Measurements of Diffractive Structure Functions at HERA

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On behalf of the H1 and ZEUS collaborations

Recent results on diffractive structure functions are summarized for both the H1 and the ZEUS collaborations. A Regge analysis of the measured diffractive structure function F_2^D indicates that pomeron and Reggeon contributions are necessary, with the Reggeon contribution increasing as $x_{\mathbb{P}}$ increases. The value of the intercept $\alpha_{\mathbb{P}}(0)$ at large photon virtuality Q^2 is measured to be greater than the "soft pomeron" intercept as measured in hadron-hadron physics. The leading proton spectrometers of both experiment allow the extension of the measurements to higher $x_{\mathbb{P}}$.

1 Introduction

Since 1992, HERA has started colliding electrons (or positrons) of 26.7 GeV (going up to 27.5 GeV one year later) with protons of 820 GeV. With the H1 and ZEUS detectors, one of the aims of HERA is to study the structure of the proton using the electron as a probe. Deep Inelastic Scattering (DIS) events are characterized by a large value of the momentum transfer squared from the lepton to the probed system ($Q^2 >> 1$ GeV^2), and a hadronic mass well beyond the resonance region ($W >> 1$ GeV).

10% of these interactions show a rapidity gap (no energy flow) between the dissociative photon system (system X, mass M_X) and the system Y (mass M_Y), which can be a proton (see figure 1). This suggests that there is no colour flow between those two systems, and that an object with no net colour is exchanged. A typical example is shown figure 2.

1.1 Experimental setup

The main detectors used in the analyses are briefly described in the following. More detailed descriptions of H1 and ZEUS can be found in [1,2]. The forward direction is defined to be the proton direction, from right to left on figure 2. Looking at this event, one can see a clear electron in the backward electromagnetic calorimeter, a jet in the central tracking chambers and energy deposit in the central region of the liquid argon calorimeter (system X), and

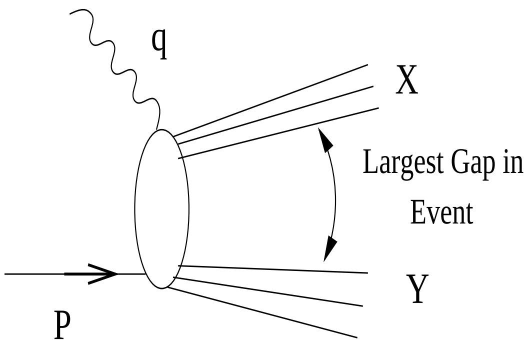

Figure 1: Diagram of a diffractive event.

no calorimetric or other significant activity in the forward region, suggesting that the Y system escapes through the beam pipe.

In addition to the forward tracking chambers, Leading Proton Spectrometers (LPS) are installed in both experiments downstream in the $+z$ direction to detect outgoing protons which are emitted at small angles with respect to the incoming proton direction. These devices use the magnets of the HERA beam line to measure the momentum p' of the scattered proton. Their acceptance is given in table 1. x_L is defined as the ratio of the energy of the measured outgoing proton over the proton beam energy. $p_\perp$ is the transverse momentum of the scattered proton.

ZEUS	$0.6 < x_L < 1.0$	$p_\perp < 1.0$ GeV
H1	$0.7 < x_L < 0.9$	$p_\perp < 0.2$ GeV

Table 1: Acceptance of the Leading Proton Spectrometers of ZEUS and H1.

2 Kinematics and Selection

2.1 Kinematics

The kinematics of diffractive events are discussed in terms of the 4-vectors q, p and p' of the incoming photon and proton and outgoing system Y respectively and the invariant masses M_X and M_Y of the two distinct final state hadronic systems.

