Isolated hard photons with jets measured in Deep Inelastic Scattering and photoproduction with the ZEUS detector at HERA.

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Some particular motivations for these measurements:

- Prompt photons emerge directly from the hard scattering process and give a particular view of this.
- Allows tests of specific QCD models.
- Photons form a potential background to "new physics" processes, should be well understood.

ZEUS publications of prompt photons in DIS:

inclusive: Phys. Lett. 687 (2010) 16

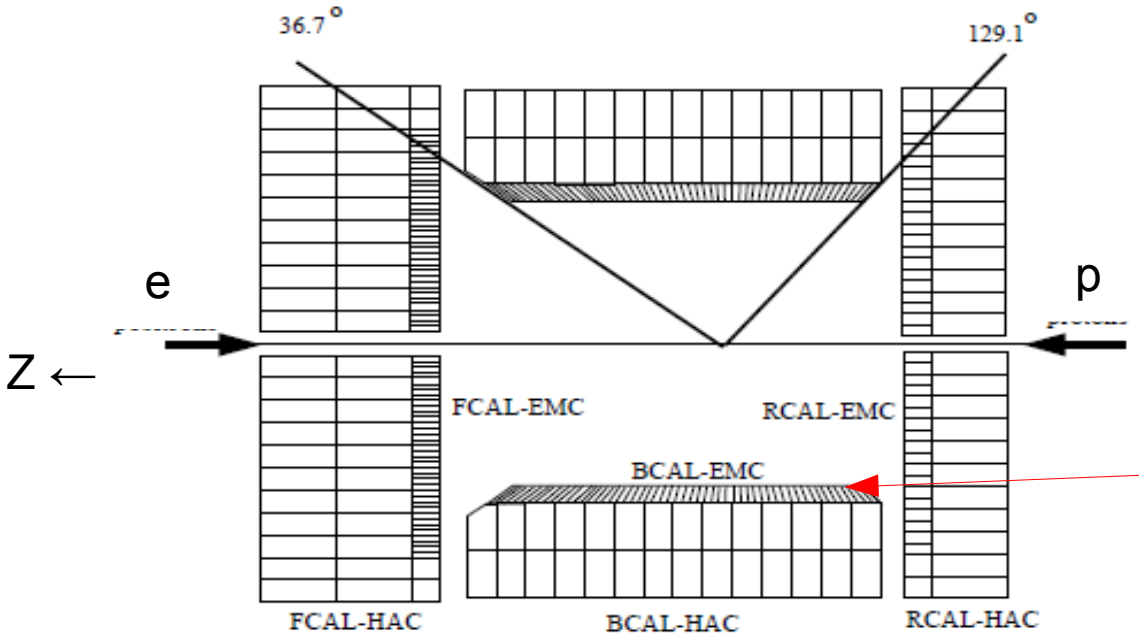
+ jet (this talk) : Phys. Lett. 715 (2012) 88

High-E_T photons produced in Deep Inelastic Scattering (**DIS**) of e^+/e^- are:

- Radiated from the incoming or outgoing lepton
- Produced in a hard partonic interaction: "prompt"
- Radiated from a quark within a jet
- A decay product of a hadron within a jet

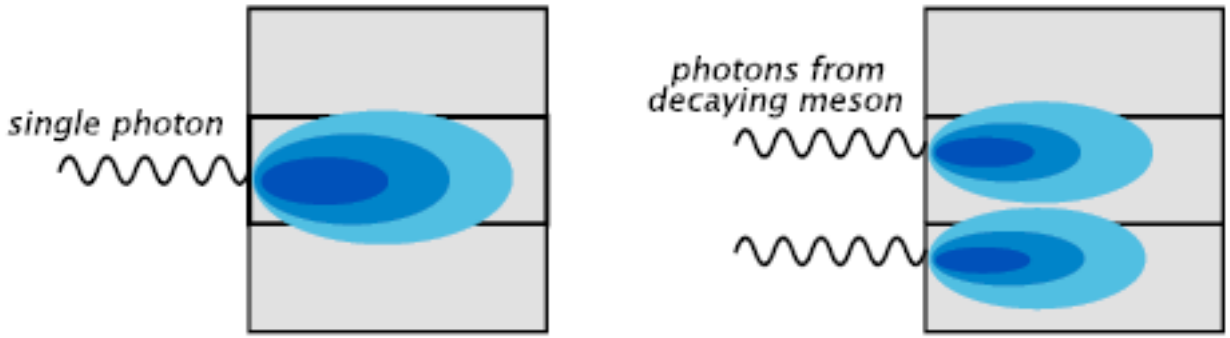
Photons in first two categories are relatively isolated from other outgoing particles, and are the subject of this study.

The ZEUS detector



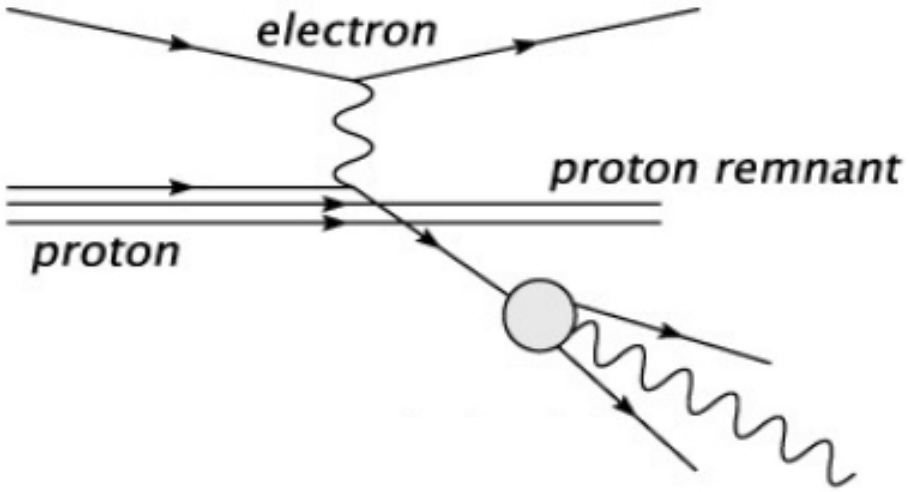
Hard scattered photons are measured in the BCAL, which is finely segmented in the Z direction.

BEMC = electromagnetic section



Groups of BEMC cells with signals, and no associated track.

