Diffraction and Forward Physics at HERA

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Measurements on diffractive processes at HERA are presented. The partonic contents of the diffractive exchange have been extracted, by QCD analysis, with decent precision, thanks to recent increase of data used in the analyses. Also reviewed are recent measurements on the leading neutron production.

§1. Introduction

HERA is the *ep* collider, built primarily for investigating the internal structure of nucleons through deep-inelastic scattering (DIS) processes. Two experiments, H1 and ZEUS, recorded about $0.5\,\mathrm{fb}^{-1}$ of collisions each. In DIS, diffractive processes occur through diffractive exchange between a virtual photon and the proton, where the virtual photon dissociates into a multi-hadron state, while the proton stays intact or dissociates into a state with small mass (proton dissociation). The diffractive exchange between the photon and the proton can be explained by either a perturbative two-gluon ladder or non-perturbative particle-like state (Pomeron). The objective of diffractive studies at HERA is to investigate the partonic nature of the diffractive exchange.

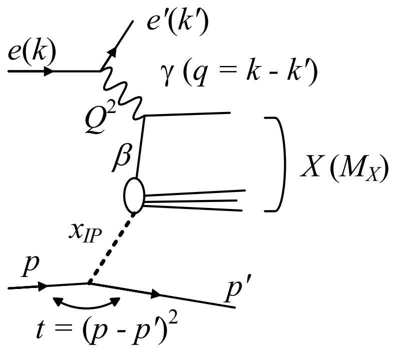

Fig. 1. (color online) Diagram of photon dissociative diffraction in DIS.

The partonic structure of the exchange can be analysed by measuring the diffractive structure function $F_2^D(\beta, Q^2; x_{\boldsymbol{P}}, t)$, where Q^2 is the negative of the mass of the virtual photon, β is the momentum fraction of the diffractive exchange carried by the struck quark, $x_{\boldsymbol{P}}$ is the longitudinal momentum fraction by the exchange relative to the incoming proton and t is square of the momentum transfer by the diffractive exchange (see Fig. 1). The latter two variables describe the behaviour of the vertex of the diffractive exchange and the proton, while the first two are the variables for scattering of the electron and the diffractive exchange, i.e. DIS of the diffractive exchange. If the cross section can be factorised into two parts, $F_2^D \propto F_2^{\boldsymbol{P}}(\beta, Q^2) \cdot f_{\boldsymbol{P}/p}(x_{\boldsymbol{P}}, t)$, the diffractive exchange can be regarded as a particle, the Pomeron (Regge factorisation). The factorisation Ansatz can be tested by verifying the independence of the Pomeron flux $f_{\boldsymbol{P}/p}$ from the kinematics at the photon vertex. More fundamentally, a QCD factorisation theorem has been proven for diffractive DIS, which allows the extraction of parton densities for diffractive processes (diffractive PDFs, DPDFs). The applicability of DPDFs to other hard diffractive processes is an indication of the validity of QCD factorisation. If such factorisation is broken, that may indicate additional scatterings between the two outgoing diffractive systems.

The diffractive events at HERA are mostly tagged by the presence of a large rapidity gap (LRG) or an explicit measurement of momentum of the outgoing proton by spectrometers (FPS and VFPS for H1, LPS for ZEUS).

HERA was one of few colliders where a calorimeter can be placed at zero degree of the incoming beam, providing precise measurement of both longitudinal and transverse spectrum of neutrons at very small angles. Recent progress on the forward physics at the LHC, e.g. LHCf, TOTEM and new cosmic ray measurements in ultra high-energy regime has attracted renewed interest in the precision measurements of leading baryon production at HERA.

