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JET PHYSICS AT HERA

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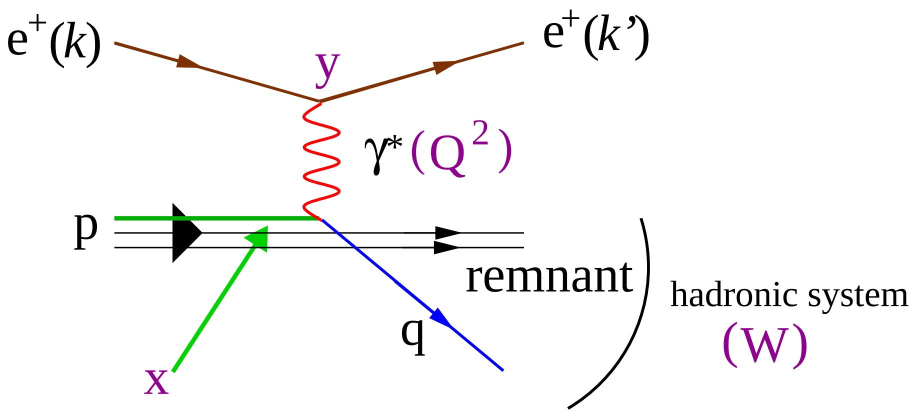
On behalf of the H1 and ZEUS Collaborations

- Photoproduction of jets
  - Structure of the photon
  - Particle production and searches
  - QCD tests
- Jet studies in deep inelastic scattering
  - Studies and precise tests of QCD
  - Determination of α_s
- QCD studies using the internal structure of jets

Jet production in ep interaction at HERA

The high-energy ep interactions at the HERA collider provides a powerful laboratory to test the predictions of the Standard Model.



Quark-Parton Model

Variables commonly used:

$$q \equiv k - k' \Longrightarrow Q^2 = -q^2$$

s$=(p+k)^2$ (center-of-mass energy²)

$$\left.\begin{aligned} y &\equiv \frac{p\cdot q}{p\cdot k} \\ x &\equiv \frac{Q^2}{2p\cdot q} \end{aligned}\right\} \Longrightarrow Q^2 = sxy$$

$$W^2 \simeq Q^2\,(1/x - 1)$$

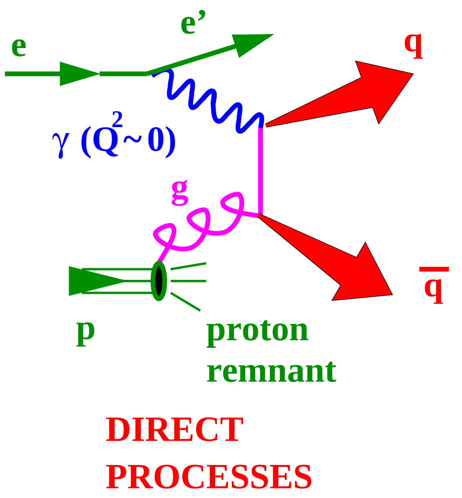
Studies of jet production at HERA allows precise tests of perturbative QCD predictions (complementary to e^+e^- and $p\bar{p}$).

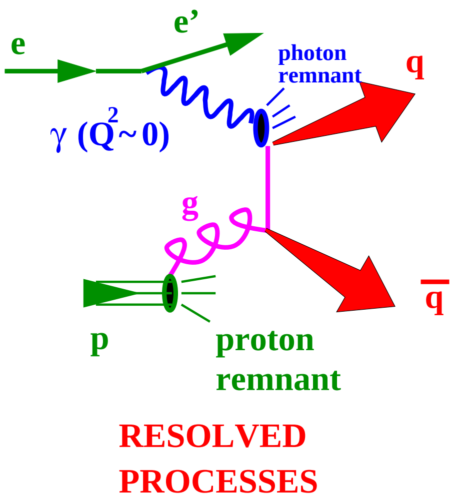
Depending on the Q^2 value, two different kinematic regimes:

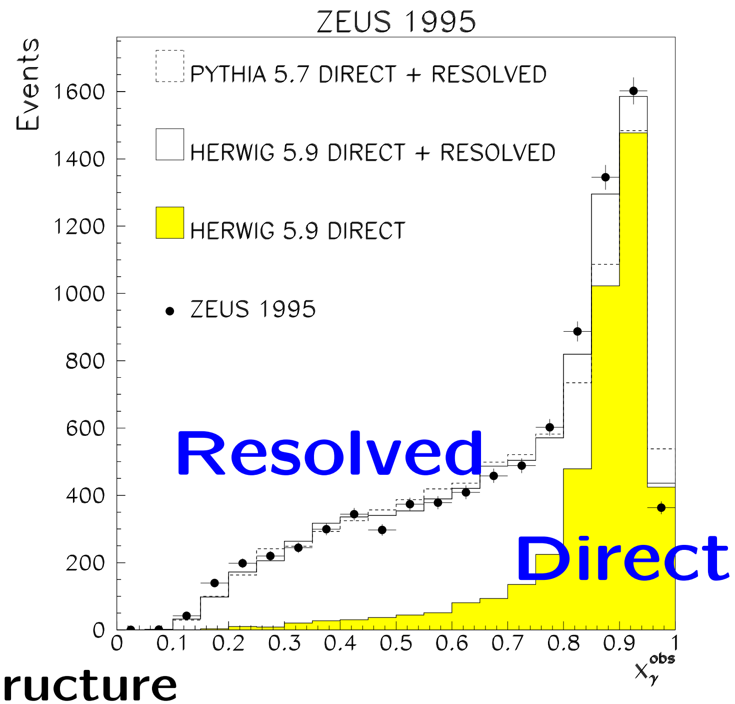
- $\rightarrow$ $Q^2 \sim 0$ (quasi-real photon): photoproduction regime or γp interactions.
- $\rightarrow$ $Q^2 >> 1$ GeV²: deep inelastic ep scattering.

Jets in the photoproduction regime

At lowest order (LO) QCD, two hard scattering processes contribute to jet production: direct and resolved photon.







Measurements of jet production informs on

Partonic content of the photon → Photon structure

Dynamics of resolved and direct processes → QCD tests

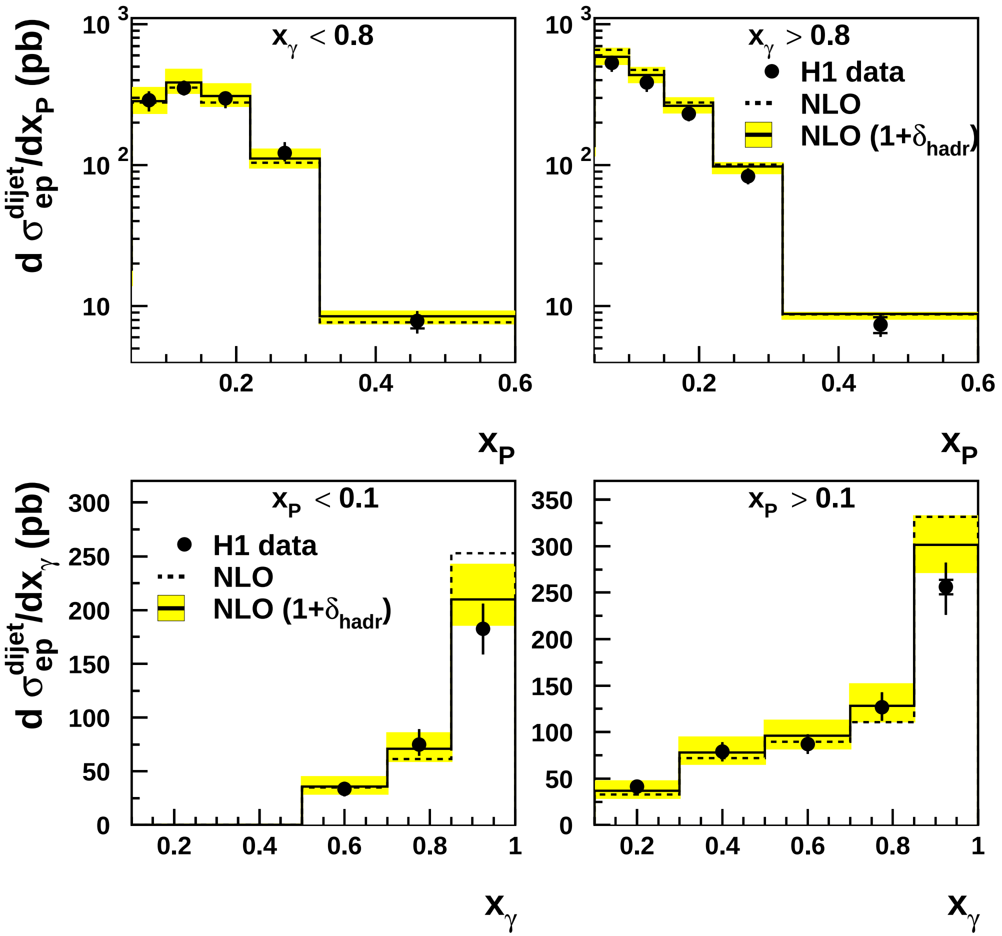
The observable to separate the contributions for to dijet production is

$$x_\gamma^{OBS} = \frac{1}{2\,E_\gamma}\left(E_{T,jet1}\,e^{-\eta_{jet1}} + E_{T,jet2}\,e^{-\eta_{jet2}}\right)\,,$$

which is the fraction of the photon's energy participating in the production of the dijet system.

