1 Physics Results and Analysis

1.1 Recent Results

Recent ZEUS results have further extended the x and Q^2 range of deep inelastic scattering measurements to $0.11 \leq Q^2 \leq 5000$ GeV^2 and x to 10^{-5}. The structure function F_2 continues to rapidly increase as x decreases. The gluon distribution extracted from F_2 appears to account for this steep increase. New measurements have shown that charm quarks contribute a significant fraction ~ 25%) to F_2 in this kinematic range. For $Q^2 \geq 1.5$ GeV^2 a perturbative QCD description is valid and works well and here the Regge (soft pomeron) picture is not appropriate. There appears to be a transition between this non-perturbative region to the region of $Q^2 \leq 0.5$ GeV^2, where a soft pomeron model alone successfully describes the almost real photoproduction. A similar picture is seen in the measurement of the dependence of the γ^*p cross section on cm energy.

ZEUS has completed the analysis of all high Q^2 neutral current data. The present situation is that, taking into account the typical systematic uncertainty of 2-3%, the 1995-7 data are consistent with the Standard Model to $Q^2 \sim 30000$ GeV^2 with two exceptional events at $Q^2 >$ 35000 GeV^2 from the 1996 sample. The rate of jet production in deep inelastic scattering events has yielded a measurement of the strong coupling constant α_s which displayed its “running” with Q^2 over the range from $100 < Q^2 < 4000$ GeV^2. Jets produced in photoproduction have been used to probe scales to 10^3 GeV^2. Dijet production in photoproduction has verified important aspects of parton dynamics. Resolved and direct photoproduction processes have been shown to result from gluon and quark exchange, respectively. ZEUS data have shown that hard diffraction has the characteristics of pomeron exchange, where the pomeron behaves as one or more gluons. The ability to tag the outgoing proton has enabled ZEUS to collect a clean sample of diffractive events, which have been used to extract a diffractive structure function. ZEUS has also identified both direct and resolved components of diffractive dijet photoproduction.

1.2 Wisconsin ZEUS Analysis

Throughout the operation of ZEUS the Wisconsin group have been active participants in the analysis. Among the specific topics whose investigation was spearheaded by Wisconsin personnel are: studies of the properties of the resolved photon jet in photoproduction, searches for first generation leptoquarks, measurements of neutral and charged current cross sections at high Q^2, measurement of prompt photon production in deep inelastic scattering, measurement of the total photoproduction cross section, the measurement of the proton structure function F_2, the extraction of the gluon momentum density in the proton, measurement of the longitudinal structure function, F_L, measurement of the xF_3 structure function from e^-p and e^+p collisions, measurement of the total photoproduction cross section, investigation of dijet photoproduction from real and virtual photons, studies of dijet photoproduction with a forward neutron or a forward proton, measurements of dijet production in deep inelastic scattering, and studies of the trigger efficiency for electron identification in neutral current deep inelastic scattering events and for jets in photoproduction and deep inelastic scattering. We provide details concerning a sample of our current analysis efforts below.

1.2.1 Total Photoproduction Cross Section

Student Richard Cross has described in his thesis the measurement of the γp total cross section at high energy. This fundamental measurement can only be precisely done at HERA. Regge theory has been quite successful in describing the total cross sections of many hadronic particles in a simple picture. The model has been extended to describe elastic scattering (and the total cross section) in similar terms. It ascribes elastic scattering to the t-channel exchange of a mythical particle, thePomeron, which carries no quantum numbers. In some instances the model also includes Reggeon exchange, which does carry quantum numbers. The Reggeon term in the total cross section is quantitatively constrained by low energy data.

The electron radiates a beam of photons, whose energy can be tagged event by event by measurement of the momentum of the parent electron. In 1996 ZEUS devoted a single fill to the measurement of the total $\gamma p \rightarrow \gamma\ X$ cross section. The HERA electron beam provided a beam of nearly real photons (virtuality $Q^2 < 0.02$ GeV^2). Events were accepted in the γp center-of-mass energy range $100 < W\gamma p < 225$ GeV. The beam conditions of the collider were carefully controlled and monitored, in order to minimize systematic errors. The final systematic error is dominated by knowledge of the acceptance of the calorimeter and that of the electron tagging calorimeter, which was located 35 m downstream. The result is shown in Figure 1. The total photoproduction cross-section at a photon-proton center-of-mass energy of 207 GeV is $\sigma_{tot}^{\gamma p} = 163 \pm 1(\text{stat.})^{+13}_{-12}(\text{syst.})\ \mu\text{b}$.

