New Results on Diffraction at HERA

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H1 Preliminary
data
signal
background

H1 data

ZEUS

H1

D* in diffractive DIS

ZEUS (prel.) 374 pb⁻¹
HERA: The World’s Only ep Collider

HERA-1 (1993-2000) \( \simeq 120 \text{ pb}^{-1} \)
HERA-2 (2003-2007) \( \simeq 380 \text{ pb}^{-1} \)

Final Data samples
H1+ZEUS: \( 2 \times 0.5 \text{ fb}^{-1} \)

- 1998 \( E_p \) upgrade: \( 820 \Rightarrow 920 \text{ GeV} \)
  \( (\sqrt{s} : 301 \Rightarrow 319 \text{ GeV}) \)
- 2001 HERA-2 upgrade: \( \mathcal{L} \times 3 \), Polarised \( e^+e^- \)
  \( \langle P \rangle = 40\% \)
Diffraction at HERA. Factorisation properties

QCD factorisation
(rigorously proven for DDIS by Collins et al.):

\[ \sigma^{D(4)}_r \propto \sum_i \hat{\sigma} \gamma^*_i(x, Q^2) \otimes f^D_i(x, Q^2; x_{IP}, t) \]

- \( \hat{\sigma} \gamma^*_i \) – hard scattering part, same as in inclusive DIS
- \( f^D_i \) – diffractive PDF's, valid at fixed \( x_{IP}, t \) which obey (NLO) DGLAP

Regge factorisation
(conjecture, e.g. RPM by Ingelman, Schlein):

\[ F^{D(4)}_2(x_{IP}, t, \beta, Q^2) = \Phi(x_{IP}, t) \cdot F^{IP}_2(\beta, Q^2) \]

- In this case shape of diffractive PDF's is independent of \( x_{IP}, t \)
  while normalization is controlled by Regge flux \( \Phi(x_{IP}, t) \)
Selection of Diffractive Events

Measure the leading proton

- Forward spectrometers (H1 FPS/VFPS)

- $x_{IP}$ and $t$ measurements
- Less statistics
- $p$-tagging systematics

Measure a Large Rapidity Gap

- Data integrated over $|t| < 1 \text{ GeV}^2$
- High statistics
- Contamination from proton dissociation events
  - Needs to be controlled

Different systematics
Different kinematic coverage
Inclusive Diffraction and DPDFs: gluon dominated $P$
Diffraction at HERA: Some old Results

Inclusive Diffraction and DPDFs: gluon dominated $P$

VM: soft vs hard $P$ transition from soft to hard regime at $\mu^2 \approx 4 \div 5$ GeV$^2$
Selected new Results

- Diffractive Photoproduction of Isolated Photons [ZEUS-prel-2015]

- $D^*$ Meson Production in Diffractive DIS at HERA [H1-prel-2016]

- Cross-section Ratio $\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}}$ in Exclusive DIS [ZEUS-pub-2016]

- Exclusive $\rho^0$ Meson Photoproduction with a Leading Neutron [H1-pub-2016]
Isolated Photons in Diffractive Photoproduction
Examples of lowest-order diagrams by which diffractive processes may generate a prompt photon

- **Direct** incoming photon gives all its energy to the hard scatter \( (x_\gamma = 1) \).
- **Resolved** incoming photon gives fraction \( x_\gamma \) of its energy.

An outgoing photon must couple to a charged particle line and so the exchanged colourless object ("pomeron") must be resolved in these lowest-order processes.

\[ 4 < E^\gamma_t < 15 \text{ GeV} \]
\[ -0.7 < \eta^\gamma < 0.9 \]

- Use energy-weighted e.m. cluster width \( \langle \delta Z \rangle \) to distinguish \( \gamma \) from \( \pi^0 \), \( \eta \) background
- Diffraction: LRG signature, and \( x_{IP} < 0.03 \)
Isolated Photon + Jet: Data vs MC model

Comparison with NLO QCD to follow

All well described, except highest $z_{IP}$.
D* in Diffractive DIS at HERA
Based on 280 pb$^{-1}$ HERA-2 data

