# Isolated Photons + Jets in DIS at ZEUS

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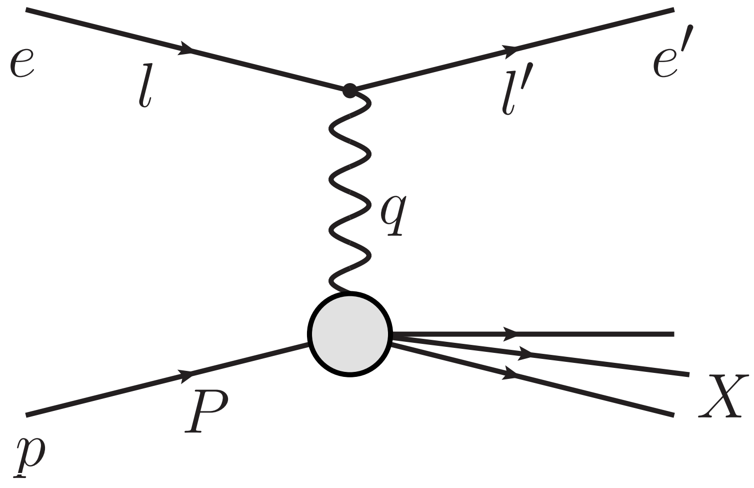
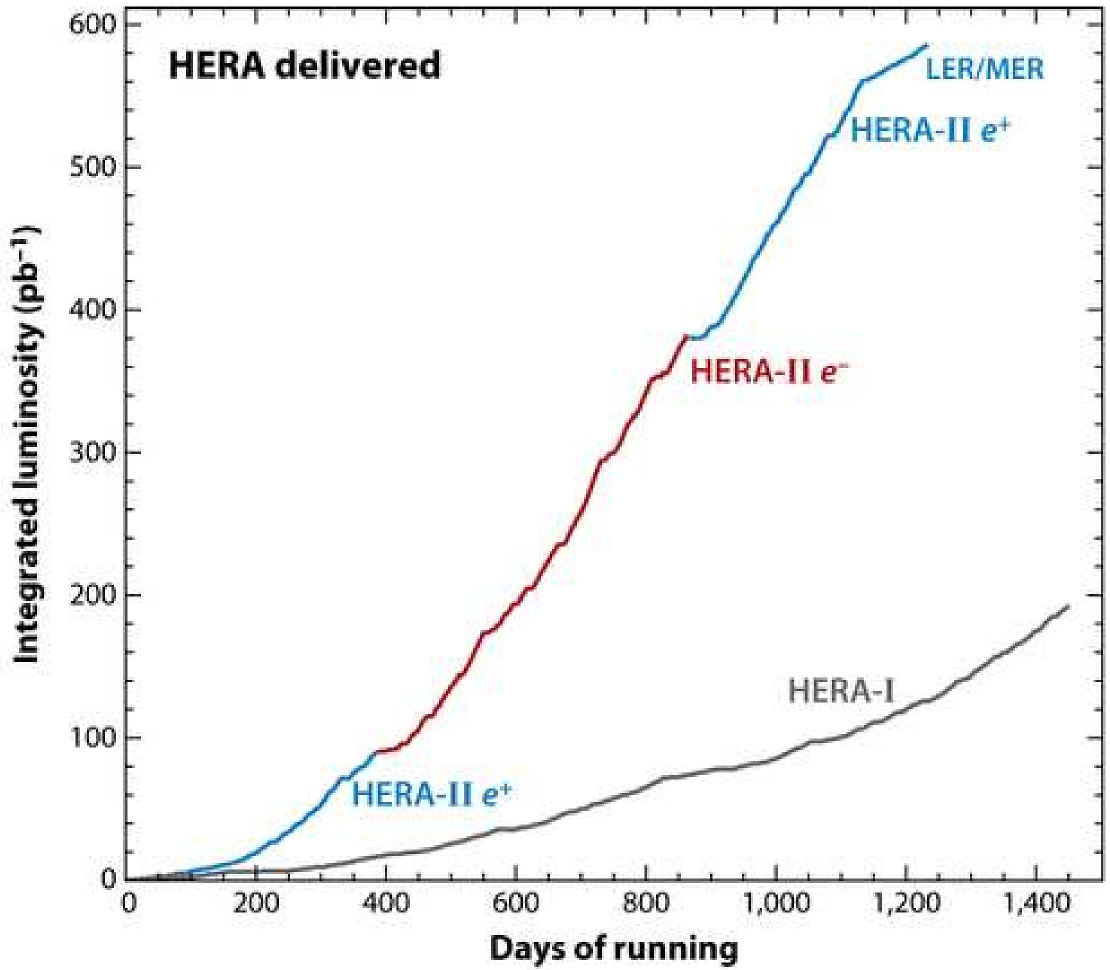
On behalf of the ZEUS collaboration

