Review of HERA Jet Results

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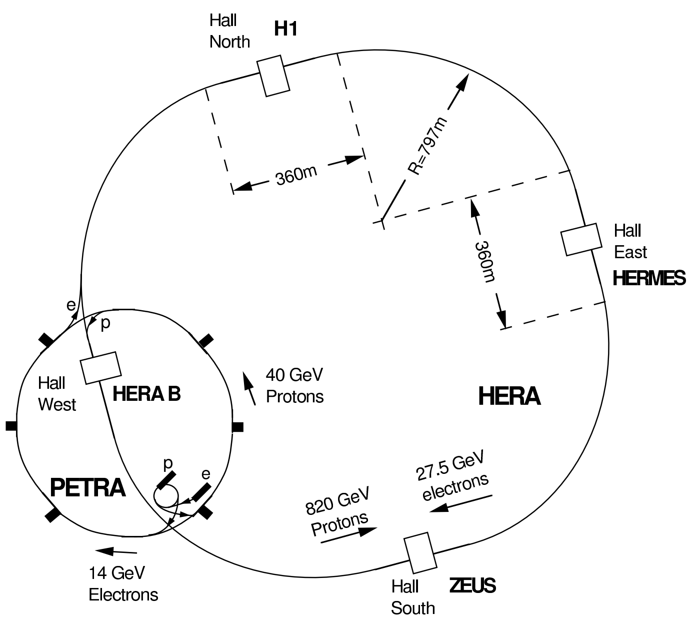
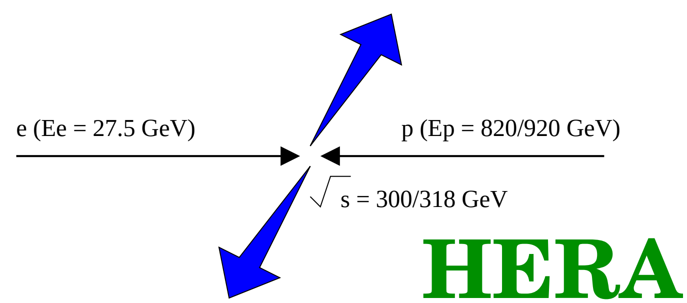
On behalf of the ZEUS and H1 Collaborations





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:

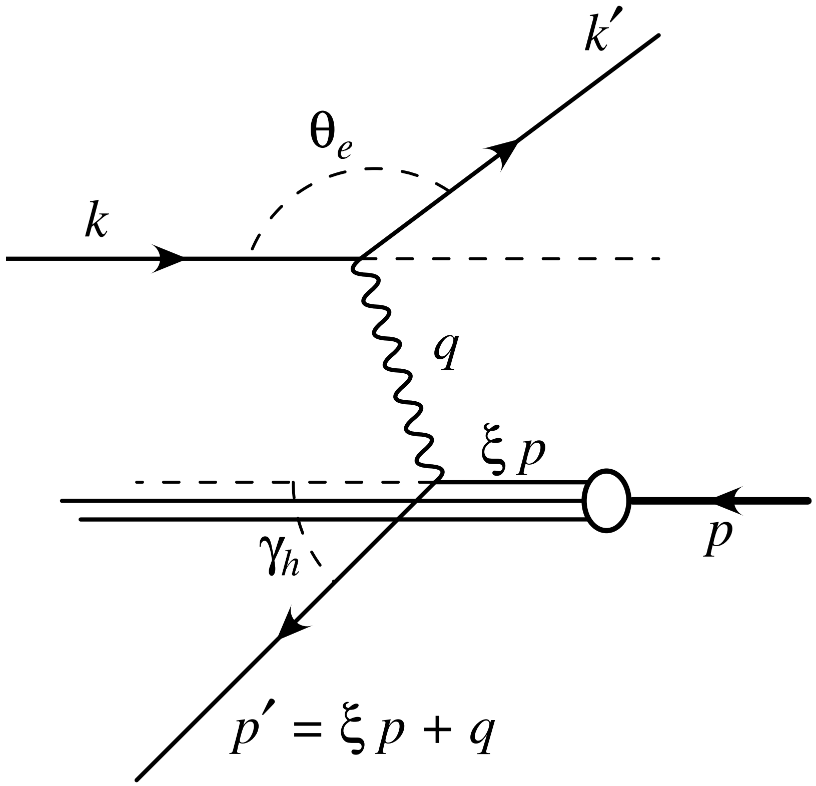
$$Q^2 = -q^2 = -(k - k')^2$$

- Bjorken scaling variable:

$$x \equiv \frac{Q^2}{2p.q}$$

- Inelasticity:

$$y \equiv \frac{p.q}{p.k}$$

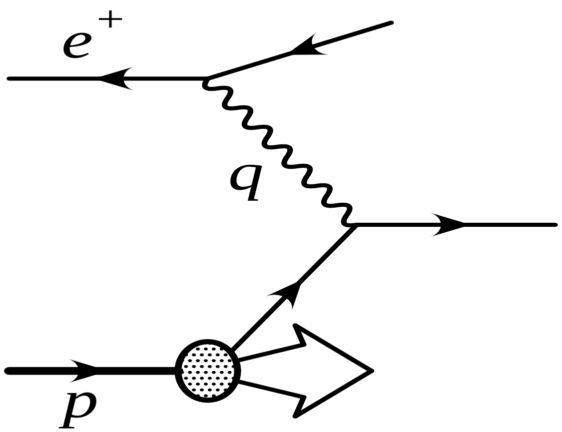


Only need two out of three variables since $Q^2 = sxy$

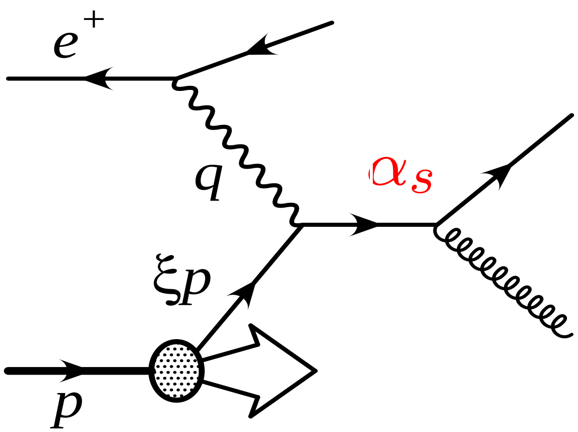
Jet Production in Deep Inelastic Scattering

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

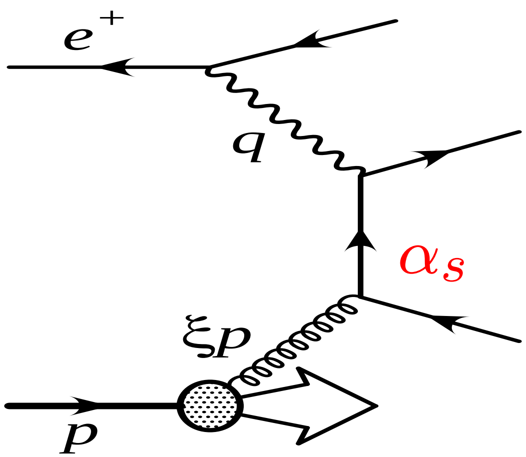
Quark-Parton Model



QCD Compton



Boson-Gluon fusion



- Jet production cross section:

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

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

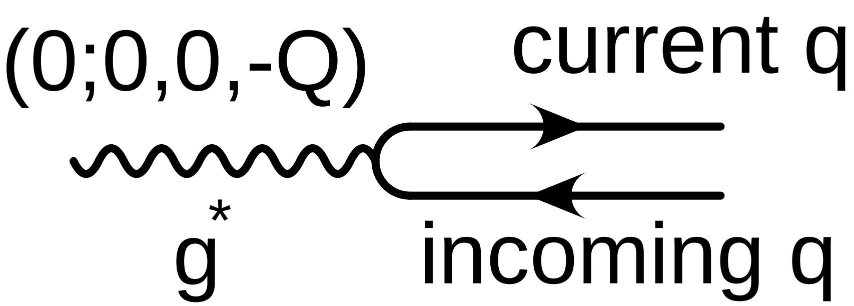
Jet Production in Deep Inelastic Scattering

- 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

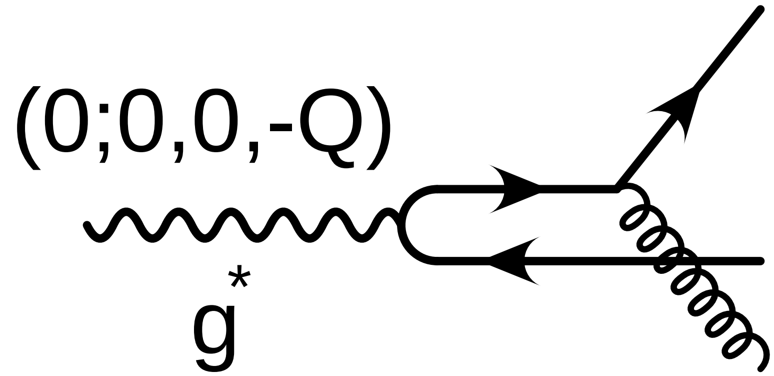
  → To provide stringent tests of pQCD predictions and precise determinations of α_s
  - Need observables for which the predictions are directly proportional to α_s
    - → Jet cross sections in the Breit frame (defined on next slide)
  - Small experimental uncertainties → jets with relatively high tranverse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

