Hadronic final states at HERA

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for the H1 and ZEUS Collaborations
Contents

H1: Measurement of charged particle spectra in deep-inelastic \( ep \) scattering at HERA.


H1: Measurement of Feynman-\( x \) spectra of photons and neutrons in the very forward direction in deep-inelastic scattering at HERA.

ArXiv 1404.0201

ZEUS: Photoproduction of isolated photons, inclusively and with a jet, at HERA.


ZEUS: Further studies of the photoproduction of isolated photons with a jet at HERA.

ArXiv 1405.7127
Charged particle spectra in DIS

As $Q^2$ and $x$ decrease, evolution should change from DGLAP to BFKL.

CCFM is a combination.

Ordering of partons in $p_T$ is different in the different models.

$Q^2 = 4$-momentum transfer to virtual photon.

$y = \text{fractional energy loss of lepton in proton rest frame.}$

$x = \frac{Q^2}{sy}$
Models tested (all LO QCD matrix elements.)

RAPGAP : DGLAP  
DJANGOH: uses colour dipole model (ARIADNE),  BFKL-like  
CASCADE: CCFM  
HERWIG: with POWHEG option, HO corrections, different ordering.

H1 experimental observables

Variables defined in hadronic CM frame, using $Q^2$ and $y$.  
$+z^*$ axis in direction of virtual photon.  
Measure charged particle densities in $\eta^*$ and $p_T^*$ in this frame integrated over $5 < Q^2 < 100 \text{ GeV}^2$. 
Results

Most of the models fail over $p_T^*$ range: DJANGOH is best.
Charged particle spectra in DIS

Bins in $Q^2$ and $x$, for **low** and **high** $p_T^*$

- $x = 0.0001 - 0.00024 \ldots 0.0005 \ldots 0.002$

$p_T^* < 1$ GeV: apart from CASCADE, distributions in $\eta^*$ are OK.

$p_T^* > 1$ GeV: DJANGOH OK, others poor especially at low $Q^2$ and $x$. 
Conclusions

- Charged hadrons measured by H1 in DIS, for $Q^2$ range 5 – 100 GeV$^2$. 89 pb$^{-1}$ HERA data taken in 2006.
- Shapes of distributions compared to various MC models.
- DJANGOH best, RAPGAP also satisfactory at low $p_T$ but not at high $p_T$.
- CASCADE (based on CCFM) is the least successful model.
Forward measurements in H1

Can measure
- photons and neutrons from decay of excited proton.
- neutrons also from colour singlet exchange process.

Feynman scaling:
distribution in $x_F = \frac{2p||}{W}$
- independent of c.m. energy $W$?
Models tested

**ep based:** (Lund string) LEPTO, RAPGAP + ARIADNE (colour dipole, CDM)

**Cosmic ray based, adapted for ep:**
- SIBYLL, QGSJET: reggeon-based, interfaced using PHOJET.
- EPOS LHC: parton constituents, modified treatment of central diffraction based on LHC measurements.

Experimental method

Variables defined in lab frame.

\[ W = \sqrt{(y_s - Q^2)} \]

Photons, neutrons with \( \eta > 7.9 \) measured in forward neutron detector.
Normalised $W$ distributions for photons and neutrons

Photons: cosmic ray models all similar, all too high.
Neutrons: very variable. EPOS LHC best.
Relative rate of photons/neutrons /DIS is independent of $W$. 
Results in $x_F$ for photons

Normalised $x_F$ distributions very similar in different $W$ ranges.

LEPTO and most cosmic ray models reproduce data shape fairly well.

CDM and SIBYLL fail.
Results in $x_F$ for neutrons

Again similar in different $W$ ranges, confirming $x_F$ scaling.

RAPGAP (diffractive) and CDM (central): a combination works well.

