Juan Terrón
Universidad Autónoma de Madrid, Spain

Dijet and 3-Jet Photoproduction at HERA:

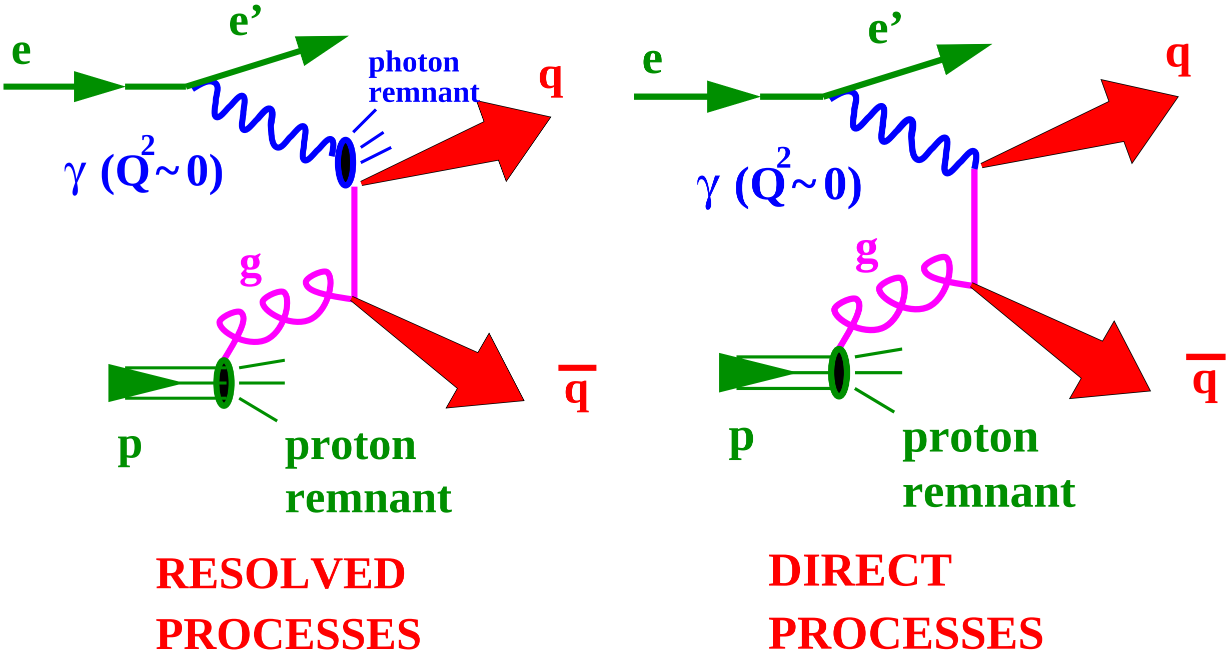
from Photon Structure to Top Quark

H1 Collab. ZEUS Collab.

PHOTON 2000
26th - 31st August 2000
Ambleside, England

Dijet Photoproduction at HERA

• At lowest order QCD, two hard scattering processes contribute to jet production:



→ $\boxed{\text{Photon structure}}$: the dijet cross sections are sensitive to both the quark and gluon densities in the photon.

→ $\boxed{\text{Dynamics of resolved and direct processes}}$: the dijet angular distribution is sensitive to the spin of the exchanged particle.

→ $\boxed{\text{Dynamics at high dijet invariant mass}}$: the dijet angular and mass distributions are sensitive to hadronic decays of new particles or resonances.

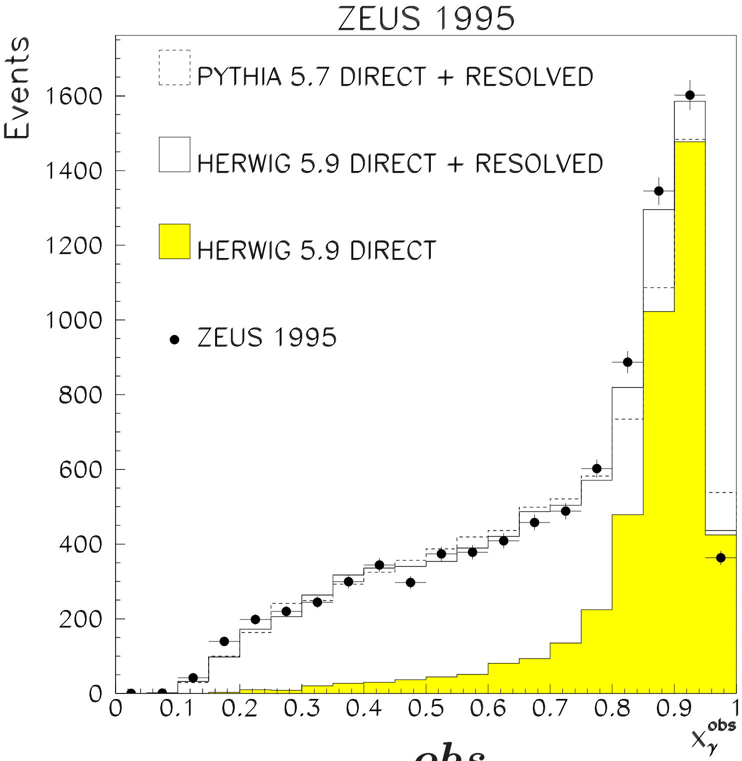
Photon Structure at HERA

• Observables whose distributions in dijet photoproduction at HERA are sensitive to the photon structure :

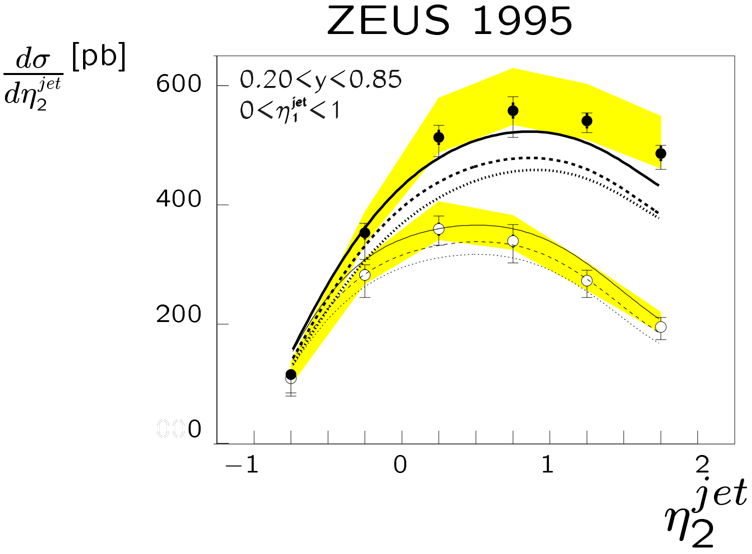
→ the fraction of the photon's energy participating in the production of the dijet system (x_γ^{obs})

$$\boxed{x_\gamma^{obs} = \frac{\sum_{i=1}^{2} E_T^{jet_i} e^{-\eta^{jet_i}}}{2E_\gamma}}$$

→ the jet pseudorapidity (η^{jet}) in the laboratory frame: at low x_γ^{obs} the dijet system is boosted more forward (proton direction) than at high x_γ^{obs}.



x_γ^{obs}



Photon Structure at HERA

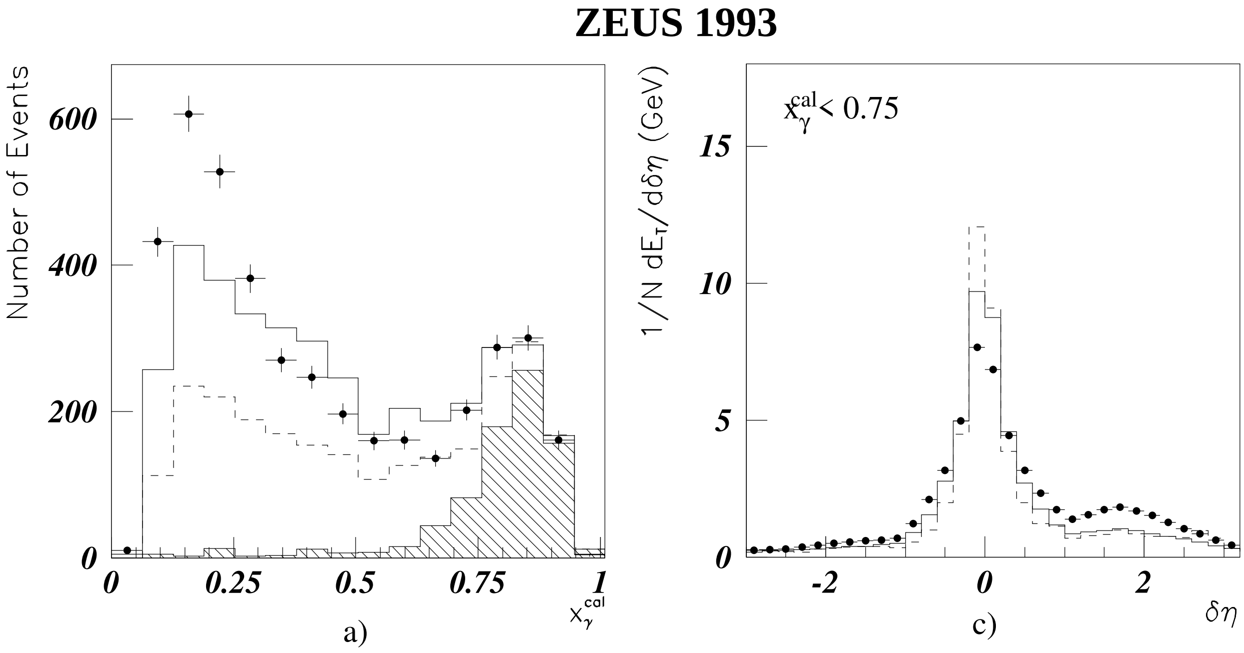
• To provide precise measurements that can be used to constrain the photon parton densities several difficulties have to be overcome:

→ jet algorithms and jet selections for which accurate (at least NLO) pQCD predictions can be performed:

the inclusive k_T-cluster algorithm!!!

asymmetric cuts on $E_T^{jet,1}$ and $E_T^{jet,2}$!!!

