Review of HERA Jet Results

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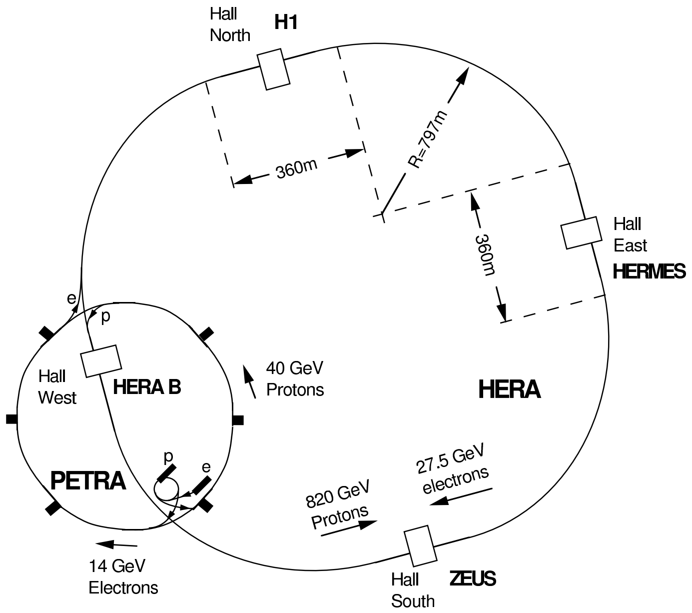
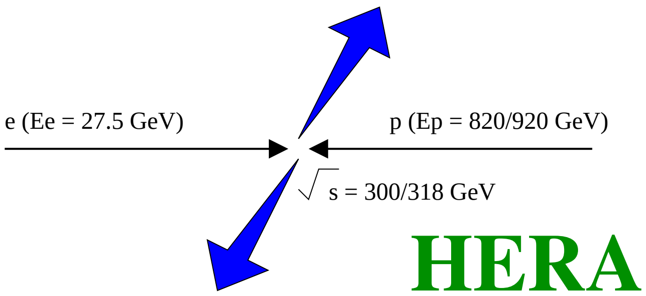




On behalf of the ZEUS and H1 Collaborations

Introduction

The HERA collider provides a unique laboratory for the study of the Hadronic Final State (HFS)

Study of jets in the hadronic final state allows ...

- Stringent tests of our understanding of QCD
  - → Study sub-processes directly proportional to α_s or higher powers
  - → Studies in regions of phase space where experimental and theoretical uncertainties are small
- Extraction of QCD parameters (if small theoretical uncertainties)
  - → Fit the data with NLO QCD calculations ⇒ extract α_s
- Constraints on the proton and photon parton distribution functions
- Highlight areas that require further theoretical understanding

In this talk we will go from high $Q^2 \rightarrow$ low Q^2 ...

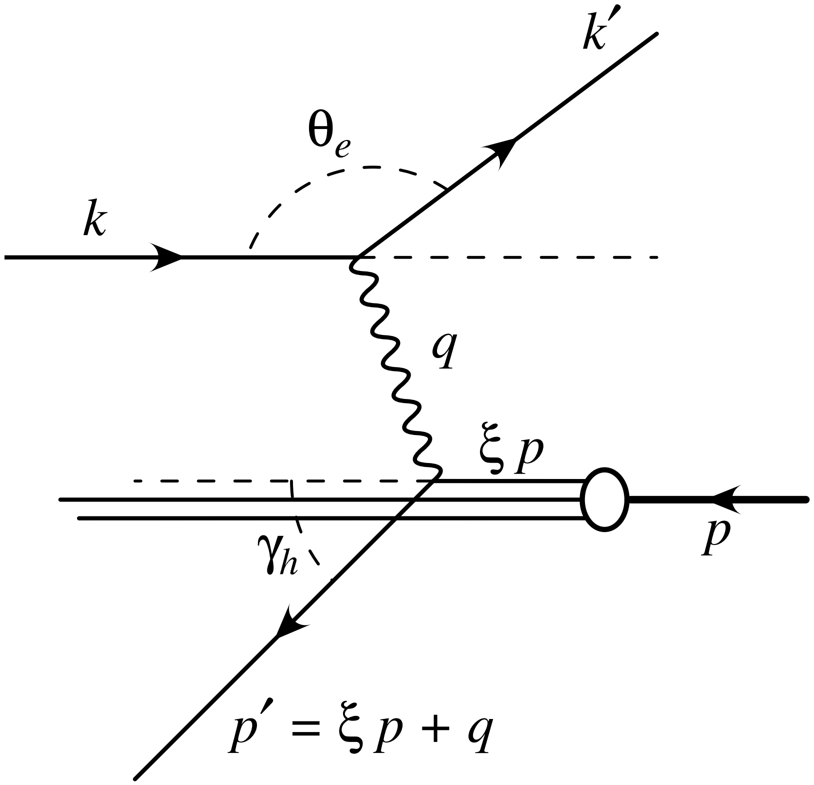
Kinematics of Lepton-Proton Scattering at HERA

HERA collides 27.5 GeV leptons with 820 (920) GeV protons
$\rightarrow \sqrt{s} = 300$ (318) GeV

- Negative four-momentum transfer squared:
$$Q^2 = -q^2 = -(k - k')^2$$

- Bjorken scaling variable:
$$x \equiv \frac{Q^2}{2p.q}$$

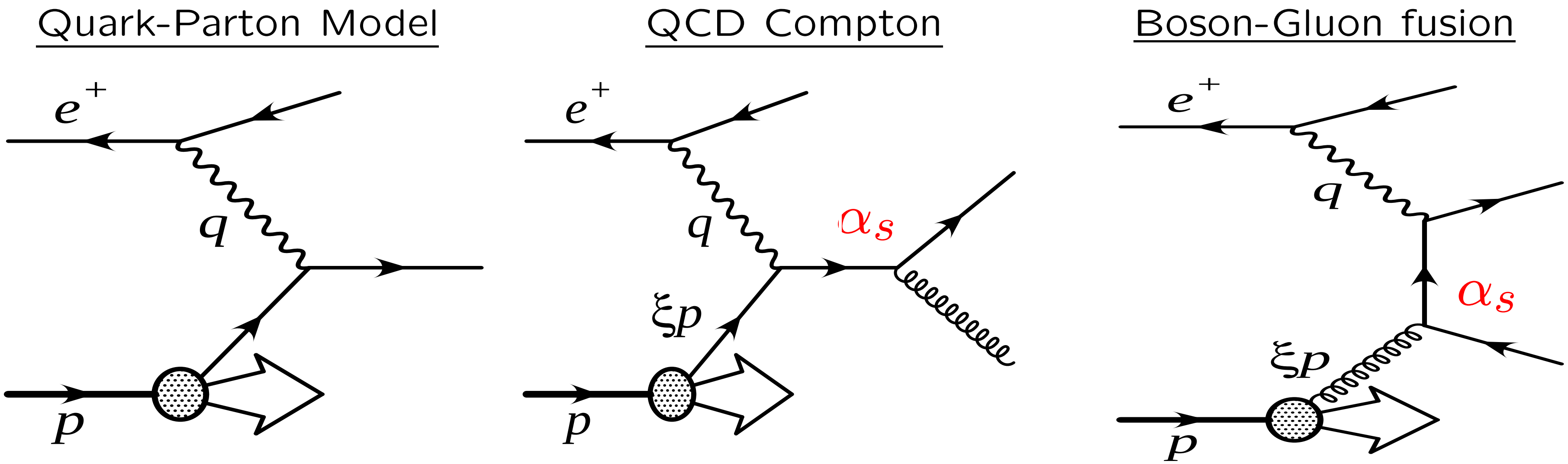
- Inelasticity:
$$y \equiv \frac{p.q}{p.k}$$



Only need two out of three variables since $Q^2 = sxy$

Jet Production in Deep Inelastic Scattering

- Jet production in Neutral Current DIS up to $\mathcal{O}(\alpha\alpha_s)$:
  $\rightarrow \gamma/Z^0$ propagator



- Jet production cross section:

$$\mathrm{d}\sigma_{\text{jet}} = \Sigma_{a=q,\bar{q},g} \int \mathrm{d}x \; f_a(x,\mu_F^2) \; \mathrm{d}\hat{\sigma}_a(x,\alpha_s(\mu_R),\mu_R^2,\mu_F^2) \;\times\; (1+\delta_{\text{had}})$$

  - f_a : parton a density (long-distance, determined from experiment)
  - $\mathrm{d}\hat{\sigma}_a$: sub-process cross section (short-distance, calculable in pQCD)

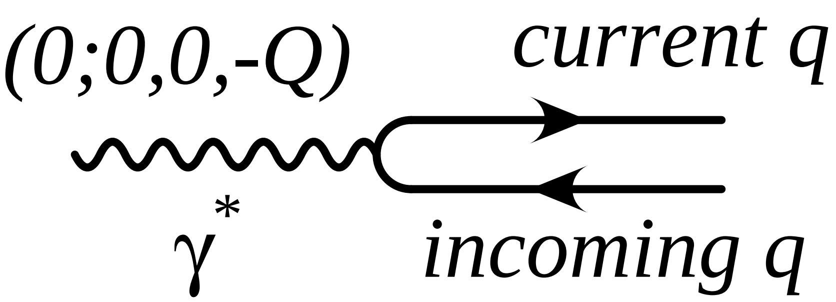
Jet Production in Deep Inelastic Scattering

- In the region where DIS data from fixed target and collider experiments have allowed an accurate determination of proton PDFs measurements of jet production in NC DIS provide:
  - sensitive tests of the predictions of pQCD
  - determination of the strong coupling constant α_s

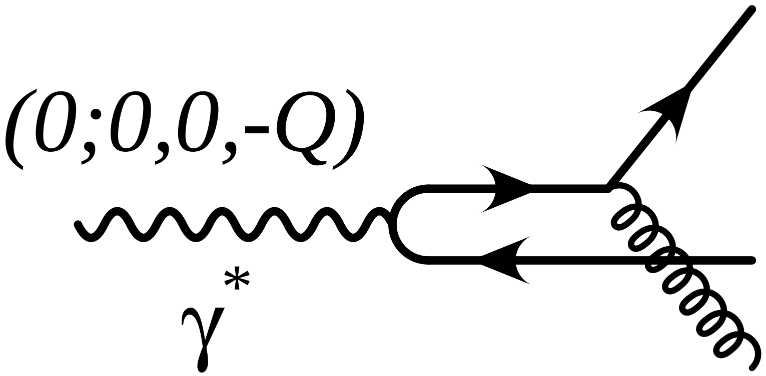
  $\longrightarrow$ To provide stringent tests of pQCD predictions and precise determinations of α_s
  - Need observables for which the predictions are directly proportional to α_s
    - $\rightarrow$ Jet cross sections in the Breit frame (defined on next slide)
  - Small experimental uncertainties $\rightarrow$ jets with relatively high tranverse energy
  - Small theoretical uncertainties
    - $\rightarrow$ NLO QCD calculations (reduction of higher order contributions)
    - $\rightarrow$ Jet algorithm: longitudinally invariant k_T clustering algorithm (Catini et al.)
    - $\rightarrow$ Jet selection criteria (inclusive jet production has smaller uncertainties than for dijets)
- Exploration of the parton evolution at low $x \longrightarrow$ BFKL effects?
- Exploration of the low Q^2 (transition) region $\longrightarrow$ resolved virtual γ?

Jet Production in the Breit Frame

Breit Frame: virtual boson collides head-on with struck quark from proton



Born level



QCD Compton

- High-E_T jet production in the Breit frame:
  - $\rightarrow$ supresses Born contribution (struck quark has zero E_T)
  - $\rightarrow$ supresses contribution from beam-remnant jet (zero E_T)
  - $\rightarrow$ lowest order (non-trivial) contributions from $\gamma^* g \rightarrow q\bar{q}$ and $\gamma^* q \rightarrow qg$
  - $\Rightarrow$ directly sensitive to hard QCD sub-processes at $\mathcal{O}(\alpha\alpha_s)$ (and higher orders)

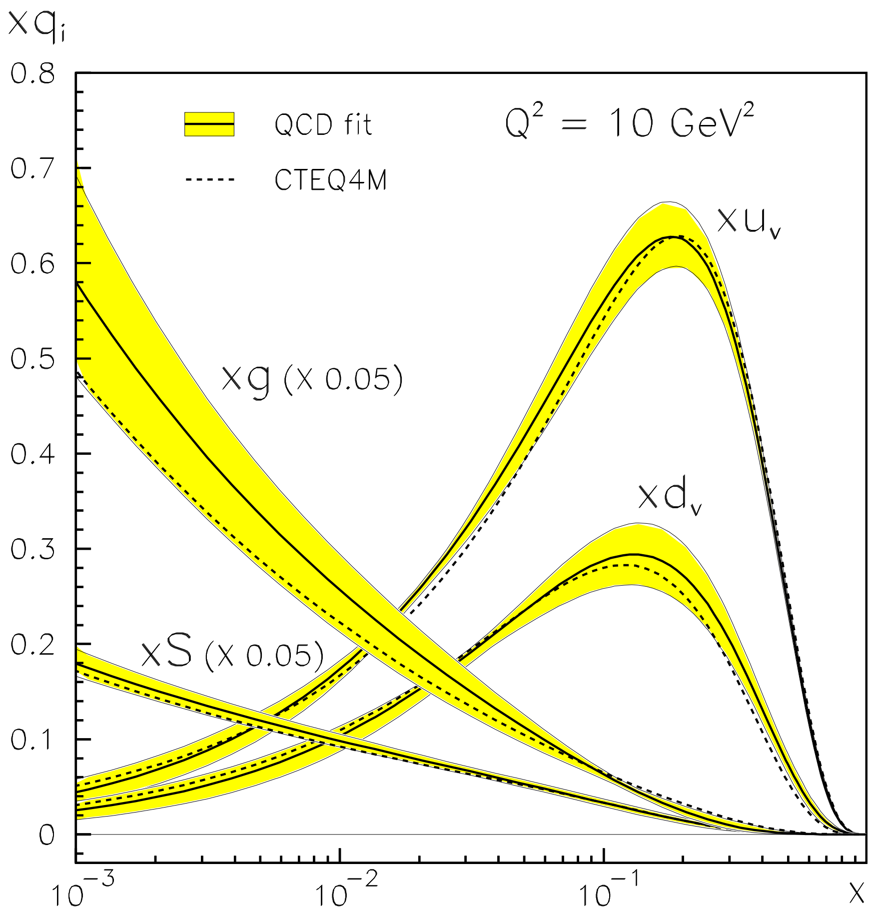
NLO QCD Calculations for Jets in NC DIS

Several NLO ($\mathcal{O}(\alpha\alpha_s^2)$) programs are available for calculating jet cross sections → DISENT, MEPJET, DISASTER++, NLOJET

