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Annual Technical Progress Report for DE-FG02-90ER-40577

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1 INTRODUCTION

This is a report on research conducted at Pennsylvania State University under grant number DE-FG02-90ER-40577, from its inception on December 1990 to the present time (November 1991).

The personnel supported by this grant are: John Collins (Principal Investigator), Glenn Ladinsky (Postdoc). In addition, graduate students were supported during the Summer of 1991. Essentially all the research was on various aspects of perturbative QCD.

Collins is also a member of CTEQ (Coordinated Theoretical and Experimental Project on Quantitative QCD and Tests of the Standard Model), that is supported by the Texas National Research Laboratory Commission. This has allowed the support of a long term visitor, and has provided more student support. It also allows a good framework for collaborative work on QCD. The work supported there is complementary to that supported under the present DOE contract.

2 COLLINS' WORK

2.1 SMALL x

The collaboration with Keith Ellis on the 'small x' problem continued. This problem concerns processes where one has a hard scattering with an intrinsic scale Q that is simultaneously large on the scale of Λ_{QCD} and small on the scale of the overall center-of-mass energy $\sqrt{s}$ in the collision under consideration. Such processes include: production of charm and bottom quarks at existing and planned colliders (Tevatron, HERA, LHC and SSC), minijet production at such colliders, small-x_{Bj} deep inelastic scattering at HERA.

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MASTER

Our overall aim is to be able to make perturbative calculations that work both in the small x region and for the normal large x region, and hence in the intermediate region. The resummations of large logarithms that are needed in the small x also produce large corrections to low order perturbative calculations in the intermediate region. Many processes of practical importance—e.g., heavy quark production—are in this intermediate region where the fully asymptotic small x behavior has not set in, but where the associated large logarithmic corrections are impairing the accuracy of conventional perturbative calculations.

Unlike other work on this subject that results [1] in a modification of the algorithms for Monte-Carlo event generators, we want to make calculations of the analytic kind for inclusive processes.

The cross section is written in terms of a certain off shell cross section, called an impact factor, and in terms of the solution to our modification of the Lipatov equation.

Our progress this year is as follows. We were able to make calculations for heavy quark production, and wrote up a summary of our methods that has been published [P1]. The main problems here concerned the organization of the numerical calculations: The analytic formula for the cross section involves four contour integrals for inverting Mellin transforms. Suitable adaptive quadrature methods for inverse Mellin transforms were developed. Then use of interpolating tables for the parton distributions as a function of x and $k_\perp$ reduces the rest of the calculation to a manageable size.

We have explored how to see the effects of our resummation on the angular correlation of the heavy quark and antiquark produced in hadron collisions. This can be presented as a ratio of same-side to opposite-side production in azimuthal angle. Substantial (factor of two) effects are seen, which would have significant effects of detection of bottom quark production at hadron colliders, for example. Our work is still preliminary. A working visit to Fermilab is planned to make further progress in December.

Collins has also collaborated with Landshoff (Cambridge) on understanding the effect of cutoffs on the standard Lipatov equation. In a recently written paper [P9], we show the effect of both infrared and ultraviolet cutoffs. These have a rather important effect. The infrared cutoff models the infrared behavior of confinement in QCD, and the ultraviolet cutoff models the physical cutoff at a nonasymptotically high energy. One of our results is that the asymptotic full solution of the standard Lipatov equation is approached rather slowly by real QCD. This is a result that the numerical calculations of Collins and Ellis had anticipated. But the method of Collins and Landshoff takes a more analytic approach—we approximate the equation by one that can be solved analytically, even with cutoffs. We are thereby able to see rather readily what is causing the slow approach to asymptopia.

2.2 Spin physics

Collins is a member of the 'RHIC Spin Collaboration' (RSC) [2], which proposes to put polarized protons in the Relativistic Heavy Ion Collider at Brookhaven. The development of 'Siberian snakes' has made it technically feasible to accelerate polarized hadrons to collider energies. This opens up the possibility of investigating polarized hadron collisions at an energy where there is hard scattering that is unambiguously accessible to perturbative QCD

on the theoretical side [3].

The RSC proposes a full program of QCD measurements. This represents an important frontier of perturbative QCD, since the full parton structure of QCD, at the leading twist level, requires a specification of the spin density matrix of the partons as well as of the unpolarized parton densities.

