ZEUS $F_2^D$ results

XIII International Workshop on Deep Inelastic Scattering
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on behalf of the ZEUS Collaboration

• Introduction
• Diffractive measurement with $M_X$ method
  ➔ hep-ex/0501060 (Accepted by Nucl, Phys. B.)
• Diffractive measurement with a leading proton
• Summary
Inclusive Diffraction in Deep Inelastic Scattering

Non-peripheral process

Kinematics of $ep \rightarrow eXp$

\[ Q^2 = -(k - k')^2 \]
\[ W = \sqrt{(p + q)^2} \]
\[ x_{IP} \approx \frac{Q^2 + M^2_X}{Q^2 + W^2} \]
\[ t = (p - p')^2 \]

\[ x = Q^2 / (2q \cdot p) \]
\[ M^2_X = (k - k' + p - p')^2 \]
\[ \beta \approx \frac{Q^2}{M^2_X + Q^2} = \frac{x}{x_{IP}} \]
\[ x_L = p'/E_p = 1 - x_{IP} \]

Present diffractive measurement in terms of

$\Rightarrow d\sigma(M_X, W, Q^2)/dM_X$ and $x_{IP} F^{D(3)}_2(\beta, x_{IP}, Q^2)$

Diffractive process

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DIS05, Madison, Apr. 27 – May 1
Event Topologies (ep → eXp)

(Diffractive scattering)

(M_X = 5 GeV, Q^2 = 19 GeV^2, W = 123 GeV)

(Non-peripheral scattering)

(M_X = 45 GeV, Q^2 = 13 GeV^2, W = 93 GeV)
**M_X method using Forward Plug Calorimeter**

**Forward Plug Calorimeter**
- Increase the accessible $M_X$ range by a factor of 1.7.
- If $M_N > 2.3$ GeV deposits $E_{\text{FPC}} > 1$ GeV, recognized and rejected

\[ \frac{dN}{d \ln M_X^2} = D + c \cdot \exp(b \cdot \ln M_X^2) \]

**Diffraction** \**Non-diffraction**

with free parameters, $D$, $b$ and $c$ from fit.

\[ \frac{d\sigma_{\text{diff}}}{d M_X} / d M_X, M_N < 2.3 \text{ GeV} \]

- $2.2 < Q^2 < 80$ GeV$^2$
- $37 < W < 245$ GeV
- $0.28 < M_X < 35$ GeV

Using 98-99 data with 4.2 pb$^{-1}$
Selection of diffractive events with Leading Proton Spectrometer

Detection of the scattered proton in LPS with $x_L > 0.9$.

- No background from proton dissociation.
- Limited statistics due to geometrical acceptance.

Photon diffractive dissociation
Double dissociation
Pion exchange

\[ 1 - x_{IP} = x_L = \frac{p}{Z} / p_Z \]

\[ \frac{d\sigma^\text{diff}}{dM_x dt} \]

Using 97 data

- $0.03 < Q^2 < 0.60 \text{ GeV}^2$ → 3.6 pb$^{-1}$
- $2 < Q^2 < 100 \text{ GeV}^2$ → 12.8 pb$^{-1}$
- $25 < W < 280 \text{ GeV}$
- $1.5 < M_x < 70 \text{ GeV}$
- $0 < |t| < 1 \text{ GeV}^2$
**Kinematical ranges**

- **M_X method**: Lower $M_X$ region (~ higher $\beta$ region) and lower $x_{IP}$ region.
- **LPS method**: Higher $x_{IP}$ region
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t dependence of Diffractive Cross Section (LPS)

- Fit t distribution to \( \frac{d\sigma}{dt} \propto \exp(-bt) \)
  \[ b = 7.9 \pm 0.5 \text{(stat.)}^{+0.9}_{-0.5} \text{(syst.)} \text{GeV}^{-2} \]

\( \frac{d\sigma}{dt} \) shows steep fall-off with \( t \) as in elastic hadron-hadron scattering.

