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

Peter Bussey
University of Glasgow

for the ZEUS Collaboration

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

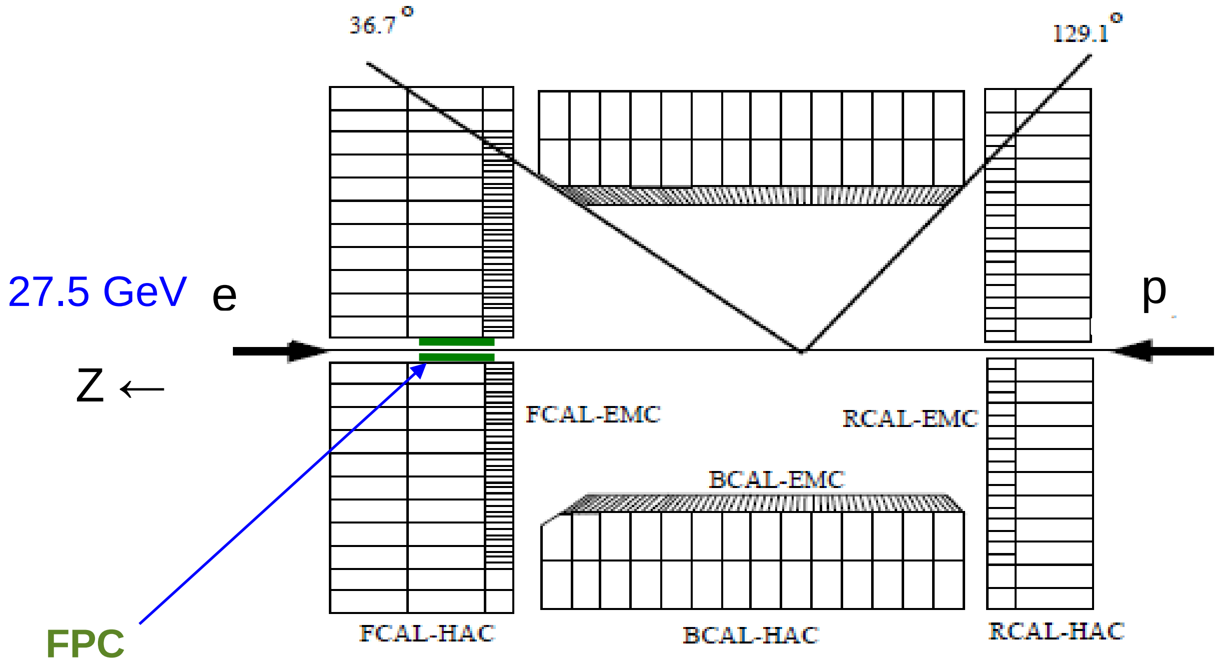
LL and QQ photons are relatively isolated from other outgoing particles. **QQ often called “prompt” photons**.

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

HERA-I data: 1998-2000
HERA-II data: 2004-2007

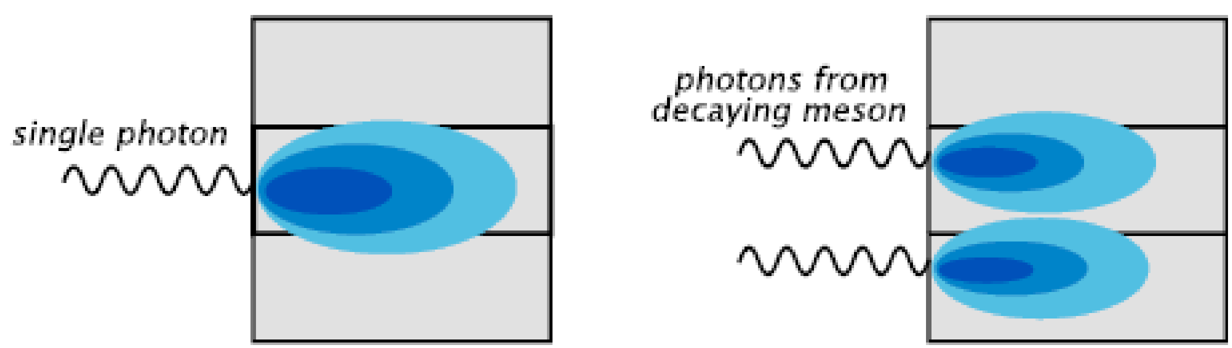


Hard scattered photons are measured in the BCAL, which is finely segmented in the Z direction.

EMC = electromagnetic section

FPC
Forward Plug Calorimeter)
(HERA-I)

Replaced by a beam focussing Magnet In HERA-II



ZEUS prompt photon analyses.

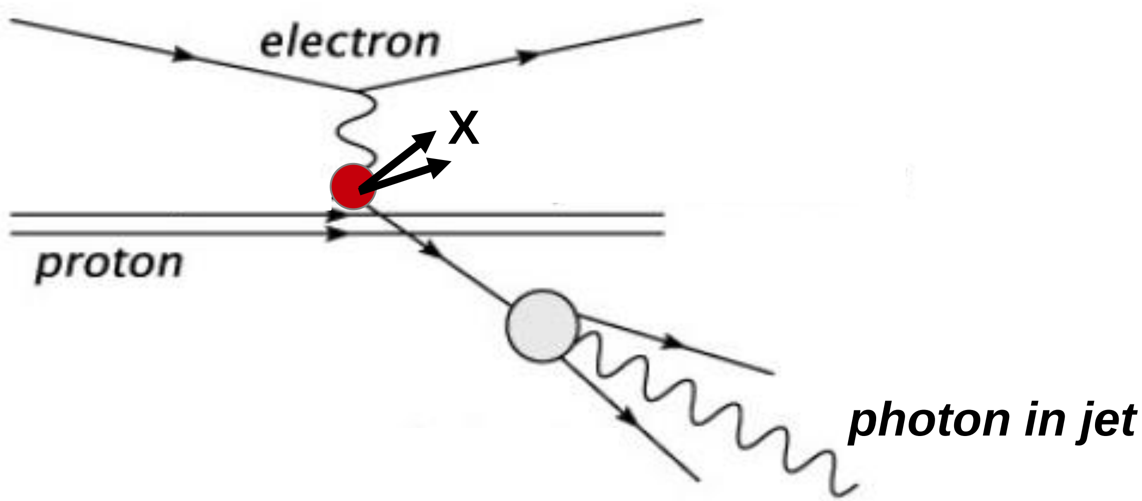
High-energy photon candidate:

- found with energy-clustering algorithm in BCAL: $E_{EMC}/(E_{EMC}+E_{HAD}) > 0.9$
- lower limit imposed on E_T^{γ}
- $-0.7 < \eta^{\gamma} < 0.9$ (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:



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^{γ} < 15 GeV

E_T^{jet}> 2.5 GeV

10 < Q^2 < 350 GeV^2

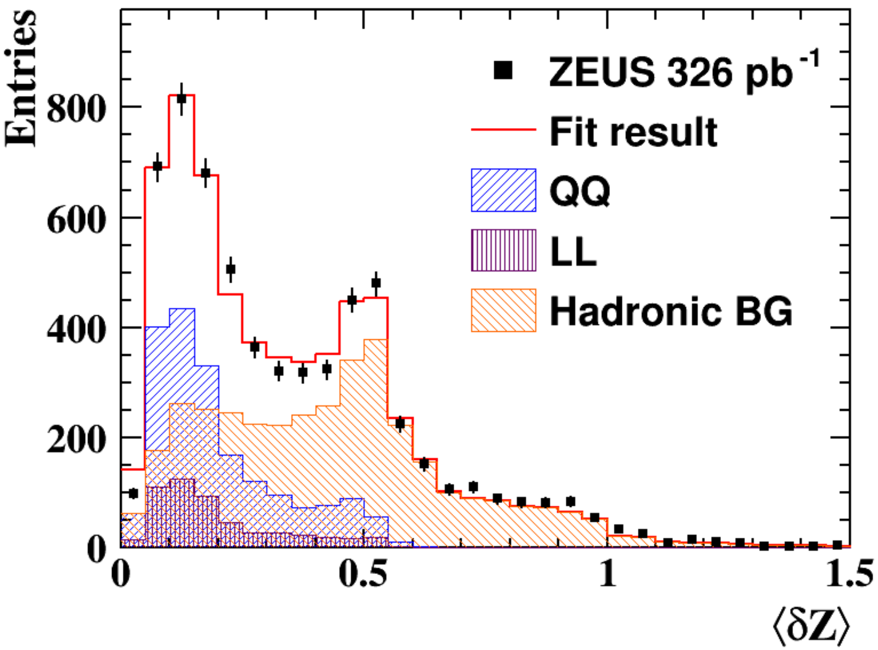
Plotted "combined" parameters:

- $x_{\gamma}^{meas} = \frac{\sum_{jet,\gamma}(E-p_z)}{2y_{JB}E_e}$
- $x_{p}^{obs} = \frac{\sum_{jet,\gamma}(E+p_z)}{2E_p}$

