QCD: Challenges for the Future *

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ABSTRACT

Despite many experimental verifications of the correctness of our basic understanding of QCD, there remain numerous open questions in strong interaction physics and we focus on the role of future colliders in addressing these questions. We discuss possible advances in the measurement of α_s, in the study of parton distribution functions, and in the understanding of low x physics at present colliders and potential new facilities. We also touch briefly on the role of spin physics in advancing our understanding of QCD.

I. INTRODUCTION

QCD is a successful theory of the strong interactions which has been tested by confronting theory and experiment in both the perturbative and non-perturbative regimes. It is an unbroken symmetry with a single coupling constant, α_s, whose measurement over a wide range of energy scales is crucial for verifying the consistency of the theory. In fact, QCD is the only theory where relativistic quantum field theory can be tested beyond a few orders in perturbation theory.

Today, we have numerous measurements where the predictions of QCD are rigorously tested. New and increasingly more precise jet data are being gathered in e^+e^-, hadron, and ep collisions to be compared with theoretical calculations beyond the lowest order. For example, the latest results from the jet E_T spectrum obtained by CDF and D0 challenge our understanding of both QCD jet calculations and our knowledge of parton distribution functions. Before we can interpret results such as these as indications of new physics, we must have a solid understanding of what we expect from QCD. Hadron collider, photoproduction, and deep inelastic scattering data are giving us new information on the parton structure functions, while recent data from HERA on the rise of the structure function, F_2, at low x are stimulating new theoretical understanding. The study of QCD is thus a perfect example of the necessary synergism between theory and experiment.

The discovery of the top quark provides a new arena for testing the predictions of QCD. Indeed, the jet energy calibration remains the dominant source of experimental error, while perturbative QCD calculations stubbornly persist in predicting a cross section slightly above the experimental measurement. The physics involving the top quark has many interesting QCD issues, but is not covered here. Instead it is discussed in a separate contribution by the Top Quark Working Group.[1].

Despite many successes, however, the regimes of the strong interactions where perturbative QCD is not applicable are in general not well understood. We have, for example, an incomplete understanding of quark confinement, of the high temperature and high density phases of QCD, of the absence or unnatural smallness of strong CP violation, and of how a partonic picture of QCD is connected with non- perturbative regimes, including bound states. The list goes on.

Some of these questions will be addressed by lattice gauge theory computations in coming years as more computing power becomes available and progress is made in the development of algorithms. Already lattice calculations of α_s are competitive in precision with experimental derivations.[2] Reliable and convincing calculations of the hadron mass spectrum and weak matrix elements are realistic goals for the near future.

The measurement of α_s is a precise test of the predictions of perturbative QCD. Current measurements at the Z mass are at the $\pm 5\%$ level, while the goal is a measurement of $\delta\alpha_s/\alpha_s \sim 1\%$ over a wide range of Q^2. Such measurements have the potential to limit new physics scenarios and to constrain physics at the GUT scale. Section II describes techniques for measuring α_s through ν physics at low Q^2, in e^+e^- and ep colliders at $Q^2 \leq (.5 - 1\ TeV)^2$, and at high energy hadron colliders such as the LHC which will probe $Q^2 \leq (4\ TeV)^2$.

The understanding of parton distribution functions is critical to many measurements at present and future colliders. Section III contains a survey of the x and Q^2 regions where progress in our knowledge of structure functions might be obtained at future facilities. Particular attention is paid to obtaining a consistent definition of the errors in the structure functions. This section also discusses some problems in jet physics.

The prospects for low x and diffractive physics are presented in Section IV. The scattering region with $x < 10^{-5}$ is a new strong interaction frontier which has begun to be probed by HERA. Extension of these studies may yield insight into the role of the BFKL pomeron. Forward physics ($.1 < x_F < .9$) and diffractive scattering can also provide information about the

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non-perturbative regime. Possible collider experiments which are sensitive to forward and diffractive physics at both the Tevatron and the LHC are discussed.

Spin physics has the potential to open a new window on QCD and is discussed in Section V. Experiments with polarized protons and electrons can lead to new measurements of polarized structure functions and asymmetries.

II. MEASUREMENTS OF α_S

Since QCD contains in principle only one free parameter, the strong interaction scale Λ, tests of the theory can be quantified in terms of comparison of measurements of Λ in different processes and at different hard scales Q. In practice most QCD calculations of observables are performed using finite-order perturbation theory, and calculations beyond leading order depend on the *renormalisation scheme* employed, implying a scheme-dependent Λ. It is conventional to work in the modified minimal subtraction scheme ($\overline{MS}$ scheme), and to use the strong interaction scale $\Lambda_{\overline{MS}}$ for five active quark flavors. If one knows $\Lambda_{\overline{MS}}$ one may calculate the strong coupling $\alpha_s(Q^2)$ from the solution of the QCD renormalisation group equation. Because of the large data samples taken in e^+e^- annihilation at the Z resonance, it has become conventional to use as a yardstick $\alpha_s(M_Z^2)$, where M_Z is the mass of the Z boson; $M_Z \approx$ 91.2 GeV. Tests of QCD can therefore be quantified in terms of the consistency of the values of $\alpha_s(M_Z^2)$ measured in different experiments; such measurements have been performed in e^+e^- annihilation, hadron-hadron collisions, and deep-inelastic lepton-hadron scattering (DIS), covering a range of Q^2 from roughly 1 to 10^5 GeV^2.

Over the past decade many measurements of $\alpha_s(M_Z^2)$ have been presented. The best measurements approach a relative precision of 3%, but 5-10% is typical. Within the errors all measurements are consistent with a central value of $\alpha_s(M_Z^2)$ = 0.118 ± 0.005, and there is no evidence of any discrepancy between measurements made at different Q^2 values or in different processes. QCD has therefore been tested to about the 5%-level of precision, which is rather modest compared with the current 0.1%-level tests of the electroweak theory. A primary aim of future high energy physics studies should therefore be the achievement of much more precise QCD tests, which are necessary to enhance our confidence in the theory, as well as to constrain possible extensions to the Standard Model (SM) and Grand Unification of the couplings at a high energy scale.

In this spirit the various techniques for measurement of $\alpha_s(M_Z^2)$ have been reviewed, and their potential for achieving a benchmark 1%-level of precision has been evaluated. This has involved detailed study of the sources of uncertainty, both experimental statistical and systematic, as well as theoretical, and projection of the reduction in these uncertainties that may be achievable in future experiments at existing or new facilities.