Dijet photoproduction

Measurement of the dijet cross section as a function of x_P and x_γ.



→ Sensitive to proton and photon PDFs.

→ In general, reasonable description of the data:

proton ⇒ CTEQ5M

photon ⇒ GRV-HO

→ At high x_γ: Large parton-to-hadron correction improve the comparison with data.

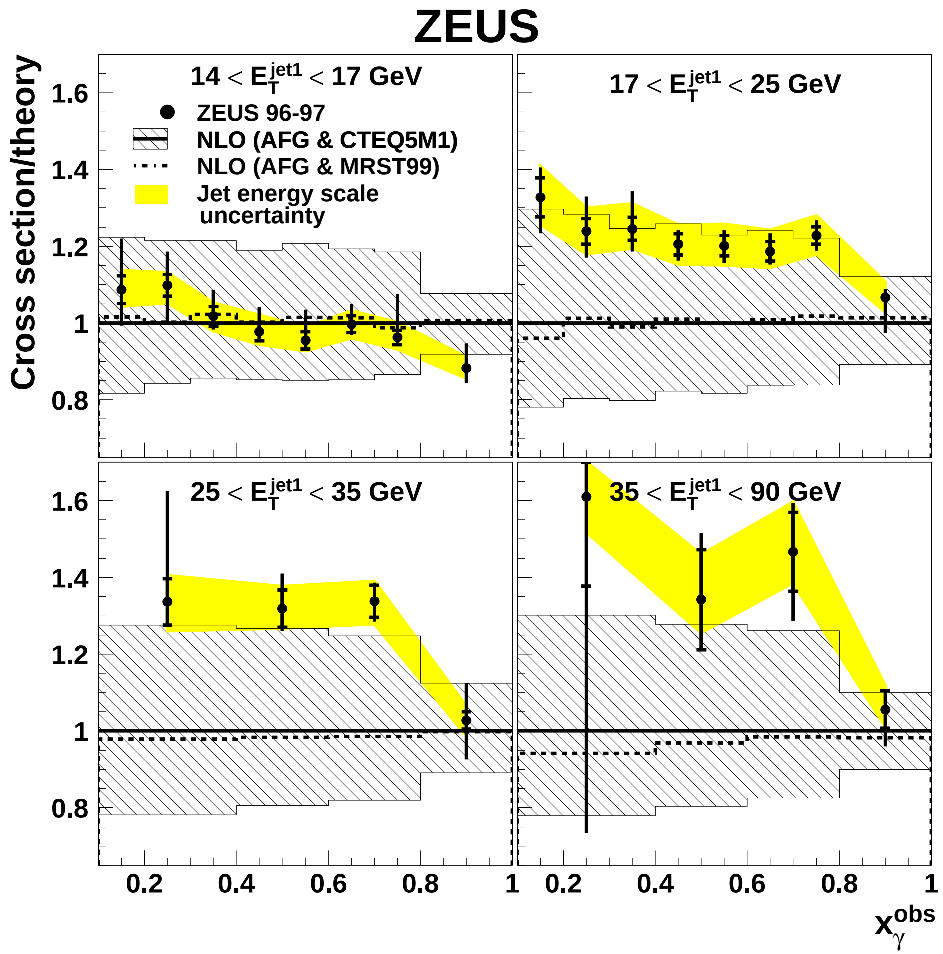
→ Small uncertainties in the proton PDFs (from DIS data).

Test of photon PDFs

The structure of the photon

The variable x_γ^{obs} is sensitive to the photon PDFs. The predictions based on the AFG set are tested in different regions of E_T^{jet1}.

- Ratio of $d\sigma^{dijet}/dx_\gamma$ between data and NLO QCD.
- Different dependence on E_T^{jet1} in data and NLO QCD.
- Very large theoretical uncertainty (20-30%).
- Note that CAL energy scale uncertainty small.
  $\longrightarrow$ Big effort to reduce uncertainty
- To constrain photon PDFS (instead of testing existing sets):
  $\longrightarrow$ Improved predictions are needed.



Searches using high-mass dijets

By using the two highest-E_T jets in the event, and measuring their invariant mass (M^{jj}).

The cross section is studied as a function of χ, defined as

$$\chi = \exp(|\Delta\eta|) = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

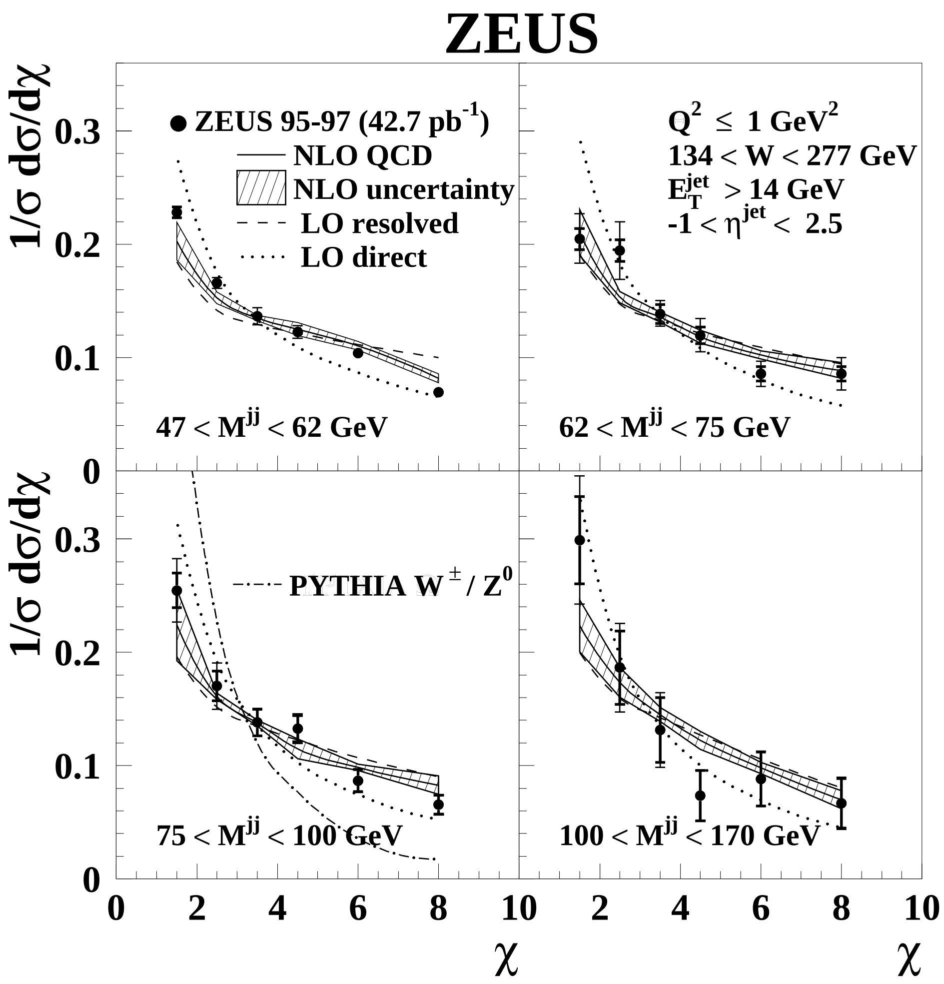
where $\Delta\eta$ is the difference in pseudorapidity between the two jets and θ^* the scattering angle in the dijet CMS.

Good description of the data by NLO QCD.

Variable sensitive to Z^0 and $W^\pm$ production.

