

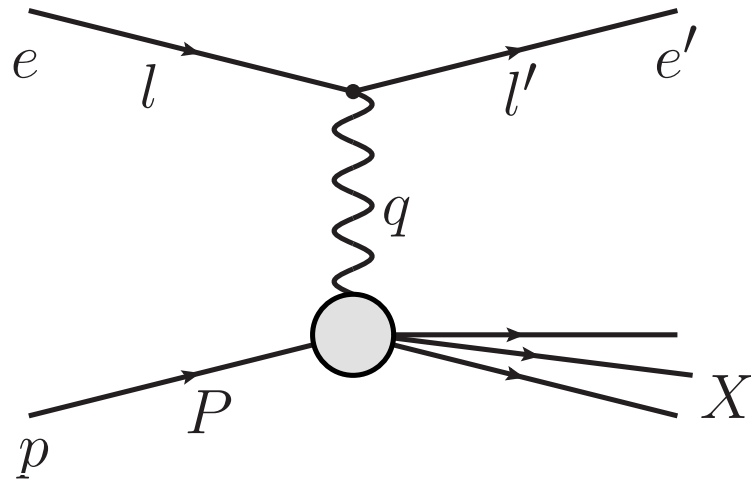
# Isolated Photons + Jets in DIS at ZEUS

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On behalf of the ZEUS collaboration

# HERA collider



Electrons: 27.5 GeV

Protons: 920 GeV

$\sqrt{s} = 318$  GeV

Kinematics:

$$Q^2 = -q^2 = -(l - l')^2$$

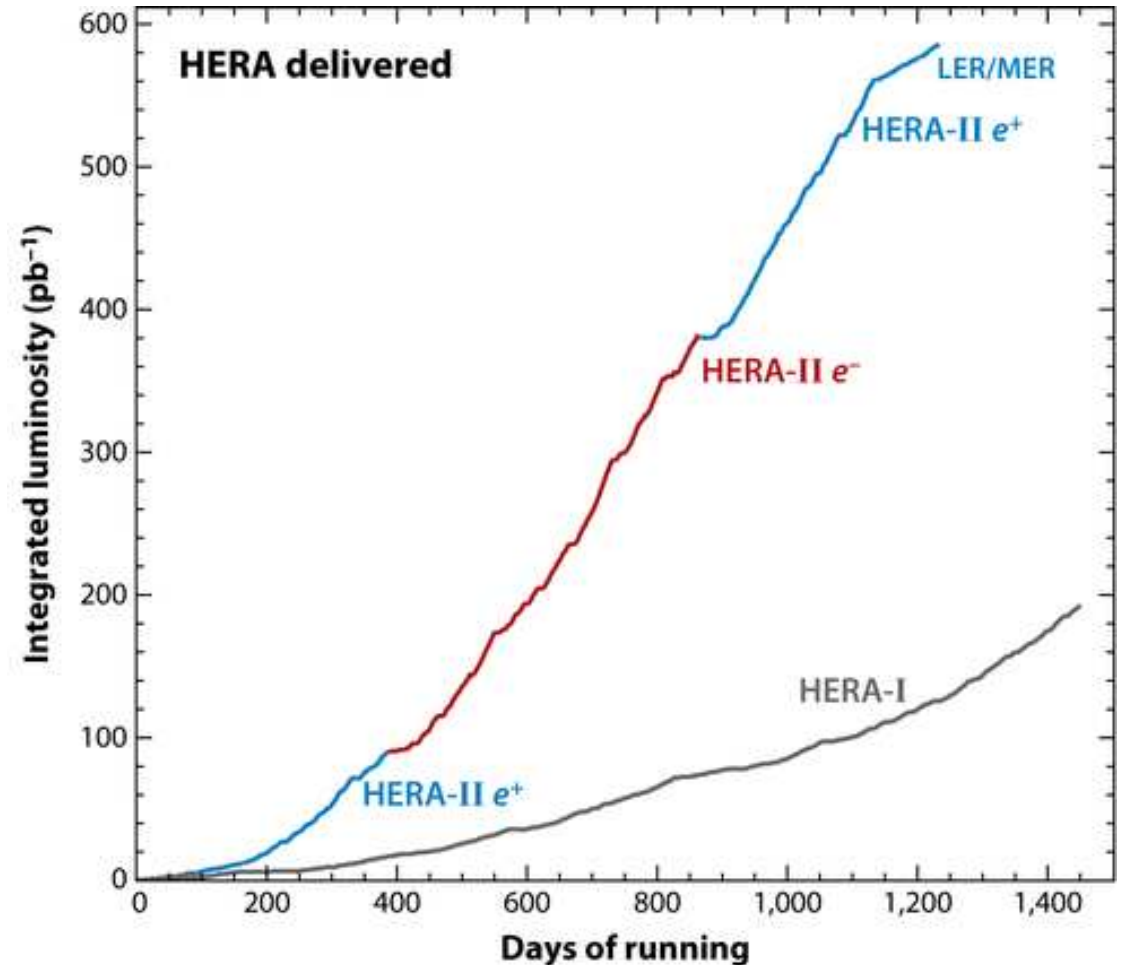
$$y = \frac{Pq}{Pl}$$

$$x_{Bj} = \frac{Q^2}{2Pq}$$

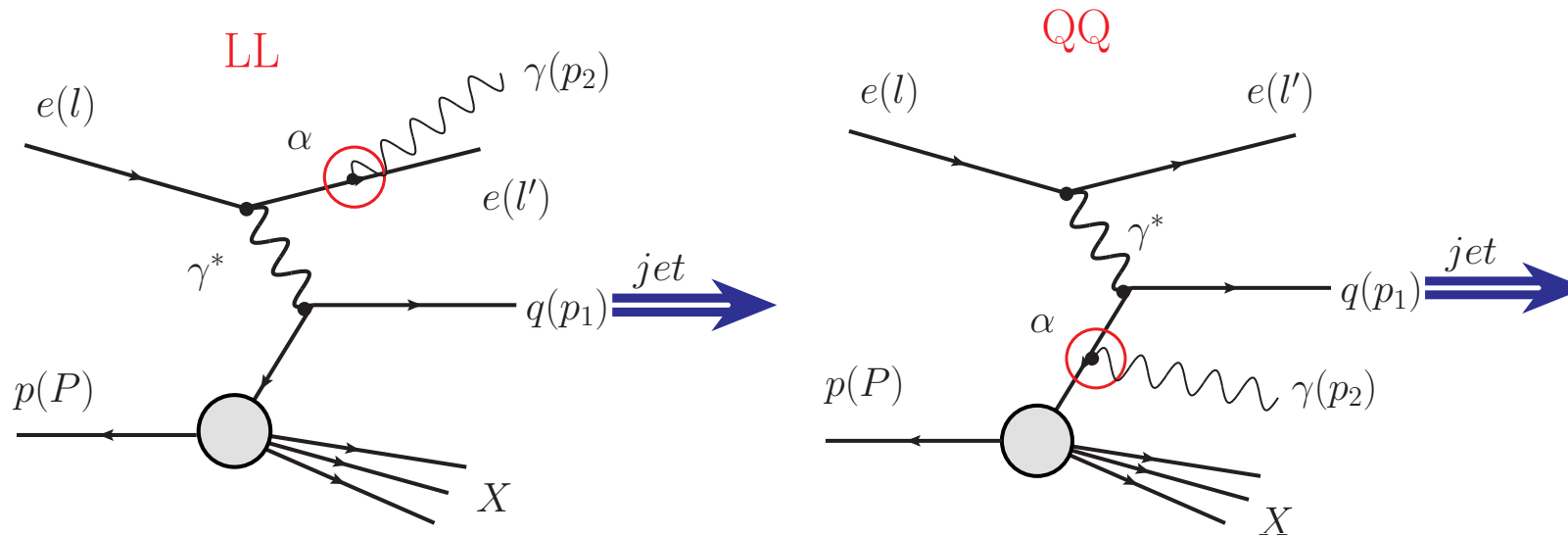
$$Q^2 = x_{Bj}ys$$

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

$Q^2 \gtrsim 1 \text{ GeV}^2$ : 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)

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- integrated luminosity of  $\approx 330 \text{ pb}^{-1}$  (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  $E_T^{\text{jet}}$  and pseudorapidity  $\eta^{\text{jet}}$  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