A cornerstone of the program is the measurement of the polarized parton densities. In the unpolarized case, much of the data on the flavor dependence of the parton densities comes from neutrino scattering. Since we do not expect data for neutrino scattering on polarized hadrons, it is important to extract as much information as possible on the flavor dependence from hadron-hadron scattering.

Collins has suggested a method to visualize the sensitivity of various processes to the polarization dependence of the partons. Ladinsky—see below—has implemented and improved on this in a very nice way, in collaboration with Steve Heppelmann. This work will contribute to determining what would be a good kinematic configuration of a detector for polarized hard collisions. This work remains to be written up.

Although phenomenological work has typically assumed the usual QCD factorization theorem for hard scattering, the explicit proof has never been fully formulated. The lack of proof has resulted in substantial confusion in the literature as to what the correct twist-2 results are, even though it is obvious to at least some experts as to what the results are. So Collins is in the process of writing up the proof.

Collins also gave the plenary talk on 'Spin Physics at hadron Colliders' at the Conference on Intersections of Nuclear and Particle Physics [P8].

2.3 Transverse Polarization and Jet Production

One traditionally tricky aspect of polarized hard scattering has been the status of transversely polarized quarks. This has now been resolved satisfactorily [4,5], and a full explanation will appear in the above mentioned proof of factorization for polarized scattering.

But it remains difficult to measure the spin asymmetry of quarks in a transversely polarized hadron. (Gluons have no twist-2 asymmetry in a transversely polarized spin $\frac{1}{2}$ hadron, as a consequence of invariance under rotations about the collision axis [6].) The Drell-Yan process is not a valence dominated process at a proton-proton collider, while the hard scattering factor for the jet cross section has a small (at most about 10%) asymmetry [7].

Now, there are known large asymmetries in *single* spin asymmetries in large $x_\perp$ particle production at lower energies. Although QCD predicts that these go away as a power of energy, they are liable to be still noticeable at collider energies, since they decrease only as a single power of energy. They may represent a serious background to the twist two measurement.

The difference between the longitudinal and transverse asymmetries is sensitive to relativistic effects in the hadron wave function [5]. It is therefore potentially an important measurement. One way to get a better measurement of the transverse spin structure is to

measure the spin of an outgoing jet in the collision where only one incoming proton is polarized. Collins, in collaboration with Heppelmann, Jaffe and Ladinsky, are working on a method to do this apparently hopeless task. We observe that the leading particle in a jet is supposed to be correlated in flavor with the parton initiating the jet. So the plane of the two leadingmost particles should be correlated with the spin. The physical separation of the two particles (10s of GeV of transverse energy with less than a GeV of relative transverse momentum) is small, but not obviously impossible to detect with suitable tracking. We continue to investigate this idea together.

2.4 Fundamental QCD

The proofs of results in perturbative QCD are typically very complicated and hard to understand. As accelerators go to higher and higher energy, much reliance is placed on perturbative QCD results for all kinds of phenomenology, and results are needed for interesting kinematic regimes, such as that of small 'x' noted above. Many results are known at the leading logarithm level. Education of new students requires comprehensible explanations of perturbative QCD that go beyond platitudes and get to the meat of the subject.

One approach that may prove fruitful to making the derivations much easier and comprehensible is due to Tkachov [8]. He makes a systematic use of distribution theory to derive asymptotic behavior of Feynman graphs. So far, his methods have been set up for Euclidean problems, like the operator product expansion. But the ideas are much more generally valid. During a long E-mail dialogue and a subsequent visit to Penn State in July, Collins and Tkachov solved the fundamental problem of extending the concepts to Minkowski space problems.

A student, Randy Scalese, has been supported to work on this project and will be supported during the coming semester. He is making excellent progress.

The SSC will support an extended visit of Tkachov to Penn State during the coming winter. We plan to get derivation of some of the main QCD results. Ultimately, one of our aims is a systematic derivation of the Lipatov equation and with luck of a method for obtaining nonleading corrections (in α_S). This will be important for accurate QCD phenomenology at the SSC.