# HERA collider




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

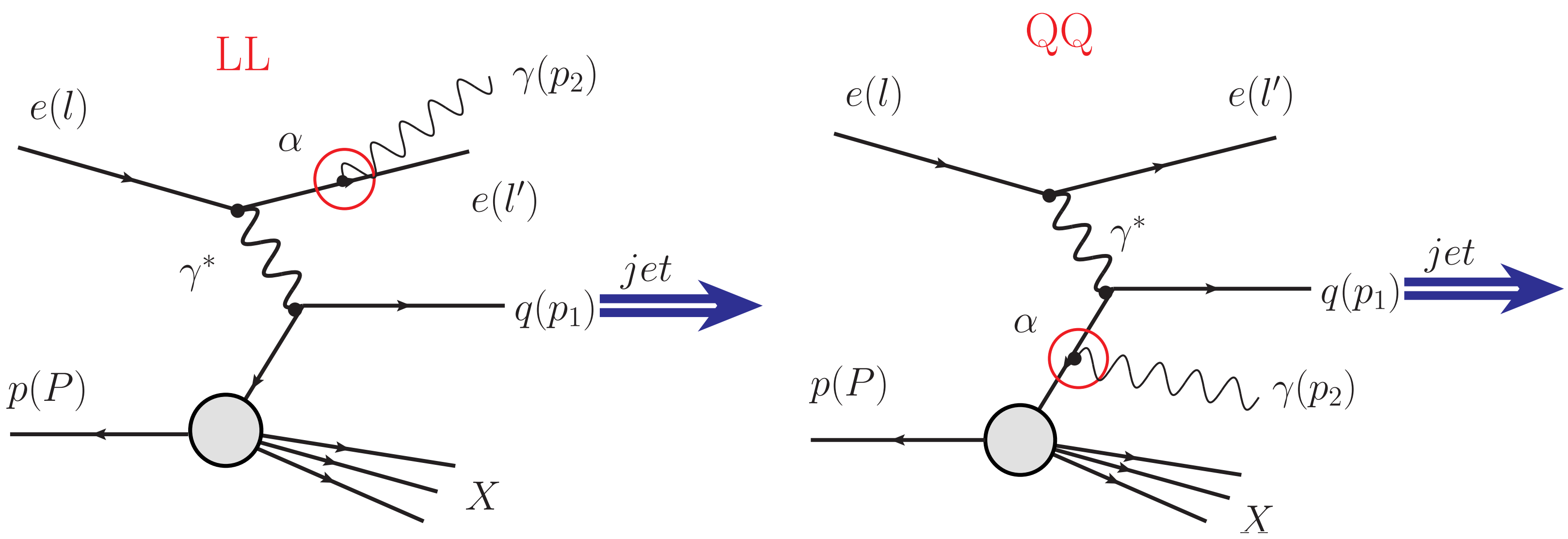
Kinematics:
$Q^2 = -q^2 = -(l - l')^2$
$y = \frac{Pq}{Pl}$
$x_{Bj} = \frac{Q^2}{2Pq}$
$Q^2 = x_{Bj} y s$




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

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

# Isolated photons 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 and matrix element
- 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 $E_T^\gamma$ and pseudorapidity $\eta^\gamma$ of the photon
- transverse energy $E_T^{\mathrm{jet}}$ and pseudorapidity $\eta^{\mathrm{jet}}$ 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**

