Isolated Photons + Jets in DIS and Photoproduction at ZEUS

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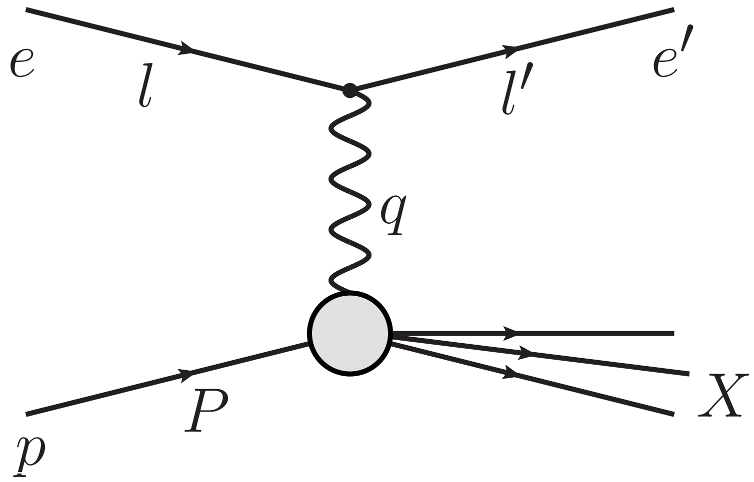
DIS: Phys. Lett. B 715 (2012) 88-97
Photoproduction: ZEUS-prel-13-001

HERA collider

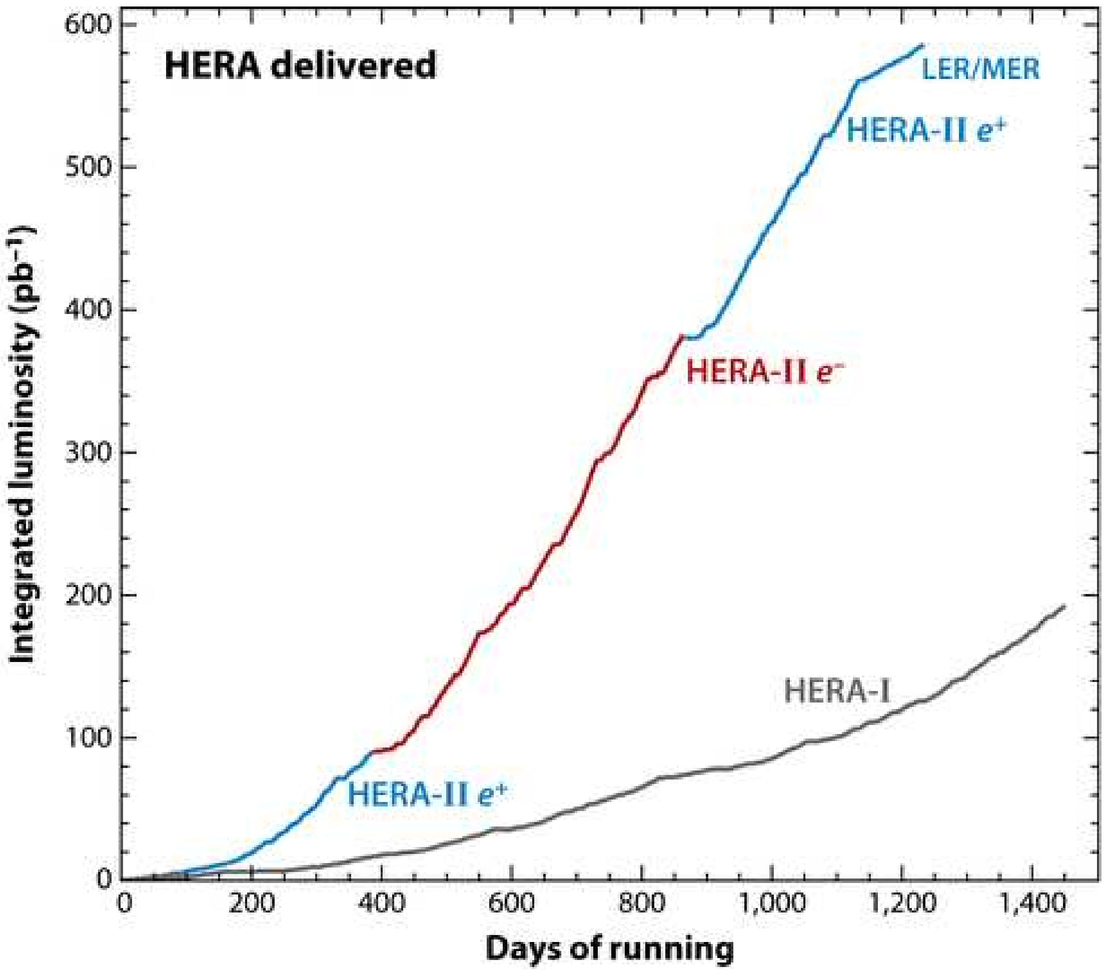


Electrons: 27.5 GeV
Protons: 920 GeV
$\sqrt{s} = 318$ GeV

Kinematics:
$Q^2 = -q^2 = -(l - l')^2$
$y = \frac{Pq}{Pl}$
$x_{Bj} = \frac{Q^2}{2Pq}$
$Q^2 = x_{Bj} y s$

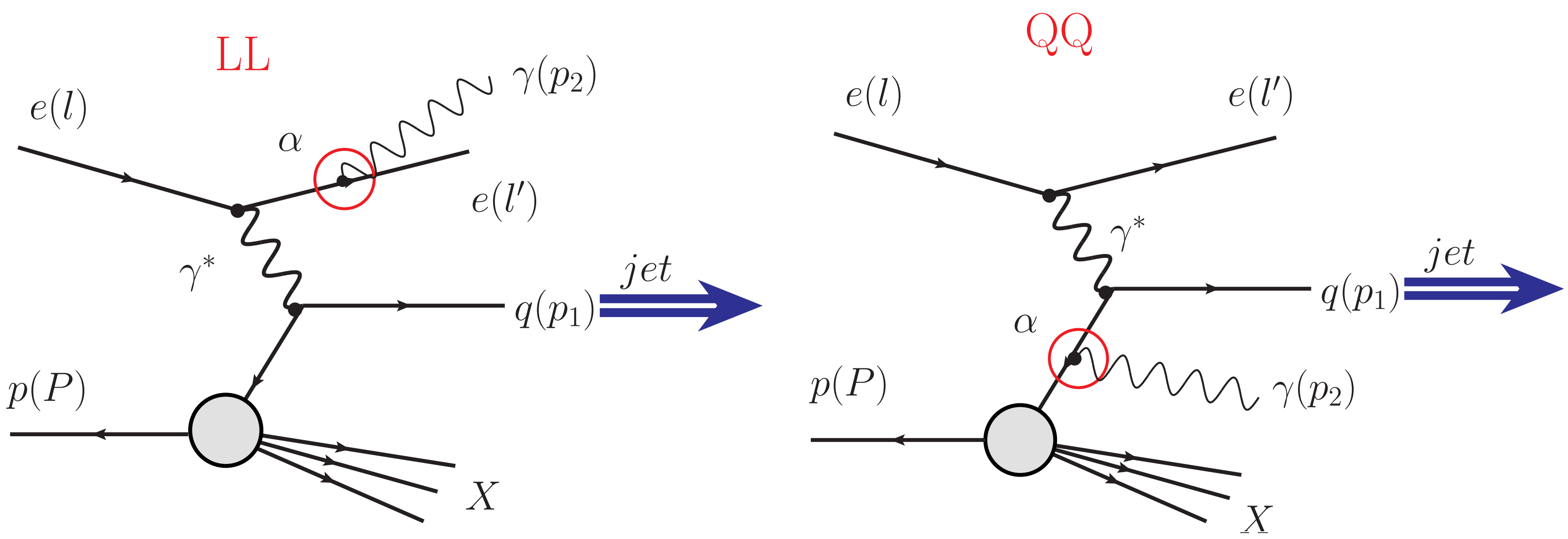
$Q^2 \lesssim 1$ GeV^2: photoproduction (PHP)