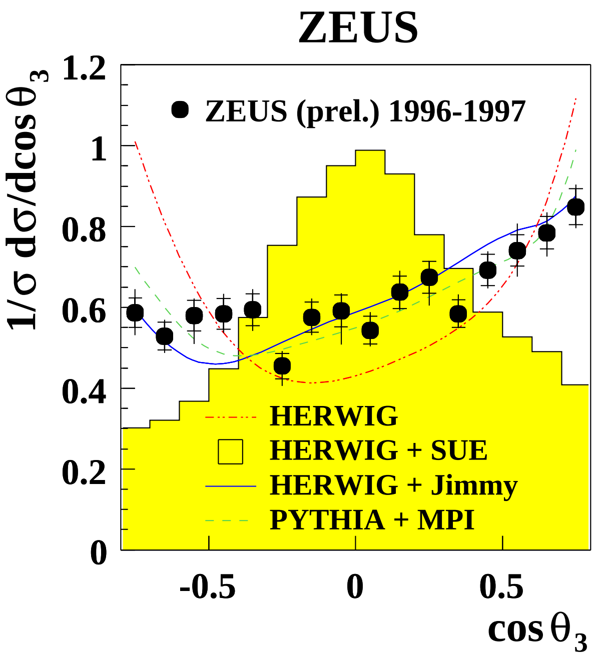
95% C.L. upper limit on the cross section for Z^0 photoproduction for the first time at HERA:

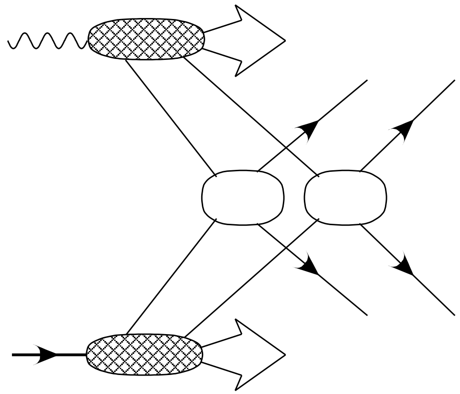
$\sigma_{e^+p\to e^+Z^0X} < 5.9$ pb (expected: 0.3 pb).



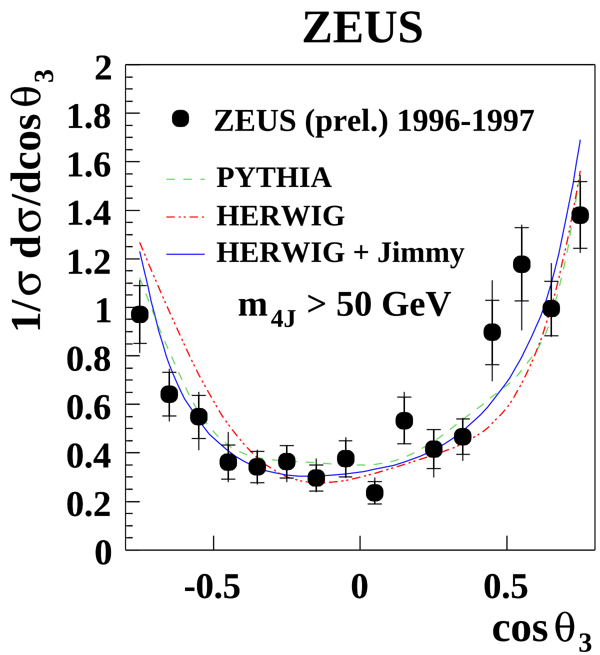
Multijets in γp interactions

Multijet photoproduction is sensitive to Multi-Parton Interactions





Models: { MPI of PYTHIA / Jimmy (HERWIG)

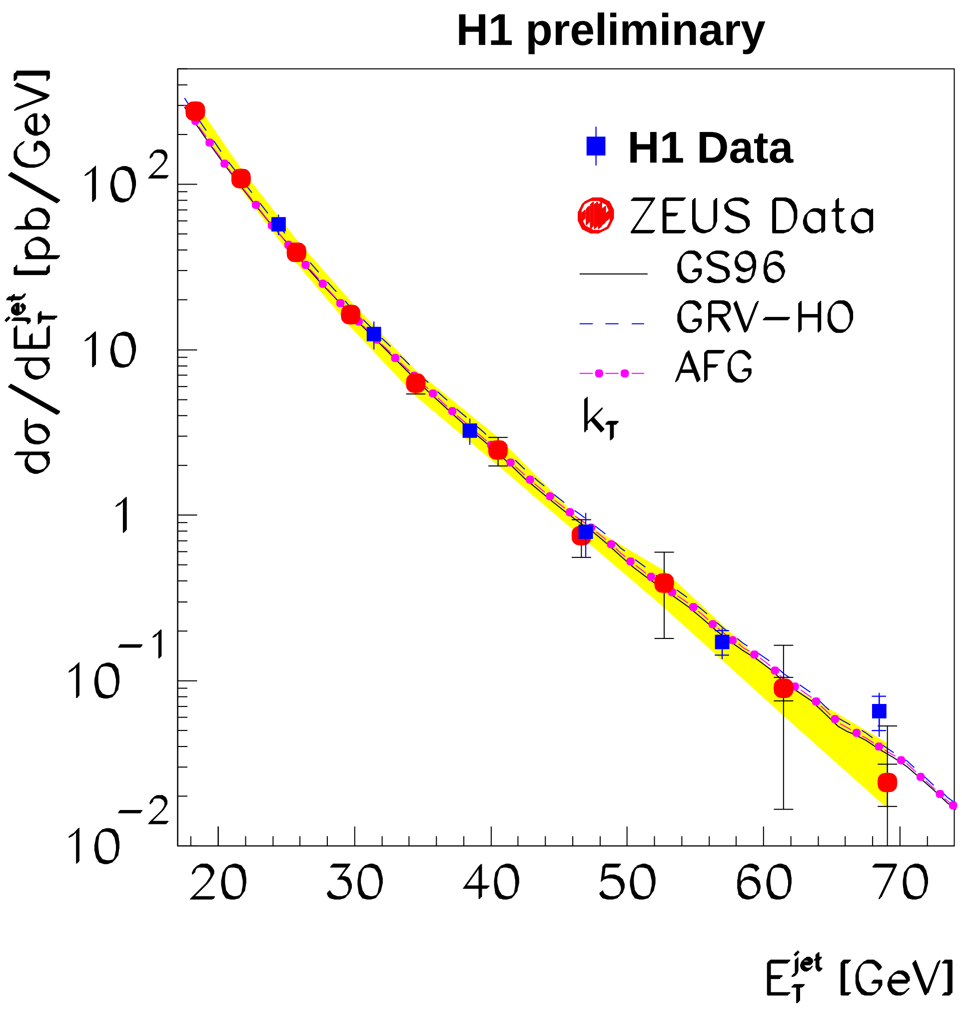


The four jets are converted into three pseudo jets by combining the two jets of lowest two-jet invariant mass.

- θ_3 is the angle between the highest-E_T pseudo-jet and the beam in the four-jet rest frame.
- For low m_{4J}: the inclusion of MPI is able to describe the data. The soft underlying event option (HERWIG) does not work.
- For high m_{4J}: the cross section is less sensitive to MPI.

Inclusive jet photoproduction

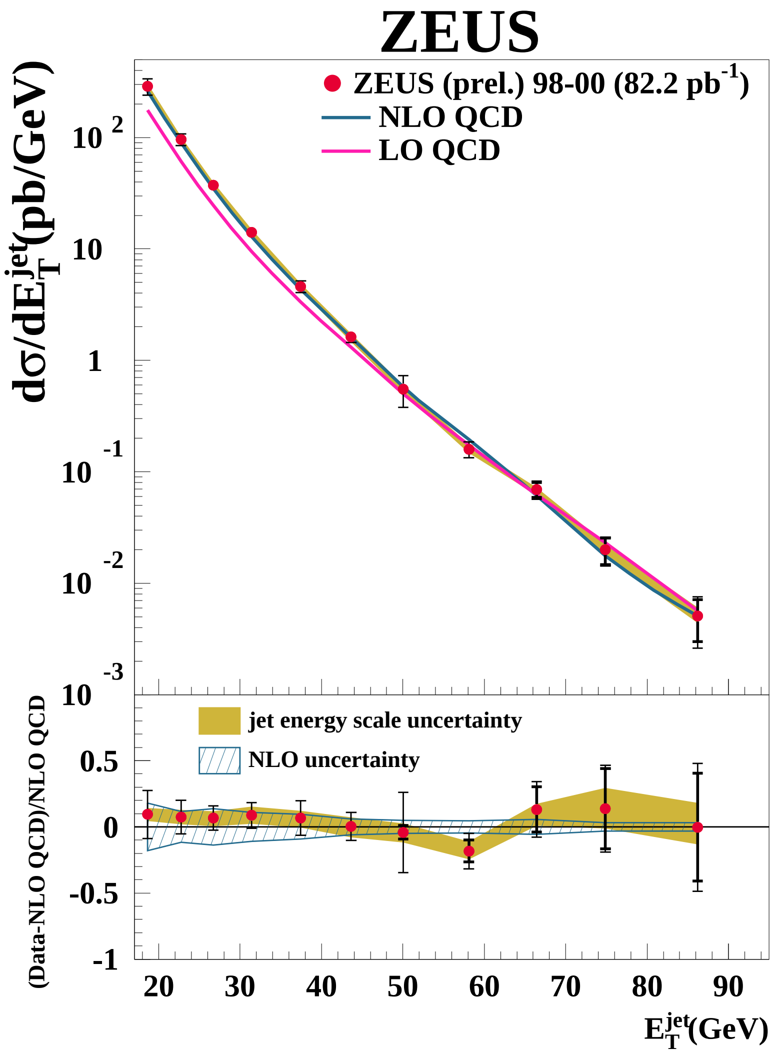
Inclusive jet production allows the performance of additional tests of QCD predictions.