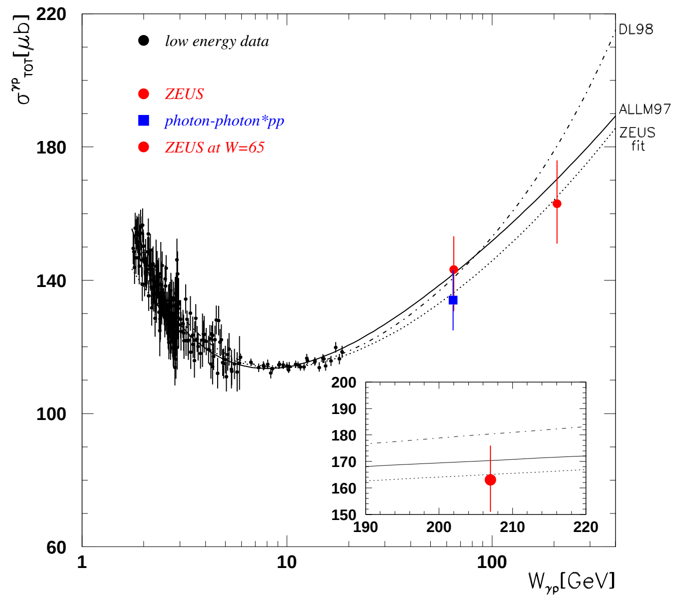

Figure 1. Total γp cross section for ZEUS data compared with previous H1 and ZEUS measurements, low energy data and Regge parameterizations.

This measurement, together with other total cross section data has been interpreted using two Regge inspired models. In ALLM97 one Reggeon and one Pomeron are used to parameterize the data, while in DL98 a second Pomeron is needed. Although this measurement agrees with both parameterizations of the total cross section, it is evident that the second pomeron is not necessary to describe the data. This measurement has been compared to the cross sections obtained by CDF and OPAL experiments using the relation $\sigma_{tot}^{\gamma\gamma} \cdot \sigma_{tot}^{pp} = \left(\sigma_{tot}^{\gamma p}\right)^2$. The photon-photon total cross section, scaled to the ZEUS and CDF energies yields a value of 425 ± 28 *nb* for a center-of-mass energy of 68 GeV, in good agreement with the OPAL measurement of 439^{+45}_{-41} *nb*.

1.2.2 Dijet Photoproduction

Wisconsin student Sean Mattingly measured, as a function of Q^2, the ratio of the dijet cross section due to resolved photoproduction (low x_{γ}.) to that of direct photoproduction (high x_{γ}.). The resolved cross section is dependent on the hadronic structure of the photon. As the photon becomes more virtual it is more likely to interact directly with the result that the resolved cross section should become smaller.

In Figure 2 the measured ratio of the low x_γ cross-section to the high x_γ cross section is clearly seen to decrease as Q^2 increases. The values shown are calculated with the Monte Carlo program *Herwig* that uses a real photon structure function (*GRV LO*) and which does not incorporate suppression of the virtual photon (the straight horizontal line). A similar calculation using a virtual photon structure function (*SaS1D*) that does include suppression of the virtual photon interaction is shown as a curved line. The prediction of the Monte Carlo *LEPTO*, in which the photon has no structure at all is shown as a dot-dashed line. This decreases relative to the direct cross section as Q^2 increases.

The calculations, which use a real photon structure function, clearly do not describe the data. Although the calculation that incorporates a structure function for the virtual photon does fall with increasing Q^2, it does not quantitatively describe the data. We note that, at the highest measured Q^2, the measured ratio is still larger than the *LEPTO* prediction, which assumes no photon structure.