In addition to the squared ep centre of mass energy, s, an azimuthal angle and 2 further independent variables are required to describe a DIS event. These are usually chosen to be Q^2 and the Bjorken scaling variable, x. The diffractive kinematics are then specified by the squared 4-momentum transfer

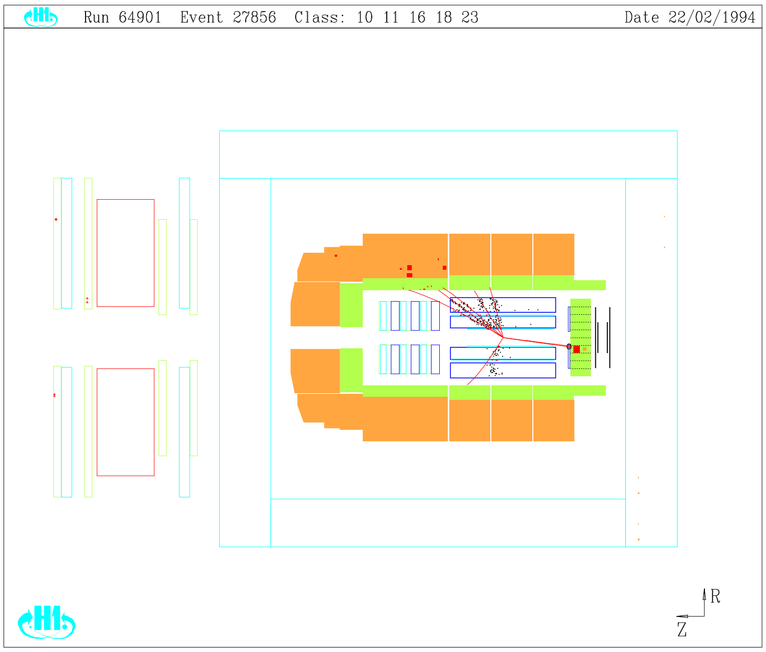

Figure 2: Example of a DIS event with a rapidity gap in the forward (large z) region.

at the proton vertex, $t = (p - p')^2$, and the mass M_X of the system X. Further useful variables can be derived:

- $x_{I\!P} = \frac{q.(p-p\prime)}{q.p} = \frac{Q^2+M_X^2-t}{Q^2+W^2-M_p^2} = 1 - x_L$: the fraction of the proton momentum taken by the colour singlet exchange.
- $\beta = \frac{Q^2}{2q.(p-p\prime)} = \frac{Q^2}{Q^2+M_X^2-t} = \frac{x}{x_{I\!P}}$: the fraction of the colour singlet exchange momentum taken by the struck parton.

2.2 Selection of Diffractive Events

Three different methods have been applied to select diffractive events.

One selection criterion is to require a large rapidity gap between the system X in the central region and the system Y which escapes into the beam pipe. The requirement is that the maximum pseudo-rapidity η_{max} of detected particles in the main calorimeter should be less than a certain value (H1: 3.2, ZEUS: 1.5). In addition, H1 requires no particle to be detected in their Forward Muon

Detector and their Proton Remnant Tagger, which extends this rapidity gap to $\eta \simeq 7.5$.

The second method (ZEUS) uses the fact that, for non diffractive events, one expects an exponential fall-off of the M_X distribution towards low masses. Fitting the M_X distribution in (Q^2/W) bins, the excess over an exponential fall-off is interpreted as diffractive events. These two methods are used to get large statistics.

The third selection method relies on tagging the outgoing proton by the LPS. The variable x_L is determined. The diffractive part corresponds to $x_L \sim 1$. Statistical accuracy is limited due to the acceptance of the LPS.

3 Diffractive Structure Function

H1 and ZEUS define diffractive structure functions without any assumptions on the dynamics of the interaction. A diffractive structure function can be defined like in DIS, but depending here on four independent variables:

$$\frac{d^4\sigma^D_{ep\to e'XY}}{d\beta dQ^2 dx_{I\!P} dt} = \frac{4\pi\alpha^2}{\beta Q^2}(1 - y + \frac{y}{2})F_2^{D(4)}(\beta,\, Q^2,\, x_{I\!P},\, t) \tag{1}$$

where the "4" stands for 4 variables. Figure 3 shows ZEUS LPS results [3] on the measurement of $x_{I\!P} \cdot F_2^{D(4)}$, where Y is a proton, with $x_L > 0.97$, $0.073 < |t| \leq 0.4$ GeV^2, $5 < Q^2 < 20$ GeV^2, for $0.015 < \beta < 0.5$. In this regime, $x_{I\!P} \cdot F_2^{D(4)}$ is flat with respect to $x_{I\!P}$, which is consistent with pomeron exchange as observed in $pp \to pX$ processes.