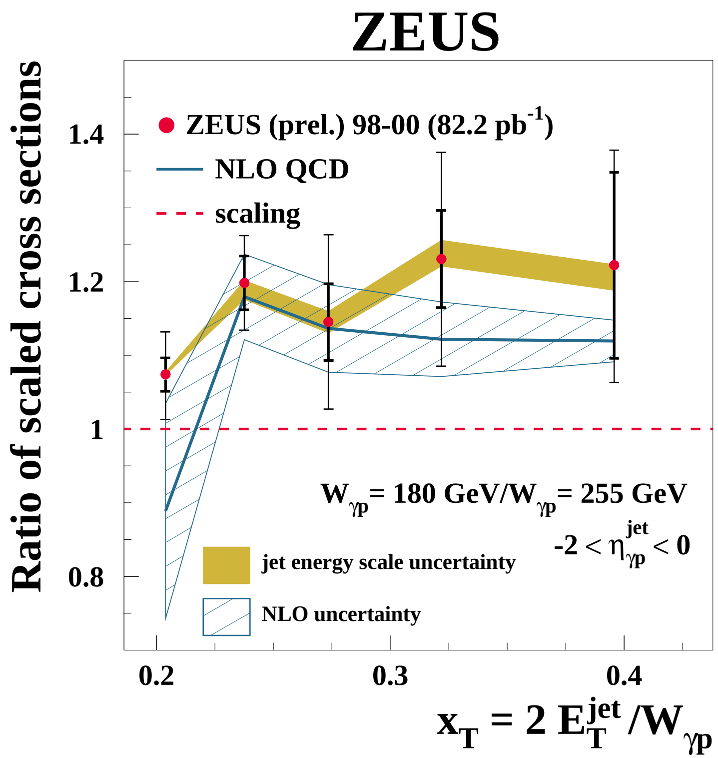
- NLO QCD describes the measurements.
- The theoretical uncertainties are smaller than for dijet production.
- The present experimental and theoretical precision does not allow discrimination between photon PDFs.
- Very good agreement between both H1 and ZEUS (95 data).

Scaling violations in γp interactions

Inclusive jet cross sections at different $W_{\gamma p}$ have been used to test the hypothesis of scaling expected in the Quark-Parton Model.



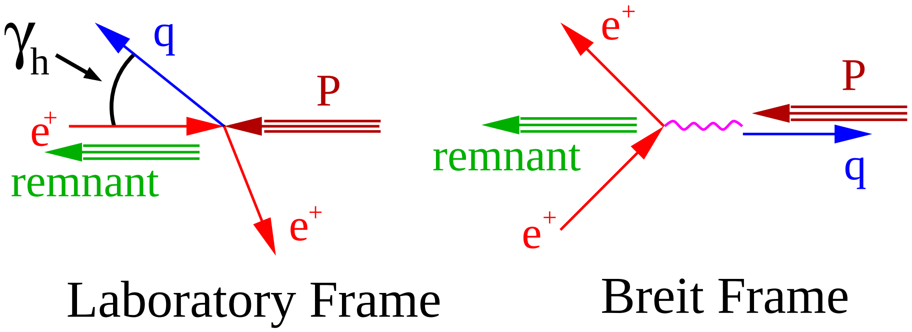
Scaled cross section: $(E_{T,jet})^4 (E_{jet}\, d^3\sigma/d(p_{jet})^3)$



- Scaling hypothesis is discarded (probab. ~ 0.005).
- NLO describes the observed scaling violations.

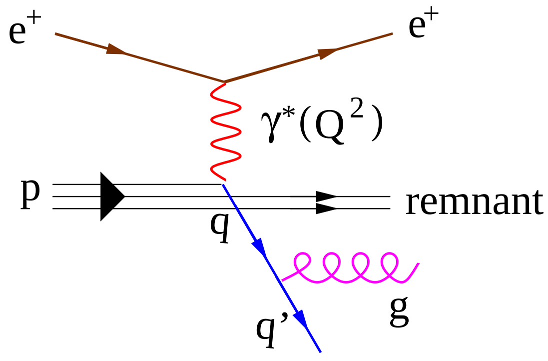
Jet production in DIS

Study of the production of high-E_T jets in the Breit frame allows the test of QCD predictions in deep inelastic scattering.

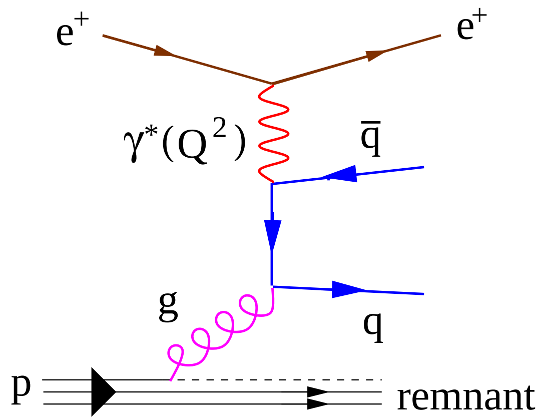


In this frame, production of high transverse energy in the hadronic final state is directly related to hard QCD processes.

At LO QCD jet production in DIS in the Breit frame is given by the processes



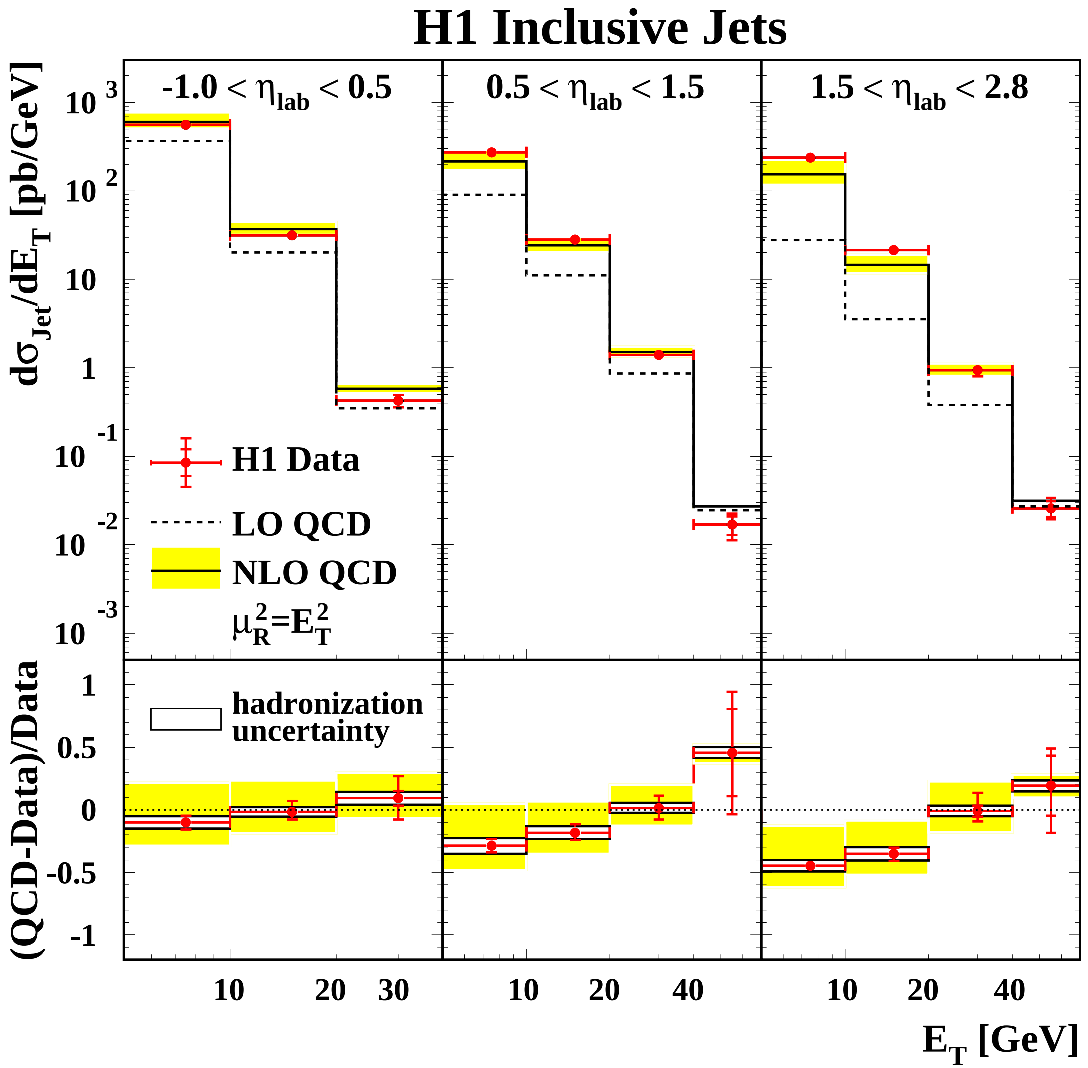
QCD-Compton



Boson-gluon fusion

Inclusive jet cross sections at low Q^2

Study of jet production at low Q^2 to test perturbative QCD



$5 < Q^2 < 100$ GeV^2

→ For backward and central η_{lab}, NLO QCD describes the data.

