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Future Experimental Studies of QCD at Fermilab
Report of the QCD Section:
Options for a Fermilab Strategic Plan

M. Albrow et. al

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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Report of the QCD section:
Options for a Fermilab Strategic Plan

by
M. Albrow (1), J. A. Appel (1), G. Blazey (1), J. Conrad (3),
A. V. Kotwal (4), E. Kovacs (1), S. E. Kuhlmann (2), J. Lach (1),
E. Levin (1), H. L. Melanson (1), J. G. Morfin (1), V. Papavassiliou (2),
C. W. Salgado (1), P. Spentzouris (5), H. Weerts (6)

(1) *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
(2) *Argonne National Laboratory, Argonne, Illinois 60439*
(3) *Columbia University, New York, New York 10027*
(4) *Harvard University, Cambridge, Massachusetts 02138*
(5) *Northwestern University, Evanston, Illinois 60208*
(6) *Michigan State University, East Lansing, Michigan 48824*

ABSTRACT

The experimental study of Quantum Chromodynamics at Fermilab benefits greatly from the wide variety of experimental methods available to address the issues. As this document will show, it is only with a major collider detector facility as well as a diverse high-energy fixed-target experimental program that the many open questions of QCD can be fully investigated. Fermilab is currently running such a broad program and is, therefore, uniquely able to contribute so significantly to the subject. An increase in primary proton energy at Fermilab to 2 TeV and above would allow this full variety of Fermilab experiments to extend their tests of QCD to increasingly important kinematic regimes.

1. Introduction

The organization of the study, and also this document, is primarily based on physics topics rather than methods or types of detectors. Our goal is to first define the problems or open questions which make each general physics topic interesting. We then review the physical processes which address the question and consider how these processes would contribute both at present energies and for future fixed target and collider possibilities at proton energies of 2 TeV and above. The possibility of using the high intensity main injector beam is also studied particularly as it would address many of the open questions of non-perturbative QCD.

The list of general physics topics we have considered is as follows:

- Parton Distribution Functions
- Structure Functions and Sum Rules
- Jet and Photon Physics
- Nucleon Spin Physics
- Heavy Quark Production
- Elastic and Diffractive Scattering
- Small-x Physics
- Nuclear Effects / Nuclear Targets
- Production Polarization Physics
- Glueballs
- Photon Structure Function
- Non-perturbative QCD

2. Structure Functions and Parton Distributions

The strong interaction is the least understood of all of the interactions, with the exception of gravity at the quantum level. Because partons are the building blocks of QCD, understanding their behavior is fundamental to understanding the theory. The following are examples of the questions which can be addressed through studying parton distributions. This list is meant to be suggestive, not complete.

2.1. Understanding the Source of the Distributions

The structure of the proton is a fundamental, unanswered question. We do not know how to go from a model that describes the static (*ie* 3 quark) properties to one which describes the data that we observe. Within a limited range we can understand the evolution of the structure functions, but we are far from understanding the original (x-dependent) distributions.

The source and size of intrinsic distributions is particularly interesting. Intrinsic u and d distributions are expected, but what is the source of intrinsic strange, and how large is the effect? If one extracts a value of the strange sea using the "5/18th" Rule to compare NMC and CCFR data, one finds a much larger value for the strange sea than is observed from opposite sign dimuon production in the CCFR data. Are there other heavy quark intrinsic distributions, such as charm?

As another surprising example: should one expect intrinsic distributions of $\overline{u}$ and $\overline{d}$ to be different? Until the NMC measurement in 1992, it was generally assumed that the non-strange sea was flavor symmetric. Recent results from NA51, a Drell-Yan Experiment, indicate that at x=.18 the difference is over 20%. In fact, there are several models which indicate a difference should be expected. The earliest argument was developed by Field and Feynman and was based on the Pauli exclusion principle. So far, there is very limited data on direct measurement of $\overline{u}/\overline{d}$.

There are phenomenologically motivated parton distributions which attempt to begin with valence distributions and dynamically generate the parton distributions in the perturbative region (the GRV parton distributions, for example). However, this has had only limited success in the sense that it must start with much more than three valence quarks.

These distributions are crucial inputs to almost all tests of Perturbative QCD. Without precision measurments of these distributions, we cannot adequately test QCD.

2.2. Tests of Perturbative QCD

Although PQCD is well accepted, in truth we are only starting to do precision measurements which really test the theory. So far qualitative agreement is good but several precision tests are missing.

There are specific predictions of the behavior of the fundamental parameters of QCD which have not been thoroughly tested. There is qualitative agreement between the measurements of α_s at various Q^2 and the QCD expectation. However, although it is small, there is a systematic disagreement between the deep inelastic and LEP Measurements. For direct comparison:

$$\alpha_s^{BCDMS}(M_Z) = 0.113 \pm 0.003(exp) \pm 0.004(th)$$

$$\alpha_s^{CCFR}(M_Z) = 0.111 \pm 0.003(exp) \pm 0.004(th)$$

$$\alpha_s^{LEP} = 0.122 \pm 0.006.$$

(for discussion, see reference 1). A statistically significant deviation could indicate physics beyond the standard model, as addressed in reference 2. Hence future precision tests of α_s can provide a window on new physics.

There are several predictions of PQCD which have never been tested. For example, $R = \sigma_L/\sigma_T$, as calculated by PQCD, will be given by

$$R_{QCD} = \frac{\frac{\alpha_s}{2\pi}\int_x^1 \frac{d\chi}{\chi}[\sum_{i=q,\bar{q}} e_i^2 q_i(x)\sigma^L_{q\gamma*}(\frac{x}{\chi}) + \sum_{i=q} e_i^2 G(x)\sigma^L_{G\gamma*}(\frac{x}{\chi})]}{\sum_{i=q,\bar{q}} q_i(x)e_i^2 + \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\chi}{\chi}[\sum_{i=q,\bar{q}} e_i^2 q_i(x)\sigma^T_{q\gamma*}(\frac{x}{\chi}) + \sum_{i=q} e_i^2 G(x)\sigma^T_{G\gamma*}(\frac{x}{\chi})]},$$

The only measurements of R are in the kinematic range $x > 0.1$ and $1 < Q^2 < 20GeV^2$, as summarized from reference 3. The errors on the data are too large to make any definitive statement about R_{QCD}.

2.3. *Regions of Large Parton Density*

The HERA F_2 results indicate that the parton distributions grow very quickly at small x (see, for example, reference 4). This is interesting as a test of QCD, since fast growth of the momentum weighted parton distributions is predicted by the DGLAP equations. Beyond that, it indicates that there may be kinematic regions where the wavefunctions of the partons overlap but α_s is small. The regime where partons overlap sufficiently to interact strongly while still in the perturbative region is a new domain in QCD.

"Hot spots," regions of large parton density, have been invoked to explain the distribution of the underlying event in $p-\bar{p}$ collisions. This is now included as an option in the Monte Carlo *Pythia* and the results are now under study.

Eugene Levin (reference 5) and other theorists have pointed out that it may be possible to have regions of large parton densities by using high A targets. In this case, the partons overlap between the nucleons resulting in "hot spots" at higher x than one might have expected.

So far, there has been no evidence of parton overlap. However, there are continuing searches for "hot spots" or regions of high parton density. So the question remains: Do these regions exist? And once they are isolated, numerous questions about parton behavior must be addressed.

2.4. *Properly Incorporating Quark Masses*

Thresholds for heavy quarks are an example where experiment can drive theory. Right now there are only models to explain how heavy quark distributions "turn on." How should threshold effects be properly incorporated into the splitting functions? This is an important question for comparing measurements of α_s which cross boundaries between quark thresholds.

2.5. *Non-perturbative Effects*

Many non-perturbative effects must be the result of the strong interactions and should be considered within any discussion of investigations of QCD. There is an array of non-perturbative effects which should be explored in depth. The most popular question at the moment is pomeron scattering. Calculations indicate that at small x, the deep inelastic structure function should have large contributions from pomeron t-channel exchange. Another example is the prediction of a large instanton contribution to the deep inelastic cross section. These are discussed in reference 4.

2.6. Other Objects than the Proton and Neutron

Until this point, the focus has been on extraction of parton distributions in the proton and the neutron. The distributions within other particles are as fundamental, very poorly measured, important as input for other physics and needed to test QCD.

As a first example, consider the structure of the pion. The structure of the pion has been calculated in lattice QCD (see reference 6). Since we believe that, in principle, lattice QCD should allow calculation within the non-perturbative regime, it is very important to test these results.

A second example is the QCD structure of the photon. In principle this is a simple object. It has a gluon distribution and a symmetric sea. The photon is thought to have three types of behavior. First, it can behave as a point-like object which couples directlyto quarks. Second, in some cases it may have structure similar to the pion, with an evolved gluon sea. At higher values of Q^2, it is expected to have quark distributions which are much harder than the pion. HERA is studying photon interactions at high Q^2. PQCD caluclations exist to second order for photon interactions.

As a third example, there is a great deal of interest in the structure of the pomeron. So far, there is no clear evidence on the structure of the pomeron. It is commonly assumed, but not demonstrated, that the pomeron consists of gluons. There are reasons to believe that the pomeron may be a very small object. Hence this is an interesting system in which to investigate such QCD-related questions as small x gluon recombination.

2.7. Conclusion

The above questions represent examples of why it is important to measure parton distributions. It should be noted that under each heading there are many other questions and ideas. Also, several headings, including nuclear effects and spin structure, were left out of this list because they will be covered by other reports.

In order to address the open questions, many different sources of data should be considered. These include deep inelastic scattering, direct photon production, W-charge asymmetry studies and Drell-Yan Production.

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3. Jet Physics, Direct Photons and Drell-Yan

3.1. Introduction

Jets, Direct Photons and Drell-Yan processes have now been studied for over 20 years. Studies in the QCD perturbative regime have been very rich for the test of PQCD calculations and for measurements of the QCD parameters. These studies are continuing at the Tevatron collider. The increase in accumulated statistics will allow for more precise tests and measurements in the same vein as already pointed out in several workshops[1,2] and proposals.[3,4] In this report we will concentrate on the open questions of QCD that could be adressed by the study of jets, direct photons and Drell-Yan production in a high energy upgrade at Fermilab.

It has been said that "QCD is only half solved",[5] in reference to the very limited knowledge we have of the non-perturbative, long range behavior of the strong interaction. A future upgrade at Fermilab, affecting both the collider and fixed target programs, could illuminate this mostly unknown region of QCD. This can be done studying the small x regime, hadronization and diffractive phenomena at the collider and fixed target experiments. The hadronization and confinement regions of QCD could be explored in quantitive ways using jets, direct photons and Drell-Yan pairs.

3.2. Jet Physics.

Jet physics, as the other topics in this section, has two aspects. One, as a tool to study partonic level kinematics, since partons manifest themself as jets at high energies; and second, the study of the jet internal structure to understand the hadronization process.

Jets have been observed by now in e^+e^-, hadron-hadron colliders and deep inelastic lepton-nucleon scattering. However, a systematic global study of jet properties among these different processes has yet to be undertaken. This is due in part to the fact that different jet definitions (algorithms) have been used for each of the processes. A future "unification" of the field whould be desirable since this will give us the opportunity of exploring different conditions of backgrounds and systematics.

The particle collimation within a jet increases with the center-of-mass energy of the production.[6,7] A high energy experiment in any area will improve the relative jet energy resolution and centroid determination. It will also reduce the corrections for hadronization when comparing to PQCD predictions. Therefore, systematic errors caused by these uncertainties in measuring the partonic system kinematics will be reduced with increasing energies.

Jets in lepton-hadron interactions have been observed at E665[8] and HERA.[9,10] A Multi-TeV muon beam at Fermilab will certainly produce a considerable cross section for the measurement of multijet rates in the PQCD regime. In a fixed target enviroment, we can obtain high luminosities and better systematic uncertainties, making possible a more precise study of PQCD and QCD parameters. For example, the strong coupling, α_s, could be measured in a wide Q^2 range, including very low values, with a precision comparable to e^+e^- machines.
In fixed target conditions we also could study the propagation of multijets in nuclear matter using heavy nuclear targets. The target could be used as a detector to study the hadronization process in the jet, as E665[11] has started to do. Nuclear effects, as shadowing or parton saturation/overlap at high densities[12] could also be studied using jets. It will be important to cover a wide range of virtual photon virtualities (Q^2) for a given small x value, making it possible to cover the perturbative and non-perturbative regions of QCD in a single experiment.

The separation between "quark" and "gluon" jets has been pursued at e^-e^- machines.[13] A similar technique, based on energy distribution within a jet, can be used for lepto-produced multi-jet events.

The study of di-jet, inclusive jet production and multijet correlations in a wide rapidity region will also be improved by going to higher energies (at the collider) as backgrounds and PQCD calculations uncertanties at large rapidities will be decreasing. Scaling problems reported by CDF measuremnts[14] can also be directly adressed with the possibility of running in a wide range of energies.

3.3. Direct Photons

The advantages of direct photons in studying QCD has long been known.[15] Direct photons coupled electromagneticly to quarks and photons are easier to reconstruct than jets. Extending the measurements to higher energies, and higher photon p_T's present experimental challanges on how to discriminate the prompt photon from the more conspicuous neutral meson backgroud. However, these experimental problems have successfully been adressed.[16]

E706 is the latest fixed target direct photon experiment in a hadronic beam.[17] Present measurements of the inclusive cross sections have found discrepancies with PQCD predictions at low p_T.[16] There also seems to be a severe scale dependence on the prediction[17] suggesting that a NNLO calculation will be necessary before additional progress can be made comparing data and theory since these uncertanties are bigger than the sensitivities to the parton distributions. A new topic that is also being explored is the production of a direct photon plus jet in the large rapidity region.[18] These measuremnts could be used to measure the gluon distribution at very small values of x, the fraction of the nucleon momentum carried by the parton, as a function of x. Increasing the beam energy will increase the reach to lower values of x and decrease statistical and systematical uncertanties.

The production of direct photons in deep inelastic scattering could also be studied in a competitive way by experiments in a Multi-TeV muon beam-line. The parton distributions in the proton and the photon could be studied and measured adding the advantages of the use of heavy targets. These studies can benefit by higher luminosities, hermetic detectors and better systematic uncertanties (as compared to collider experiments) possible in a fixed target enviroment.

3.4. Drell-Yan production.

The production of low-mass Drell-Yan pairs at central rapidities is very sensitive to the parton distributions. It has been recently measured by CDF.[19] Dell-Yan physics, at one order higher on pertubation, is similar to the physics reachs of direct photons. However, lepton pairs give a much cleaner signal for experimetalist. Cross sections are smaller and experiments will greatly benefit from large accumulated luminosities for precision measuremnts.