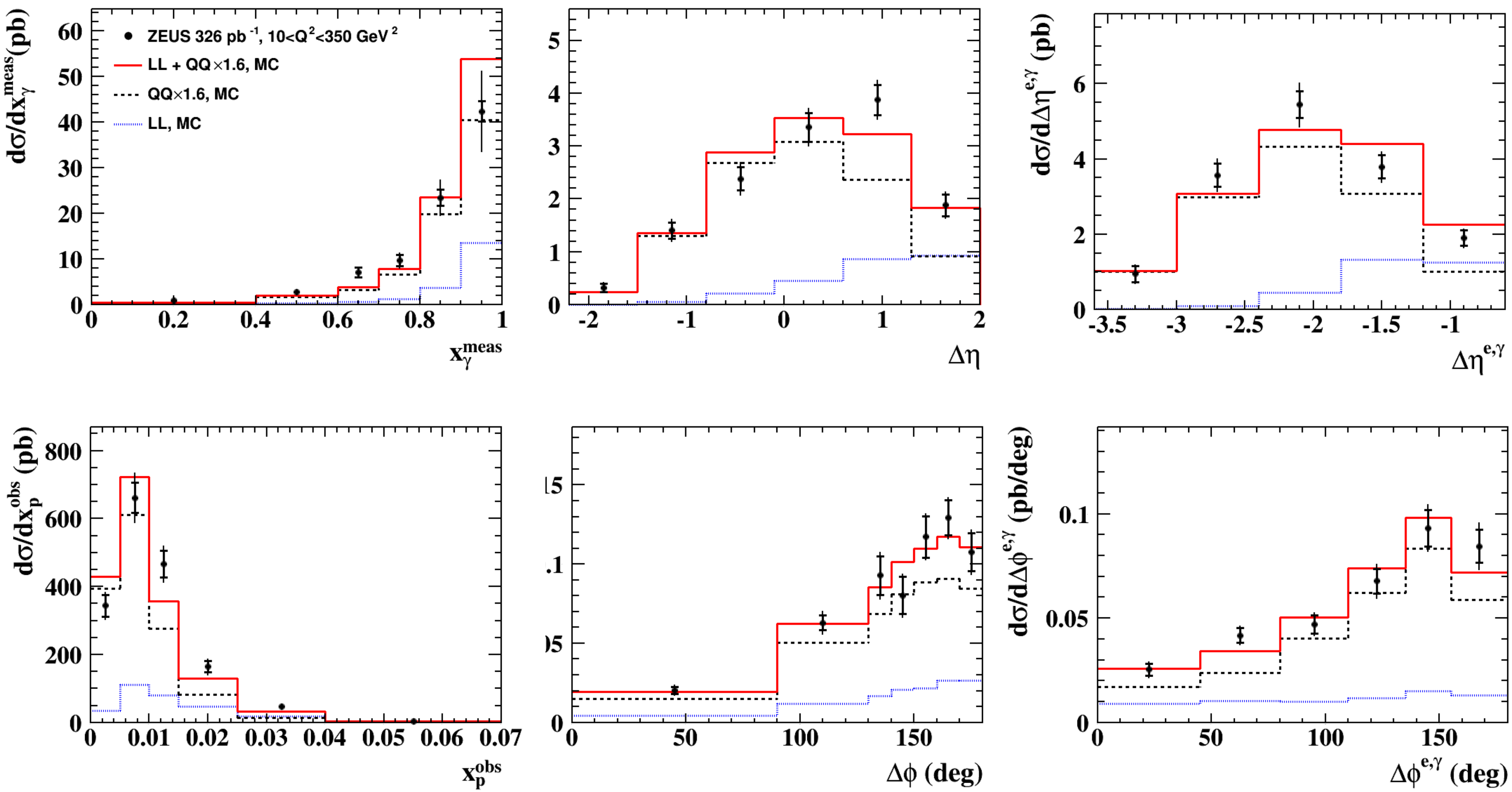
- $\Delta\eta = \eta_{jet} - \eta_{\gamma}$
- $\Delta\varphi = \varphi_{jet} - \varphi_{\gamma}$
- $\Delta\varphi_{e,\gamma} = \varphi_e - \varphi_{\gamma}$
- $\Delta\eta_{e,\gamma} = \eta_e - \eta_{\gamma}$

Width of BEMC photon candidate

Fit for number of photons in each measured bin.

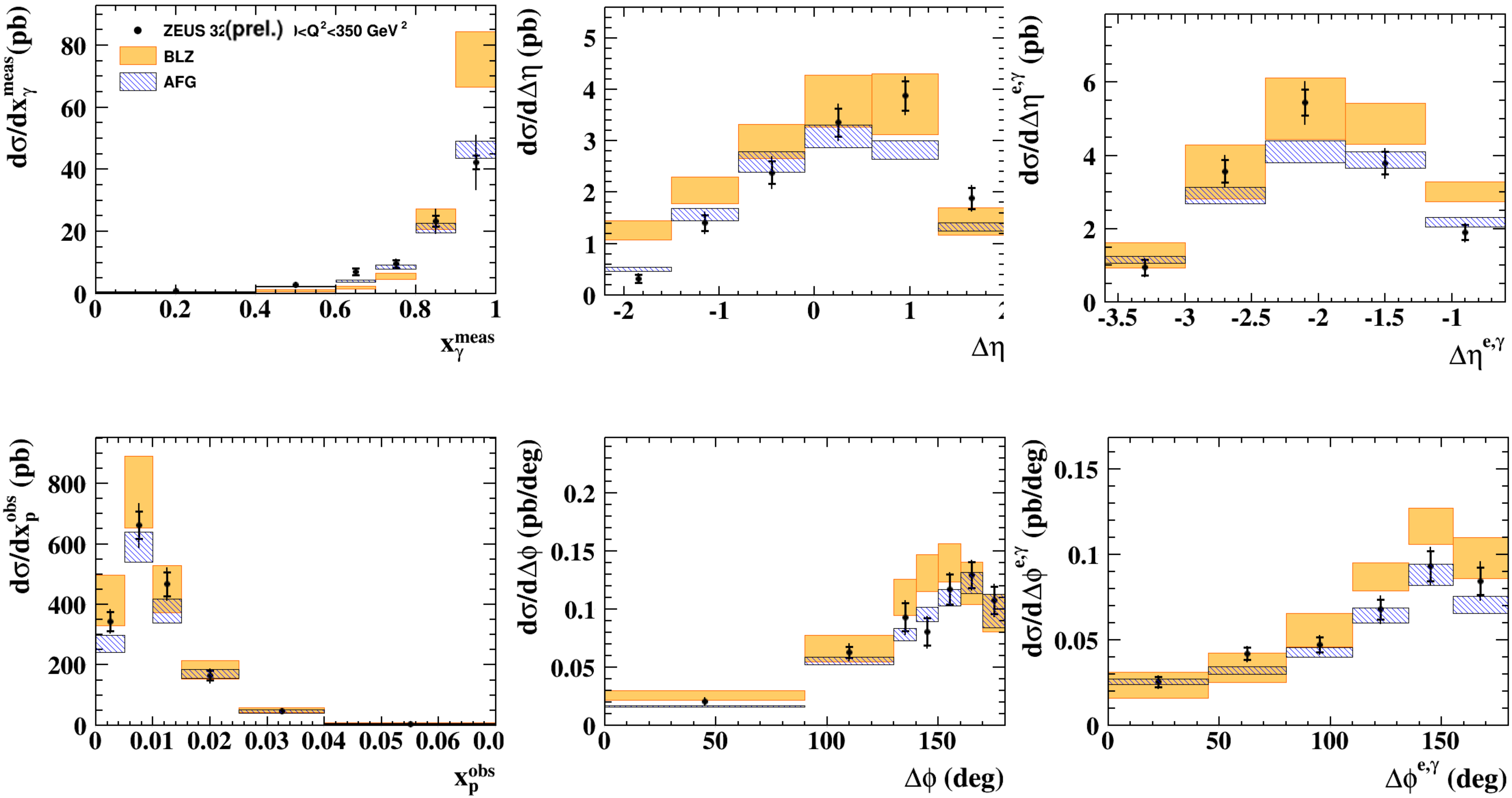


Results for full Q2 range, compared to PYTHIA*1.6   (QQ)   + HERACLES (LL)



A reasonable description is obtained.

AFG: Aurenche, Fontannaz and Guillet : EPJ C44 (2005) 395 NLO
BLZ: Baranov, Lipatov and Zotov: PRD81 (2010) 094034 kT-factorisation



AFG is better, especially for x_γ, though not perfect here.