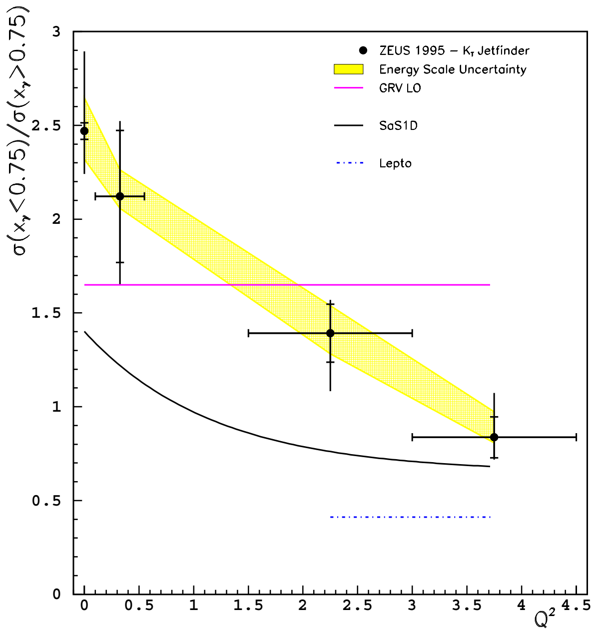

Figure 2. Ratio of the low x_γ cross-section to the high x_γ cross-section as a function of Q^2.

1.2.3 Photon Structure

HERA can be used to study both the proton and the photon structure. The structure of the proton is now well constrained over a large range of the kinematic region.

In the so-called photoproduction region, where the virtuality of the exchanged photon is very small (nearly zero) the structure of the real photons is studied. These processes are characterized by two outgoing partons of large transverse energy that result in dijet events in the final state. The transverse energy of the jets constitutes the hard scale of the process.

The HERA measurements as well as earlier studies at electron-positron colliders have established that the real photon, in addition to its point-like couplings to charged quarks and leptons, also has a partonic structure. The point-like couplings give rise to the direct photon processes, where the photon enters as a whole into the hard interaction. In contrast, the non-point like couplings give rise to the resolved photon processes. In the case of the resolved photon processes the photon structure is commonly described*via* parton distribution functions (PDFs), determined by both perturbative and non-perturbative calculation.

Wisconsin Scientist Dr. Dorian Kçira is extending the studies on photon structure also to virtual photons As noted above the virtual photons are expected to have a partonic structure as well. The language of the photon parton distribution functions may still be retained. As the photon virtuality becomes non-zero, the non-perturbative contributions to the photon structure are expected to diminish and here the photon PDFs are in principle calculable using perturbative Quantum Chromodynamics (pQCD).

In the case of virtual photons, the problem has two scales: the transverse energy of the outgoing jets of particles and the photon virtuality itself. The calculations in this region are determined by the interplay of these two scales. The existence of two scales makes this region more interesting but also more difficult and challenging. Also, only a few measurements exist here from the previous experiments, since in electron-positron colliders it is difficult to do measurements on virtual photons as this requires tagging each of the outgoing electrons in the final state.

The ZEUS experiment has now gathered data over a large photon virtuality range: 0.1 ÷ 10000 GeV^2. This permits a detailed study of the two-scale problem. Our data show differences with leading order (LO) calculations which use the current parameterizations of the virtual photon PDFs.

Comparisons with next-to-leading order (NLO) theoretical predictions need to be done. The goal of the measurements is to be able to determine the PDFs of virtual photons.

