Factorization in ep diffractive interactions

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on behalf of H1 and ZEUS Collaborations
HERA collider experiments

- 27.5 GeV electrons/positrons on 920 GeV protons \( \rightarrow \sqrt{s}=318 \text{ GeV} \)
- HERA I,II: \( \sim 500 \text{ pb}^{-1} \) per experiment
- H 1 & ZEUS - 4\pi detectors

\[ e^\pm 27.5 \text{ GeV} \quad p 920 \text{ GeV} \]

\[ \sqrt{s} = 318 \text{ GeV} \]

**Virtuality** of exchanged boson \( Q^2 = -q^2 = -(k-k')^2 \)

**Inelasticity** \( y = Pq/Pk \)

**Bjorken scaling variable** \( x = \frac{Q^2}{2qP} \)

Two regimes:
- \( Q^2 < 1 \text{ GeV}^2 \) photoproduction \((\gamma p)\)
- \( Q^2 > 1 \text{ GeV}^2 \) Deep Inelastic Scattering \((\text{DIS})\)
Diffractive kinematics

Non-diffractive ep interaction

- $Q^2$ - virtuality of the photon
- $Q^2 \sim 0 \text{ GeV}^2 \rightarrow$ photoproduction
- $Q^2 \gg 0 \text{ GeV}^2 \rightarrow$ DIS
- $W$ – total hadronic energy

Diffractive scattering

- momentum fraction of color singlet exchange
  \[ x_{IP} = \xi = \frac{Q^2 + M_X^2}{Q^2 + W^2} \]
- fraction of exchange momentum, coupling to $\gamma$
  \[ \beta = \frac{Q^2}{Q^2 + M_X^2} = x_q/IP = \frac{x}{x_{IP}} \]
- 4-momentum transfer squared (if proton is measured)
  \[ t = (p - p')^2 \]

$M_y = m_p$ proton stays intact

$M_y > m_p$ proton dissociates, contribution should be understood

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Methods of diffraction selection

Proton spectrometers

H1: VFPS (2005-2007)
FPS (1997-2007)
ZEUS: LPS (1997-2000)

- free of p-dissociation background
- \( x_{IP} \) and \( t \) measurements
- access to high \( x_{IP} \) range (IP and IR)
- small acceptance, small statistics

Large Rapidity Gap
require no activity beyond \( \eta_{max} \)
- \( t \) not measured, integrated over \(|t|<1\text{GeV}^2\)
- very good acceptance at low \( x_{IP} \)
- p-diss background about 20%

Different phase space and systematics – non-trivial to compare!
**QCD collinear factorisation theorem**

Breit frame - proton very fast

\[
\sigma^D(\gamma^* p \rightarrow Xp) = \sum_{\text{parton}_i} f_i^D(x, Q^2, x_{IP}, t) \cdot \sigma^{\gamma^*_i}(x, Q^2)
\]

DPDFs – obey DGLAP
universal for diff. ep DIS

**Proton vertex factorisation** (conjecture, e.g. Resolved Pomeron Model by Ingelman&Schlein)

\[
f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_{IP}^p(\beta = x / x_{IP}, Q^2)
\]

Pomeron flux factor

diffarctive DPDF

Then DPDFs extracted from DIS data

**Dipole models**

Proton rest frame - dipoles

\[
d\sigma_{\text{diff}}^{\gamma^*p}/dt \propto \int dz dr^2 \Psi^* q^2(x, r^2, t) \Psi
\]

\(\gamma^*\) fluctuates into \(q\bar{q}, q\bar{q}g\) states
(color dipoles) of transverse size proportional to

\[
1/\sqrt{Q^2 + M_{qq}^2}
\]

No extra parameters needed for DDIS
DPDFs in DIS- H1 and ZEUS

- DPDFs extracted from NLO DGLAP fit, using Regge factorisation
- DPDFs: H1 fit B, H1 fit Jets, ZEUS fit SJ
- Gluon exchange dominates (~70-75% of the Pomeron momentum), main differences in fits
- DPDFs used in NLO calculations to predict diffractive production of charm and dijets

\[ z_{IP} = \frac{\sum (E+p_z)_{jets}}{(E+p_z)_{hadrons}} \]

\[ z = z_{IP} = \frac{Q^2+M_{12}^2}{Q^2+M_X^2} \]
Diffractive dijet production in DIS

**DIS**

$4 < Q^2 < 100 \text{ GeV}^2$

$0.1 < y < 0.7$

**2-jets**

$p_{T,1}^* > 5.5 \text{ GeV}$

$p_{T,2}^* > 4.0 \text{ GeV}$

$-1 < \eta_{1,2}^{\text{lab}} < 2$

$M_Y < 1.6 \text{ GeV}$

**Diffraction**

$x_P < 0.03$

$|t| < 1 \text{ GeV}^2$

**Most precise DDIS dijet measurement from HERA**

→ based on ~ 290 pb$^{-1}$ of HERA-2 H1 data

→ LRG selection used

→ proton dissociation contribution up to $M_Y < 1.6 \text{ GeV}$

→ detector effects controlled very well by simulation

→ data corrected with regularized unfolding (TUnfold)