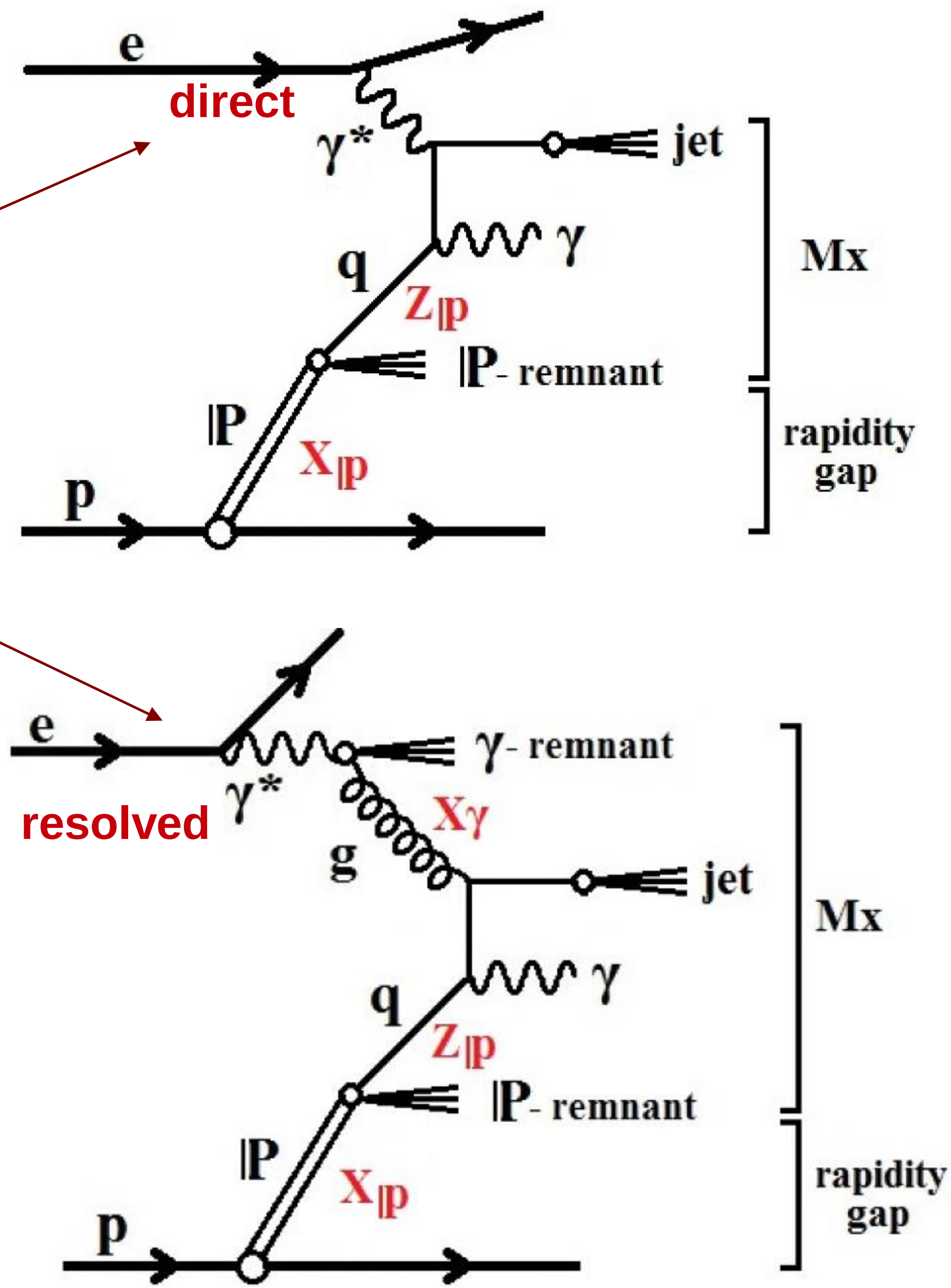
Diffractive processes at HERA

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 ($x_\gamma = 1$).

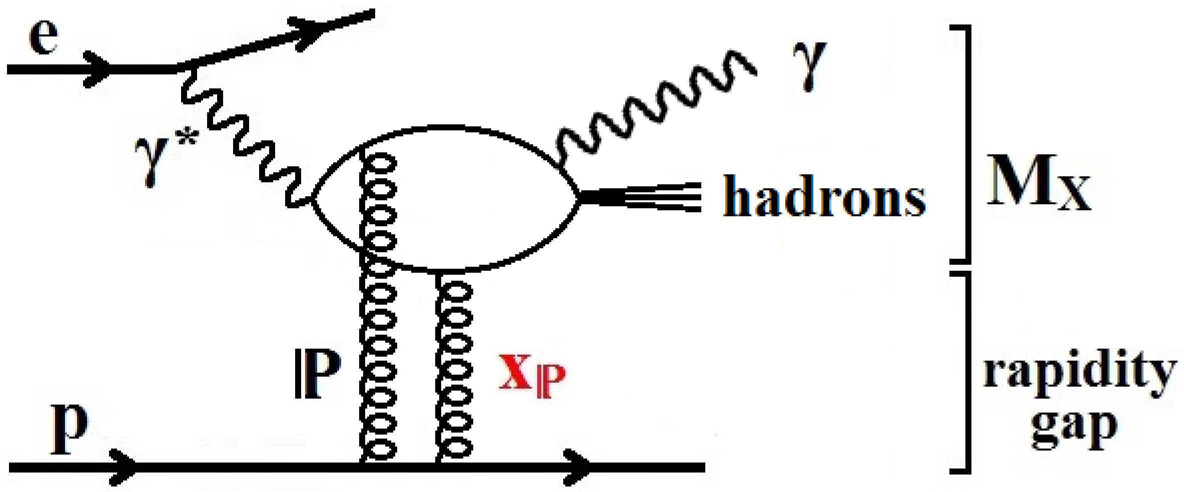
Resolved incoming photon gives fraction x_γ of its energy.

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

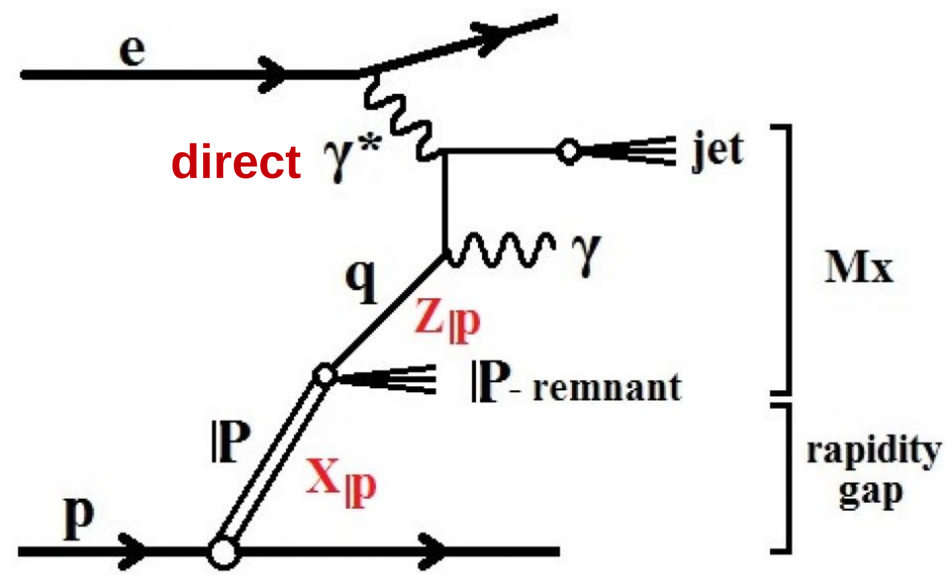
$$\Sigma_{\text{all EFOs}} (E + p_z) \,/\, 2\,E_p$$

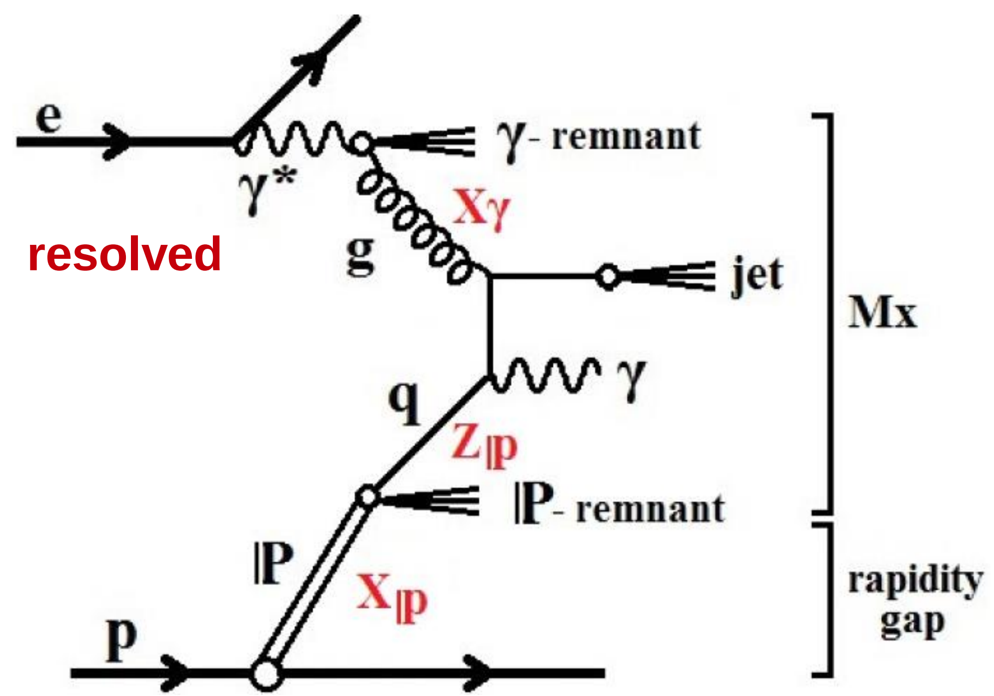
z_{IP} = fraction of Pomeron **E+p$_z$** taken by photon + jet measured as

$$\Sigma_{\gamma\,+\,\text{jet}}(E + p_z) \,/\, \Sigma_{\text{all EFOs}}(E + p_z)$$

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

Diffractive processes are characterised by a low value of η_{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:
Phys. Lett. 730 (2014) 293 JHEP 08 (2014) 03

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

Diffractive photoproduced dijets:
(H1) Eur. Phys. J. 6 ((1999) Eur. Phys. J. 421, 70 (2008)15
(ZEUS) Eur. Phys. J 55 (2008) 171

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 $\eta_{max} < 2.5$ and $x_{IP} < 0.03$
   η_{max} is evaluated from ZEUS energy flow objects (EFOs), which combine tracking and calorimeter cluster information.