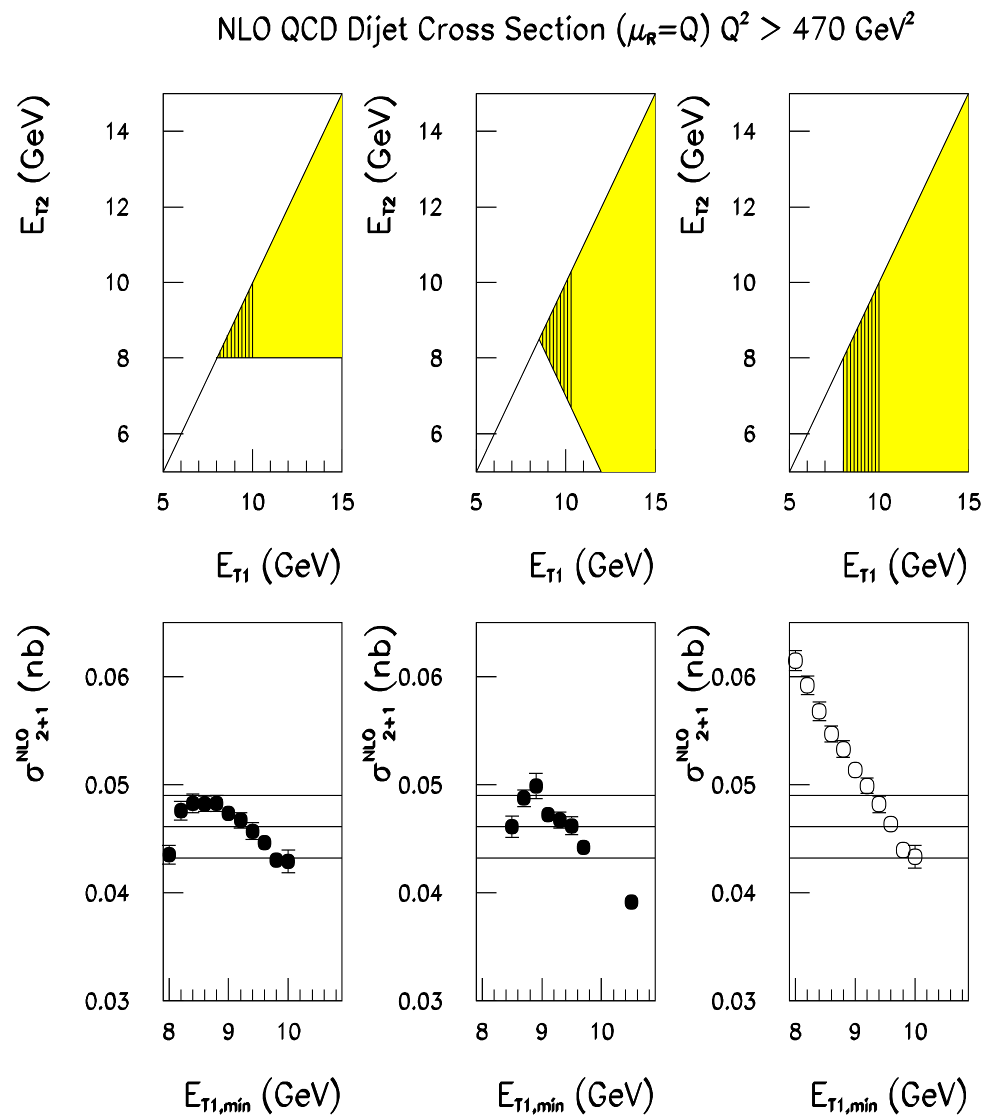
NLO QCD Calculations for Jets in NC DIS

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

Infrared Sensitivity to Jet Selection in NLO Calculations

- Dijet Selection Criteria:
  - → Symmetric cuts on $E_T^{\text{jet1,2}}$
    DANGER! → unphysical dependence
  - → Symmetric cuts on $E_T^{\text{jet1,2}}$ and cut on sum $(E_T^{\text{jet1}} + E_T^{\text{jet2}})$
  - → Asymmetric cuts on $E_T^{\text{jet1,2}}$



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

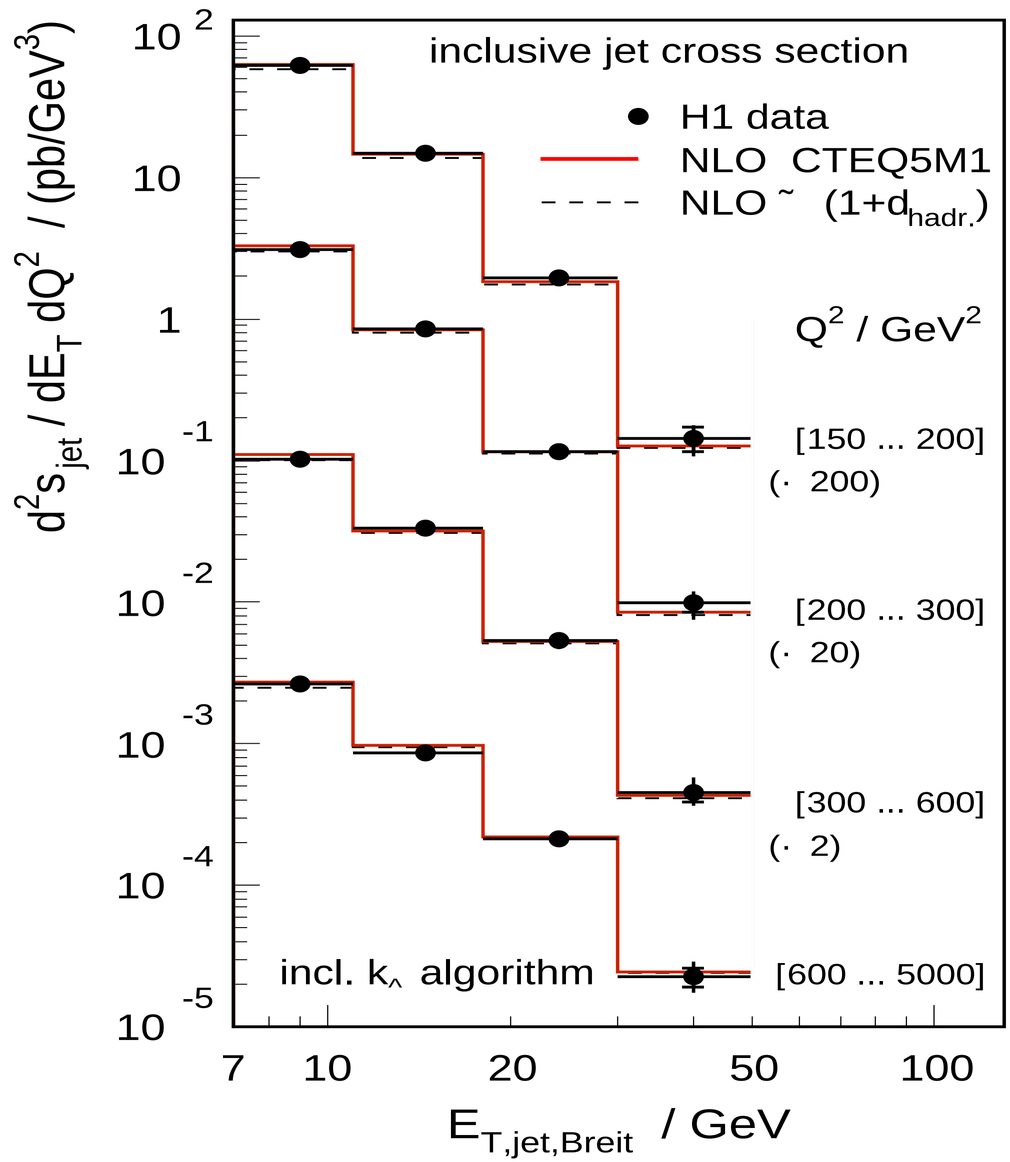
This complication is absent for inclusive jet cross sections!

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)

  → infrared insensitive

  → 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)

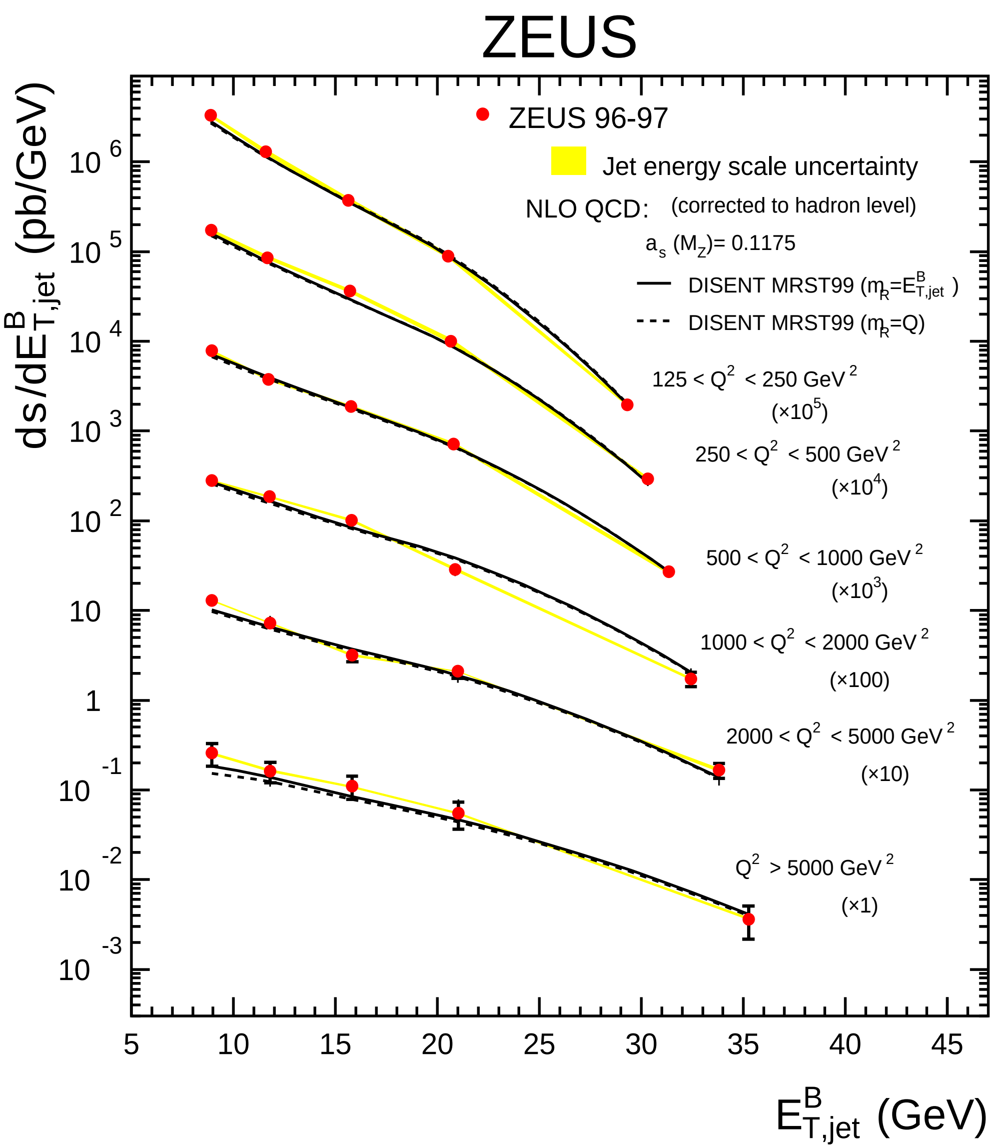
[Abs. 507, EPS03, Aachen, Germany]

