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TESTS OF THE STANDARD MODEL AT HERA

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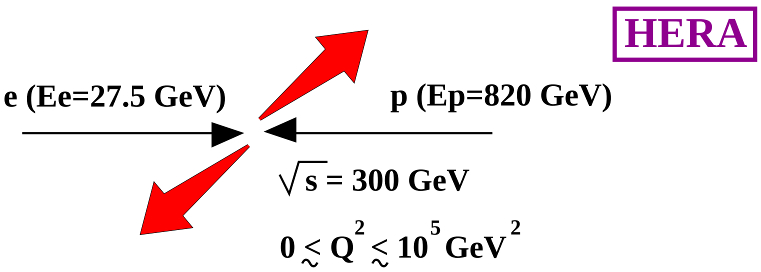
from

ZEUS Collab.   H1 Collab.

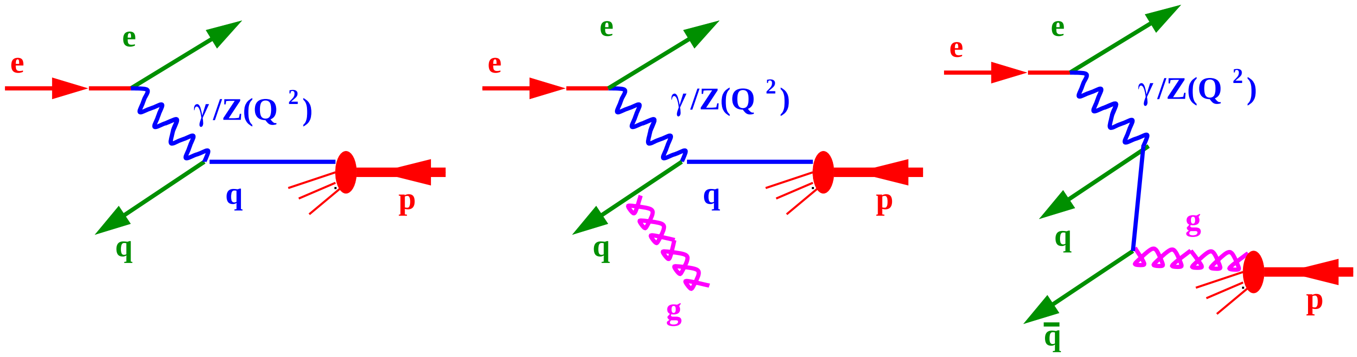


Jet production in NC DIS

- The Standard Model cross section for inclusive jet production in neutral-current interactions at high Q^2

$$e^+ p \rightarrow e^+ + \mathrm{jet(s)} + X$$

is given by the contributions:



Leading order QCD - Compton Boson-Gluon Fusion

$$\sigma_{DIS} = \int d\Omega \quad f_{i/p}(x_i, \mu_F^2) \times d\hat{\sigma}^i(x_i \cdot P, \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

$f_{i/p}$: parton densities in the proton

$d\hat{\sigma}^i$: subprocess cross section

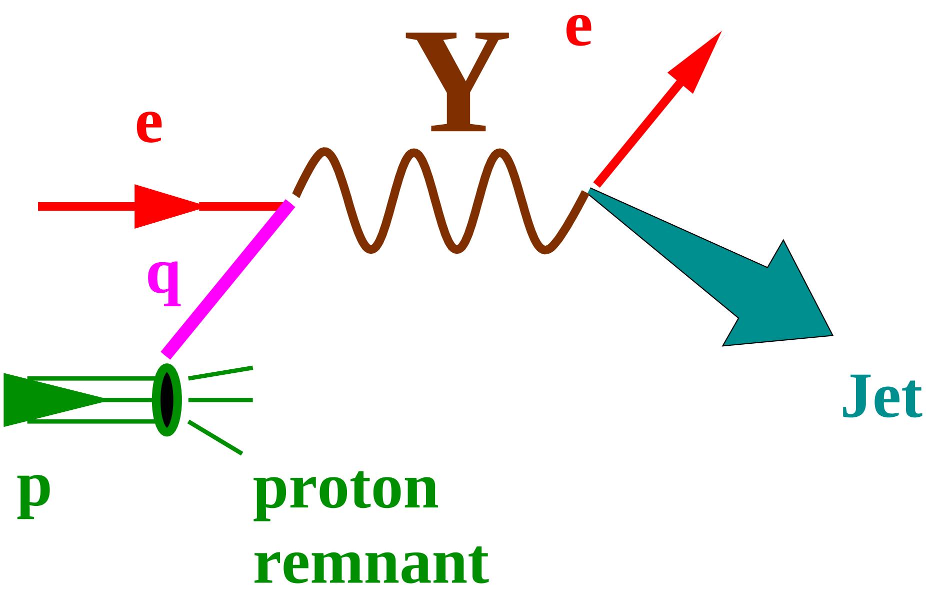
Anomalous jet production

- New particles or resonances (Y) that decay into

$$Y \to e^+ + \mathrm{jet(s)}$$

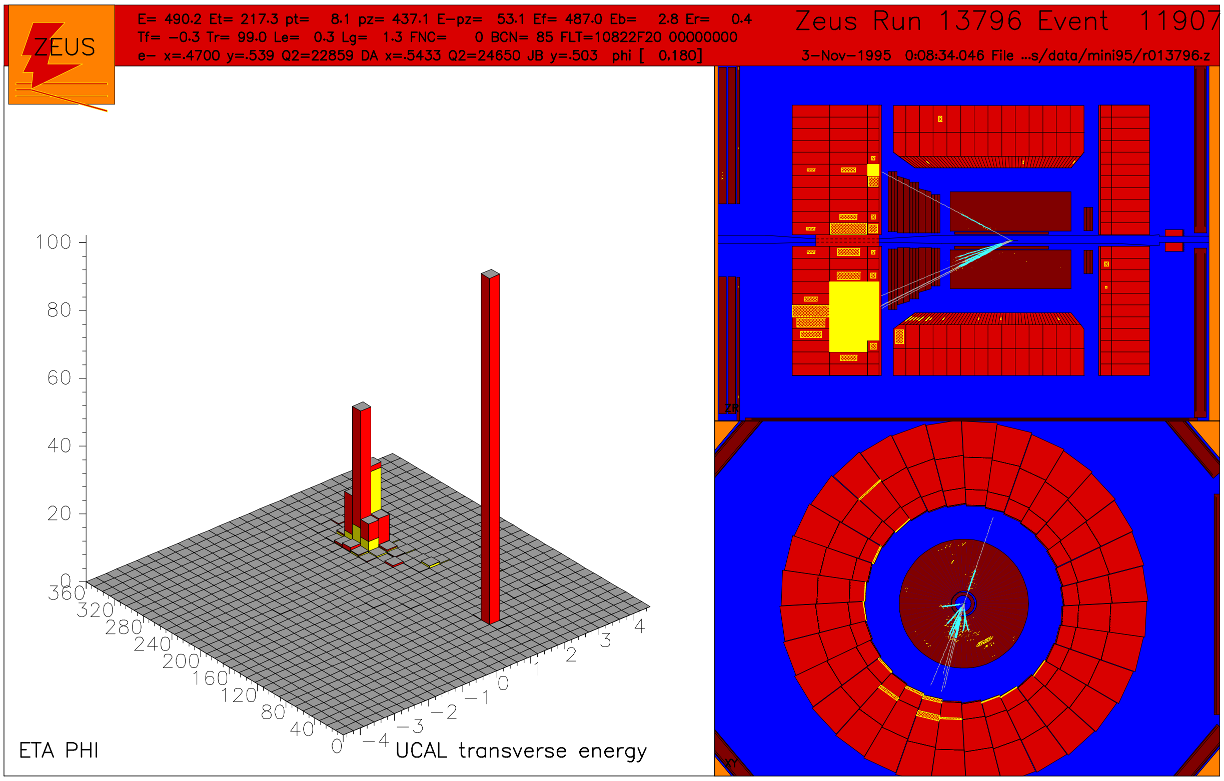
would lead to deviations in the differential cross sections for inclusive jet production wrt the expectations of the Standard Model

- For example, a narrow resonance in $e^+ - \mathrm{quark}$ scattering would show up as a Jacobean peak in $\frac{d\sigma}{dE_T^{jet}}$



Anomalous jet production (contd)

- In neutral-current interactions at high Q^2 the most probable final state in the Standard Model consists of **a single jet balancing the positron's transverse momentum, $E_T^{jet} \sim Q$.**



- A resonance in $e^+ - \mathrm{quark}$ scattering decaying into **e^+ plus several jets** would populate the region $E_T^{jet} \ll Q$, where multijet production in the Standard Model is suppressed by higher powers of the strong coupling constant α_s.

