# High transverse energy jet production at HERA

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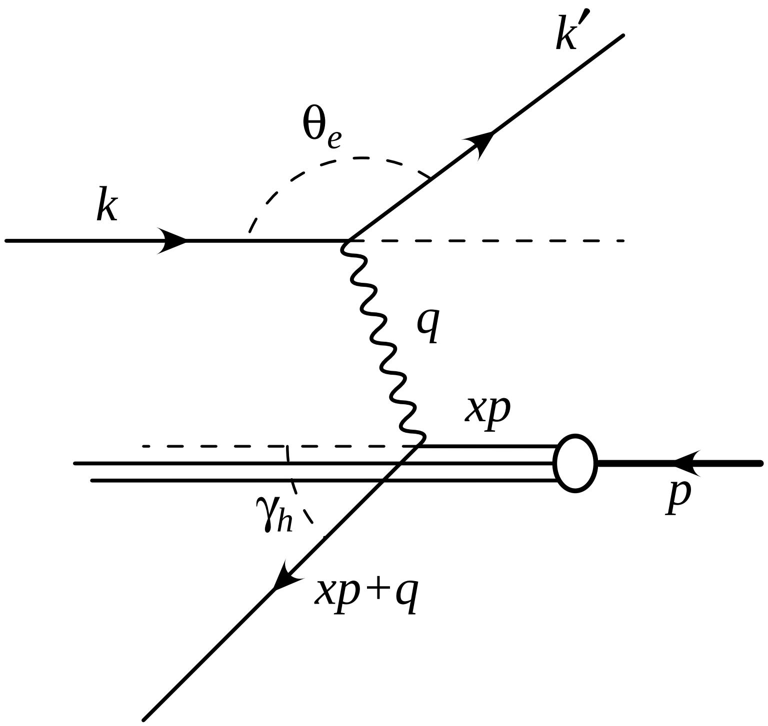
On behalf of the ZEUS and H1 Collaborations

# Introduction

- The HERA collider provides a unique laboratory for the study of the hadronic final state, completing the coverage from $e^+e^-$ to $p\bar{p}$.
- Jet data are now very precise at high transverse energy where experimental uncertainties and non-perturbative effects are small...
  - ▷ Precision tests of our understanding of QCD.
  - ▷ Constraints on proton (and photon) parton distribution functions.
  - ▷ Study where theoretical uncertainties are small, and where large.
  - ▷ Where small, allows extraction of QCD parameters.
- Study sub-processes directly proportional to $\alpha_s$ or higher powers.
- Explore low $Q^2$ transition region.

# HERA kinematics

- HERA $ep$ collider, colliding 27.5 GeV leptons with 820 (920) GeV protons; $\sqrt{s} = 300\ (318)$ GeV




- (Negative) squared 4-momentum transfer

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

- Bjorken scaling variable

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

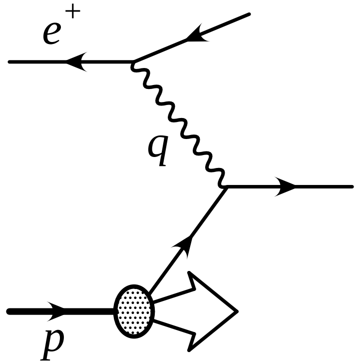
- Inelasticity

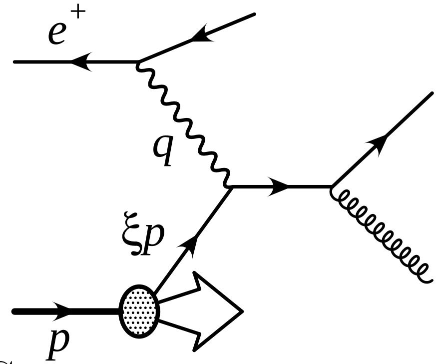
$$y \equiv \frac{p.q}{p.k}.$$

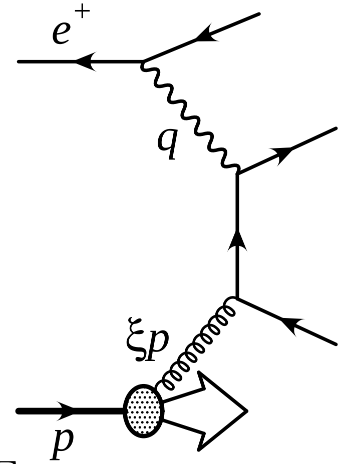
- Total hadronic centre-of-mass energy squared

$$W^2 = (q + p)^2 = ys - Q^2$$

# Jets in deep inelastic scattering



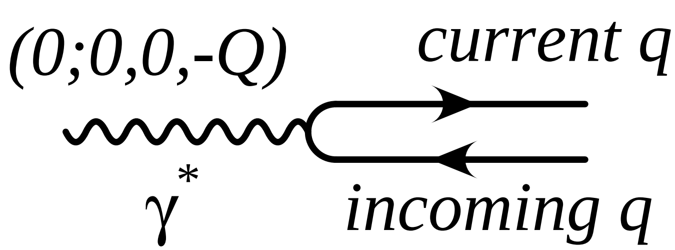




- Factorise jet cross-section into a convolution of PDF's in the proton, $f_a$, with short distance subprocess, $\mathrm{d}\hat{\sigma}_a$....

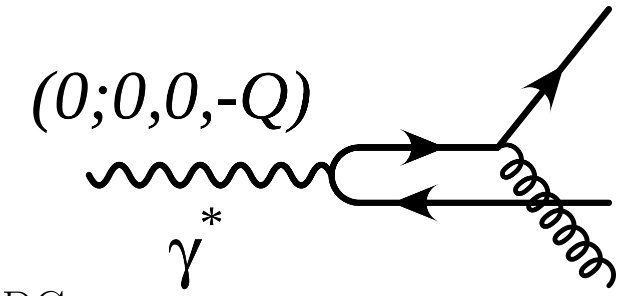
$$d\sigma_{\text{jet}} = \sum_{a=q,\bar{q},g} \int \mathrm{d}x \; f_a(x, \mu_F^2) \; \mathrm{d}\hat{\sigma}_a(x, \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) \times (1 + \delta_{\text{had}})$$

- Longitudinally invariant $k_T$ algorithm (Catani et al).
  ⇒ At high $E_T$ hadronisation effects are small ⇒ more reliable QCD predictions.
- Large scale variation possible in both $Q^2$ and $E_T$ ⇒ what is the appropriate scale?

# Jet production in the Breit frame




Born




QCDC

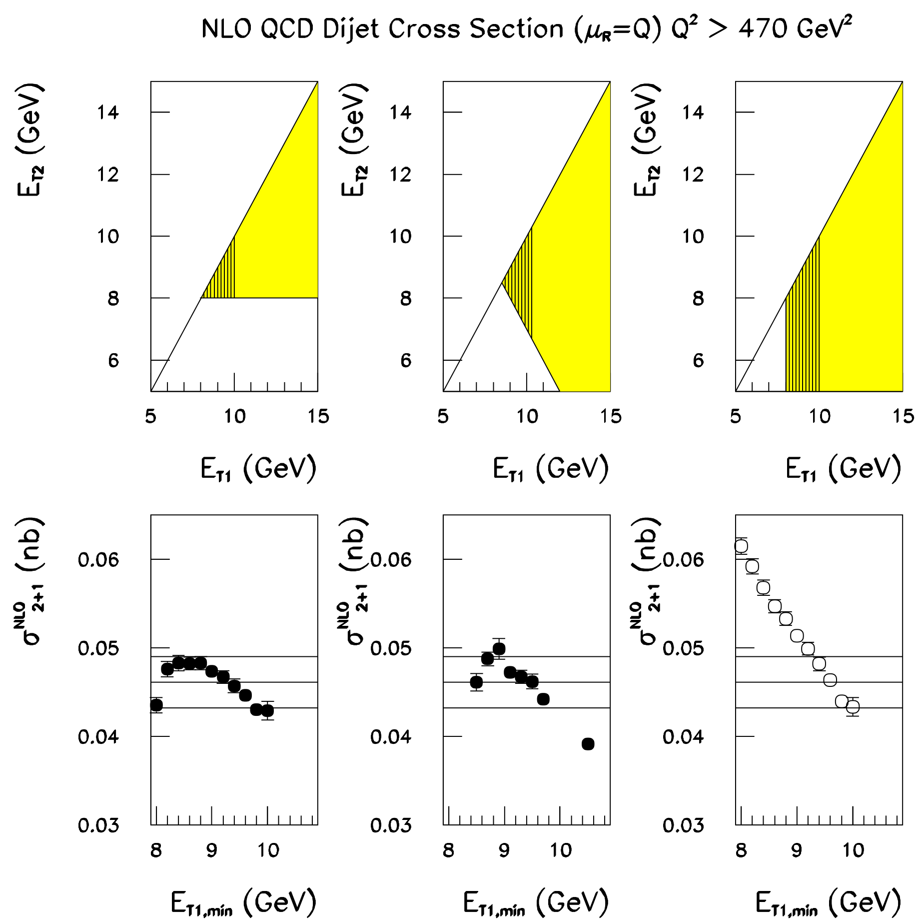
- Breit frame ⇒ purely space-like photon.
- Inclusive jet production in LAB frame $\mathcal{O}(\alpha\alpha_s^0)$ at lowest order.
- Jets with high $E_T$ in the Breit frame
  - ▷ Suppresses Born contribution (in Breit frame current quark has no $E_T$).
  - ▷ Lowest order contributions from $\gamma^* g \longrightarrow q\bar{q}$ and $\gamma^* q \longrightarrow qg$.

⇒ Directly sensitive to QCD subprocess at $\mathcal{O}(\alpha\alpha_s)$ and higher oders.

# NLO QCD calculations of jet production in DIS

- Several calculations available, virtual and collinear singluarities cancelled using subtraction or phase space slicing methods,
  - ▷ Dijet production
    DISENT (Catani and Seymour) – subtraction method.
    DISASTER++ (Graudenz) – subtraction method.
    MEPJET (Mikes and Zepenfeld) – phase space slicing method.
  - ▷ Two and Three jet productuion
    NLOJET (Nagy and Trocsanyi) – subtraction method.
- Two "natural" scales in jet production, Q and $E_T^{\rm jet}$, renormalisation and factorisation scales, $\mu_R$, $\mu_F = Q$ or $E_T^{\rm jet}$.
- Calculations at parton level ➡ correct calculations for hadronisation effects.
- Theoretical uncertainties...
  - ▷ Terms beyond NLO, usually estimated by varying scale, $\mu_R$ by factor of 2.
  - ▷ Uncertainty on $\alpha_s$ and the proton parton distribution functions.
  - ▷ Hadronisation corrections.

# Dijet selection criteria

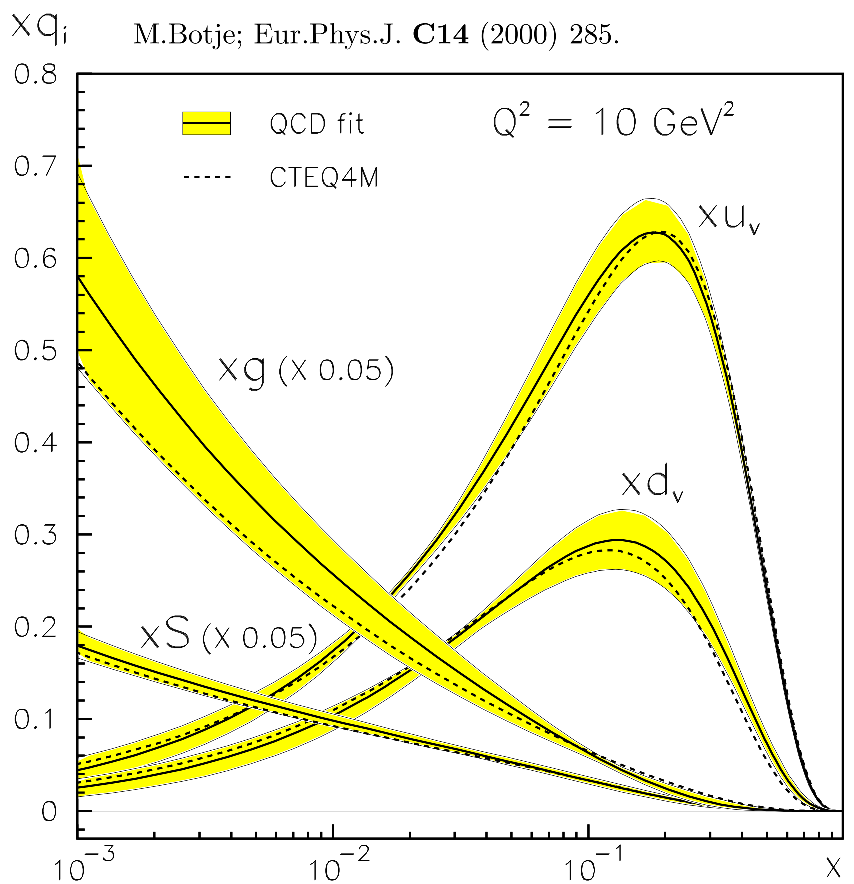



- NLO calculations can exhibit unphysical infrared sensitivity...
  - ▷ Symmetric cuts on Jet $E_T$
    ➡ unphysical cross section dependence.
  - ▷ Symmetric cuts on Jet $E_T$, but also cut on Sum, or invariant mass.
  - ▷ Asymmetric cuts on both jets.
- Last two criteria better, but still need to be careful, ➡ large renormalisation scale uncertainties.