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4. Spin Physics

The scattering of polarized leptons with a polarized nucleon may be characterized by two spin-dependent structure functions $G_{1,2}$ using

$$\frac{d^2\sigma^{\uparrow\downarrow}}{dQ^2d\nu} - \frac{d^2\sigma^{\uparrow\uparrow}}{dQ^2d\nu} = \frac{4\pi\alpha^2}{Q^2E^2}\left[M(E+E'cos\theta)G_1(\nu,Q^2) - Q^2G_2(\nu,Q^2)\right]. \qquad (1)$$

$G_{1,2}$ are related to $g_{1,2}$ through

$$\frac{\nu}{M^2}G_1(\nu,Q^2) \equiv g_1(x,Q^2) \qquad (2)$$

$$\left(\frac{\nu}{M^2}\right)^2 G_2(\nu,Q^2) \equiv g_2(x,Q^2) \qquad (3)$$

which in the Bjorken scaling limit ($\nu \to \infty$, $Q^2 \to \infty$, x fixed) are only functions of x. In this limit, $g_1(x)$ can be related to the distribution of quarks with spins parallel or antiparallel to the nucleon via

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\left[q_\uparrow(x) - q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)\right] \equiv \frac{1}{2}\sum_q \Delta q(x) \qquad (4)$$

This then relates to the overall spin of the nucleon through

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \Delta G + \langle L_z\rangle \qquad (5)$$

where ΔG and $\langle L_z\rangle$ represent contributions from gluons and orbital angular momentum.

In 1966, Bjorken derived a sum rule[1] which relates g_1 of the proton and neutron with the vector and axial-vector coupling constants measurable in beta decay. At leading-order in perturbative QCD this sum rule may be written as

$$\int_0^1 \left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right]dx = \frac{g_a}{g_v} \times \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) + \ldots, \qquad (6)$$

which in the Quark Parton Model may be related to Δu and Δd through

$$\int_0^1 \left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right] dx = \frac{1}{6}\left(\Delta u - \Delta d\right) \times \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) + \ldots . \tag{7}$$

Using neutron β-decay and assuming $SU(2)$ isospin symmetry, one has

$$\Delta u - \Delta d = F + D \tag{8}$$

where F and D are the matrix elements of the axial currents. Combining hyperon β-decays and $SU(3)$ symmetry yields

$$\frac{\Delta u + \Delta d - 2\Delta s}{\sqrt{3}} = \frac{3F - D}{\sqrt{3}}. \tag{9}$$

Thus, by combining measurements of g_1^p and g_1^n with beta decay measurements, one may test the Bjorken sum rule. If instead one assumes the sum rule, and for example, SU(3) symmetry, then a measurement of g_1^p allows the extraction of individual quark contributions to the proton spin (Δu,Δd and Δs).

In a recent analysis of existing data, including those from a deuteron target taken by the SMC at CERN and from a Helium-3 target taken by the E142 experiment at SLAC, Ellis and Karliner[2] have used the above equations to test the Bjorken sum rule and to extract the quark contributions to the proton spin. After including higher-order perturbative QCD corrections, mass corrections and updated estimates of higher-twist effects, they find that "the Bjorken sum rule is satisfied within one standard deviation", and characterize the precision of this verification to be at the 16% level. They also conclude that the total quark contribution to the proton spin is

$$\Delta\Sigma \equiv \Delta u + \Delta d + \Delta s = 0.27 \pm 0.11,$$

with individual contributions of

$$\Delta u = 0.82 \pm 0.04, \Delta d = -0.44 \pm 0.04, \Delta s = -0.11 \pm 0.04.$$

These results indicate several things. The first is that we are far from a precision test of the Bjorken sum rule. There are a few reasons for this. The statistics of many of the data samples are small. Where the statistics are large (ie. SLAC), the data only extend to moderately small values of x, and so extrapolations to $x \to 0$ must be made to perform the sum rule integrals. In addition, the data are all at relatively small values of Q^2, where higher order perturbative corrections and higher-twist contributions are important.

Another result is that the strange sea appears to be polarized. While not forbidden by QCD, this result came as somewhat of a surprise when first noticed.

Finally, it is clear that there are non-quark contributions to the proton's spin (using Equation 5). While not universally accepted, one possibility is that there is a very large contribution from the gluons (ΔG). A non-zero value for ΔG is expected from perturbative QCD, growing with $log(Q^2)$ via the evolution equation, however the absolute magnitude of the contribution is unknown.

In the near future, SMC will take more data with a deuteron target. In addition, E142 is currently analyzing data taken in 1993 with a solid ammonia target (polarized protons and neutrons) and should have results soon. In the slightly longer-term future, HERMES at HERA will take data using the 23 GeV electron beam and a gas-jet target. Also, SLAC has approved running at 50 GeV. While these expected data will help, they will still suffer from being at relative low Q^2 and moderate x. In addition, they will not directly probe the non-quark contributions.

One possibility to address these issues is to consider using a very high energy muon beam produced in the fixed target area of a high energy proton accelerator. For example, a 2 TeV proton beam would be able to create a muon beam of average energy 1.2 TeV, while a 7 TeV beam could supply muons of average energy 4.3 TeV. Such beams would be able to reach much lower x values, for given cuts on Q^2, than any of the above experiments. With a minimum Q^2 of 4 GeV^2, one could reach x values of 2.5×10^{-3} with a 2 TeV proton beam and 6.3×10^{-4} with a 7 TeV beam. Data taken in these regions would greatly improve our ability to test the Bjorken sum rule.

In addition, these high energies would result in virtual-photon–proton center-of-mass energies (W) of up to 40 GeV (90 GeV). Such high energies permit the observation of multi-jet events. Based on the Fermilab experiment E665, by analyzing in the virtual-photon–proton center-of-mass frame, these multi-jet events are reconstructable for W's greater than about 20 GeV,[3] with the systematic errors associated with such reconstruction greatly diminished at higher W. These multi-jet events are sensitive to the gluon spin contribution,[4,5] and thus direct measurements of ΔG would be possible.

Finally, if the experiment could distinguish π's and K's, measuring the π^+/π^- and K^+/K^- asymmetries might enable the separate extraction of Δu, Δd and Δs.

If such a high energy beam existed, a "classic" polarized deep-inelastic scattering experiment with the ability to detect the produced hadrons would be able to significantly expand our knowledge of the spin of the proton. Data taken at high Q^2 and low x would permit precise tests of the Bjorken sum rule. The importance of this sum rule was described by Ellis and Karliner: "all QCD theorists would have to eat their collective hat if it turned out to be violated." In the same experiment, direct extraction of the individual quark and gluon contributions would be possible. Thus a comprehensive study of the spin of the proton would be achievable within a single experiment.

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5. Diffractive events and Glueballs

5.1. *Inelastic Diffraction at the Tevatron*

Despite the great success of the Standard Model of Quantum Chromo-dynamics, QCD, and of the electroweak theory, there are still many areas of particle physics even at current energies where we have little or no understanding of the physics. Theorists are unable to make calculations because, for example, the strong coupling becomes large and the perturbative calculations do not converge. They have to resort to making approximate calculations using very time-consuming techniques like lattice gauge theory or, alternatively, to phenomenology such as bag models of hadrons or Regge theory for reactions. These methods have their domains of applicability but are very unsatisfactory for many reasons. Regge theory became too complicated when, to obtain good agreement with data, one had to add "cuts" (equivalent to multiple pole exchanges). Furthermore it is difficult, at least for experimentalists, to visualize "trajectories in the plane of complex angular momentum" and such things; quarks and gluons seem much easier to picture. We behave as if we had, in QCD, a good theory of strong interactions; yet approximately 25% of the total $p-\bar{p}$ cross section at the Tevatron is elastic scattering and we cannot calculate it. Another sizeable fraction, about 10%, is diffractive excitation of one or both of the incoming hadrons; this is also not calculable in QCD. These processes are intimately related, with the "Pomeron" exchanged between the hadrons. This somehow carries 4-momentum from one hadron to the other but we do not know what it is, even if we know something of its phenomenology (such as its couplings and its propagator). It has the quantum numbers of the vacuum, and understanding it better might teach us something interesting about the vacuum, as well as about confinement and who knows what else.

We now have, in the Tevatron, a really good opportunity to make experiments to determine the nature of the Pomeron. In good HEP tradition we can make it collide with something we think we do understand and study the results. At the very high energy of the Tevatron it is possible to use hard physics probes. Take single diffractive excitation as the prime test reaction: the antiproton emits a Pomeron, P, which is absorbed by the proton, exciting it into a high mass state. The masses attainable reach of order 300 GeV, to be compared with 100 GeV at the CERN Collider and 10 GeV at the ISR, where it was discovered that one could excite the proton beyond the resonance region. Even higher masses are excited diffractively but the background from non-diffractive processes then becomes relatively large. These limits correspond to about $x(p) > 0.95$. We can now picture this excitation as resulting from a Pp collision at $\sqrt{s} = 300$ GeV and below, where P is (is it?) a quasi-particle which has negative mass**2 (equal to t, the four-momentum transfer squared which, incidentally, we can vary). Now hadron-hadron collisions at this $\sqrt{s}$, five times that of the ISR, show all the hard phenomena we can relate to the quark and gluon structure of the colliding hadrons. There are high p_T jets from the parton scatters, and by measuring jet-pairs in pp one can extract an effective parton structure function of the proton [q(x) + 4/9 g(x)]. By measuring such jet pairs in Pp collisions, and knowing the proton structure, we can extract an effective parton structure for the P. This will not tell us whether it "contains" predominantly quarks or gluons - for that we need other measurements - but it should at least establish whether such a constituent picture has validity for P as it does for hadrons, and if so is it a hard or soft distribution, does it depend on mass (t) and so on. Such an experiment was done at three times lower Rt(s) at the CERN Collider (Experiment R608, P.Schlein inter alia) [R.Bonino et al., Phys. Lett. B211 (1988) 239; A.Brandt et al., Phys. Lett. B297 (1992) 417]. They observed rather clean di-jet events and concluded that the structure function of P is hard, more like x(1-x) rather than soft, like (1-x)**5. They also claim a significant (30%) delta-function-like component, in which the entire momentum of P seems to participate in the hard scattering. However, in order to study "high" masses they allowed the high-x proton to have x as low as 0.9 (M=200 GeV) where the non-diffractive background (in the Regge picture, exchanges of meson trajectories) dominates over P-exchange. In order to probe the Pomeron, x should exceed about 0.95, a region which is excluded from their study by the requirement of two jets with $E_T > 8$ GeV. In any case, if it is true that there is a delta-function-like component it is a very important discovery; taken literally it implies a colorless, pointlike, strong or semi-strong exchange which is not single gluon exchange. This would have repercussions also in other processes such as double diffraction dissociation where both incoming hadrons get excited. The exchange of this "hard P" could give events where we have two high-pT jets separated by a large rapidity gap, where there are no hadrons, as can happen with a colorless exchange. This process is being searched for now in CDF and D0. CDF is finding evidence for this at the level less than 1% of jet pairs events.

Returning to the SDE process, we can unravel the nature of the constituents and tell whether they are quarks or gluons by making other measurements. A classic study would be to measure Drell-Yan lepton pair production, say with pair masses between the J/psi and the Upsilon (also below and above if possible). This process measures the $q - \bar{q}$ product distribution. The simple observation of Drell-Yan pairs in high mass diffraction is proof of the existence of $q - \bar{q}$ inside P (they must be there at some level even if only as a gluon-created sea). Measuring the mass and rapidity distributions tells us, by inputting the proton structure function, their distribution. It is very interesting to see whether W and Z are produced diffractively with sufficient cross-section to be detectable. Another important measurement, which can be well done in CDF given the vertex detectors, is the production of heavy flavors, charm and beauty. In p-pbar, these occur mostly through gg fusion reactions, and in Pp the rates will tell us about the gluon structure function of P. In particular, if P is predominantly gluonic, and especially if there is a hard gluon component, these high mass diffractive events could be relatively rich in heavy flavors. The simultaneous study, in high mass SDE, of jets, lepton pairs and heavy flavors will show whether a consistent picture emerges of P as an object with q/g constituents similar to a real hadron. We would measure different t-values and different $\sqrt{s}$ at the same time, and could thus check scaling properties and so on. There is an extensive program of work, provided we can get enough data to do a thorough study. It may of course turn out that this attempt to understand P as if it were a real hadron with G(x,Q^2) and Q(x,Q^2) functions fails; that it is not self-consistent. This could be even more interesting.

In order to carry out the measurements on SDE physics one needs to detect the quasi-elastically scattered (anti)proton. Quasi-elastic means $x > 0.95$ (approximately) and small p_T (less than about 2 GeV/c). This can be done by inserting precision track detectors in Roman Pots that can be moved close to the circulating beam, some 50m downstream of B0 and after the $\bar{p}$r have traversed quadrupoles and dipoles. The track measurement there, together with the vertex of the interaction, gives the momentum. That can be used to trigger on diffractive events, where the other proton was excited to a mass M, through the relation $M^2/s = (1 - x)$ where x = p(out)/p(in) for the antiproton. Note that unlike the previous diffractive studies in CDF [PRD,submitted] we are only interested in high mass diffraction and do not need precision measurements of the momentum transfer t. This should make life easier than in the earlier experiment; we can be farther from the beams and halo should be less of a problem. The events in CDF should be full of activity but fairly well confined to the hemisphere opposite the antiproton, quite unlike "minimum bias" background. There should be a correspondence between the total mass detected in CDF (calculating "mass" from the calorimeter "energy vectors") and the missing mass to the antiproton (calculated from $x(\bar{p})$. It should be possible to get a clean sample of SDE events, although to determine exactly what fraction of the events correspond to P-exchange (at a given M,t) rather than some other exchange (e.g. the rho trajectory) might require some running at a different $\sqrt{s}$. As the mass M increases there is more contamination from exchanges other than P. However for masses of 300 GeV the data should be predominantly P-exchange, i.e. diffractive.