Many current measurements are limited by theoretical uncertainties that result from truncation of the QCD perturbation series at low order and/or from lack of knowledge of non-perturbative effects. Only the inclusive observables R, R_τ, and the Bjorken and Gross-Llewellyn-Smith (GLS) sum rules have been calculated perturbatively at next-to-next-to-leading order (NNLO). Calculations of jet final states in e^+e^- annihilation, hadron-hadron collisions and deep-inelastic scattering are presently limited to next-to-leading order (NLO), resulting in estimated $\pm$5-10%-level uncertainties on $\alpha_s(M_Z^2)$ due to the missing higher order contributions. NNLO calculations of jet final states are hence a prerequisite for improving precision beyond the 5%-level. Though much progress towards this goal has been made, the task is difficult and requires further considerable theoretical effort. It was assumed for the projection of the precisions of future $\alpha_s(M_Z^2)$ measurements that these calculations will be available, and that residual higher-order uncertainties will contribute at or below the 1%-level.

Uncertainties arising from non-perturbative contributions, often called 'hadronisation' or 'higher-twist' effects, are expected to have the form of a series of inverse powers of the scale Q; they are hence potentially most important for α_s measurements made at low scales, such as from some structure function determinations in deep-inelastic scattering. Though lattice gauge theory provides a successful tool for performing non-perturbative QCD calculations, it is currently limited in applicability to static properties of hadrons and cannot be used to calculate power-law corrections to hadronic final-state observables. Instead these are usually estimated using *ad hoc* parameterizations and models of hadronisation. Recently progress has been made towards a deeper level of understanding in the form of studies of 'renormalon ambiguities', which may represent the first step towards a 'theory of hadronisation'.

Four techniques were identified that offer the best prospects for 1%-level $\alpha_s(M_Z^2)$ measurements: (1) the Q^2 evolution of the parity violating structure function xF_3, (2) the Gross-Llewellyn-Smith (GLS) sum rule, (3) spin-averaged splittings in the Υ and Ψ systems, and (4) hadronic observables in e^+e^- annihilations. (1) and (2) are measured in deep-inelastic neutrino scattering experiments; (3) is based on lattice QCD; all other methods use perturbative QCD.

The Q^2 evolution of xF_3 has the attractive feature that it is independent of the gluon distribution function of the nucleon. It is best measured using the difference between ν and $\bar{\nu}$ cross sections for scattering on unpolarized targets. A NLO calculation is available and the NuTeV experiment at Fermilab hopes to achieve a precision on $\alpha_s(M_Z^2)$ of ± 2.5% within the next few years. Further improvement towards the 1%-level would require a high-statistics tagged neutrino beam facility, perhaps at the upgraded TeVatron ('TeV33') or at the LHC, and a NNLO calculation of the DGLAP splitting functions.

The GLS sum rule has already been calculated at NNLO, but because of the low Q^2-value, about 3 GeV^2, of present experiments, higher-twist effects are important. The NuTeV experiment expects to obtain a precision of $\pm$3% on $\alpha_s(M_Z^2)$ using this technique. The larger Q^2 values and lower x-reach potentially attainable with neutrino beams at TeV33 or LHC would allow the possibility of 1%-level measurements.

Heavy quarkonium systems can be used to determine α_s by comparing the measured energy-level splittings with a lattice QCD calculation. The most precise determinations of $\alpha_s(M_Z^2)$ with this technique to date, at the $\pm$3%-level, have

been obtained by the FNAL/SCRI and NRQCD groups using spin-averaged splittings in the Υ and Ψ systems. The precision is limited by uncertainties relating to lattice discretization, treatment of sea quarks, and matching between the different renormalisation schemes used in lattice and perturbative calculations. All of these issues can be addressed by first-principles calculation with current computational resources, and it is expected that an $\alpha_s(M_Z^2)$ determination with 1% precision can be achieved.

The measurement of α_s via hadronic event shape observables in e^+e^- annihilation has been studied in detail over the past decade by experiments at the CESR, PETRA, PEP, TRISTAN, SLC and LEP colliders. The current experimental precision on $\alpha_s(M_Z^2)$ achieved by a single experiment is at the 2-3%-level, but all experiments are limited by the fact that the observables are calculated only at NLO, yielding uncertainties estimated to be at the 7%-level from the uncalculated higher-order contributions. NNLO calculations are required to improve this situation. Hadronisation uncertainties at the Z energy are at the 3%-level, but are expected to drop below 1% for c.m. energies above 300 GeV, so that an e^+e^- collider operating in the range $500 \leq Q \leq 1500$ GeV would be expected to achieve a 1%-level $\alpha_s(M_Z^2)$ measurement, provided NNLO calculations were available.

In addition, two other methods, the Q^2-evolution of the parity non-violating structure function F_2 at high x, and the jet E_T spectrum in high energy proton-(anti)proton collisions, offer the possibility to determine α_s with good accuracy in regions of Q^2 which are complementary to those of the other measurements. The feasibility of both of these techniques is currently the focus of studies at HERA and the TeVatron, respectively; until the results are known it is not possible to evaluate the potential precision of these methods. However, it is already clear that, to obtain sufficient events in the kinematic region $Q^2 \sim 10^4$ GeV^2 and $x \sim 0.5$ for an $\alpha_s(M_Z^2)$ measurement at the percent level, a HERA data sample of about 1000 pb^{-1}, or a 'LEP $\times$ LHC' DIS facility, would be required. It is also clear that the TeVatron and LHC offer the greatest lever-arm for constraining the Q^2-evolution of α_s, so that feasibility studies for these measurements are strongly encouraged.

In summary, the goal of measuring $\alpha_s(M_Z^2)$ to a precision of $1\,\%$, with a number of complementary approaches and over a wide range of Q^2, seems feasible. The determination of $\alpha_s(M_Z^2)$ from the hadron spectrum using lattice QCD is the only method without facility implications. A more complete program will likely require new facilities. These include a tagged neutrino facility utilizing either the full energy Tevatron beam or one of the LHC proton beams, and a high-energy e^+e^- collider. The potential for complementary α_s determinations in $p\overline{p}$ collisions at the TeVatron and pp collisions at the LHC needs further study.