- $Q^2 > 125$ GeV^2
- $E_T^{\rm Breit} > 8$ GeV
- $-2 < \eta^{\rm Breit} < 1.8$

→ NO cuts applied in lab. frame

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

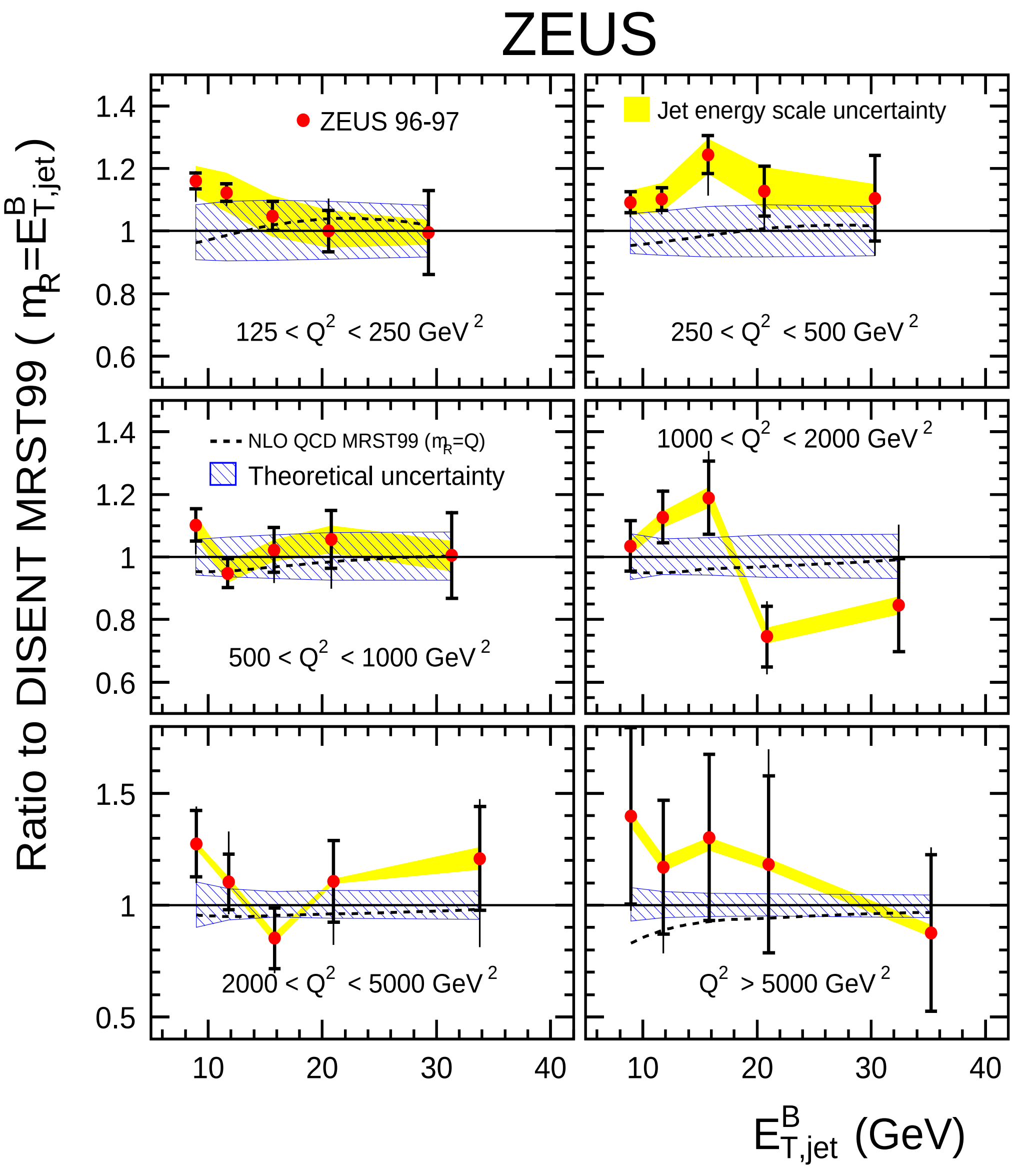
Precision test of the description of the dynamics of inclusive jet production by pQCD at $\mathcal{O}(\alpha\alpha_s^2)$



Inclusive Jet Production at High-E_T in NC DIS

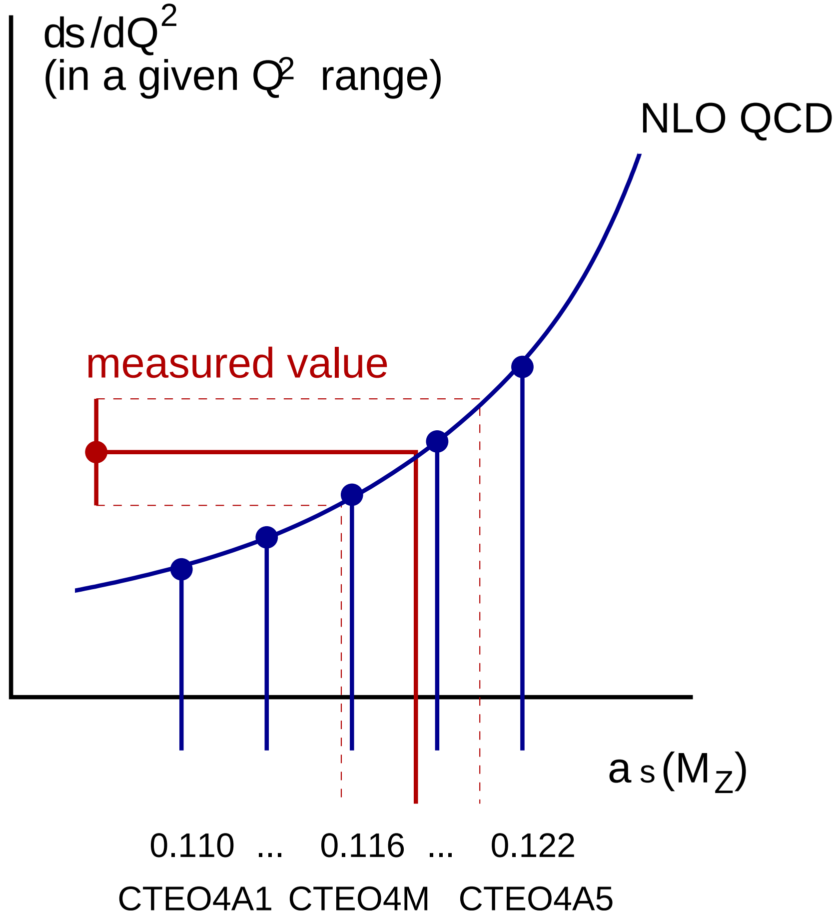
- Small theoretical uncertainties:
  - $\rightarrow$ high order terms (>NLO); $E_T^{\text{Breit}}/2 < \mu_R < 2E_T^{\text{Breit}} \Rightarrow \pm 5\%$
  - $\rightarrow$ uncertainty on $\alpha_s(M_Z)$ (± 0.003) $\Rightarrow \pm 5\%$
  - $\rightarrow$ uncertainties on the proton PDFs
    - – experimental 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_T^{Breit} data lie above NLO QCD
- Overall, agreement is reasonable within experimental and theoretical uncertainties

  $\rightarrow$ extraction of α_s is possible

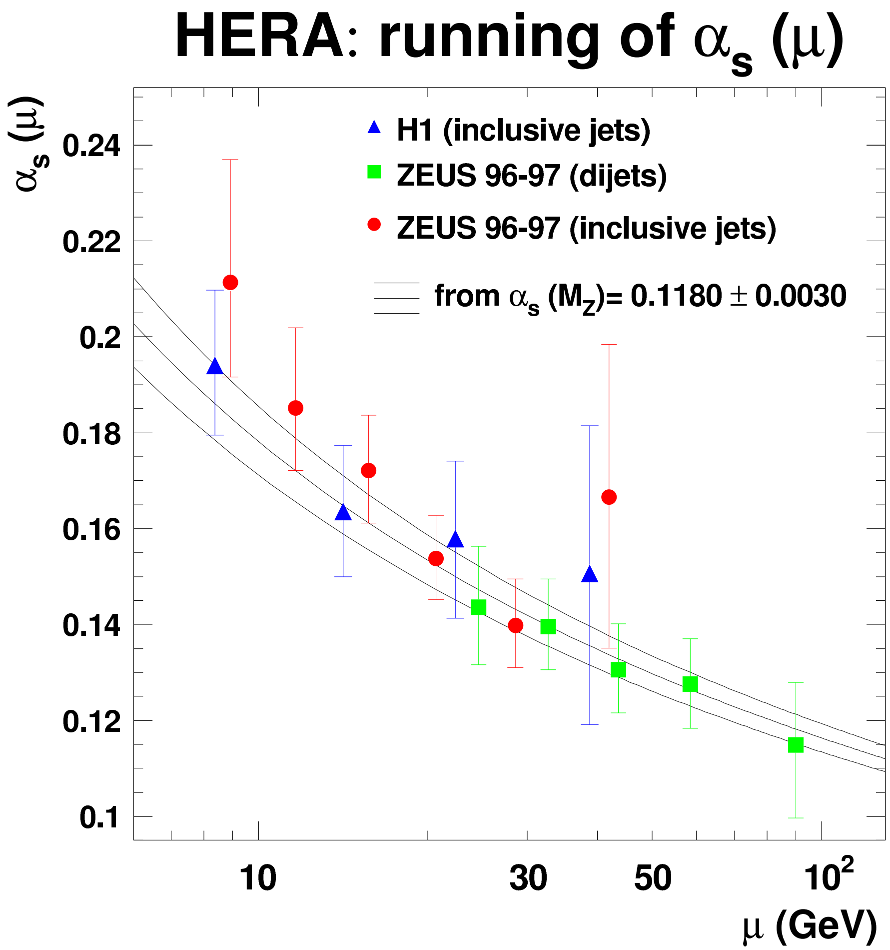


Extraction of the QCD Coupling α_s

- NLO QCD calculations of $d\sigma/dQ^2$ depend on $\alpha_s(M_Z)$ through:
  - → matrix elements: $\hat{\sigma} \sim A.\alpha_s + B.\alpha_s^2$
  - → 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

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

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

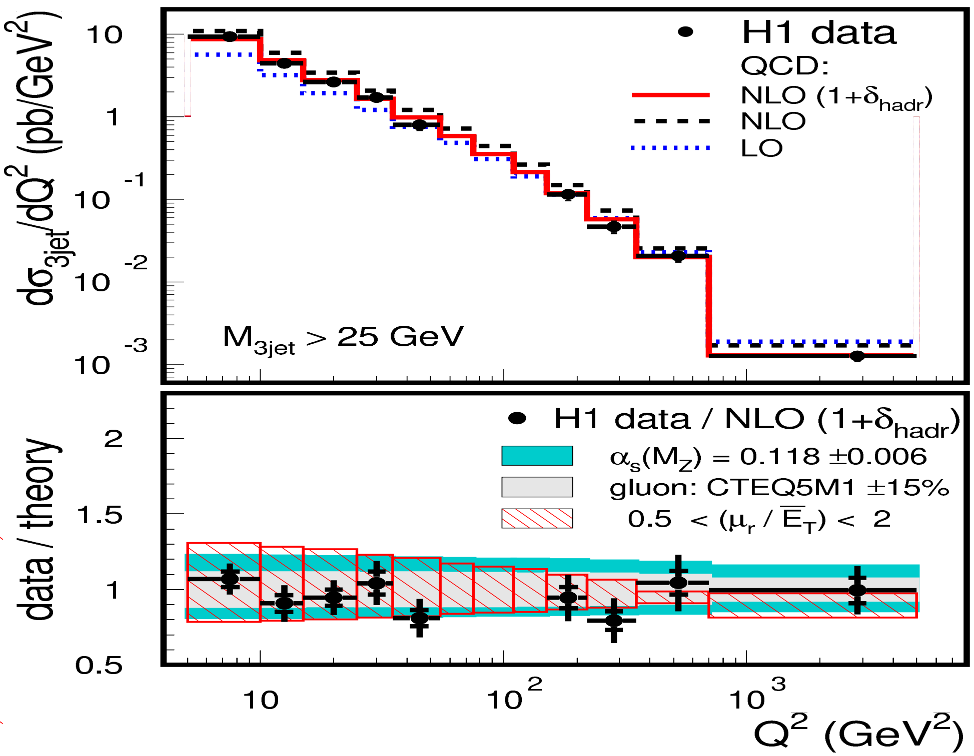
  → ZEUS value ($Q^2 > 125$ GeV^2):

