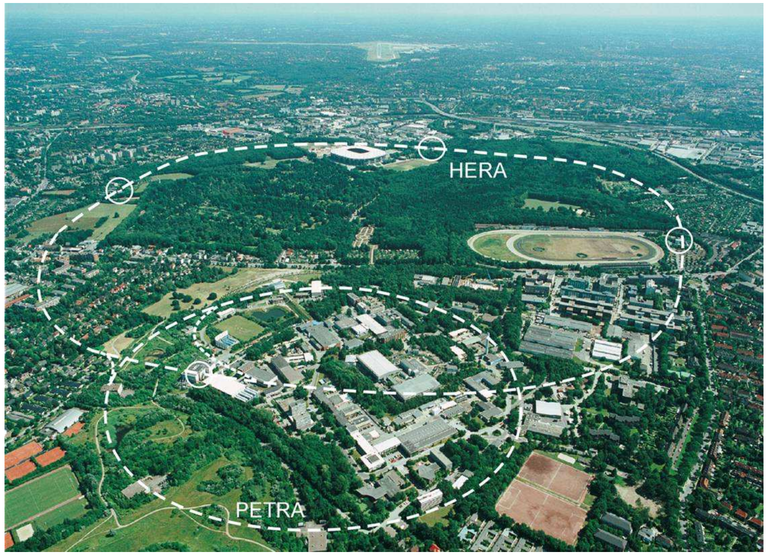
Photoproduction of isolated photons, inclusively and with a jet, at HERA

Oleg Kuprash (on behalf of the ZEUS collaboration)
DESY

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects
Warsaw, Poland

photoproduction of γ and $\gamma + \mathrm{jet}$: Physics Letters B 730 (2014) 293-301
further studies: ZEUS-prel-14-001

HERA Hadron-Elektron-RingAnlage



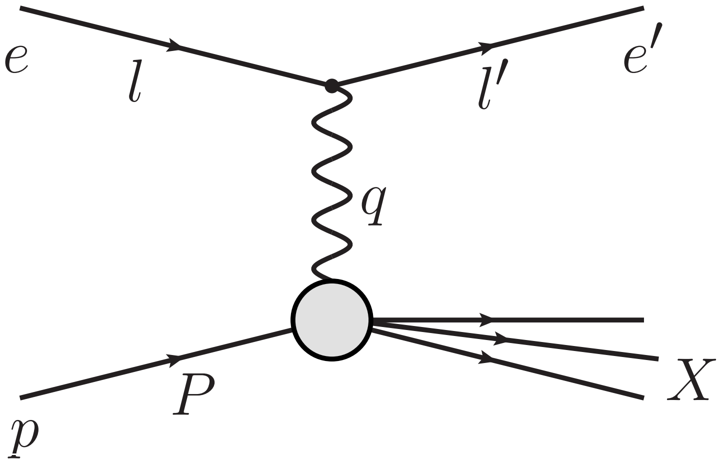
years of operation: 1992-2000 (HERAI), 2003-2007 (HERAII)

Electrons/Positrons: 27.5 GeV

Protons: 920 GeV (820 GeV until 1998)

$\sqrt{s} = 318$ GeV (300 GeV until 1998)

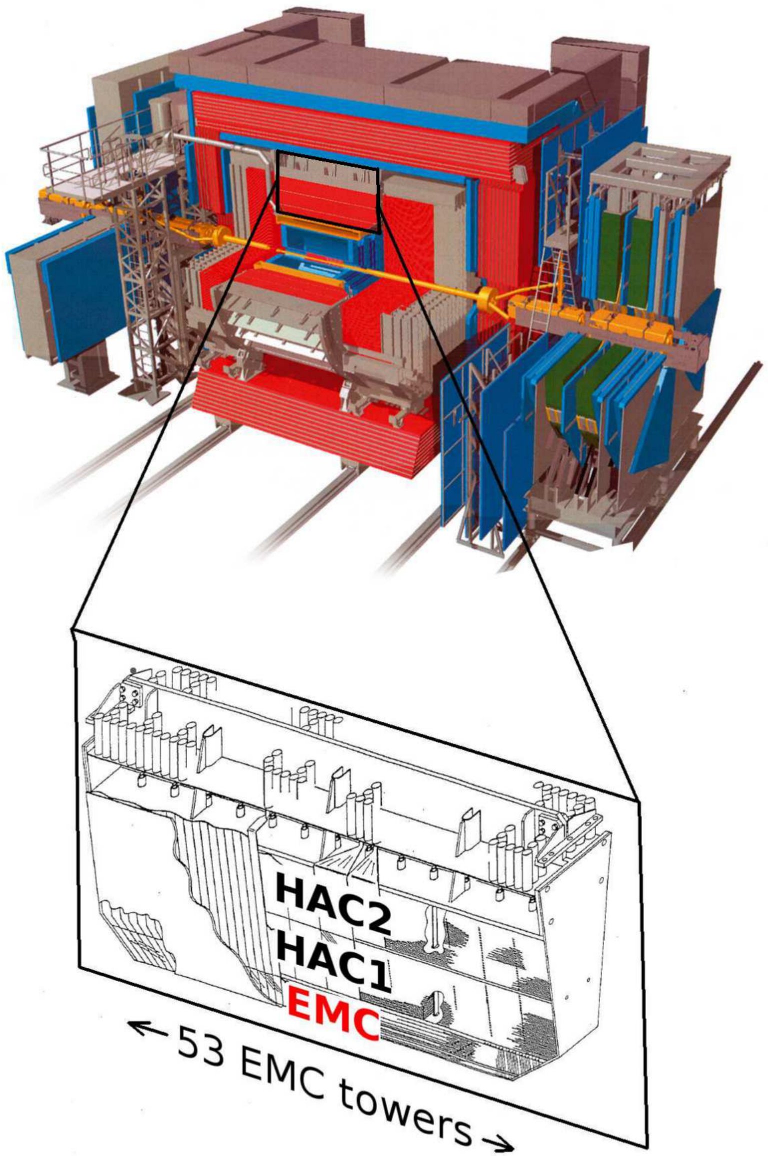
integrated luminosity: $\mathcal{L}_{\mathrm{tot}} = 0.5\ \mathrm{fb}^{-1}$



Kinematics:

- $Q^2 = -q^2$ **virtuality of the exchanged boson**
  $Q^2 \lesssim 1$ GeV^2: photoproduction (PHP)
  $Q^2 \gtrsim 1$ GeV^2: DIS
- $y = \frac{P \cdot q}{P \cdot l}$ **inelasticity**
- $x = \frac{Q^2}{2P \cdot q}$ **longitudinal momentum fraction carried by the incoming parton**

ZEUS detector and its Calorimeter



- multi-purpose detector
- 4π geometry
- tracking detectors operating in 1.43 T magnetic field
- high-resolution Calorimeter

Uranium-Scintillator Calorimeter:

- alternating layers of depleted Uranium absorber and scintillator

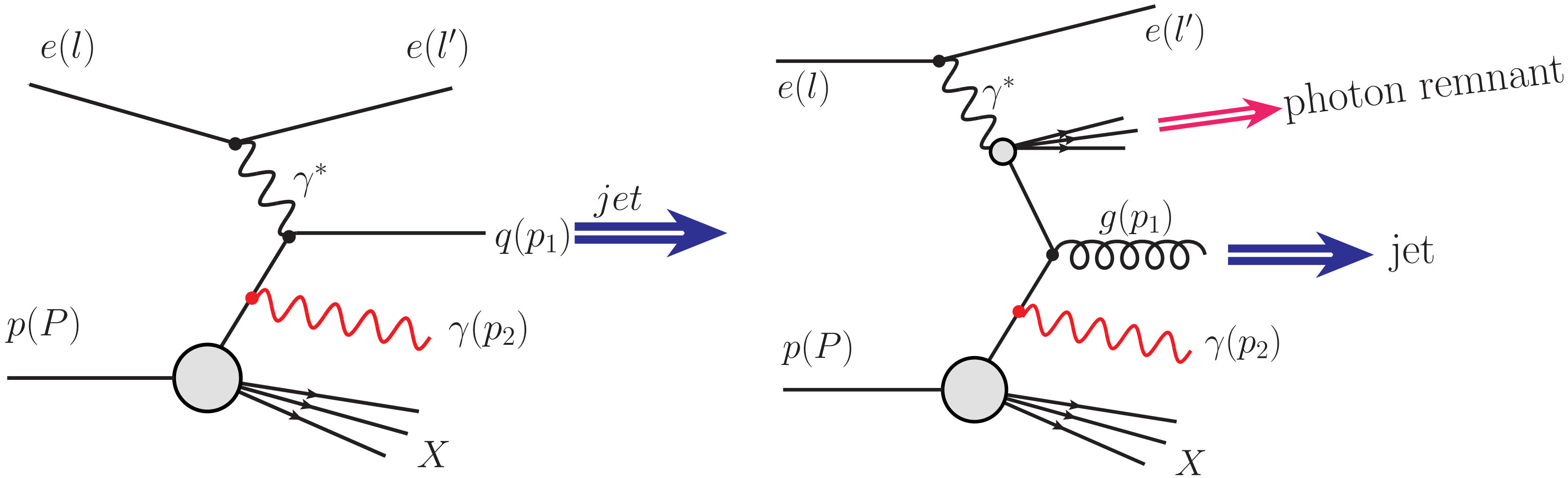
$\Rightarrow$ **compensating:** equal (within 5%) responce to electrons and hadrons of the same energy

