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QCD Tests at HERA

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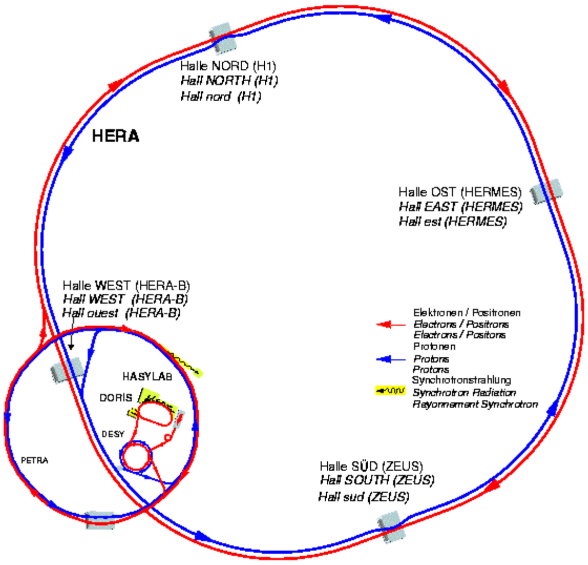
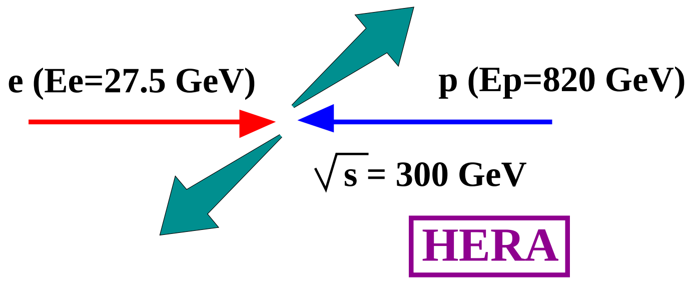
from

ZEUS Collab.

H1 Collab.

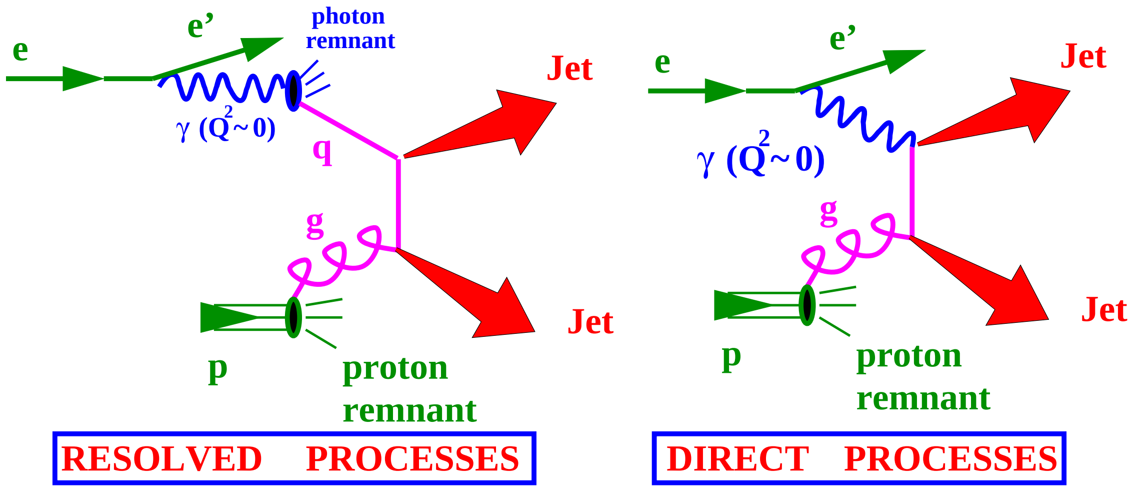
at





Jet production at LO QCD in photoproduction

$$ep \rightarrow e + \text{jet} + \text{jet} + X$$



direct: $$\sigma_{LO}^{ep\rightarrow 2jet} = \int d\Omega\; f_{\gamma/e}(y)\; f_{j/p}(x_p, \mu_F^2) \times d\sigma(\gamma j \rightarrow \text{jet jet})$$

resolved: $$\sigma_{LO}^{ep\rightarrow 2jet} = \int d\Omega\; f_{\gamma/e}(y)\; f_{j/p}(x_p, \mu_F^2) \times f_{i/\gamma}(x_\gamma, \mu_F^2)\; d\sigma(ij \rightarrow \text{jet jet})$$

$f_{\gamma/e}(y)$: flux of photons in e (Weizsäcker-Williams approximation)

$f_{j/p}(x_p, \mu_F^2)$: parton j density in p (determined from e.g. global fits)

$f_{i/\gamma}(x_\gamma, \mu_F^2)$: parton i density in γ (partial information from other measurements, e.g. F_2^γ) $\rightarrow \delta(1 - x_i)$ for direct

$d\sigma(i(\gamma)j \rightarrow \text{jet jet})$: subprocess cross section (calculable in pQCD)

Inclusive jet cross sections

• Measurement of cross sections for processes with a hard interaction scale (e.g. E_T^{jet} in jet production)

→ comparison to NLO calculations: tests of QCD

→ test of parametrisations of the photon parton densities: universality of the photon structure

→ global fits *à la* F_2^p

Cone jet algorithm

• Experimentally, jets are searched in the

pseudorapidity (η) − azimuth (φ)

plane using the transverse-energy flow of the event

• Definition of jet variables: Snowmass Convention

$$\boxed{\begin{aligned} E_T^{jet} &= \textstyle\sum_i E_T^i \\ \eta^{jet} &= \frac{\sum_i E_T^i \cdot \eta_i}{E_T^{jet}} \\ \varphi^{jet} &= \frac{\sum_i E_T^i \cdot \varphi_i}{E_T^{jet}} \end{aligned}}$$

• Iterative cone algorithm: (used in hadron interactions) jets are searched by maximizing the summed E_T within a cone of radius R: $E_T^{jet} = \sum_i E_T^i$ for every particle i such that

$$R_{i\ jet}^2 = (\eta_i - \eta^{jet})^2 + (\varphi_i - \varphi^{jet})^2 \le R^2$$

NLO QCD calculations of jet cross sections

- The calculations shown here were performed by:

→ M Klasen, T Kleinwort and G Kramer
(Eur Phys J C1 (1998) 1)
→ B Harris and J Owens
(Phys Rev D57 (1998) 5555)

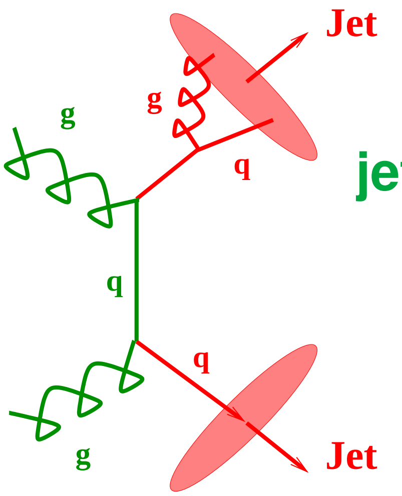
- NLO corrections:

→ virtual corrections with internal particle loops
→ real corrections with a third parton in the final state

- Different methods to calculate real corrections:

→ phase space slicing method with invariant mass cut to isolate singular regions of phase space (Klasen et al)
→ phase space slicing method with two small cut-offs to delineate soft and collinear regions (Harris et al)

- Calculations differ by up to $\sim 5\%$



In NLO,

jet algorithms are applied on partons:

