Hard diffraction at HERA

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for the H1 and ZEUS collaborations

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HERA $e^\pm p$ Collider at DESY

- $E_e = 27.6$ GeV
- $E_p = 920$ (460) GeV
- $\sqrt{s} = 319$ GeV
- $L_{int} \sim 0.5$ fb$^{-1}$ per experiment

**Status: 1-July-2007**

**Days of running**

**HERA Delivered Luminosity / pb$^{-1}$**

[H1 Collaboration]
Diffractive \( ep \) Scattering at HERA

deep-inelastic scattering (DIS): \( ep \rightarrow e'X \)

```
\begin{center}
\begin{tikzpicture}
  \node (e) at (0,0) {e};
  \node (ep) at (1,0) {\( e \)};
  \node (p) at (1,-1) {p};
  \node (X) at (2,-1) {X};
  \draw (e) -- (ep);
  \draw (e) -- (p);
  \draw (p) -- (X);
  \node (ep) at (3,0) {e'};
  \node (p) at (3,-1) {p'};
  \node (X) at (4,-1) {X};
  \draw (ep) -- (p');
  \draw (ep) -- (X);
  \draw (p') -- (X);
  \node (gamma) at (1.5,0) {\( \gamma^* \)};
\end{tikzpicture}
\end{center}
```

“forward” particle flow
\( \rightarrow \) proton remnant
\( \rightarrow \) colour flow

\[ \Rightarrow \text{probe proton structure} \]

diffractive scattering (DDIS): \( ep \rightarrow e'Xp' \sim 10\% \) of DIS events

```
\begin{center}
\begin{tikzpicture}
  \node (e) at (0,0) {e};
  \node (ep) at (1,0) {\( e' \)};
  \node (p) at (1,-1) {p};
  \node (X) at (2,-1) {X};
  \node (IP) at (3.5,0) {I P};
  \node (p') at (4.5,0) {p'};
  \draw (e) -- (ep);
  \draw (ep) -- (p');
  \draw (e) -- (p);
  \draw (p) -- (X);
  \draw (p') -- (X);
  \node (gamma) at (1.5,0) {\( \gamma^* \)};
\end{tikzpicture}
\end{center}
```

no “forward” activity
\( \rightarrow \) rapidity gap
\( \rightarrow p' \rightarrow \) beampipe
\( \rightarrow X \rightarrow \) “central”
\( \rightarrow \) no colour flow in between

\[ \Rightarrow \text{probe structure of the color singlet exchange ("Pomeron" I P)} \]
Kinematics of DIS and Diffractive DIS

deep-inelastic scattering (DIS): $ep \rightarrow e'X$

- $Q^2$ virtuality of the exchanged photon: $Q^2 = -q^2$
- $Q^2 \lesssim 2 \text{ GeV}^2$ photoproduction, $Q^2 > 4 \text{ GeV}^2$ DIS
- $W$ $\gamma^* - p$ system energy
- $x$ Bjorken-$x$: proton momentum fraction carried by the struck quark
- $y$ $\gamma^*$ inelasticity: $y = \frac{Q^2}{s \times}$

diffractive scattering (DDIS): $ep \rightarrow e'Xp'$

- $t$ squared momentum transfer at the proton vertex: $t = (p - p')^2$
- $x_{IP}$ proton momentum fraction of the color singlet exchange: $x_{IP} \simeq \frac{Q^2 + M_X^2}{Q^2 + W^2}$
- $z_{IP}$ IP momentum fraction carried by the quark “seen” by the $\gamma^*$: $z_{IP} = \frac{x}{x_{IP}}$
Factorisation in Diffractive DIS

perturbative QCD: only if “hard scale” is present
→ diffractive factorisation theorem in analogy with proton PDFs

collinear factorisation: (proven for DDIS by J. Collins)

\[
\sigma^D(\gamma^* p \rightarrow Xp) = \sum_i \hat{\sigma}(z_{IP}, Q^2) \otimes f^D_i(z_{IP}, Q^2, x_{IP}, t)
\]
→ hard subprocess matrix element, calculable in pQCD
→ universal diffractive parton distribution functions (DPDFs)

proton-vertex factorisation assumption: (supported by H1 and ZEUS data)

\[
f^D_i(z_{IP}, Q^2, x_{IP}, t) = f^P_{IP/IR}(x_{IP}, t) f^P_{IR}(z_{IP}, Q^2)
\]
→ flux parametrisation, Pomeron/Reggeon PDFs