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

4) Remove remaining DIS events and Bethe-Heitler and DVCS events (γ e) by excluding events with identified electron or ≤ 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
(H. Jung Comp Phys Commun 86 (1995) 147)

Based on leading order parton-level QCD matrix elements.

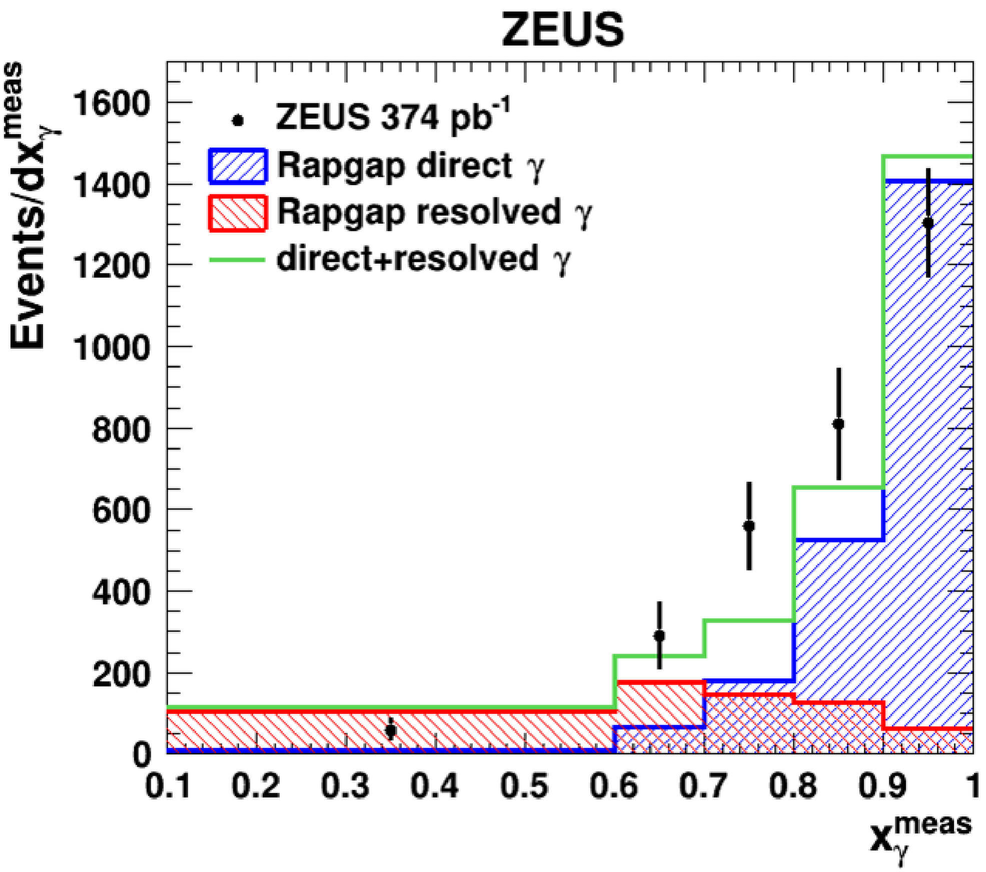
Some higher orders are modelled by initial and final state leading-logarithm parton showers.

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_γ distribution to direct-photon and resolved-photon RAPGAP components.

A 70:30 mixture is found and used throughout.

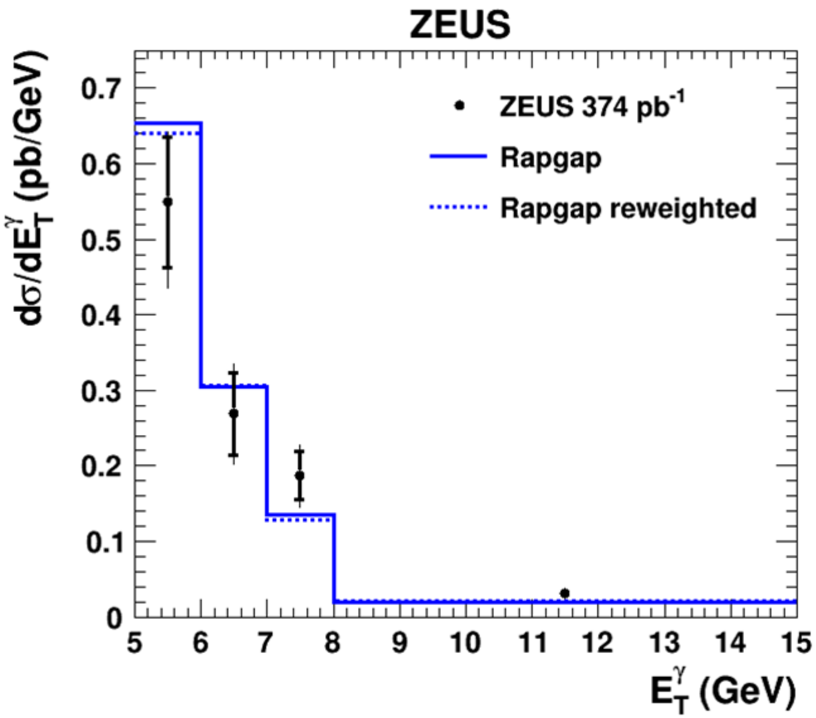


$$x_\gamma^{meas} = \Sigma_{\gamma + jet}(E - p_z) / \Sigma_{all\ EFOs}(E - p_z)$$

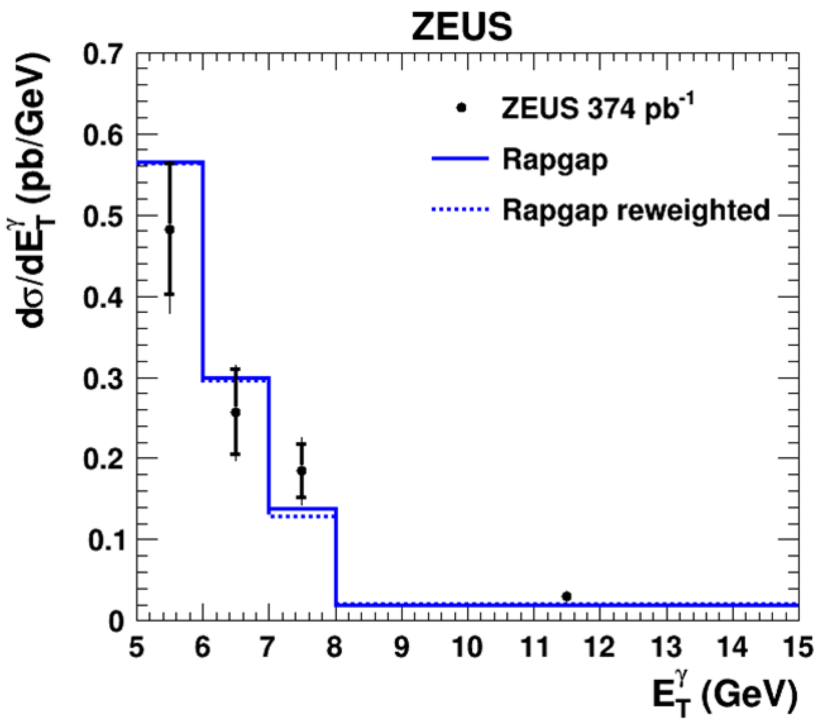
Results

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.



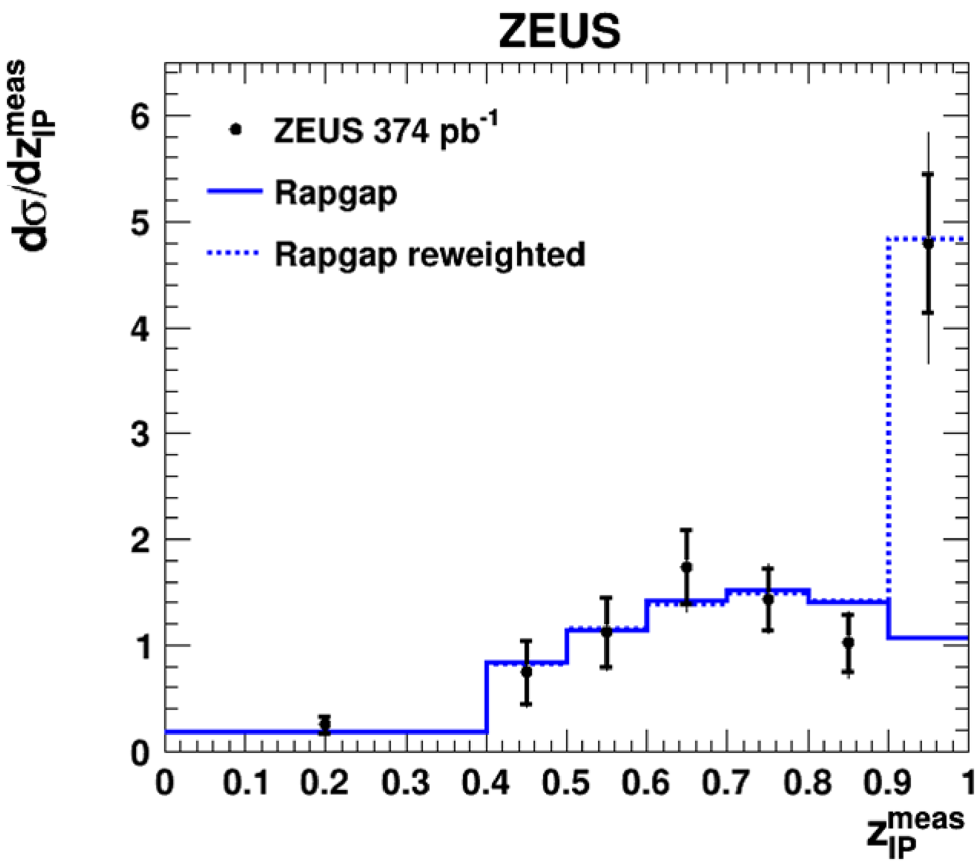
Inclusive photon



Photon + jet with E_T > 4 GeV

Shape of data well described by Rapgap. **Most photons are accompanied by a jet**.

