PHOTON 2007

Jets and α_s measurements in DIS at HERA

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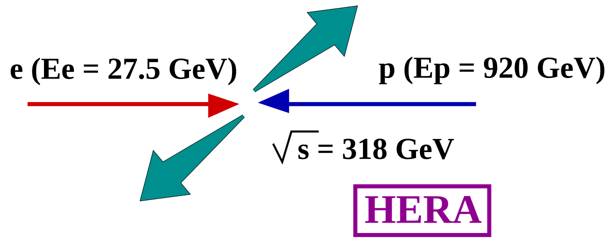


On behalf of H1 and ZEUS collaborations

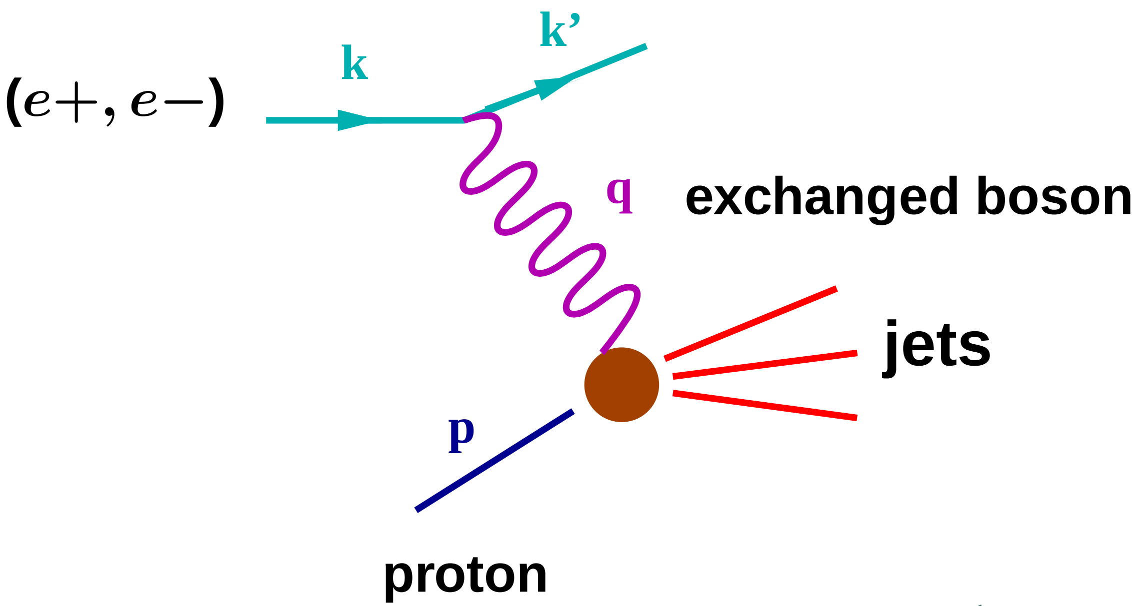
DIS at HERA

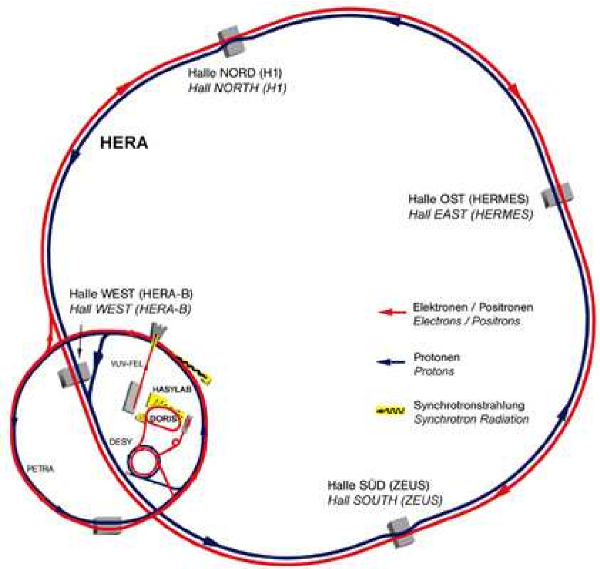
- **For a given center-of-mass $\sqrt{s}$, the kinematics of a DIS event can be described by any two of these three kinematic variables**

$$Q^2 = -(k - k')^2$$ ← **Virtuality of the exchanged boson**

$$x = \frac{Q^2}{2p \cdot q}$$ ← **In QP model, fraction of proton momentum carried by struck parton**

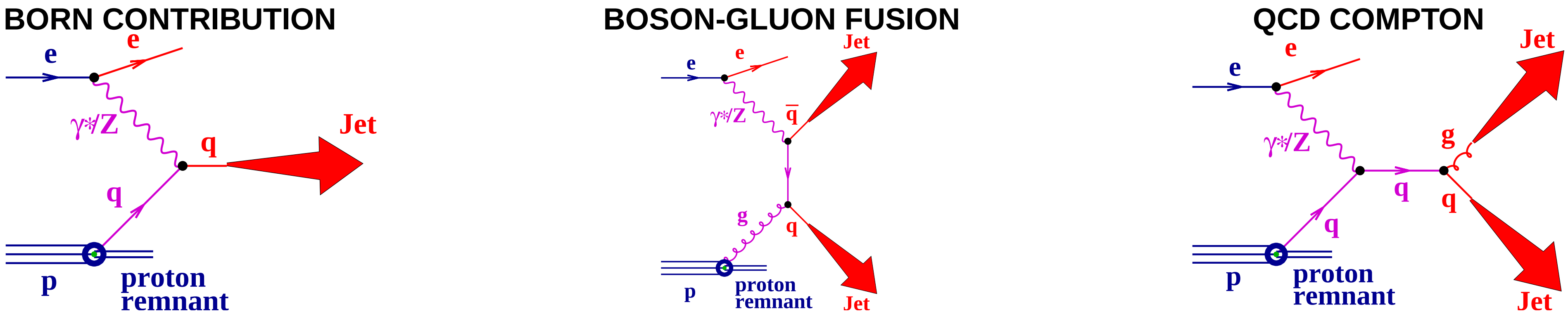
$$y = \frac{p \cdot q}{p \cdot k} = \frac{Q^2}{sx}$$ ← **Inelasticity variable**





DIS cross section

- At HERA, jet production in DIS provides a testing ground for QCD
- Up to LO in α_s, these are the diagrams that contribute to the jet production cross section in DIS ($Q^2 \gg \Lambda^2_{QCD}$):

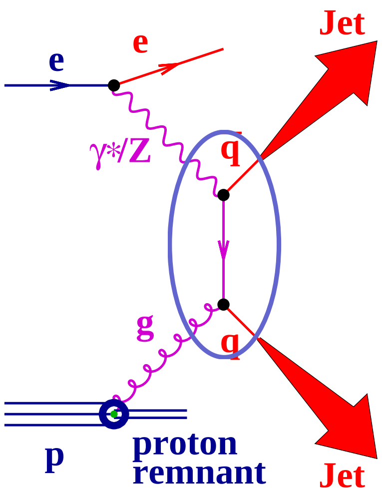


- The cross section in QCD is given by:

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

- f_a are the experimentally determined parton distribution functions
  $\longrightarrow$ long-distance structure of the interaction

- $d\hat{\sigma}_a$ is the subprocess cross section, calculable in pQCD
  $\longrightarrow$ short-distance structure of the interaction



- In regions where the PDFs are well constrained

$\longrightarrow$ Low Q^2 region allows high statistics

$\longrightarrow$ test general aspects of pQCD

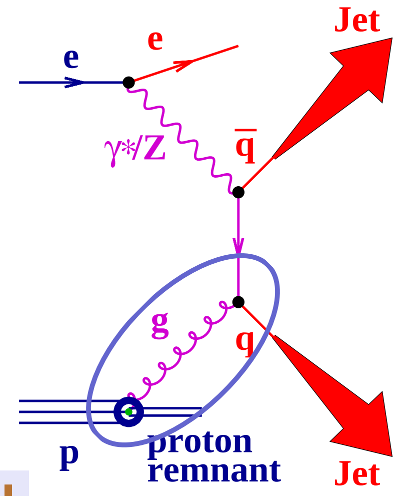
$\longrightarrow$ High Q^2 region allows small theoretical uncertainties

