Diffraction @ HERA
K. Wichmann
on behalf of the H1 and ZEUS Collaborations

- **Something old** (mature measurements)
  - Inclusive diffractive cross sections
- **Something new** (never done before)
  - Diffractive data combination
- **Something out of the blue** (a puzzle)
  - Diffractive factorization
- **Horn of plenty**
  - Vector meson production
**20 years of diffraction @ HERA**

**First:**


Observation of Events with a Large Rapidity Gap in Deep Inelastic Scattering at HERA

**Latest (not last!):**


Elastic and Proton-Dissociative Photoproduction of J/psi Mesons at HERA
HERA Accelerator

- HERA: ep collider, $\sqrt{s} = 320$ GeV
- 2 colliding-beam experiments: H1 & ZEUS
- collected 0.5 fb$^{-1}$/exp of luminosity in 1992-2007
Diffractive kinematics

Deep Inelastic Scattering (DIS) variables

\[ Q^2 = -q^2 = -(k - k')^2 \]
\[ x = \frac{Q^2}{2p \cdot q} \]
\[ y = \frac{p \cdot q}{p \cdot k} \]
\[ s = (p + k)^2 \]
\[ Q^2 = x \cdot y \cdot s \]

Diffractive variables

\[ x_{IP} = \frac{q(P' - P)}{qP} = 1 - E'p/Ep \]
\[ \beta_s = \frac{x}{x_{IP}} \]
\[ z_{IP} = \frac{(Q^2 + M_{jj}^2)}{x_{IP}ys} \]
\[ M_Y = m_p \ldots \text{intact proton} \]
\[ m_p \leq M_Y \leq 1.6 \text{ GeV} \ldots \text{intact proton or proton dissociation} \]
Experimental Methods

- Selecting Large Rapidity Gap (LRG) events
  - For example with $\eta_{\text{max}}$
  - Proton measured with Roman pots 60-220 m from interaction point
Scope of Diffraction @ HERA

- Amazing amount of precise measurement based on various experimental techniques and compared to various theory predictions

It took >15 years of analysis to reach this:
Inclusive Diffractive DIS

EPJ C72 (2012) 2074

- H1 diffractive measurements combined to one LRG cross sections set
- Increase in statistics 3-33 times
- Large reduction of uncertainties

- Comparison with H1 2006 DPDF FitB and dipole model
  - Low $Q^2$: better description by dipole model
  - High $Q^2$: better description by H1 2006 DPDF FitB

High precision HERA data available for comparison with various models
Pomeron Trajectory

- Pomeron trajectory measured

\[ \alpha_{IP}(0) = 1.113 \pm 0.002 \, (\exp)^{+0.029}_{-0.015} \, (\text{mod}) \]

- No \( Q^2 \) dependence
- Agreement with previous measurements
- \( \alpha_{IP}(0) \) consistent with "soft" pomeron

Supports proton vertex factorization hypothesis
Combination of H1 and ZEUS Results
Combined inclusive diffractive cross sections measured with forward proton spectrometers in deep inelastic ep scattering at HERA

2175

- First combined inclusive diffractive cross sections
- Measurements using forward proton spectrometers
  - EPJ C71 (2011) 1578
  - EPJ C48 (2006) 749
  - Nucl. Phys B816 (2009) 1
  - EPJ C38 (2004) 43

- H1 and ZEUS employed different experimental techniques
  - reduced uncertainties in combination
Combined Diffractive Measurements

- Wide kinematic range and improved precision
  - \( Q^2 \): 2.5 - 200 GeV\(^2\)
  - \( \beta \): 0.0018 - 0.816
  - \( x_{IP} \): 0.00035 - 0.09
  - \(|t|\): 0.9 - 0.55

- Diffractive DIS allows to probe the parton content in the colorless nucleon

**Important input to diffractive PDFs**
Diffractive factorization puzzle
Factorization in diffraction

QCD versus Regge factorisation

Collins factorisation, proven:
\[ d \sigma^{ep \rightarrow eXp}(\beta, Q^2, x_{IP}, t) = \sum_i f_{ip}^D(\beta, Q^2, x_{IP}, t) \cdot d \sigma^{ei}(\beta, Q^2) \]

Proton Vertex Factorisation, consistent with data:
\[ f_{ip}^D(\beta, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_{i}(\beta, Q^2) \]

PDF from inclusive diffraction -> predict cross sections for exclusive diffraction

still being tested
Diffractive PDFs in DIS

- Obtained from inclusive, dijet and $D^*$ measurements
  - H1 fit B, H1 fit Jets, ZEUS SJ
  - Difference mainly in gluons
Diffractive dijets in DIS