Cross section in $z_{IP}^{meas} = \Sigma_{\gamma + jet}(E + p_z) \, / \, \Sigma_{all\ EFOs}(E + p_z)$



Evidence for direct Pomeron interactions

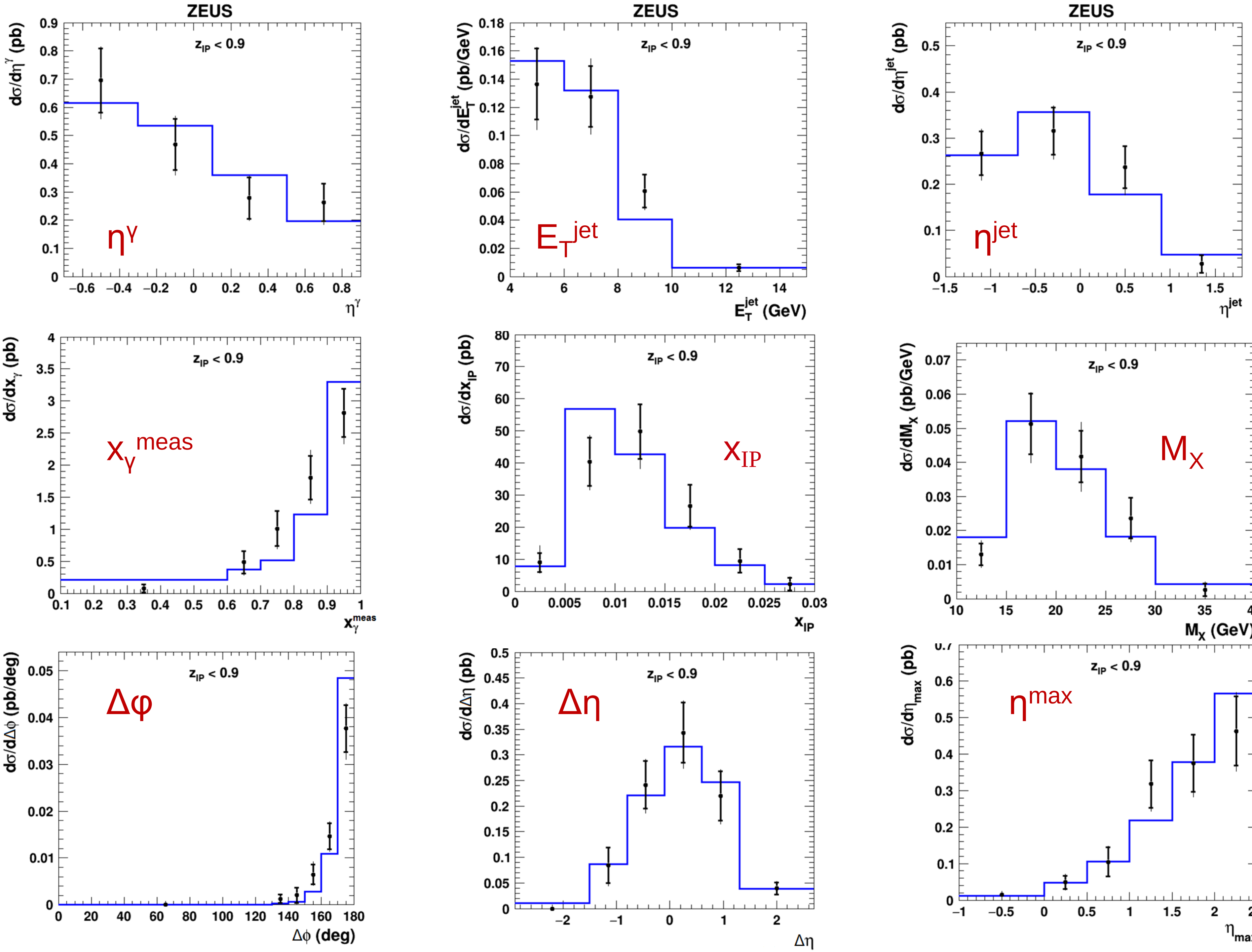
Photon-electron events have been removed.
($ep \rightarrow ep\gamma$)

Other backgrounds estimated and found to be at a low level

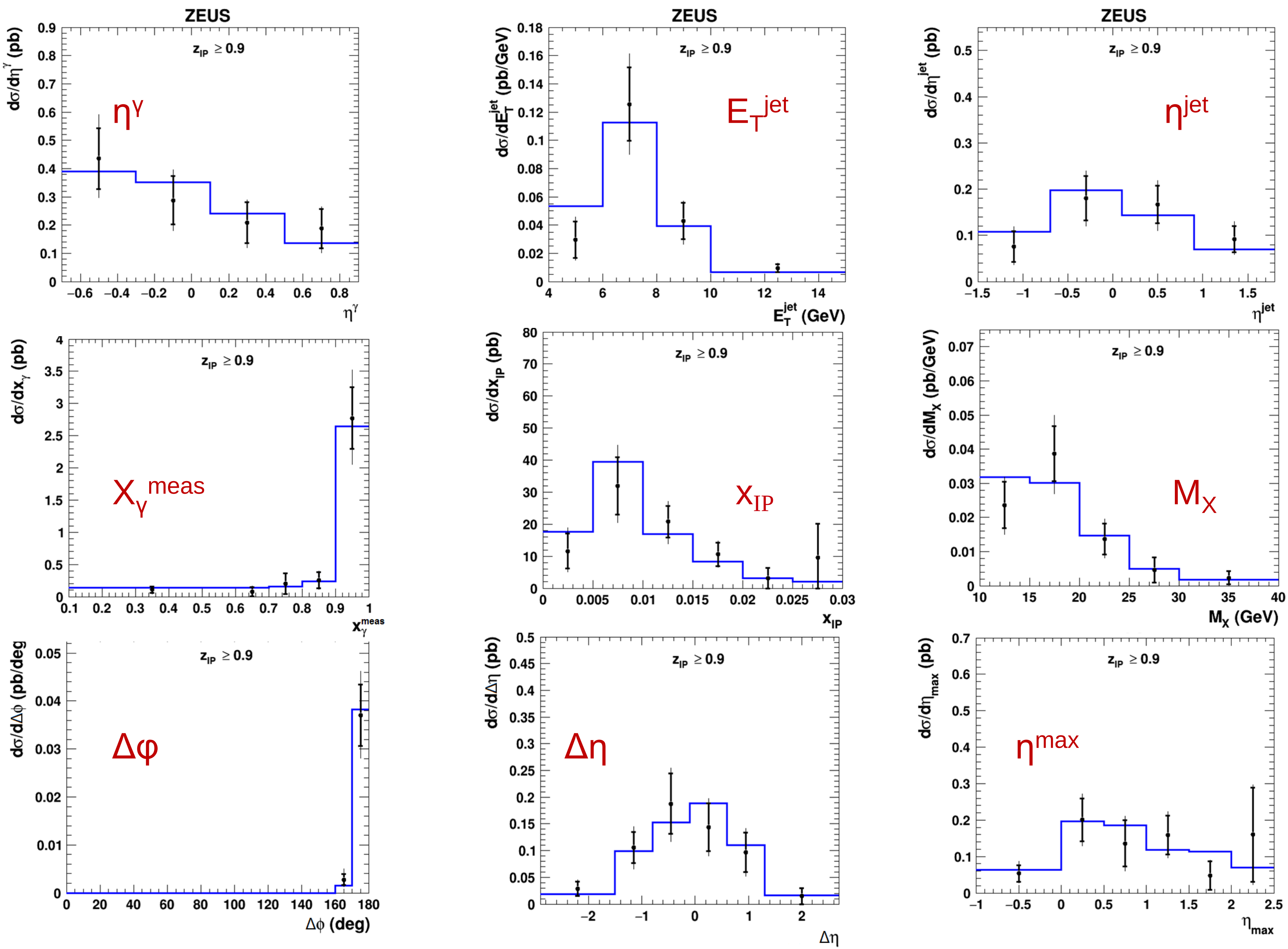
Using HERA-I data, integrated cross section for $\mathbf{z_{IP}^{meas} < 0.9}$ = $0.68 \pm 0.14 \, ^{+0.06}_{-0.07}$ pb

Rapgap gives 0.68 pb. No allowance for proton dissociation which is ~ 16 ± 4%.

Cross sections for region $z_{IP}^{meas} < 0.9$ Rapgap is normalised to data in this region.



Cross sections for region $z_{IP}^{meas} \geq 0.9$ 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 η_{max} and x_{IP}

Most of the detected photons are accompanied by a jet.

