Inclusive Diffraction at HERA

Armen Bunyatyan

MPI-K, Heidelberg and YerPhI, Yerevan

On behalf of the H1 and ZEUS Collaborations

- Diffractive DIS at HERA
- Measurements of diffractive structure function
- QCD fits
- Comparison with hadronic final states
- Conclusions
The world’s only electron/positron-proton collider. $E_e = 27.6$ GeV $E_p = 920$ GeV
Two colliding experiments: H1 and ZEUS ($\sqrt{s} \approx 320$ GeV),
fixed target experiment: HERMES

The results presented in this talk are based on HERA-I data

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• t-channel exchange of vacuum quantum numbers
• proton survives the collision intact or
dissociates to low mass state, \( M_Y \sim O(m_p) \)
• large rapidity gap
• small \( t \) (four-momentum transfer) and \( x_{IP} \) (fraction of proton momentum)
• \( M_X \ll W \)

\[
\begin{align*}
Q^2 &= -q^2 & \text{photon virtuality} \\
x &= \frac{Q^2}{2q \cdot p} & \text{Bjorken scaling variable} \\
W^2 &= (p + q)^2 & \gamma^* p \text{ CM energy squared} \\
4\text{-momentum transfer squared} \\
x_P &= \frac{q \cdot (p - Y)}{q \cdot p} & \text{fraction of } p \text{ momentum transferred to } IP (x_P \sim 1 - E_Y / E_P) \\
\beta &= \frac{Q^2}{2q \cdot (p - Y)} & \text{fraction of } IP \text{ momentum carried by struck quark } (x_{IP} \beta = x) \\
M_X &\text{ Inv. mass of system } X 
\end{align*}
\]
Diffraction at HERA

If no hard scale - $Q^2, |t| \approx 0$: similar to soft hadron-hadron interactions
- Regge theory: diffraction is exchange of Pomeron
→ Weak energy dependence

If hard scale (large $Q^2, |t|, p_T^{jet}, m_Q$) present: study diffractive phenomena in terms of QCD
- Resolved Pomeron: probe the structure of exchanged object
- Colour dipole: diffraction is exchange of colour singlet gluon ladder between ($\gamma^* \rightarrow q\bar{q}, q\bar{q}g$) and the proton
→ Steep energy dependence

HERA - unique facility to study transition from soft to hard regime and to probe partonic content of diffractive exchange.

~10% of DIS events at HERA are diffractive
Diffractive event selection

- 'Leading proton' method (LPS) - scattered proton detected in 'Roman Pots' (LPS, FPS) free of p-diss. background, $t$ and $x_{IP}$ measurement, but low acceptance/statistics.

- Large Rapidity Gap' method (LRG) $t$ is not measured, some p-diss. background (for H1 measurements $M_Y<1.6$ GeV)

- 'M_X' method - non-diffractive contribution subtracted from fit to $M_X$ distribution
Diffractive event selection - $M_X$ method

- Exponential rise with $M_X$ for non-diffractive events
- Flat behavior vs $\ln M_X^2$ for diffractive events

$\ln M_X^2$ distribution

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

- Non-diffractive events can be subtracted from fit to $M_X$
  - Some p-diss. background ($M_Y < 2.3$ GeV)
  - $t$ is not measured
Cross-section of inclusive diffractive DIS

\[ t = (p - p')^2 \quad \text{4-momentum transfer squared} \]
\[ x_P = \frac{q \cdot (p - p')}{q \cdot p} \quad \text{fraction of } p \text{ momentum transferred to } P \]
\[ \beta = \frac{Q^2}{2q \cdot (p - p')} \quad \text{fraction of } P \text{ momentum carried by struck quark} \]

Diffractive DIS cross-section:

\[ \frac{d\sigma^D}{d\beta dQ^2 dx_P dt} = \frac{2\pi\alpha}{\beta Q^4} (1 - y + y^2/2) \cdot \sigma_R^{D(4)}(\beta, Q^2, x_P, t) \]