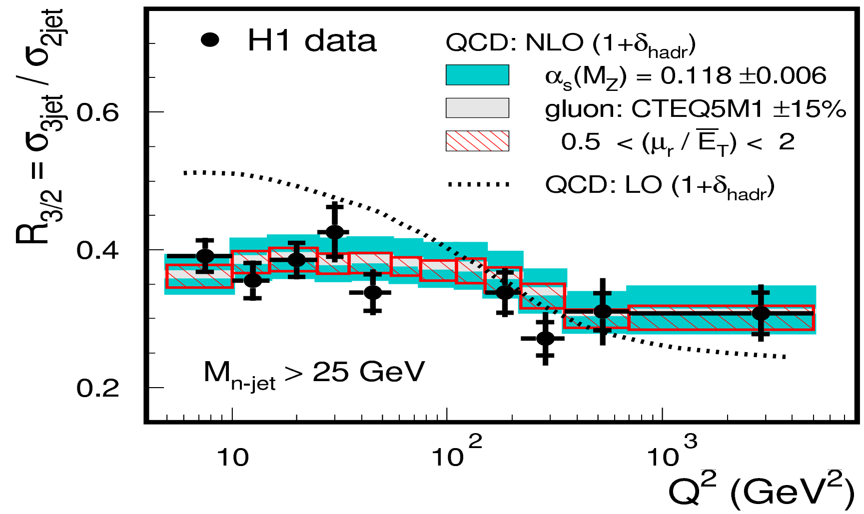
  $$\alpha_s(M_Z) = 0.1212 \pm 0.0017(\text{exp.}) {}^{+0.0023}_{-0.0031}(\text{theory}) {}^{+0.0028}_{-0.0027}(\text{pdf})$$

- Dominant uncertainties from theory:
  - → terms beyond NLO $\sim 3\%$
  - → uncertainties in proton PDF $\sim 1\%$
  - → 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





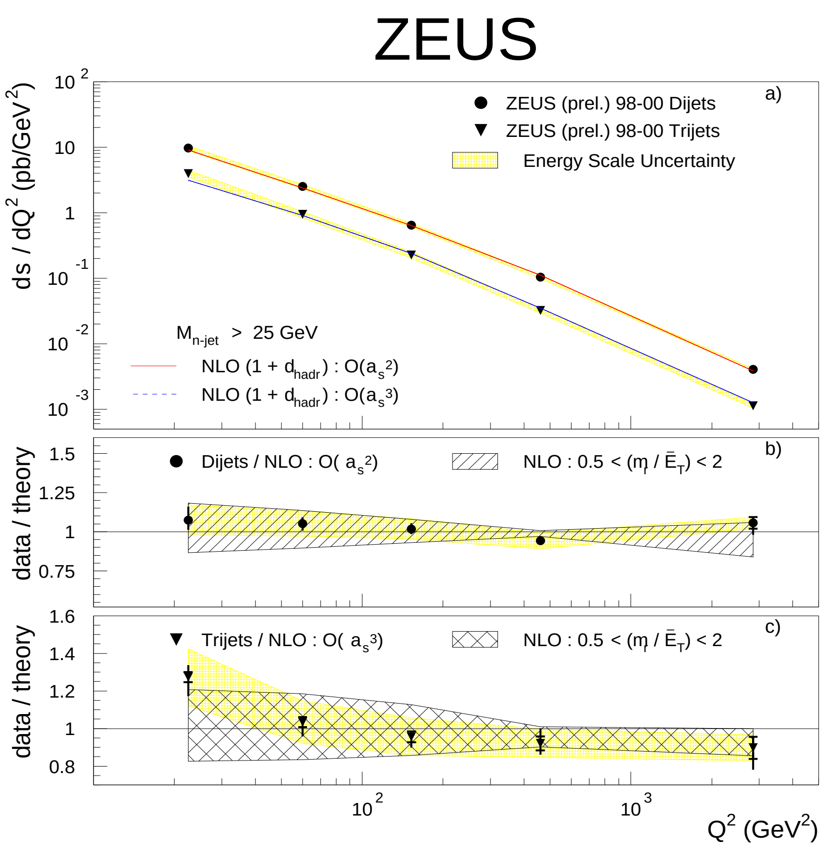
Three-Jet Production (H1 Data)

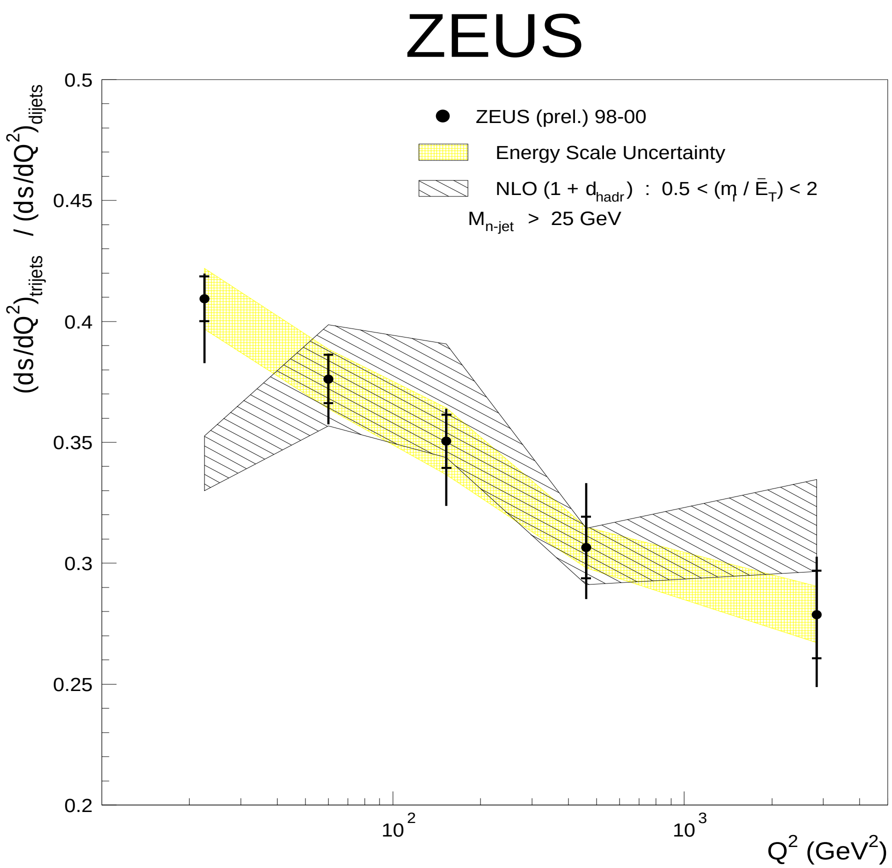
[Phys. Lett. B515 (2001) 17]

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

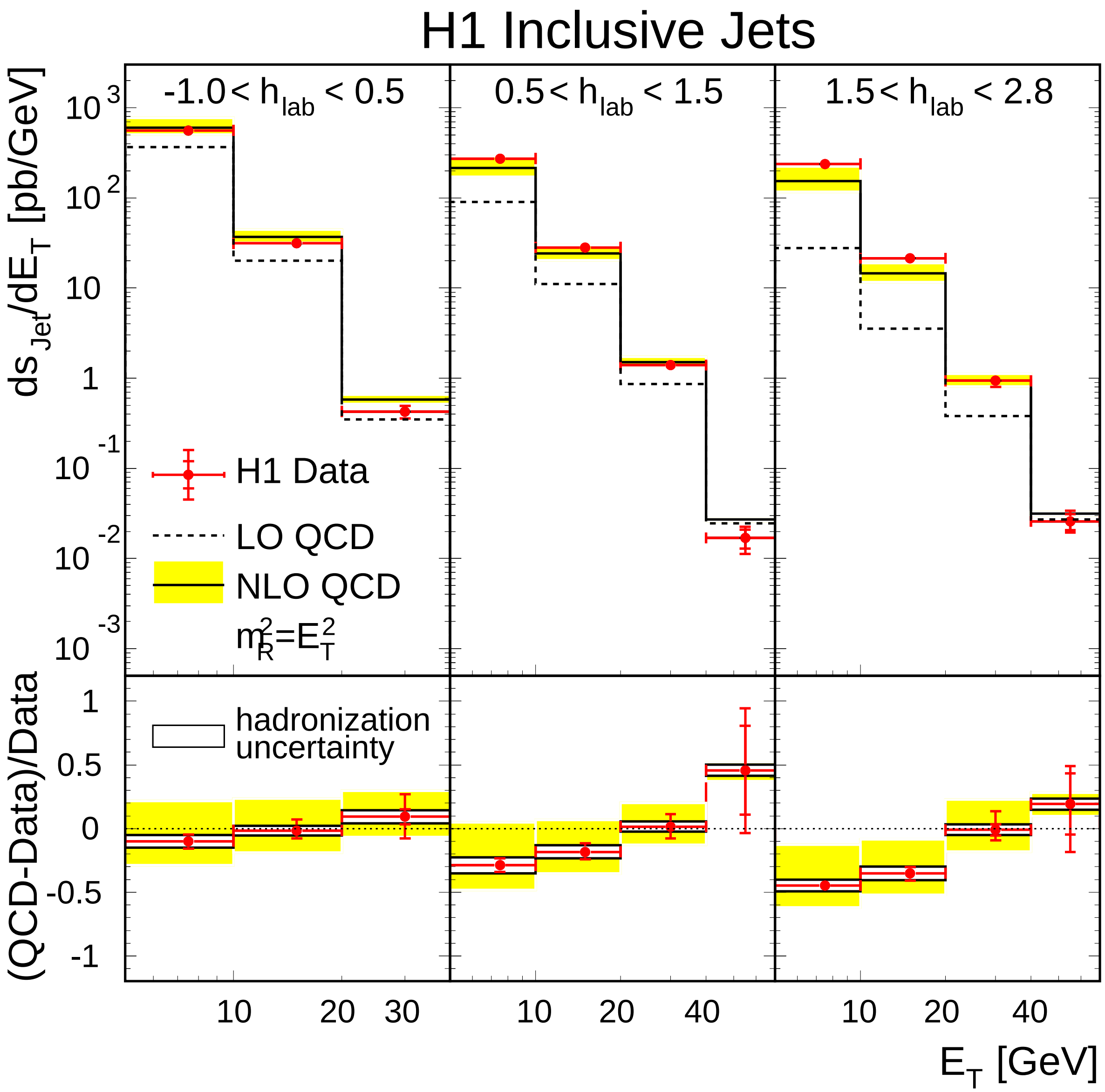
[Abs. 504, EPS03, Aachen, Germany]

- $10 < Q^2 < 5000$ 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 → Lower Q^2