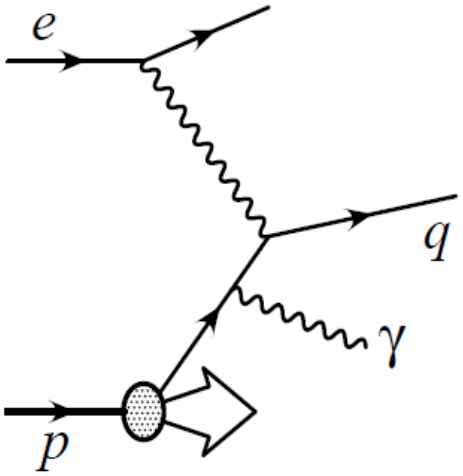
Why we select isolated photons:

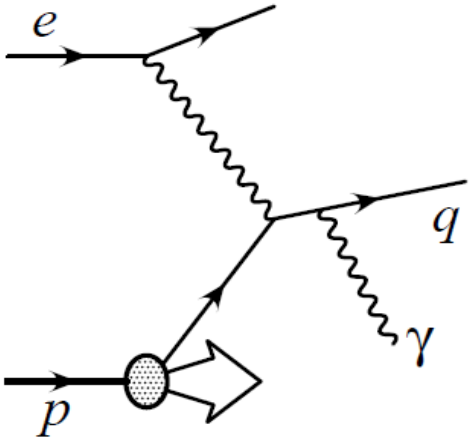


Photons in or near jets require a quark fragmentation function which is not easy to determine – requires non-perturbative input.

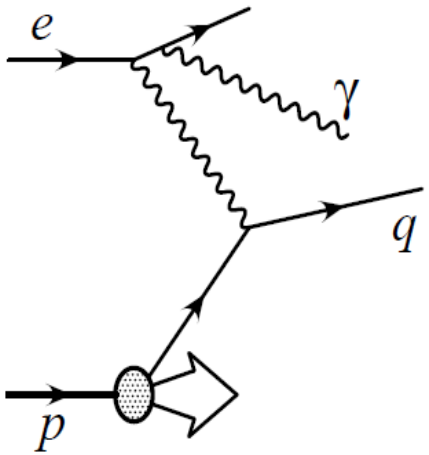
Also, the background from neutral mesons is large.

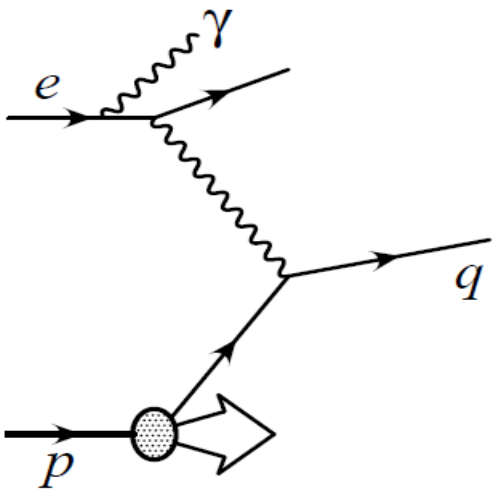
The main LO diagrams in DIS:





QQ diagrams





LL diagrams

(LL+QQ interference is small and neglected here)

The ZEUS DIS analysis.

Uses 332 pb^{-1} of HERA 2 data.

Photon candidates: found with an energy-clustering algorithm in the BCAL

$$E_{EMC}/(E_{EMC}+E_{HAD}) > 0.9$$

Jets: use k_T-clus algorithm (include photon candidates)

DIS electron (or positron):

- $E > 10$ GeV
- 140-180° from proton beam direction
- $10 < Q^2 < 350$ GeV^2 where Q^2 = squared momentum transfer

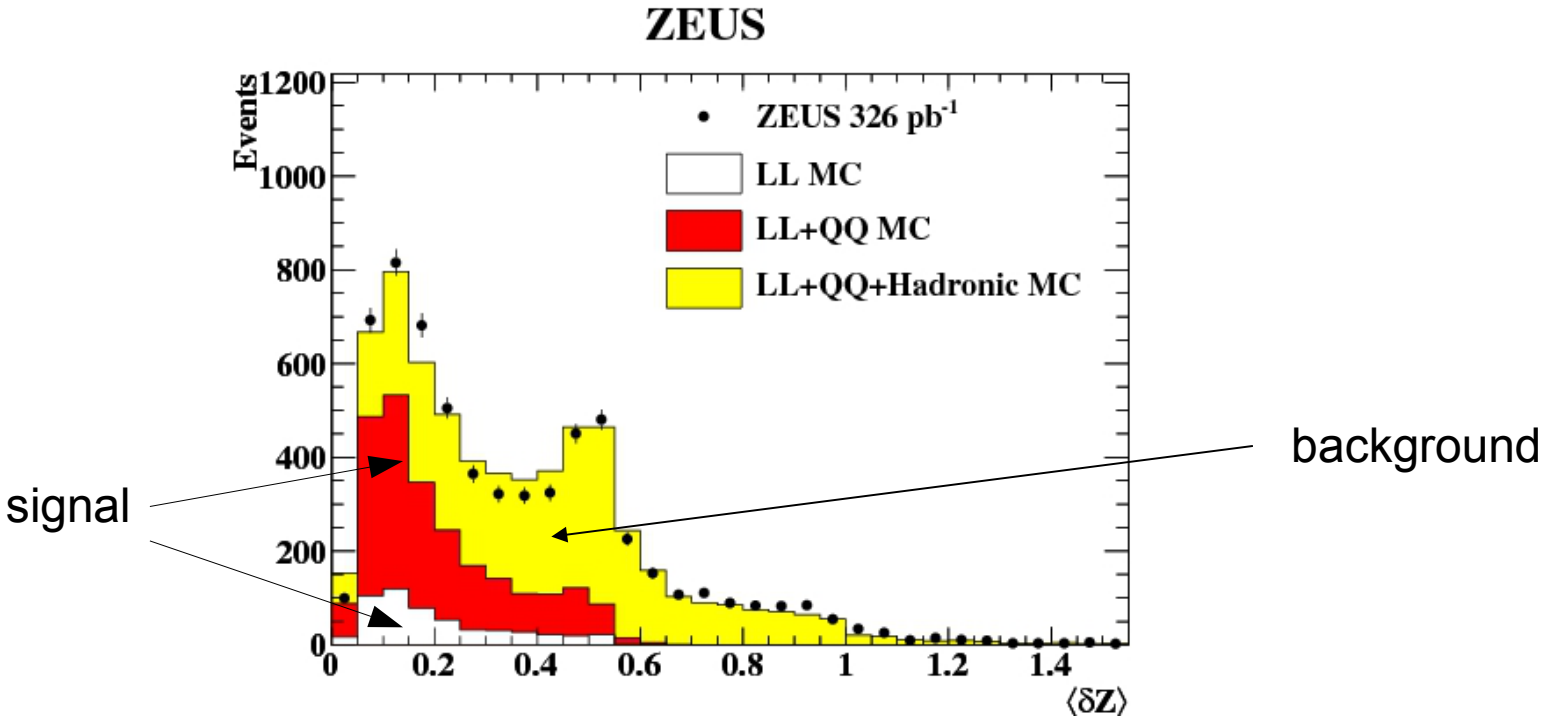
Hard photon candidate:

- $E_T > 4$ GeV
- $-0.7 < \eta^\gamma < 0.9$ where $\eta \equiv$ pseudorapidity. (i.e. within ZEUS barrel calorimeter)
- **Isolated.** In the "jet" containing the photon candidate, this must contain at least 0.9 of the "jet" E_T

Jet conditions

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

Challenge: separate photons from backgrounds from decays of neutral mesons.
Use transverse shower width.



Photon candidates: groups of signals in BEMC cells.
Each has a Z-position, Z_{CELL}. E_T-weighted mean of Z_{CELL} is Z_{Mean}.
<dZ> = E_T-weighted mean of $|Z_{CELL} - Z_{Mean}|$.
Peaks correspond to photon and π^0, other background is η + multi-π^0.

In each bin of each measured quantity, **fit QQ photon signal + hadronic bgd. including a fixed calculated LL photon contribution.**

LL contribution

Evaluated with ARIADNE 4.12 Monte Carlo

QQ contribution

Evaluated with PYTHIA 6.416

Neutral meson background

Evaluated using ARIADNE 4.12

Systematic uncertainties

dominated by:

- jet energy scale

- photon energy scale

- modelling of background

Theoretical calculations

1) **GKS**

A. Gehrmann-de Ridder, G. Kramer, H Spiesberger,
Nucl. Phys. B 58 (2000) 56

A. Gehrmann-de Ridder, G. Kramer, E. Poulsen,
Phys. Rev. Lett. 96 (2006) 132002

A .Gehrmann-de Ridder, G. Kramer, E. Poulsen,
Eur. Phys. J. C47 (2006) 95

Calculations of the process $ep \rightarrow e\gamma X$ to orders α^3 and $\alpha^3 \alpha_s$

QQ and LL processes included, interference small and neglected.

HERAPDF 1.0 parton set is used.

2) **BLZ**

S. Baranov, A. Lipatov, and N. Zotov,
Phys. Rev. D81 (2010) 094034

Uses unintegrated proton parton densities, to LO,
and gives enhanced photon radiation from quarks.

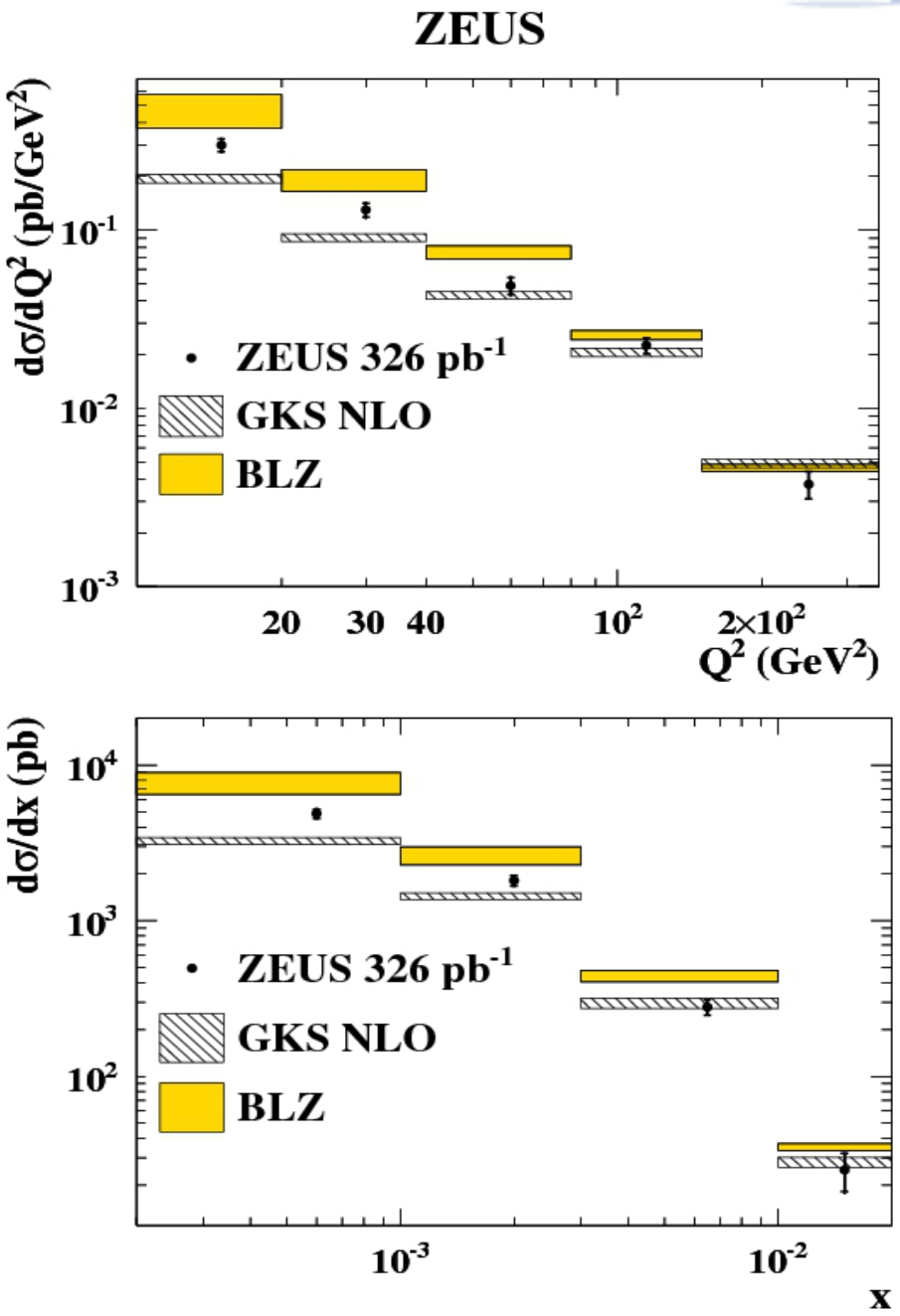
Results

Full photon+jet cross section QQ + LL.

