Jets in deep-inelastic scattering and measurements of α_s

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(On behalf of the H1 and ZEUS collaborations)

- Introduction
- Measurements
  - Inclusive jet cross sections
  - Dijet cross sections
  - 3-jet cross sections
  - Subjet multiplicities
- Measurements of α_s and extraction of the gluon density
- Summary and conclusions

Introduction

DIS jet cross section:

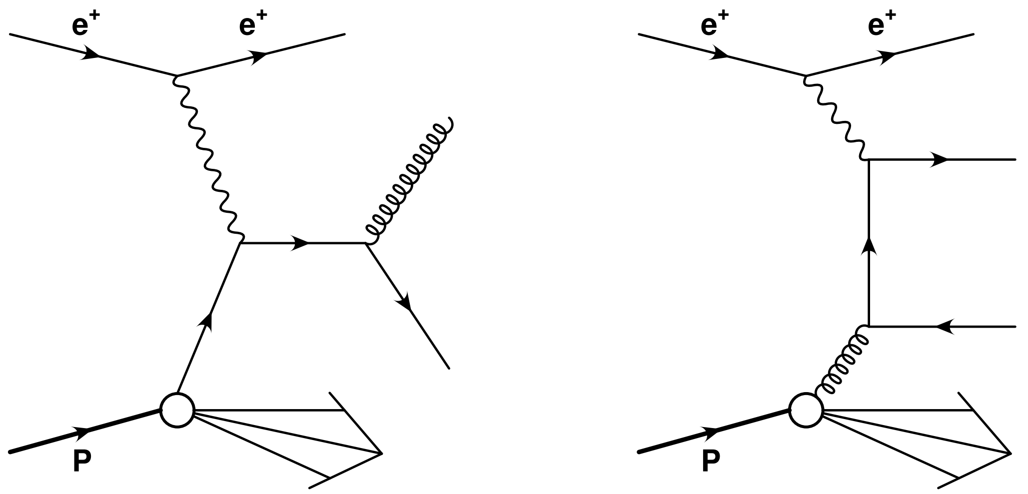
$$d\sigma = \sum_{a=q,\bar{q},g} \int dx\; f_a(x,\mu_F^2)\; d\hat{\sigma}_a(x,\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2)$$

convolution of:

short distance cross section, $d\hat{\sigma}_a(x,\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2)$

parton densities in the proton, $f_a(x,\mu_F^2)$

Order α_S processes:



Simple process and expression $\Rightarrow$ simple extraction of fundamental physics?

What is of interest?

Measuring DIS jet cross sections $\Rightarrow$

- Test pQCD calculations
- New measurements of strong coupling constant, α_s
- Constraining the parton (in particular gluon) density in the proton

Issues in the measurements $\Rightarrow$

- Expect more reliable predictions at high Q^2; how reliable?
- We have two "natural" scales in the event; Q^2 and E_T^2. Variation by factor 4 is always the dominant theoretical uncertainty
- Test "safe" region using DGLAP formalism. Any deviations come from BFKL?
- Measurements of DIS at HERA start at $Q^2 \sim 1\ \mathrm{GeV}^2$; what is the effect of the resolved photon?

What do measurements of jets in DIS add to our understanding?

Inclusive jets

- Consider "safe" region for precise test of QCD and extraction of α_s

$$Q^2 > 125\mathrm{GeV}^2, \quad -0.7 < \cos\gamma_h < 0.5$$

$$E_{T,\mathrm{B}}^{\mathrm{jet}} > 8\ \mathrm{GeV}, \quad -2 < \eta_{\mathrm{B}}^{\mathrm{jet}} < 1.8$$

  – Precise tests of pQCD

  – Extraction of α_s

- Look at low Q^2 and forward region

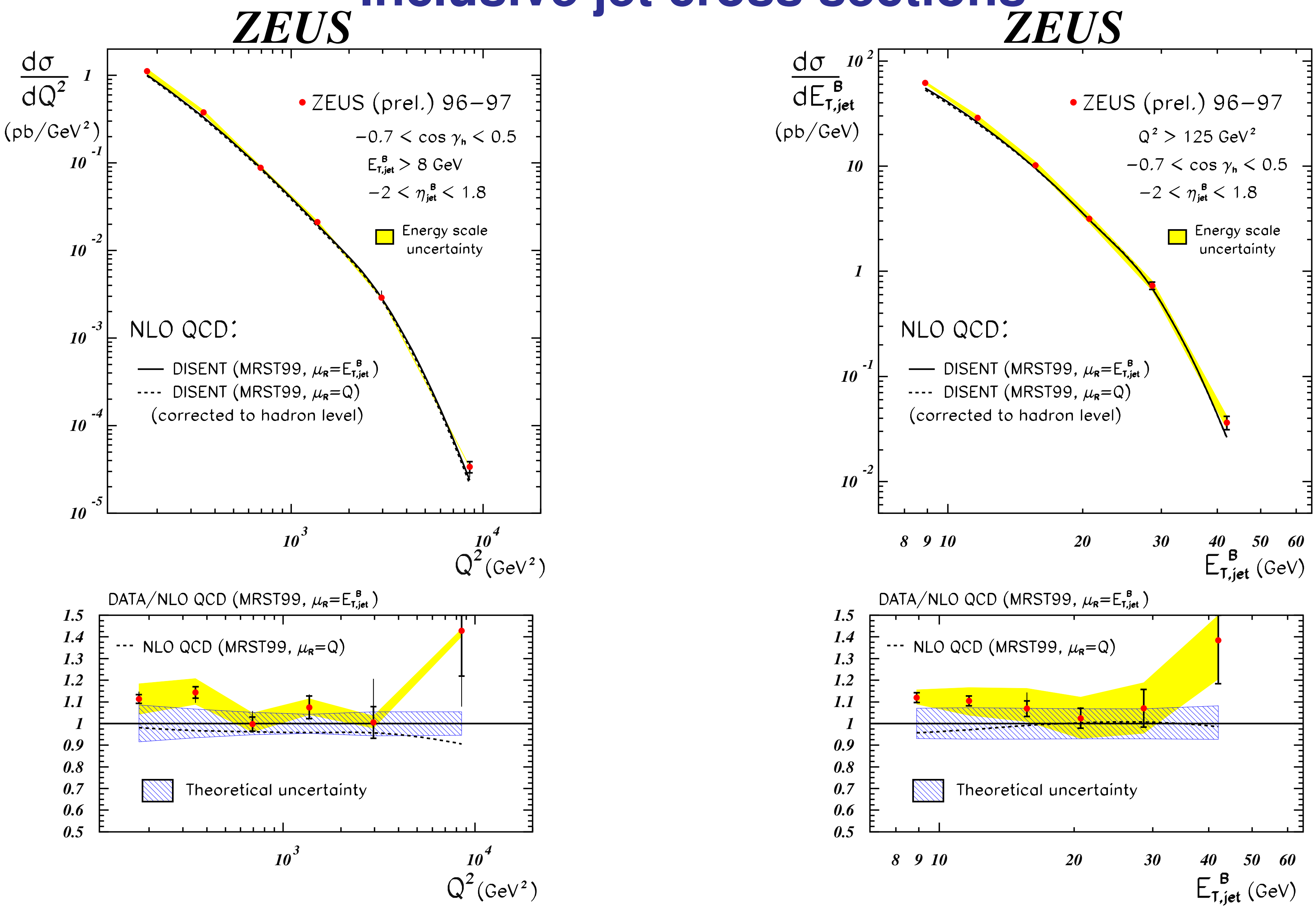
$$5 < Q^2 < 100\mathrm{GeV}^2, \quad 0.2 < y < 0.6$$

$$E_{T,\mathrm{B}}^{\mathrm{jet}} > 5\ \mathrm{GeV}, \quad -1 < \eta_{\mathrm{LAB}}^{\mathrm{jet}} < 2.8$$

  – Sensitivity to BFKL effects?

  – Need for a resolved photon?

Inclusive jet cross sections



NLO gives reasonable description of data

Extract α_s at high Q^2 (> 500 GeV^2)

Azimuthal cross section

ϕ **is the angle between the lepton scattering plane and the jet production plane**

- **QCD predicts:**

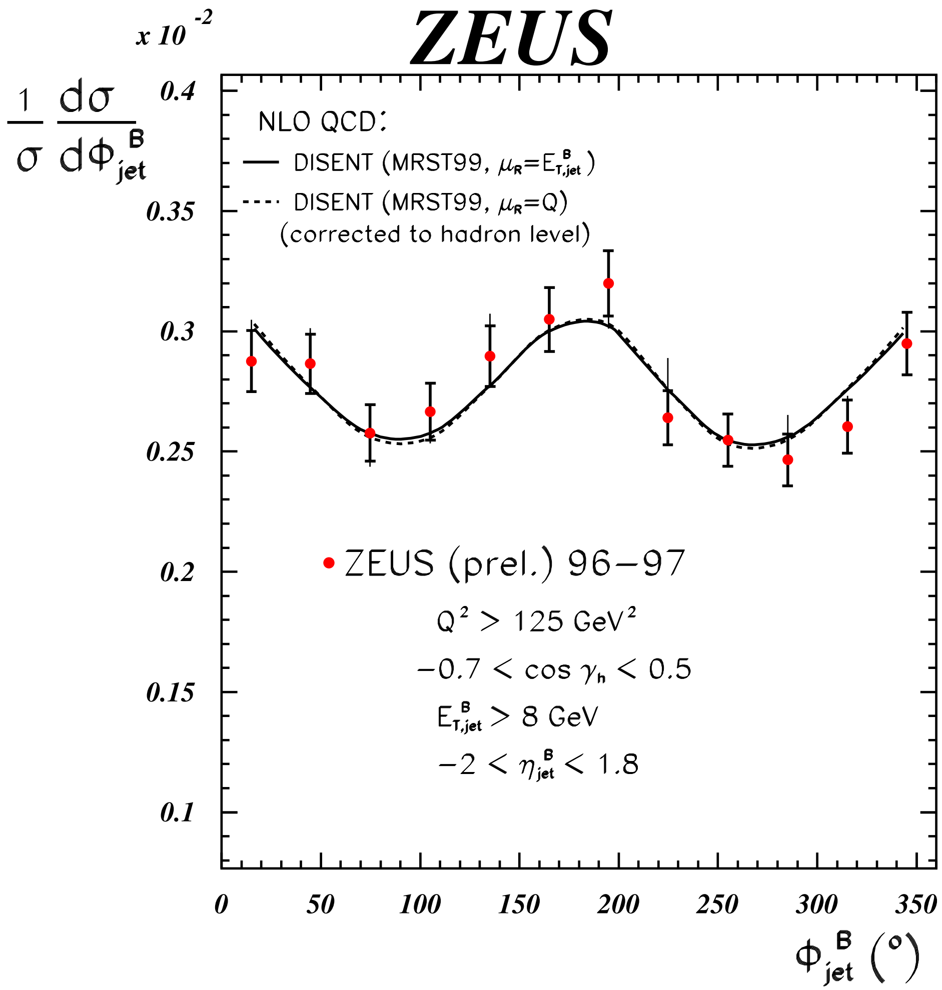
$$\frac{d\sigma}{d\phi} = A + B\cos\phi + C\cos 2\phi$$