DPDFs:
→ have no firm basis in QCD, but can be extracted from inclusive DDIS data
→ test universality in semi-inclusive states
Diffractive PDFs

→ DPDFs obtained by H1 and ZEUS in inclusive diffractive DIS measurements and NLO QCD fits

\[ \mu^2 = 25 \text{ GeV}^2, x_{IP} = 0.01 \]

- H1 Data
- H1 2006 DPDF Fit A (extrapol. fit)
- H1 Fit B - z G(z)
- H1 Fit B - z Σ(z)
- ZEUS SJ - z G(z) × 1.2
- ZEUS SJ - z Σ(z) × 1.2
- H1 Fit Jets - z G(z)
- H1 Fit Jets - z Σ(z)

\[ e(e') \rightarrow γ^∗, γ^∗, γ, \gamma, γ \]

→ gluons: probed with dijets

\[ (p(p), x_p, p'(p')) \rightarrow \text{jet} \rightarrow \text{IP, X, P, remnant} \]

→ quarks: probed with prompt photon

\[ (e, e') \rightarrow γ^∗, γ^∗, γ, γ \]

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inclusive dijet production in diffractive DIS:

- HERA-II data: $L = 290$ pb$^{-1}$
- 6 times more data than previous analysis
- diffractive events identified by “large rapidity gap” (LRG) ($\eta_{\text{max}} < 3.2$)
- using $R = 1$ $k_T$-jets
- hadron level cross sections via regularised unfolding in extended phase space

<table>
<thead>
<tr>
<th></th>
<th>Extended Analysis Phase Space</th>
<th>Measurement Cross Section Phase Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS</td>
<td>$3 &lt; Q^2 &lt; 100 \text{ GeV}^2$</td>
<td>$4 &lt; Q^2 &lt; 100 \text{ GeV}^2$</td>
</tr>
<tr>
<td></td>
<td>$y &lt; 0.7$</td>
<td>$0.1 &lt; y &lt; 0.7$</td>
</tr>
<tr>
<td>Diffraction</td>
<td>$x_p &lt; 0.04$</td>
<td>$x_p &lt; 0.03$</td>
</tr>
<tr>
<td></td>
<td>LRG requirements</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$M_Y &lt; 1.6 \text{ GeV}$</td>
<td>$M_Y &lt; 1.6 \text{ GeV}$</td>
</tr>
<tr>
<td>Dijets</td>
<td>$p^*_{T,1} &gt; 3.0 \text{ GeV}$</td>
<td>$p^*_{T,1} &gt; 5.5 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>$p^*_{T,2} &gt; 3.0 \text{ GeV}$</td>
<td>$p^*_{T,2} &gt; 4.0 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>$-2 &lt; \eta_{1,2}^{\text{lab}} &lt; 2$</td>
<td>$-1 &lt; \eta_{1,2}^{\text{lab}} &lt; 2$</td>
</tr>
</tbody>
</table>
measurement of single differential cross sections:

**NLO predictions**
- using NLOJet++ (adapted to DDIS) and H1 2006 Fit-B DPDFs
- data well described
- large uncertainty from PDF and theory

**Data precision**
- better than theory
- mostly limited by systematic effects
- 7% normalisation uncertainty (LRG selection)
measurement of double differential cross sections: e.g. \( d\sigma / d(Q^2, p_{T,1}^*) \)

first measurement of \( \alpha_s \) in hard diffraction at HERA:

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

\( \rightarrow \) agreement with world average
\( \rightarrow \) not competitive with other \( \alpha_s \) measurements
\( \rightarrow \) but supports concept of DDIS dijet calculations in pQCD
Factorisation Breaking

factorisation properties of diffractive dijets:

→ factorisation holds for dijets in DDIS
→ factorisation is broken in hadron-hadron scattering:

$$\frac{\sigma(\text{data})}{\sigma(\text{NLO})} \sim 0.1$$

at Tevatron and LHC with HERA DPDFs

dijets in diffractive photoproduction $\gamma p$:
real photon has hadronic structure

$$e \rightarrow e' \gamma_{\text{remnant}}$$
$$x^*_{\gamma} \rightarrow \gamma \rightarrow \gamma_{\text{remnant}}$$
$$p \rightarrow p' \eta_{\Delta}$$
$$\eta_{\Delta} \rightarrow \text{dijets } X$$

2 LRG+$\gamma$-tag analyses ($L = 18 \text{ pb}^{-1}$ & $L = 47 \text{ pb}^{-1}$)

CDF: dijets in diffractive $p\bar{p}$

H1:
“suppression” w.r.t. NLO observed in $\gamma p$

ZEUS:
no indication of suppression

H1: $\gamma p$ data correlated uncertainty
$\sigma_{\text{NLO}}(1+\delta_{\text{had}})$
$\delta_{\text{had}}$ factors 0.5 and 2 and the full band includes the uncertainty due to the hadronisation corrections added linearly.