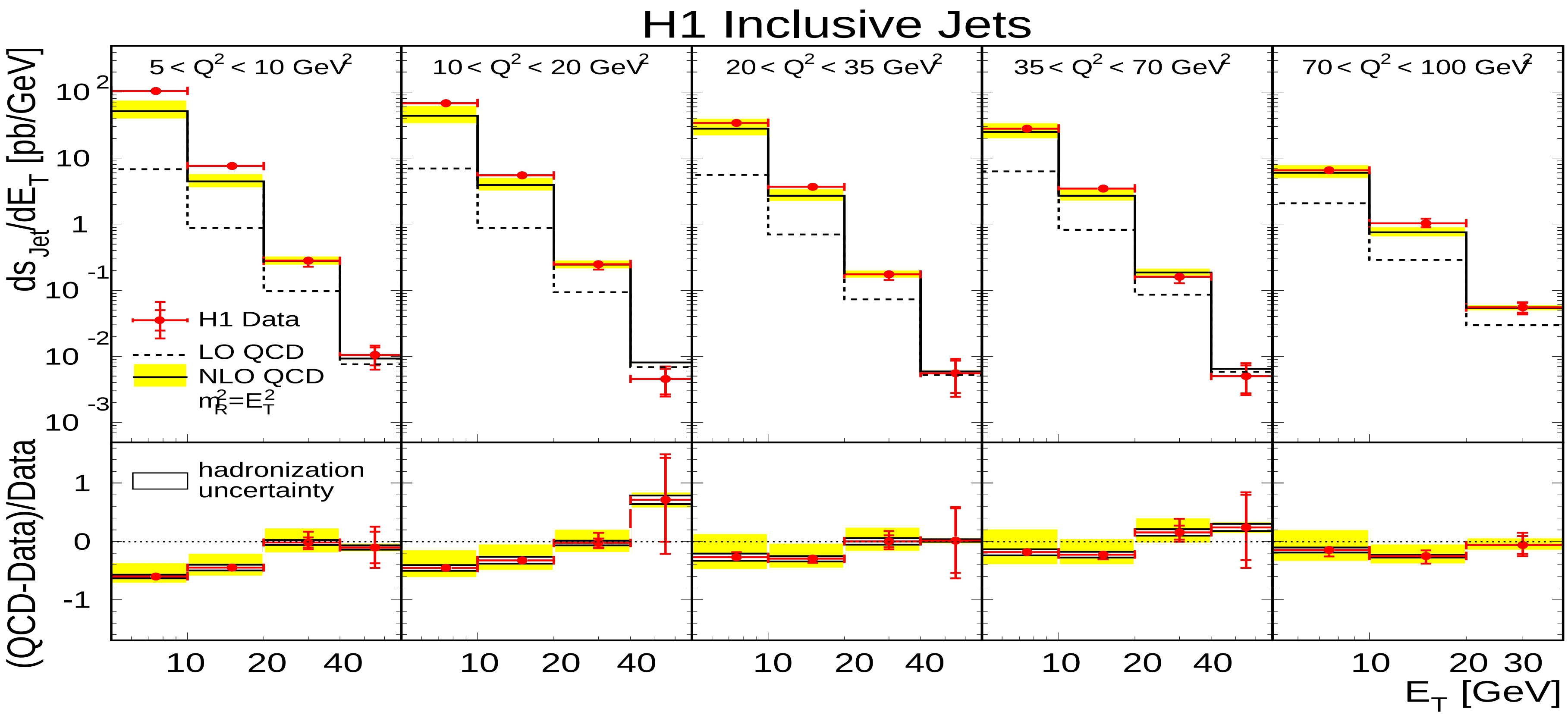
Inclusive Production in the Breit Frame (H1 Data)

[Phys. Lett. B542 (2002) 193]

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

- Good description in the region $-1 < \eta < 0.5$
- NLO is below data at low E_T and forward η^{Lab}
  → 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)

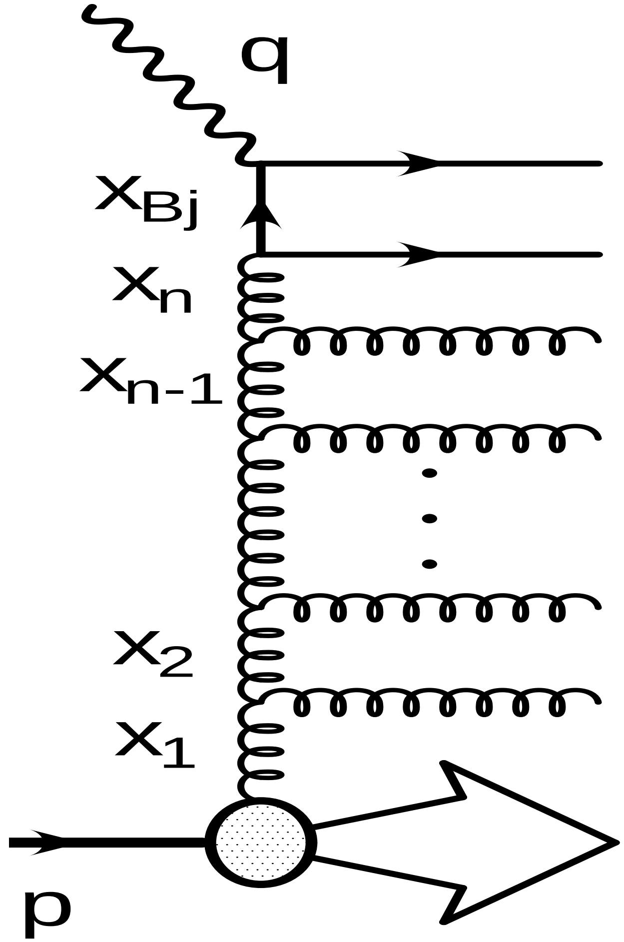
- Discrepancy between data and NLO large at low Q^2 and low E_T

  → 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

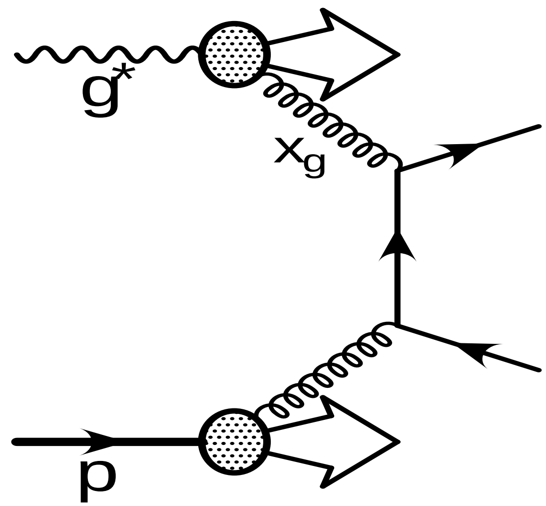


CCFM is another evolution scheme which reduces to DGLAP at high Q^2 and to BFKL at low x

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

Virtual Photon Structure in Two Jet Production → Low Q^2

- In two jet production, at low Q^2, $E_T^{jet} \gg Q$
  - → large logarithmics $\ln E_T/Q$ can be resummed by defining PDFs for a **virtual photon** in a similar fashion as for the proton
  - → photon can interact directly
  - → or photon can interact via a parton → with some momentum fraction $x_\gamma < 1$



- Possible contribution from longitudinally polarised "resolved" photons
  - → vanishes as $Q^2 \to 0$ and $y \to 1$

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

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

→ $x_\gamma^{OBS} < 0.75$ is resolved enhanced

→ $x_\gamma^{OBS} > 0.75$ direct enhanced

- Virtual photon PDF parameterisations:
  - → interpolate between:
    - leading log part of real photon PDFs ($\ln E_T/\Lambda_{QCD}$)
    - asymptotic behaviour predicted by pQCD ($\ln E_T/Q$)
  - → parameterisations: Drees & Godbole, Schuler & Sjöstrand, Glück et al.

Virtual Photon Structure

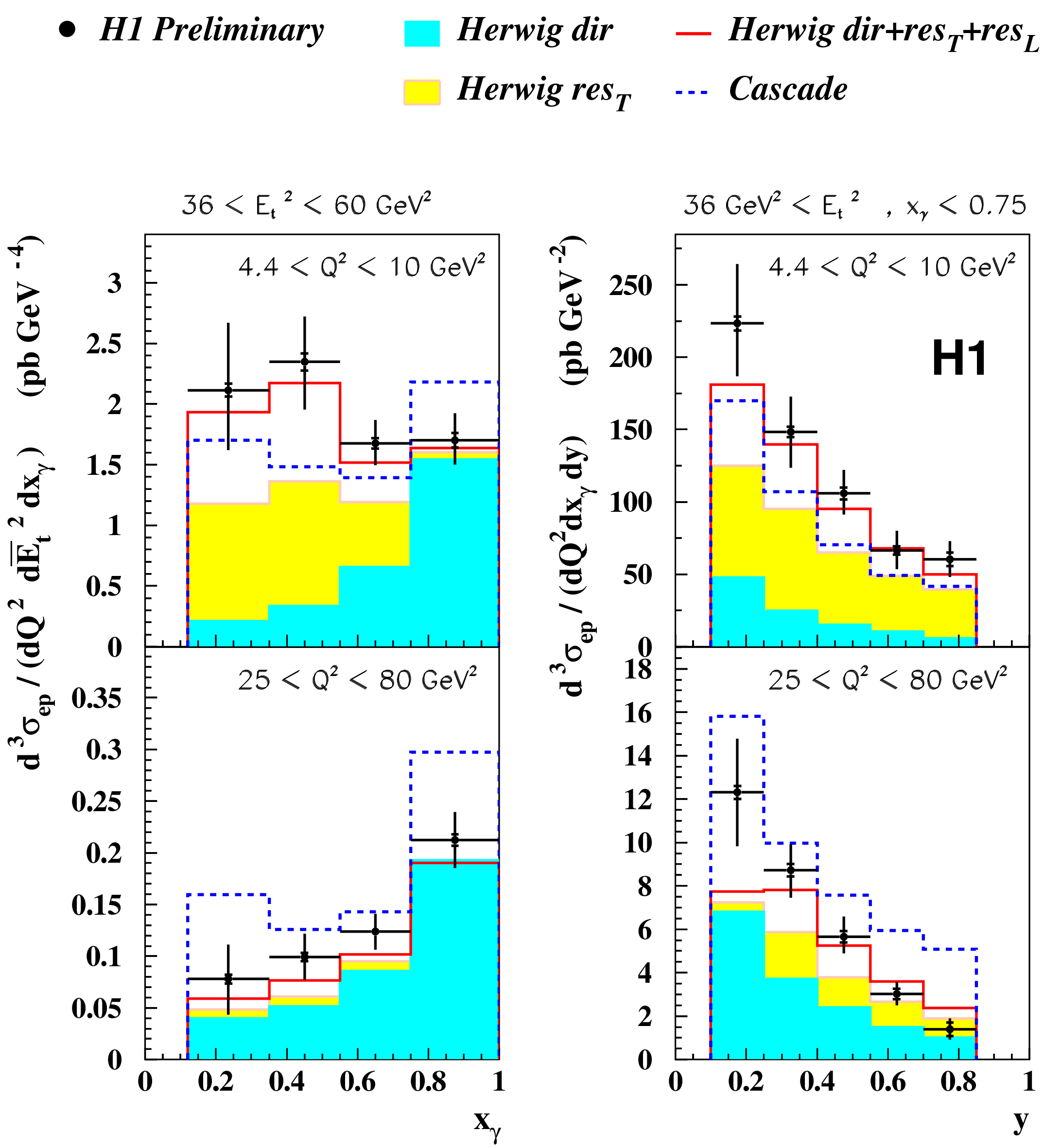
Virtual Photon Structure (H1 Data)
(in $\gamma^* p$ centre-of-mass system)