EPJ C72 (2012) 1970

- Data well described by QCD predictions with inclusive DPDFs
  - 2 central dijets
  - 1 central + 1 forward jet

Supports universality of DPDFs

- $t$-slope consistent with measurement in inclusive DDIS with leading proton

confirms validity of proton vertex factorisation for dijet production in diffractive DIS
Diffractive dijets in PhP

- Resolved photoproduction: theory predicts suppression
  - Previous measurements
  - EPJ C51 (2007) 549
    - Suppression 0.5 ± 0.1
  - EPJ C68 (2010) 381
    - Suppression 0.58 ± 0.21
    - NO suppression

- Different phase space
- ZEUS larger $E_T$ dependence
- tagged/untagged PhP
New H1 measurement

- H1 measured dijets in photoproduction with VFPS
- Measured cross sections lower than NLO prediction

\[
\frac{\sigma_{ DATA }}{\sigma_{ NLO }} = 0.67 \pm 0.04{\text{(stat.)}} \pm 0.09{\text{(syst.)}} \pm 0.20{\text{(scale)}} \pm 0.14{\text{(DPDF)}}
\]

Even with new H1 measurement “suppression puzzle” remains.
Horn of plenty
Diffractive Vector Meson Production

Proton stays intact or dissociates

ZEUS

Events

Signals

H1 $J/\psi \rightarrow \mu^+\mu^-$ photoproduction

H1 $J/\psi \rightarrow e^+e^-$ photoproduction

Events / (0.02 GeV)

$M_{\mu^+\mu^-}$ (GeV)

$M_{ee}$ (GeV)
**Y(1s) Production**


- U(1s) photoproduction
- First measure of U(1s) b-slope
- $60 < W < 220$ GeV
- $Q^2 < 1$ GeV$^2$
- 0.5 fb$^{-1}$ of data used

**Graphical Representation**

- ZEUS 96/07 (468 pb$^{-1}$)
- BH + $\Upsilon(1S)$ (exclusive + pdiss)
- BH $\gamma\gamma \rightarrow \mu^+\mu^-$
- $\Upsilon(1S) \rightarrow \mu^+\mu^-$ (exclusive)
- $\Upsilon(1S) \rightarrow \mu^+\mu^-$ (pdiss)

**Equation**

$$b = 4.3 \pm^{+2.0}_{-1.2} \text{ (stat)} \pm^{+0.5}_{-0.6} \text{ (syst)} \text{ GeV}^{-2}$$
Y(1S) Production

- Highest so far value of $Q^2 + M_{vm}^2$ of $\sim 90$ GeV$^2$
- In agreement with asymptotic behavior of $b$-slope in terms of $Q^2 + M_{vm}^2$
  - Reflects proton radius
- Consistent with pQCD models predictions of $b = 3.68$ GeV$^{-2}$ (JHEP 0906 (2009) 034)
Elastic $J/\psi$ Photoproduction

**EPJ C73 (2013) 2466**

- Elastic and proton-dissociative cross sections as a function of $|t|$
  - difference in shape
- High energy (HE) and low energy (LE) data
- Includes previous H1 high $t$-data (hep-ex/0306013)
- Fitted simultaneously using phenomenological models:
  - elastic
    \[
    \frac{d\sigma}{dt} = N_{el} e^{-b_{el}|t|}
    \]
    \[b = (4.88 \pm 0.15) \text{ GeV}^{-2}\]
  - P-diss
    \[
    \frac{d\sigma}{dt} = N_{pd} \left(1 + \left(\frac{b_{pd}}{n}\right)|t|\right)^{-n}
    \]
    \[b = (1.79 \pm 0.12) \text{ GeV}^{-2}\]
t-dependence of $J/\psi$ photoproduction

- HE proton-diss data extend to low values of $|t|$
- Good agreement in overlap region
- High-t data included in fits

- Good separation of p-dissoc from elastic down to lowest $|t|$
**W-dependence of elastic $J/\psi$ photoproduction**

- H1 measurement cover region between fix target and LHCb results
- Compatible with previous HERA measurements
- Fixed target: lower normalization, steeper slope
- Fit to H1 data extrapolated to higher $W$ in agreement with LHCb

![Elastic $J/\psi$ photoproduction graph](image)
Summary

- HERA delivers diffractive results since 20 years
  - Still more to come!
- Many beautiful inclusive diffractive measurements implementing various experimental techniques
- First diffractive combination done
- Diffractive factorization confirmed by dijet measurements in DIS
- Data to study diffractive PDFs in PhP available, but no results so far
- Vector mesons measured with high precision
  - Extended range of diffractive variables
  - HERA precise measurements fill phase-space between fixed target experiments and LHCb