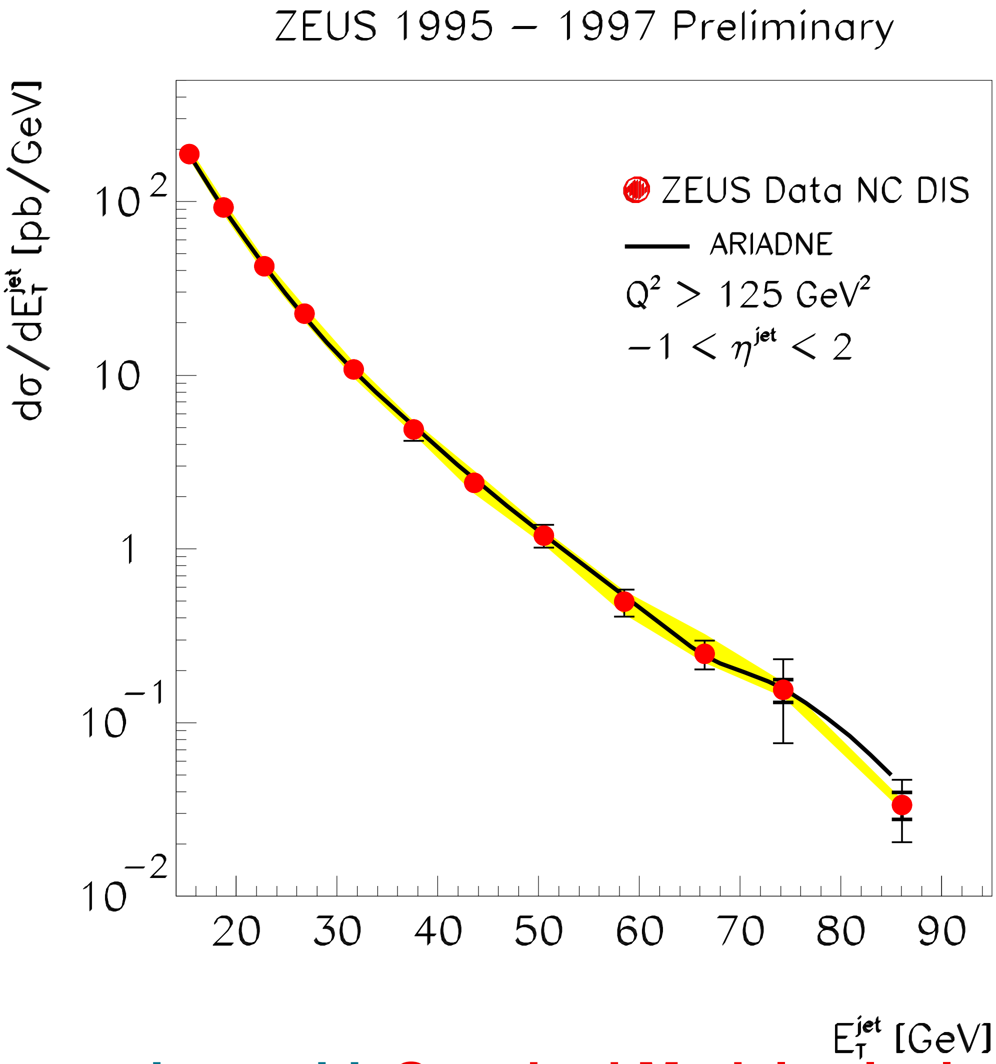
Inclusive jet cross sections in NC DIS

Measurement of differential cross sections for inclusive jet production in the reaction

$$e^+ p \to e^+ \; + \; \mathrm{jet(s)} \; + \; X$$

- ZEUS 1995-1997 data: $\mathcal{L} = 43$ pb^{-1}
- Isolated positron with $E_{e'} > 10$ GeV
- Kinematic region: $Q^2 > 125$ GeV^2
- Jet search:
  - in the laboratory frame
    $\to$ to search for resonances in e^+-quark scattering
  - using the longitudinally invariant k_T cluster algorithm (S. Catani et al, NPB406 (1993) 187) in the inclusive mode (S.D. Ellis and D.E. Soper, PRD48 (1993) 3160) $\to$ infrared safe for multijet configurations
  - counting jets with $E_T^{jet} > 14$ GeV and $-1 < \eta^{jet} < 2$

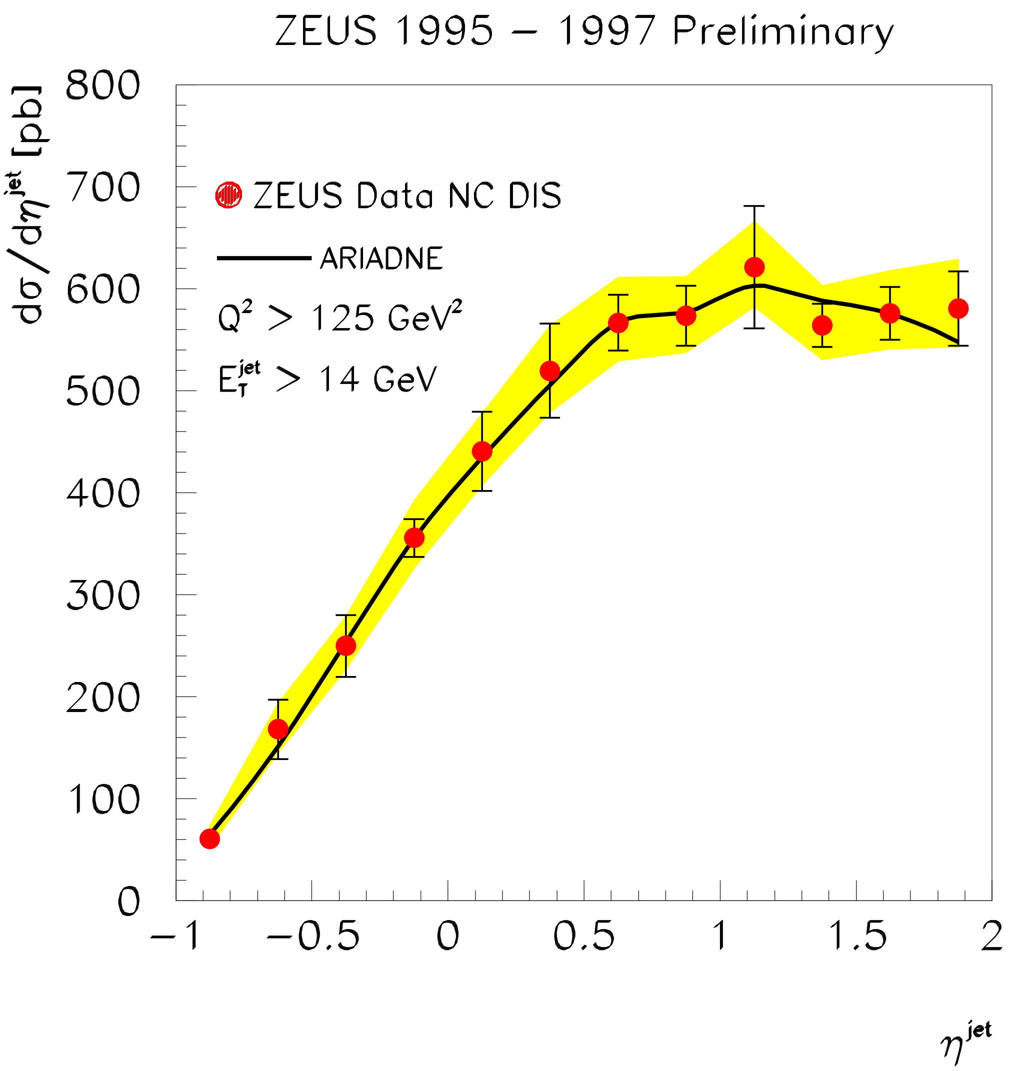
Inclusive jet cross sections in NC DIS: E_T^{jet} dependence



- **Comparison with Standard Model calculations:**
  - → **Photon and Z° exchanges**
  - → **First-order electroweak radiative corrections**
  - → **$O(\alpha_s)$ QCD corrections plus parton showers (colour dipole model; Monte Carlo ARIADNE)**
  - → **CTEQ4D proton pdf's**

No evidence for significant deviations from the Standard Model expectations up to $E_T^{jet} \sim 85$ GeV

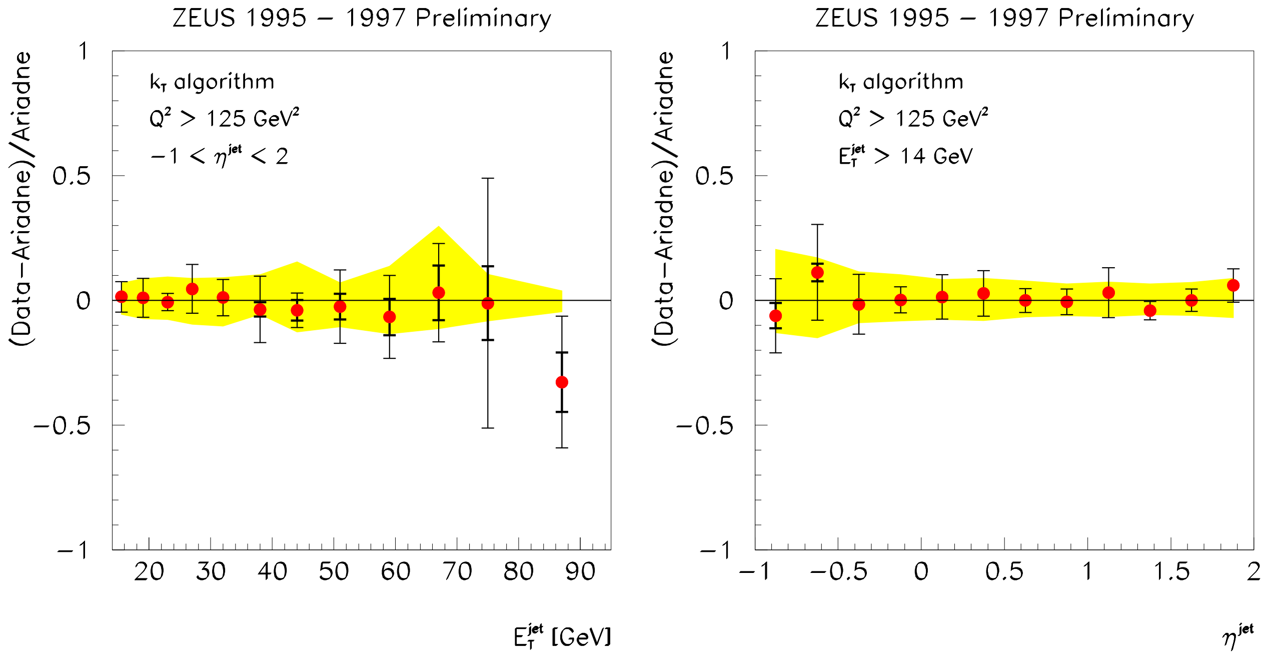
Inclusive jet cross sections in NC DIS: η^{jet} dependence