[Abs. 085, EPS03, Aachen, Germany]

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

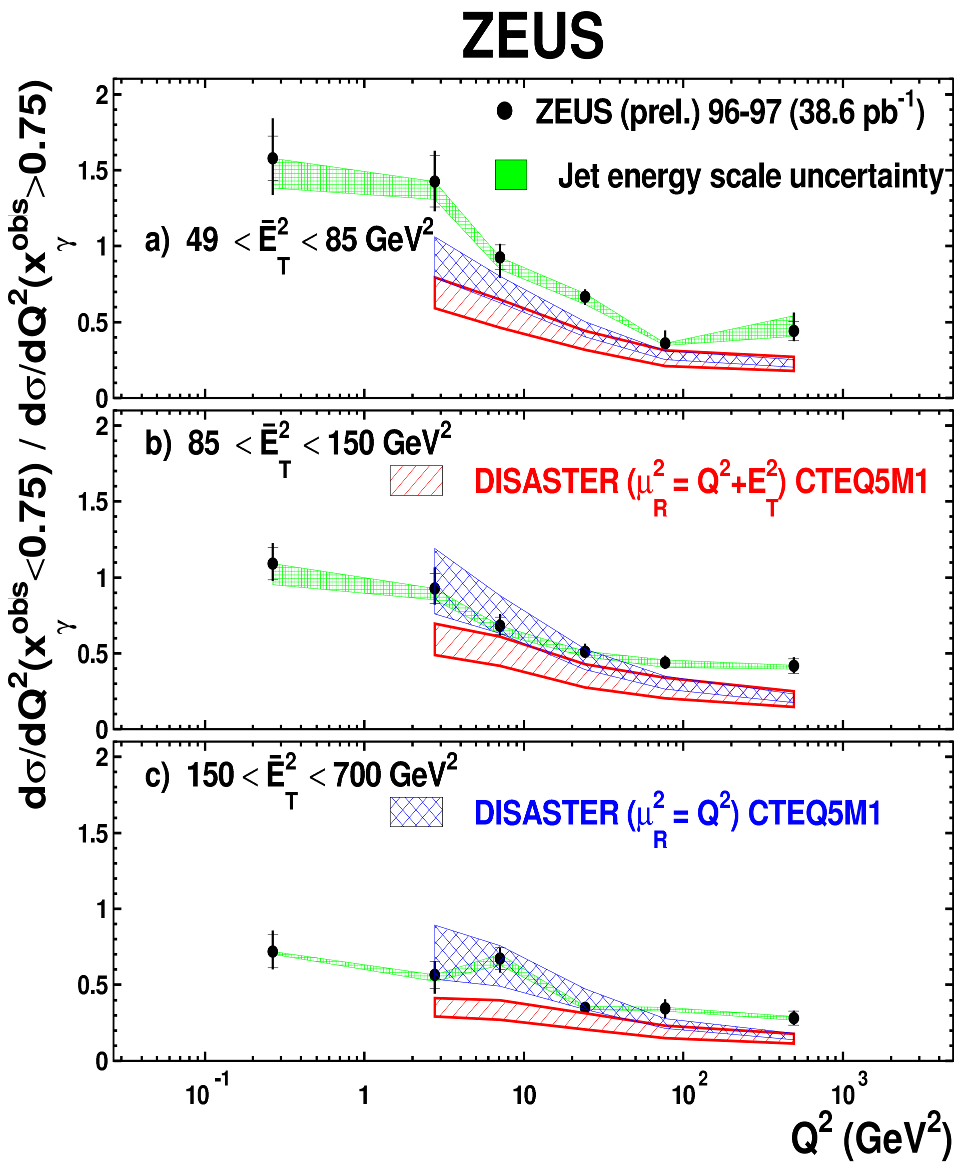
- As Q^2 increases at fixed $\bar{E}_T$ the $x_\gamma < 0.75$ cross section ("resolved" photon) decreases
- Models incorporating:
  - → only "direct" photon contribution
  - → trans. polarised "resolved" photon
  - → long. polarised "resolved" photon

  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):
  - → contains no resolved photon
  - → 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 virtual photon
- Need additional/improved calculations ...



Virtual Photon Structure (ZEUS Data)

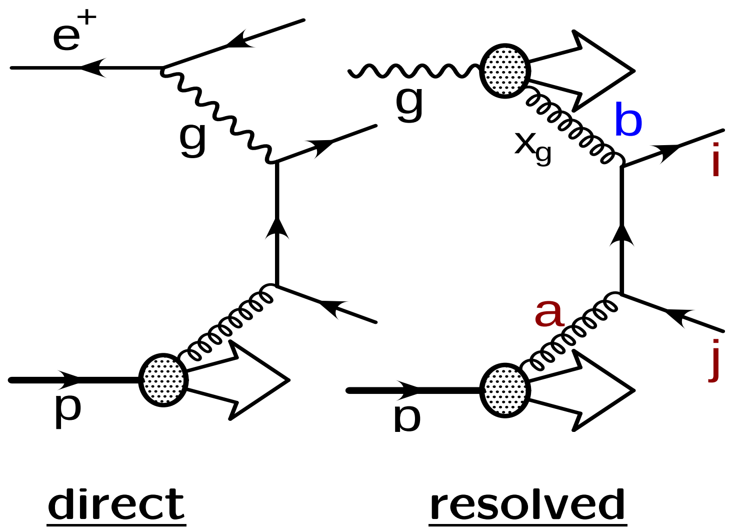
[Abs. 585, EPS03, Aachen, Germany]

- $0.1 < Q^2 < 2000$ 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:

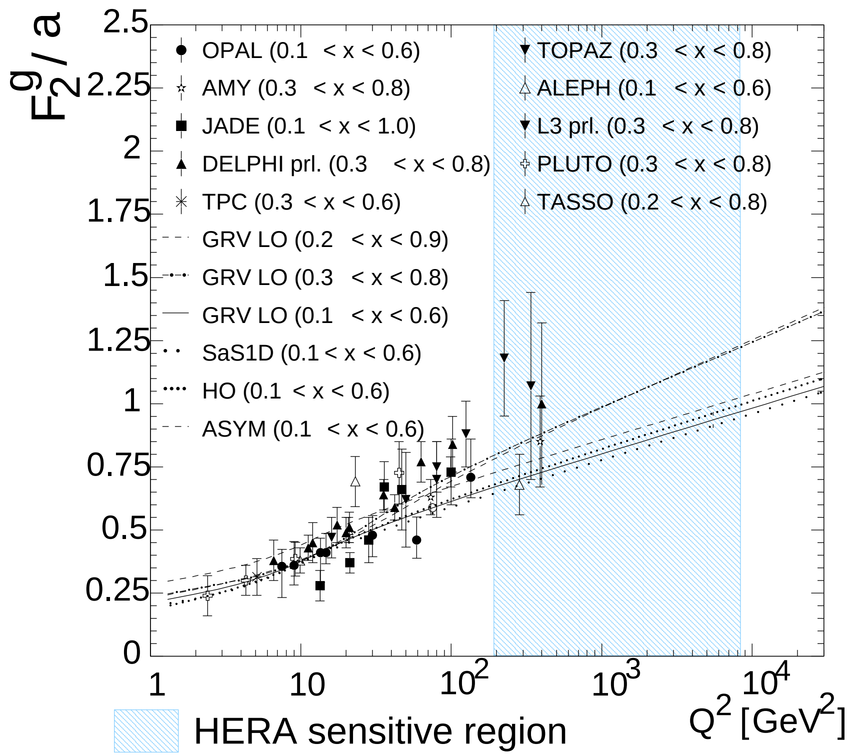
→ Photon structure determined from fits to F_2^γ in e-γ DIS at e^+e^- colliders

→ only sensitive to quark distribution at LO

$\Rightarrow$ 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)

→ Klasen & Kramer, Harris & Owens, Frixione & Ridolfi, Aurenche et al.

- Longitudinally invariant k_T cluster algorithm in the $\eta - \phi$ plane of the lab. frame
  - → asymmetric dijet E_T cuts, cut on invariant mass (m_{JJ})
- Jet photoproduction has one hard scale E_T ($Q^2 \approx 0$)
  - → renormalisation and factorisation scales $\mu_R, \mu_F = E_T$
- Available PDF parameterisations (NLO fits)
  - → Proton: CTEQ5M, CTEQ5HJ, MRST99
  - → Photon: GRV-HO, AFG-HO
- Calculations at parton level ⇒ corrected for hadronisation effects
  - → 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)
  - → reduced sensitivity at high jet transverse energy

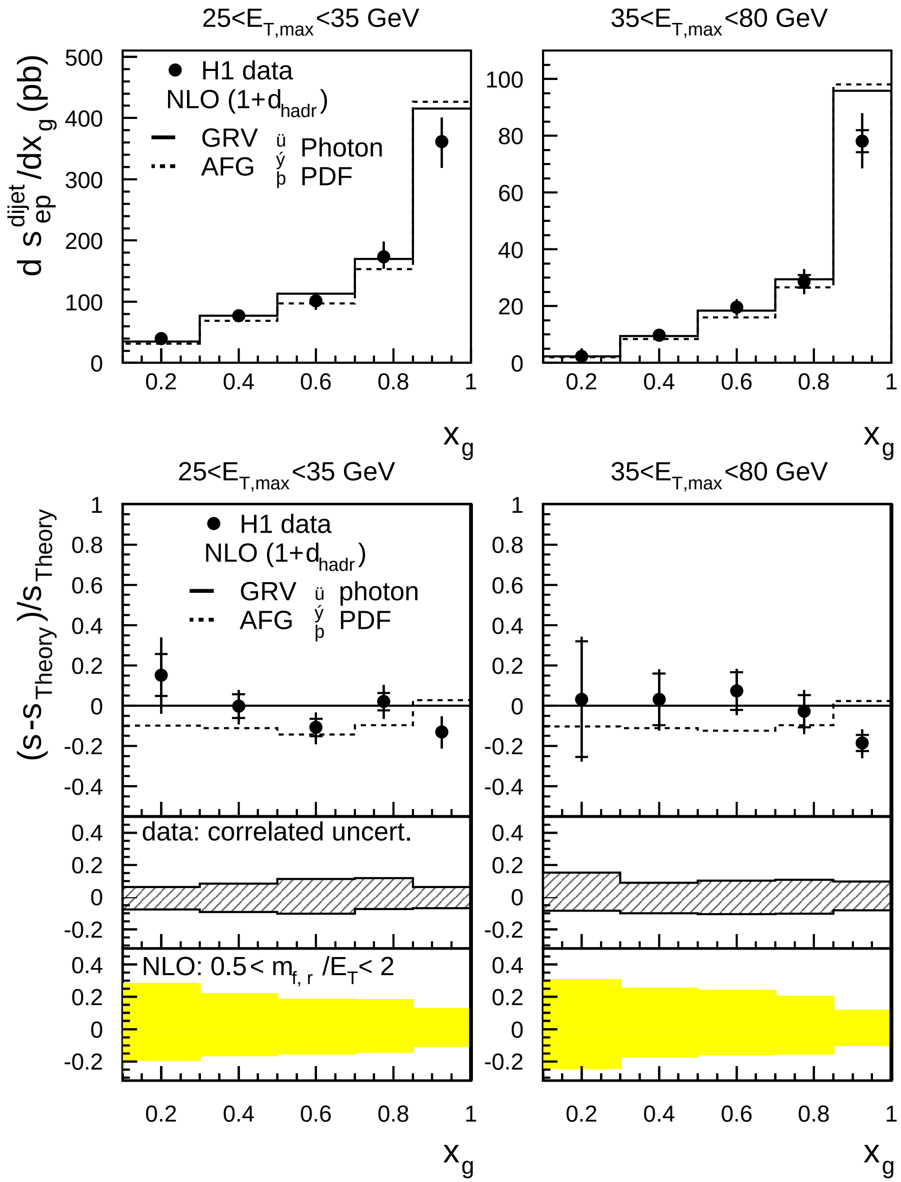
Dijet Cross Sections in Photoproduction

Dijet Production in Photoproduction (H1 Data)