- Regge phenomenology predicts “shrinkage” of the diffractive peak:
  \[ b = b_0 + 2\alpha' \ln \frac{W^2}{M_X^2} \approx b_0 + 2\alpha'_{IP} \ln \frac{1}{x_{IP}} \]

- Additional \( \beta \) dependence expected in models.
Diffractive Cross Section ($M_X$)

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$\frac{d\sigma_{\text{diff}}}{dM_X}$, $M_X < 2.3$ GeV

- For $M_X < 2$ GeV, $d\sigma/dM_X$ depends weakly on $W$.

- For $M_X > 2$ GeV, $d\sigma/dM_X$ rises rapidly with $W$. 

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W dependence of Diffractive Cross Section

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- **Fit to the diffractive cross section**:
  
  \[
  \frac{d\sigma^{\text{diff}}_{\gamma^* p \to X N}}{d M_X} = h \cdot W^{a^{\text{diff}}} \sim (W^2)^{(2\alpha_{IP} - 2)}
  \]

  (h, \( a^{\text{diff}} \) free parameters)

  Assuming \( d\sigma / dt \propto e^{b \cdot t} \) and

  \[
  \alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP} \cdot t
  \]

  \[
  \therefore \alpha_{IP}(0) = \overline{\alpha_{IP}} + \frac{\alpha'_{IP}}{b} \approx (a^{\text{diff}} / 4 + 1) + 0.03
  \]

  from LPS

- **For \( M_X < 2 \text{ GeV} \)**
  
  \( \Rightarrow \) \( \alpha_{IP}^{\text{diff}}(0) \) compatible with the soft Pomeron.

- **For larger \( M_X \) and \( Q^2 > 20 \text{ GeV}^2 \)**
  
  \( \Rightarrow \) \( \alpha_{IP}^{\text{diff}}(0) \) lies above the results expected from soft Pomeron and increases with \( Q^2 \).

\[\alpha_{IP}^{\text{soft}}(0) = 1.096^{+0.012}_{-0.009} \text{ from had-had scattering}\]
\[ Q^2 \text{ dependence of } \alpha_{\text{IP}}^{\text{diff}}(0) \]

- **Fit to data with** \( 2 < M_X < 15 \text{ GeV} \)
  \[
  \Delta \alpha_{\text{IP}}^{\text{diff}} \equiv \alpha_{\text{IP}}^{\text{diff}}(0; 2.7 < Q^2 < 20 \text{ GeV}^2) - \alpha_{\text{IP}}^{\text{diff}}(0; 20 < Q^2 < 80 \text{ GeV}^2) = 0.0714 \pm 0.0140(\text{stat.})^{+0.0047}_{-0.0100}(\text{syst.})
  \]

- **Conclusion:**
  - \( \alpha_{\text{IP}}^{\text{diff}}(0) \) is rising with \( Q^2 \), with a significance of 4.2 s.d.
  - Assuming single Pomeron exchange, this observation **contradicts** Regge factorisation.

- **Fit to data with** \( 2 < M_X < 15 \text{ GeV} \) and \( x_{\text{IP}} < 0.01 \)
  \[
  \alpha_{\text{IP}}^{\text{diff}}(0; 2.7 < Q^2 < 20 \text{ GeV}^2) = 1.1209 \pm 0.0051(\text{stat.})^{+0.0136}_{-0.0122}(\text{syst.})
  \]

  \[
  \Delta \alpha_{\text{IP}}^{\text{diff}} = 0.0578 \pm 0.0178(\text{stat.})^{+0.0081}_{-0.0118}(\text{syst.}) \quad \Leftarrow \text{Affected from the limited } x_{\text{IP}} \text{ range.}
  \]

  - **Consistent with LPS** \( \alpha_{\text{IP}}^{\text{diff}}(0; 0.03 < Q^2 < 39 \text{ GeV}^2) = 1.16 \pm 0.02(\text{stat.}) \pm 0.02(\text{syst.}) \)
**M_X dependence of diffractive cross section**

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![Graph](image)

\[ Q^2 \frac{d\sigma_{\text{diff}}^{\gamma^* p \rightarrow XN}}{dM_X} \] vs. \( M_X \) at \( W = 220 \text{ GeV} \)

- **For** \( M_X < 4 \text{ GeV} \),
  - rapid decrease with \( Q^2 \).
  - \( \Rightarrow \) predominantly higher twist.