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

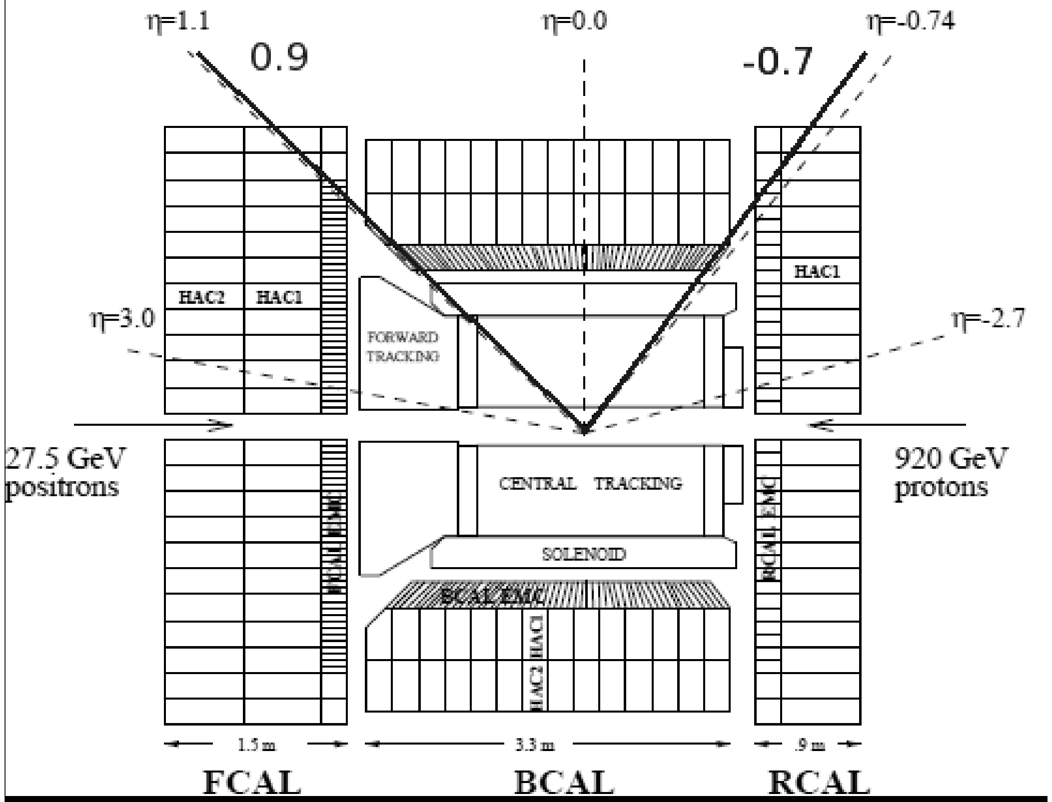
- $-40 < Z_{\text{vtx}} < 40\,\text{cm}$
- $35 < E - p_z < 65$
- $E_{electron} > 10$ GeV
- $140^\circ < \theta_{el} < 180^\circ$

