Extended studies of isolated photon production in deep inelastic scattering at HERA

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Outline

• Introduction

• Event selection
  • Separating direct photons from other sources

• Differential cross-section measurements

• Summary
HERA and ZEUS

- $e^\pm p$ collisions at $\sqrt{s} = 318$ GeV
  - $\sim 0.5$ fb$^{-1}$ per experiment

- HERA 1:
  - 1996 - 2000

- HERA 2 (longitudinal $e^\pm$ polarisation)
  - 2004 - 2007

Measurement uses 326 pb$^{-1}$ from HERA 2

\[ \theta \text{ w.r.t. } p \text{ beam} \]
\[ \eta = -\ln \tan \frac{\theta}{2} \]
DIS events and kinematics

• Characterise events:
  • $Q^2$ \[ Q^2 = s \times y \]
  • Bjorken $x$, $(0 < x < 1)$
  • Inelasticity $y$, $(0 < y < 1)$

DIS $\Rightarrow$ scattered $e$ in detector

$Q^2 \gtrsim 1 \, \text{GeV}^2$

NC - scattered $e$

CC - scattered $\nu$
Kinematic regions

Parameterise structure functions as a function of $x$

Use DGLAP equations to evolve from HERA to LHC
Why isolated photons?

- Use dynamics to probe modes such as $k_t$-factorisation and pQCD approaches
- See if dynamics changes with virtuality
- Check proton PDFs
- Photons can be a background to new physics
Where do isolated photons come from?

- Can be emitted from lepton (LL) or proton (quark, QQ)
- Assume lepton emission is well known
- Use photon to probe proton
- Trick is to find these photons

\[ e \rightarrow \gamma \rightarrow q \rightarrow p \] (LL)  
\[ e \rightarrow \gamma \rightarrow q \rightarrow p \] (QQ)
Selection criteria

- Event
  - \(10 < Q^2 < 350\ \text{GeV}^2\)
  - \(E_e > 10\ \text{GeV}\) and \(\theta_e > 140^\circ\)
  - \(35 < E - p_Z < 65\ \text{GeV}\)

- Jets
  - \(k_t\) clustering, \(R=1.0\)
  - \(E_{\text{jet}} > 2.5\ \text{GeV}\)
  - \(-1.5 < \eta_{\text{jet}} < 1.8\)

Photon selection

- \(4 < E_T < 15\ \text{GeV}\)
- \(-0.7 < \eta_\gamma < 0.9\)
- Isolation:
  - \(\Delta R > 0.2\) from tracks
  - >90 % jet energy
  - Look in detail at shower shape in \(Z\)

\(\approx 6000\) events selected
Separating photons from hadrons

- ZEUS barrel electromagnetic calorimeter finely segmented in $Z$

$<\delta Z>$ is energy-weighted width of EM shower in $Z$
Uncertainties (typical sizes)

- Statistics: 13 %
- Acceptance: 3-4 %
- Systematics: 10 %
  - Dominated by energy scale
- Fraction of QQ events: 1 %
- Luminosity: 2 % (not included in plots)
Comparison with generators

\[
x_\gamma = \frac{\sum_{\text{jet, } \gamma} (E - p_z)}{2 y_{\text{JB}} E_e} \quad x_p = \frac{\sum_{\text{jet, } \gamma} (E + p_z)}{2 E_p}
\]

\[\Delta \phi = \phi_{\text{jet}} - \phi_{\gamma}\]

\[
\Delta \eta = \eta_{\text{jet}} - \eta_{\gamma} \\
\Delta \phi_{e, \gamma} = \phi_e - \phi_{\gamma} \\
\Delta \eta_{e, \gamma} = \eta_e - \eta_{\gamma}
\]
Comparison with generators

$10 < Q^2 < 30 \text{ GeV}^2$

$30 < Q^2 < 350 \text{ GeV}^2$

LO + LL QQ (PYTHIA) and LL (Ariadne)
Comparison with generators

**LO + LL QQ (PYTHIA) and LL (Ariadne)**

**10 < Q^2 < 30 GeV^2**

**30 < Q^2 < 350 GeV^2**
Comparison with theory

Collinear: AFG: Aurenche, Fontonnaz, Guillet - LAPTH-005/17 LPT-Orsay 16-88
Summary


• Extracted differential cross-sections for correlated observables: $x_\gamma$, $x_p$, $\Delta\eta$, $\Delta\varphi$, $\Delta\eta_{e\gamma}$ and $\Delta\varphi_{e\gamma}$

• PYTHIA x 1.6 describes data in both $Q^2$ regions

• AFG (NLO) calculations describe data well

• $k_t$-factorisation (BLZ) does OK except for $x_\gamma$ and $\Delta\eta$
Backup
Cross-section calculation

- Production cross-section for variable $Y$:

$$\frac{d\sigma}{dY} = \frac{N(\gamma_{QQ})}{A_{QQ} \cdot \mathcal{L} \cdot \Delta Y} + \frac{d\sigma_{LL}^{MC}}{dY}$$

- $N(\gamma_{QQ})$: number of QQ photons from fit
- $\Delta Y$: bin width
- $\mathcal{L}$: integrated luminosity
- $d\sigma_{LL}^{MC}/dY$: cross-section for LL photons
- $A_{QQ}$: events reconstructed / events generated in bin
Theory models

- Baranov, Lipatov, Zotov (BLZ)
  - Calculation of cross-section based on convolution of off-shell matrix element and unintegrated parton densities ($k_t$-factorisation)
  - Some final-state jets can come from parton evolution cascade - model uses approximations (especially for $y$)
  - $\Lambda_{\text{QCD}} = 200$ MeV, $\text{NF}=4$, $\mu_R^2 = \mu_F^2 = Q^2$, MSTW2008 PDF
- Aurenche, Fontannaz, Guillet (AFG)
  - NLO theory with conventional PDFs
Previous results

![Graphs showing various distributions and cross-sections for different variables such as $Q^2$ (GeV$^2$), $x$, $E_T$ (GeV), and $\eta$ for the ZEUS experiment. The graphs compare data from ZEUS, LL + QQ (x1.6) MC, and QQ (x1.6) MC.](image_url)
Previous results

[Graphs showing data distributions for different quantities such as $Q^2$, $x$, $E_T$, and $\eta$ for ZEUS, with comparisons to GKS NLO and BLZ models.]

Basic equations

• $e^\pm p$ cross-section and structure functions

\[
\frac{d^2\sigma(e^\pm p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ Y_+ F_2(x, Q^2) \mp Y_- x F_3(x, Q^2) - y^2 F_L(x, Q^2) \right]
\]

• (Unpolarised) reduced cross-sections often used:

\[
\sigma_r (\text{or } \tilde{\sigma}) = \frac{d^2\sigma}{dx\,dQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2 Y_+} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)
\]

$Y_\pm = 1 \pm (1 - y)^2$