$\longrightarrow$ study jet algorithm

- In regions where the PDFs are not as well constrained

$\longrightarrow$ e.g. Gluon PDF at mid-to-high x

$\longrightarrow$ Jet cross sections help constrain gluon PDF

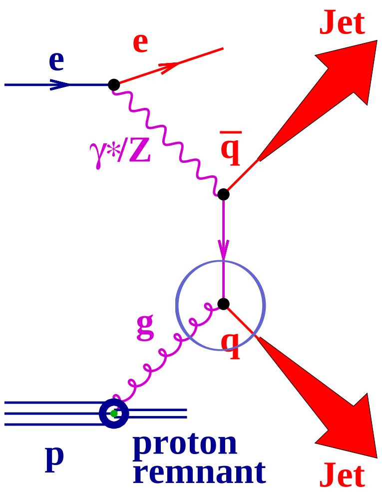


- Variables that allow smallest theoretical and experimental uncertainties

$\longrightarrow$ Inclusive-jet cross sections at high Q^2

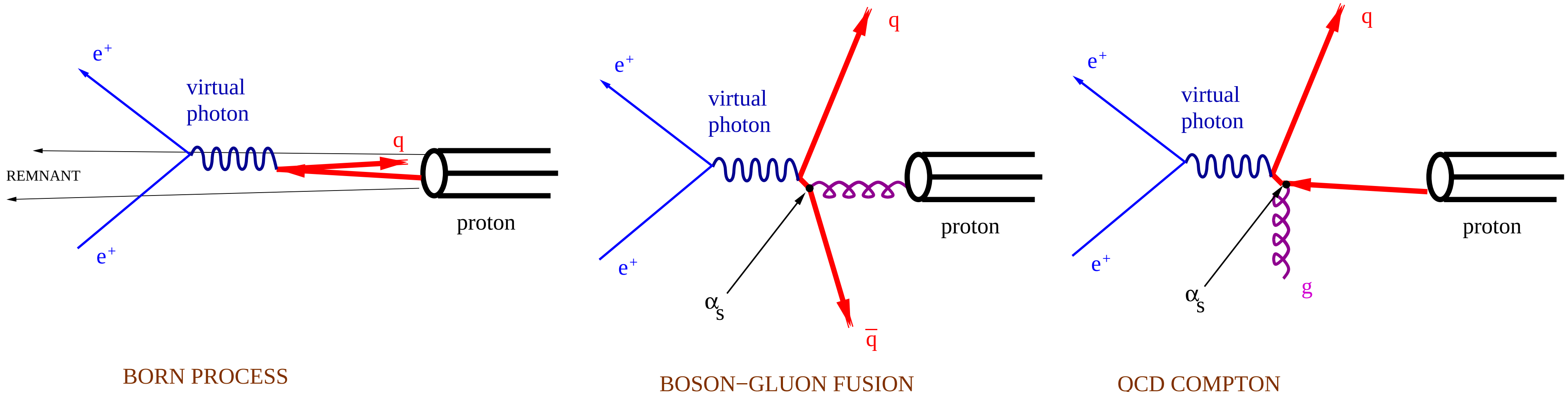
$\longrightarrow$ extraction of α_s with high precision

$\longrightarrow$ test scale-dependence of α_s



The Breit frame

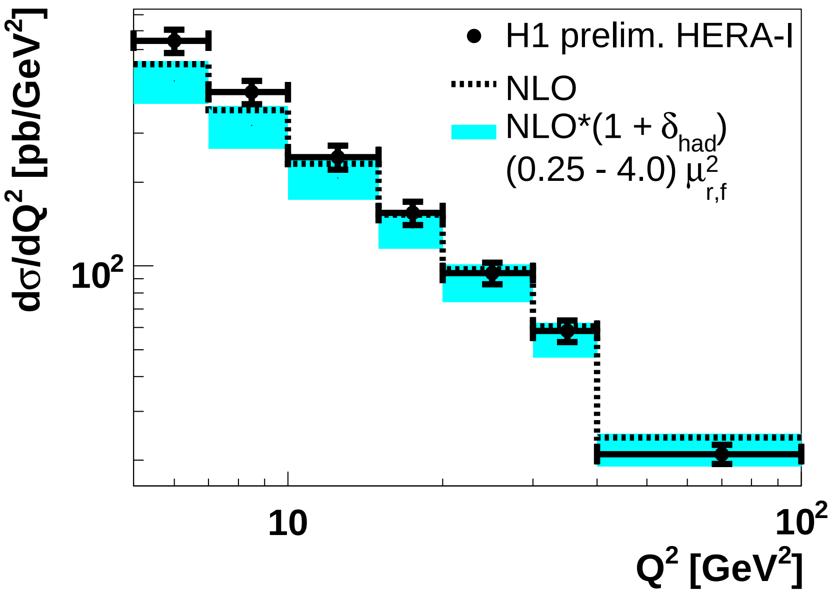
- The Breit frame is ideal for studying QCD with high E_T jets
  - $\longrightarrow$ suppression of the Born contribution (struck quark has zero E_T)
  - $\longrightarrow$ suppression of beam remnant jet (zero E_T)
  - $\longrightarrow$ lowest order non-trivial contributions from $\gamma^* g \longrightarrow q\bar{q}$ and $\gamma^* g \longrightarrow qg$
  - $\longrightarrow$ directly sensitive to QCD hard processes (α_s)

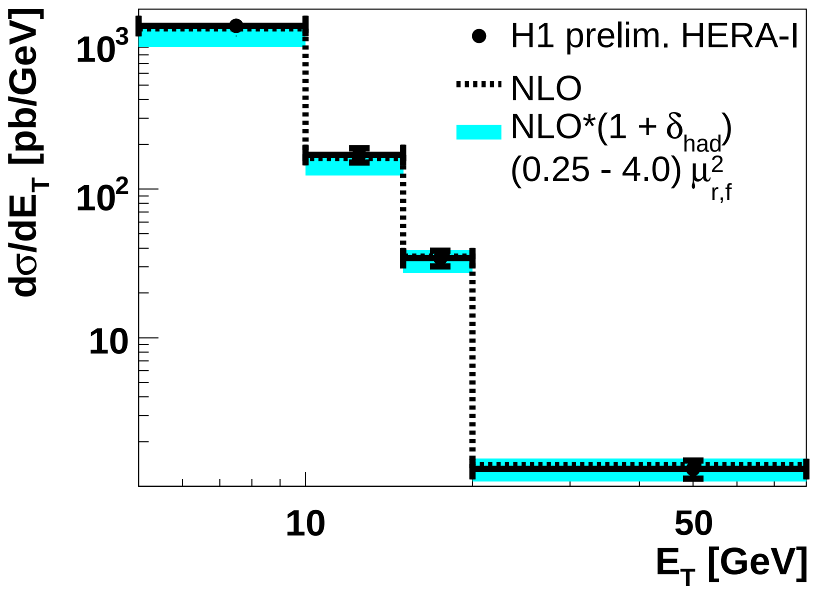


- Jets are reconstructed in the Breit frame using a k_T-cluster algorithm
  - $\longrightarrow$ invariant under longitudinal boosts
  - $\longrightarrow$ infrared and collinear safe

INCLUSIVE JET PRODUCTION IN LOW Q^2 DIS

H1 Inclusive Jet Cross Sections $\frac{d\sigma}{dQ^2}$, $\frac{d\sigma}{dE_T}$



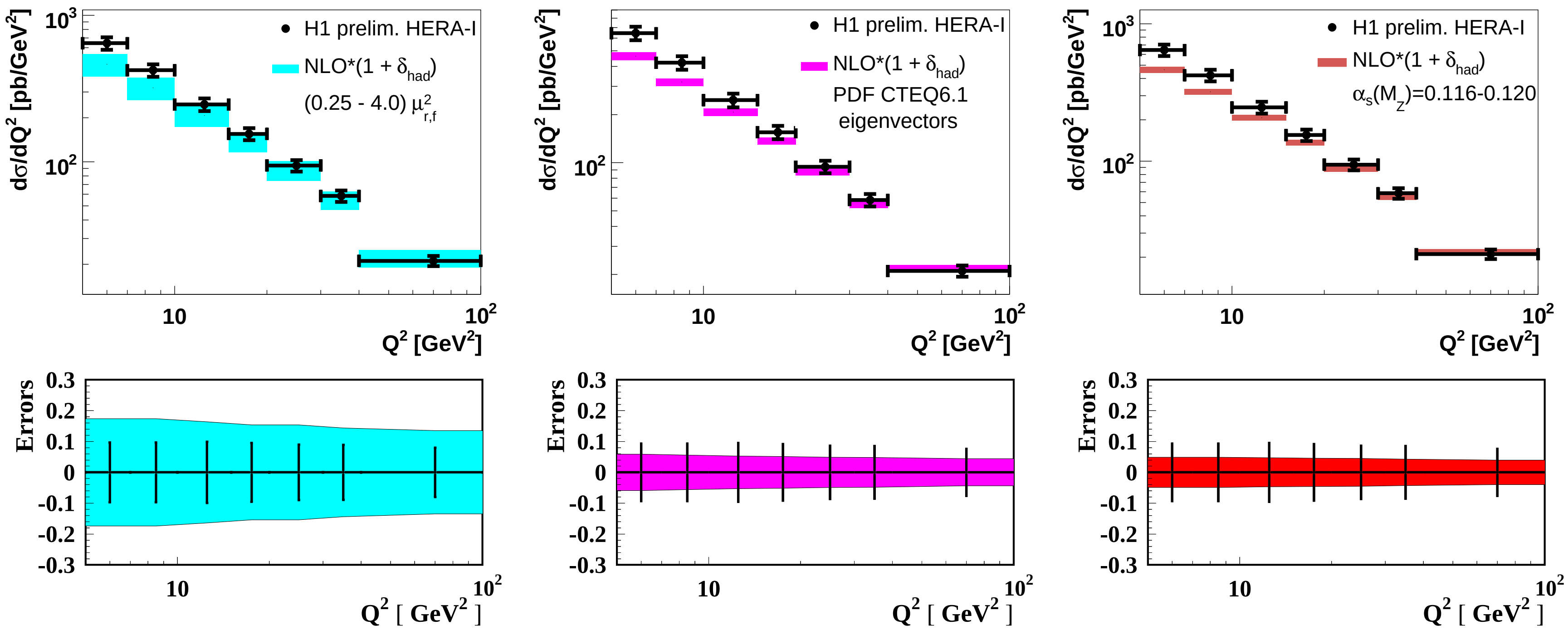


- **Motivation: how low in Q^2 and E_T is pQCD at NLO reliable?**
- **Kinematic region defined by:**
  - $5 < Q^2 < 100$ GeV^2
  - $0.2 < y < 0.7$
  - $\mathcal{L} = 44$ pb^{-1}
  - $E_{T,\mathrm{B}}^{\mathrm{jet}} > 5$ GeV
  - $-1 < \eta_{LAB} < 2.5$
- **This study shows that pQCD at NLO provides a good description of inclusive jet production down to the region of $Q^2 > 10$ GeV^2 and $E_{T,\mathrm{B}}^{\mathrm{jet}} > 10$ GeV**