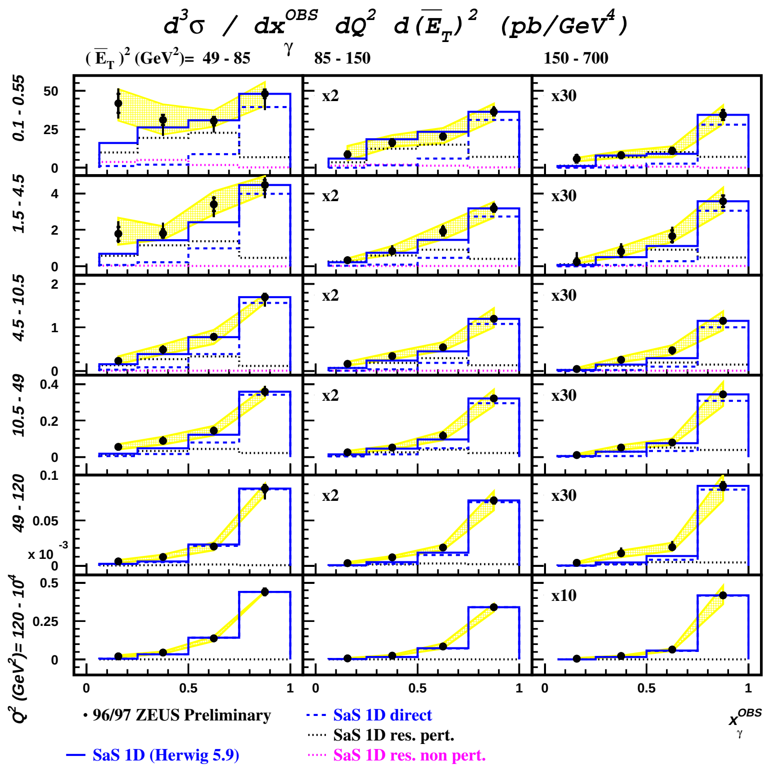

Figure 3. The triple differential cross section in different bins of photon virtuality and mean square transverse energy of the two leading outgoing jets: The measurements are compared to leading order QCD predictions using current parameterizations of the parton distribution functions of virtual photons. Discrepancies are seen in those regions where the resolved photon structure is expected to be important. Conversely, the agreement is good in the regions where the photon is expected to be point like.

1.2.4 Forward Jet Cross Section

The proton is a complex and structured system. A set of kinematic variables that can completely describe its structure has been devised. The proton's structure can be determined iteratively from an initial determination of these variables. One example of this "evolution", is the DGLAP (named for their conceivers: Dokshitzer, Gribov, Lipatov, Alterelli, Parisi) equations, which has been tested extensively because the kinematic range of validity these equations possess is easily accessible at HERA. However, there is another set of equations, the BFKL (Balitski, Fadin, Kuraev, and Lipatov) equations, which, according to QCD, are completely valid in another kinematic regime. Until recently, these BFKL equations have not been able to be tested because of the difficulty in collecting data in the kinematic range where BFKL dynamics are expected to be important. Now that HERA has been running for a few years, we are just on the cusp of having enough data to make interesting tests of BFKL dynamics.

In Figure 4, the forward jet cross-section is plotted as a function of Bjorken-x. It is in the low Bjorken-x region that the BFKL signature is predicted to be revealed. As one can see in the plot, the theory curves do not agree with the data points, particularly for small Bjorken-x. The *LEPTO, HERWIG*, and *ARIADNE* theory curves are meant to model DGLAP behavior, so the deviation of the data away from these curves at small Bjorken-x is expected. However, the LDC curve is meant to include BFKL dynamics, and the disparity between the measured data points and the theory prediction was not understood at the time of this analysis.

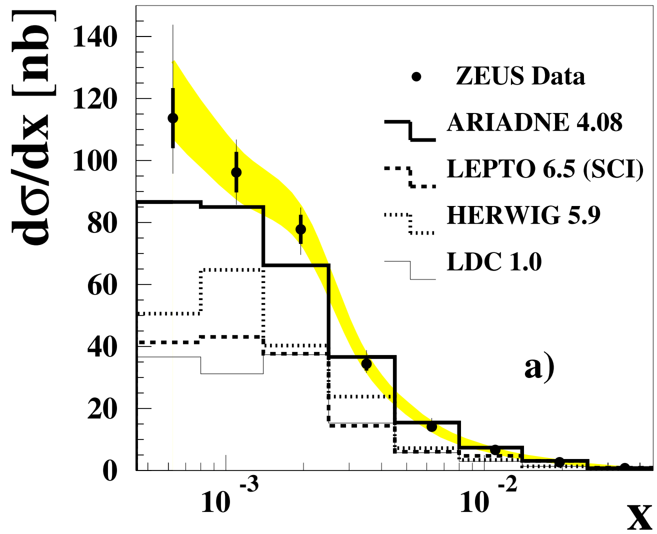

Figure 4. Forward jet cross section as a function of x compared with different models.

The analysis that generated this plot incorporated data taken in 1995, and the question of BFKL has not been studied since then at ZEUS. There have been many advances in the theoretical description of BFKL in the last several years. These advances, combined with the large amount of data collected in the last 5 years makes the subject of BFKL dynamics an exciting one. The ZEUS sister experiment at HERA, H1, has undertaken the question again and has recently done significant work. Wisconsin graduate student S. Lammers will measure the forward jet cross section in the low Bjorken-x region using the new data, with the goal of elucidating the differences between DGLAP and BFKL dynamics.