5.2. *Double Diffractive Excitation & Jet-Gap-Jet*

We alluded above to DDE or double diffraction with a hard P exchange. In the standard Regge phenomenology this process exists with a t-slope that is less than that of SDE, into two excited states of uncorrelated masses M_1 and M_2. The events look like a balancing di-jet at some angle to the beams but with small p_T, a few GeV at most. This reaction has not actually been studied much at all, and it has been ignored at collider energies. What if there is a hard component to P, as suggested by the R608 data? Then it is quite likely that this colorless pointlike exchange would kick partons out of each incident hadron giving forward/backward high p_T jets, plus the beam jet fragments, but without any hadronization between these high pT jets [of course there may be some, from some other soft gluon exchange, but the important point is that relatively often (1events in CDF would show a high p_T (say greater than 20 GeV) jet in each plug, say $\eta > 2.0$, balancing each other, and the central (say 3) units of rapidity would be empty : no charged tracks and no calorimeter energy. That looks as if a P has carried a 4-momentum transfer exceeding -400 GeV^2, impossible in the old phenomenology. In minimum bias events the probability of having no particles at all in the central three units of rapidity is very small. A search for an excess of JET-GAP-JET events has been made both in D0 and in CDF. D0 look in the rapidity interval $\Delta\eta$ between two high pT jet cones. They plot the probability of finding no calorimeter clusters, f(0), in this interval as $\Delta\eta$ is increased. The probability drops steeply from 1.0 as one would expect, but the slope decreases and it becomes rather flat for large $\Delta\eta$ (greater than 2.5 or so). This is suggestive, but the statistics and the rapidity range are limiting, one has to worry about noise and inefficiencies, and we do not really know what the shape should be for "normal" non-diffractive events. So D0 claim only an upper limit (around 1%) on a new class of "gap" events. CDF are also doing a study with a different method : use just the sample with jets far apart in rapidity and look in the interval between the cones at the charged particle multiplicity distribution. This study shows an excess of events with no charged tracks between two plug jets, corresponding to 0.7% percent of the di-jet sample. Unfortunately the statistics are small, corresponding to less than a thousand events. This can easily be rectified by triggering on two forward jets with more modest pT (The first study, by Tom Devlin, used a "1-jet greater than 60 GeV at any η" trigger). This trigger has now been added. It is unfortunate that this study relies so heavily on the plug calorimeters with their poor characteristics compared to the central calorimeter. However, that will change with the Plug Upgrade, for which this is ideal physics. As well as increasing the statistics compared with the present study by perhaps two orders of magnitude (100,000 events?), we consider it important to measure the ratio of gap:normal events as a function of pT, starting in the range 20 - 100 GeV. This would surely provide important clues as to the mechanism of any new process and could indicate whether it is important to push it to lower or higher pT values.

5.3. Double Pomeron Exchange

There is another diffractive reaction which might turn out to be extremely interesting, especially if does indeed have a delta-function-like component, in which both beam hadrons pass through emitting P's which interact in the central region. This is Double Pomeron Exchange (DPE), which is like a diffractive excitation of the vacuum, Central Vacuum Excitation (CVE). The produced hadrons are mainly central and so CDF is well suited to study them. Are their characteristics (jets, Drell-Yan, heavy flavor) consistent with the structure of P deduced from SDE? Do we see a component with both P's apparently behaving as a single hard object, e.g. with PP —¿ b-$\bar{b}$ and nothing else? The mass limit (for $x_{min} = 0.95$) is 100 GeV for the central system at the Tevatron. Of course higher masses are produced but with increased background. So observation of b.$\bar{b}$ production by CVE here would imply that at LHC energies, PP —¿ t.$bart$ + nothing might occur. To study CVE one ideally would like to insert Roman Pot Spectrometers on both downstream arms and to measure both "quasi-elastic" ($x > 0.95$) protons. This might be possible in Run II.

5.4. Glueballs

There is a completely different reason for studying Double Pomeron Exchange, to do with hadron spectroscopy. We still do not have a satisfactory understanding of the spectrum of light mesons, and whether it is possible to have mesons with no valence quarks, ie gluonia or glueballs. If these do not exist in Nature we should understand why not, and if they do then what are their masses and widths, and how do they mix with q-qbar mesons? One might think that probably the Pomeron is mostly glue, so DPE is colliding gluon beams, and what better way to produce glueballs? This may be true, but there is another very important advantage of this reaction: it is a QUANTUM NUMBER FILTER. One of the major difficulties with meson spectroscopy is establishing the quantum numbers of states, and having so many different states produced in superposition that it is a mess. Electron positron annihilation produces only $J^{pc} = 1^{--}$ which is nice and clean. DPE produces only $I^gJ^{pc} = 0^+, 0^{++}, 2^{++}$, even++ states, because we have two identical bosons in the initial state. This is very powerful; for example at the ISR ($\sqrt{s} = 63$ GeV, about the minimum for this process to be clean) the DPE produced π^+pi^- spectrum showed no $\rho(770)$ ... a good test of the QN filter... and a very strong S*(980) = f(975), the lightest known 0^+0^{++} meson. One could easily exclude a "lightest scalar glueball" below 950 MeV unless it was unreasonably narrow. There was a theoretical proposal that the complicated KK threshold region with the f(975) might contain also a glueball, but this seems now unlikely. It may seem odd to use the Tevatron to study hadron spectroscopy in the less than 3 GeV region! But the fact is that this the only place in the world to have this clean QN Filter. The ISR experiment [Nucl.Phys.B264 (1986) p154] showed structures in the $\pi\pi$ spectrum around 1.5 GeV and above, that are not understood. It measured also K^+K^- and p-$\bar{p}$, but what one would really like to do, at the much higher $\sqrt{s}$ of the Tevatron, is to measure channels like DPE -¿ $\phi-\phi, \eta-\eta, K^*-K^*$ as well as more mundane things like 4π. The experiment consists of two downstream "Roman Pot" spectrometers to trigger on and measure the two beam particles with x above about 0.998, and a central detector (say $\theta > 5$ deg) with momentum measurement (but only for low p_T tracks), particle ID, em calorimetry ... perhaps no hadron calorimetry, or just something modest to see if a KL was present. Neither CDF or D0 are well suited to this, although they could relatively easily have a quick look. A proper investigation probably requires of order 10^6 (small) events, and CDF and D0 would surely object to a major disruption to their high p_T/top program. A dedicated experiment would be the best approach, perhaps after some modest studies in CDF or D0.

5.5. Closing Remarks

To summarize, there is a whole field of strong interaction physics waiting to be explored at the Tevatron. The goal is to understand diffraction or the Pomeron (the "vacuum trajectory") in relation to QCD. This will extend the range of validity of QCD or modify it. Glueballs are part of this program ... are they on the Pomeron trajectory? Perhaps there are qualitatively new phenomena to be discovered (think of superconductivity, superfluidity, phase transitions etc at the parton level). What exactly is the relation between the Pomeron and the vacuum? How can we expect to understand the relation between the Higgs and the vacuum if we can't answer THAT question after many decades?

6. Heavy Quarks

6.1. Open Questions in QCD and Heavy Quarks

Heavy quarks (charm and beauty) are of interest in QCD both as a subject in their own right and as tools in the study of other systems. Perturbative QCD enters in the context of production dynamics; non-perturbative effects occur in both hadronization of the produced charm quarks and in the decay of charm particles. In all of these processes, our understanding of QCD is tested and fundamental parameters are measured. However, heavy quarks are also a useful tagging mechanism for such things as gluon and strange sea parton distributions.

A surprising number of outstanding issues remain to be adequately addressed with current data. Among the outstanding issues are

Those which are of interest for heavy flavor physics directly:

- Disparities between data and NLO production predictions of b's at collider energies - total cross section and differential shapes
- Hardness of charm particles hadroproduced at fixed target energies and the source of particle/anti-particle production asymmetries
- Size of and source of smearing in azimuthal angle of charm and beauty particles produced at fixed target energies
- Precision measurements of decay form factors as a test of Heavy Quark Effective Theory predictions and/or lattice calculations

- Magnetic moments and polarization of hyperons which would benefit from similar measurements, where possible, of heavier flavor baryons

And one in which the heavy flavor is only a tag of a particular QCD diagram:

Measurements of gluon distributions in nucleons and long lived mesons

Some of these questions would benefit from more data at facilities which are currently operational. However, all of them would benefit from experiments which have higher energy available. Such higher energies can be used to increase the flux of secondary particles in fixed target experiments or increase the laboratory lifetimes of short lived particles. The higher energies can extend the range of physical parameters and test theory by extrapolating them beyond the point where the parameters have been fit. Let us take the above list and examine how knowledge might be extended in the future.

6.2. Disparities between data and NLO production predictions of b's at collider energies

The disparity between NLO QCD calculations and data increases in going from UA1 (530 GeV) to CDF (1800 GeV). Current theoretical ideas focus on terms which have been ignored in earlier calculations, namely, summing terms of the form ln**n(m**2/s). Even for the b quark, the value of m**2/s is small at 1800 GeV. The summation can be tested by increasing s by factors of (1800/530)**2 or more. The disparity with NLO QCD should increase by an amount predicted by more recent summations. (Levin could provide numbers for 2x2 Tev, 4x4 Tev and 8x8 Tev.)

In the pt distributions of the B mesons produced at the Tevatron, there is a consistent rise at lower transverse momenta which is faster than predicted by NLO calculations. The origin of this discrepancy is unknown at this point and additional information at higher energy would be useful. If the cause is gluon emission, this discrepancy should increase at higher energy.

6.3. Hardness of charm particles hadroproduced at fixed target energies and Source of particle/anti-particle production asymmetries

The Feynman x distribution of charm particles in fixed target experiments has been shown to look like the NLO QCD predictions for charm quarks. The data does not yet allow us to say whether the distribution is independent of energy, much less compel us toward any particular model. Leading particle asymmetries may give a clue here. It is interesting that current evidence on D+- asymmetries is invariant in Feynman x (250 GeV vs 500 GeV incident pions). Many believe that similar information on b quarks/mesons would be a direct test of ideas on the source of this surprising observation for charm. Here, fixed target energies currently available do not allow sufficient b production to make a test. Only the advent of higher fixed target energies and a concerted experimental effort can change this. (A plot of the b and c cross section vs energy can be used to see at what energy the b cross section equals the charm cross section at, say, 300 GeV where relevant charm measurements first have been made. Such an energy is, of course, just a minimum since the B branching fractions are an order of magnitude smaller than for charm and efficiencies for complete resonstruction are lower. However, one can be more clever, perhaps, and use semi-inclusive B decays to charm to make up for this additional prob- lem.)

6.4. *Size of and source of smearing in azimuthal angle of charm and beauty particles produced at fixed target energies*

Here again, the origin of the deviation from back to back peaking of charm and beauty particles is unknown. NLO QCD predicts some smearing due to gluon emission, but not enough to explain the data. Only a very few beauty pairs have been ovserved so far. Clearly, higher energy beams are required to bring these measurements for beauty to a precise state. In the case of charm, higher rate experiments will allow the effect to be observed at higher pt values where the perturbative nature of the interaction is more definitive.

6.5. *Precision measurements of decay form factors as a test of Heavy Quark Effective Theory predictions*

The heavy quark symmetry of QCD is only now being exploited to enhance our understanding. An effective theory, called the Heavy Quark Effective Theory (HQET), is used to make predictions. One of the more precise current predict- ion areas due to HQET is that of the form factors of decaying heavy mesons and baryons. At one kinematic limit point in decays, the symmetry predicts the form factor value exactly. Deviations from this point are calculated as corrections. As so often the case, reaching the well understood limiting point is a question of statistical limitations. Both the limiting point value and the slope on approaching it contain information and a test of the HQET ideas.

6.6. *Magnetic moments and polarization of hyperons which would benefit from similar measurements, where possible, of heavier flavor baryons*

6.7. *Measurements of gluon distributions in nucleons and long lived mesons*

One of the more basic questions is the makeup of elementary particles. While the valence quark structure is well established and quark distribution functions are measured over a broad range of parameter space for nucleons, there is little quantitative for gluon distributions even for the nucleon. How much less is known for mesons! Heavy quark production provides a (somewhat underutilized) mechanism for studying the gluon distributions for both nucleons and the more common charged mesons. In this case, the heavy flavor particles are used as a tag of the dominant gluon-gluon fusion production subprocess, rather than as a subject unto themselves.

The interpretation of the data is clouded by hadronization processes. Nevertheless, many comparitive measurements are possible among nucleon and meson incident beam data. To what extent is the gluon distribution harder for a quark-antiquark meson than for a three quark nucleon? Is the gluon distribution equally hard for pions and kaons, or does the heavier strange quark change the situation for the kaon.

Resolving hadronization effects would benefit greatly if one could have fixed target b production data comparable to what exists today for charm quarks. This requires beams of higher energy protons and charged mesons. It also requires a next generation fixed target experiment using next generation detector capabilities (e.g., possibly sparcifying pixel silicon detectors, fiber or straw tube tracking). Furthermore, the x range of such studies would be extended by the joint use of c and b data.

7. Photon Physics

7.1. Introduction

The photon is one of the most ubiquitous of all the particles we come across. It has been studied in one way or the other for centuries, and the theory of photons has been formulated many times in the history of physics. However there are still aspects of physics in which the interactions of photons are not completely understood.

In the modern theory the photon is in fact a prediction of gauge field theories. In this sense it belongs in a special class of particles, the gauge bosons, that are almost completely described by the theory. The electro-weak symmetry breaking that is invoked to explain the masses of the W and Z bosons is still somewhat arbitrary. The gluons of QCD are almost on the same footing as photons, however their confinement is not completely understood. This makes the photon a very special particle, one that offers a unique facility to explore the fundamentals of modern physics ideas.

The interaction of photons with matter at low energies can be described very well by its point-like interaction according to the rules of QED. However at relativistic energies the photon can no longer behave like a purely point-like object, unless one ensures that its lifetime is very short by making it highly virtual. This is because a real or quasi-real photon at high energies can mix with the states that it couples to. In the relativistic field theory, particle number is not conserved so that particle-antiparticle states can be produced from the vacuum. In the limit of high energies such states become degenerate with the photon. Then there can be a large mixing between the bare point-like photon and these states. Since the interaction of high energy photons can be mediated through these intermediate states, we are faced with photons that are not always point-like but have structure.

7.2. Photon Structure Function

The electromagnetic structure functions of hadrons have been defined in terms of the photon-hadron cross-section. Similarly, the structure function of the photon may be defined in terms of the photon-photon cross-section. Since there is no direct coupling between photons, this process directly probes the hadronic components of the photon*.

The advantage of photons is that they can be produced by radiation from leptons, and the photon-lepton coupling is understood very well. Hence one knows exactly what one is starting with. The measurement of the photon structure function offers a unique opportunity to observe the evolution of a point-like object into a many-body state. This is perhaps the first instance of a structure function calculable from first principles such as QCD, and so could lead to a better understanding of strong interactions. The deep inelastic structure function of the photon in an asymptotically free gauge theory has been calculated by Witten (Nuclear Physics B120, 1977).