INCLUSIVE-JET PRODUCTION IN LOW Q^2 DIS

- **Theoretical uncertainties in the NLO calculations of $d\sigma/dQ^2$**
- **NLO ingredients: • PDF: CTEQ6.1M • $\mu_F = Q$ • $\mu_R = E_{T,\mathrm{B}}^{\mathrm{jet}}$**

μ_R **unc.** $\rightarrow$ **up to** $\pm 20\%$ | PDF **unc.** $\rightarrow \pm 5\%$ | $\alpha_s(M_Z)$ **unc.** $\rightarrow \pm 5\%$



- **In the region $5 < Q^2 < 10$ GeV^2 there are discrepancies between NLO and data**
- **The largest contribution to the uncertainty comes from terms beyond NLO**
  $\longrightarrow$ **study suggests NNLO is needed to describe low Q^2 region**

- So far, all the measurements of jet production in DIS use the k_T cluster algorithm with the jet radius R=1

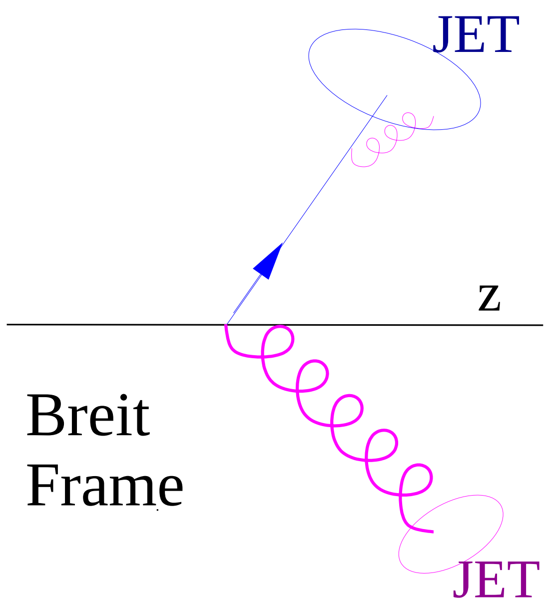
→ DIS provides a well understood environment to study the dependence of jet production on R

→ Of particular interest for the identification of heavy particles decaying into jets

- k_T-cluster metric

$$d_{ij} = min(E_T^i, E_T^j)^2 \cdot (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2)$$

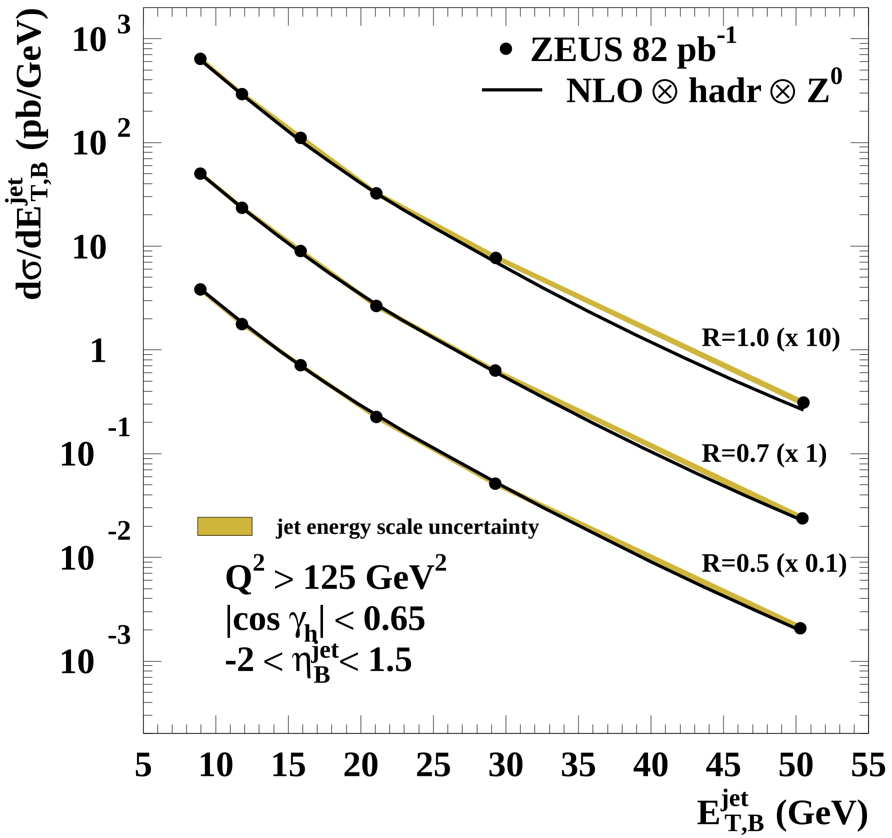
$$d_i = E_T^{i,2} * R^2$$

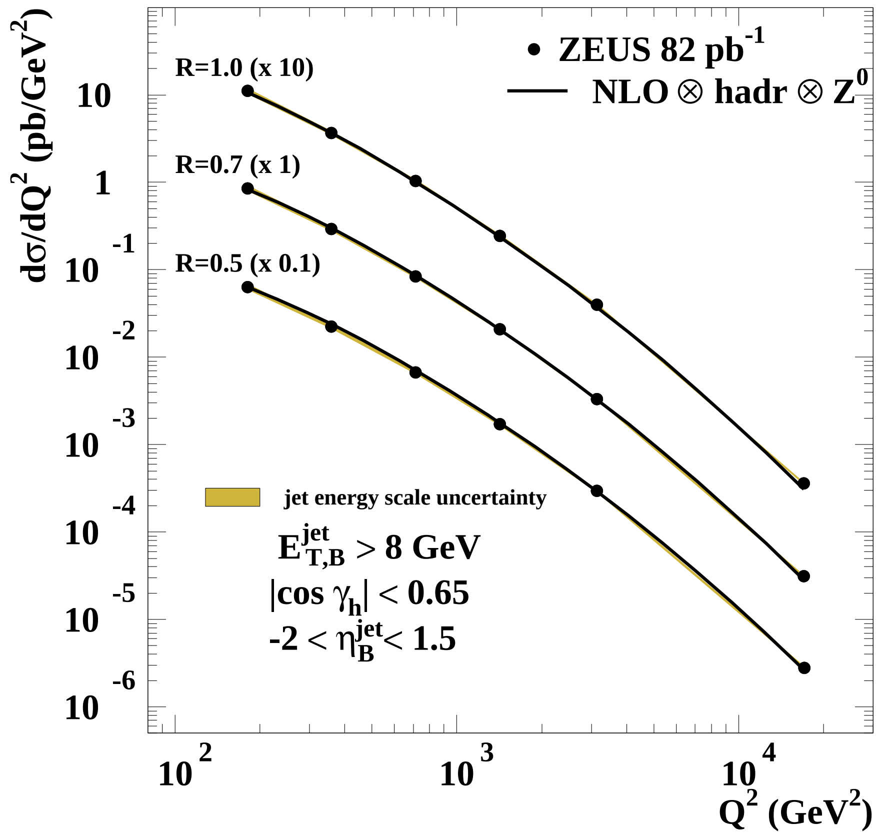


→ no R dependence of cross section at LO in the Breit frame (partons are back-to-back)

Differential cross sections' dependence on R parameter

- Cross section measurements for: $Q^2 > 125$ GeV^2 , $E_{T,\mathrm{B}}^{\mathrm{jet}} > 8$ GeV, $-2 < \eta_{\mathrm{B}}^{\mathrm{jet}} < 1.5$ and $|cos\gamma_h| < 0.65$