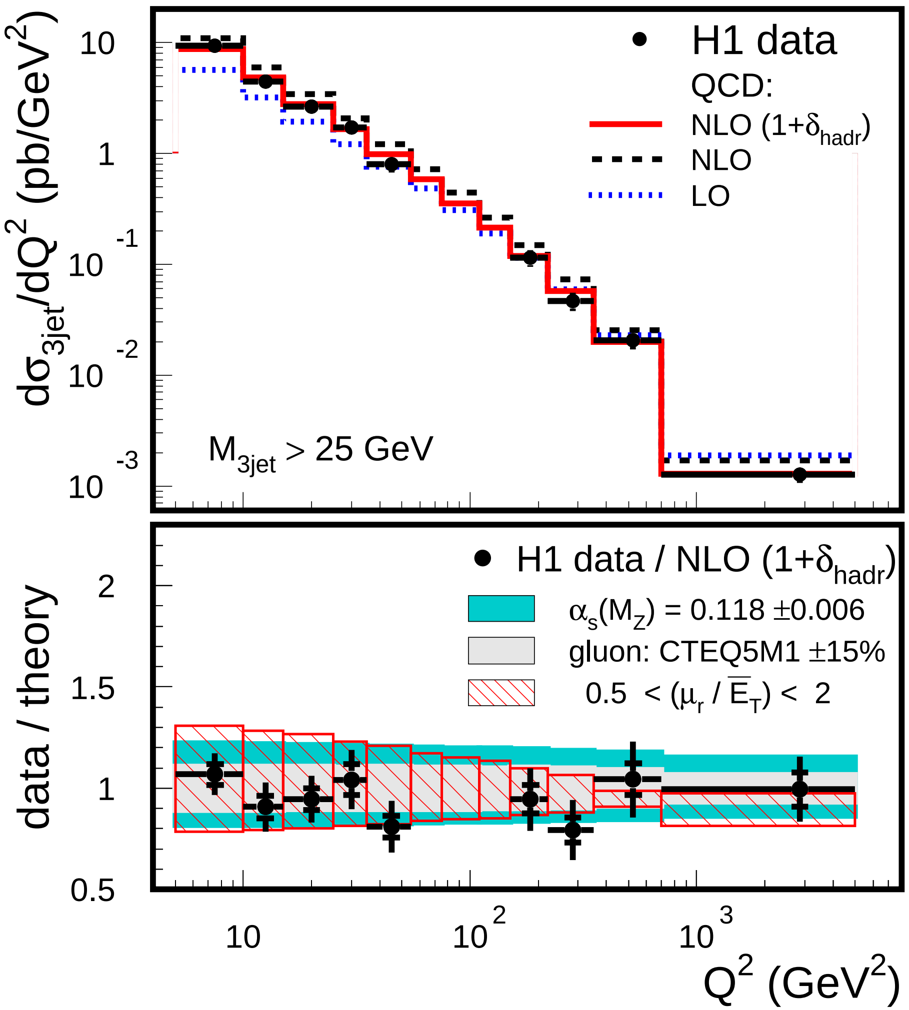
→ NLO corrections are large for low E_T and in the forward region.

→ Theoretical uncertainties are large (20%).

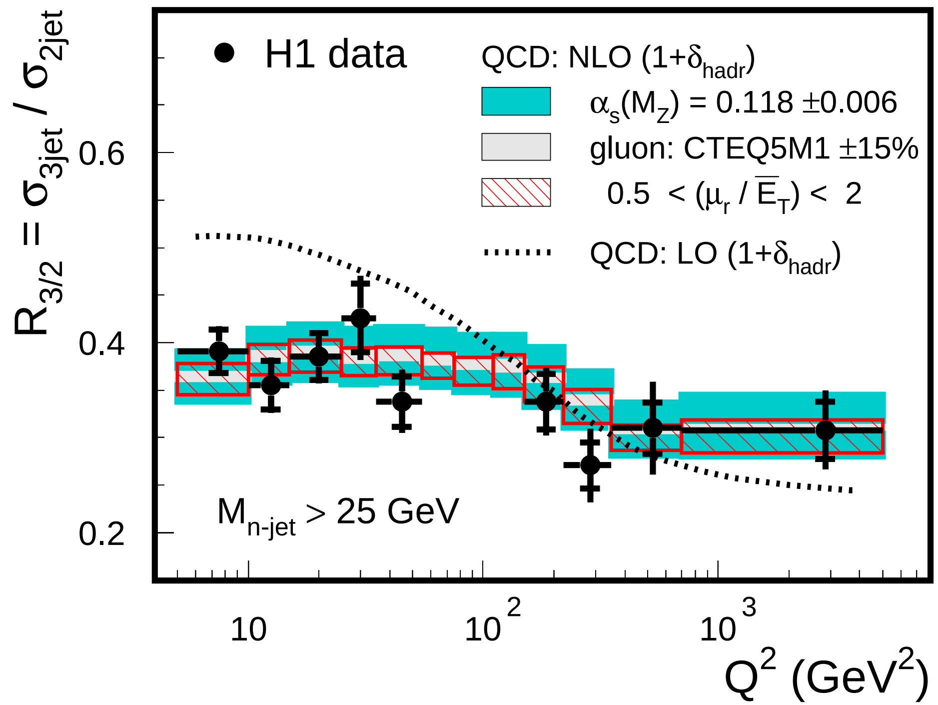
Improvement of calculations is needed to understand low Q^2 and low E_T jet production in DIS.

Three jet production in DIS

Three-jet cross section is well described by NLO QCD, i.e. $\mathcal{O}(\alpha_s^3)$



Ratio of three to two jet cross sections



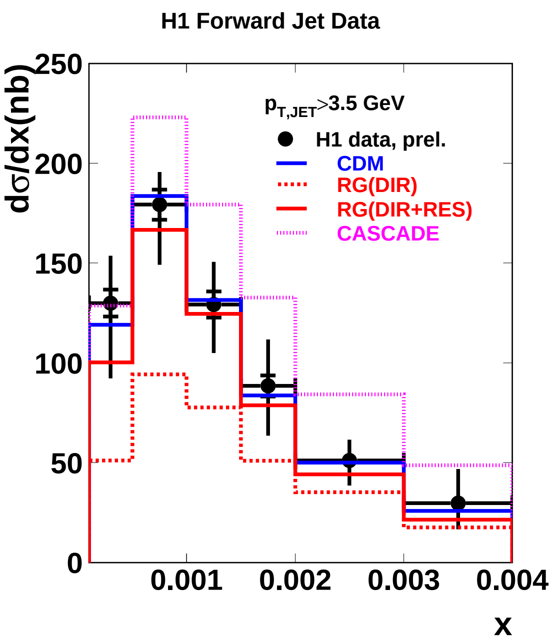
Large NLO correction, but data well described at NLO QCD.

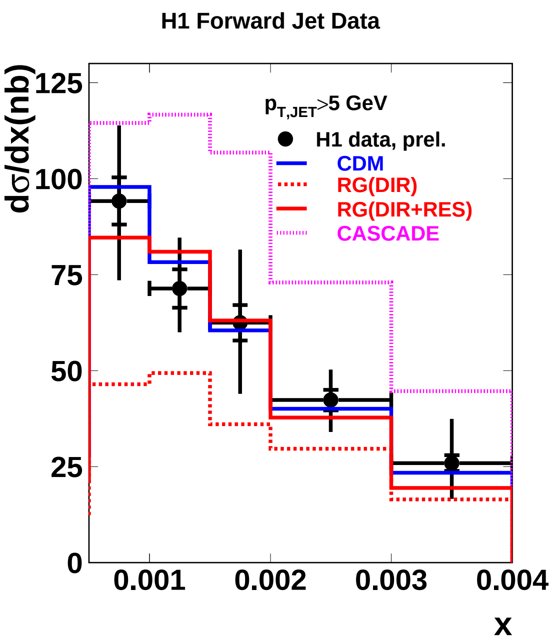
Reduced uncertainties: gluon content, renormalisation scale...