**Photon**

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

**Accompanying jet**

- $E^{corr}_{T,jet} > 2.5$ GeV
- $-1.5 < \eta_{jet} < 1.8$



# 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 %)

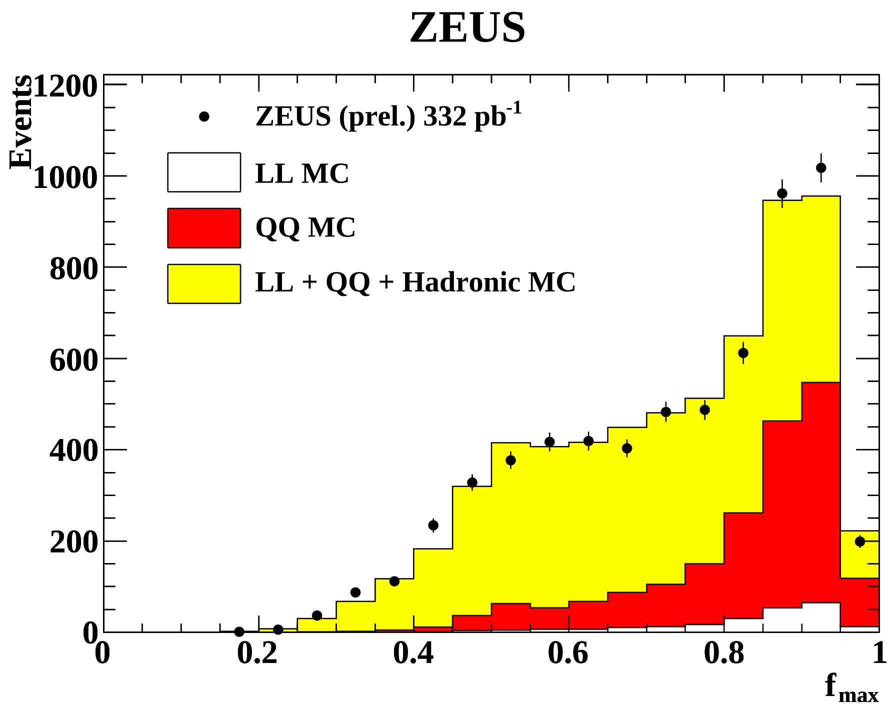
  $\to$ it is the main source of the background
  $\to$ opening angle of two photons after $\pi^0$ decay:

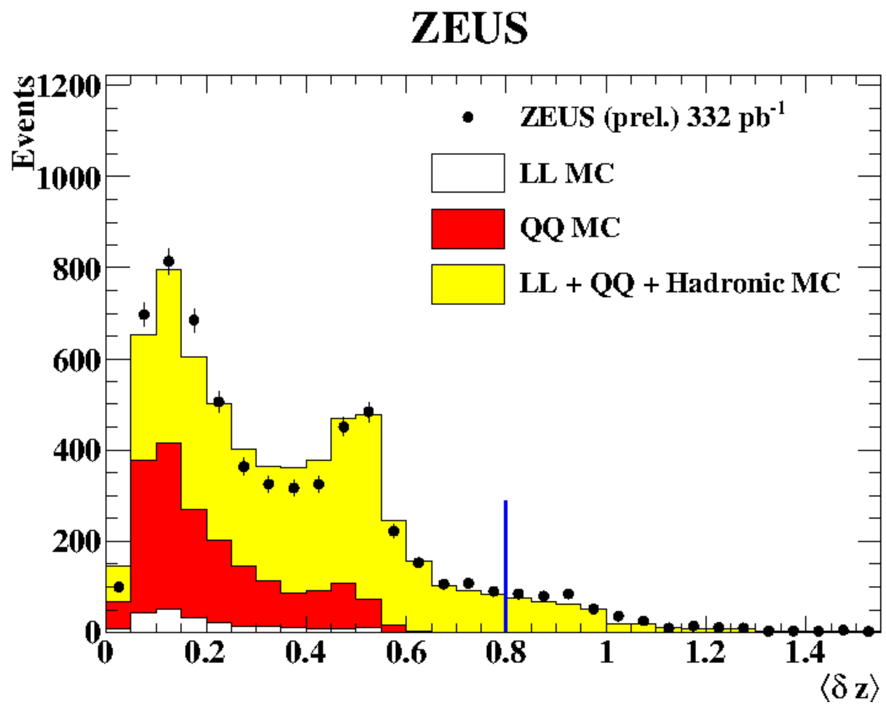
  $$\sin\frac{\phi}{2} = \frac{m}{E}$$

  At $E = 5$ GeV $\phi = 1.55^\circ$ for $\pi^0$ and $\phi = 6.3^\circ$ for $\eta$-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:

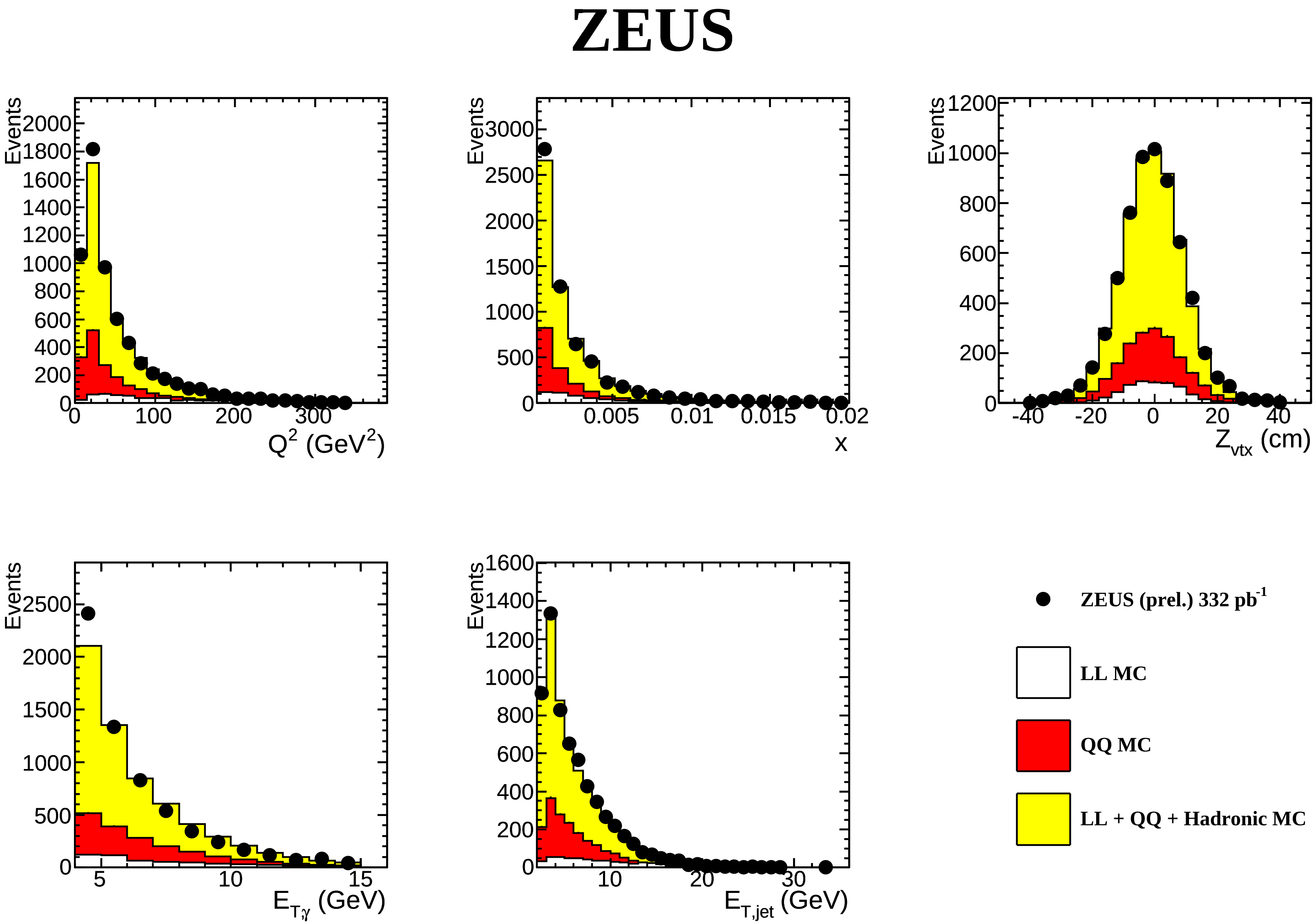



$$f_{max} = \frac{\text{Energy in the most energetic BEMC cell}}{\text{Total energy of the cluster}} \qquad \langle \delta z \rangle = \frac{\Sigma |z_i - z_{cluster}| \cdot E_i}{l_{cell} \Sigma \text{ E}_\text{i}}$$