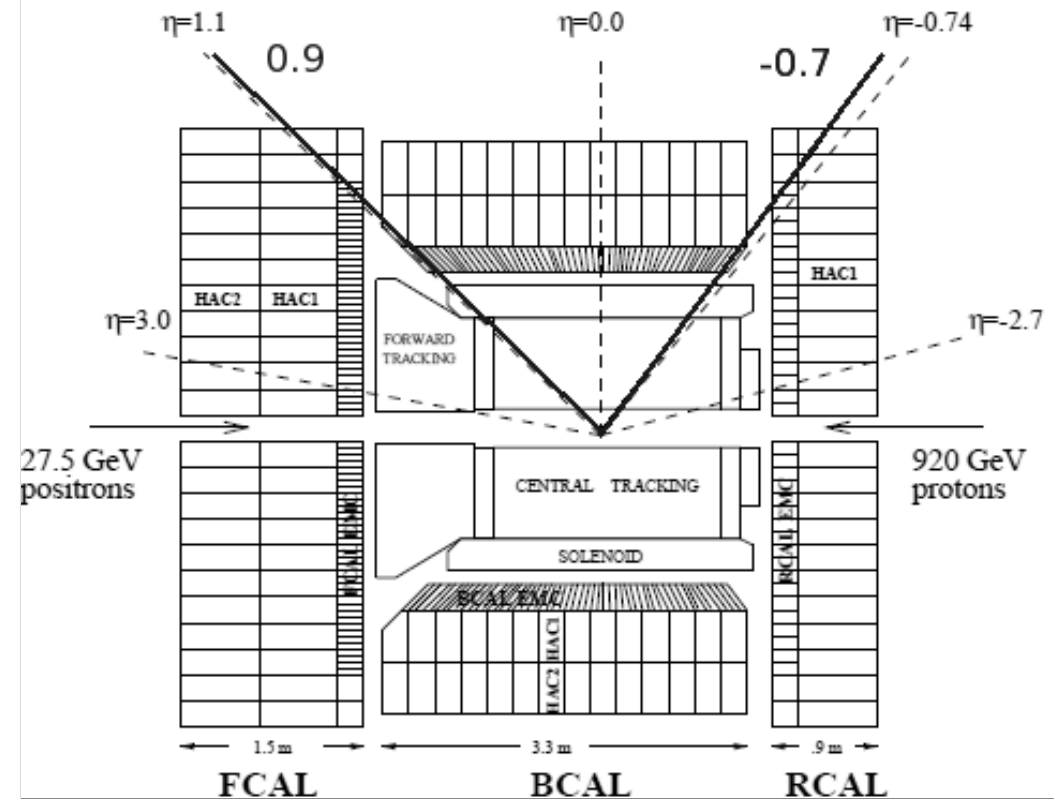
- $10 < Q^2 < 350 \text{ GeV}^2$
- $-40 < Z_{\text{vtx}} < 40 \text{ cm}$
- $35 < E - p_z < 65$
- $E_{\text{electron}} > 10 \text{ GeV}$
- $140^\circ < \theta_{el} < 180^\circ$

## Photon

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

## Accompanying jet

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



# Background to isolated photons

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## □ Photons from decays of neutral mesons:

- $\pi_0 \rightarrow \gamma\gamma$  (98.8 %)
- $\eta \rightarrow \gamma\gamma$  (39.3 %)
- $\eta \rightarrow \pi_0\pi_0\pi_0$  (32.6 %)