- **Comparison with Standard Model (MC ARIADNE)**

No evidence for deviations from the expectations of the Standard Model in the range $-1 < \eta^{jet} < 2$

Inclusive jet cross sections in NC DIS: E_T^{jet} and η^{jet} dependence



- **Comparison with Standard Model (MC ARIADNE):**

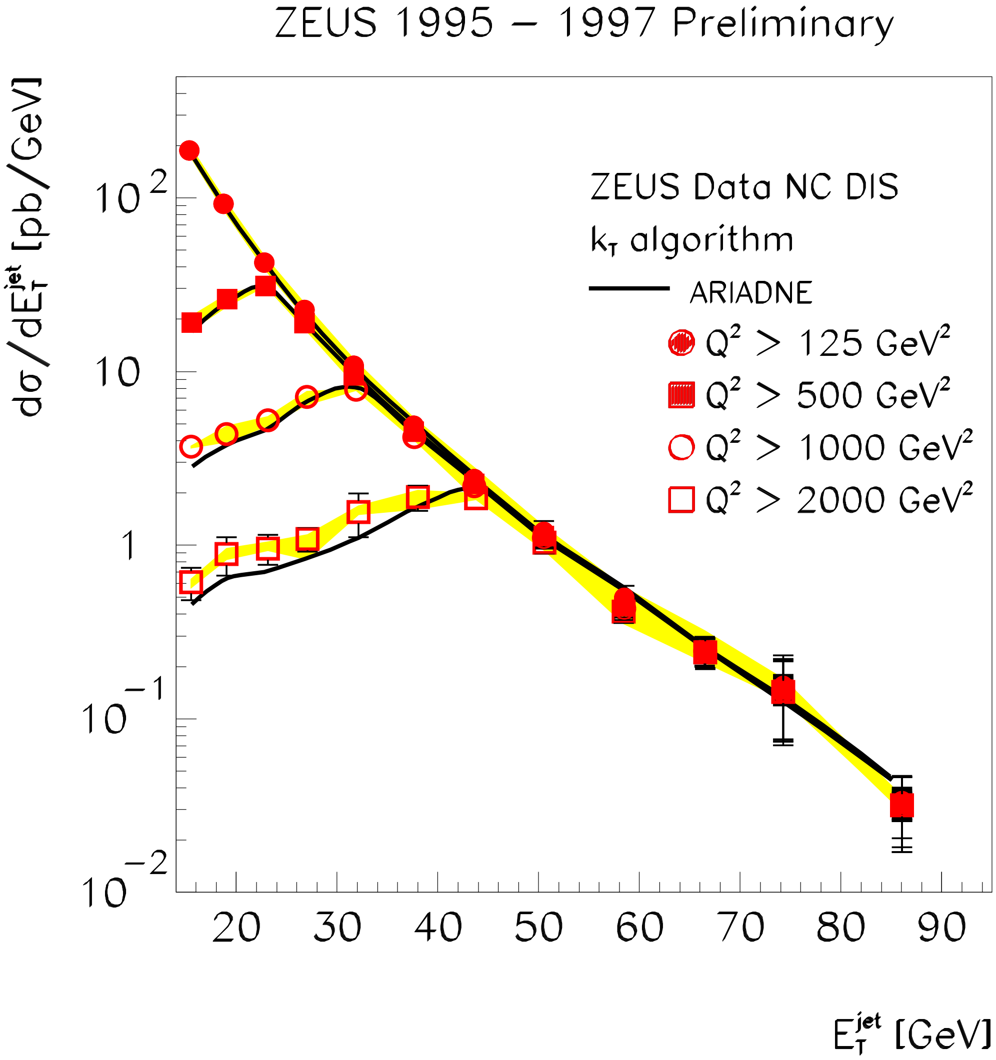
$$\frac{\mathrm{DATA-ARIADNE}}{\mathrm{ARIADNE}}$$

The agreement between the measured cross sections and the Standard Model (MC ARIADNE) expectations typically better than 10%

Inclusive jet cross sections in NC DIS:

- **Measurements of** $\frac{d\sigma}{dE_T^{jet}}$

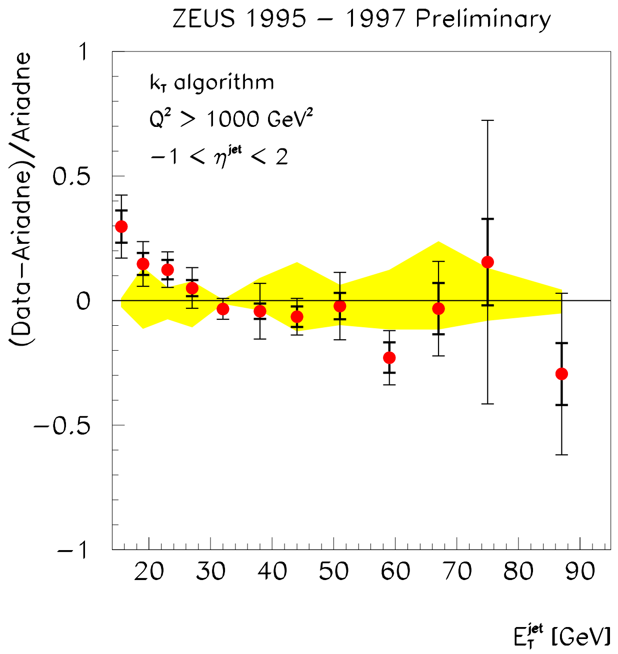
  for $Q^2 > 125$**, 500, 1000 and 2000 GeV**^{2}

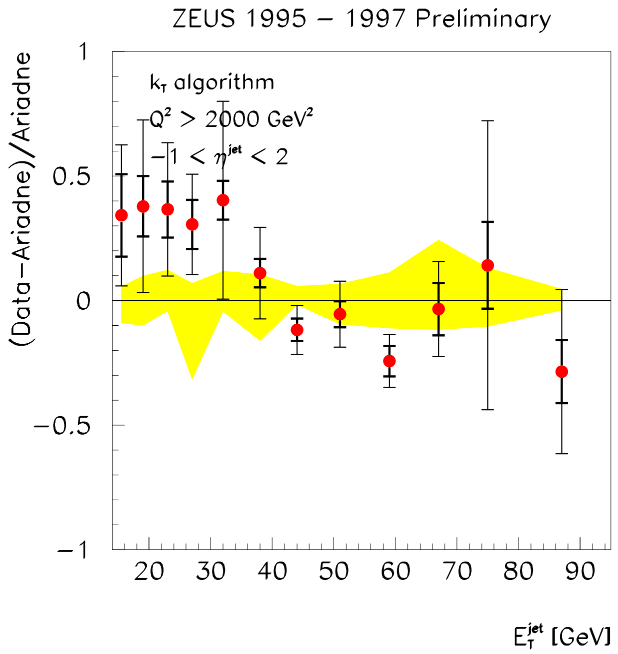


- **Comparison with Standard Model (MC ARIADNE):**

$\rightarrow$ **tendency in the data to be above the calculations for** $Q^2 > 1000$ **GeV**^{2} **and low values of** E_T^{jet} **(**$\ll Q$**).**

Inclusive jet cross sections in NC DIS: $\frac{d\sigma}{dE_T^{jet}}$ for $Q^2 > 1000$ and 2000 GeV^2





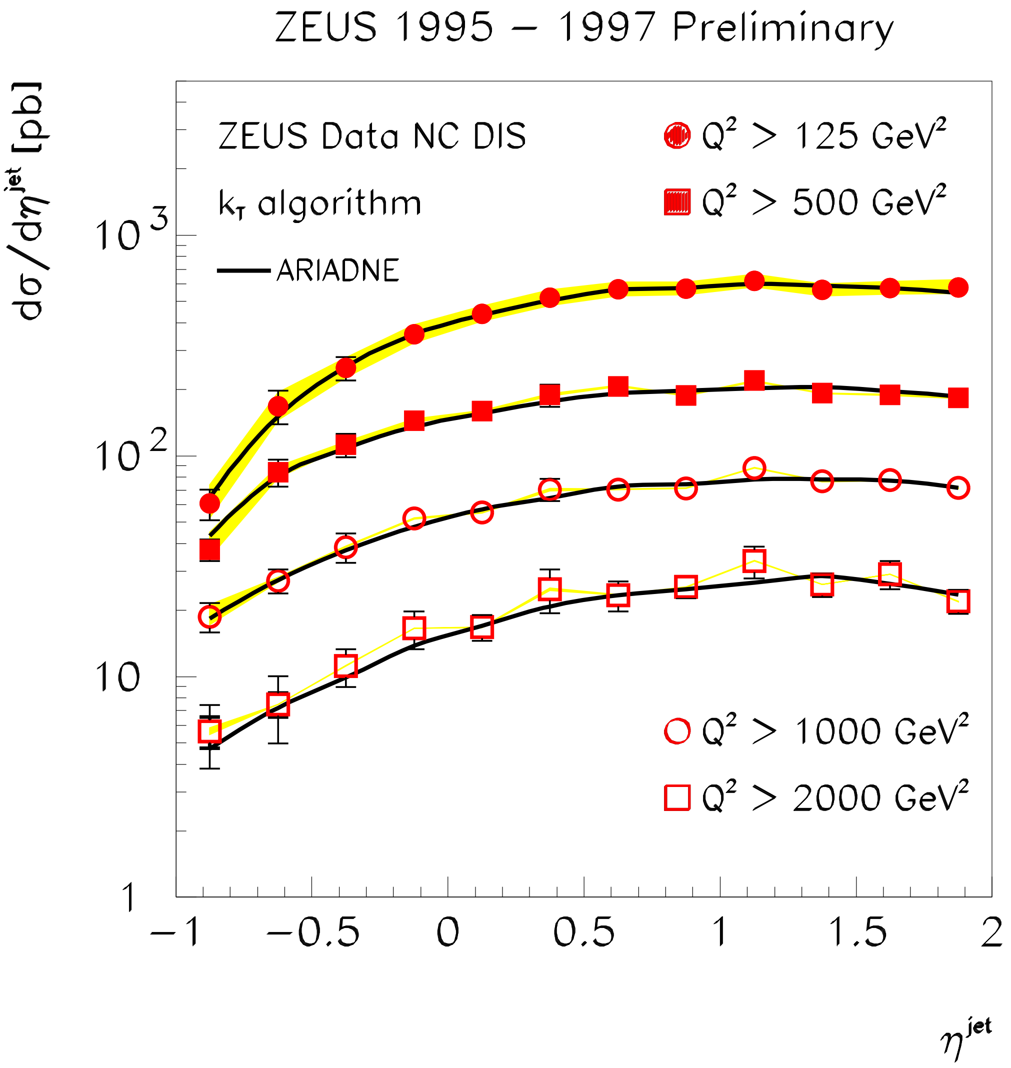
- **Comparison with Standard Model (MC ARIADNE):**

