IMPLICATION OF THE HERA MEASUREMENTS ON ASTROPARTICLE DATA INTERPRETATION[a]

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Accelerator experiments can provide a solid basis for the interpretation of cosmic ray data which, however, may surpass their energy reach by several orders of magnitude. We present here some recent data on deep-inelastic electron-proton scattering at HERA and review the analysis of these data in terms of parton distribution functions. We also discuss the HERA data on charged current interactions relevant for some more exotic interpretations in the multi-EeV region near the GZK cutoff.

1 Introduction

One of the prime motivations to discuss HERA data at a workshop covering the physics of cosmic rays is the fact that electron-proton (ep) reactions can be viewed as collisions of ultra-high-energy photons - emitted by the electron - with nuclear matter. Comparing to the cosmic ray energy spectrum impinging on the earth's atmosphere, the HERA collider provides a photon beam equivalent to 50 TeV on a stationary proton target, lying about half way (on a logarithmic scale) between the "knee" and the "ankle" of the cosmic ray energy spectrum, i.e. at about almost 10^{14} eV. Such high energy photon-proton collisions are of utmost importance for observational astrophysics, in particular for the understanding of the interactions of ultra-high-energy cosmic photons with our atmosphere which serves, in many cosmic ray experiments, as target and detector.

High energy photon interactions with hadronic matter are governed mainly by the strong interaction, which can be successfully described by quantum chromodynamics (QCD) as long as some "hard scale" of order several GeV is present in the reactions under study. Owing to the photon in the initial state, the overall size of the cross sections is proportional to the square of the fine-structure constant α. The HERA data give direct information on quantities related to QCD, most importantly the parton distribution functions (pdfs) within the nucleon, and the running strong coupling α_S, determining the overall strength of the partonic branching processes. These quantities are important ingredients to the Monte Carlo programs simulating cosmic ray showers in the atmosphere. There is, however, another interesting area in cosmic ray research, where HERA can provide important information, namely ultra-high energy neutrino scattering, which can be inferred from $ep \rightarrow \nu X$ reactions at HERA. Also here, the neutrino energy accessible at HERA is equivalent to about 50 TeV on a stationary proton target.

In this report we briefly summarize some recent data on inclusive scattering from HERA, and discuss the extraction of the parton distribution functions using a combined data set from the two collider experiments H1 and ZEUS. We then will shortly discuss jet final states which

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enable a unique measurement of the running strong coupling and provide new insight into QCD dynamics at very low values of the Bjorken variable x. We finally discuss the relevance of the HERA charged current cross sections for the expectation of ultra-high energy neutrino nucleon cross sections, which may play a role at the very high end of the cosmic ray energy spectrum close to the GZK cutoff.

2 The HERA Electron-Proton-Collider

One of the most successful tools for unraveling the structure of hadrons, most importantly of the nucleons, is deep-inelastic scattering (DIS) using charged leptons as probes. The HERA collider at the Deutsches Elektronen-Synchrotron DESY in Hamburg has provided the highest available center-of-mass energies for the collision of electrons and positrons with protons. HERA has been running from 1992 until mid 2007, accumulating a total of about 500 pb^{-1} for each of the two colliding beam experiments H1[1] and ZEUS[2]. The data taking was divided into two phases, separated by a massive luminosity upgrade program in the years 2001-2002. As a further benefit of the upgrade, HERA also provided longitudinally polarized electron and positron beams, giving access to sensitive tests of the electroweak theory and allowing to carry out unique searches for the production of new heavy particles.