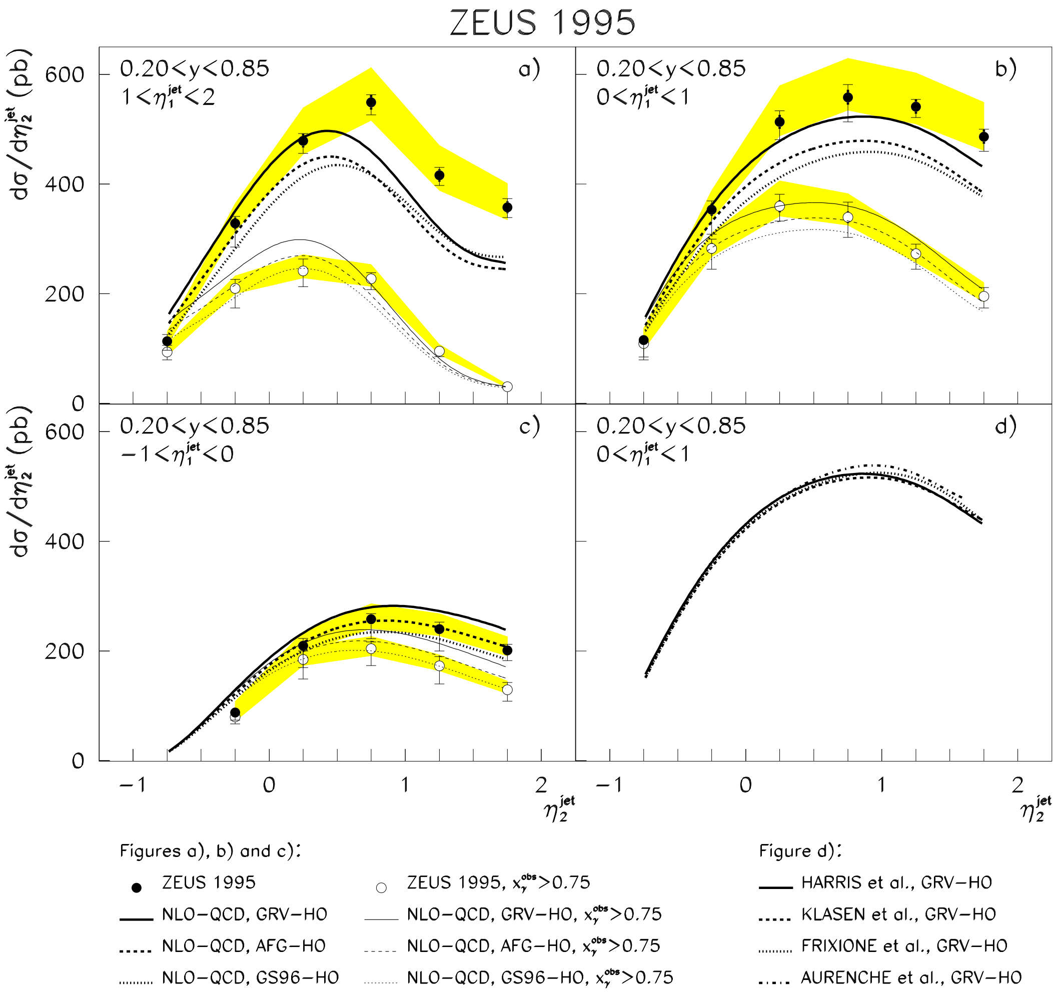
→ Suppression of non-perturbative effects: underlying event and fragmentation.



jets with higher E_T^{jet} are required!!!

Photon Structure at HERA

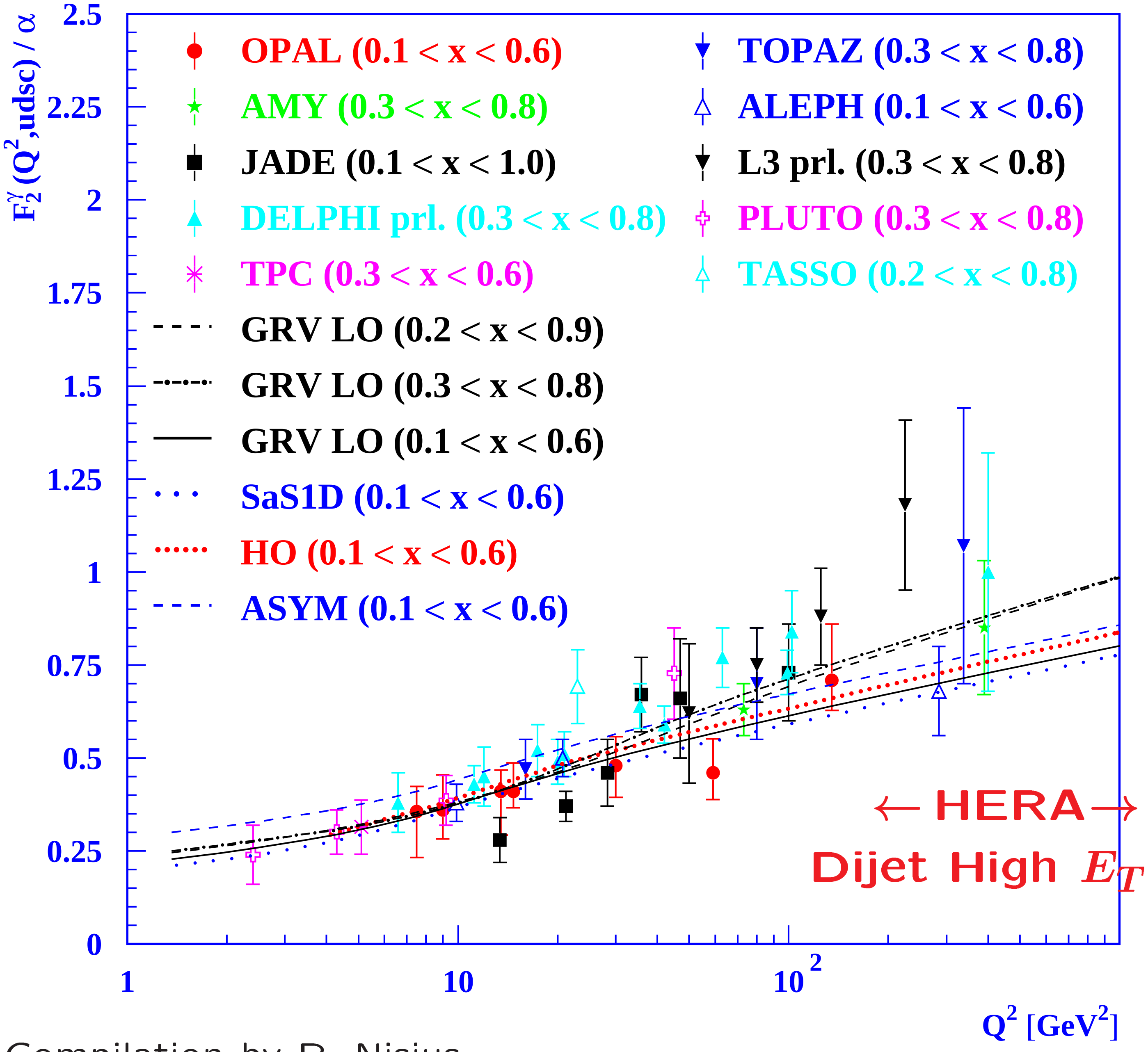
- Measurements of differential cross sections for dijet photoproduction using the inclusive k_T-cluster algorithm at high E_T^{jet}: $E_T^{jet,1} > 14$ GeV and $E_T^{jet,2} > 11$ GeV



The measured cross sections are higher than the NLO QCD calculations in a region where the theoretical uncertainties are small.