- **Effect has been seen in charged hadron production in DIS**

- **No tagging of quark/gluon jets, form is:**

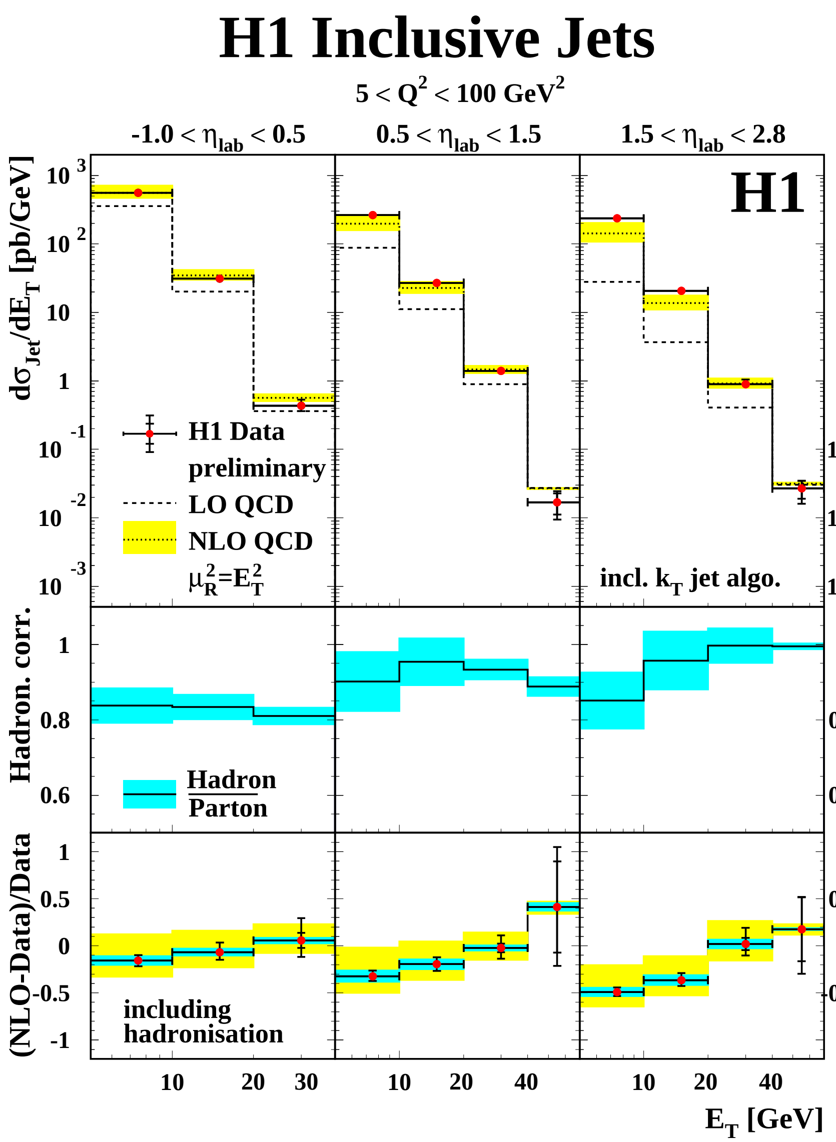
$$\frac{d\sigma}{d\phi} \sim A + C\cos 2\phi$$

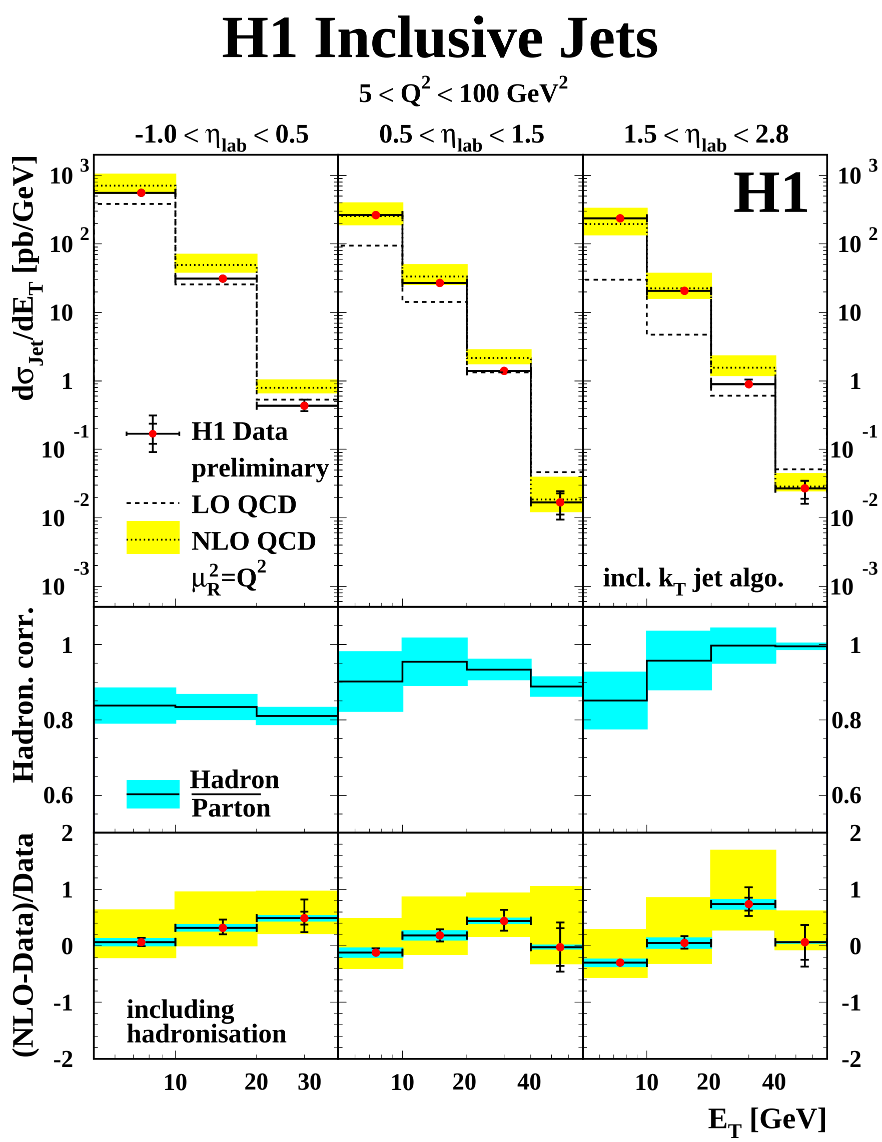
- **Cross section normalised for shape comparison**



First observation of azimuthal asymmetry in NC DIS jet production

Forward jet cross sections

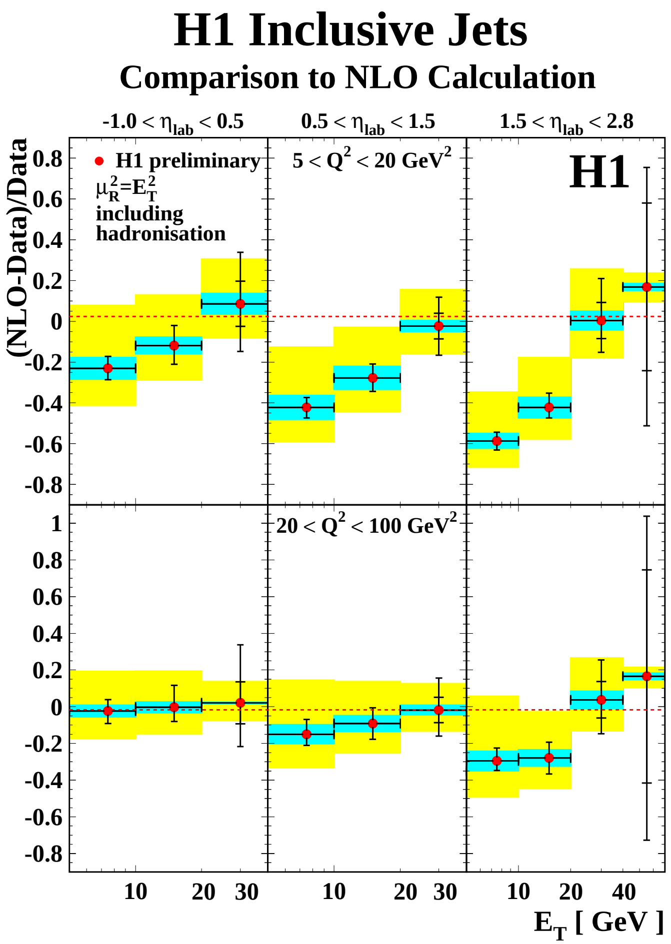


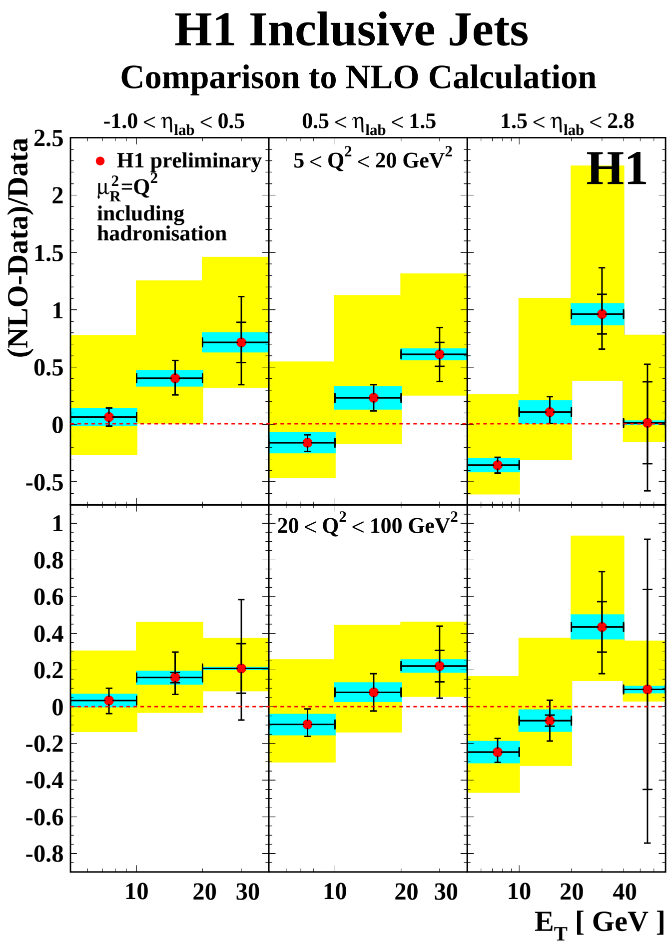


LO $\rightarrow$ NLO K-factors $\sim$ 10 at low E_T and forward η_{LAB}

QCD generally describes the data, however theoretical errors are large

Forward jet cross section ratios





NLO describes data at higher Q^2.

