Diffractive Physics at HERA

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1. 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), part of the Standard Model, seems to be the best candidate. An important characteristic of this theory is that the coupling constant α_S tends to zero when the transverse distance between matter constituents, quarks and gluons, two quarks tends to zero. 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 transfer or a large mass.

The lepton beam of the high energy $e-p$ collider HERA is a prolific source of photon in a large virtuality range such that the study of $\gamma^* p$ interaction 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 [1] and well described by the Regge phenomenological theory. After a transition around $Q^2 = 1$ GeV^2, the steep energy dependence of the total cross section in DIS is related to the fast increase of the gluon density in the proton at high energy [1].

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 success of this theory, as reviewed at this conference [1], is the correct prediction of the evolution of the proton structure function with Q^2, for $Q^2 > 1$ GeV^2. This evolution allows the extraction of the gluon density in the proton, which is not directly measurable.

The other main opened window 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 ($I\!\!P$). Whilst Regge-based models give a unified description of all pre-HERA diffractive data, this approach is not linked to the underlying QCD theory.

The second major result at HERA is thus the observation in deep inelastic scattering that $8-10\%$ of the events present a large rapidity gap (LRG) without hadronic activity between the two hadronic sub-systems, X and Y, as illustrated in Fig. 1. [2]. The gaps being significantly larger than implied by particle density fluctuation during the hadronisation process, these events are attributed to diffraction, i.e. to the exchange of a colourless object at the proton vertex.

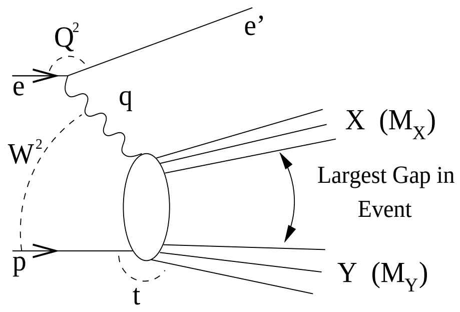

Figure 1. Sketch of the diffractive $e-p$ interaction

2. Exclusive vector meson production

In exclusive elastic vector meson production study, $\gamma^* p \to Vp$, the hadronic system X consists only in a vector meson $(\rho, \omega, ...)$, and the system Y in the scattered proton. This process provides a very interesting way to test the mechanism of diffraction and our understanding of the pomeron structure. Fig. 2 summarizes the W dependence of various elastic exclusive vector meson production. Fig. 2.a) presents the exclusive ρ, ω, ϕ, J/Ψ and Υ production in photoproduction [3,4], together with the total photoproduction cross section [6]. The light mesons (ρ, ω and ϕ) show a soft dependence in W, equivalent to that of the total cross section dependence, while this energy dependence is much steeper for J/Ψ production. This is interpreted as being due to the presence of a hard scale, the charm quark mass, making the J/Ψ meson smaller than the confinement scale ($\sim 1fm$). 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 to a cross section proportional to the gluon density squared, which is in good agreement (full line) with the data (points) shown on Fig. 2.b) [5]. This figure also shows the agreement of the 2 gluons exchange model with measurement of exclusive J/Ψ production in the DIS regime, where a second hard scale, $Q^2$is present.

As illustrated on Fig. 2.c), a modification of the W dependence also occurs for the elastic ρ production when the Q^2 increases.

3. Inclusive DIS cross section and partonic structure of the pomeron

The diffractive DIS process can be defined by four kinematic variables conveniently chosen as Q^2, $x_{I\!P}$, β and t, where t is the squared four-momentum transfer to the proton, and $x_{I\!P}$ and β are defined as

$$x_{I\!P} \simeq \frac{Q^2 + M_X^2}{Q^2 + W^2} \qquad \beta \simeq \frac{Q^2}{Q^2 + M_X^2}; \tag{1}$$