7.3. Input to Nucleon Structure Function

The second reason to measure photon structure functions is that the nature of the photon is intimately connected with the electromagnetic structure function of the nucleon. In the Bjorken limit, the photon acts like a point-like probe of the nucleon, so that the measured cross-sections can be uniquely parametrized as nucleon properties. This is sometimes referred to as 'direct' component of the photon-nucleon cross-section (Schuler and Sjostrand, NP B407, 1993). Two other components have also been defined. The photon can split into a highly virtual quark-antiquark pair, which can then interact with the nucleon. This is called the 'anomalous' component, and can be calculated using the proton parton distributions parametrized from the 'direct' cross-section as inputs.

The third component, where the photon mixes into a low virtuality hadronic state which then interacts with the nucleon, is called the 'VMD' component. This follows from the idea that the spectrum of the low mass states will be dominated by the vector mesons ρ, ω and ϕ.

The association of the low mass $q\bar{q}$ state with the photon is not completely unambiguous. This cross-section could also be interpreted as the effect of 'higher-twists' in the proton, which arise theoretically due to multi-parton correlation functions in the proton. The study of multi-parton correlations is interesting and the combined knowledge of photon-photon and photon-nucleon cross-sections could shed some light on this subject.

The connection between photon-photon and photon-nucleon cross-sections can be extended to include hadron-hadron interactions as well. For instance, multi-parton correlations are also measured in hadron-hadron production such as double-Drell-

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*The hadronic intermediate states will interact more strongly than the leptonic ones and hence dominate the cross-section.

Yan production of opposite sign di-leptons. Another example is Pomeron factorization applied to the assumption that photon interactions are mediated through its hadronic components. If hadron-hadron scattering occurs via pomeron exchange, then the Pomeron factorization gives the following relation:

$$\sigma^2_{\gamma p} = \sigma_{\gamma\gamma}.\sigma_{pp} \tag{10}$$

Such connections help in elucidating the nature of the particles and their interactions.

7.4. Experimental Issues

There are two ways to explore the photon structure function. One way is to create a photon-photon collider. Such a collider is a natural by-product of an e^+e^- collider, where the two beams each radiate a photon (Sau Lan Wu, Physics Reports 107, numbers 2-5, may 1984). Although this cross-section is suppressed by α^2 compared to the e^+e^- annihilation, there are some enhancements. Firstly, the annihilation cross-section is inversely proportional to c.m.s energy while the 2-photon cross-section is weakly dependent on energy. At high c.m.s energies like LEPII this is a large enhancement. Secondly, if the photons are close to on-shell the propagators become large and lead to an increase in the cross-section. Two-photon physics has been pursued at PETRA upto c.m.s. energies of 10 GeV, and LEPII offers an order of magnitude increase in energy.

The experimental needs are the ability to tag and reconstruct the electrons and positrons at small angles. The ability to trigger inclusively on the scattered electrons and positrons alone is a great advantage in any experiment to measure cross-sections. The small-angle luminosity monitors in the existing LEP experiments may offer some opportunities in this regard.

The second method is to look at the final state characteristics in high energy photon-hadron interactions. This is being pursued at HERA using the small angle electron taggers to tag quasi-real photon emission. However the acceptance for the final state is limited due to the beam-pipe in the collider geometry. In this regard a high energy fixed-target experiment at Fermilab, with a photon beam has a clear advantage. An open-geometry spectrometer can be designed to have full acceptance for forward hadrons. The important issue is how to deconvolute photon properties and nucleon properties from the measured cross-section. As indicated earlier this is probably not a meaningful separation for the total cross-section. However for some semi-inclusive cross-section like the jet cross-section this may be possible. We expect the 'anomalous' component to produce two high p_t jets with no beam jet. The 'direct' component will produce hadron spectra similar to those observed in high Q^2 deep-inelastic scattering. The 'VMD' component will probably produce hadron spectra similar to those observed in hadron-hadron collisions. One would expect these spectra to be softer than those in the 'direct' interactions, since we have a collision between two 'mushy' objects rather than a collision between a point-like photon and a 'mushy' object. Another interesting possibility is the production of two high p_t jets, in addition to a beam jet and a target jet. This would indicate a hard scatter between partons in the proton and the photon. This part of the cross-section is probably factorizable into parton distributions in the proton and photon, and parton-parton cross-section. For this it is necessary to have enough c.m.s energy to produce two high p_t jets, since the parton in the photon will carry only some fraction of the photon momentum. In addition the large lorentz boost causes all particles to be produced at small angles, so the experimental resolution needs to be high to resolve the jets.

7.5. Conclusion

Studying photons using photon-photon collisions in an e^+e^- machine and studying photon-hadron interactions in a high energy photon-proton fixed target experiment at Fermilab are complementary ways of exploring the photon coupling to hadronic states. In this fashion the photon provides a very nice window to observe the evolution of hadronic states.

8. Small x Physics

8.1. Introduction

The study of the partonic structure of matter provides tests of the perturbative regime of QCD and insight into the non calculable perturbatively structure of hadrons. For a better understanding of these issues, the study should extent to arbitrary x and Q^2, where x is the ratio $x = \frac{Q^2}{S}$ between the typical transferred momentum Q in the process examined and $\sqrt{S}$ is the centre of mass energy. Here we will try to address the issues that are specific to the small x domain (x much smaller than unity) of the 1/x and Q^2 plane.

Based on the magnitude of Q compared to the QCD scale Λ small x physics can be furthermore divided to perturbative and non perturbative regions.

Perturbative If Q is much larger than Λ then the strong coupling $\alpha_s(Q^2)$ is small and cross-sections and hadron distributions can be computed in perturbation theory. However the expansion is slowly (or badly) convergent, due to the large logarithmic corrections of the type $\alpha_s(Q^2)^n \ln^m x$ (m < n). These corrections have to be estimated at higher orders and resumed to all orders in $\alpha_s(Q^2)$. At present the QCD multiparton matrix elements have been computed to double logarithmic accuracy in the small x region. They predict new distinctive features such as the increase of particle multiplicity and the suppression of large rapidity gaps (ref [1]).

Parton densities at small x are dominated by the gluon channel. The leading high energy corrections are single logarithmic terms $(\alpha_s(Q^2)^n \ln x)^n$, which have been resumed to all orders in α_s (using the resulting non-linear evolution equations, ref[2]) with a predicted gluon distribution that behaves as

$$xf_g \sim x^{-\lambda}$$

with λ about 0.5, thus leading to a steep behaviour of the structure functions at small x and large Q.

Non Perturbative Regge theory provides a successful explanation of the low Q data. It is likely that the behaviour of the structure functions in the photoproduction limit (x,$Q^2 \rightarrow 0$, but $Q^2/x = const.$) holds also for small but fixed Q^2. Therefore it is given by the Reggeon and Pomeron powers that govern $\sigma_{\gamma p} \sim S^{\alpha(0)-1}$, in the high energy limit. The exponent $\alpha(0) = 1 + \epsilon$ is related to the soft Pomeron and it is phenomenologicaly determined (see for example ref [3]) to be ≈ 0.08. Since for fixed Q^2 $S \sim 1/x$ this results to a structure function that has a much softer x dependence. Eventually the structure function F_2 has to vanish at the $Q^2 \rightarrow 0$ limit due to conservation of the electromagnetic current (neglecting the small axial-current contribution).

8.2. Open Questions - Experiments

Inclusive measurements This involves scattering of charged and neutral leptons from nucleon and nuclear targets. Neutrino experiments with high luminocities (untagged neutrino beams) cannot reach the small x region due to resolution problems, so here we will concentrate on the charged lepton beams. FNAL with a primary proton beam of 2 TeV and upgraded (longer) beam line can provide muon beams up to $\sim 1TeV$ to fix target experiments that will extend the measurement of the structure functions to small x in a wide Q^2 range.

1. R(x,Q^2) ($Q^2 \equiv$ minus the 4-momentum transfer from the lepton to the target nucleon). R is currently measured over the kinematic range $0.6 < Q^2 < 20.0(GeV/c)^2$ and $0.1 \leq x \leq 0.9$ (SLAC global analysis [10] (electron beam)). HERA has the ability to change the beam energies for the electron and the proton and will probably provide an R measurement down to x $\sim 10^{-3}$ for large Q^2. FNAL can provide a wide spectrum of muons by momentum selecting the particles in the secondary beam line. R can be measured at small x in both perturbative and non perturbative Q^2 regions. QCD predicts that R increases as x decreases, on the other hand R is constrained to vanish as $Q^2 \rightarrow 0$ and it will be interesting to measure also the transition to that limit.
2. $F_2(x, Q^2)$. In the perturbative region fixed target experiments ([6]) have been limited to x $> 8 \times 10^{-3}$, while HERA experiments ([5] and [4]) extend the measurements down to x $\sim 10^{-4}$ at $Q^2 > 10(GeV/c)^2$, starting to test the new ideas in the evolution of the parton density distributions. Future fixed target experiments at FNAL can provide measurements in the perturbative region ($Q^2 > 2(GeV/c)^2$) down to x $\sim 10^{-3}$. Experiment 665 at FNAL has proven that acceptance at small scattering angles $\theta \sim 0.5 mrads$ can be achieved, so the measurement can be extended to the non perturbative region x $\sim 5 \times 10^{-4}$ and $Q^2 \sim 1(GeV/c)^2$. Using the runs with reduced

beam energy for the R measurement and assuming the above θ acceptance the Q^2 range can be furthermore extended towards the lower end.

3. Structure Function Ratios, F_2^D/F_2^H. Accurate measurement of this ratio put strong constrains on parton distributions. NMC (7) determined the ratio down to x=0.003 and $Q^2 \sim 0.6(GeV/c)^2$ with high statistics. FNAL E665 (8 and recent results presented at Moriond 1994) extend the measurement to $x \sim 10^{-5}$ and $Q^2 \sim 0.01(GeV/c)^2$. An upgraded Tevatron will allow measurement down to $x \sim 5 \times 10^{-4}$ and $Q^2 \sim 1(GeV/c)^2$ allowing a check of the Gottfried sum rule.

The A dependence of small x structure functions is very interesting. In the perturbative region screening corrections can be viewed as overlapping parton interactions. How does that connect with the Generalized Vector Meson Dominance behaviour (virtual photon fluctuates to a long lived qqbar pair, that behaves like a hadron) at the low end of the Q^2 scale. FNAL will have the unique capability of providing high energy, small x and wide Q^2 range measurements on that subject.

Exclusive processes The collider can provide a direct determination of the gluon distribution at small x, using the two-jet hadroproduction and comparing jet rates with equal rapidities to those with equal in magnitude and opposite sign (9).

The study of the heavy flavor production in the final state at high c.m energy is also very important. The collider experiments at FNAL can do much better than HERA (luminocity, higher c.m energy).

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9. Non-perturbative QCD

The main goal of this paper is to outline the most important experiments that could give some impetus to new understanding of our unique microscopic theory - QCD. We cannot fulfill our goal without clear understanding of the current status of QCD: what QCD predictions has been confirmed experimentally and what QCD pproperty is still open for discussions.

9.1. Basics of QCD (Where we stand).

We firmly believe that at the present moment the basic property of QCD has been established and confirmed experimentally. Here we list these basics of QCD:

1. Running of α_s or the fact that the coupling constant of QCD ($\alpha_s(r^2)$) becomes small at short distances $(r)^1$(the exact opposite behaviour occurs in QED):

$$\alpha_s(r^2) \;=\; \frac{4\pi}{b\ln\frac{1}{r^2\Lambda^2}} \;=\; \frac{\alpha_s(\mu^2)}{1\;+\;\alpha_s(\mu^2)\frac{b}{4\pi}\ln 1/r^2\Lambda^2} \tag{11}$$

where $b = 11-\frac{2}{3}n_f$, n_f is the number of quarks (the number of colors we take $N_c = 3$), Λ is the confinement scale and μ is the renormalization scale.

The running α_s has been checked experimentally,see for example the DPF talk of K.Ellis.[2]

2. All vertices in QCD Lagrangian has been confirmed by LEP and Tevatron data (see for example[34]). We think that this result is one of the most important because it establishes the belief that our basic principles that we used to construct the QCD Lagrangian are right.

3. Main property of gluon bremsstrahlung (jet structure of the final state for hard processes, correlations in one jet and so on) has been investigated theoretically[5] and checked experimentally mostly at LEP.

4. Factorization theorem for hard processes in hadron collision formulated in ref.[6] and confirmed by CDF at the Tevatron[3]in the kinematic region where the cross section for high transverse momentum jet production falls down in ten orders.

We would like to stress that all experiments have been done in the kinematic region where

A. the scale of hardness was obvious,namely, the largest transverse momentum in the process.

B. the parton (quark and /or gluon) density was small.

Therefore we can summarize the result of theoretical activity and experimental efforts till now as a prove that QCD is correct theory for so called "hard" processes or in other word for the pQCD region in Fig.1.

9.2. The map of QCD.

As we have mentioned the goal of this paper is to discuss what fundamental questions in QCD could be answered in future experiments. However before such a

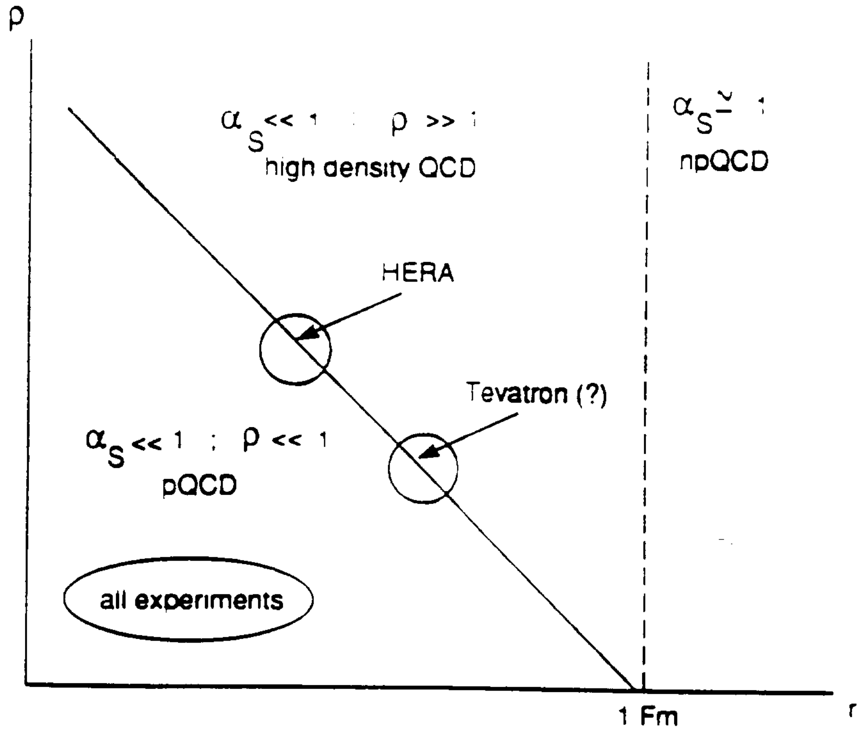

Figure 1: The map of QCD. ρ is the density of partons (gluons) in transverse plane and r is the distances resolved in an experiment.

discussion we present the map of QCD in Fig.1. Shown are three separate regions, distinguished by the size of the distances that can be resolved in the process and by the value of parton densities that can be reached in the process.

