Summary of DIS05

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APOLOGIES

I wish to issue the usual apologies - this talk is not really a summary of the conference, but rather a discussion of some selected topics. No attempt is made to summarize in a balanced way all the material presented in the different sessions. These sessions were expertly summarized already by the conveners of the sessions. In particular, I will not have anything to say about the status of Pentaquark searches. The situation is quite confusing and requires a review of its own. For this topic, I refer the reader to the summaries of R. Jaffe and S. Maxfield and to the individual presentations. I will also not cover any topics in electroweak physics and searches for physics beyond the Standard Model. These are clearly interesting and will be a major focus of HERA II. However, they are outside the scope of my selected topics. I will not do justice to the theoretical developments, nor to the work at JLAB, nor the spin community, ... Rather, this 'summary' is really a commentary on where we stand in our understanding of the structure of hadrons and a discussion of possibilities for future research. It should be read in the right spirit - as a qualitative look at the state of DIS physics.

THE KEY TOPICS

In my view, the key topics addressed in experimental and theoretical studies of deep-inelastic scattering are:

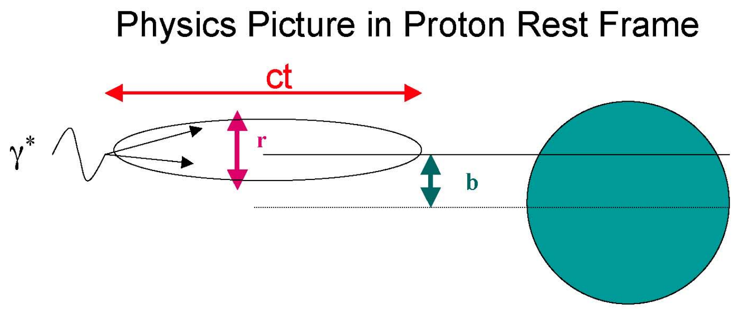
- the study of the structure of hadronic matter;
- small-x physics, or the universal QCD fuzz;
- the value and running of the strong coupling constant, α_S;
- the precision to which we can predict cross sections involving strong interactions;
- the decomposition of the spin of the proton into its different components.

Many other topics are addressed in deep-inelastic scattering, such as measuring electroweak parameters, testing the Standard Model, searches for new physics such as Leptoquark production, searches for exotic physics such as Pentaquark production, etc. These are all important aspects of the research program, but DIS makes a more unique contribution to the topics listed above.

In the following, I will give my view on selected topics in the list, giving more weight to the topics where I consider myself more expert. I will conclude with a discussion of possible future projects.

HADRONIC STRUCTURE

How would we describe a proton to non-experts ? Would we resort to the infinite momentum frame, use light-cone variables, ... ? We would clearly like to describe the proton, or any particle, in its rest frame. The goal should be something like this: the 6-D (position and momentum) distribution of the quarks and gluons. We immediately run into the problem that the usual variables we use to describe proton structure, Q^2 and x need to be translated into a space-time picture. For Q^2, this is straightforward - the transverse distance scale probed is conjugate to Q, and we have the simple relation $r \sim 0.2\text{fm}/Q$, with Q in GeV. What about x ? The Bjorken-frame identification of x as a longitudinal momentum fraction is certainly not applicable in the proton rest frame, where the longitudinal momentum of a parton can be positive or negative and averages to zero. We would therefore like a different, more intuitive, variable to describe the proton scattering data at small-x. One possibility is to view the scattering as an (evolved) dipole-proton interaction.



The distance scale over which the photon fluctuations survive scale as $1/x$, and this coherence length can be considered as a possible variable to describe the scattering. To ensure that we are studying proton structure, we should require $x > 0.1$, which corresponds to a coherence length of $ct < 1$ fm. For $x < 0.01$, we are measuring something else - the general properties of radiation in QCD or the time structure of the fluctuations. More on this later. We therefore make the classification:

- hadron structure $x \geq 0.1$;
- small-x physics $x \leq 0.01$.

The region in between is some mix of the two.

Recent Results

We have seen many interesting results on hadronic structure in this workshop. For example, S. Kuhn presented results on the structure functions of bound neutrons measured

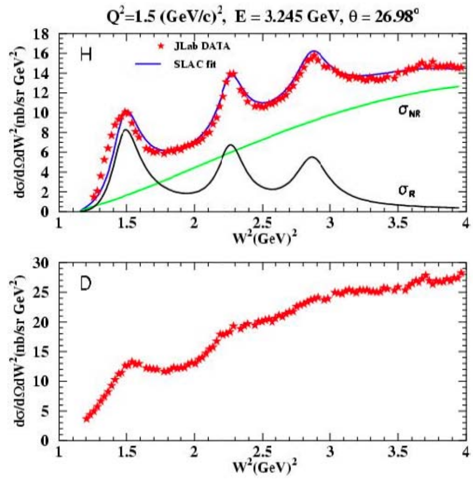


FIGURE 1. Proton and deuteron structure at small Q^2 and small W measured at JLAB.

at JLAB. An example of the extensive data available is given in Fig. 1. Here the data are plotted as a function of W, the center-of-mass energy of the final hadronic system, and the familiar resonances are very clearly seen when the scattering takes place on a proton, but are strongly suppressed when the scattering takes place on a deuteron.