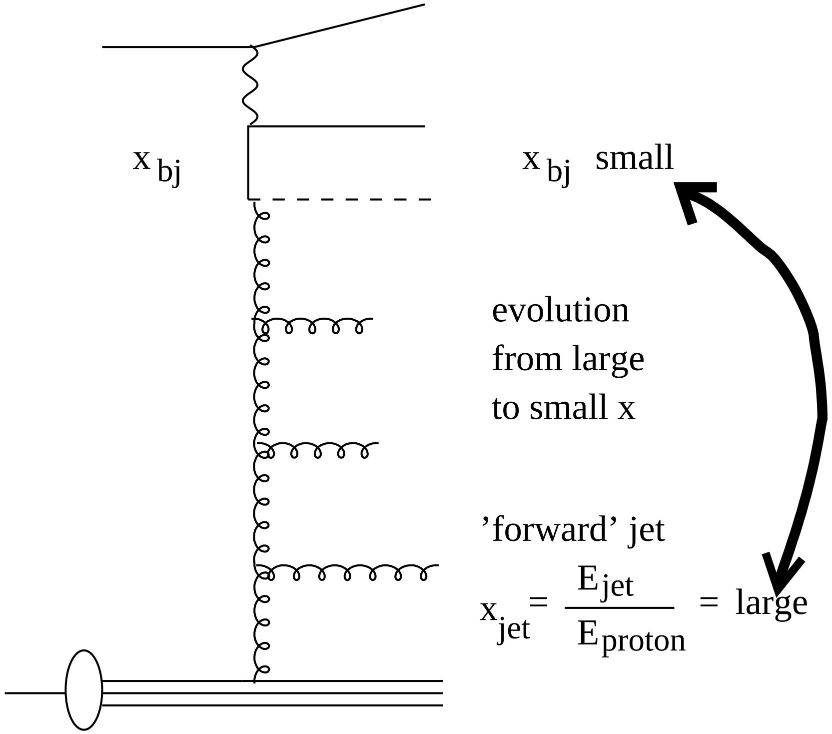
Forward jet production

Sensitive to QCD evolution schemes (specially at low Bjorken x):

- DGLAP (RAPGAP=RG) $\rightarrow$ k_T ordering
- BFKL ($\sim$ ARIADNE=CDM) $\rightarrow$ random walk in k_T
- CCFM (CASCADE) $\rightarrow$ k_T factorisation







- DGLAP needs contribution from resolved virtual photon.
- ARIADNE describes the data.
- CASCADE predicts too high a rate of forward-going jets.

Jet production in DIS and precise tests of QCD

- Studies of jet production in DIS in the Breit frame allows the realisation of precise tests of QCD.
- Big improvement in the knowledge needed to perform QCD studies during the last years:

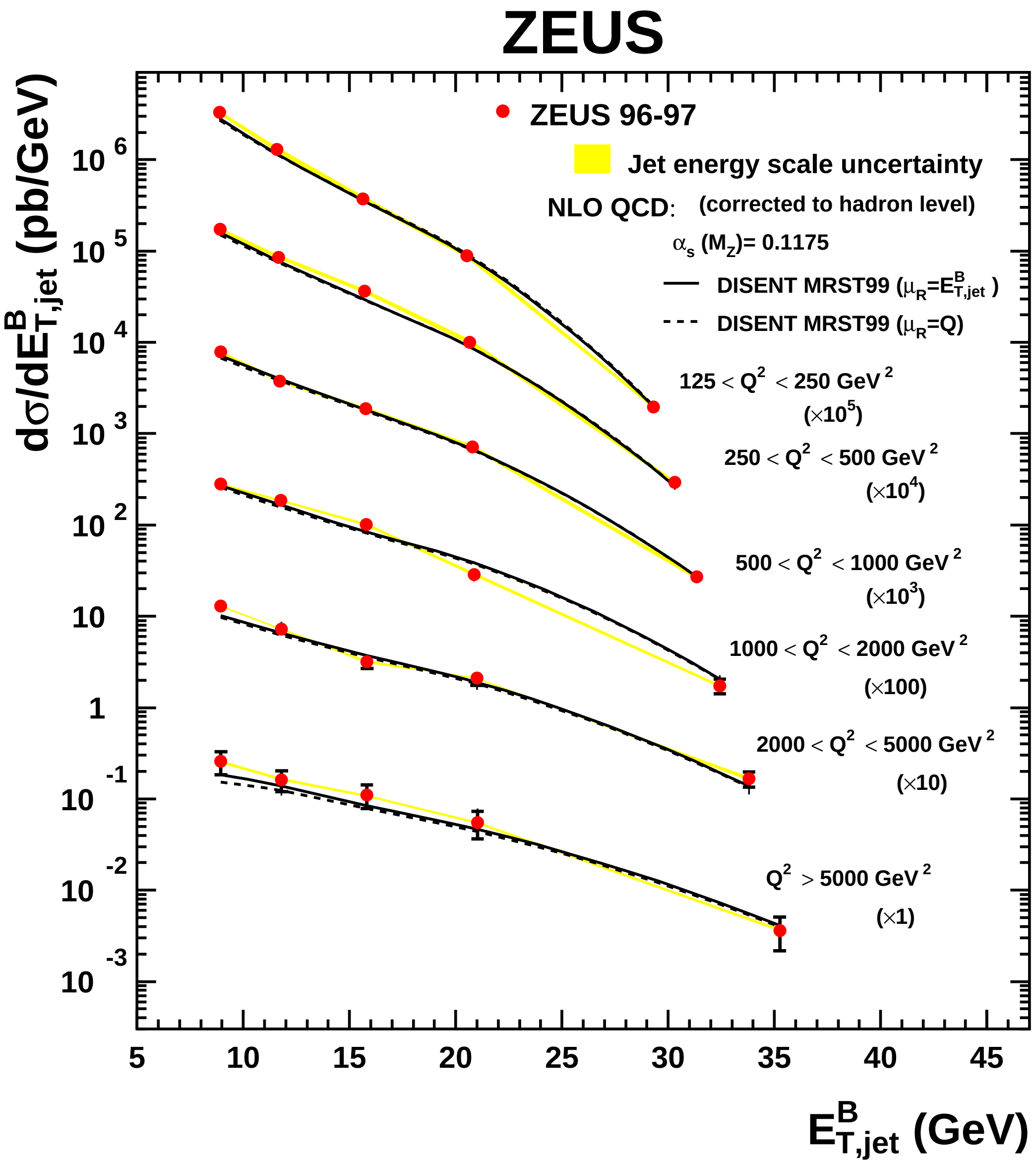
→ Jets are defined in the Breit frame.
- using the k_T cluster algorithm.
- cuts in the Breit frame only (theoretically motivated).

→ Jets produced in the high Q^2 region.
- small uncertainties due to terms beyond NLO.
- small uncertainty in proton PDFs.

→ Inclusive jet production vs dijet production.
- dijet case: additional cuts are needed to remove IR-sensitive regions→ larger theoretical uncertainties.

This knowledge has been translated into precise QCD studies with jets and precise determinations of α_s from jet production at HERA

Inclusive jet production at high Q^2



Inclusive jet cross sections measured with cuts in the Breit frame only

$$Q^2 > 125 \text{ GeV}^2$$

$$E^B_{T,jet} > 8 \text{ GeV} \qquad -2 < \eta^B_{jet} < 1.8$$

Very precise test of QCD predictions.