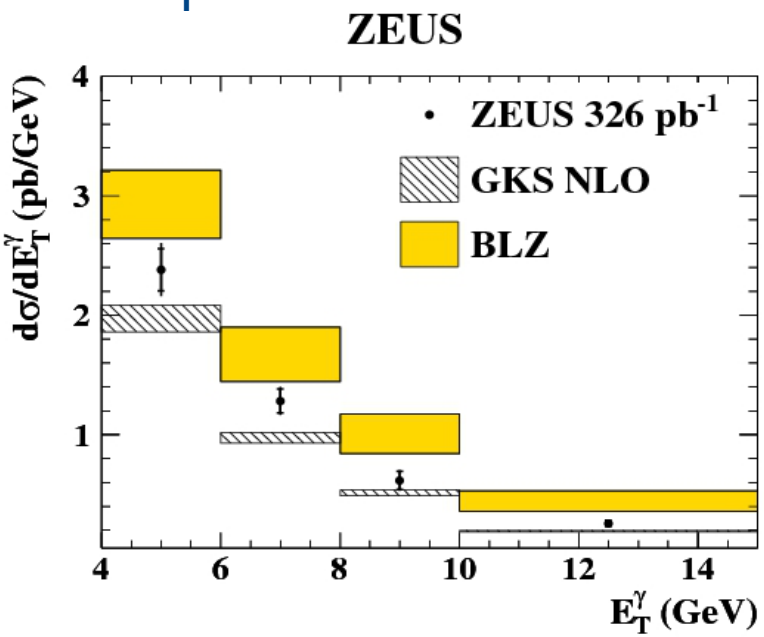
Q^2 = squared momentum transferred from initial to outgoing lepton

x = Bjorken variable

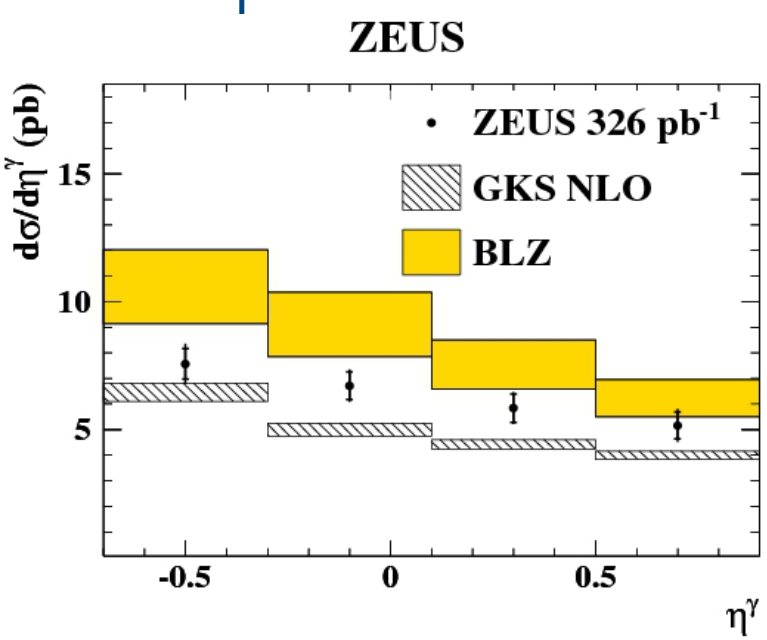
The two models both describe the shape of the cross section reasonably well, but not the absolute magnitude.



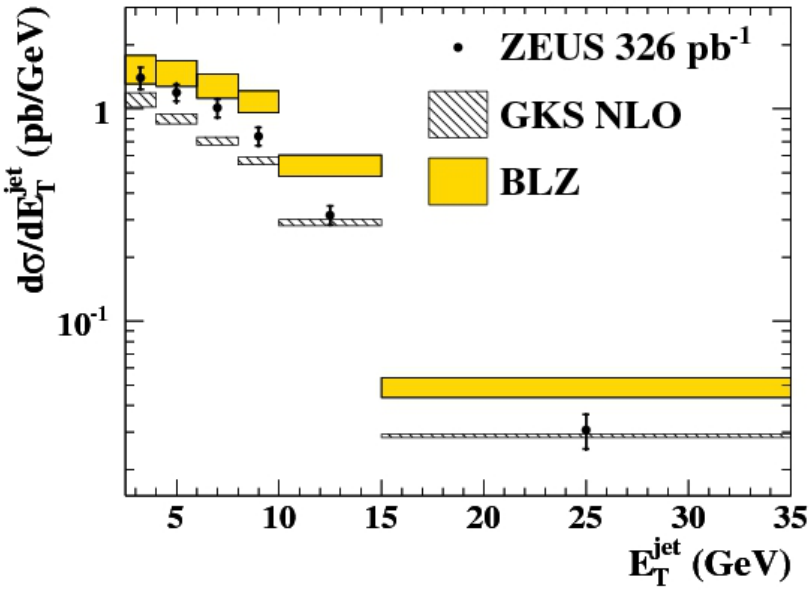
E_T^{γ}



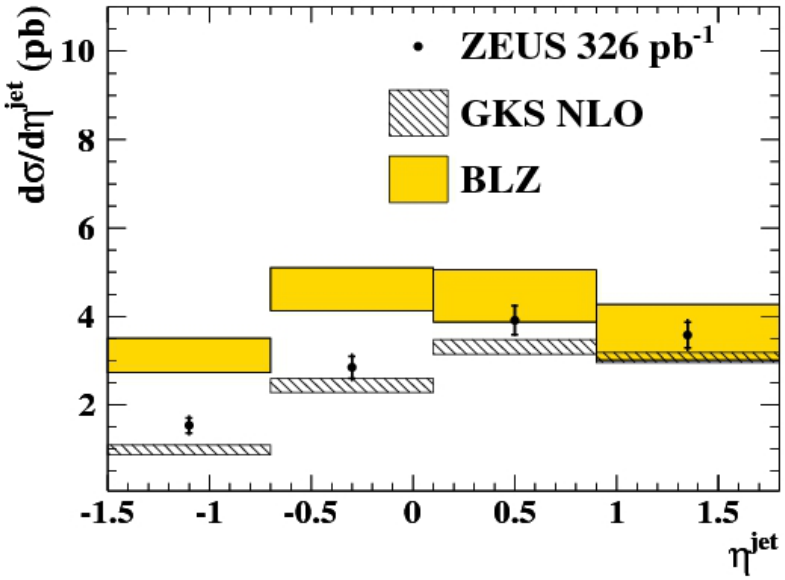
E_T^{jet}



η^{γ}



η^{jet}



Isolated photons in photoproduction.

