The Pomeron and Vector Mesons at HERA

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- Diffraction in ep scattering
- Latest inclusive diffractive ep results
- QCD fits and diffractive PDFs extraction
- Latest results on exclusive VM production
0.5 fb$^{-1}$ collected by H1 and ZEUS experiments
Final analyses of HERA data are underway
Diffraction in Hadron Scattering

Diffraction is a feature of hadron-hadron interactions (30% of $\sigma_{\text{tot}}$).

- Beam particles emerge intact or dissociated into low-mass states
  - Very small fractional momentum losses (within a few %)
- Final-state systems separated by a large polar angle (or pseudorapidity $\eta = -\ln(\tan(\theta/2))$)
  - Large Rapidity Gap (LRG)
- Interaction mediated by t-channel exchange of an object with vacuum quantum numbers (no colour)
  - Pomeron (IP)
Why Diffraction?

Optics:

\[ I(\theta) \]

\[ I(\theta) \approx 1 - \frac{R_0^2}{4} (k \theta)^2 \]

Forward peak for \( q=0 \) (diffractive peak)
Diffraction pattern related to size of target and wavelength of beam

Particle Physics:

Propogation/interaction of a hadron \( \Rightarrow \) absorption of its wave function

\[ \frac{d\sigma}{dt(t)} \approx e^{-b|t|} \approx 1 - b(p\theta)^2 \]

\( |t| \approx (p\theta)^2 \) 4-momentum transfer
\( \theta \) scattering angle
\( b = R^2/4 \)
\( R \) transverse distance projectile-target
Real and virtual photons can fluctuate in hadronic states ($q\bar{q}$, $q\bar{q}g$, ...)

$$\gamma^* \rightarrow q\bar{q} \propto E_{\gamma} \sim W^2 \sim 1/x$$
(as seen in the proton rest-frame)

$Q^2$ = photon virtuality
$x$ = Bjorken scaling variable

Diffractive events contribute up to 15% of the inclusive DIS cross section

✓ Lifetime of $q\bar{q}$ dipole (hadron!) long because of large Lorentz boost ($E_\gamma \sim 50$ TeV at HERA)

$\rightarrow$ Dipole interacts hadronically with the proton

✓ Transverse size proportional to $1/\sqrt{Q^2 + M_{qq}^2}$

$\rightarrow$ If dipole size small, its interaction with the proton can be treated perturbatively
**Kinematics and Cross Sections**

\( Q^2 \) = virtuality of exchanged photon  
\( x \) = Bjorken scaling variable  
\( y \) = inelasticity of virtual photon  
\( W \) = invariant mass of \( \gamma^*-p \) system  
\( M_X \) = invariant mass of \( \gamma^*-\text{IP} \) system  
\( x_{\text{IP}} \) = fraction of proton momentum carried by IP  
\( \beta = x/x_{\text{IP}} \) = fraction of IP momentum carried by struck parton  
\( t \) = (4-momentum exchanged at p vertex)\(^2\)  

typically: \(|t| < 1 \text{ GeV}^2\)

\[
\frac{d^4\sigma^{\text{ep} \rightarrow e'\gamma p'}}{d\beta dQ^2 dx_{\text{IP}} dt} = \frac{2\pi\alpha^2}{\beta Q^4} Y_+ [F_2^{D(4)}(\beta, Q^2, x_{\text{IP}}, t) - \frac{y^2}{Y_+} F_L^{D(4)}(\beta, Q^2, x_{\text{IP}}, t)]
\]

where \( Y_+ = 1 + (1-y)^2 \)

When \( t \) is not measured  
\[
\sigma_r^{D(3)}(\beta, Q^2, x_{\text{IP}}) = \int \sigma_r^{D(4)}(\beta, Q^2, x_{\text{IP}}, t) dt
\]

\( \bowtie N = \text{proton} \rightarrow \text{SD events} \)

\( \bowtie N = \text{proton dissociative system} \rightarrow \text{DD events (background)} \)

\( \text{DIS } Q^2 \geq 1 \text{ GeV}^2 \)