1.2.5 J/ψ Photoproduction

Wisconsin Scientist Dr. A. Savin is studying the photoproduction of J/ψ mesons, $\gamma p \rightarrow J/\psi p$, using the e^+e^- decay mode. In Figure 5 the increase of the total cross section measured as a function of the photon-proton center-of-mass energy W is shown. It is suggested that this behavior is directly proportional to the gluon density of the proton squared. A fit of the form W^δ to the data yields a value of $\delta = 0.66 \pm 0.02(\text{stat.})\ ^{+0.05}_{-0.08}\ (\text{syst.}) \bullet t/\text{GeV}^2$.

In the framework of Regge phenomenology a direct determination of the Pomeron trajectory can be obtained by measuring the energy dependence of the elastic cross section at fixed values of momentum transfer t. The resulting trajectory is inconsistent with the soft Pomeron and also with the so-called hard Pomeron trajectories but is in agreement with the NLO BFKL calculation.

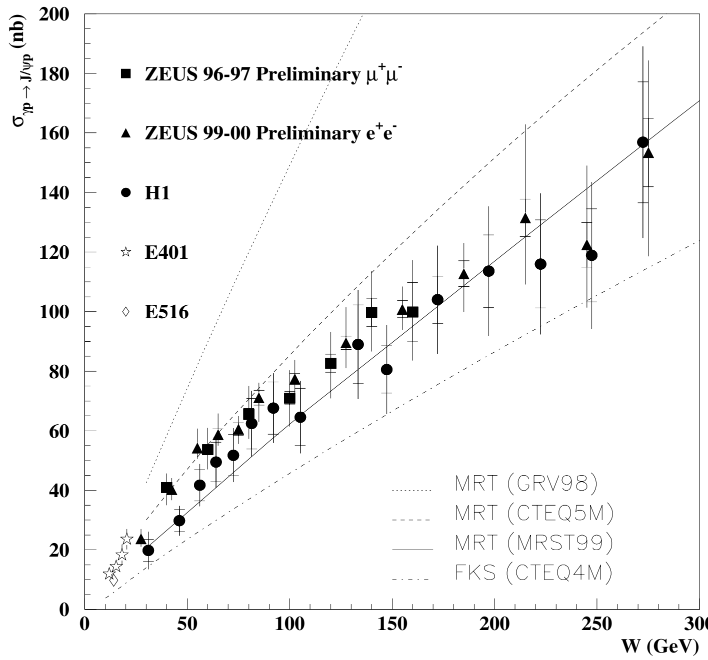

Figure 5. The elastic J/ψ photoproduction cross section as a function of W from HERA and from fixed-target experiments. The QCD predictions using various parameterizations of the gluon density in the proton are shown.

1.2.6 Neutral Current DIS Dijet Cross Sections

As his thesis topic Wisconsin student Doug Chapin measured inclusive dijet production cross sections in neutral current deep inelastic scattering for $10 < Q^2 < 10000$ GeV^2 using the ZEUS 1996 and 1997 data samples. Dijet events are identified using the k_T algorithm. The measured cross sections are compared to theoretical next-to-leading order pQCD calculations.

In Figure 6 the inclusive dijet differential cross section, $d\sigma/d\log_{10}Q^2$, for hadron jets of is compared with the predictions of NLO pQCD. In order to examine possible deviations of the predictions compared to the measure-ments, the ratios of the measured to predicted cross sections are shown. Here the predictions are those of the monte carlo calculation *DISENT*, which use the renormalization scale $\mu_R{}^2 = Q^2$,. The scale uncertainty of the NLO pQCD calculation from *DISENT*, determined by varying $\mu_R{}^2 = Q^2$ in the range ($Q^2/4$, $4Q^2$), is shown as a shaded band. The Q^2 distribution falls by two orders of magnitude and agrees with the NLO calculation to within 10% when the renormalization scale is set to Q^2.