- electromagnetic (EMC) and hadronic (HAC) cells
- Forward (FCAL), Barrel (BCAL) and Rear (RCAL)
- front face dimensions of BCAL EMC: 5 x 20 cm^2

$\Rightarrow$ enough granularity to separate electromagnetic showers

- energy resolution $\sigma(E)/E = 18\%/\sqrt{E}$ for electrons $\sigma(E)/E = 35\%/\sqrt{E}$ for hadrons

Photoproduction of isolated photons



direct exchanged photon γ^* **resolved exchanged photon γ^***

- Isolated photons in photoproduction:

- do not undergo hadronisation process $\Rightarrow$ direct probe of the underlying partonic process
- allow test of different models (see further)
- sensitivity to the proton structure (u/d PDF ratio)

$\gamma + \text{jet}$:

- it is expected for isolated photons + jets to be more sensitive to the underlying partonic process, compared to inclusive photons
- fraction of the background is smaller for photons + jets compared to inclusive photons

Event selection and reconstruction (1/2)

- integrated luminosity of $\approx 374\,\mathrm{pb}^{-1}$ (data taken between 2004-2007)

Observables: cross section as function of
- transverse energy E_T^γ and pseudorapidity η^γ of the photon
- transverse energy E_T^{jet} and pseudorapidity η^{jet} of the accompanying jet
- x_γ^{meas} (will be defined later)
- $x_p^{\mathrm{obs}} = (E_T^\gamma \exp \eta^\gamma + E_T^{\mathrm{jet}} \exp \eta^{\mathrm{jet}})/2E_p$
- $\eta^\gamma - \eta^{\mathrm{jet}}$
- $\Delta\phi = |\phi^\gamma - \phi^{\mathrm{jet}}|$

Photon isolation:
- no tracks within $\Delta R(\eta, \phi) = 0.2$ cone around the photon candidate
- ratio of the energy of the photon candidate to the energy of the jet containing it greater than 0.9

Monte Carlo:
- Pythia 6.416 (string hadronisation) - default
- Herwig 6.510 (cluster-based hadronisation) - for cross-check

Event selection and reconstruction (2/2)

Photoproduction

- no scattered electron registered

- $-40 < Z_{\rm vtx} < 40\,\text{cm}$
- $0.2 < y_{\rm JB} < 0.7\,\text{GeV}$

$$y_{JB} = \frac{E^{\rm all} - p_Z^{\rm all}}{2E_{el}}$$

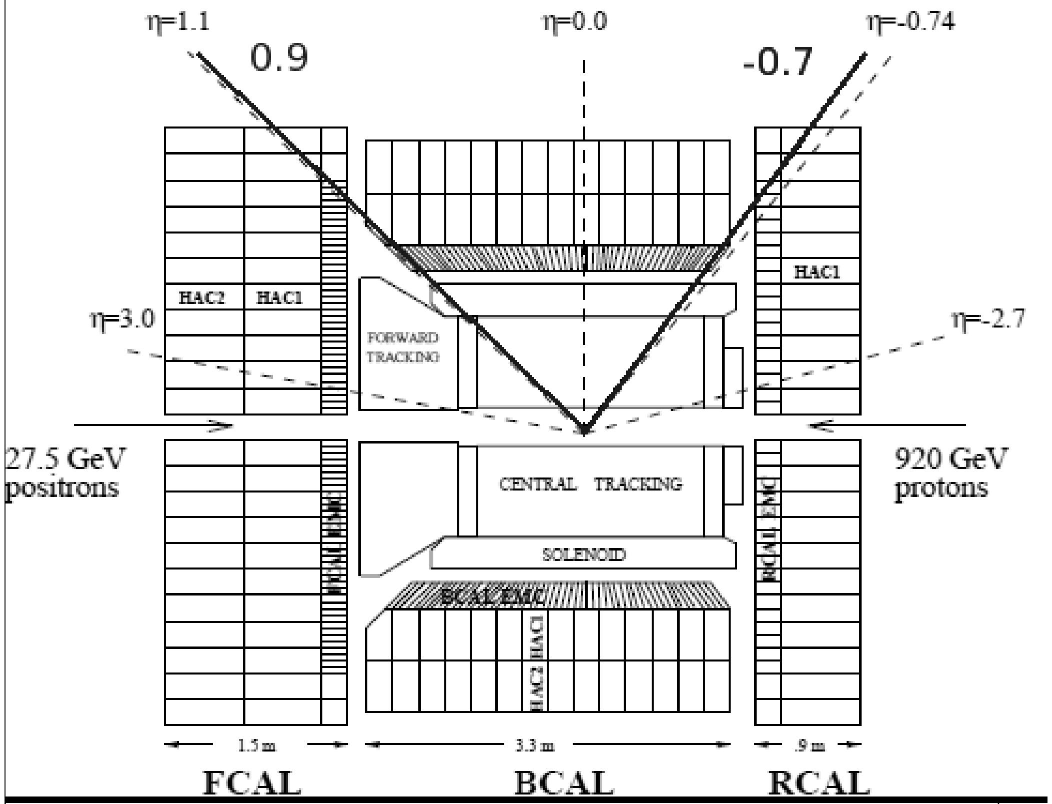
Photon

- $6 < E_T^{\gamma}/\text{GeV} < 15$
- $-0.7 < \eta^{\gamma} < 0.9$
- photon isolation
- electromagnetic energy fraction:

$$\frac{E_{EMC}}{E_{HAC} + E_{EMC}} > 0.9$$

Accompanying jet

- $4 < E_T^{\rm jet} < 35\,\text{GeV}$
- $-1.5 < \eta^{\rm jet} < 1.8$



Background to isolated photons

- Photons from decays of neutral mesons:
  - $\pi^0 \to \gamma\gamma$ (98.8 %)
  - $\eta \to \gamma\gamma$ (39.3 %)
  - $\eta \to \pi^0\pi^0\pi^0$ (32.6 %)

  $\to$ it is the main source of the background
  $\to$ opening angle of two photons after π^0 decay:

$$\sin\frac{\alpha}{2} = \frac{m}{E}$$

  At $E = 5$ GeV $\alpha = 1.55^\circ$ for π^0 and $\alpha = 6.3^\circ$ for η-mesons
  $\to$ there is a possibility to use shower shape method