\( \text{PHP } Q^2 \sim 0 \)
The QCD factorization theorem in diffractive DIS allows to write the diffractive cross section as a convolution of universal diffractive parton densities $f_i^D(x, Q^2, x_{IP}, t)$ and partonic cross sections

$$\sigma^D(\gamma^* p \rightarrow X p) \sim f_i^D(x, Q^2, x_{IP}, t) \otimes \sigma_{\gamma^* i}(x, Q^2)$$

Additionally, assuming Regge factorization, the diffractive parton densities are written as a term depending on $x_{IP}$ (Pomeron flux) times the Pomeron parton densities

$$f_i^D(x, Q^2, x_{IP}, t) \sim f_{IP/p}(x_{IP}, t) \otimes f_{i/IP}^D(x/x_{IP}, Q^2)$$

$\Rightarrow$ Universal DPDFs apply in DIS when vacuum quantum numbers are exchanged
Signatures and Selection Methods

Proton Spectrometer (PS) method

**H1-VFPS**

- **PROS:** no DD background, direct measurement of $t$, $x_{IP}$, high $x_{IP}$ accessible
- **CONS:** low statistics

Large Rapidity Gap (LRG) method

**H1-FPS**

- **PROS:** high statistics, near perfect acceptance at low $x_{IP}$
- **CONS:** DD background
\[ \frac{d\sigma}{dt} \sim e^{bt} \]

- t-slope does not change with \( Q^2 \) and \( M_X \) (or \( \beta \)) at fixed \( x_{IP} \) → data consistent with Regge factorization

- H1 results exhibit an \( x_{IP} \) dependence of t-slope in \( (Q^2, \beta) \) bins → contributions other than IP at high \( x_{IP} \)
\( x_{IP} \) Dependence of \( \sigma_r^{D(4)} \)

**H1 FPS**

- \( \beta = 0.0018 \)
- \( \beta = 0.0056 \)
- \( \beta = 0.018 \)
- \( \beta = 0.056 \)
- \( \beta = 0.18 \)
- \( \beta = 0.56 \)

H1 HERA-II FPS data (156 pb\(^{-1}\)) improve stats by factor of 20 and reach higher \( Q^2 \)

- syst uncertainty \( \sim 8\% \)
- norm uncertainty \( \sim 4.3\% \)
**x_{IP} Dependence of \( \sigma_r^{D(3)} \)**

All available PS data used by both Collaborations (integrated over t)

Fair agreement in normalization between H1 and ZEUS

H1 FPS norm unc \( \sim \pm 6\% \)
ZEUS LPS norm unc \( \sim +11\% - 7\% \)

H1/ZEUS = 0.85 \( \pm 0.01 \) (stat) \( \pm 0.03 \) (syst) + 0.09 – 0.12 (norm)

Reasonable agreement in shape between H1 and ZEUS
All available LRG data used by both Collaborations

Very precise measurements of the scaling violation for diffractive processes

Reduced cross section constrains quark density

\( \ln Q^2 \) dependence constrains gluon density

\( \Rightarrow \) QCD fits to data provide sets of diffractive PDFs

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Q\(^2\) Dependence of \( \sigma_r^{D(3)} \)

ZEUS corrected to \( M_N < 1.6 \text{ GeV} \) with PYTHIA MC

\( x_{ip} = 0.003 \) [H1 preliminary]

\( x_{ip} = 0.01 \) [H1 preliminary]
Diffractive PDFs from NLO Fits

Inclusive Data

NLO QCD Fits:
- parametrize quark singlet and gluon at $Q^2_0 = 1.8 \text{ GeV}^2$
  
  $z f_{u,d,s} (z, Q^2_0) = A_q \, z^{B_q} (1-z)^{C_q}$

  $z f_g(z, Q^2_0) = A_g \, z^{B_g} (1-z)^{C_g}$

- evolve with NLO DGLAP and fit

Different parametrizations

Well constrained singlet

Gluon weakly constrained in the high $z_{IP}$ region (gluon density from $\ln Q^2$ dependence of $\sigma_r^D$)

DPDFs are gluon dominated

($z =$ momentum fraction of the diffr exchange entering the hard scattering)
Diffractive PDFs from NLO Fits

Inclusive and Dijet Data

Diffractive dijet data are directly sensitive to the gluon as the photon-gluon fusion contributes at first order.