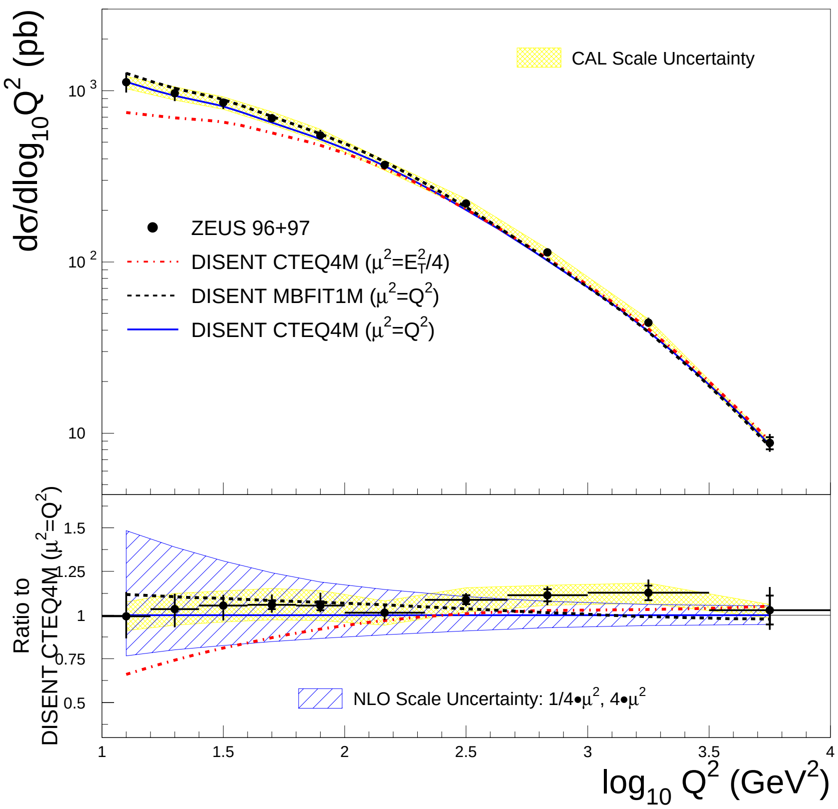

Figure 6. The differential inclusive dijet cross section with respect to Q^2. NLO pQCD calculations using the program DISENT with different proton parton density parameterizations are compared to the data..

This agreement with the data is good considering the theoretical uncertainties of up to 50% for $Q^2 < 20$ GeV^2 due to the variation in the renormalization scale. Only at values greater than 200 GeV^2 are the theoretical uncertainties compatible with those of the data.

1.2.7 Neutral Current Deep Inelastic Scattering at High Q^2

There are now substantial data obtained by both electron-proton and positron-proton collisions. Wisconsin student Jason Breitweg is studying the differential cross sections for e^-p and e^+p collisions at high Q^2. The measurement of neutral current deep inelastic scattering events, in which the electron interacts with the proton *via* the exchange of a photon or Z-boson, provides knowledge of the proton structure. The larger the momentum of the exchanged photon the smaller the scale that can be probed inside the proton.

The analysis uses events in which the momentum of the exchanged photon is very large (~200 GeV^2). A pure sample of these events is selected by means of various criteria; such as the scattered electron’s position and energy. Events that mimic a neutral current deep inelastic scattering event are removed so as to reduce contamination of the sample.

With this sample in hand it is possible to determine how the cross section for the neutral current deep inelastic scattering process depends on the momentum of the exchanged photon. As can be seen in Figure 7 there is good agreement between the measurement and the theoretical prediction using the CTEQ5D Parton Distribution Function. At large values of the photon momentum squared we are limited by the number of events we have, hence the large statistical errors.