Integration of equation (1) over t leads to:

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

$F_2^{D(3)}$ has been measured by H1 in the region $M_Y < 1.6$ GeV and $|t| < 1$ GeV^2 and by ZEUS for $M_Y < 4$ GeV. In the Regge approach, $F_2^{D(3)}$ can be written as a superposition of contributions from different Regge trajectories. In addition, the assumption can be made that each trajectory i can be expressed using factorization into a flux $\Phi_i(x_{I\!P})$ and a structure function F_2^i:

$$F_2^{D(3)} = \sum_{i=1,n} \Phi_i(x_{I\!P}) \cdot F_2^i(\beta, Q^2)(+\text{interferences}) \tag{3}$$

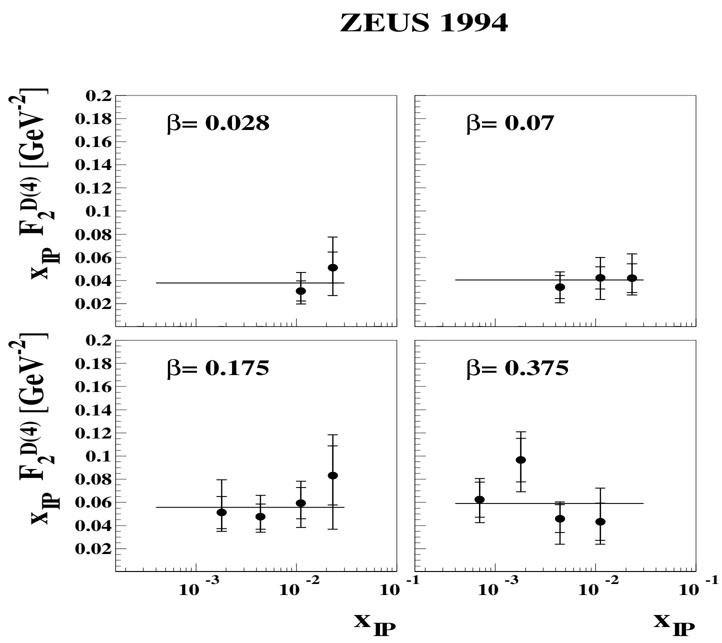

Figure 3: $x_{I\!P} \cdot F_2^{D(4)}$ in 4 β bins, for $0.073 < |t| < 0.4\mathrm{GeV}^2$, with the 1994 ZEUS data.

Interference is possible between the terms which describe the $I\!P$ and the f meson trajectory. In the Regge framework, the flux $\Phi_i(x_{I\!P})$ is:

$$\Phi_i(x_{I\!P}) = \int \mathrm{d}t \left(\frac{1}{x_{IP}}\right)^{2\alpha_i(t)-1} e^{bt}$$

where b is the slope parameter, and $\alpha_i(t) = \alpha_i(0) + \alpha_i' t$ is the Regge trajectory for the exchange i. Different $x_{I\!P}$ dependences are therefore expected for different exchanges:

- $\alpha_{I\!P}(0) \simeq 1 + \varepsilon$ for the pomeron ; $\varepsilon \simeq 0.08$ in the case of the Donnachie-Landshoff [6] parametrization of the soft pomeron exchange (IP), like in hadron-hadron colliders. The flux decreases with increasing $x_{I\!P}$.

- $\alpha_{I\!P}(0) \simeq 1/2$ for Reggeon (IR) exchange, with a flat flux with $x_{I\!P}$.

- $\alpha_{I\!P}(0) \simeq 0$ for pion π exchange, leading to an increasing flux with increasing $x_{I\!P}$.

The H1 measurement of $F_2^{D(3)}$ with the 1994 data [5] using the large rapidity gap technique is shown figure 4. It covers the range $2.5 < Q^2 < 65\mathrm{GeV}^2$, $0.01 < \beta < 0.9$, and $0.0001 < x_{I\!P} < 0.05$. In addition to pomeron exchange, a Reggeon term is needed to fit the data, essentially for large $x_{I\!P}$ and low β.