$Q^2 \gtrsim 1$ GeV^2: DIS



Isolated photons with jets in DIS

Isolated photons production in DIS



- Isolated photon production:
  - LL-radiation (ISR, FSR)
  - QQ-radiation (incoming or outgoing quark)
- Isolated photons:

- do not undergo hadronisation process, therefore provide a direct probe of the underlying partonic process
- allow to test QCD matrix elements
- 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 $\approx 330\,\mathrm{pb}^{-1}$ (data taken between 2004-2007)

Observables:
- $Q^2 = -q^2 = -(l - l')^2$
- $x = \frac{Q^2}{2pq}$
- 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

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 for the simulation of the QQ-radiation
- Ariadne for the simulation of the LL-radiation and background

Event selection and reconstruction (2/2)

Deep inelastic scattering

- $10 < Q^2 < 350\,\text{GeV}^2$

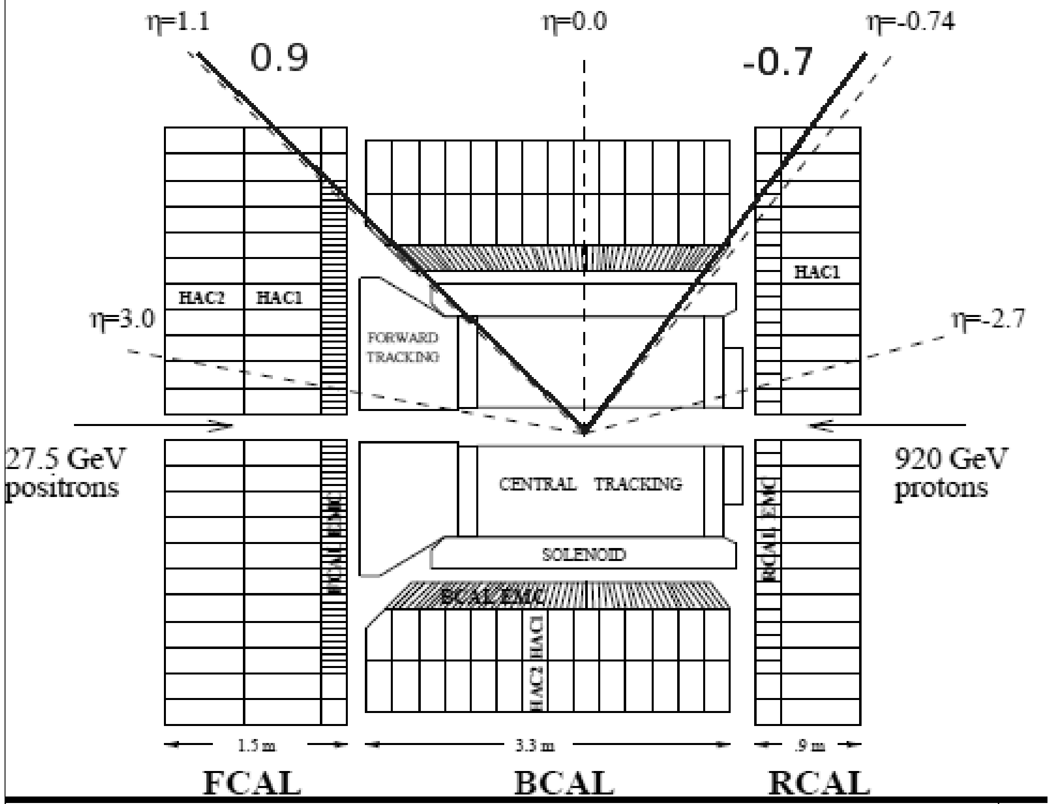
- $-40 < Z_{\text{vtx}} < 40\,\text{cm}$
- $35 < E - p_z < 65\,\text{GeV}$
- $E_{electron} > 10\ \text{GeV}$
- $140° < \theta_{el} < 180°$

Photon

- $4 < E_T^{\gamma}/\text{GeV} < 15$
- $-0.7 < \eta^{\gamma} < 0.9$
- $\Delta R < 0.2$
- $\frac{E_{EMC}}{E_{HAC}+E_{EMC}} > 0.9$
- $\frac{E_T^{\gamma}}{E_{jet\ containing\ \gamma}} > 0.9$

Accompanying jet

- $E_T^{\text{jet}} > 2.5\,\text{GeV}$
- $-1.5 < \eta^{\text{jet}} < 1.8$



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 %)

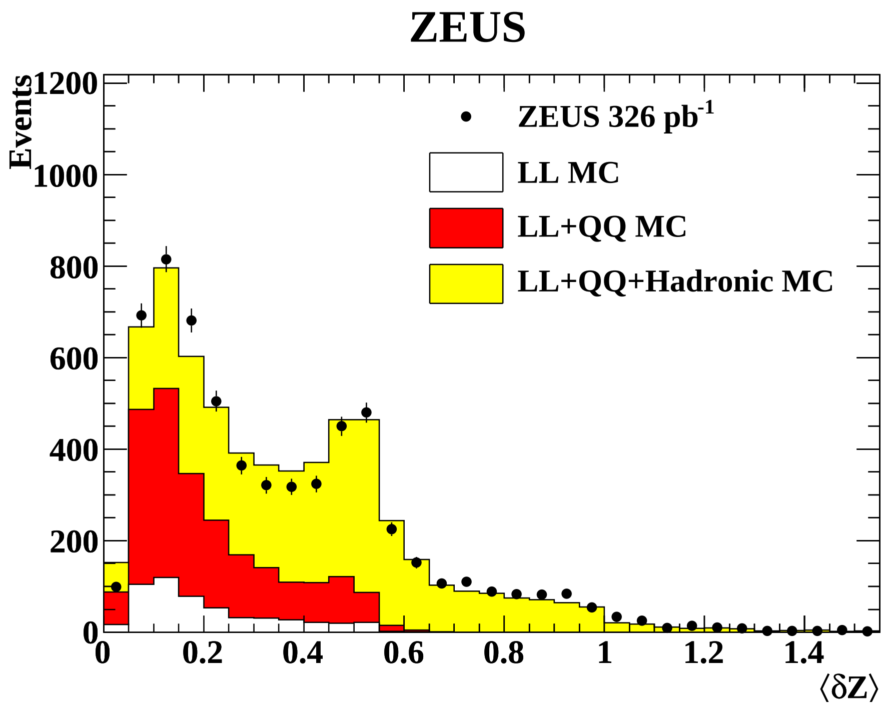
  $\to$ it is the main source of the background
  $\to$ opening angle of two photons after π^0 decay:

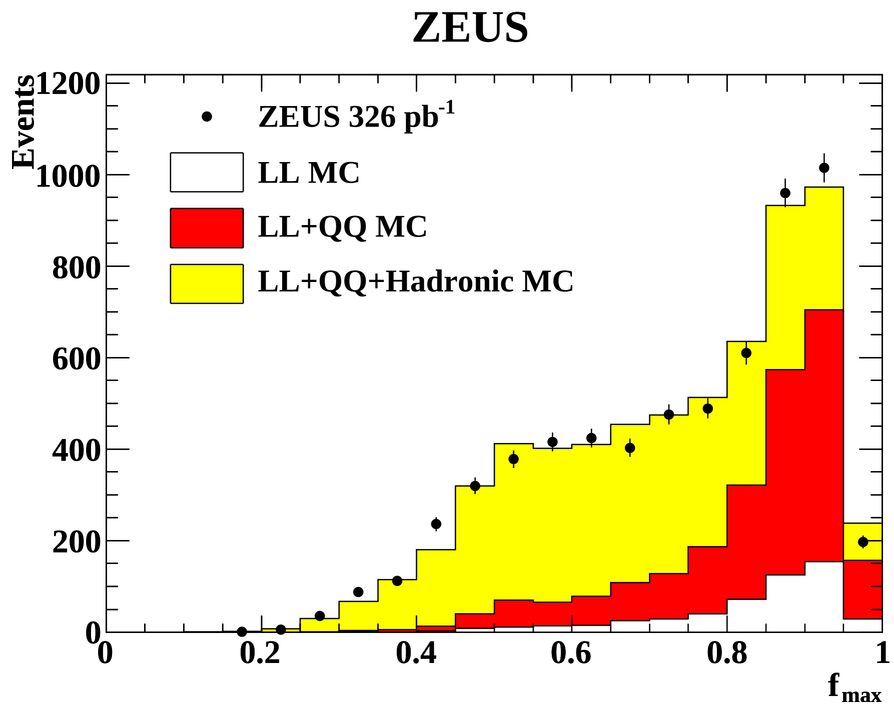
  $$\sin\frac{\phi}{2} = \frac{m}{E}$$

  At $E = 5$ GeV $\phi = 1.55^\circ$ for π^0 and $\phi = 6.3^\circ$ for η-mesons
  $\to$ there is a possibility to use shower shape method
- Photons from quark to photon fragmentation
  $\to$ this process occurs over long distances and cannot be calculated perturbatively
  $\to$ easy to suppress by applying of the isolation cut

Extraction of the signal

Following variables are using to describe the shower shape:



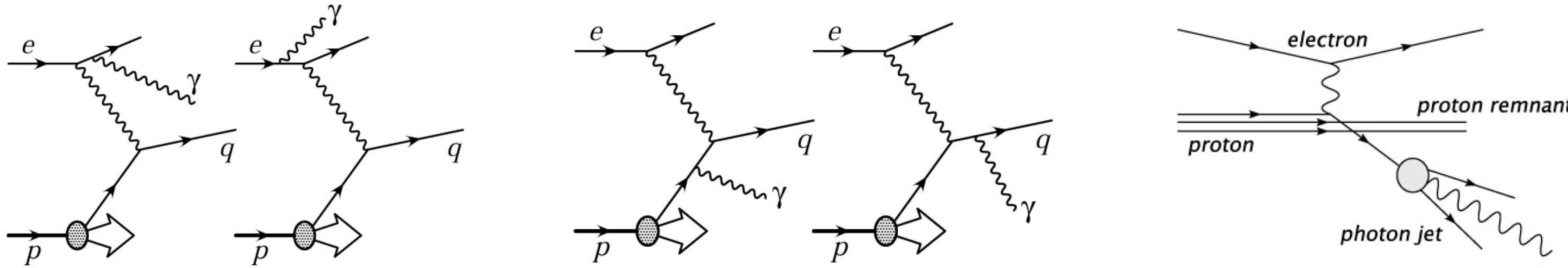


$$\langle \delta z \rangle = \frac{\Sigma |z_i - z_{cluster}| \cdot E_i}{l_{cell} \Sigma \ \mathrm{E_i}} \qquad f_{max} = \frac{\text{Energy in the most energetic BEMC cell}}{\text{Total energy of the cluster}}$$

$\rightarrow$ mixture of different type Monte Carlo events is used to fit the data distribution
$\rightarrow$ $\langle \delta z \rangle$ variable is used for the signal extraction, because it carries more information

Theoretical predictions: fixed order calculations

- Theoretical prediction of A. Gehrmann-De Ridder, G. Kramer and H. Spiesberger (Nucl. Phys. B. 578 (2000) 326) (GKS)
- LO(α^3) with three components:



- (LEFT) LL radiation, (MIDDLE) QQ radiation, (RIGHT) photon from jet fragmentation
- LO(α^3) and NLO($\alpha^3\alpha_s$) predictions are calculated
- renormalisation and factorisation scales $\mu_R = \mu_F = \sqrt{Q^2 + (p_T^{\mathrm{jet}})^2}$

$$d\sigma = \sum_n \alpha_s^n \sum_{a=q,\bar{q}} \int dx f_a\left(x, \mu_F^2; \alpha_s\right) \cdot d\hat{\sigma}_a^{(n)}\left(xP, \mu_R, \mu_F\right)$$

- HERAPDF1.0 for PDF parametrisation

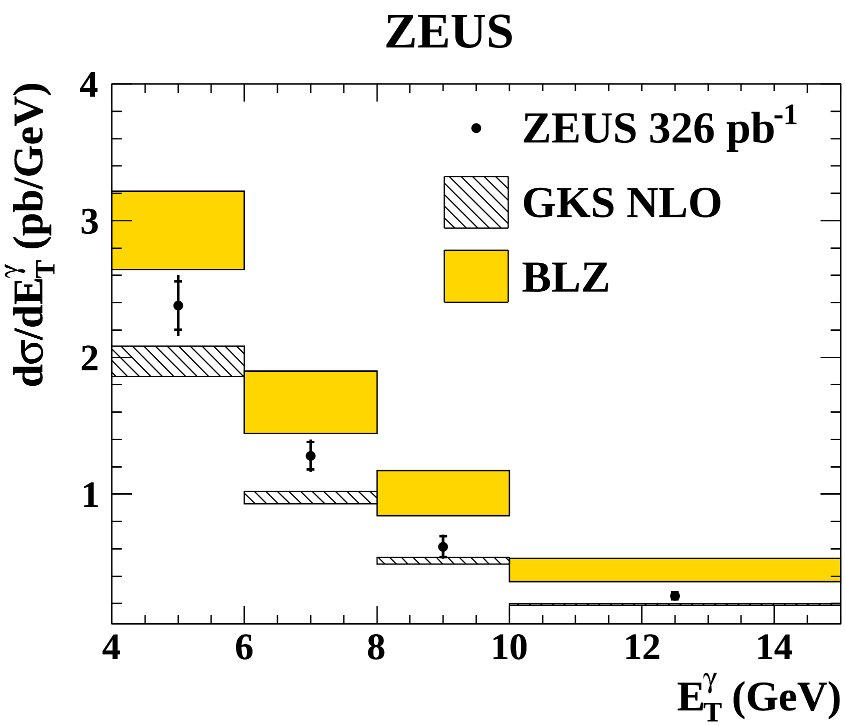
Theoretical predictions: k_T-factorisation approach