Inclusive photon cross sections,
and photon + jet

Preliminary results are shown.

The ZEUS photoproduction analysis.

Uses 370 pb^{-1} of HERA 2 data.

Photon candidates: found with an energy-clustering algorithm in the BCAL

$$E_{EMC}/(E_{EMC}+E_{HAD}) > 0.9$$

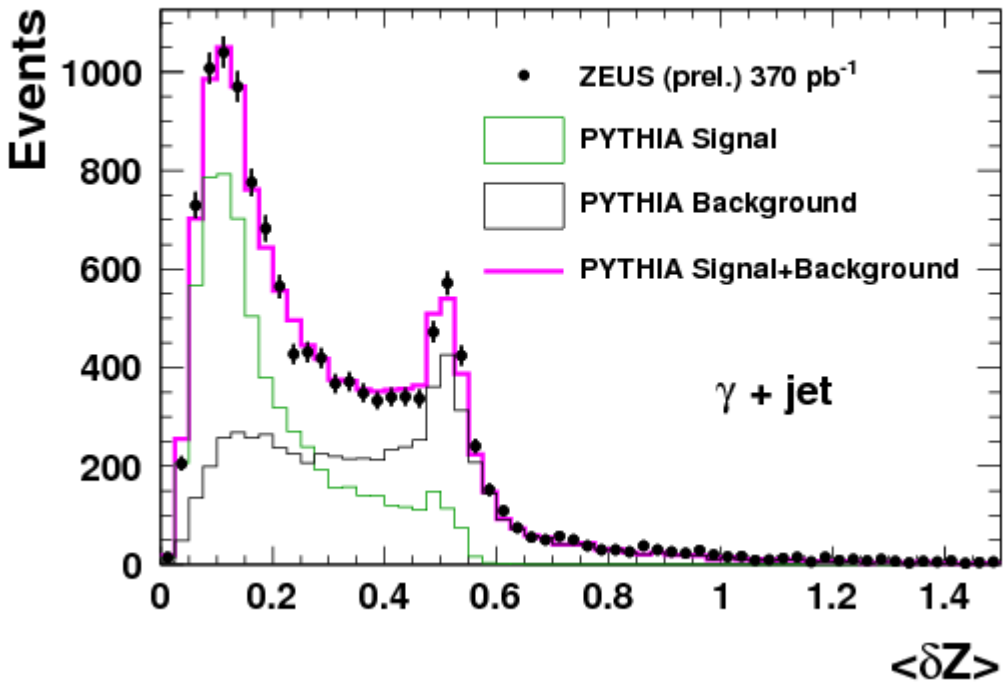
Jets: use k_T-clus algorithm (include photon candidates)

Hard photon candidate:

- $E_T > 6$ GeV
- $-0.7 < \eta^{\gamma} < 0.9$
- **Isolated.** In the "jet" containing the photon candidate, this must contain at least 0.9 of the "jet" E_T

Jet conditions

- $-1.5 < \eta^{jet} < 1.8$
- $E_T^{jet} > 4$ GeV

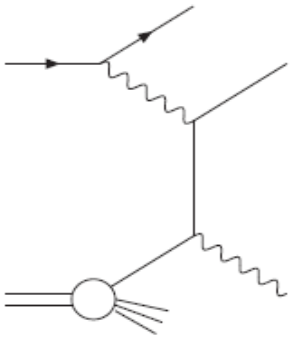


As before, for each measured binned quantity, <dZ> is fitted to

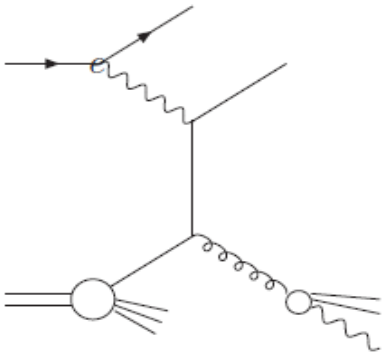
signal (Pythia prompt photon events)

\+ neutral meson background (Pythia dijet photoproduction events)

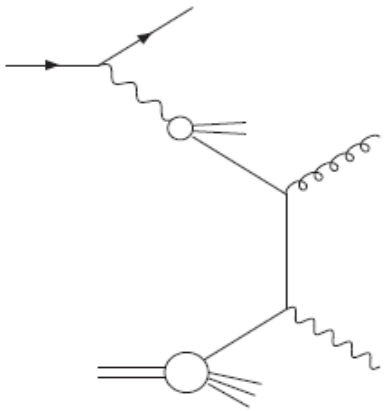
Examples of lowest-order photoproduction diagrams, and with fragmentation.