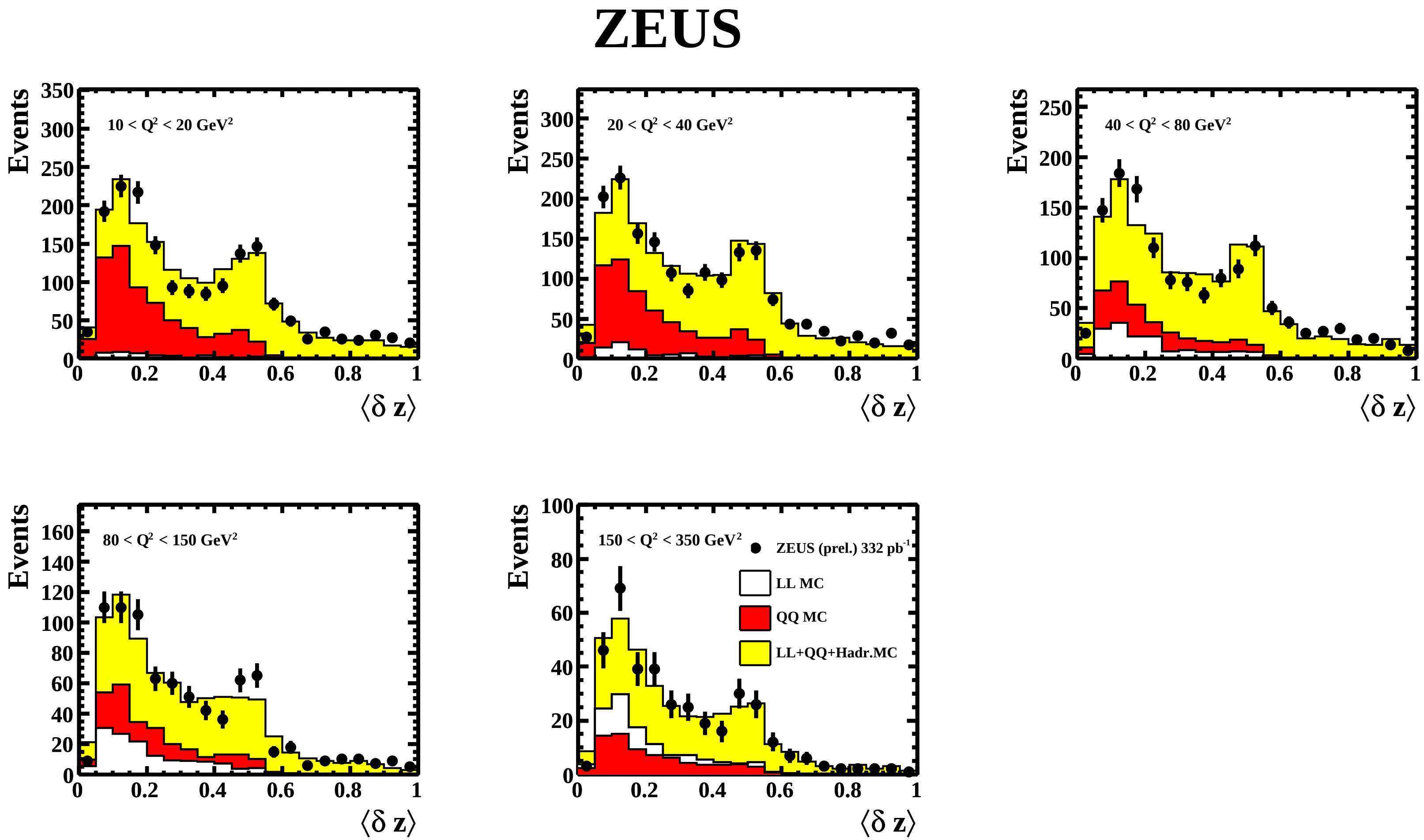
$\rightarrow$ mixture of different type Monte Carlo events is used to fit the data distribution
$\rightarrow$ $\langle \delta z \rangle$ variable is used for the signal extraction, because it carries more information