Reduced cross-section:

\[ \sigma_R^D = F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D \quad (\sigma_R^D = F_2^D \text{ if } F_L^D = 0) \]
Diffractive structure functions $F_2^{D(3)}$, $\sigma_r^{D(3)} - x_{IP}$, $\beta$ and $Q^2$ dependence

- Large kinematic region covered $1.5 < Q^2 < 1600 \text{ GeV}^2$
- Large statistical precision
- Good agreement between two experiments and different methods
$\beta$-dependence of $F_2^D$

$F_2^D(\beta,Q^2)$ vs $\beta$

$\beta$-dependence relatively flat

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**β- dependence of $F_2^D$**

\[ F_2^D(\beta, Q^2) \text{ vs } \beta \]

\[ F_2^P(x, Q^2) \text{ vs } x \]

β-dependence relatively flat - different from $F_2$ (recall $x = x_{IP} \cdot \beta$)

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**Q^2 dependence of F_2^D**

F_2^D increases with Q^2 ⇒ positive scaling violation up to large β → different from F_2

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Diffractive cross section: $W$ dependence of $\sigma^{\text{diff}}$

Quantify $W$ dependence as

$$d\sigma^{\text{diff}}/dM_X \propto W^{\alpha^{\text{diff}}} \approx W^{4(\alpha^{\text{diff}}(0) - 1.03)}$$

In Regge approach relation between $\alpha^{\text{diff}}$ and pomeron trajectory $\alpha^{\text{IP}}$, averaged over $t$

Effective pomeron trajectory $\alpha^{\text{IP}}(0)$ should be independent of $Q^2$ in Regge approach

$M_X < 2$ GeV: weak rise with $W$

$M_X > 2$ GeV: strong rise with $W$

consistent with soft Pomeron at low $Q^2$,

increase with $Q^2$ \(\Rightarrow\) not consistent with Regge factorization

(H1 data consistent within the errors)

lower than for inclusive DIS cross section \(F_2 \propto (W^2)^{\alpha^{\text{IP}}(0) - 1}\)

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for $M_x > 2$ GeV ratio is independent of $W$
→ same energy behavior in diffr. and incl. DIS
→ not consistent with naïve picture

expect rise with $W$

for $M_x < 2$ GeV (high $\beta$) ratio decreases with increasing $W$: contribution of vector mesons

high $M_x > 8$ GeV—no $Q^2$ dependence
→ same DGLAP evolution

low $M_x < 2$ GeV (high $\beta$)—strong decrease with $Q^2$

diffractive contribution to $\sigma^{tot}$

$(200 < W < 245 \text{ GeV}, 0.28 < M_x < 25 \text{ GeV}, M_N < 2.3 \text{ GeV})$

$$r^{\diff\text{tot}} = 15.8^{+1.2}_{-1.0}\% \text{ at } Q^2 = 4 \text{ GeV}^2$$

$$r^{\diff\text{tot}} = 9.6^{+0.7}_{-0.7}\% \text{ at } Q^2 = 27 \text{ GeV}^2$$
Extract diffractive parton densities from $F_2^D$ data and use to predict the diffractive final states ➔

**are these PDFs universal?**

**Make use of different data sets, theoretical models and approaches**

Diffractive PDFs from HERA are essential ingredients for the prediction of diffractive cross sections at the LHC, e.g. diffractive Higgs production. Along with understanding of factorization breaking mechanism in the diffractive $p\bar{p}$ interactions, the precise measurements and understanding of diffractive PDFs are needed for reliable predictions.
Factorization properties of diffractive cross sections

QCD factorization in diffractive DIS (Collins 1997)

\[
\sigma^D(\gamma^* p \rightarrow Xp) \propto \sum_i f^D_{i,p}(x_{IP},t,x,Q^2) \otimes \sigma^{\gamma^* i}(x,Q^2)
\]

- diffractive parton distribution function - conditional proton parton probability distributions with final state proton at fixed \(x_{IP},t\)

\(\sigma^{\gamma^* i}\) - universal hard scattering cross section

Regge factorization (assumption-no firm basis in QCD):