→ it is the main source of the background

→ 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

→ there is a possibility to use shower shape method

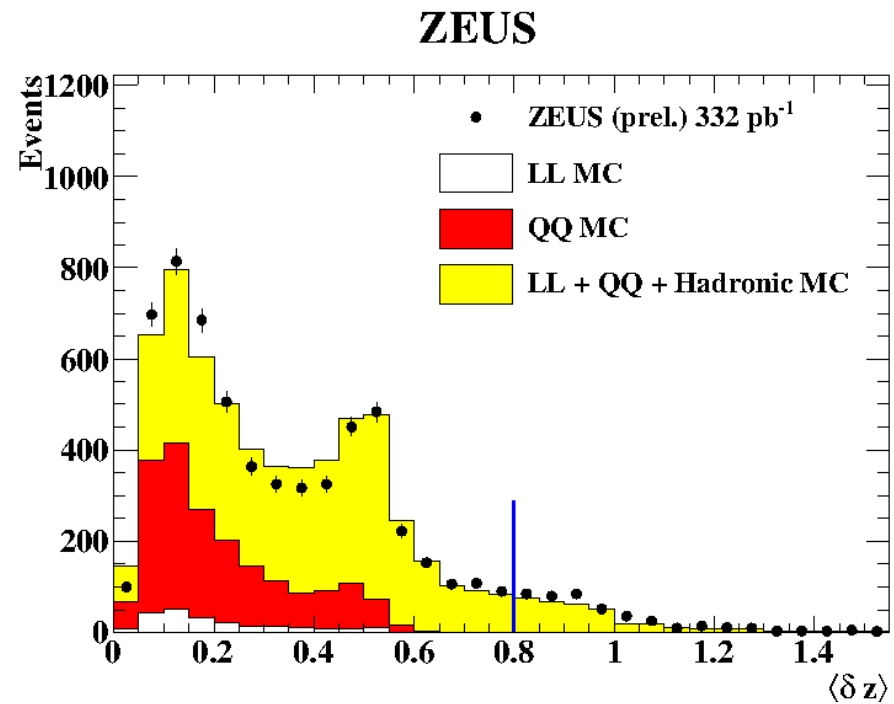
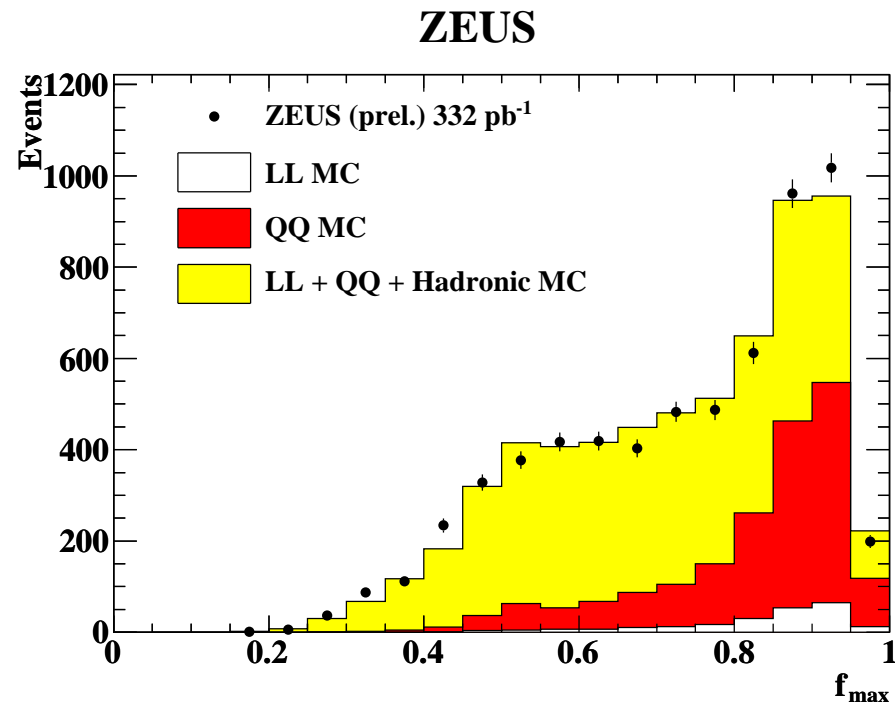
## □ Photons from quark to photon fragmentation

→ this process occurs over long distances and cannot be calculated perturbatively

→ easy to suppress by applying of the isolation cut

# Extraction of the signal

Following variables are using to describe the shower shape:



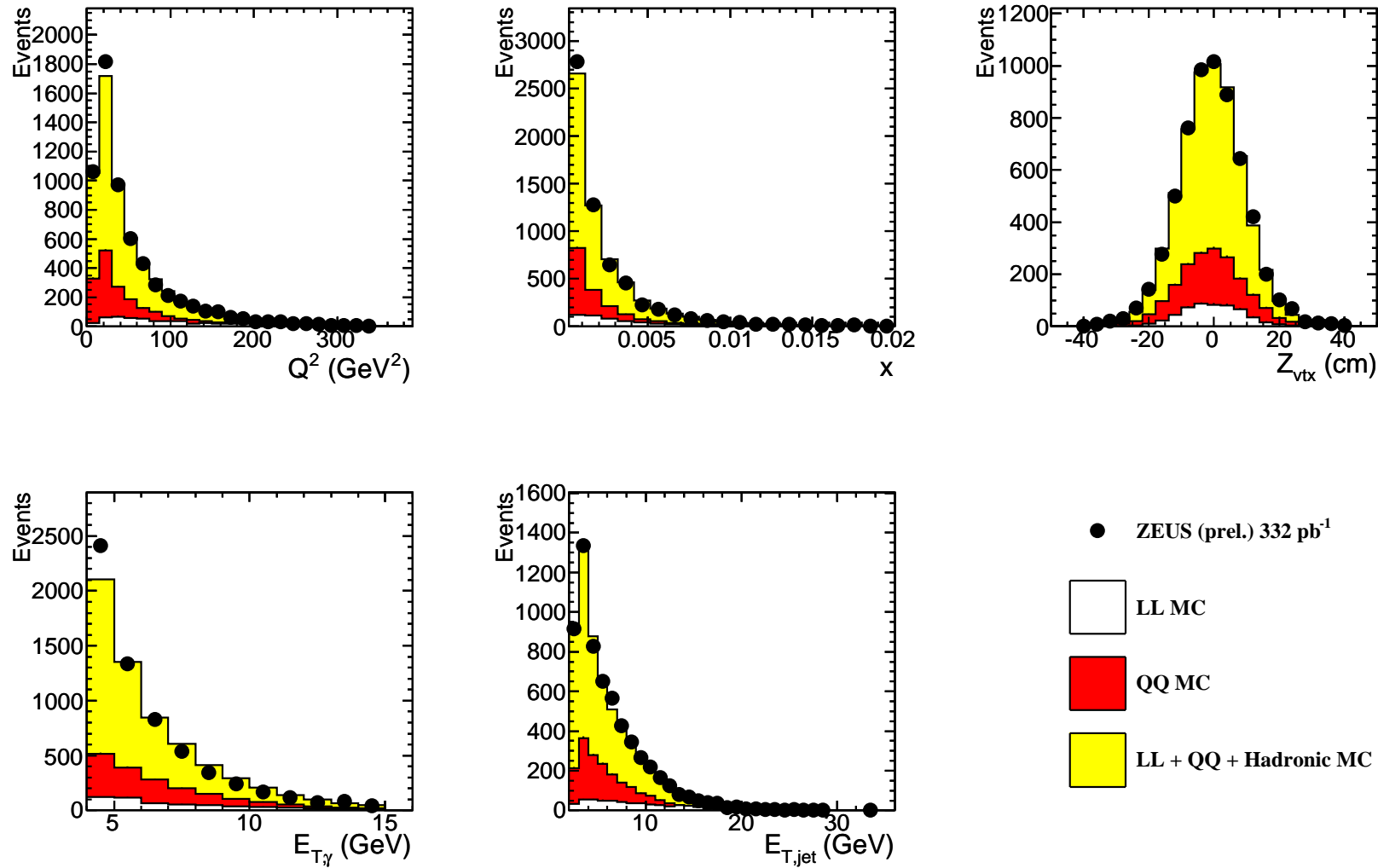
$$f_{max} = \frac{\text{Energy in the most energetic BEMC cell}}{\text{Total energy of the cluster}}$$

