Diffractive and forward physics results from HERA

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on behalf of H1 and ZEUS Collaborations
- 27.5 GeV electrons/positrons on 920 GeV protons → $\sqrt{s}=318$ GeV
- HERA I,II: ~ 500 pb$^{-1}$ per experiment
- H 1 & ZEUS - 4π detectors

**Diffraction**

New era started with HERA:

H1: 31 publications about diffraction

ZEUS: 31 publications about diffraction

+ one common H1/ZEUS publication

At HERA 10% of events are diffractive
Diffractive kinematics

Deep inelastic scattering - DIS

- $Q^2$ - virtuality of the photon
- $Q^2 \sim 0 \text{ GeV}^2 \rightarrow$ photoproduction
- $Q^2 \gg 0 \text{ GeV}^2 \rightarrow$ DIS
- $W$ - total hadronic energy

Diffractive scattering

- momentum fraction of color singlet exchange
  $$x_{IP} = \xi = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$
- fraction of exchange momentum, coupling to $\gamma$
  $$\beta = \frac{Q^2}{Q^2 + M_X^2} = x_{q/IP} = \frac{x}{x_{IP}}$$

- 4-momentum transfer squared (if proton is measured)
  $$t = (p - p')^2$$

$M_y = m_p$ proton stays intact

$M_y > m_p$ proton dissociates, contribution should be understood

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Methods of diffraction selection

Proton spectrometers

**H1:** VFPS (2005-2007)
FPS (1997-2007)

**ZEUS:** LPS (1997-2000)

- free of p-dissociation background
- $x_{IP}$ and $t$ measurements
- access to high $x_{IP}$ range (IP and IR)
- small acceptance, small statistics

Large Rapidity Gap

require no activity beyond $\eta_{\text{max}}$

- $t$ not measured, integrated over $|t|<1\text{GeV}^2$
- very good acceptance at low $x_{IP}$
- p-diss background about 20% ☠

Different phase space and systematics - non-trivial to compare!
Modelling of diffraction

QCD collinear factorisation theorem

\[ \sigma^D(\gamma^* p \rightarrow Xp) = \sum_{\text{parton}_i} f^D_i(x, Q^2, x_{IP}, t) \cdot \sigma^{\gamma^*_i}(x, Q^2) \]

DPDFs - obey DGLAP universal for diff. ep DIS

Proton vertex factorisation (conjecture, e.g. Resolved Pomeron Model by Ingelman & Schlein)

\[ f^D_i(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f^p_i(\beta = x / x_{IP}, Q^2) \]

Dipole model

Proton rest frame - dipoles

\[ d\sigma_{\text{diff}}^\gamma p/dt \propto \int dz dr^2 \Psi^* \sigma^2_{qq}(x, r^2, t) \Psi \]

Long living quark pairs interact with gluons of the proton

Then DPDFs extracted from DIS data

No extra parameters needed for DDIS

Pomerlon flux factor

Diffractive DPDF

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Most recent diffractive dijet production in DIS

4 \leq Q^2 < 100 \text{ GeV}^2, E^*_{\text{jet}1(2)} > 5.5(4) \text{ GeV}

Measurements in agreement with NLO QCD calculations, factorisation confirmed.

Data/NLO

\begin{align*}
\text{H1} & \quad d\sigma/dQ^2 \ [\text{pb/GeV}^2] \\
\text{Data/NLO} & \quad 10 \\
& \quad 1 \\
& \quad 10^{-1} \\
& \quad 1 \\
& \quad 10^{-2} \\
& \quad 1 \\
& \quad 10^{-3} \\
& \quad 1 \\
\end{align*}

\begin{align*}
\text{H1} & \quad d\sigma/dz_{\text{IP}} \ [\text{pb}] \\
\text{Data/NLO} & \quad 200 \\
& \quad 150 \\
& \quad 100 \\
& \quad 50 \\
& \quad 2 \\
& \quad 0.2 \\
& \quad 0.4 \\
& \quad 0.6 \\
& \quad 0.8 \\
& \quad 1 \\
\end{align*}
Most recent -diffractive dijet production in DIS

\[ \alpha_s(M_Z) = 0.119 \pm 0.004 \text{(exp)} \pm 0.012 \text{(DPDF, theo)} \]

Result is consistent within uncertainties with the world average.
**Direct Photoproduction:**
- Photon directly involved in hard scattering → $x_\gamma = 1$

**Resolved Photoproduction:**
- Photon fluctuates into hadronic system, which takes part in hadronic scattering, dominant at $Q^2 \approx 0$ → $x_\gamma < 1$

**In LO QCD!**
- $x_\gamma = x_\gamma^{OBS} = \frac{\sum (E - p_z)_{jets}}{(E - p_z)_{hadrons}}$
- $Z_{IP} = \frac{\sum (E + p_z)_{jets}}{(E + p_z)_{hadrons}}$

**Theoretical prediction of Kaidalov, Khoze, Martin, Ryskin**
(European Journal of Physics 66,373 (2010))

**Suppression:**
- Quarks: $0.71(0.75)$, $E_T^{jet} > 5$ (7.5) GeV
- Gluons: $0.53(0.58)$, $E_T^{jet} > 5$ (7.5) GeV

**ISMD, Wildbad Kreuth**
Not evident that factorisation should be valid also for photoproduction, in LO photoproduction contributions of resolved photon process.