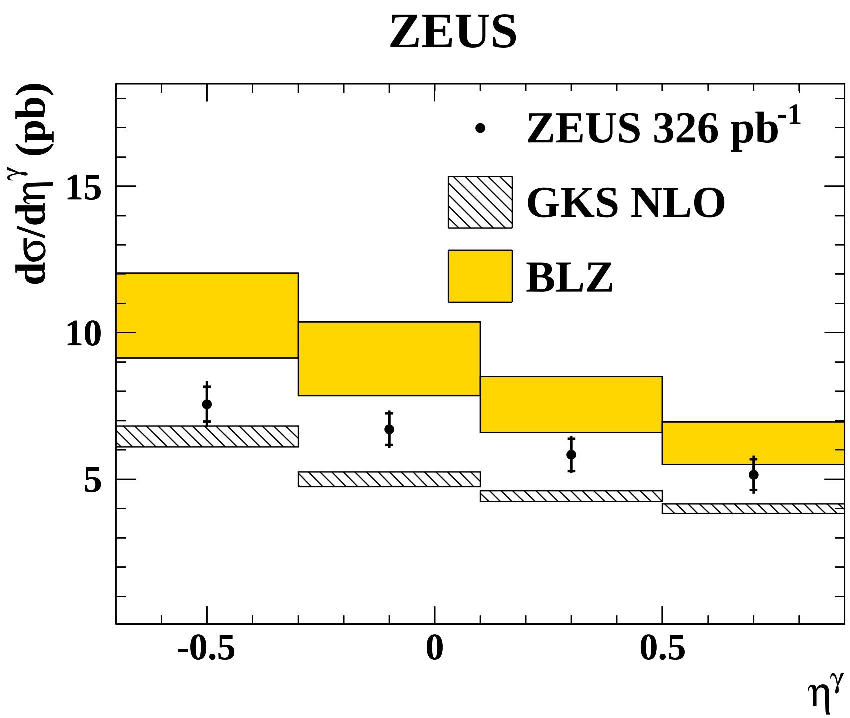
• Calculated by S.P.Baranov, A.V.Lipatov, N.P.Zotov (Phys.Rev.D81:094034,2010) (BLZ):
• investigation of the prompt photon production in DIS at HERA in the framework of kt-factorisation QCD approach
• based on the off-shell partonic amplitude $eq^* \to e\gamma q$
• taken into account photon radiation from the leptons as well as from the quarks
• unintegrated proton parton densities are used in the KMR form

$$\sigma_{LL,\,QQ}(ep \to e\gamma X) = \sum_q \int \frac{1}{256\pi^3 x^2 s\sqrt{s}|\mathbf{p}_{\gamma\,T}|\exp(y_\gamma)} |\bar{\mathcal{M}}_{LL,\,QQ}(eq^* \to e\gamma q)|^2 \times$$
$$\times f_q(x, \mathbf{k}_T^2, \mu^2) d\mathbf{p}_{e'\,T}^2 d\mathbf{p}_{q\,T}^2 d\mathbf{k}_T^2 dy_{e'} dy_q \frac{d\phi_{e'}}{2\pi}\frac{d\phi_q}{2\pi}\frac{d\phi}{2\pi},$$

• In the kt-factorisation approach the contribution from the quark radiation subprocess (QQ mechanism) is enhanced compared to the leading-order collinear approximation

Cross sections (1/2)

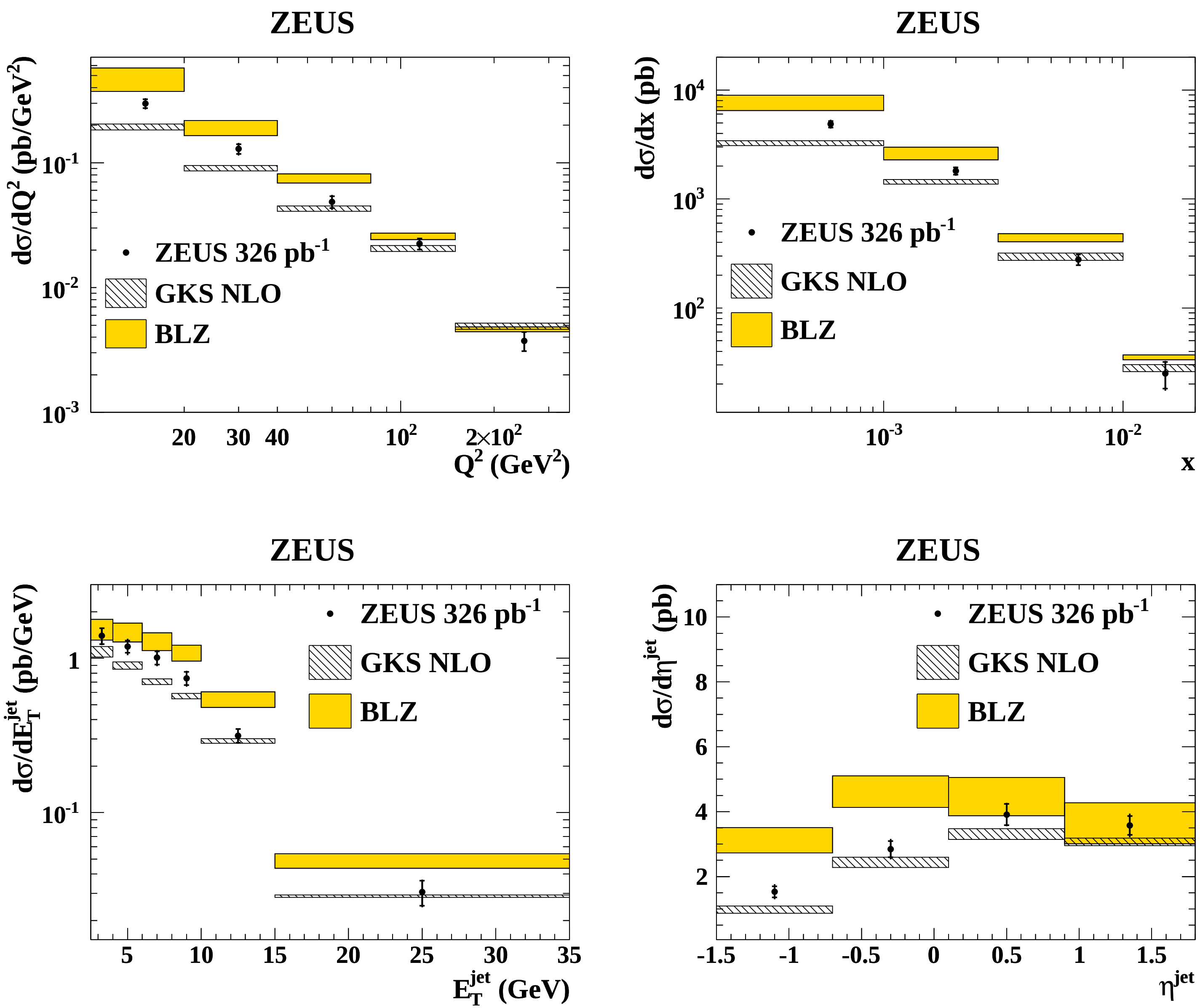




$4 < E_T^\gamma < 15\,\mathrm{GeV},\ -0.7 < \eta^\gamma < 0.9,\ \frac{\mathrm{E}^\gamma}{\mathrm{E}^{\mathrm{jet\ containing\ }\gamma}} > 0.9,$
$10 < Q^2 < 350\,\mathrm{GeV}^2,\ \mathrm{E_{elec}} > 10\,\mathrm{GeV},\ 140^\circ < \theta_{\mathrm{elec}} < 180^\circ,$
$E_T^{\mathrm{jet}} > 2.5\,\mathrm{GeV},\ -1.5 < \eta^{\mathrm{jet}} < 1.8$