- NLO corrections:
  - → Virtual with internal particle loops
  - → Real with a third parton in the final state
- Different methods used to calculate real corrections:
  - → Phase space slicing method (MEPJET)
  - → Subtraction method (DISENT,DISASTER++,NLOJET)
- Jet production has two hard scales Q and E_{T}
  - → Renormalisation and factorisation scales $\mu_R, \mu_F = Q$ or E_{T}
- Calculations at parton level ⇒ corrected for hadronisation effects
- Theoretical uncertainties:
  - → Terms beyond NLO, usually estimated by varying μ_R by a factor of 2
  - → Hadronisation corrections
  - → Uncertainties in α_s and the proton parton distribution functions

Uncertainties in the Proton Parton Densities and α_s

- Comparison of jet cross section calcs. using different parameterisations of the proton PDFs (e.g. MRST vs CTEQ) DOES NOT give a reliable) estimation of the uncertainties due to proton PDFs
- Several groups have developed methods (using correlation matrices) to quantify these uncertainties by properly accounting for
  - → the statistical and correlated systematics
  - → the theoretical uncertainties affecting the extraction of the PDFs in the DGLAP fits



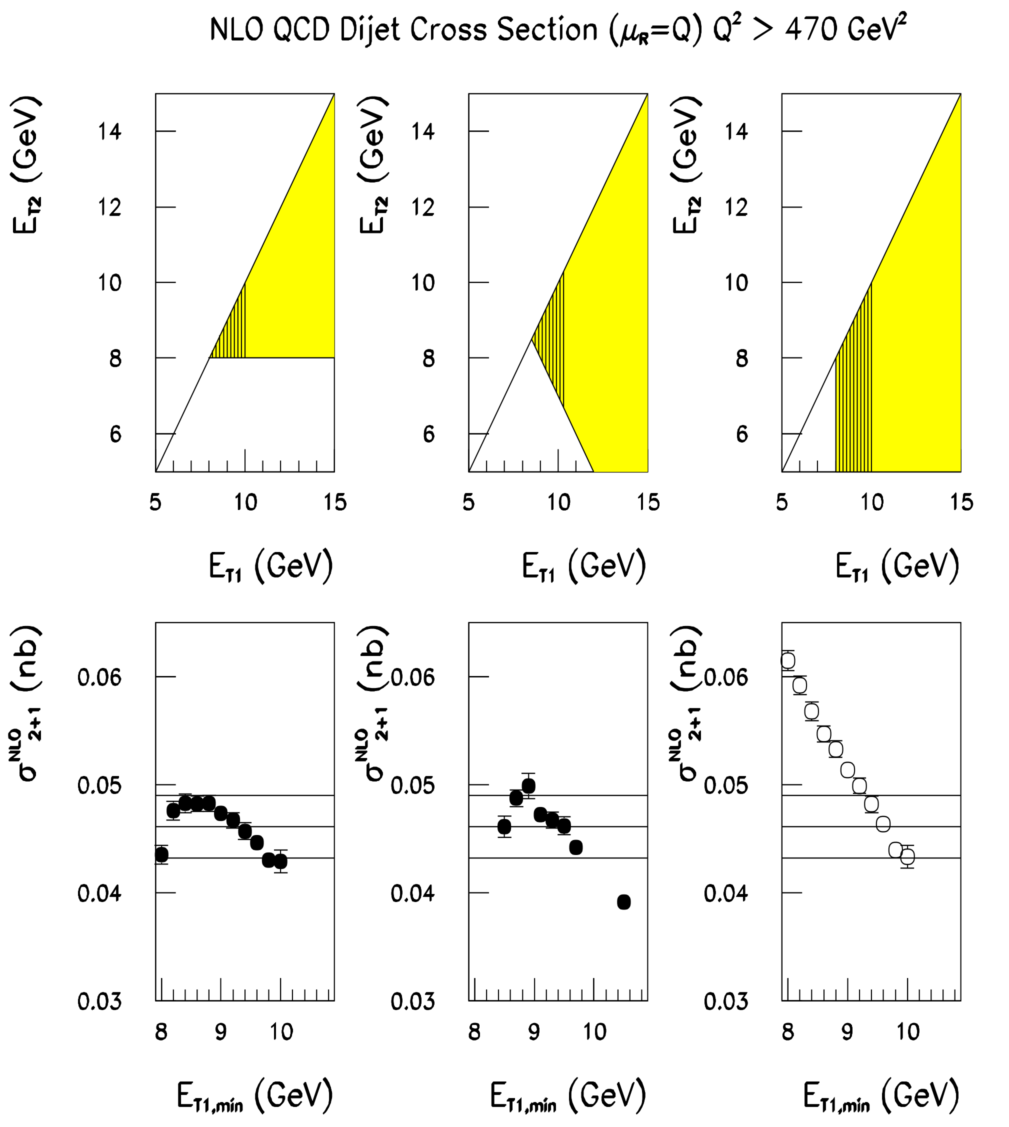
- Extreme ranges used to estimate reliable correlated PDF uncertainty
- PDF uncertainty and α_s are correlated
  - → several sets available (MRST99, CTEQ4A series) with consistent fits at different α_s values

Infrared Sensitivity to Jet Selection in NLO Calculations

- Dijet Selection Criteria:
  - → Symmetric cuts on $E_T^{\text{jet}1,2}$
    DANGER! → unphysical dependence
  - → Symmetric cuts on $E_T^{\text{jet}1,2}$
    and cut on sum $(E_T^{\text{jet}1} + E_T^{\text{jet}2})$
  - → Asymmetric cuts on $E_T^{\text{jet}1,2}$

NLO calculations for dijet cross sections can be (infrared) sensitive to the selection criteria

This complication is absent for inclusive jet cross sections!



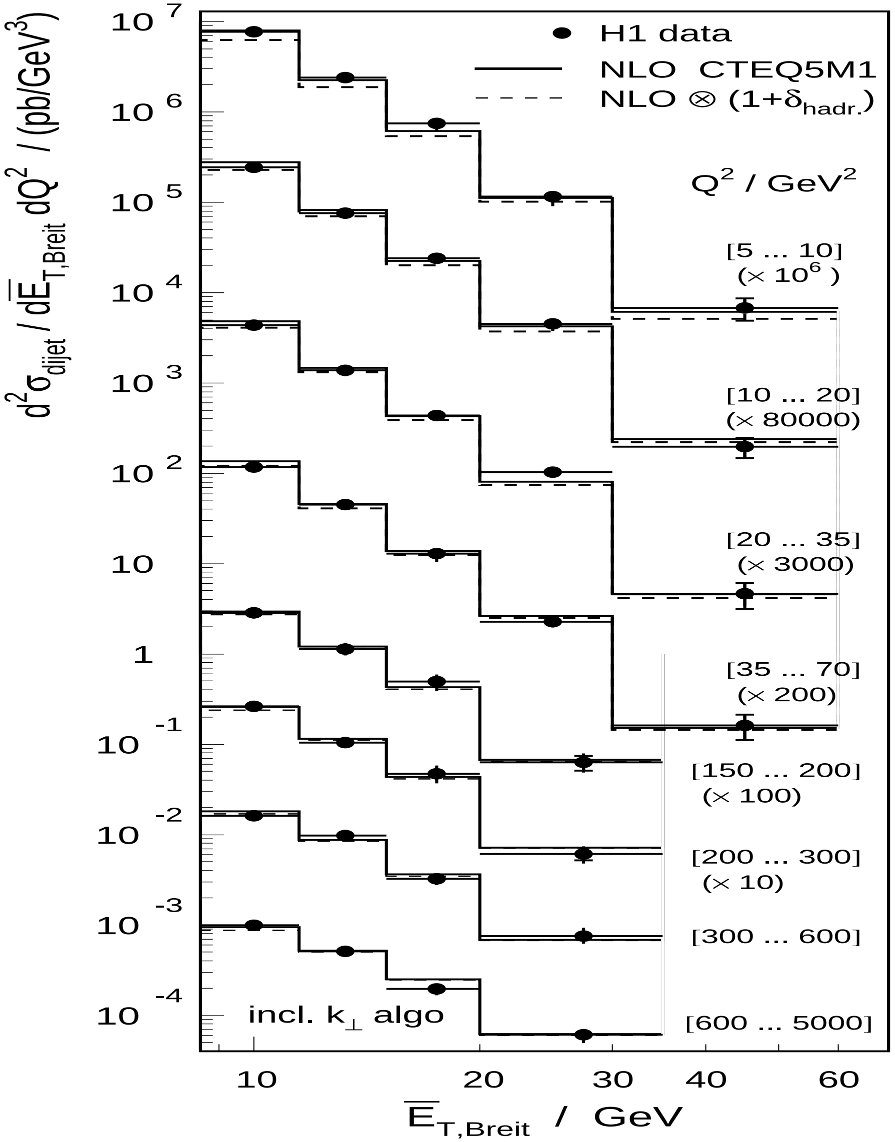
Dijet Jet Production in Neutral Current DIS

Dijet Production in the Breit Frame (H1 Data)

[Eur. Phys. J. C19 (2001) 289]

- $5 < Q^2 < 5000$ GeV^2
- $0.2 < y < 0.6$
- $E_T^{\text{Breit1,2}} > 5$ GeV, $E_T^{\text{Breit1}} + E_T^{\text{Breit2}} > 17$
- $-1 < \eta^{\text{Lab}} < 2.5$

- Cut on sum to reduce infrared sens.
- Spectrum gets harder as Q^2 increases
- Parton-to-hadron corrections generally small except at low Q^2 and low $\bar{E}_T^{\text{Breit}}$
- Reasonable description by NLO QCD (DISENT) with CTEQ5M1 and hadronisation corrections, except at lowest Q^2 where the shape is OK but not the normalisation



Dijet Jet Production at High-E_T in NC DIS

ISMD, Kraków, 5–11 September 2003

Dijet Production in the Breit Frame (ZEUS Data)

[Phys. Lett. B 507 (2001) 70]

- $470 < Q^2 < 20000$ GeV^2
- $E_\mathrm{T}^{\mathrm{Breit}1,2} > 8,5$ GeV$, -1 < \eta^{\mathrm{Lab}} < 2$

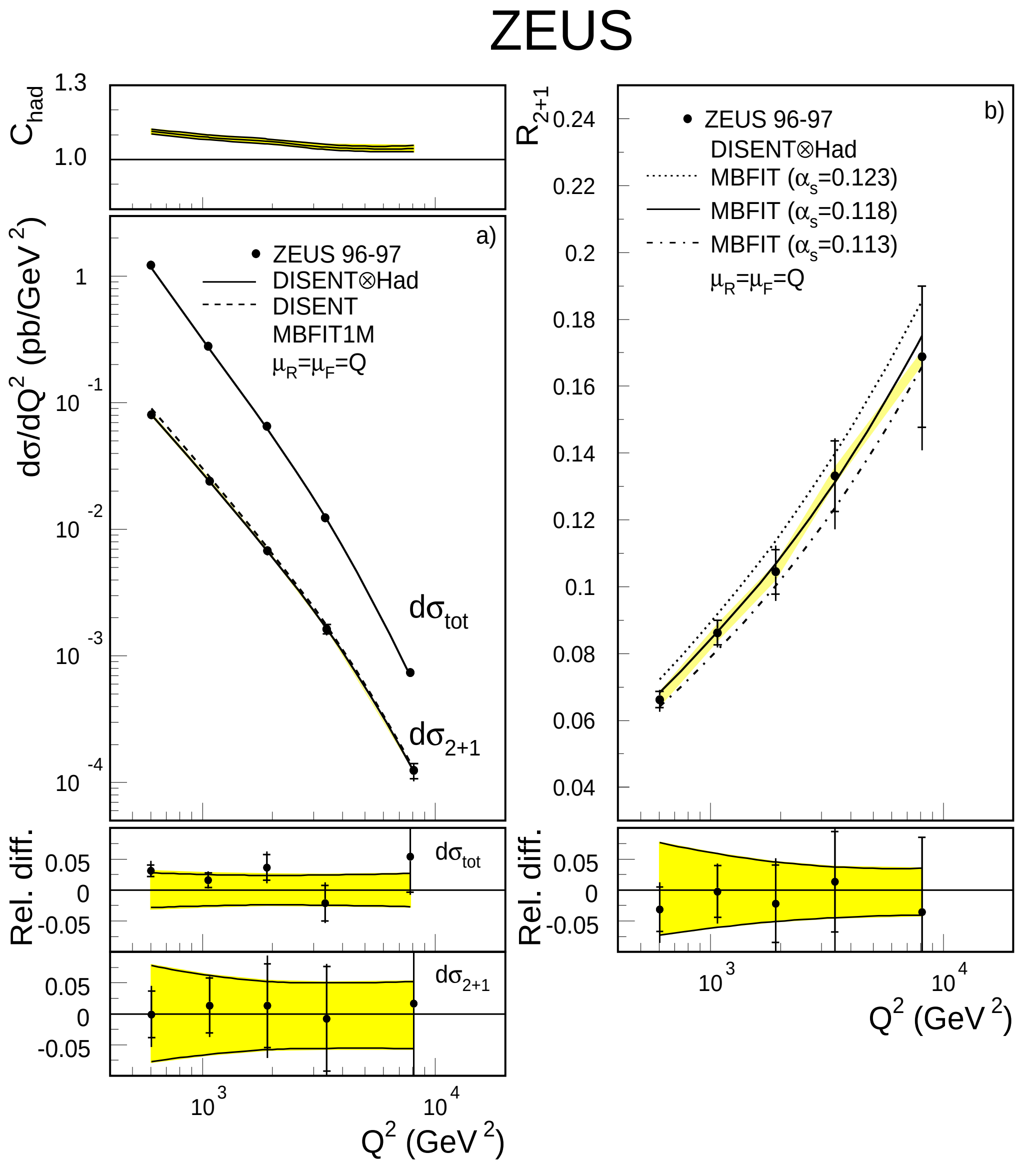
- Asymmetric cut on jet E_T's
- Small experimental uncertainties
- Small theoretical uncertainties
  $\rightarrow$ PDFs, had. correction, higher orders
- Good description by NLO QCD
  $\rightarrow$ extract α_s:

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

Ratio $R_{2+1} \equiv \dfrac{d\sigma_{2+1}/dQ^2}{d\sigma_{tot}/dQ^2}$

$d\sigma_{2+1}/dQ^2$: dijet cross section

$d\sigma_{tot}/dQ^2$: total cross section



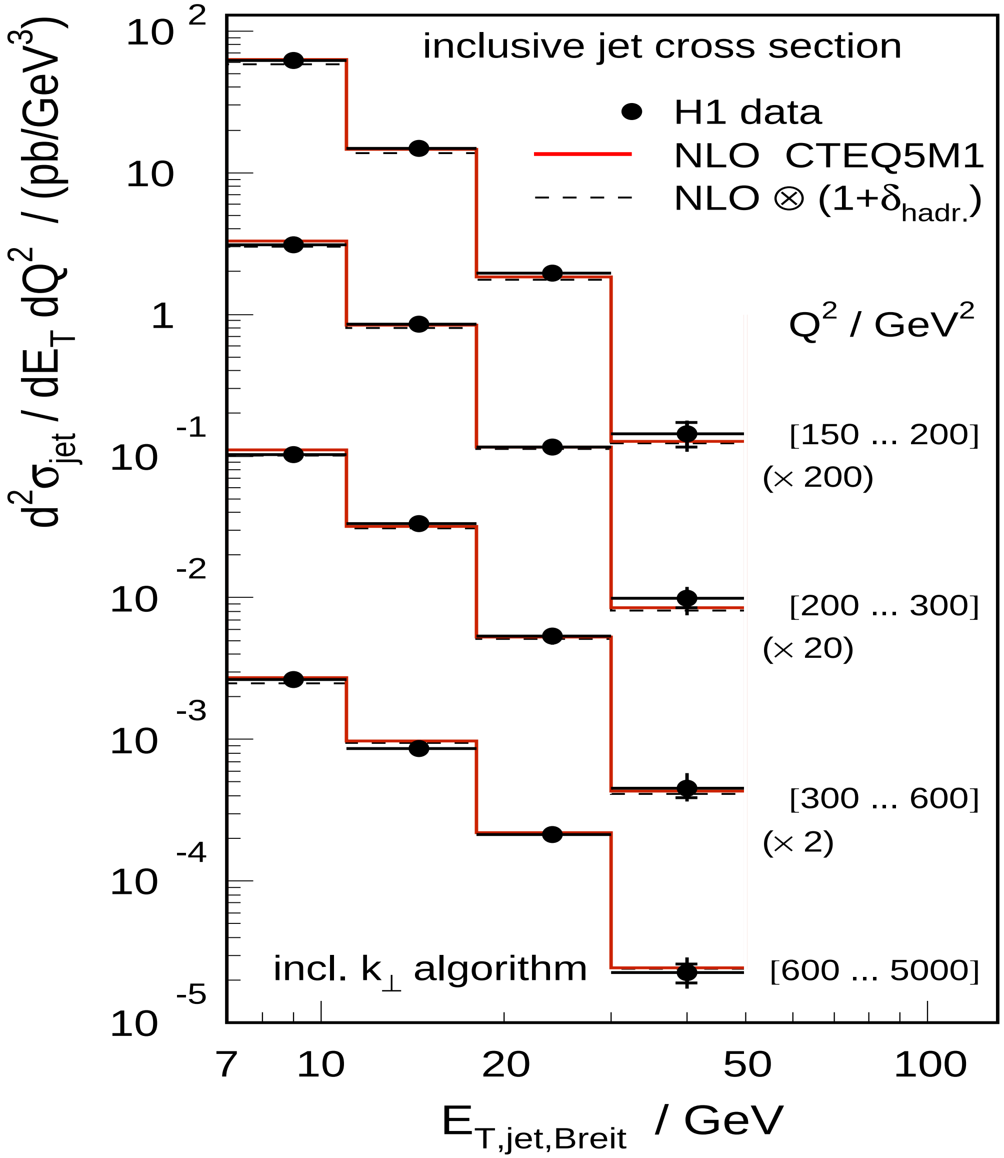
Inclusive Jet Production at High-E_T in NC DIS

Inclusive Jet Production in the Breit Frame (H1 Data)

[Eur. Phys. J. C19 (2001) 289]

- $150 < Q^2 < 5000$ GeV^2
- $0.2 < y < 0.6$
- $E_T^{\text{Breit}} > 7$ GeV
- $-1 < \eta^{\text{Lab}} < 2.5$

- NO requirement on second jet (can be unobserved)
  $\rightarrow$ infrared insensitive
  $\rightarrow$ smaller theoretical uncertainties than for dijet selection
- NLO QCD (DISENT) with CTEQ5M1 proton PDF gives good description over measured range of Q^2 and E_T



Inclusive Jet Production at High-E_{T} in NC DIS

Inclusive Jet Production in the Breit Frame (ZEUS)

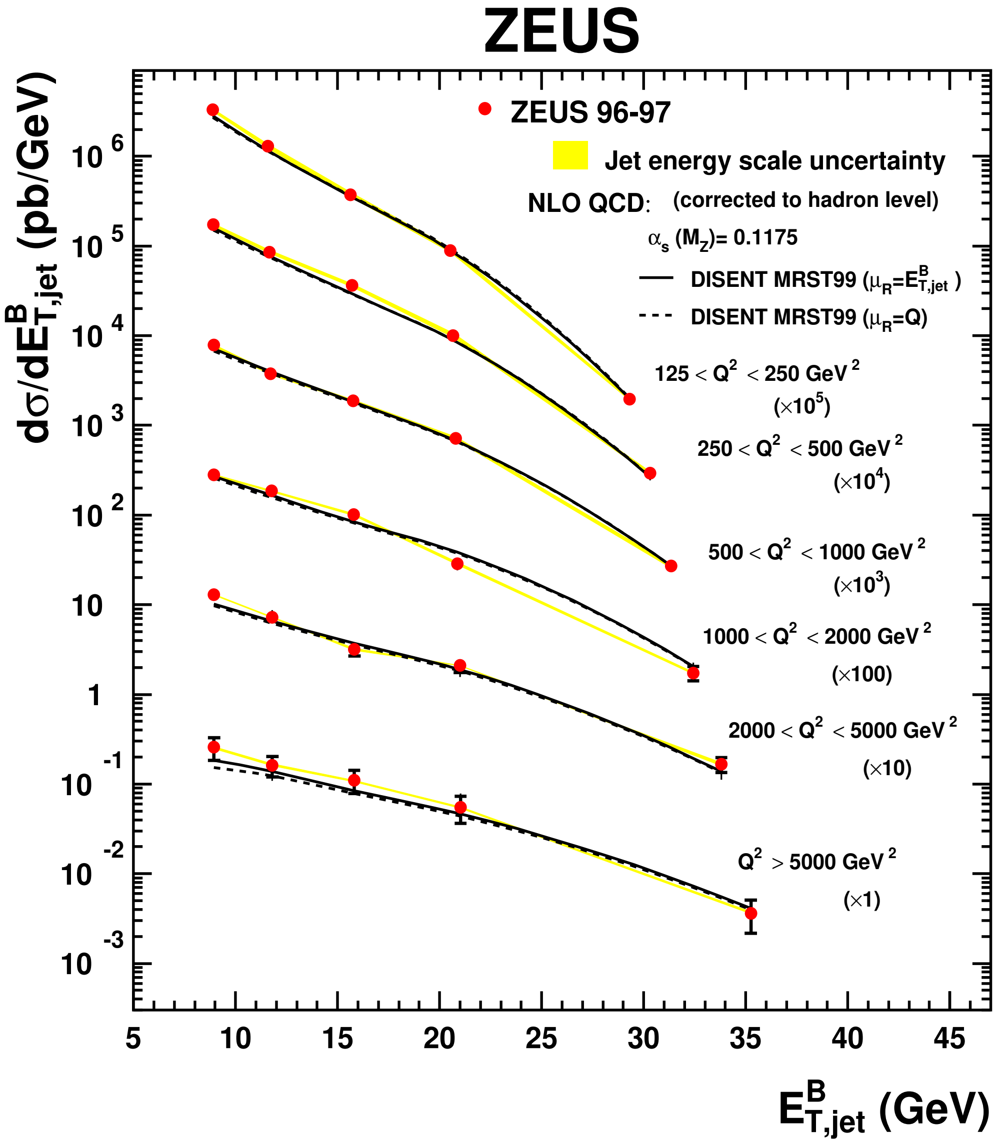
[Abs. 507, EPS03, Aachen, Germany]

- $Q^2 > 125$ GeV^2
- $E_{\mathrm{T}}^{\mathrm{Breit}} > 8$ GeV
- $-2 < \eta^{\mathrm{Breit}} < 1.8$

$\rightarrow$ NO cuts applied in lab. frame

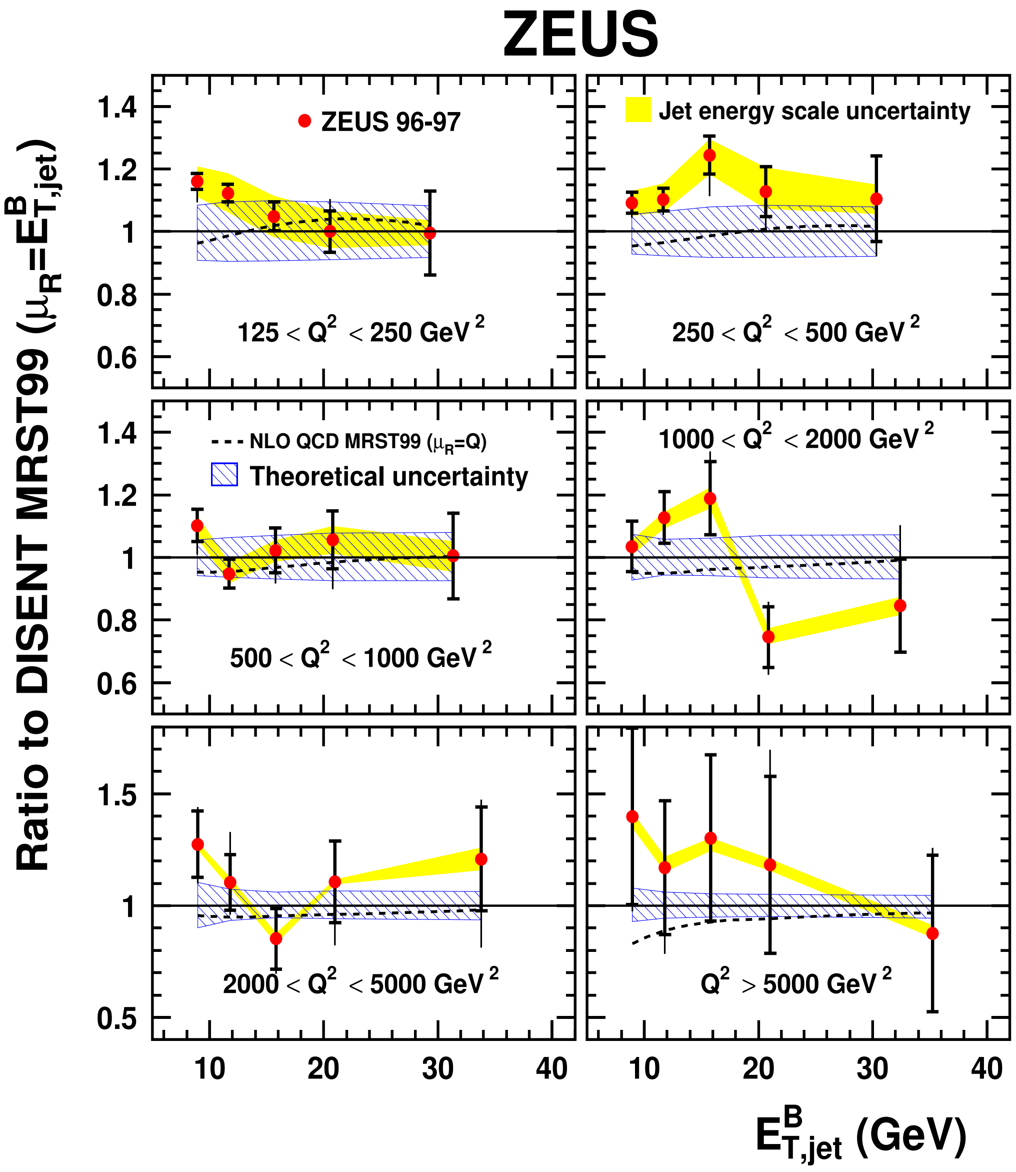
- NLO QCD (DISENT) using MRST99 proton PDF gives reasonable description over wide range of Q^2 and $E_{\mathrm{T}}^{\mathrm{Breit}}$

Precision test of the description of the dynamics of inclusive jet production by pQCD at $\mathcal{O}(\alpha\alpha_s^2)$



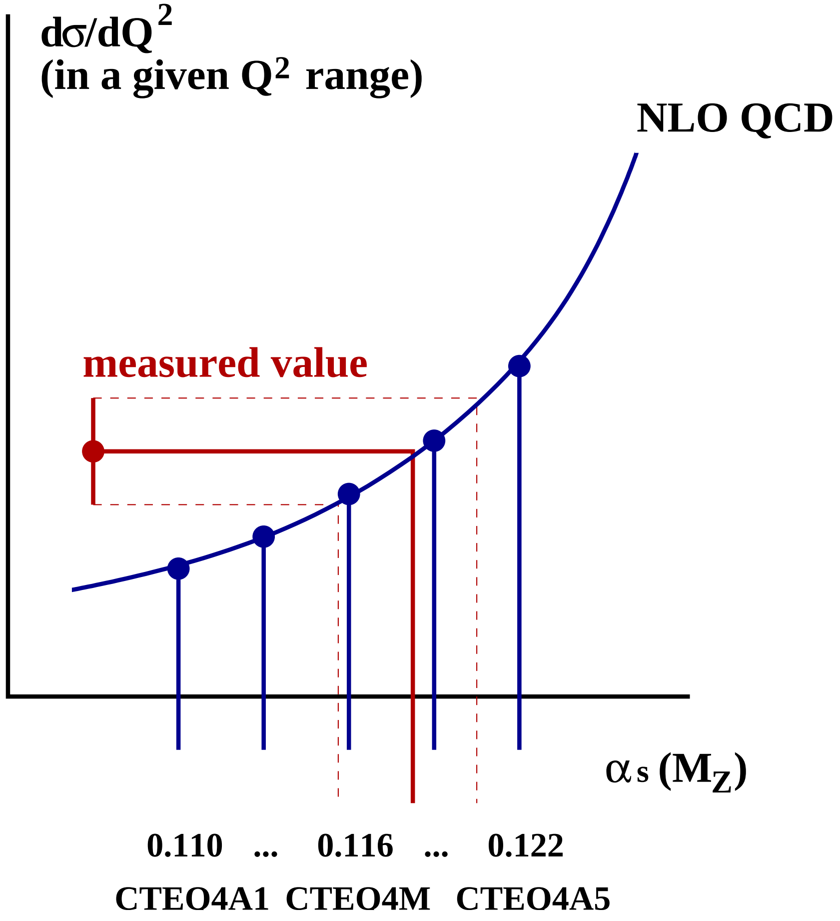
Inclusive Jet Production at High-E_T in NC DIS

