ZEUS inclusive diffraction (final) data

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- Diffractive structure function data
to introduce the talk on QCD fits by W. Slominsky
  - Regge fits
  - comparison among selection methods
  - proton dissociation background treatment

- H1/ZEUS comparison
to introduce the discussion at the end of the session
**HERA collider experiments**

- 27.5 GeV electrons/positrons on 920 GeV protons \(\rightarrow \sqrt{s}=318\) GeV

- 2 collider experiments: **H1** and **ZEUS**

- HERA I: 16 pb\(^{-1}\) e-p, 120 pb\(^{-1}\) e+p
  - HERA II (after lumi upgrade): 500 pb\(^{-1}\), polarisation of e+,e-

*Closed July 2007, still lot of excellent data to analyse……*

**Detectors not originally designed for forward physics, but diffraction at HERA great success story!**

**ZEUS** forward instrumentation no longer available in HERA II → ZEUS final diffractive structure function measurements based on HERA I data
Diffractive DIS at HERA

Standard DIS

Probes proton structure

Diffractive DIS

Probes structure of color-singlet exchange

According to Regge phenomenology:
- exchanged Pomeron (IP) trajectory
- exchanged Reggeon (IR) and $\pi$ when proton loses a higher energy fraction, $x_{IP}$
Diffractive DIS at HERA

- **Single diffractive dissociation**: $N=$proton
- **Double diffractive dissociation**: proton-dissociative system $N$
  - represents a relevant background
Kinematics of diffractive DIS

- $Q^2 = \text{virtuality of photon} = (4\text{-momentum exchanged at } e \text{ vertex})^2$
- $W = \text{invariant mass of } \gamma^* - p \text{ system}$
- $M_{\chi} = \text{invariant mass of } \gamma^* - \text{IP system}$
- $x_{IP} = \text{fraction of proton's momentum carried by IP}$
- $\beta = \text{fraction of IP momentum carried by struck quark}$
- $x = \beta \cdot x_{IP}, \text{Bjorken's scaling variable}$
- $t = (4\text{-momentum exchanged at } p \text{ vertex})^2$
  typically: $|t| < 1 \text{ GeV}^2$

- **Single diffractive dissociation:** $N=\text{proton}$
- **Double diffractive dissociation:** proton-dissociative system $N$
  → represents a relevant background
### Diffractive structure function

**Diffractive cross section**

\[
\frac{d\sigma_D^{\gamma p}}{dM_X} = \frac{\pi Q^2 W}{\alpha(1 + (1 - y)^2)} \frac{d^3\sigma_{ep \rightarrow Xp'}}{dQ^2 dM_X dW}
\]

**Diffractive structure function** \(F_2^{D(4)}\) and reduced cross section \(\sigma_r^{D(4)}\)

\[
\frac{d^2\sigma}{d\beta dQ^2 dx_{Wp} dt} = \frac{4\pi\alpha^2}{\beta Q^4} \left[ 1 - y + \frac{y^2}{2(1 + R_D)} \right] \cdot F_2^{nq}(\beta, Q^2, x_{Wp}, t)
\]

\[
= \frac{4\pi\alpha^2}{\beta Q^4} \left[ 1 - y + \frac{y^2}{2} \right] \cdot \sigma_r^{Dq}(\beta, Q^2, x_{Wp}, t)
\]

**When \(t\) is not measured**

\[
\sigma_r^{Dq}(\beta, Q^2, x_{Wp}) = \int \sigma_r^{Dq}(\beta, Q^2, x_{Wp}, t) dt
\]

**\(R_D = \sigma_L^{\gamma p \rightarrow Xp} / \sigma_T^{\gamma p \rightarrow Xp}\)**; \(\sigma_r^D = F_2^D\) when \(R_D = 0\)
QCD factorization in hard diffraction

- **Diffractive DIS**, like inclusive DIS, is factorisable:
  
  \[ \sigma (\gamma^* p \rightarrow X p) \approx f_{i/p}(z,Q^2,x_{IP},t) \times \sigma_{\gamma^* q}(z,Q^2) \]

- \( f_{i/p}(z,Q^2,x_{IP},t) \) expresses the probability to find, with a probe of resolution \( Q^2 \), in a proton, parton \( i \) with momentum fraction \( z \), under the condition that the proton remains intact, and emerges with small energy loss, \( x_{IP} \), and momentum transfer, \( t \) - the DPDFs are a feature of the proton and evolve according to DGLAP.