- The width of the GKS NLO predictions represents theoretical uncertainty due to factorisation and renormalisation scales, varied independently by factor 2 up and down
- The width of the BLZ predictions shows the uncertainty due mainly to the procedure of fixing the rapidity of the jets from the evolution cascade in the factorisation approach
- GKS predictions systematically underestimate data and BLZ overestimate them

Cross sections (2/2)



- GKS predictions give better description of the η^{jet} shape

Isolated photons with and without jets in photoproduction

Event selection and signal extraction

- integrated luminosity of $\approx 370\,\mathrm{pb}^{-1}$ (HERA-II data)

Phase space:
- PHP: $Q^2 < 1\,\mathrm{GeV}^2$
- photon: $6 < E_T^{\gamma}/\mathrm{GeV} < 15$, $-0.7 < \eta^{\gamma} < 0.9$
- accompanying jet: $4 < E^{\mathrm{jet}}/\mathrm{GeV} < 35$, $-1.5 < \eta^{\mathrm{jet}} < 1.8$

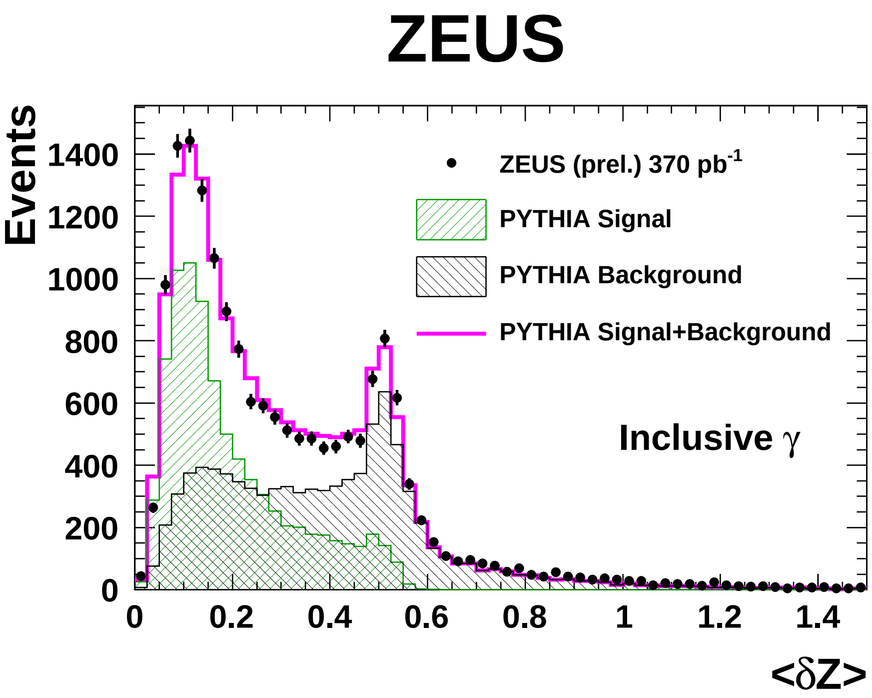
Photon isolation:
- no tracks within $\Delta R(\eta, \phi) = 0.2$ cone around the photon candidate
- ratio of the energy of the photon candidate to the energy of the jet containing it greater than 0.9

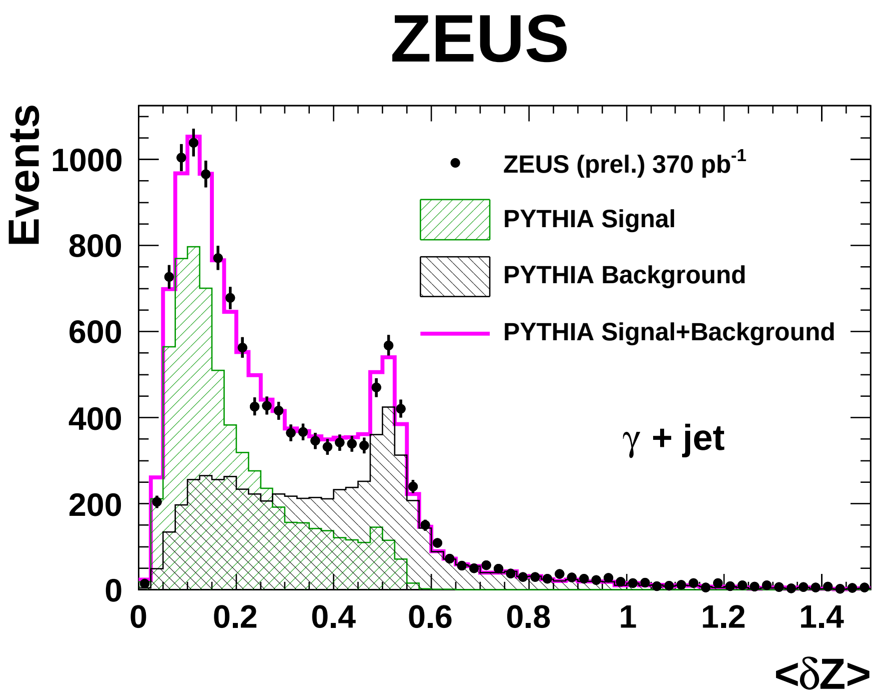
Observables:
- transverse energy E_T^{γ} and pseudorapidity η^{γ} of the photon
- transverse energy E_T^{jet} and pseudorapidity η^{jet} of the accompanying jet