PDF = Pomeron-flux \(\times\) Pomeron-PDF

\[
f^D_i(x,Q^2,x_{IP},t) = f^D_{IP/p}(x_{IP},t) \times f^D_{i}(\beta = x / x_{IP},Q^2)
\]

where Pomeron flux

\[
f^D_{IP/p}(x_{IP},t) = \frac{e^{Bt}}{x_{IP}^{2\alpha(t)-1}}, \alpha(t) = \alpha(0) + \alpha'(t)
\]
Diffractive PDFs: H1 NLO QCD fit (H1 LRG data)

• assume Regge factorization
• apply NLO QCD DGLAP analysis technique to $Q^2$ and $\beta$ dependencies of diffractive structure function as for inclusive DIS

- quark density directly from $F_2^D$
- gluon density from scaling violation

• low $z$ behavior similar to $F_2$
• hard gluon distribution extended to high $z$
• gluon carries $75\% \pm 15\%$ of $IP$ momentum
• $\alpha_{IP}(0)=1.173$

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Diffractive PDFs: more QCD NLO fits (ZEUS-M\(_X\) data)

Several analyses done in the framework of HERA-LHC workshop

NLO QCD fits to H1 and ZEUS data

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<th>G(z,Q(^2))</th>
<th>Q(^2) [GeV(^2)]</th>
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<td>15</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>90</td>
</tr>
</tbody>
</table>

- Significat difference between diffractive gluon densities from H1-LRG and ZEUS-M\(_X\) data
- Singlet similar at low Q\(^2\), evolving differently to higher Q\(^2\)
- Fraction of gluon momentum: 55%
- \(\alpha_{IP}(0)=1.132\)

NLO-QCD fit to ZEUS-M\(_X\) data:
(Laycock, Newman and Schilling)

similar procedure as for H1-2002-
NLO fit to H1-LRG data

Differences in the fits to the H1-LRG and ZEUS-M\(_X\) data are due to the difference in Q\(^2\) dependence in the measurements
At closer look there is a difference between the two measurements at high $\beta$ (low $M_x$) region, and smaller positive scaling violations in ZEUS-M$_x$ data, e.g. less gluons. The differences between the measurements are not yet understood.
ZEUS NLO QCD fit to $F_2^D$ (ZEUS-LPS) and $F_2^D$, charm

- Regge factorization, $x_{IP} < 0.01$
- Include diffractive charm data

$$\alpha_{IP}(0) = 1.16 \pm 0.02 \pm 0.02$$

Fractional gluon momentum at initial scale of $Q^2 = 2 \text{ GeV}^2$

$$82 \pm 8 \text{(stat)} \pm 9 \text{(sys)} \%$$

$\rightarrow$ consistent with H1-LRG data
More NLO QCD fits

Evident discrepancies between the different fits and approaches

Need more work for precise and consistent determination of diffractive PDFs

Groys, Levy, Proskuryakov (GLP)

(Fits to H1-LRG, ZEUS-LPS and ZEUS-Mx data)
Comparison with theoretical models

Bartels, Ellis, Kowalski, Wüsthoff (BEKW)

Colour Dipole model

$\gamma^*$ fluctuates into $(q\bar{q})_T$, $(q\bar{q})_L$ or $(q\bar{q}g)_T$ before interaction with the proton

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

$$F_{qqg}^T \propto (1 - \beta)$$

$$F_{qq}^T \propto \beta (1 - \beta)$$

$$F_{qqg}^L \propto \beta^3 (1 - 2\beta)^2$$

5 free model parameters

Model reasonably describes data
Comparison with theoretical models

Forshaw, Shaw → hep-ph/0411337

- Diffraction is color singlet exchange between dipole and proton
- fit $F_2$ data and predict $F_2^{D(3)}$
- need gluon saturation at low $x$ to describe data

Iancu, Itakura, Munier → hep/0310338

- Color glass condensate model:
  - non-linear saturation effects at high gluon densities
  - prediction consistent with data

Considerable theoretical interest to HERA diffractive data
Test the universality of parton distributions extracted from the fits to $F_{D_2}^-$ - use the PDFs in the QCD calculations for other diffractive processes, e.g. diffractive jet and $D^*$ production