III. STRUCTURE FUNCTIONS AND JETS

QCD is a theory of quarks and gluons. The strongly interacting particles observed in experiments are *not* quarks and gluons, but hadrons. To make contact between theory and experiment we need to make a connection between the partons in the theory and the particles that are actually involved in our experiments and that show up in our detectors. This connection is provided by the parton distribution functions obtained from nucleon structure function measurements and by models of jet fragmentation and algorithms for jet definition. Making use of *any* physics measurement with hadrons in the initial or final state necessarily involves taking into account parton distributions and/or jet physics. In addition, many new physics signals (and 'old' ones as well) have QCD processes as major backgrounds. The work of this subgroup is therefore not only integral to QCD studies, but is directly relevant to the other physics working groups as well.

At the 1996 Snowmass, more emphasis was placed on structure functions than jet physics, as will be reflected in this summary. We will also see, however, that recent results from the Tevatron collider have closely intertwined some aspects of the two subjects. For a more complete discussion the reader is referred to the Structure Functions Subgroup Summary[3] and to individual contributions to these proceedings.

A. Parton Distributions: Where They Come From and Where They Might Be Going

We understand the structure of nucleons in terms of their parton constituents. From measurements of structure functions in such processes as deep inelastic scattering we obtain quantitative descriptions of those constituents in the form of parton distributions functions (PDFs), which describe the momentum density of the partons inside the proton. Such descriptions are necessary not only to interpret experiments in the context of QCD (and thereby test the theory), but also to make predictions for experiments with hadrons in the initial state, for example at the Tevatron and LHC colliders.

At Snowmass the PDF working group focussed on how the x and Q^2 ranges might be further extended, and how we might make better use of the measurements we already have through more detailed exploration of the processes by which the PDFs are obtained. This includes preliminary efforts to understand, and wherever possible to quantify, the sources of uncertainties associated with PDFs. The latter subject is discussed in the next subsection.

The quark distributions are determined primarily from deep inelastic scattering of both charged leptons and neutrinos off of nuclei, with additional constraints coming e.g. from the Drell-Yan process. The gluon distribution is considerably less well known and is determined from direct photon production (through the subprocess $qg \rightarrow q\gamma$) and also (at low x) from measuring the Q^2-evolution of the structure function F_2.

A recent development is the increased use of hadron collider data as input to parton distribution determinations. In particular, the asymmetry in the rapidity distribution of leptons from W decays has been used to constrain the difference between the u and d quark valence distributions, and the inclusive jet E_T spectrum contains information about the gluon at large x. When used judiciously, hadron collider data have the potential to give information about parton distributions in previously inaccessi-

ble, or at least not very well constrained, kinematic regimes. We will certainly see more of this trend in the future.

Our knowledge of the PDFs has seen a marked increase in recent years, in both precision and range in momentum fraction x and scale Q^2, with the advent of the HERA ep collider and with the availability of other new data. Figures 1–4 of Ref. [3] summarize the experiments currently used in PDF determination, and show the x and Q ranges covered by each one. Present experiments extend down to x values of 10^{-4} and up to values of Q approaching 100 GeV.

The process of extracting parton distributions from fits to structure function data works roughly as follows. QCD predicts the evolution of the structure functions with the scale Q^2, but it does *not* predict their absolute values. In particular QCD does not predict (except in certain asymptotic regimes) the x dependence. Therefore global fitters begin with a parameterization for the x dependence of parton distributions at some low starting scale Q_0 — typically on the order of a few GeV — and evolve them to the higher scales relevant to the experiments. They then perform global fits to the structure function data at next-to-leading order in QCD to determine the values of the parameters in their starting distributions.

In principle this process is straightforward. In practice, however, the relevant experiments vary widely in origin (collider vs. fixed-target, lepton-hadron vs. hadron-hadron initial states, etc.) and in quantity and quality — in particular, in the sources and sizes of errors, which tend to be dominated by systematics. Further complications arise on the theory side from the necessity of making an ansatz for the starting distributions as well as from issues such as renormalization-scale dependence. The bottom line is that, in practice, fitting PDFs requires making many judgement calls and as much art as science. The people who do global fits have known this all along, of course, but as more and better data accumulate and new questions arise (e.g. regarding jet E_T distributions; see below), it is becoming more clear that users of PDFs should be aware of the subtleties involved.

Global PDF fits are performed by two groups: MRS (Martin, Roberts, Stirling) [4] and CTEQ (Coordinated Theoretical-Experimental Project on QCD) [5]. The fits are more or less continuously updated as new data become available. It is important to realize that *MRS and CTEQ are doing essentially the same thing*; they are performing global fits to more or less the same data using the procedure outlined above. Differences between their parton distributions arise from differences in judgement calls they are required to make in the process of fitting the data. The basic differences between CTEQ and MRS — which translate into *small* differences in the partons they generate — can be summarized as follows.

1. Their starting parameterizations for the x-dependence at the scale Q_0 are slightly different; CTEQ uses one more parameter than MRS does.

2. CTEQ does not include CCFR neutrino DIS data at small x, which do not appear to agree with lepton DIS data. MRS includes the CCFR small x data.

3. MRS uses a fixed renormalization scale for their fits to direct photon data; CTEQ allows the scale to float.

4. Adjustment of the overall normalization of the various data sets differs slightly between MRS and CTEQ.

5. Minor details of the computation of structure functions in their fitting routines are likely to differ somewhat.

Thus parton distributions generated by CTEQ and MRS are very similar, but not identical.

The Structure Functions Subgroup considered how the kinematic range of PDF determinations can be extended in future experiments. It is desirable to go to higher Q^2 and especially to lower x, for example to study diffractive phenomena and study BFKL physics. Because it is unlikely that a dedicated structure function facility is a realistic option for the future, the working group examined the reach achievable by combining the various lepton and hadron beams proposed for the overall Snowmass studies. Results are presented in Table V and Figures 21 and 23 (for $\sqrt{s} \approx 1\ \mathrm{TeV}$ and $2\ \mathrm{TeV}$, respectively) of the Structure Functions summary [3], with the reach of present and planned (i.e., approved) facilities shown in Figure 22 for comparison. These results include kinematic cuts that represent practical limitations on measuring the final states. The bottom line is that, at lower values of Q^2, x values down to 10^{-7} are in principle achievable, and for x closer to 1, the high-Q^2 regions can be better filled in. In general, for a given $\sqrt{s}$, the smallest values of x are best achieved with a high energy hadron beam colliding with a low energy lepton beam, with only minimal loss at high Q^2.