Monte Carlo:
- Pythia for both signal and background samples

$\langle \delta z \rangle$ variable to extract an isolated photon signal

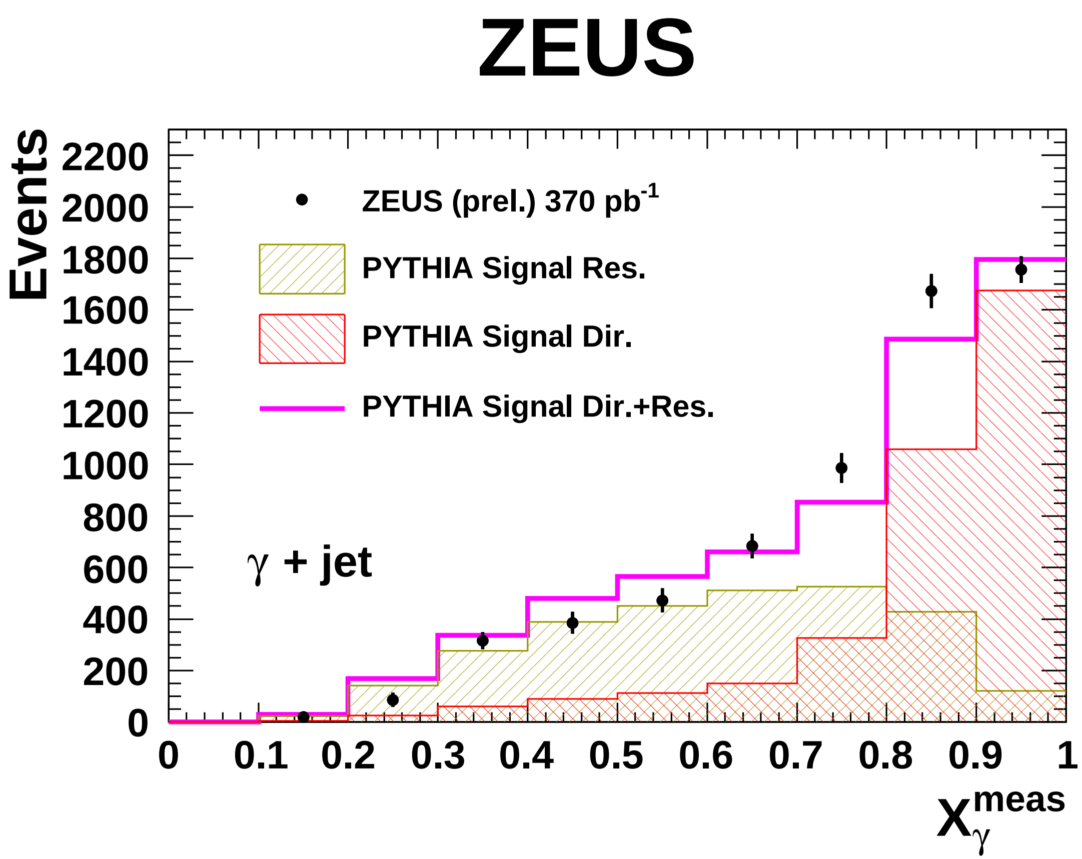
Fit of $\langle \delta z \rangle$





- fit was performed in each cross section bin
- fraction of signal events is enhanced when measuring γ + jet

Direct/resolved fractions in the MC mixture



Fit Monte Carlo to the data using x_γ variable

$$x_\gamma^{meas} = \frac{E^\gamma + E^{\text{jet}} - p_Z^\gamma - p_Z^{\text{jet}}}{E^{\text{event}} - p_Z^{\text{event}}}$$

In LO, x_γ is a fraction of the incoming photon energy given to the final state photon and jet

Theoretical predictions

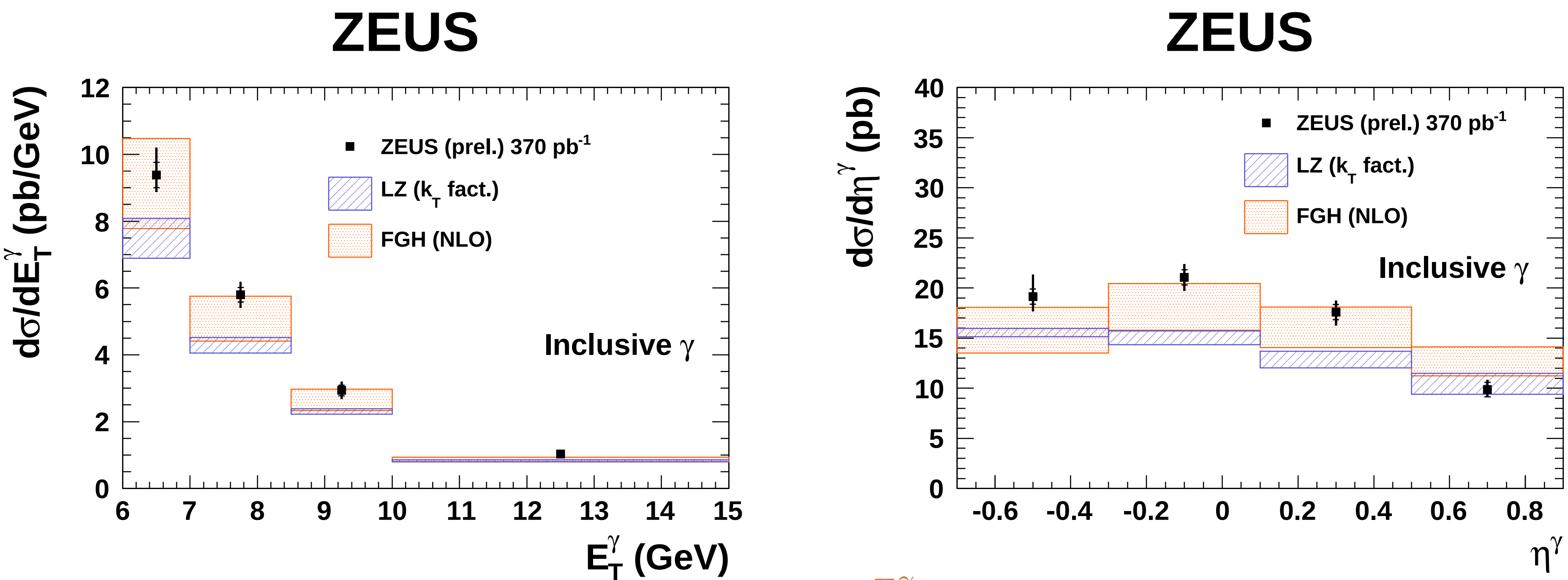
Fixed order calculations by M. Fontannaz, J.-P. Guillet, G. Heinrich (FGH)

- LO and NLO and the box diagram term calculated explicitly
- Fragmentation processes calculated in terms of a fragmentation function.
- Renormalisation scale gives an uncertainty
- MRST03 for proton and AFG04 for photon PDFs

k_T-factorisation method A. V. Lipatov, N. P. Zotov (LZ):

- use of unintegrated proton and photon parton densities at LO
- Uncertainties come from renormalisation and factorisation scales varied by factors 0.5 and 2 simultaneously
- MSTW2008 for proton and GRV92 for photon PDFs

