Studies of prompt photons plus jets in DIS and diffractive photoproduction at HERA

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High-$p_T$ photons produced in ep scattering may be:

- Radiated from the incoming or outgoing lepton (LL photons)
- **Produced in a hard partonic interaction** (QQ photons)
- Radiated from a quark in a jet
- Decay product of a hadron in a jet

LL and QQ photons are relatively isolated from other outgoing particles. **QQ often called “prompt” photons.**

**New prompt photon results from ZEUS since ICHEP 2018:**

Deep inelastic scattering, combined variables.
- JHEP 1801 (2018) 032

Prompt photons in diffractive photoproduction.
- Phys. Rev. D 96 (2017) 032006
The ZEUS detector

Hard scattered photons are measured in the BCAL, which is finely segmented in the Z direction.

$27.5 \text{ GeV}$  
$e$  
$Z \leftarrow$  
$920 \text{ GeV}$  
$p$  

EMC = electromagnetic section

Replaced by a beam focussing Magnet In HERA-II

HERA-I data: 1998-2000
HERA-II data: 2004-2007
ZEUS prompt photon analyses.

High-energy photon candidate:

- found with energy-clustering algorithm in BCAL: \( \frac{E_{EMC}}{E_{EMC} + E_{HAD}} > 0.9 \)
- lower limit imposed on \( E_T^\gamma \)
- \(-0.7 < \eta^\gamma < 0.9\) (i.e. in ZEUS barrel calorimeter)
- **Isolated.** In the “jet” containing the photon candidate, the photon must contain at least 0.9 of the “jet” \( E_T \)

**Jets**

- \( k_T \)-cluster algorithm
- \(-1.5 < \eta^{jet} < 1.8\)
- lower limit imposed on \( E_T^{jet} \)
Why we isolate the measured photon:

![Diagram](image)

Photons associated with jets require a quark fragmentation function which is not easy to determine – requires non-perturbative input.

Reduce large background from neutral mesons.
The DIS Analysis

Main further selections:

\[ 4 \ < \ E_T^\gamma \ < \ 15 \ \text{GeV} \]
\[ E_T^{\text{jet}}> 2.5 \ \text{GeV} \]
\[ 10 < Q^2 < 350 \ \text{GeV}^2 \]

Plotted “combined” parameters:

\[ \chi_{\gamma}^{\text{meas}} = \frac{\sum_{\text{jet},\gamma}(E-p_z)}{2y_JBE_e} \]
\[ \chi_{\gamma}^{\text{obs}} = \frac{\sum_{\text{jet},\gamma}(E+p_z)}{2E_p} \]

\[ \Delta \eta = \eta_{\text{jet}} - \eta_\gamma \]
\[ \Delta \varphi = \varphi_{\text{jet}} - \varphi_\gamma \]
\[ \Delta \varphi_{e,\gamma} = \varphi_e - \varphi_\gamma \]
\[ \Delta \eta_{e,\gamma} = \eta_e - \eta_\gamma \]

Width of BEMC photon candidate

Fit for number of photons in each measured bin.
Results for full Q2 range, compared to PYTHIA*1.6 (QQ) + HERACLES (LL)

A reasonable description is obtained.

NLO kT-factorisation

AFG is better, especially for $x_\gamma$, though not perfect here.
Examples of lowest-order resolved–Pomeron diagrams by which diffractive processes may generate a prompt photon.

**Direct** incoming photon gives all its energy to the hard scatter ($x_\gamma = 1$).

**Resolved** incoming photon gives fraction $x_\gamma$ of its energy.

An outgoing photon must couple to a charged particle Line. So the exchanged colourless object (“Pomeron”) must have a quark content in this type of diagram.
Possible direct Pomeron interactions require a different type of diagram.

e.g.

Direct photon + direct Pomeron

Resolved photons also a possibility.

_N.B. The proton may become dissociated in diffractive processes_
More kinematics:

\( x_{IP} = \) fraction of proton energy taken by Pomeron, measured as
\[
\frac{\Sigma_{all \ EFOs} (E + p_z)}{2 E_p}
\]

\( z_{IP} = \) fraction of Pomeron \( E + p_z \) taken by photon + jet measured as
\[
\frac{\Sigma_{\gamma + jet}(E + p_z)}{\Sigma_{all \ EFOs}(E + p_z)}
\]

\( \eta_{\text{max}} = \) maximum pseudorapidity of observed outgoing particles \( (E > 0.4 \text{ GeV}) \) (ignore forward proton).

**Diffractive processes are characterised by a low value of** \( \eta_{\text{max}} \) **and/or low** \( x_{IP} \).
Here we measure prompt diffractive photons with and without a jet, using the ZEUS detector, in photoproduction. (i.e small $Q^2$)

- **Prompt photons emerge directly from the hard scattering process and give a particular view of this.**

- **Allows tests of Pomeron models and explores the non-gluonic aspects of the Pomeron and Pomeron-photon physics in general.**

ZEUS publications of prompt photons in photoproduction:

H1 on inclusive diffractive prompt photons in photoproduction:
- Phys. Lett. 672 (2009) 219

Diffractive photoproduced dijets:
The diffractive analysis.

1) The forward scattered proton is not measured in these analyses.

