A great interest for diffraction has been generated these last years by the HERA data. They give us the first opportunity to understand high energy diffractive physics in terms of a fundamental theory, i.e. QCD. A review of the main results from H1 and ZEUS in this field is presented and the relation with the proton structure function at small x-Bjorken values is discussed.

Introduction

Presently, one of the most important tasks in particle physics is the understanding of the strong force. For this purpose, the Quantum Chromodynamics theory (QCD) seems to be the best candidate. An important characteristic of this theory is that the coupling constant \( \alpha_S \) is larger than 1 when the interaction between the different actors, quarks and gluons, does not take place at distances small enough. This means that to be calculable within a perturbative approach, the interaction between these constituents requires the presence in the process of a “hard” scale, i.e. a large transverse momentum or a large mass.

The lepton beam of the high energy \( e^- p \) collider HERA (reaching an energy in the center of mass system \( \sqrt{s} = 300 \text{ GeV} \)) is a prolific source of photons in a large virtuality range such that the study of \( \gamma^* p \) interactions provides a completely new and deep insight into the QCD dynamics.

A major discovery at HERA is the observation of the strong rise of the total cross section at high energy in the deep inelastic scattering (DIS) i.e. \( \gamma^* p \) interactions with large \( Q^2 \) values (\( Q^2 \) being the negative of the squared four-momentum of the exchanged photon). This is inconsistent with the case of the photoproduction (\( Q^2 \simeq 0 \)), which shows a soft dependence in the total hadronic energy, \( W \), similar to the hadron-hadron interaction case and well described by the Regge phenomenological theory.
HERA is thus a unique device to test QCD in the perturbative regime and to study the transition between perturbative and non-perturbative domains. One of the remarkable successes of this theory is the correct prediction of the evolution of the proton structure function with $Q^2$, for $Q^2 > 1 \text{ GeV}^2$, now measured with a very good accuracy\(^1\). This evolution allows the extraction of the gluon density in the proton, which is not directly measurable. The fast rise of the gluon density for decreasing $x$, shown in Fig. 1 reflects the fast rise of the cross section with $W$.

The other main window opened at HERA for the understanding of the strong force is the study of diffractive interaction. Diffraction has been successfully described, already more than 30 years ago, via the introduction of an exchanged object carrying the vacuum quantum numbers, called the Pomeron ($P$). Whilst Regge-based models give a unified description of all pre-HERA diffractive data, this approach is not linked to an underlying fundamental theory.

The second major result at HERA is the observation that 8 – 10% of the events in the deep inelastic regime ($Q^2 > 1 \text{ GeV}^2$) present the characteristics of diffractively produced events\(^2\), i.e. a large rapidity gap (LRG) without hadronic activity between the two hadronic low mass sub-systems, $X$ and $Y$, as illustrated in Fig. 2. The gaps being significantly larger than implied by particle density fluctuation during the hadronisation process, these events are attributed to “hard” diffraction, i.e. to the exchange of a colourless object at the proton vertex, for the first time observed in a hard regime. HERA offers a unique possibility to study the nature of diffraction and determine the Pomeron structure in terms of QCD.
1 Inclusive DIS cross section and partonic structure of the Pomeron

The hard diffractive cross section can be defined by four kinematic variables conveniently chosen as $Q^2$, $x_{F'}$, $\beta$ and $t$, where $t$ is the squared four-momentum transfer to the proton, and $x_{F'}$ and $\beta$ are defined as

$$x_{F'} \simeq \frac{Q^2 + M_X^2}{Q^2 + W^2}, \quad \beta \simeq \frac{Q^2}{Q^2 + M_X^2},$$

(1)

$x_{F'}$ can be interpreted as the fraction of the proton momentum carried by the exchanged Pomeron and $\beta$ is the fraction of the exchanged momentum carried by the quark struck by the photon. These variables are related to the Bjorken $x$ scaling variable by the relation $x = \beta \cdot x_{F'}$.