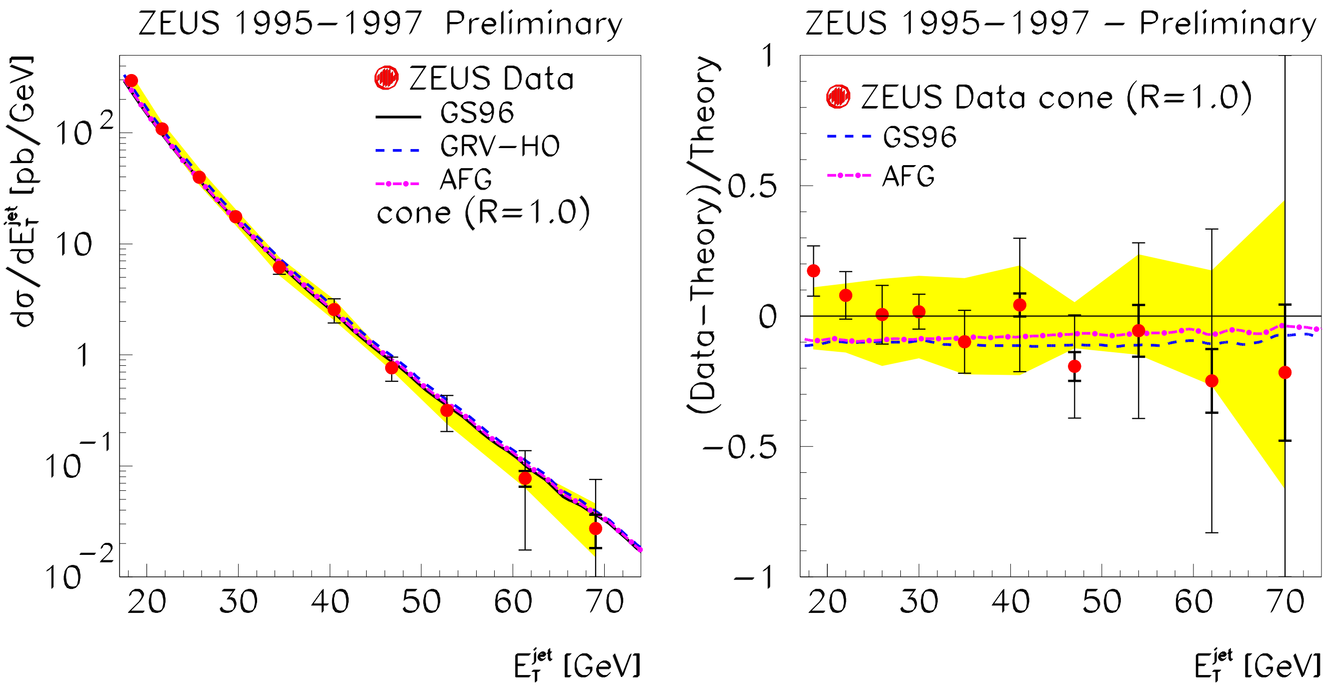
up to two partons in a jet

Measurement of $\frac{d\sigma}{dE_T^{jet}}$ in inclusive jet production

- Jets searched using an iterative cone algorithm
- Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 4$ GeV^2
- $\frac{d\sigma}{dE_T^{jet}}$ for E_T^{jet} between 17 and 74 GeV

  integrated over $-0.75 < \eta^{jet} < 2.5$

$\boldsymbol{R = 1.0}$



- The NLO calculations give a reasonable description of the measured differential cross section in magnitude and shape

Comparing theory and experiment

- To perform tests of QCD and to extract information on the photon parton densities, the experimental and theoretical uncertainties must be reduced as much as possible

- Main experimental uncertainty:
  $\rightarrow$ "underlying event", non-perturbative effect not included in the calculations

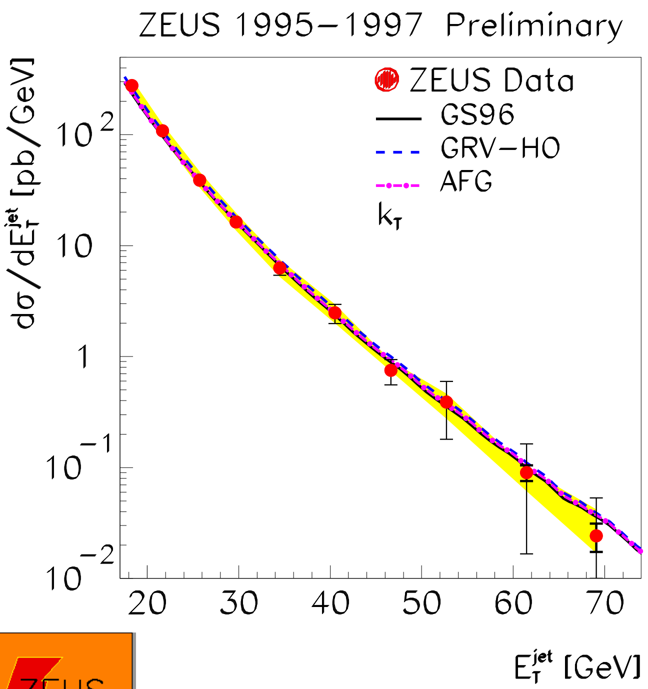
- To reduce the uncertainty of the measurements:
  $\rightarrow$ reduce the cone radius ($R = 1.0 \rightarrow R = 0.7$, area of the cone is halved)
  $\rightarrow$ increase E_T^{jet} (as E_T^{jet} increases the jet pedestal stays approximately constant and becomes less relevant)

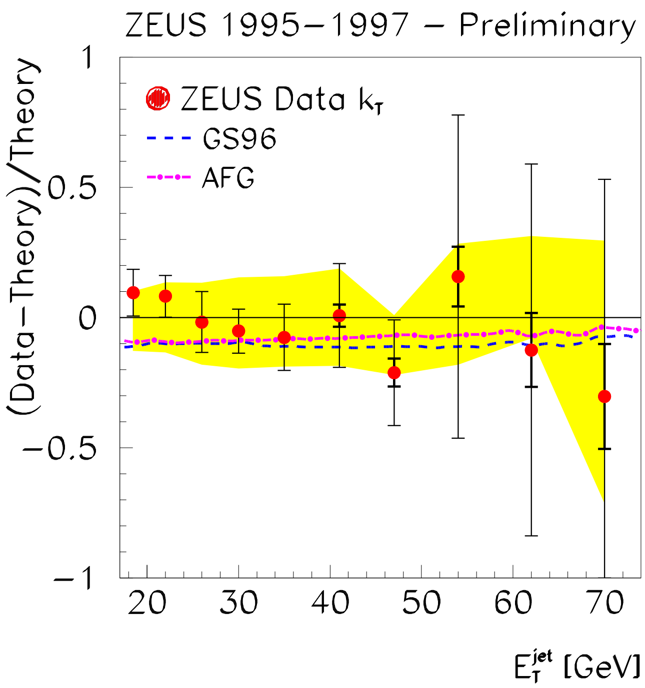
- Main theoretical uncertainty:
  $\rightarrow$ matching experimental jet algorithm, introduction of ad-hoc parameter R_{SEP} to control parton recombination in the theoretical jet algorithm

- To reduce the theoretical uncertainty:
  $\rightarrow$ use the longitudinally invariant k_T cluster algorithm which allows a transparent translation of the theoretical jet algorithm to the experimental set-up and it is infrared safe to all orders

Measurement of $\frac{d\sigma}{dE_T^{jet}}$ in inclusive jet production

- Jets searched using the **longitudinally invariant k_T cluster algorithm in the inclusive mode** (S D Ellis et al)
- **k_T algorithm** (S Catani et al) : (used in e^+e^- collisions)
jets are identified by successively combining nearby pairs of particles until a jet is complete