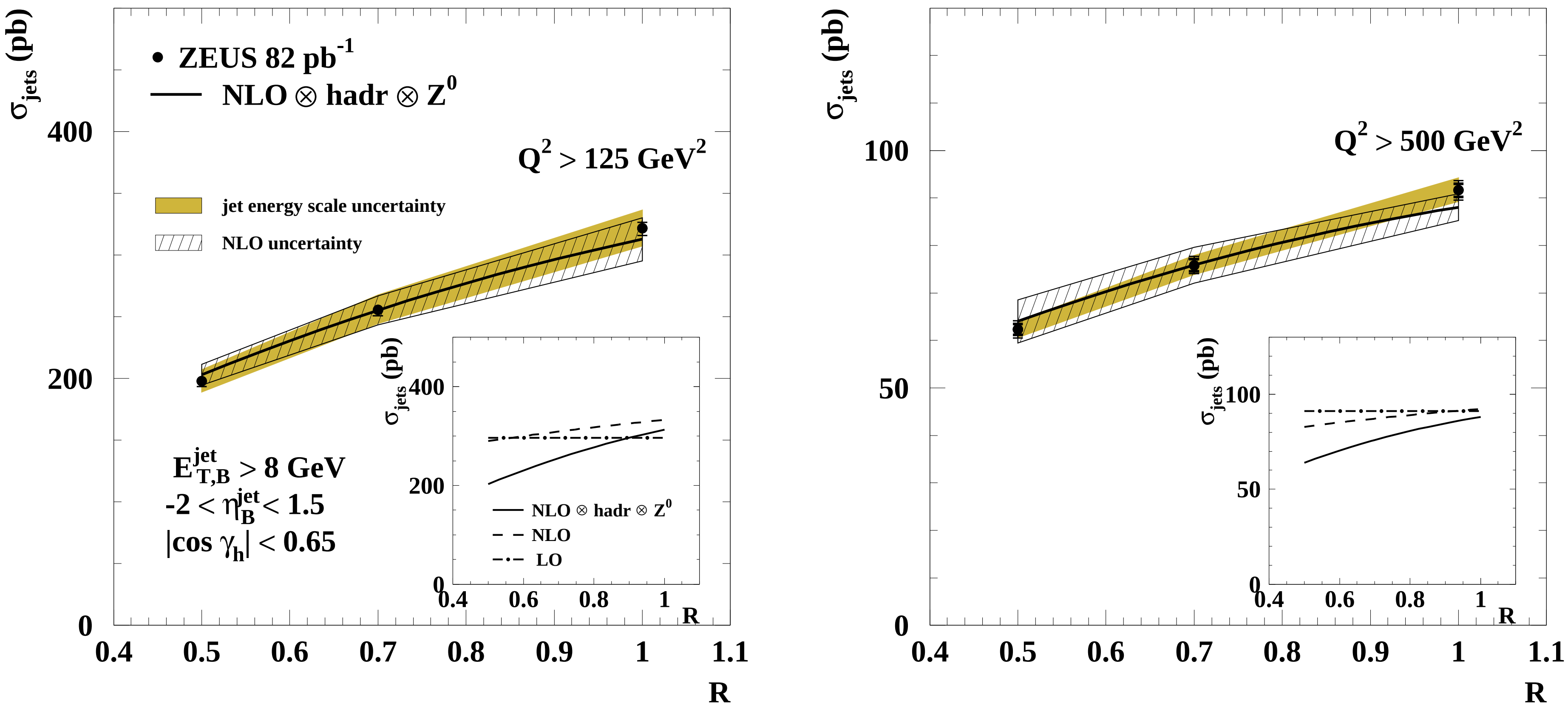


- NLO ingredients:
  - $\alpha_s(M_Z) = 0.118$
  - PDF ZEUS-2002-RT
  - $\mu_R = E_{T,\mathrm{B}}^{\mathrm{jet}}$ of each jet
  - $\mu_F = Q$

$\longrightarrow$ **Good agreement between data and NLO calculations for R=1, R=0.7 and R=0.5**

Total cross sections' dependence on R parameter

- Integrated jet cross sections for the regions $Q^2 > 125$ GeV^2 and $Q^2 > 500$ GeV^2

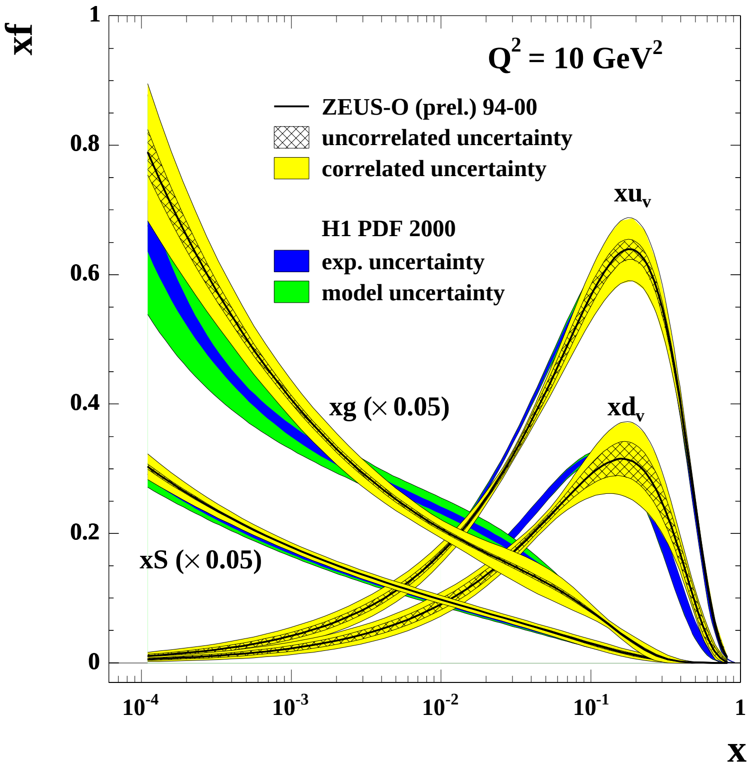


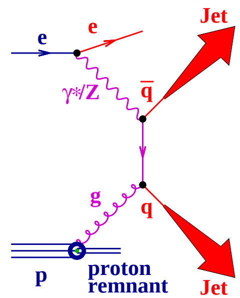
→ Total cross section shows an approximately linear dependence with R

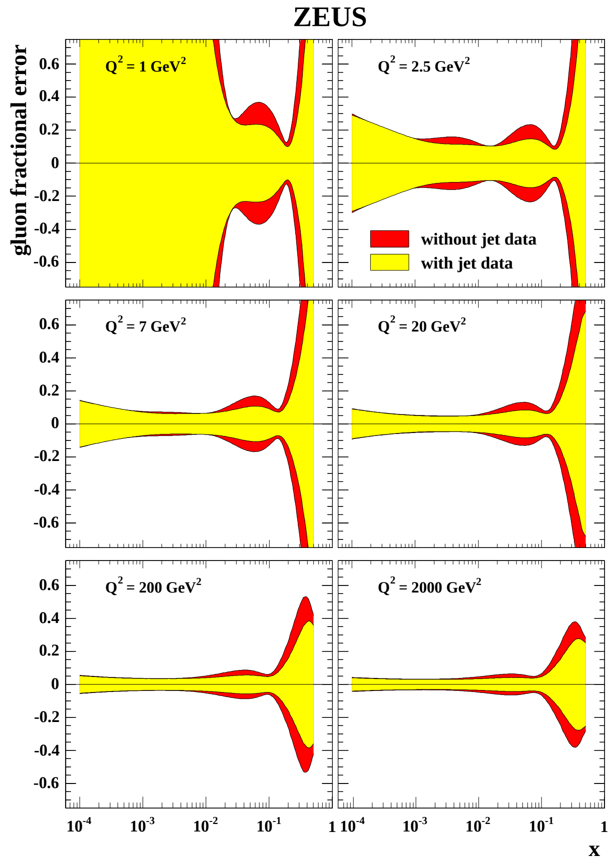
→ Region for safe variation of R determined → $0.5 < R < 1.0$

INCLUSIVE JETS AND DIJETS IN HIGH Q^2 DIS

- As a result of including jet cross sections, the gluon PDF uncertainty was reduced