Experimentally, the $t$ variable is usually not measured or is integrated over. In analogy with non-diffractive DIS scattering, the measured cross section is expressed in the form of a three-fold diffractive structure function $F^D_2(3)$:

$$\frac{\mathrm{d}^3 \sigma (ep \to eXY)}{\mathrm{d}Q^2 \, \mathrm{d}x_{F'} \, \mathrm{d}\beta} = \frac{4 \pi \alpha^2}{\beta Q^4} \left(1 - \frac{y}{2}\right) F^D_2(3)(Q^2, x_{F'}, \beta),$$

(2)

where $y$ is the usual scaling variable, with $y \simeq W^2/s$. Conveniently, $F^D_2(3)$ is factorised in the form $F^D_2(3)(Q^2, x_{F'}, \beta) = f_{F'/p}(x_{F'}) \cdot F_2^D(Q^2, \beta)$, assuming that the $F'$ flux $f_{F'/p}(x_{F'})$ is independent of the $F'$ structure $F_2^D(Q^2, \beta)$, by analogy with the hadron structure functions, $\beta$ playing the role of Bjorken $x$. The $F'$ flux is parametrized in a Regge inspired form. Including the reggeon ($R$) trajectory in addition to the Pomeron, a good description of the data is obtained throughout the measured kinematic domain ($6.5 < Q^2 < 800 \text{ GeV}^2$ $x_{F'} < 0.05$ and $0.01 < \beta < 0.9$).

The reggeon contribution gets larger for increasing values of $x_{F'}$, which correspond to smaller energy (for given $Q^2$ and $\beta$ values). It also gets larger for smaller values of $\beta$, which is consistent with the expected decrease with $\beta$ of the reggeon structure function, following the meson example, whereas the Pomeron structure function is observed to be approximately flat in $\beta$. The comparison of $F^D_2(2)(Q^2, \beta)$ with the inclusive proton structure function, $F_2(Q^2, x)$, shows that the dynamic is different in the Pomeron and in the proton (see Fig. 3) for large $\beta$ values. By analogy to the QCD evolution of the proton structure function, one can attempt to extract the partonic structure of the Pomeron from the $Q^2$ evolution of $F^D_2(2)(Q^2, \beta)$. The extracted
distributions are shown in Fig. separately for the gluon and the singlet quark components as a function of $z$, the Pomeron momentum fraction carried by the parton entering the hard interaction. This distribution shows the dominance of gluons up to the high $z$ values in the Pomeron partonic structure.

The dominance of hard gluons in the Pomeron is confirmed by various analyses of the diffractive hadronic final state (jet production, energy flow, particle spectra and multiplicities, and event shape) providing a global consistent picture of diffraction.

2 Exclusive diffractive final states

During these last decades, our knowledge of the hadronic structure has progressed a lot, mostly with the study of the inclusive inelastic reactions.
The study of exclusive reactions will probably be dominant in the coming years, in this field, as they allow us to go one step deeper in our understanding of the hadronic structure. In particular they give access to momenta and helicity correlations of the hadron structure.

Furthermore, the exclusive elastic vector meson production and the deeply virtual Compton scattering (DVCS) studies: $\gamma^* p \rightarrow X p$, where the hadronic system $X$ consists only in a vector meson ($\rho, \omega, ...$) or a photon (DVCS), provide a very interesting way to test the mechanism of diffraction and our understanding of the Pomeron structure.
Fig. 5 summarizes the $W$ dependence of various elastic exclusive vector meson photo-production, together with the total photoproduction cross section. 

The light mesons ($\rho$, $\omega$ and $\phi$) show a soft dependence in $W$, equivalent to that of the total cross section dependence, while this energy dependence is much steeper for $J/\psi$ production. This regime change is interpreted as being due to the presence of a hard scale in the process, the (high) charm quark mass,
making the $J/\psi$ meson smaller than the confinement scale ($\sim 1 \text{fm}$). In this case, it is natural to attempt a perturbative QCD description of the process, where the photon fluctuates into a quark-antiquark pair and the exchanged Pomeron is modeled by a pair of gluons. This leads, in a first approximation, to a cross section proportional to the gluon density squared, which is in good agreement (full line) with the data (points) shown on Fig. 6.

