

DIS 2010

**XVIII International Workshop on
Deep-Inelastic Scattering and Related Subjects**

April 19 - 23, 2010

Florence, Italy



Jet cross sections in NC DIS at HERA

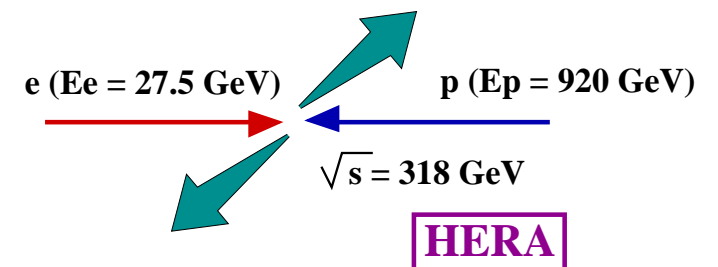
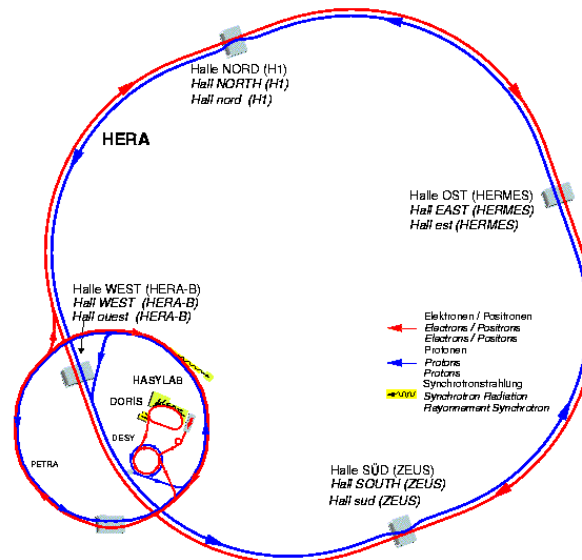
**Claudia Glasman
Universidad Autónoma de Madrid**



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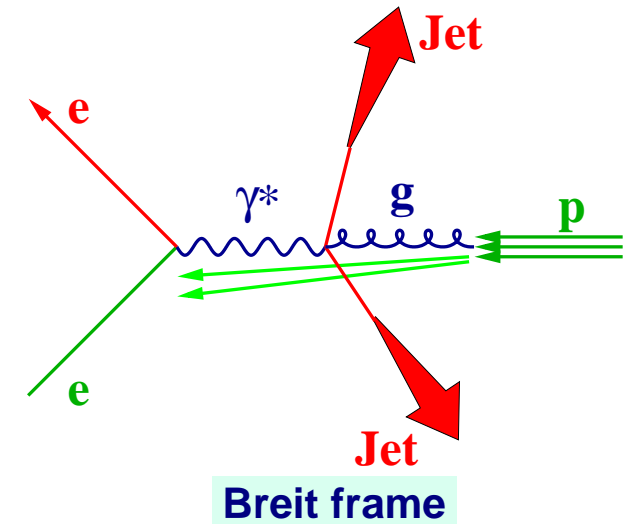
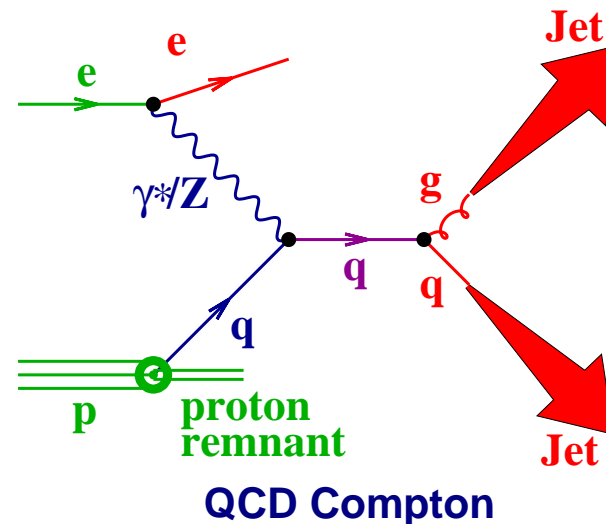
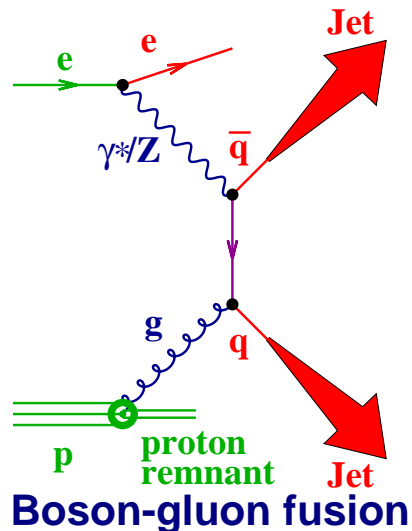


