant interest to perform such an analysis, for example, for events with and without mini-jets, the presence of which is in general difficult to isolate. One obvious consequence of this type of analysis technique is the somewhat urgent need for more realistic RHIC event and plasma event generators to assess the physical significance and interpretation of fluctuations and correlation's which may be observed.

In conclusion, to search for evidence of a transition to a deconfined phase the STAR detector will measure and correlate a number of global observables on an event-by-event basis. STAR will also provide important information on the initial conditions, using jet-direct photon coincidences to probe the gluon distribution of a nucleon in the nucleus via the QCD Comtpon process. Work is continuing on refining the STAR capability to use hard-scattered partons as a penetrating probe to provide information on the medium in the early stages of relativistic AuAu interactions.

References

[1] Further details of the STAR experimental program may be found in the STAR Conceptual Design Report, LBL PUB-5347, June 1992.

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