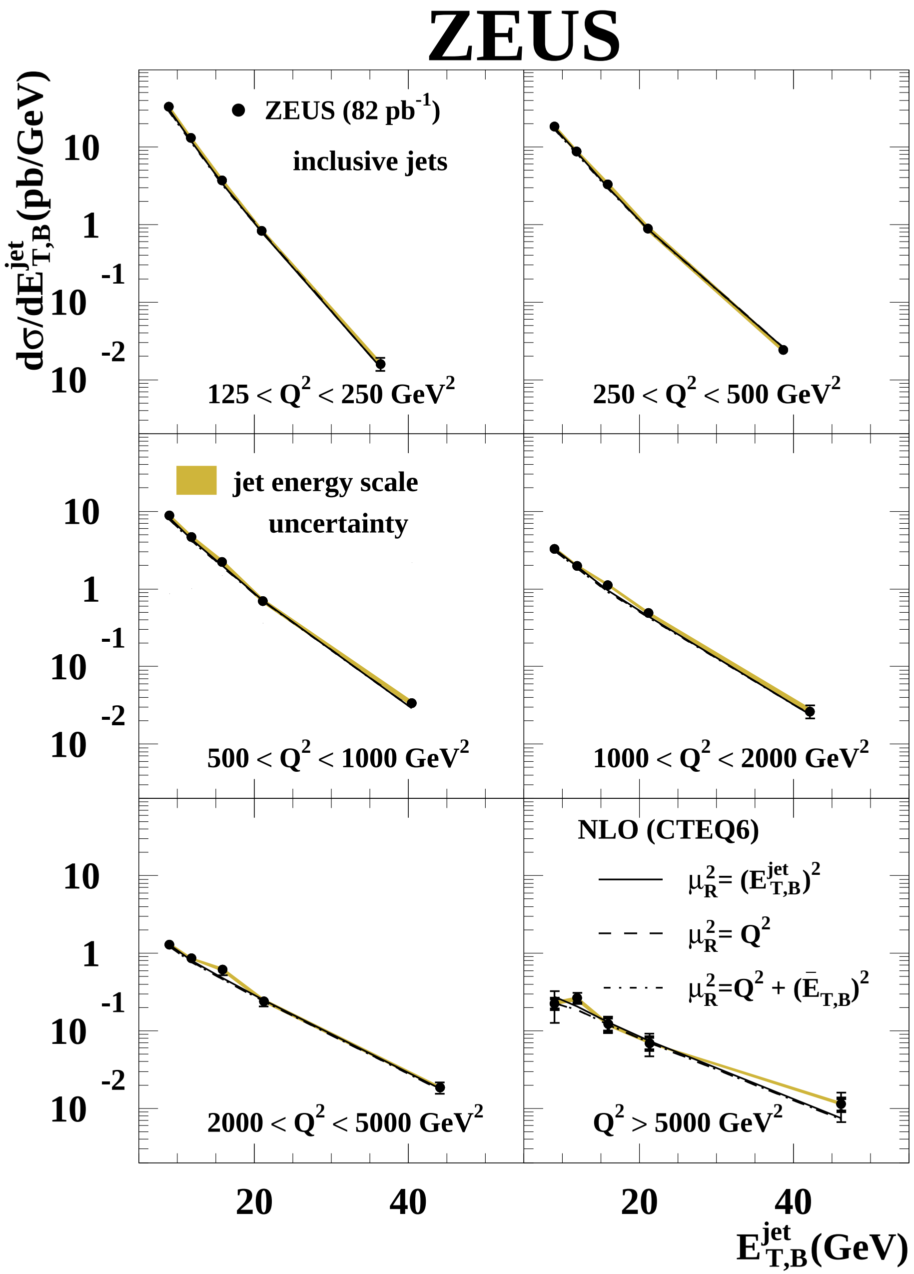


- Gluon PDFs dominate in low x region

- **Jet data has large effect on the gluon PDF in mid-to-high x region**

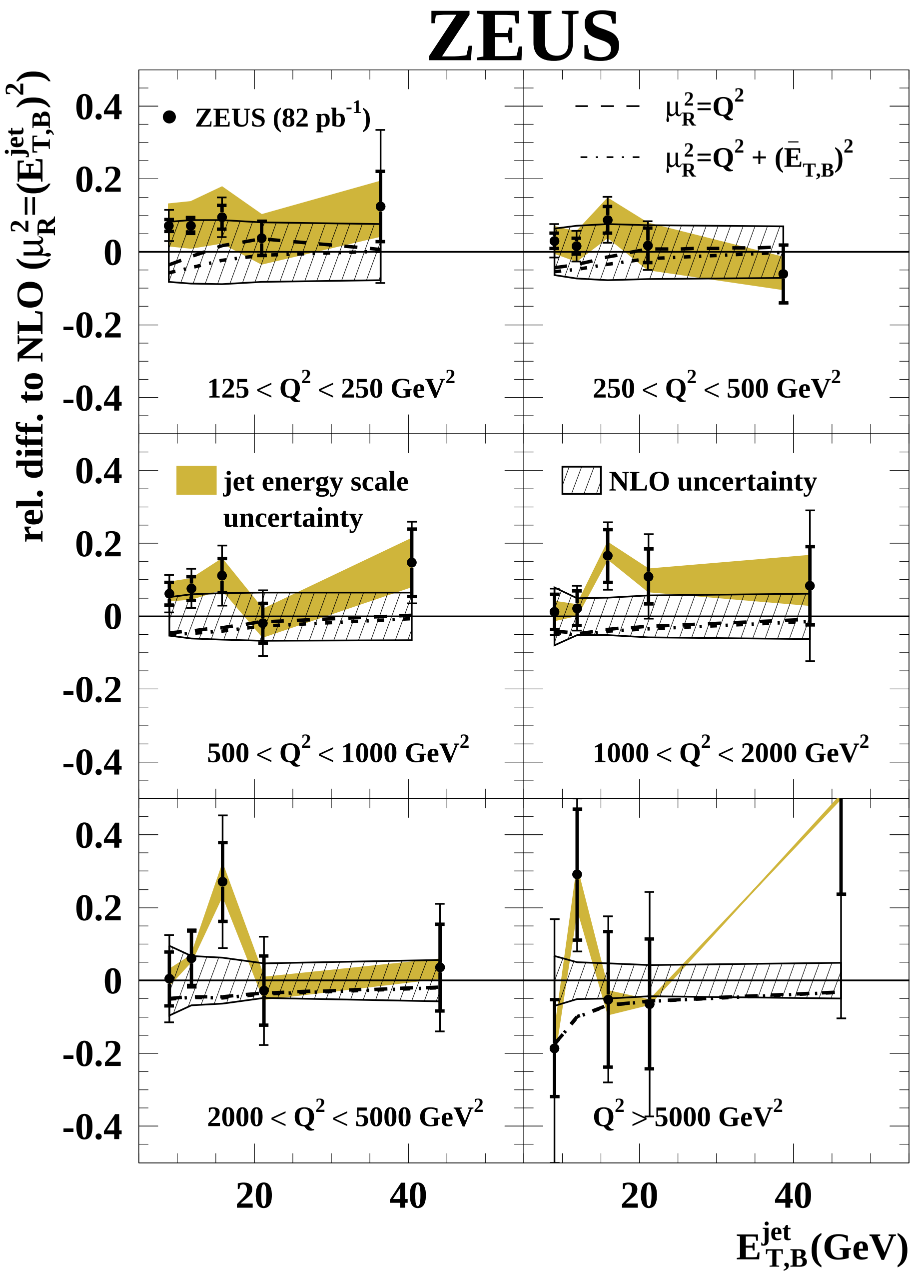
INCLUSIVE JETS AND DIJETS IN HIGH Q^2 DIS

- Measurements of $d\sigma/dE_{T,B}^{jet}$ in regions of Q^2
- Kinematic region defined by:
  - $E_{T,\mathrm{B}}^{\mathrm{jet}} > 8$ GeV
  - $|cos\gamma_h| < 0.65$
  - $Q^2 > 125$ GeV^2
  - $\mathcal{L} = 82$ pb^{-1}
- Uncertainty in the data dominated by jet energy scale
  - E-scale unc. $\pm 1\%$ for $E_{T,L}^{jet} > 10$ GeV
  - E-scale unc. in cross sections $\pm 5\%$
- The dependence of $E_{T,\mathrm{B}}^{\mathrm{jet}}$ with Q^2 becomes less steep as Q^2 increases



INCLUSIVE JETS AND DIJETS IN HIGH Q^2 DIS

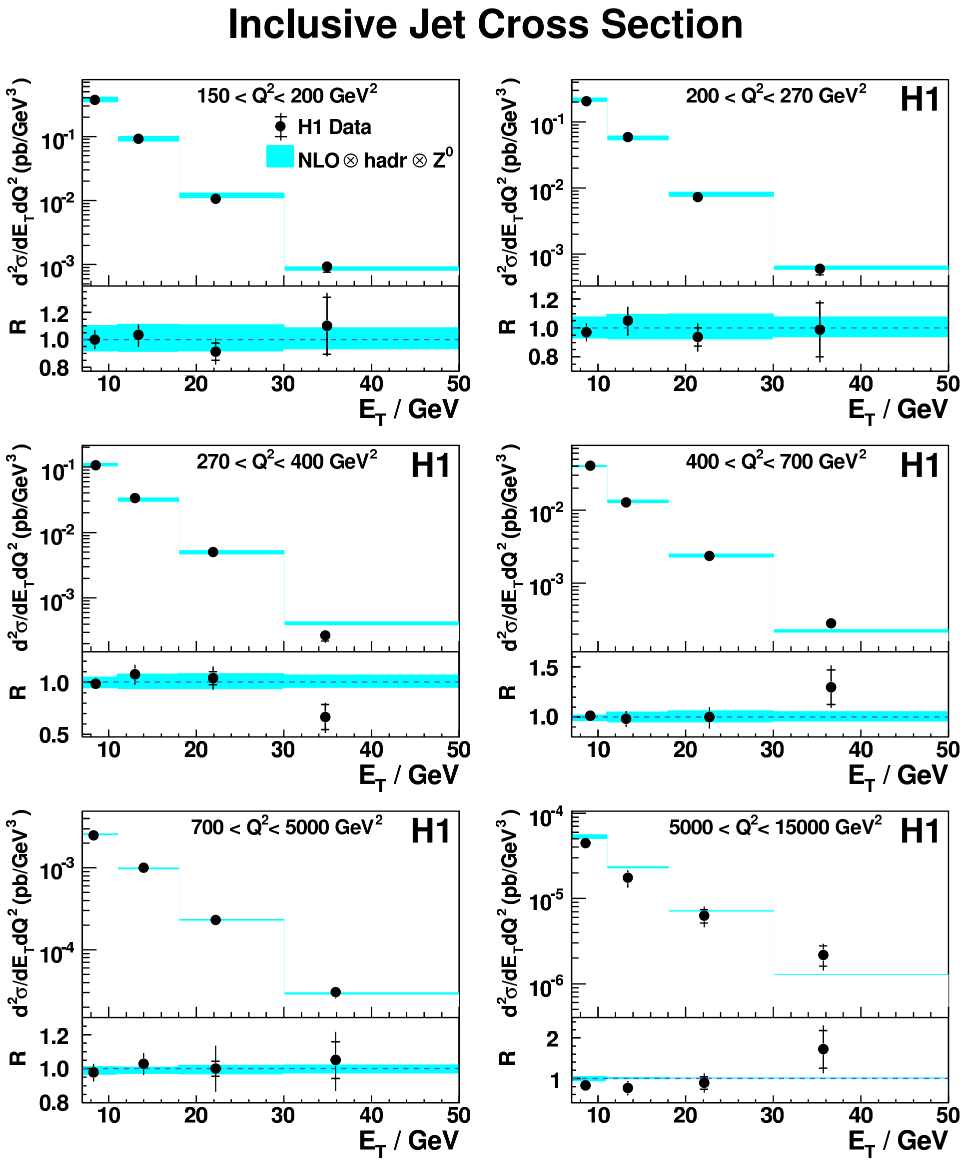
- Comparison of $d\sigma/dE_{T,B}^{jet}$ in regions of Q^2 with NLO predictions corrected for hadronisation ($< 10\%$ from unity)