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

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

# Control distributions

## ZEUS

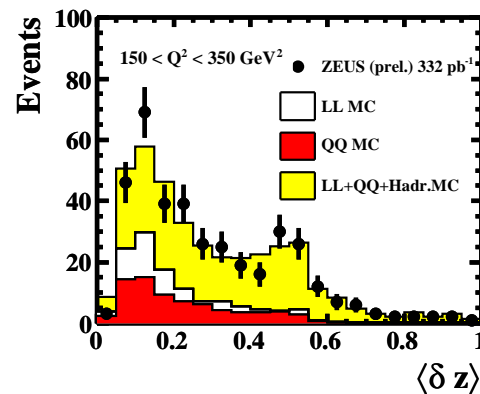
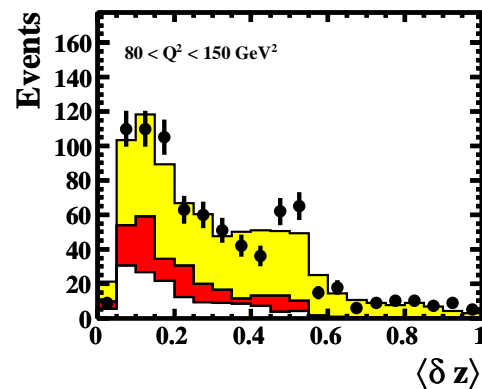
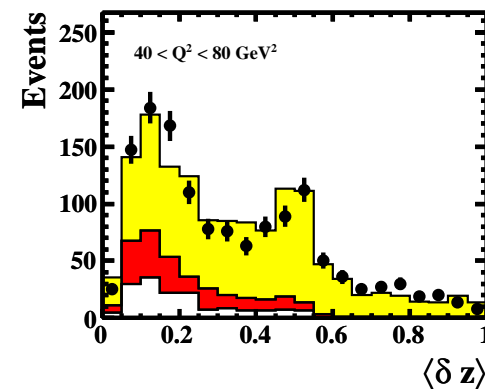
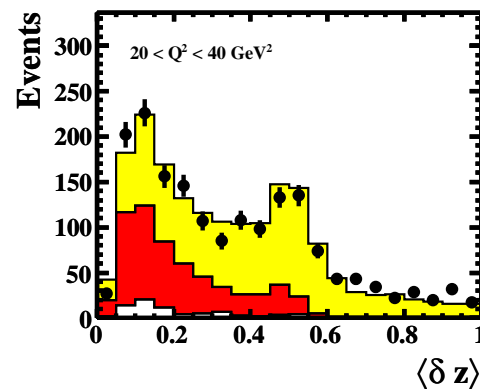
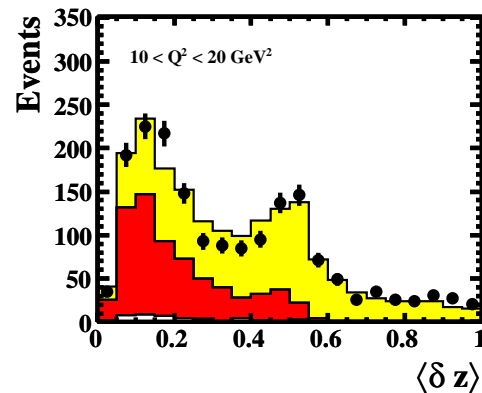


- good description of the data by Monte Carlo



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

## ZEUS



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

# Systematic uncertainties

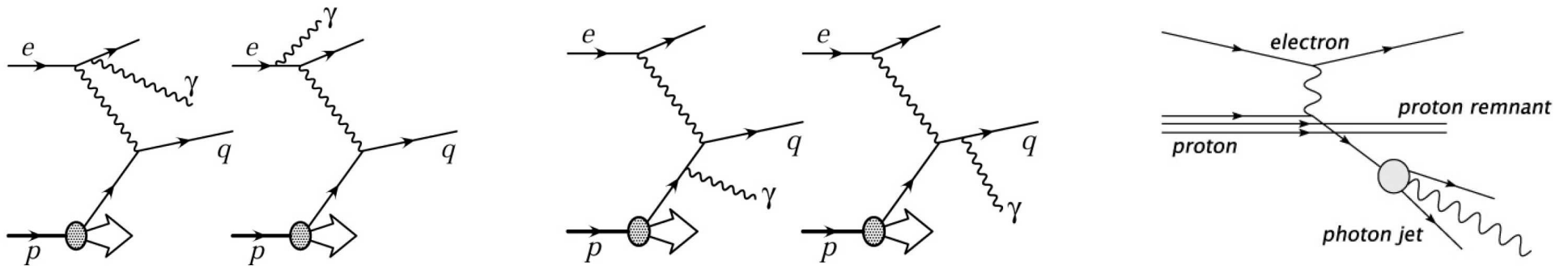
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Main sources:

- 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  $\pm 5\%$  increasing up to  $\pm 12\%$  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)
- $\text{LO}(\alpha^3)$  with three components:



- (LEFT) LL radiation, (MIDDLE) QQ radiation, (RIGHT) photon from jet fragmentation
- $\text{LO}(\alpha^3)$  and  $\text{NLO}(\alpha^3\alpha_s)$  predictions are calculated