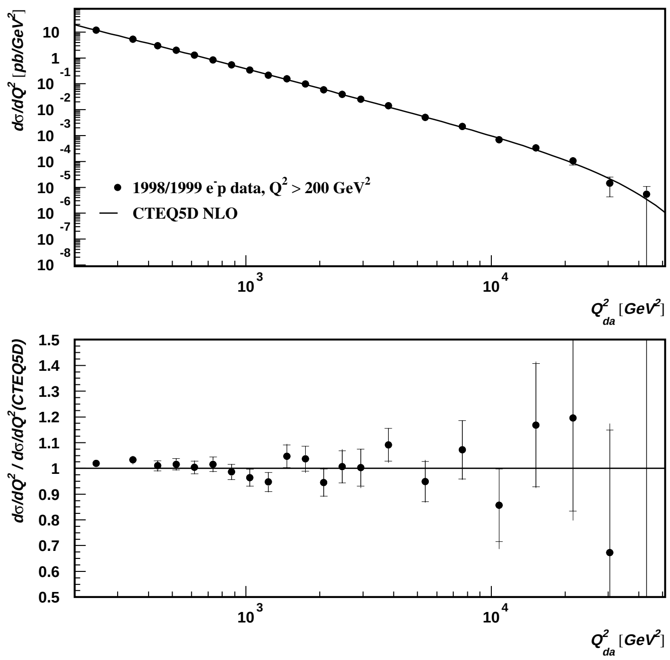

Figure 7. Neutral current cross section for electron data as a function of Q^2 compared with theory using the Parton Distribution Function from CTEQ5D.

1.3 Plans For Physics Analysis

Recent HERA running has been superb. We have in hand large data samples with collisions of 27 GeV electrons and positrons with 920 GeV. We have accumulated a total positron-proton luminosity of 113 pb^{-1}. Upgrades to HERA and ZEUS have been made during a nine month shutdown that ends late this summer. These improvements are expected to provide an order of magnitude increase in integrated luminosity (~ 1000 $pb^{-1)}$ over 4-5 years. In addition, spin rotators will be installed to allow ZEUS to exploit the 60-70% polarization of the electron and positron beams. We note below a few of the large number of physics opportunities that can be addressed in future ZEUS running.

One of our highest priorities will be to continue to search for new phenomena observed in NC and CC events at high Q^2 and x. We will search for such signals in electron proton and positron proton scattering.

Detailed analysis of ZEUS 1998 running, where an integrated luminosity of 45pb^{-1} was accumulated, showed very interesting behavior of the structure functions at low x. The increase in luminosity will open up the high Q^2, high W^2 regime to detailed quantitative study. At some point the Gribov-Lipatov-Altarelli-Parisi QCD evolution must fail.

At ZEUS we will also continue to explore the nature of diffractive dissociation in order to understand the nature of the colorless exchange observed in events with rapidity gaps. In hard photoproduction we also observe events with a large rapidity gap and for which the W dependence agrees with a Pomeron interpretation. In future running we will attempt to determine whether this is indeed an indication of the absence of initial state radiation and color flow between the jet and the photon remnant characteristic of “color bleaching”. It will also explore the very nature of the photon as it undergoes the transition from virtual to real particle. There are indications that, as a virtual particle, the photon 'resolves' itself into quarks and gluons and we hope future data will indicate what happens as the photon becomes 'almost real'.

As the understanding of DIS processes deepens and the statistics grow, ZEUS will continue to search with ever increasing sensitivity for leptoquark and excited electron signals. After the luminosity upgrade is made we hope to explore the full physics capability of HERA by running with polarized electrons and positrons (to explore the left and right handed currents), possibly by running with a deuteron beam (to separately measure neutron and proton structure functions), and by running at different beam energies to measure the longitudinal structure function (F_L).

We intend to continue to pursue these physics goals at ZEUS. As noted earlier ten UW students have completed their thesis work using ZEUS data. In 1995-6, four students graduated: S. Silverstein on a high statistics search for leptoquarks, I. Ali on an analysis of high Q^2 charged and neutral current processes, B. Behrens on the characteristics of the remnant photon jet in resolved photoproduction and A. Goussiou on analysis of the structure function F_2 and the extraction of the gluon density. In 1998, H. Zhang completed his thesis on high Q^2 neutral current events and in 1999 T. Vaiciulis completed his on prompt photons, M. Wodarczyk on the definitive ZEUS measurement of the F_2 structure function, S. Mattingly on photon structure, D. Chapin on DIS dijets and R. Cross on the photoproduction total cross-section. J. Breitweg should graduate this year with a thesis on the *ep* NC cross section. S. Lammers is working on an analysis of forward jets and L. Li will soon begin his analysis work. Students A. Everett and P. Ryan will begin their physics analysis after they have gained experience and worked on the Calorimeter trigger hardware. This summer, students S. Chuang, J. Day and M. Goldschen will start with our group. We expect to add additional students as time goes on. All of these students pursue their analyses under the day-to-day supervision of Assistant Scientist, A. Savin and Postdoc D. Kçira, who reside on-site. Direction is also provided by D. Reeder and W. Smith through frequent visits, and weekly Wisconsin Group videoconferences between Madison and DESY.