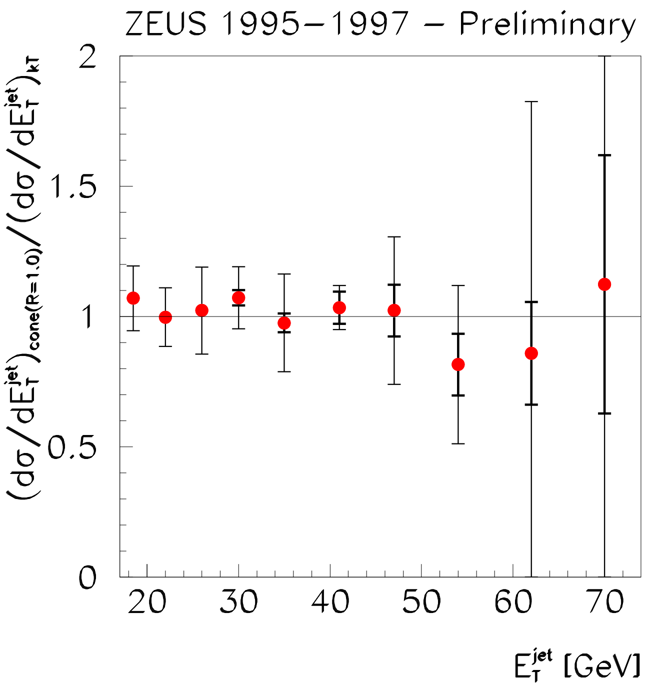


- **cone vs. k_T algorithm:**

→ **measured**

$$\frac{d\sigma/dE_T^{jet}|_{cone}}{d\sigma/dE_T^{jet}|_{k_T}} \approx 1$$

typically within $\pm 10\%$



Jet substructure

- **Subjets:** jet-like objects within a jet

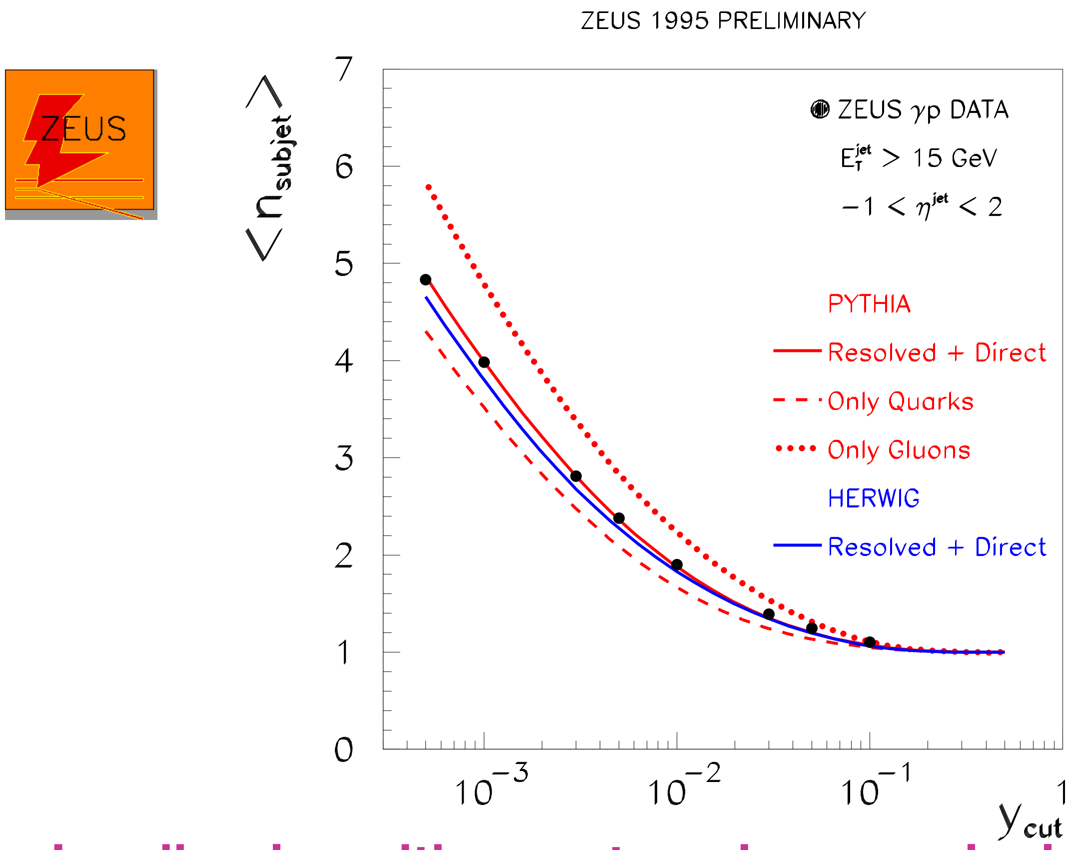
- Subjets are resolved within a jet by reapplying the k_T cluster algorithm until for every pair of particles i, j

$$d_{ij} = min(E_{Ti}, E_{Tj})^2[(\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2] \geq y_{cut}(E_T^{jet})^2$$

- Measurements of $< n_{subjet} >$ for the inclusive sample of jets with $E_T^{jet} > 15$ GeV and $-1 < \eta^{jet} < 2$

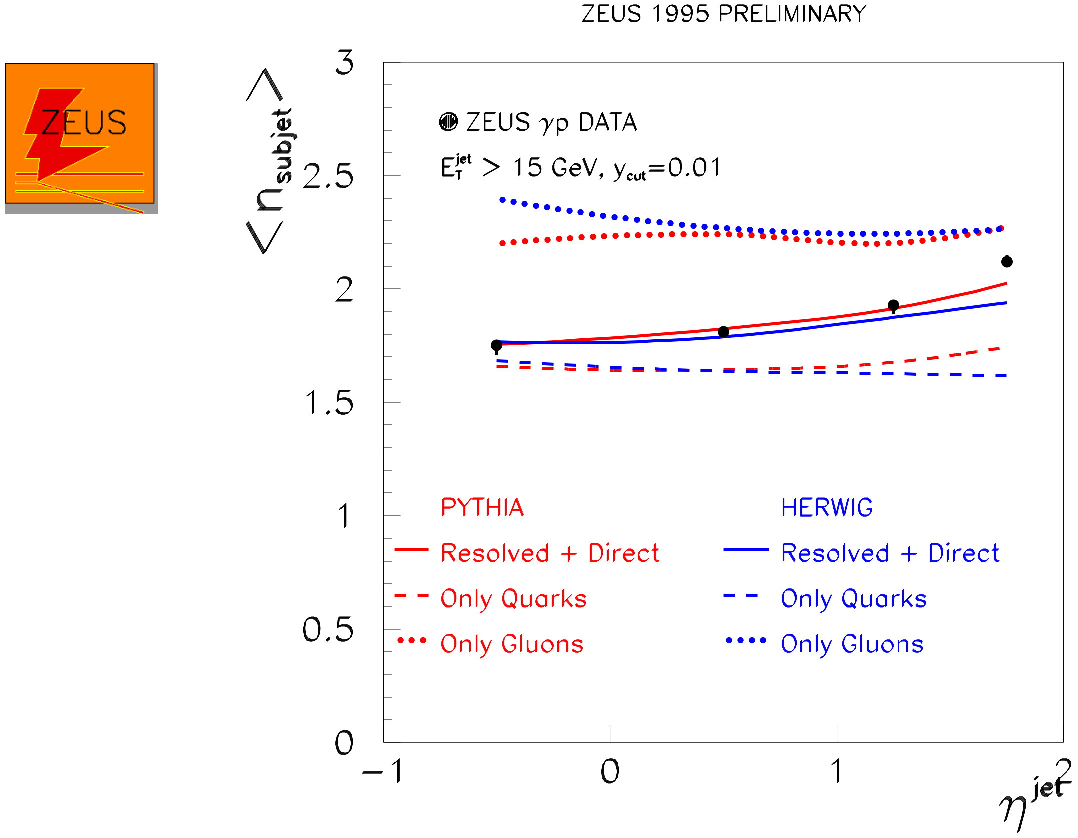
- Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 4$ GeV^2

Mean subjet multiplicity vs. y_{cut}



- Leading-logarithm parton-shower calculations using PYTHIA give a good description of the data

Mean subjet multiplicity vs η^{jet} for fixed $y_{cut} = 10^{-2}$

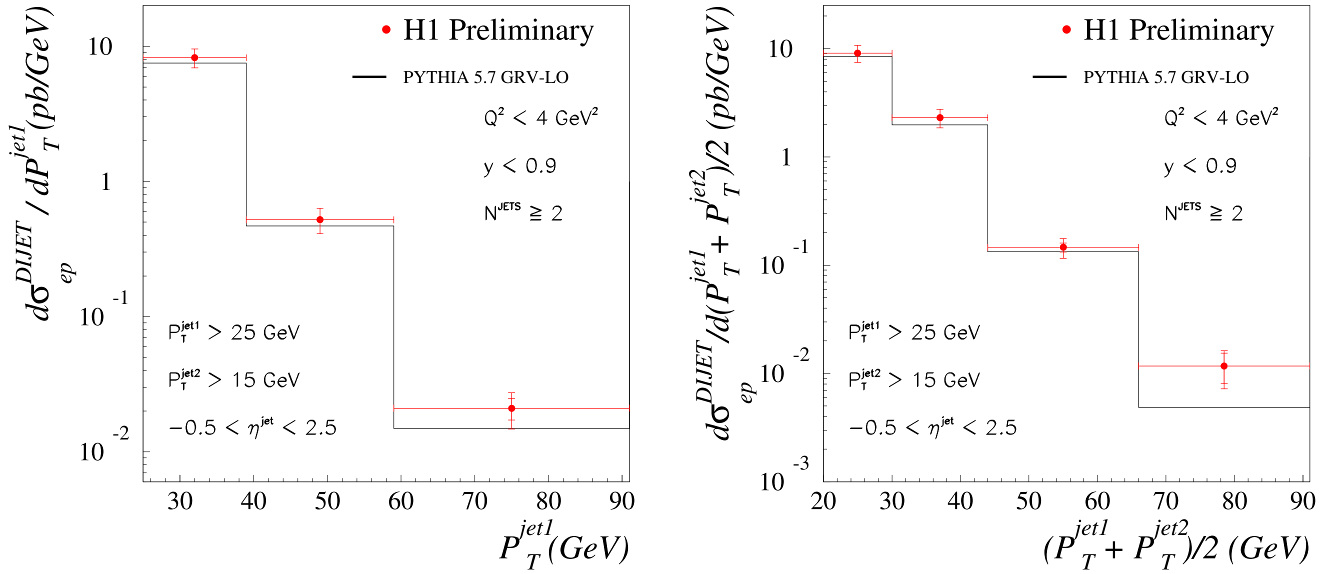


- $< n_{subjet} >$ **increases as η^{jet} increases**
- **Comparison with the predictions for quark and gluon jets:**