see talk by W. Slominski
QCD factorization in hard diffraction

**Diffractive DIS, like inclusive DIS, is factorisable:**

[Collins (1998); Trentadue, Veneziano (1994); Berera, Soper (1996)...]

\[ \sigma (γ^* p \rightarrow Xp) \approx f_{i/p}(z,Q^2,x_{IP},t) \times \sigma_{γ^*q}(z,Q^2) \]

\( f_{i/p}(z,Q^2,x_{IP},t) \) expresses the probability to find, with a probe of resolution \( Q^2 \), in a proton, parton \( i \) with momentum fraction \( z \), under the condition that the proton remains intact, and emerges with small energy loss, \( x_{IP} \), and momentum transfer, \( t \) - the DPDFs are a feature of the proton and evolve according to DGLAP

**Assumption → proton vertex factorisation:**

\[ \sigma (γ^* p \rightarrow Xp) \approx f_{IP/p}(x_{IP},t) \times f_{i/IP}(z,Q^2) \times \sigma_{γ^*q}(z,Q^2) \]

At large \( x_{IP} \), a separately factorisable sub-leading exchange (IR), with different \( x_{IP} \) dependence and partonic composition

universal partonic cross section
Diffractive Parton Distribution Function (DPDF)

Regge-motivated IP flux
Diffractive event selection

**LPS method**

**PROS:** no p-diss. background
direct measurement of $t$, $x_{IP}$
high $x_{IP}$, $M_X$ accessible

**CONS:** low statistics

**M$_X$ method**

$\Delta \eta$

**PROS:** near-perfect acceptance at low $x_{IP}$

**CONS:** p.-diss background
How do diffractive data look vs $t, x_{IP}, Q^2$?
Data sets

**ZEUS**

"**ZEUS LPS**"  
[NPB 816 (2009)]

"**ZEUS LRG**"  
[NPB 816 (2009)]

"**ZEUS FPC II** (\(M_X\) method)  
[NPB 800 (2008)]

"**ZEUS FPC I**" (\(M_X\) method)  
[NPB 713 (2005)]

\(x_{IP}\) coverage

\(x_{IP}\) up to 0.1

IR suppressed

\(x_{IP}\) up to 0.02

IR suppressed
$t$ dependence
LPS data

**Fit to** $e^{-b|t|} \Rightarrow b = 7.0 \pm 0.4 \text{ GeV}^{-2}$

*used in DPDF fits*  
*see talk by W. Slominski*

**Lack of** $Q^2$ dependence and $b$ much larger than in vector meson production  
$\Rightarrow$ features of a soft process
$x_{IP}$ dependence of $\sigma_{r}^{D(4)}$

LPS data

First measurement in two $t$ bins

→ Low $x_{IP}$: $\sigma_{r}^{D(4)}$ falls with $x_{IP}$ faster than $1/x_{IP}$

→ High $x_{IP}$: $x_{IP}\sigma_{r}^{D(4)}$ flattens or increases with $x_{IP}$ (Reggeon and $\pi$)

→ Same $x_{IP}$ dependence in two $t$ bins
\[ F_2^{D(4)}(\beta, Q^2, x_{IP}, t) = f_{IP}(x_{IP}, t)F_2^{IP}(\beta, Q^2) + n_{IR} f_{IR}(x_{IR}, t)F_2^{IR}(\beta, Q^2) \]
\[ f_{IP, IR} = \exp(B_{IP} t)/x_{IP}^{2\alpha(t)-1}, \quad \alpha_{IP/IR}(t) = \alpha_{IP/IR}(0) + \alpha'_{IP/IR} \cdot t \]

(\text{red: parameters fitted})

\[ \alpha_{IP}(0) = +1.11 \pm 0.02 \text{(stat)} + 0.01 - 0.02 \text{(syst)} + 0.02 \text{(model)} \]

\[ \alpha'_{IP} = -0.01 \pm 0.06 \text{(stat)} + 0.04 - 0.08 \text{(syst)} \text{GeV}^{-2} \]