B. Towards a Better Understanding of PDF Uncertainties

Any prediction that uses parton distributions has some uncertainty associated with the PDFs that comes from uncertainties in the original structure function data and from the method used to fit the data. Obviously we would like to be able to quantify that uncertainty. As our high energy physics measurements become more and more precise, this issue becomes more and more important, and can mean the difference between discovering new physics and recognizing 'old' physics for what it is. Or worse, missing out on some new physics signal altogether. Therefore a great deal of effort was expended at Snowmass by the Structure Functions working group to attempt to better understand, and eventually to quantify, PDF uncertainties.

It has been common to estimate the contribution of these uncertainties by performing the same calculation using different sets of parton distributions and identifying the resulting variation with the PDF error. It should be obvious from the previous subsection that this is *not* the appropriate thing to do. MRS and CTEQ use the same data in their fits, and uncertainties in these data are not reflected directly in the fits. A CTEQ-MRS comparison gives, at best, an estimate of the uncertainty due to the differences in their procedures outlined above; it does not give anything remotely resembling the sort of $\pm 1\sigma$ errors we would like to be able to compare with experimental measurements. This becomes more true as new data constrain the

partons ever more tightly. This is illustrated in a study [3] of W mass and asymmetry measurements at the Tevatron. The W mass measurement has improved to the point where the associated PDF uncertainty is becoming very important. An attempt to bracket the PDF errors simply by varying PDF sets is not sufficient; see Section IV of [3] for details.

What then *is* the appropriate thing to do to estimate PDF uncertainties? There is no clear answer yet. Some of the difficulties and potential pitfalls involved in determining PDF errors are already implied above. The Structure Functions subgroup identified a number of such issues that deserve further study which we summarize here; see [3] for details of their studies.

1. *Sources of uncertainties*

(1) *Data used in the fits.*

If all of the data were independent and all sources of uncertainty statistical, a straightforward χ^2 analysis would be valid and the results could be taken at face value. But in the real world the data that go into PDFs come from widely varying experiments and are dominated by systematic errors, and the sources of these systematic errors also vary widely because of the differences in physical processes involved. For example, jet energy uncertainties may dominate one experiment, while another is complicated by nuclear effects, for which corrections must be applied, and so on. In addition, some measurements are more difficult or complicated than others, and some systematic uncertainties correspondingly more difficult to estimate. While in some cases systematic errors can be estimated quite reliably, in others the best we can do is an educated guess.

To confound matters further still, the errors within (and sometimes between) experiments are often correlated. A proper treatment would require taking this into account, which would in turn require having detailed information about the correlations, e.g. in the form of correlation matrices. Such information has not been available until recently, when several experimental groups have begun providing it[6].

(2) *Theory.*

There are uncertainties on the theory side as well, stemming mostly from the fact that we can only calculate to finite order in perturbation theory. This is manifest in things like renormalization scale dependence and higher twist corrections. There are also questions such as how to correct for nuclear effects and how to handle the charm mass in DIS. It is tricky to estimate uncertainties associated with these issues; the very reason we need to estimate them in the first place — viz., that we don't know the exact results — also guarantees that we cannot know how large an error we are really making. In general our best bet is to perform calculations to the highest order manageable, thereby minimizing the errors themselves. For estimating those errors, we must use sophisticated guesses, for example from varying the renormalization and factorization scales. In addition, some of these errors are also correlated, and even if we could estimate them reliably, it is far from obvious how to set up a theoretical error matrix.

(3) *The fitting procedure itself.*

In addition to those with the data and the theory, the fitting procedure itself introduces some uncertainties. These involve the judgement calls indicated above. For example, what should be done when two sets of data disagree outright, or if a good fit to one set comes only at the expense of a good fit to another? What constraints should be applied to the data, e.g. sum rules from the theory, or precision measurements (such as that of α_s) from other experiments? How should we choose a starting parameterization for the parton distributions in the absence of guidance from the theory? Is it better to have more parameters for more flexibility, or fewer parameters for less arbitrariness? Should the experimentalists' (and theorists') estimation of their errors be taken at face value? Each of the myriad choices required in performing global fits to such disparate experiments is a potential source of uncertainty. How to quantify those uncertainties is at this point as subjective as the choices themselves.

In fact a preliminary study has been done for one of these issues; see section IIE of [3]. The uncertainties associated with differences in parameterization can be quantified, at least in the context of the particular parameterizations used by MRS and CTEQ. The purpose was to investigate how well CTEQ partons could be modeled by MRS. A fit was performed to CTEQ3M partons at the starting scale Q_0 using the more restrictive MRS parameterization.[1] The study compared the MRS-parameterized fit to the original CTEQ fit as a function of x for the gluon, u valence, and d valence distributions. The deviation between the two sets is never more than 2%, and is less than 1% for most of the x range, the exception being for values of x approaching 1. This preliminary study shows that the difference in parameterizations is relatively minor source of differences between MRS and CTEQ, and presumably the lack of sensitivity of the fits to the details of the parameterization also shows that it is not a significant source of uncertainty in the fits themselves.

2. *A realistic goal: 'custom' parton distributions*

The preceeding discussion suggests that it is very difficult — and possibly even meaningless — to attempt to distill the disparate sources of uncertainty into a single, all-purpose PDF error. It is perhaps more sensible, and certainly more realistic, to tailor the estimation of PDF uncertainties to a given physical process. That is, we can determine what particular distributions in what x range dominate in the specific physical process of interest. Then global fits to parton distributions can be generated by varying within their allowed ranges the data sets that contribute in the relevant region, while still requiring a good fit to the remaining data. In fact such an approach has already been taken for distributions relevant to inclusive jet E_T distributions at the Tevatron. In [7], the MRS collaboration generated PDFs with different values of α_s allowed by various data sets, and the CTEQ collaboration has generated a set of PDFs (CTEQHJ [8]) which are tailored specifically to accommodate the high E_T jet data. Another possible application is to the W mass measurement, which is sensitive to the u and d quark valence distributions; one can vary them to the extent permitted by the W asymmetry data to get a first shot at estimating the PDF uncer-

[1] Note that the difference is largest at the starting scale Q_0 because QCD evolution washes out differences as Q^2 increases.

tainty.