- Inclusive jet production ➡ no restriction on phase space of second jet.
  ➡ Smaller scale uncerrtainty.
  ➡ More reliable QCD prediction, but less information on event kinematics.

# Uncertainties in $\alpha_s$ and the proton parton-densities

M.Botje; Eur.Phys.J. **C14** (2000) 285.




- Cross sections using different PDF's (eg MRST cf CTEQ) do not give a reliable estimation of the true uncertainty.
- Several fits (Botje, ZEUS...) include correlation matrices to account for
  - ▷ Statistical and correlated systematic experimental uncerrtainties.
  - ▷ Theoretical uncertainties from extraction of PDF's in the DGLAP evolution.
- Extreme ranges used to estimate reliable correlated PDF uncertainty.
- PDF (gluon) and $\alpha_s$ uncertainty correlated ➡ several sets available (MRST99 series, CTEQ4 A series) with consistent fits at different $\alpha_s$ values.

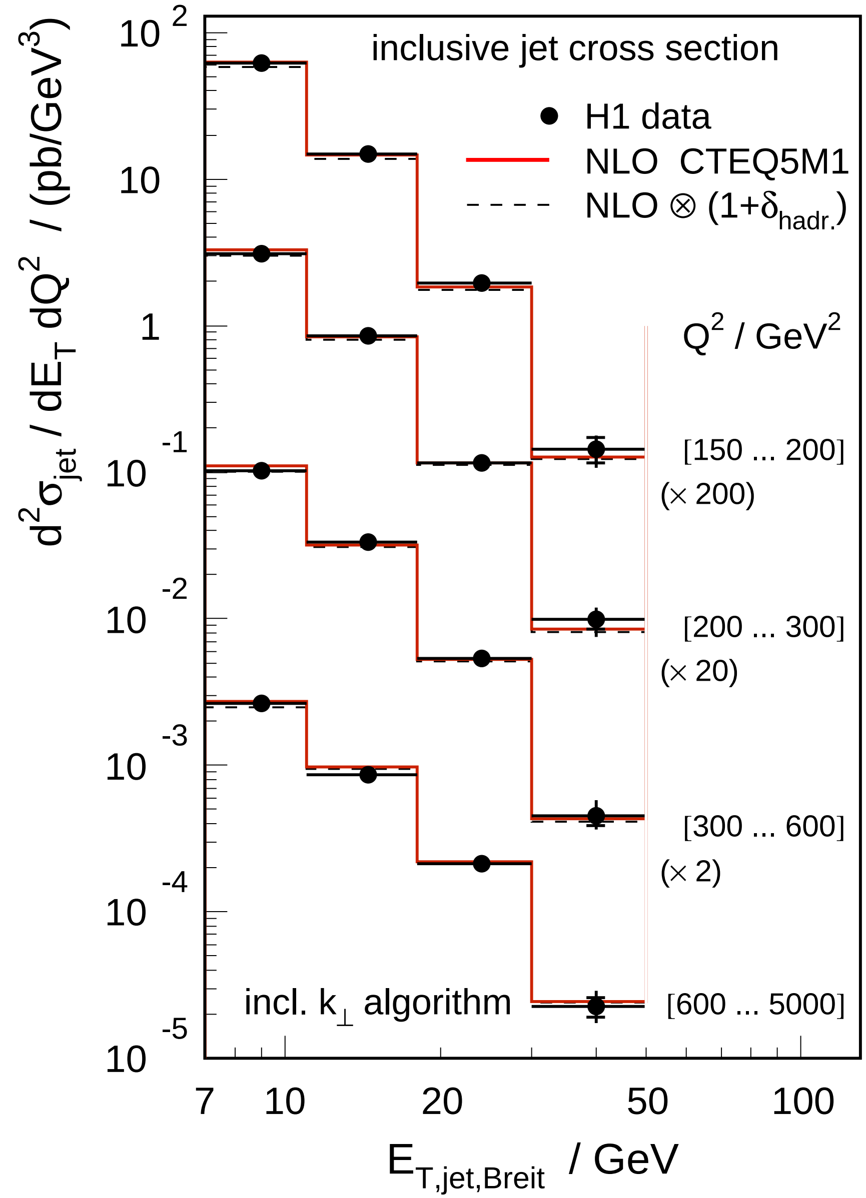
# Inclusive jet production at high $E_T$

- Inclusive single jet production in Breit frame,

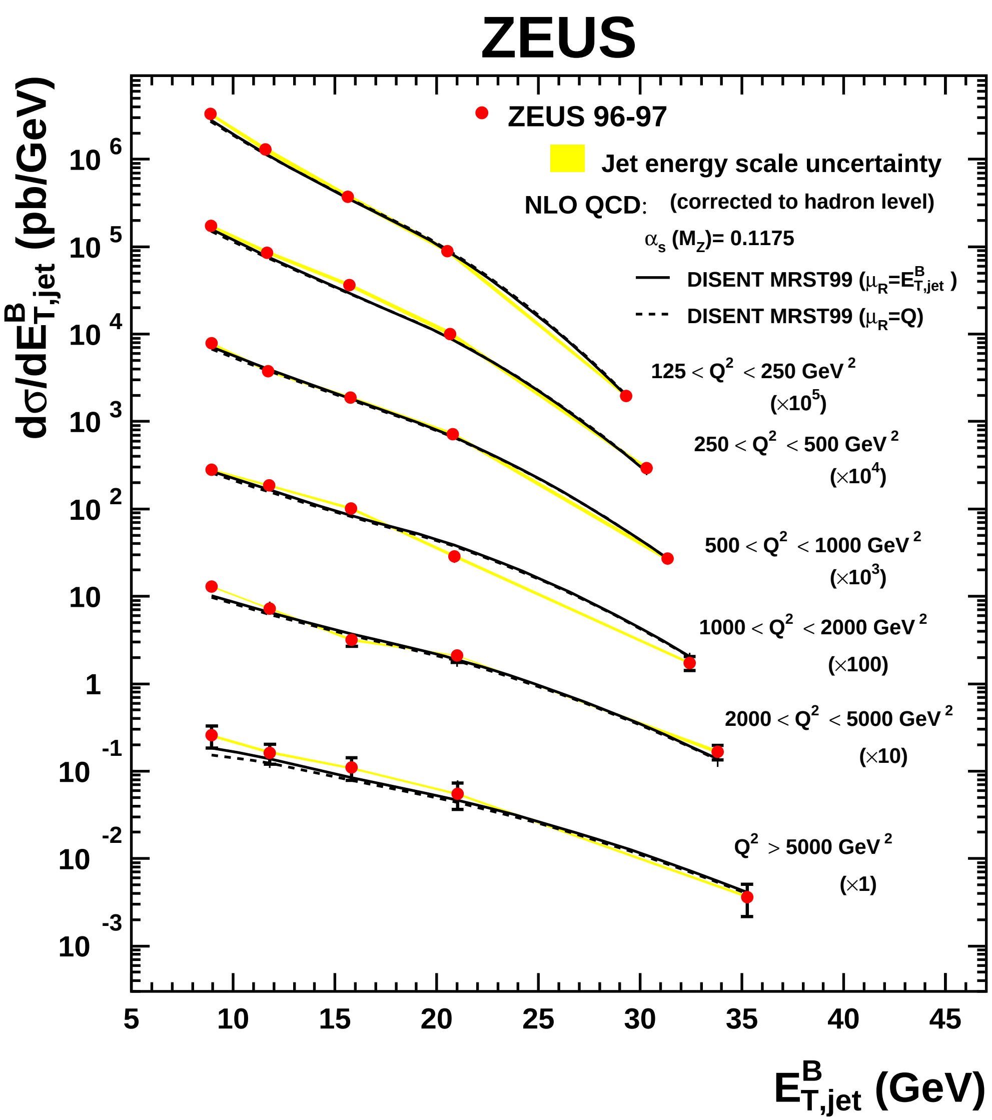
$$150 < Q^2 < 5000\ \text{GeV}^2$$

$$E_T^{\text{Breit}} > 7\ \text{GeV}, \quad -1 < \eta^{\text{Lab}} < 2.5$$

- NO requirement on second jet (can be unobserved).
- NLO QCD gives a good secription of entire range of $Q^2$ and $E_T$.