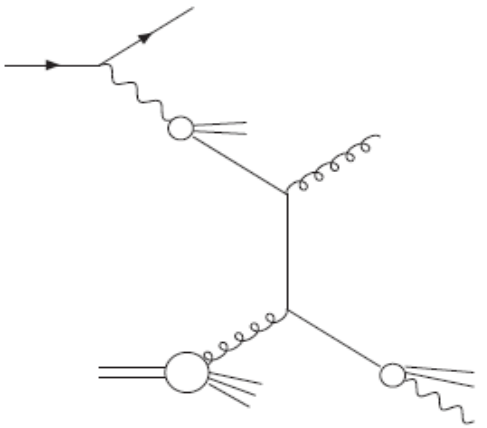
Direct



Direct fragmentation



Resolved

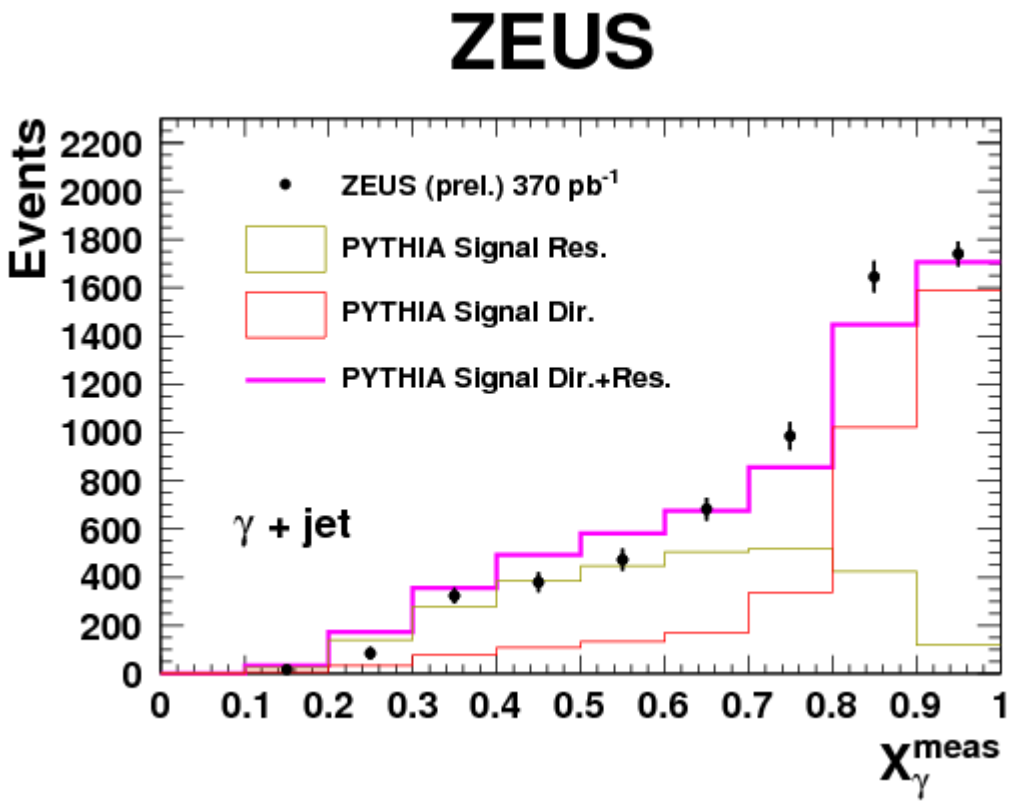


Resolved fragmentation

Pythia simulates these, and initial-state radiative processes.
Herwig is used as a check and to estimate systematics.

In lowest-order, the fraction of the incoming photon energy taken by the interaction can be written as

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



Theoretical calculations

1) **FGH**
M Fontannaz, J-P Guillet, G Heinrich, Eur. Phys. J C 21 (2001) 303

Full NLO calculation of resolved and direct processes,
including box diagrams and fragmentation component.

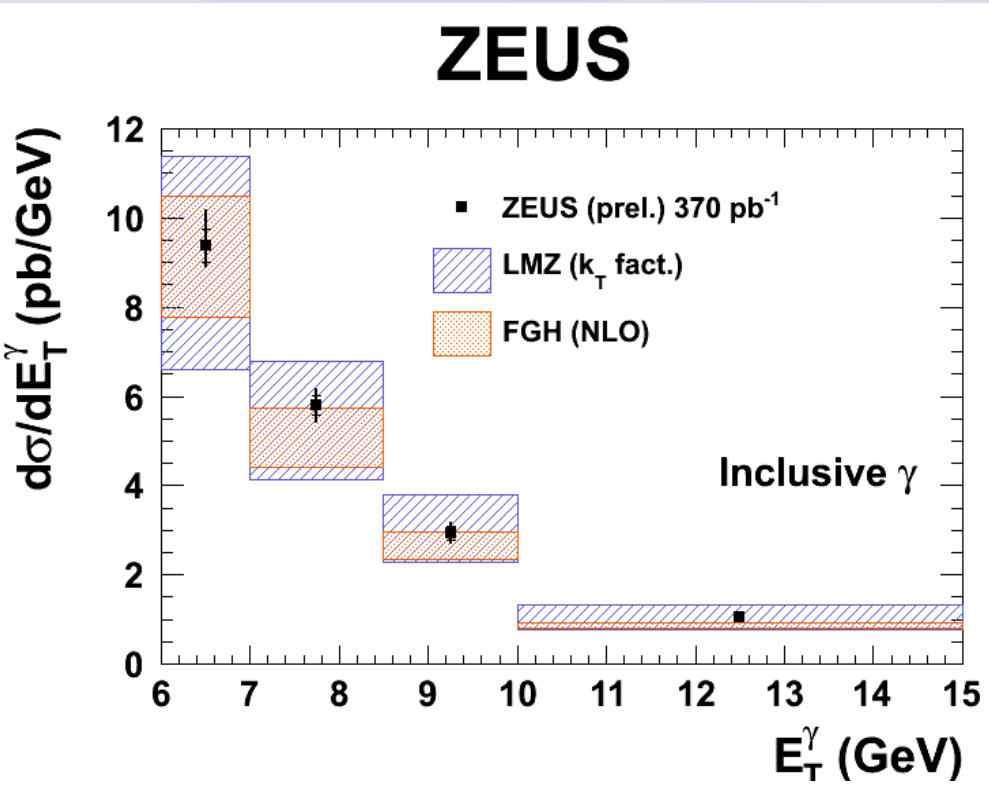
2) **LMZ**
A Lipatov, and N Zotov, Phys. Rev. D 81 (2010) 094027
A Lipatov, M Malyshev, N Zotov, arXiv 1307.3644 (2013)