# Control distributions




- good description of the data by Monte Carlo

# $\langle \delta z \rangle$ fit in bins of $Q^2$




- The LL contribution increases with increasing $Q^2$ and QQ decreases

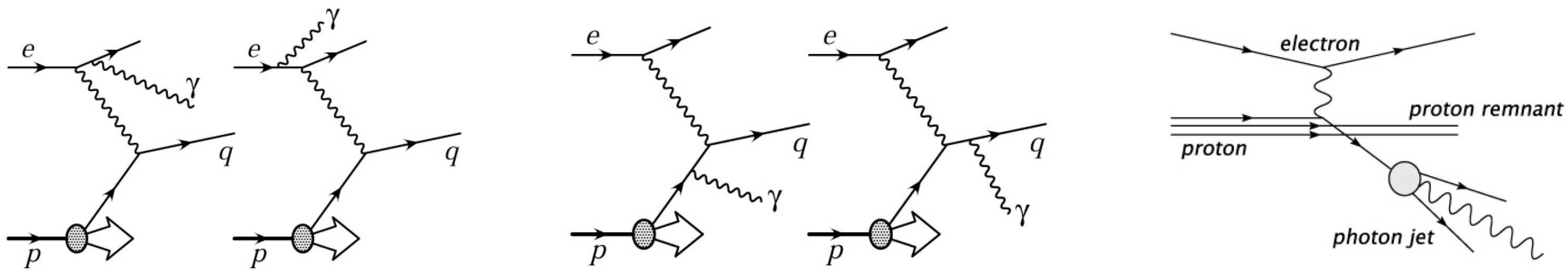
# Systematic uncertainties

Main sources:

- due to scattered electron energy uncertainty: up to $5\%$
- due to isolated photon energy uncertainty: up to $5\%$
- due to jet energy uncertainty: up to $10\%$
- due to fit range: typically variations of $\pm5\%$ increasing up to $\pm12\%$ in some bins

# 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($\alpha^3$) with three components:




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

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

• HERAPDF10 for PDF parametrisation

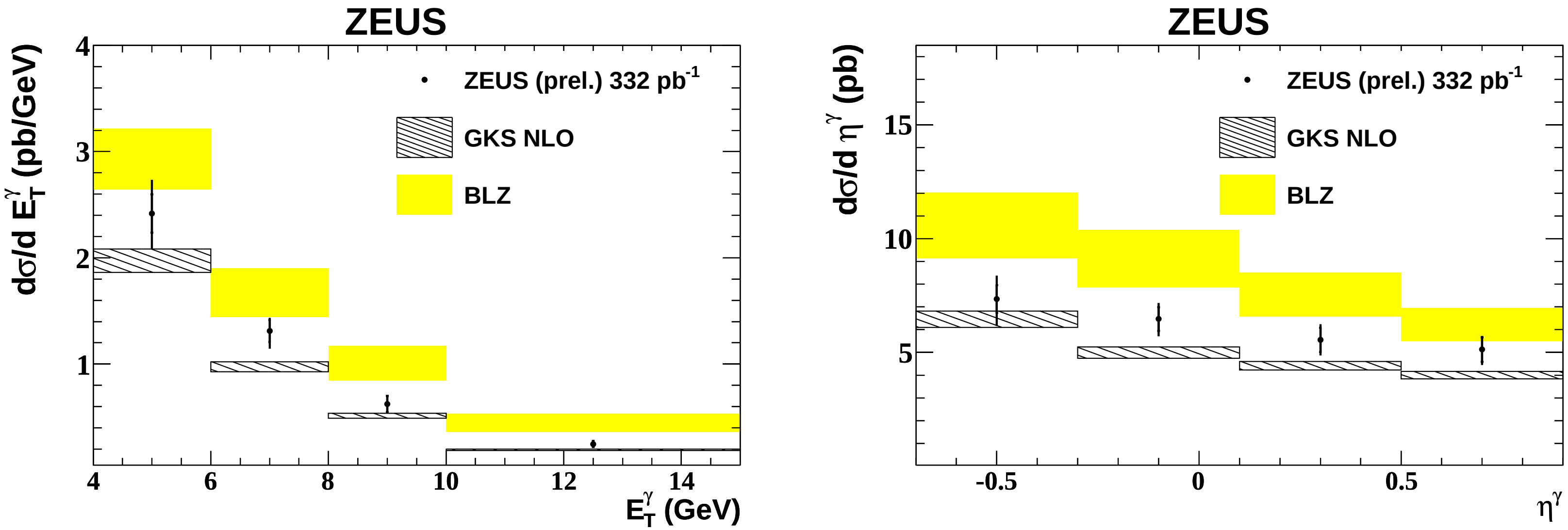
# Theoretical predictions: $k_T$-factorisation approach