3 LADINSKY'S WORK

From September 1990 to September 1991 my research in elementary particle physics covered various topics with major emphasis on the phenomenology of quantum chromodynamics and electroweak theories. These studies are from the perspective of experiments that will be performed at the Fermi National Accelerator Laboratory (FNAL), the Large Hadron Collider (LHC), the Superconducting Super Collider (SSC), and the Relativistic Heavy Ion Collider (RHIC). Though some of the work has been a continuation of collaborations, I have gained some breadth to my work through my participation in the Polarized Collider Workshop at the Pennsylvania State University which was held in November 1990 and the

electroweak/symmetry breaking (EWSB) workshop hosted by Prof. J. Gunion at the University of California at Davis (UCD) in July 1991.

3.1 W AND TOP PRODUCTION

One focal point of my research has been related to the new physics which appears with a heavy top quark. Following the publication of "The W-Boson Top-Quark Background to Heavy Higgs Production" [12] in February 1991, I continued my collaboration with Dr. Chien–Peng Yuan and joined with Prof. Gordon Kane in a study using the top quark as a *signal*. Taking advantage of some recent theory development (e.g., Dharmaratna and Goldstein's work on polarized quark-antiquark production in gluon–gluon fusion), we were able [P10] to develop experimental tests which could be done at the FNAL, the LHC, and the SSC with the idea of not only testing the Standard Model of particle interactions, but also to search for new physics. Using the most general Lagrangian for the decay of the top quark, we were able to find methods of searching for new physics in both the production and decay of the top quark using final state polarization effects. Tests for CP violation were also discussed.

3.2 STRONGLY INTERACTING Ws

A significant portion of my time has also been spent on a large project which examines the strongly interacting W sector. This project stemmed from one of the working groups at the EWSB meeting held at UCD and is directly related to experiments which can be performed at the SSC. If the Higgs particle is not found to have a mass below 1 TeV, the gauge particle sector of our theories is expected to become strongly interacting due to a "No–Lose Theorem" with the longitudinal polarization modes of the gauge bosons becoming of popular concern. If this happens, the picture becomes quite complicated as many different theories may be able to describe the resulting physics. It therefore becomes important to analyze the features of each model so they may be distinguished through experimentation. With this in mind, our collaboration is investigating enhancements in cross sections due to the Low Energy Theorem, the Standard Model, the O(2N) Model, and several Chiral Lagrangian Models to find ways of making the distinction. This work is nearing completion [P16]. When it is done, I will be extending our studies in a second paper with a smaller subgroup of this collaboration in an investigation which will include the effects of the transverse modes of the gauge bosons.

3.3 POLARIZED HADRON COLLISIONS

Another facet of my research involves the study of reactions involving collisions between polarized hadrons. At the Polarized Collider Workshop I presented a paper in which I was a coauthor with Prof. John Collins titled "New Bosons in Polarized Hadronic Collisions." [P3] Though the paper related to the study of new particles, it was also written to be a clear demonstration of the necessity of having polarization capabilities in hadron-hadron colliders. Using a Drell-Yan production mechanism, we showed that both transverse and longitudinal

polarizations would be required for the initial hadrons if we were to have a definite handle on the couplings which governed any new gauge boson interactions. The results obtained are typical of such studies.

Other work involving polarized hadron collisions has been done in conjunction with both Prof. John Collins and Prof. Steve Heppelmann. Important for designing detectors and experiments at RHIC and possibly the SSC will be our ability to analyze polarization asymmetries in the parton distribution functions of the proton. With Prof. Heppelmann's assistance, I have written a program that uses the CERN programming library which can be used as a tool to determine where our experiments will be most sensitive to these asymmetries and how we may extract the polarized parton distribution functions. This work was recently presented at a RSC (RHIC Spin Collaboration) meeting.

3.4 Transverse Polarization and Jet Production

Another project which I have been doing with Prof. Collins is basically completed and only needs to be written for publication. This work involves a first level study of the plausibility of using correlations between the two leading particles in a QCD jet for determining the polarization of the initial parton. Using the Sigma Model to govern the fragmentation, the techniques which Prof. Collins has developed have been applied to generate the fragmentation functions for a quark–initiated QCD jet which contains two pions. Maintaining an imaginary part to the amplitudes though the width of the sigma particle allowed us to obtain a nonzero correlation between the two pions.

3.5 Sudakov

Finally, there was some work done with Prof. Collins involving a pedagogical paper describing his methods of gluon resummation in low transverse momentum processes such as Drell-Yan. This paper would also include discussion on how to handle non-negligible quark mass effects through the application of the proper renormalization schemes. For the time being, though 30+ pages are written, this project has been shelved.

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