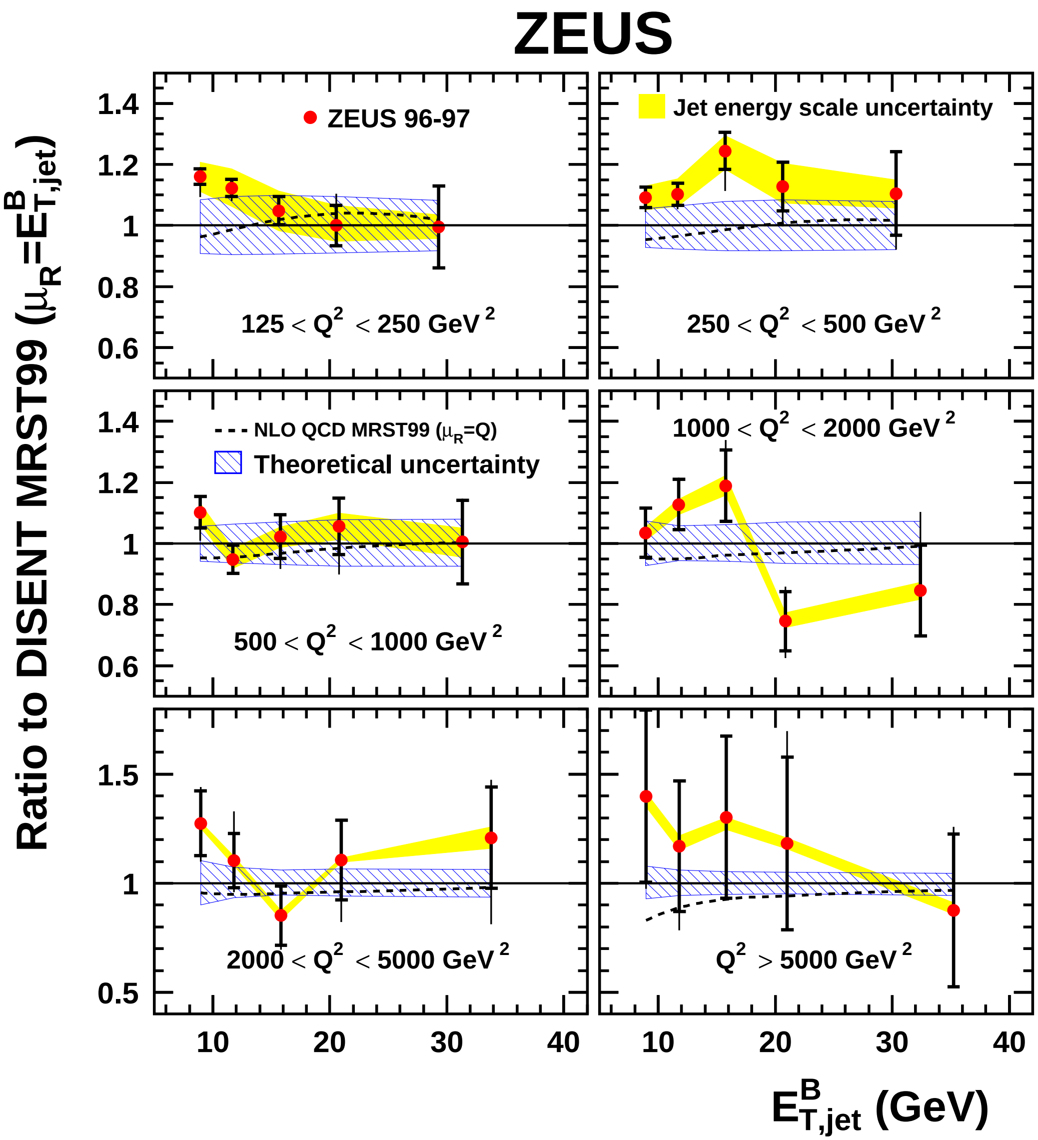


# Inclusive jet production at high $E_T$



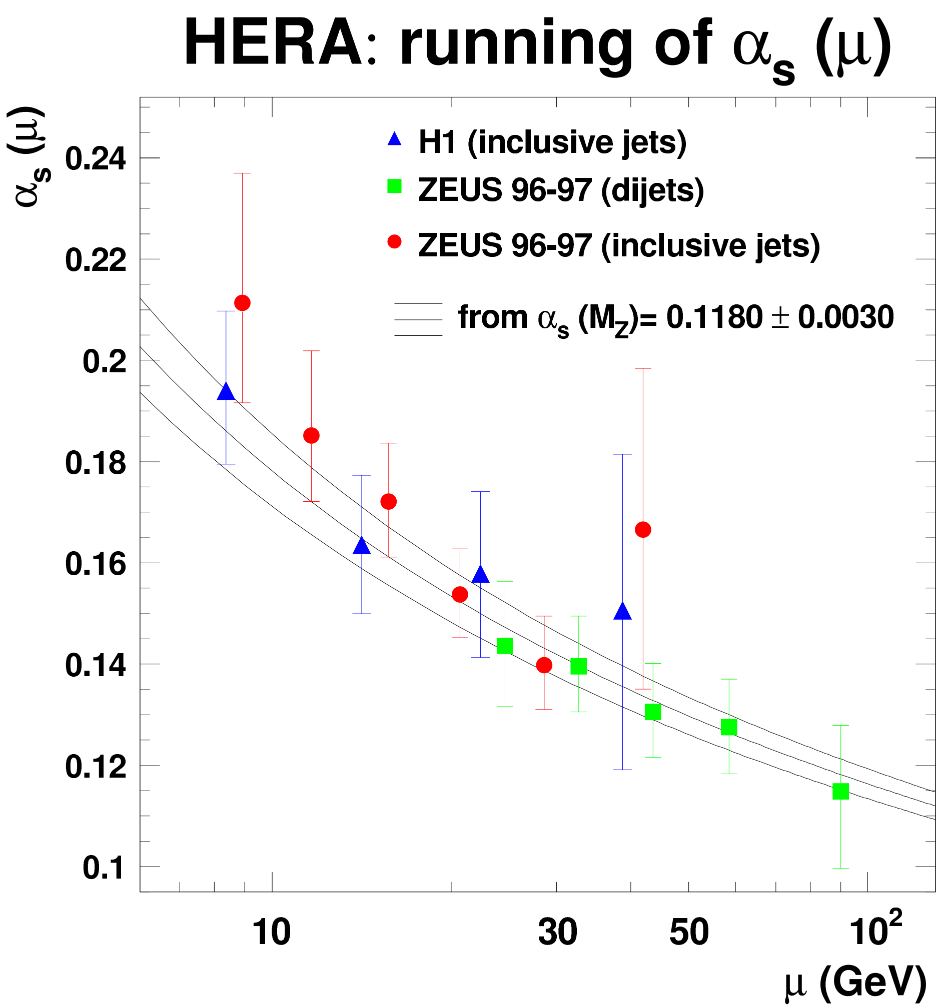

- High $Q^2 > 125$ GeV$^2$
- Inclusive jet cross sections measured in the Breit frame in DIS.
  $E_T^{\text{Breit}} > 8$ GeV, $\quad -2 < \eta_{\text{jet}}^{\text{Breit}} < 1.8$
- NO cuts on jets in the Lab frame.
- Precision test of our understanding of perturbative QCD.
- Reasonable agreement with NLO QCD prediction over many orders of magnitude in $Q^2$ and $E_T^{\text{Breit}}$.

# Inclusive jet production at high $E_T$




- Hatched band: NLO scale uncertainty for $E_T^{\text{Breit}}/2 < \mu_R < 2E_T^{\text{Breit}}$.
- At low $Q^2$ and $E_T^{\text{Breit}}$, the data are above the predictions of NLO QCD.
- Overall, reasonable agreement within the experimental and theoretical uncertainties. ⇒ Extraction of the QCD coupling $\alpha_s$.

# Extraction of the QCD coupling – $\alpha_s$




- Clear running observed with jet $E_T$.
- H1 value for $150 < Q^2 < 5000$ GeV$^2$,

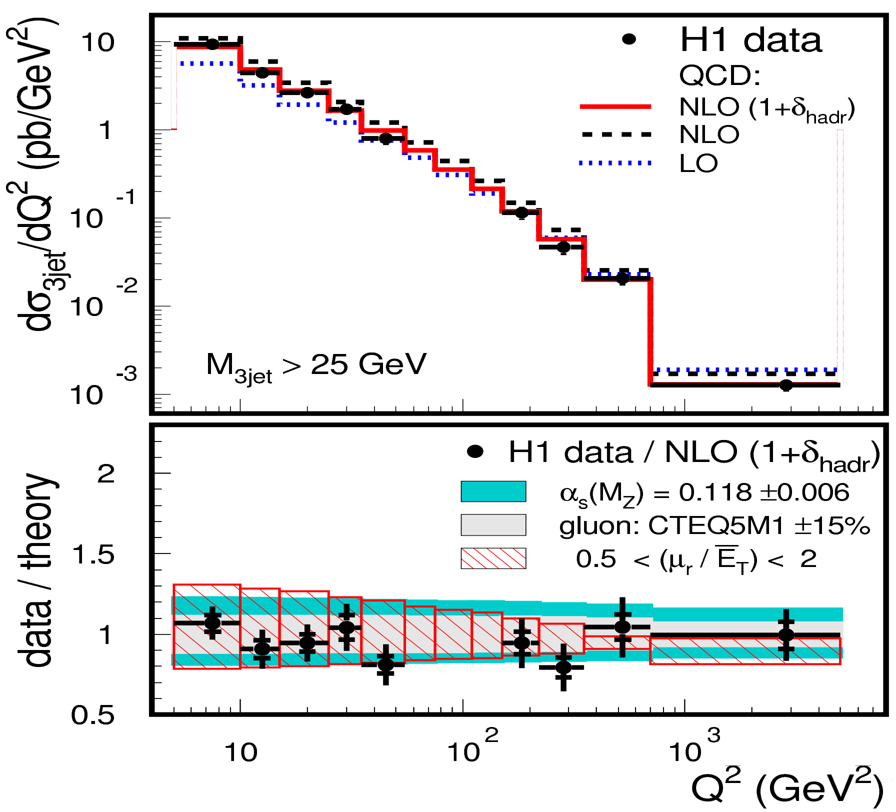
$$\alpha_s(M_Z) = 0.1186 \pm 0.0030(\text{exp.})^{+0.0039}_{-0.0045}(\text{theor.})^{+0.0033}_{-0.0023}(\text{pdf})$$

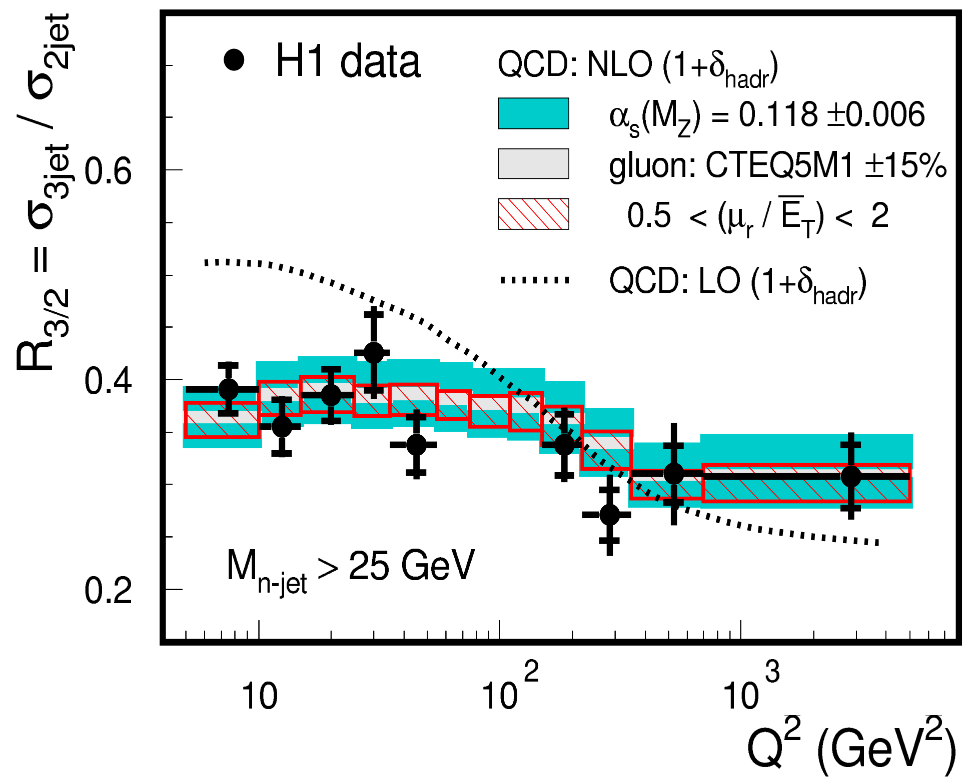
- ZEUS value for high $Q^2 > 500$ GeV$^2$,

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

- Dominant uncertainty from theory.
  - ▷ Scale uncertainty $\sim 3\%$.
  - ▷ Proton PDF $\sim 1\%$.
  - ▷ Hadronisation $\sim 0.2\%$.
- Precision compatible with best measurements from elsewhere.

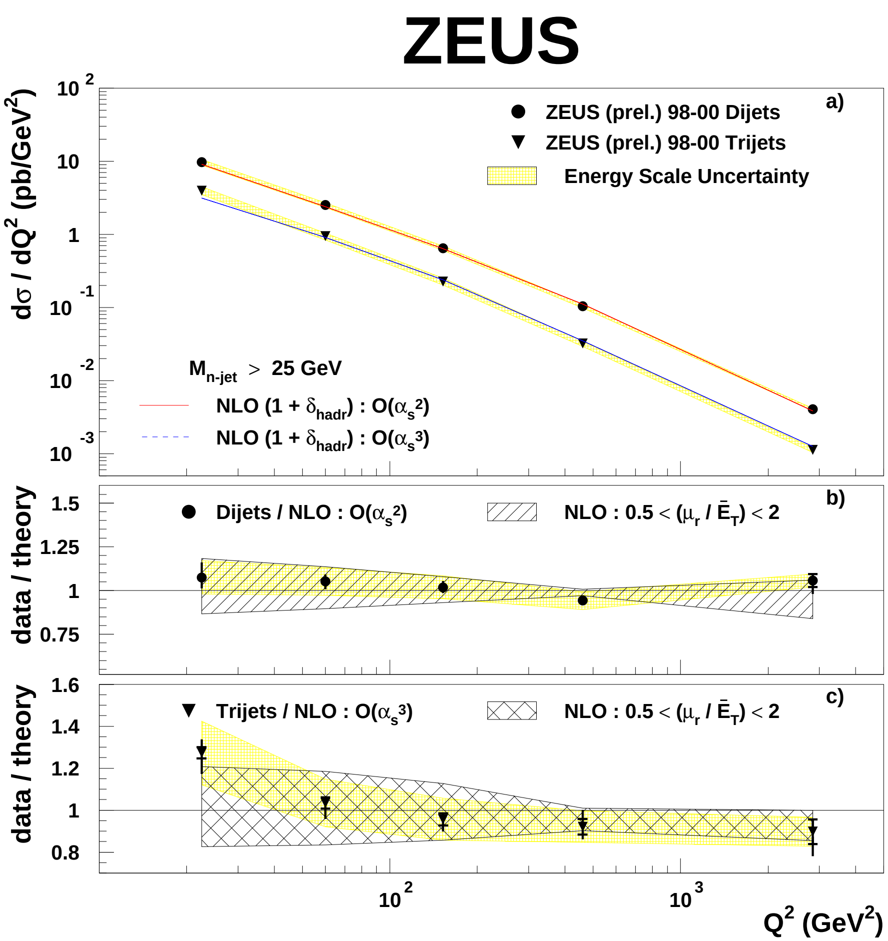
# Three jet production

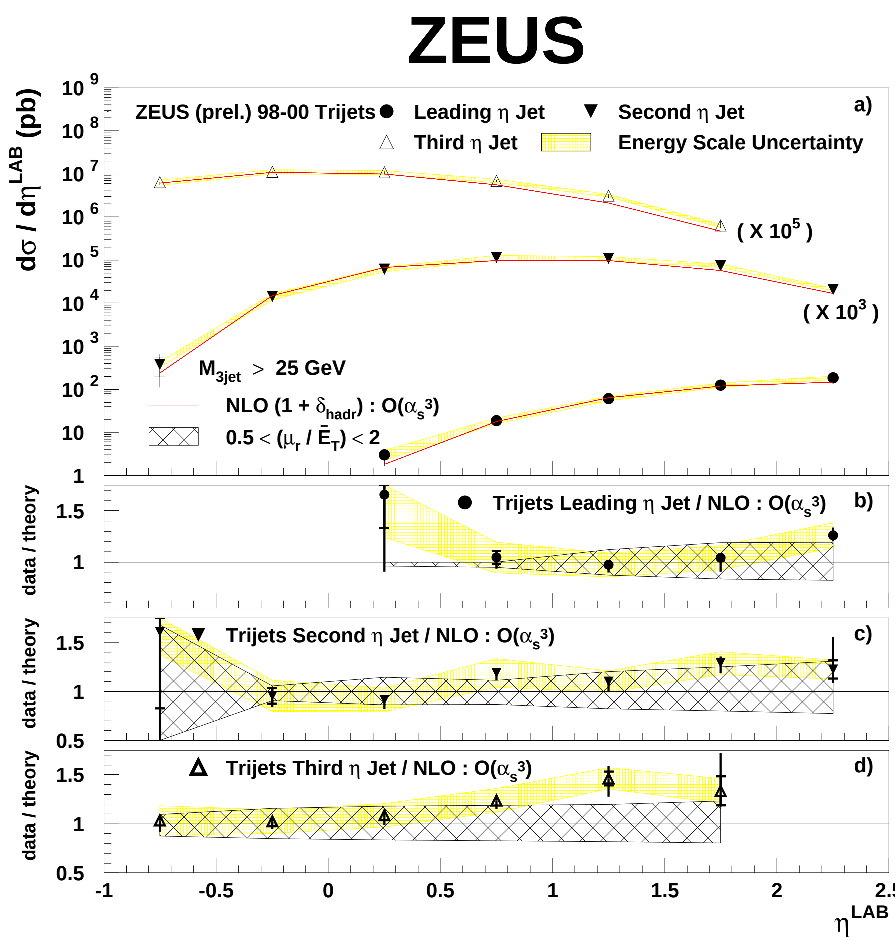



- Three-jet cross sections in Breit frame ⇒ $\mathcal{O}(\alpha\alpha_s^2)$ process at leading order, $5 < Q^2 < 5000$ GeV$^2$, $-1 < \eta_{\rm lab} < 2.5$, $M_{\rm jets} > 25$ GeV
- Large NLO corrections, good agreement between data and NLO calculation.
- Ratio of three-to-two jet rate, $R_{3/2}$ ⇒ Reduced uncertainties from the gluon density in the proton and renormalisation scale.