This approach was strongly advocated at Snowmass [3]. It requires a bit more sophistication on the part of PDF users (not to mention more work for the people who perform the global fits!), but for the forseeable future it seems to be our best bet for obtaining reasonable estimates of PDF uncertainties.

C. Case in Point: Jet E_T Distributions

1. *High* E_T

Many of the points mentioned above are nicely illustrated by the study of the jet E_T distributions recently measured by CDF and DØ [9, 10]. The inclusive jet E_T distribution has long been held up as evidence for how well QCD works; the agreement between data and NLO QCD as the cross section falls by at least six orders of magnitude is indeed impressive. But recently CDF measured an excess above NLO QCD expectations [11] for $E_T > 200\ \mathrm{GeV}$ [9]. Is this new physics, or is there simply something missing in our comparison? It is our duty to rule out every possible Standard Model explanation before concluding, e.g., that we have observed compositeness. This is particularly true because DØ does not see a clear excess at high E_T [10]; however, their results are not inconsistent with CDF's, because their (DØ's) errors are larger.

A number of questions then arise as to how well we really know the uncertainties in the theory and the experiment. On the experimental side, how well is jet energy measured at high E_T? Are uncertainties associated with such factors as the jet algorithm and the various necessary corrections under control? On the theoretical side, how large can we expect higher-order corrections to be? What about renormalization- and factorization-scale dependence?[2] What is the uncertainty in the QCD prediction due to parton distributions — is there enough leeway there to bring theory and experiment back into agreement?

The latter question was of considerable interest to this working group. MRS have shown [13] that it is not possible to bring the CDF results into agreement with the theory by adjusting the quark distributions without spoiling the global fit to other data. The CTEQ collaboration focussed on the gluon [8] and showed that, with an additional parameter, it is possible to adjust the gluon distribution at large x to accommodate the CDF data, because the gluon is not so well constrained in that region.

There are several points to be made here. First, this exercise shows that comparing PDF sets does not give a realistic reckoning of how much variation is possible in the PDFs. A comparison of MRS and CTEQ gluons in this region would give a difference on the order of 10–20%. But the CTEQHJ gluon wound up larger by as much as a factor of two than previous ones, and that was without a significant sacrifice in the quality of the fit. Second, we see that some distributions are more tightly constrained by existing data than others. Third, we want our parameterizations to be flexible but not arbitrary. Fourth, this provides an example of the 'custom' parton distributions described above. Finally, we will soon have independent information about the gluon in this region from the E706 prompt photon experiment.

[2] A recent paper suggests [12] that the discrepancy may be accounted for by factorization *scheme* dependence.

2. *Medium* E_T

The bottom line of the above exercise is that the high-E_T jet data *can* be brought into agreement with the theory by exploiting the flexibility in the gluon distribution at large x. Before breathing a collective sigh of relief, however, we must come to terms with a problem that has yet to be resolved: the medium-E_T jet distribution. In 1995 the Tevatron ran briefly at a center of mass energy of 630 GeV, and CDF measured the inclusive jet E_T distribution [14]. If the distribution is expressed in terms of the variable $x_T \equiv 2E_T/\sqrt{s}$, it scales: the distribution is independent of center of mass energy and the parton distribution dependence cancels out. Thus the jet x_T distributions measured at 630 and 1800 GeV should agree. They do not, as shown in Figure 1. There is less room for possible explanations here than above; in particular, the disagreement *cannot* be fixed with partons. It may be that we do not understand QCD as well as we think we do, or it may be that we do not understand jet measurements as well as we think we do. In either case, it is clear that there is *something* we still don't understand, and until we resolve the questions about medium-E_T jets, we cannot be confident that we understand high-E_T jets.

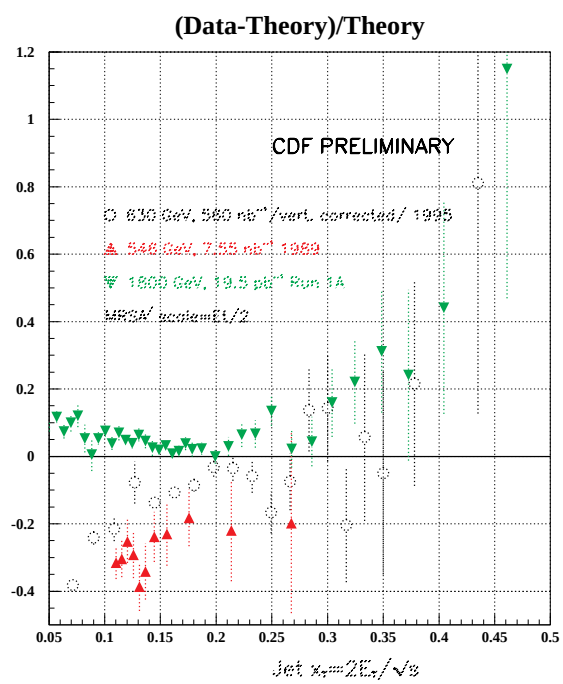

Figure 1: Preliminary CDF measurement of inclusive jet x_T distribution at center-of-mass energies 546, 630, and 1800 GeV [14].

D. Structure Functions and α_s Measurements

The strong coupling constant α_s can be determined from measurements of deep inelastic structure functions, either from their Q^2 evolution, or via sum rules. The Snowmass studies focussed

on what is required to improve these measurements to an accuracy of a few percent or better. We summarize these issues here; for more details and how this fits in with other methods, see [3] and [2]. See also Section II above.

1. Q^2 evolution of structure functions

At lowest order, deep inelastic structure functions depend only on x and are independent of Q^2. But QCD predicts that at order α_s, the structure functions evolve with Q^2. Therefore an observation of this evolution provides a measurement of α_s. The best measurements in this method are obtained from non-(flavor-)singlet structure functions because their evolution is independent of the gluon distribution, which, as we saw above, is not as well determined as those of the quarks. Further gains can be made by using large values of x, which virtually eliminates any sea quark dependence as well. This can be done in either charged lepton or neutrino DIS.

Experimental errors in these measurements are dominated not by statistics but by systematics — in particular, energy uncertainties. Thus improved measurements would require better calorimetry and better calibration techniques. Theoretical uncertainties are dominated by renormalization and factorization scale dependence; these could be dealt with by computing the necessary higher order terms or by allowing the two scales to float and fitting from data.