- NLO ingredients:
  - $\alpha_s(M_Z) = 0.118$
  - PDF ZEUS-2002
  - $\mu_R = E_{T,\mathrm{B}}^{\mathrm{jet}}$ of each jet
  - $\mu_F = Q$
- Sources of theoretical uncertainty in NLO calculations due to:
  - that in $\alpha_s(M_Z) \rightarrow (< \pm 4\%)$
  - that in PDFs $\rightarrow (< \pm 2\%)$
  - absent higher orders $\rightarrow (< \pm 7\%)$

INCLUSIVE JETS AND DIJETS IN HIGH Q^2 DIS

- New inclusive-jet cross sections measured over a wide range of Q^2 at H1



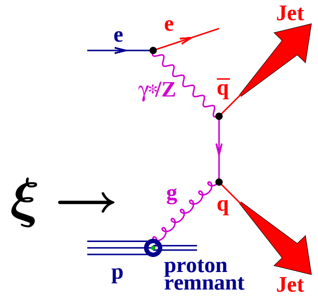
- Uncertainties similar to those of ZEUS measurements

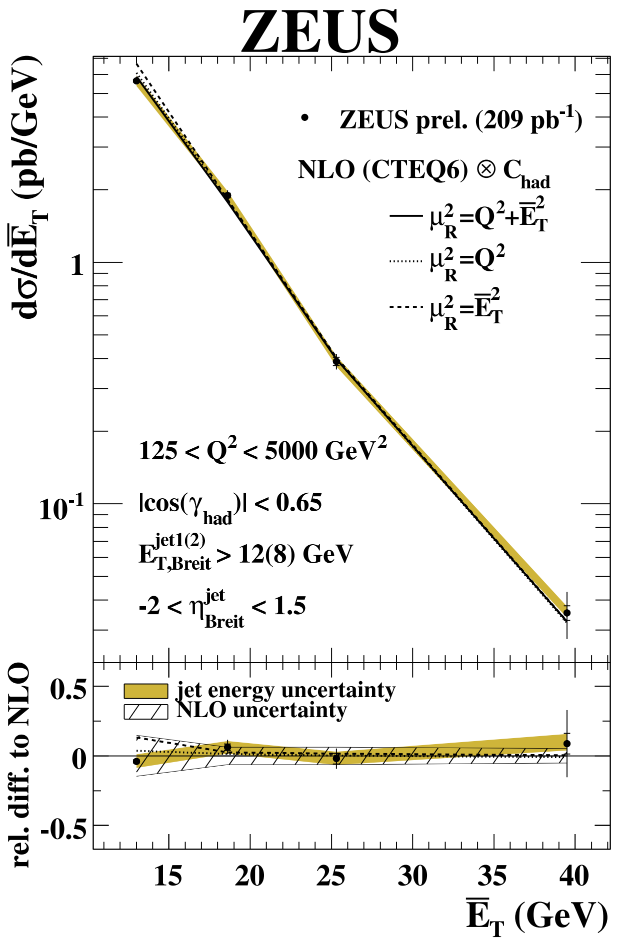
- Kinematic region defined by:
  - $E_{T,\mathrm{B}}^{\mathrm{jet}} > 7$ GeV
  - $0.2 < y < 0.7$
  - $Q^2 > 150$ GeV^2
  - $\mathcal{L} = 65$ pb$^{-}1$

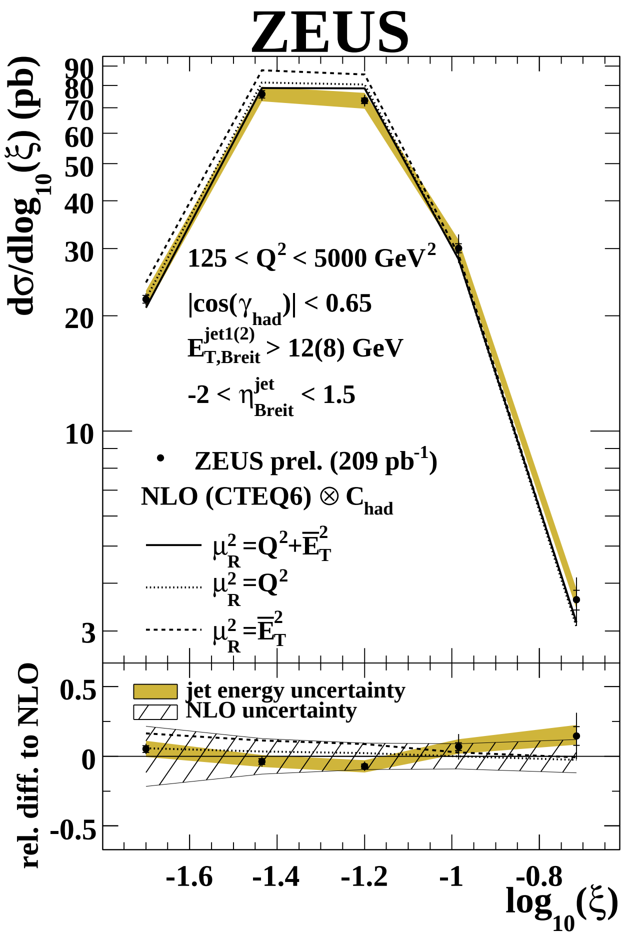
- NLO ingredients:
  - $\alpha_s(M_Z) = 0.118$
  - PDF = CTEQ6.5M
  - $\mu_R = E_{T,\mathrm{B}}^{\mathrm{jet}}$ of each jet
  - $\mu_F = Q$

DIJET MEASUREMENTS AT HIGH Q^2

- First measurements of dijet cross sections in NC DIS done using HERA II
- Improved statistics! $\rightarrow \mathcal{L} = 209$ pb $^{-1}$
- The **variable** ξ is the fraction of the proton momentum carried by the interacting parton







Determinations of $\alpha_s(M_Z)$

- Inclusive-jet cross sections at high Q^2 allow small theoretical and experimental uncertainties

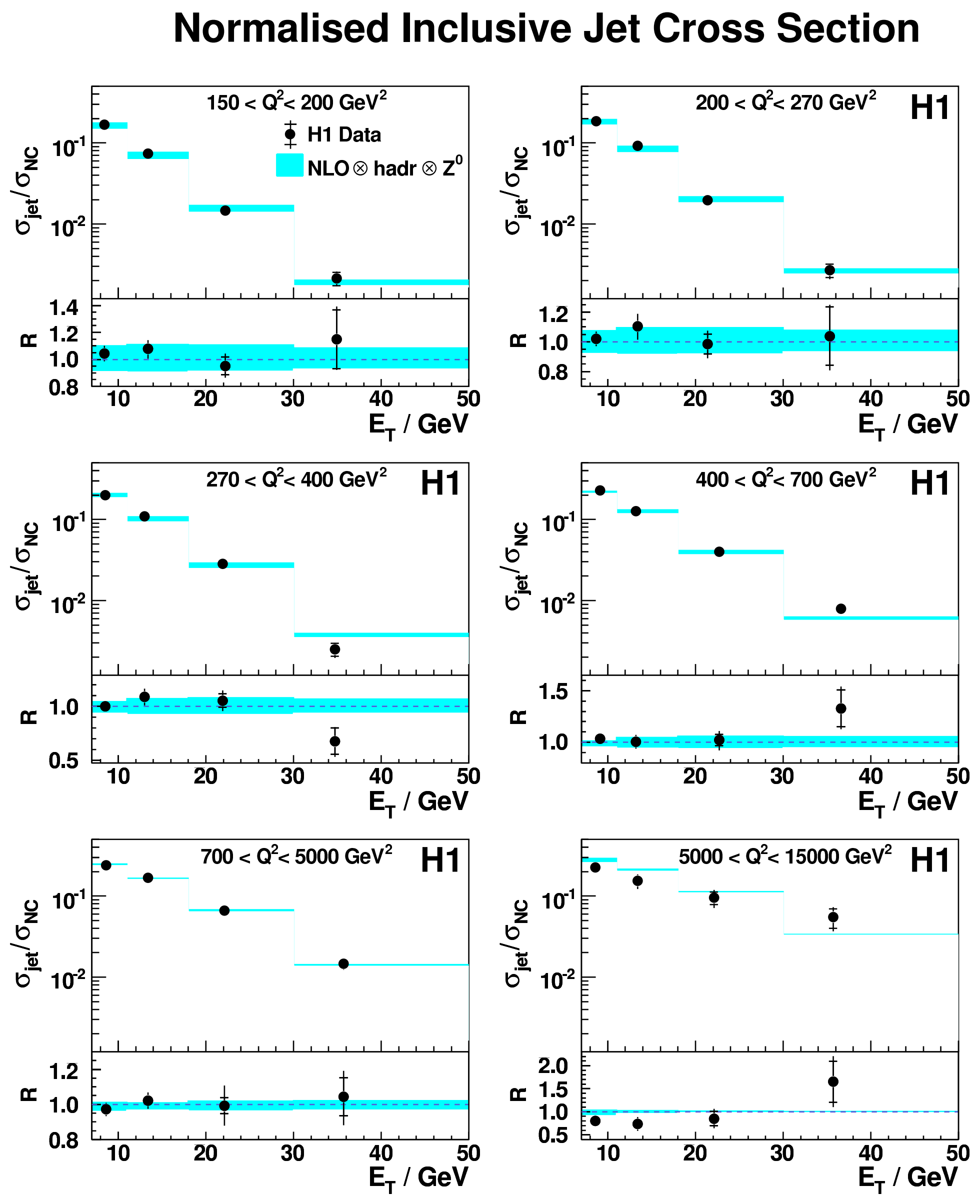
  $\longrightarrow$ extraction of $\alpha_s(M_Z)$