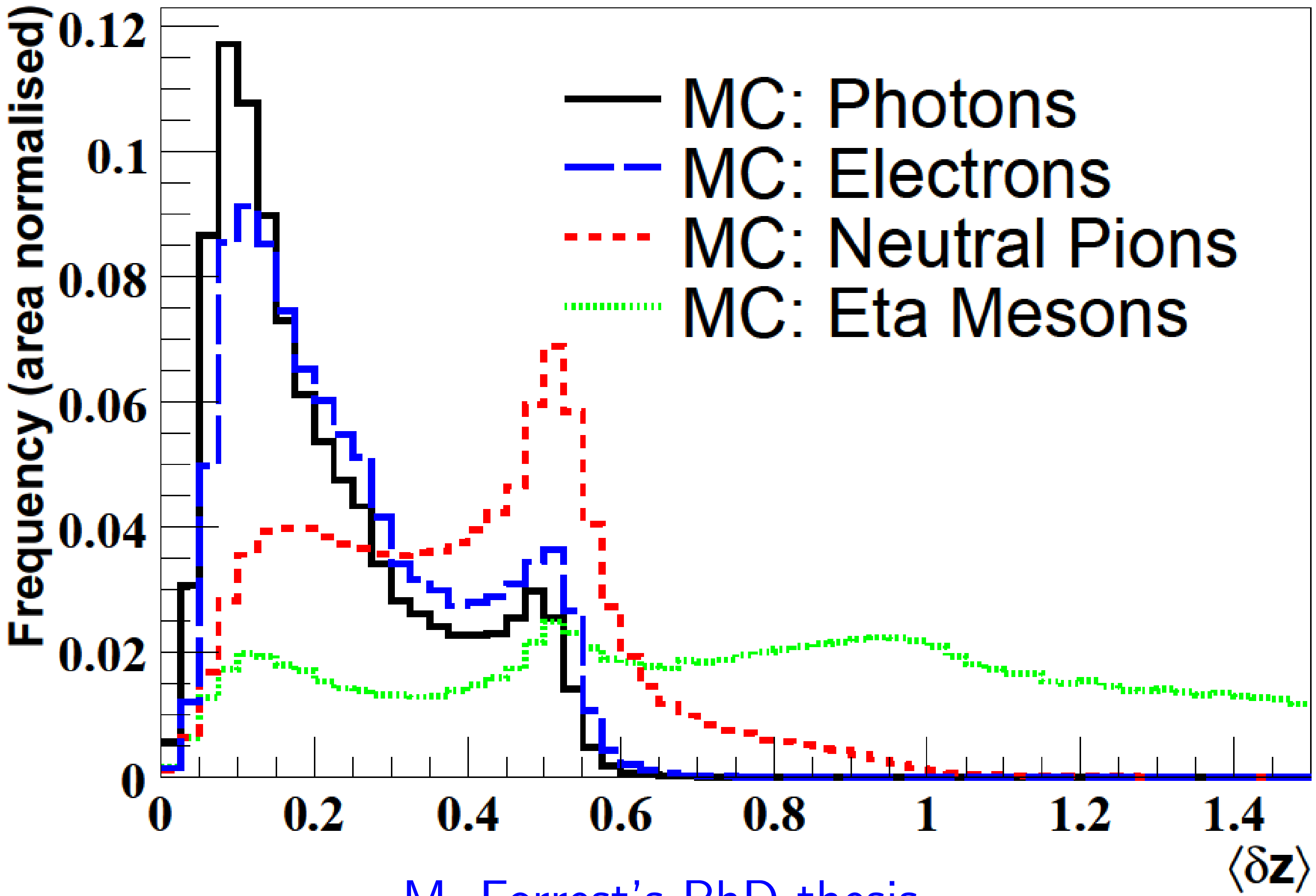
- quark-to-photon fragmentation
  $\to$ this process occurs over long distances and cannot be calculated perturbatively
  $\to$ suppressed by the isolation requirements

Extraction of the signal (1/2)

Following variable is used to separate signal from background:

$$\langle \delta z \rangle = \frac{\sum |z_i - z_{cluster}| \cdot E_i}{l_{cell} \sum \mathrm{E_i}}$$

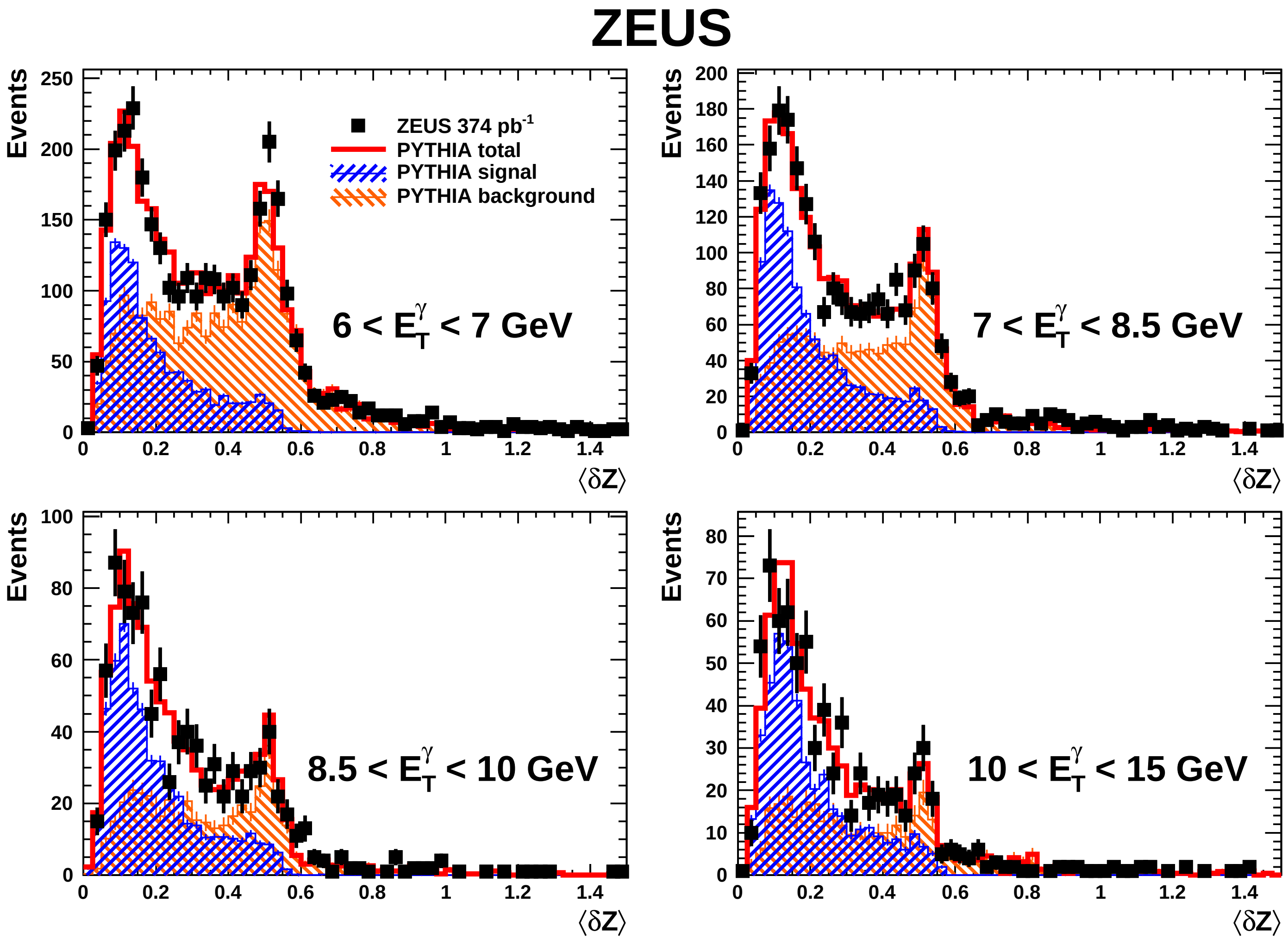
describes width of the electromagnetic shower in calorimeter



M. Forrest's PhD thesis

Extraction of the signal (2/2)

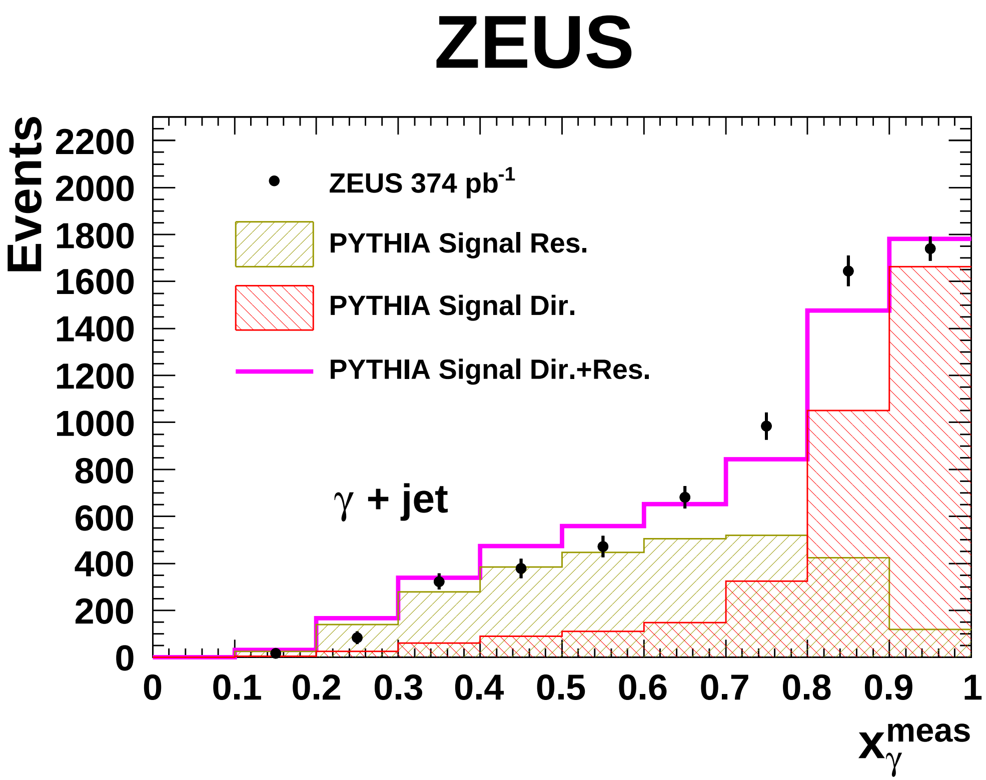
$\rightarrow$ mixture of signal and background MC is used to fit the data distribution
$\rightarrow$ $\langle \delta z \rangle$ distribution was fitted in each bin of the cross section
- fit in bins of E_T^γ:



- typically $\chi^2/\mathrm{dof} \approx 1.1$ (i.e. 31/28)

$x_\gamma^{\rm meas}$ variable

• $x_\gamma^{\rm meas}$ is the fraction of the virtual photon's momentum participating in the production of $\gamma + {\rm jet}$ system



$$x_\gamma^{\rm meas} = \frac{E^\gamma - p_Z^\gamma + E^{\rm jet} - p_Z^{\rm jet}}{E^{\rm all} - p_Z^{\rm all}}$$

Direct LO process final state:

• jet
• photon
• scattered electron (escape undetected)
• proton remnant $(E - p_Z = 0)$

$\Rightarrow \; x_\gamma^{\rm meas} = 1$

Resolved LO process final state:

• all mentioned above

+ resolved photon remnant

$\Rightarrow \; \mathbf{x}_\gamma^{\rm meas} < 1$

• fractions of direct and resolved events in Monte Carlo:
55% direct, 45% resolved
• fractions were varied for the systematics

Sources of systematic uncertainty

• simulation of the hadronic final state: use Herwig instead of Pythia $\rightarrow$ typical uncertainties of 8% rising to 18% in the highest x_γ^{meas} bin

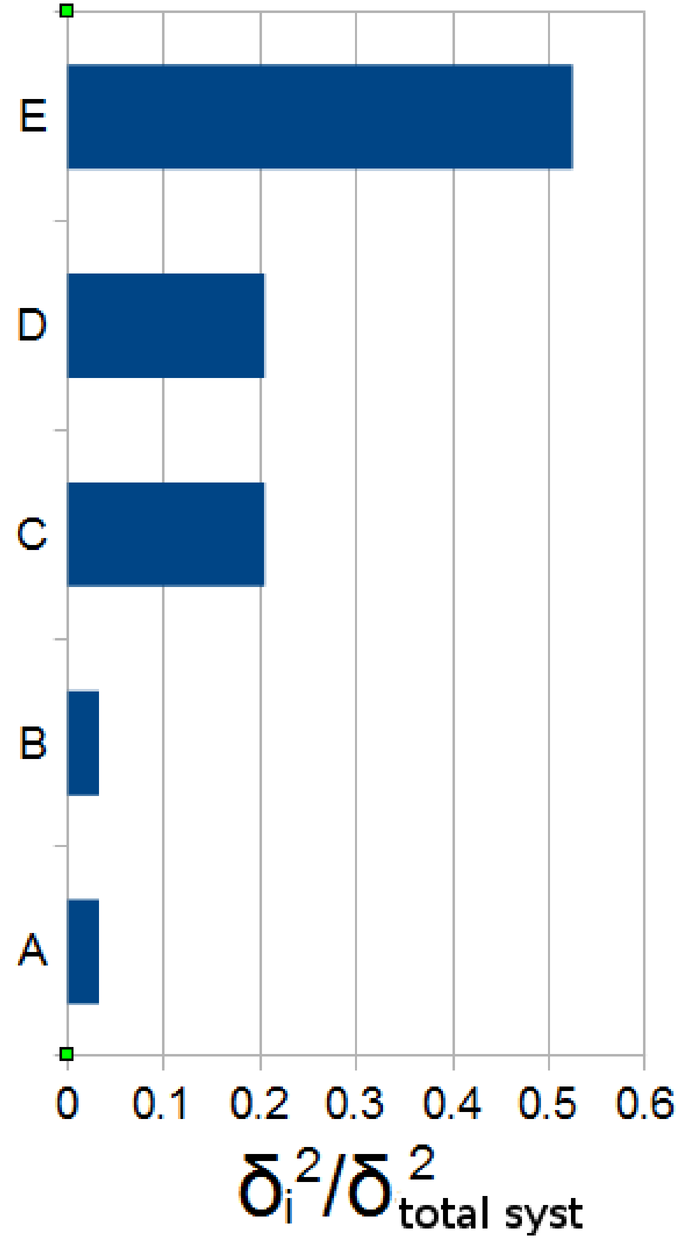
• photon energy scale: varied by $\pm 2\%$ $\rightarrow$ about 5% uncertainty on the cross section

• jet energy scale: varied by $\pm 4.5\% \ldots 2.5\%$ depending on the jet energy $\rightarrow$ about 5% uncertainty on the cross section

• variation of the direct & resolved fractions $\rightarrow$ typically 2%

• variation of the $\langle \delta Z \rangle$ fit range: $\rightarrow$ typically 2%

systematical uncertainties typically of the same order as statistical



Theoretical predictions: fixed order calculations

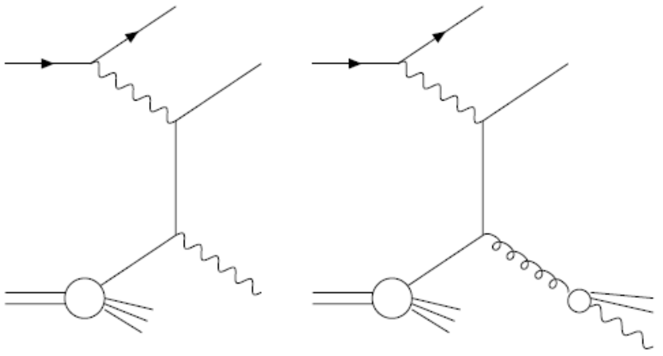


Fig. 1. Examples of direct direct and direct fragmentation contributions at leading order

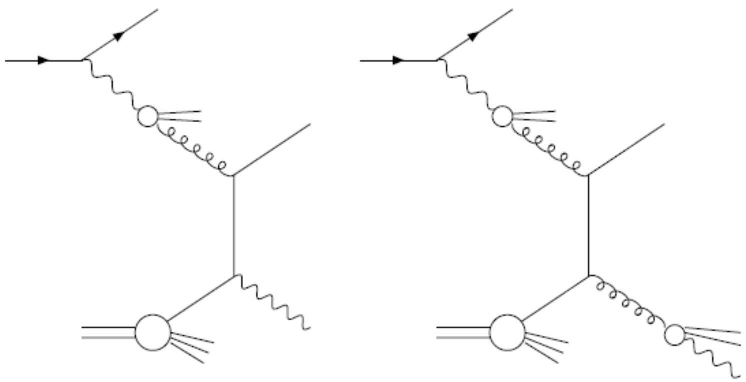


Fig. 2. Examples of resolved direct and resolved fragmentation contributions at leading order

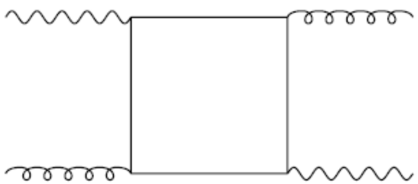


Fig. 3. The box contribution

• by M. Fontannaz, J.Ph. Guillet and G. Heinrich
Eur. Phys. J. C 21 (2001) 303,
Eur. Phys. J. C 34 (2004) 191 (FGH)

• components:
▷ direct direct, ▷ direct fragmentation
▷ resolved direct, ▷ resolved fragmentation
▷ box diagram (direct direct)

• the box contribution is known to be sizable and therefore included, although is formally a NNLO contribution
• fragmentation, renormalisation and factorisation scales where set to $\mu = p_T^\gamma$
• CTEQ6 for the proton and AFG04 for the photon PDFs, respectively