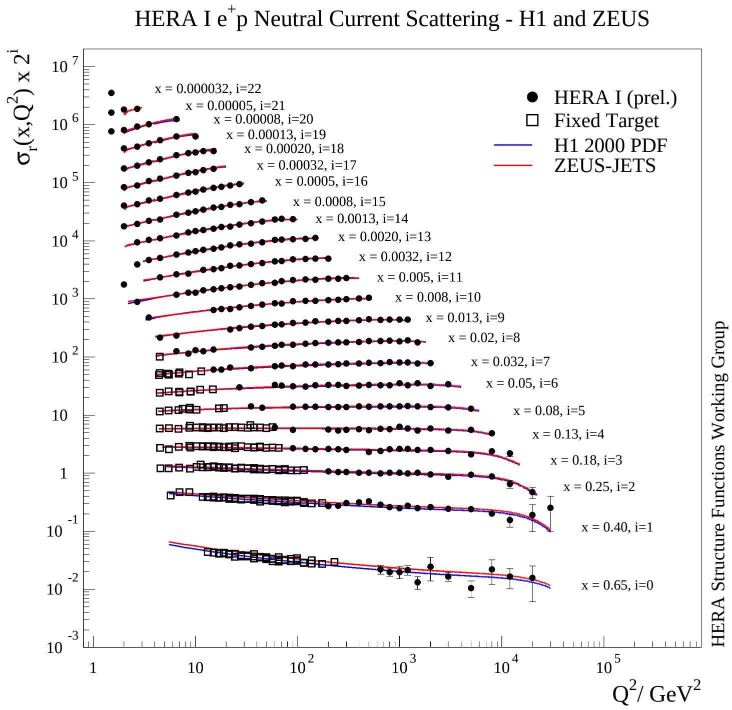

Figure 1: *Measurements of the reduced cross section $\sigma_r(x, Q^2)$ for positron-proton scattering, based on the combined data of H1 [3] and ZEUS [4]. The data show clear evidence for scaling violations, as expected from gluon emission of the initial quarks participating in the hard scattering process. The scaling violations are very well described by pQCD (see the curves). At low Q^2, the data from some fixed target experiments are also shown.*

3 Inclusive Scattering

At distances small compared to the nucleon radius, or equivalently large momentum transfer Q^2 between the incoming and outgoing leptons, perturbative QCD (pQCD) gives an adequate quantitative account of hadronic processes in DIS. The most "elementary" observable in electron-proton scattering is the inclusive DIS cross section, where basically only the 4-vectors of the scattered lepton or the produced hadronic final state are measured.

Inclusive ep scattering can be divided into two distinct classes: Neutral current (NC) reactions ($ep \to eX$), and Charged Current (CC) reactions ($ep \to \nu X$). In NC reactions, a photon or a Z^0 is exchanged between the electron and a quark emitted from the proton. The corresponding double-differential cross section $d^2\sigma/dxdQ^2$, or the so-called "reduced" cross section σ_r factorizing out known kinematic terms, can be written in the following way (similar expressions hold for the CC reactions):

$$\sigma_r(x, Q^2) \equiv \left(\frac{xQ^4}{2\pi\alpha^2 Y_+}\right) \frac{d^2\sigma\,(e^\pm p)}{dx\,dQ^2} = F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3 \qquad (1)$$

Here, the three (positive definite) structure functions F_2, F_L and xF_3 depend both on x and Q^2, and contain the (non-perturbative) parton distribution functions (pdfs). The scaling variable y is related to x and Q^2 via $Q^2 = sxy$, where s is the square of the electron-proton center-of-mass energy. The functions $Y_\pm$ are purely kinematic and are given by $Y_\pm = 1 \pm (1-y)^2$. The structure function F_2 contains contributions from quarks and antiquarks ($\sim x(q+\bar{q})$), F_L is dominated by the gluon distribution ($\sim xg$), and xF_3 is sensitive to the valence quarks ($\sim x(q-\bar{q})$).

At low Q^2 and low y the structure functions xF_3 (from Z^0 exchange) and F_L (suppressed by the factor y^2) can be safely neglected. Residual (small) contributions from F_L can also be modeled using pQCD. In this case the structure function F_2 can be extracted at each point of x and Q^2 from the "reduced" cross section σ_r (see eq. (1)). Measurements of σ_r from the combined H1 and ZEUS data [3, 4] are shown in fig. 1. The data, most importantly their Q^2 dependence, are very well described by NLO pQCD.

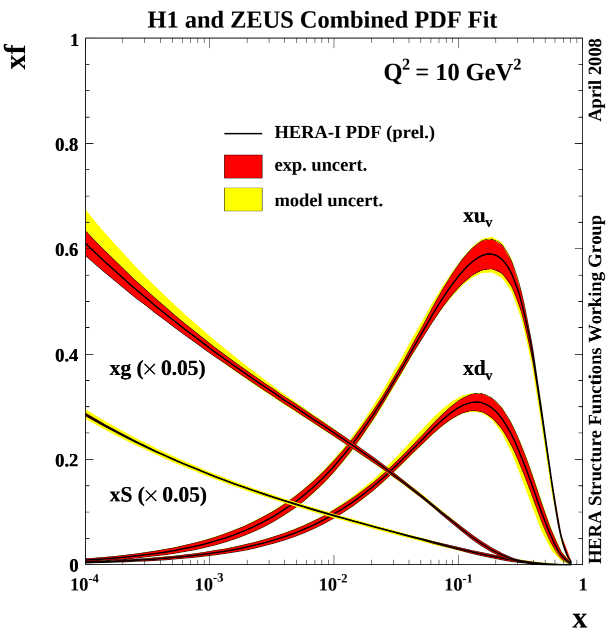

Figure 2: *The parton distribution functions from QCD fits to the HERA data on NC and CC inclusive reactions, using the combined data from H1 [3] and ZEUS [4].*

Figure 2 shows the pdfs resulting from the NLO pQCD fit to the combined NC and CC double-differential cross sections[3, 4]. The resulting uncertainties of the pdfs have drastically shrunk due to the combination of the HERA data. It should also be noted that the pdfs for the gluon and the sea quarks, even at the lowest values of Bjorken x, and for all values of Q^2, keep rising with decreasing x. This means that parton saturation has not been observed within the kinematic range of HERA.