→ single and double-differential x-sections measured

**Compared with theory**

→ in NLO QCD (nlojet++)

→ hadronization corrections from MC

→ using H1 2006 DPDF Fit B
Diffractive dijet production in DIS

Data more precise than theory
- DPDF uncertainties
- DPDF & scale uncertainties

Data well described by theory

\[
\sigma_{\text{dijet}}^{\text{meas}}(ep \rightarrow eXY) = 73 \pm 2 \text{ (stat.)} \pm 7 \text{ (syst.) pb}
\]

\[
\sigma_{\text{dijet}}^{\text{theo}}(ep \rightarrow eXY) = 77 \, ^{+25}_{-20} \text{ (scale)} \, ^{+4}_{-14} \text{ (DPDF)} \pm 3 \text{ (had) pb}
\]
**Double-differential cross sections**

→ agreement with QCD at NLO

→ precision of the data allows the extraction of $\alpha_s$ ... in agreement with world average

... not a competitive means for $\alpha_s$ extraction

... supports readiness of the data for DPDF fits

$$\alpha_s(M_Z) = 0.119 \pm 0.004 \text{ (exp)} \pm 0.012 \text{ (DPDF, theo)}$$
Factorisation tests in diffractive production

DPDFs are not portable to diffractive hadron-hadron (pp) processes!

- order of magnitude overestimation of predicted $\bar{p}p$ dijet rates first observed by CDF → Factorization breaking

$$S^2 = \frac{\sigma(\text{data})}{\sigma(\text{theory (NLO QCD)})}$$

Absorptive effects occur

- change of event kinematics
- rescattering or unitarity corrections
- several approaches exist to calculate so-called Survival probability $<S^2>$

... i.e. probability of diffractive event to retain the diffractive signature

Tested in diffractive dijet photoproduction at HERA due to $\gamma$'s partonic fluctuations (hadron-like object)
**Factorisation tests in diffractive dijet photoproduction**

**In LO QCD!**

- **Direct photoproduction:** Photon directly involved in hard scattering $\Rightarrow x_\gamma = 1$
  - No suppression expected

- **Resolved photoproduction:** Photon fluctuates into hadronic system, which takes part in hadronic scattering, dominant at $Q^2 \approx 0$ $\Rightarrow x_\gamma < 1$
  - Theor. prediction of Kaidalov, Khoze, Martin, Ryskin (European Journal of Physics 66, 373 (2010))
  - Suppression: quarks 0.71(0.75) $E_T^{jet1} > 5$ (7.5) GeV, gluons 0.53(0.58) $E_T^{jet1} > 5$ (7.5) GeV

\[
\begin{align*}
 x_\gamma &= x_\gamma^{OBS} = \frac{\sum(E - p_z)_{jets}}{(E - p_z)_{hadrons}} \\
 Z_{IP} &= \frac{\sum(E + p_z)_{jets}}{(E + p_z)_{hadrons}}
\end{align*}
\]
Previous H1 and ZEUS (LRG) analyses

→ H1: 2007 ($S^2 \sim 0.5$), 2010 ($S^2 \sim 0.6$)

→ ZEUS: 2010 ($S^2 \sim 1$)

Suppression is not dependent on $x_\gamma$
**Diffractive dijet photoproduction & DIS- measurement in Very Forward Proton Spectrometer**

**DIS & photoproduction**

\[ 4 < Q^2 < 80 \text{ GeV}^2 \quad \text{Q}^2 < 2 \text{ GeV}^2 \]

Other cuts identical:

\[ 0.01 < x_{IP} < 0.024 \]
\[ |t| < 0.6 \text{ GeV}^2 \]
\[ z_{IP} < 0.8 \]
\[ E_T^{* \text{jet1(2)}} > 5.5(4) \text{ GeV} \]
\[ -1 < \eta_{\text{jet1(2)}} < 2.5 \]

Independent cross-check of LRG measurements – without proton dissociation!
Diffractive dijet photoproduction & DIS

Data in agreement with NLO in DIS, within uncertainties

Data suppressed in comparison with NLO in photoproduction
The suppression seems to be not dependent on $x_{\gamma}$. It is in agreement with previous H1 and ZEUS observations!
Diffractive dijet photoproduction & DIS

Profits from cancellations of scale uncertainties
→ theory / theory, if varied simultaneously
No significant dependence on kinematics
→ only global ratios are shown

1.08±0.11 (data)\textsuperscript{+0.45}_{-0.29} (theory)

0.551±0.078 (data)\textsuperscript{+0.230}_{-0.149} (theory)

0.511±0.085 (data)\textsuperscript{+0.022}_{-0.021} (theory)

Previous H1 measurement confirmed!
Diffractive $D^*$ production in DIS

- hard scale $\rightarrow$ mass of $D^*$
- sensitive to gluon content

Charm contribution to $F_2^D \sim 20\%$ - similar as for inclusive DIS

$\rightarrow$ based on 280 pb$^{-1}$ HERA-2 data
(previous H1 publ. at 50 pb$^{-1}$ H1 HERA 1)