EPOS LHC OK, other cosmic ray models fail.
Conclusions

- Very forward photons and neutrons measured by H1 for $Q^2$ range 6 – 100 GeV$^2$, $0.05 < y < 0.6$. 131 pb$^{-1}$ HERA data in 2006-7.
- Relative rate of photons/neutrons / DIS independent of $W$, consistent with limiting fragmentation hypothesis.
- Feynman-x scaling confirmed in measured range.
- MC models overestimate the photon rate, but are mostly reasonable.
- Neutron distributions described well by RAPGAP+CDM or by EPOS LHC.
Prompt photons in photoproduction.

- "Prompt" photons emerge directly from the hard scattering process and give a particular view of this.
- Tests of specific QCD models.
- As potential background to "new physics", should be well understood.

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(p) direct
\[ e \to q \to \gamma \]
\[ P \to \gamma \]

(b) resolved
\[ e \to g \to \gamma \]
\[ P \to \gamma \]
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(e) direct, fragmentation
\[ e \to q \to \text{jet} \to \gamma \]
\[ P \to \gamma \]

(d) resolved, fragmentation
\[ e \to g \to \text{jet} \to \gamma \]
\[ P \to \gamma \]
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Hard photons in finely segmented central ZEUS calorimeter

Width of shower is evaluated.

Fit to narrow photon peak

+ broader mesonic background:
Models tested

Fontannaz, Guillet and Heinrich (FGH, EPHOX):
  NLO + box diagram and a contribution from fragmentation.
Lipatov, Malyshev, Zotov (LMZ): \( k_T \)-factorisation with
  unintegrated parton distributions and initial-state parton cascade.
  Upgraded for second ZEUS analysis.

Experimental quantities:

Photons: \( E_T > 6 \) GeV  
  central: \(-0.7 < \eta^\gamma < 0.9\)
  Isolated: to reduce fragmentation component and backgrounds,
  \( E > 0.9^\star \) energy of jet-like object containing photon.

Jets: use \( k_T \) clustering algorithm. \( E_T > 4 \) GeV

Make use of \( \chi^\text{meas}_\gamma = \sum_{\text{photon+jet}} (E - p_z) / \sum_{\text{all final-state hadrons}} (E - p_z) \)
Results

Inclusive isolated photon cross sections

Both FGH and LMZ give a satisfactory description. But large theory uncertainties.
Photon plus jet.

Prompt photons in photoproduction

$d\sigma/dE_T^\gamma$ (pb/GeV)

$d\sigma/dE_T^{jet}$ (pb/GeV)

$E_T^\gamma$ (GeV)

$E_T^{jet}$ (GeV)

$\eta^\gamma$

$\eta^{jet}$
The $x_\gamma^{\text{meas}}$ distribution shows a peak near unity corresponding to the direct process.

To investigate resolved-enhanced and direct-enhanced regions further, apply selections $x_\gamma^{\text{meas}} < 0.8$ and $x_\gamma^{\text{meas}} > 0.8$.
Prompt photons in photoproduction

\[ x'_\gamma \text{meas} < 0.8 \quad \text{(upper)} \quad x'_\gamma \text{meas} > 0.8 \quad \text{(lower)} \]

**photon**

**jet**

All distributions good for both models, except \( \eta(\text{jet}) \) for LMZ, \( x'_\gamma \text{meas} < 0.8 \).

Perhaps due to mismodelling of initial-state cascade.
Further variables: $\eta^\gamma - \eta^{\text{jet}}$ and $|\phi^\gamma - \phi^{\text{jet}}|$

FGH is again fine, LMZ poorer on pseudorapidity difference.

PYTHIA and HERWIG also do well in the azimuth difference.
Conclusions:

- Prompt photon photoproduction measured in many variables by ZEUS.
- The FGH (EPHOX) program gives the better account of the physics, but LMZ is satisfactory for most variables.

Overall summary

H1 and ZEUS at HERA continue to bear fruitful analyses of ep physics to test QCD models!
Backup
ZEUS calorimeter

Hard scattered photons measured in the BCAL (finely segmented in the Z direction).
Summary:

- Measurements of prompt photons with jets in photoproduction have been made by ZEUS using the full HERA II data sample.
- Results are well described by NLO theories next.