Jet and photon production and extraction of $\alpha_s$ at HERA

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HERA Collider

- The only existing ep collider (1992 - 2007)
- About 0.5 fb\(^{-1}\) of data per experiment
- Two multi-purpose detectors (H1 + ZEUS)

\[
\begin{align*}
e & \pm & p \\
27.6 \text{ GeV} & + & 920 \text{ GeV} \\
\sqrt{s} & = & 319 \text{ GeV}
\end{align*}
\]

Inelasticity
\[
y = \frac{p \cdot q}{p \cdot k}
\]

Photon virtuality
\[
Q^2 = -(k - k')^2
\]

Photoproduction
\[
Q^2 \approx 0
\]

Deep-inelastic scattering (DIS)
\[
Q^2 \gg 0
\]
Diffractive photoproduction of the isolated photon (ZEUS)

DESY-17-077 [arXiv:1705.10251]
submitted to Phys. Rev. D
Diffractive photoproduction of isolated photon

- $Q^2 \approx 0 \rightarrow$ photon may dissociate into low mass hadronic system (structure of such resolved photon described by $\gamma$PDF)
- $Q^2 \approx 0 \rightarrow \theta_e \approx 180^\circ$ (electron leaves detector undetected)

**Phonon** momentum fraction entering the hard subprocess:

$$x_\gamma = \frac{\sum_{\gamma+\text{jet}} (E - p_z)}{\sum_{EFO} (E - p_z)}$$

Direct photon interaction

$$x_\gamma = 1$$

Resolved photon interaction

$$x_\gamma < 1$$
Diffractive photoproduction of isolated photon

- Diffraction → beam proton stays intact and leaves detector undetected
- Standardly described by exchange of an hadronic object with vacuum quantum numbers (pomeron)

\[ z_{IP} = \frac{\sum_{\gamma+\text{jet}} (E + p_z)}{\sum_{EFO} (E + p_z)} \]

Direct Pomeron
\[ z_{IP} = 1 \]

Resolved Pomeron
\[ z_{IP} < 1 \]
Large Rapidity Gap

Hadronic activity in forward part of detector

Without hadronic activity in forward part of detector

Non-diffractive event

Diffractive event

Here H1 detector
## Theoretical predictions

**Diffractive predictions (Resolved pomeron)**

- Resolved pomeron model (Ingelman Schlein)
- Implemented in the MC generator **RAPGAP** (LO matrix element + LL parton shower + Lund string fragmentation)
- Contains direct and resolved photon processes

- The partonic structure of the resolved pomeron described by **H1 2006 DPDF Fit B** (from fits of inclusive diffractive DIS)
- The partonic structure of the resolved photon described by **SASGAM-2D γPDF**

- Non-diffractive background simulated by Pythia 6

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No model for the possible direct pomeron interaction available
Event selection

\[ e + p \rightarrow e + \gamma + X + p(Y) \]

- Veto on scattered electron
- Diffractive events dominate for small pomeron momentum fraction wrt proton \( x_{IP} + \text{large rapidity gap} \)

**Photon**

\[
\begin{align*}
5 < E_T^\gamma &< 15 \text{ GeV} \\
-0.7 < \eta^\gamma &< 0.9
\end{align*}
\]

**Jet**

\[
\begin{align*}
4 < E_T^{jet} &< 35 \text{ GeV} \\
-1.5 < \eta^{jet} &< 1.8
\end{align*}
\]

**Photoproduction**

\[
y = \frac{\sum_{EFO}(E - p_z)}{2E_e}
\]

\[
Q^2 < 1 \text{ GeV}^2 \\
0.2 < y < 0.7
\]

**Diffraction**

\[
x_{IP} < 0.03
\]

\[
\eta_{E>0.4} < 2.5
\]

\[
x_{IP} = \frac{\sum_{EFO}(E + p_z)}{2E_P}
\]

Forward detector's region without hadronic activity

\[ \eta = 1.1 \]

\[ \eta_{max} \]

\[ \eta = -0.75 \]

Nondiffractive background
Extraction of prompt photons signal

- Template fit to obtain the signal and background contribution
- Background mainly from \( \pi^0(\eta) \rightarrow \gamma\gamma \)
- Width of the photon candidate cluster in the beam direction in units of cell width \( \delta_{cell} \)

\[
\langle \delta Z \rangle = \frac{\sum_i E_i |Z_i - Z_{cluster}|}{\delta_{cell} \sum_i E_i}
\]

- 90% of photon candidate energy required to be measured in EM calorimeter

<table>
<thead>
<tr>
<th></th>
<th>Gamma events</th>
<th>Gamma+jet events</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA I (82 pb⁻¹)</td>
<td>91</td>
<td>76</td>
</tr>
<tr>
<td>HERA II (374 pb⁻¹)</td>
<td>366</td>
<td>311</td>
</tr>
</tbody>
</table>
Direct pomeron exchange?