# Multi-jets in DIS



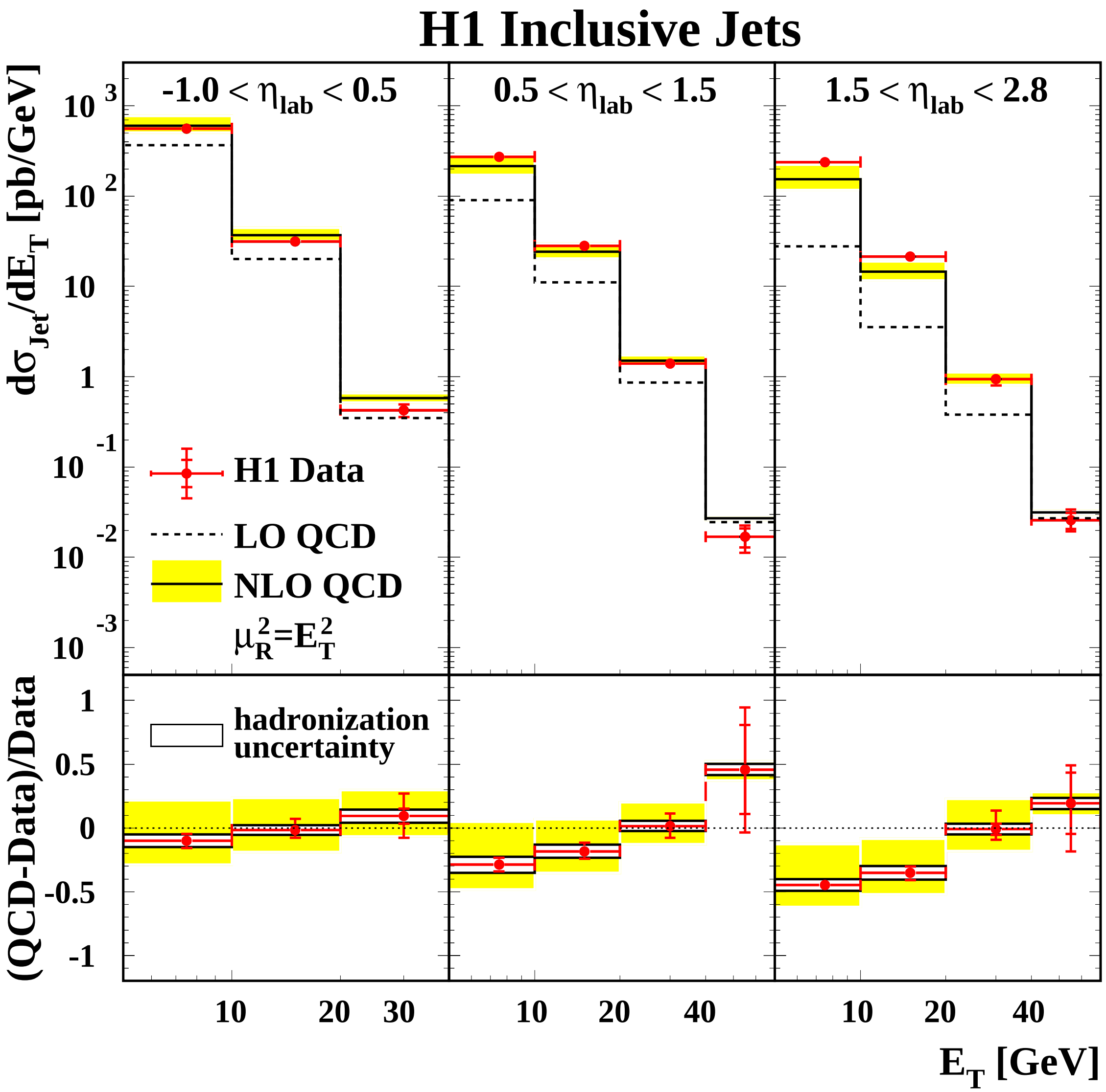




- Two and three-jet production in Breit frame,

$$10 < Q^2 < 5000 \text{ GeV}^2, \quad E_T^{\text{Breit}} > 5 \text{ GeV}, \quad -1 < \eta^{\text{LAB}} < 2.5, \quad M_{\text{jets}} > 25 \text{ GeV}$$

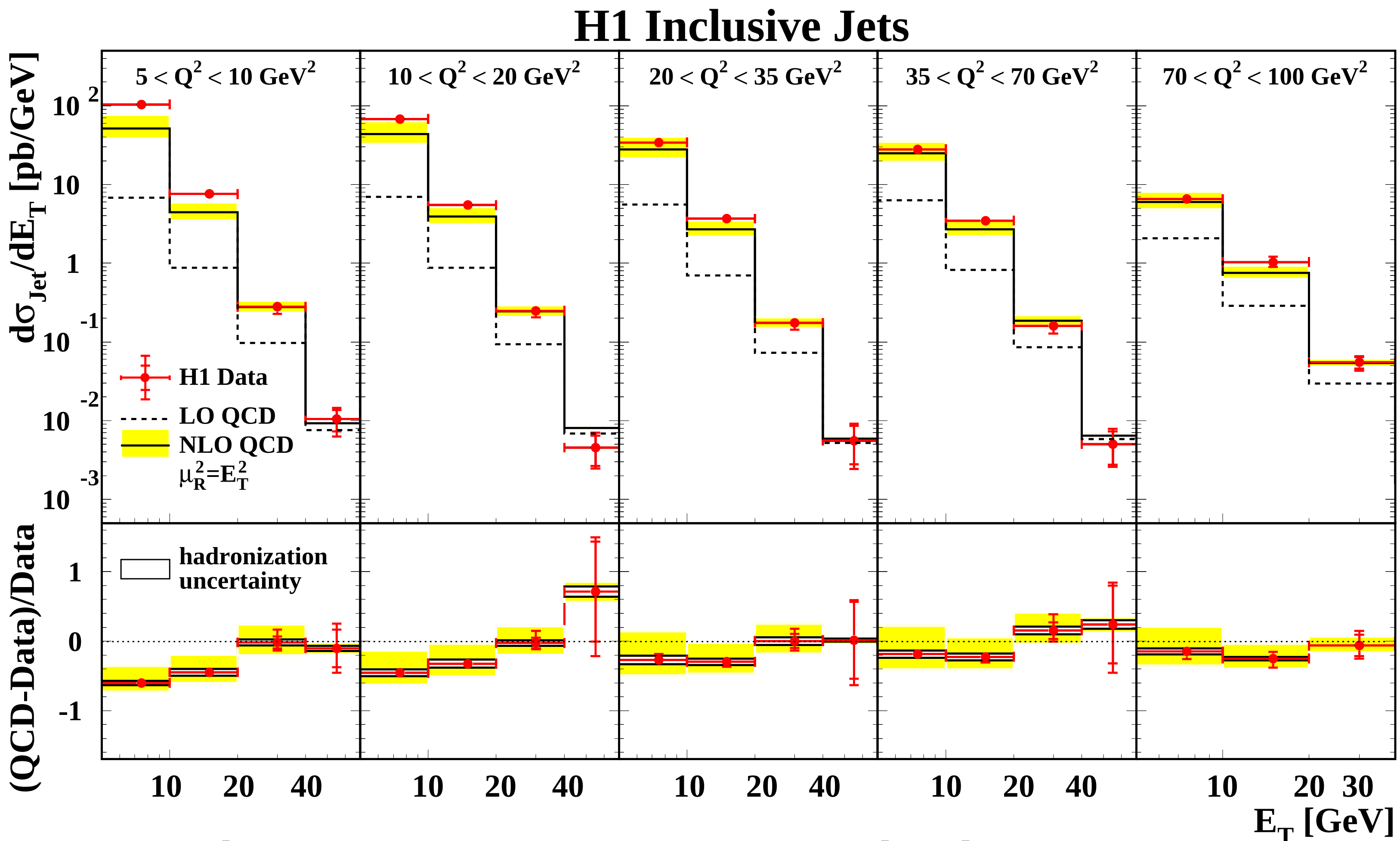
- Dynamics well described.

# Inclusive jet production towards lower $Q^2$




- Low $Q^2$ region,
  $E_T^{\mathrm{Breit}} > 5$ GeV,
  $5 < Q^2 < 100$ GeV$^2$,
  $0.2 < y < 0.6$
- NLO corrections large for low $E_T$ and forward $\eta_{\mathrm{lab}} > 1.5$
  ⇒ Theory lies below data.

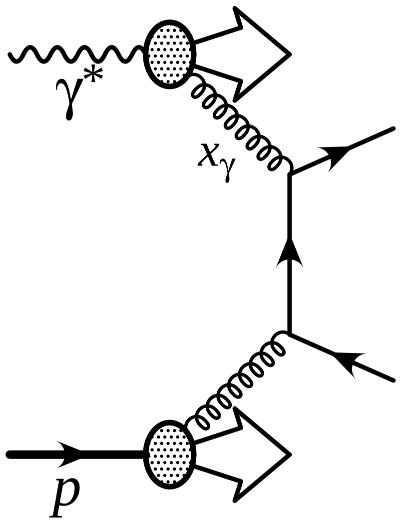
# Inclusive jet production – foward region




- Forward region, $1.5 < \eta_{\rm lab} < 2.8$ in more detail.
- Discrepancy between data and NLO large at low $Q^2$ and low $E_T$.

  ⇒ Improved calculations are needed; Contributions proton PDF's? virtual photon structure? alternative evolution schemes (CCFM, BFKL)?

# Low $Q^2$ and virtual-photon structure

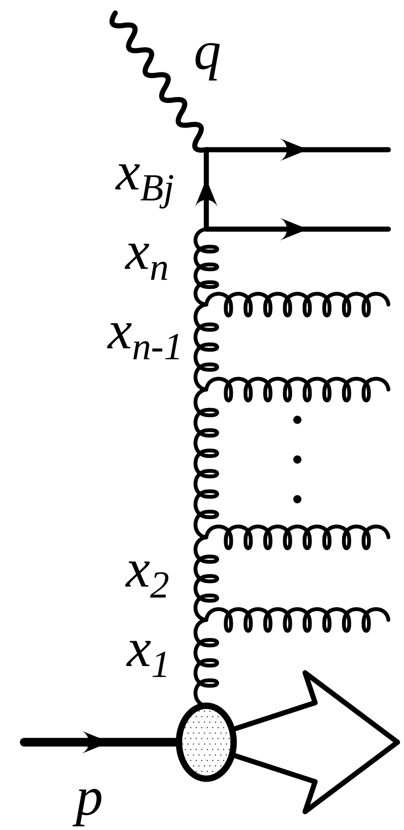



- In dijet production, at very low $Q^2$, then $Q^2 < E_T^2$ ➡ large logarithms of $\ln E_T/Q^2$, ➡ formally resum into "resolved" photon structure.
  ➡ Photon can interact directly or via a parton with some momentum fraction $x_\gamma < 1$.
- Possible contribution from longitudinally-polarised "resolved" photons ➡ vanishes as $Q^2 \to 0$ and $y \to 1$.