New results were also presented for much high Q^2 and W. The final NuTeV structure functions were shown by M. Tzanov, and are now seen to be in good agreement with CDHS measurements. The discrepancy with previous CCFR results at the higher values of x is understood. These data represent the most precise data on neutrino-nucleon scattering we are likely to have for quite some time. Y. Ning presented a new technique for measuring cross sections up to $x = 1$ at HERA. The technique relies on the observation that the scattered electron is measured with full acceptance at high-x for $Q \geq 500$ GeV^2. At the highest x, the value of x cannot be determined, but an integrated cross section up to $x = 1$ can be extracted. The ZEUS results using this technique are shown in Fig. 2. Precise nucleon structure data is available over a wide range of Q^2 and provides a genuine challenge to models purporting to describe this structure.

Our final understanding of hadronic structure will likely come from the lattice. Interesting results were shown in the workshop by D. Renner on quark densities as a function of x and distance from the center of the proton, indicating that steady progress is being made on this front. A. Belitsky presented beautiful pictures on quark imaging via quantum phase space distributions, albeit in a fast-moving frame. One of his pictures is reproduced in Fig. 3. Maybe we will eventually have a 6-D picture of hadrons !

SMALL-*X* PHYSICS

Small-x physics means long radiation chains. Given that every subsequent fluctuation has a shorter duration than the parent, this implies that small-x physics can be interpreted as the study of QCD radiation at very short time scales. The higher the energy available in the scattering, the shorter the time fluctuations which can be observed. The source

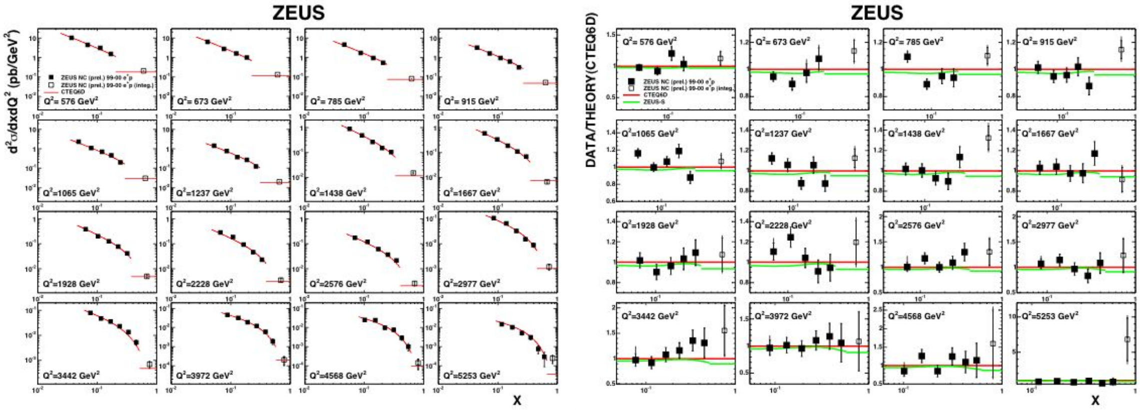


FIGURE 2. Differential cross sections measured by ZEUS as a function of x in Q^2 bins. The right-hand plot shows the ratio of the measurements to expectations based on the CTEQ6D pdf. The cross section in the highest x bin is $\int \frac{d^2\sigma}{dxdQ^2} dx/\Delta x$, where Δx is the size of the bin. This value is plotted at the center of the bin.

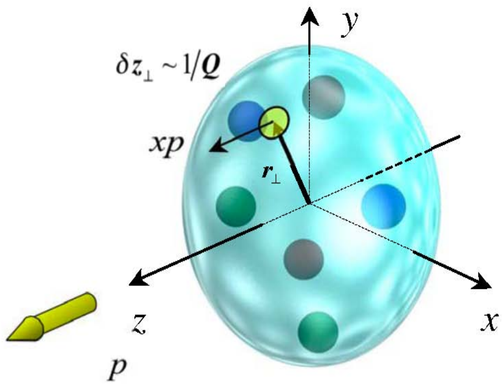


FIGURE 3. Quark imaging in the proton, from A. Belitsky.

of the radiation in a scattering process cannot be identified uniquely, and the intuition depends on the reference frame chosen. However, in a long chain one can suppose that the knowledge of the initial conditions has been forgotten and the behavior of the scattering cross sections with energy should become universal. This appears to be supported by the data. As Donnachie and Landshoff pointed out, hadronic total cross sections can be described by a universal energy dependence at high energies. This same energy dependence fits the HERA photoproduction data. It therefore appears that for soft scattering, this universality is present. What about at larger Q^2 values ? HERA discovered the rise of the structure functions at small-x, and this rise is clearly Q^2 dependent (see Fig. 4). A transition from the soft scattering behavior to a steeper dependence of the cross section on energy is seen around $Q^2 \approx 0.5$ GeV^2. However,