- renormalisation and factorisation scales  $\mu_R = \mu_F = \sqrt{Q^2 + (p_T^{\text{jet}})^2}$

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

- HERAPDF10 for PDF parametrisation

# Theoretical predictions: $k_T$ -factorisation approach

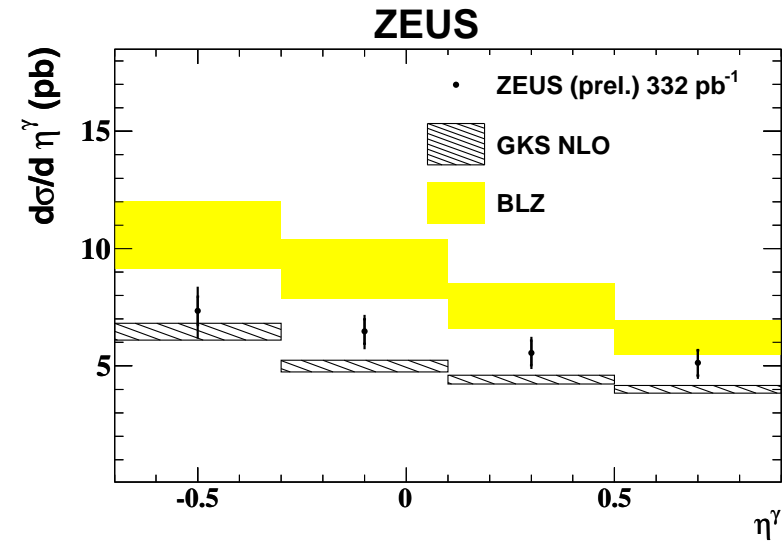
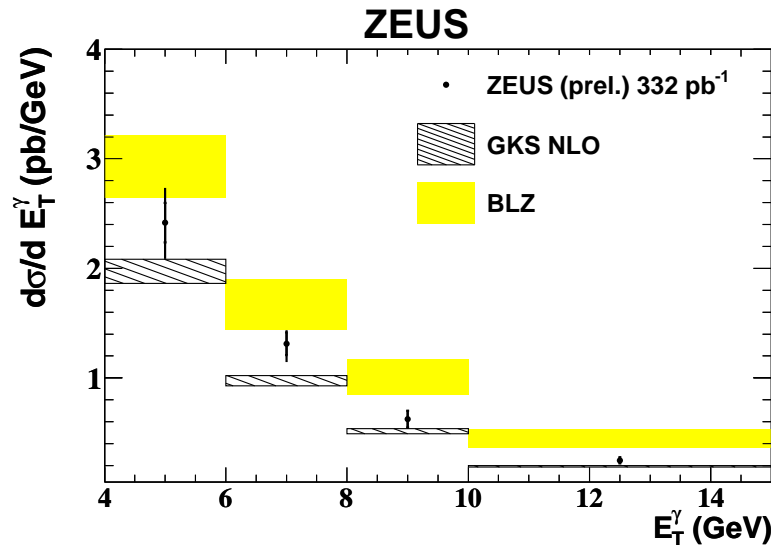
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- Calculated by [S.P.Baranov, A.V.Lipatov, N.P.Zotov \(Phys.Rev.D81:094034,2010\)](#) (BLZ):
- investigation of the prompt photon production in DIS at HERA in the framework of  $k_T$ -factorisation QCD approach
- based on the off-shell partonic amplitude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