1. *The region of small parton density at small distances (low density (pQCD) region).*

This is the region where we can apply the powerful methods of perturbative QCD since the value of running coupling constant $\alpha_s(1/r^2)$ is small ($\alpha_s(1/r^2) \ll 1$). As been discussed during two decades remarkable theoretical progress has been achieved here (GLAP evolution equation, gluon bremshtrahlung for jet decay , factorization theorem (J.Collins,D.Soper and G.Sterman (1983)) and the main property of "hard" processes has been experimentally confirmed at LEP and at the Tevatron.

2. *The region of large distances (npQCD region).*

Here we have to deal with the confinement problems of QCD, since $\alpha_s(1/r^2) \gg 1$. In this kinematical region we need to use nonperturbative methods.

3 *The region of small distances but high parton density (hdQCD region).*

Here we have a unique situation in which the coupling constant α_s is still small but the density is so large that we cannot use the usual methods of perturbation theory.

In essence the theoretical problem here is also a nonperturbative one but the origin of the nonperturbative effects here is quite different from that in the previous region. Here we face the situation where we have to develop new methods that let deal with a dense relativistic system of gluons in a nonequilibrium state. Unfortunately we are only at the beginning of this road.

Fortunately, we can control theoretically this dense system of partons in some transition region on the border of the pQCD and hdQCD regions and here we can study this remarkable system of partons in great detail. Thus the right strategy is to approach this interesting kinematic region from the low density pQCD region.

9.3. "Hard" processes.

We would like to outline what kind of experiment are needed to push forward our understanding in each these there kinematic regions. Let start with the pQCD region in which at first sight all problems have been solved during two decades of the development of QCD.

We think that the aim of future experiments in this region should be:

1. Extraction of the parton densities from experiment(CTEQ programm). It should be stressed that the big variety of different "hard" processes shall be studied including the "hard" processes with different beam particles like pion,kaon and so on.

2. Experiments in the kinematic regions where a new scale of hardness can appear ($x \rightarrow 1$, $x \rightarrow 0$, semi-inclusive processes and ...).

Comments: The above two goals have different physical grounds:

A.the first is the way to provide a community service or in other words to provide the reliable estimates for rare processes as top - quark production, Higgs search and so on;

B. while the second one is the way to penetrate into the region of nonperturbative QCD but in the situation when the nonperturbative corrections are small. I think this is the only correct strategy to check our theoretical approach in nonperturbative region.

9.4. What fundamental questions could be answered ?

Discussing the processes in the hd QCD kinematic region we need first to ask ourselve why we need to study this region. Indeed, the fact that QCD is the selfconsistent theory of strong interaction has been proven in the pQCD region and in the best tradition of the whole previous stage of the development of high energy physics we must leave the field claiming that all fundamental problems have been solved. Such opinion as well as behaviour is mostly a survival of the whole history of high energy physics when people tried to find a theory. We have not prepared mentally to find the theory and to have a quite different goal: to solve the theory.

This is why we want to list here the fundamental problems that we hope to solve penetrating high density QCD region. We hope:

1. to specify the kinematical region in which we can trust pQCD (GLAP evolution equation, gluon bremstrahlung, factorization theorem ...);
2. to find new collective phenomena for nonabelian theories such as QCD ;
3. to find the analytic solution of hd QCD which is nonperturbative but looks simpler than np QCD since $\alpha_s \ll 1$ here;
4. to develop methods with which build an effective theory for hd QCD.

9.5. High density QCD.

9.6. Present theoretical status = Regeneration of Reggeon Calculus.

The QCD Pomeron is not an invention but naturally appears in perturbative QCD in the leading $log(1/x)$ approximation (LL (x)A) to the scattering amplitude at high energy (the Balitski - Fadin -Kuraev - Lipatov (BFKL) equation[7]). It means that in a restricted kinematical region the BFKL Pomeron describes the high energy interaction within a certain guaranteed theoretical accuracy. This fact makes it unavoidable that one should build an effective theory starting with the BFKL Pomeron.

This past year a significant advance has been made in understanding the structure of the BFKL Pomeron. A.Mueller (1993) and N.Nikolaev with collaborators (but six months later)[8] constructed the partonic infinite momentum wave function of a hadron at low x and opened a new way in understanding of physical meaning and formal derivation of the BFKL equation as well as its generalization .

However the BFKL Pomeron violates the unitarity constraints even at small distances. It means that the problem of Pomeron - Pomeron interaction should be solved. The first attempt to solve this problem was made by Gribov, Levin and Ryskin (1981) (the GLR equation).[9] By now we have reached a better understanding of the main properties of the shadowing corrections, their relations with high twist contributions to deeply inelastic processes. The anomalous dimensions of high twist gluonic operators have been calculated (E.Laenen, E.Levin and A.Shuvaev (1993)[13]) and the generalization of the GLR equation has been suggested.

9.7. New phenomena at high density QCD region.

- Mainly nonperturbative problem but we can approach it from small densities and try to study matching with routine perturbative QCD approach (low density QCD).
- Two new ideas that came from perturbative QCD in the region of high density :

1. The new scale of hardness

$$\left\langle ln(p_t^2/Q_0^2)\right\rangle = \sqrt{\frac{14N_c\alpha_s}{\pi}\zeta(3)\ln(1/x_B)}$$

The question arises what is larger : the measured momentum of jet q_t or $\left\langle \ln(p_t^2/Q_0^2)\right\rangle$???

2. The shadowing correction (SC) induced by the parton - parton annihilation processses enter to the game.

Saturation of gluon density as a result of the annihilation is the working hypothesis ???

9.8. How to penetrate in high density QCD region.

Access to this interesting kinematical region is actually easily achieved in our scattering processes. We know at least three ways to prepare a large density system of partons.

1. The first is given by nature, which supplies us with large and heavy nucleii. In ion-ion collisions we can already reach a very high density of partons at not so high energies, because the partons from different nucleons in a nucleus are freed.

2. The second relates to hard processes in hadron-hadron collisions or in deep inelastic scattering. These also give us access to a high density of partons because we expect a substantial increase in the parton density in the region of small Bjorken x. The experimental data from HERA show the significant increase of the deep inelastic structure function:

$$F_2(Q^2, x_B) \propto \left(\frac{1}{x_B}\right)^{0.33} \; at \; Q^2 \sim 10\, GeV^2 .$$

3. The third is to measure the event with sufficiently large multiplicity of produced particles, larger than the multiplicity in the typical inelastic (bias) event.

Of course one can use hard processes with large multiplicity in ion-ion collisions to utilize three effects: increase of gluon density combined with a large number of nucleons in a target.

9.9. What density is large.

From GLR evolution equation which takes into account the screening (shadowing) correction one can estimate the maximum value of so called packing factor:

$$PF \; = \; \left\langle r^2_{constituent} \right\rangle \cdot \rho \; .$$

It turns out that for parton with $\langle r^2_{constituent} \rangle \; = \; \frac{1}{Q^2}$

$$(PF)_{max} = 0.21 \; for \; N_c = 3 \; .$$

However we need to know the value of radius R in the definition of the parton density through the deep inelastic structure function. At the moment we have two working hypothesis : i) $R = R_{hadron}$ and ii) $R \approx \frac{1}{3} R_{proton} < R_{proton}$. In the first case the parton density saturation starts from

$$x_B G(Q^2, x_B) > 150 \ at \ Q^2 = 10 GeV^2$$

while in the second picture

$$x_B G(Q^2, x_B) > 15 \ at \ Q^2 = 10 GeV^2 \ .$$

9.10. What x is small.

Using HERA data and the maximum value of the packing factor from the GLR equation we are able to estimate the value of x_B at which we expect the new physics related to the parton density saturation. For this purpose we use the simplest paramentrization for gluon deep inelastic structure function that describes the HERA data:

$$x_B G(Q^2, x_B) \ = \ 4(100 x_B)^{-0.33} \ at \ Q^2 == \ 10 \, GeV^2.$$

From this oversimplify expression for $x_B G(Q^2, x_B)$ we get that the limiting packing factor our system can reach at $Q^2 = 10 GeV^2$ at $x_B^{saturation} = 0.2 \, 10^{-7}$ or $x_B^{saturation} = 0.2 \, 10^{-4}$ for $R = R_{proton}$ and $R = \frac{1}{3} R_{proton}$ respectively.

For nucleus with the number of nucleons A the critical value of the packing factor decreases in $1 + A^{\frac{1}{3}} \cdot \frac{R^2}{R^2_{proton}}$ times. It results in an increase of the value of x_B at which the parton density reaches the saturation,namely

$$(x_B^{saturation})_A \ = \ (1 \ + \ A^{\frac{1}{3}} \cdot \frac{R^2}{R^2_{proton}})^3 \cdot (x_B^{saturation})_N \ .$$

9.11. How to measure the high density event.

Let me list here the main ideas how to measure the new physics that we anticipate at high density system of partons:

1. The probability of double parton interaction should be large (of the order of the maximum value of the packing factor) about 20%.

The double parton interaction can be seen not only as cross section for production of two pair of hard jets with the same value of rapidity,but also as a cross section of the inclusive production of hadrons in the window of rapidity $y + \Delta y, y - \Delta y$ where y is the rapidity of a hard jet with transverse momentum p_t and $\Delta y \ = \ \ln \frac{p_t}{p_0}$, where p_0 is the transverse momentum of produced hadron. It could be also seen as a long range correlation in rapidity between produced hard jet and produced hadron which is not specially hard.

2. In the high density event we should see the Landau - Pomeranchuk suppression of the emission of gluons with transverse momentum smaller that the typical momentum $q_0(x_B)$ which can be found from the equation:

$$\frac{x_B G(q_0^2(x_B), x_B)}{q_0^2(x_B)\pi R^2} = (PF)_{max} \, . \tag{12}$$

Such a suppression can be seen as the deviation from the factorization theorem for jets with $p_t \leq q_0(x_B)$.

3. . Decorrelation effect for jets with transverse momentum p_t of the order of q_0. The value of transverse momentum for such a jet is compensated not by one jet in the opposite direction but by a number of jets with average transverse momentum about q_0.

4. Polarization of produced hadrons allows us to measure the typical transverse momentum in the process since in the region of pQCD polarization should be equal to zero.Below we collect the substantial amount of polarization data that show not only the lack of our understanding of the origin of polarization buit also the fact that the typical transverse momentum in hadron-hadron collisions turns to be rather large ($\geq 2GeV$).

5. It is seen directly from eq.(2) that the saturation reaches in the system with small size at larger transverse momentum (smaller value of the gluon structure function). So this is why we have to create experimentally such compact system. We have three ideas how to confine the gluons in the disc of the small size:

A. to find a carrier of partons with small size. Even hadron could be such a carrier if the hypothesis of constituent quarks with small radius will be confirmed experimentally. However better to use the virtual photon or Pomeron. The last is not well theoretically defined object and what is Pomeron is one of the questions that the future experiment should answer. However even available experimentall information confirm the idea that Pomeron's size is much smaller that hadron one and of the order of $R_P \approx \sqrt{\alpha'_P} \sim 0.5 GeV^{-1} \sim 0.1 Fm$. Thus hard diffraction with Pomeron can give a good possibility to localize the parton system in small disc and to see high density phenomena in the most clear way.

B. to find the experiment (microscope) that can resolve the small part of the hadrom and investigate it in detail. This idea is realized in so called Mueller - Navalet process[10] or "hot spot" hunting[11] and Fig.2 shows a sketch of this experiment.

This process allows us to measure the small $\propto \frac{1}{p_{t2}}$ part of the hadron and using the two jets with sufficiently large transverse momentum as a trigger e can study the system with large parton density in many details.

C. Bjorken[12] pointed out that the large rapidity gap (LRG) processes can give us new way to look inside the high density parton system. Indeed, due to intimate

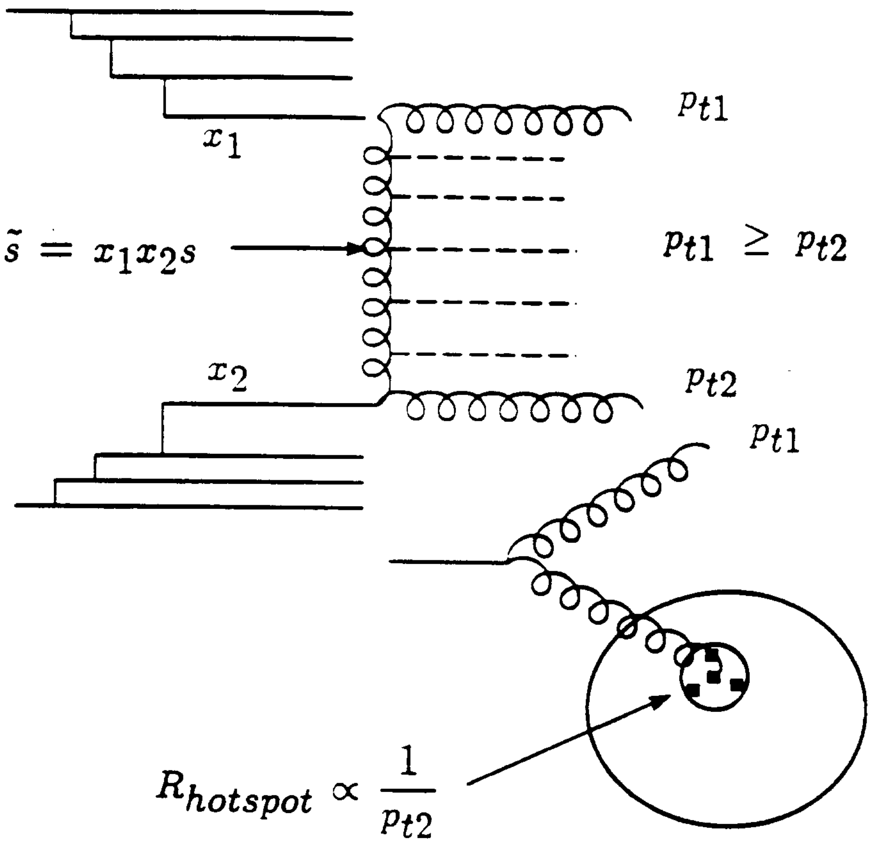

Figure 2: The Mueller - Navalet experiment for "hot spot" observation in hadron - hadron collisions.

relation between inelastic processes and elastic one coming from new reggeon-like approach the process with the LRG such as two high transverse momentum jet production with rapidities y_1 and y_2 but without any hadron with rapidities $y_1 > y_h > y_2$ can be described as the exchange of "hard" Pomeron. The properties of the " hard" Pomeron exchange is well known theoretically (see ref.[7]) and can be checked experimentally.