Description becomes worse at low Q^2, low E_T^{jet} and forward η^{jet}.

Data and NLO have difference in shape.

But the errors are large.

Need more precise calculations

Low Q^2 dijet production

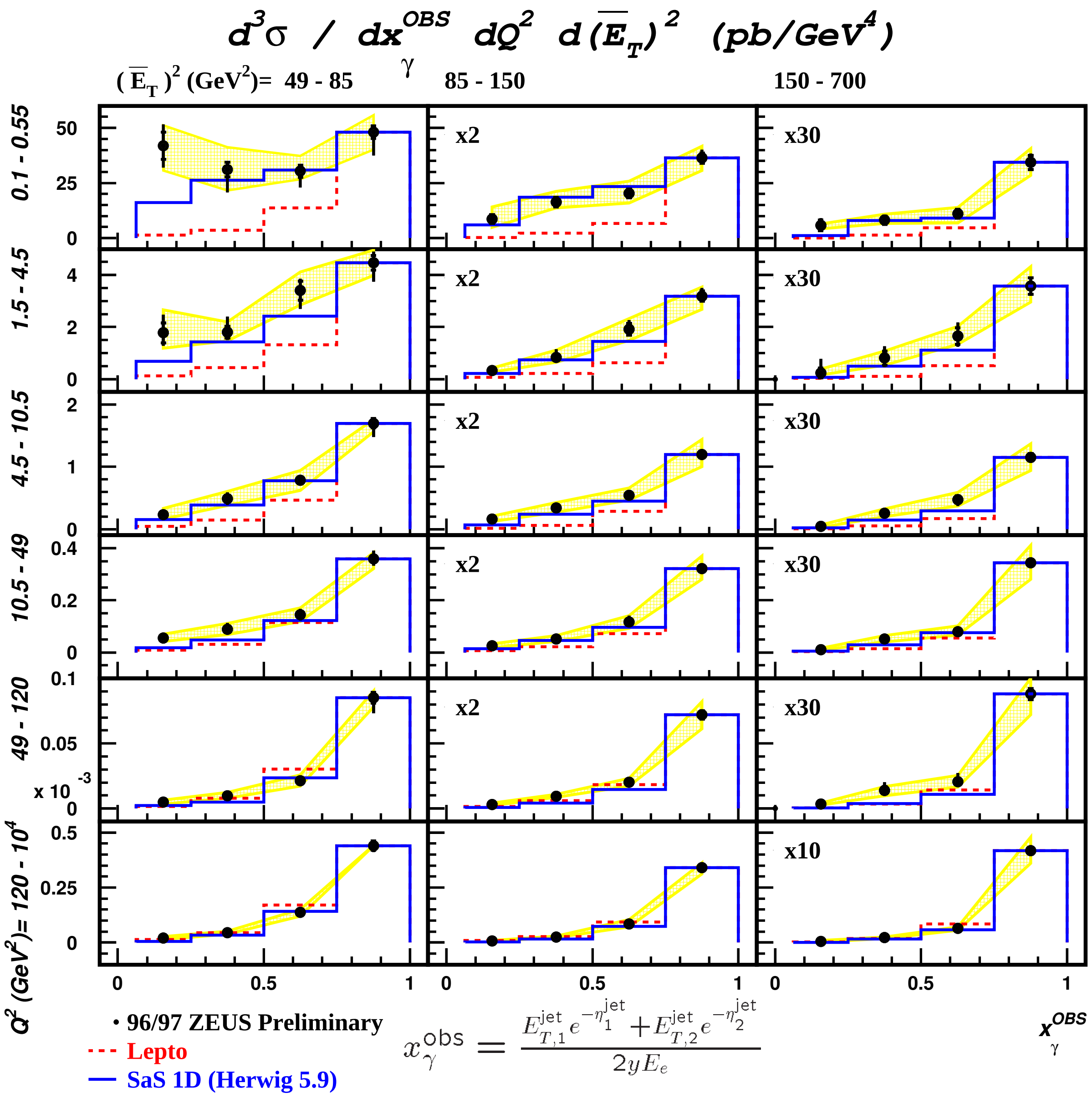
LO analysis shows need for resolved photon at low Q^2

Description when using a resolved photon is also not adequate

Resolved component becomes negligible in range $Q^2 > 10 - 50\ \mathrm{GeV}^2$

For $Q^2 > 100\ \mathrm{GeV}^2$, region for DIS is free from these uncertainties.

Need NLO comparison.



$$x_\gamma^{\text{obs}} = \frac{E_{T,1}^{\text{jet}} e^{-\eta_1^{\text{jet}}} + E_{T,2}^{\text{jet}} e^{-\eta_2^{\text{jet}}}}{2yE_e}$$

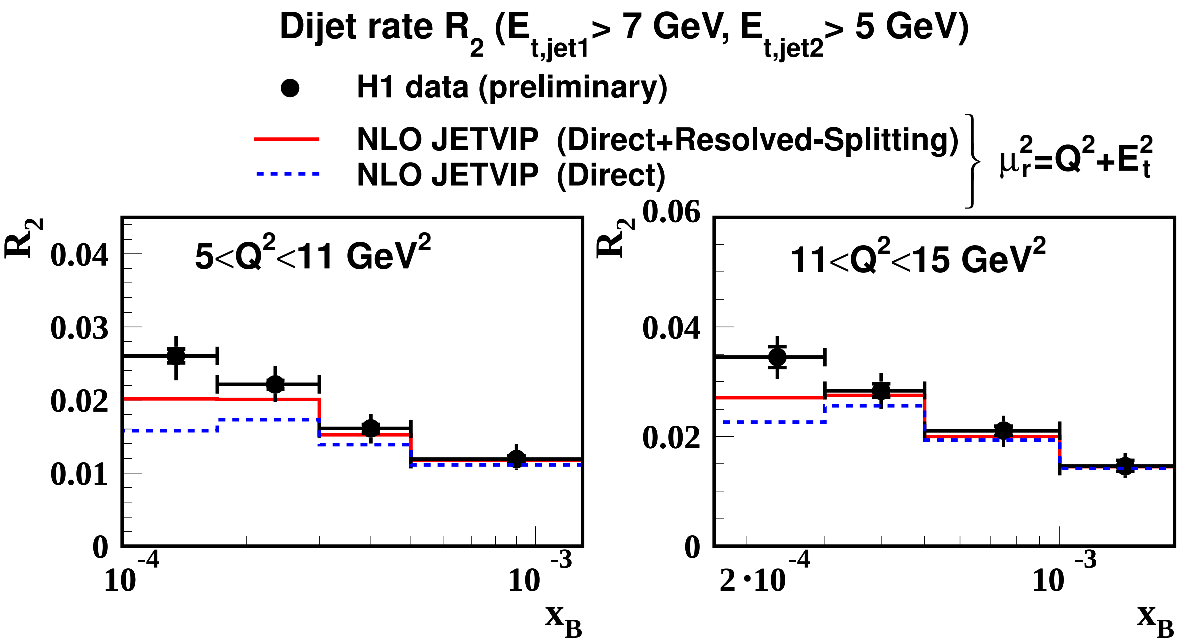
Dijet rate at low Q^2

Like inclusive data,

- $\mu_R^2 = Q^2 + E_T^2$ **undershoots dijets rate.**
- $\mu_R^2 = Q^2$**, describes the data with large error.**

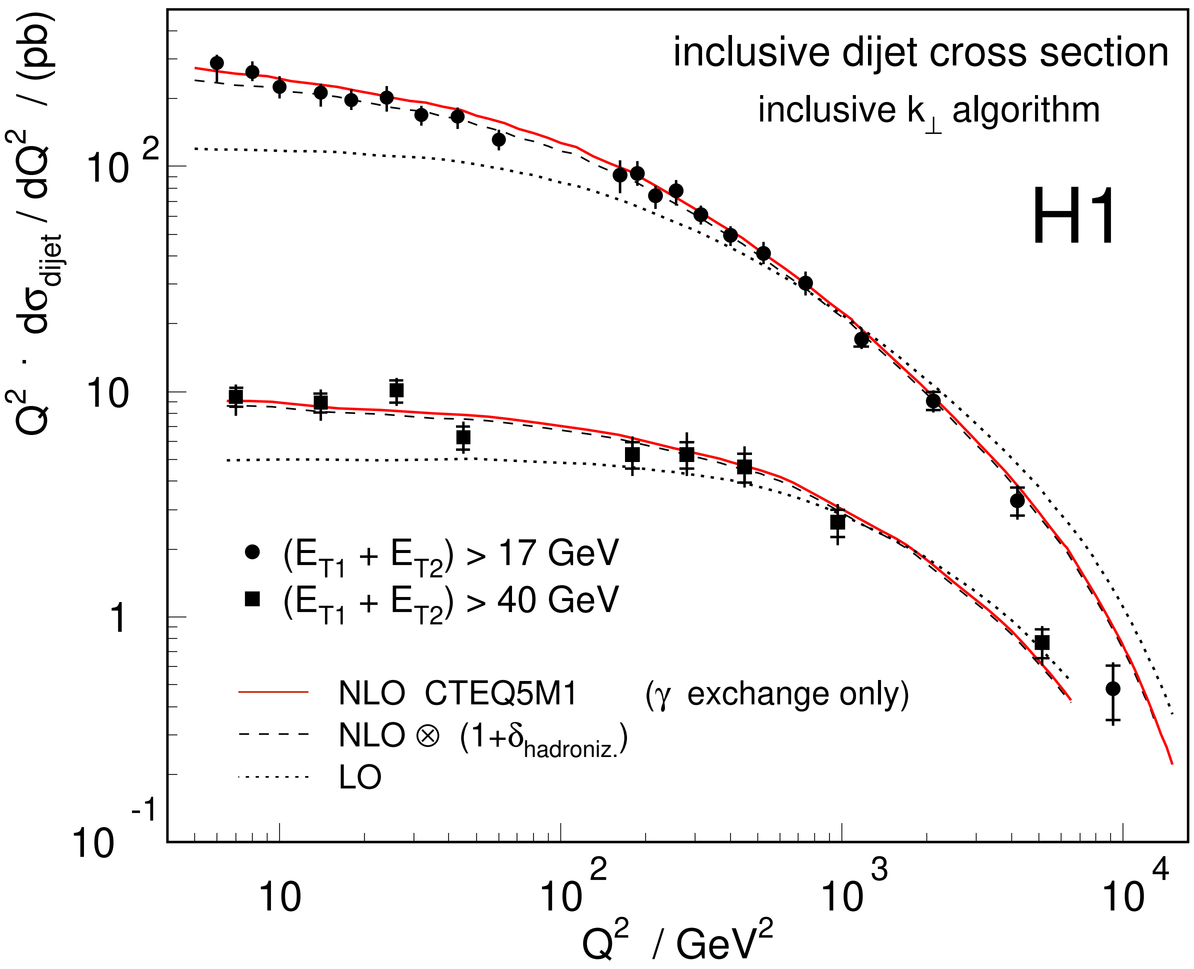
Does the resolved photon play a rôle at this low Q^2?