• 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

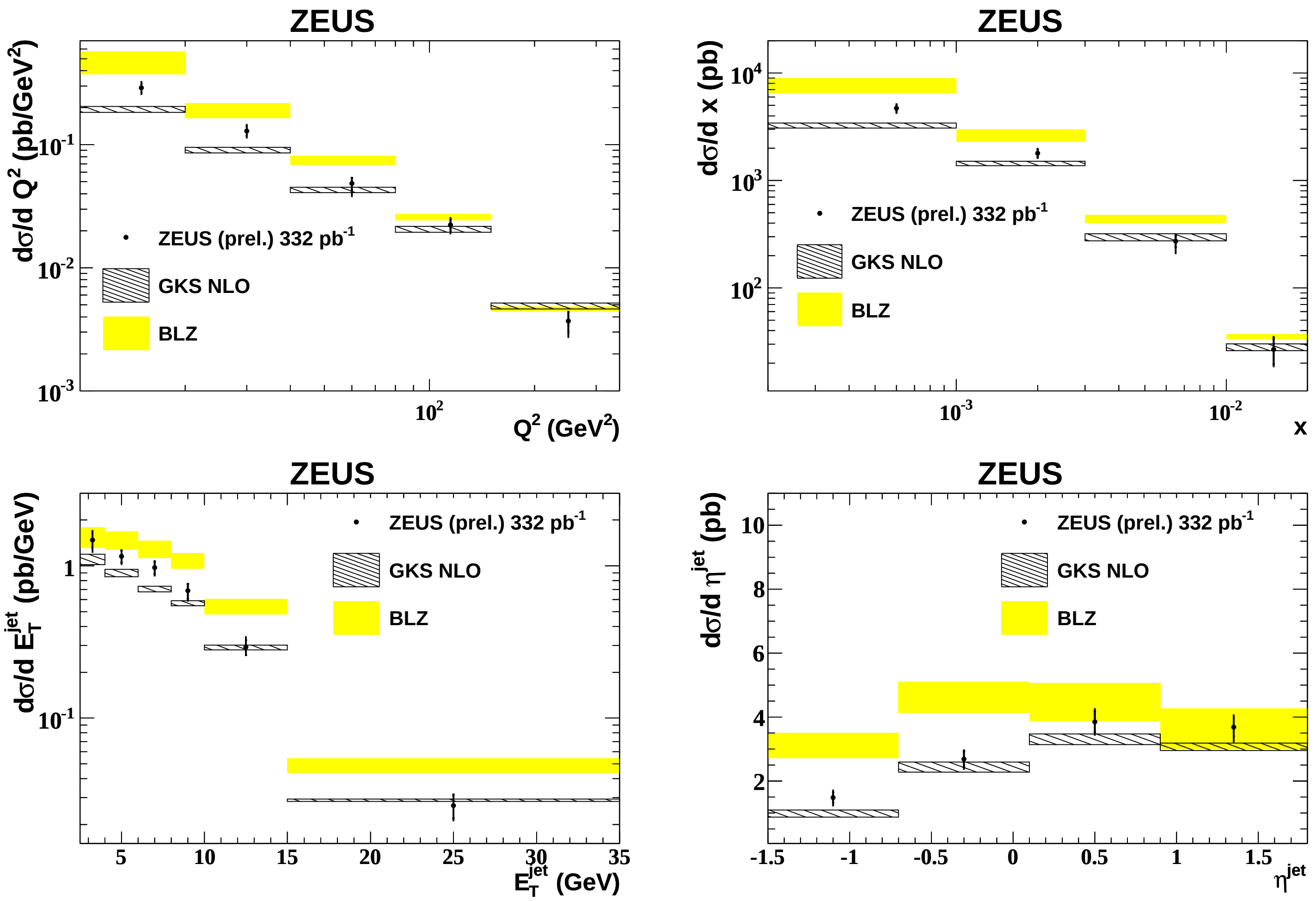
# Cross sections (1/2)




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

- 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 $\eta^{\rm jet}$ shape

## Summary

- cross sections of inclusive production of isolated photon and jet at the ZEUS experiment have been measured and compared to the theoretical predictions
- 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 PDF's)
- hopefully, results can be utilised to constrain PDF