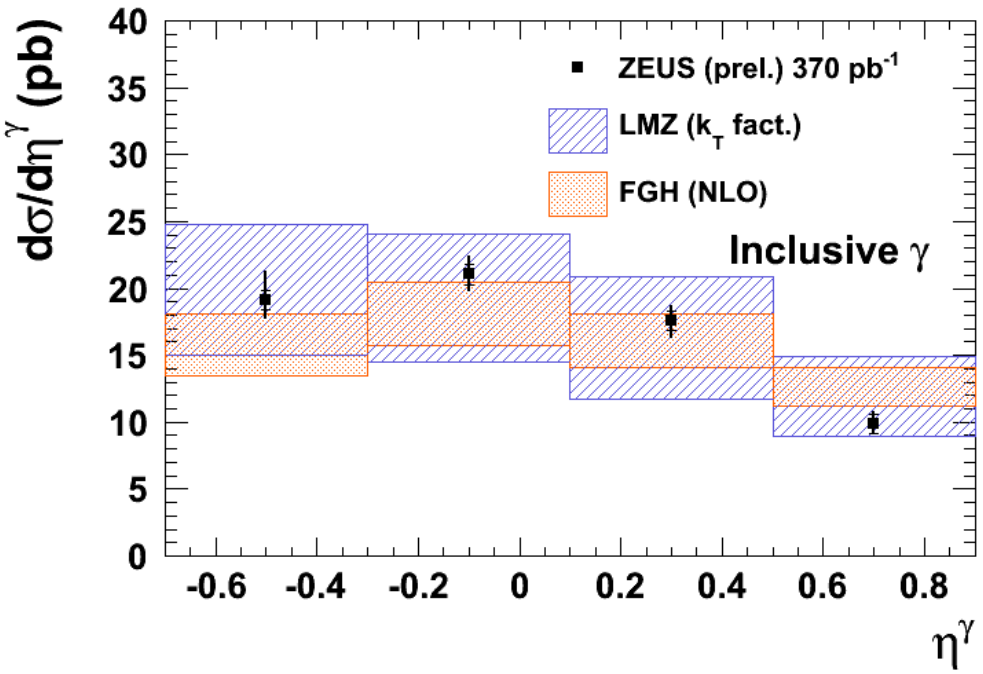
Tree-level 2→3 diagrams using unintegrated parton distributions.
box diagrams also included.

In both cases:
- Uncertainty due to fragmentation and renormalisation scales.

Results

Inclusive isolated photon cross sections



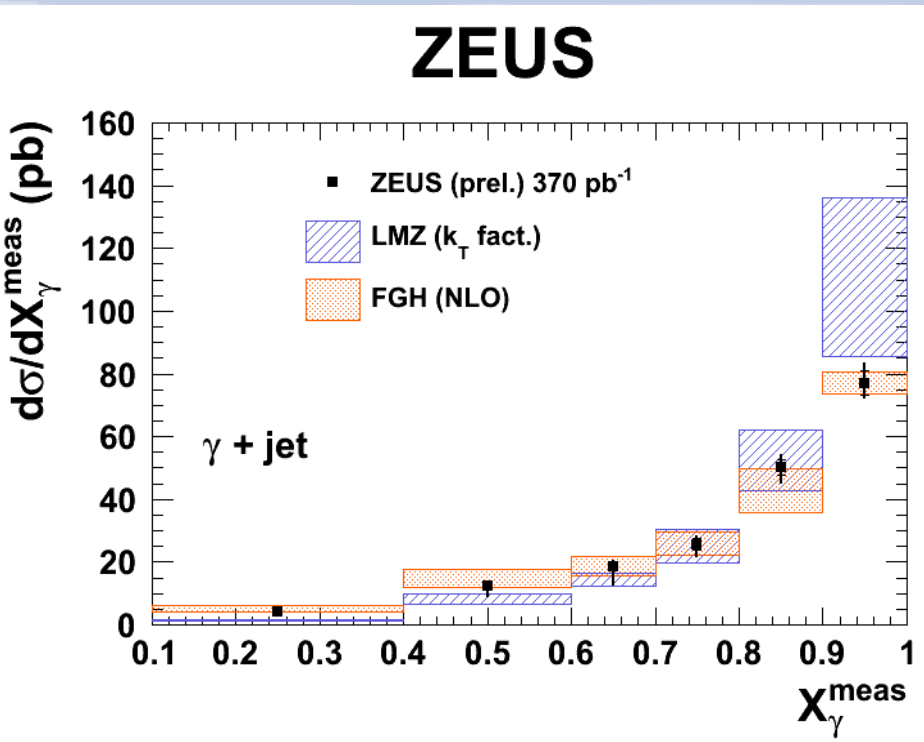


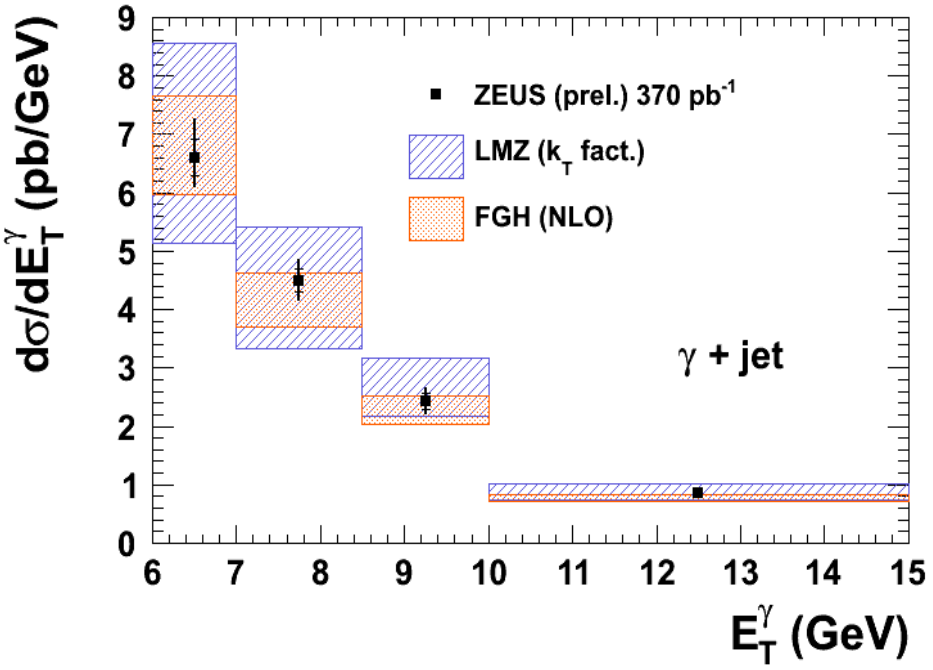
Both theories give a satisfactory description but the theory uncertainties are large.