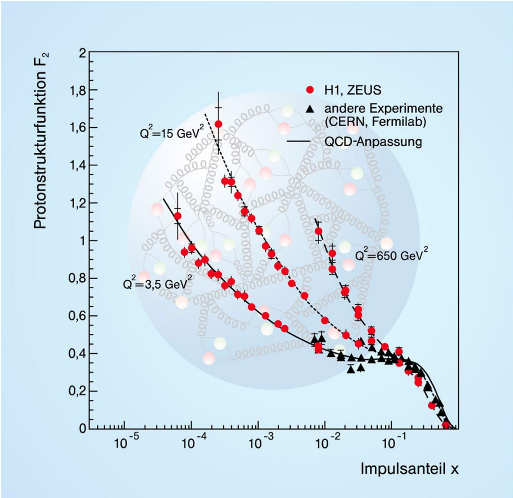


FIGURE 4. Sample of proton F_2 data, showing the change in the x-dependence as Q^2 changes.

it appears that, for fixed Q^2, the energy dependence is again universal. For example, the ratio of the diffractive cross section to the total DIS cross section at HERA is flat vs energy (see Fig. 5). The structure function data for events with a leading neutron, dominated by electron-pion scattering, also shows the same behavior as the total cross section. The implication is that whether the electron is scattering on a quark from the proton, or from a constituent of the proton such as a Pomeron or pion, the energy dependence of the cross section is the same. I.e., the quark and gluon densities evolve in a universal way.

The behavior of the total cross section at small-x is strikingly simple. The cross section rises as a power of W which is Q^2 dependent, and is otherwise featureless. This is in contrast to the large-x behavior, where the real structure of the proton is seen. However, the simplicity of the data has not led to a simple theoretical modelling. Despite the efforts of a large number of theorists over a period covering twenty years, we still do not have a satisfactory theoretical understanding of the high energy behavior of the scattering cross sections. In the language used earlier, we do not have a description of the QCD fluctuations in the time domain, in particular for very short times. The Golec-Biernat, Wüsthoff model has helped tremendously, in that it provided a framework for explaining simultaneously the total as well as diffractive cross sections. Further developments of this model have allowed for better fits and for the mapping of the hadronic matter profile in the proton. The discovery that this model contained a new type of scaling - geometric scaling - has prompted many theorists to look for new ways to attack the small-x physics, and we heard interesting talks, e.g., from A. Stasto and R. Enberg about the relationship of the small-x physics to travelling wave solutions to known nonlinear differential equations. The Color Glass Condensate is a related approach to the small-x physics which also provides an appealing physical picture of small-x physics. The point made by L. McLerran, R. Venugopalan et al., is that there should exist a kinematical region where perturbative calculations are possible although the Q^2 scale is small. The large gluon density at small-x introduces a new scale, the saturation scale, Q_S, which

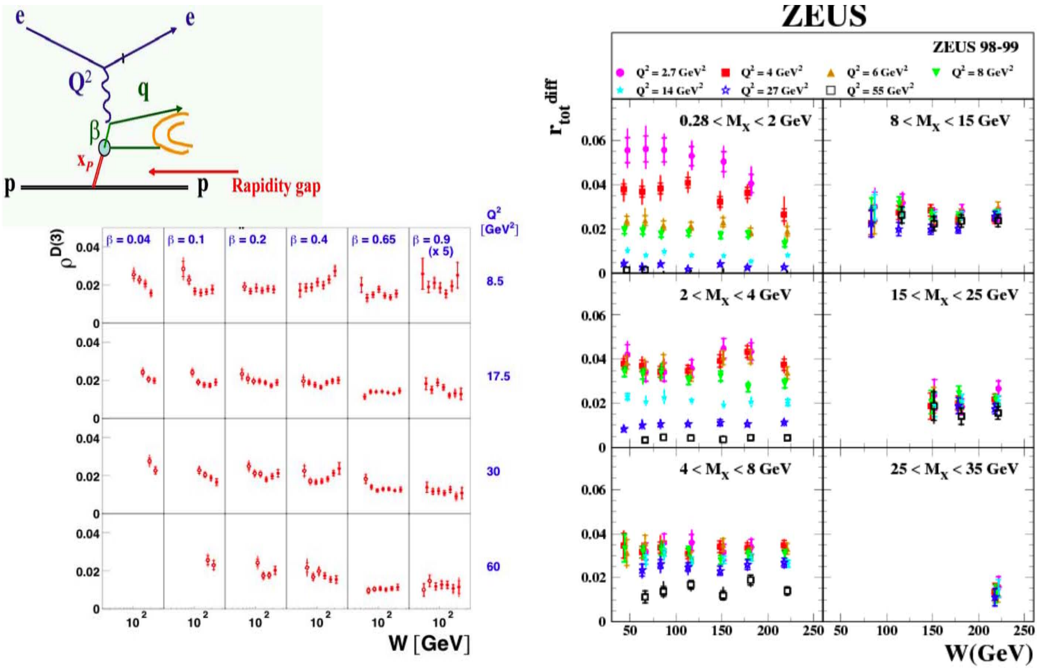


FIGURE 5. Ratio of diffractive to total scattering cross sections versus W and binned in different variables. The left plot shows H1 data, whereas the right plot shows ZEUS data.

can be large enough so that the tools of classical field theory can be used. J. Jalilian-Marian made the point that the CGC made predictions for RHIC which have indeed been validated. Nevertheless, I think it is still fair to say that we are still some ways from a satisfactory understanding of the small-x physics.