- The $z_{IP} < 0.9$ region well described by MC both in shape and normalization
  \[ \sigma_{data}^{z_{IP} < 0.9} = 0.57 \pm 0.13 \text{ pb} \]
  \[ \sigma_{MC}^{z_{IP} < 0.9} = 0.68 \text{ pb} \]

- The $z_{IP} > 0.9$ region overshot in data

Resolved pomeron model prediction

Rapgap reweighted: MC reweighted separately for $z_{IP} < 0.9$ and $z_{IP} > 0.9$ to data
Prompt photon transverse momentum

- Shape of the gamma transverse momentum well described by MC prediction (MC always normalized to data)
- 85% of events with prompt photon contain jet as well
Spectrum of $x_{IP}$

- The relative energy loss of the leading proton with respect to the incoming beam proton ($\sim 1\%$)

- As leading proton directly not measured, reconstructed from EFO

\[ x_{IP} = 1 - \frac{E'_p}{E_p} \]

\[ x_{IP} = \frac{\sum_{\text{EFO}} (E + p_z)}{2E_p} \]

Prompt photons

![Diagram of proton interaction](image)
Direct vs Resolved pomeron

Resolved pomeron enriched ($z_{IP} < 0.9$)

Direct pomeron enriched ($z_{IP} \geq 0.9$)

Photon + jet

Photon momentum fraction entering hard process

Gamma/jet $p_T$ balance

Resolved photon enriched

Direct photon enriched
Conclusion 1

- The first measurement of diffractively produced prompt photon
- The peak in $z_{IP}$ distribution suggests direct pomeron interactions (occurring mostly in direct photon interactions)
- Other distributions well described by MC prediction
Extraction of $\alpha_S$ at NNLO from jet cross sections in DIS (H1)

H1prelim-17-031
[http://www-h1.desy.de/publications/H1preliminary.short_list.html]
NNLO $\alpha_S$ fit of H1 jets data in DIS

**Why $\alpha_S$ ?**

- Among the least known SM parameters
  
  \[ G_F = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2} \]
  \[ \alpha_S = 0.1181(11) \] [PDG16]
- Great importance for LHC physics

**Why now?**

- NNLO revolution in the last years
- NNLO predictions now available for both $pp$ and $ep$ dijets
- LHC has not fitted their jet data with NNLO yet

First NNLO $\alpha_S$ fit of the jet ep data
NNLO calculations

- New NNLO predictions for ep dijets based on antenna subtraction

- **Matrix element** tables precalculated by NNLOJET program
  (~1M CPU hours)

- Then convoluted with PDFs and $\alpha_S$ using fastNLO (<1s)

\[
\sigma_i = \sum_{k=g,q,\bar{q}} \int dx f_k(x, \mu_F) \hat{\sigma}_{i,k}(x, \mu_R, \mu_F) \cdot c_{\text{had},i}
\]

A bit of history

- **1973** Asymptotic freedom of QCD
- **1993** NLO studies of DIS jets
- **2016** NNLO corrections for DIS jets
Double-diff.
- $Q^2$ and $\langle p_T \rangle_2$
- Mean dijet $p_T$

$$\langle p_T \rangle_2 = \frac{p_T^{\text{jet1}} + p_T^{\text{jet2}}}{2}$$

jets found in $\gamma^* p$
with $k_t$ algo ($R=1$)

### NLO predictions
- **NNPDF 3.0 NLO**
- Larger scale unc.
- Chi 2/ndf = 1.4

### NNLO predictions
- **NNPDF 3.0 NNLO**
- Smaller scale unc.
- Chi 2/ndf = 0.6
H1 Data – Inclusive jets

Double-diff.

- $Q^2$ and $p_T^{\text{jet}}$
- Mean dijet $p_T$
- $0.2 < y < 0.6$
- $-1 < \eta^{\text{jet}}_\text{lab} < 2.5$
- jets found in $\gamma^* p$
  with $k_t$ algo (R=1)

NLO predictions

- **NNPDF 3.0 NLO**
- Larger scale unc.
- Chi $2/\text{ndf} = 1.7$

NNLO predictions

- **NNPDF 3.0 NNLO**
- Smaller scale unc.
- Chi $2/\text{ndf} = 1.3$
Scale dependence

- The NNLO predictions depend less on the renormalization scale (= have smaller theor. unc.)
- To estimate the uncertainty the scale varied up and down by the factor of 2
- As a scale we use $\mu_R = \sqrt{Q^2 + p_T^2}$.