The increase in $< n_{subjet} >$ as η^{jet} increases is consistent with the predicted increase in the fraction of gluon jets

Measurements of $\frac{d\sigma}{dE_T^{jet}}$ in dijet production

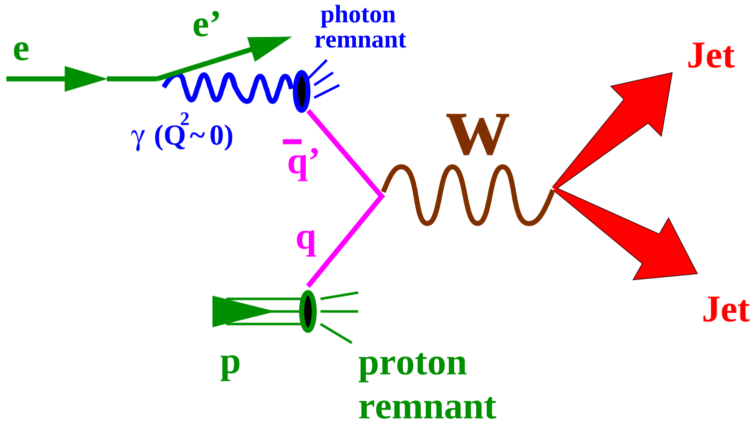
- Tests of QCD in dijet photoproduction
- Jets searched using the k_T cluster algorithm
- Kinematic region: $y < 0.9$ and $Q^2 < 4$ GeV^2
- $\frac{d\sigma}{dp_T^{jet1}}$ for p_T^{jet1} between 25 and 90 GeV and $\frac{d\sigma}{d(p_T^{jet1}+p_T^{jet2})/2}$ for $(p_T^{jet1}+p_T^{jet2})/2$ between 20 and 90 GeV integrated over $-0.5 < \eta^{jet} < 2.5$



- The leading-logarithm parton shower Monte Carlo gives a good description of the data in shape

High-mass dijet cross sections

• The dijet mass (M^{JJ}) distribution provides a test of QCD and is sensitive to the presence of new particles or resonances that decay into two jets



• The distribution of the angle between the jet-jet axis and the beam direction in the dijet centre-of-mass system ($\cos\theta^*$) reflects the underlying parton dynamics

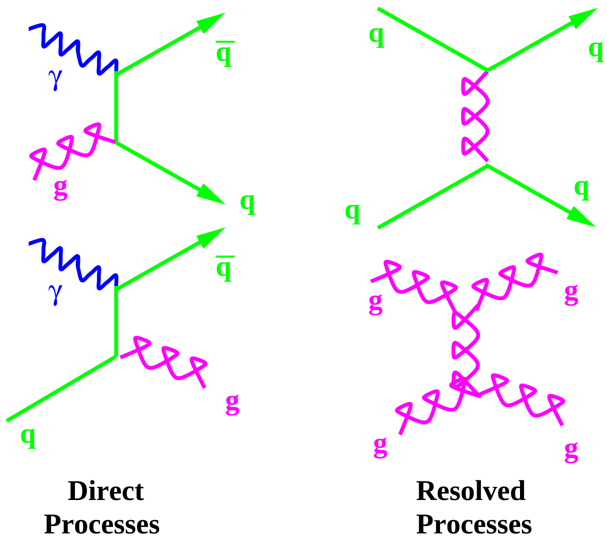
$\rightarrow$ sensitive to the spin of the exchanged particle in two-body processes:

resolved: gluon exchange

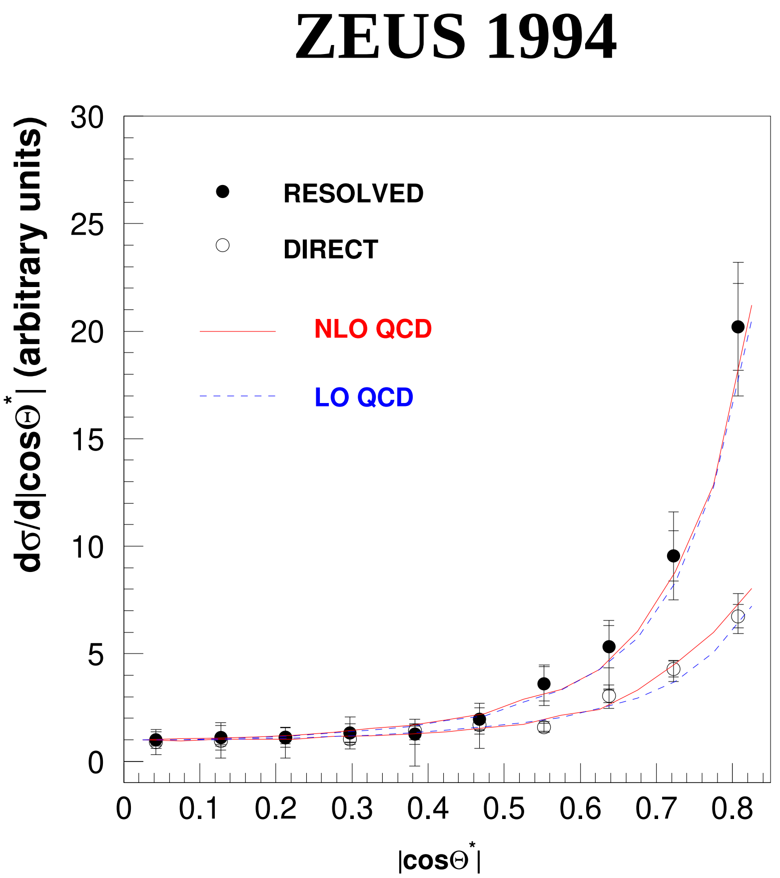
$\sim (1 - |\cos\theta^*|)^{-2}$

direct: quark exchange

$\sim (1 - |\cos\theta^*|)^{-1}$



- **The dijet angular distribution $d\sigma/d|\cos\theta^*|$ for resolved processes rises more steeply than that of direct processes for $|\cos\theta^*| \to 1$:**



$M^{JJ} > 23$ GeV

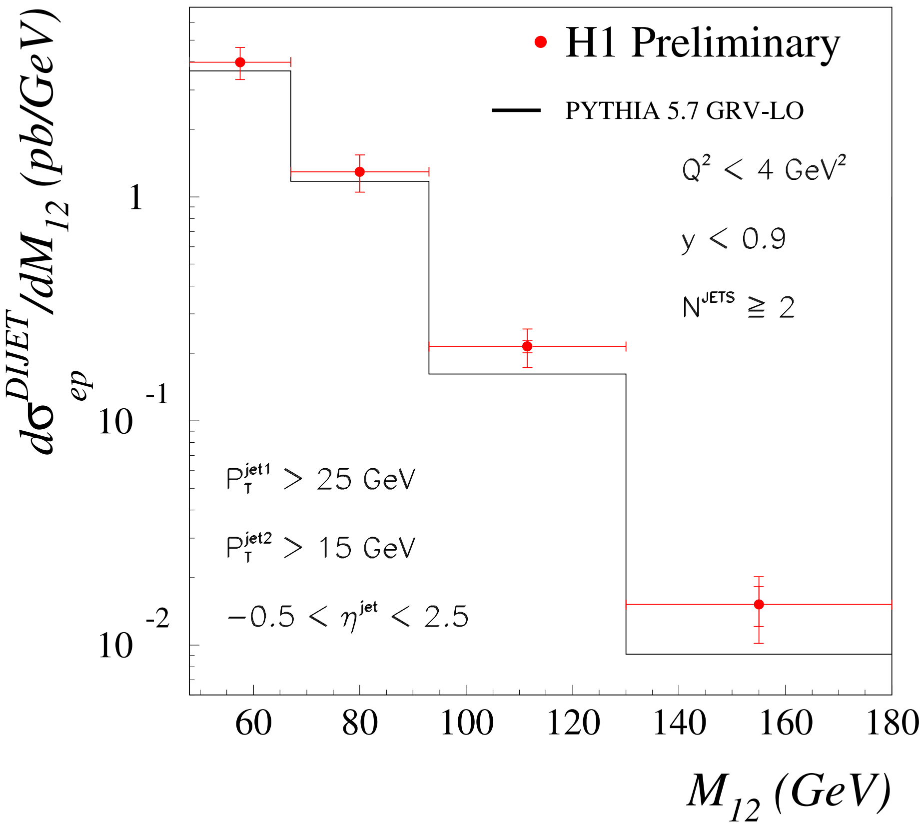
ZEUS Collab., Phys. Lett. B384 (1996) 401