The Gluon Density

Understanding small-x processes means understanding **the** gluon density. The **the** is in bold face because I refer to the universal gluon density present around all particles (in all interactions). In DIS, we customarily call this the gluon density of the proton, but as discussed we could also view the scattering as an evolved dipole scattering on the proton. We would then be talking about the gluon density of the electron or photon. Figure 6 gives an indication of our present knowledge of the gluon density. There are clearly large uncertainties at both small- and large-x. The ZEUS collaboration has shown in this workshop that adding jet production data can help reduce the strong correlation between the gluon density and α_S found in fits to structure function data. This is clearly an important step and will result in more reliable parton densities from HERA.

I will focus here on the small-x gluon density. Eleven years ago, we held a workshop at Nevis Labs, Columbia University, dedicated to investigating the different possibilities for measuring the gluon density at HERA. Many processes were considered, from a measurement of F_L, to vector meson production, jet production, etc. At the conclusion of the workshop, the mood was rather gloomy - although many techniques were shown

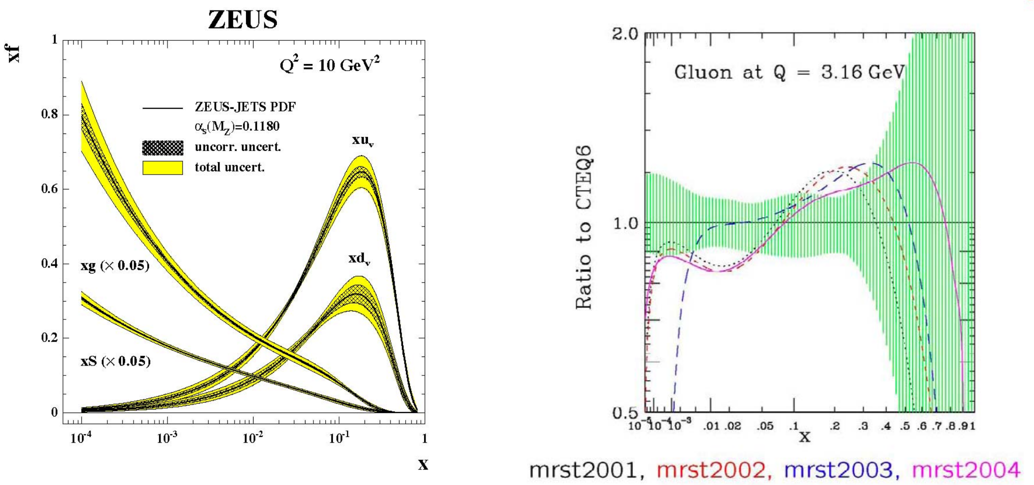


FIGURE 6. Recent result on parton densities from ZEUS (left). The right-hand plot shows the ratio of different gluon densities to that from CTEQ6.

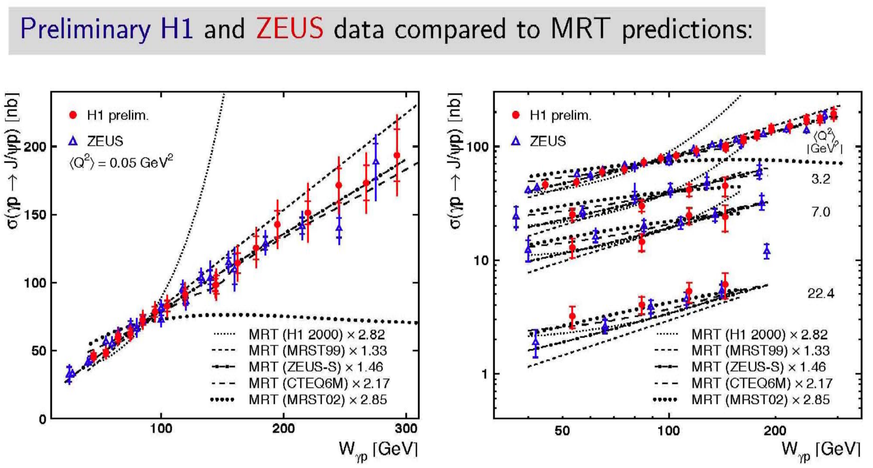


FIGURE 7. W dependence of the J/ψ cross section compared to calculations by Martin, Ryskin and Teubner using different gluon densities.

to in principle give access to the gluon density, the theory was clearly not advanced enough to make quantitative statements. It appears we are now on the brink of a new era, where exclusive processes can be used to help pin down the gluon. As mentioned above, HERA jet data are now used in pdf extraction fits. In addition, M. Teubner showed at this conference that predictions for exclusive J/ψ production depend very strongly on the gluon density. The calculations are compared to H1 data in Fig. 7. While the normalization of the calculations is still very uncertain, the shapes are less so. If the curves in the figure are to be taken seriously, then it is clear that many gluon density parametrizations could immediately be ruled out. The claim, and hope, is that we are now close to this goal.