2. Sum rules

QCD predicts order α_s corrections to the various sum rules for combinations of structure functions integrated over all values of x. Measuring these integrals — the Gross-Llewellyn-Smith and Bjorken sum rules are used in practice — therefore provides a complementary method for measuring α_s, with a complementary set of uncertainties. The sums predicted by the theory are not subject to scale uncertainties at the level seen in measuring Q^2 evolution; the difficulties here are mostly experimental in nature. One has to do with low x: in principle the integration extends to $x = 0$, but in practice the measurements can only go to finite x. Therefore it is necessary to extrapolate, which introduces uncertainties that can be difficult to estimate. In addition, low-x measurements tend to be made at low Q^2, which introduces complications associated with higher twist effects. But avoiding higher twist effects by going to higher Q^2 introduces a new problem, namely that α_s is smaller at higher Q^2, which reduces the size of the effect one is trying to measure (which is a correction to the overall sum). This can be mitigated somewhat with sufficient statistics.

E. Heavy Quark Hadroproduction

Finally, some attention was devoted to heavy quark hadroproduction. For some time measurements of heavy quark production have significantly exceeded theoretical predictions. Apparently the problem was that fixed-order perturbative calculations were unable to account for large logarithms that involved the heavy quark mass and the center of mass energy or transverse momentum. Efforts to solve this problem by using heavy quark fragmentation functions have led to improved agreement; recent efforts [15] incorporating flavor-excitation and flavor-fragmentation diagrams have improved agreement further still. See [3] and references therein for details.

IV. LOW-x & DIFFRACTIVE PHYSICS

A. ep collisions

A renewed interest in diffractive phenomena has been sparked by ep events that occur at high Q^2 and small x. The observation at HERA of deep inelastic scattering events with a large rapidity gap in the final state between the proton direction and the first energy deposit in the detector is an indication of diffractive scattering [16]. The flatness of the rapidity gap distribution, as well as other properties of the events such as independence of the cross section on W, are consistent with photon diffractive dissociation off a Pomeron. Studies of these events are providing insights into the transition from perturbative to non-perturbative scattering and promise to provide more information as the low-Q^2 transition region is further mapped out.

The strong rise in the proton structure function, $F_2(x, Q^2)$ at small x and large Q^2, which indicates a strong rise in the $\gamma^* p$ total cross section, underscores the importance of understanding the role of diffraction at low x[18].

While previous studies of diffraction at HERA are based on the rapidity gap method, more recent data have been collected with Leading Proton Spectrometers (LPS) involving "Roman Pot Detectors". These data provide a sample of events with smaller statistics and different systematics but also with a cleaner interpretation as diffraction and with less background from Reggeon exchanges[18].

Exclusive reactions, such as elastic vector meson production, provide stringent tests of calculations in perturbative QCD, as well as new methods for extracting gluon distributions.

Inclusive reactions both in deep inelastic scattering and photoproduction have produced insights into diffractive phenomena. Rapidity gap events form about 10% of the total deep inelastic scattering cross section and have been used to measure a diffractive proton structure function. Studies of hard diffractive photoproduction at HERA have focussed on high p_T jet production and jets separated by a large rapidity gap. These studies suggest a dominant gluon content to the pomeron and also that production may be taking place by a direct photoproduction in addition to resolved photoproduction.

Additional diffraction studies at HERA with increased luminosity and extended coverage (i.e. LPS) in the very forward proton region will undoubtedly lead to a better understanding of the nature of the diffractive process and how it relates to QCD.

Increased statistics will enable the study of the diffractive charm structure function which is very sensitive to the gluonic component of the exchange mechanism [17].

However, it is also important to consider the advantages of going to higher CM energies for a lepton-hadron (ie lepton-quark) collider. Studies suggest that in order to reach values of $x < 10^{-6}$ for $Q^2 >$2 GeV^2, one should consider a high energy lepton-hadron collider option at one of the future hadron-hadron colliders under consideration[3].

Further exploration of color singlet exchange and searches for an enhancement in its cross section would be enabled by an increase in the rapidity coverage either from increased luminosity and an extended detector coverage at HERA or from an increase in the CM energy that would be available at a higher energy lepton-hadron collider.

B. pp collisions

Rapidity gaps have been found at the Tevatron[19, 20] and are now a subject of considerable interest. In principle, such events are an excellent place to study high energy semi-hard physics including the BFKL Pomeron. However, the analysis is complicated by the presence of hadrons coming from soft interactions involving the spectator quarks in the colliding hadrons. BFKL phenomena are observed in pp collisions in events with either a rapidity gap between two jets or between a jet and a beam fragment.

Single diffractive exchange occurs when one of the protons scatters almost elastically and the other becomes a massive multiparticle system[18]. Such events are used to study the structure of the pomeron in the context of a model where the pomeron is composed of quarks and gluons. If the quasi-elastically scattered proton is measured, the t of the pomeron and its momentum fraction are known. If the quasi-elastically scattered particle is not measured, then diffractive events are tagged by the presence of a rapidity gap of typically more than 3 units. While there is a higher rate of such events, their analysis requires integration over t of the pomeron and its momentum fraction.

When there are two high-E_T jets in pomeron-proton collisions, it is possible to reconstruct the momentum fractions of the scattered partons. Both CDF and D0 have very good evidence for diffractive dijets from observation of an excess of rapidity gaps in one beam direction. These are single diffractive events where the high x_F particle is not seen. They correspond to about 1% of the dijet cross section. CDF also has evidence for diffractive W production. With additional statistics, both experiments should be able to constrain the pomeron structure function. Other venues for exploration include diffractive heavy flavor production, and looking for double pomeron exchange in events with two rapidity gaps. Both of these processes will require substantially more statistics than presently available.

The increased luminosity of Tevatron Run II and the upgrade of CDF and D0 will provide an important opportunity to enhance understanding of diffractive physics. The principal difficulty will be the increased rate of multiple interactions, which will tend to obscure rapidity gaps. CDF and D0 plan to substantially increase their statistics for diffractive and forward physics during Run II. An increase in statistics of more than 2 orders of magnitude over that acquired in Run 1c is needed to provide an adequate study of single diffractive exchange with tagged quasi-elastically scattered (anti)protons. This will require longer running time with a constantly active diffractive trigger (not dedicated runs), improved acceptance, the installation of pots on both downstream arms if possible, and improved triggers that veto on multiple interactions. If the detectors are equipped with pots on both arms, they will be able to study fully constrained double pomeron events. If CDF and D0 are able to increase their rapidity coverage, they will enhance their gap detection and also extend their very-forward gap physics.