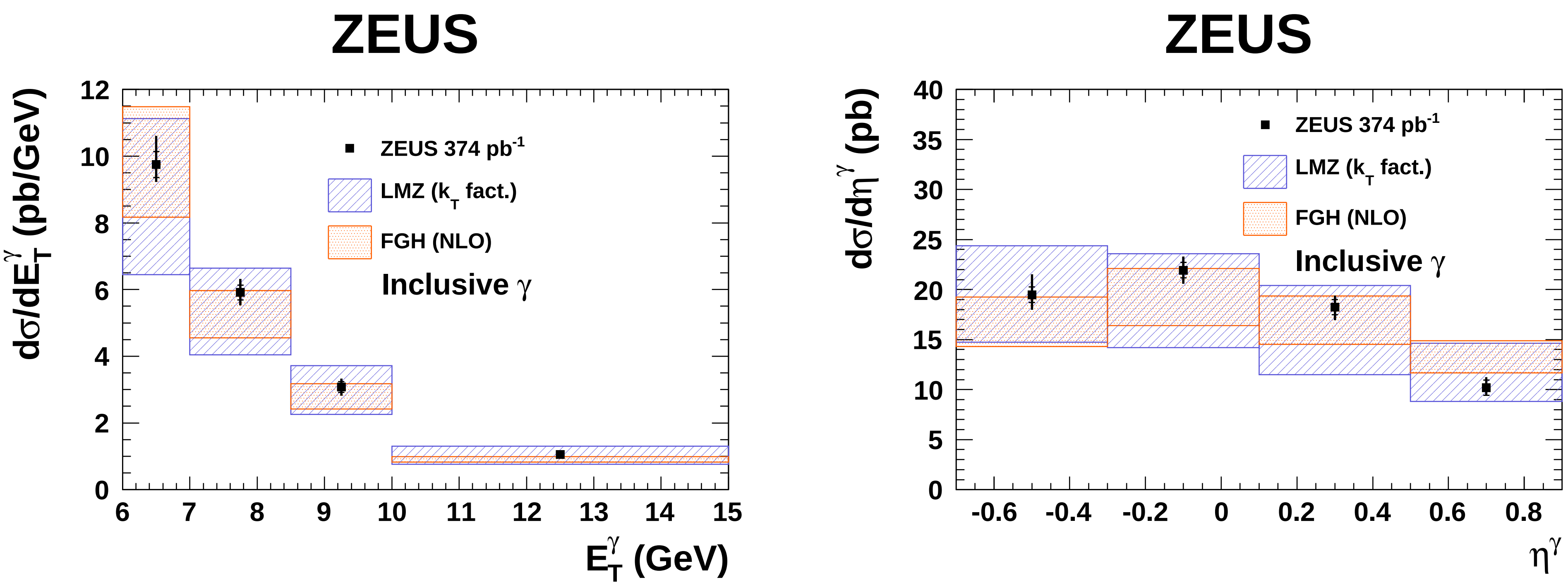
Theoretical predictions: k_T-factorisation approach

• by A.V.Lipatov, M.A. Malyshev, N.P.Zotov: Phys. Rev. D 72 (2005) 054002 (LZ)
Phys. Rev. D 81 (2010) 094027 (LZ)
Phys. Rev. D 88 (2013) 074001 (LMZ)

• investigation of the photoproduction of the isolated photon at HERA in the framework of kt-factorisation QCD approach
• both direct and resolved processes are considered
• the box contribution was included
• fragmentation contribution is neglected
• $\mu_R = \mu_F = E_T^\gamma$
• unintegrated proton parton densities are obtained from the MRST08 PDFs using the KMR formalism

$\rightarrow$ hadronisation corrections were evaluated by MC and applied to both theoretical predictions

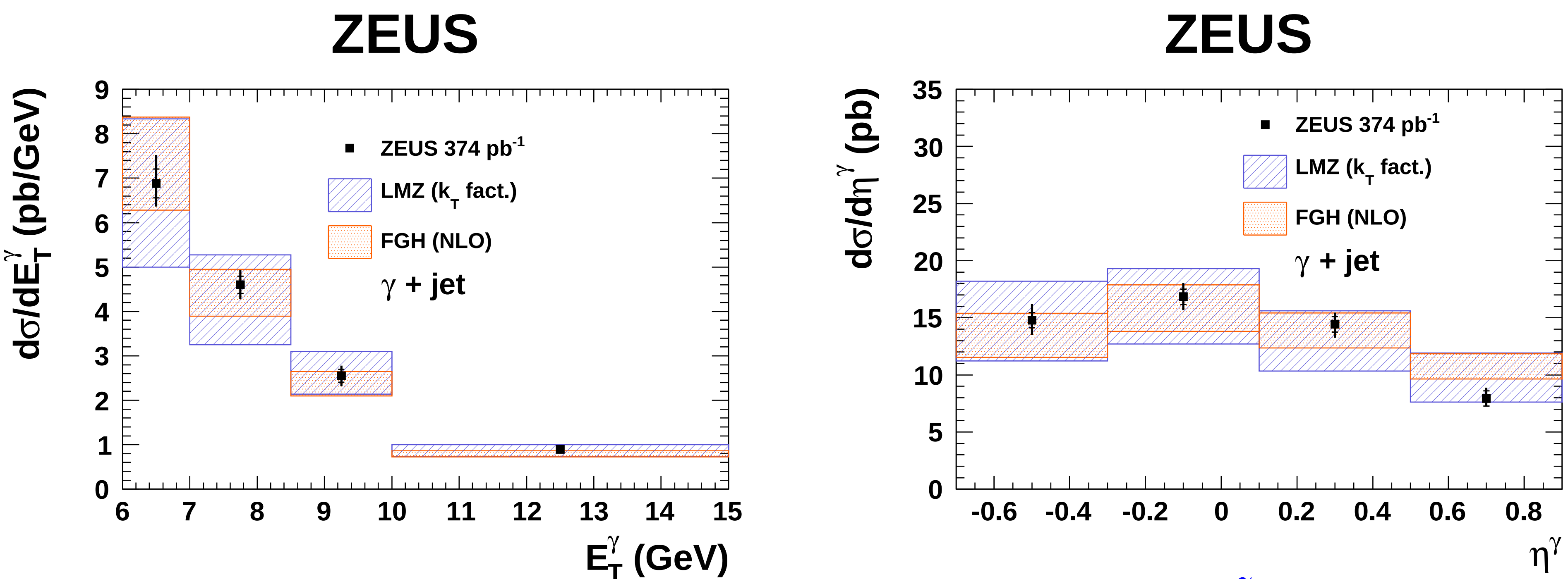
Cross sections: inclusive γ production



$\gamma^* p \to \gamma + \mathrm{X}: \quad 6 < E_T^\gamma < 15\,\mathrm{GeV},\ -0.7 < \eta^\gamma < 0.9,\ \frac{\mathrm{E}^\gamma}{\mathrm{E}^{\mathrm{jet\ containing\ }\gamma}} > 0.9,$
$0.2 < y < 0.7$

- FGH NLO theoretical uncertainty due to missing higher orders: renormalisation scale varied by factor 2 up and down
- uncertainties of the LMZ predictions are mainly due to the scale variation
- both predictions agree very well with the data
- experimental uncertainties are substantially smaller than those on theory

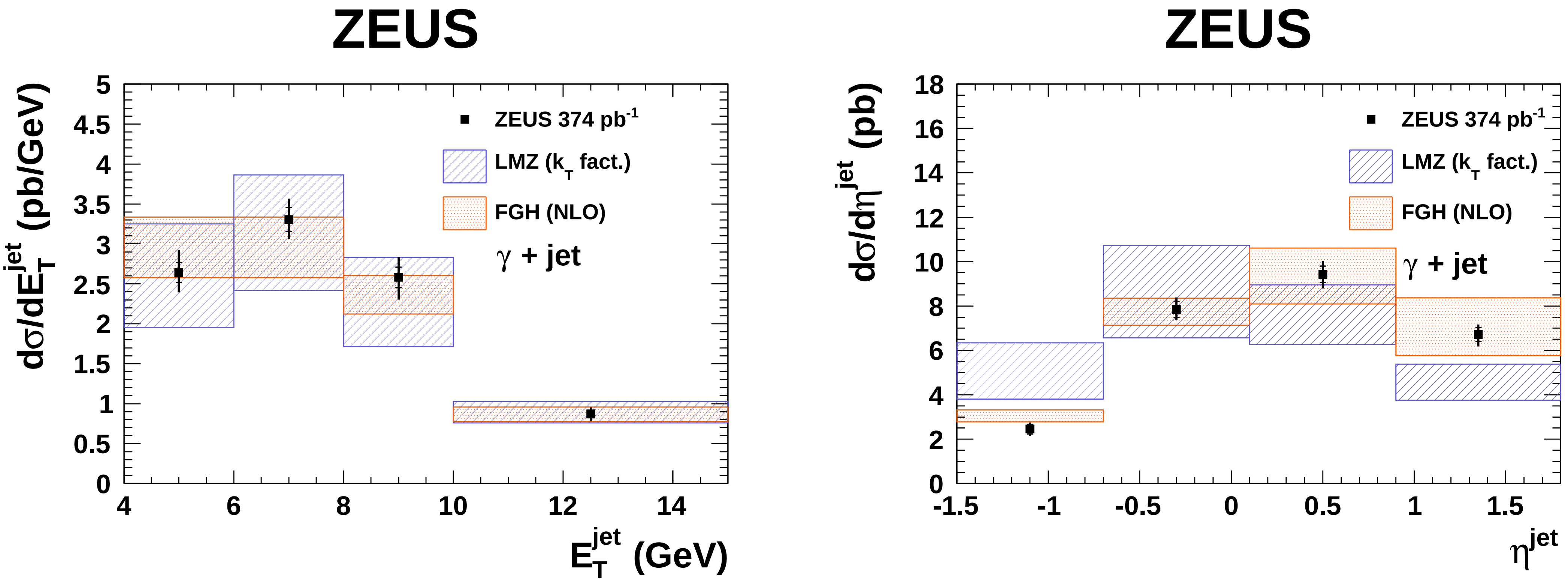
Cross sections: γ + jet (1/3)