- cross sections are calculable in pQCD
- production mechanisms are directly sensitive to the gluon content of colour singlet exchange → give constrain of shape and normalization of gluon density in diffractive exchange
- can be compared to theoretical models and approaches
Comparison of NLO with diffractive jets and D* in DIS

- NLO calculations with diffractive PDFs from the fits to $F_2^D$ measurements provide in general a reasonable description of diffractive jets and D* in DIS
  - suggest validity of QCD factorization in diffractive DIS
- However results depend on the choice of diffractive PDFs
- Situation is more complicated in photoproduction regime and in $p\bar{p}$:
  - rescattering corrections, survival probability, ... (see talk of Alessia Bruni)
Conclusions

- The partonic structure of diffraction is measured by H1 and ZEUS with improved precision and extended kinematical range.

- Diffractive PDFs extracted from the NLO fits to the data: QCD factorization, NLO DGLAP evolution, dominated by gluons. Differences between the measurements to be understood.

- Considerable theoretical interest to HERA diffractive data.

- Understanding of factorization breaking mechanism ep vs pp is needed to make predictions for the LHC (e.g. diffractive Higgs production).
  - Need better measurements and understanding of diffractive PDFs.
  - Need diffractive PDFs in kinematic range relevant for LHC.

- Outlook: presented results are based on HERA-1 data. More exciting results to come in HERA-2 - (x5 increase of integrated luminosity, new H1-VFPS detector with high acceptance for low $x_{IP}$).
**pp (CDF) data vs H1/ZEUS PDF fits**

- Use diffractive PDFs from HERA to predict cross sections at $p\bar{p}$
- QCD factorization breaks in $p\bar{p}$ hard scattering
- Factorization not expected to hold in $p\bar{p}$ due to soft rescattering of spectator partons.

**Diffractive jet production**

- Rapidity gap 'survival probability' due to multi-Pomeron exchange in $p\bar{p}$
- But other approaches exist

(Kaidalov, Khoze, Martin, Ryskin; Goulianos; Gotsman, Levin, Maor, ...)

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Diffractive reduced cross section quantify scaling violations at fixed $x_{IP}$ and $\beta$:

$$\sigma_r^D = A + B \ln Q^2$$

$$B = \frac{d \sigma_r^D}{d \ln Q^2}$$

- large positive scaling violations up to $\beta \approx 0.6$
- large gluon contribution
Fit $Q^2$ dependence at fixed $x_{IP}$ and $\beta$:

$$R = a + b \ln Q^2$$

- Ratio is flat vs $Q^2$ up to $\beta \sim 0.6$
- Similar $Q^2$ dynamics in diffractive and inclusive DIS
- Consistent with ZEUS $Q^2$ dependence at low $M_X$
Probe diffractive processes via weak interactions: $e^+p \rightarrow \nu W^+p \rightarrow \nu XY$

Ratio of LRG to inclusive CC cross section:

**ZEUSS**: $\frac{\sigma^{CC}_{LRG}}{\sigma^{CC}_{Incl}} = 2.9 \pm 1.2\text{(st.)} \pm 0.8\text{(sys)}\%$

**H1**: $\frac{\sigma^{CC}_{LRG}}{\sigma^{CC}_{Incl}} = 2.5 \pm 0.8\text{(st.)} \pm 0.6\text{(sys)}\%$

- good agreement between measurements

- Diffractive PDFs from QCD fits describe LRG CC cross sections
Combined MRW analysis of $F_2$ and $F_2^{D}$

Combined H1+ZEUS $F_2^{D(3)}$ data

$$F_2^{D(3)} = F_2^{P,D(3)} + F_2^{NP,D(3)} + F_{L,IP}^{D(3)} + F_2^{IR,D(3)}$$

$F_2(x,Q^2) = F_2^{DGLAP}(x,Q^2) + \Delta F_2^{abs}(x,Q^2)$

- No Regge factorization assumption
- Input quark singlet and gluon from LO QCD diagrams
- Non-linear power corrections slow down DGLAP evolution
  $\Rightarrow$ smaller gluon than H1-2002 fit