Inadequacy of the current parametrisations of the photon parton densities at high x_γ^{obs}

World Data on F_2^γ



Compilation by R. Nisius

Measurement of Dijet Cross Sections in Photoproduction

(ZEUS Collaboration, Preliminary)

- Jet search using the inclusive k_T-cluster algorithm in the laboratory frame

- Kinematic Region: $Q^2 < 1$ GeV^2 (median $\approx 10^{-3}$ GeV^2) and $134 < W < 277$ GeV

- Measurement of the differential cross section $d\sigma/dx_\gamma^{obs}$ for dijet photoproduction with

$$E_T^{jet}\text{(leading)} > 14 \text{ GeV},$$

$$E_T^{jet}\text{(next-to-leading)} > 11 \text{ GeV and}$$

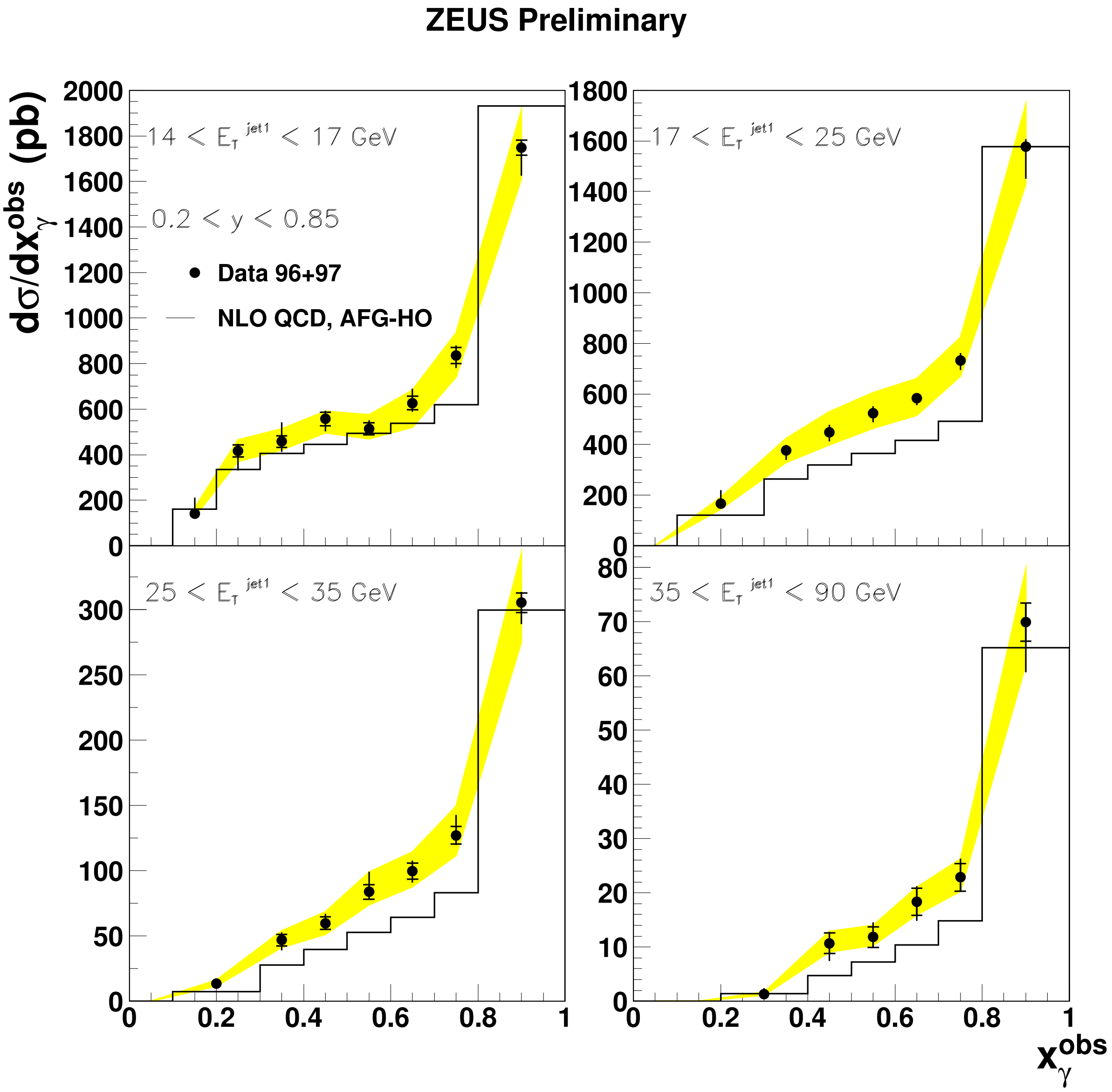
$$-1 < \eta^{jet} < 2$$

- The dijet cross section, $d\sigma/dx_\gamma^{obs}$, has been corrected to the hadron level and studied as a function of E_T^{jet}(leading).

$\rightarrow$ Comparison to NLO QCD calculations at the parton level using current parametrisations of the photon parton densities.

$\rightarrow$ Hadron-to-parton effects $\sim 10-15\%$; estimated using PYTHIA and HERWIG Monte Carlo programs; not included!

Measurement of $d\sigma/dx_\gamma^{obs}$



- NLO QCD calculations:

→ NLO parametrisations of the photon parton densities by Aurenche, Fontannaz and Guillet (AFG-HO)

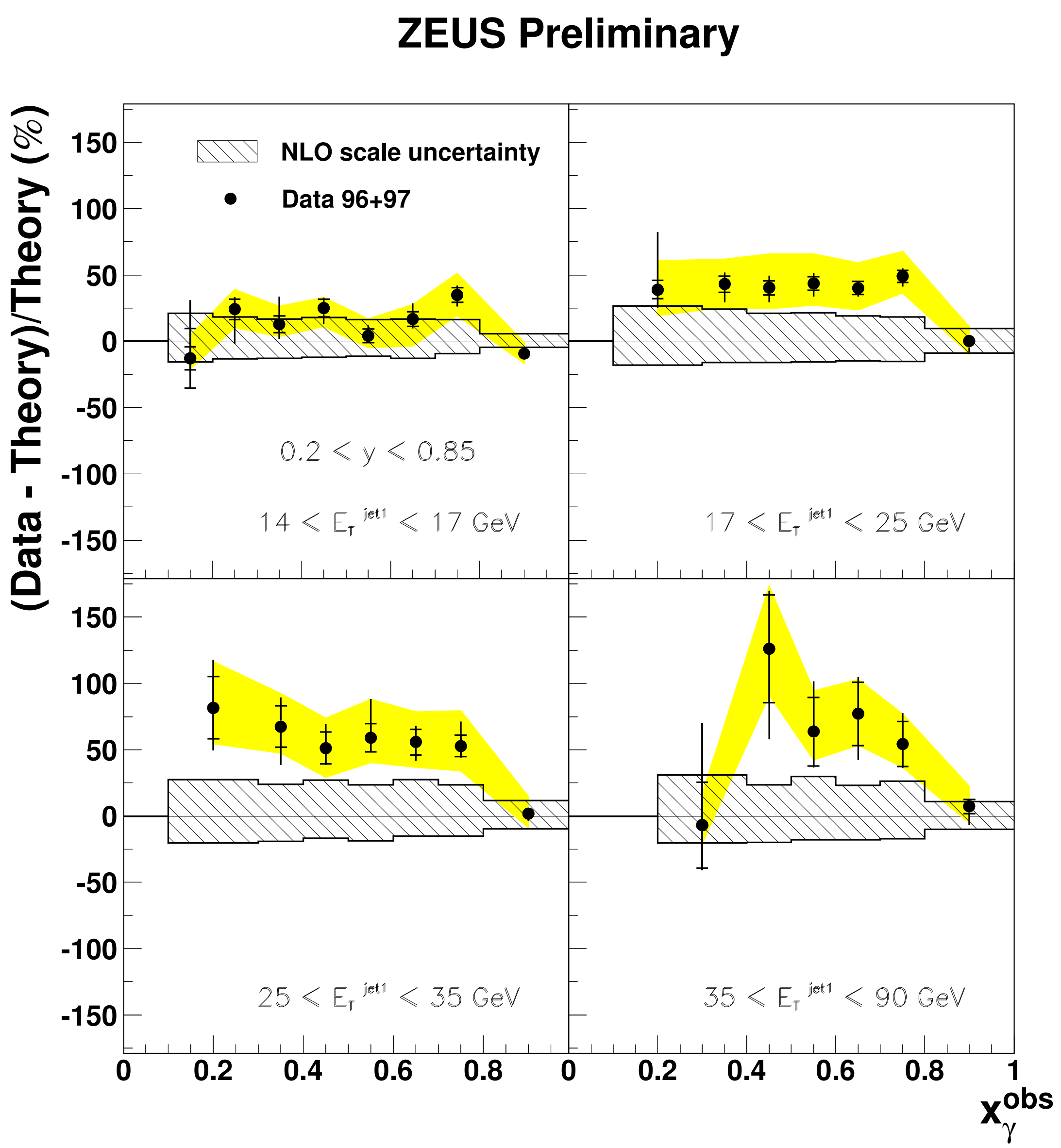
→ NLO parametrisations of the proton by CTEQ (CTEQ4M)

→ Subtraction method (S. Frixione and G. Ridolfi)

Agreement at high x_γ^{obs} for all E_T^{jet}

Data above NLO QCD for $x_\gamma^{obs} < 0.8$

Measurement of $d\sigma/dx_\gamma^{obs}$



- Dominant Experimental Uncertainty: Energy scale of the jets ($\pm 3\%$) $\rightarrow \sim \pm 15\%$ on the cross section
- Dominant Theoretical Uncertainty: scale dependence of the calculations $\sim \pm 15\%$

$\rightarrow$ Discrepancies between data and NLO QCD cannot be accounted for by the uncertainties:

Current parametrisations of the photon parton densities are inadequate!