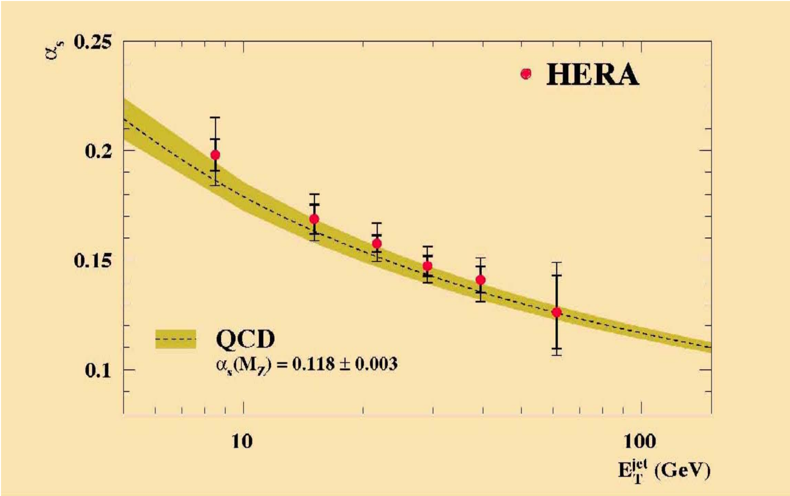


FIGURE 8. The strong coupling constant, α_S, measured from jet rates.

The gold-plated measurement for the gluon density has always been the measurement of F_L. This is a difficult measurement, requiring running HERA with different beam energies. A study by M. Klein and C. Gwenlan-Barr indicates that a limited low energy run at HERA would indeed be able to discriminate between different gluon densities. This running option should certainly be considered very seriously. The small-x behavior of the parton densities, and in particular the gluon, are likely to be the legacy of HERA.

α_S

The strong coupling constant, α_S, is the least well known of the fundamental coupling constants, and therefore merits all the attention it receives. Not only is the absolute value important, but the running of the coupling is also important for understanding the unification of the different forces. Many different techniques are available in DIS to extract this parameter, from the evolution of the structure functions with Q^2, to the measurement of jet rates, events shapes, etc. Getting consistent answers from these different approaches is a valuable test of how well we can calculate using QCD. A summary of α_S measurements at HERA using jet rate data, presented by C. Glasman, is shown in Fig. 8. The HERA data provides not only precise information on the value of α_S, but also provides clear evidence for the 'running' of α_S as a function of scale. The dominant uncertainty on α_S has been, and continues to be, the theoretical uncertainty - in particular the definition of the scale at which α_S is measured. Further progress on our knowledge of α_S is contingent on getting better theoretical control of the scales involved.

PRECISION QCD TESTS

X. Zu quoted a translation (by J. Legge) of Confucius: "... The mechanic, who wishes to do his work well, must first sharpen his tools ...". Now that there is general agreement that QCD is the correct theory to describe the strong interactions, the task is to understand what QCD tells us. We still do not have a first-principles understanding of some of our most basic observations, such as how color confinement comes about, why the constituent quark model works so well, the chiral phase transition, how spin is built up in a hadron, or why the high-energy behavior of the cross sections are as they are.

In addition to trying to understand what is implied by QCD, we need precise calculations so we can distinguish new physics from 'known' physics. Our standard calculational tool is perturbative QCD, and the standard approach has been to make more and more precise perturbative calculations. L. Dixon presented a summary of where theorists stand in this task. Steady progress is visible, despite the fact that the complexity of the calculations is growing enormously. On the non-pQCD front, lattice QCD is becoming ever more reliable, but also here the calculational barrier is tremendous. Meanwhile, the search goes on for different calculational approaches. A recent favorite is the application of the twistor-space approach to multi-parton scattering which has brought string theorists and QCD experts closer together. On the phenomenological side, there is continued progress on producing more reliable parton densities, in particular with respect to the uncertainties on the pdfs. J. Pumplin showed us the pitfalls awaiting those who attempt to produce global fits to world data to extract the pdfs. The standard rules of statistics are thrown out the window and pragmatic approaches are required - i.e., this is the business of experts. A very important element for practically all predictions involving QCD at colliders is the event simulator. Models are employed to simulate the QCD radiation processes and the later recombination of the partons into hadrons. New developments here are always welcome. In an interesting contribution, X. Zu described her efforts at making event generators more true to QCD by including correct parton kinematics.

Beauty Production

As an example of the difficulty in trying to discern new physics from 'known' QCD, consider the status of open beauty production. The HERA results are summarized in Fig. 9. According to the standard rules of statistics, one would say that the theory (QCD at NLO) does not reproduce the data. I.e., we either need higher order calculations or we have found new physics. However, we were told on at least two occasions (S. Frixione in his opening plenary talk, M. Corradi in his summary talk on heavy flavors) that this level of disagreement does not indicate a problem with the calculations. In a Bayesian language, we could phrase the situation as follows:

$$P(theory+model|data)P(data) = P(data|theory+model)P(theory+model)$$

where *theory* is the prediction of NLO QCD and *model* contains the fragmentation and hadronization. The data is Fig. 9 is clearly at odds with the prediction, i.e., *P(data | theory)* is very small. Saying that we are happy with the result implies that either *P(data)* is quite small - i.e., we have a problem with the measurements (in this case, we would be using QCD as a guide for making proper measurements), or *P(theory+model | data)* is quite small. But we believe that QCD is correct. So, the problem must be in the modelling or the lack of higher order calculations. It would certainly be useful to have