$$\frac{\mathrm{DATA}-\mathrm{ARIADNE}}{\mathrm{ARIADNE}}$$

$\rightarrow$ **tendency in the data to be above the calculations for $Q^2 > 1000$ GeV^2 and low values of E_T^{jet} ($\ll Q$).**

Inclusive jet cross sections in NC DIS:

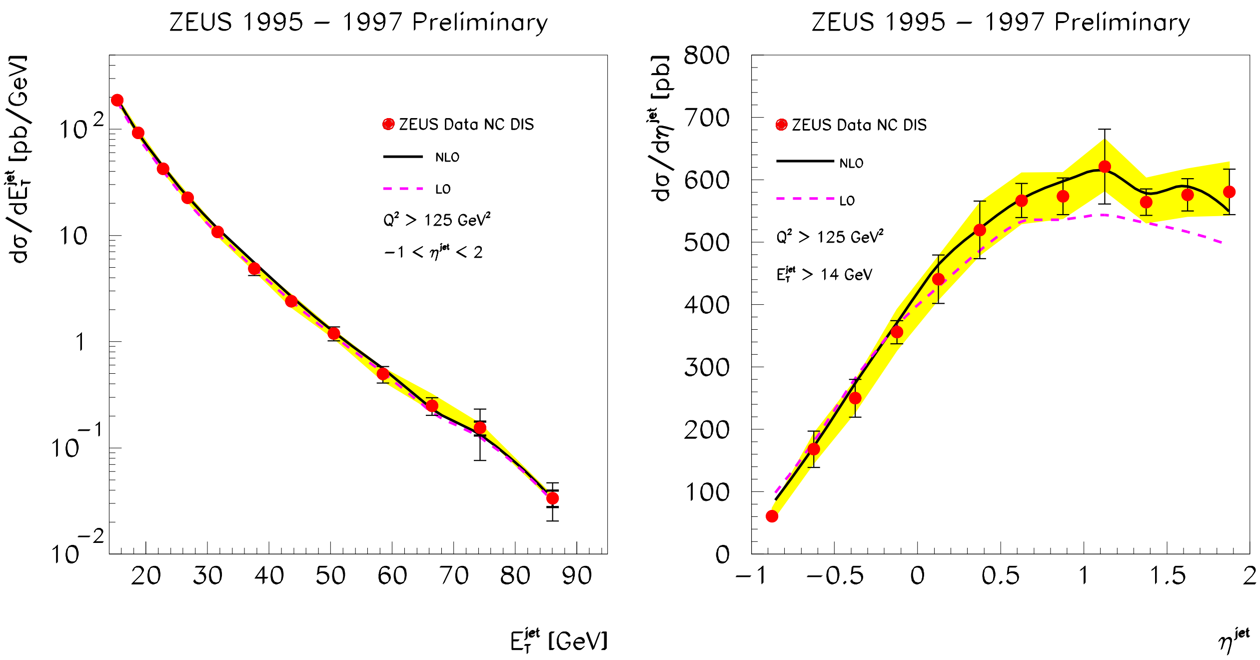
- **Measurements of** $\frac{d\sigma}{d\eta^{jet}}$ **for** $Q^2 > 125$, **500, 1000 and 2000 GeV**^{2}



- **Comparison with Standard Model (MC ARIADNE)**

No evidence for deviations from the expectations of the Standard Model in the range $-1 < \eta^{jet} < 2$

Inclusive jet cross sections in NC DIS:

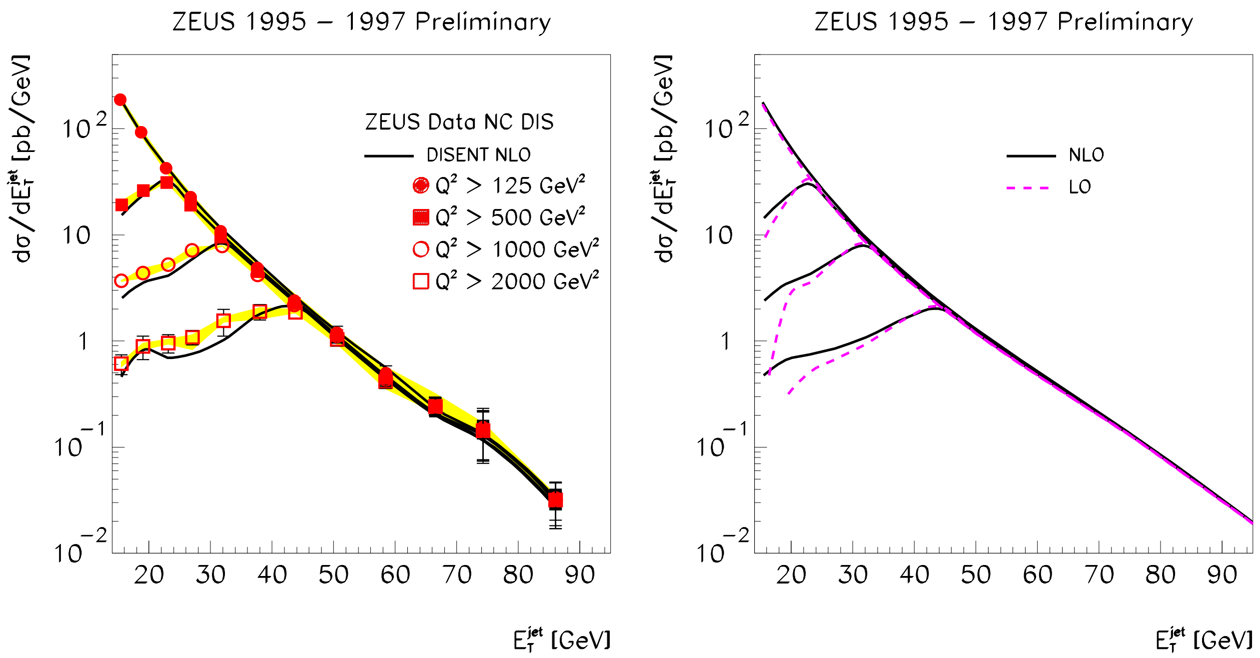


- **Comparison with Standard Model calculations:**
  - $\rightarrow$ **LO and NLO QCD calculations using the DISENT program** (S. Catani and M.H. Seymour, NPB485 (1997) 291)
  - $\rightarrow$ **CTEQ4L (CTEQ4M) proton pdf's**
  - $\rightarrow$ **Factorisation/Renormalisation scales** $= Q^2$
  - $\rightarrow$ **Supplemented with** Z° **exchange and first-order electroweak radiative effects**

$\Longrightarrow$ **Hadronisation corrections smaller than 5%**

No evidence for significant deviations from the Standard Model (NLO QCD) expectations

Inclusive jet cross sections in NC DIS:

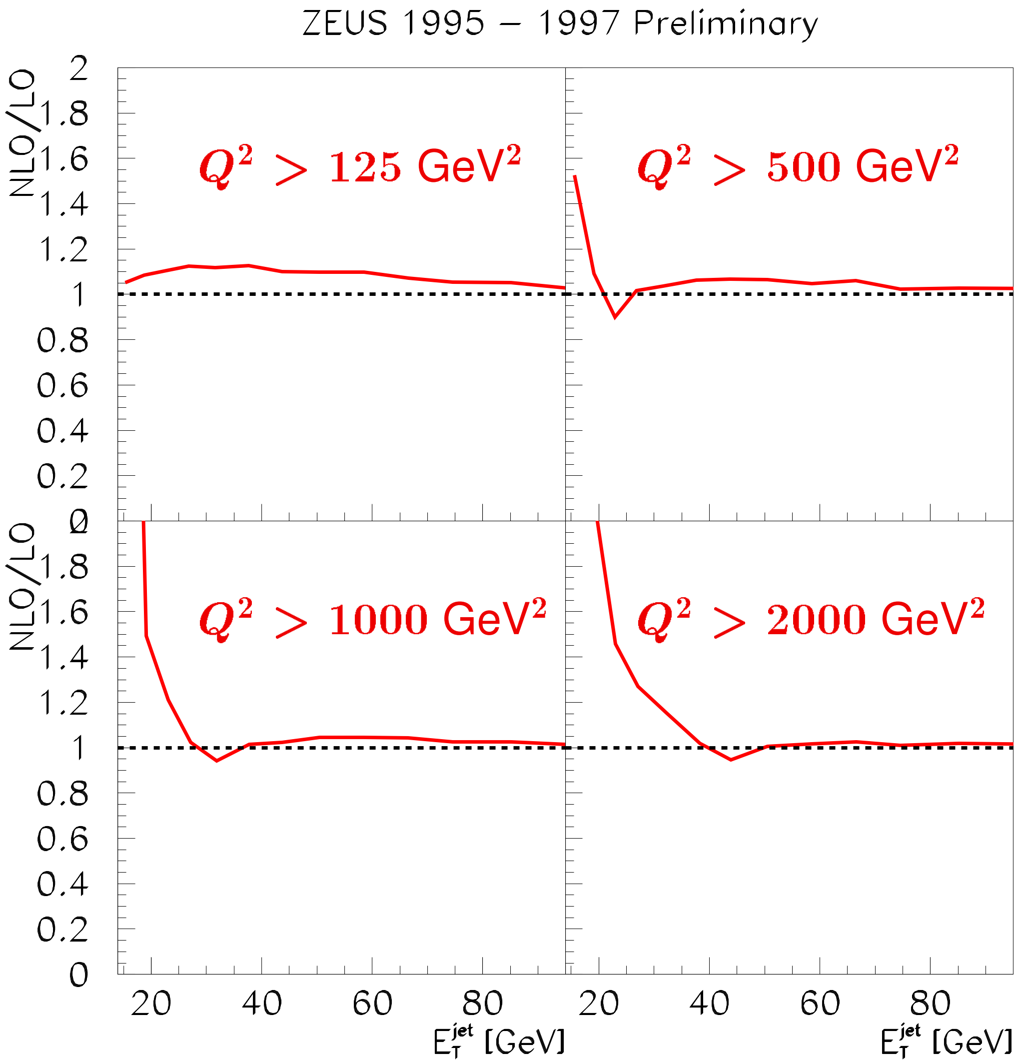


- Comparison with Standard Model (NLO QCD using DISENT) calculations $\rightarrow$ tendency in the data to be above the calculations for $Q^2 > 1000$ GeV^2 and low values of E_T^{jet} ($\ll Q$).

- Accuracy of the Standard Model calculations: NLO QCD corrections are smaller than 10% except for $Q^2 > 1000$ GeV^2 and low values of E_T^{jet}
$\rightarrow$ at $E_T^{jet} \sim 20$ GeV the NLO QCD correction is 50% (100%) for $Q^2 > 1000$ GeV^2 (2000 GeV^2).

- Improved QCD calculations are needed!

Inclusive jet cross sections in NC DIS: LO vs. NLO QCD calculations



• The NLO QCD corrections are found to be largest in the low-E_T^{jet} region at large Q^2.

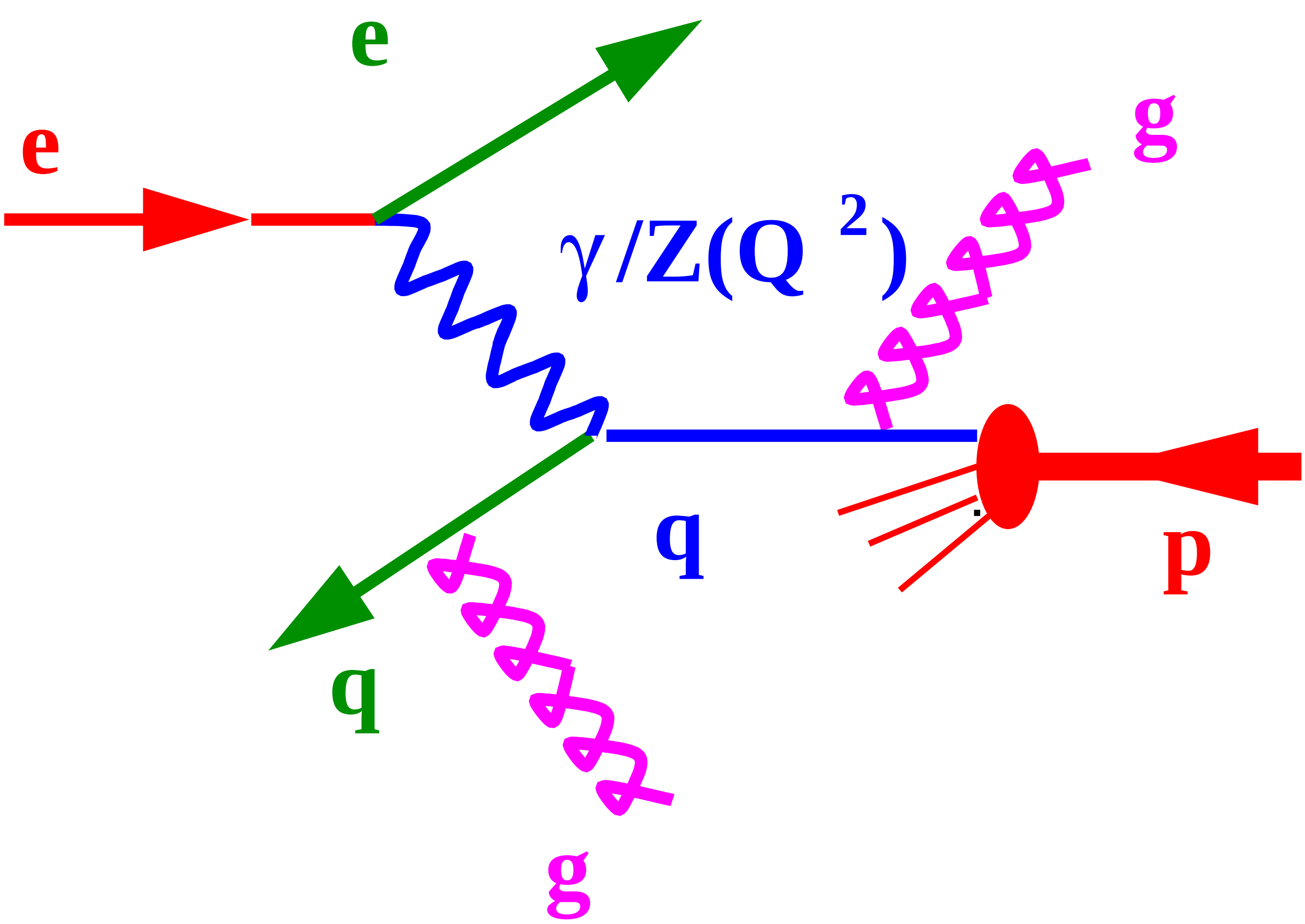
• The NLO QCD correction at $E_T^{jet} \sim 20$ GeV for $Q^2 > 1000$ GeV^2 (2000 GeV^2) increases the cross section by **50% (100%)** and suggests that higher-order QCD corrections can be very large.

Three-jet production in DIS NC

• The large centre-of-mass energy in e^+p collisions at HERA ($\sqrt{s_{ep}} = 300$ GeV) allows the study of multi-jet production in neutral-current interactions in a wide range of Q^2, e.g.

$$e^+p \to e^+ + (3 - \text{jet}) + X$$

$\to$ test of the perturbative QCD predictions at $O(\alpha_s^2)$



Topology of three-jet events

• The topology of three-jet events in their CM-system has been studied in terms of the following variables

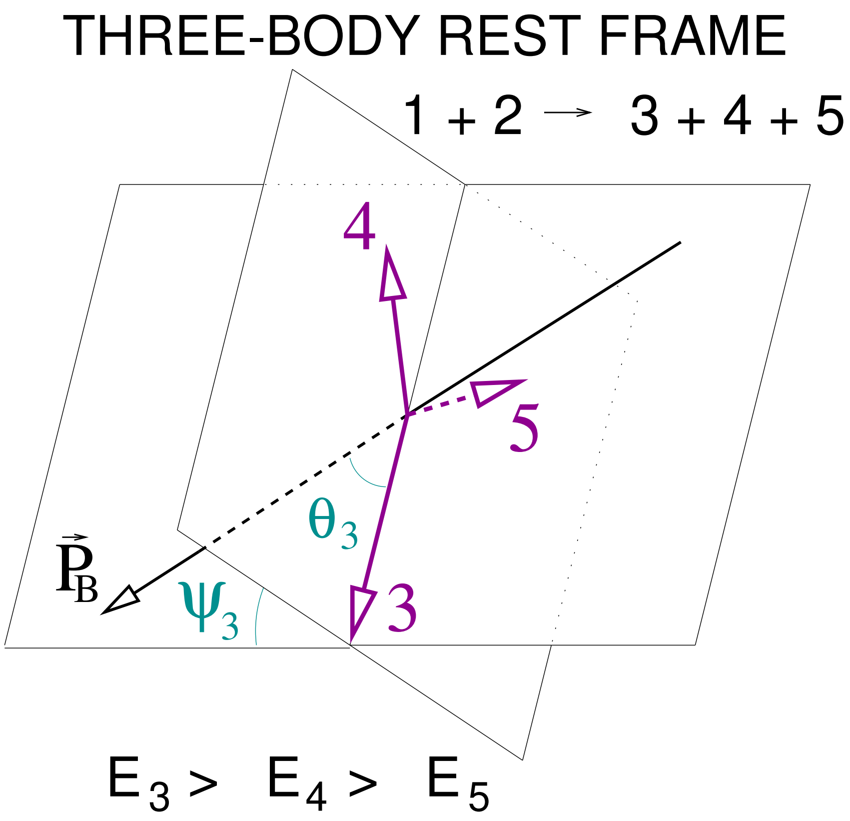
→ Three-jet invariant mass $\boxed{M_{3\rm jet}}$