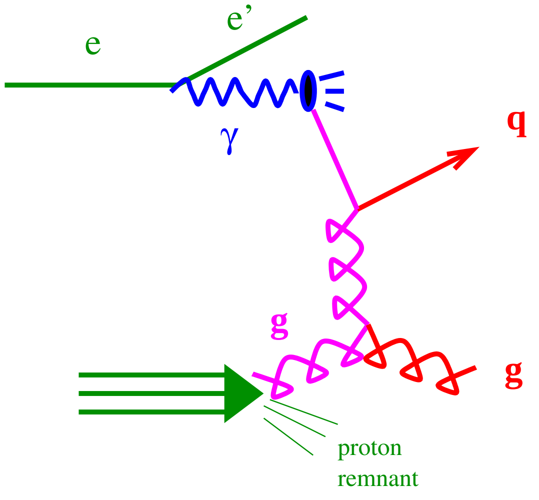
Dynamics of Dijet Photoproduction

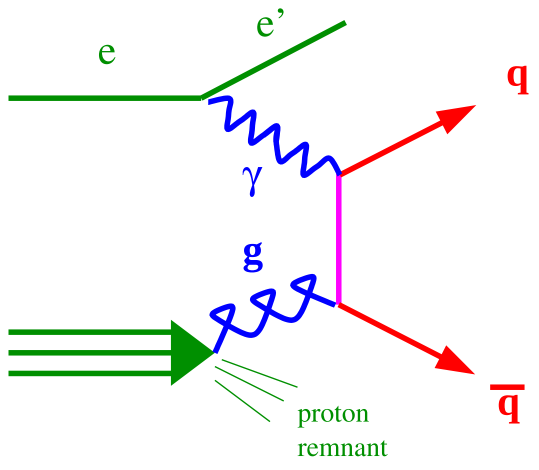
- To understand the discrepancy between data and NLO QCD at low x_γ^{obs} the dynamics of the resolved and direct processes has been investigated:

$$\boxed{\cos\theta^* \equiv tanh(\frac{\eta^{jet,1}-\eta^{jet,2}}{2})}$$

$\rightarrow$ For two-to-two parton scattering this variable coincides with the cosine of the scattering angle in the dijet centre-of-mass system.

- QCD predicts different dijet angular distributions for resolved and direct processes:





Resolved Process (gluon exchange dominated)
$d\sigma/d|\cos\theta^*| \sim (1-|\cos\theta^*|)^{-2}$

Direct Process (quark exchange only)
$d\sigma/d|\cos\theta^*| \sim (1-|\cos\theta^*|)^{-1}$

Measurement of $d\sigma/d|\cos\theta^*|$

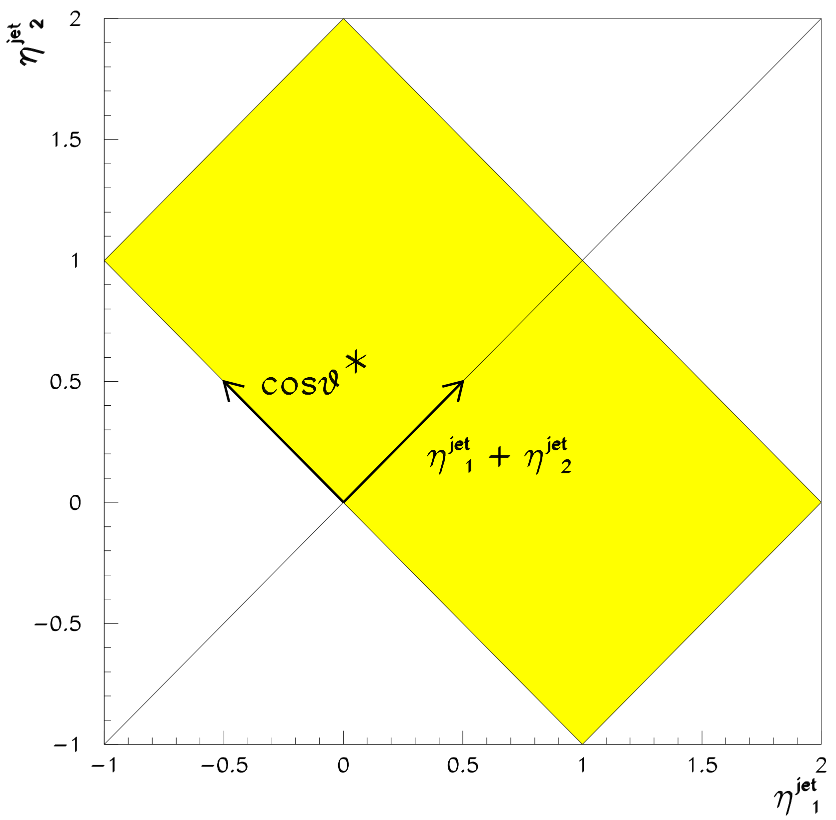
- Measurement of the differential cross section $d\sigma/d|\cos\theta^*|$ for dijet photoproduction in the region

$$|\cos\theta^*| < 0.76 \quad , \quad M^{JJ} > 39 \text{ GeV and}$$

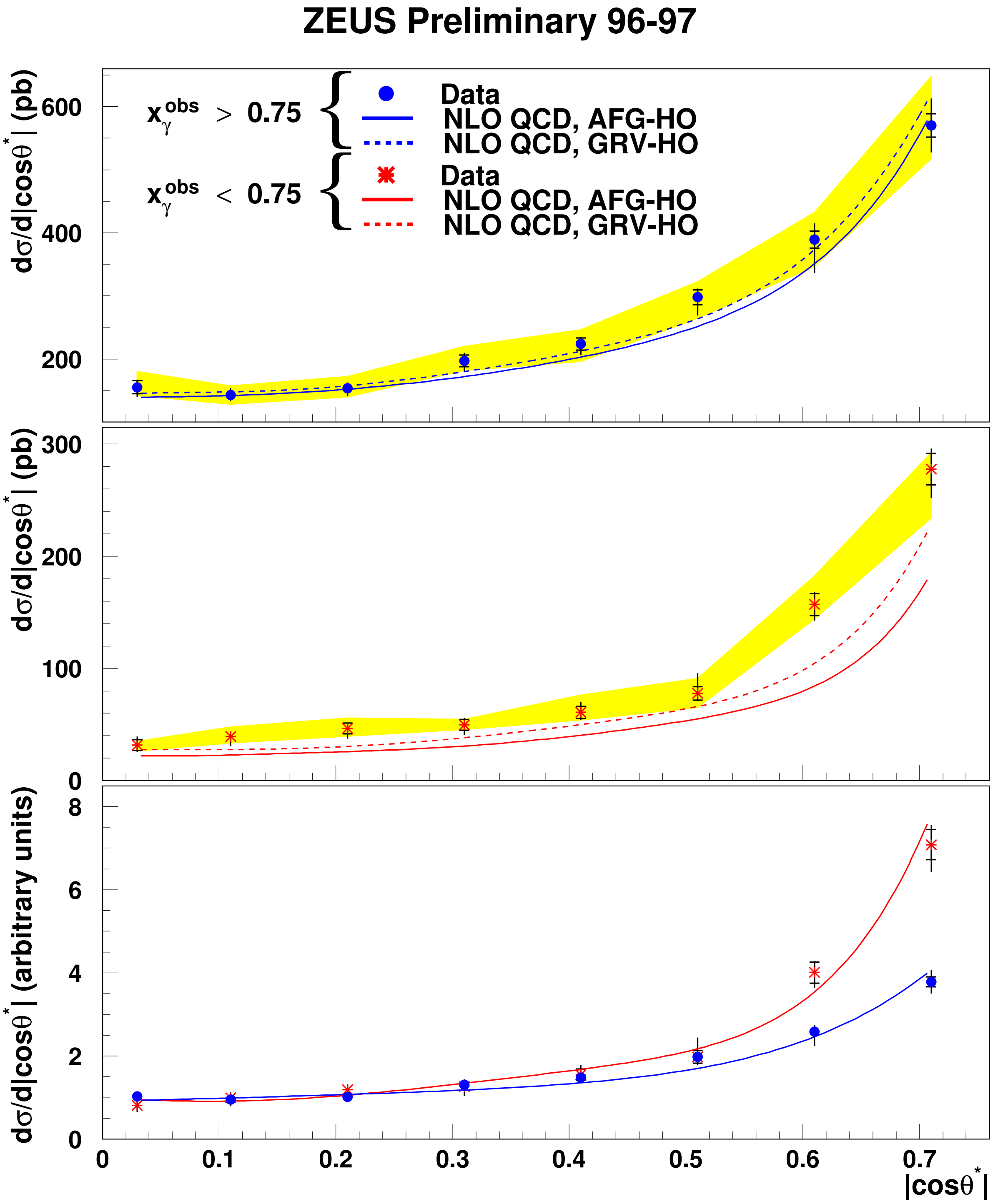
$$0 < \frac{1}{2}(\eta^{jet,1} + \eta^{jet,2}) < 1$$

$\rightarrow$ cut on the dijet invariant mass, M^{JJ}, to avoid bias due to E_T^{jet} requirements.

$\rightarrow$ cut on the boost, $(\eta^{jet,1}+\eta^{jet,2})/2$, to have uniform acceptance in $|\cos\theta^*|$.