Using JetViP gives a better description of the data.



Go to higher Q^2 for extraction of fundamental parameters

Dijet cross sections



$E_{T,\mathrm{B}}^{\mathrm{jet}} > 5$ **GeV,** $-1 < \eta_{\mathrm{LAB}}^{\mathrm{jet}} < 2.5$

Good description of data over range $5 < Q^2 < 15000$ GeV^2**.**

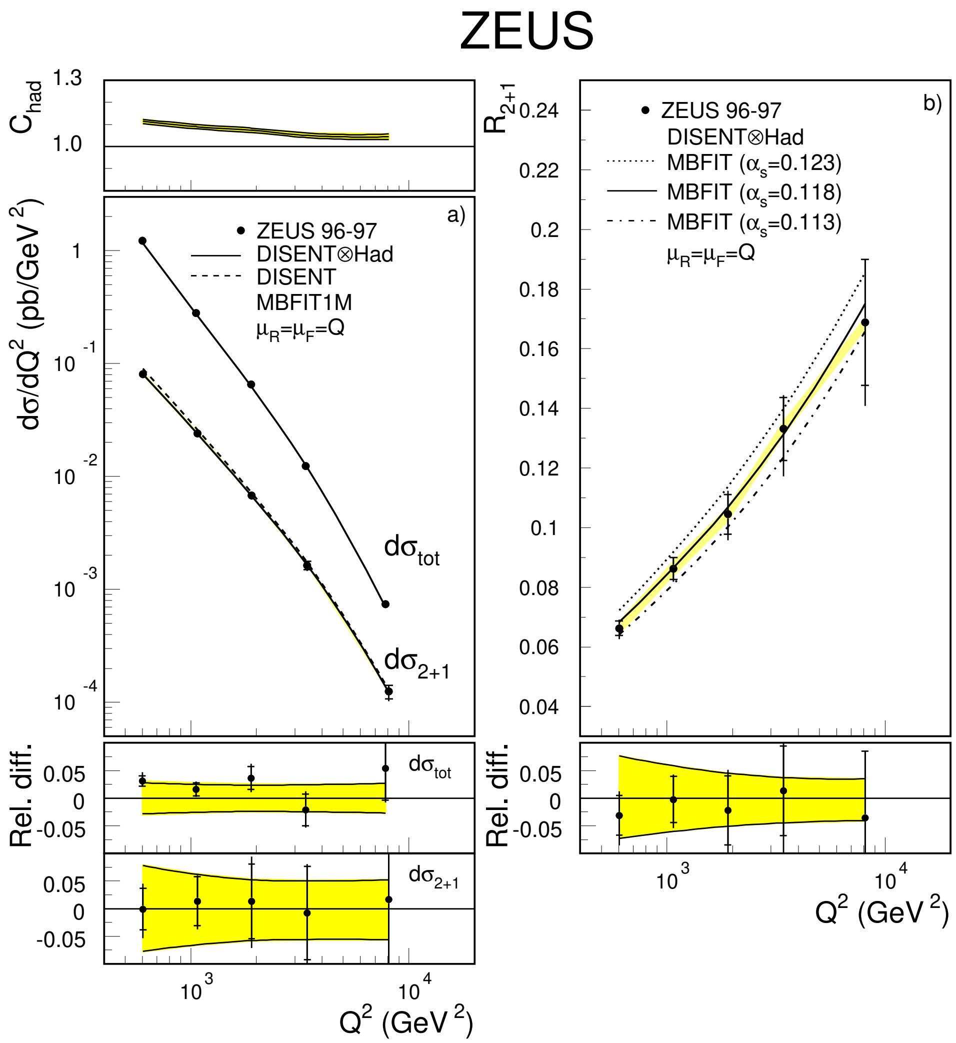
NLO K-factor is large at low Q^2**.**

Scale error decreases with increasing Q^2

Data and NLO both scale similarly with $E_{T,1} + E_{T,2}$**.**

Overall NLO reproduces measured cross sections in all variables

Dijet rate at high Q^2



Theory gives a good description of data:

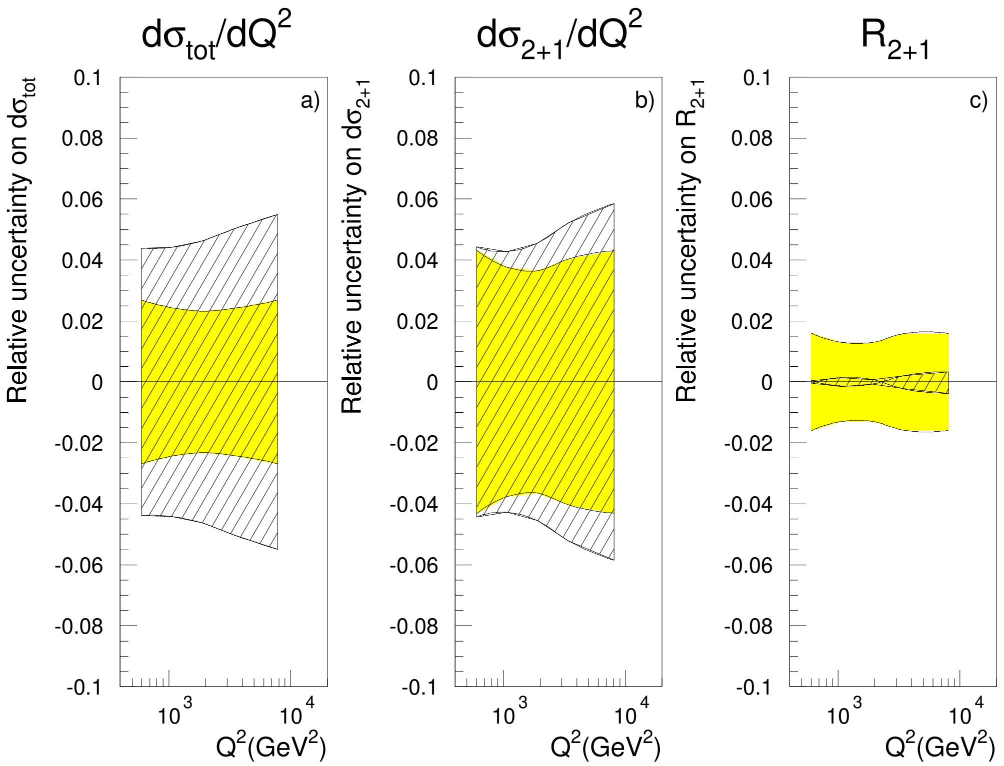
- **No need for BFKL effects, resolved photon.**
- **Much reduced theoretical error.**

Ratio, R_{2+1}, is a good variable to measure:

- **Sensitivity to α_s.**
- **Experimental uncertainties cancel.**
- **Reduced sensitivity to the PDFs.**

Perform QCD fit to extract α_s, including full PDF uncertainty

PDF uncertainties



Yellow - with correlation

Hatched - without correlation

Estimated using M. Botje's EPDFLIB (EPJ C14 (2000) 285)

Statistical and systematic uncertainties of each data set used in MBFIT are fully propagated.

Additional PDF sets provided to quantify theoretical uncertainties.

Uncertainty 1.5% on R_{2+1}.

Demonstration of power of measuring the ratio

Measurement of three jets

More complex final state $\rightarrow$ more stringent test of pQCD.