![Graph showing scale dependence for inclusive jets and dijets](image)

Others functional forms also tested
Functional form of the scale

- 7 possible functions studied
- NNLO $\alpha_s$ is usually smaller than the NLO one
- The NNLO $\chi^2$ is usually better
- NNLO scale uncertainty is smaller

$$\mu^2 = Q^2$$
$$\mu^2 = p_T^2$$
$$\mu^2 = Q^2 + p_T^2$$
$$\mu^2 = \frac{Q^2 + p_T^2}{2}$$
$$\mu^2 = \sqrt{Q^4 + p_T^4}$$
$$\mu^2 = Q^2/4 + p_T^2$$
$$\mu^2 = 400 \text{GeV}^2$$

All data above $m_b$ threshold used
**$\alpha_S$ in PDF and $\alpha_S$ in ME**

- Alpha strong affecting both, PDFs and matrix element
- Both effects considered, $\alpha_S$ in ME more prominent

$$\sigma_i = \sum_{k=g,q,\bar{q}} \int dx f_k(x, \mu_F) \hat{\sigma}_{i,k}(x, \mu_R, \mu_F) \cdot c_{\text{had},i}$$

$$\hat{\sigma}_{i,k}(x, \mu_R, \mu_F) = \sum_n \alpha_S^n(\mu_R) \hat{\sigma}_{i,k}^{(n)}(x, \mu_R, \mu_F)$$

**DGLAP equations**

$$\mu_F^2 \frac{df}{d\mu_F^2} = P(z, \alpha_s) \otimes f(x, \mu_F^2)$$

PDFs at scale $\mu_0 = 30$ GeV very well constrained by lot of data → $\alpha_S$ - "independent"

Original PDFs from scale $\mu_0 = 30$ GeV evolved to higher/lower scales by DGLAP with $\alpha_S = \alpha_S(\text{fit par.})$
Independent fitting of two $\alpha_S$

- The alpha strong from PDF and ME consistent

\[
\sigma_i = f(\alpha_S^f(m_Z)) \otimes \hat{\sigma}_i(\alpha_S^\hat{\sigma}(m_Z)) \cdot c_{\text{had},i}
\]
Which data use in the fit?

- The scale uncertainty gets higher with smaller scales
  \( \mu = \sqrt{p_T^2 + Q^2} \)
- We use only data \( \mu > \mu_{\text{cut}} \)

Small \( \mu_{\text{cut}} \) → high theor. unc.
Large \( \mu_{\text{cut}} \) → high exp. unc.

Compromise \( \mu_{\text{cut}} = 28 \text{ GeV} \)
Running of alpha strong

\[ \alpha_s = 0.1181(11) \]
History of Alpha Strong

- The current world average value $\alpha_s(m_Z) = 0.1181(11)$
- Mostly driven by lattice and tau-decays
- From LHC the most precise estimate is from $t\bar{t}$bar (NNLO)

[PDG16]
Measured alpha strong value

- Consistent with the “world average value”
- Consistent with $\alpha_S$ from global PDF fits
- The NNLO reduces the scale uncertainty by half
- The theoretical scale uncertainty still dominant

$$\alpha_S(m_Z) = 0.1156(19)_{\text{exp}}(6)_{\text{had}}(3)_{\text{PDF}}(1)_{\text{PDF}}\alpha_S(3)_{\text{PDF/Set}}(25)_{\text{scale}}$$

[Diagram showing world average DIS values with contributions from various collaborations like H1 et al., ABM, ABMP, BBG, HERAPDF2.0Jets, JR, NNPDF, MMHT, H1PDF2017, and pre-average DIS (PDG)].

[Annotations on the diagram indicating contributions from Hadronisation, PDFs from 5 collaborations, Data unc., NNPDF 3.1 unc., NNPDF 3.1 $\alpha_S$ variants, and Scale unc.].
Conclusion 2

- The $\alpha_s$ from the jet DIS data estimated with NNLO precision for the first time
- The obtained value competitive with LHC and LEP measurements
- The uncertainty of H1 data even now smaller than the theoretical one → waiting for N3LO


<table>
<thead>
<tr>
<th>Subclass</th>
<th>$\alpha_s(M_Z^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$-decays</td>
<td>$0.1192 \pm 0.0018$</td>
</tr>
<tr>
<td>lattice QCD</td>
<td>$0.1188 \pm 0.0011$</td>
</tr>
<tr>
<td>structure functions</td>
<td>$0.1156 \pm 0.0021$</td>
</tr>
<tr>
<td>$e^+e^-$ [jets &amp; shps]</td>
<td>$0.1169 \pm 0.0034$</td>
</tr>
<tr>
<td>hadron collider</td>
<td>$0.1151 \pm 0.0028$</td>
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<tr>
<td></td>
<td>$-0.0027$</td>
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<tr>
<td>ew precision fits</td>
<td>$0.1196 \pm 0.0030$</td>
</tr>
<tr>
<td>H1 NNLO jets</td>
<td>$0.1156 \pm 0.0032$</td>
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