ZEUS Collaboration



Jet production in NC DIS at HERA

- Jet production in neutral current deep inelastic ep scattering at $\mathcal{O}(\alpha_s)$ in Breit frame:



- Jet production cross section for NC DIS is given in pQCD by:

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

Kinematics:

– momentum transfer:

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

– Bjorken x : $x = \frac{Q^2}{2P \cdot q}$

– inelasticity:

$$y = \frac{P \cdot q}{P \cdot k} = 1 - \frac{E'_e(1 - \cos \theta_e)}{2E_e}$$

- f_a : parton a density, determined from experiment
→ **long-distance structure of the target**
- $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD
→ **short-distance structure of the interaction**

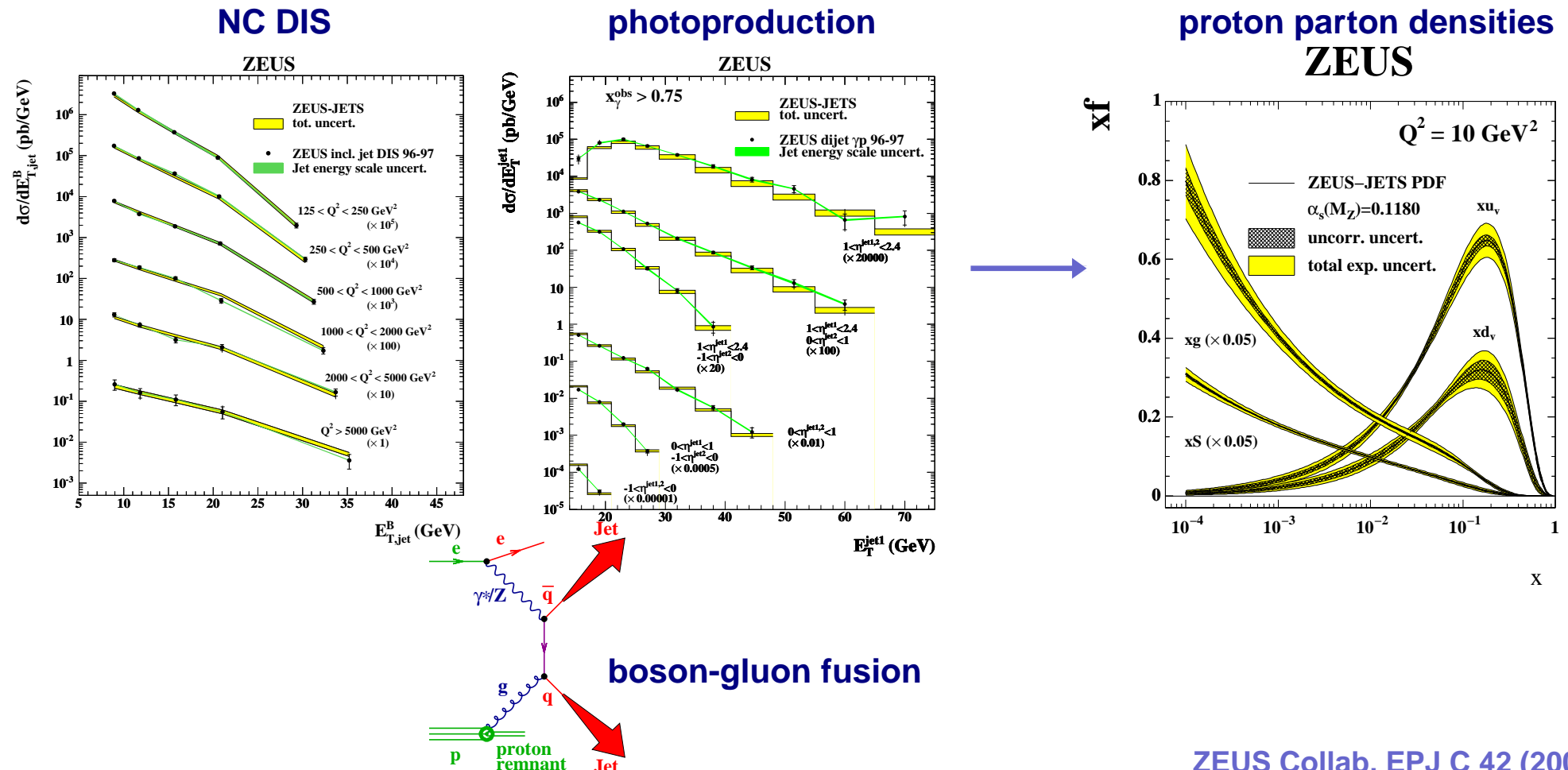
Jets in NC DIS at HERA

- **QCD processes dominant at hadron colliders**
 - background to new physics searches (eg at LHC)
 - need good understanding of QCD processes
- **Measurements of jet production in NC DIS at HERA provide a clean hadron-induced reaction and are a powerful tool**
 - to test perturbative QCD calculations
 - to extract $\alpha_s(M_Z)$
 - to determine the energy dependence (running) of $\alpha_s(\mu)$
 - to constrain the proton PDFs (particularly the gluon)
- **NEW MEASUREMENTS FROM ZEUS:**
 - Inclusive-jet and dijet cross sections with more than three-fold increase in statistics wrt previous analyses:
 - further constrains on proton PDFs
 - Inclusive-jet cross sections with more than three-fold increase in statistics:
 - precise test of pQCD and extraction of α_s
 - Inclusive-jet cross sections with different jet algorithms:
 - test performance of new jet algorithms in a well-understood environment