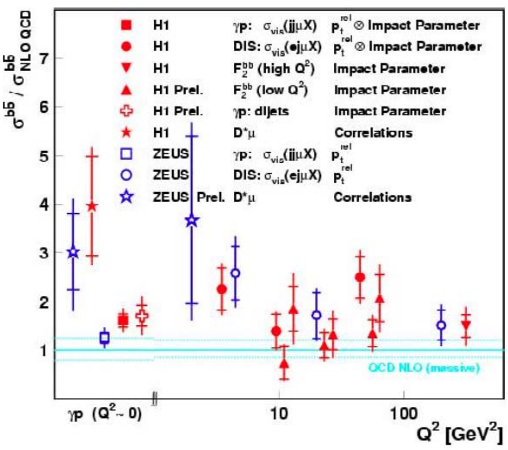


FIGURE 9. Summary of open beauty production at HERA.

some idea of our degree of belief in each of 1) the data; 2) the NLO predictions; 3) the modelling of the fragmentation and hadronization.

Jet Rates at the Tevatron

The example given in the last section is far from unique. There is the famous story of the high-E_T jet rates observed at the Tevatron and trying to puzzle out whether or not new physics was being observed. In the end, the discrepancy between data & theory was ascribed to uncertainties in the gluon density of the proton. The current status of the comparison of measured to predicted cross sections is shown in Fig. 10. The data and predictions have become much more precise, and currently no significant deviation is observed.

Parton Density Functions

The lesson from the jet rates was that we needed to understand the uncertainties in the parton density functions, and a tremendous effort was made by CTEQ and MRST to incorporate uncertainties with the pdfs. This effort has been taken up by other groups (H1 &ZEUS, Alekhin). There are also completely new approaches under study, such as the use of neural nets to extract pdfs and their uncertainties. J. Chacon presented the latest results from the NNPDF collaboration, and made the point that neural networks are the least biased approach, requiring only the assumption of smoothness of the pdfs. As an exercize for the method, the knowledge of the pdfs using only data prior to HERA was shown (see Fig. 11), and it was clear that all solutions, from rising structure functions at small-*x* to falling structure functions were compatible with existing data and QCD. This example shows that: 1) we cannot predict the *x*-dependence of structure functions, 2) the

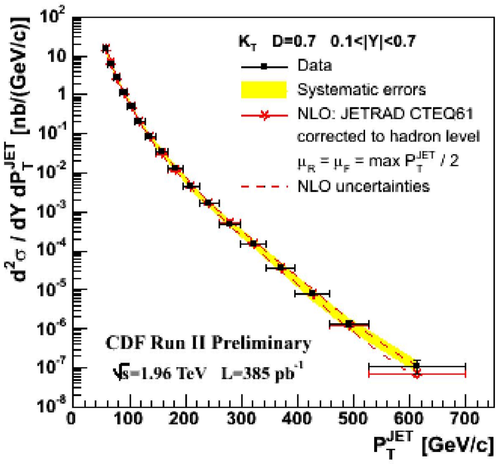


FIGURE 10. Jet differential cross section measured at the Tevatron by the CDF collaboration.

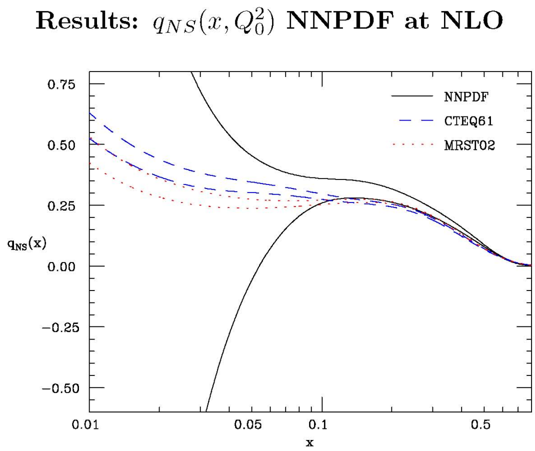


FIGURE 11. Neural-net results on the non-singlet structure function at small-*x* resulting from using pre-HERA data only.

rise of the structure functions with decreasing *x* at small *x* is therefore an experimental discovery, and 3) the NN approach appears to indeed produce sensible results.

J. Pumplin reiterated that the most serious problem in determining uncertainty bands on the pdfs is the problem of incompatible data sets. The point was made using with the plot shown in Fig. 12. Two different data sets are shown which are clearly incompatible given the quoted errors. All analysis methods assume Gaussian distributions of the observed values around the true values, and the toy data shown in Fig. 12 clearly violate this assumption. Someone made a mistake - to paraphrase Donald Rumsfled, there are ‘unknown unknowns’. All pdf fitting groups have to deal with this issue, and different choices are made on how to modify standard statistical methods to extract a best fit and uncertainty for the pdfs. I.e., the results are necessarily subjective and require expert