Following equation 3, one can define :

$$\begin{aligned} F_2^{D(3)} = \quad & (\tfrac{1}{x_{I\!P}})^{(2\alpha_{I\!P}-1)} \cdot F_2^{I\!P}(\beta, Q^2) && \Rightarrow I\!P \\ & +C_{I\!R}(\tfrac{1}{x_{I\!P}})^{(2\alpha_{I\!R}-1)} \cdot F_2^{I\!R}(\beta, Q^2) && \Rightarrow I\!R \\ & +I_{I\!P+I\!R} && \Rightarrow \text{Interference} \end{aligned}$$

Fits with full or no interference were performed and led to similar results. Fitting $F_2^{D(3)}$ allows the extraction of $\alpha_{I\!P}(0)$ and $\alpha_{I\!R}(0)$ for $Q^2 > 0$ resulting in $\alpha_{I\!P}(0) = 1.20 \pm 0.02(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})^{+0.03}_{-0.04}(\mathrm{model})$. This result is presented in figure 5 together with the ZEUS analysis [4] (preliminary). The $\alpha_{I\!P}(0)$ for $Q^2 > 0$ for both experiments are significantly greater than the "soft pomeron" intercept as measured in hadron-hadron physics [6].

An increase of $F_2^{I\!P}$ with Q^2 is observed [5], even at high β, which is in contrast with the behaviour of the inclusive F_2 structure function at high x. This reflects the presence of a large gluon contribution in the pomeron, even at large parton momenta. A QCD analysis, confirmed by the study of several features of the diffractive final states [7,8] (not presented), indicates that 80 to 90% of the pomeron momentum is carried by gluons.

4 Leading Baryon Analysis: Extension of $F_2^{D(3)}$ to higher $x_{I\!P}$

Using the LPS, a measurement of $F_2^{D(3)}$ in a higher $x_{I\!P}$ regime is possible. Figure 6 shows the uncorrected energy spectra of the leading proton measured with the ZEUS LPS [9], in two Q^2 regimes: photoproduction ($Q^2 \simeq 0$) and DIS ($Q^2 > 0$). Two domains can be defined:

- at $x_L > 0.98$ (low $x_{I\!P}$), where the diffractive peak is clearly visible. The relative size of this peak depends on Q^2.

- at $x_L < 0.98$ (higher $x_{I\!P}$), a different regime is appearing, the spectra of which does not depend on Q^2 and, therefore, hints for a factorization of the proton and lepton vertices.