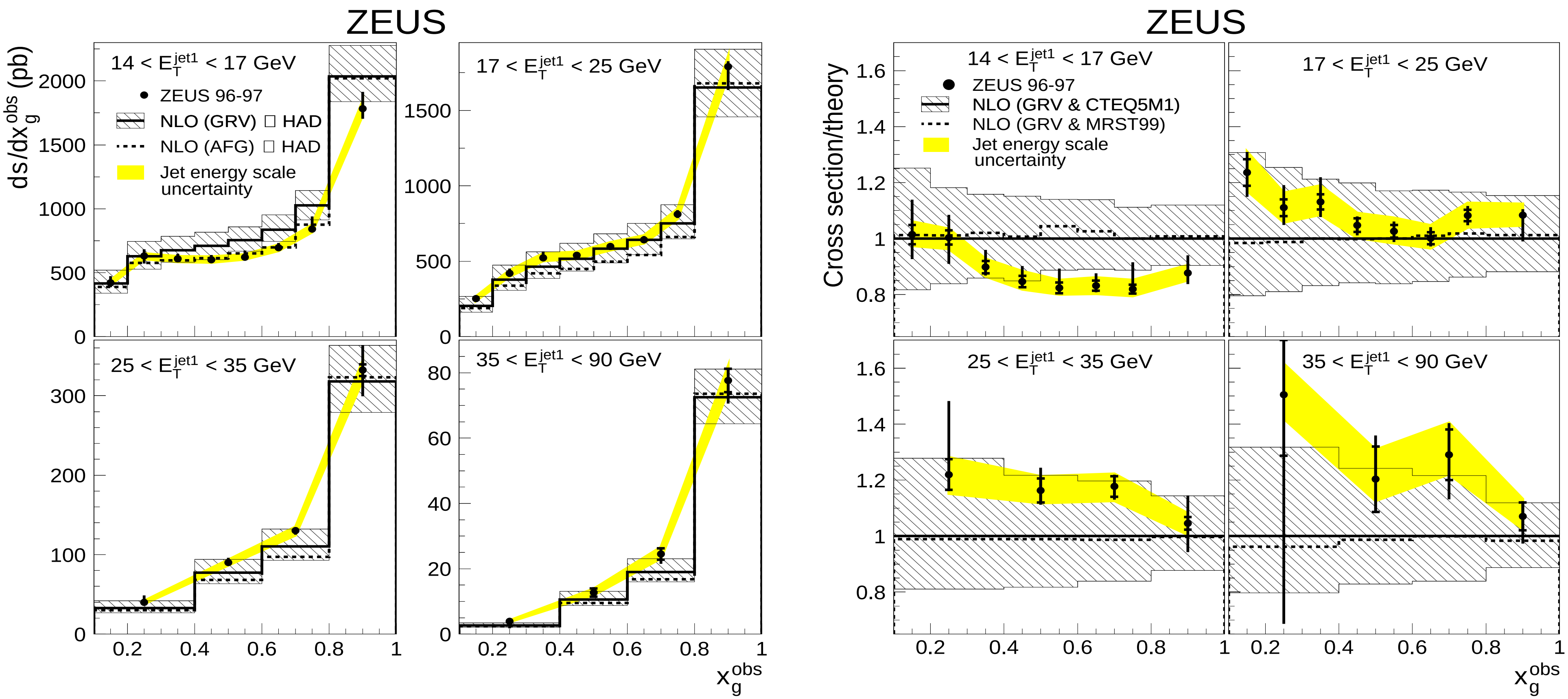
[Eur. Phys. J. C25 (2002) 1, 13]

- $Q^2 < 1$ 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



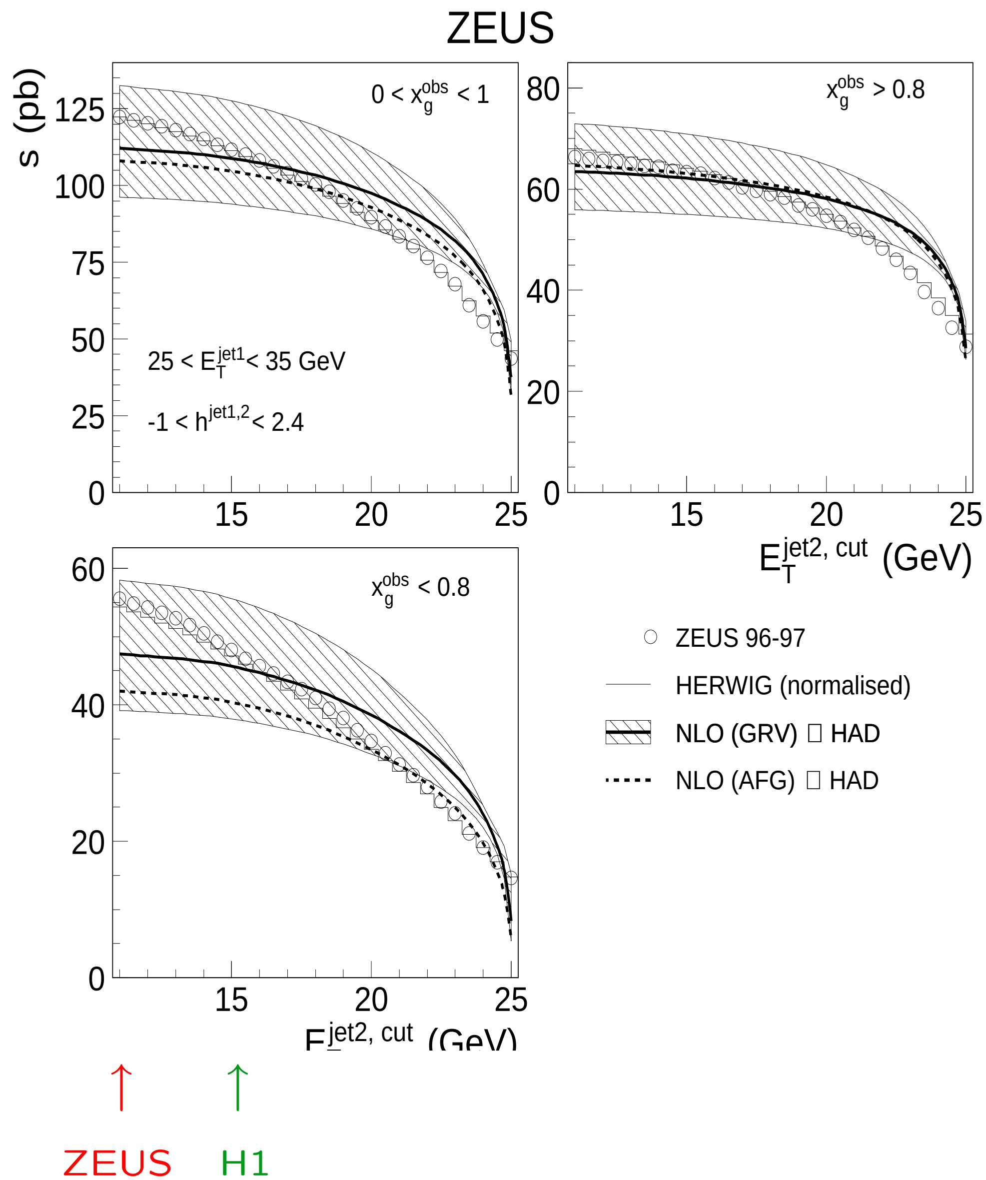
Dijet Production in Photoproduction (ZEUS Data) [Eur. Phys. J. C23 (2002) 4, 615]

- $Q^2 < 1$ 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 ?