§2. Cross section measurements and QCD interpretation of diffractive events

The cross section behaviour as a function of the diffractive variable $x_{\boldsymbol{P}}$ is investigated prior to the extraction of DPDF. The $x_{\boldsymbol{P}}$ dependence was measured to be approximately independent of β and Q^2,[1)–4)] supporting Regge factorisation. Parton densities are then extracted through QCD fits using DGLAP evolutions assuming the Pomeron flux is universal. The result shows larger gluonic content than quarks in the exchange,[1),3)] as expected from the assumption that the lowest order colourless object at low-x is a two-gluon state. Note that the fit underestimates the data at low Q^2, an indication of the presence of higher twist diagrams.

Events with a proton observed in spectrometers guarantee that the process is single dissociation of the photon, while LRG events contain also the proton-dissociative processes where the mass of the dissociated system is small enough to escape the beam hole of the central detectors and therefore identified as single-dissociative events. The ratio $\sigma_{\text{spectrometer}}/\sigma_{LRG}$ is found to be independent[3),4)] of the kinematical variables β, Q^2 and $x_{\boldsymbol{P}}$, a proof that the LRG data preserve the shape of single diffractive events.

Data with the spectrometers provide unique measurements in the high-$x_{\boldsymbol{P}}$ range ($x_{\boldsymbol{P}} > 0.03$), since the photon dissociation system is boosted towards incoming proton (forward) direction and

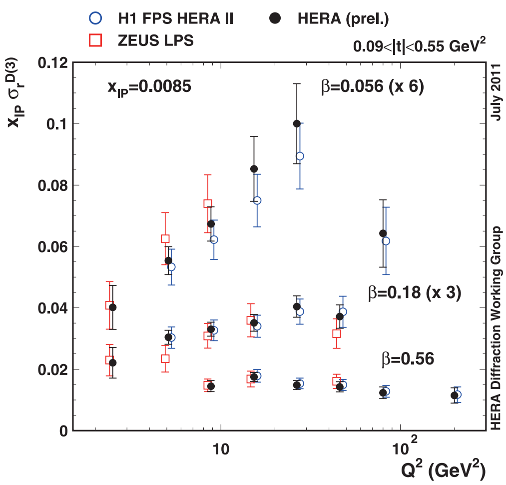

Fig. 2. (color online) An example of diffractive scattering cross sections using forward proton spectrometers[6)] obtained by combining H1 and ZEUS results.

the rapidity gaps cannot be observed due to the finite coverage of central detectors in the forward direction. New VFPS data from H1 show that the parameterisation of the subleading exchange to Pomeron, the Reggeon exchange, describe the data well. Recently, H1 and ZEUS diffractive cross section measurements with proton spectrometer were combined[6] in order to increase statistical precision and also cross-calibrate the two measurements (Fig. 2).

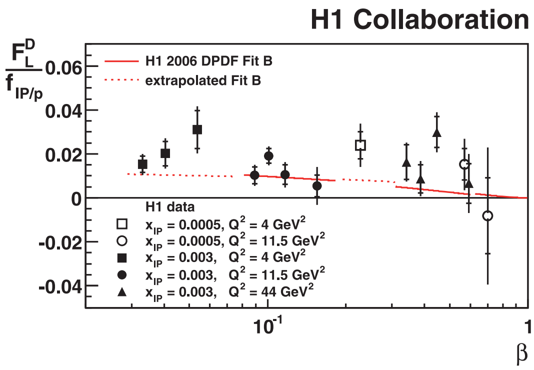

Fig. 3. (color online) F_L^D divided by Pomeron flux $f_{\boldsymbol{P}/p}$ as a function of β for various Q^2 and $x_{\boldsymbol{P}}$ values.[9]

QCD factorisation tests have been performed using diffractive dijet cross sections, which are more sensitive to the gluon densities of diffractive exchange. New DIS dijet measurements with VFPS[5] show that the DPDFs in the high-$x_{\boldsymbol{P}}$ region describe the data well, the first proof of QCD factorisation in this kinematic range. The dijet cross sections in resolved photoproduction are expected to be suppressed as the photon is "large" enough to have secondary scattering. The results at HERA are not conclusive: H1 observed suppression of both direct and resolved processes,[7] while ZEUS found no indication of suppression.[8]

H1 has measured the longitudinal structure function for diffractive DIS, F_L^D.[9] The longitudinal structure function is directly proportional to the gluon density of the diffractive exchange and also sensitive to the presence of longitudinal cross sections from diagrams like a dipole from γ_L^* scattering with a proton through two-gluon exchange.[10] The result (Fig. 3) shows consistency with the F_L^D prediction using extracted DPDFs, with a slight tendency of data being higher than the prediction.