- **For** \( M_X > 10 \text{ GeV} \),
  - constant or slow rise with \( Q^2 \).
  - \( \Rightarrow \) leading twist.
**Diffractive contribution of the total cross section**

\[
\Gamma_{tot}^{diff} = \frac{\int_{M_a}^{M_b} dM_X d\sigma_{\gamma^* p \rightarrow XN, M_N < 2.3 GeV}^{diff}}{dM_X}
\]

- For \( M_X < 2 \) GeV, falling with \( W \).
- For \( M_X > 2 \) GeV, constant with \( W \).

- For \( M_X < 2 \) GeV, decreasing with rising \( Q^2 \).
- For \( M_X > 8 \) GeV, no \( Q^2 \) dependence.

→ For larger \( M_X \), \( \sigma^{diff} \) has the similar \( W \) and \( Q^2 \) dependences as \( \sigma^{tot} \).

- For the highest \( W \) bin (200<\( W < 245 \) GeV),
  \( \sigma^{diff} (0.28< M_X < 35 \text{ GeV}, M_N < 2.3 \text{ GeV}) / \sigma^{tot} \)
  
  \[
  15.8^{+1.2}_{-1.0} \% \text{ at } Q^2 = 4 \text{ GeV}^2 \\
  9.6^{+0.7}_{-0.7} \% \text{ at } Q^2 = 27 \text{ GeV}^2
  \]
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Diffractive structure function of the proton

- For $M_X < 2$ GeV, $x_{IP}F_2^{D(3)}$ is constant with $x_{IP}$.
- For $M_X > 2$ GeV, rapid increase as $x_{IP} \to 0$.

Data are compared with the color dipole model in BEKW parametrisation.

$$x_{IP}F_2^{D(3)} = c_T \cdot F_{qq}^T + c_L \cdot F_{qq}^L + c_g \cdot F_{qg}^T$$

$F_{qq}^T \propto \beta(1 - \beta)$ dominates at $\beta > 0.15$

$F_{qq}^L \propto \beta^3 (1 - 2\beta)^2$ substantial at large $\beta$

$F_{qg}^T \propto (1 - \beta)\gamma$ dominates at small $\beta$
Comparison of LPS and $M_X$ method

$\gamma^* p \rightarrow X p$ via the exchange of a Reggeon $\alpha_j$.

\[
\frac{d\sigma}{d \ln M_X^2} \propto \exp \left( 1 + \alpha_k(0) - 2\alpha_j \right) \cdot \ln M_X^2
\]

- $M_X$ method suppresses the Reggeon contributions.
- Good agreement between LPS and $M_X$ method ($\times 0.7$ for $M_N < 2.3$ GeV) except for the region of $x_{IP} > 0.01$ where Reggeon contributions may dominate LPS.
Comparison with Colour Dipole Model - I


Comparison with FS04 (Forshaw & Shaw) Regge dipole model with/without saturation and CGC (Colour Glass Condensate) model → Refer to hep-ph/0411337.

Thanks to J. Forshaw.

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Dipole model predictions for $F_2^{D(3)}$

- ZEUS LPS97
  - $Q^2=2.4$ GeV$^2$
  - $Q^2=3.7$ GeV$^2$
  - $Q^2=6.9$ GeV$^2$
  - $Q^2=13.5$ GeV$^2$
  - $Q^2=39$ GeV$^2$

Fit $F_2$ and then predict $x_{IP}F_2^{(3)}$
Comparison with Colour Dipole Model - II