H1: \[ \alpha'_{IP} = +0.06 + 0.19 - 0.06 \text{ GeV}^{-2} \]

\[ \alpha_{IP}(0) = +1.14 \pm 0.018 \text{(stat)} \pm 0.013 \text{(syst)} + 0.040 - 0.020 \text{(model)} \]

\[ \rightarrow \text{IP intercept consistent with soft IP (1.096)} \]

\[ \rightarrow \alpha'_{IP} \text{ significantly smaller than 0.25 GeV}^{-2} \text{ of hadron-hadron collisions} \]

\[ \alpha'_{IP}, B_{IP} \text{ used in DPDF fits} \]

see talk by W. Slominski

\[ \rightarrow \text{Assumption of Regge factorisation works} \]
$x_{IP}$ dependence of $\sigma_r^{D(3)}$

LRG data

$\rightarrow$ Rise with $x_{IP}$ not visible as $x_{IP} < 0.02$
$x_{IP}$ dependence of $\sigma_{rD(3)}^D$

LRG data

$\rightarrow$ Rise with $x_{IP}$ not visible as $x_{IP} < 0.02$

$\rightarrow$ Wide kinematic coverage and very good statistical precision
Regge fit LRG data

\[ F_2^{D(4)}(\beta, Q^2, x_{IP}, t) = f_{IP}(x_{IP}, t)F_2^{IP}(\beta, Q^2) + n_{IR} \cdot f_{IR}(x_{IR}, t)F_2^{IR}(\beta, Q^2) \]

\[ f_{IP,IR} = \exp(B_{IP}t)/x_{IP}^{2\alpha(t)-1}, \quad \alpha_{IP/IR}(t) = \alpha_{IP/IR}(0) + \alpha'_{IP/IR} \cdot t \]

\[ \alpha_{IP}(0) = 1.108 \pm 0.008 \text{(stat+syst)} +0.022 - 0.007 \text{(model)} \]

\[ \Rightarrow \text{Rise with } x_{IP} \text{ not visible as } x_{IP} < 0.02 \]

\[ \Rightarrow \text{Assumption of Regge factorisation works} \]
$Q^2$ dependence of $\sigma_r^{D(3)}$ 
$M_X$ data

$F_2$

HERA I $e^+p$ Neutral Current Scattering – H1 and ZEUS

$\sigma_r^{D(3)}$ shows positive scaling violations up to high-$\beta$ values

$\rightarrow$ Diffractive exchange is gluon-dominated

see talk by W. Slominski
Comparison among selection methods
### Data sets

<table>
<thead>
<tr>
<th>ZEUS</th>
<th>x&lt;sub&gt;IP&lt;/sub&gt; coverage</th>
<th>M&lt;sub&gt;N&lt;/sub&gt; coverage</th>
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<tr>
<td>&quot;ZEUS LPS&quot;</td>
<td>x&lt;sub&gt;IP&lt;/sub&gt; up to 0.1</td>
<td>M&lt;sub&gt;N&lt;/sub&gt;=m&lt;sub&gt;p&lt;/sub&gt;</td>
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<td>[NPB 816 (2009)]</td>
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<tr>
<td>&quot;ZEUS LRG&quot;</td>
<td>x&lt;sub&gt;IP&lt;/sub&gt; up to 0.02</td>
<td>M&lt;sub&gt;N&lt;/sub&gt;=m&lt;sub&gt;p&lt;/sub&gt;</td>
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35% of LPS events selected by LRG
Overlap LRG-M<sub>X</sub> ~75%

Precise knowleage (and correction) of p.-diss background key point in the data comparison!
Corrected to $M_N = m_p$

How?
LRG: correction to $M_N = m_p$

i) ratio LPS/LRG

$\rightarrow$ LPS/LRG independent of $Q^2$, $x_{IP}$, $\beta$

$LPS/LRG = 0.76 \pm 0.01^{\text{stat}} +0.03-0.02^{\text{sys}} +0.08-0.05^{\text{norm}}$

$\rightarrow$ p-diss. background in LRG data:

$[24 \pm 1^{\text{stat}} +2-3^{\text{sys}} +5-8^{\text{norm}}]$

In itself a comparison LRG vs LPS!
**LRG: correction to** \( M_N = m_p \)

ii) Monte Carlo (PYTHIA)

- 2 samples of proton-dissociative data, one with LPS (“LPS P-DISS”) and one with Forward Plug Calorimeter (“LRG P-DISS”) → coverage of full \( M_N \) spectrum

- PYTHIA reweighted to best describe \( E_{FP} \) and \( x_L \)