Measure ratio of cross sections for three jets and two jets:

- **As with dijet to total cross section ratio, expect cancellation of some experimental and PDF related uncertainties.**

- **Opportunity to extract α_s.**

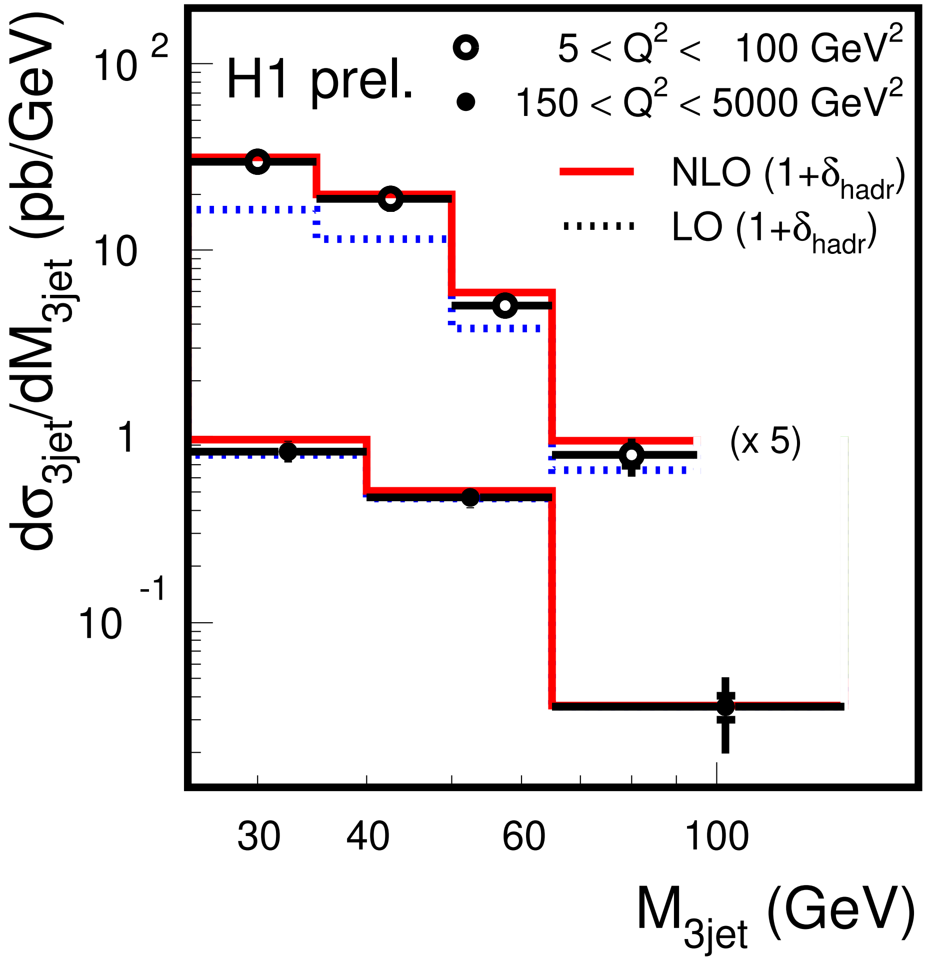
New NLO three jet calculation: Z. Nagy, Z. Trócsányi, `hep-ph/0104315`

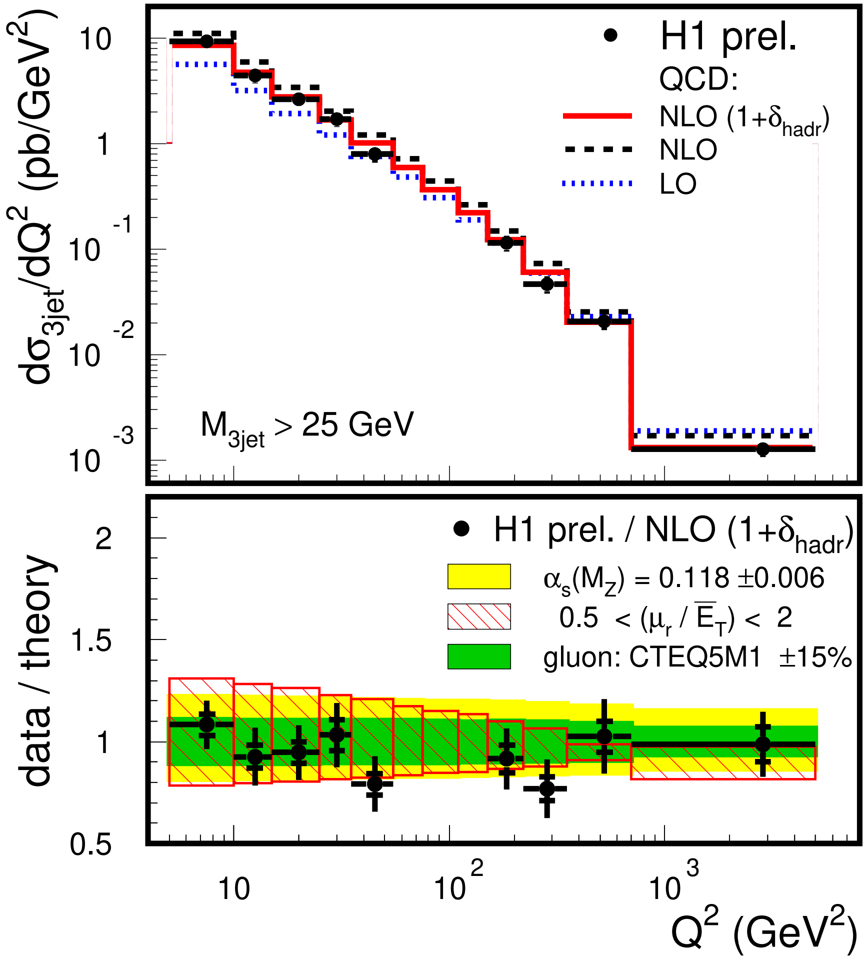
Phase space of analysis:

$$5 < Q^2 < 5000\ \mathrm{GeV}^2, \quad 0.2 < y < 0.6$$

$$-1 < \eta^{\mathrm{jet}}_{\mathrm{LAB}} < 2.5, \quad E^{\mathrm{jet}}_{T,\mathrm{B}} > 5\ \mathrm{GeV}, \quad M_{3-\mathrm{jet}} > 25\ \mathrm{GeV}$$

Three jet cross sections





Very good agreement over whole kinematic region

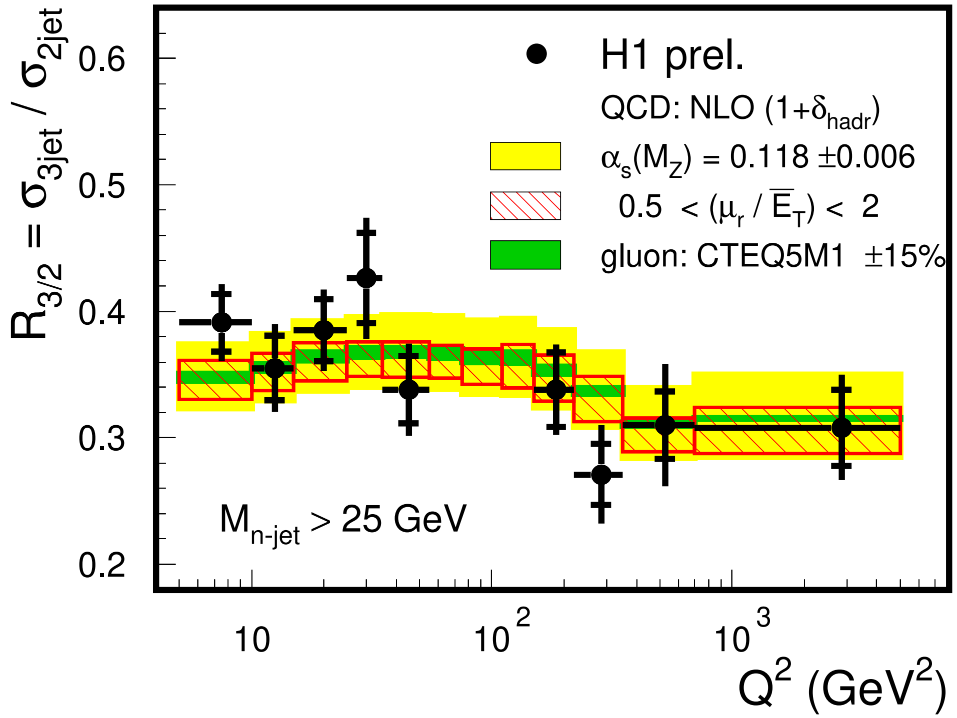
Angular and energy fraction variables also well described by NLO (and LO)

Small renormalisation scale uncertainty

Ratio of three jet and two jet cross sections, $R_{3/2}$

Same cut on the invariant mass, $M_{\mathrm{n-jet}} > 25$ GeV

- **Good agreement between NLO and data**
- **Effect of gluon in the proton reduced**
- **Small renormalisation scale uncertainty**

