New Results on Diffraction at HERA

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**HERA: The World’s Only ep Collider**

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

**HERA-1** (1993-2000) $\approx 120$ pb$^{-1}$

**HERA-2** (2003-2007) $\approx 380$ pb$^{-1}$

**Final Data samples**  
H1+ZEUS: $2 \times 0.5$ fb$^{-1}$
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 $dP$

![Plot of DPDFs and diffraction data](image)
Diffraction at HERA: Some old Results

Inclusive Diffraction and DPDFs: gluon dominated $\mathcal{P}$

$\alpha_{F}(t) = \alpha(0) + \alpha' t$

$\gamma P(t) = \gamma + \gamma'$

$\sigma_{\gamma p}(0)$

$\sigma(\gamma p \rightarrow \gamma p)$

$\sigma(\gamma p \rightarrow \gamma p)$

$\sigma(\gamma p \rightarrow J/\psi p)$

$\sigma(\gamma p \rightarrow \psi(2S)p)$

$\sigma(\gamma p \rightarrow \tau(1S)p)$

VM: soft vs hard $\mathcal{P}$ transition from soft to hard regime at $\mu^2 \simeq 4 \div 5 \text{ GeV}^2$
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
Isolated Photons in Diffractive PHP

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 exchanged line and so the exchanged colourless object ("pomeron") must be resolved in these lowest-order processes.

$4 < E_t^\gamma < 15$ 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 $z_P$. 

Photon
Jet
D* in Diffractive DIS at HERA
**D* Production in Diffractive DIS: Data sample**

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 \((\sim 1100D^*)\)

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**D* in diffractive DIS**

- **H1 Preliminary**
  - data
  - signal
  - background

![Graph showing the distribution of D* in diffractive DIS](image)

**Axes:**
- \(m(K\pi\pi_s) - m(K\pi)\) GeV

**Legend:**
- \(N(D^*)\)
- \(\sigma_{ep \rightarrow eX(D^*)} \) [nb]

**Fitter:**
- NLO QCD, H1 2006 Fit B
- \(m_t \oplus \text{scale variation}\)

**Requirements:**
- \(5 < Q^2 < 100 \text{ GeV}^2\)
- \(x_{ip} < 0.03\)
- \(0.02 < y < 0.65\)
- \(M_Y < 1.6 \text{ GeV}\)
- \(p_{T,D^*} > 1.5 \text{ GeV}\)
- \(|t| < 1 \text{ GeV}^2\)
- \(-1.5 < \eta_{D^*} < 1.5\)
**D* Production in Diffractive DIS: Data vs NLO**

- NLO QCD by HQVDIS in FFNS (H1 DPDF-2006, $m_c = 1.5\text{GeV}$, $\mu_r^2 = \mu_f^2 = m_c^2 + 4Q^2$) 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

\[ \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} \text{ in DIS} \]

**Ratio**

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

gives information about the dynamics of hard process

sensitive to radial wave function of charmonium

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

- Has a node at \( \approx 0.35 \text{ fm} \)
- \( \langle r^2 \rangle_{\psi(2S)} \approx 2 \langle r^2 \rangle_{J/\psi(1S)} \)

**pQCD predictions:** \( R(Q^2 = 0) \approx 0.17 \) and rises with \( Q^2 \)
Data samples and Decay channels

**J/ψ(1S) → μ⁺μ⁻**

**ψ(2S) → J/ψ(1S) π⁺π⁻**

ψ(2S) → J/ψ(1S) π⁺π⁻; J/ψ(1S) → μ⁺μ⁻

ψ(2S) → μ⁺μ⁻

J/ψ(1S) → μ⁺μ⁻

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

\[ 5 < Q^2 < 80 \text{GeV}^2 \quad \mathcal{L} = 468 \text{pb}^{-1} \]
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

HERA enables to study structure of

\[ \text{Proton} - F_2, F_L, \ldots \]

\[ \text{Photon} - g/\gamma \]

\[ \text{Pomeron} - F_2^D, F_L^D \]

\[ \text{Pion} - F_2^\pi \]

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: \( \mathcal{L} = 1.16 \) pb\(^{-1} \)
\( \sim 7000 \) events

Precision:
\( \delta_{\text{stat}} = 2\% \)
\( \delta_{\text{sys}} = 14\% \)

\( E_{t'N} \)
\[ B / (S + B) \]

\( F_{bg} = 0.34 \pm 0.05 \)

Data points are shown with statistical errors only;
green band represents estimated background fraction uncertainty
$\rho^0$ with Forward Neutron

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

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

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

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

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

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

**VMD:**

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

**OPE:**

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

\[ \sigma_{\gamma p} \] [GeV]

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

20 40 60 80 1000

100 200 300 400 500

H1 data

POMPYT

fit \( W^2(\delta = -0.26 \pm 0.06_{\text{stat}} \pm 0.07_{\text{sys}}) \)

H1 data

H1

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

VMD:

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

OPE:

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

\[ d\sigma / dx_L \] \[ \mu b \]

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

\[ (2.33 \pm 0.56) \mu b \]

\[ (9.5 \pm 0.5) \mu b \]

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

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

Optical Theorem: \[ \frac{d\sigma_{el}}{dt} \bigg|_{t=0} = b_{el}\sigma_{el} \propto \sigma_{tot}^{2} \]

Eikonal approach: \[ b = \langle R^{2} \rangle ; \quad b_{12} = b_{1} + b_{2} \]

World data: \[ (b_{pp} \simeq 11.7, \quad b_{\pi+p} \simeq 9.6, \quad b_{\gamma p} \simeq 9.75) \ \text{GeV}^{-2} \]
Differential cross section in $p_{T,\rho}^2$

**Geometric interpretation:** $\langle r^2 \rangle = 2b_1 \cdot (\hbar c)^2 \simeq 2 \text{ fm}^2 \Rightarrow (1.6R_p)^2 \Rightarrow$ 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 $z_{IP}$.

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

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