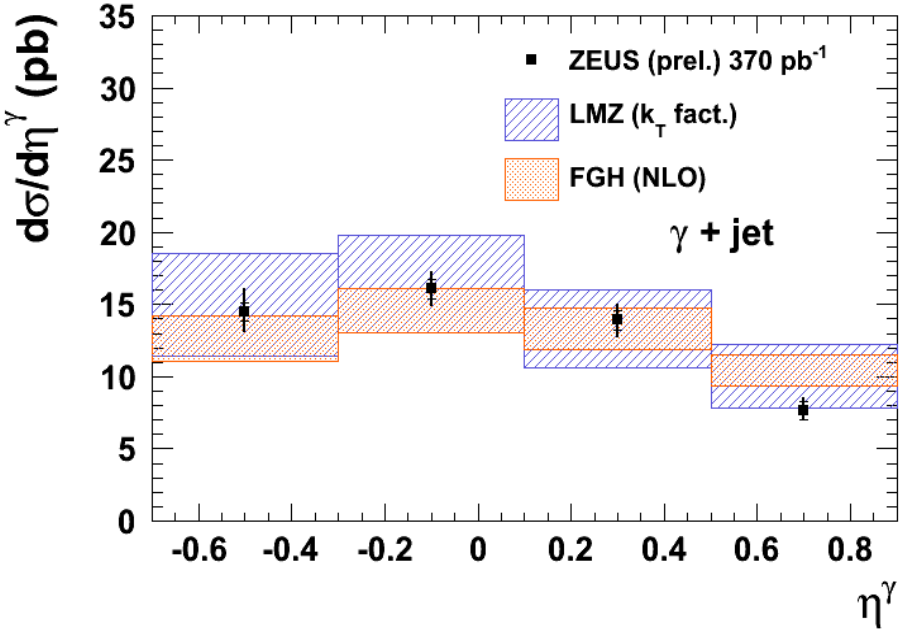
Photon plus jet.

The x_γ shape shows the direct peak.

Theories reasonably satisfactory but with large uncertainty.





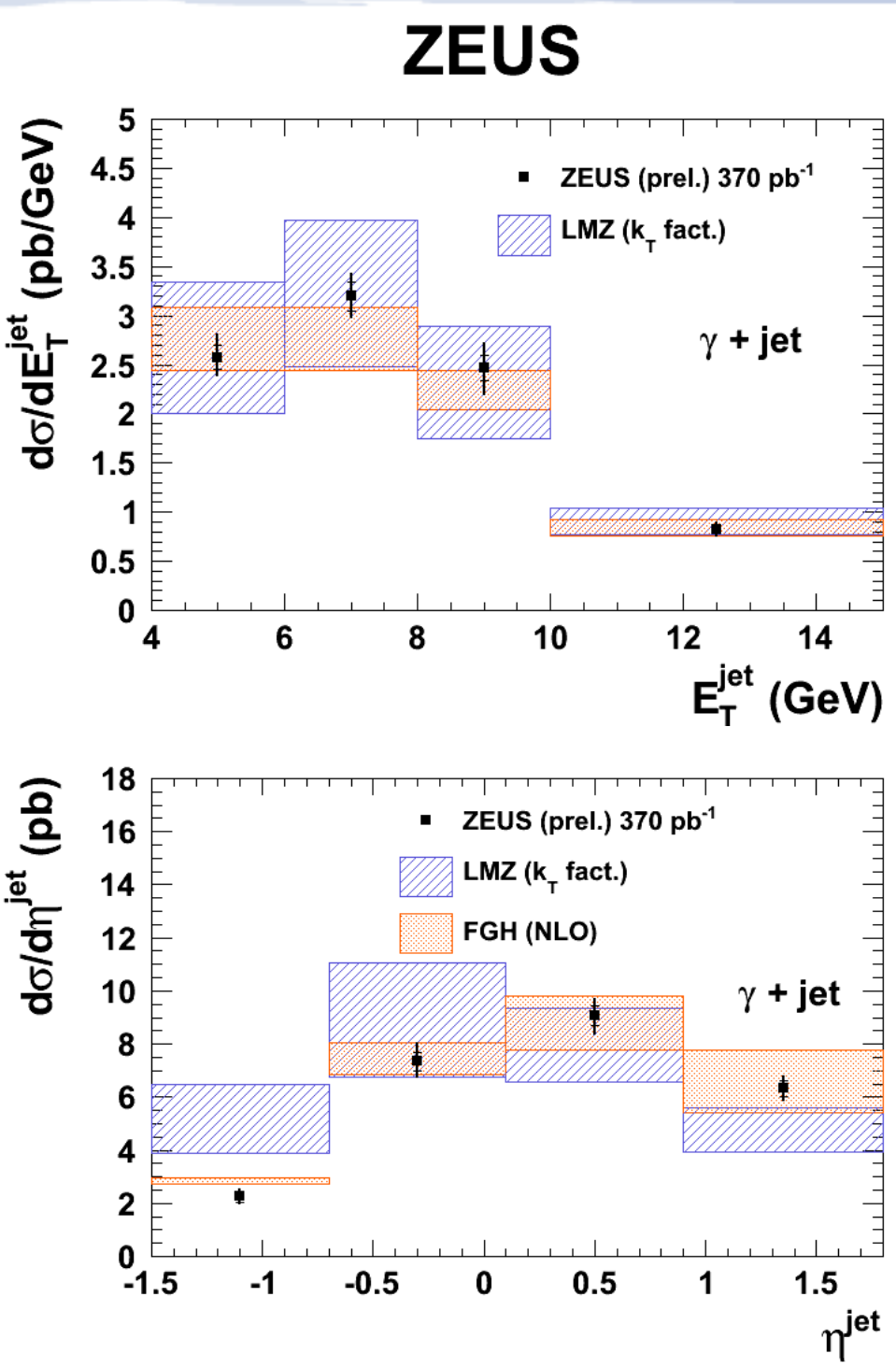


Photon plus jet.

Jet variables.

Theories reasonably satisfactory again, but with large uncertainty.

Perhaps a disagreement with very backward jets.



Summary:

- Measurements of prompt photons with jets in DIS have been made by ZEUS using full HERA 2 data sample.

- Available theories describe shape of distributions well but less well the absolute value.

- Measurements of prompt photons inclusively and with jets in photoproduction have been made by ZEUS using full HERA 2 data sample.

- Available theories are in satisfactory overall agreement with data but the theory uncertainties are large.