→ Scaled jet energies ($E_3 > E_4 > E_5$)

$\boxed{X_3 = \frac{2E_3}{M_{3\rm jet}}}$ and $\boxed{X_4 = \frac{2E_4}{M_{3\rm jet}}}$

→ Polar angle of the leading jet $\boxed{\cos\theta_3}$

→ Orientation of the 3-jet plane wrt the plane containing the beam direction and the leading jet $\boxed{\Psi_3}$



• Sensitive to the pattern of parton radiation

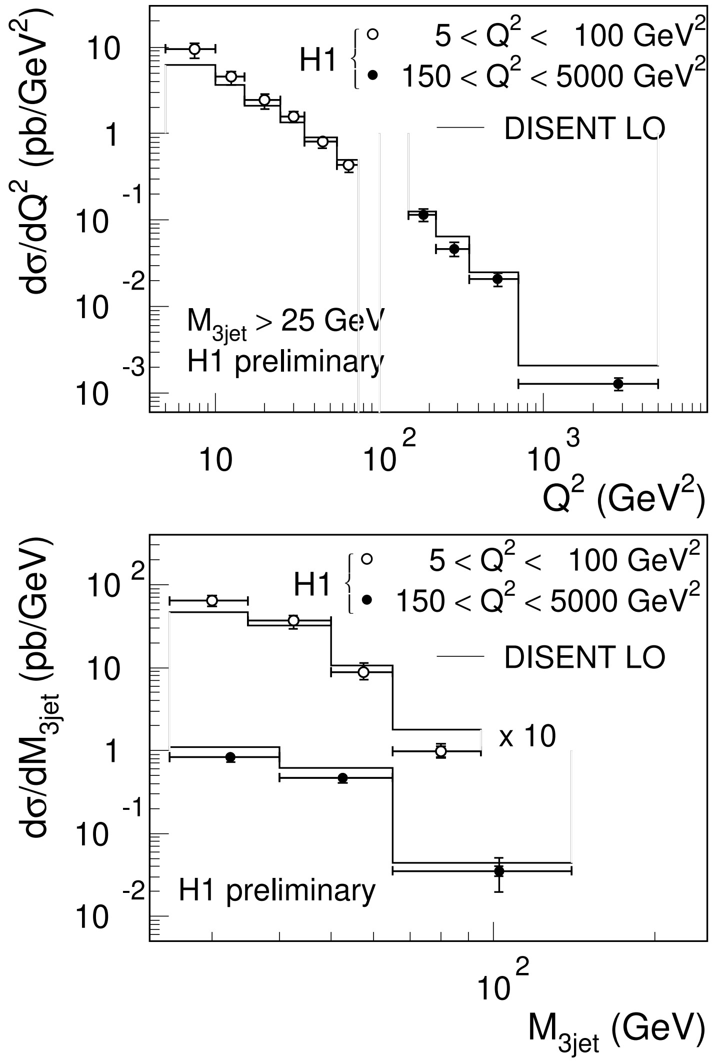
Three-jet cross sections in NC DIS

Measurement of differential cross sections for three-jet production in the reaction

$$e^+ p \to e^+ \ + \ (3-\mathrm{jet}) \ + \ X$$

- **H1 1995-1997 data: $\mathcal{L} = 33$ pb^{-1}**
- **Kinematic regions: $5 < Q^2 < 100$ GeV^2 and $150 < Q^2 < 5000$ GeV^2**
- **Jet search:**
  - **in the Breit frame (the virtual photon interacts head-on with the proton)**
    $\rightarrow$ to test pQCD as in $p\bar{p}$ collisions, but in a cleaner environment
  - **using the longitudinally invariant k_T cluster algorithm in the inclusive mode**
    $\rightarrow$ infrared safe for multijet configurations
  - **each jet has to fulfill $E_T^{jet}(\mathrm{Breit}) > 5$ GeV and $-1 < \eta^{jet}(\mathrm{Lab}) < 2.5$**
- **Data corrected for QED radiation from the incoming and outgoing lepton.**

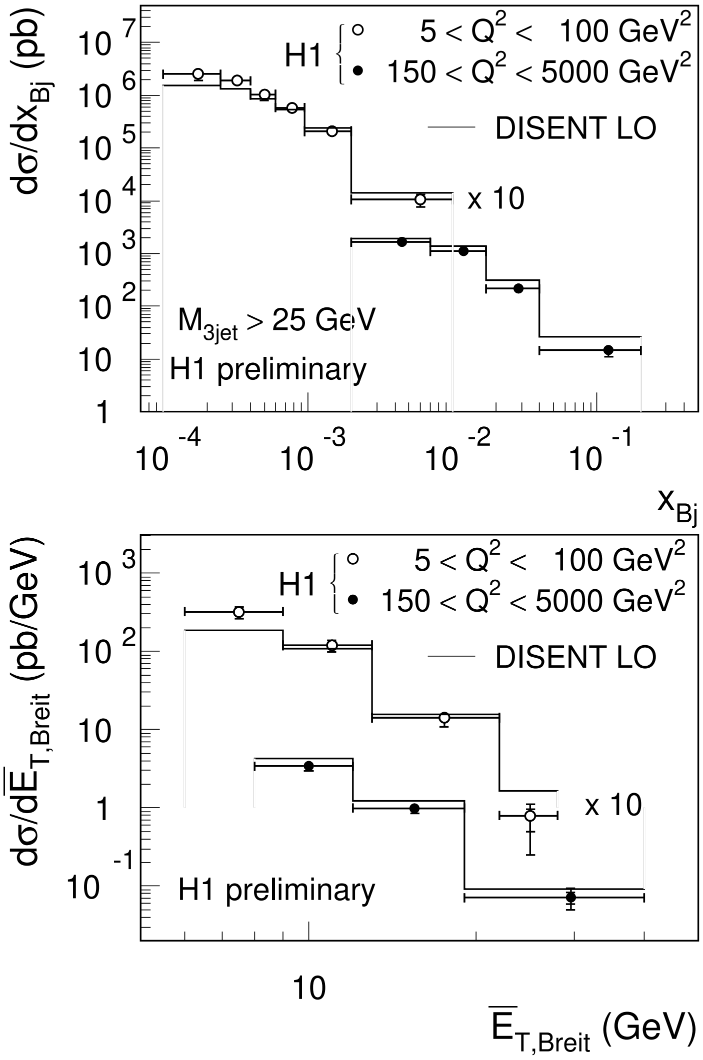
Three-jet cross sections in NC DIS: Q^2 and $M_{3\mathrm{jet}}$ dependence



• **Comparison with LO QCD ($O(\alpha_s^2)$ for three-parton final states) calculations using the DISENT program (CTEQ5L proton pdf's)** $\rightarrow$ Hadronisation corrections lower the predictions by 20-30%

Fair description of the data by the LO QCD calculations for $Q^2 > 40$ GeV^2 and $M_{3\mathrm{jet}} > 50$ GeV

Three-jet cross sections in NC DIS: $x_{\rm Bj}$ and $E_T^{jet}(\rm Breit)$ dependence