Singlet and gluon constrained with similar precision across the whole kinematic range.
Vector Meson Production

\[ ep \rightarrow eVMp \]

VM (\(J^{PC} = 1^{--}\)): \(\rho, \phi, J/\psi, Y, \ldots\)

DVCS: real \(\gamma\)

Soft - Regge

IP exchange
(Regge trajectory)

Cross section proportional to probability of finding 2 gluons in the proton

With increasing scale (\(Q^2, M_{VM}, t\))

\[ \sigma(W) \propto W^\delta \]

\[ \frac{d\sigma}{dt} \propto e^{-b|t|} \]

- Expect \(\delta\) to increase from soft (~0.2 'soft Pomeron' value) to hard (~0.8 reflecting large gluon density at low \(x\))

- Expect \(b\) to decrease from soft (~10 GeV\(^{-2}\)) to hard (~4-5 GeV\(^{-2}\))

Hard - pQCD

2-gluon exchange
(LO realization of vacuum quantum numbers in QCD)

\[ \sigma \propto [xg]^2 \]
$M_{VM}$ is the scale
→ same feature observed when varying $Q^2$ for a given $VM$

$Q^2 = 0$

small $M_{VM}$ (~ 1 GeV$^2$)
transverse size of dipole
~ size of proton

large $M_{VM}$
small dipole size
→ cross section much smaller (color screening)
→ dipole resolves partons in the proton
$\sigma \sim (xg)^2$ ⇒ large $\delta$

⇒ VM data can help determine gluon density!
W Dependence in Bins of $Q^2$

At fixed $M_{VM}$ → the value of the slope $\delta$ increase with $Q^2$

ZEUS

$\sigma(\gamma^* p \rightarrow J/\psi p) (\text{nb})$

- ZEUS Photoproduction
- ZEUS DIS 98-00
- H1 DIS

Fit with $W^0$

$Q^2 (\text{GeV}^2)$:
- 0. (x 1)
- 0.4 (x 0.2)
- 3.1 (x 0.1)
- 6.8 (x 0.05)
- 16. (x 0.03)

The $W$ dependence of the $J/\psi$ cross section does not change with $Q^2$ up to 16 GeV$^2$ → the value of $(M_{J/\psi})^2$ already provide a sufficient hard scale

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Soft to Hard Transition – $\sigma(W)$

$\Rightarrow$ Process becomes harder as the scale ($Q^2 + M^2$) becomes larger
Soft to Hard Transition - \( t \)-slope

\[
\frac{d\sigma}{dt} \propto e^{-b|t|}
\]

Slope \( b \) becomes smaller as the scale increases

Size of diffractive cone related to size of interacting objects (as in optical diffraction)

\[ b \sim b_{VM} + b_p \]

\[ \langle r^2 \rangle = b(hc)^2 \]

\( r_{\text{gluons}} \sim 0.6 \text{ fm} \) - radius of gluon density in proton

\( r_{\text{proton}} \sim 0.8 \text{ fm} \) - radius of charge density in the proton
Summary

✓ After 15 years of running HERA provided unique diffractive data
✓ Consistency reached between different experiments, methods and data sets
  ⇒ Ready to combine inclusive cross sections between experiments
✓ DPDFs well constrained which can be used to predict other processes in DDIS
  ⇒ Inclusion of dijet data in the QCD fits provides a much better constraint of the gluon density at high fractional momentum
✓ Lots of inputs from exclusive vector meson production
  ⇒ Precision measurements can constrain the gluon density
  ⇒ Transition from soft to hard regime is visible
Thank You
**QCD Factorization in Hard Diffraction**