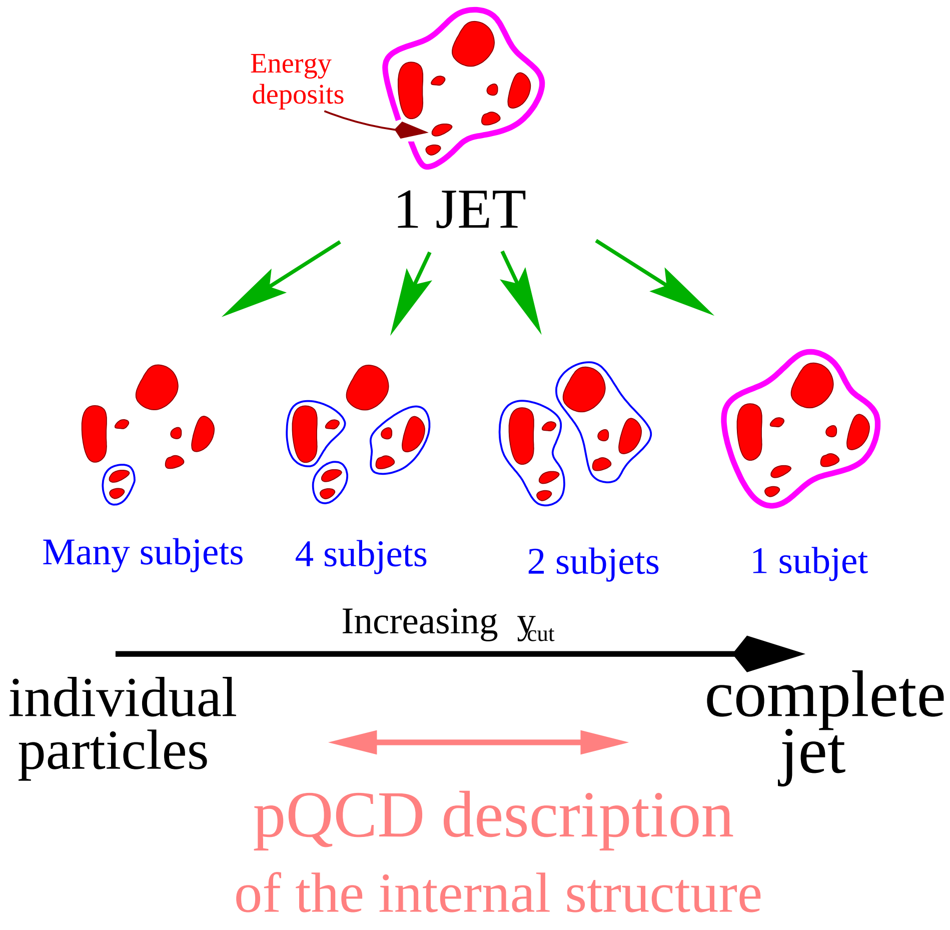


New NLO calculation agrees well with the data

Measurement has potential for accurate extraction of α_s

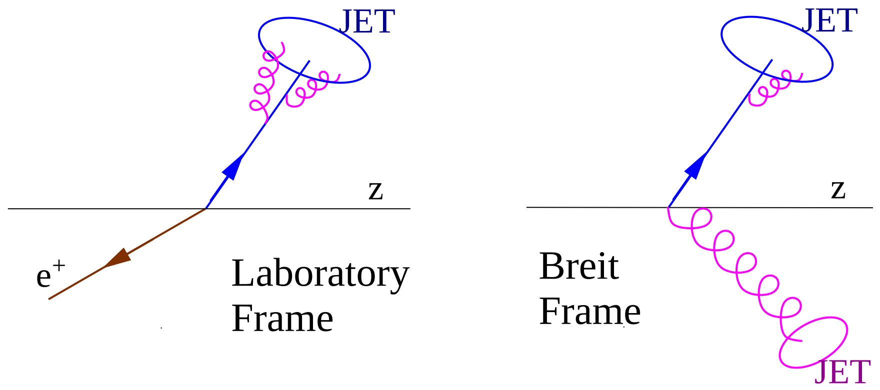
Subjet multiplicities

In the k_T algorithm subjets are resolved by successively combining pairs of particles within the jet and reapplying the algorithm for different values of the "resolution scale", $y_{\rm cut}$, such that $d_{ij} > d_{\rm cut} = y_{\rm cut} \cdot \left(E_T^{\rm jet}\right)^2$



Compare to NLO and extract α_s

Jets defined in the laboratory frame
$\Rightarrow$ possible 3 partons in a jet.

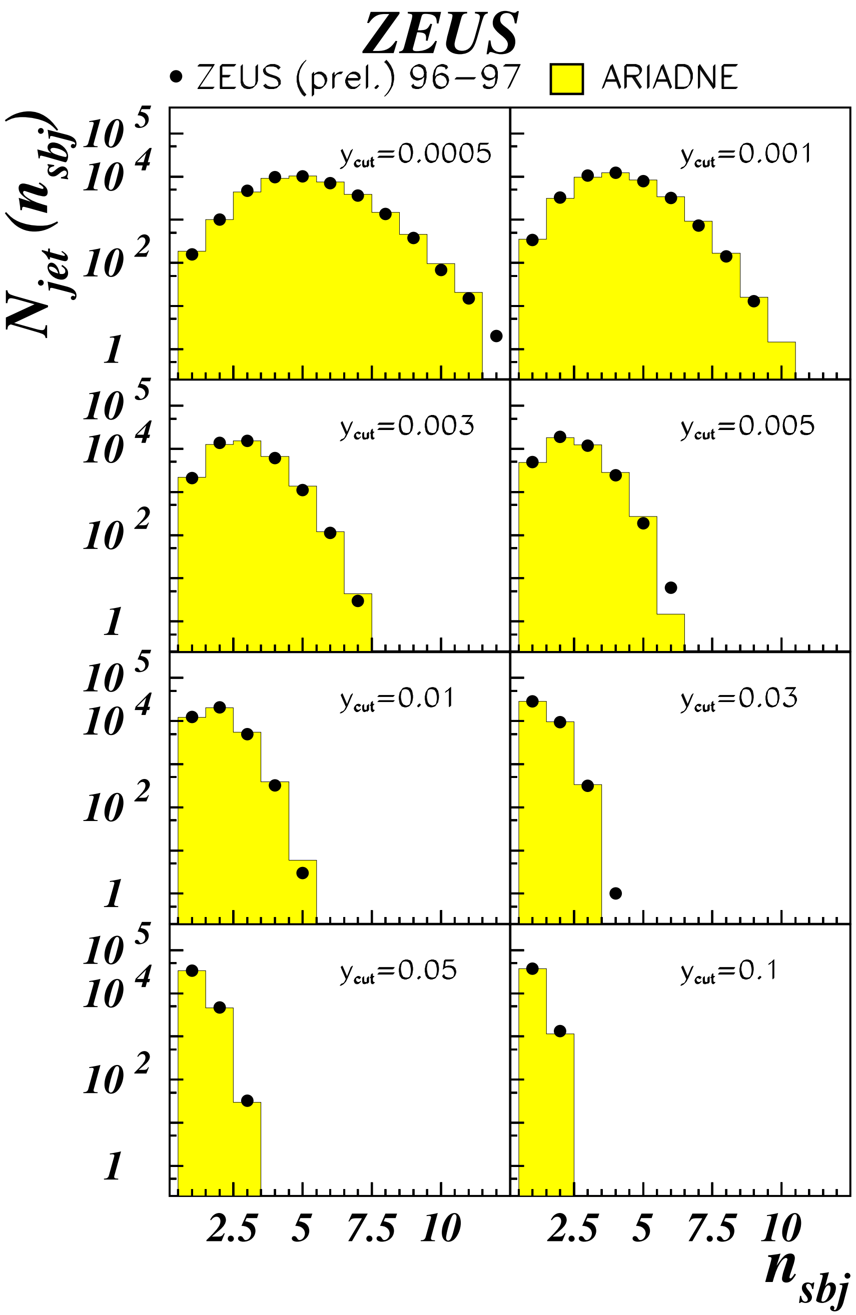


Phase space:

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

$$E_{T,\rm LAB}^{\rm jet} > 15 \text{ GeV}, \quad -1 < \eta_{\rm LAB}^{\rm jet} < 2$$

Subjet multiplicity in data and MC



MC predictions area normalised to data

ARIADNE gives a good description at all values of y_{cut}

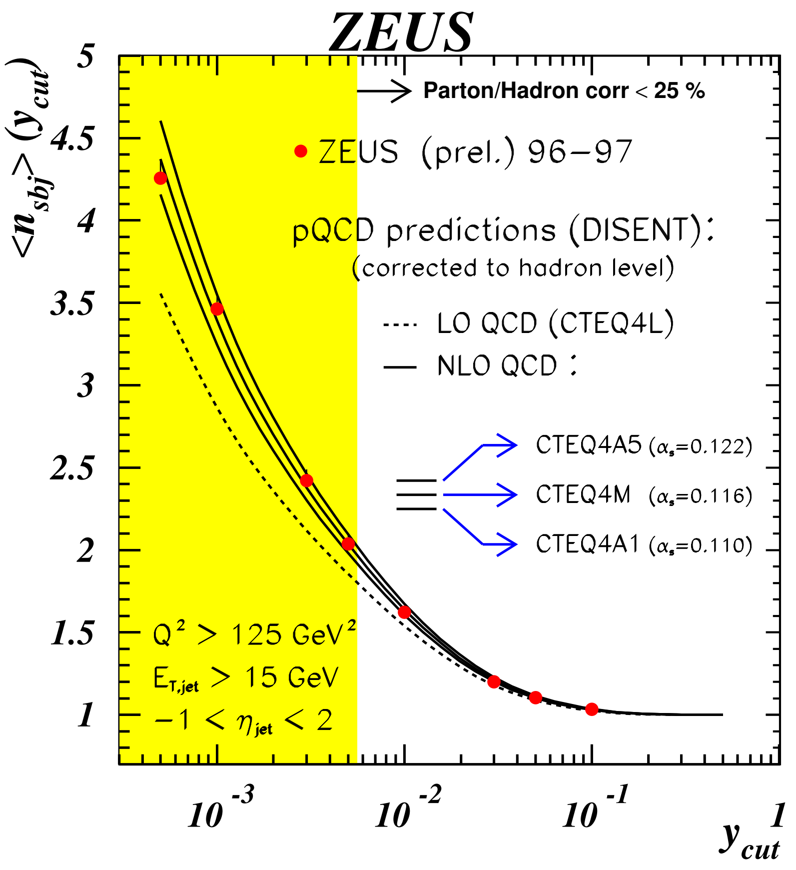
LEPTO predicts more subjets → largest systematic

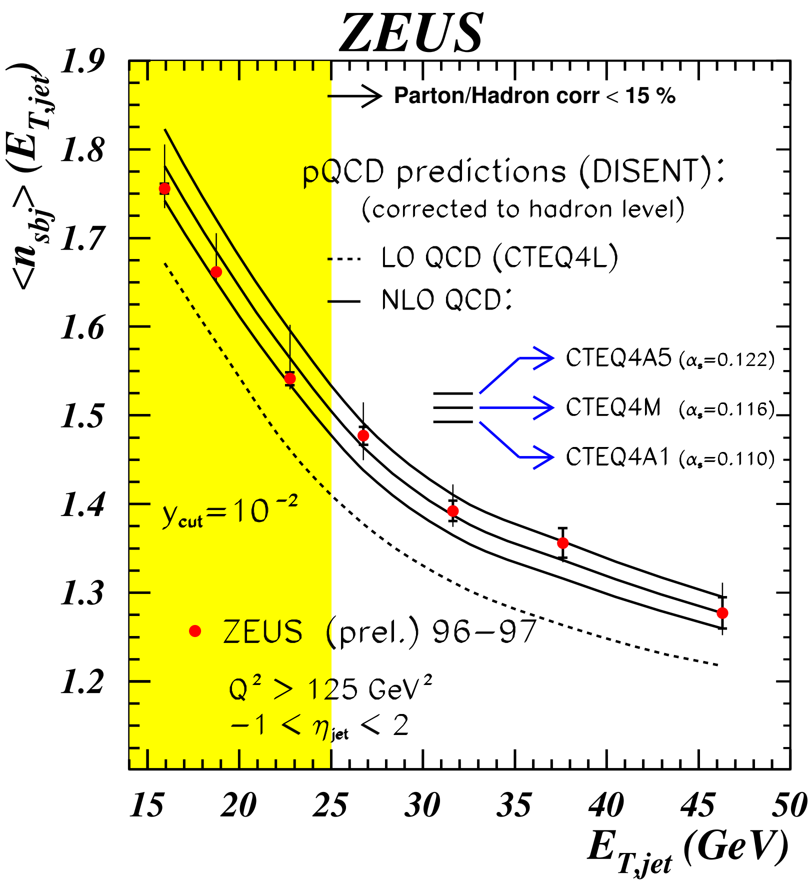
Similar picture for η^{jet} and E_T^{jet} dependence:

- **ARIADNE describes the data well**
- **LEPTO has too many subjets**

Compare to NLO QCD →

Subjet multiplicity comparison to NLO



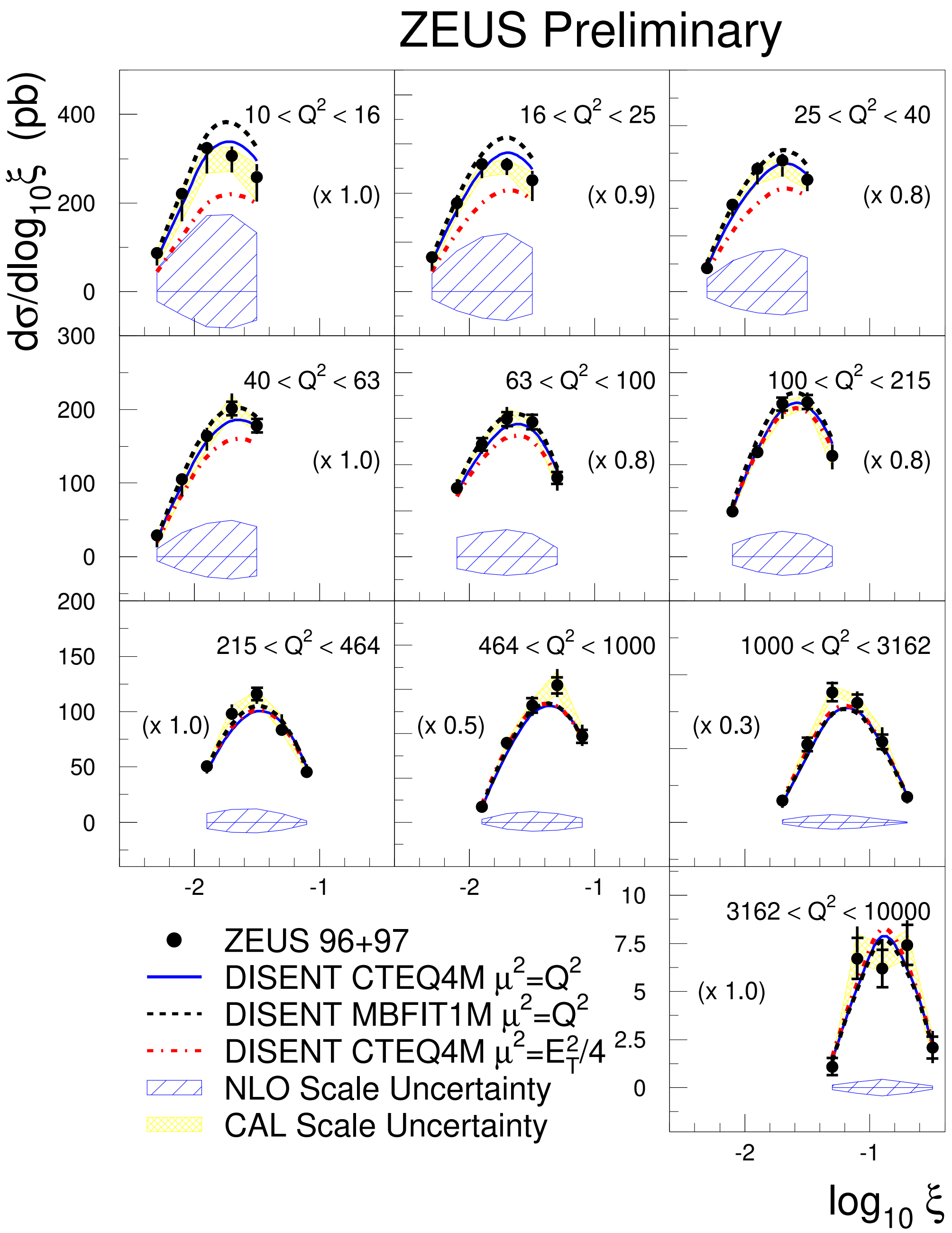


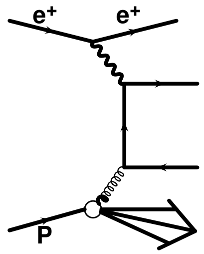
Description by NLO is good (LO not enough)

At high y_{cut} and E_T^{jet}, hadronisation corrections are small

Extract value of α_s in this well-understood region

Gluon density in the proton I





Fraction of proton's momentum carried by the struck quark is related to the observable, ξ:

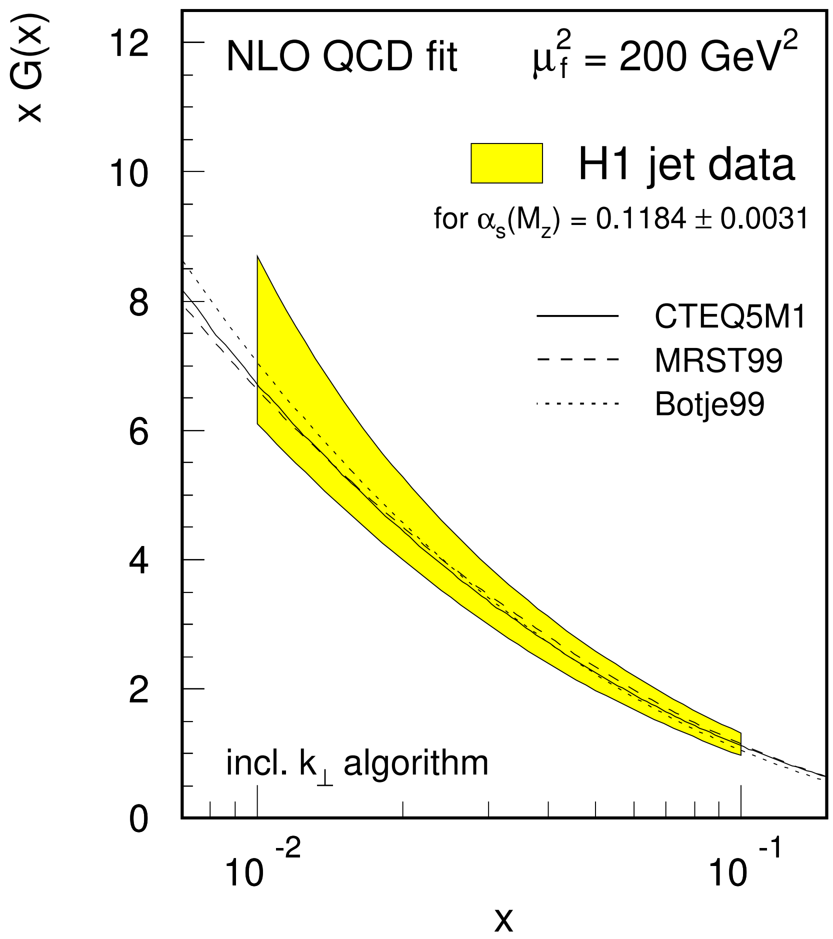
$$\xi = x\left(1 + \frac{M_{jj}^2}{Q^2}\right)$$

Proton PDFs differ at low Q^2

At high Q^2, NLO predictions similar and describe the data

But theory errors are large - precludes an accurate extraction where the sensitivity is greatest

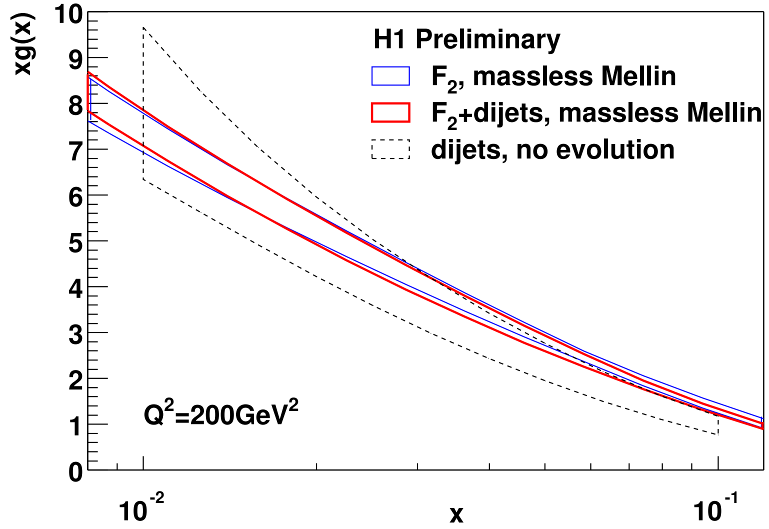
Gluon density in the proton II



Simultaneous fit to:

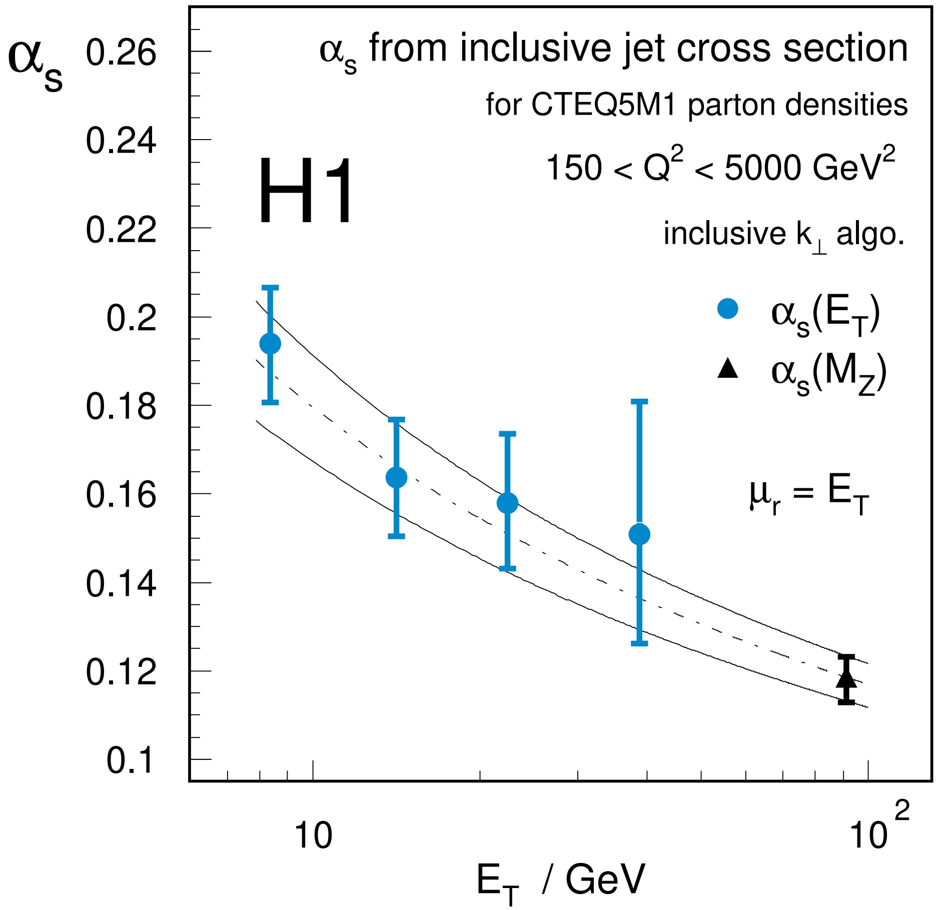
- $d^2\sigma_{\text{dijet}}/d\xi dQ^2$, $150 < Q^2 < 5000$ GeV^2
- $d^2\sigma_{\text{jet}}/d\xi dQ^2$, $150 < Q^2 < 5000$ GeV^2
- $\tilde{\sigma}(x_{\text{Bj}}, Q^2)$, $150 < Q^2 < 1000$ GeV^2