- Small theoretical uncertainties:
  - $\rightarrow$ high order terms (>NLO);
    $E_\mathrm{T}^\mathrm{Breit}/2 < \mu_R < 2E_\mathrm{T}^\mathrm{Breit} \Rightarrow \pm 5\%$
  - $\rightarrow$ uncertainty on $\alpha_s(M_Z)$ (± 0.003)
    $\Rightarrow \pm 5\%$
  - $\rightarrow$ uncertainties on the proton PDFs
    - experimental uncertainties $\Rightarrow \pm 3\%$
    - theoretical assumptions $\Rightarrow \pm 3\%$
  - $\rightarrow$ hadronisation corrections $\Rightarrow < 1\%$
    (ARIADNE,LEPTO-MEPS,HERWIG)
- At lower Q^2 and low $E_\mathrm{T}^\mathrm{Breit}$ data lie above NLO QCD
- Overall, agreement is reasonable within experimental and theoretical uncertainties
  $\rightarrow$ extraction of α_s is possible

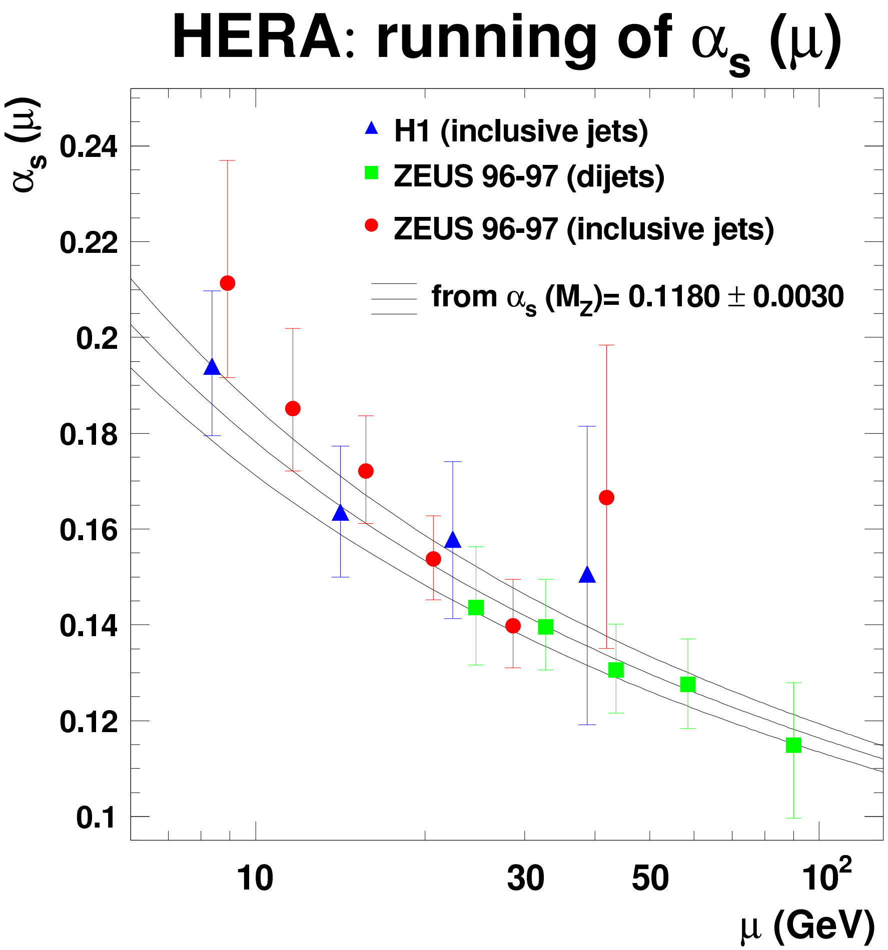


Extraction of the QCD Coupling α_s

- NLO QCD calculations of $d\sigma/dQ^2$ depend on $\alpha_s(M_Z)$ through:
  - $\rightarrow$ matrix elements: $\hat{\sigma} \sim A.\alpha_s + B.\alpha_s^2$
  - $\rightarrow$ proton PDFs: α_s assumed in evolution
- To take into account the correlation, the NLO QCD calculations are performed using various sets of proton PDFs which assume different values of α_s
- Resulting NLO QCD calculations are parameterised as a function of $\alpha_s(M_Z)$ in each region of Q^2 of the measurements
- From the measured value of $d\sigma/dQ^2$ in each region of Q^2, the value $\alpha_s(M_Z)$ and its uncertainty are extracted



Extraction of the QCD Coupling α_s



- Inclusive jet cross section in NC DIS used to extract α_s

  $\rightarrow$ H1 value ($150 < Q^2 < 5000$ GeV^2):

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

  $\rightarrow$ ZEUS value ($Q^2 > 125$ GeV^2):

  $$\alpha_s(M_Z) = 0.1212 \pm 0.0017(\text{exp.})\,^{+0.0023}_{-0.0031}(\text{theory})\,^{+0.0028}_{-0.0027}(\text{pdf})$$

- Dominant uncertainties from theory:

  $\rightarrow$ terms beyond NLO $\sim 3\%$

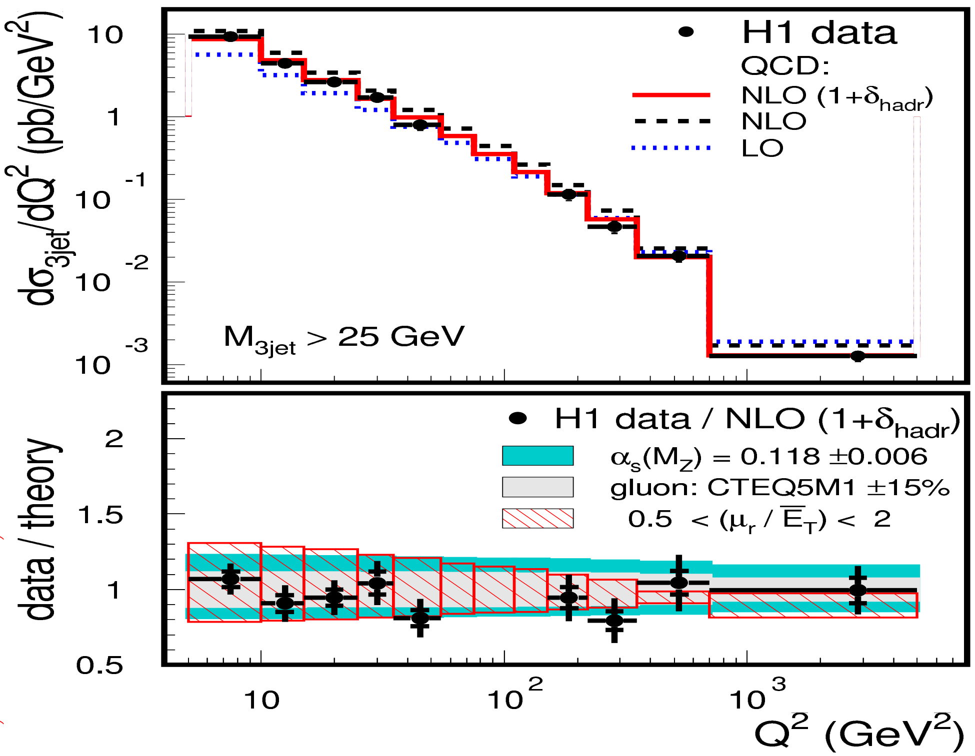
  $\rightarrow$ uncertainties in proton PDF $\sim 1\%$

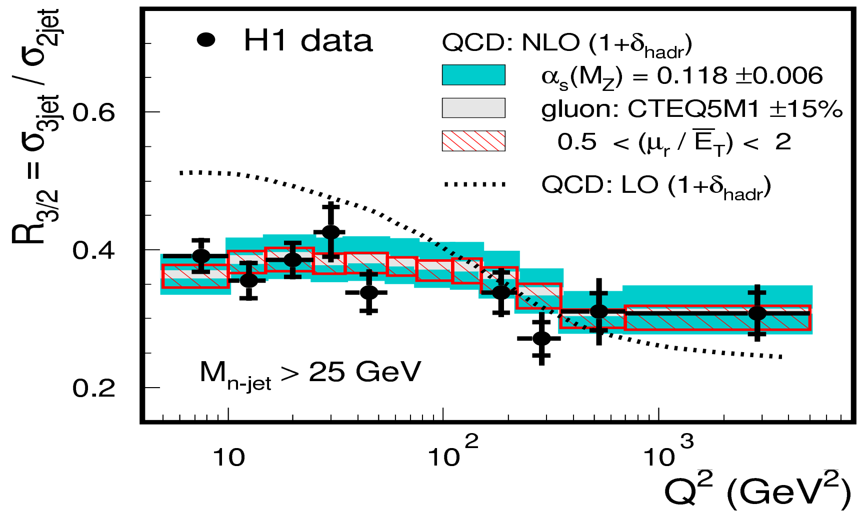
  $\rightarrow$ hadronisation corrections $\sim 0.2\%$

- Consistent with the running of α_s predicted by pQCD

Very precise determination from HERA data with a value consistent with other determinations of α_s and with PDG value

Three-Jet Production in NC DIS





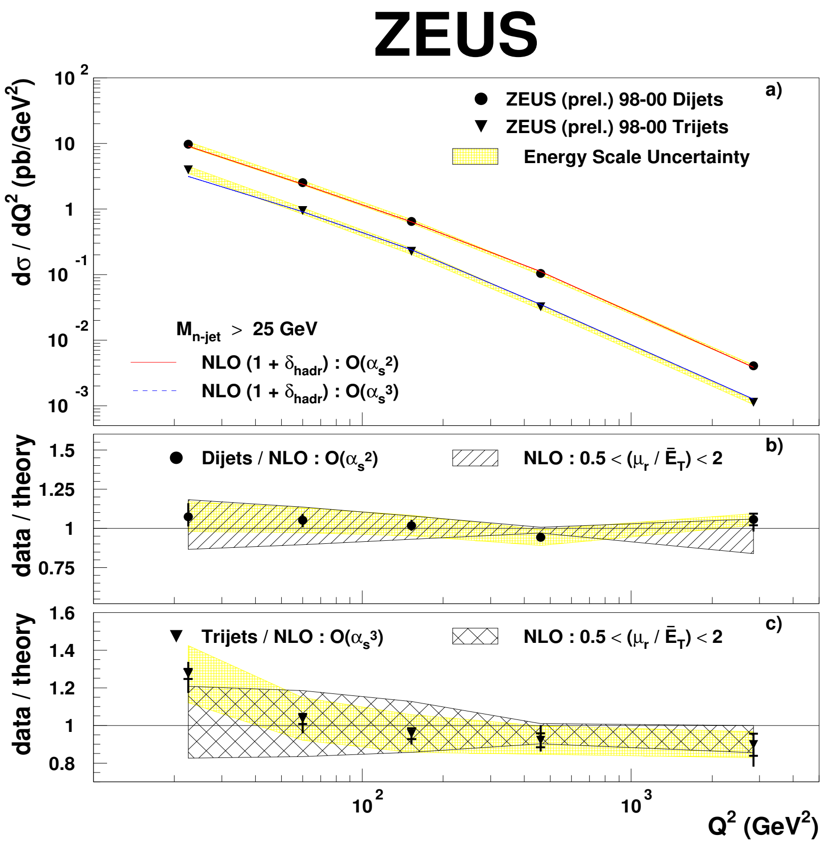
Three-Jet Production (H1 Data)

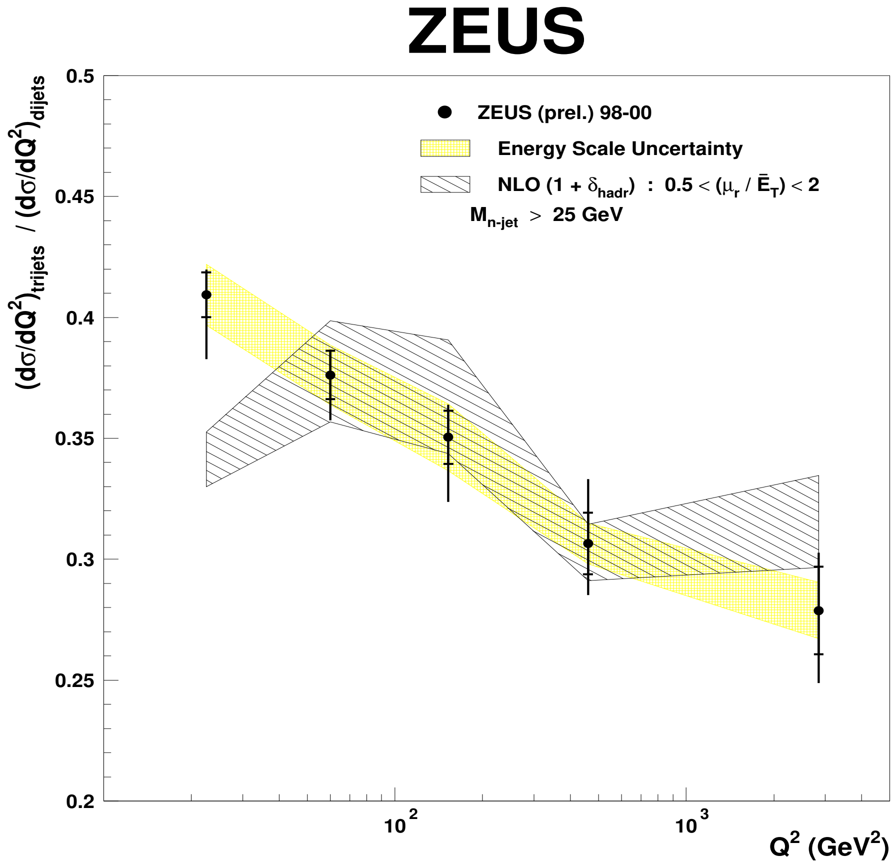
[Phys. Lett. B515 (2001) 17]

- $5 < Q^2 < 5000$ GeV^2
- $E_T^{\rm Breit} > 5$ GeV, $-1 < \eta^{\rm Lab} < 2.5$, $m_{3\rm jet} > 25$ GeV