Open charm tagged with $D^*$

$D^{*+} \rightarrow D^0\pi^+_\text{slow} \rightarrow (K^-\pi^+)\pi^+_\text{slow} + C.C.$

LRG selection of diffraction ($\sim 1100D^*$)
**$D^*$ Production in Diffractive DIS: Data vs NLO**

- NLO QCD by HQVDIS in FFNS (H1 DPDF-2006, $m_c = 1.5$ GeV, $\mu_r^2 = \mu_f^2 = m_c^2 + 4Q^2$)
  - in good agreement with data

- Charm fragm. func. as determined in H1 non-diffractive $D^*$ analysis
  - works here $\Rightarrow$ supports universality of charm fragmentation

- Data could be used as additional input to the global DPDF fit
Cross–section Ratio $\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}}$ in DIS
Motivation

$\frac{\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}}{\sigma_{\gamma p \rightarrow \psi(2S)p}}$ gives information about the dynamics of hard process sensitive to radial wave function of charmonium.

pQCD predictions: $R(Q^2 = 0) \simeq 0.17$ and rises with $Q^2$.

$\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in DIS

$R = \frac{\sigma_{\gamma p \rightarrow \psi(2S)p}}{\sigma_{\gamma p \rightarrow J/\psi p}}$

$\psi(2S)$ wave function different from $J/\psi$ wave function:

- Has a node at $\approx 0.35$ fm
- $\langle r^2 \rangle_{\psi(2S)} \approx 2 \langle r^2 \rangle_{J/\psi(1S)}$
Data samples and Decay channels

\[
J/\psi(1S) \rightarrow \mu^+\mu^- \quad \psi(2S) \rightarrow J/\psi(1S) \pi^+\pi^- \\
\psi(2S) \rightarrow J/\psi(1S) \pi^+\pi^- ; \ J/\psi(1S) \rightarrow \mu^+\mu^- \\
J/\psi(1S) \rightarrow \mu^+\mu^- \quad \langle Q^2 \rangle < 80 \text{GeV}^2 \quad \mathcal{L} = 468 \text{ pb}^{-1}
\]

Data samples

HERA I + HERA II data (1996 — 2007)
Integrated luminosity: 468 pb^{-1}

MC-data samples

Signal MC: DIFFVM for exclusive VM production
Background MC: GRAPE
for Bethe–Heitler
mu–pair production

\[\begin{align*}
5 < Q^2 < 80 \text{GeV}^2 \\
\mathcal{L} = 468 \text{ pb}^{-1}
\end{align*}\]
Results: \( \sigma_{\psi(2S)}/\sigma_{J/\psi(1S)} \) vs \( Q^2, W \) and \( |t| \)

- Ratio rises with \( Q^2 \) and is constant in \( W \) and \( |t| \)
- HERA data in qualitative agreement with pQCD models
- Some discriminating power (albeit statistically limited)
Rho−0 with a Leading Neutron at HERA
HERA as a ‘4P’ facility

HERA enables to study structure of

- **Proton** – $F_2, F_L, ...$
- **Photon** – $g/\gamma$
- **Pomeron** – $F_2^D, F_L^D$
- **Pion** – $F_2^\pi$
HERA as a ‘4P’ facility

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- Proton – $F_2$, $F_L$, ...
- Photon – $g/\gamma$
- Pomeron – $F_2^D$, $F_L^D$
- Pion – $F_2^\pi$

Here for the first time we investigate the reaction involving all these objects simultaneously:

$$\gamma + p \rightarrow \rho^0 \pi^+ n$$

Photoproduction: $Q^2 < 2 \text{ GeV}^2$ ($\langle Q^2 \rangle = 0.04 \text{ GeV}^2$)
Low $p_t$: $|t| < 1 \text{ GeV}^2$ ($\langle |t| \rangle = 0.20 \text{ GeV}^2$)
Small mass: $0.3 < m_{\pi\pi} < 1.5 \text{ GeV}$ ($m_{\rho^0}$)
$\pi^+, \pi^-$ in CT: $20 < W_{\gamma p} < 100 \text{ GeV}$ ($\langle W_{\gamma p} \rangle = 45 \text{ GeV}$)
Leading $n$: $E_n > 120 \text{ GeV}$; $\theta_n < 0.75 \text{ mrad}$