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

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

# Cross sections (1/2)



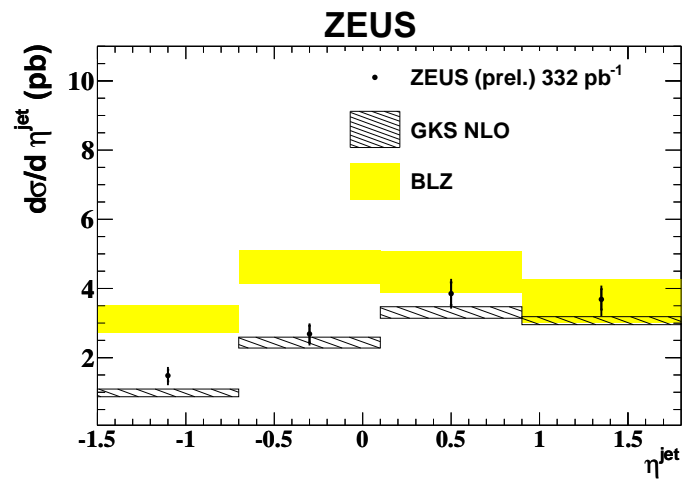
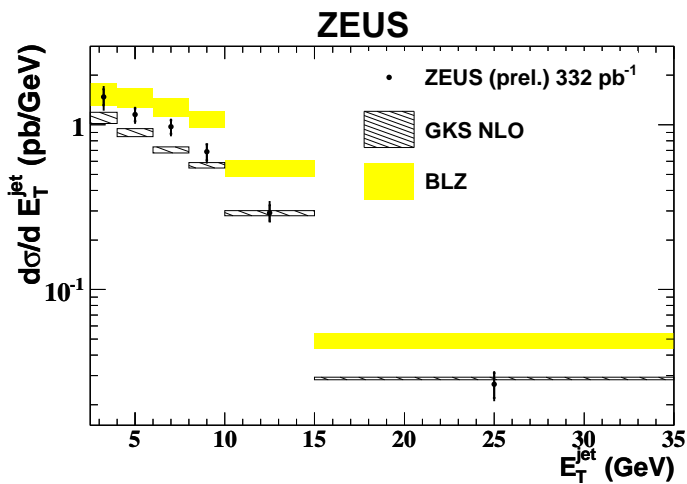
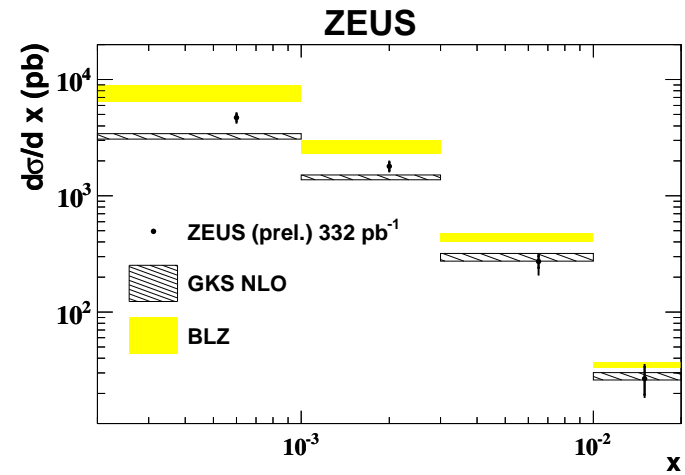
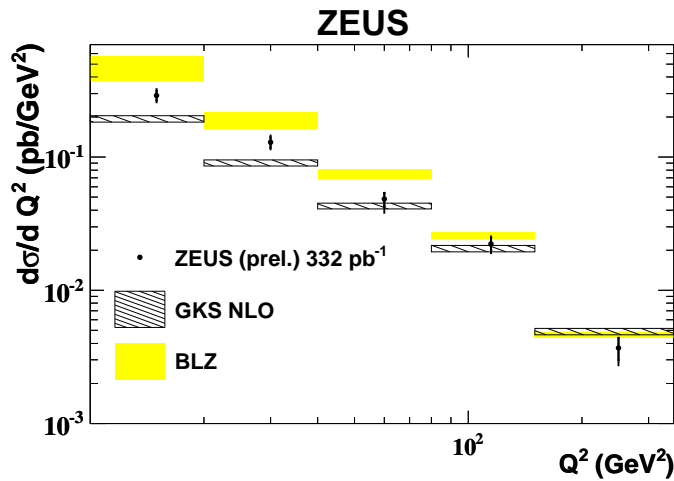
$$4 < E_T^\gamma < 15 \text{ GeV}, \quad -0.7 < \eta^\gamma < 0.9, \quad \frac{E^\gamma}{E_{\text{jetcontaining}\gamma}} > 0.9,$$

$$10 < Q^2 < 350 \text{ GeV}^2, \quad E_{\text{elec}} > 10 \text{ GeV}, \quad 140^\circ < \theta_{\text{elec}} < 180^\circ,$$

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

- 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  $\eta^{jet}$  shape

# Summary

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- 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