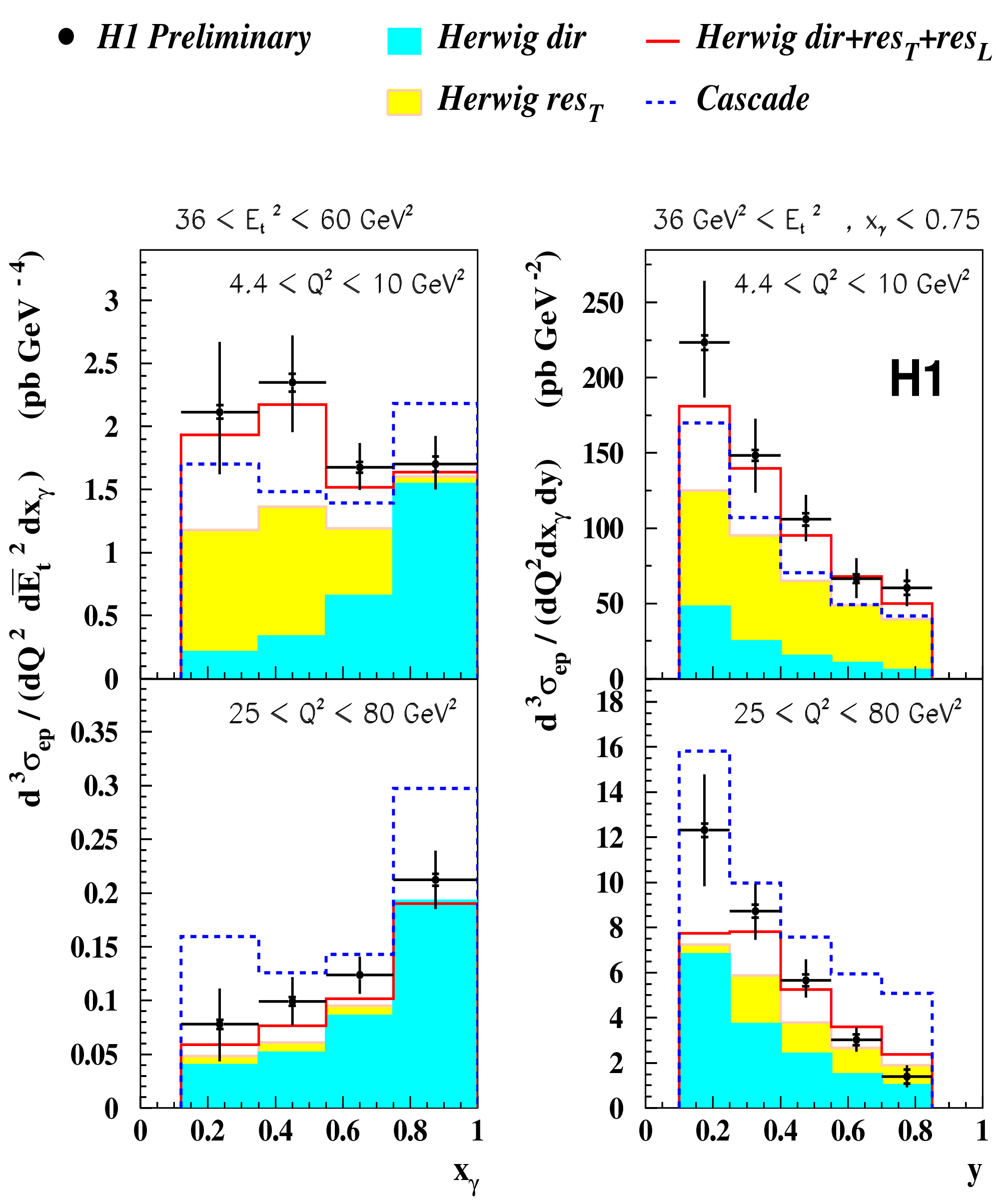
- Virtual photon PDF's modeled using
  - ▷ Leading Log part of real photon ➡ $\ln E_T/\Lambda_{\rm QCD}$
  - ▷ Assymtotic behaviour from perturbative QCD ➡ $\ln E_T/Q$
- Parameterisations of virtual photon PDF's,
  - ▷ Drees and Godbole,
  - ▷ Schuler and Sjöstrand,
  - ▷ Glück et al.

# Alternative evolution schemes

- Unordered parton evolution, eg CCFM (CASCADE),
  - ▷ Strong order in $x$: $x_1 \gg x_2 \gg \ldots \gg x_{Bj}$, unordered in $k_T$.
  - ▷ Allows the highest two $E_T$ jets in an event to come from anywhere along the ladder.
- Uses only unintegrated gluon density in the proton.
- Qualitatively similar to resolved photon picture, but without explicit photon structure.

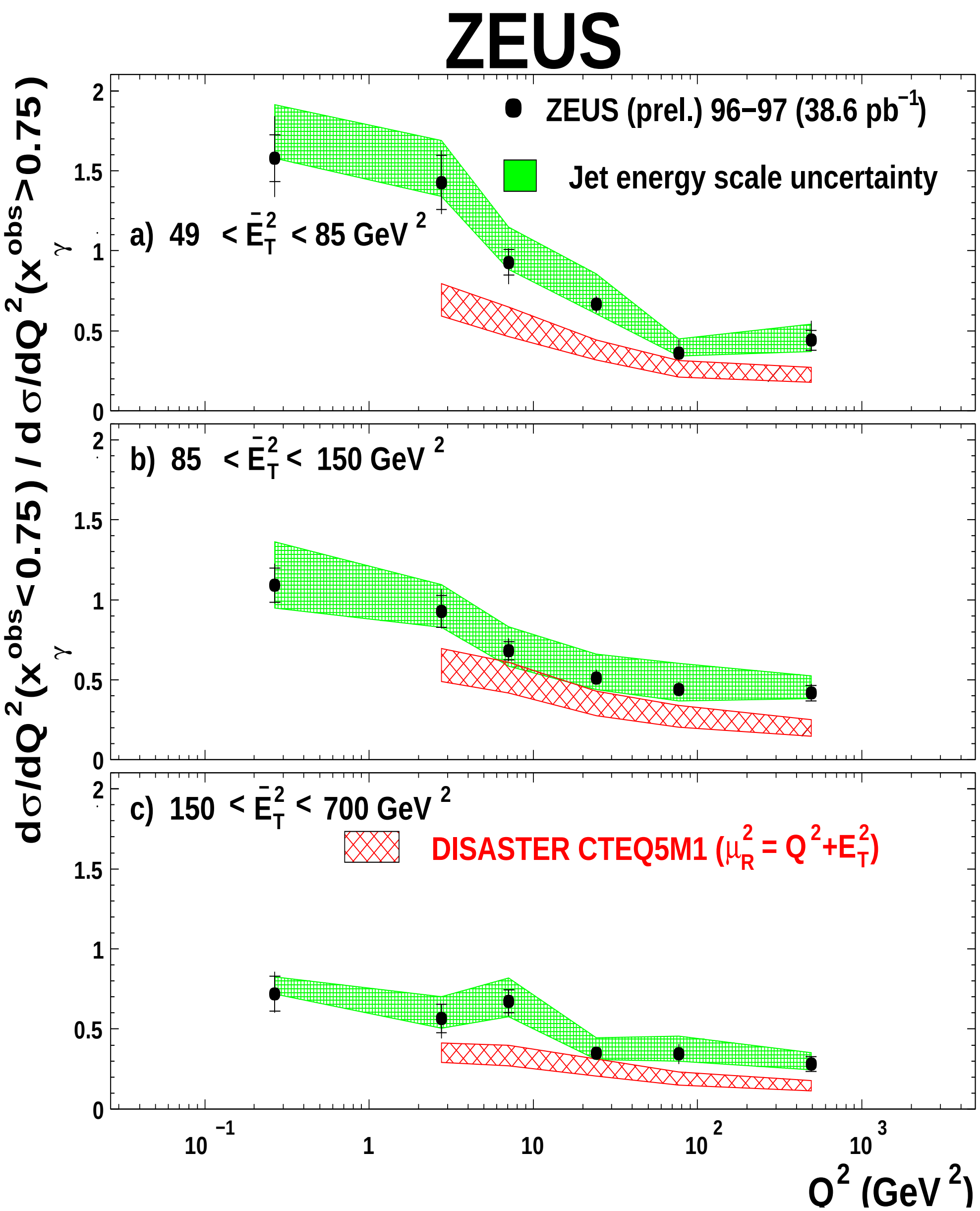


# Virtual photon structure




- Data suggest "resolved" component neccessary at low $Q^2$ or when $\bar{E}_T$ is large.
- Leading-order resolved component alone is not adequate.
- Longitudinally polarised photon improves the description.
- Unordered CCFM parton cascade with NO resolved photon predicts higher contrbution.
- Need NLO comparison...

# Virtual photon structure – comparison with NLO theory

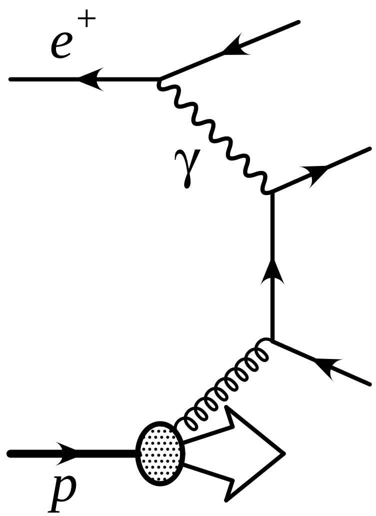



- DISASTER ⇒ NLO DIS no resolved photon.
- DISASTER ratio too low at lower $Q^2$.
- Expect larger resolved fraction when including resolved virtual photon.
- Need additional NLO calculations.

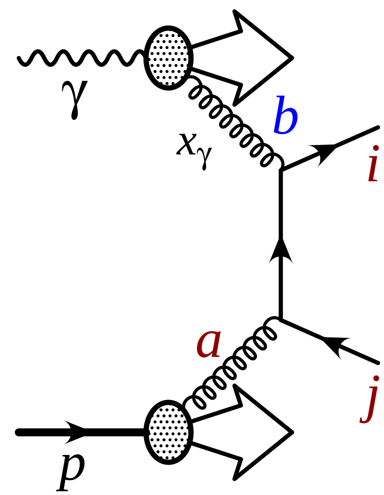
# Photoproduction at HERA

- Photoproduction, very low photon virtuality $\sim 10^{-3}$ GeV$^2$ ➡ perturbatively calculable when there is a hard scale provided by high transverse energy jets.
- To $\mathcal{O}(\alpha\alpha_s)$, two types of process contribute to the high $E_T$ jet production.

Direct




Resolved

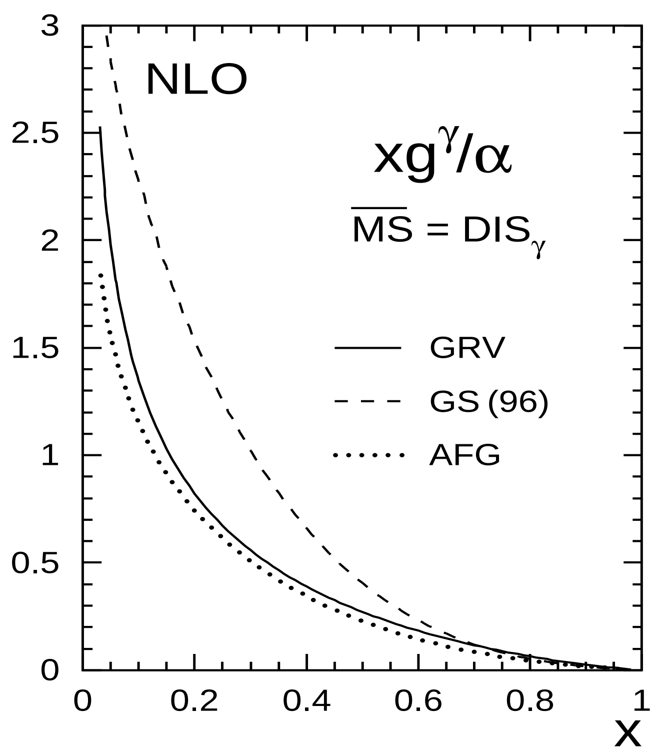



$$d\sigma^{res}(\gamma p \to ij) = \sum_{ab} \int_y dy f_{e\to\gamma}(y) \int_{x_p} dx_p f_{p\to a}(x_p, t) \int_{x_\gamma} dx_\gamma f_{\gamma\to b}(x_\gamma, t) d\sigma(ab \to ij)$$

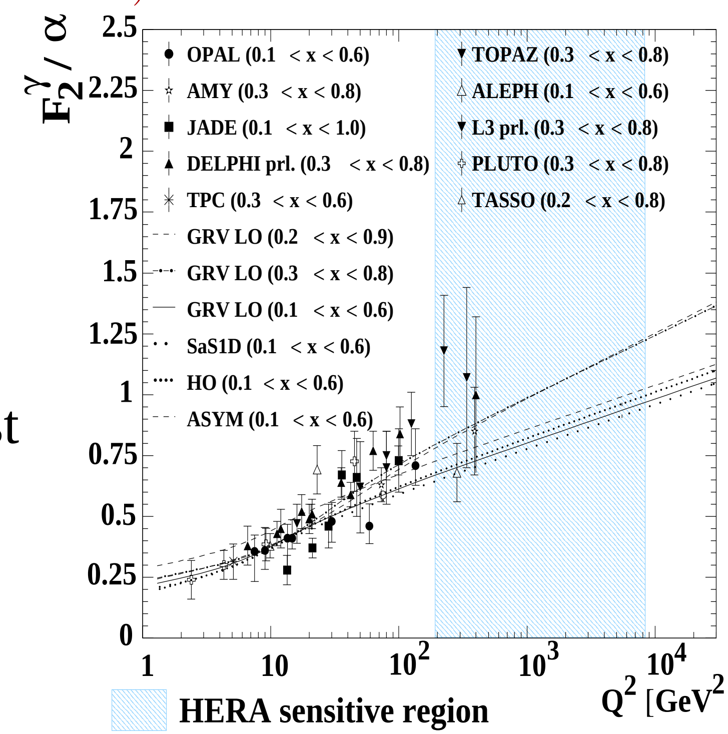
Photon flux, $f_{e\to\gamma}(y)$, PDF's in the proton, $f_{p\to a}(x_p, t)$, and photon, $f_{\gamma\to b}(x_\gamma, t)$.