→ p-diss. background in LRG data \( R_{diss} = [25 \pm 1 \text{(stat)} \pm 3 \text{(sys)}] \%

→ consistent with the ratio LPS/LRG

→ 25% correction applied to LRG data
**LRG vs \( M_x \)**

\( M_x \) data (\( M_N < 2.3 \text{ GeV} \)) normalised to LRG (\( M_N=M_p \)): factor \( 0.83 \pm 0.04 \) determined via a global fit estimates residual p-diss. background in \( M_x \) sample

\[
\begin{array}{cccc}
55 \text{ GeV} & 70 \text{ GeV} & 90 \text{ GeV} & 120 \text{ GeV} \\
\hline
Q^2 = 45 \text{ GeV}^2 & X_{IP} & 6 \text{ GeV}^2 & 8 \text{ GeV}^2 & 14 \text{ GeV}^2 & 27 \text{ GeV}^2 & Q^2 = 190 \text{ GeV}^2
\end{array}
\]

\( \rightarrow \) Overall agreement satisfactory

\( \rightarrow \) Different \( x_{IP} \) dependence ascribed to IR suppressed in \( M_x \) data
Comparison with H1
Data sets

**ZEUS**

“ZEUS LPS”  
[NPB, 816 (2009)]

“ZEUS LRG”  
[NPB, 816 (2009)]

“ZEUS FPC II” (M_X method)  
[NPB 800 (2008)]

“ZEUS FPC I” (M_X method)  
[NPB 713 (2005)]

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Overlap LRG-M_X ~75%

**H1**

“H1 FPS”  
[EPJ C48 (2006)]

“H1 LRG”  
[EPJ C48 (2006)]

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<td>M_N &lt; 1.6 GeV</td>
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FPS and LRG measurements statistically independent and only very weakly correlated through systematics.
ZEUS LPS vs H1 FPS

The cleanest possible comparison in principle...

...but large normalisation uncertainties (LPS:+11-7%, FPS: +-10%)

→ ZEUS and H1 proton-tagged data agree within normalisation uncertainties
ZEUS corrected to $M_N < 1.6$ GeV with PYTHIA

→ Remaining normalisation difference of 13% (global fit) covered by uncertainty on p-diss. correction (8%) and relative normalisation uncertainty (7%)

→ Shape agreement ok except low $Q^2$
Towards HERA inclusive diffraction!

→ Time for data combination, global fits!
Towards HERA inclusive diffraction!

→ Time for data combination, global fits!
Summary and beyond

- Final ZEUS results on inclusive diffraction - same data analysed in three independent ways:
  - Proton tag requirement
  - Large rapidity gap requirement
  - Shape of the mass distribution of the hadronic final state

- Proton dissociation background under control

- Vertex factorisation assumption works to a good approximation

  → QCD fits, talk by W. Slominsky

- Consistent results between different methods and data sets

- ZEUS results consistent with H1 results within uncertainties

  → Discussion on data combination
Backup
First step towards the data combination

Error weighted average:

- before averaging, H1 points swum to ZEUS \( Q^2 \) values with H1 fit B
- ZEUS normalised to H1 applying 13% factor (see slide 36) → normalisation uncertainty of combined data beyond 10%
- correlations between systematic errors ignored so far

Hints at precision achievable through combination: for many points errors at 3–4% level (excluding normalisation uncertainty)
First step towards the data combination

Error weighted average:
- before averaging, H1 points swum to ZEUS $Q^2$ values with H1 fit B
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Hints at precision achievable through combination: for many points errors at 3-4% level (excluding normalisation uncertainty)
The plot in attachment shows MN distribution at generated level by red histogram and after all selection cuts by black histogram. When we apply all selection cuts in LRG analysis the MN shape of p-diss background looks like black histogram. We calculate acceptance using SATRAP which knows nothing about MN. It means that after acceptance correction the remaining p-diss background still has the shape of the black histogram. The integral under this black histogram is our 25%. If we want to compare with H1 we should remove from the acceptance corrected cross section the remaining p-diss background (25%) and add the integral over generated MN shape (red histogram) up to Mn=1.6 GeV. The correction factor is

\[
\frac{\text{sigma}_{\text{elastic\_data}} + \text{sigma}_{\text{p\_diss\_MC(MN<1.6)}}}{\text{sigma}_{\text{data}}}\]

where

- \text{sigma}_{\text{data}} = acceptance corrected cross section with p-diss background
- \text{sigma}_{\text{elastic\_data}} = acceptance corrected cross section without p-diss background, it is just \text{sigma}_{\text{data}} \times 0.75
- \text{sigma}_{\text{p\_diss\_MC(MN<1.6)}} - p\text{-diss MC prediction for Mn<1.6 GeV}
ZEUS