$\rightarrow$ open charm tagged with $D^*$

$$D^{*+} \rightarrow D^0 \pi^+ \rightarrow (K^- \pi^+) \pi^+_{\text{slow}} + C.C.$$  

$\rightarrow$ fits of $\Delta m = m(D^*_{\text{cand}}) - m(D^0_{\text{cand}})$

$\rightarrow$ large rapidity gap selection

$5 < Q^2 < 100$ GeV$^2$  
$0.02 < y < 0.65$

$p_{t,D^*} > 1.5$ GeV  
$|\eta_{D^*}| < 1.5$  
... in lab

$x_{lP} < 0.03$
D* in diffractive DIS

NLO QCD prediction agree well within errors with measured cross sections

→ new test of factorization

Final measurement might serve as an input to DPDF fits
Prompt photons in DIS

LL-photons are emitted from incoming or outgoing lepton

QQ-photons are emitted from a quark as a part of hard process

Test of QCD, unaffected by hadronisation

- Free of hadronisation corr. for photon -> direct link to parton level
- Sensitivity to parton and photon PDFs
- Important SM background to possible New physics
- Low statistics as compared to jets
- Difficult background from $\pi/\eta$ decays -> systematics $\sim$5-10%
Extraction of the photon signal

Method to distinguish the signal from hadronic background based on MC fit of $\delta Z$ distribution

In each bin of each measured physical quantity, photon signal + hadronic background is fitted.

This fit allows to separate statistically prompt photon signal (left peak) from background dominated by photons from $\pi^0$ decay (right peak).

$Z_i$ ($Z_{\text{cluster}}$) - $Z$ position of the $i$-th cell (centroid of the electromagnetic cluster), $l_{\text{cell}}$ - width of the cell, $E_i$ - energy recorded in the cell.

\[
\langle \delta Z \rangle = \frac{\sum_i |Z_i - Z_{\text{cluster}}| \cdot E_i}{l_{\text{cell}} \sum E_i}
\]
Models used for comparison

Signal: QQ photons - MC PYTHIA, DIS events with additional radiation from the quark line
LL photons - MC HERACLES & DJANGOH, higher QCD effects included using color-dipole model as implemented in ARIADNE

Background: Photonic decays of neutral mesons produced in DIS - DJANGOH

Theoretical calculations (BLZ):

$k_t$ - factorization QCD approach
Photon radiation from the quarks as well as from the lepton is taken into account
Cross sections compared to models

\[ \sigma / d x_\gamma (pb) \]

- ZEUS (prel.)
- QQ*1.6, MC
- LL, MC
- LL + QQ*1.6, MC

Cross sections compared to LL(DJANGOHH) + QQ(PYTHIA) *1.6
Shapes are fairly described

\[ \Delta \eta = \eta_{jet} - \eta_\gamma \]

BLZ calculations describe shapes of data distributions not so well (mainly \( x_\gamma \) and \( \Delta \eta \))
Conclusions

• New H1 measurement of **diffractive dijet** production in **DIS** → measurements described by NLO QCD predictions using H1 DPDF, value of $\alpha_s(M_Z)$ obtained from this measurement is in agreement with world average.

• New H1 measurement of **diffractive photoproduction & DIS dijets** using VFPS proton spectrometer → **DIS dijets** in agreement with NLO QCD prediction, suppression factor $0.5 \pm 0.1$ in **photoproduction dijets** observed, consistent with factorisation breaking!

• Recent H1 preliminary result on **D* production in DIS** supports the validity of collinear factorization

• **Prompt photons in DIS** measured by ZEUS. Predictions for the sum of the expected LL contributions (DJANGOH) and QQ contributions (PYTHIA) rescaled by factor 1.6 → good description of the shapes of the kinematic variables. The calculations of BLZ describe the data not so well.
Backup
**Diffractive prompt (isolated) photons**

HERA II (374pb\(^{-1}\)) and I data (91pb\(^{-1}\), used for normalization), untagged photoproduction.

**Diffractive selection – LRG,**

- **Photons**
  - \( E_T^{\gamma} > 5 \text{ GeV} \)
  - \(-0.7 < \eta^{\gamma} < 0.9 \)
- **Jets**
  - \( -1.5 < \eta^{\text{jet}} < 1.8 \)
  - \( E_T^{\text{jet}} > 4 \text{ GeV} \)

**Signal MC = RAPGAP with H1 fitB DPDF and \(\gamma\)-PDF SASG 1D LO**
Diffractive production of prompt (isolated) photons

A peak at \( z_{IP} \) close to 1 is not described by RAPGAP. Note, that H1 fit B not fitted in this region, it is only extrapolated.

Region \( z_{IP} \sim 1 \), no activity except jet and \( \gamma \).

Fair description by RAPGAP within uncertainties

Preliminary – in future planned comparison with NLO calculations – first test of QCD factorisation using this process