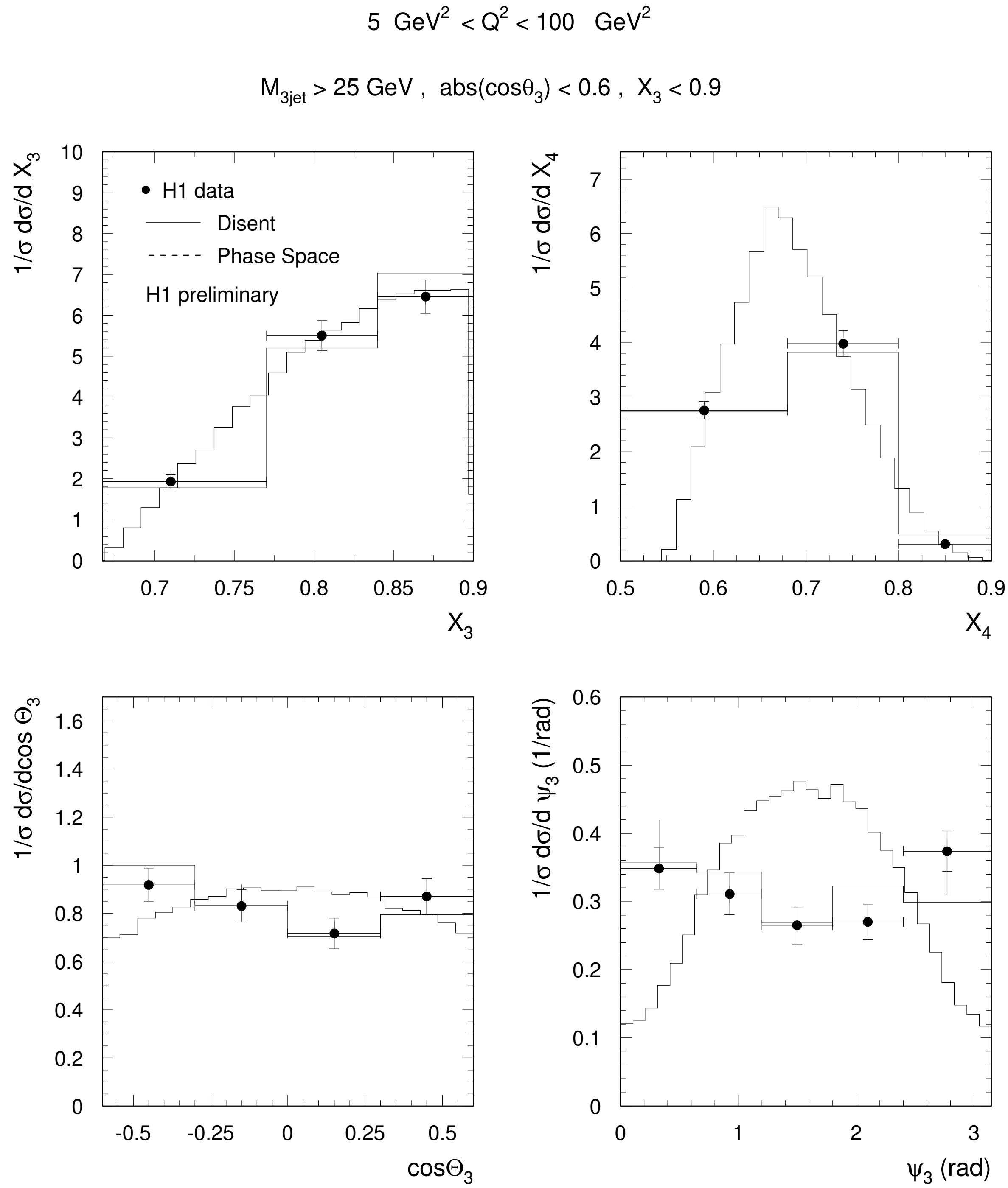


- Comparison with **LO QCD** calculations using **DISENT**

$\longrightarrow$ The calculations fail to describe the data at **low values of Q^2 and $E_T^{jet}(\rm Breit)$.**

Fair description of the data by the LO QCD calculations for $x_{\rm Bj} > 4 \cdot 10^{-3}$ and $E_T^{jet}(\rm Breit) > 10$ GeV

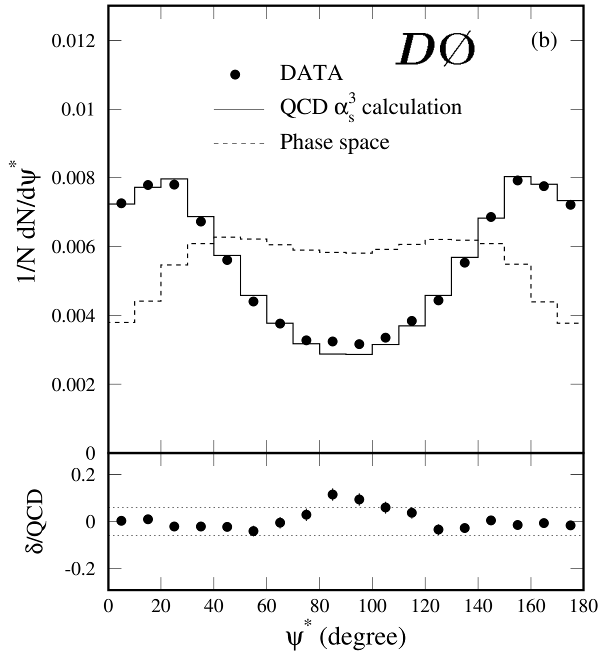
Topology of three-jet events in DIS NC: $5 < Q^2 < 100$ GeV^2 region



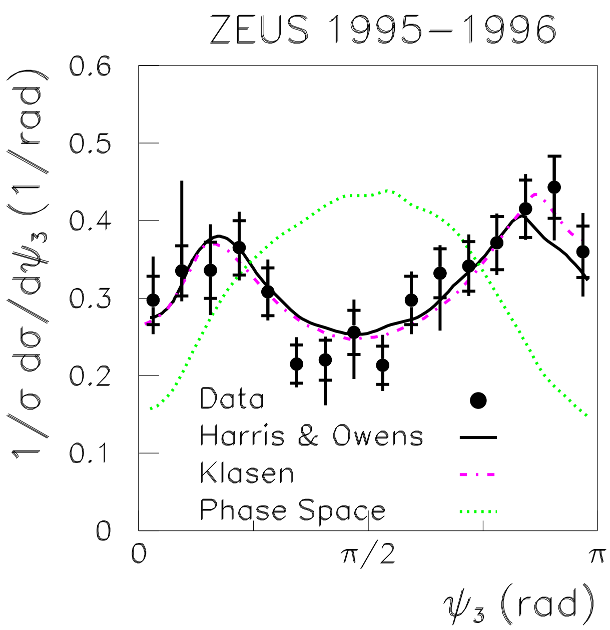
Good description of the topological distributions in the data by the LO QCD calculations (DISENT)

Topology of three-jet events in DIS NC: comparison with other reactions

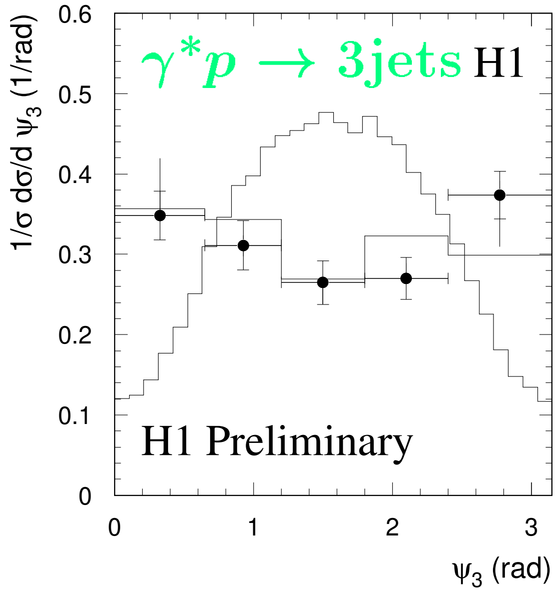
$p\bar{p} \rightarrow$ 3jets



$\gamma p \rightarrow$ 3jets

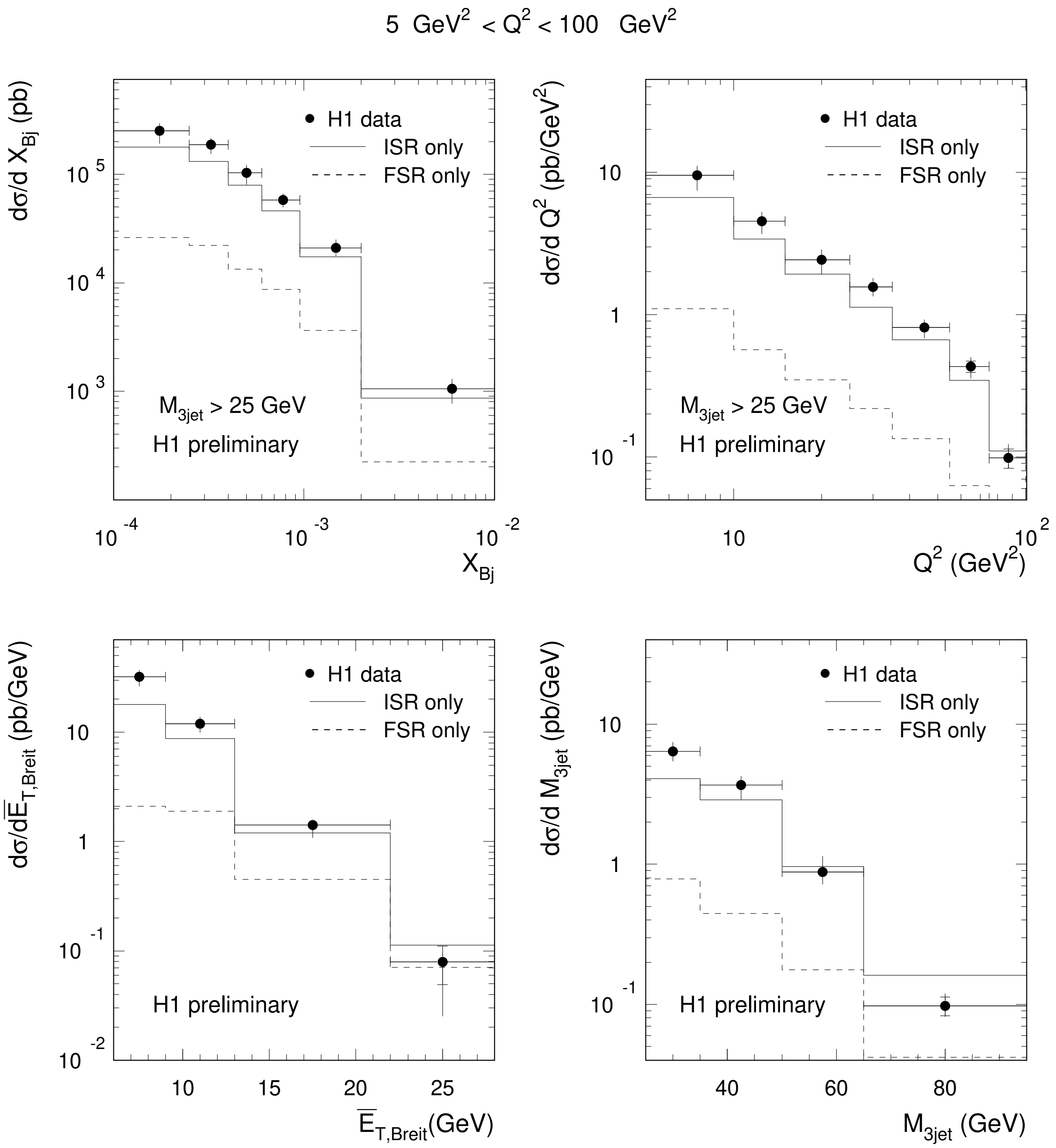


Depletion near $\Psi_3 \sim 0$ and π due to jet requirements (see phase space curves).