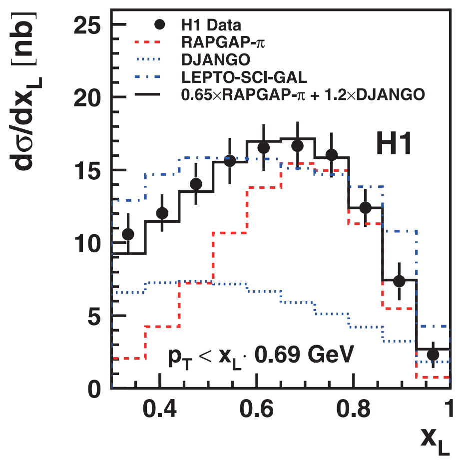

Fig. 4. (color online) The x_L distribution of leading neutrons as measured by H1.[12]

§3. Forward neutrons

Leading neutrons in DIS are modelled by either a generic fragmentation of scattered protons or by the charge-exchange reaction e.g. $p \rightarrow \pi^+ n$, with a subsequent interaction between the pion and a virtual photon. HERA data strongly support the presence of a one-pion exchange (OPE) diagram. The x_L spectrum was measured,[11),12] where x_L is the longitudinal momentum fraction of the leading neutron to the incoming proton. A maximum around $x_L \simeq 0.7$ was observed, which can only be reproduced by adding the OPE contribution to the fragmentation model (Fig. 4).

The probability of having a leading neutron in a DIS event was measured. The cross sections divided by the pion flux are compared to parameterisations of F_2^π as well as to $(2/3)F_2$, motivated by a simple quark counting rule, as they represent the pion structure function in the OPE picture.

The result shows about 20–30% suppression of the yield.[11),12)] The data were also compared to the yield of leading protons in the same kinematic range.[11)] It turned out that protons are produced more than neutrons, as shown in Fig. 5, in contradiction to naive isovector exchange expectations, giving (proton):(neutron) = 1:2.

The yield for photoproduction events are also investigated with the same motivation as for diffractive suppression.[11)] The yield in photoproduction is about 20% lower in middle x_L range, which is consistent with models of absorption (rescattering between the photon and the spectator particles). Also the comparison of resolved to direct processes in dijet photoproduction has shown similar suppression of about 20%. All observations indicate that rescattering is present in leading baryon production.

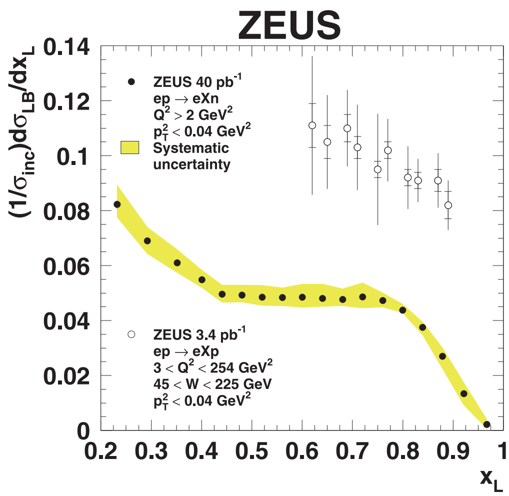

Fig. 5. (color onine) Comparison of the fraction of events having either a neutron or a proton with very small transverse momentum, $p_T^2 < 0.04\,\mathrm{GeV}^2$, in DIS events.

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