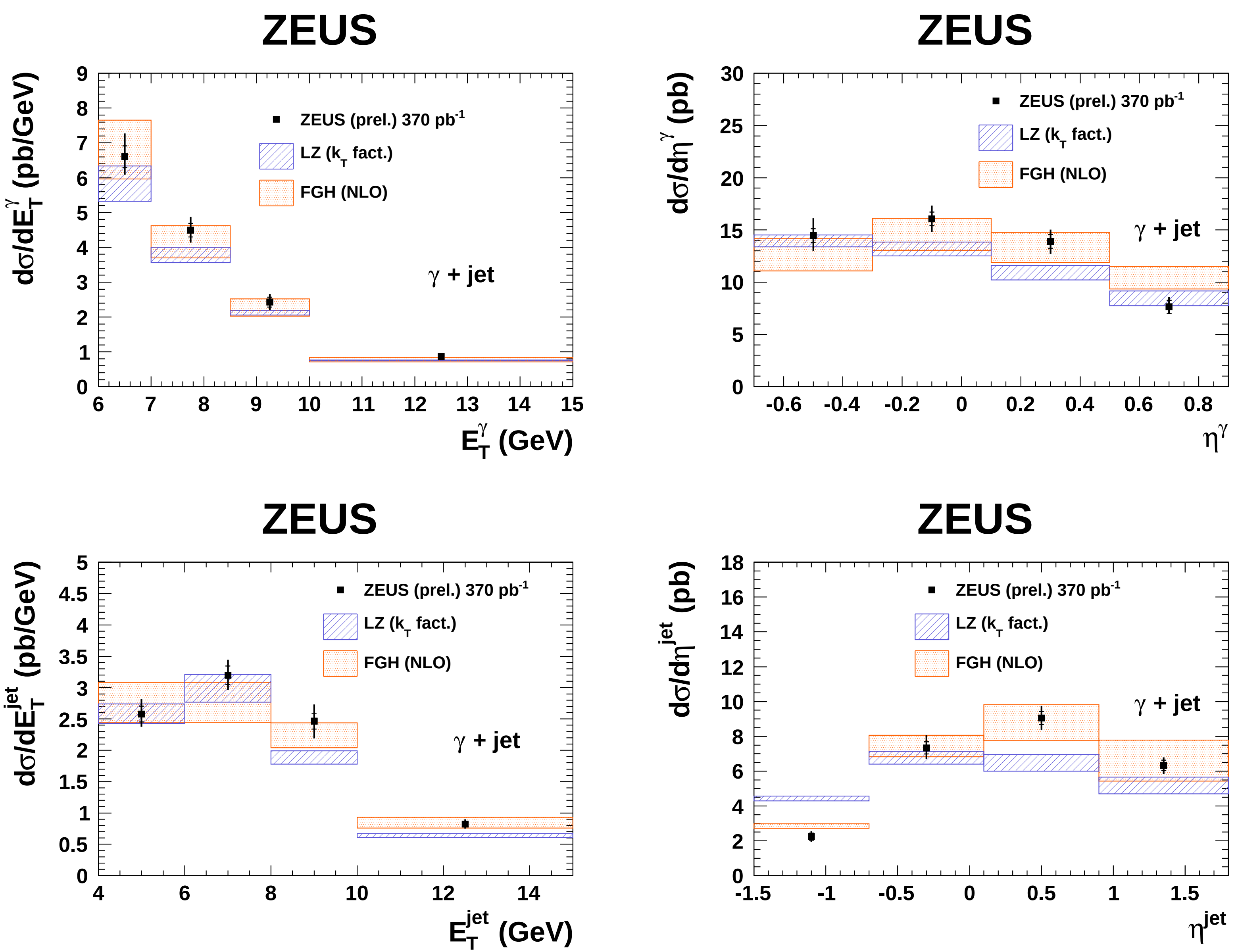
Inclusive photon production



$\gamma p,\ 6 < E_T^\gamma < 15\,\mathrm{GeV},\ -0.7 < \eta^\gamma < 0.9,\ \frac{E^\gamma}{E^{\text{jet containing }\gamma}} > 0.9$

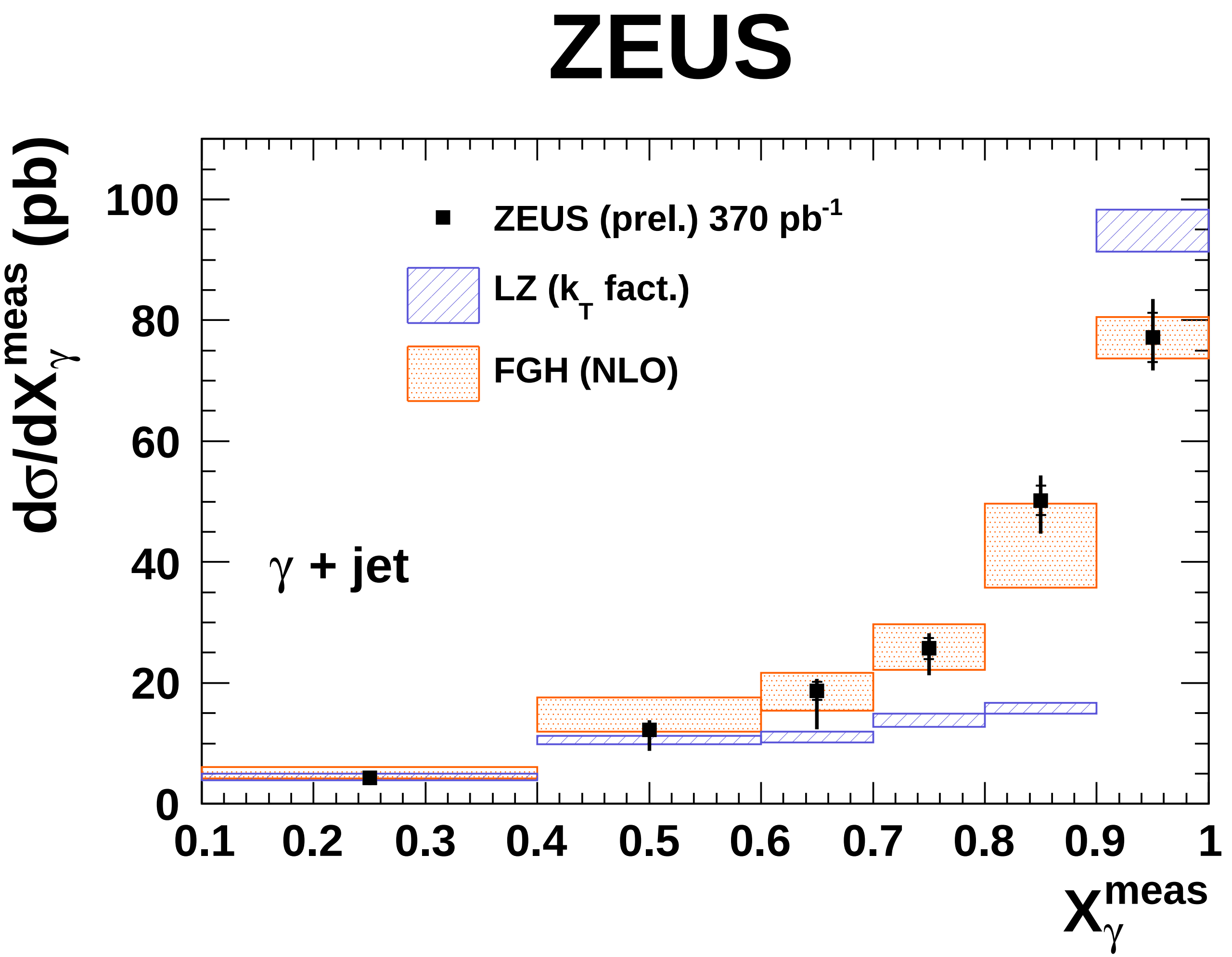
- The systematic uncertainty is mainly due to the photon and jet energy scale uncertainties
- Good agreemnet between data and NLO predictions within uncertainties
- LZ slightly underestimates data

Photon with accompanying jet $4 < E_T^{\mathrm{jet}} < 35\,\mathrm{GeV},\ -1.5 < \eta^{\mathrm{jet}} < 1.8$



- FGH provide better description of the cross sections in both shape and normalisation

Photon with accompanying jet: x_γ



- Very good description of x_γ by FGH

Summary

DIS:

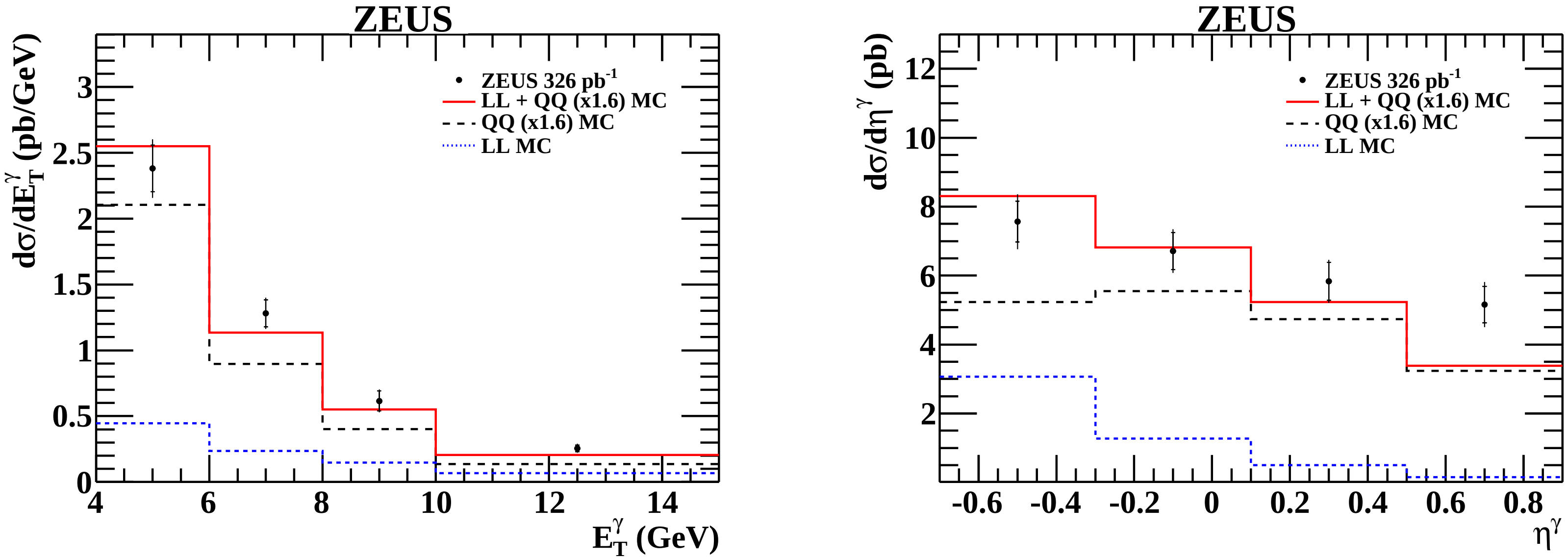
- cross sections of the production of isolated photons with jets in DIS have been measured by ZEUS
- predictions give adequate description of the data but systematically overestimate (for k_T-factorisation approach) or underestimate (for fixed order NLO calculations) them
- results indicate the desirability of further QCD calculations ($\mathcal{O}(\alpha^3\alpha_s^2)$, check unintegrated PDFs)
- hopefully, results can be utilised to constrain proton PDFs

Photoproduction:

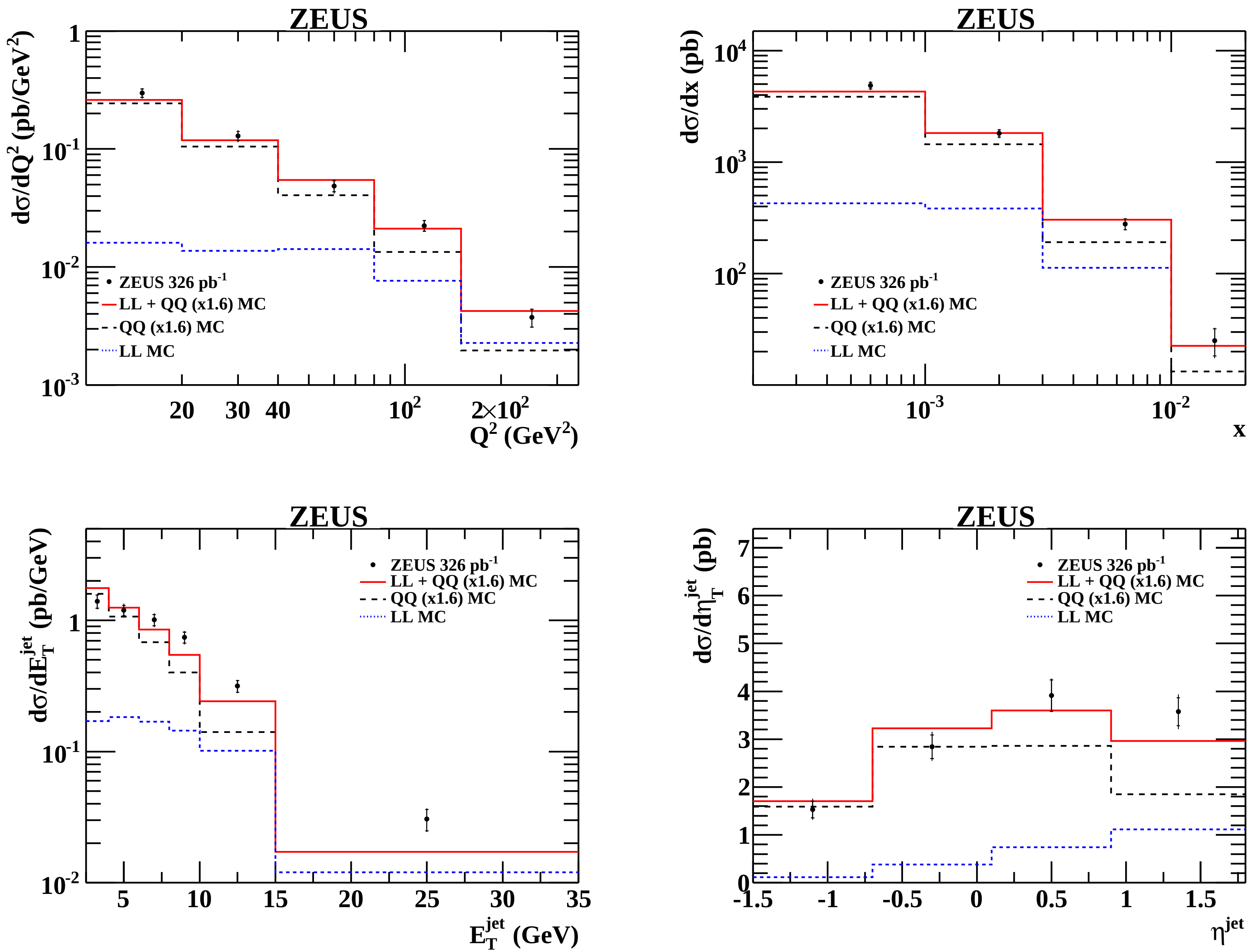
- new results from ZEUS: production of isolated photon with and without accompanying jet is measured with much higher luminosity than in previous papers
- within uncertainties, the NLO predictions by FGH describe the data well
- k_T-factorisation approach by LZ gives reasonable description of the experimental cross sections except maybe the shape for some variables

Backup

Photons in DIS: comparison to MC models (1/2)



Photons in DIS: comparison to MC models (1/2)



Photons in DIS: systematics

Main sources:

• due to e, γ, jet energy scales: $5 - 7\%$

• the dependence on the modelling of the hadronic background by Ariadne was investigated by varying the upper limit for the $\langle \delta Z \rangle$ fit in the range 0.6, 1.0 giving typically variations of $\pm 5\%$ increasing to $+12\%$ and -14% in the most forward η^{γ} and highest-x bins respectively

Photons in PHP: systematics

Main sources:
• using alternative signal MC (Herwig vs Pythia): up to 8%, rising to 30% in the lower bins of x_γ
• due to γ and jet energy scales: $5 - 10\%$ (5% for inclusive photons
• variation of relative fractions of direct, resolved and fragmentation events: $\pm 3\%$
• the dependence on the modelling of the hadronic background by Ariadne was investigated by varying the upper limit for the $\langle \delta Z \rangle$ fit in the range 0.6, 1.0 giving typically variations of $\pm 2\%$