- **Good description of data by QCD calculations**

- **At higher invariant masses, new particles or resonances decaying into two jets may also be identified by deviations in the measured $|\cos\theta^*|$ distribution w.r.t. the predictions of QCD**

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

- Jets searched using the k_T cluster algorithm
- Kinematic region: $y < 0.9$ and $Q^2 < 4$ GeV^2
- $\frac{d\sigma}{dM^{JJ}}$ for M^{JJ} between 48 and 180 GeV for jets with $p_T^{jet1} > 25$ GeV and $p_T^{jet2} > 15$ GeV integrated over $-0.5 < \eta^{jet} < 2.5$

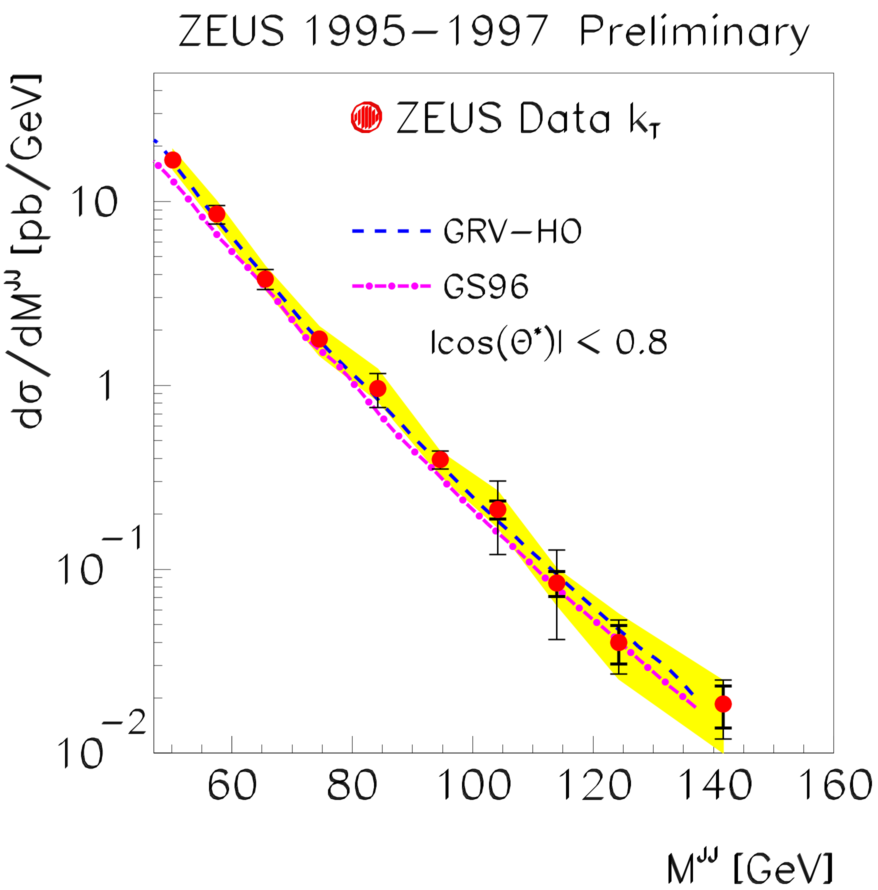


- The leading-logarithm parton shower Monte Carlo calculations agree reasonably well in shape with the measured distribution

- Large uncertainty in the normalisation of the LO QCD calculations → need NLO corrections

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

- Jets searched using the k_T cluster algorithm
- Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 4$ GeV^2
- $\frac{d\sigma}{dM^{JJ}}$ for M^{JJ} between 47 and 160 GeV integrated over $|\cos\theta^*| < 0.8$



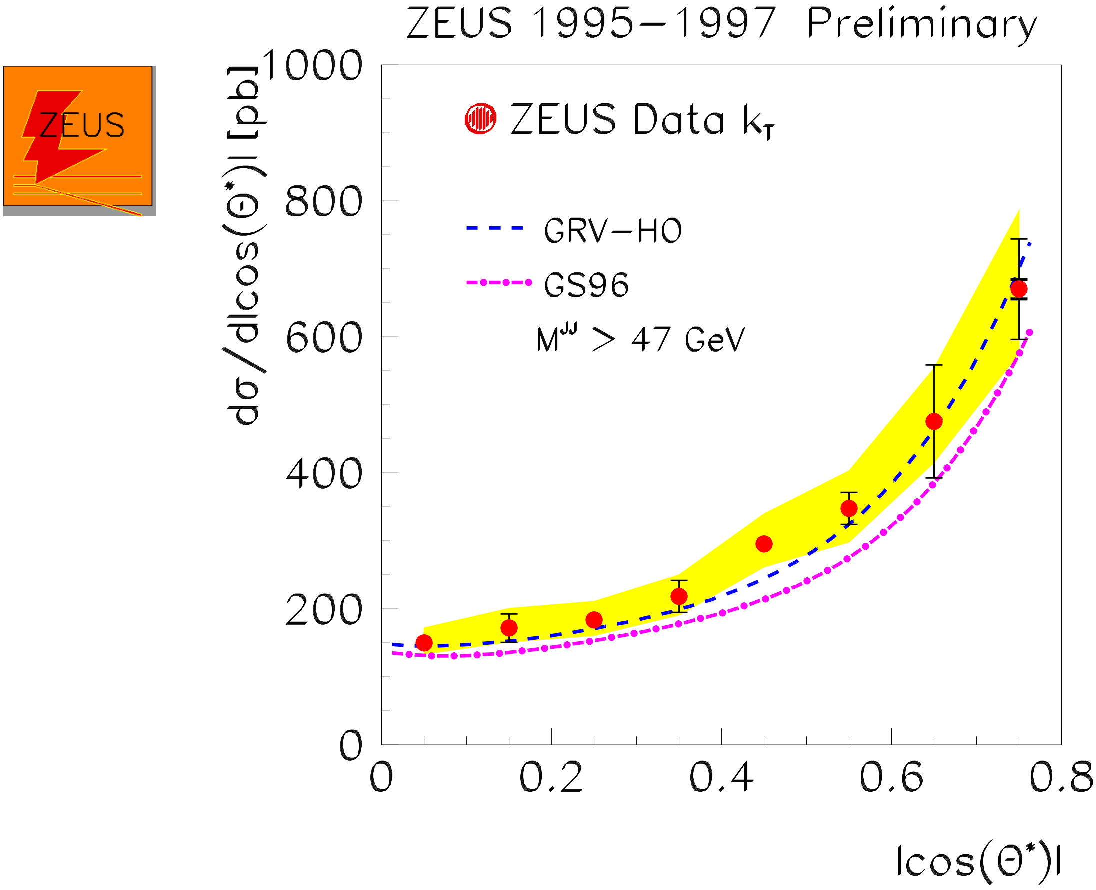
- The NLO calculations agree reasonably well in shape and magnitude with the measured distribution

- No significant deviation between data and NLO calculations is observed up to the highest M^{JJ} value studied

Measurement of $\frac{d\sigma}{d|\cos\theta^*|}$

- Jets searched using the k_T cluster algorithm
- Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 4$ GeV^2
- $\frac{d\sigma}{d|\cos\theta^*|}$ for $|\cos\theta^*|$ between 0 and 0.8

  integrated over $M^{JJ} > 47$ GeV



- The NLO calculations agree reasonably well in shape with the measured distribution. The predictions based on GRV-HO are closer in magnitude to the measured cross sections

- No significant deviation between data and NLO calculations is observed in the entire $|\cos\theta^*|$ range measured

Three-jet cross sections

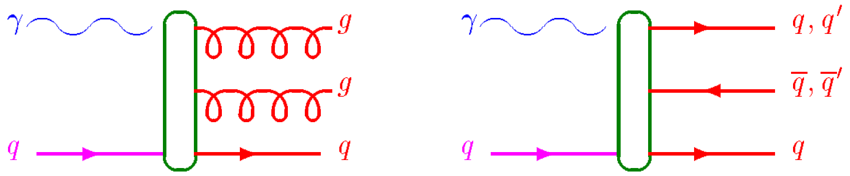
• Cross section measurements in three-jet events provide a test of QCD beyond LO and allow the search for new phenomena