- In leading order picture, two jets, balanced in $E_T$, back to back in $\phi$.

# Photon Structure




- Photon structure from fits to $F_2^\gamma$ from $\gamma$-DIS at $e^+e^-$ colliders ⇒ gluon in photon poorly constrained.
- Lowest order jet cross sections in photoproduction sensitive to both quark and gluon densities
- Data at even larger scales, $\mu_{F\gamma}^2 \sim E_{T,\text{jet}}^2\ (200 - 10^4)\ \text{GeV}^2$.



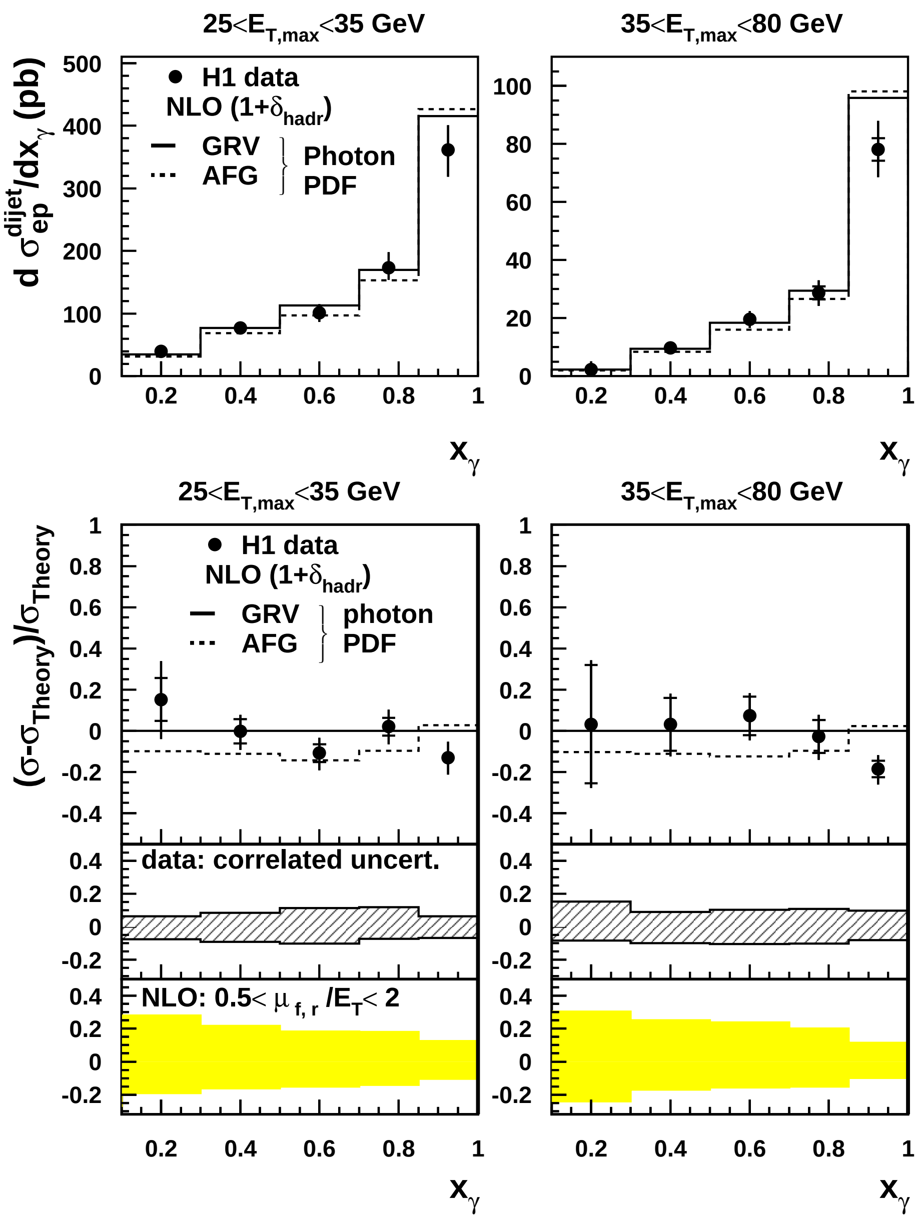

- Longitudinally invariant $k_T$ algorithm.
- Study fraction of photon energy in two highest $E_T$ jets,

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

# NLO photoproduction calculations

- Longitudinally invariant $k_T$ algorithm, in $\eta$-$\phi$ space in Laboratory frame (Ellis and Soper scheme).
- Several NLO calculations (phase space slicing, subtraction method).
  - ▷ Klasen and Kramer, Harris and Owens, Frixione and Ridolfi , Aurenche et al
- $\mu_R = \mu_F = E_T^{\rm jet}$, ($Q^2 \approx 0$).
- Proton PDF's, NLO fits, CTEQ5M, MRST99.
- Photon PDF's, NLO fits, GRV-HO, AFG-HO.
- Parton to hadron corrections estimated using HERWIG or PYTHIA.
- Underlying event estimated using Multi-parton interaction or Soft underlying event models, parameters tuned to describe energy flow around the jets.
- To avoid infrared sensitive jet cross sections again defined with
  - ▷ Asymmetric jet cuts.

# The H1 dijet cross section



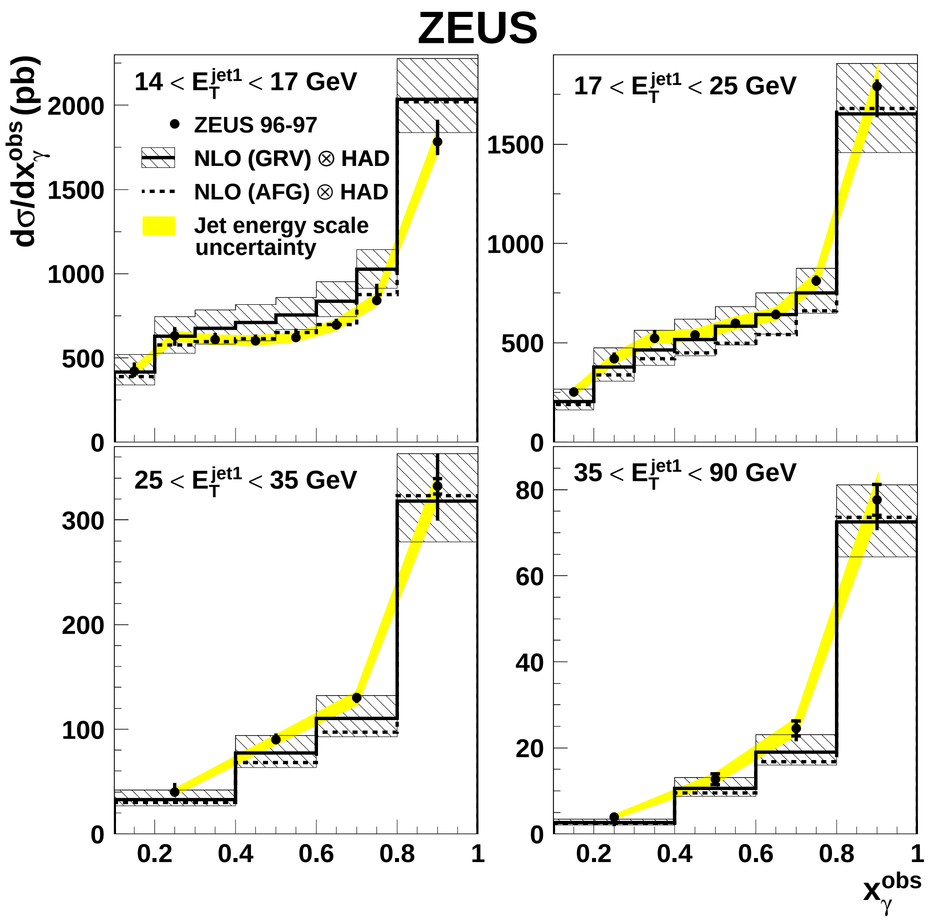

- Dijet cross secions

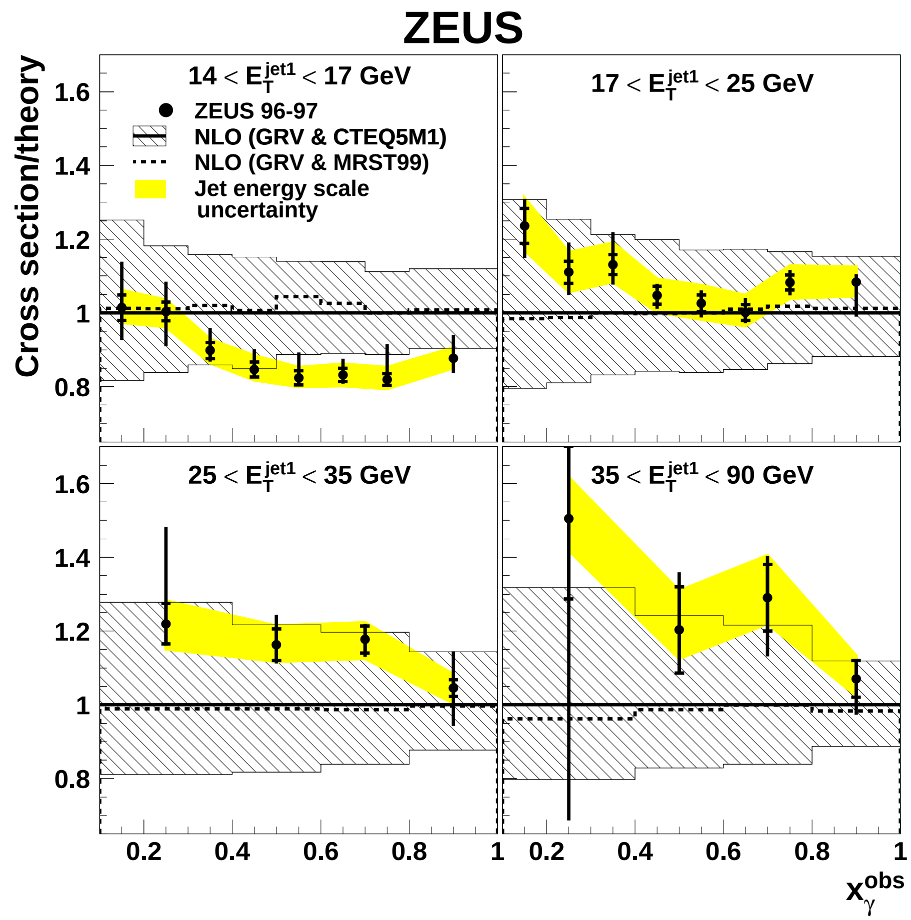
  $E_T^{\text{jet1, 2}} > 25,\ 15\,\text{GeV}, \quad -0.5 < \eta^{\text{jet}} < 2.5$

  $Q^2 < 1\text{GeV}^2, \quad 95 < W_{\gamma p} < 285\text{GeV}$

- CTEQ5M proton and GRV/AFG photon PDF's.
- NLO describes the data well at low $x_\gamma$.
- Difference in predictions from photon PDF's smaller than scale uncertainty ⇒ Need improved theoretical predictions.

