Hard diffraction and factorization breaking

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on behalf of the H1 and ZEUS Collaborations

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HERA, ep collider  
(DESY, Hamburg, 1993-2007)

\[ E_p = 920 \text{ GeV} \quad E_{e^\pm} = 27.5 \text{ GeV} \]

0.5 fb\(^{-1}\) … per experiment
**ep interactions proceed mainly via γ* exchange**

\[ s = (k + P)^2 \]  ... CMS energy of collision

\[ Q^2 = -q^2 = -(k - k')^2 \]  ... four-momentum transfer at e vertex

\[ W = \sqrt{(q + P)^2} \]  ... hadronic c.m.s. energy

\[ x = \frac{Q^2}{2q . P} \]  ... Bjorken x

**Diffractive dissociation**

**HERA domain**

→ continuum of masses of X

**Diffractive exchange (IP)**

→ quantum numbers of vacuum

→ \[ \beta = x / x_{IP} \]  ... mom. fraction of IP participating

\[ t = (P - P_Y)^2 \]  ... four-momentum transfer at p vertex

\[ x_{IP} = \frac{q . (P - P_Y)}{q . P} \]  ... fractional long. mom. loss of proton
Diffractive dissociation in DIS

- virtual photon dissociates into system X ($M_x^2 << W^2$)
- small momentum transfer to proton, $|t| << W^2$
- proton stays intact or dissociates into system Y ($M_Y^2 << W^2$)
- large rapidity gap (non-exponentially suppressed) between Y and X
- hard scale present ($Q^2$, $p_T^2$, $m_Q^2$)
  - inclusive
  - jet data
  - open charm / beauty
  - $\gamma$
- represents ~10% of low x DIS $\sigma$

\[ ep \rightarrow eXY \]
**Diffractive dissociation in DIS**

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$ep \rightarrow eXY$
Diffractive dissociation

Diffractive dissociation in DIS

- virtual photon dissociates into system X ($M_x^2 \ll W^2$)
- small momentum transfer to proton, $|t| \ll W^2$
- proton stays intact or dissociates into system Y ($M_y^2 \ll W^2$)
- large rapidity gap (non-exponentially suppressed) between Y and X
- **hard scale present** ($Q^2$, $p_T^2$, $m_Q^2$)
  - inclusive
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$ep \rightarrow eXY$
Due to vacuum quantum number exchange

→ leading particle at relatively small $t$

→ rapidity distributions of final state (VM, $X$) separated from leading particle by non-exponentially suppressed gaps – **Large Rapidity Gap (LRG)**

Both leading proton tagging or LRG detection used in H1 and ZEUS
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proton tagging method
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proton tagging method
Collinear factorization

**Central assumption:** Collinear factorization valid for diffractive DIS, Collins

→ diffractive parton distribution functions (DPDFs) factorized from predictions of hard X states cross sections

\[ d\sigma^{ep\rightarrow eXp}(x,Q^2,x_{IP},t) = \sum_i f_i^D(x,Q^2,x_{IP},t) \otimes d\hat{\sigma}(x,Q^2) \]

**Optionally:** Resolved Pomeron approach Ingelman and Schlein

→ virtual photon interacts with partonic diffractive exchange

→ leading proton \((t,x_{IP})\) treated separately aka Proton vertex factorization

\[ f_i^D(x,Q^2,x_{IP},t) = f_{IP/p}(x_{IP},t).f_i(\beta,Q^2) \]
**Dijets in diffractive DIS**

**DIS**
- $4 < Q^2 < 100 \text{ GeV}^2$
- $0.1 < y < 0.7$
- $p_{T,1}^* > 5.5 \text{ GeV}$
- $p_{T,2}^* > 4.0 \text{ GeV}$
- $-1 < \eta_{1,2}^{\text{lab}} < 2$
- $x_P < 0.03$
- $|t| < 1 \text{ GeV}^2$
- $M_Y < 1.6 \text{ GeV}$

**2-jets**

**Diffraction**

**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

**$z_{IP}$ variable**
- fraction of IP momentum participating in the hard process giving rise to jets

**Compared with theory**
- in NLO QCD (nlojet++)
- hadronization corrections from MC
- using H1 2006 DPDF Fit B
DIS variables