No hard scale present $\Rightarrow$ Regge framework is most appropriate
**$\rho^0$ with Leading Neutron: S/B decomposition**

Data sample: $L = 1.16 \text{ pb}^{-1}$

$\sim 7000$ events

Precision:
- $\delta_{\text{stat}} = 2\%$
- $\delta_{\text{sys}} = 14\%$

(a) $W_{\gamma p}$
(b) $W_{\gamma N}$
(c) $W_{\gamma n}$
(d) $M_Y$

**$\rho^0$ with Forward Neutron**

- $E_{\eta k}$
- $B/(S+B)$

$F_{bg} = 0.34 \pm 0.05$

Data points are shown with statistical errors only;
green band represents estimated
total background fraction uncertainty
**ρ-meson shape**

### ρ⁰ with Forward Neutron

![Graph](image)

**H1 data**
- H1 data
- ρ⁰: BW
- ρ⁰: BW×RS
- interference term
- ω reflection
- full fit

\[
\frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} \propto BW_\rho(M_{\pi\pi}) \left( \frac{M_\rho}{M_{\pi\pi}} \right)^n_{RS}
\]

- \( M = 764 \pm 3 \text{ MeV} \)
- \( \Gamma = 155 \pm 5 \text{ MeV} \)

### Exclusive ρ⁰ photoproduction

![Graph](image)

- H1 data
- ZEUS-1994 (γp → ρ⁰p)
- fit \( n_0(p_T^2 + M^2)^\beta \)

**Analysis region:** \( 0.6 < M_{\pi^+ \pi^-} < 1.1 \text{ GeV} \) extrapolated using BW to the full range: \( 0.28 < M_{\rho^0} < 1.5 \text{ GeV} \)
Cross sections definitions

\[ \sigma_{\gamma p} = \frac{\sigma_{e p}}{\Phi_{\gamma}} \]

\[ \Phi_{\gamma} = \int f_{\gamma/e}(y, Q^2)dydQ^2 \]

\[ \sigma_{\gamma\pi} = \frac{\sigma_{\gamma p}}{\Gamma_{\pi}} \]

\[ \Gamma_{\pi} = \int f_{\pi/p}(x_L, t)dx_L dt \]

**VMD:**

\[ f_{\gamma/e}(y, Q^2) = \frac{\alpha}{2\pi Q^2 y} \left\{ 1 + (1 - y)^2 - 2(1 - y) \left( \frac{Q_{\text{min}}^2}{Q^2} - \frac{Q^2}{M_\rho^2} \right) \right\} \frac{1}{\left(1 + \frac{Q^2}{M_\rho^2} \right)^2} \]

**OPE:**

\[ f_{\pi/p}(x_L, t) = \frac{1}{2\pi} \frac{g^2_{\rho\pi N}}{4\pi} \frac{-t}{(m_\pi^2 - t)^2} \exp\left[ -R_{\pi n}^2 \frac{m_\pi^2 - t}{1 - x_L} \right] \]
Cross sections definitions

\[ \sigma_{\gamma p} [\text{nb}] \]

\[ W_{\gamma} \]

\[ \rho^0 \text{ with Forward Neutron} \]

\[ H1 \]

\[ e' \]

\[ e \]

\[ f_{\gamma/e} \]

\[ f_{\pi/p} \]

\[ p \]

\[ n \]

\[ \pi^+ \]

\[ \pi^- \]

\[ \gamma \]

\[ \rho^0 \]

\[ \pi^+ \]

\[ \pi^- \]

\[ \pi^0 \text{ with Forward Neutron} \]

\[ H1 \]

\[ H1 \text{ data} \]

\[ \rho^0 (\gamma \pi^+ \pi^-) \, [\mu\text{b}] \]

\[ W_{\pi} \text{ [GeV]} \]

**VMD:**

\[
 f_{\gamma/e}(y, Q^2) = \frac{\alpha}{2\pi Q^2 y} \left\{ \left[ 1 + (1 - y)^2 - 2(1 - y) \left( \frac{Q^2_{\text{min}}}{Q^2} - \frac{Q^2}{M^2_{\rho}} \right) \right] \frac{1}{(1 + \left( \frac{Q^2}{M^2_{\rho}} \right)^2)} \right\}
\]