- Tests understanding of pQCD at higher orders
  → three jet production is $\mathcal{O}(\alpha\alpha_s^2)$ at Leading Order
- Good agreement between data and NLO calculation (NLOJET)
- In three-to-two jet rate, $R_{3/2}$:
  → systematics partially cancel; reduced dependence on dynamics of jet production
  → reduced uncertainties from proton gluon density and renormalisation scale

Three-Jet Production in NC DIS





Three-Jet Production (ZEUS Data)

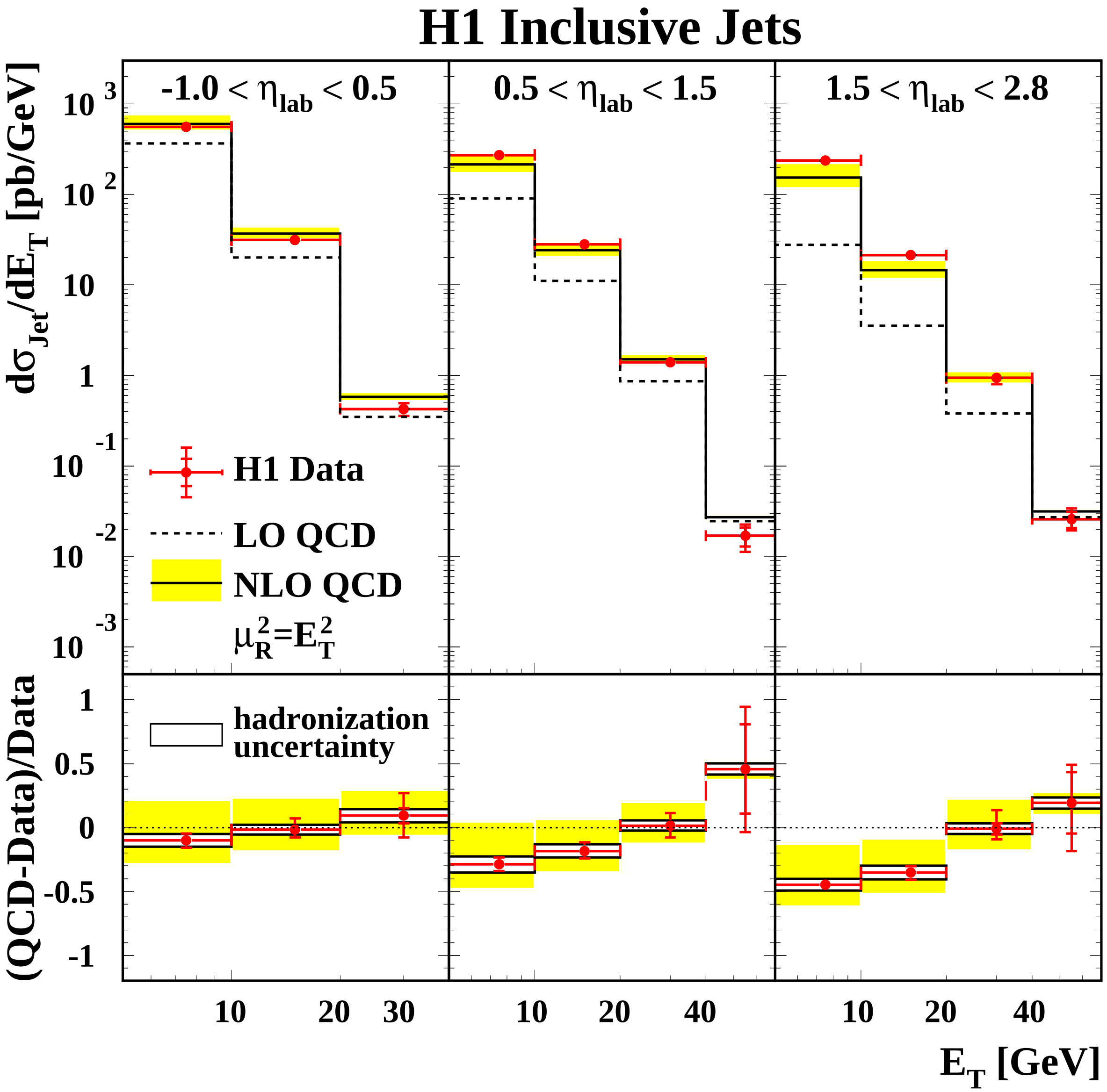
[Abs. 504, EPS03, Aachen, Germany]

- $10 < Q^2 < 5000$ GeV^2
- $E_T^{\text{Breit}} > 5$ GeV, $-1 < \eta^{\text{Lab}} < 2.5$
- $m_{3\text{jet}} > 25$ GeV

The ratio (above) is a potentially useful variable to extract α_s

- Dynamics of two and three jet production well described by NLO QCD (NLOJET)

NC Inclusive Jet Production $\rightarrow$ Lower Q^2



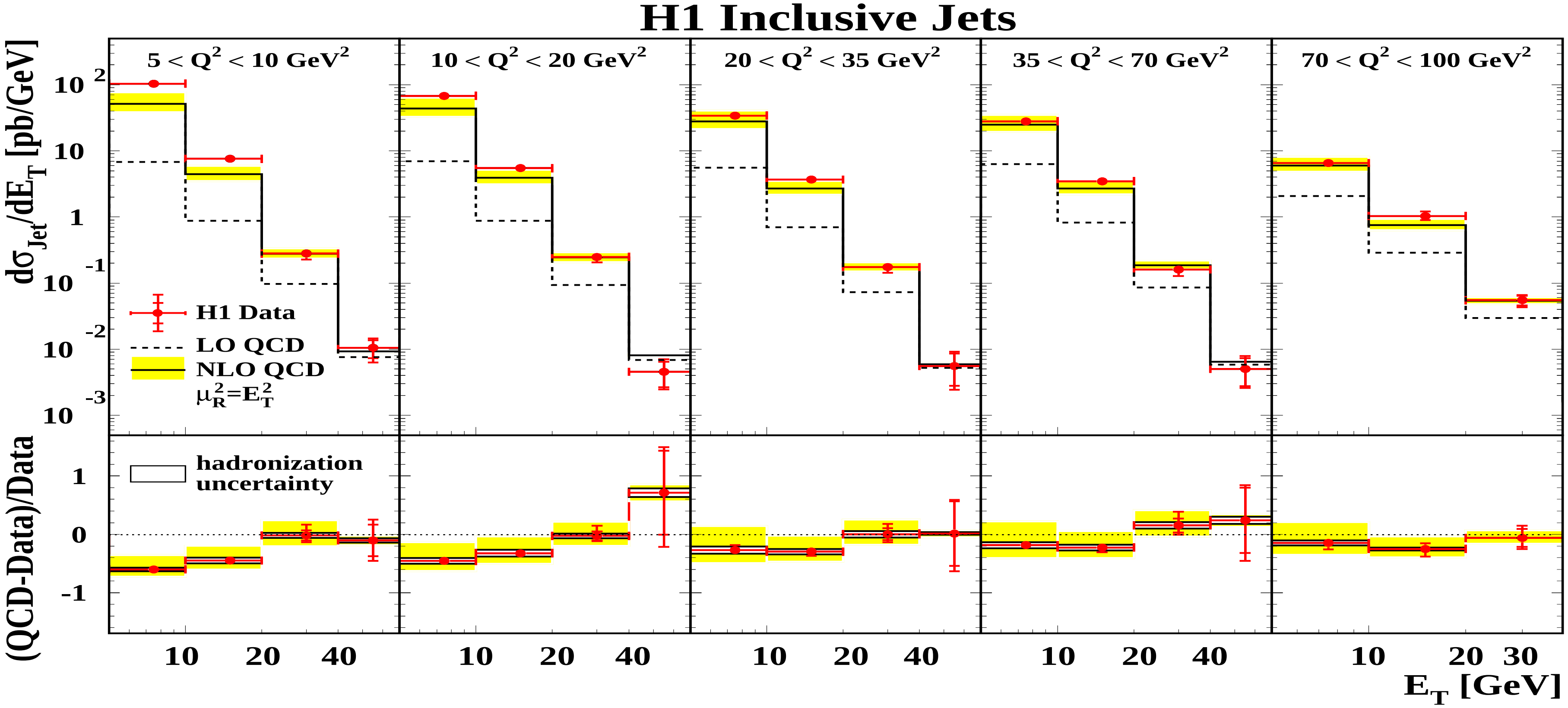
Inclusive Production in the Breit Frame (H1 Data)

[Phys. Lett. B542 (2002) 193]

- $5 < Q^2 < 100$ GeV^2
- $0.2 < y < 0.6$
- $E_T^{\mathrm{Breit}} > 5$ GeV

- Good description in the region $-1 < \eta < 0.5$
- NLO is below data at low E_T and forward η^{Lab}
  $\rightarrow$ where NLO corrections and uncertainties (due to higher order terms) are largest

NC Inclusive Jet Production → Forward Region



Forward Region: $1.5 < \eta^{\mathrm{Lab}} < 2.8$ (Look in more detail in this region)

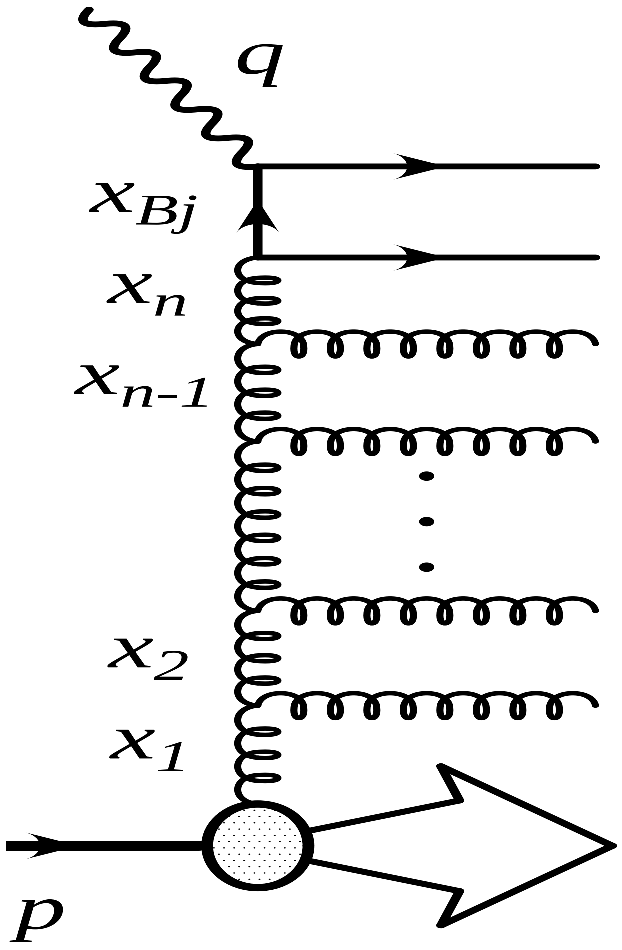
- Discrepancy between data and NLO large at low Q^2 and low E_T

  → improved calculations needed to understand jet production at low Q^2
  e.g. alternative evolution schemes (BFKL, CCFM)? virtual photon structure?

Parton Evolution at Low x

Searching for BFKL induced effects

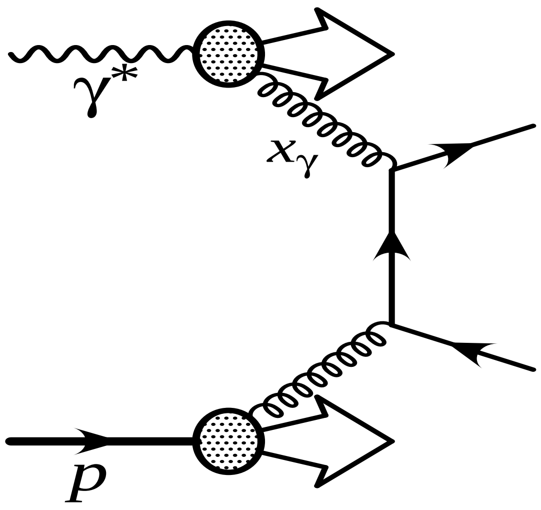
- DGLAP equations sum the leading powers of $\alpha_s \ln Q^2$ in the region of strongly ordered transverse momenta
  $Q^2 >> k^2_{Tn} >> ... >> k^2_{T2} >> k^2_{T1}$
- When $\ln Q^2 << \ln 1/x$, terms proportional to $\alpha_s \ln 1/x$ become important and need to be summed
  $\rightarrow$ BFKL equation; integrate over full k_T space of the gluons
  - no k_T ordering
    $\rightarrow$ allows two highest E_T jets to come from anywhere along the ladder



CCFM is another evolution scheme which reduces to DGLAP at high Q^2 and to BFKL at low x

Forward Jets: see talk by S. Magill in "Small-x physics and saturation effects" Working Group

Virtual Photon Structure in Two Jet Production $\rightarrow$ Low Q^2



- In two jet production, at low Q^2, $E_T^{\text{jet}} \gg Q$
  - $\rightarrow$ large logarithmics $\ln E_T/Q$ can be resummed by defining PDFs for a **virtual photon** in a similar fashion as for the proton
  - $\rightarrow$ photon can interact directly
  - $\rightarrow$ or photon can interact via a parton $\rightarrow$ with some momentum fraction $x_\gamma < 1$
- Possible contribution from longitudinally polarised "resolved" photons
  - $\rightarrow$ vanishes as $Q^2 \rightarrow 0$ and $y \rightarrow 1$
- Virtual photon PDF parameterisations:
  - $\rightarrow$ interpolate between:
    - leading log part of real photon PDFs ($\ln E_T/\Lambda_{QCD}$)
    - asymptotic behaviour predicted by pQCD ($\ln E_T/Q$)

Observable representing the long. photon momentum fraction participating in the hard scatter:

$$x_\gamma^{\text{OBS}} = \frac{\sum_{i=1}^{2} E_T^{\text{jet}\ i} \exp(-\eta^{\text{jet}\ i})}{2yE_e}$$

$\rightarrow$ $x_\gamma^{\text{OBS}} < 0.75$ is resolved enhanced
$\rightarrow$ $x_\gamma^{\text{OBS}} > 0.75$ direct enhanced

$\rightarrow$ parameterisations: Drees & Godbole, Schuler & Sjöstrand, Glück et al.