Jet variables

Diffractive variables

Data more precise than theory

$\sigma_{\text{meas}}^{dijet}(e p \rightarrow eXY) = 73 \pm 2 \text{ (stat.)} \pm 7 \text{ (syst.)} \text{ pb}$

$\sigma_{\text{theo}}^{dijet}(e p \rightarrow eXY) = 77^{+25}_{-20} \text{ (scale)}^{+4}_{-14} \text{ (DPDF)} \pm 3 \text{ (had)} \text{ pb}$
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

\[
\alpha_s(M_Z) = 0.119 \pm 0.004 \text{ (exp)} \pm 0.012 \text{ (DPDF, theo)}
\]
Dijets in diffractive photoproduction and DIS with leading proton

Independent of previous analyses from HERA
→ leading proton detected in VFPS

Photoproduction regime
→ $Q^2 < 2 \text{ GeV}^2$
→ direct $\gamma$ DIS-like
→ resolved $\gamma$ pp-like
→ $x_\gamma$ fraction $x_\gamma = \frac{p \cdot u}{p \cdot q}$ ... dir/res classification

Performed also in DIS regime
→ $4 \text{ GeV}^2 < Q^2 < 80 \text{ GeV}^2$

$$0.010 < x_{IP} < 0.024$$
$$|t| < 0.6 \text{ GeV}^2$$
$$z_{IP} < 0.8$$
$$E_{T}^{*\text{jet}1} > 5.5 \text{ GeV}$$
$$E_{T}^{*\text{jet}2} > 4.0 \text{ GeV}$$
$$-1 < \eta_{\text{jet}1,2} < 2.5$$
Dijets in diffractive photoproduction and DIS with leading proton

Independent of previous analyses from HERA → leading proton detected in VFPS

- order of magnitude overestimation of predicted pp dijet rates first observed by CDF → **Factorization breaking**

- **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 γ 's partonic fluctuations (hadron-like object)**

\[ z_{IP} < 0.8 \]
\[ -1 < \eta_{jet1,2}^{1,2} < 2.5 \]
Dijets in diffractive photoproduction and DIS with leading proton

Independent of previous analyses from HERA

→ leading proton detected in VFPS

Previous H1 and ZEUS (LRG) analyses

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

→ ZEUS: 2010 ($s^2 \sim 1$)

\[ z_{IP} < 0.8 \quad \quad -1 < \eta_{jet1,2} < 2.5 \]
**DIS results**

**Single differential x-sections**
- based on ~ 50 pb$^{-1}$ of HERA-2 H1 data
- detector effects (H1 and VFPS) well simulated
- data corrected with regularized unfolding

**Compared with theory**
- in NLO QCD (nlojet++)
- hadronization corrections from MC
- using H1 2006 DPDF Fit B (corrected to $M_Y = m_p$)

**Well described in shape and normalization**
**Photoproduction**

**Single differential x-sections**
- based on ~ 30 pb\(^{-1}\) of HERA 2-H1 data
- data corrected with regularized unfolding

**Compared with theory**
- in NLO QCD (Frixione et al.)
- hadronization corrections from MC
- using H1 2006 DPDF Fit B (corrected to \(M_\gamma = m_p\))
- GRV, AFG γ-PDF

**Within errors well described in shape**
**Global overestimation of normalization**
- \(x_\gamma\) independent (again)
Ratios of $\gamma p / DIS$

**Profits from cancellations of scale uncertainties**
→ theory / theory, if varied simultaneously

**No significant dependence on kinematics**
→ only global ratios are shown

$$1.08 \pm 0.11 \text{ (data)}^{+0.45}_{-0.29} \text{ (theory)}$$

$$0.551 \pm 0.078 \text{ (data)}^{+0.230}_{-0.149} \text{ (theory)}$$

$$0.511 \pm 0.085 \text{ (data)}^{+0.022}_{-0.021} \text{ (theory)}$$
Open charm production in diffractive deep inelastic scattering at HERA