Measurement of $d\sigma/d|\cos\theta^*|$



High-x_γ^{obs} region: NLO QCD describes the shape and normalisation of the cross section

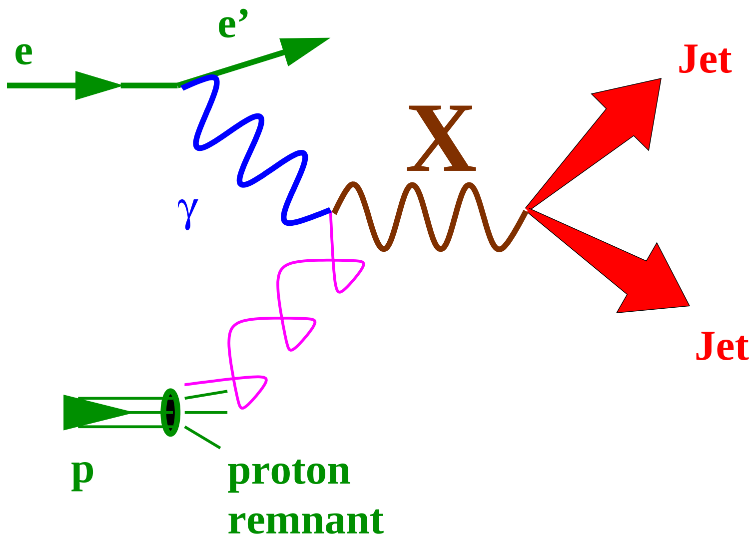
Low-x_γ^{obs} region: NLO QCD describes the shape, but not the normalisation of the data

Dynamics OK! Parametrisations Inadequate!

Dijet and 3-jet Photoproduction at High M^{JJ}

- A means to study the dynamics of parton-parton and photon-parton interactions at high invariant mass (M^{JJ} and M^{123}).

- New particles decaying to two (three) jets may be identified



$\rightarrow$ as a bump in the dijet (three-jet) mass distribution

$\rightarrow$ as a deviation in the dijet angular distribution from the Standard Model predictions

- Measurements in $p\bar{p}$ collisions have constrained possible deviations due to new particles or quark substructure in parton-parton collisions.

$\rightarrow$ Direct processes in photoproduction allow an extension of the search to photon-parton interactions.

High-Mass Dijet Cross Sections in Photoproduction

(ZEUS Collaboration, Preliminary)

- Jet search using the inclusive k_T-cluster algorithm in the laboratory frame

- Kinematic Region: $Q^2 < 1$ GeV^2 (median $\approx 10^{-3}$ GeV^2) and $134 < W < 277$ GeV

- Measurement of the differential cross sections $d\sigma/dM^{JJ}$ and $d\sigma/d\chi$ for dijet photoproduction with

$$E_T^{jet} > 14 \text{ GeV and } -1 < \eta^{jet} < 2.5$$

(both jets) in the region

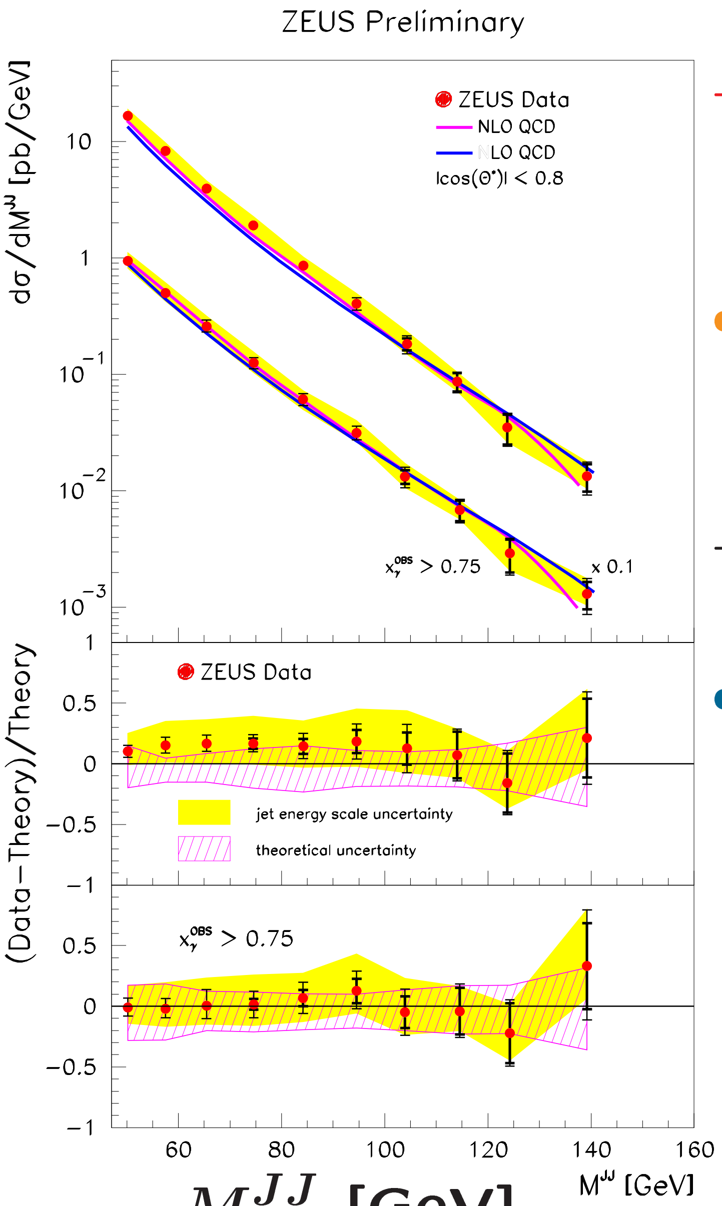
$$M^{JJ} > 47 \text{ GeV and } |\cos\theta^*| < 0.8$$

- The dijet cross sections have been corrected to the hadron level and studied as a function of M^{JJ}.

$\rightarrow$ Comparison to NLO QCD calculations at the parton level using current parametrisations of the photon parton densities.

$\rightarrow$ Hadron-to-parton effects $\sim 5\%$; estimated using PYTHIA and HERWIG Monte Carlo programs; not included!

Measurement of $d\sigma/dM^{JJ}$



M^{JJ} [GeV]

$\rightarrow$ M^{JJ} up to 170 GeV with 43 pb^{-1}.

- Dominant Experimental Uncertainty: energy scale of the jets ($\pm 3\%$)

$\rightarrow$ $\pm 15\%$ on cross section

- NLO QCD calculations:

  GRV-HO $\rightarrow$ photon

  CTEQ4M $\rightarrow$ proton

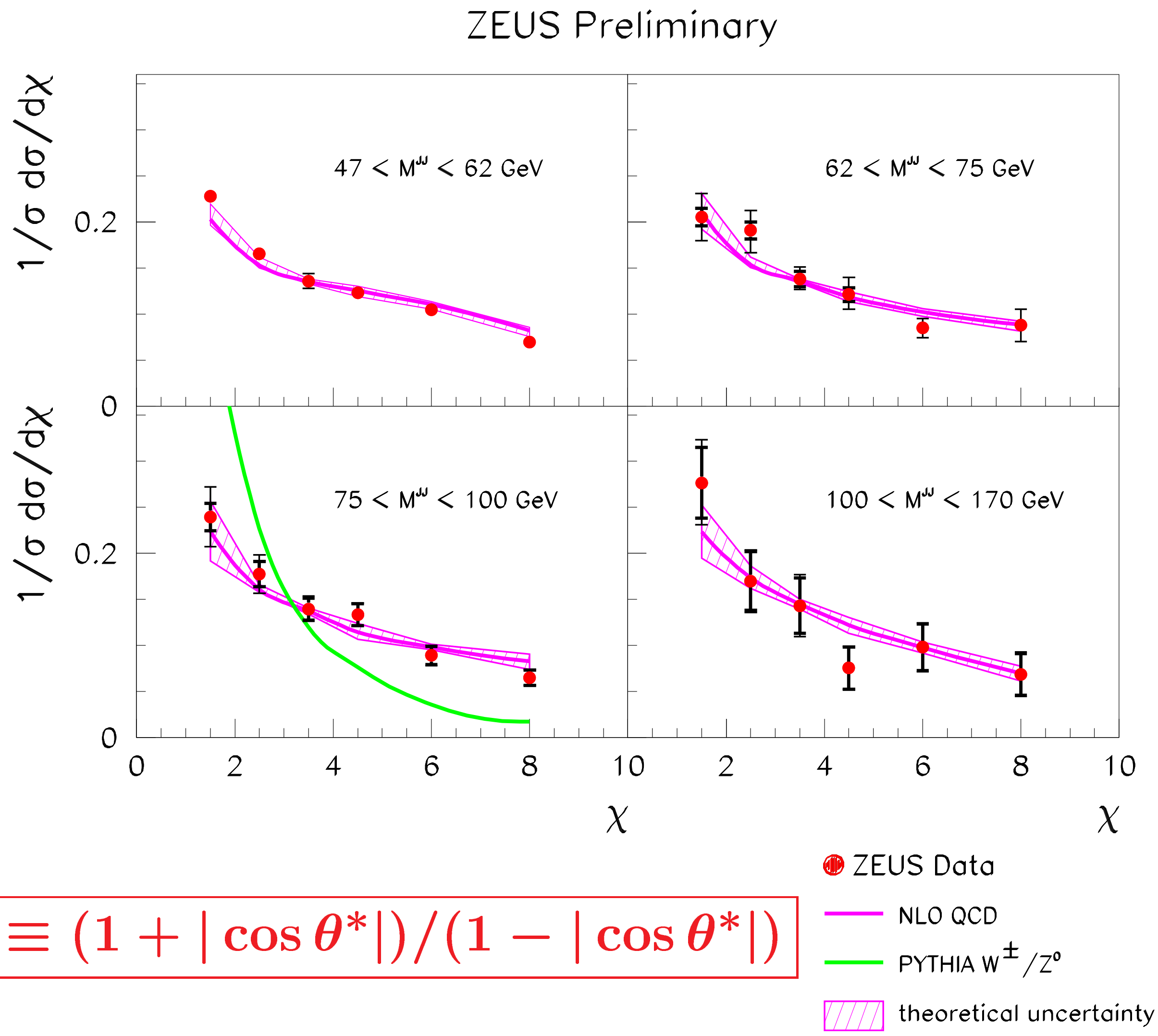
  Theoretical uncertainty: $\pm 15\%$ scale dependence (M. Klasen, G. Kramer)

Good description of the shape by NLO QCD
$\rightarrow$ No evidence for new particle...