There is also the possibility that a new experiment might be carried out in the C0 intersection region at the Tevatron Collider for Run II. One option for C0 is a detector devoted to forward and full acceptance physics proposed by the T864 group. This experiment proposes to study rapidity gaps in soft and hard diffraction, double diffractive dissociation, the onset of BFKL enhancement, forward strangeness, charm and beauty production, multiparticle correlations, and forward neutrons.

Diffractive physics at the LHC promises to be a rich source of information since certain topologies will be cleaner due to cleaner events. It will be possible to look for diffractive Higgs events with reduced hadronic activity in the rapidity region near the Higgs particle[21]. Both single and double pomeron exchange can be observed, particularly in $H \rightarrow \gamma\gamma$ events. In addition, single diffraction at the LHC can be studied in $b\bar{b}$ production.

The overall rapidity span at the LHC increases from that of the Tevatron by 15 to 19 units. The mass reach of diffractively produced states also increases dramatically. An example is that for double pomeron exchange, (with $x_F > 0.95$) central masses extend to 90 GeV at the Tevatron and to 700 GeV at the LHC. This extended range enables the LHC to go beyond high-E_T jet physics to electroweak probes, W, Z.

A concern with rapidity gap physics at the LHC is the multiple interactions caused by the high luminosity. The general purpose detectors, ATLAS and CMS, also cover only about half of the rapidity range with their present designs. A proposal that addresses these concerns is being developed for a full acceptance detector called FELIX. It is composed of recycled components from ALEPH and UA1 along with very forward calorimeters and trackers extending for 450 m to enable elastic and diffractive measurements. The goal is to measure charged particles, photons, muons and jets over the entire rapidity range. Being a detector devoted to this physics program, it could run with reduced luminosity to improve identification of rapidity gaps. ATLAS and CMS could also improve their measurement of diffractive physics by installing Roman pots to tag high-x_F protons and to provide diffractive jet triggers. These collaborations have such options under active investigation.

Beyond the LHC, the best venue for diffractive physics appears to be a very large hadron collider with energy of 50 - 100 TeV per beam. This would yield a rapidity range of 25 units. Pomeron-pomeron collisions of up to 5 - 10 TeV may be reached, which puts them well into possible SUSY and Higgs sectors. However, a machine with such beam energy will also require very high luminosity and therefore experience as many as 100 interactions per crossing. This suggests consideration of a second lower-luminosity interaction region, dedicated to diffractive and forward physics, where single interactions could be observed. One option would be to use 2 km long partially instrumented straight sections on either side of a modest (i.e. upgraded CDF or D0) central detector. This suggests incorporating a 4 km straight section into future very large hadron collider designs.

V. SPIN PHYSICS

Polarized processes involving hadrons satisfy a simple generalization of the factorization theorems used in hadronic physics,

$$\sigma \sim (\text{Structure Function}) \times \sigma(\text{Hard Scattering}) \times (\text{Fragmentation Function}). \quad (1)$$

The hard scattering cross sections can be calculated in perturbative QCD, but the parton structure and fragmentation functions must be determined experimentally. A primary focus of spin experiments will clearly be the measurement of polarized structure functions and the verification of the sum rules relating the various structure functions. One would also like to measure the x and Q^2 dependences of the various structure functions and sum rules and compare with the predictions of NLO QCD.

In 1988, the EMC μN scattering experiment obtained a measurement of the nucleon spin structure function that violated the Ellis -Jaffe sum rule. The interpretation of this violation was that either the strange sea in the proton is highly polarized or that the valence quarks carry little spin, while the remainder of the spin is carried either by the gluons or by orbital angular momentum. This result and the apparent violation of the sum rule has stimulated a variety of spin experiments.

A. Polarized Structure Functions

Current experiments at SLAC E143 and CERN SMC have provided measurements of the g_1 structure function on protons with $x > 4 \times 10^{-3}$. Higher energies at HERA with a polarized proton beam or at a fixed target experiment at an NLC, could allow for measurements down to $x \sim 6 \times 10^{-3}$. The study of structure functions at low x is particularly interesting since current data show a rise in g_1^p at low x. The QCD evolution equations, however, predict that g_1^p will change sign at low x and higher Q^2 and actually become negative.[22] This prediction challenges our theoretical understanding of QCD at low x and of higher twist effects which become relevant in this regime, as well as requiring new experimental data to verify the theoretical predictions. Ref. [23] discusses the statistical accuracy which could be obtained at HERA or an NLC.

The polarized beam capability proposed for RHIC offers a unique array of spin measurements. Both protons will be highly polarized ($> 70\%$, either transversely or longitudinally), with high luminosity, $\mathcal{L} = 2 \times 10^{32}/cm^2/sec$, and energies between $\sqrt{s} = 200$ and 500 GeV. This allows the measurements of the gluon structure function $G(x)$ for nuclei, $\Delta G(x)$ for pN, and $h_1(x)$, (which counts the valence quark polarization). The distribution h_1 will be measured with transverse spin asymmetries using both γ^* and Z^* production. Gluon polarizations, $G(x)$ and $\Delta G(x)$, can be measured by using direct photons from the dominant quark- gluon Compton scattering process, $qg \to \gamma q$, and through medium p_T jets, ($p_T \sim 20 - 50\ GeV$), which are predominantly quark- gluon produced. $\Delta G(x)$ can then be extracted from the longitudinal spin asymmetry, A_{LL}, which is predicted in NLO QCD to be $10 - 20\ \%$. [24]

Polarized protons at RHIC can also measure parity violating asymmetries involving $W^\pm$ production (where the W decays leptonically). Assuming Δq is known from deep inelastic scattering experiments, a precise measurement of the quark structure functions Δu and Δd can be extracted from the parity violating W decays as shown in Fig. 2.[25]