6. One of the way to measure the high parton density is to select the event with large multiplicity of produced hadrons. In more detail such an experiment we will discuss belowe.

9.12. Confinement region- np QCD

In the kinematic region without a hard scale we also know a lot about QCD mostly because of computer lattice calculation. This is direct and theoretically self-consistent way to study the main properties of confinement od quarks and gluons starting from the QCD Lagrangian. The success of this approach is quite remarkable. L:attice QCD is able to describe the spectrum of observed hadrons with an accuracy compatible with the experimental data (see the review of A.S.Kronfeld and P.B.Mackenzie[14]). Unfortunately, at the moment lattice QCD cannor yet be applied to scattering processes.

However even at the present time we see many approaches that incorporate the properties of vaccum which originated from lattice QCD to built the theory for so called soft processes (see ref.[15] as well as the attempts to construct the effective Lagrangian for high energy QCD[16] that will be suited for the direct lattice calculation.

This is the reason why the new measurements of so called soft processes are needed at high energies such as diffraction dissociation processes,double diffraction, polarization of produced hadrons and other processes that we will discuss below. The important element of the new strategy is to measure such traditionally soft processes but starting from the kinematic region where they are hard. For example,diffraction dissociation should be stadied from the big value of momentum transferred along the Pomeron where it is hard process to small its value where it is a typical soft process.

9.13. High multiplicity events.

Here I want to suggest the experiment in which we can reach the high parton density using the multiplicity of produced hadrons as a trigger for such a situation. The lego-plot of the event is shown in Fig.3.

The formula that describes the structure of the "hot spot" looks as follows;

$$\frac{d\sigma_{G+\text{“hotspot”}}}{dp_{t1}^2\, dp_{t2}^2\, d\phi} = \frac{C_A^2 \alpha_s^2}{8 p_{t1}^3 p_{t2}^3} \cdot \left(\frac{\omega_0 \Delta y}{n+1}\right)^{(n+1)} \cdot \frac{e^{n+1}}{\sqrt{\pi \delta n}} \cdot exp\left(-\frac{\ln^2(p_{t1}^2/p_{t2}^2)}{4\delta n}\right) \qquad (13)$$

where

$$\omega_0 = \frac{4C_A\alpha_s}{\pi}\ln 2\ ;\ \ \delta = \frac{14\zeta(3)}{4\ln 2}\ .$$

The qualitative features of this formula is quite obvious:

1. The width of p_{t2} distribution around the value $p_{t2} = p_{t1}$ depends only on value of the multiplicity of produced hadrons (parton).

2. This width is the same for different Δy and I think this observation allows us to check this prediction experimentally without too firm beliefe in theoretical estimates.

3.At fixed " n " the Δy dependance can be describerd by factor

$$\frac{d\sigma_{G\text{``hotspot''}}}{dp_{t1}^2 dp_{t2}^2 d\phi} \propto \{\frac{\omega_0 \Delta y}{n+1}\}^{n+1}\ .$$

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10. Nuclear Effects

The subject of Nuclear Physics at higher energies was not discussed during the meetings of the QCD subgroup, so the following writeup inevitably reflects the preferences of the author. The emphasis is on particle physics topics that can be studied using nuclei, rather than on more conventional nuclear physics.

The last decade has seen increased interest from the part of the high-energy physics community in the physics of multi-nucleon systems. The beginning of the current trend can be traced to the original observation[1] by EMC that the structure functions of the nucleons bound in nuclei are not the same as those of free nucleons. Data accumulated since then,[2] mainly from deep-inelastic charged-lepton scattering, show a non-trivial dependence of the ratio of the structure functions of bound and free nucleons on the Bjorken scaling variable x. At intermediate x values, $0.2 < x < 0.7$, a depletion is observed in the parton densities in bound nucleons, which increases with x (the EMC effect). At $x < 0.1$, the per-nucleon cross section in nuclear targets is decreasing with decreasing x, a phenomenon commonly called "shadowing." In-between those two regions, a small enhancement is seen in the nuclear structure functions, sometimes termed "antishadowing." A comprehensive theoretical understanding of the nuclear effects on the structure functions in the entire x range is still not available.

The main interest in nuclear structure functions is the information they can provide on the strong interaction. The importance of the nuclear environment as a laboratory, or a tool for studying QCD, is more and more appreciated. In particular, long-range aspects of the strong interaction can be studied using relatively well understood short-range processes, such as deep inelastic scattering and Drell-Yan production, involving nuclei.

Until recently, almost all the information on the nuclear-medium–induced modification of the nucleon structure functions came from DIS of electrons and muons off nuclear targets. The bulk of the experimental data on neutrino scattering comes from heavy targets, with very poor statistics from hydrogen or deuterium tagets, and therefore they provide no clear evidence for nuclear effects. The situation is changing however, as important new information[3] has appeared lately from the Drell-Yan experiment E772 at Fermilab, and this provides constraints for theoretical models attempting to explain the nuclear effects.

In the region of shadowing, it has been argued that low-x partons can extend longitudinally, due to the uncertainty principle, beyond the range of the nucleon to which they belong. The spacial overlap can give rise to recombination of partons from different nucleons in the nucleus, resulting in an effective depletion in the density of low-momentum partons in nuclei.[4] Alternatively,[5] low-x scattering can be viewed as propagation of quark-antiquark pairs, created by the virtual photon, in nuclei, and the depletion or enhancement of the per-nucleon cross section (shadowing or antishadowing) arises naturally as the result of quantum coherence: destructive or constructive interference, respectively, from several nucleons. That the two pictures are not equivallent can be seen by the fact that, in the first picture, the universality of the parton distributions is maintained in nuclei, while in the second it is violated: significantly less depletion is expected at low x in Drell-Yan production than is seen in DIS.

Experiment E772[3] has provided the first evidence that the anti-quark sea is depleted at low x in Drell-Yan, by an amount similar in magnitude to the depletion of the total cross section seen in DIS. However, the data only extend down to the x values where shadowing just begins to manifest itself. In addition, there may be hints that for very heavy nuclei, shadowing is less pronounced than in DIS. Clearly, more data are needed at yet lower x before the important question of the universality of the structure functions in nuclei can be answered.

In Drell-Yan, the low-x reach of an experiment is limited by the lowest dimuon invariant mass that can be studied. The fractional momenta x_b and x_t of the beam and target partons are related to the dimuon mass M and center-of-mass energy squared s by

$$x_b x_t = \frac{M^2}{s} \tag{14}$$

For a minimum M of 4 GeV (in order to stay above the ψ resonances) and s of 1600 GeV^2, for a beam energy of 800 GeV, the minimum x_b is about 0.04, considering that very little parton densities remain for $x_t > 0.25$. A 2-TeV primary beam would allow reaching $x_b \simeq 0.015$, while 8 TeV would reach down to 0.004. This is the region where shadowing increases from $\sim 5\%$ to $\sim 30\%$, for heavy nuclei, and precise Drell-Yan data would allow a definite answer to the question of whether shadowing is process-independent. In addition, it will allow studies of shadowing at much larger values of Q^2 than currently available from DIS experiments, which at the moment see little, if any, scale dependence, within their limited range.

At higher x, several models exist for the EMC effect. The recent Drell-Yan data[3] indicate that nuclear antiquarks do not carry significantly more momentum than their free-nucleon counterparts. This is not consistent with predictions from nuclear-pion models[6] for the EMC effect, which predict momentum transfer from valence to sea quarks in a nuclear environment. The data are consistent with the idea that a change of scale takes place in a nucleus.[7] They are not, however, precise enough to prove conclusively that nuclear aniquarks exhibit the same depletion as valence quarks at intermediate x, as proposed by the rescaling model. Here, the dramatic beam intensity increases that will be afforded by the Main Injector should allow a better test of the rescaling explanation of the EMC effect, but higher energies are not necessary. Answering the question of whether the nucleon size changes inside a nuclear environment will provide important hints about the QCD vacuum.

It is worth repeating here that nuclear effects have not yet been observed with adequate statistical significance in neutrino experiments. It is clear from charged-lepton experiments that it is not necessary to compare heavy targets to deuterium in order to observe nuclear effects, and that a comparison to a carbon target is sufficient. This implies that a future neutrino experiment to measure the nuclear modification of the structure functions should be feasible, allowing in addition a separation of the contributions from different quark species. Verification that nuclear effects are the same in charged- and neutral-lepton DIS is important before the strange-quark sea can be extracted by comparing low-x data from the two types of experiments.[8] Higher primary-beam energies will provide larger neutrino cross sections, and in addition will allow studies at higher Q^2 than at present data.

Another interesting suggestion[9] of novel physics effects that can be studied with lepton scattering off a heavy target comes from the observation that, at low x, parton overlap from different nucleons results in an effective increase of the parton densities in the nucleus. In this picture, the densities in an $A = 100$ nucleus at $x = 10^{-3}$ would equal those in a nucleon at $x = 10^{-5}$ (assuming the usual $1/x$ dependence of the parton densities). This region has been suggested as the place where to look for novel QCD effects arising from the high densities, at HERA, but it would appear that a Fermilab fixed target experiment can be very competitive, by using heavy targets. It is not quite clear yet what the manifestation of these effects would be. E665 has obtained data[10] from targets as heavy as Pb ($A \simeq 200$). For $x = 10^{-2}$, data are available for Q^2 in the range 1–10 GeV^2; no obvious difference is observed in the Q^2 dependence of the cross section compared to that from deuterium. On the other hand, the observed depletion of the nuclear structure functions at low x could well be an indication of such high-density effects (saturation of the parton densities, or screening). This is a new field, and more theoretical input should become available in the near future. It may well turn out that higher-energy muon-scattering experiments on heavy targets is a valuable tool for searching for such effects.

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11. Hyperon Polarization - An Unfolding Mystery

Significant Λ° polarization was measured in the early Fermilab neutral hyperon beam [1]. Figure 1 shows data [2] for Λ° and $\overline{\Lambda}^\circ$ produced by 400 GeV protons. The polarization is plotted as a function of the transverse momentum, p_t , of the produced hyperon relative to the incident proton momentum. The Λ° polarization was found to be zero in the forward direction (as required by rotational symmetry for production from an unpolarized beam and target) and decreased linearly to $\approx$ 20% at a transverse momentum (pt) of $\approx$ 1.5 GeV/c. These early experiments also indicated that the polarization had little dependence on the initial energy of the proton or the target material. We use the conventional sign definition [3] for the inclusive hyperon polarization: a positive polarization is in the same direction as the cross product of the incident beam direction with the produced hyperon direction.

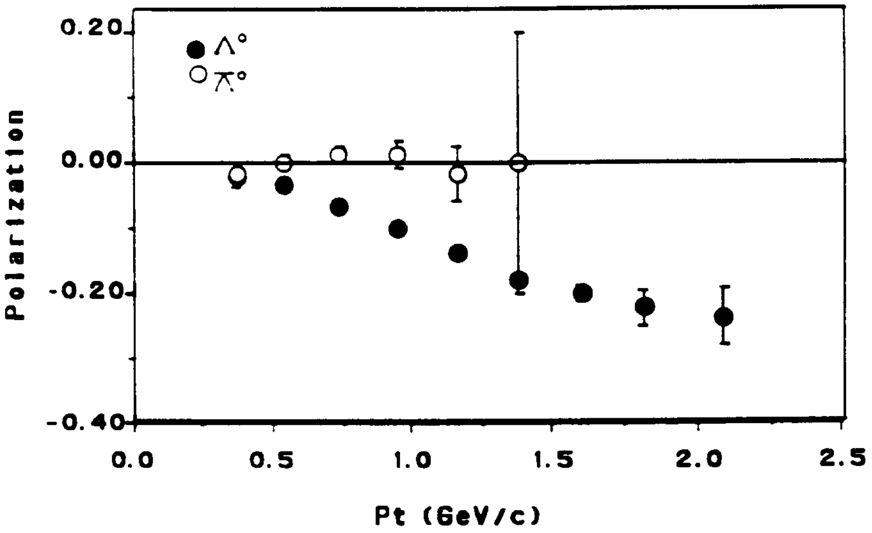

Figure 1 Polarizations of particle Λ° and $\overline{\Lambda}^\circ$

The clear evidence (Figure 1) that Λ° are produced with significant polarization came as a surprise. These polarizations have generally been attributed to peripheral mechanisms in which some of the proton valence quarks assimilate a strange quark from the sea to form a polarized hyperon.

The empirical conjecture that the more quarks incorporated from the sea reduces the produced hyperon polarization seemed to be confirmed by measurements of the polarization [4-12], of $\Sigma^\pm$, Ξ^-, and Ω^- hyperons. Figure 2 shows the measured polarizations [13] of some other hyperons. Plotted here is the polarization as a function of the hyperon momentum at a fixed production

the near future. It may well turn out that higher-energy muon-scattering experiments angle. Since p_t= P_h sin ÷, where P_h is the hyperon momentum and Θ the production angle, the horizontal axis is proportional to p_t. These are all produced by 400 GeV protons. Significant polarizations seem to be a general property of hyperon production at high energies.

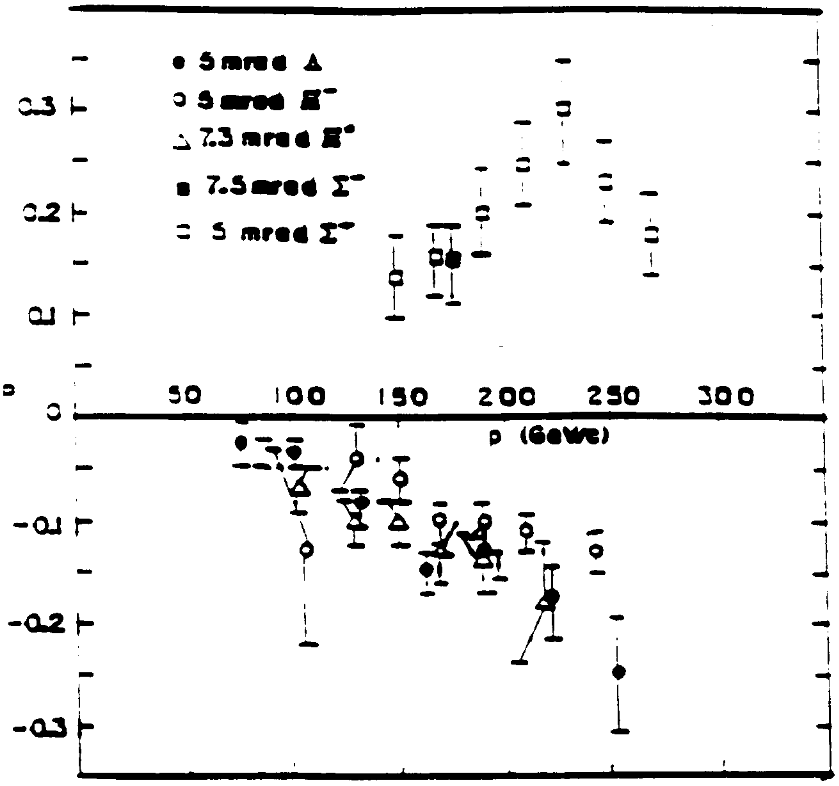

Figure 2 Polarization of other hyperons.. Plotted is the polarization vs hyperon momentum at fixed angles. The horizontal axis is thus proportional p_t.