Virtual Photon Structure

Virtual Photon Structure (H1 Data)

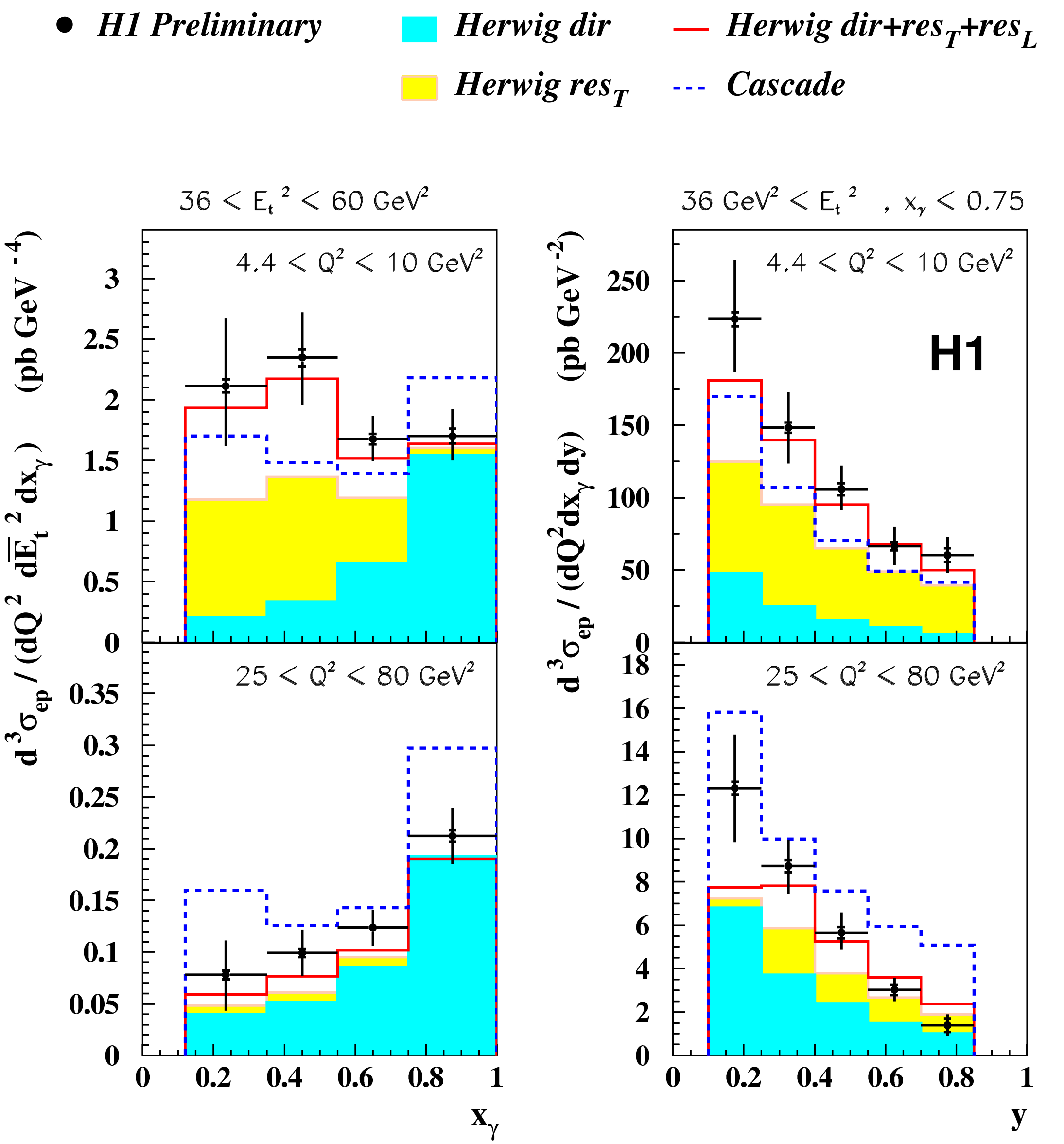
(in $\gamma^* p$ centre-of-mass system)

[Abs. 085, EPS03, Aachen, Germany]

- $2 < Q^2 < 80$ GeV, $0.1 < y < 0.85$
- $E_T^{\text{jet1,2}} > 5$, $\bar{E}_T > 6$ GeV
- $-2.5 < \eta^{\text{jet1,2}}(\gamma^* p \text{ CMS}) < 0$

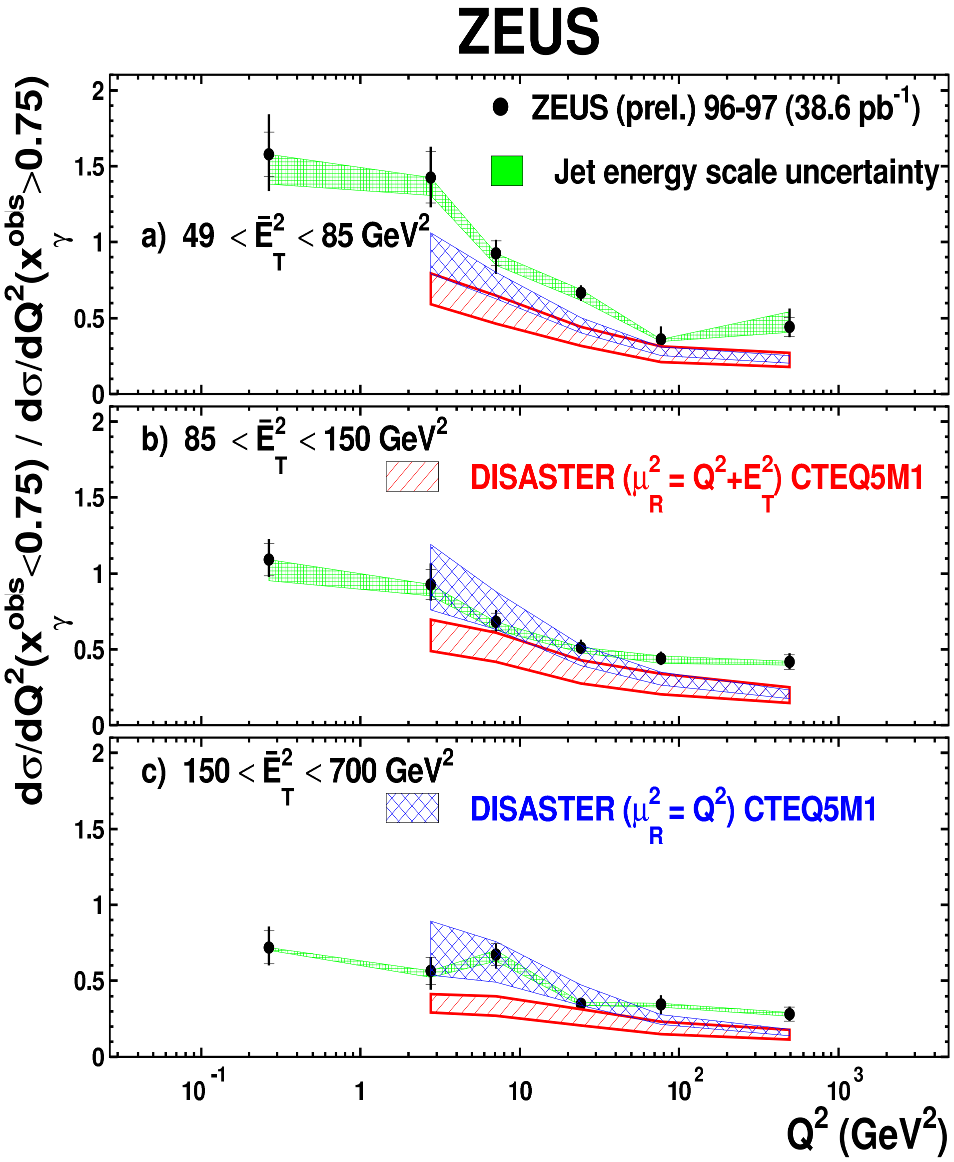
- As Q^2 increases at fixed $\bar{E}_T$ the $x_\gamma < 0.75$ cross section ("resolved" photon) decreases
- Models incorporating:
  - → only "direct" photon contribution
  - → trans. polarised "resolved" photon
  - → long. polarised "resolved" photon

  suggest "resolved" component necessary at low Q^2; long. polarised photon improves description further
- Cascade (CCFM) is too high
- Need NLO comparsion



Virtual Photon Structure

- NLO DIS (DISASTER):
  - $\rightarrow$ contains no resolved photon
  - $\rightarrow$ better agreement with NLO DIS with $\mu_R^2 = Q^2$ BUT still too low at low $\bar{E}_T^2$
- Would expect larger resolved fraction when including resolved <u>virtual</u> photon
- Need additional/improved calculations ...



Virtual Photon Structure (ZEUS Data)

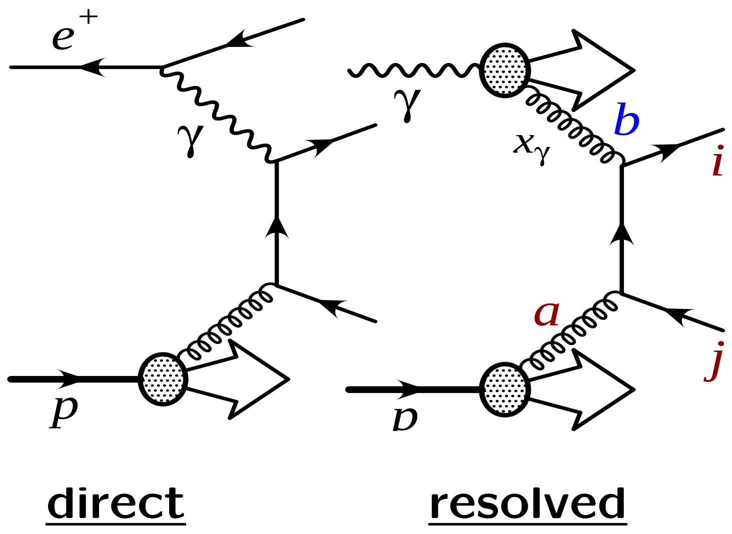
[Abs. 585, EPS03, Aachen, Germany]

- $0.1 < Q^2 < 2000$ GeV, $0.1 < y < 0.55$
- $E_T^{\text{jet1,2}} > 7.5, 6.5$
- $-3 < \eta^{\text{jet1,2}}(\gamma^* p \text{ CMS}) < 0$

Figure 5: *Measured ratio $R = \frac{d\sigma}{dQ^2}(x_\gamma^{obs} < 0.75)/\frac{d\sigma}{dQ^2}(x_\gamma^{obs} > 0.75)$ as a function of Q^2 in different regions of $\overline{E}_T^2$ (black dots). The NLO QCD calculations of DISAS-*

The Photoproduction Regime $Q^2 \sim 0$ GeV^2

- Exchanged photon has very low virtuality
  $\rightarrow$ perturbatively calculable if E_T ($\gg \Lambda_{QCD}$) of the jets taken as the hard scale
- At $\mathcal{O}(\alpha\alpha_s)$ two processes contribute:
  $\rightarrow$ direct (photon interacts directly)
  $\rightarrow$ resolved (parton from photon interacts)



- Jet cross section:

$$d\sigma^{res}(\gamma p \rightarrow ij) = \Sigma_{ab} \int_y dy \; f_{e\rightarrow\gamma}(y) \int_{x_p} dx_p \; f_{p\rightarrow a}(x_p, \mu^2_{F_p}) \; \int_{x_\gamma} dx_\gamma \; f_{\gamma\rightarrow b}(x_\gamma, \mu^2_{F_\gamma}) \; d\hat{\sigma}(ab \rightarrow ij)$$

longitudinal momentum fraction of γ/e^+ (y), parton b/γ (x_γ), parton a/p (x_p)

- $d\hat{\sigma}(ab \rightarrow ij)$: sub-process cross section (short-distance, calculable in pQCD)
- $f_{e\rightarrow\gamma}(y)$: photon flux (Weizacker-Williams Approximation)
- $f_{p\rightarrow a}(x_p, t)$: proton PDF
- $f_{\gamma\rightarrow b}(x_\gamma, t)$: photon PDF

(In direct case $\int_{x_\gamma} f_{\gamma\rightarrow b}(x_\gamma, t)$ is a delta function at $x_\gamma = 1$)

Photoproduction and Photon Structure

- Measurements of jets in photoproduction provide:
  - → tests of NLO QCD predictions based on current PDF parametersations
  - → constraints on proton and photon PDFs where pQCD expected to be valid

Information on photon structure:

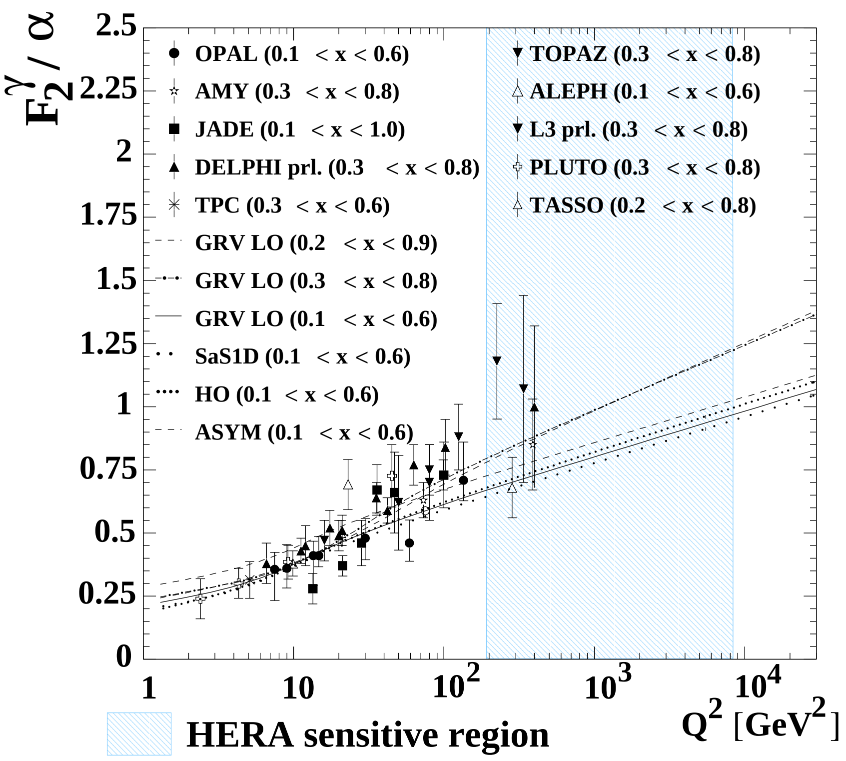
→ Photon structure determined from fits to F_2^γ in e-γ DIS at e^+e^- colliders

→ only sensitive to quark distribution at LO

⇒ gluon density is poorly constrained

→ LO cross sections in photoproduction sensitive to both quark and gluon densities

→ Larger scales are reachable at HERA ($\mu_{F_2^\gamma} \sim E^2_{\mathrm{T,jet}} \approx (200 - 10^4)$ GeV^2)



NLO QCD Calculations for Jets in Photoproduction

Several NLO ($\mathcal{O}(\alpha\alpha_s^2)$) programs are available (phase space slicing method, subtraction methods)
$\rightarrow$ Klasen & Kramer, Harris & Owens, Frixione & Ridolfi, Aurenche et al.