$\rightarrow$ **All x_γ^{obs}:** Data above the calculations, but consistent within the uncertainties.

$\rightarrow$ **High x_γ^{obs}:** NLO QCD reproduces the normalisation of the data.

Measurement of $1/\sigma d\sigma/d\chi$ for all x_γ^{obs}



$$\chi \equiv (1 + |\cos\theta^*|)/(1 - |\cos\theta^*|)$$

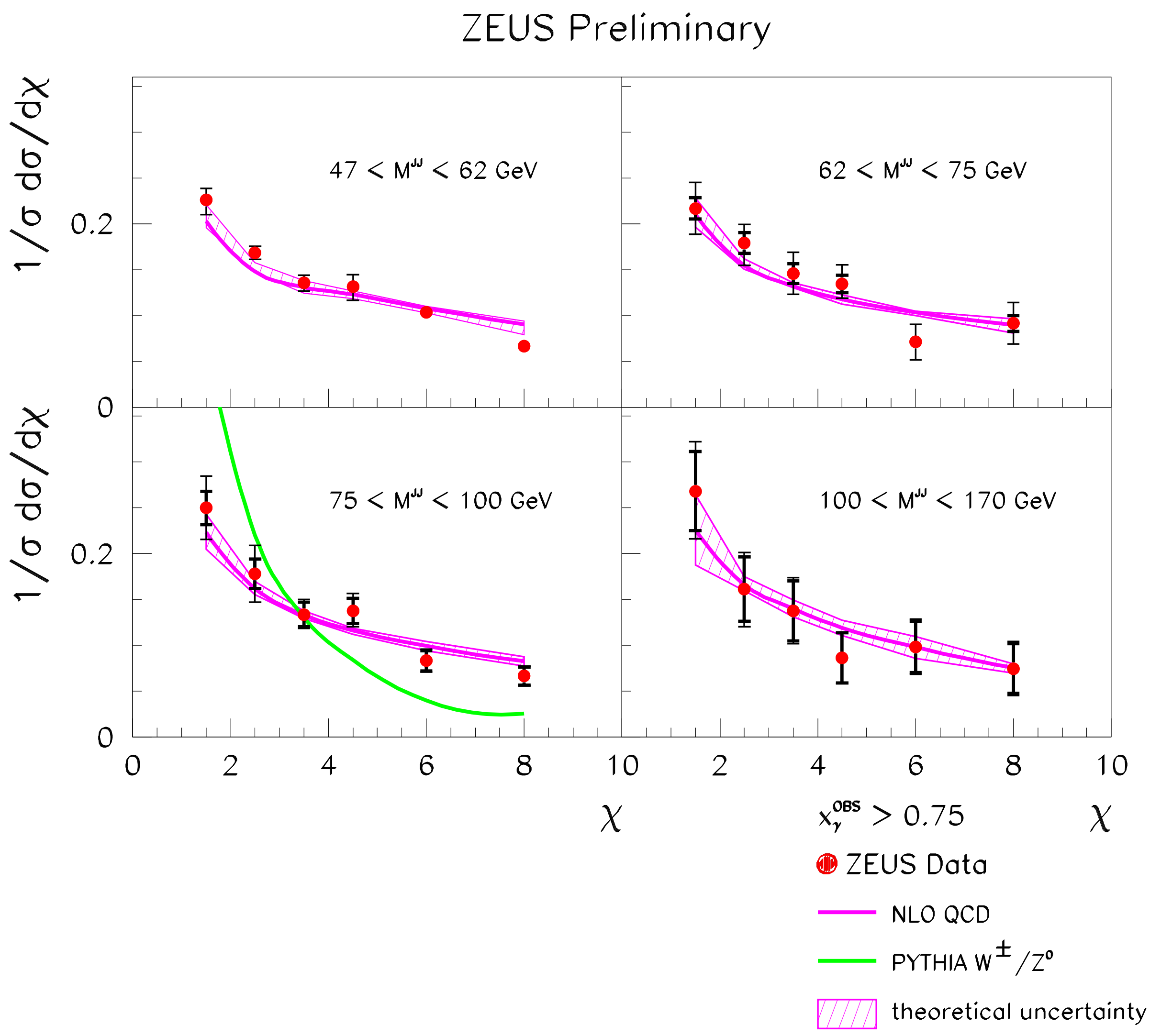
- Smaller theoretical and experimental uncertainties

$\rightarrow$ Dijet angular distribution from $W^\pm$ and Z° production: inconsistent with the data.

$\rightarrow$ NLO QCD agrees reasonably well with the data:

Measured dijet angular distribution consistent with PQCD description in terms of parton exchange

Measurement of $1/\sigma d\sigma/d\chi$ for $x_\gamma^{obs} > 0.75$



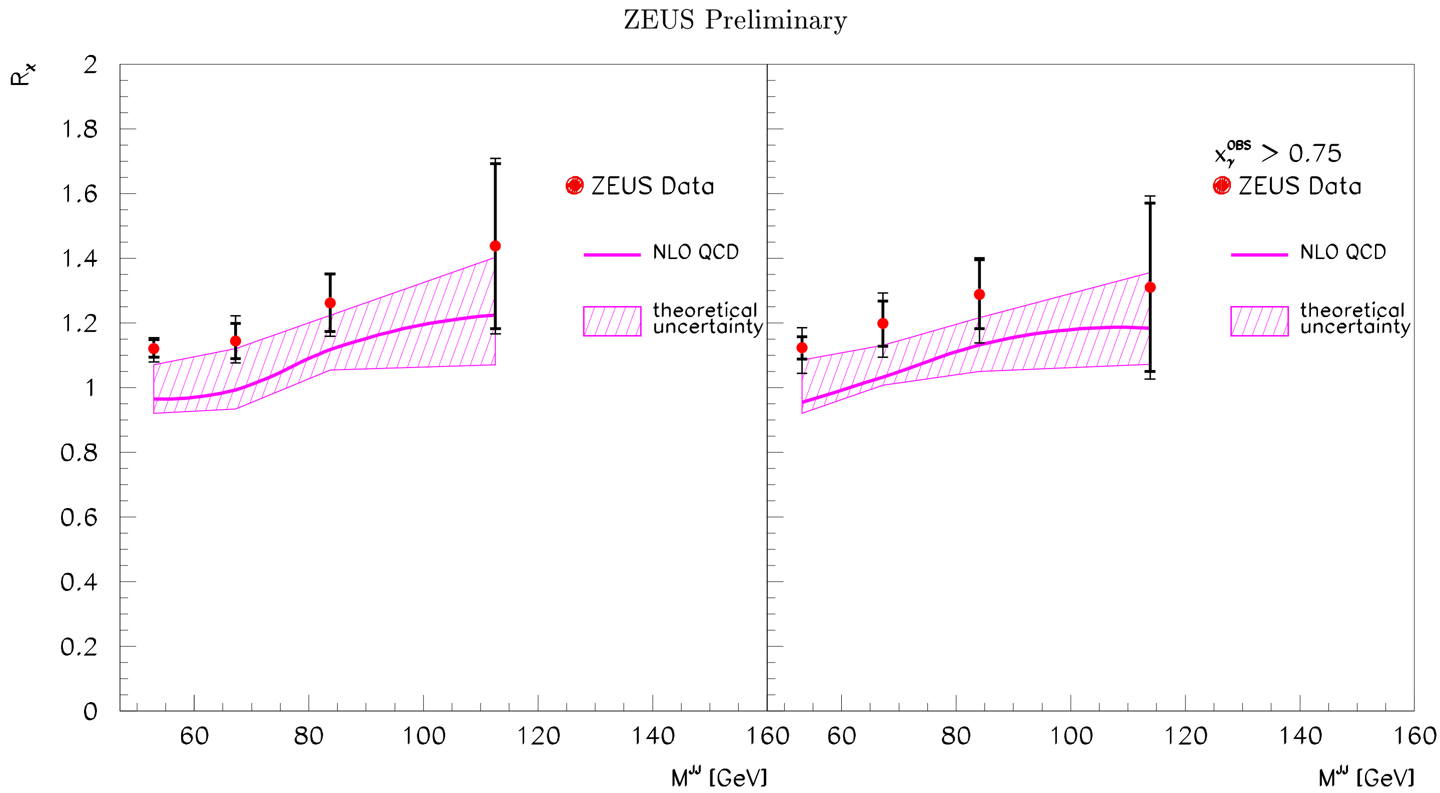
→ Equally good description of the measured dijet angular distribution with $x_\gamma^{obs} > 0.75$ by NLO QCD.