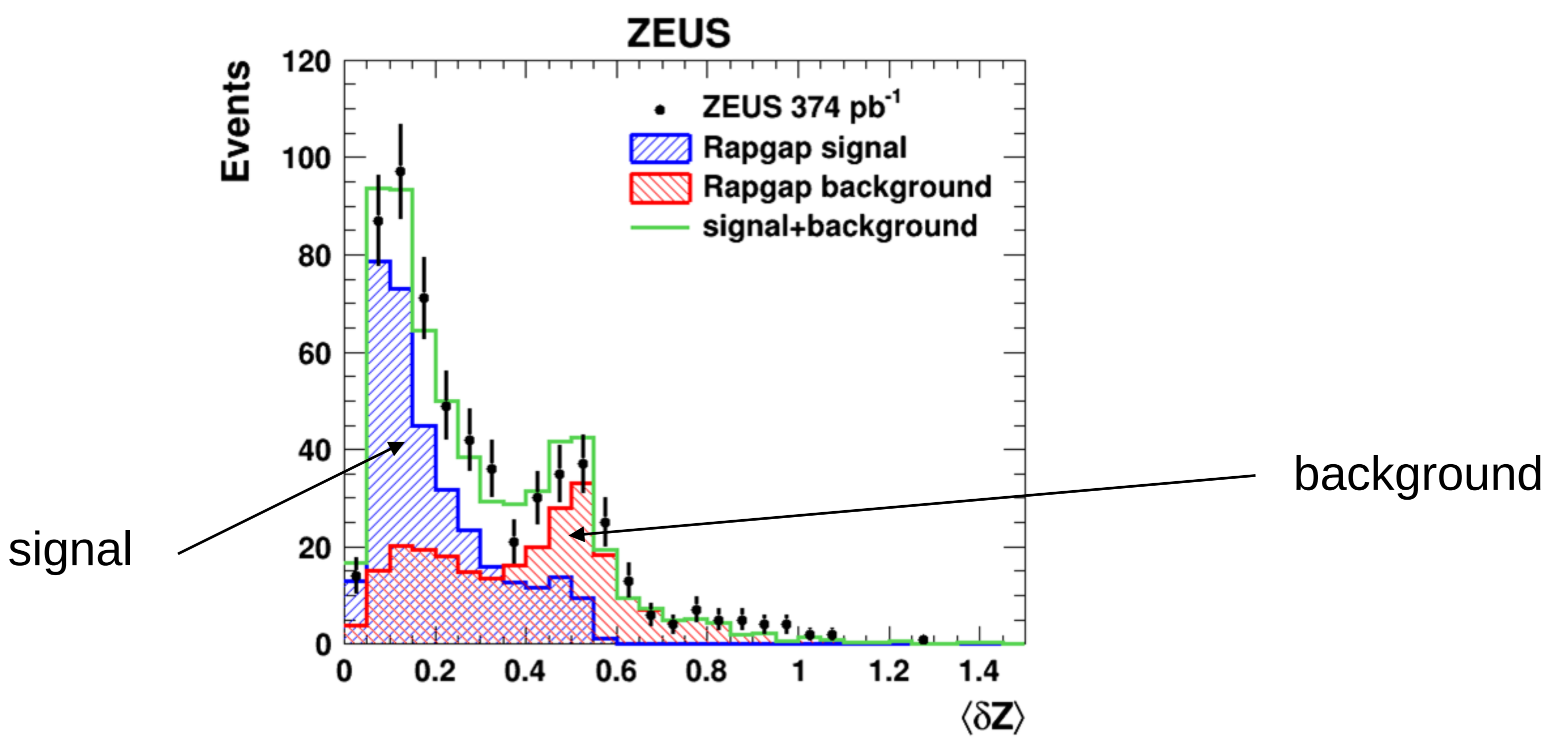
The variable z_{IP}^{meas} shows a peak at high values that gives evidence for a direct-Pomeron process not modelled by RAPGAP

In both regions of z_{IP}^{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 $z_{IP}^{meas} < 0.9$.

Backups

Photon candidates: groups of signals in cells in the BEMC.
Each has a Z-position, Z_{CELL}. E-weighted mean of Z_{CELL} is Z_{Mean}.

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

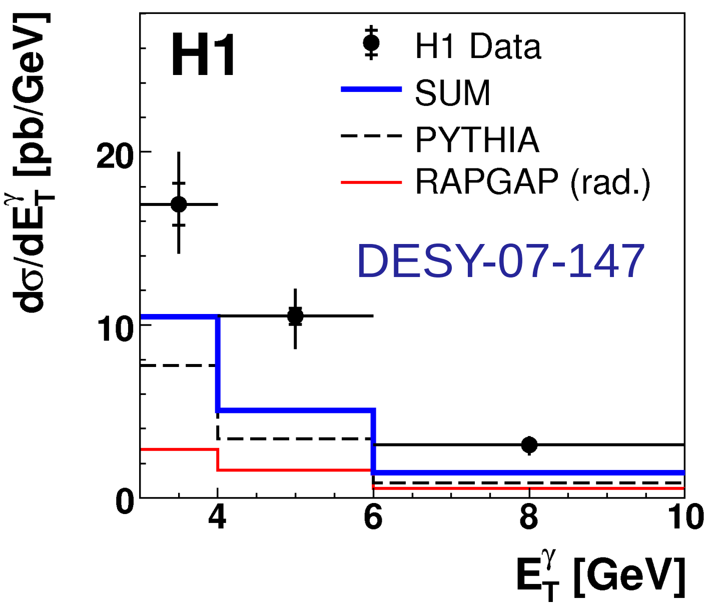


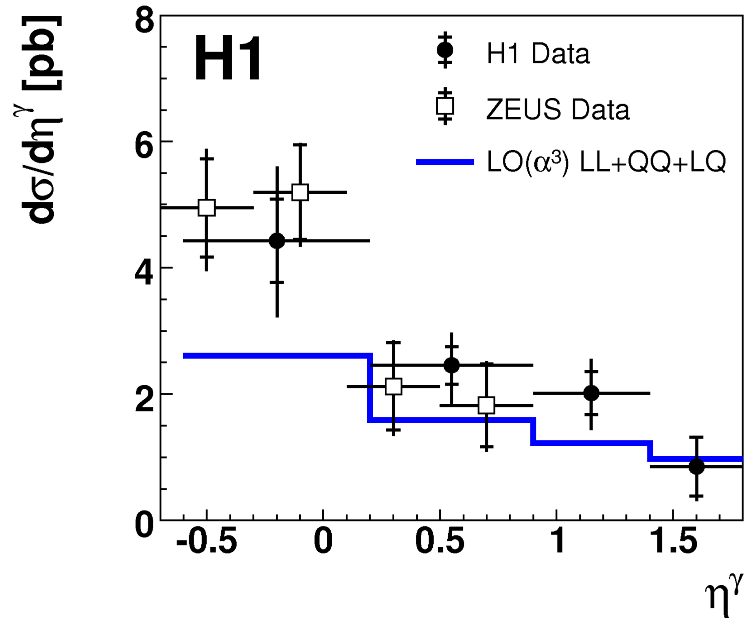
<dZ> = E-weighted mean of $|Z_{CELL} - Z_{Mean}|$.

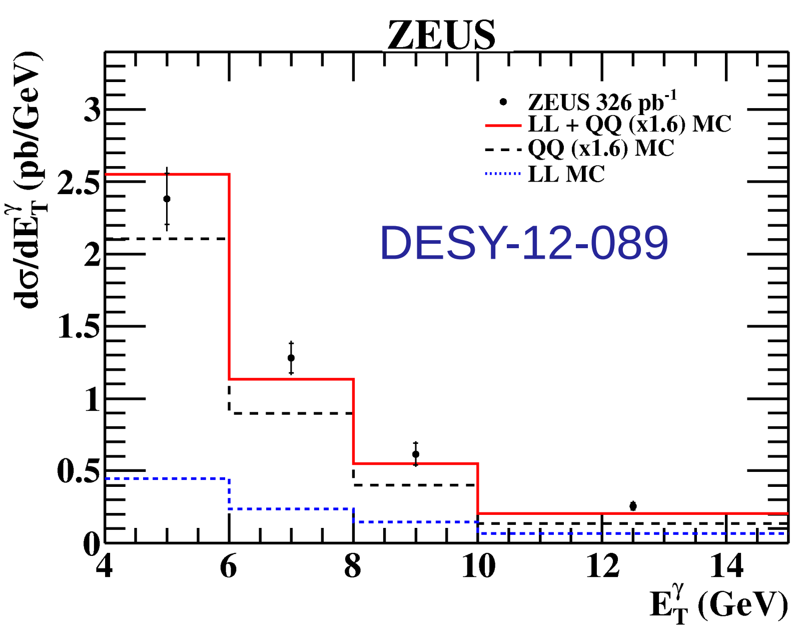
Peaks correspond to photon and π^0 signals, other background is η + multi-π^0.