- Longitudinally invariant k_T cluster algorithm in the $\eta - \phi$ plane of the lab. frame
  $\rightarrow$ asymmetric dijet E_T cuts, cut on invariant mass (m_{JJ})
- Jet photoproduction has one hard scale E_T ($Q^2 \approx 0$)
  $\rightarrow$ renormalisation and factorisation scales $\mu_R, \mu_F = E_\mathrm{T}$
- Available PDF parameterisations (NLO fits)
  $\rightarrow$ Proton: CTEQ5M, CTEQ5HJ, MRST99
  $\rightarrow$ Photon: GRV-HO, AFG-HO
- Calculations at parton level $\Rightarrow$ corrected for hadronisation effects
  $\rightarrow$ usually using HERWIG, PYTHIA or PHOJET
- Effects of underlying event estimated using HERWIG (soft underlying event or multi-parton interactions if used in conjunction with Jimmy), PYTHIA (multi-parton interactions), PHOJET (dual topological unitarization)
  $\rightarrow$ reduced sensitivity at high jet transverse energy

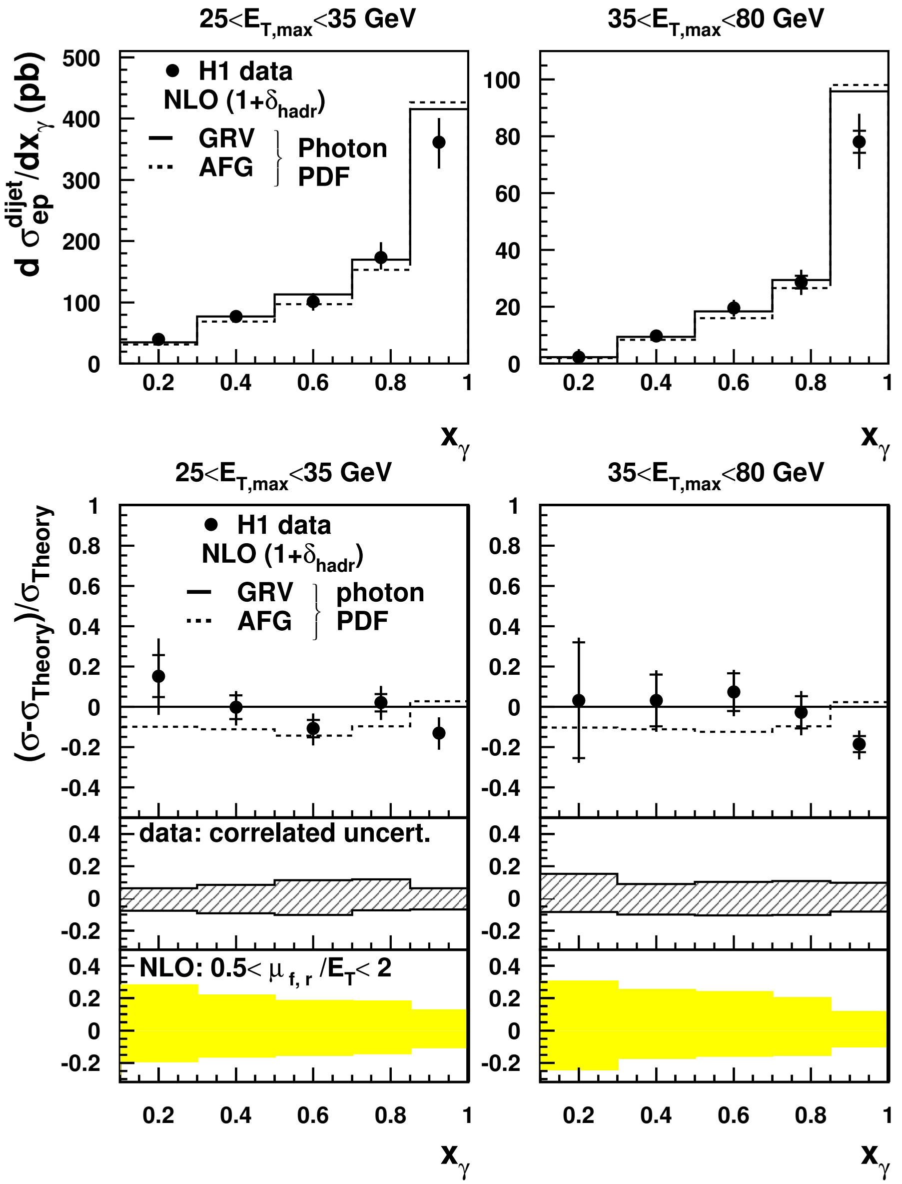
Dijet Cross Sections in Photoproduction

Dijet Production in Photoproduction (H1 Data)

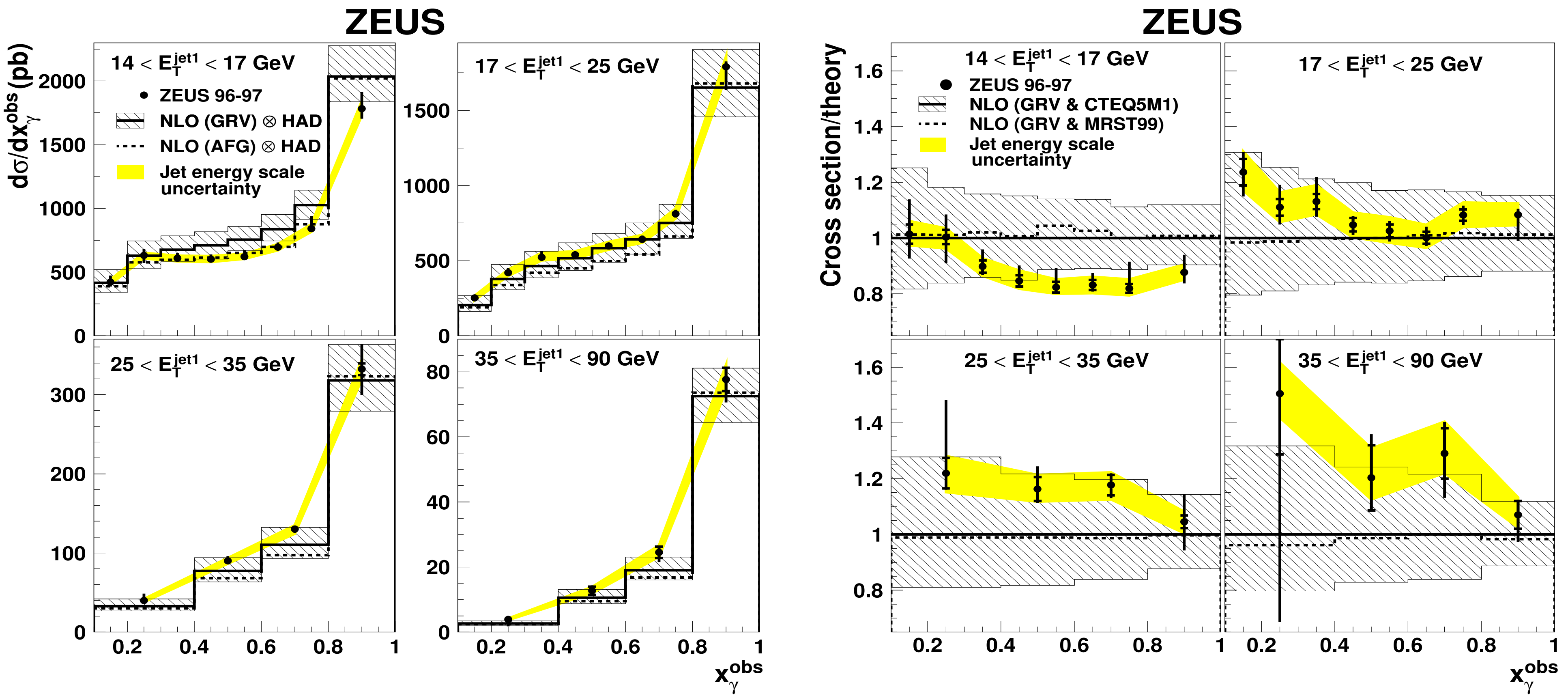
[Eur. Phys. J. C25 (2002) 1, 13]

- $Q^2 < 1$ GeV^2, $0.1 < y < 0.9$
- $E_T^{1,2} > 25, 15$ GeV, $-0.5 < \eta^{1,2} < 2.5$

- NLO describes the data well
  - → largest uncertainties:
    - terms beyond NLO (10-20%)
    - PDFs (1-15%)
- Differences due to choice of photon PDF is smaller than NLO uncertainty due to higher orders and correlated exp. uncertainties (jet energy scale)
- To constrain photon PDFs further
  - → reduction of experimental uncertainties
  - → need improved calculations



Dijet Photoproduction and Photon Structure



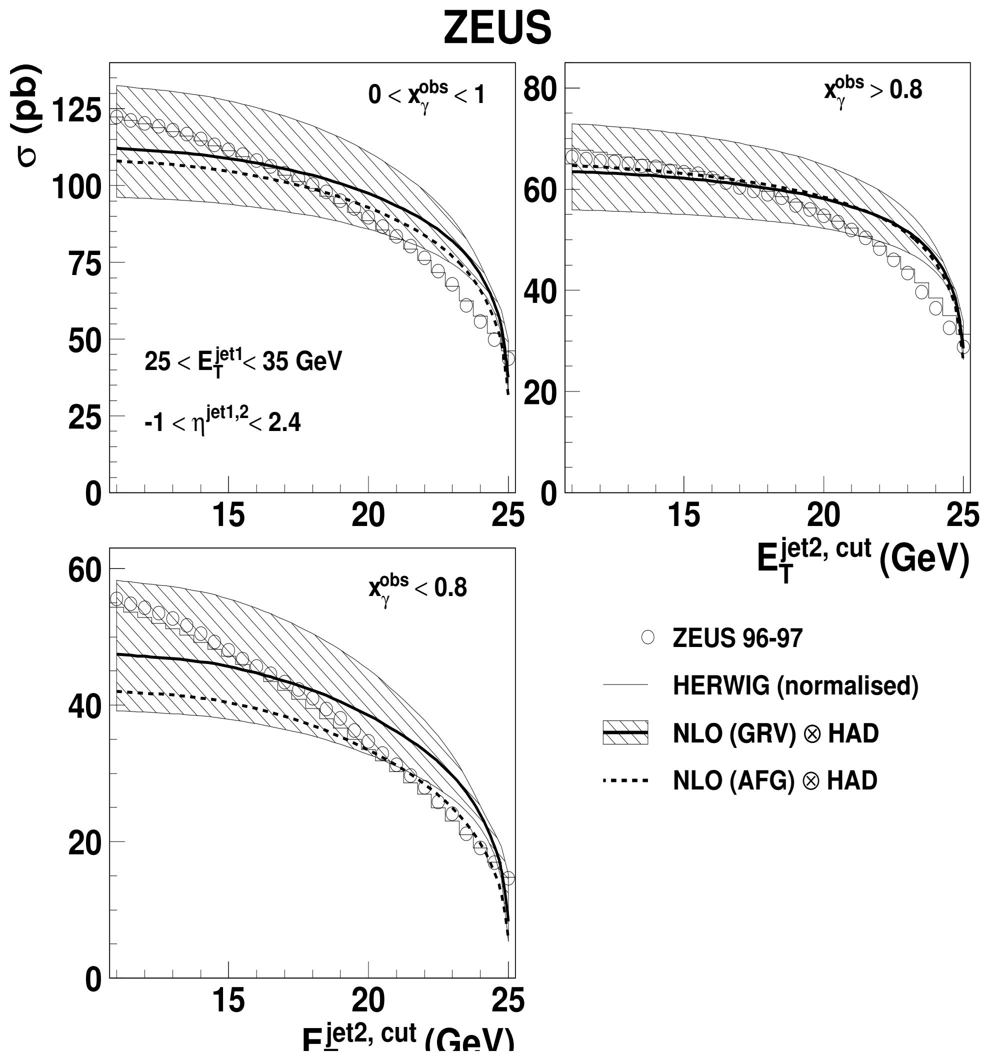
Dijet Production in Photoproduction (ZEUS Data) [Eur. Phys. J. C23 (2002) 4, 615]

- $Q^2 < 1$ GeV^2, $0.2 < y < 0.85$
- $E_T^{1,2} > 14, 11$ GeV, $-1 < \eta^{1,2} < 2.4$

- Small experimental uncertainties (jet energy scale known to 1%)
- Data lies above NLO prediction at low x_γ → contradicts H1 ?

Dependence on Cut on Second Jet

- H1 and ZEUS cuts differ:
  - → H1: $E_T^2 > 15$ GeV
  - → ZEUS: $E_T^2 > 11$ GeV
- HERWIG reproduces dependence
- Dependence of cross section not reproduced by NLO calculation
  - → comparison of data versus NLO appears to depend on cut value
  - → accounted for by large renormalisation uncertainties (just!)
- Improved theoretical understanding required
  - → higher order corrections ?
  - → resummed calculations ?
  - → improved jet selection ?