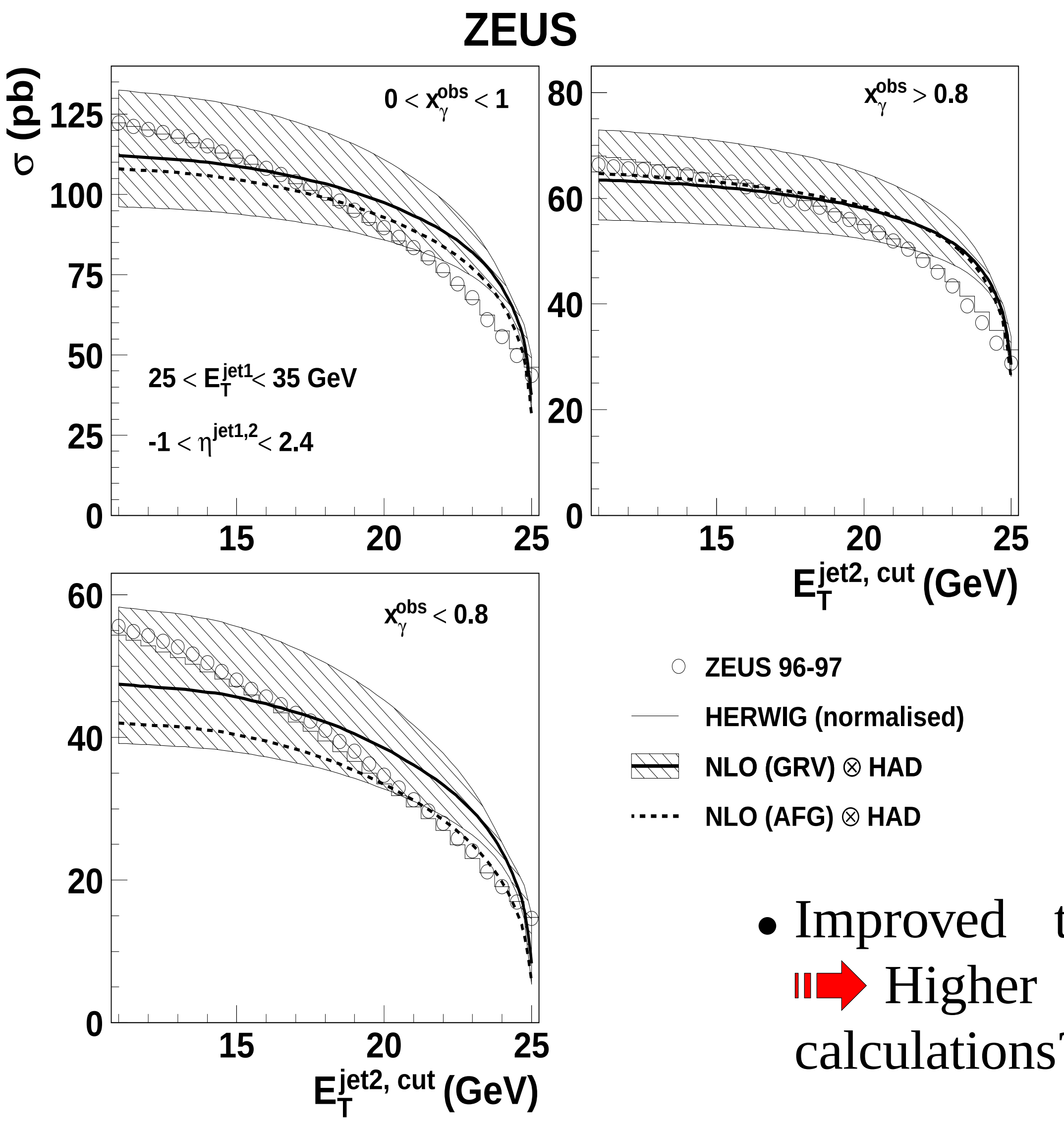
# The ZEUS dijet cross section




- Dijet phase space $E_T^{\text{jet1, 2}} > 14,\ 11\ \text{GeV}, \quad -1 < \eta^{\text{jet}} < 2.4$.
- Small experimental uncertainties, large scale uncertainty.
- NLO prediction below the data for low $x_\gamma$ ➡ contradicts H1 measurement?

# Dependence on sub-leading jet transverse energy.




- $25 < E_T^{\rm jet1} < 35$GeV: H1 and ZEUS use different cuts on $E_T$ of the sub-leading jet.
  - ▷ H1: $E_T^{\rm jet2} > 15$ GeV.
  - ▷ ZEUS: $E_T^{\rm jet2} > 11$ GeV.
- Dependence of cross section not reproduced by NLO calculation. ⇒ Large renormalisation uncer-rtainties.
- Improved theoretical understanding required ⇒ Higher order corrections? Resummed calculations? Improved jet selection?

# Inclusive jet photoproduction

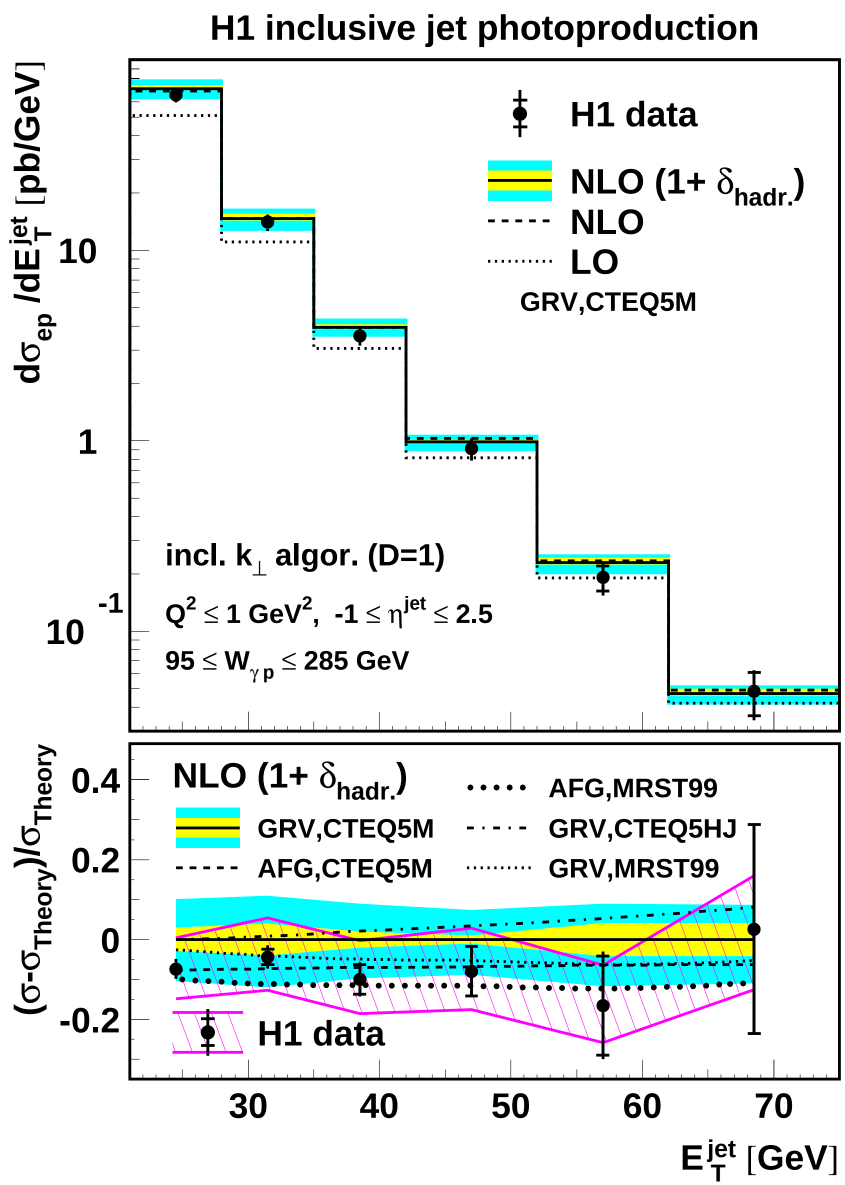
- Inclusive jet production does not restrict the phase space of the second jet, or even require it to be within the detector acceptance.

- Reduced theoretical uncertainties, ⇒ more reliable QCD predictions but less complete information on event kinematics.

- Cross section for all jets with all jets

$$E_T^{\rm jet} > 21 \text{ GeV}, \quad -1 < \eta^{\rm jet} < 2.4$$

$$(95 < W_{\gamma p} < 285 \text{ GeV}, \quad Q^2 < 1 \text{ GeV}^2)$$



# The inclusive cross section

- Cross section for all jets,

  $17 < E_T^{\rm jet} < 95$ GeV, $\quad -1 < \eta^{\rm jet} < 2.5$

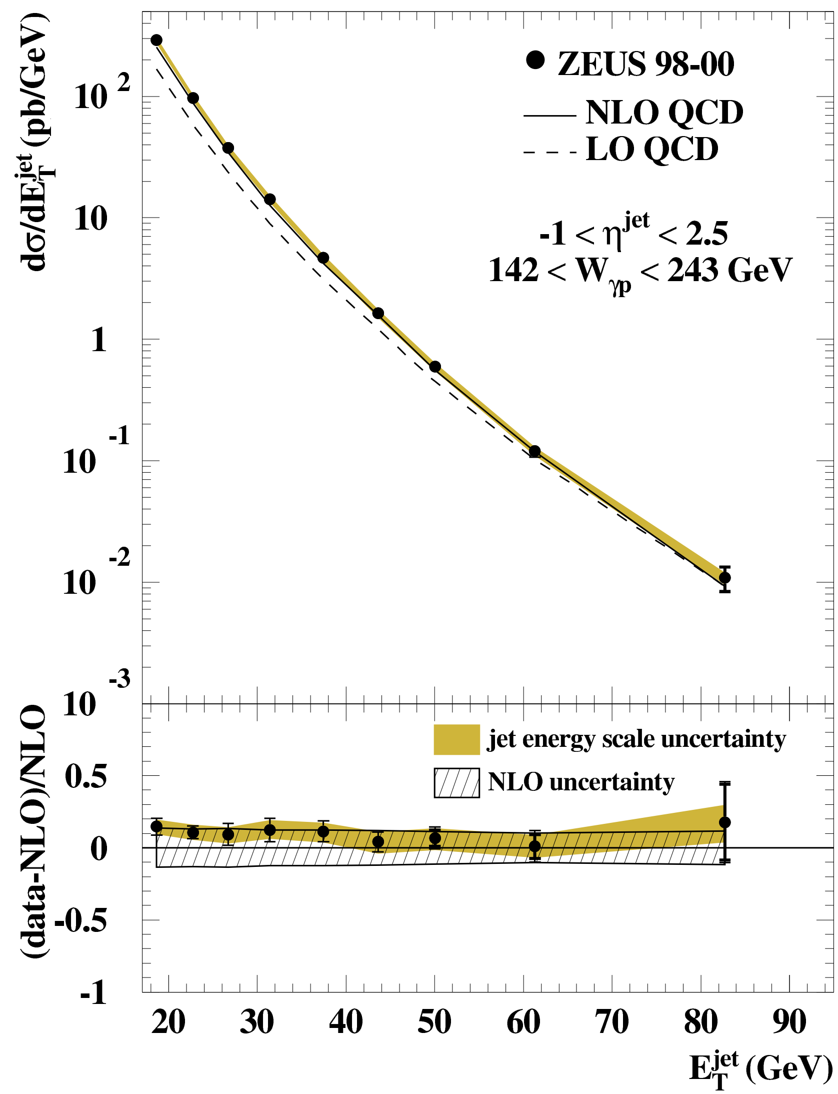
  $142 < W_{\gamma p} < 293$ GeV, $\quad Q^2 \leq 1$ GeV$^2$

- For $E_T^{\rm jet} < 45$ GeV, resolved processes dominant.

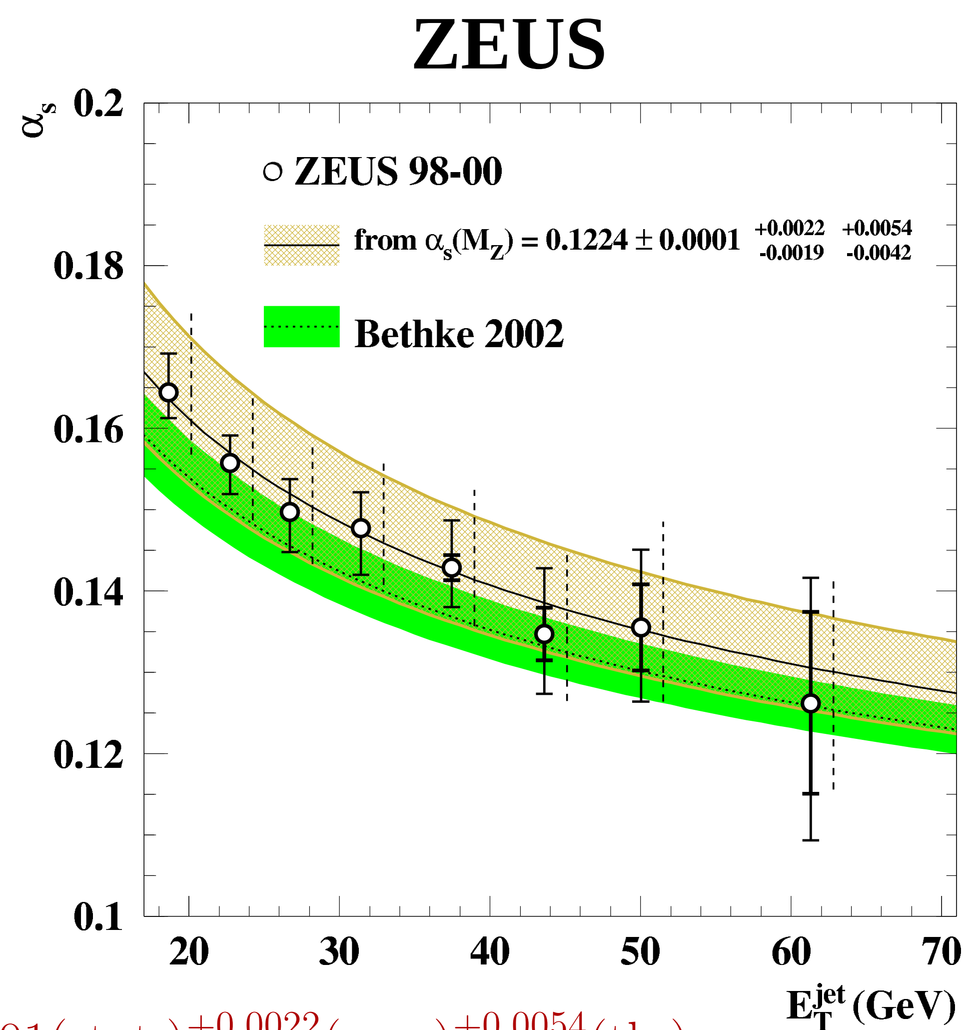
- Small theoretical uncertainties...
  - ▷ Renormalisation scale $\sim$ 10%,
  - ▷ Photon and proton pdfs $\sim$ 5%,
  - ▷ $\alpha_s \sim$ 8% at low $E_T^{\rm jet}$.