In these interactions, the Λ° is a leading particle and the $\overline{\Lambda}^\circ$ is not. Might this be significant? One sees each of the hyperons being produced with polarization of Ú10-20% at p_t Ú1 GeV/c. The fact that early experiments had shown $\overline{\Lambda}^\circ$ to be unpolarized, where in the same kinematic range Λ° was polarized, lent credence to the idea that polarization is a leading particle effect. This was supported by measurements [11] showing the Ω^- to be unpolarized in this same kinematical region. Since the Ω^- is composed of three strange valence quarks it contains none of the valence quarks of the incident proton.

However, recent data have cast great doubt on this picture. Measurement of the Ξ^+ polarization by the Fermilab E756 group [14], (Figure 3) shows $\overline{\Xi}^+$ to be polarized by about the same amount as the Ξ^-.

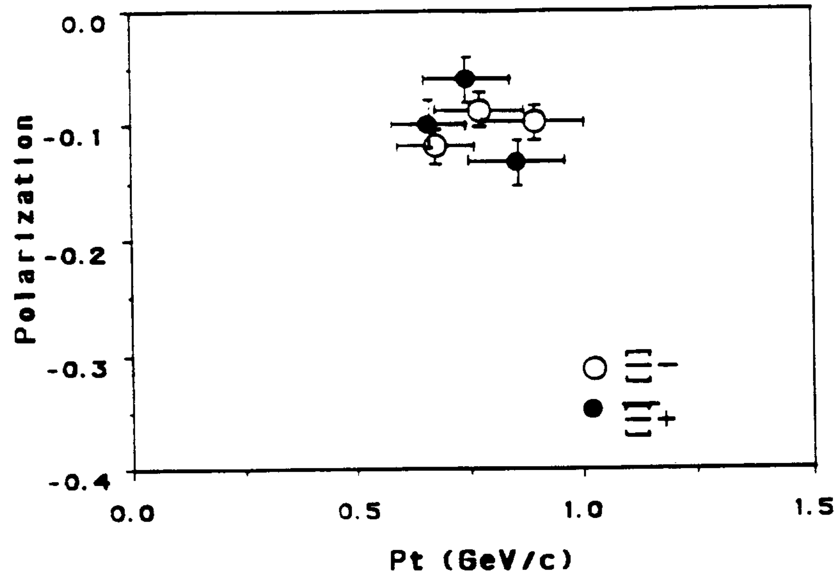

Figure 3 Ξ^- and $\bar{\Xi}^+$ polarization

Figure 4 shows the measured polarizations[15] of Σ^+ and $\bar{\Sigma}^-$ as a function of p_t. In this data one sees that $\bar{\Sigma}^-$ are also produced with ≈ 8% polarization near $p_t \approx 1$ GeV/c.

This Σ^+ data shows that the polarization increases with p_t, goes through a maximum near $p_t = 1$ GeV/c and then decreases. This is the first time this decrease has been observed in a high energy hyperon polarization.

The data of Figure 4 show points taken with both horizontal and vertical targeting for Σ^+ and $\bar{\Sigma}^-$. In horizontal targeting, the incident beam direction is changed in the horizontal (H) plane producing polarization in the same plane (vertical) as the magnetic field of the hyperon magnet Thus there is no spin rotation as the hyperons traverse the magnet. Targeting in the vertical (V) plane produces a polarization in the horizontal plane, perpendicular to the magnet field, thus producing maximum spin rotation as would be desired for measurement of a magnetic moment.

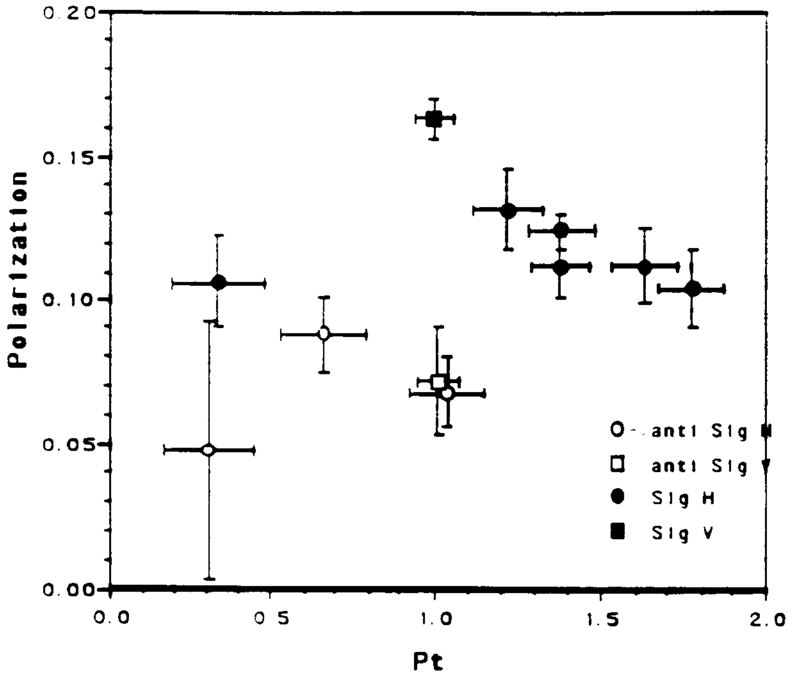

Figure 4 Σ^- and $\bar{\Sigma}^-$ polarization as a function of Pt

This experiment demonstrated that $\bar{\Sigma}^-$ hyperons are produced in high energy collisions with polarization of the same sign though of smaller magnitude than that of Σ^-. This observation is similar to the recent Fermilab results [14] which showed that both Ξ^- and $\bar{\Xi}^+$ are polarized with about the same magnitude. This would indicate that the polarization of antihyperons is a common phenomenon, and we should now turn our attention to why the $\bar{\Lambda}^0$ are not produced polarized.

The early data indicated that there was no strong energy dependence to hyperon polarization. However, recent high statistics data comparing hyperon production at 400 and 800 GeV indicate a much more complex phenomena. Figure 5 shows data from Fermilab E756 comparing Ξ^- production at 400 and 800 GeV [9, 16]. The 400 GeV protons used a 5 mrad production angle whereas the 800 GeV experiment was a 2.5 mrad. Thus the data was matched in both x_F and p_t. One sees that the magnitude of the polarization increases with the incident proton energy.

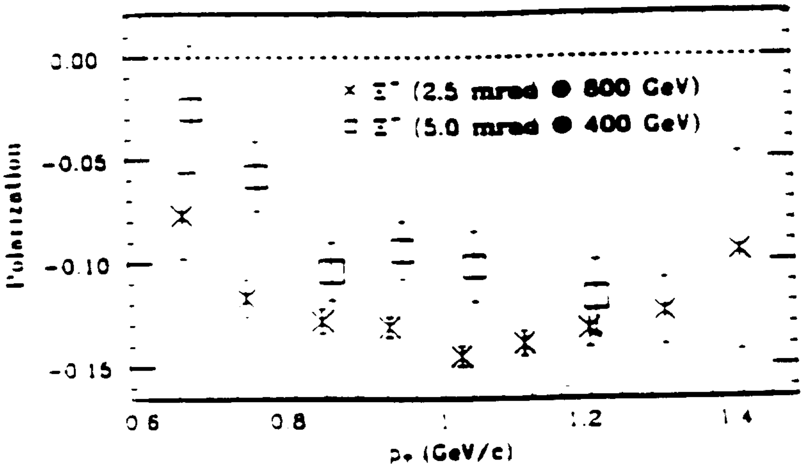

Figure 5 Comparison of Ξ^- polarization at 400 and 800 GeV.

Figure 6 show the polarization as a function of p_t for Σ^+ at 400 GeV from Fermilab experiments E497 [4] and E620 [5] and compares them with E761 [17] at 800 GeV. Note that the E620 data is from production on a Be target. The others use a Cu target.However, at least for Λ° production, the nature of the target material does not seem to have a major effect on hyperon polarization. Pondrom [18] has a good summary of target material dependence of hyperon production and polarization data. All of the Σ^+ data are in a range $0.47< x_F <0.53$. This data also shows a clear energy dependence of the Σ^+ polarization. Here, in contrast to the Ξ^- data of Figure 5, the polarization decreases in the same energy range.

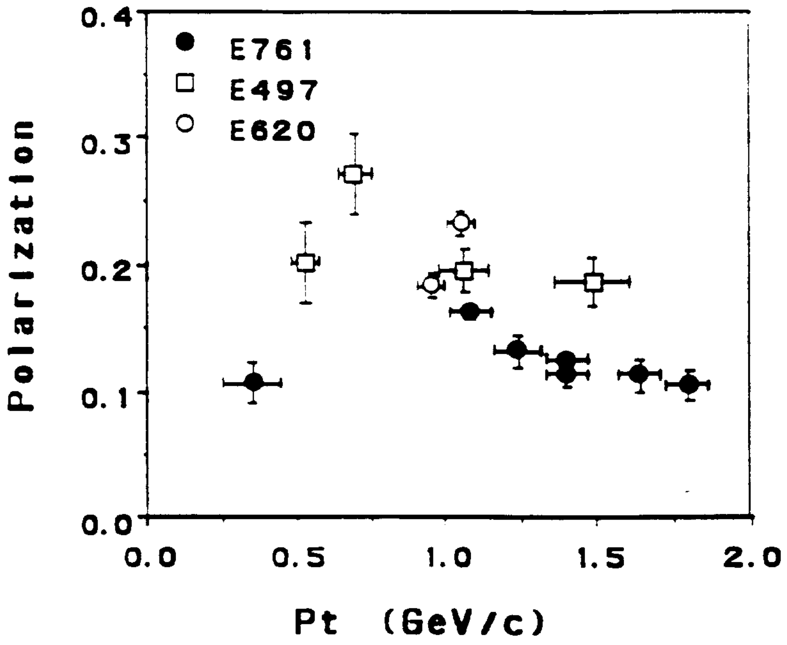

Figure 6 Comparison of Σ^- polarization at 400 (open points) and 800 GeV (black points).

Fermilab E799, in a very recent preliminary result,[19] used the Λ° contamination in their Kò beam to measure the Λ° polarization at 800 GeV. This measurement and the comparison with a previous measurements [20] at 400 GeV is shown in Figure 7. This very nice comparison shows no energy dependence of the polarization!

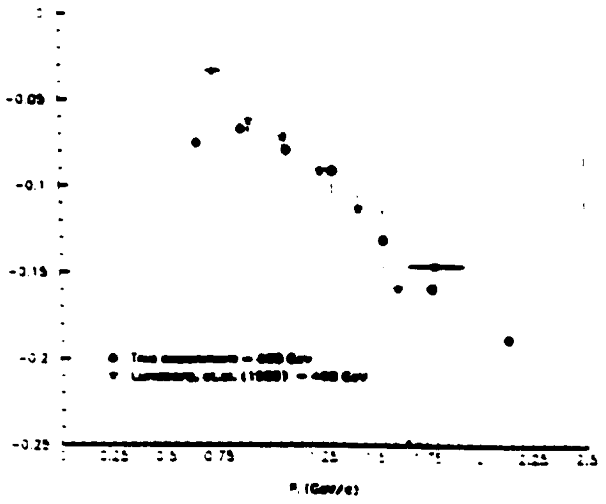

Figure 7 Comparison of Λ° polarization at 400 and 800 GeV.

We now have good comparisons of the Σ^-, Ξ^-, and Λ° polarizations at 400 and 800 GeV and find the astonishing result that the first decreases, the second increases, and the last remains constant with energy.

The plots of Figure 8 show the differing behavior of the X_F dependence of the polarization[15, 16, 20] for Σ^-, Λ°, and Ξ^- at two different values of P_t. In looking at the Σ^+ and Λ° plots one first notices that the signs of the polarizations are opposite. All models which incorporate the constituent quark picture are in agreement with this fact and also with the sign of the Ξ^- polarization. Taking into account the differing sign of the Σ^+ and Λ° polarizations, we see that their slopes, dP/dX_F, are of equal magnitude. In contrast the Ξ^- polarization is independent of X_F. In the constituent quark picture the Σ^- and Λ° may contain two of the three incident proton quarks whereas in the Ξ^- case at most only one of the proton quarks may be incorporated into the hyperon. This suggests that the mechanisms for producing the polarization may be very different.

Among the many proposed models for hyperon (but not antihyperon) polarization [21-24], let me mention two approaches to the polarization question - both involving similar leading particle effects. One is that of the Lund group [25] whose model assumes qŸq pairs are produced from the sea via the breaking of a QCD string but conserving local angular momentum. DeGrand and Miettinen [26] propose two simple rules: quarks which gain longitudinal momentum combine with spins down; quarks which lose longitudinal momentum combine with spins up. This is equivalent to a Thomas precession and a spin orbit coupling. Both models explain much of the hyperon data. The magnitudes of some of the polarizations are at odds with each of the models. Other models are discussed in a review by P. Kroll [27] and is recommended although it was done before the polarizations of the $\overline{\Xi}^+$ and $\overline{\Sigma}^-$ were known. A recent model using a Regge pole approach [28] gives qualitatively good agreement with Σ^+ polarization data. None of the above models address the polarizations of the antihyperons or the above mentioned hyperon polarization energy dependence.

The only publication [29] that I am aware of that offers an explanation for hyperon (and antihyperon) polarization does so in the framework an optical potential model. In this model the polarization occurs at the surface of the nucleon and the process applies naturally to both hyperons and antihyperons.