2) Non-diffractive events are characterised by a forward proton shower. To remove them, require $\eta_{\text{max}} < 2.5$ and $x_{\text{IP}} < 0.03$

   $\eta_{\text{max}}$ is evaluated from ZEUS energy flow objects (EFOs), which combine tracking and calorimeter cluster information.

3) A cut $0.2 < y_{\text{JB}} < 0.7$ removes most DIS events.

4) Remove remaining DIS events and Bethe-Heitler and DVCS events ($\gamma e$) by excluding events with identified electron or $\leq 5$ EFOs

5) Remaining non-diffractive events neglected, could be 0-10% of our cross sections. Treated as a systematic.

6) **HERA I** data: use the FPC to remove more non-diffractive background. It also suppressed many proton dissociation events.

Use HERA-I data to measure total cross section. 82 pb$^{-1}$
Use HERA-II data to study shapes of distributions. 374 pb$^{-1}$
Monte Carlo simulation

Uses the RAPGAP generator

Based on leading order parton-level QCD matrix elements. Some higher orders are modelled by initial and final state leading-logarithm parton showers.
Fragmentation uses the Lund string model as implemented in PYTHIA.

The H1 2006 DPDF fit B set is used to describe the density of partons in the diffractively scattered proton. For resolved photons, the SASGAM-2D pdf is used.
Fit the $x_\gamma$ distribution to direct-photon and resolved-photon RAPGAP components.

A 70:30 mixture is found and used throughout.

$$x_\gamma^{\text{meas}} = \frac{\Sigma_{\gamma + \text{jet}}(E - p_z)}{\Sigma_{\text{all EFOs}}(E - p_z)}$$
Results

Cross sections compared to RAPGAP normalised to total observed cross section. Inner error bar is statistical. Outer (total) includes correlated normalisation and non-diffractive subtraction uncertainty.

Transverse energy of photon.

Shape of data well described by Rapgap. **Most photons are accompanied by a jet.**
Cross section in $z_{\text{IP}}^{\text{meas}} = \frac{\Sigma_{\gamma + \text{jet}}(E + p_z)}{\Sigma_{\text{all EFOs}}(E + p_z)}$

Evidence for direct Pomeron interactions

Photon-electron events have been removed.
(ep → eγ)

Other backgrounds estimated and found to be at a low level

Using HERA-I data, integrated cross section for $z_{\text{IP}}^{\text{meas}} < 0.9 = 0.68 \pm 0.14 ^{+0.06}_{-0.07} \text{ pb}$

Rapgap gives 0.68 pb. No allowance for proton dissociation which is ~ 16 ± 4%.
Cross sections for region $z_{IP}^{\text{meas}} < 0.9$ Rapgap is normalised to data in this region.
Cross sections for region $z_{IP}^{\text{meas}} \geq 0.9$ Rapgap is normalised to data in this region.
Summary

ZEUS at HERA have measured isolated (“prompt”) photons in
- Deep Inelastic Scattering, measuring new combinations of variables
- diffractive photoproduction, for the first time with an accompanying jet.

DIS: results are in better agreement with AFG model than with BLA but agree well, after rescaling, with Pythia + Heracles/Ariadne

- diffractive results were defined by cuts on $\eta_{\text{max}}$ and $x_{IP}$
Most of the detected photons are accompanied by a jet.

The variable $z_{IP}^{\text{meas}}$ shows a peak at high values that gives evidence for a direct-Pomeron process not modelled by RAPGAP

In both regions of $z_{IP}^{\text{meas}}$, cross sections of kinematic variables are well described in shape by Rapgap, confirming a common set of PDFs in diffractive DIS (where they were determined) and photoproduction at $z_{IP}^{\text{meas}} < 0.9$. 
Backups
Photon candidates: groups of signals in cells in the BEMC. Each has a $Z$-position, $Z_{\text{CELL}}$. $E$-weighted mean of $Z_{\text{CELL}}$ is $Z_{\text{Mean}}$.

Task: to separate photons from background of candidates from photon decays of neutral mesons.

$$<dZ> = \text{E-weighted mean of } |Z_{\text{CELL}} - Z_{\text{Mean}}|.$$  

Peaks correspond to photon and $\pi^0$ signals, other background is $\eta + \text{multi-}\pi^0$.

In each bin of each measured physical quantity, fit for photon signal + hadronic bgd.
Some comparisons with earlier results. Always a need to scale up the LO theory.
Plot $z_{IP}^{\text{meas}}$ and compare with Rapgap

**Shape does not agree.**

An excess is seen in the top bin.
Can reweight Rapgap to describe the shape.

Unreweighted Rapgap here normalised to $z_{IP}^{\text{meas}} < 0.9$ data. Otherwise, unless stated, Rapgap is normalised to the full plotted range of data.

The $\eta_{\text{max}}$ distribution is described better by the reweighted Rapgap.

Red histogram shows what 10% of non-diffractive Pythia photoproduction (subject to present cuts) would look like. (Not added into the Rapgap.)
etamax distribution for HERA-2.
Compare diffractive photon distribution with those from nondiffractive process.

Diffractive more resembles direct but seems slightly more forward.
Compare diffractive distribution with that for nondiffractive photoproduction:

The diffractive process (left) is more strongly direct-dominated than the photoproduction (right). Rapgap gives a good description.