• Inclusive jet and dijet data have shown no deviation from NLO QCD calculations

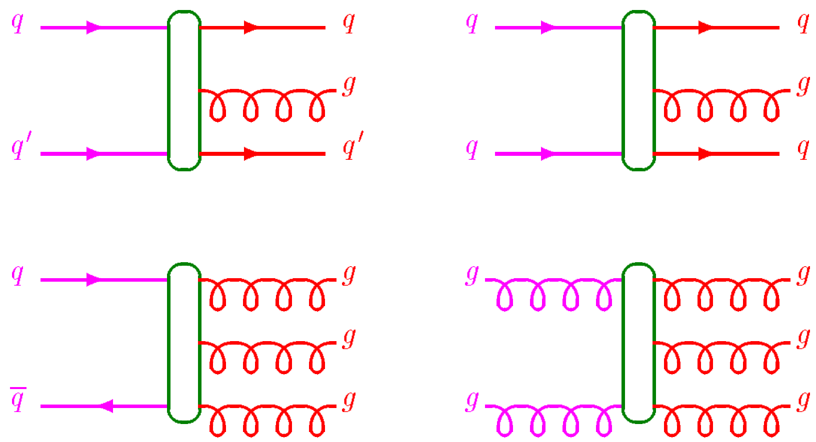
• NLO QCD calculations for three-jet cross sections in γp are not available $\to$ LO calculations subject to large renormalisation and factorisation scale uncertainties

$$\sigma_{LO}^{ep\to 3jet} = \int d\Omega \;\; f_{\gamma/e}(y) \;\; f_{j/p}(x_p,\mu_F^2) \;\times$$
$$[f_{i/\gamma}(x_\gamma,\mu_F^2)] \;\; d\sigma(i(\gamma)j \to \text{jet jet jet})$$

e.g.



direct



resolved

Three-body phase space

- Five parameters are necessary to uniquely determine the three-body phase space

M_{3j} $\qquad X_i \equiv \frac{2E_i}{M_{3j}}$, with $x_3 + x_4 + x_5 = 2$

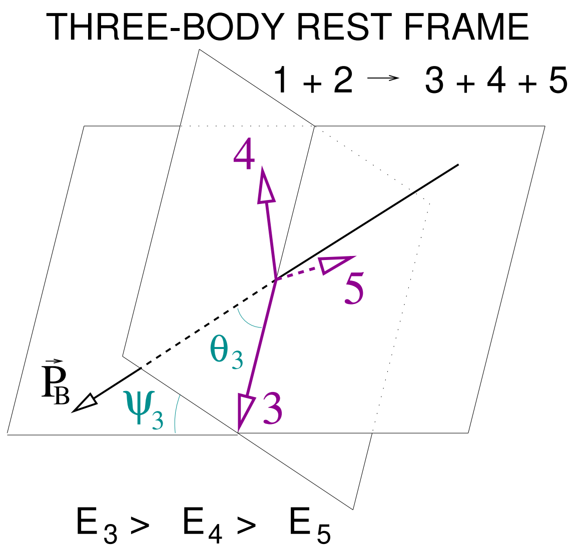
only two X_i are linearly independent

$\cos\theta_3 \equiv \frac{\vec{p}_B \cdot \vec{p}_3}{|\vec{p}_B||\vec{p}_3|}$

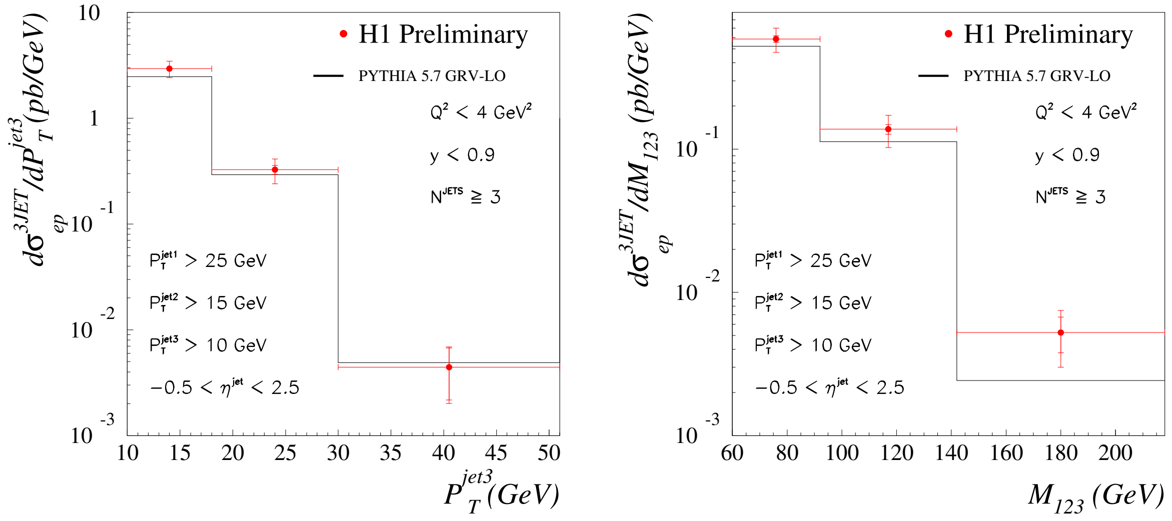
sensitive to the spin of the exchanged particle

$\cos\psi_3 \equiv \frac{(\vec{p}_3 \times \vec{p}_B)\cdot(\vec{p}_4 \times \vec{p}_5)}{|\vec{p}_3 \times \vec{p}_B||\vec{p}_4 \times \vec{p}_5|}$

radiated jet tends to lie in the plane of beam and highest E-jet ($\psi_3 \sim 0$ or π)



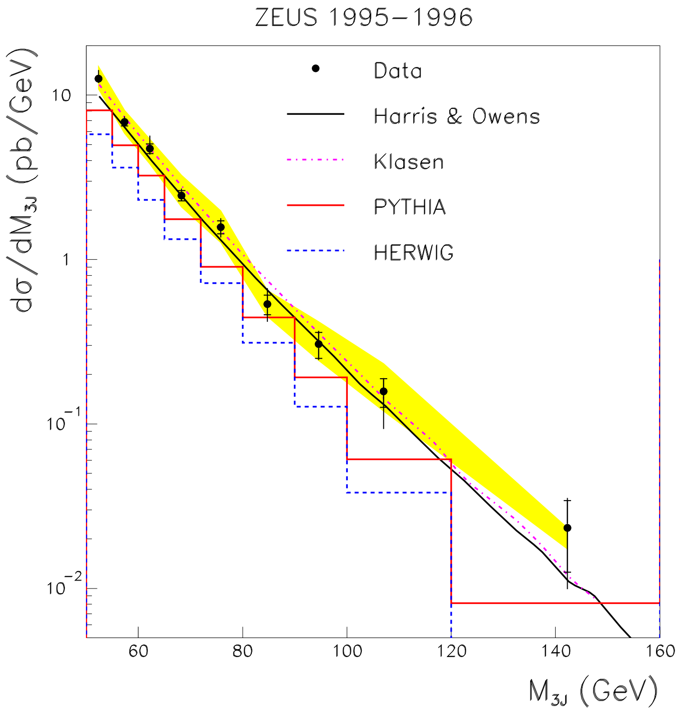
- p_T^{jet3} and M_{3j} distributions:
- Jets searched using the k_T cluster algorithm
- Kinematic region: $y < 0.9$ and $Q^2 < 4$ GeV^2



- Parton shower models describe shape of the measured three-jet cross sections

Measurement of $\frac{d\sigma}{dM_{3j}}$

- Jets searched using the k_T cluster algorithm
- Kinematic region: $0.2 < y < 0.8$ and $Q^2 \leq 1$ GeV^2
- $\frac{d\sigma}{dM_{3j}}$ for M_{3j} between 50 and 160 GeV integrated over $|\cos\theta_3| < 0.8$ and $X_3 < 0.95$