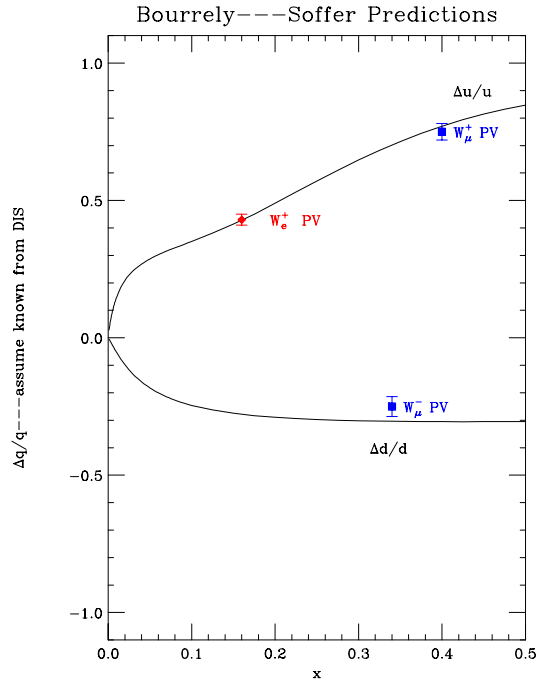

Figure 2: Expected sensitivities for $\Delta u/u$ and $\Delta d/d$ from the measurement of parity violating effects in $W^\pm$ production at RHIC with $800/pb^{-1}$ at $\sqrt{s} = 500\ GeV$. The solid curves are the theoretical predictions. This figure from Ref.[25].

B. Spin Asymmetries

Both single (one polarized beam) and double (both beams polarized) spin asymmetries can yield useful information about QCD. Single spin effects in hard scattering processes are negligible and so the measurement of single spin asymmetries tests our understanding of higher twist and non-perturbative physics. The double spin asymmetries can be used to extract moments such as $g_1(x, Q^2)$ and $g_2(x, q^2)$, giving information on the scale dependence and small x behaviour of the polarized structure functions.

VI. CONCLUSIONS

There remains much to be learned from the study of QCD and strong interactions. A precise test of the predictions of perturbative QCD will be possible with the measurement of $\alpha_s(M_Z)$ to 1%. This now appears to be a realizable goal for a combination of experiments spanning a large range of Q^2. Results can be expected from the hadronic event shapes at the NLC and also from the evolution of the structure functions and the jet E_T spectrum at future running of HERA and the TeVatron. The ultimate resolution would be provided by the full fb^{-1} sample planned for the HERA upgrade or a LEP $\times$ LHC DIS facility.

The largest lever arm in Q^2 of the planned facilities would be provided by the LHC. We can also could expect important contributions from the GLS sum rule measured with fixed target neutrino beams from present running with the TeVatron and improved resolution at TeV33. Even better resolution would be provided by a neutrino beam from the LHC or possibly from a muon collider if it is feasible. There is also an expectation of 1% measurements from lattice gauge calculations of the spin-averaged splittings in the Υ and Ψ systems.

The measurement of structure functions and the parton density functions (PDFs) determined from them are necessary for understanding high momentum processes involving hadrons and also contain information themselves about the underlying physics of hadrons. Understanding them is critical to understanding the fundamental particles and their interactions. The PDFs are now determined over a wide kinematic range from the HERA data at small x to the TeVatron jet data at high Q^2. There has been substantial recent progress on the determination of the PDFs and their dependence on experimental data, but there is much to be learned and considerable challenges in combining experiments with vastly different numbers of data points and complex systematic errors. Nevertheless, this work is very important due to the ubiquitous use of PDFs in almost all experimental measurements. Examples include measurements of the W mass and heavy quark hadroproduction. Future facilities such as LEP $\times$ LHC, a low energy lepton beam colliding with a very large hadron collider beam, an NLC colliding with a conventional proton collider beam, or a muon collider beam on a conventional proton collider beam would all illuminate different regions of the $x-Q^2$ plane as shown in ref.[3]. The dramatic rise of the F_2 with decreasing x at low x observed in the HERA data must eventually lead to saturation of the parton densities. Future facilities such as these may answer where these saturation effects become manifest. In addition, the small x region can provide tests of diffractive phenomena and resummation techniques. It appears that for fixed $\sqrt{s}$, the best opportunities for probing small x occur for a high energy hadron beam colliding with a low energy lepton beam, in particular the preferred ep facility would be to match the highest hadron beam energy with a modest lepton beam energy.

We are just beginning to explore and comprehend the new information on QCD from diffractive phenomena at high energies. Additional diffractive studies at HERA with measurement of the leading proton and higher statistics should provide new insights into the structure of diffraction and the nature of the Pomeron. The increased luminosity of TeV II and the upgrade of the CDF and D0 detectors should also enhance the understanding of diffractive physics. If these detectors are able to increase their rapidity coverage in order to better detect rapidity gaps, they will yield even more results. A dedicated full acceptance experiment at C0 would provide additional opportunities. The increased rapidity range at the LHC and the extension of the mass reach of diffractively produced states will enable the LHC to go beyond high-E_T jets physics to electroweak probes, W, Z. The multiple interactions experienced by the general purpose LHC detectors would be alleviated a dedicated lower luminosity full acceptance detector which could be specifically built to have a much larger rapidity coverage. Beyond the LHC, the best opportunity would be a very large hadron collider with an energy of 50 to 100 TeV per beam. At such a facility, pomeron-pomeron collisions are possible with energies high enough to cover the Higgs and SUSY sectors.

Spin physics is opening a new window on QCD. Measurements of the polarized structure functions and tests of their sum rules will provide important information. We can expect that results from both HERA collider and NLC fixed target data would provide a strong test of the Q^2 dependence of the spin structure functions and provide information about the polarization of the quarks and gluons. The RHIC spin program will provide complementary tests of spin physics in a hadronic environment. Here, there is the opportunity to search for QCD effects beyond the leading power so that the dynamics of QCD can be studied beyond the parton model.

These investigations of QCD are important to pursue because QCD is an essential component of particle physics. Each of the facilities considered provides different and often complementary opportunities to investigate the wide range of QCD phenomena. The vast range of QCD effects also underscores its importance because it will affect almost every measurement proposed in this summer study. This means that understanding QCD is critical to understanding the new physics that might be observed at new facilities. The study of QCD must progress along side the search for new phenomena and the more precise measurements of electroweak parameters if we are to realize the full benefit of future facilities.

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