**OPE:**

\[
 f_{\pi/p}(x_L, t) = \frac{1}{2\pi} \frac{g_{p\pi N}^2}{4\pi} \frac{1}{(1 - x_L)} \left( \frac{m^2_{\pi} - t}{(m^2_{\pi} - t)^2} \right) \exp\left[ -R^2_{\pi n} \frac{m^2_{\pi} - t}{1 - x_L} \right]
\]
Constraining pion flux

Failure to describe $b_n(x_L)$ suggests strong absorptive effects ($n$ rescattering) $\Rightarrow$ try to quantify
Estimate of absorption corrections

\[ r_{el} = \frac{\sigma_{\gamma\pi \to \rho^0 \pi}}{\sigma_{\gamma p \to \rho^0 p}} = \begin{cases} 
0.25 \pm 0.06 \quad \text{(exp.extracted)} \\
0.57 \pm 0.03 \quad \text{(theo.expected)} 
\end{cases} \]

\[ K_{\text{abs}} = 0.44 \pm 0.11 \]

- Optical Theorem: \[ \frac{d\sigma_{el}}{dt} \Big|_{t=0} = b_{el}\sigma_{el} \propto \sigma_{\text{tot}}^2 \]
- Eikonal approach: \[ b = \langle R^2 \rangle; \quad b_{12} = b_1 + b_2 \]
- World data: \( b_{pp} \simeq 11.7, \quad b_{\pi^+p} \simeq 9.6, \quad b_{\gamma p} \simeq 9.75 \) GeV\(^{-2}\)
Differential cross section in $p^2_{T,\rho}$

$$d\sigma_{\gamma p}/dt' [\mu b/GeV^2]$$

<table>
<thead>
<tr>
<th>$t'$ [GeV$^2$]</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
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</thead>
<tbody>
<tr>
<td>$d\sigma_{\gamma p}/dt'$ [\mu b/GeV^2]</td>
<td>10</td>
<td>1</td>
<td>0.1</td>
<td>0.01</td>
<td>0.001</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

- H1 data
- Fit: $a_1 e^{b_1 t'} + a_2 e^{b_2 t'}$
  - $b_1 = 25.7 \pm 3.2$ GeV$^{-2}$, $b_2 = 3.62 \pm 0.32$ GeV$^{-2}$

Geometric interpretation: $\langle r^2 \rangle = 2b_1 \cdot (\hbar c)^2 \simeq 2$ fm$^2 \Rightarrow (1.6R_p)^2 \Rightarrow$ ultra-peripheral process

DPP explanation: low mass $\pi^+ n$ state $\rightarrow$ large slope, high masses $\rightarrow$ less steep slope
Summary

- Diffraction is an important part of HERA physics landscape. Despite overall consistent picture, the field is challenging, as it represents a complicated interplay of soft and hard phenomena.

- Statistically limited channels have been studied with full HERA data sample. Whenever a hard scale is present, pQCD calculations are successful.

- The data show sensitivity to some QCD models parameters. They can also be used to further constrain DPDF, especially at high $z_P$.

- Photon-pion elastic cross section is extracted experimentally (in OPE approximation) for the first time.

- Strong absorptive effects are confirmed in Leading Neutron production. Since the nature of these is non-perturbative, exp. results are essential for tuning models of ‘Survival Gap Probability’.
Backup Slides
Open questions

■ $F_2^{D(4)}$ from HERA-II VFPS data and final DPDF determination without assumption on Regge factorisation.

■ Explain factorisation breaking mechanism in PHP, in particular independence of Gap Survival Probability on $x_\gamma$.

■ Multiscale problem: $(Q^2, E_T, M_V, t)$.

■ Where is an Odderon?

■ Can one observe Glueball in a double Pomeron reaction in PHP?

\[ \gamma p \rightarrow (IP\overline{IP}) \rightarrow M_X \quad (M_X = \sqrt{x_{IP1}x_{IP2}}W_{\gamma p} = 2 \div 4 \text{ GeV}) \]

HERA has finished, but not DIS physics.
What’s next? eRHIC? LHeC?