This figure also shows the agreement of the 2 gluons exchange model with measurement of exclusive $J/\psi$ production in the DIS regime, where a second hard scale, $Q^2$ is present. As illustrated on Fig. 7, a modification of the $W$ dependence also occurs for the elastic $\rho$ production when the $Q^2$ increases, which highlights the appearance of $Q^2$ as a hard scale for a light vector meson production.

It is remarkable to see that the different vector meson cross sections present a universal behaviour as a function of the variable $Q^2 + M_V^2$, where $M_V$ is the vector meson mass, as shown in Fig. 8 for $W = 75 \text{ GeV}$. The cross sections were scaled by SU(4) factors, according to the quark content of the vector mesons. This indicates that this variable choice seems to be a good scale to describe the vector meson production in a universal way, and that the cross section is at the first order not sensitive to the quark flavour (which would probably not be valid at lower energy).
Figure 8. H1 and ZEUS measurements of the $\gamma p \to VMp$ total cross sections as a function of $(Q^2 + M^2)/4$ for $\rho, \omega, \phi, J/\psi$ and $\Upsilon$ vector meson elastic production, at the fixed value of $W = 75$ GeV. The insert presents the distance of the points to the fitted curve.

However, the exclusive $\Upsilon$ cross section seems to be too high for this universal behaviour. In fact, the cross section measurement does not agree with simple QCD predictions. This is due to the fact that the transition from a virtual photon coming from an electron to an on shell particle forces the fractional momenta of the two gluons involved to be unequal. Therefore, in the cross section expression, the gluon density cannot just be squared, but two different $x$ values have to be considered. When such skewing effects are included the agreement with QCD can be found again. This effect becomes important at high $Q^2$ values or high vector meson masses. To include such effects in the cross section calculations, the very powerful formalism of Generalised Parton Distributions (GPD) has been introduced\cite{9}.

For vector meson production GPD appear quadratically in the cross section expression. A unique feature of DVCS is that they appear linearly in
Figure 9. The H1 DVCS cross section measurement as a function of $W$ (left) and of $Q^2$ (right). The measurement is compared to dipole model (DD) and QCD predictions (FFS for LO and right plot at NLO with different GPD inputs).

the interference term with the purely QED Bethe-Heitler process. Compared to vector meson production, DVCS is theoretically simpler (fully calculable) because the composite meson in the final state is replaced by the photon, thus avoiding large uncertainties due to the unknown meson wave functions. Therefore the DVCS measurement offers a particularly suitable channel to extract GPD. The first cross section measurement, shown in Fig. 9, as a function of $W$ and $Q^2$, is in good agreement with the perturbative QCD prediction and provides the first constrains on GPD.

Conclusion

HERA experiments have produced a large amount of results in diffraction, which allow confrontations with QCD predictions, when one of the hard scales $Q^2$, the quark mass or $t$ (not reported in this summary) is present in the process.

The QCD analysis of the total diffractive cross section, assuming factorisation into a Pomeron flux in the proton, shows that the corresponding parton distributions favors the dominance of hard gluons in the Pomeron. This is confirmed by the analysis of inclusive final states and of jet production.
For the case of exclusive final state production, in the presence of a hard scale the transition from soft to hard regime is observed as in inclusive DIS. Models based on the fluctuation of the photon in a quark-antiquark pair which subsequently exchange a pair of gluons with the proton parton successfully reproduce the enhanced energy dependence for the $J/\psi$ production and for the $\Upsilon$ when skewed effects are included. The DVCS cross section, the only fully calculable diffractive process, has been measured for the first time and is in good agreement with QCD predictions.

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