- Good agreement of NLO with the data over many orders of magnitude.

ZEUS



# The running of $\alpha_s$

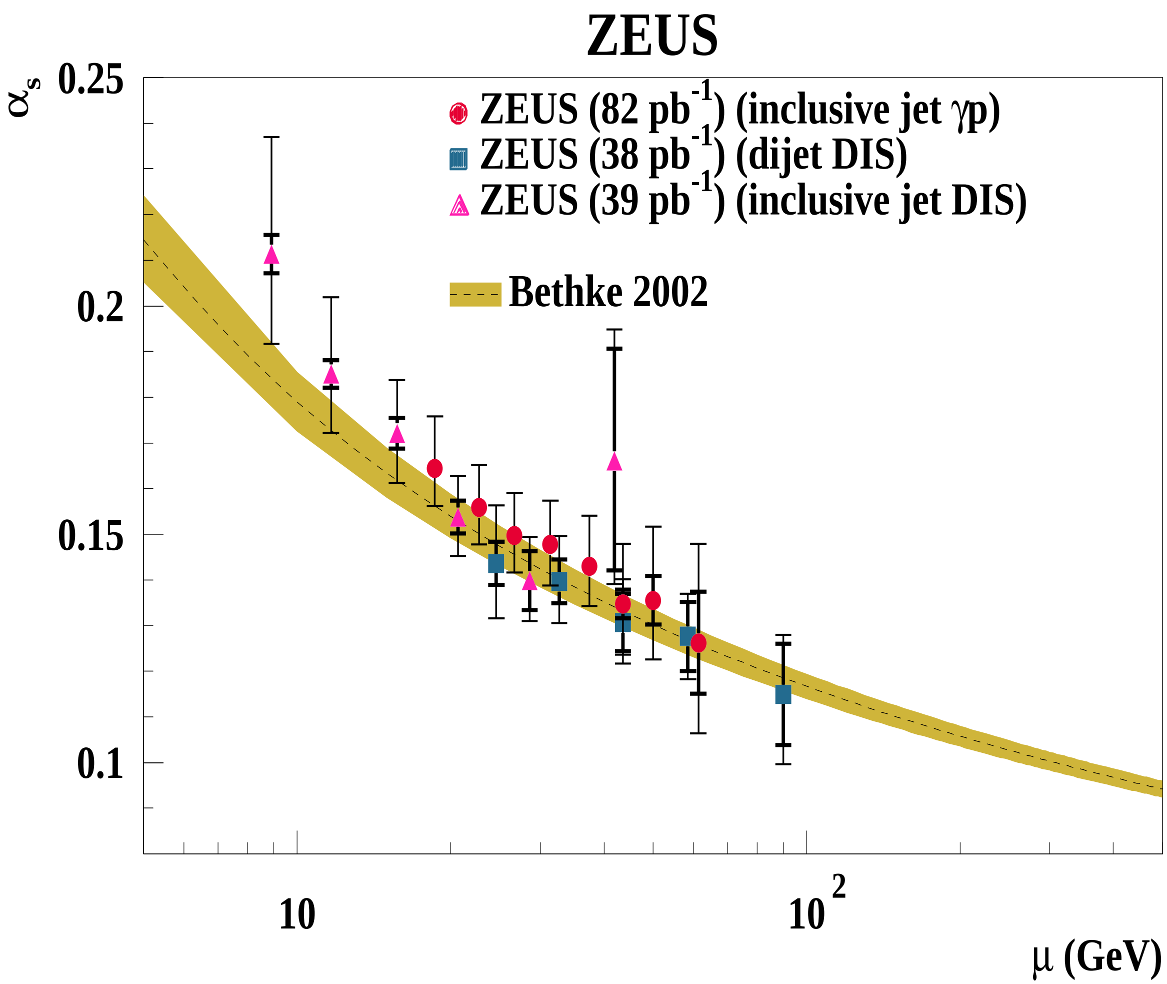



- Extract $\alpha_s$ in each $E_T^{\mathrm{jet}}$ bin using the MRST99 pdf sets.
- Clear running of $\alpha_s$ in a single measurement.
- Running back to the $Z^0$ mass...

$$\alpha_s(M_Z) = 0.1224 \pm 0.0001(\mathrm{stat.})^{+0.0022}_{-0.0019}(\mathrm{exp.})^{+0.0054}_{-0.0042}(\mathrm{th.})$$

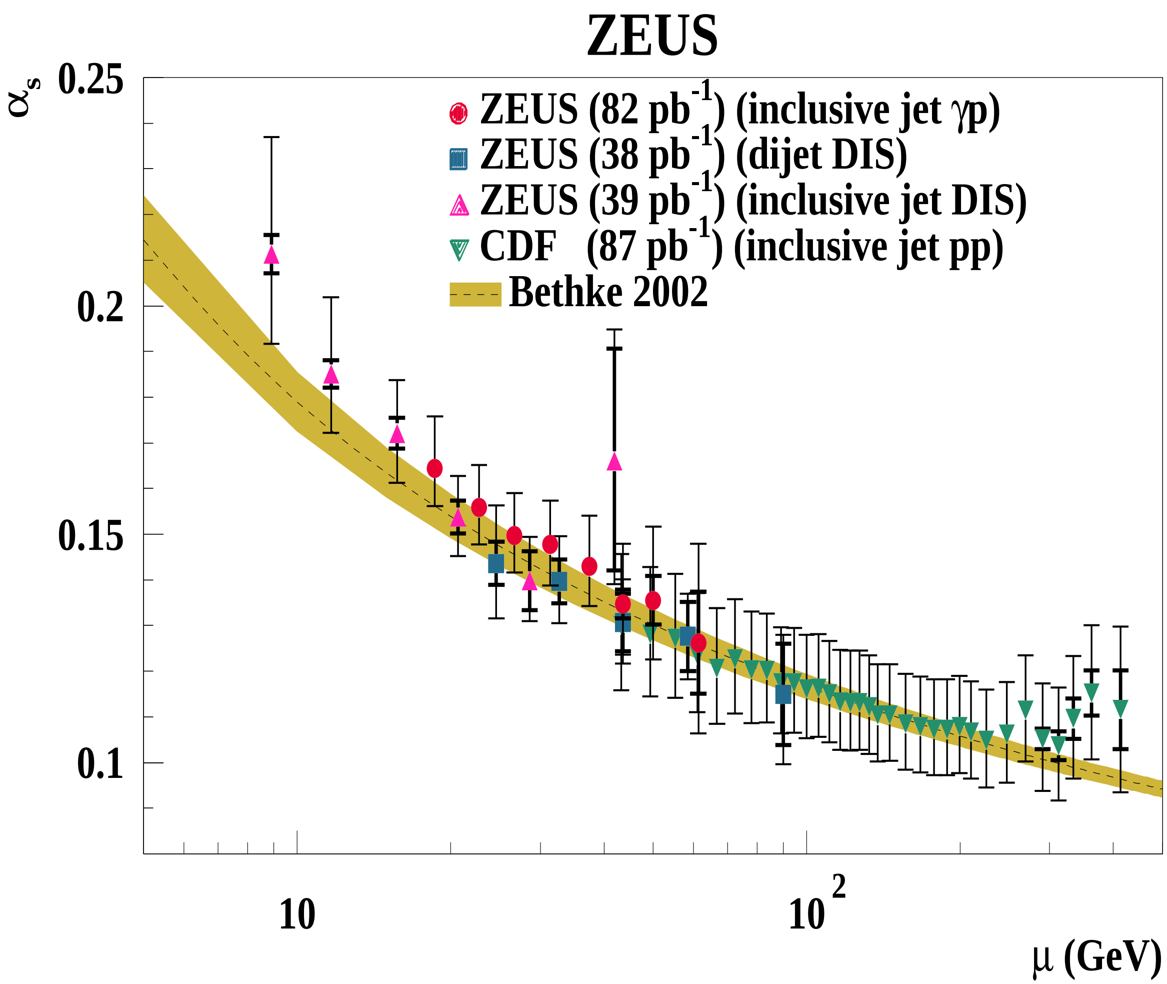
- Consistent with recent fit of Bethke, theory error still dominates.

# The running of $\alpha_s$




- Spans the overlap region of existing ZEUS data.
- Running seen over an order of magnitude in scale variation from ZEUS data alone.

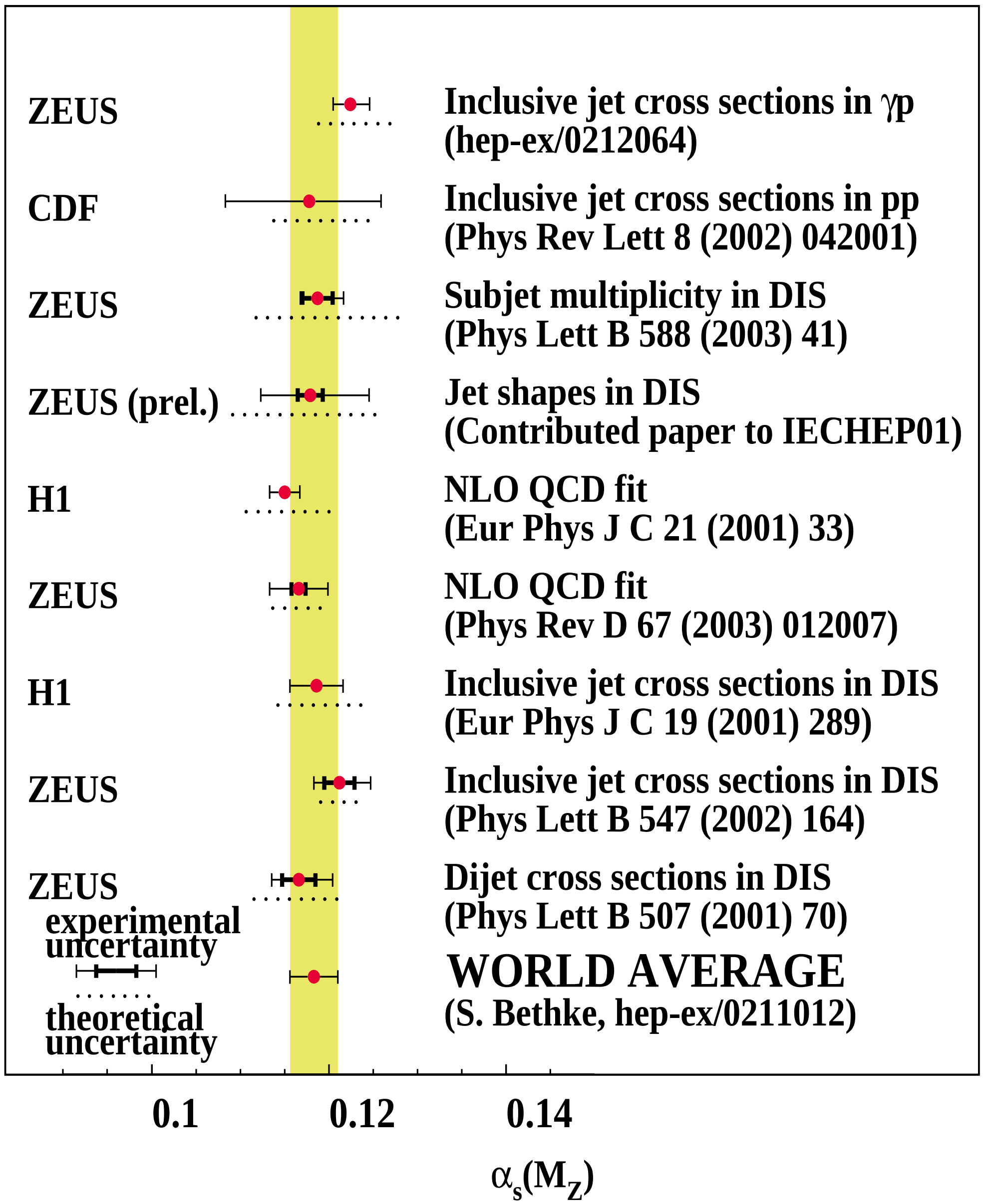
# The running of $\alpha_s$




- Spans the overlap region of existing ZEUS data.
- Running seen over an order of magnitude in scale variation from ZEUS data alone.

- Including CDF data, see $\alpha_s$ running with scale variation well over an order of magnitude.

# Comparison with other measurements




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

# Summary and Outlook

- HERA is now producing a wealth of precision jet data at high $E_T$ in deep inelastic scattering, photoproduction and the transition region.
- Many extractions of the QCD coupling constant, $\alpha_s$ with a statistical precision competitive with the world average, running behaviour clearly seen.
- At high $E_T^{\text{jet}}$ in inclusive cross sections, theoretical uncertainties are small, and prediction is able to reproduce cross sections over many orders of magnitude.
- At lower $Q^2$ and in dijet photoproduction, theoretical uncertainties are dominant. ➡ Theoretical developments, resummed calculations etc. are needed.
- Experimental precision and coverage of data now very good, ➡ Time for inclusion of these data in global PDF fits.