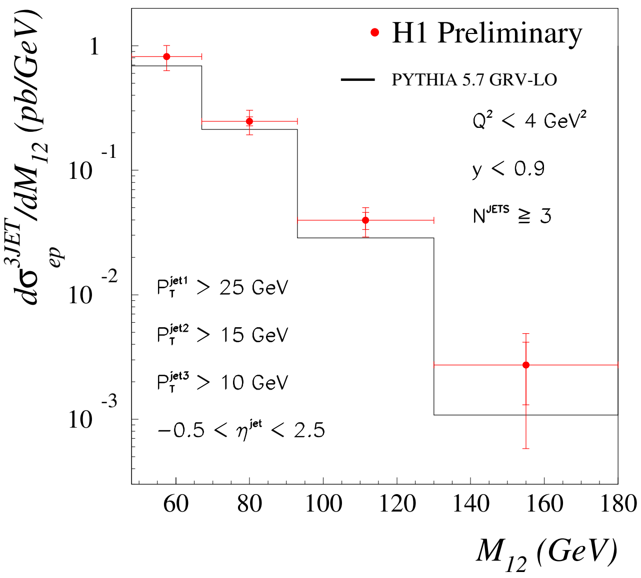


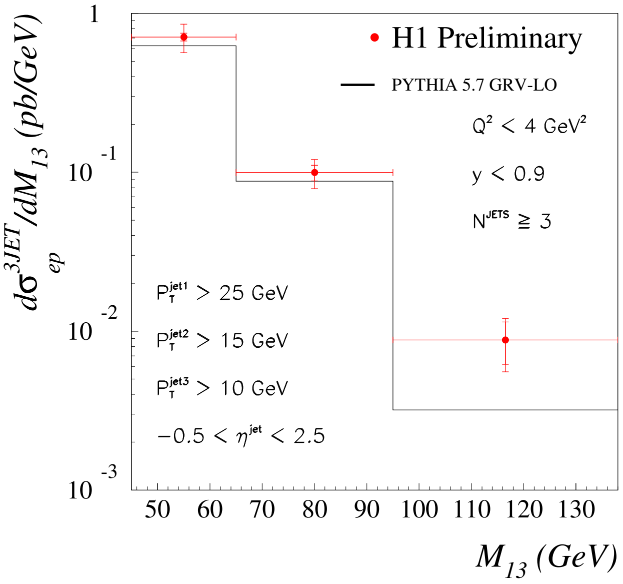
- The $\mathcal{O}(\alpha\alpha_s^2)$ calculations are in good agreement with the measured cross section

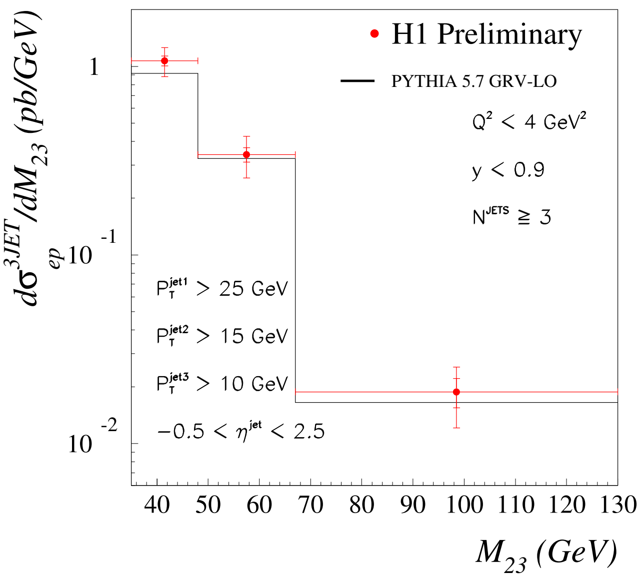
- The M_{3j} distributions predicted by the leading-logarithm parton shower Monte Carlo models are also in agreement with the data in shape. The magnitude is $30-40\%$ too low

Invariant mass cross sections in 3-jet events

- Jets searched using the k_T cluster algorithm
- Kinematic region: $y < 0.9$ and $Q^2 < 4$ GeV^2
- New particles or resonances decaying into two jets may be identified by deviations in the measured invariant mass distribution w.r.t. the predictions of QCD



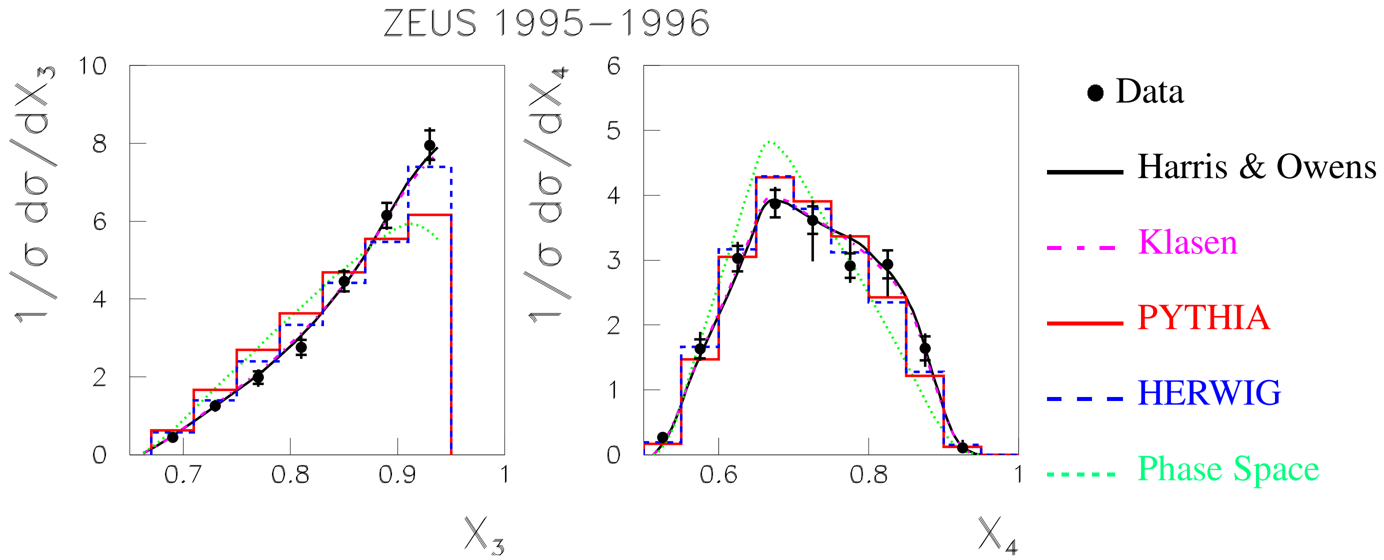




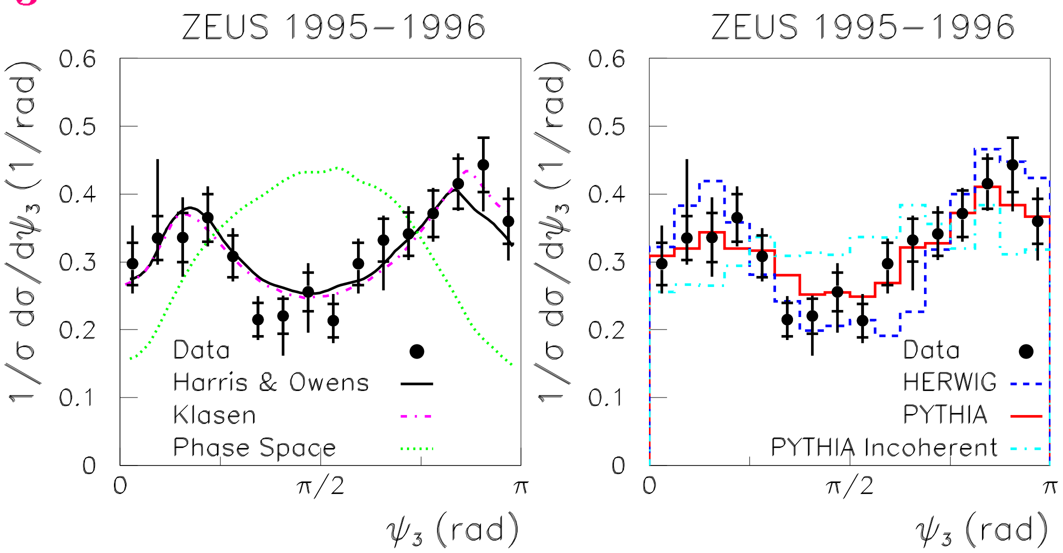
- No significant deviation between data and calculations is observed up to the highest M^{JJ} value studied

Measurement of 3-jet cross sections

- Jets searched using the k_T cluster algorithm
- Kinematic region: $0.2 < y < 0.8$ and $Q^2 \leq 1$ GeV^2
- Fraction of the available energy taken by the highest and second-highest energy jets:

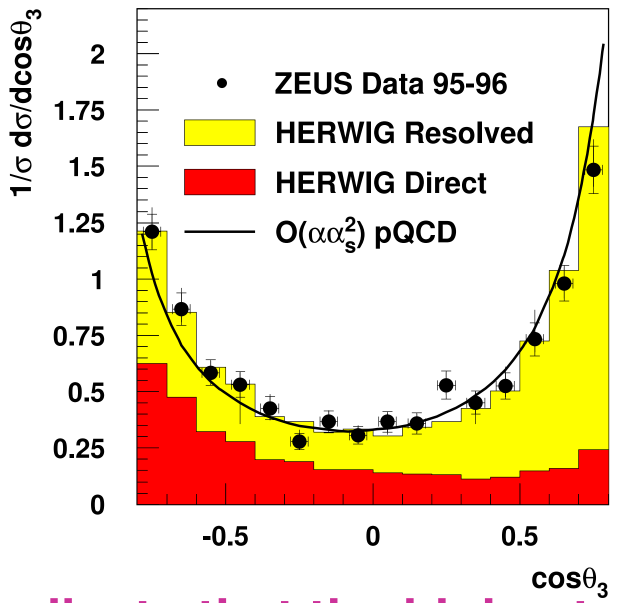


- QCD calculations are in good agreement with the measurements
- ψ_3 distribution:



- Measured ψ_3 distribution drastically different from phase space and in agreement with QCD calculations
- Data favour color coherence in parton shower models

Measurement of $\frac{d\sigma}{d\cos\theta_3}$



- The data indicate that the highest energy jet tends to go either forward or towards the rear
- The $\mathcal{O}(\alpha\alpha_s^2)$ calculations are in **good agreement** with the measured cross section
- The HERWIG Monte Carlo gives also a **good** description of the data
- x_γ^{OBS} distribution:

$$x_\gamma^{OBS} \equiv \frac{\sum_{jets} E_T^{jet} e^{-\eta^{jet}}}{2yE_e}$$

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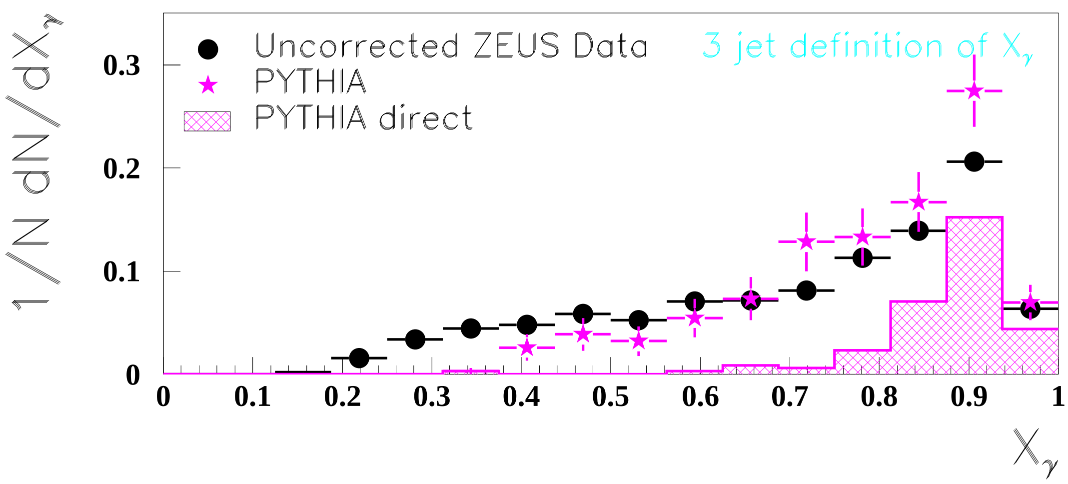
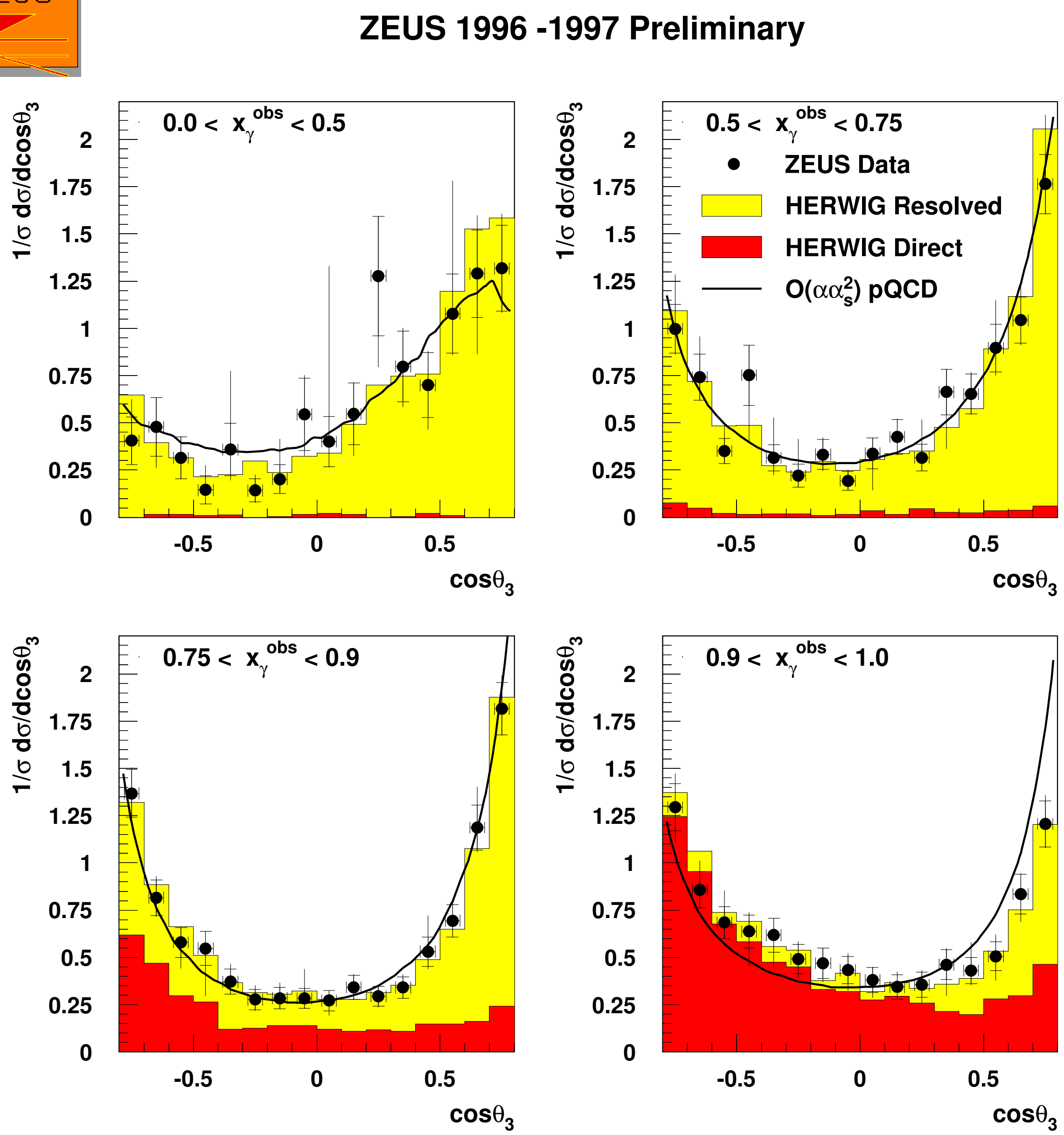


Measurement of $\frac{d\sigma}{d\cos\theta_3}$



- The data indicate that the highest energy jet tends to go in the forward direction when $x_\gamma^{OBS} < 0.5$
- The highest energy jet tends to go more backward as x_γ^{OBS} increases
- The $\mathcal{O}(\alpha\alpha_s^2)$ calculations are in good agreement with the data except for $0.9 < x_\gamma^{OBS} < 1$

CONCLUSIONS

- Significant progress in comparing measurements and QCD calculations of jet cross sections in photoproduction has been achieved: experimental and theoretical uncertainties have been reduced

- NLO QCD calculations of inclusive jet and dijet cross sections and $\mathcal{O}(\alpha\alpha_s^2)$ calculations of 3-jet cross sections describe reasonably well the measurements

- Comparison of the measurements to calculations which include higher order corrections (when they become available) will allow for stringent tests of QCD