Rapgap
$\gamma_{\text{dijet}}$ varying $\mu_R$ and $\mu_F$ by factors of 0.5 and 2.0. In all figures, the predictions of the RAPGAP MC model are also shown.

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could $p$-dissociative contribution be the reason?

**H1 Very Forward Proton Spectrometer (VFPS):**
- VFPS is 220m from interaction point:
  - 2 stations at 218 and 220m
  - high acceptance (90%) and efficiency (95%)
  - low background (<1%)
- directly measure scattered proton:
  - exclude $p$ dissociation
  - directly reconstruct $x_{IP}$ and $t$

**new cross section measurement:**
- tag scattered proton in VFPS
- simultaneously performed in
  - photoproduction and
  - DIS
- regularised unfolding to hadron level in extended phasespace

<table>
<thead>
<tr>
<th>Event kinematics</th>
<th>Photoproduction</th>
<th>DIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2 &lt; 2 \text{ GeV}^2$</td>
<td>$4 \text{ GeV}^2 &lt; Q^2 &lt; 80 \text{ GeV}^2$</td>
<td></td>
</tr>
<tr>
<td>$0.2 &lt; y &lt; 0.7$</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Diffractive phase space</th>
<th>$0.010 &lt; x_{IP} &lt; 0.024$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>t</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Jet phase space</th>
<th>$E_{T}^{*\text{jet1}} &gt; 5.5 \text{ GeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_{T}^{*\text{jet2}} &gt; 4.0 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>$-1 &lt; \eta^{\text{jet1,2}} &lt; 2.5$</td>
</tr>
</tbody>
</table>
Diffractive Dijets with a Leading Proton (VFPS) [JHEP 1505, 056 (2015)]

dijets in DDIS:
⇒ shape and normalisation well described by NLO

⇒ luminosity: $L \sim 50 \text{ pb}^{-1}$
⇒ NLO by NLOJet++
⇒ H1 2006 Fit-B DPDFs

dijets in diffractive $\gamma p$:
⇒ shape well described by NLO
⇒ normalisation overestimated $\sim \times 2$

⇒ luminosity: $L \sim 30 \text{ pb}^{-1}$
⇒ NLO by FKS (Frixione et al.)
⇒ H1 2006 Fit-B DPDFs
⇒ GRV and AFG $\gamma$-PDFs
double ratios of cross section $\gamma p/\text{DIS}$: $\rightarrow$ much reduced theory uncertainties

$\frac{\text{(data/NLO)}_{\gamma p}}{\text{(data/NLO)}_{\text{DIS}}}$

$\rightarrow$ suppression factor:

$0.511 \pm 0.085 \text{(data)} \pm 0.022 \text{(theo)}$

$\rightarrow$ confirms previous results w/ complimentary experimental method

$\rightarrow$ no hint for suppression dependence on $z_{IP}$, $E_{T}^{*\text{jet1}}$, ...
Prompt Photons in Diffractive Photoproduction (LRG)

\( e e^\prime \gamma^* \rightarrow e e^\prime \gamma \) with and without accompanying jet

- HERA I+II data: luminosity \( L = 374 \text{ pb}^{-1} \)
- LRG selection
- measure prompt photon with and without accompanying jet
- photon must couple to charged particle
- explore quark structure of the Pomeron
- channel sensitive to factorisation breaking

**Analysis phasespace:**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q^2 [\text{GeV}^2] )</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>( x_{IP} )</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>( 5 &lt; E_{T,\gamma} [\text{GeV}] )</td>
<td></td>
</tr>
<tr>
<td>( -0.7 &lt; \eta_{\gamma} )</td>
<td>&lt; 0.9</td>
</tr>
<tr>
<td>( 4 &lt; E_{T,jet} [\text{GeV}] )</td>
<td></td>
</tr>
<tr>
<td>( -1.5 &lt; \eta_{jet} )</td>
<td>&lt; 1.8</td>
</tr>
</tbody>
</table>