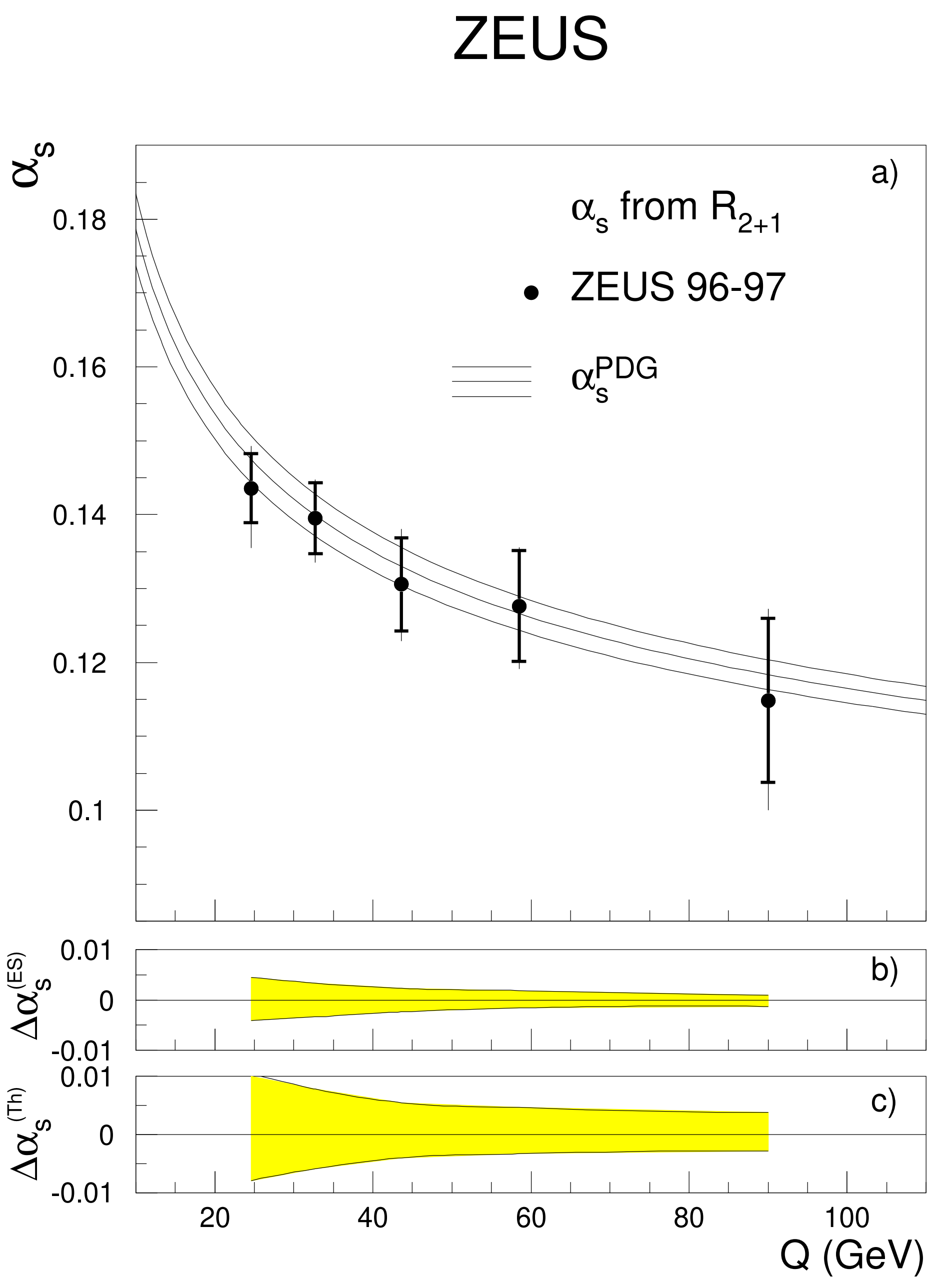
Jet data consistent with PDFs from (predominantly) scaling violations



Consistent picture, but the jet data does not add too much.

Running of α_s





The value of α_s is clearly seen to "run" over large range in scale

The running is consistent with that from the renormalisation group equation

Measurements of α_s

Inclusive jets (H1)

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

Inclusive jets (ZEUS prel.)

$$\alpha_s(M_Z) = 0.1190 \pm 0.0017(\mathrm{stat.})^{+0.0049}_{-0.0023}(\mathrm{syst.})^{+0.0026}_{-0.0026}(\mathrm{th.})$$

Dijet rate (ZEUS)

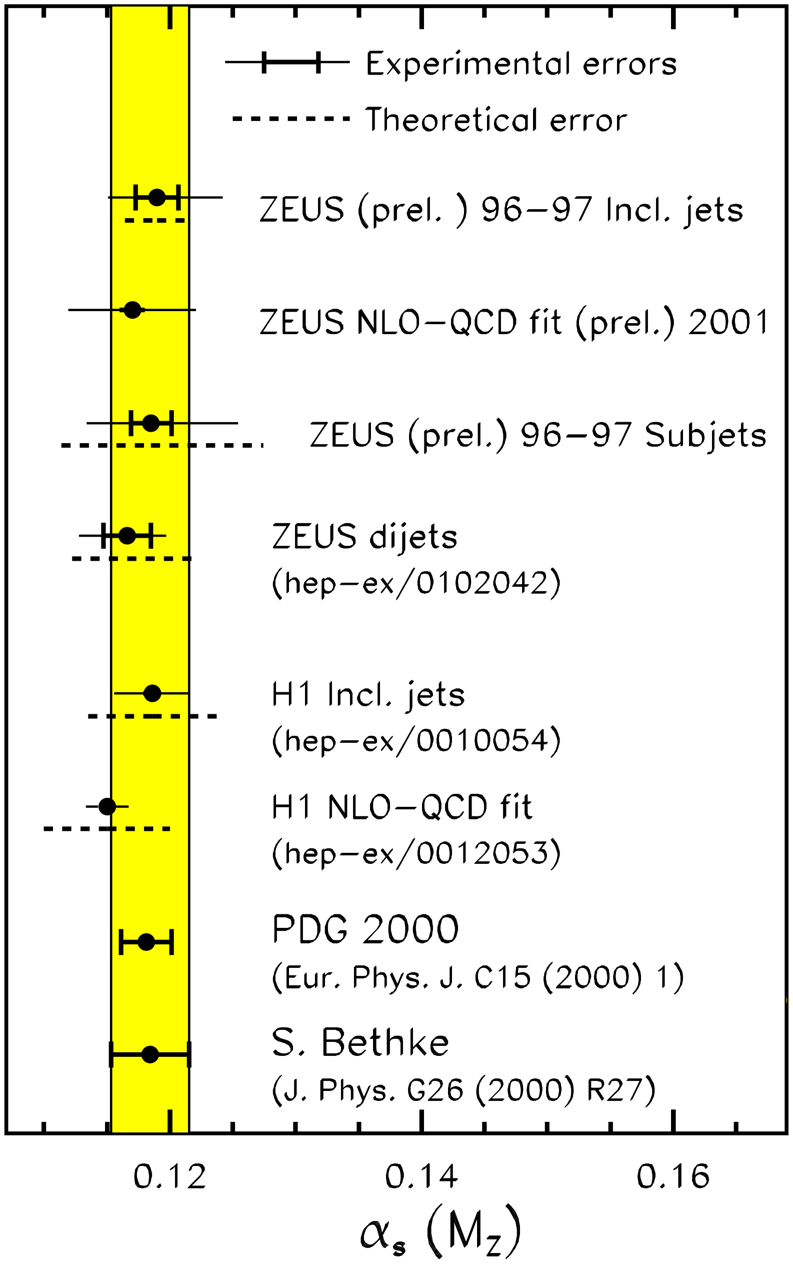
$$\alpha_s(M_Z) = 0.1166 \pm 0.0019(\mathrm{stat.})^{+0.0024}_{-0.0033}(\mathrm{syst.})^{+0.0057}_{-0.0044}(\mathrm{th.})$$

Subjets (ZEUS prel.)

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

Accuracy $\sim 5\%$ - three of four measurements dominated by theoretical error

Summary of α_s from HERA



All HERA jet measurements are consistent with each other and with the world average(s).

Errors are also competitive with those of the world average.

Impact of HERA data on world average...?

Conclusions

Many measurements of jets in DIS have been made at HERA.

In general the data is well described by NLO QCD calculations and the current proton parton densities ($\otimes$ hadronisation), particularly at high scales.

From these data, several measurements of α_s have been made.

The measurements of α_s all agree with the world average and have competitive errors.

Further experimental and theoretical advances are needed...

Outlook

Work on experimental errors

Most analyses shown were on $\sim 20-40\ \mathrm{pb}^{-1}$, have $\sim 100\ \mathrm{pb}^{-1}$ on tape and expect $\sim 1000\ \mathrm{pb}^{-1}$ in the future.

Jet measurements are usually systematically limited by the jet energy scale uncertainty $\sim 3-5\%$.

Now trying to achieve (and achieving) jet energy scale uncertainty $\sim 1-2\%$.

Work needed on theoretical errors

At low Q^2 the renormalisation scale error is often $> 50\% \rightarrow$ too large.

Even at high Q^2, this is generally the largest source of error.

Need to have NNLO programs, resummed NLO programs...