**History** - three independent measurements

- **H1** - LRG method, tagged photoproduction, $S^2 = 0.5 \pm 0.1$

- **H1** - LRG method, tagged photoproduction, $S^2 = 0.58 \pm 0.01 \pm 0.12 (\text{exp}) \pm 0.14 \pm 0.09 (\text{th})$

- **ZEUS** - LRG method, untagged photoproduction $E_{T\text{jet}1(2)}> 7.5 (6.5) \text{ GeV}$

A new H1 measurement with different diffractive method selection - proton measured in forward proton spectrometer VFPS

Suppression factor

$$S^2 = \frac{\sigma (\text{data})}{\sigma (\text{theory} (\text{NLO QCD}))}$$
**Diffractive dijet photoproduction & DIS-measurement in Very Forward Proton Spectrometer**

**DIS & photoproduction**

\[ 4 < Q^2 < 80 \text{ GeV}^2 \quad Q^2 < 2 \text{ GeV}^2 \]

Other cuts identical:

\[ 0.01 < x_{IP} < 0.024 \]

\[ |t| < 0.6 \text{ GeV}^2 \]

\[ z_{IP} < 0.8 \]

\[ E_T^{*\, \text{jet1(2)}} > 5.5(4) \text{ GeV} \]

\[ -1 < \eta_{\text{jet1(2)}} < 2.5 \]

**Independent cross-check of LRG measurements - without proton dissociation!**

*ISMD, Wildbad Kreuth*
Diffractive dijet photoproduction & DIS

Data in agreement with NLO in DIS, within uncertainties

Data suppressed in comparison with NLO in photoproduction
Diffractive dijet photoproduction

The suppression seems to be not dependent on $x_\gamma$. It is in agreement with previous H1 and ZEUS observations!
Previous H1 measurements confirmed, factorisation breaking in diffractive dijet photoproduction by factor ~ 0.5 observed.
**New - diffractive prompt (isolated) photons**


![Diagram showing jet, photon, and pomeron remnant interactions](image)

HERA II (374pb⁻¹) and I data (91pb⁻¹, used for normalization), untagged photoproduction

**Diffractive selection - LRG**, \( \eta_{\text{max}} < 2.5 \) \( x_{\text{IP}} < 0.03 \)

- **Photons**
  - \( E_T^\gamma > 5 \text{ GeV} \)
  - \(-0.7 < \eta^\gamma < 0.9\)

- **Jets**
  - \(-1.5 < \eta^{\text{jet}} < 1.8\)
  - \(E_T^{\text{jet}} > 4 \text{ GeV}\)

**Signal MC** = RAPGAP with H1 fitB DP\( \gamma \)DF and \( \gamma \)-PDF SASG 1D LO

ISMD, Wildbad Kreuth

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Diffractive production of prompt (isolated) photons

A peak at $z_{IP}$ close to 1 is not described by RAPGAP. Note, that H1 fit B not fitted in this region, it is only extrapolated.

Region $z_{IP} \sim 1$, no activity except jet and $\gamma$.

Fair description by RAPGAP within uncertainties

Preliminary – in future planned comparison with NLO calculations – first test of QCD factorisation using this process

ISMD, Wildbad Kreuth
How to distinguish between diffractive models???

\[ e + p \rightarrow e' + p' + \text{jet} + \text{jet} \]

\[ \Phi \] - angle between lepton and jet planes
\[ \Theta \] - polar angle of jet

\[ \frac{d\sigma}{d\phi} \propto 1 + A \cos(2\phi) \]

- Two gluon exchange - negative A
- Boson-Gluon fusion - positive A

BGF - Resolved-Pomeron model (Ingelman, Schlein et al.)

Two-Gluon-Exchange model (Bartels, Jung et al.)

DESY-15-070 (2015), sent to EPJC


New exclusive dijets in diffractive DIS
exclusive dijets in diffractive DIS

e + p \rightarrow e' + p' + \text{jet} + \text{jet} \quad \text{only dijet, electron and proton in the final state}

Durham jet algorithm in γ*IP rest frame in exclusive mode – all objects in jets

\( Y_{\text{cut}} = 0.15 \)

Proton dissociation background

\( f_{\text{pdiss}} = 45\% \pm 4\%(\text{stat.}) \pm 15\%(\text{syst.}) \)

Measured cross sections reweighted by

\[
(1 - f_{\text{pdiss}}) = 0.55
\]

Hadron cross sections unfolded as a function of \( \beta \) and \( \Phi \)

- \( Q^2 > 25 \text{ GeV}^2 \)
- \( 90 < W < 250 \text{ GeV} \)
- \( x_{\text{IP}} < 0.01 \)
- \( M_X > 5 \text{ GeV} \)
- \( N_{\text{jets}} = 2 \) (with \( Y_{\text{cut}} = 0.15 \))
- \( p_{T,\text{jet}} > 2 \text{ GeV} \)
Exclusive dijets in diffractive DIS

The measured and predicted cross sections do not agree by factor about 2. NLO corrections large???

The Two Gluon model is more successful in describing of data (region $\beta > 0.3$) than Resolved Pomeron model (large uncertainty due to p-diss subtraction, is not shown here)
Conclusions

• New H1 measurement of diffractive dijet production in DIS → measurements described by NLO QCD predictions using H1 DPDF, value of $\alpha_s(M_Z)$ obtained from this measurement is in agreement with world average.

• New H1 measurement of diffractive photoproduction & DIS dijets using VFPS proton spectrometer → DIS dijets in agreement with NLO QCD prediction, suppression factor $0.5 \pm 0.1$ in photoproduction dijets observed, consistent with factorisation breaking!

• New ZEUS measurement of prompt inclusive photons and photons with a jet in diffractive photoproduction. Shapes of diff. cross sections agree with RAPGAP except of $z_{IP}$.

• New ZEUS measurement of exclusive dijets in DIS diffraction, MC cross section significantly larger than predicted by models, Two-Gluon-Exchange model predicts reasonably well the measured value of $A$ as a function of $\beta$ for $\beta>0.3$. 