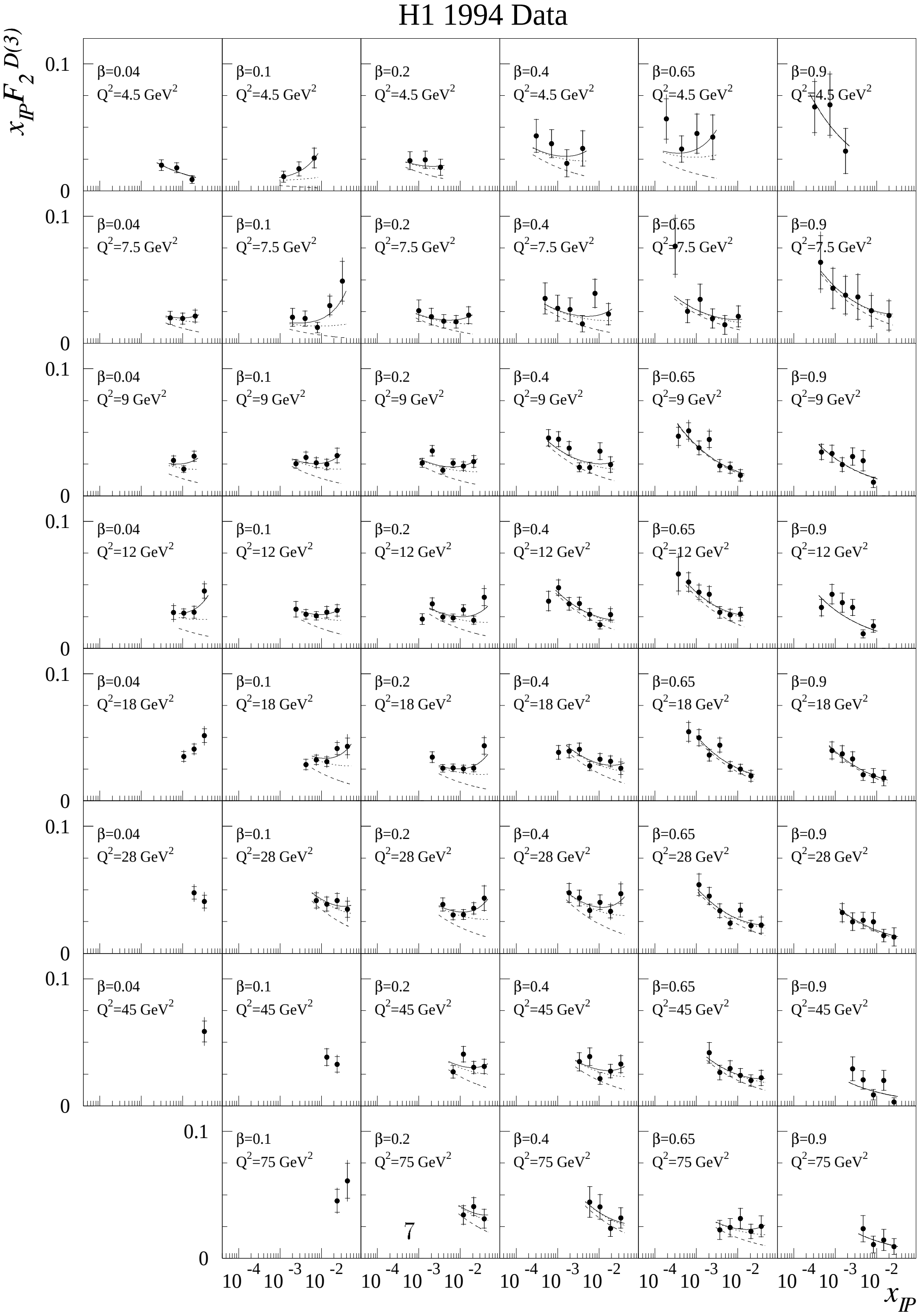

Figure 4: Solid points show $x_{I\!P} \cdot F_2^{D(3)}$ against $x_{I\!P}$ for various β and Q^2 values, from the H1 1994 data. The curve shows the result of the pomeron and Reggeon fit, the dashed curve is the contribution from the pomeron alone, the dotted curve is the pomeron plus interference, and the continuous curve is the total contribution.

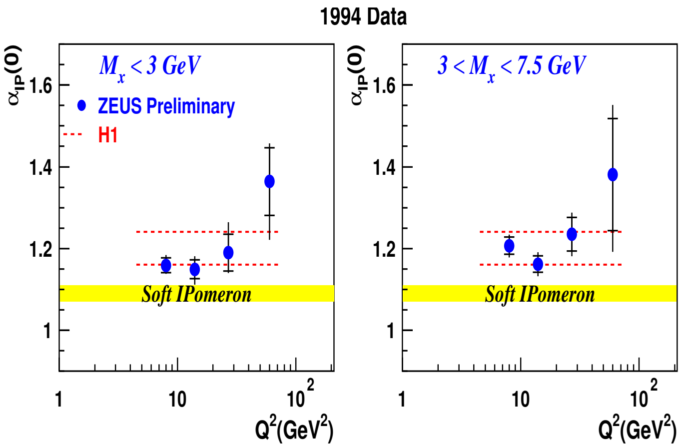

Figure 5: Measurements of $\alpha_{I\!P}(0)$ by the H1 and ZEUS experiments, the dashed line indicating the limits of the H1 measurement and the dots the ZEUS results.

With 1995 data, H1[10] has defined the structure function $F_2^{LP(3)}(x,\,Q^2,\,x_{I\!P})$, equivalent to $F_2^{D(3)}$, in the kinematic domain $0.7 < x_L < 0.9$, $p_\perp(\text{proton}) < 0.2$ GeV, $2 < Q^2 < 50\,\text{GeV}^2$, and $6 \cdot 10^{-5} < x < 6 \cdot 10^{-3}$.

Figure 7 shows the measurement of $F_2^{LP\,(3)}$ in 12 (x, Q^2) bins as a function of $x_{I\!P}$. $F_2^{LP\,(3)}$ appears to rise slowly with Q^2. This indicates scaling violation. The shape is well described by the RAPGAP[11] Monte-Carlo (implementation of π^0 exchange).