- Normalised cross section

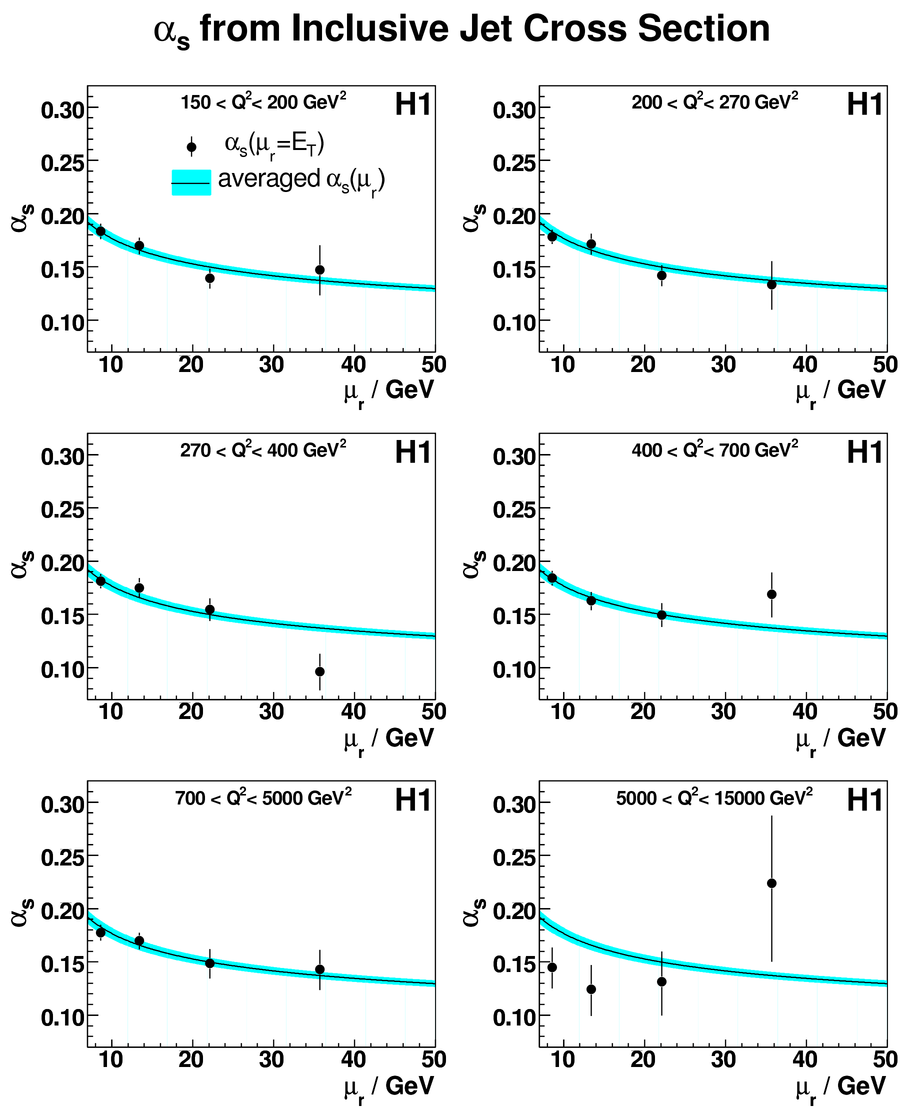
  In a given bin: $\frac{\#jets}{\#events}$

- Kinematic region defined by:
  - $E_{T,\mathrm{B}}^{\mathrm{jet}} > 7$ GeV
  - $0.2 < y < 0.7$
  - $Q^2 > 150$ GeV^2
  - $\mathcal{L} = 65$ pb^{-1}

- NLO ingredients:
  - $\alpha_s(M_Z) = 0.118$
  - PDF $=$ CTEQ6.5M
  - $\mu_R = E_{T,\mathrm{B}}^{\mathrm{jet}}$ of each jet
  - $\mu_F = Q$



Determinations of $\alpha_s(E_{T,\mathrm{B}}^{\mathrm{jet}})$



- **The running of α_s has been tested in different regions of Q^2 using the normalised $d\sigma/dE_{T,B}^{jet}$**
- **In normalised cross sections**
  - $\longrightarrow$ **PDF uncertainties largely cancel**
  - $\longrightarrow$ **LUMI uncertainty cancels completely**
- **The 24 measurements were combined to yield a precise value of $\alpha_s(M_Z)$**

  Total uncertainty $\rightarrow \pm 4.3\%$

$\longrightarrow$ $\alpha_s(M_Z)$ = **0.1193 $\pm$ 0.0014**$(exp.)^{+0.0047}_{-0.0030}(th.) \pm 0.0016(pdf)$

- **For $Q^2 > 700$ GeV^2 $\rightarrow$ $\alpha_s(M_Z)$ = 0.1171 $\pm$ 0.0023$(exp.)^{+0.0032}_{-0.0010}(th.) \pm 0.0010(pdf)$ (lower theo. unc.)**

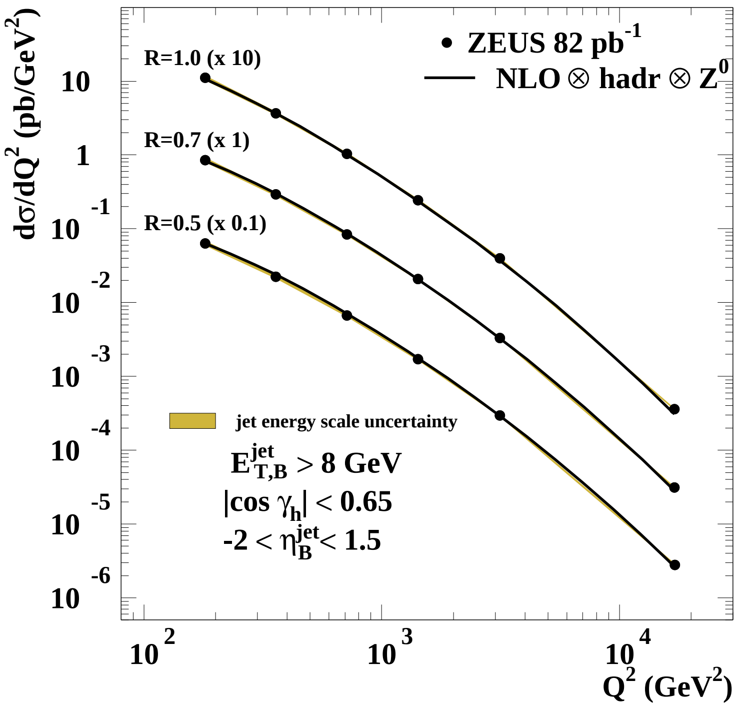
Determinations of $\alpha_s(M_Z)$

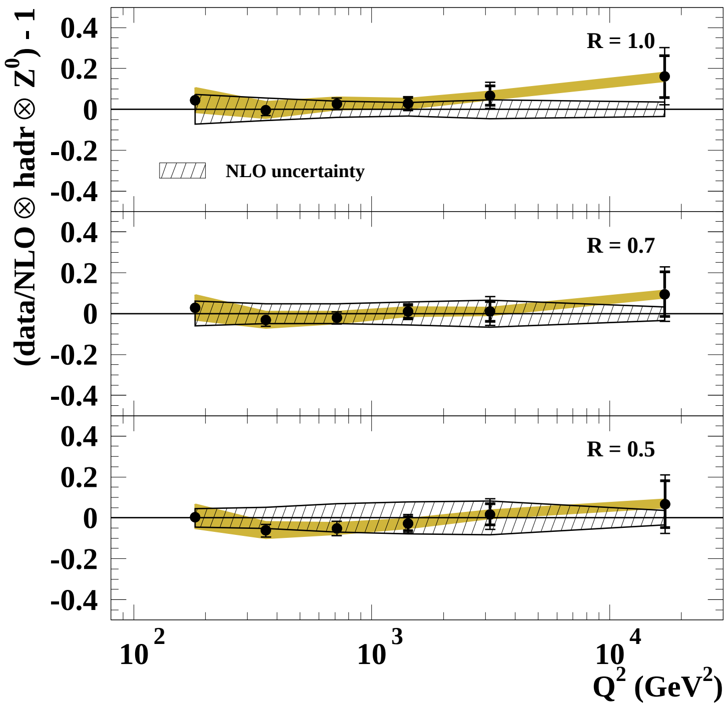
- Good agreement between data and NLO is also found for single differential cross sections $d\sigma/dQ^2$ and $d\sigma/dE_{T,B}^{jet}$ $\rightarrow$ stringent test of pQCD

$\rightarrow$ Theoretical uncertainties are small (Higher orders $< \pm 7\%$)