**QCD factorisation theorem**, proven for DDIS by J. Collins [PR D57 (1998) 3051]

\[ \sigma^D(\gamma^* p \rightarrow X p) = \sum_i \hat{\sigma} \otimes f_i^D(x_{IP}, t, z, Q^2) \]

- Hard subprocess ME
- pQCD calculable
- DPDFs, universal for diffractive DIS processes

**Proton-vertex factorisation assumption**, supported by H1 and ZEUS data

\[ f_i^D(x_{IP}, t, z, Q^2) = f_{IP}(x_{IP}, t) f_{IP}^I(z, Q^2) + f_{IR}(x_{IP}, t) f_{IR}^I(z, Q^2) \]

- Flux parametrisation
- Pomeron PDFs
- Reggeon PDFs taken from pion (GRV)

\[ f(x_{IP}, t) = \frac{A e^{Bt}}{x_{IP}^{2\alpha(t) - 1}} \]

with \( \alpha(t) = \alpha(0) + \alpha' t \)

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Fit \( z \) and \( Q^2 \) dependence at fixed \( x_{IP} \) and \( t \)

\( z = \) momentum fraction of the diffr exchange entering the hard scattering
**LRG vs PS**

**ZEUS**

Estimation of DD contribution in LRG method → ratio flat both in ZEUS and H1 → quantity of DD ~ 20%
$x_{IP}$ Dependence of $\sigma_D^{D(3)}$

Wide kinematic coverage and very good statistical precision

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Factorization Test in Diffractive DIS

Use DPDFs extracted from inclusive DDIS for calculating NLO predictions to semi-inclusive final states: test universality of DPDFs

$\rightarrow$ Open charm and dijets in DIS: hard scales in the process ensure use of pQCD

Open charm: $H_1$, EPJ C50 (2007) 1
ZEUS, NP B672 (2003) 3

Dijets: $H_1$, JHEP 0710:042 (2007)
ZEUS, EPJ C52 (2007) 813

First measurement of dijets in DDIS with a tagged proton (H1 FPS) - H1prelim-10-013

Deviations might be related to missing pomeron remnant in NLO predictions (NLOJET++)
Deviations at high $\Delta \eta^*$ → interesting to look at forward jets
Factorization Test in PHP at HERA

Direct
Less hadron-like

Resolved
More hadron-like

Use photoproduction at HERA as a hadron-hadron process

How hadron-like the proton is depends on the $x_\gamma$ variable

Expect Resolved (low $x_\gamma$) to be more suppressed than Direct (high $x_\gamma$)

⇒ No evidence of suppression of resolved contribution

(different $E_T$ region and different sets of DPDFs between ZEUS and H1)
Factorization Test in PHP at HERA

Dijet photoproduction vs \( E_T \)

Data compared to NLO calculations using HERA DPDFs to test \( E_T \) dependence

Small suppression at small \( E_T \)
Both data still compatible
Factorisation Test at Tevatron

When trying to use universal DPDFs extracted at HERA to predict diffractive dijets at CDF we find a large suppression factor.

Suppression expected in QCD and understood in terms of soft interactions between the hadrons and their remnants suppressing the Large Rapidity Gap.

⇒ To understand diffraction at LHC a detailed understanding on this mechanism is needed.
First Measurement of $F_L^D$

$$\sigma_r^D = F_2^D - \frac{Y^2}{Y^+} F_L^D$$

$F_L^D \sim \alpha_S \times g(x)$

Challenging measurement, requires good understanding of the detector
Measurement is performed with data taken at 3 proton beam energies:
920, 460 and 575 GeV

$(Q^2 = s_{xy}, x = \beta x_{IP})$

⇒ At fixed $Q^2$ and $x_{IP}$, high $y$ corresponds to low $\beta$
Flash on Exclusive Results (ep → epVM)

DVCS

ν*p → νp

Γ

\[ e \rightarrow e^* \]

\[ W \]

\[ \gamma^* \]

\[ p \]

\[ VM \]

Some spin density matrix elements

⇒ Lot of new physics results on this subject

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