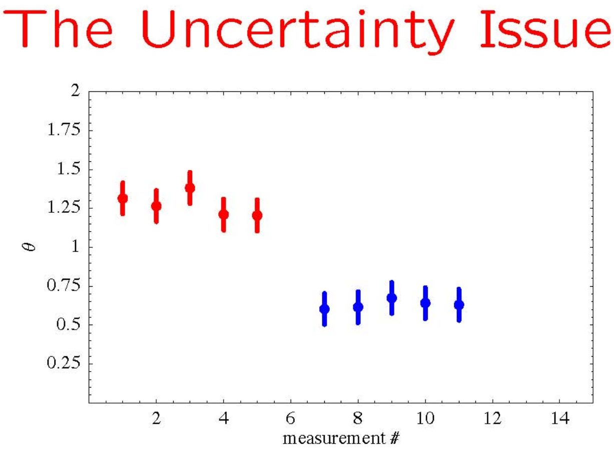


FIGURE 12. Representation of incompatible data sets used in pdf extraction, from J. Pumplin.

knowledge. Efforts to extract pdfs from a single or a limited number of data sets reduce this problem, but at the price of having less discerning data.

SPIN

We have no idea how the spin of a hadron is built up out of the constituent parton spins and orbital angular momenta. This is probably too strong a statement - the constituent quark model does very well at explaining the magnetic moments, and must contain some truth. So perhaps it is better to say that we have no idea how to build up the spin of a constituent quark from the partons. While the question seems rather straightforward, the techniques used to experimentally address this issue get ever more complicated. As D. Ryckbosch pointed out, traditionally lepton-nucleon spin physics meant measuring the structure function $g_1(x)$, and using this to extract the net spin carried by quarks and antiquarks. This resulted in the now well-known fact that we cannot build up the spin of a nucleon simply by adding the spins of the quarks and antiquarks, and the focus turned toward the spin carried by gluons and the spin contained in orbital angular momentum. A summary of the data on g_1/F_1 on protons and deuterons is shown in Fig. 13. The data are measured at many different Q^2, and yet match beautifully when plotted as a function of x. This implies that g_1 and F_1 have a very similar Q^2 dependence.

The (sparse) data on the spin carried by gluons is shown in Fig. 14. There are different approaches discussed to accessing the gluon content of the spin structure. One is to study the Q^2 evolution of g_1. This is limited by the relatively small lever arm available in Q^2. Other approaches mentioned include heavy flavor production or jet production. I note that similar processes have also been discussed for some time in the unpolarized community as techniques for extracting the gluon density, and only recently have been found to be useful. It is very difficult to improve on the scaling violations as a technique for extracting the gluon density.

Newer topics have arisen in spin physics in the last several years. It has become clear

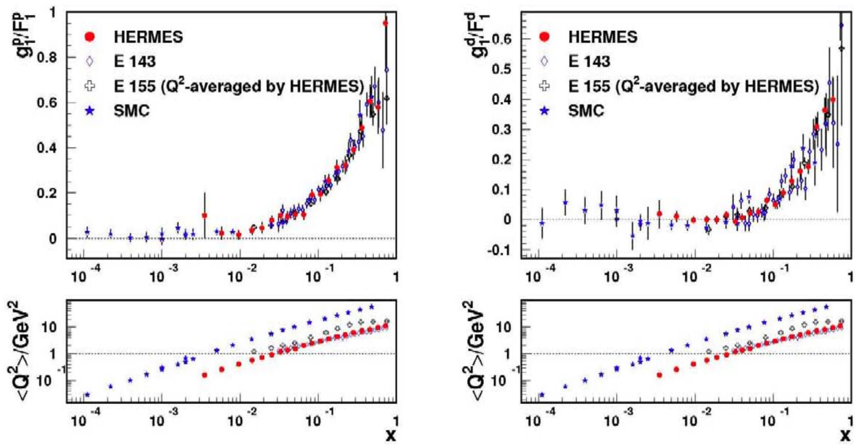


FIGURE 13. Summary of the world's data on the structure function g_1, scaled to F_1.

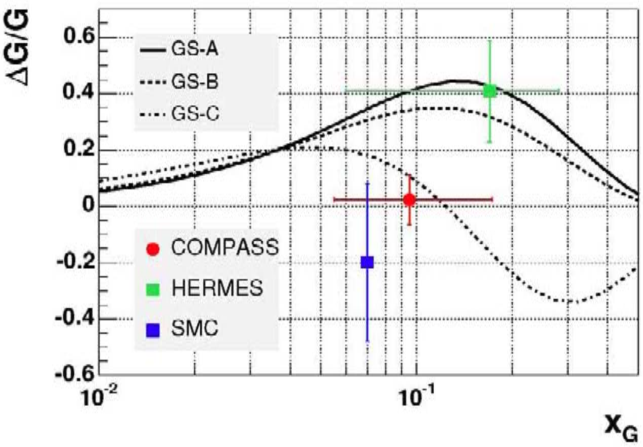


FIGURE 14. Available data on the net spin carried by gluons, compared with various calculations.

that a complete description will require also an understanding of the transverse spin distributions. New effects, such as the Collins or Sivers effects involving the transverse polarization of quarks have been introduced and are under study. One thing is obvious - new experiments over a broad kinematic range will be necessary to measure the required quantities over a large enough phase space to really understand how spin is built up from the constituents.