4 Jet Physics and the Strong Coupling

Collimated bundles of particles ("jets"), making up the hadronic final states, are believed to carry the kinematic information of the primary partons emerging from DIS reactions at HERA and other colliding beam experiments. The study of jet production is therefore a sensitive tool to test the predictions of perturbative QCD and provides a way to determine the strong coupling constant α_S over a wide range of Q^2.

The jet finding, most commonly using the so-called k_T clustering algorithm [5], is usually executed in the hadronic center of mass system, which is, up to a Lorentz boost, equivalent to the Breit frame. In jet physics, two different "hard" scales can be used to enable pQCD calculations: the four-momentum transfer Q, and the transverse energy E_T of the jets.

At leading order (LO) in α_S, jet production at HERA proceeds via the QCD Compton process ($\gamma^* q \to qg$, where γ^* is the virtual exchanged photon), and boson-gluon fusion ($\gamma^* g \to q\bar{q}$). Such processes produce two jets, not counting the "target jet" generated by the spectator di-quark system. Events with three jets are of order $\mathcal{O}(\alpha_S^2)$. These events can be interpreted as coming from a di-jet process with additional gluon radiation or gluon splitting, bringing the QCD calculation to next-to-leading order (NLO). The NLO calculations are able to describe the jet data very well (see, for example, [6, 7]), indicating the validity of the DGLAP approach. Given the present experimental and theoretical uncertainties, no higher order corrections (beyond NLO) seem necessary.

One of the most important measurements using multi-jet final states is the determination of the strong coupling constant α_S. At HERA, this measurement is particularly interesting, since α_S can be determined in a single experiment over a large range of Q or E_T. A recent compilation of α_S determinations [8] from the two HERA experiments H1 and ZEUS, using various jet observables, is shown in fig. 3. The dominating error on α_S is still of theoretical nature and arises from the uncertainty due to terms beyond NLO, which is usually estimated by varying the renormalization scale.

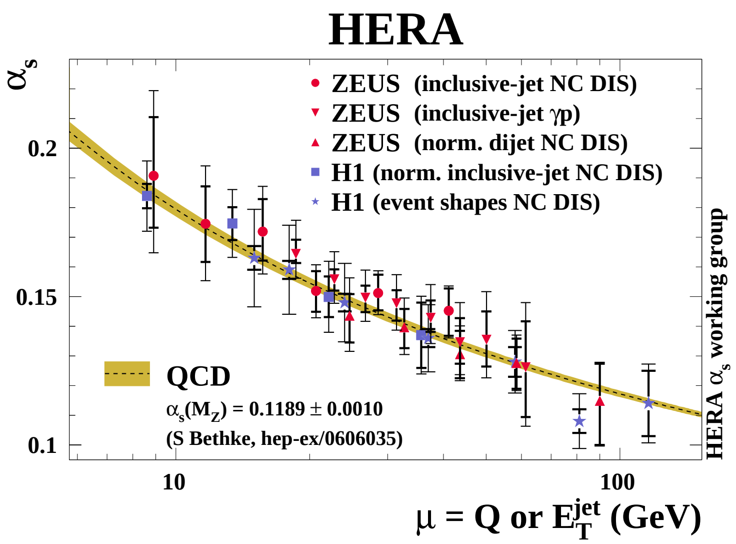

Figure 3: *Measurements from H1 and ZEUS of the strong coupling α_S using observables from (multi) jet final states [8]. The shaded curve is the prediction for the running α_S from a global analysis.*

For very low values of x, there is a technical reason to question the validity of the DGLAP evolution approach: Since in DGLAP only leading $\log(Q^2)$ terms are resummed, the approximation may become inadequate for very small x, where $\log(1/x)$ terms become important in the evolution equations. In this region the BFKL scheme [9] is expected to describe the data better, since in this scheme terms in $\log(1/x)$ are resummed.