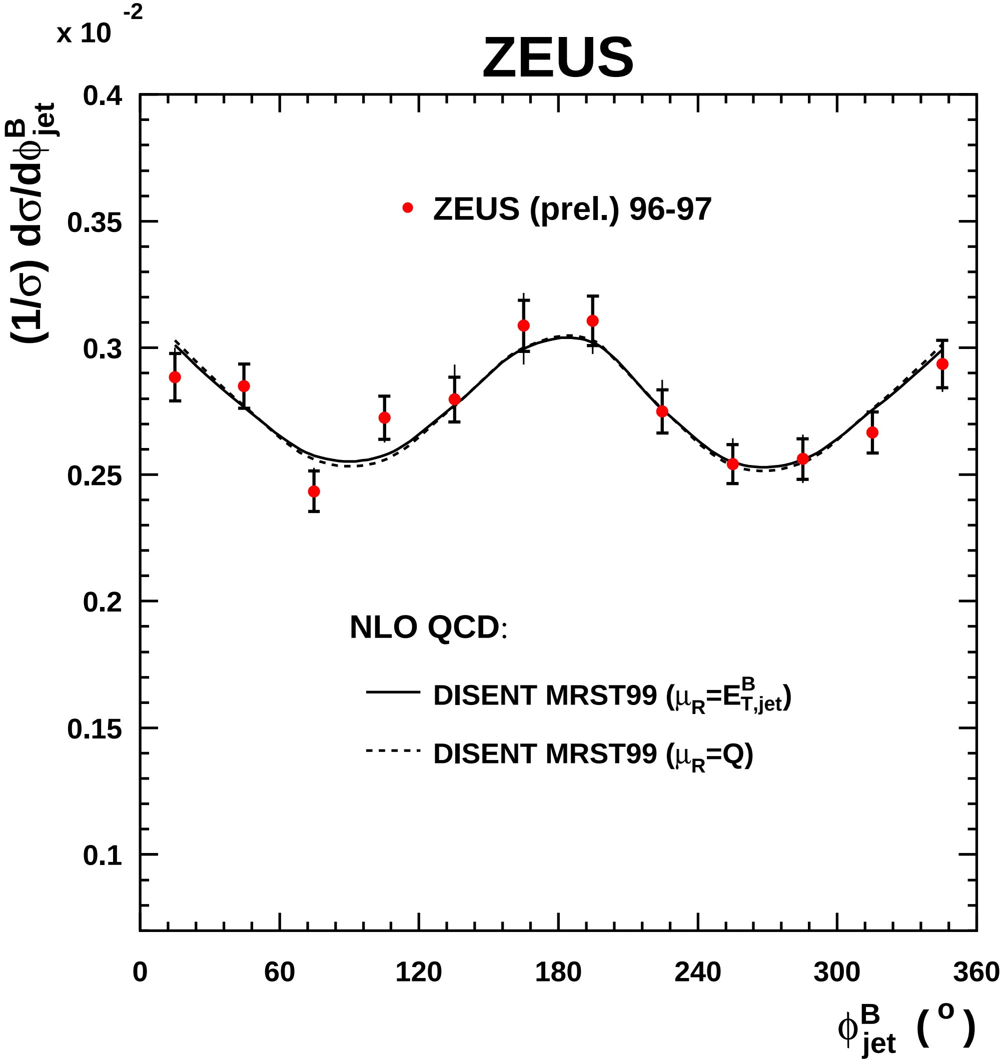
Experimental and theoretical uncertainties: $\sim 10\%$

Agreement ($\sim 10\%$) with NLO QCD prediction over many orders of magnitude in Q^2 and $E^B_{T,jet}$.

Differences of the same order as uncertainties.

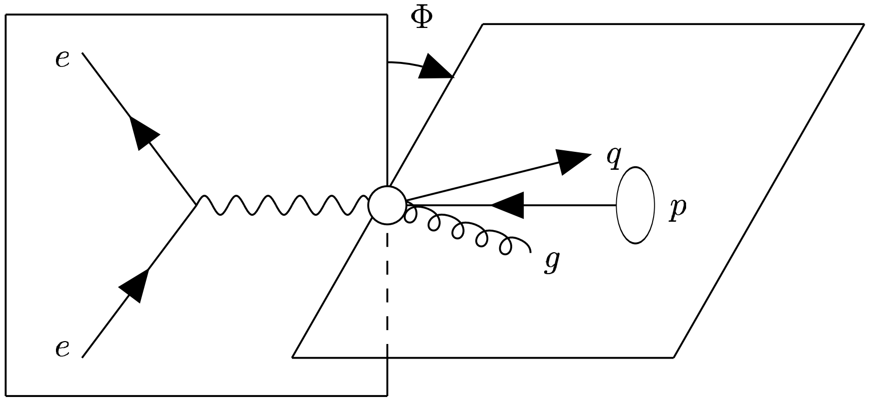
Used to extract α_s

Azimuthal distribution of jets in the Breit frame



Normalised cross section in order to compare the measured and predicted shape of the distribution.

- ϕ^B_{jet} is the angle in the Breit frame of the jet with respect to the positron scattering plane.



- Perturbative QCD predicts

$$\frac{d\sigma}{d\phi^B_{jet}} = A + B\cos\phi^B_{jet} + C\cos 2\phi^B_{jet}$$

- NLO QCD in very good agreement with the data.

HERA data and the running of $\alpha_s(\mu)$

Inclusive and dijet cross sections in the Breit frame were used to extract the value of the strong coupling constant at different scales.

Data in good agreement with the running predicted by QCD

The values extracted from inclusive jet production in DIS:

- H1 ($150 < Q^2 < 5000$ GeV^2):

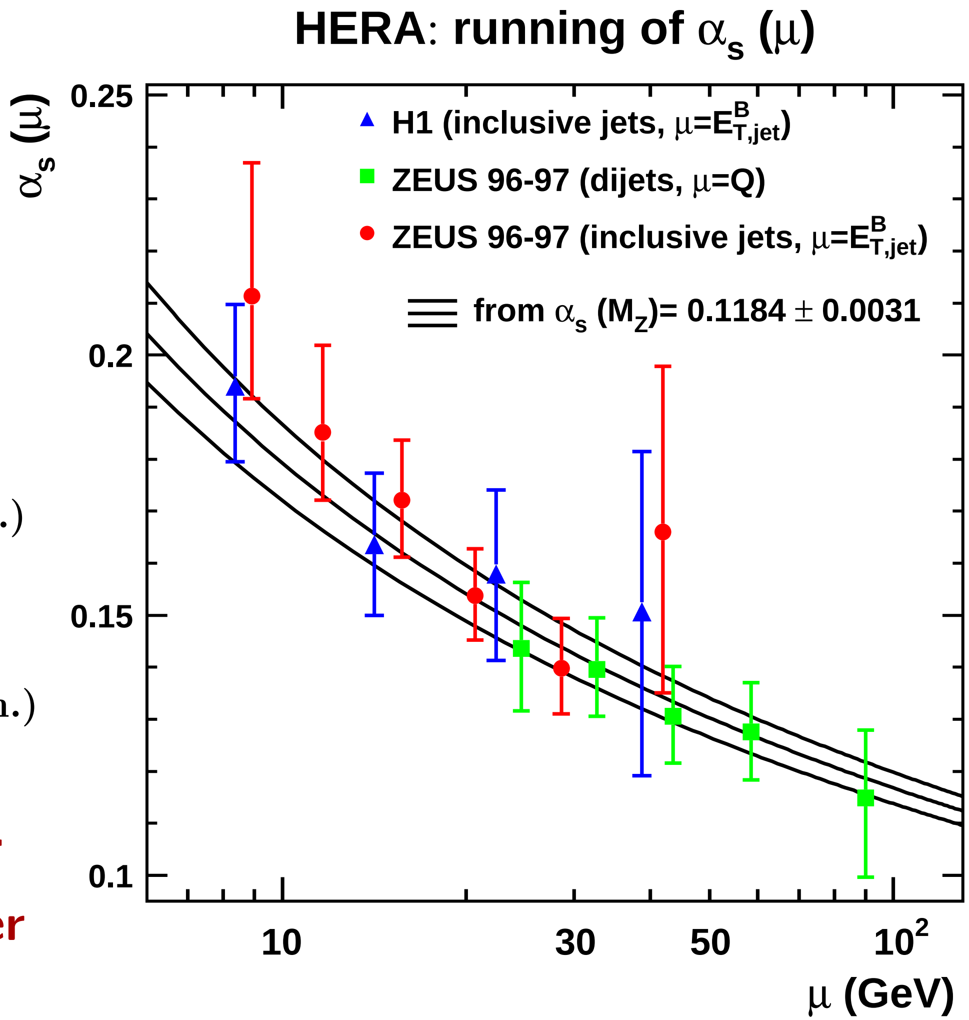
$$\alpha_s(M_Z) = 0.1186 \pm 0.0030\,(\text{exp.})^{+0.0039}_{-0.0045}\,(\text{th.})^{+0.0033}_{-0.0023}\,(\text{pdf.})$$

- ZEUS ($Q^2 > 500$ GeV^2):

$$\alpha_s(M_Z) = 0.1212 \pm 0.0017\,(\text{stat.})^{+0.0023}_{-0.0031}\,(\text{syst.})^{+0.0028}_{-0.0027}\,(\text{th.})$$