Open charm from $c \rightarrow$ with $D^*$ fragmentation

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

→ gluon initiated process at LO

→ open charm tagged with $D^*$

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

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

→ large rapidity gap selection

$$5 < Q^2 < 100 \text{ GeV}^2 \quad 0.02 < y < 0.65$$

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

$$x_{IP} < 0.03$$
**Detector level distributions**

→ satisfactory description with simulation
→ inv. mass fits performed in each bin
→ proton dissociation contr. simulated
→ non-diffractive background negligible
→ corrected for detector effects

**Measurement compared with theory**

→ NLO QCD (HVQDIS in FFNS)
→ using H1 2006 DPDF Fit B
→ H1 tune of fragmentation

→ theoretical uncertainties (scale, $m_c$)

... $\mu = \mu_r = \mu_f$ varied by 0.5 and 2
... $1.3 < m_c < 1.7$ GeV
New preliminary measurement with a larger statistics

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
Studies of the diffractive photoproduction of isolated photons at HERA.

First diffractive analysis of isolated (prompt) photon production

→ based on 91 pb⁻¹ and 374 pb⁻¹ HERA-1 and HERA-2 data, respectively
→ photons directly from hard process
→ sensitive to quark content of IP
→ photoproduction → resolved / direct component
→ photon isolation selection to suppress background
→ data corrected to hadron level and compared with theory provided by Rapgap MC
→ inclusive photon and photon+jet measurements performed
**inclusive $\gamma$**

**$\gamma +$ jet events**

Most photon events accompanied by jet

MC prediction normalised to the data

Reasonable description of shapes MC

NLO needed to test factorization in this channel
$x_\gamma$: Direct processes dominate

$z_{lp}$: Models at high $z_{lp}$ do not peak
→ seen at detector level already
→ to be studied
Production of exclusive dijets in diffractive deep inelastic scattering at HERA

Resolved pomeron models in DDIS for dijet analyses describes well various event observables → in limit of large $z_{IP}$ all energy exclusively in jets … no IP remnant

Two-gluon exchange well suited for exclusive dijets

Distribution of lepton-dijet angle plane differs for both theoretical approaches

$$\phi \sim 1 + A \cos 2\phi$$

A > 0 … resolved IP
A < 0 … two-gluon exchange
Measurement performed corrected to hadron level
→ control distributions well described
→ unfolding with TSVDUnfold

- $Q^2 > 25 \text{ GeV}^2$
- $90 < W < 250 \text{ GeV}$
- $x_{IP} < 0.01$
- $M_X > 5 \text{ GeV}$
- $N_{jets} = 2$
- $p_{T,jet} > 2 \text{ GeV}$.

$\phi$ distribution obey $1 + A \cos 2\phi$
in bins of $\beta = x / x_{IP}$
→ fitted A parameters $\beta$ dependence extracted
None of the models does particularly well as to the normalization of $d\sigma/d\beta$ → NLO?

→ $q\bar{q}g$ final state included in two-gluon exchange model

Study of $A$ indicates two-gluon exchange may be relevant for $\beta > 0.3$

Resolved IP does not reproduce $A(\beta)$
Collinear factorization tested by H1 and ZEUS in diffractive DIS

1) Factorization approach with QCD NLO predictions successfully describes diffractive DIS dijet data
   → most recent dijet measurement precise enough to contribute in DPDF fits

2) Recent preliminary result on D* production (together with previous ZEUS and H1 results) results supports validity of collinear factorization

3) Prompt photons in diffractive photoproduction measured for the first time indicating reasonable description of x-section shapes with LO prediction

Collinear factorization breaking repeatedly tested in diffractive photoproduction of dijets at HERA
   → inconsistency remains in the size of the survival probability between H1 and ZEUS
   → H1 and ZEUS consistently observe lack of dependence of the s.p. on kinematics
   → most recent H1 result experimentally “orthogonal” to previous H1 results

Recent result of ZEUS on exclusive dijet production in diffractive DIS provide indication of applicability of two gluon exchange
Thank you for your attention!
Double ratios $p\bar{p}$/DIS diffractive dijets