A distinction between the DGLAP and the BFKL evolution may be possible studying forward jet production, i.e. high $p_\perp$ jets close to the direction of the incoming proton: In the DGLAP scheme, the parton cascade resulting from hard scattering of the virtual photon with a parton emitted from the proton is ordered in parton virtuality. This ordering along the parton ladder implies an ordering in transverse energy E_T of the partons, so that the parton participating in the hard scatter has the highest E_T. In the BFKL scheme there is no strict ordering in virtuality or transverse energy. The BFKL evolution therefore predicts that a larger fraction of low x events will contain high-E_T forward jets than is predicted by the DGLAP evolution. There are indeed some hints in the data[10, 11] that BFKL dynamics might be at work in this special kinematic region.

5 Ultra-High Energy Neutrino Reactions

With the era of high energy neutrino astrophysics approaching, it is interesting to review our knowledge about the neutrino-nucleon cross section at ultra-high energies beyond $\mathcal{O}(10$ TeV). Such energies can indeed be reached with the HERA collider, as was discussed in the introduction. Looking at the charged current reaction $ep \to \nu X$ measured at HERA, a cut in the transverse neutrino momentum of $p_\perp > 25$ GeV is necessary for a clean separation of CC events from the background. The extrapolation to $p_\perp = 0$ can be done within the Standard model, yielding a cross section for νN on a stationary target of about 200 pb at 50 TeV neutrino energy. Figure 4 shows the measurements from fixed target experiments and the HERA point. Also given are the linear extrapolation (corresponding to $M_W = \infty$) and the prediction of the Standard Model ($M_W = 80$ GeV). As one can see, the neutrino nucleon cross section shows no anomaly, as could, for example, be expected by electroweak instanton effects proposed [12] as a source of possible cosmic ray events beyond the GZK cutoff. While the evidence for such events has become weaker recently [13], the search for instanton effects at HERA [14, 15] has also been inconclusive so far.

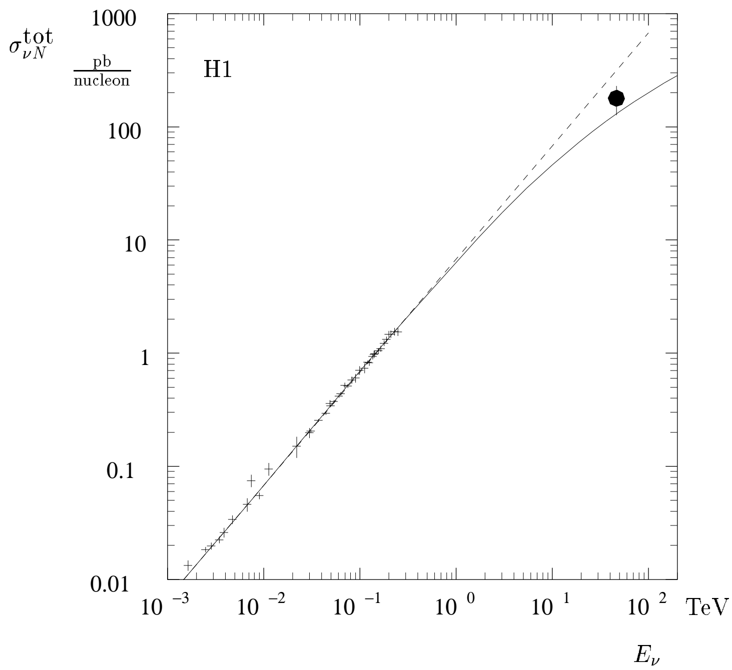

Figure 4: *Measurement of the neutrino nucleon total cross section inferred from the HERA charged current data (full circle), and various fixed target neutrino experiments (crosses).*

6 Summary and Conclusions

The HERA electron-proton-collider with a photon beam equivalent to 50 TeV on a stationary proton target provides access to values of Bjorken x down to about a few times 10^{-5}. The inclusive NC and CC measurements demonstrate the validity of pQCD from very low momentum transfer of a few GeV^2 up to the kinematic limit. Using the DGLAP evolution equations, the parton distribution functions have been extracted from the combined HERA inclusive data with high precision. Down to the lowest values of x (few $\times 10^{-5}$), the gluon and sea quark distributions continue to rise, with no sign of parton saturation in the HERA regime.

The HERA data on jet production have been used to extract the running coupling α_S, the data can be well described by DGLAP. Studies of forward jet production may have provided first evidence for BFKL dynamics.

Translating the HERA CC cross section to a neutrino-nucleon cross section on a stationary proton target yields a value as predicted by the Standard Model for energies up to 50 TeV, indicating a normal behavior to be expected in future ultra-high energy neutrino astrophysics experiments.

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