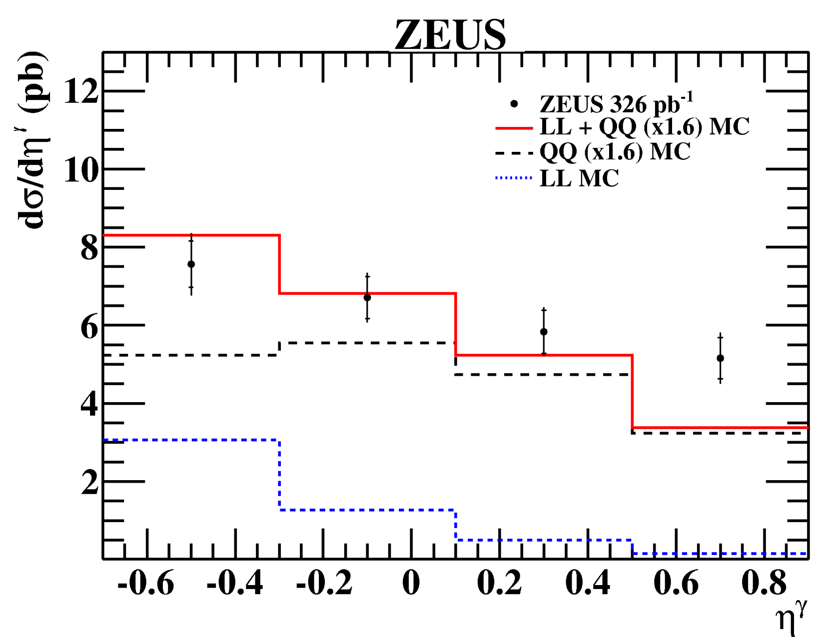
In each bin of each measured physical quantity, fit for **photon signal** + hadronic bgd.

Some comparisons with earlier results. Always a need to scale up the LO theory









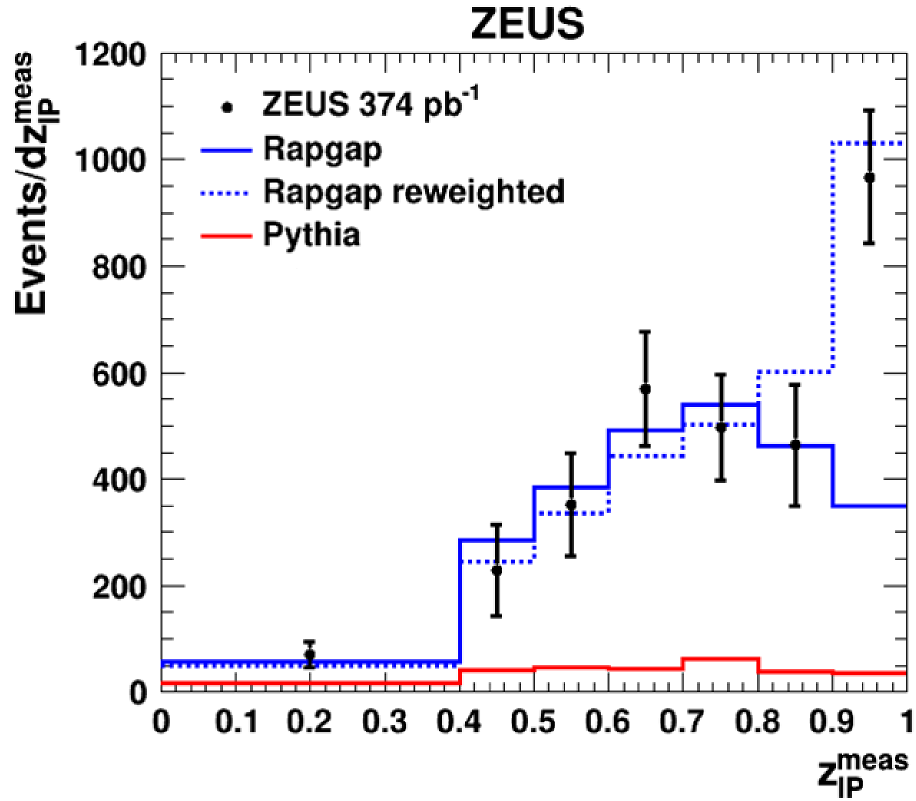
Plot z_{IP}^{meas} and compare with Rapgap

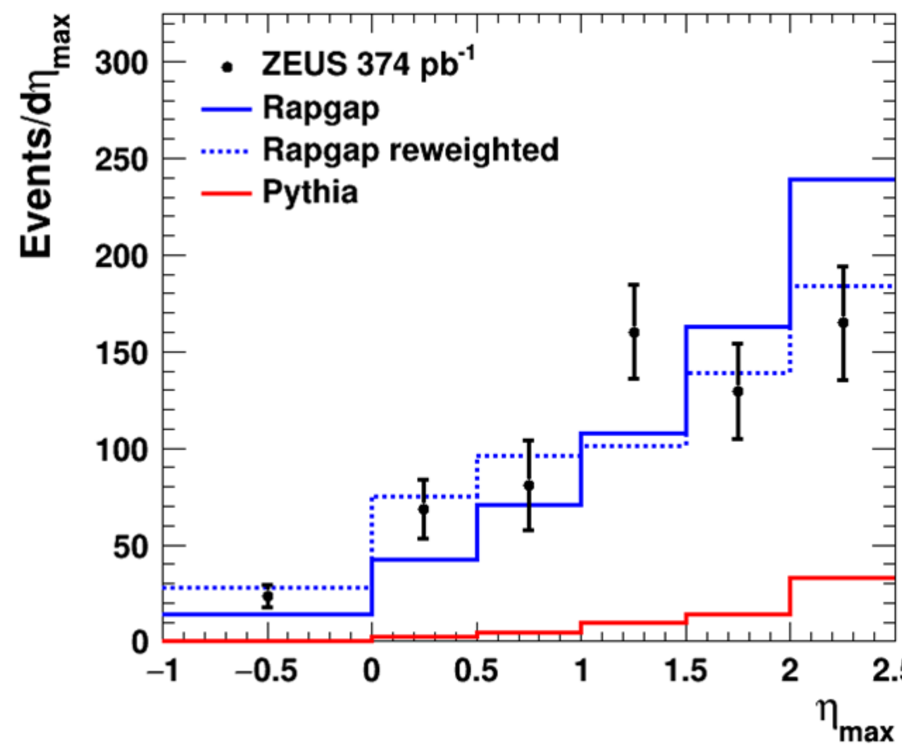
Shape does not agree.
An excess is seen in the top bin.
Can reweight Rapgap to describe the shape.

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

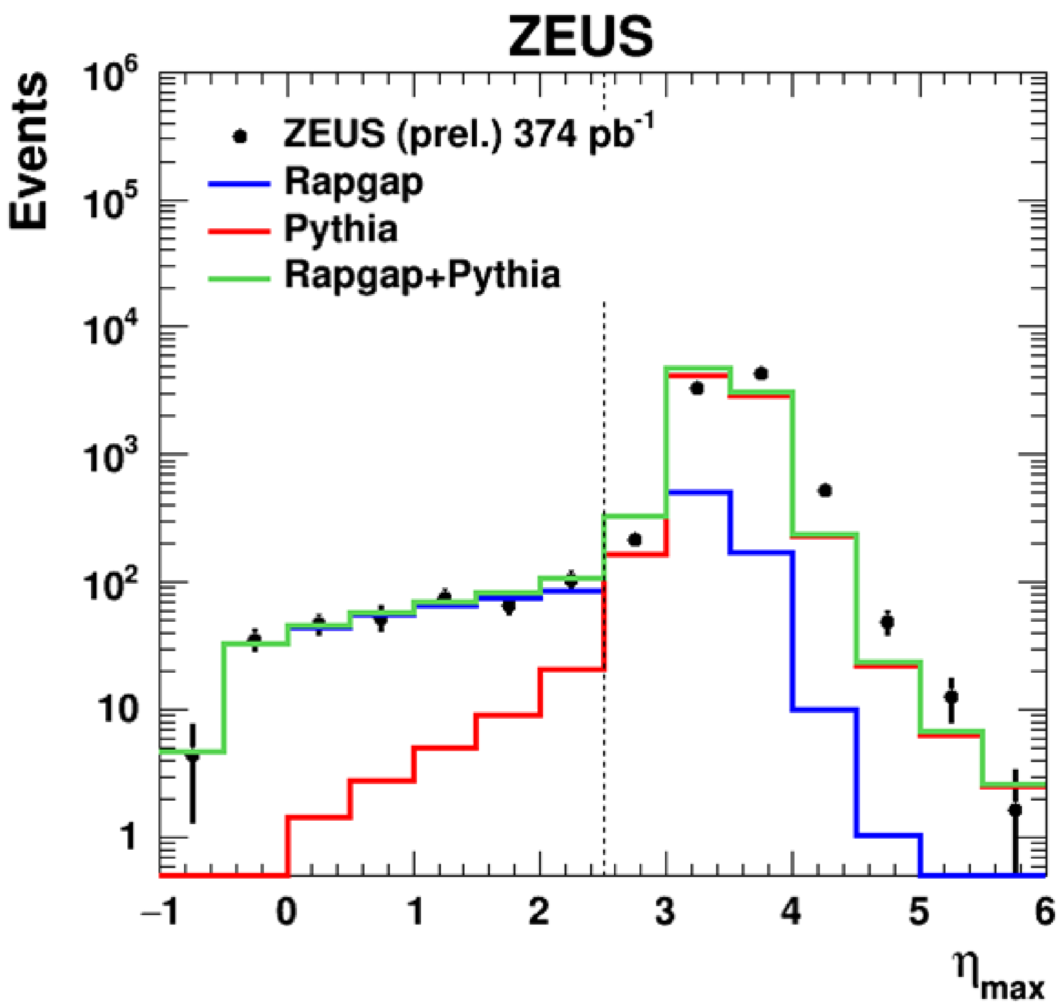
The η_{max} distribution is described better by the reweighted Rapgap.