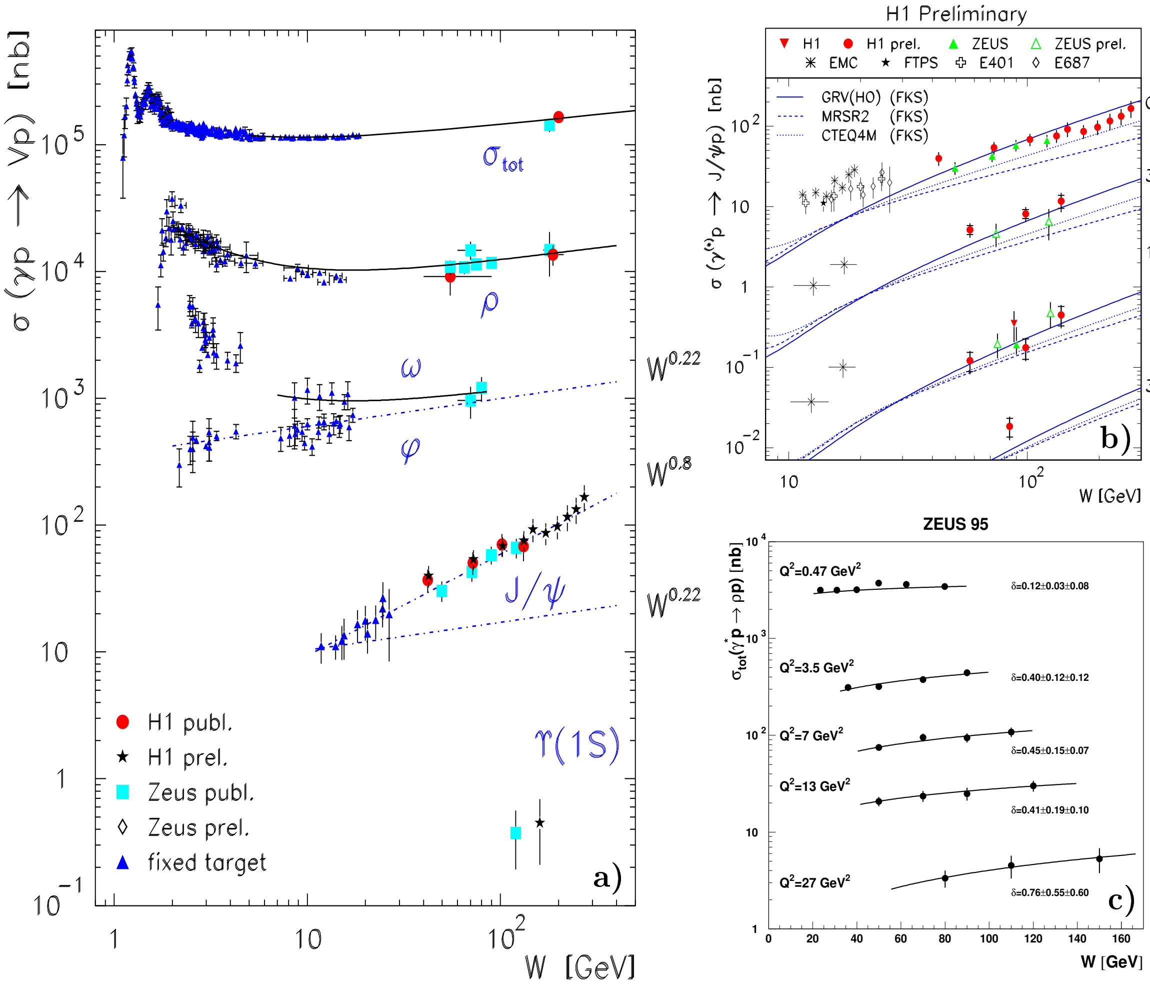

Figure 2. Diffractive cross sections as a function of the $\gamma^* - p$ system energy for: a) various vector mesons in photoproduction together with the total photoproduction cross section, b) J/Ψ in photoproduction and DIS, and c) ρ in DIS for different Q^2 values.

$x_{I\!P}$ can be interpreted as the fraction of the proton momentum carried by the exchanged pomeron and β 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 (with $W^2 \simeq Q^2/x - Q^2$) by the relation $x = \beta \cdot x_{I\!P}$.

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 $F_2^{D(3)}(Q^2, x_{I\!P}, \beta)$:

$$\frac{\mathrm{d}^3\sigma\ (ep \to eXY)}{\mathrm{d}Q^2\ \mathrm{d}x_{I\!P}\ \mathrm{d}\beta} = \frac{4\pi\alpha^2}{\beta Q^4}\ (1 - y + \frac{y^2}{2})\ F_2^{D(3)}(Q^2, x_{I\!P}, \beta), \tag{2}$$

where y is the usual scaling variable, with $y \simeq W^2/s$. $F_2^{D(3)}$ is conveniently factorised in the form $F_2^{D(3)}(Q^2, x_{I\!P}, \beta) = f_{I\!P/p}(x_{I\!P}) \cdot F_2^D(Q^2, \beta)$, assuming that the $I\!P$ flux $f_{I\!P/p}(x_{I\!P})$ is independent of the $I\!P$ structure $F_2^D(Q^2, \beta)$, by analogy with the hadron structure functions, β playing the role of Bjorken x. The $I\!P$ flux is parametrized in a Regge inspired form. The fit of HERA data according to the Regge form has shown that factorization is broken. This feature is explained in Regge theory by the need to include sub-leading