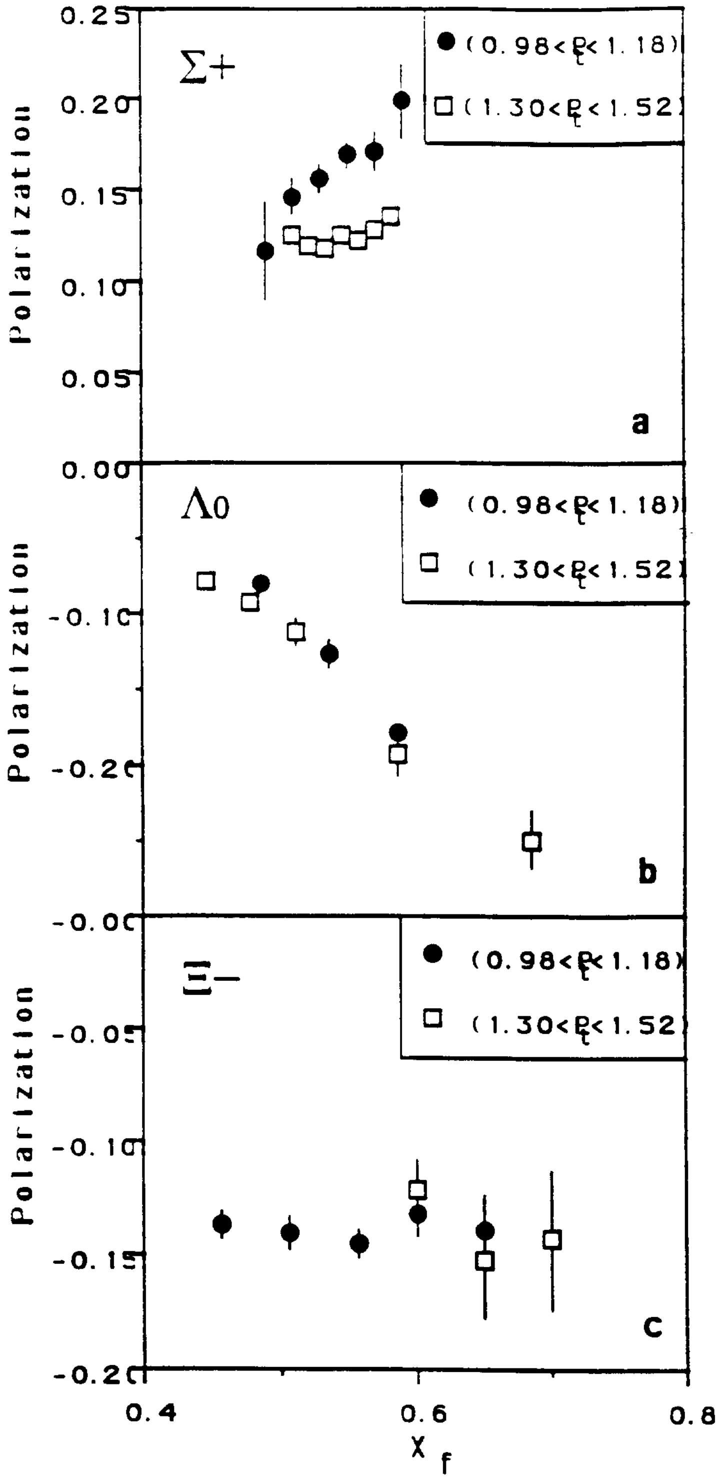

Figure 8 Polarization of Σ^-, Λ^0 and Ξ^- as a function of Pt

The last couple of years have seen a major addition to the available data on the polarization of both hyperons and antihyperons. Clearly the $\Lambda^\circ/\overline{\Lambda}^\circ$, Ξ^-/Ξ^+, and $\Sigma^+/\overline{\Sigma}^-$ systems exhibit a rich and challenging set of polarization phenomena that cry out for insightful ideas.

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12. Future Plans for QCD at the Tevatron Collider

12.1. *Introduction*

Over the next ten years data gathered at the Tevatron will yield new and rigorous tests of QCD. Three to five years will be required just to fully exploit data taken at present energies and increasing luminosity. In particular, new differential cross-sections for jet, photon, and intermediate vector boson production will investigate new regions of phase space particularly sensitive to proton distribution functions and third order QCD calculations. These multi-dimensional cross-sections will also guide the way from perturbative to non-perturbative descriptions of partonic interactions. The large total luminosities expected will also encourage searches for new phenomena such as quark compositeness and excited quarks, rare diffractive processes, and vacuum polarization. In the longer run, an increase of beam energy to 2 TeV will provide accurate tests of all aspects of QCD mainly because the theoretically and experimentally well described W/Z + jet samples will have statistical significance rivalling that of the present dijet samples. As QCD moves into the era of precision, rather than qualitative, tests both higher luminosity and energy will be of utmost importance.

12.2. *Parton Distributions*

Until recently cross-sections measured at the Tevatron have been used to verify the accuracy of current parton distribution parametrizations. This is one of the best tests of QCD because it requires the perturbative calculation of the QCD hard parton cross-sections using the QCD evolution equations to extrapolate the parton distributions from low energy fixed target experiments to the Tevatron energy scales. This is a rigorous test of factorization since the tested energy scales differ by more than an order of magnitude. Measurement of the total inclusive jet or photon cross-sections are examples of such tests.

However, up to the present, the Tevatron results have not been able to make unique measurements of the parton distributions in new regions of phase space. This will change in the next few years as studies focus on more differential cross sections for jets, photons, and W/Z final states with larger statistics. For example, consider the triple differential cross-section $d^3\sigma/dp_{t1}d\eta_1 d\eta_2$ where p_{t1} and η_1 are the leading jet transverse momentum and η_2 the rapidity of the second leading jet [1]. At small leading momentum and rapidity, $p_{t1} = 50GeV$ and $\eta_1 = 0$, and large values of rapidity for the second jet , $\eta_2 = 2.5$, the cross-section is sensitive to extreme parton momentum fractions (between 0.003 and 0.7). At future high luminosities the fractions measured will approach zero and unity. As a second example of the power of differential cross-sections, the photon inclusive cross-section $d^2\sigma/dp_t d\eta$ at large rapidities is sensitive to the gluon content of the proton at $x = .001$.

Dijet production at large rapidity differences, $\Delta\eta$ larger than four, with little or no activity between the jets may signal the presence of Pomeron exchange [2]. The Pomeron content of the proton can also be probed by examining events with a single forward or two forward gaps. All these "rapidity gap" configurations are extremely rare and can not be properly studied except at large luminosities or perhaps at larger energies where the production cross-sections will increase. DZERO and CDF have embarked on agressive programs to pursue rapidity gap and diffractive physics.

With an increase in energy; and, perhaps, the possibility of accumulating data at many different energies, parton distributions can be further tested at very different energy scales. The availability of different center of mass energies would enable a multitude of detailed comparisons between perturbative QCD parton distribution predictions and cross-sections.

In summary, reliable QCD predictions require a good knowledge of the parton distributions. Distributions that are currently not well known can be extracted from collider data.

- Gluon distributions from σ(jet), $\sigma(\gamma)$..
- Sea-quark dsitributions from σ(Drell-Yan).
- distributions at very low and high x from σ(jet), $\sigma(\gamma)$. at high η.
- Heavy flavor distributions from V + Q production.
- Asymmetry in flavor distributions from W production and asymmetry.

Goals:

- Incorporate collider data into global fits.
- Extend the kinemastic range.

12.3. Next-to-Leading Order and Resummation Tests

The differential jet, photon, and W and Z cross-sections just discussed also prove precise tests of QCD calculations at order α_s^3. The Next-to-Leading Order calculations (NLO) for differential jet production are still under development [3],[4]. In very forward regions leading order calculations seriously underestimate jet production. The ability of NLO calculations to compensate for this shortfall remains an open question. The advent of NLO calculations also provides, for the first time, serious inquiries into the partonic contributions to jet shape. In addition, the inclusive jet cross-sections can now also be studied as a function of jet algorithm. Central jet cross-sections and profiles have already been measured and consistent with the observation that jets are characterized by hard radiation rather than soft fragmentation [5]. The examination of rare high p_t and very forward jets, possible only with high luminosity or high energies, will be a further revealing test of NLO calculations and deepen our knowledge of jet structure.

The cross-sections for jet production at very large rapidity differences is expected to be described, not by perturbative calculation, but by resummation techniques which properly account for radiated gluons [6]. However, divergences from

NLO calculations are not expected to be large until the rapidity differences exceed four or five units of rapidity - a region of very low cross-section. Thus, in order to test the transition from perturbative to non-perturbative calculations, both wide acceptance and the large luminosities and, perhaps, higher energies of the future are necessary. The W and Z p_t spectra also test the transition since the low p_t portion of the spectra are calculated by resummation techniques and matched to the high p_t perturbative portion of the spectra.

NLO calculations for di-photon and intermediate vector boson production have been available but not precisely tested [7], [8]. The high statistics samples required for these NLO tests simply must wait for higher luminosities or, equivalently, energies. In addition, to being a purely NLO process, di-photon production may also be a signature for Higgs production.

12.4. Drell-Yan (W/Z) Production

Drell-Yan pairs are one of the best final states to study QCD in a very quantitative way. The clean and colorless final state muons or electrons can be accurately identified. Typically, cross sections are small, and as a result Drell-Yan production has not been used to full potential. However, the special cases of Z and W production have recently been used to test perturbative, resummed, or parton shower based predictions of QCD. Two examples include the determination of α_s from $W + jets$ and Z and W p_t distributions [9],[10].

Z production alone can be considered an outstanding QCD test laboratory. Because the final state Z can be reconstructed very accurately and without background, the measurement of p_t, $p_{longitudinal}$, rapidity dependence, and energy flow around the Z can be made in an unambiguous and unique way. This kind of detailed study of QCD is just starting to become feasible with currently available luminosities. However it can reach the statistical precision of jet cross sections without the hindering systematics. To reach this statistical precision one would need a sample of roughly 10^5 Z's, which corresponds to about $2fb^{-1}$ if one only uses the $Z \rightarrow e^+e^-$ decays. In fact, the entire menu of differential jet and photon cross-sections can be replaced with differential $Z + jet$ final state cross-sections. This will truly move QCD into the realm of precision physics.

An increase in energy would greatly reduce the luminosity requirement for W/Z QCD studies. The special case of Z production could be generalized by introducing the Drell-Yan pair mass as a parameter. In particular, measurement of the Drell-Yan pair p_t distribution as a function of mass provides a test of resummation techniques. With sufficient statistics the angular distribution of the final state leptons may also analyze the polarization state of the vacuum [11]. A possibility that has, of yet, not been investigated at the collider.

12.5. New Developments

Departures from the Standard Model are quite often first noted as departures from expected QCD cross-sections. For example, quark compositness could be seen as an excess of very high transverse momentum jets. These jets would be produced by an exchange of constituents between the scattering quarks. As a second example, excited quarks could be observed as an excess in jet-photon invariant mass spectrum. If an excited quark existed and decayed radiatively, a clear reasonance would appear in the jet-photon mass spectrum. No signals for compositness or quark excitation have yet been detected [5],[12]. Obviously, increased luminosity and, more effectively, increased beam energies will increase the sensitivity of Tevatron detectors to such departures from the standard model.

12.6. Precision Tests of Perturbative QCD

Testing the predictions of perturbative QCD in a systematic way requires detailed comparisons of data with the predictions of LO, NLO, NNLO and resummed QCD. Such comparisons have already been made for selected processes:

- LO QCD predictions are in qualitative agreement with the data for a large class of processes, but are subject to large theoretical uncertainties.

- NLO QCD predictions have been tested for a variety of jet cross section and jet structure measurements. The predictions for

  - $d\sigma/dE_T$,
  - $d\sigma/dM_{jj}$,
  - $d\sigma/d\chi_{jj}$,
  - $d\sigma/dE_T d\eta_1\eta_2$,
  - jet shapes,

  are in quantitative agreement with the data. However, there are also a number of NLO QCD predictions that show significant discrepancies with the measured values

  - $d\sigma/dE_T$ for direct photons at low E_T,
  - $\sigma(b)$,
  - $\sigma(\Psi)$, $\sigma(\Psi')$,
  - $R = (d\sigma(\sqrt{s} = 546)/dx_T)/(d\sigma(\sqrt{s} = 1800)/dx_T)$,
  - $d\sigma/d\cos\theta^*$ for Drell-Yan.

- NNLO QCD predictions exist fro the Drell-Yan cross section $d\sigma/dM$, but have not been compared with the data.

- Resummed QCD predictions are available for

  - $d\sigma/dM$ for Drell Yan,

  - $d\sigma(W,Z)/dp_T$.

  The W and Z p_T distributions have been measured and found to be in good agreement with the predictions.

  Goals for the next generation of collider measurements:

- Resolve the existing discrepancies between data and NLO theory.
  - Special run at $\sqrt{s} = 630$ GeV.
  - Photon fragmentation function?
  - Resum predictions for heavy flavor production?
  - Analyze new collider data for Drel-Yan.
- Test QCD at NLO for a large variety of processes as the calculations become available.
- Probe the regions of phase space near kinematic boundaries since this is where NLO corrections and resummation corrections are expected to become important.
- Test NNLO QCD and resummed QCD predictions by comparing the absolute normalizations and p_T distributions for the data and the theory.
- Study the effects of different jet clustering algorithms, jet merging and jet fragmentation properties ($e.g. g \to b\bar{b}$).

12.7. Test of QCD Approximations

Since even LO QCD predictions are lacking for many processes such as n-jet production for $n > 4$, many comparisons of data and theory demand the use of parton shower (PS) Monte Carlos. This is to be contrasted with the use of matrix element (ME) Monte Carlos, which are now becoming available for some processes, and generate the LO predictions for processes with n partons in the final state. Despite the fact that these programs contain a number of approximations, they have been able to produce satisfactory descriptions of the data for a number of cases

- global properties of the ΣE_T data sample (HERWIG PS),
- $\sigma(W + n\text{jets})(VECBOSME)$,
- kinematics and event topologies for multijet events (ΣE_T sample),
- color coherence effects in jets (HERWIG, PHYTHIA PS)

Goals for the next generation of collider measurements:

- Test the validity and range of applicability of the approximations by comparing the results of PS and ME MC's for a variety of processes (*e.g.*kinematics, event topologies for W + n jets),
- Test the extent to which various physics effects can be included (*e.g.*angular ordering).
- Merge the PS and ME approaches.

12.8. Nonperturbative QCD

- diffractive physics (*e.g.*rapidity gaps)
- transition to the nonperturbative regime (Altarelli-Parisi versus Gribov-Lipatov evolution)
- jet fragmentation functions

Goals:

- Search for and study the signals for colorless exchange in a variety of channels.
- Test the breakdown of standard AP evolution.
- Test the predictions of small x evolution.
- Search for the effects of "overlapping" partons
- Measure jet fragmentation properties, test for universality.

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