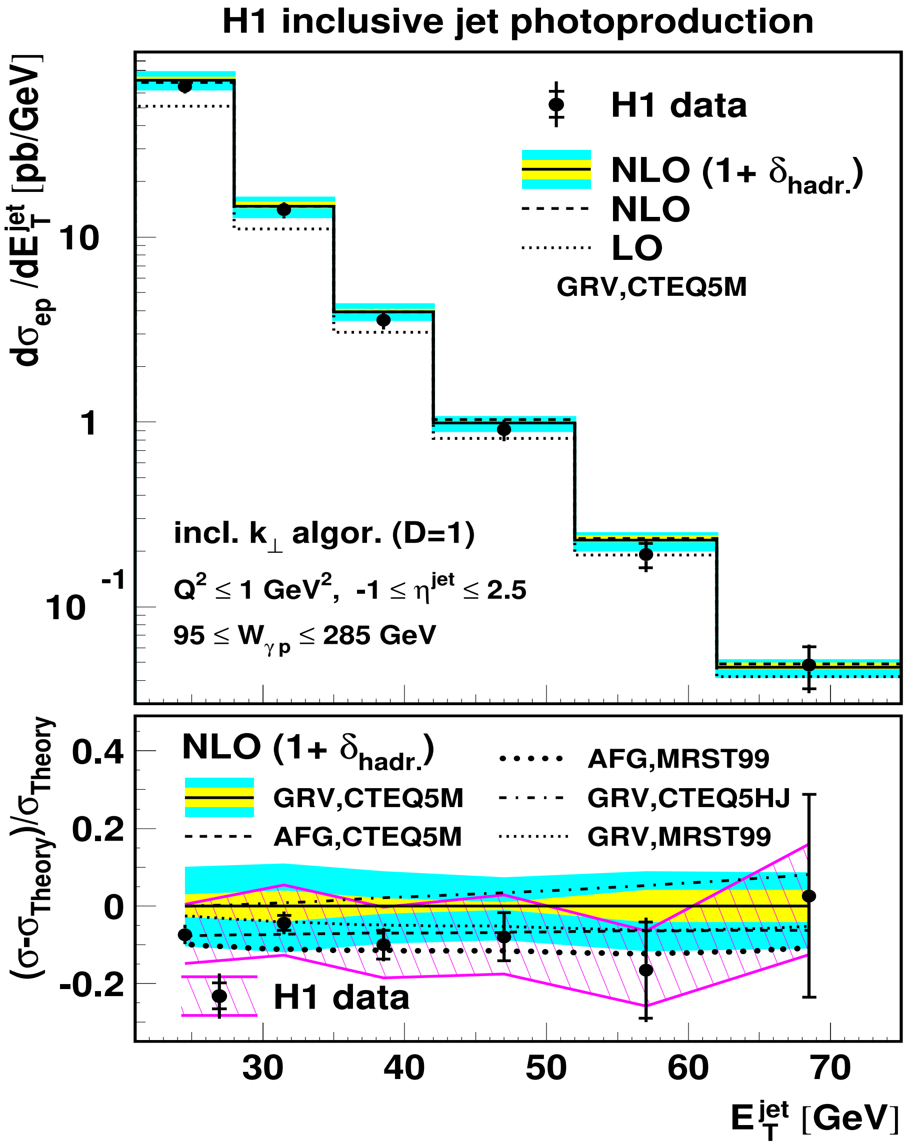
Inclusive Cross Sections in Photoproduction

Inclusive Cross Sections in Photoproduction (H1 Data)

[hep-ex/0302034]

- $Q^2 < 1$ GeV, $95 < W_{\gamma p} < 285$
- $E_T > 21$ GeV, $-1 < \eta < 2.5$

- No restriction on phase space of second jet
  $\rightarrow$ reduced theoretical uncertainties
  - more reliable QCD predictions
    BUT less complete information
    on event kinematics
- Reasonable description by NLO QCD
  $\rightarrow$ differences between different
  PDFs within uncertainties



Inclusive Cross Sections in Photoproduction and α_s

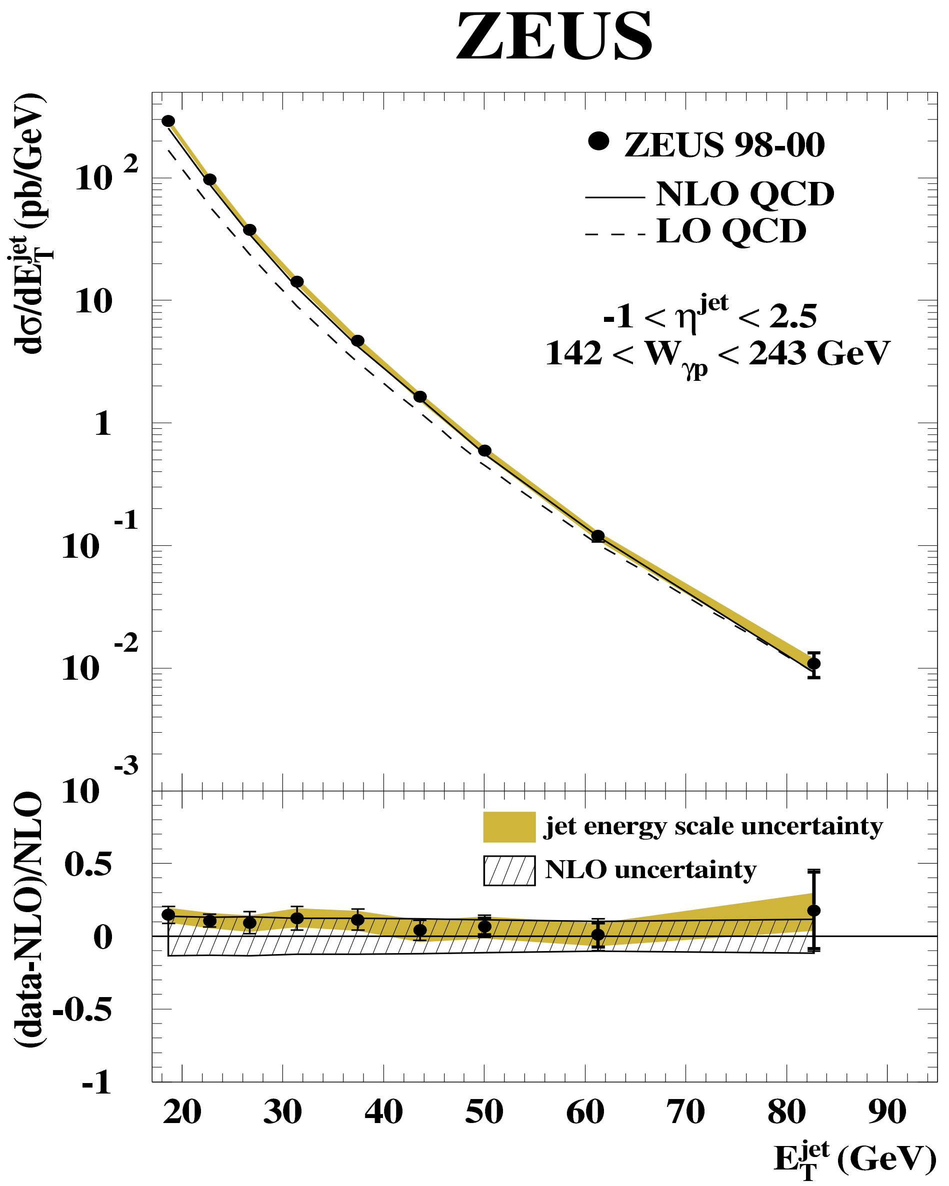
Inclusive Cross Sections in Photoproduction (ZEUS Data)

[Phys. Lett. B560 (2003) 7]

- $Q^2 \leq 1$ GeV, $0.2 < y < 0.85$
- $E_T > 17$ GeV, $-1 < \eta < 2.5$

- Small theoretical uncertainties
- Good agreement with NLO over many orders of mag.

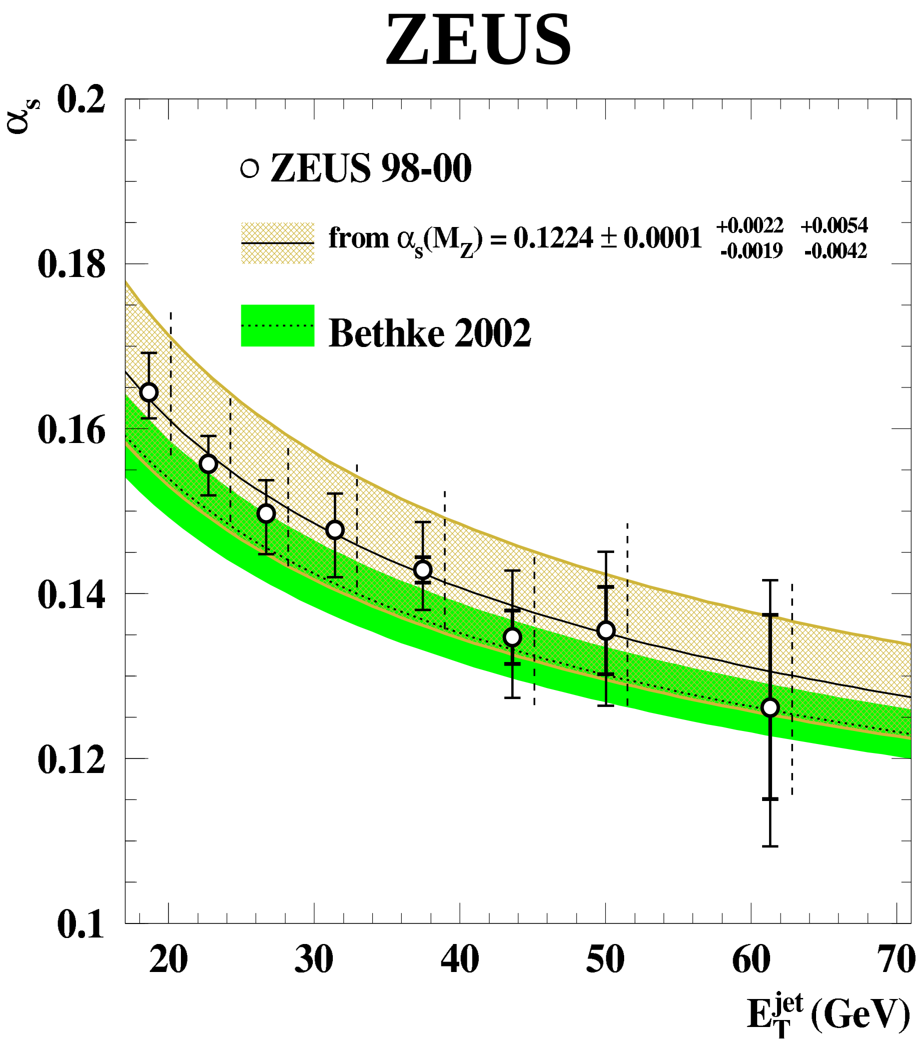
  $\rightarrow$ Determination of α_s



ISMD, Krakow, 5–11 September 2003

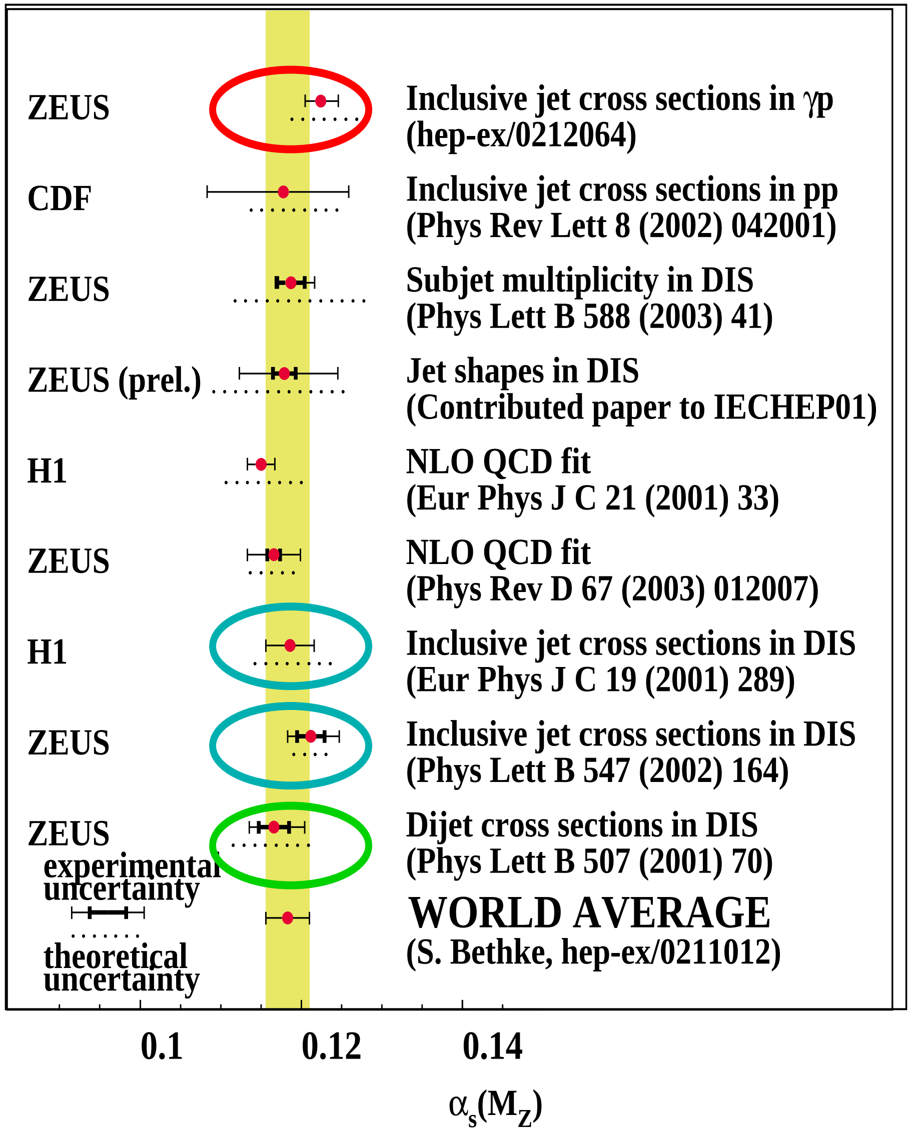
Extraction of α_s

- α_s extracted in each E_T bin using MRST99 PDF sets
  - $\rightarrow$ first extraction in photoproduction!
  - $\rightarrow$ running clearly observed
  - $\rightarrow$ at Z^0 mass:
    - $\alpha_s(M_Z) = 0.1224 \pm 0.0001(\text{stat.})^{+0.0022}_{-0.0019}(\text{exp.})^{+0.0054}_{-0.0042}(\text{theory})$
  - $\rightarrow$ consistent with recent fit of Bethke
    - theory error still dominates



Comparison with Other Measurements

- All values consistent with other recent measurements and Bethke world average
- Competitively small experimental uncertainties



Summary and Outlook

- HERA is producing a wealth of precision jet data in DIS, transition region and photoproduction
- Many extractions of α_s with competitive precision
  $\rightarrow$ running behaviour clearly observed
- At high Q^2 and jet transverse energy, theoretical uncertainties are small and pQCD is able to reproduce cross sections over many orders of magnitude
- At lower Q^2 (transition region, photoproduction), theoretical uncertainties are dominant
  $\rightarrow$ new theoretical developments, resummed calculations needed
- Experimental precision and coverage of data is now good
  $\rightarrow$ include in global PDF fits