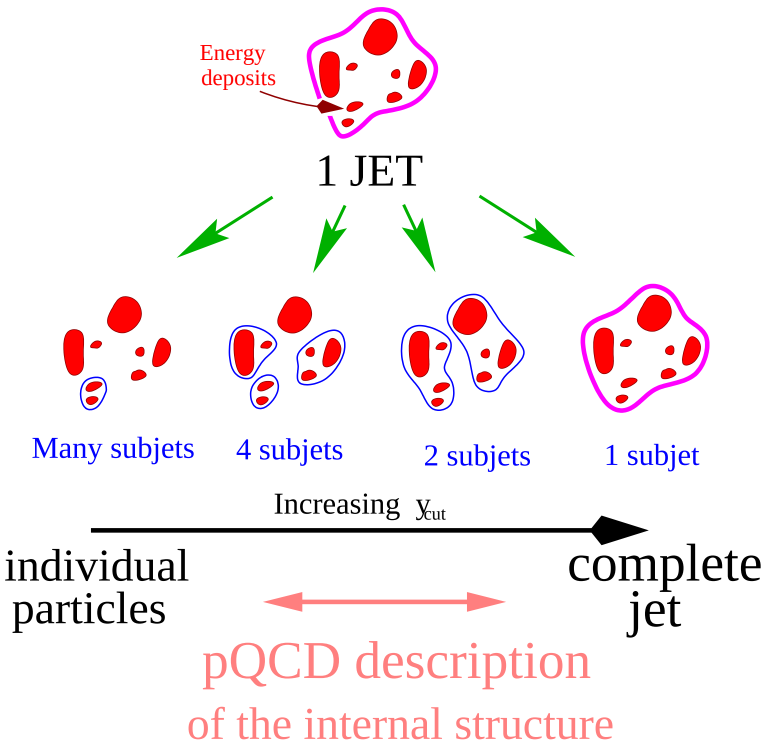
→ Dominated by uncertainty from theory.

→ Precision is comparable with best other individual measurements.



QCD studies using the internal structure of jets

The internal structure of the jets informs in the transition from the partons originating the jets to the observed hadrons.



Jets → partons in the hard process

Subjets → partons in the jet

One simple way to study the internal struture of the jets is by means of the subjet multiplicity.

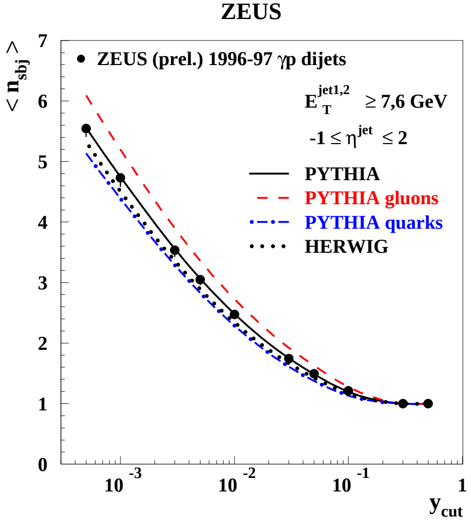
Subjets are jet-like objects within a jet

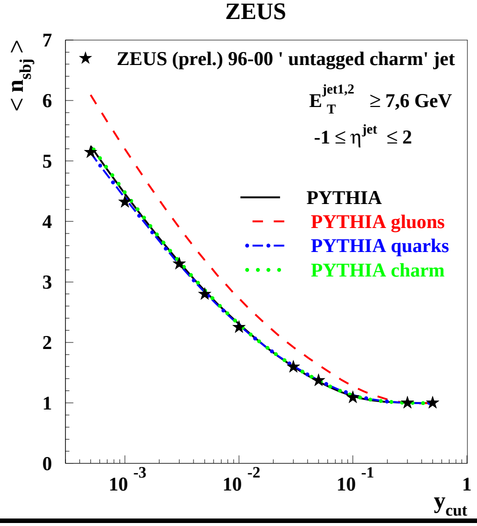
The study of the internal structure of jets allows the performance of QCD studies.

- Differences between quarks and gluons.
- Test of NLO QCD predictions.
- Determination of α_s.

Quark and gluon initiated jets

In QCD it is expected that the jets initiated by gluons have larger multiplicities than those initiated by quarks.

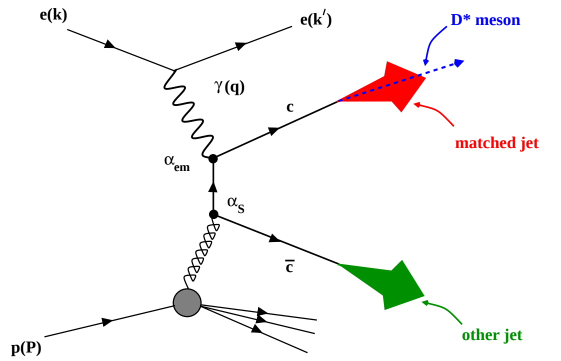




The dijet sample which includes quark and gluon initiated jets is well described by PYTHIA.

PYTHIA predicts different multiplicities for quarks and gluons.

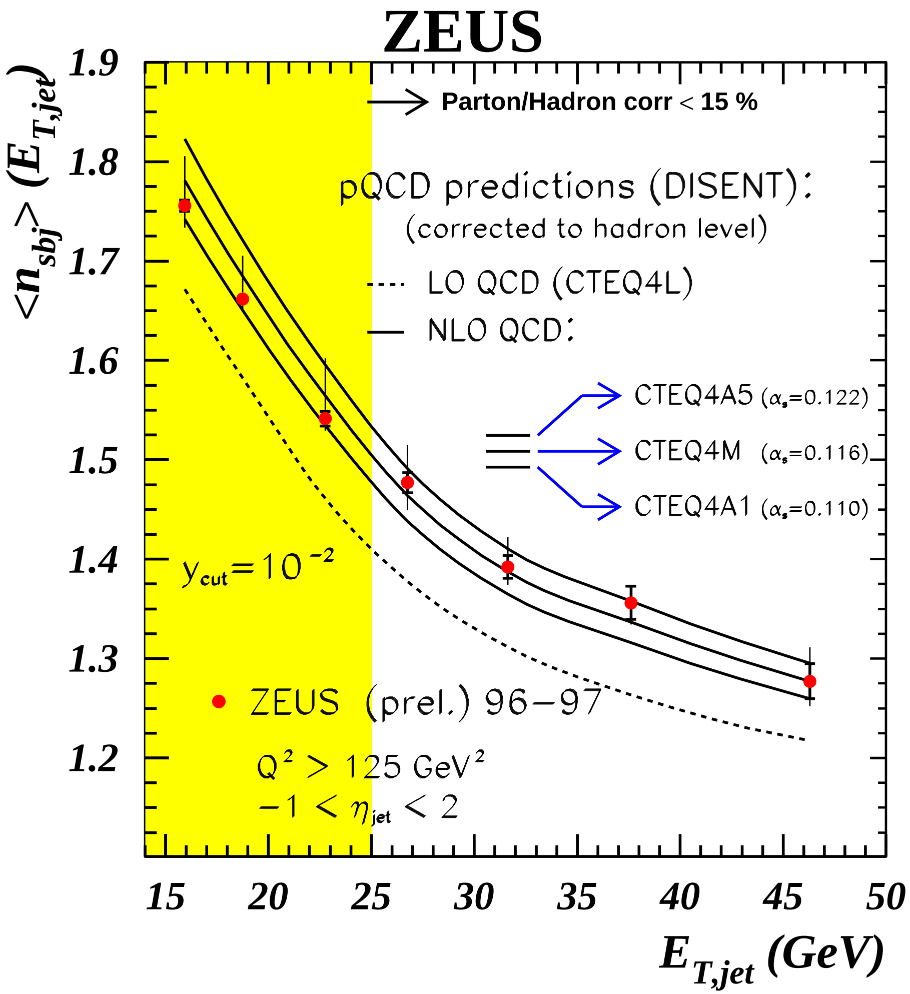
By tagging $c\bar{c}$ dijet events in photoproduction it has been possible to obtain a pure and unbiased sample of quark-initiated jets.



Good agreement between PYTHIA predictions for quarks and the jets opposite to the tagged charm jet.

The internal structure of jets in DIS

NLO QCD predictions for the internal structure of jets are available for jets produced in DIS in the laboratory frame.



Improved comparison with theory

- NLO QCD predictions corrected for hadronisation effects describe the data.
- Sensitivity to α_s.
- Data for $E_{T,jet} > 25$ GeV were used to extract α_s:

$$\alpha_s(M_Z) = 0.1185 \pm 0.0016\,(\text{stat.})^{+0.0067}_{-0.0048}\,(\text{syst.})^{+0.0089}_{-0.0071}\,(\text{th.})$$

Summary

Jet studies at HERA allow very precise tests of QCD predictions.

- The measurements provide:
  - $\longrightarrow$ tests of perturbative QCD beyond LO.
  - $\longrightarrow$ tests of the photon PDFs.
  - $\longrightarrow$ precise determinations of α_s.
- A big effort done in order to reduce the experimental uncertainties
  - $\longrightarrow$ Energy scale uncertainty to 1%.
- In many analyses the uncertainties of the theoretical predictions are limiting the precision of the results.
- Higher orders or resummed calculations are needed.