Dijet mass and angular distributions:
no significant deviation between data and NLO QCD calculations is observed up to $M^{JJ} \sim 140$ GeV

Measurement of R_χ

- Characterisation of the shape of the angular distribution as a function of M^{JJ}:

$$\boxed{R_\chi \equiv \frac{\sigma(1<\chi<4)}{\sigma(4<\chi<9)}}$$



NLO QCD calculations of the ratio R_χ are compatible with the data within the (reduced!) theoretical (10%) and experimental (8%) uncertainties.

Dijet and 3-jet Cross Sections in Photoproduction

(H1 Collaboration, Preliminary)

• Jet search using the inclusive k_T-cluster algorithm in the laboratory frame

• Kinematic Region: $Q^2 < 4$ GeV^2 and $W < 285$ GeV

• Measurement of the differential cross sections for dijet (3-jet) photoproduction with

E_T^{jet}(leading)> 25 GeV,

E_T^{jet}(next-to-leading)> 15 GeV,

(E_T^{jet}(next-to-next-to-leading)> 10 GeV) and

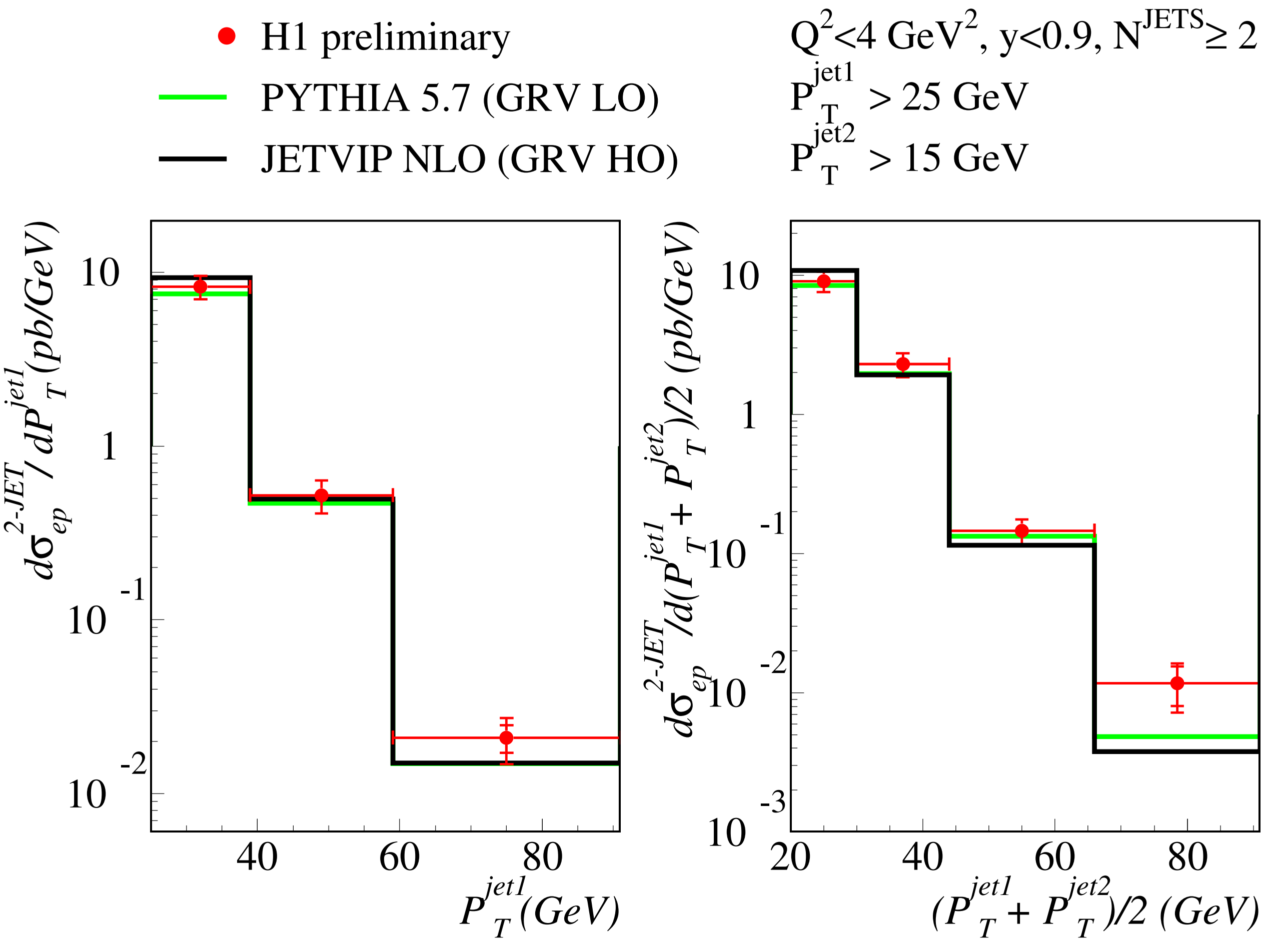
$$-0.5 < \eta^{jet} < 2.5$$

• The cross sections have been corrected to the hadron level.

→ Comparison to Monte Carlo predictions and NLO (LO) QCD calculations for dijet (3-jet) photoproduction.

→ Hadron-to-parton effects $\sim 10\%$; estimated using PYTHIA and HERWIG Monte Carlo programs; not included!

Dijet Differential Cross Sections



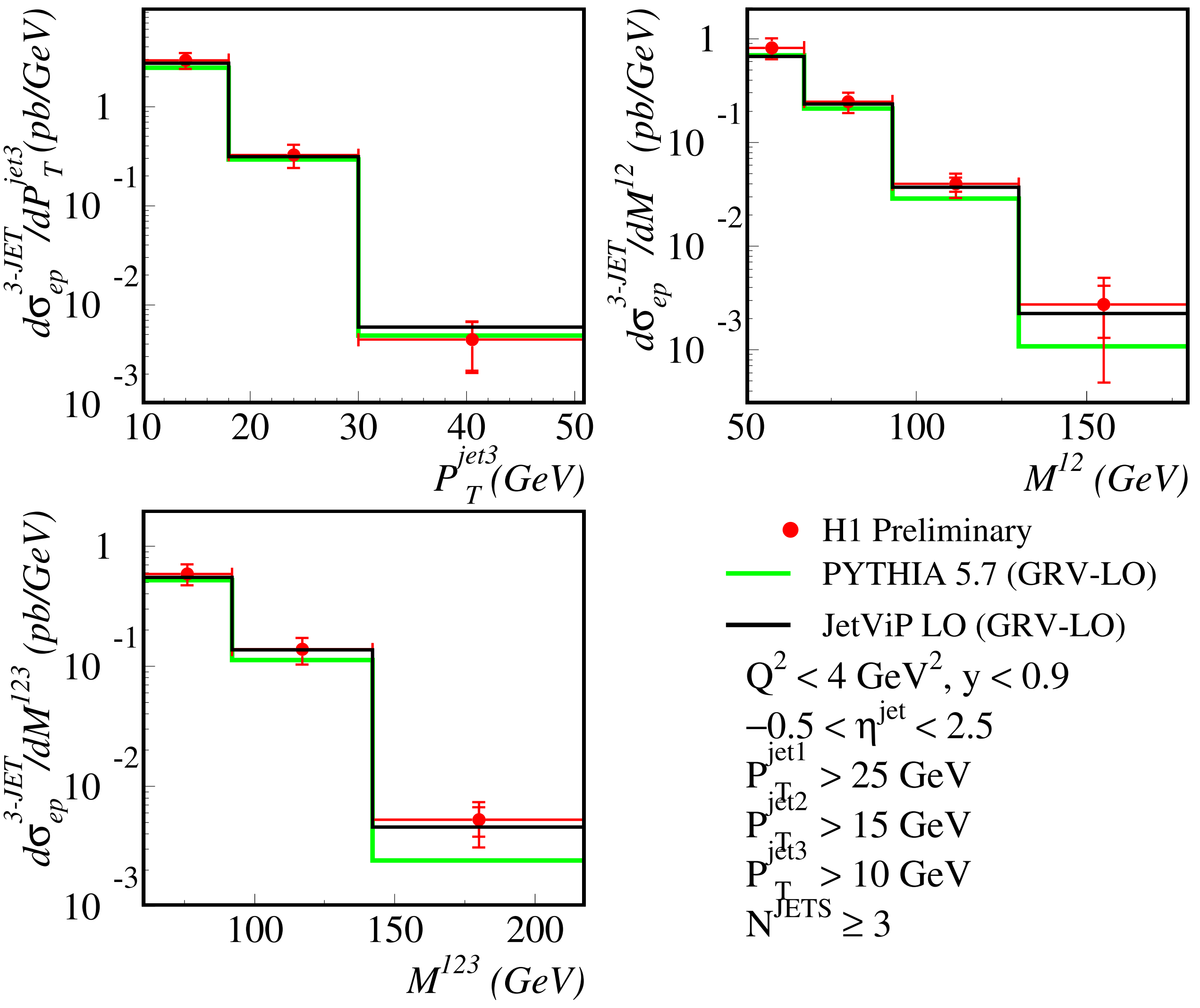
- Dominant Experimental Uncertainty: Energy scale of the jets ($\pm 4\%$) $\rightarrow \sim \pm 15 - 20\%$ on the cross section

- NLO QCD calculations: GRV-HO parametrisations of the photon and proton parton densities; phase-space slicing method (JetVip by B. Pötter)

Good description of the shape and normalisation of the data by NLO QCD up to $E_T^{jet} \sim 75$ GeV

3-jet Differential Cross Sections

- Search for a heavy particle or resonance decaying to three-jets: measurement of the three-jet mass (M^{123}) and dijet invariant mass (M^{12}) distributions in 3-jet photoproduction.