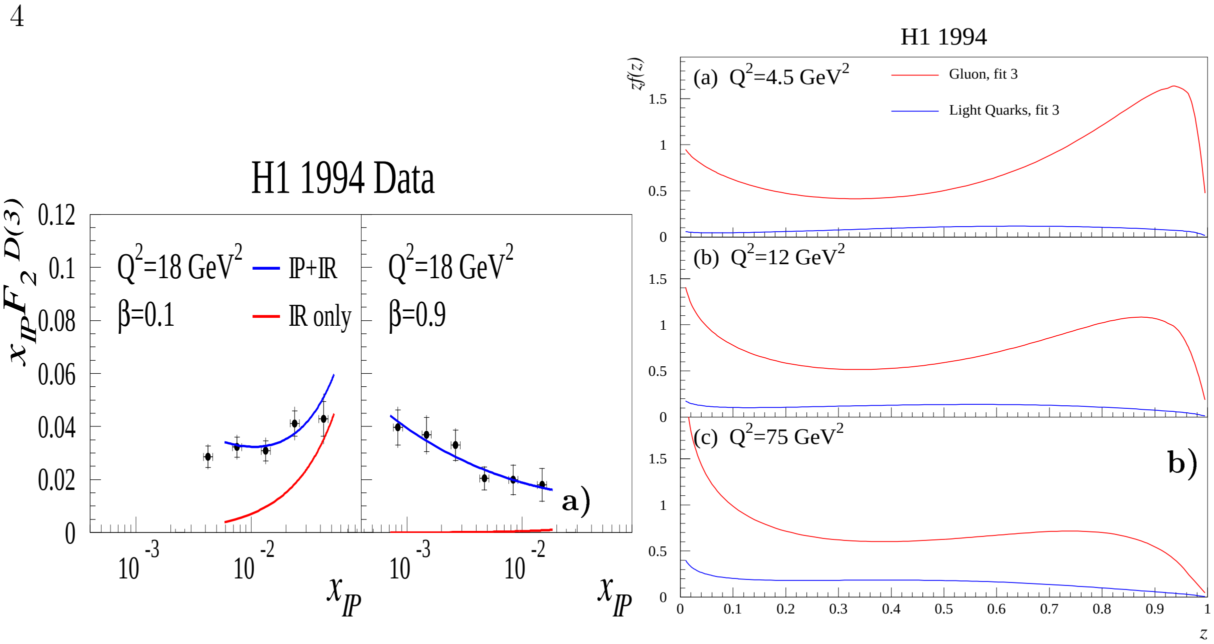

Figure 3. a) Diffractive structure function measurement in two bins in β and Q^2, as a function of $x_{I\!P}$. Regge based phenomenological fit are overlaid with $I\!P$ and $I\!R$ or $I\!R$ only contributions. b) Gluons and quark densities in the $I\!P$ extracted from the QCD fit of $F_2^{D(3)}$.

trajectories in addition to the $I\!P$. Including one further trajectory, the reggeon ($I\!R$), in addition to the pomeron:

$$F_2^{D(3)}\,(Q^2, x_{I\!P}, \beta) = f_{I\!P/p}(x_{I\!P}) \cdot F_2^{I\!P}(Q^2, \beta) + f_{I\!R/p}(x_{I\!P}) \cdot F_2^{I\!R}(Q^2, \beta), \tag{3}$$

is sufficient to obtain a good description of the data throughout the measured kinematic domain ($0.4 < Q^2 < 800$ GeV^2 $x_{I\!P} < 0.05$ and $0.001 < \beta < 0.9$) [7].

The contributions of pomeron and reggeon exchange are illustrated on Fig. 3.a). The reggeon contribution gets larger for increasing values of $x_{I\!P}$, which correspond to smaller energy (for given Q^2 and β values). It gets also larger for smaller values of β, which is consistent with the expected decrease with β of the reggeon structure function, following the meson example, whereas the pomeron structure function is observed to be approximately flat in β.

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 $F_2^{D(2)}(Q^2, \beta)$. The extracted distributions are shown in Fig. 3.b) [7] separately for the gluon and the 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 hard gluons (high z values) in the pomeron partonic structure.

The dominance of hard gluons into the pomeron has been confirmed by various analysis of the diffractive hadronic final state (jet production, energy flow, particle spectra and multiplicities, and event shape) providing a global consistent picture of diffraction [8–10].

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.

For the case of exclusive vector meson production, in the presence of a hard scale, 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.

The QCD analysis of the total diffractive cross section, assuming factorization into a pomeron flux in the proton the corresponding parton distributions, favors the dominance of hard gluons in the pomeron, confirmed by the analysis of inclusive final states and of jet production.

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