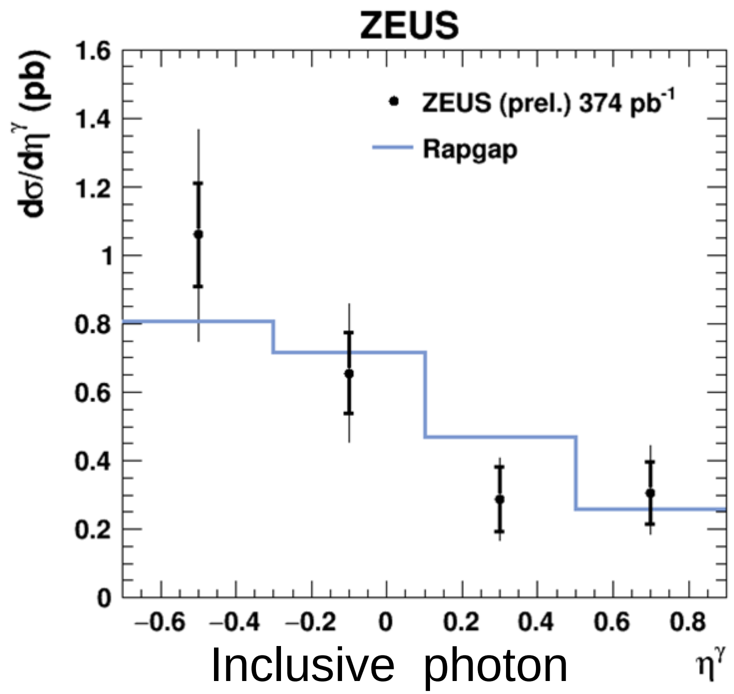
Red histogram shows what 10% of non-diffractive Pythia photoproduction (subject to present cuts) would look like. (Not added into the Rapgap.)





etamax distribution for HERA-2.

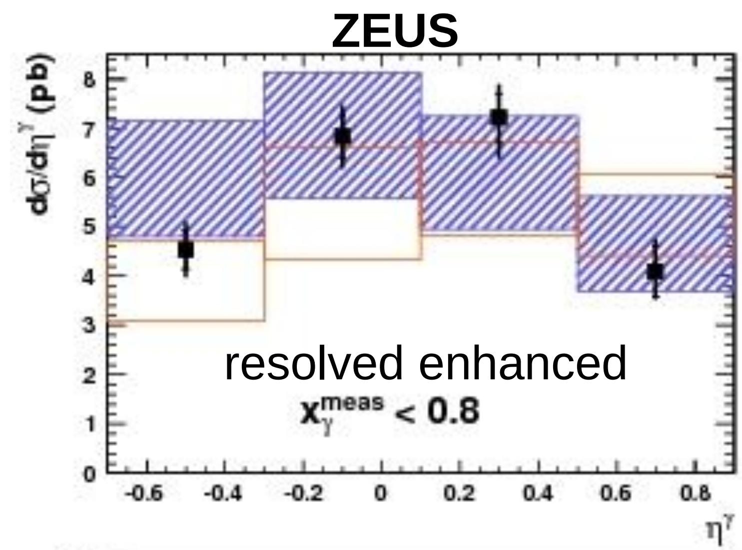


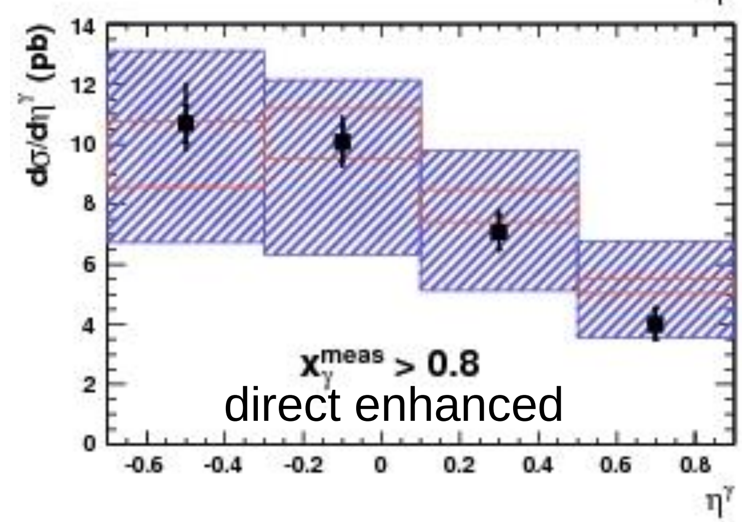


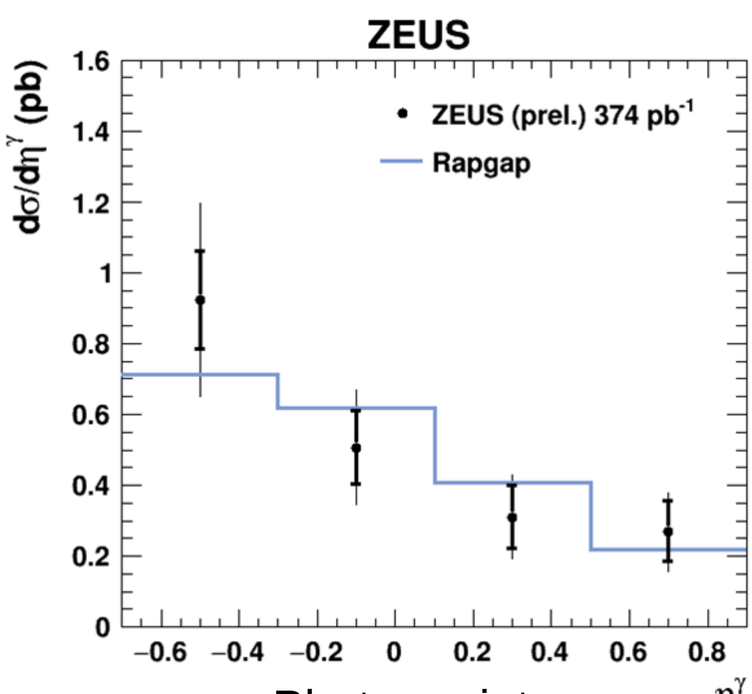
Inclusive photon pseudorapidity

Compare diffractive photon distribution with those from nondiffractive process.

Diffractive more resembles direct but seems slightly more forward.

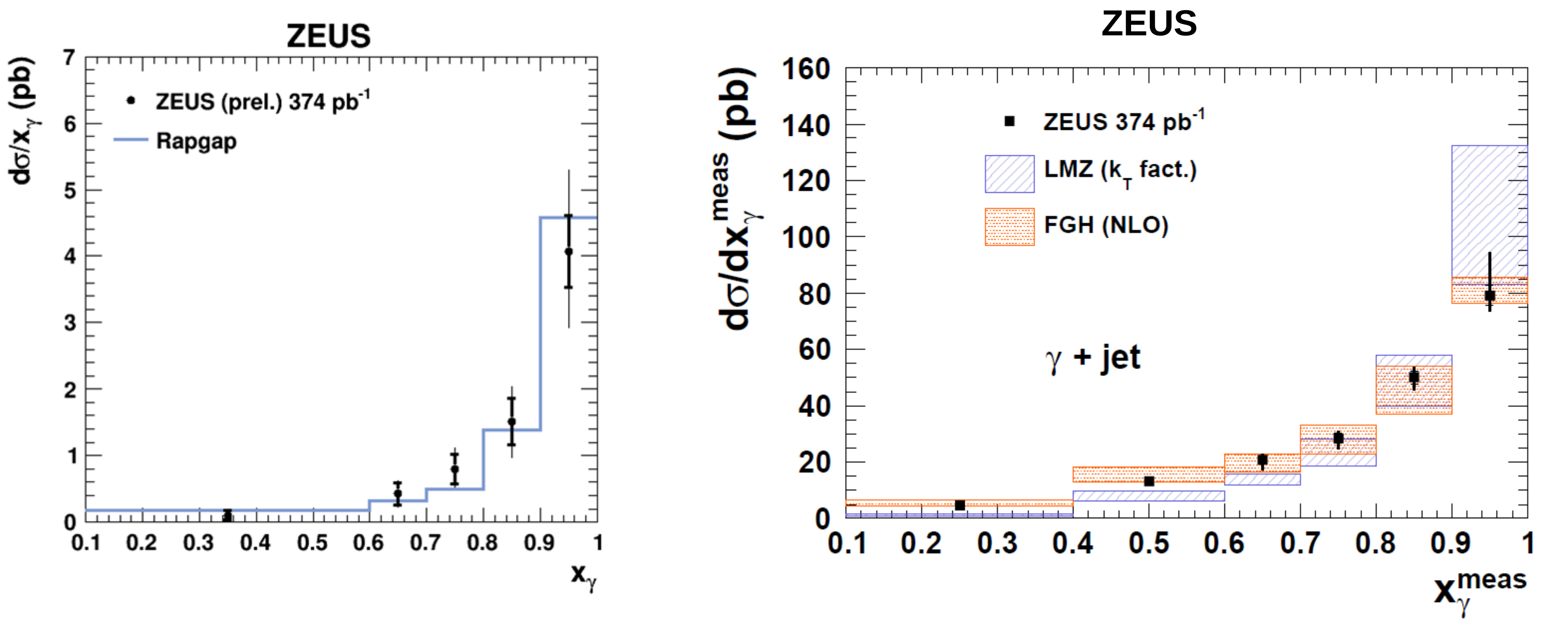






Photon + jet

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.