5 Conclusion

Many analyses have been performed by the H1 and ZEUS experiments to understand the diffractive processes. Among those, the diffractive structure function $F_2^{D(3)}$ has been measured over a wide range of $x_{I\!P}$, from 10^{-3} up to 0.05. Our present understanding of the colour singlet exchange fits with pomeron exchange for $x_{I\!P} \lesssim 0.05$, together with a Reggeon term. The value of the intercept of the $I\!P$ trajectory extracted at high Q^2 is however greater than the one from soft pomeron exchange in hadron-hadron physics. The Reggeon contribution increases with $x_{I\!P}$. In both experiments, hints have been shown for a gluon dominated pomeron, and were confirmed by final state analyses. The measurements have been extended to $x_{I\!P} = 0.3$ using the LPS.

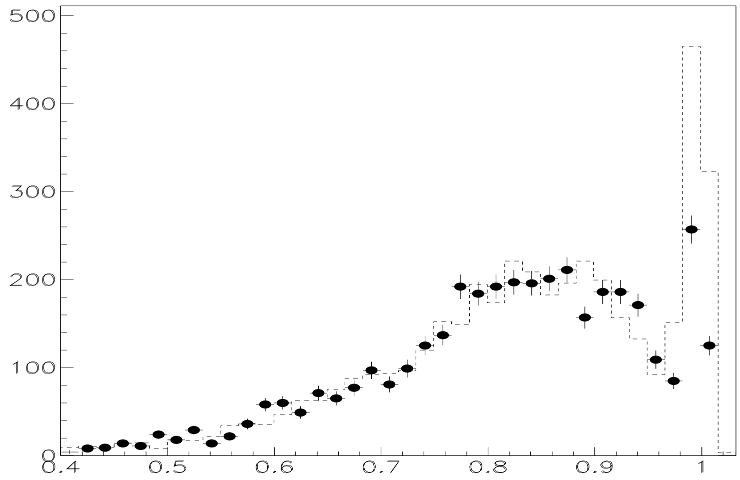

Figure 6: ZEUS x_L spectra for $Q^2 = 0$ (histogram) and $Q^2 > 0$ (points) for the 1994 data.

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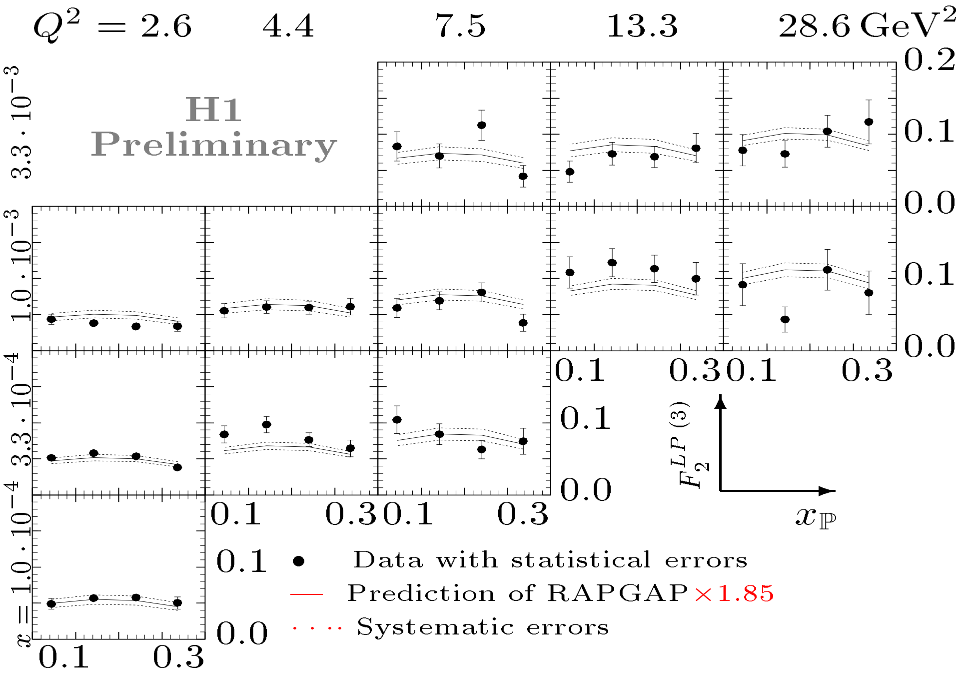

Figure 7: Measurement of $F_2^{LP\,(3)}$ in 12 (x, Q^2) bins as a function of $x_{I\!P}$ (H1 1995 data).

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