FUTURE PROSPECTS

There are several ongoing and proposed experiments to further our understanding of hadron structure (which I roughly defined as $x > 0.1$). These are

- The JLAB upgrade to 12 GeV electron beam energy and the subsequent experiments (described by C. Keppel);
- The MINERVA experiment at FNAL to study nuclear structure with a high-intensity neutrino beam (J. Morfin);
- Continued operation of COMPASS and future fixed target experiments at CERN (E. Rondio).

These experiments will primarily study the spin and flavor structure of the nucleon in the valence region. Very large data sets will be available so that multiply differential cross sections can be measured, and a genuine 3-D picture of hadronic matter extracted. E. Rondio also stressed the possibility for Compass to make precision measurements in the Q^2 range where HERA has observed a transition from a soft energy dependence to a Q^2 dependent variation of the W-dependence of the cross section. Decisions on going ahead with these projects, in particular the JLAB upgrade, are expected in the near future.

The eRHIC program, described by A. Deshpande, would cover the major topics of DIS: the mapping out of the flavor and spin structure of hadronic matter, and the detailed study of small-x physics, particularly in the realm of heavier nuclei. Given that RHIC exists, the expensive part of eRHIC has already been built. What is needed is an electron beam - the concept is for a ring to intersect RHIC at one interaction region. The strong points of eRHIC in relation to HERA would be the much larger expected luminosity, the ability to run with a variety of nuclei, the availability of polarized proton beam, and the variability of the beam energies over a wide range. The disadvantage relative to HERA is the considerably smaller center-of-mass energy. As B. Surrow has discussed, one detector will not be enough to get all the physics out of eRHIC: for the small-x physics and QCD studies, the ideal detector has acceptance over the largest possible rapidity range. This detector would require a lot of free space along the beam line. A design for such a detector is shown in Fig. 15, and follows in the lines of ideas from J. Bjorken regarding a full acceptance spectrometer. For spin structure function measurements, however, the key is luminosity, which is maximized by putting accelerator elements as near the interaction point as possible. If only one IP is possible, then a staged approach could be considered: first the low luminosity, large acceptance detector is built, and then the high luminosity version of the accelerator and detector are introduced.

Continuing on the road to higher energies and smaller-x, three other experimental possibilities were discussed. H. Kowalski presented calculations showing the acceptance and physics which could be reached with a very forward (420m) detector at the LHC. The basic reaction studied is shown in Fig. 16. This type of reaction has many advantages, as repeatedly stressed by V. Khoze: the quantum numbers of the produced system can be disentangled and the signal-to-background ratio for some processes, such as Higgs production, can be considerably improved. These reactions also allow the continued study of the gluon in the proton in an interesting kinematic region, and could allow the measurement of the energy dependence of pp diffractive reactions with a hard scale.

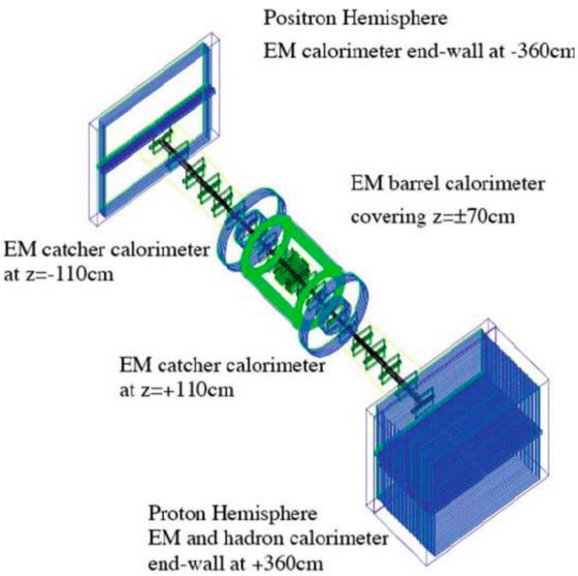


FIGURE 15. Conceptual design for a large acceptance detector for eRHIC.

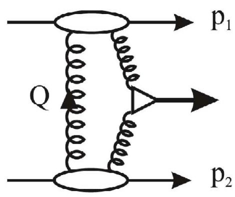


FIGURE 16. Diagram for a $pp \to ppX$ reaction at the LHC mediated by gluon exchange.

In principle, the ILC will also give access to small-x. However, the e^+e^- option is not ideal, since the rates will be low, and forward detectors would be difficult to implement. A better option for DIS type physics is an $e\gamma$ collider.

At the very highest energies, one could also consider building a linear electron accelerator to collide with the LHC. One could extend the HERA reach by one order of magnitude in x and thereby pursue the study of small-x physics in a completely new domain. The time scale for such a project is clearly very long.

There are clearly many ideas being discussed for future projects. The choice(s) of which of these projects to follow should obviously be driven by the physics. However, the time scale on which such projects could be realized should be considered in conjunction with the physics arguments, and a reasonable balance should be struck between the ultimate physics program and a realizeable program.

ACKNOWLEDGMENTS

I would like to thank the Wesley Smith and his team for organizing such an informative and pleasant workshop. I would also like to thank all those I had the pleasure of learning from and discussing with during DIS05.