$\gamma^* p \to \gamma + \mathrm{jet} + \mathrm{X}: \quad 6 < E_T^\gamma < 15\,\mathrm{GeV},\ -0.7 < \eta^\gamma < 0.9,\ \frac{\mathrm{E}^\gamma}{\mathrm{E}^{\mathrm{jet\ containing\ \gamma}}} > 0.9,$
$0.2 < y < 0.7,\ 4 < E_T^{\mathrm{jet}} < 35\,\mathrm{GeV},\ -1.5 < \eta^{\mathrm{jet}} < 1.8$

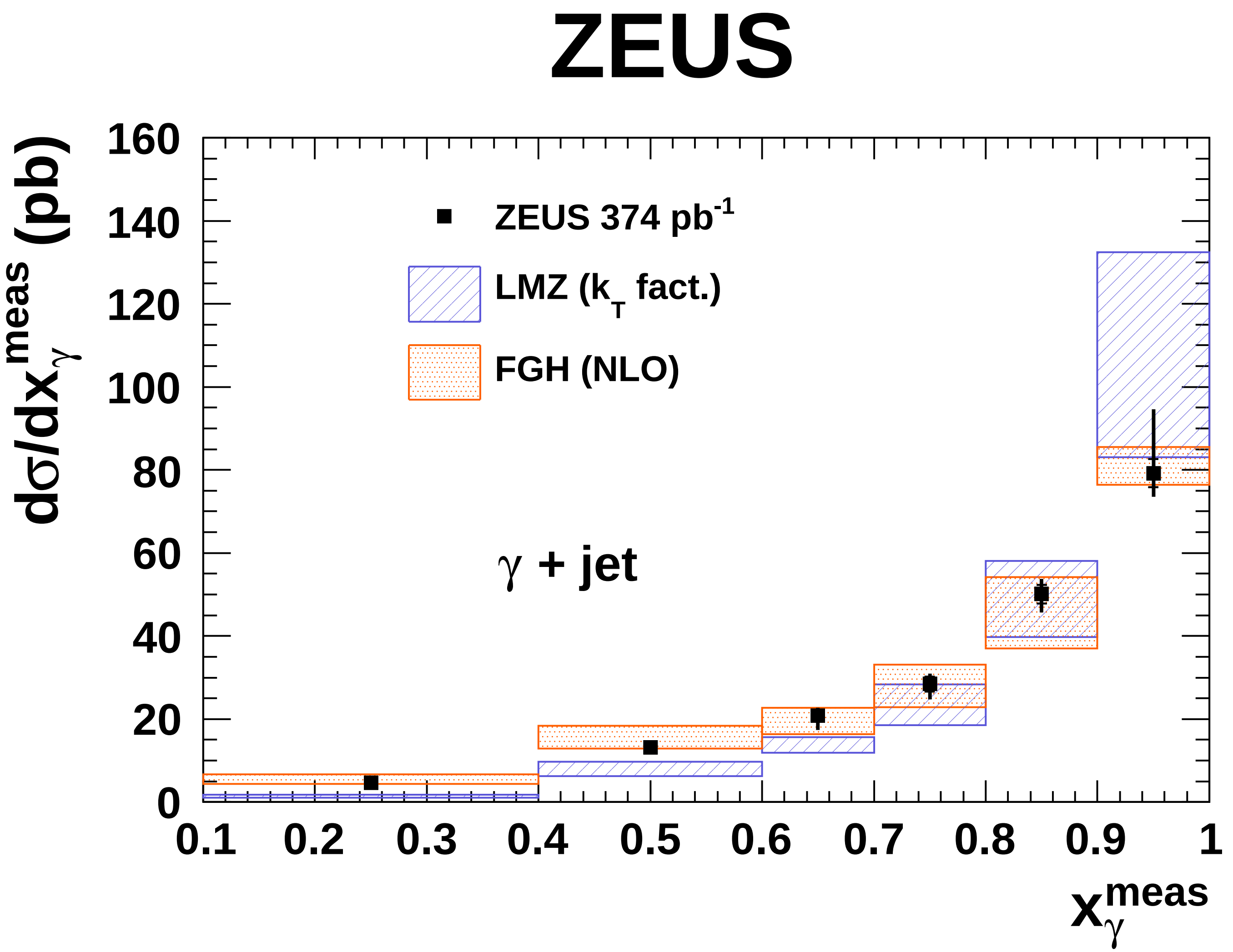
- FGH NLO theoretical uncertainty due to missing higher orders: renormalisation scale varied by factor 2 up and down
- uncertainties of the LMZ predictions are mainly due to the scale variation
- both predictions agree very well with the data
- theoretical uncertainties for both predictions are smaller for $\gamma + \mathrm{jet}$ compared with inclusive γ production

Cross sections: γ + jet (2/3)



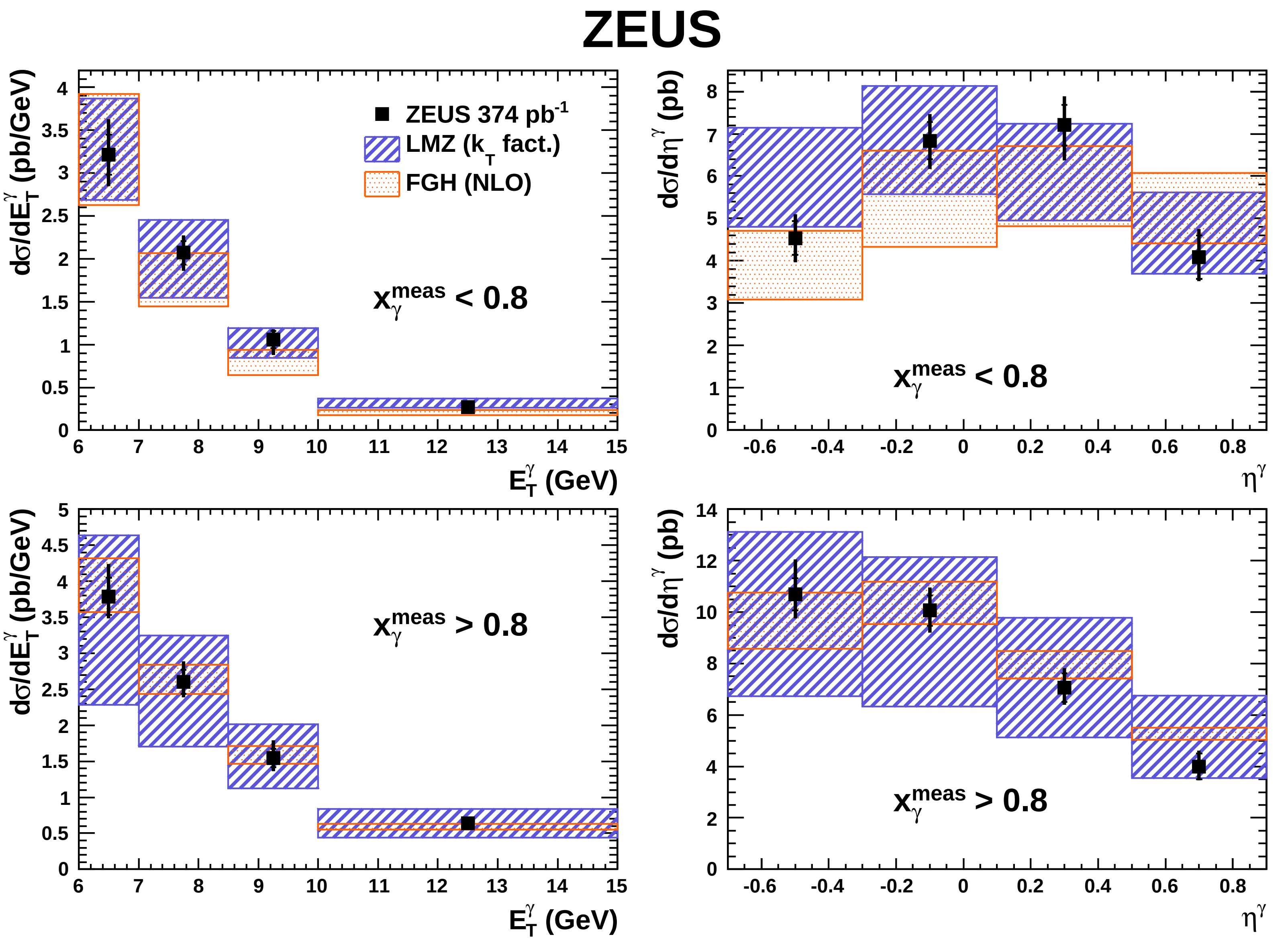
- fixed order FGH predictions give better description of the $\eta^{\rm jet}$ shape
- in normalisation both agree well with experimental results