$Q^2 = 6 \text{ GeV}^2$

- ZEUS (prel.) DPDF C incl
- ZEUS (prel.) DPDF C incl FFNS
- H1-2006B $\times 0.81$

$Q^2 = 20 \text{ GeV}^2$

$Q^2 = 60 \text{ GeV}^2$

$Q^2 = 200 \text{ GeV}^2$
**ZEUS**

- $Q^2 = 6 \text{ GeV}^2$
- $Q^2 = 20 \text{ GeV}^2$
- $Q^2 = 60 \text{ GeV}^2$
- $Q^2 = 200 \text{ GeV}^2$

Different curves represent:
- ZEUS (prelim.) DPDF C incl
- ZEUS (prelim.) DPDF C incl FFNS
- H1-2006B \times 0.81

The plots show variations in $z$ and $d$ with $Q^2$.
$W = 75$ GeV

$Q^2$ [GeV$^2$]

$\sigma (\gamma p \rightarrow r p)$ [nb]
Regge factorisation: yes or no?  
(my interpretation)

**Apparent contradiction:**
- Regge fit works within errors for LPS/FPS and LRG data
- FPC and LRG (see later) show violation of Regge factorisation

- Data consistent with Regge factorisation; violation too mild to have impact on the fit quality

What if we fitted LPS/FPS/LRG without assuming Regge factorisation?
Not done yet but done for the FPC data → **BEKW fit works well!**

[Bartels, Ellis, Kowalski, Wustoff, see NPB 800 (008)]

Mild violations should not affect QCD fits, which assume factorisation
$x_{IP}$ dependence of $\sigma^D_{r(4)}$

FPS data
\* Dependence

LPS/FPS data

\[ 0.0002 < x_{IP} < 0.03 \]

\[ 0.03 < x_{IP} < 0.1 \]

\[ 2 < M_X < 5 \text{ GeV} \]

\[ 5 < M_X < 10 \text{ GeV} \]

\[ 10 < M_X < 40 \text{ GeV} \]

\[ Q^2 (\text{GeV}^2) \]

\[ \beta \]

→ Support Regge factorisation hypothesis
**H1 LRG vs H1 FPS**

Proton dissociation-background in the H1 LRG data

Data first corrected to $M_N < 1.6$ GeV  
(corr. factor: $-8.6\% \pm 5.8\%$)

→ Proton dissociation left in H1 LRG data: $[19^{+11}_{-11}]\%$

Consistent number obtained with DIFFVM: $[13^{+11}_{-6}]\%$

→ LRG/FPS independent of $x_{IP}$, $Q^2$, $\beta$
W dependence of $d\sigma^{\text{diff}}/dM_X$

ZEUS $M_X$ data

→ Low $M_X$: moderate increase with $W$ and steep reduction with $Q^2$
→ Higher $M_X$: substantial rise with $W$ and slower decrease with $Q^2$
W dependence of $d\sigma^{\text{diff}}/dM_X$

**ZEUS $M_X$ data**

- **ZEUS**
  - *FPC I*
  - *FPC II*
  - 11 GeV, 20 GeV, 30 GeV
  - 45 GeV, 55 GeV, 70 GeV, 90 GeV, 120 GeV
  - $Q^2 = 320$ GeV$^2$, 190 GeV$^2$

> Substantial rise with W
Towards HERA inclusive diffraction!

→ Time for data combination, global fits!
Towards HERA inclusive diffraction!

→ Time for data combination, global fits!
Fit with BEKW parameterisation
(Bartels, Ellis, Kowalski, Wustoff 1988)

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

\[ F_{qq}^T \sim \beta(1 - \beta) \]

\[ F_{qqg}^T \sim (1 - \beta)^\gamma \]

\[ F_{qq}^L \sim \text{limited to } \beta \sim 1 \]

→ Fit gives a good description of the 427 data points FPC I + II

\[ x_{IP} = 0.02 \]
$Q^2$ dependence of $\alpha_{IP}(0)$

$\alpha_{IP}(0)$ does not exhibit a significant dependence on $Q^2$.