→ bin by bin detector corrections
→ data compared to RAPGAP with H1 2006 Fit-B DPDFs
→ normalized to data
→ RAPGAP normalized to data gives reasonable description of most variables within uncertainties
→ not at $z_{IP} \sim 1$, where H1 2006 Fit-B was not fitted
→ most photons are accompanied by a hard jet
→ further studies ongoing
Open Charm Production in DDIS (LRG) [H1–PREL–16–011]

\[ \rightarrow \text{HERA II data: luminosity: } L \sim 280 \text{ pb}^{-1} \]

\[ \rightarrow \text{LRG selection} \]

\[ \rightarrow \text{open charm tagged with } D^* \text{ in} \]

\[ D^{**} \rightarrow D^0 \pi^+_{\text{slow}} \rightarrow (K^- \pi^+) \pi^+_{\text{slow}} + c.c. \]

\[ \rightarrow \text{signal extraction via mass fit} \]

\[ \rightarrow \text{binwise efficiency/acceptance correction} \]

\[ \rightarrow \text{charm mass } \rightarrow \text{“natural” hard scale} \]

\[ \rightarrow \text{NLO by HVQDIS in FFNS} \]

\[ \rightarrow \text{H1 2006 Fit-B DPDFs} \]

\[ \text{analysis phasespace:} \]

\[ \begin{align*}
5 &< Q^2 [\text{GeV}^2] < 100 \\
1.5 &< p_{t,D^*} [\text{GeV}] \\
\times\bar{p} &< 0.03 \\
0.02 &< y < 0.65 \\
|\eta_{D^*, \text{lab}}| &< 1.5
\end{align*} \]
Open Charm Production in DDIS (LRG) [H1-PREL-16-011]

\[ d \sigma / dy [\text{nb}] \]

\[ d \sigma / (d \log_{10}(x_{ip}) [\text{nb}] \]

\[ D^* \text{ in diffractive DIS} \]

H1 Preliminary data

- NLO QCD, H1 2006 Fit B
- \( m_c \) @ scale variation

- shape and normalisation well described by NLO + DPDFs
- exp. uncertainties dominated by gap selection and proton dissociative contribution

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Summary

inclusive dijets in diffractive DIS:
- data well described by NLO+H1 DPDFs,
- data precision overshoots theory precision,
- first $\alpha_s$ extraction in diffraction,

inclusive dijets in $\gamma p$ (and DIS):
- measurement using VFPS proton spectrometer
- DIS: VFPS data well described by NLO + H1 DPDFs
- $\gamma p$: cross sections overestimated by NLO + H1 DPDFs
- confirms previous H1 observations of factorisation breaking
- ZEUS: no suppression observed

prompt photons in diffractive $\gamma p$:
- another hard process sensitive to factorisation breaking,
- data compared to RAPGAP,
- agreement in most cross section shapes,

open charm production in diffractive DIS:
- well suited for factorisation tests due to hard charm mass scale,
- data well described by NLO in normalisation and shape,
- may be used to further constrain DPDFs,
- H1 analysis ongoing

see also talk on exclusive production at HERA by Mariusz Przybycien
The H1 and ZEUS Multi Purpose Experiments

→ recorded integrated luminosity: $\sim 0.5 \text{ fb}^{-1}$ per experiment
→ excellent control over experimental uncertainties:
  ⇒ over-constrained system in deep inelastic scattering
  ⇒ electron measurement scale uncertainty: 0.5 - 1%
  ⇒ jet energy scale uncertainty: 1%
  ⇒ trigger and normalisation uncertainty: 1-2%
  ⇒ luminosity uncertainty: 1.8 - 2.5%
Diffractive $ep$ Scattering at HERA

ep scattering mainly via $\gamma^*$ exchange:
- $\gamma^*$ virtual photon: Deep Inelastic Scattering (DIS)
  $\Rightarrow$ reconstruct $e'$: $Q^2 = -q^2 \gtrsim 4 \text{ GeV}^2$
- $\gamma$ real photon: photoproduction
  $\Rightarrow$ don't reconstruct $e'$: $Q^2 \lesssim 2 \text{ GeV}^2$

diffractive scattering:
- a kind of strong interaction with “vacuum quantum number” exchange
- outside the reach of perturbative QCD
- phenomenological model: Regge theory
- illustration: Pomeron $I_P$ exchange
- also affects $\gamma p$ interactions

i) hadronic structure of the $\gamma$:
- quantum fluctuations:
  $\gamma \rightarrow q\bar{q}$: vector mesons $\rho, \phi, ...$
- effective $h + h$ scattering
- “whole” $I_P$ participates
- mostly in photoproduction

ii) hard diffraction:
- $I_P$ is composite object
- hard scattering with $I_P$ “parton”
- only “part” of $I_P$ participates
- this talk: recent HERA results
References