Cross sections: γ + jet (3/3)



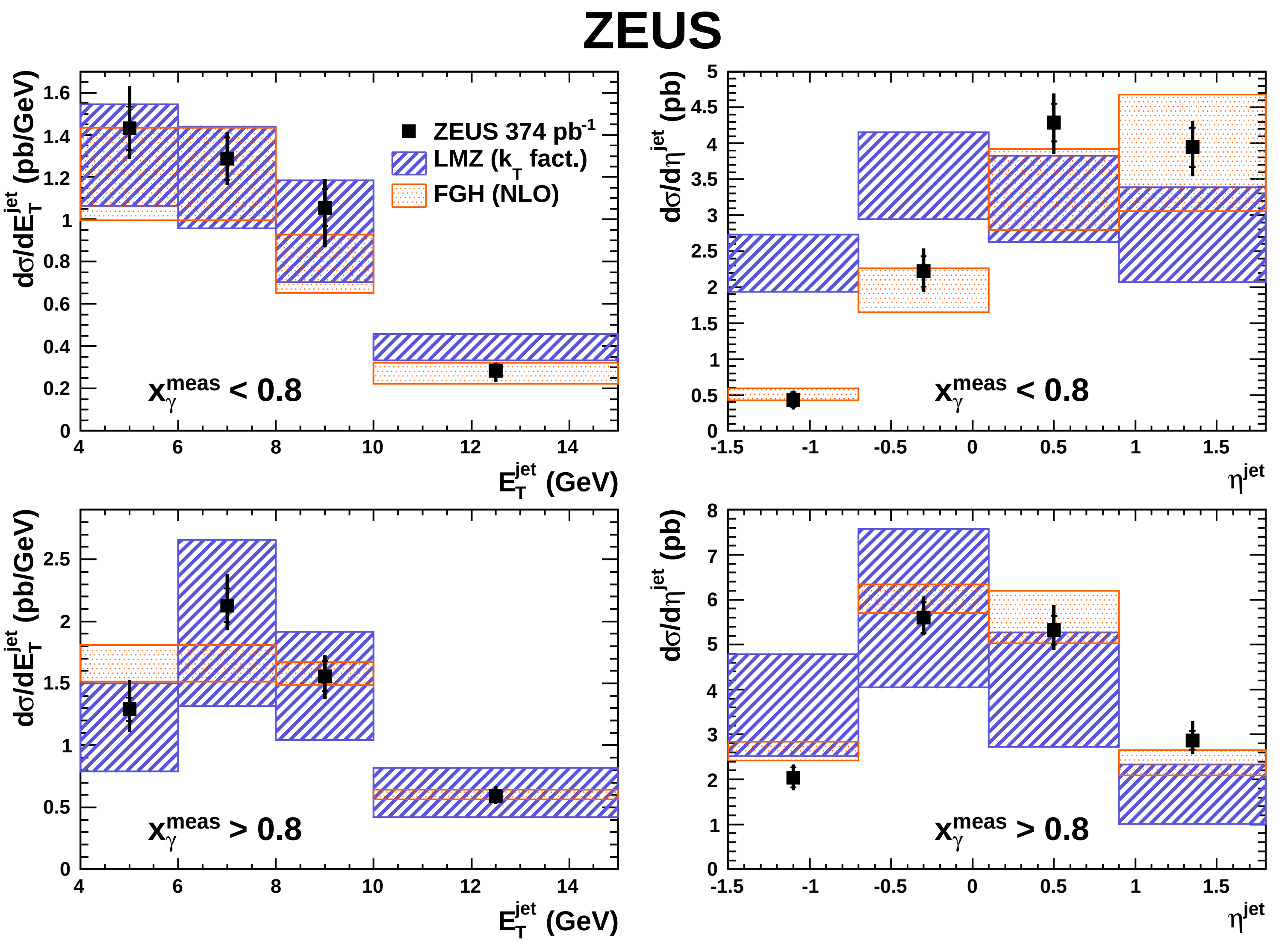
- very good description of the x_γ^{meas} by FGH
- reasonable description by LMZ (typically theory within 1-2 sigma from data)

Cross section as function of photon variables in bins of x_γ^{meas}



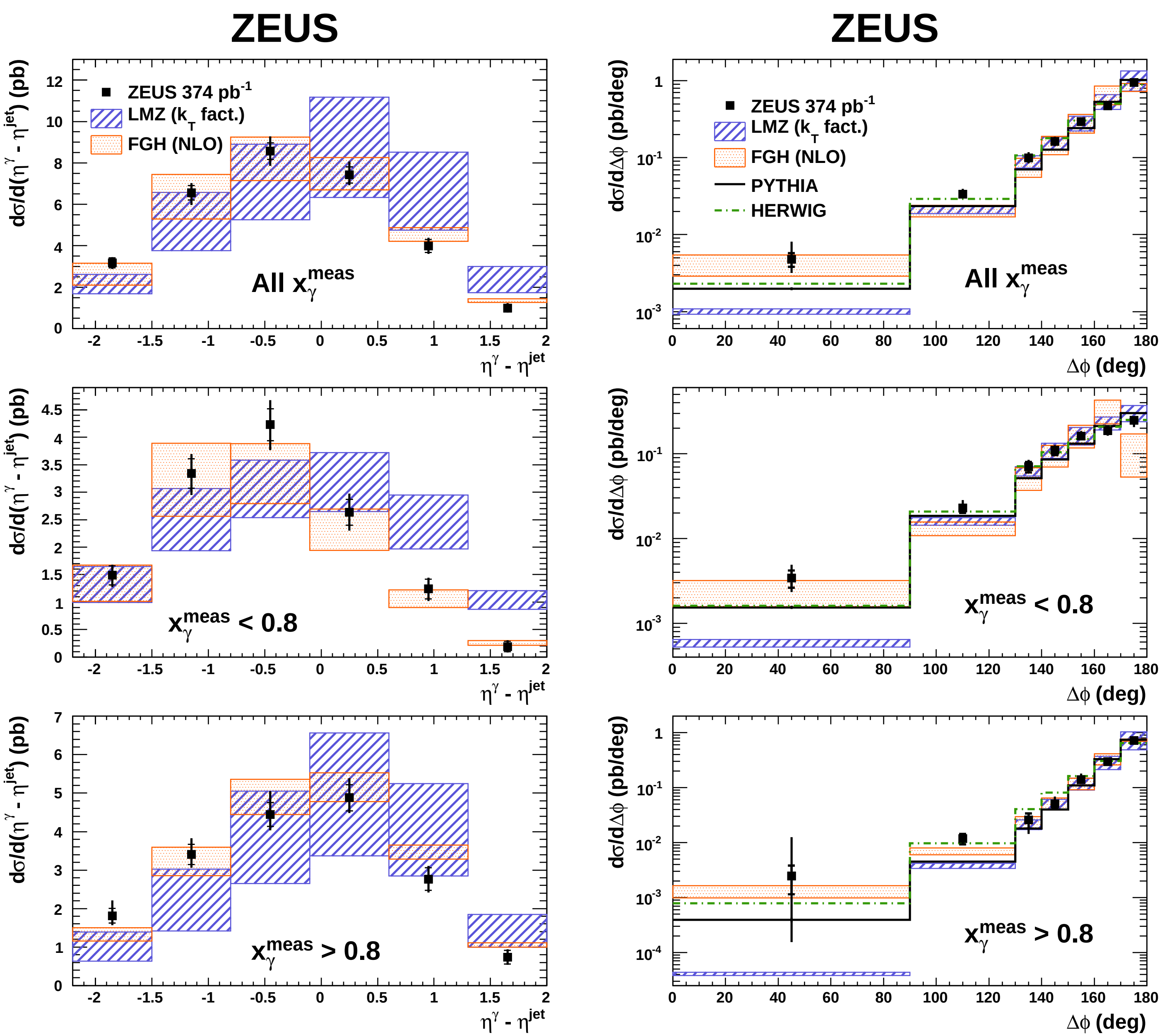
- both theories within large uncertainties agree well with the data