Data behave in opposite way, in agreement with QCD: initial-state radiation pole $\rightarrow$ enhanced radiation close to the beam line

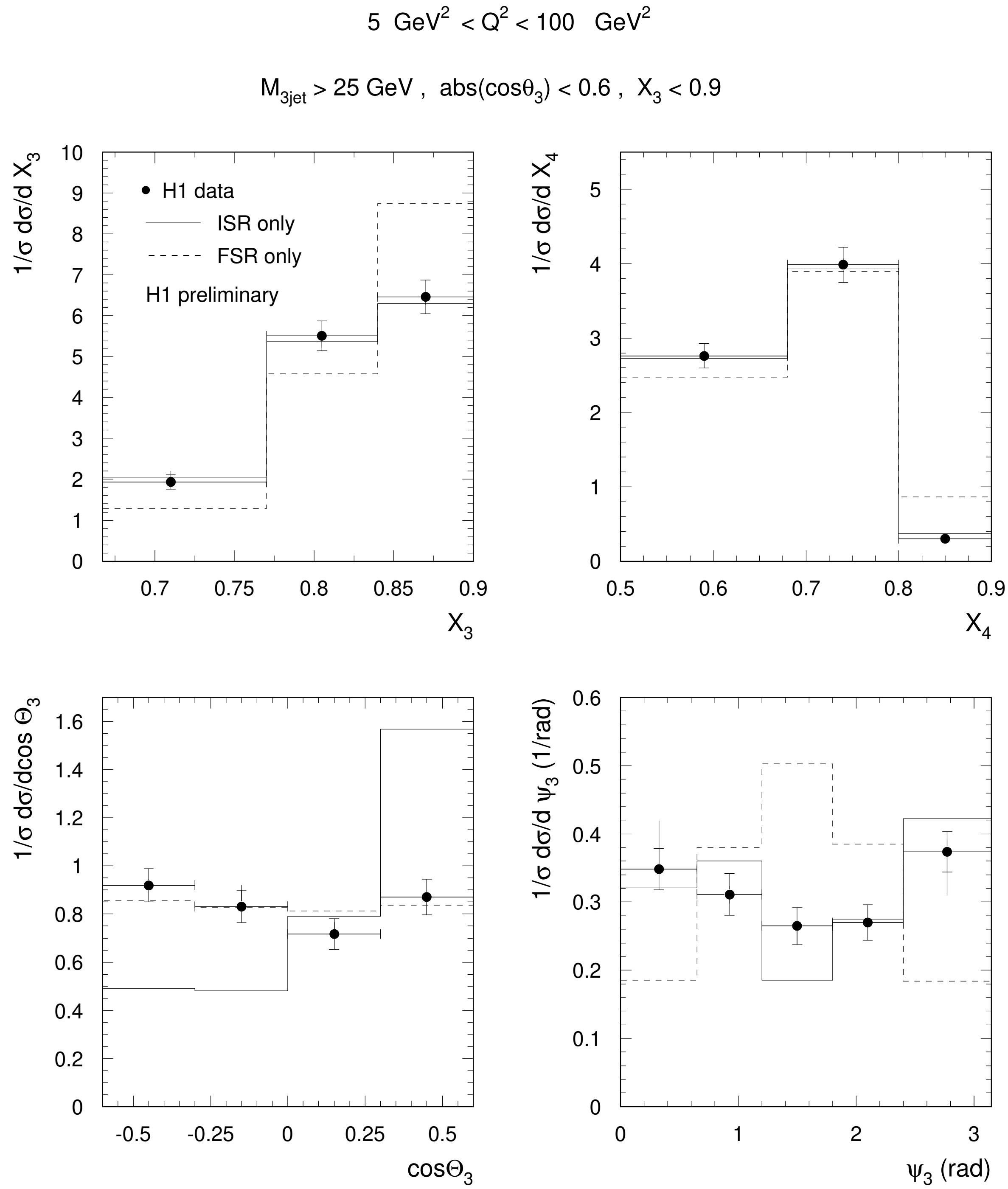
Three-jet cross sections in NC DIS: Initial- vs. final-state parton radiation



- **Comparison with Monte Carlo calculations using the LEPTO program, which includes $O(\alpha_s)$ matrix elements plus parton showers (initial and final state)**

$\rightarrow$ Initial-state parton radiation is expected to be the dominant contribution to three-jet production

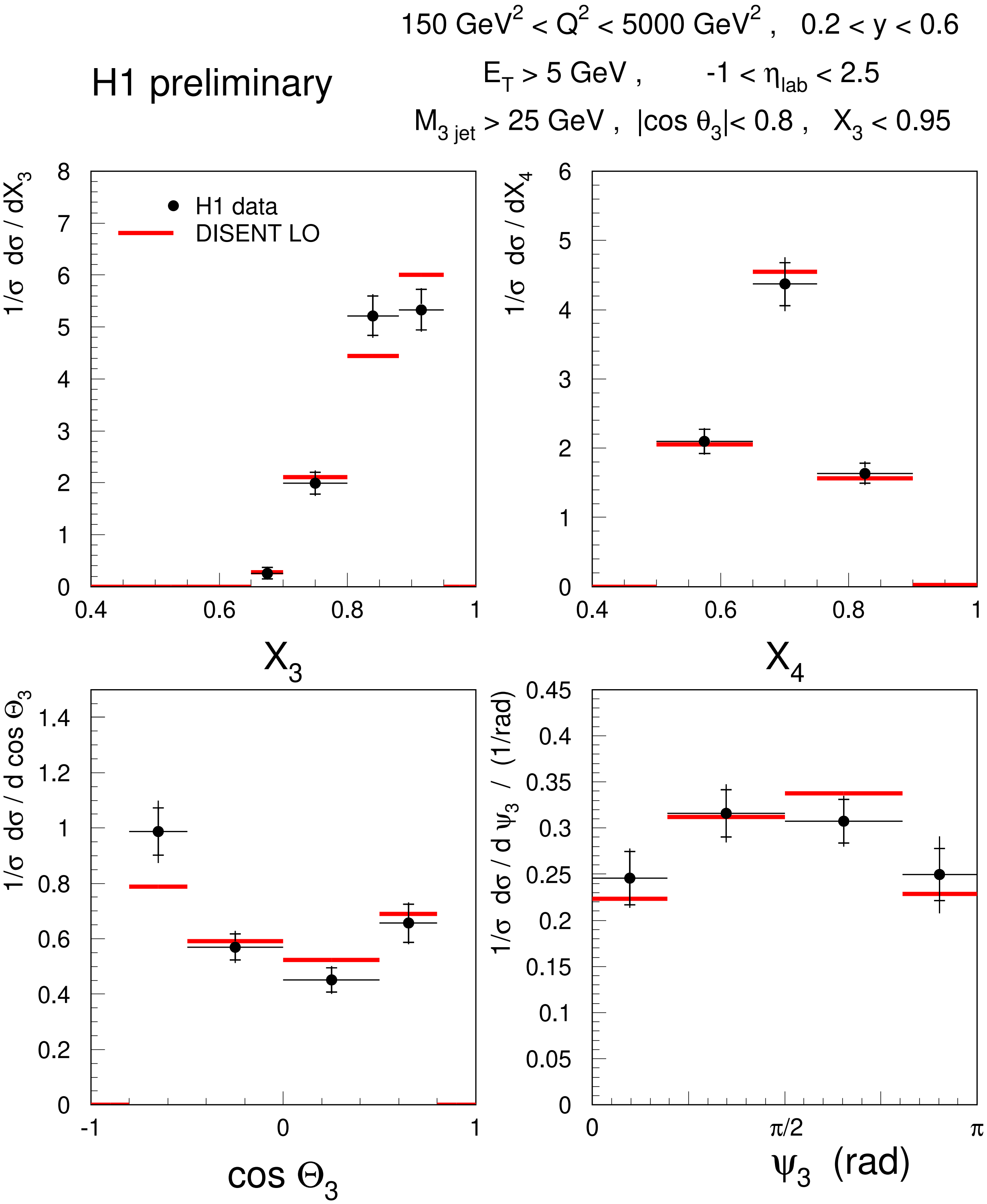
Topology of three-jet events in DIS NC: $5 < Q^2 < 100$ GeV^2 region; ISR vs. FSR



- Comparison with MC calculations (LEPTO)
  $\rightarrow$ FSR fails to describe the data

$\rightarrow$ Data consistent with the pattern of ISR

Topology of three-jet events in DIS NC: $150 < Q^2 < 5000$ GeV^2 region



Good description of the topological distributions in the data by the LO QCD calculations (DISENT)

Conclusions

- Measurement of differential cross sections $\frac{d\sigma}{dE_T^{jet}}$ and $\frac{d\sigma}{d\eta^{jet}}$ for inclusive jet production in the reaction

$$e^+p \to e^+ \ + \ \mathrm{jet(s)} \ + \ X$$

with $Q^2 > 125$, 500, 1000 and 2000 GeV^2 by ZEUS using $\mathcal{L} = 43$ pb^{-1}

No evidence for significant deviations from the Standard Model expectations up to $E_T^{jet} \sim 85$ GeV

$\to$ tendency in the data to be above the calculations for $Q^2 > 1000$ GeV^2 and low values of E_T^{jet} ($\ll Q$).

- Measurement of topological distributions in three-jet production

$$e^+p \to e^+ \ + \ (3-\mathrm{jet}) \ + \ X$$

with $5 < Q^2 < 5000$ GeV^2 by H1 using $\mathcal{L} = 33$ pb^{-1}

The measured Ψ_3 distribution shows the expected characteristics of QCD: enhanced radiation close to the beam line due to initial-state radiation pole