$\rightarrow$ Experimental uncertainties dominated by energy scale ($< \pm 5\%$)

- NLO ingredients:
  - $\alpha_s(M_Z) = 0.118$
  - PDF ZEUS-2002-RT
  - $\mu_R = E_{T,\mathrm{B}}^{\mathrm{jet}}$ of each jet
  - $\mu_F = Q$





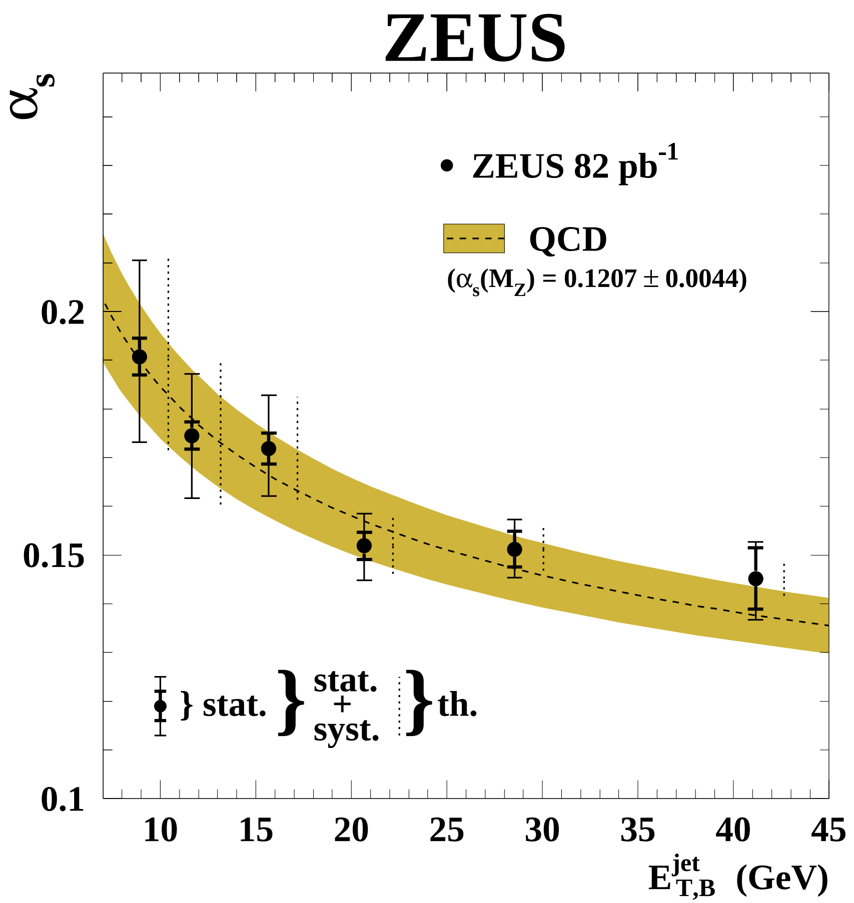
Determinations of $\alpha_s(E_{T,\mathrm{B}}^{\mathrm{jet}})$

- The measured cross sections $d\sigma/dQ^2$ and $d\sigma/dE_{T,B}^{jet}$ were used to obtain precise determinations of $\alpha_s(M_Z)$
- The region $Q^2 > 500$ GeV^2 yielded the value with the smallest uncertainty:

  $\longrightarrow$ $\alpha_s(M_Z)$ = 0.1207 $\pm$ 0.0014$(stat.)^{+0.0035}_{-0.0033}(exp.)^{+0.0022}_{-0.0023}(th.)$

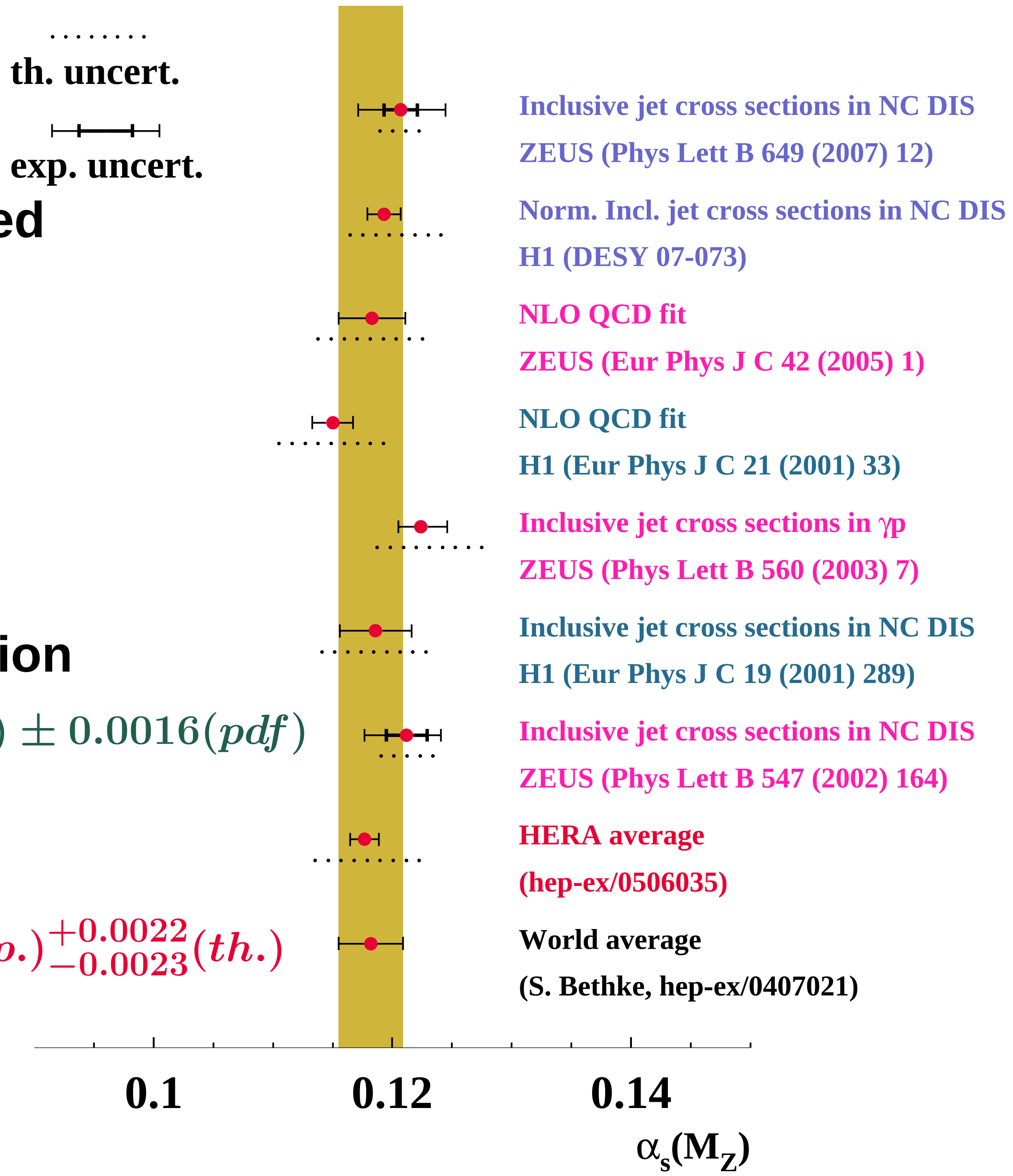
  $\longrightarrow$ Total uncertainty $\pm 3.7\%$

- The measured $d\sigma/dE_{T,B}^{jet}$ have been used to test the energy-scale dependence of α_s
- The running of α_s as predicted by pQCD is in agreement with the data
- Asymptotic freedom of QCD!



Determinations of $\alpha_s(M_Z)$

- All HERA determinations of $\alpha_s(M_Z)$ are consistent with each other and with the world average



- Measurements' precision is constrained by theoretical uncertainties

- Inclusive-jets at high Q^2 allow smallest theoretical and experimental uncertainties

H1 normalised cross section determination

$\rightarrow \alpha_s(M_Z) = 0.1193 \pm 0.0014(exp.)^{+0.0047}_{-0.0030}(th.) \pm 0.0016(pdf)$

ZEUS $Q^2 > 500$ GeV^2 determination

$\rightarrow \alpha_s(M_Z) = 0.1207 \pm 0.0014(stat.)^{+0.0035}_{-0.0033}(exp.)^{+0.0022}_{-0.0023}(th.)$

Summary

● Jet production in DIS at HERA continues to be a rich field for QCD studies

→ New stringent tests of pQCD predictions have been made

- Jet production at low Q^2
- Study of the jet radius dependence of inclusive-jet cross sections

→ New input for the determination of the proton PDFs

- Inclusive-jet and dijet cross sections will help constrain gluon PDF in mid-to-high x region

→ Improved determinations of $\alpha_s(M_Z)$ by H1 and ZEUS have been presented

● H1 determination of $\alpha_s(M_Z)$

→ $\alpha_s(M_Z) = 0.1193 \pm 0.0014(exp.)^{+0.0047}_{-0.0030}(th.) \pm 0.0016(pdf)$

● ZEUS determination of $\alpha_s(M_Z)$

→ $\alpha_s(M_Z) = 0.1207 \pm 0.0014(stat.)^{+0.0035}_{-0.0033}(exp.)^{+0.0022}_{-0.0023}(th.)$

→ Tests of the scale dependence of α_s