Low $Q^2$ from ZEUS $M_X$ 98-99

Dipole model predictions for $F_{D(3)}^{D(3)}$

$\beta = 0.003$

$\beta = 0.0044$

$\beta = 0.0066$

$\beta = 0.0067$

$\beta = 0.0099$

$\beta = 0.0148$

$\beta = 0.0218$

$\beta = 0.032$

$\beta = 0.0472$

$\beta = 0.0698$

$\beta = 0.1$

$\beta = 0.1429$

$\beta = 0.2306$

$\beta = 0.3077$

$\beta = 0.4$

$\beta = 0.6522$

$\beta = 0.7353$

$\beta = 0.8065$

$Q^2 = 2.7$ GeV$^2$

$Q^2 = 4$ GeV$^2$

$Q^2 = 6$ GeV$^2$

$M_X = 30$ GeV

$M_X = 20$ GeV

$M_X = 11$ GeV

$M_X = 6$ GeV

$M_X = 3$ GeV

$M_X = 1.2$ GeV

$\Rightarrow$ Predictions of model are corrected by $1/0.7$ for the $M_N<2.3$ GeV of ZEUS $M_X$ method.
Comparison with Colour Dipole Model - III

High $Q^2$ from ZEUS $M_X$ 98-99

Dipole model predictions for $F_{2D}^{(3)}$

- CGC and FS04(sat) are able simultaneously to describe $F_2$ and $x_{IP}F_2D^{(3)}$.
- Forshaw & Shaw have not been able to find a good fit which does not invoke saturation.
$Q^2$ dependence of $x_{IP}F_2^{D(3)}$

- For $\beta = 0.9$
  - (dominated events with $M_X < 2$ GeV),
  - Constant or slowly decreasing with $Q^2$.
  - Expect higher twist effect from $(q\bar{q})_L$.

- For $\beta \leq 0.7$ and $x = \beta x_{IP} < 0.002$,
  - $x_{IP}F_2^{D(3)}$ increases with increasing $Q^2$.
  - Positive scaling violations.
  - Suggest perturbative effects such as gluon emission

- For fixed $\beta$,
  - $Q_2$ dependence of $x_{IP}F_2^{D(3)}$ changes with $x_{IP}$.
  - Inconsistent with the Regge factorisation hypothesis
\[ \beta \text{ dependence of } x_{IP}F_2^{D(3)} \text{ at } x_{IP}=0.01 \]

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- \( x_{IP}F_2^{D(3)} \) for \( x_{IP}=x_0=0.01 \)
  - expect this to represent the structure function of Pomeron, up to a normalisation constant.

- For \( \beta > 0.1 \)
  - \( x_{IP}F_2^{D(3)} \) has a maximum around \( \beta=0.5 \).
  - The \( \beta(1-\beta) \) dependence observed is expected in dipole models of diffraction by \( \gamma^* \rightarrow q\bar{q} \) splitting and two gluon exchange.

- For \( \beta < 0.1 \)
  - \( x_{IP}F_2^{D(3)} \) rises as \( \beta \rightarrow 0 \) and the rise accelerates with growing \( Q^2 \).
  - Similar to the logarithmic scaling violation of \( F_2 \) at low \( x \) due to QCD evolution.
Summary

- The measurements of diffraction in DIS with $M_X$ method and with a leading proton show:
  - Slope of $d\sigma/d|t|$ is compatible with soft interaction at the proton vertex.
  - Indication for Regge factorisation breaking seen in
    - $Q^2$ dependence of $\alpha_{IP}^{\text{diff}}(0)$
    - $Q^2$ dependence of $x_{IP}F_2^{D(3)}$ for fixed $\beta$ and fixed $x_{IP}$
  - Diffractive contribution of the total cross section

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<th>$\sigma_{\text{diff}}/\sigma_{\text{tot}}$</th>
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<td>$Q^2$ dependence</td>
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<td>Leading twist behaviour</td>
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- Diffraction shows evidence for pQCD evolution with $Q^2$ as $x_{IP} \to 0$ or $\beta \to 0$.
- Data can be described by color dipole model (BEKW, GBW, FS04, CGC ......).

- Expect new diffractive results with high statistics for an extended kinematic range (especially $Q^2 < 500 \text{ GeV}^2$) soon.