Cross section as function of jet variables in bins of x_γ^{meas}



• both theories within large uncertainties agree well with the data, except LMZ in η_{jet} at $x_\gamma^{\mathrm{meas}} < 0.8$ (probably connected with setting the rapidity of the jet coming from the evolution cascade)

Comparison to NLO in bins of x_γ^{meas}



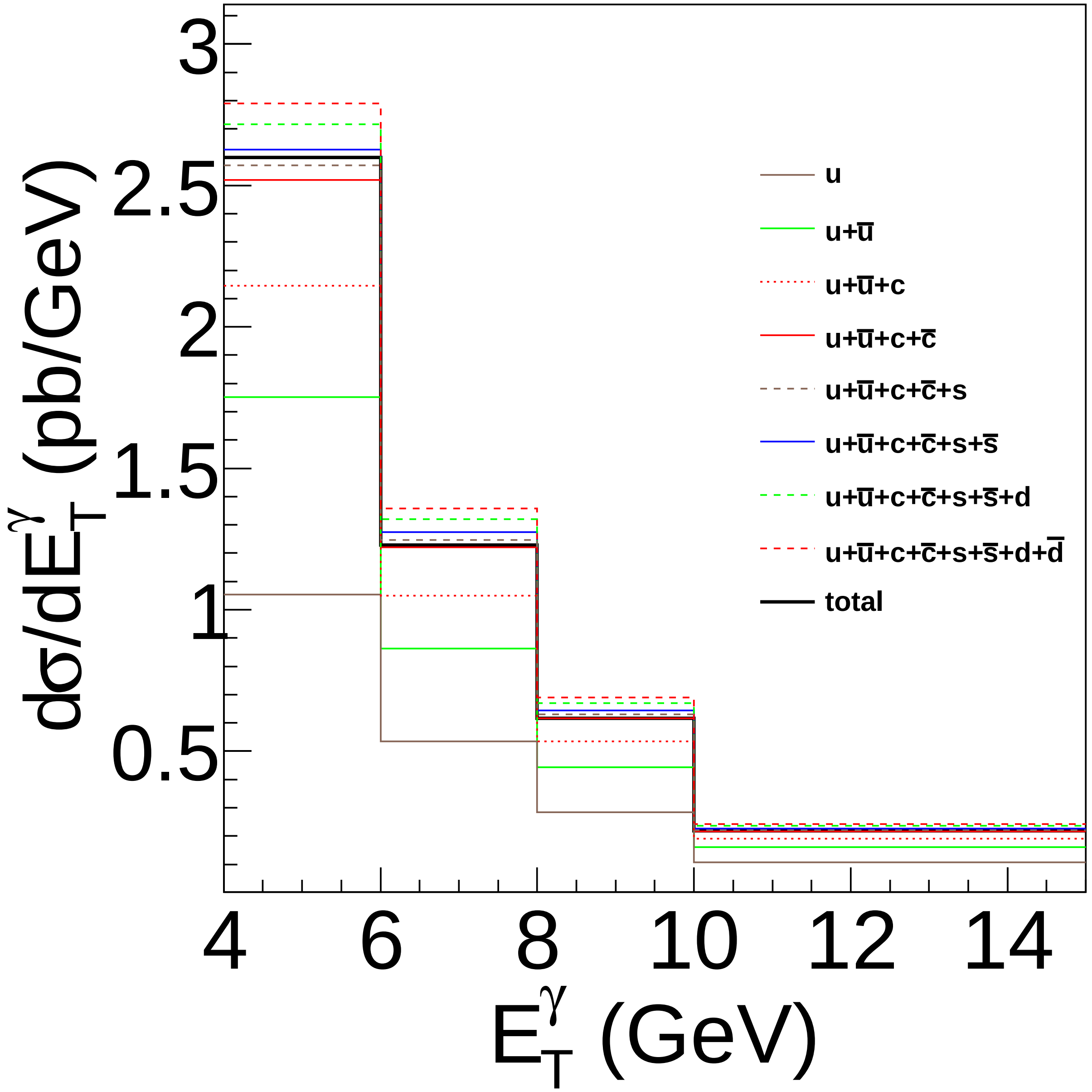
- good agreement within large theoretical uncertainties

Summary

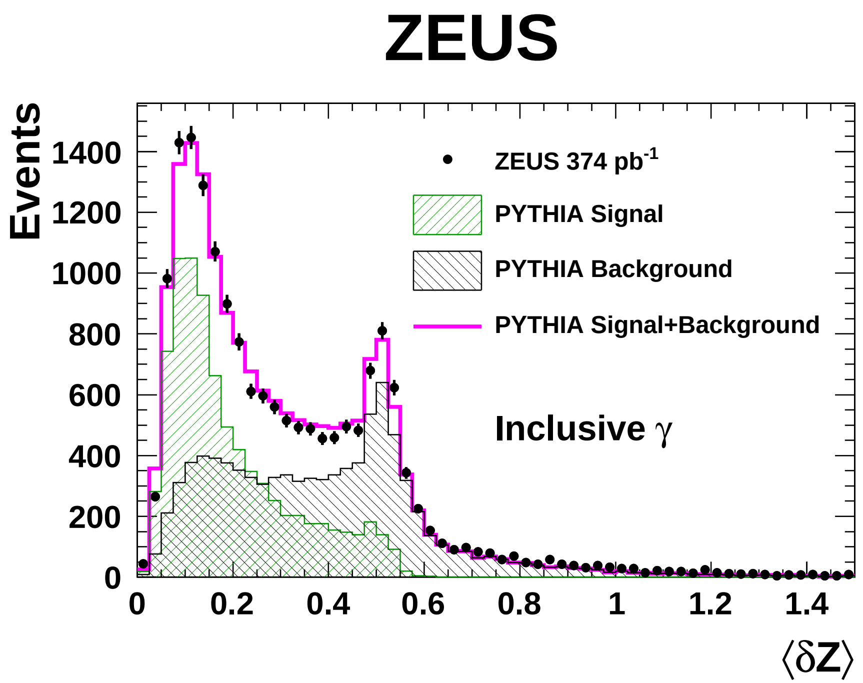
Photoproduction of γ and $\gamma + \mathrm{jet}$

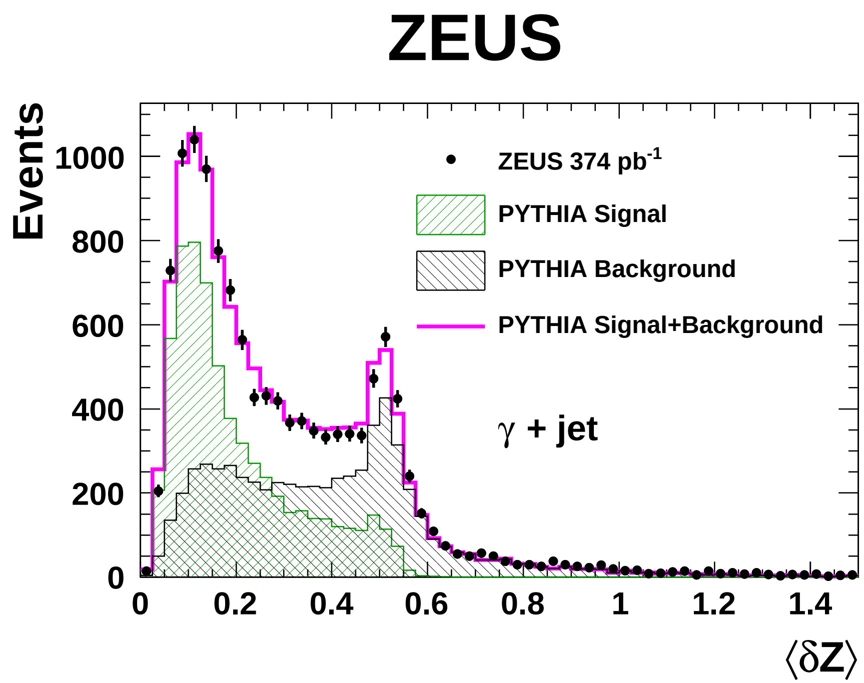
- cross sections of the photoproduction of isolated photons, both inclusive and with accompanying jet, have been measured by ZEUS
- ... and compared to two theoretical models: fixed order NLO and k_T factorisation approach
- predictions give good description of the data
- uncertainties of the data are much smaller than uncertainties of both predictions
- cross sections were measured differentially in resolved-enhanced and direct-enhanced regions $\Rightarrow$ **more detailed study of photoproduction process**
- new observables measured that are sensitive to higher order radiation
- the double differential cross sections are potentially significant input to future photon PDF fits

Contributions from different flavours to the NLO cross section



Extraction of the signal





More cross sections