Good description of the measured shape by LO QCD up to $M^{123} \sim 180$ GeV

Anomalous Single-Top Production at HERA?

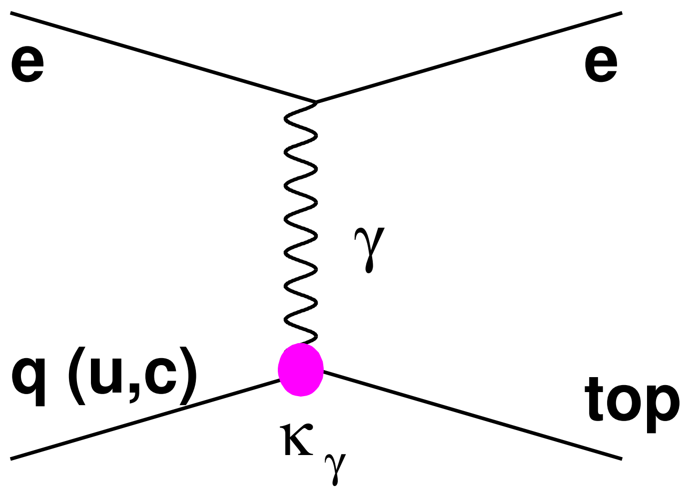
- The H1 Collaboration reported the observation of events with high-p_T isolated leptons and missing transverse momentum. In particular, events were found containing a high-p_T hadronic system: a configuration atypical for direct $W^{\pm}$-boson production.

$\rightarrow$ single top production?

$$t \rightarrow b + W \rightarrow b + e\nu(\mu\nu)$$

then $t \rightarrow b + W \rightarrow b + \mathrm{jet} + \mathrm{jet}$

- Standard Model expectation is negligible
$\rightarrow$ anomalous single-top production through flavour-changing neutral-current interactions?



Search for Single Top Production at HERA

(H1 Collaboration, Preliminary)

- Search for single top production in the hadronic channel using $36.5\ \mathrm{pb}^{-1}$ of data at $\sqrt{s(e^+p)} = 300$ GeV

- Kinematic Region: $Q^2 < 4$ GeV^2

- Jet search using the inclusive k_T-cluster algorithm in the laboratory frame: events are required to have at least three jets with

$$E_T^{jet,1} > 25 \text{ GeV}, \quad E^{jet,2} > 15 \text{ GeV},$$

$$E^{jet,3} > 10 \text{ GeV}$$

$\rightarrow$ Selection of top candidates:

$$150 < M^{tot} < 180 \text{ GeV},$$

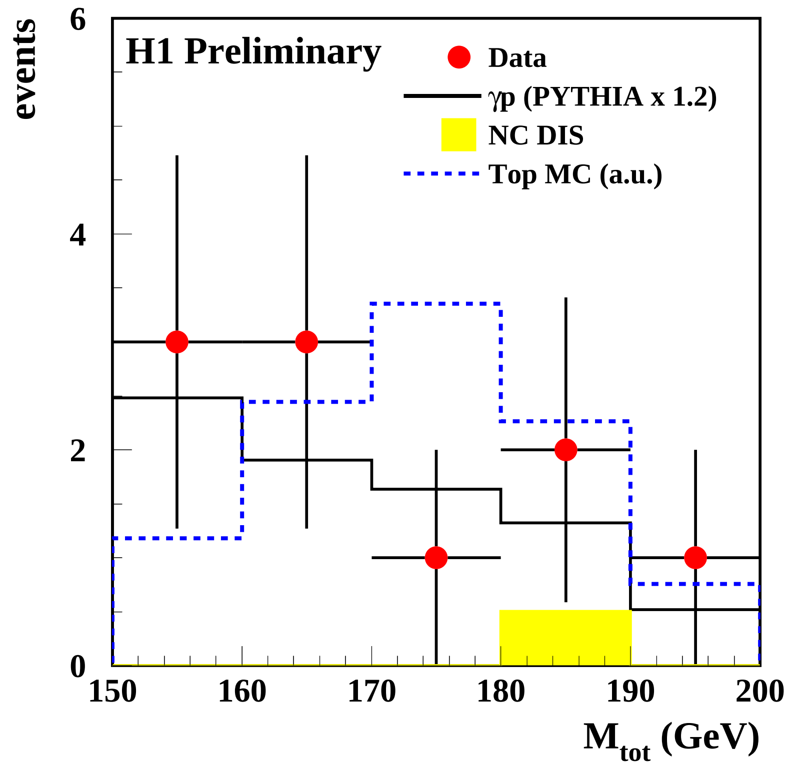
$$70 < M^{ij} < 90 \text{ GeV},$$

$$\text{and } E_{T,tot} > 120 \text{ GeV}$$

(M^{tot} and $E_{T,tot}$ calculated using all jets in an event)

$\rightarrow$ Top selection efficiency: 31%

Search for Single Top Production at HERA



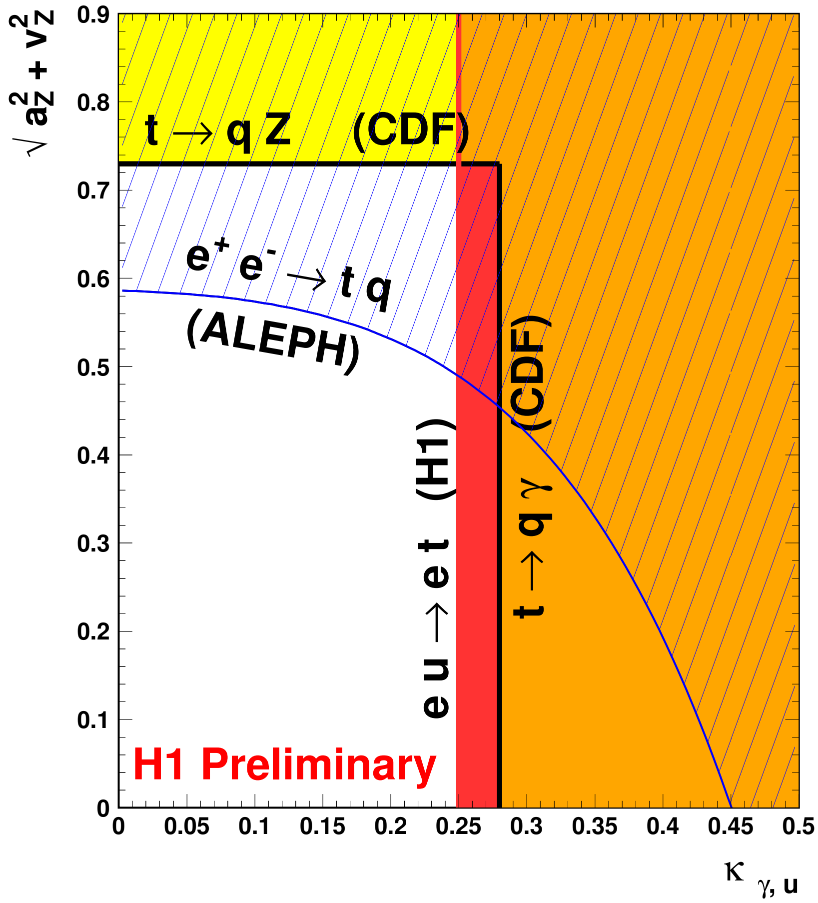
10 candidates
in good agreement
with the Standard
Model expectation
of 8.3 events

$(8.3^{+4.2}_{-1.9}(\mathrm{exp}) \pm 4.2(\mathrm{the}))$

Photoproduction: $7.8^{+4.1}_{-1.8}$

NC DIS: 0.5 ± 0.5

$\rightarrow$ Upper limit
$\sigma(top) < 1.17$ pb



$\rightarrow$ Leptonic plus
Hadronic channels
combined:
upper limit on
anomalous coupling

$\boxed{\kappa_{\gamma,u} < 0.25}$

SUMMARY

• Direct processes in photoproduction are well understood: NLO QCD describes well the shape and normalisation of the differential cross sections for dijet production with high x_γ^{obs} ($x_\gamma^{obs} > 0.75$).

→ the dynamics of photon-parton interactions up to $M^{JJ} \sim 170$ GeV

→ Substantial contribution to 3-jet production in the phase space region for top search!

• Resolved processes in photoproduction are partially understood: NLO QCD describes well the shape

→ the dynamics of parton-parton interactions

..but NLO QCD calculations fail to describe the normalisation of the differential cross sections with lower x_γ^{obs} values ($x_\gamma^{obs} < 0.75$)

Time to review the current parametrisations of the photon parton densities in the light of dijet photoproduction data from HERA