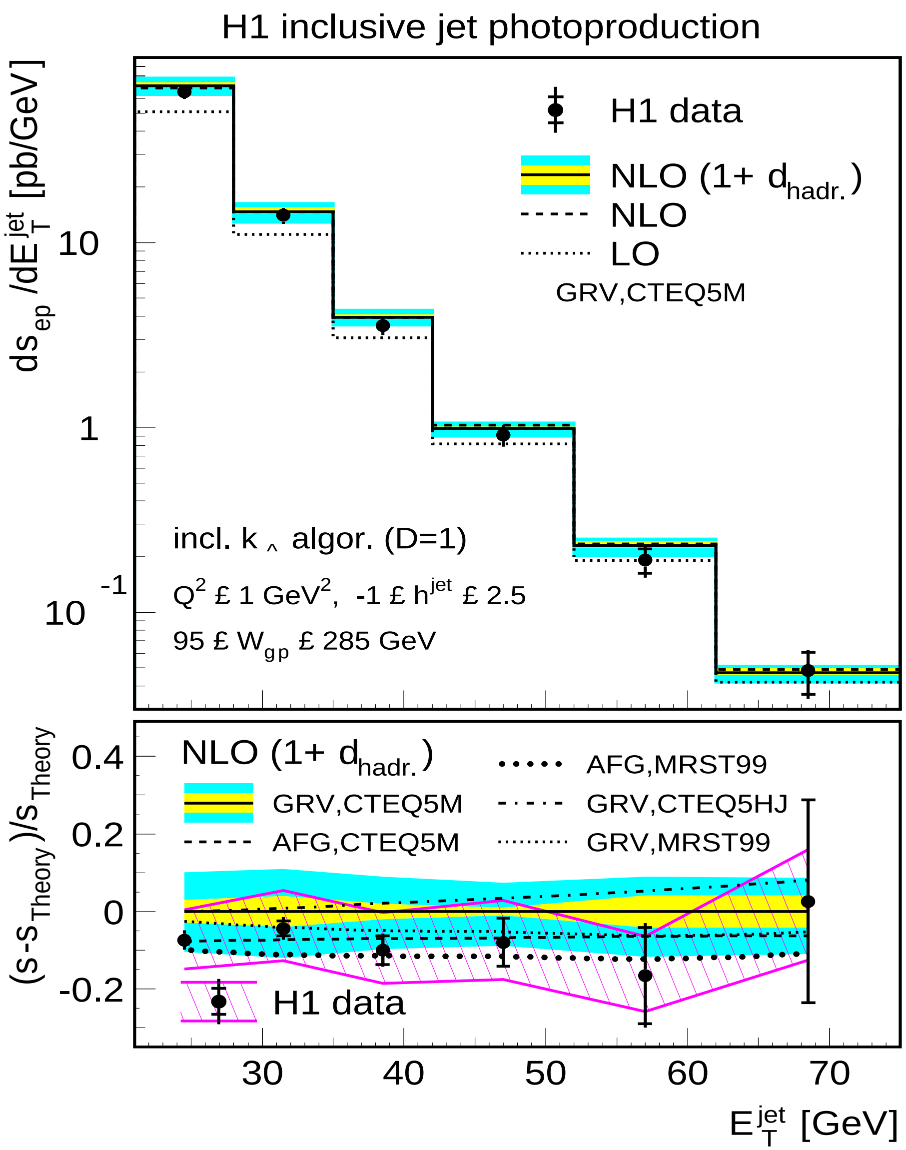


Inclusive Cross Sections in Photoproduction

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

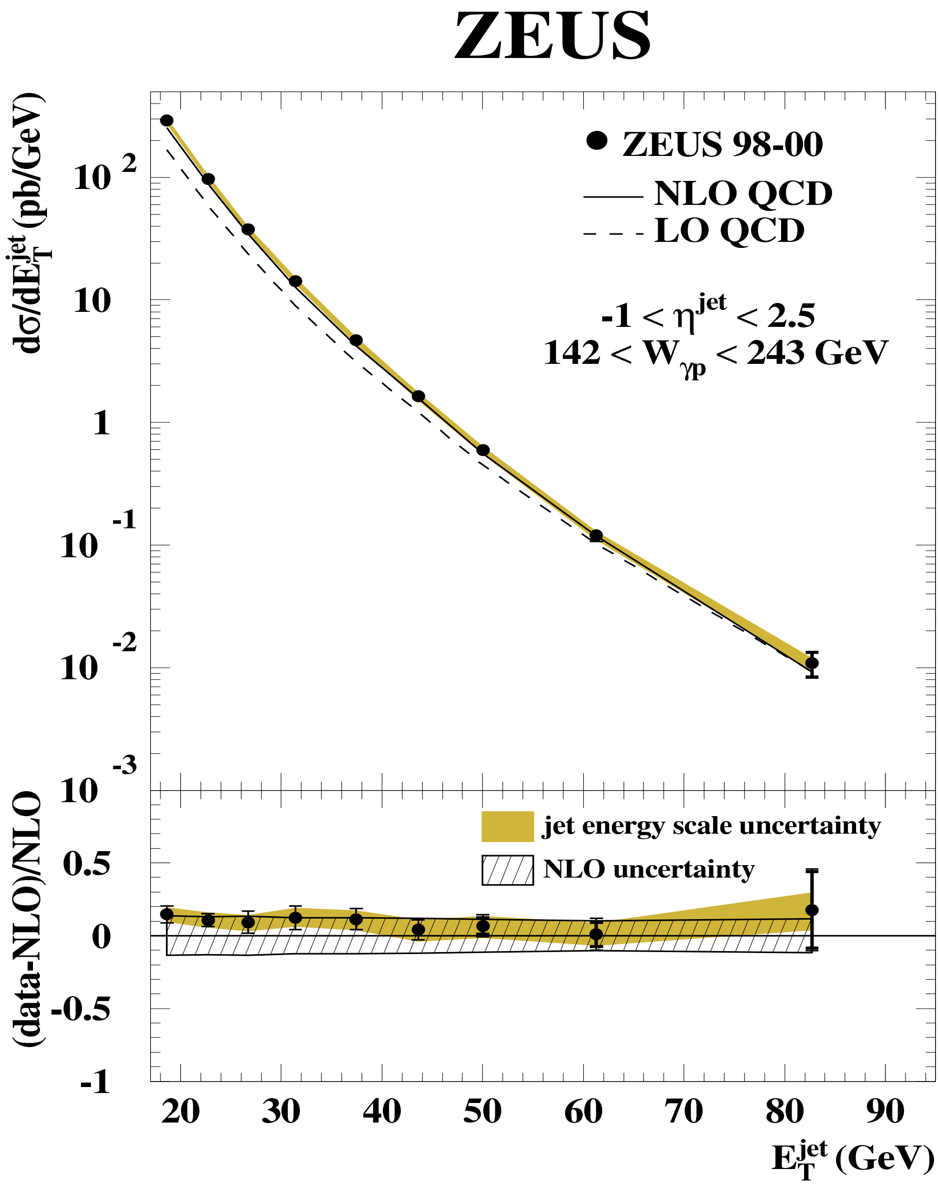
Inclusive Cross Sections in Photoproduction (ZEUS Data)

[Phys. Lett. B560 (2003) 7]

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

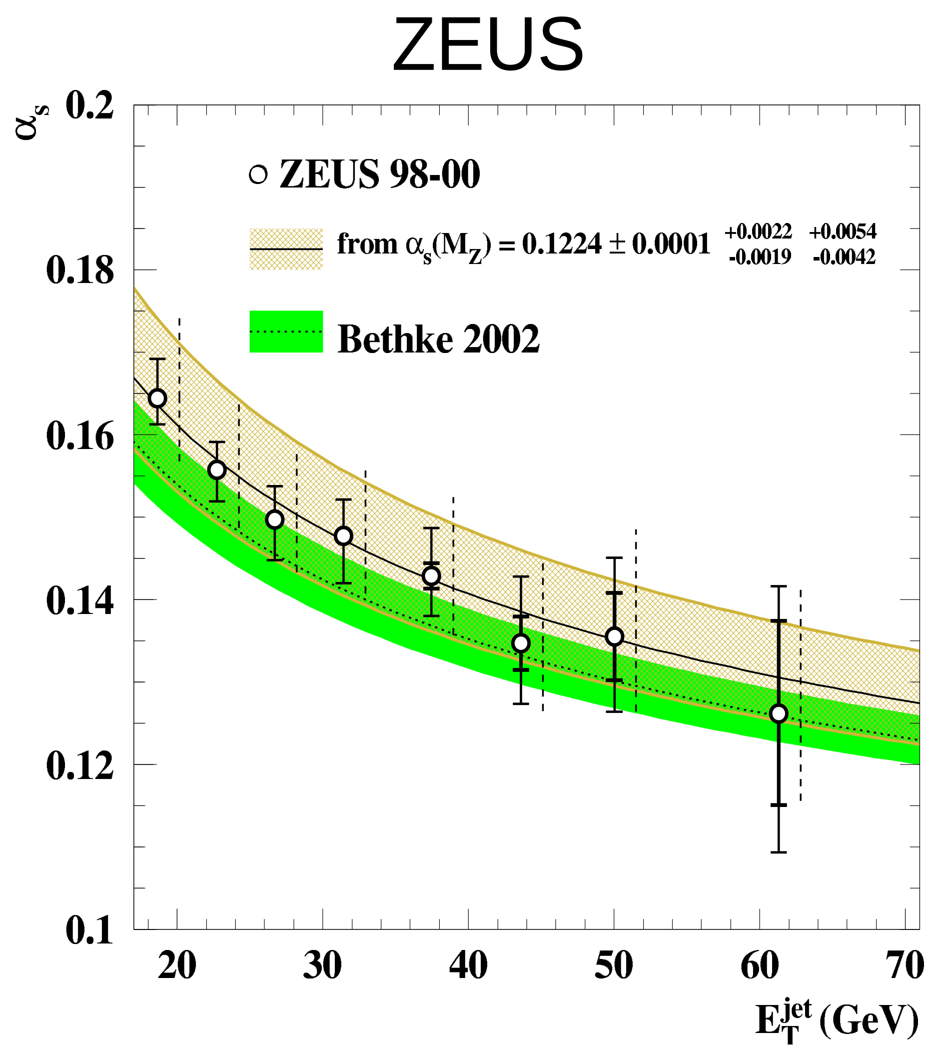
- Small theoretical uncertainties
- Good agreement with NLO over many orders of mag.

  $\rightarrow$ Determination of α_s



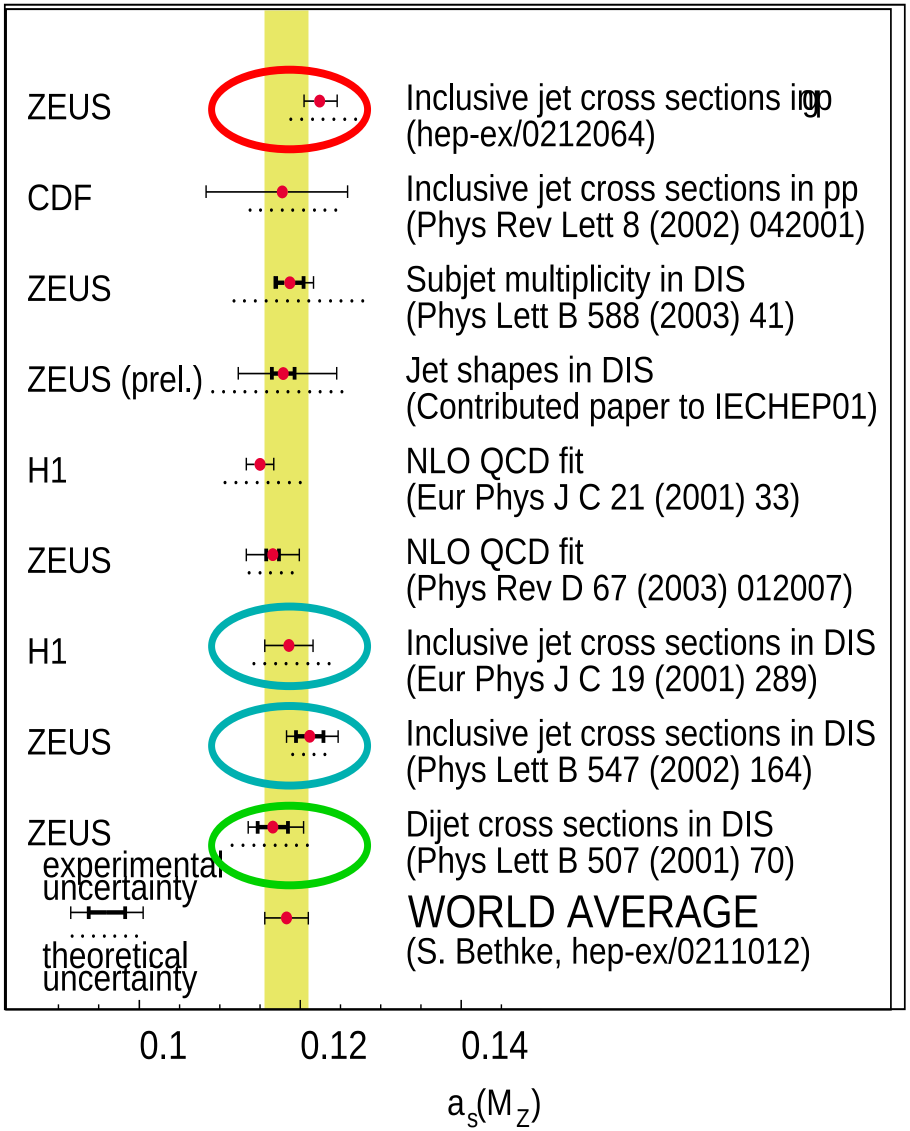
Extraction of α_s

- 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
  → 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
  → new theoretical developments, resummed calculations needed
- Experimental precision and coverage of data is now good
  → include in global PDF fits