Jets and PDFs at HERA



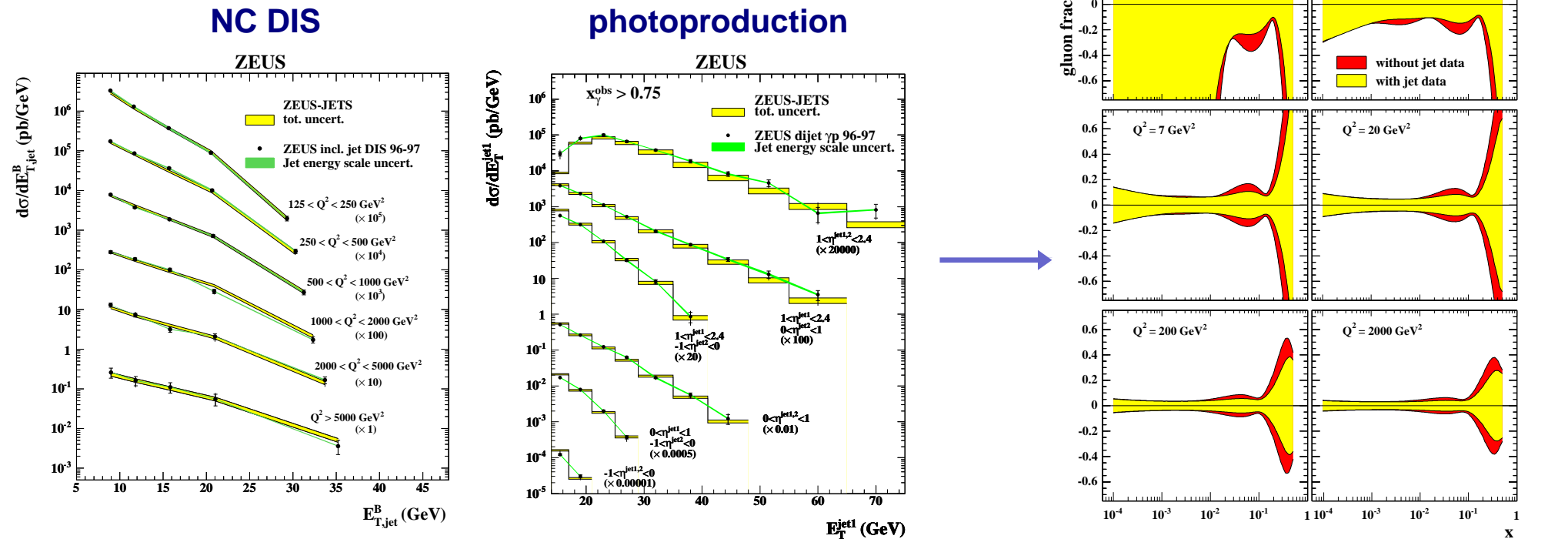
- Very precise jet cross sections in NC DIS and photoproduction (directly sensitive to the gluon content of proton): **constraints on gluon density**
- Measurements incorporated in a QCD fit (together with structure function data from ZEUS) to determine PDFs parametrisations:



Jets and PDFs at HERA



- Very precise jet cross sections in NC DIS and photoproduction (directly sensitive to the gluon content of proton): **constraints on gluon density**
- Measurements incorporated in a QCD fit (together with data from ZEUS) to determine PDFs parametrisations:



- The result was an improvement of the determination of the gluon density
 - the uncertainty in the gluon density decreased up to a factor of **two** for mid- to high- x
 - **relevant for new physics searches at LHC**

Dijet cross sections: constraints on pPDFs



$$e^\pm p \rightarrow e^\pm + \text{jet} + \text{jet} + X \text{ (dijets)}$$

- Jets searched using the k_T cluster algorithm in Breit frame
- **Kinematic region:** $125 < Q^2 < 20000 \text{ GeV}^2$ and $0.2 < y < 0.6$
- **Two jets with** $E_{T,B}^{\text{jet}} > 8 \text{ GeV}$ and $-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5$
- $M^{\text{jj}} > 20 \text{ GeV}$

$$\mathcal{L} = 374 \text{ pb}^{-1} \text{ !!!}$$

- $\xi = x_{Bj}(1 + (M^{\text{jj}})^2/Q^2)$ estimator of the fractional momentum carried by the struck parton

- **Small experimental uncertainties:**

→ **uncorrelated uncertainties:** $\sim \pm 2$ (10)% at low (high) Q^2

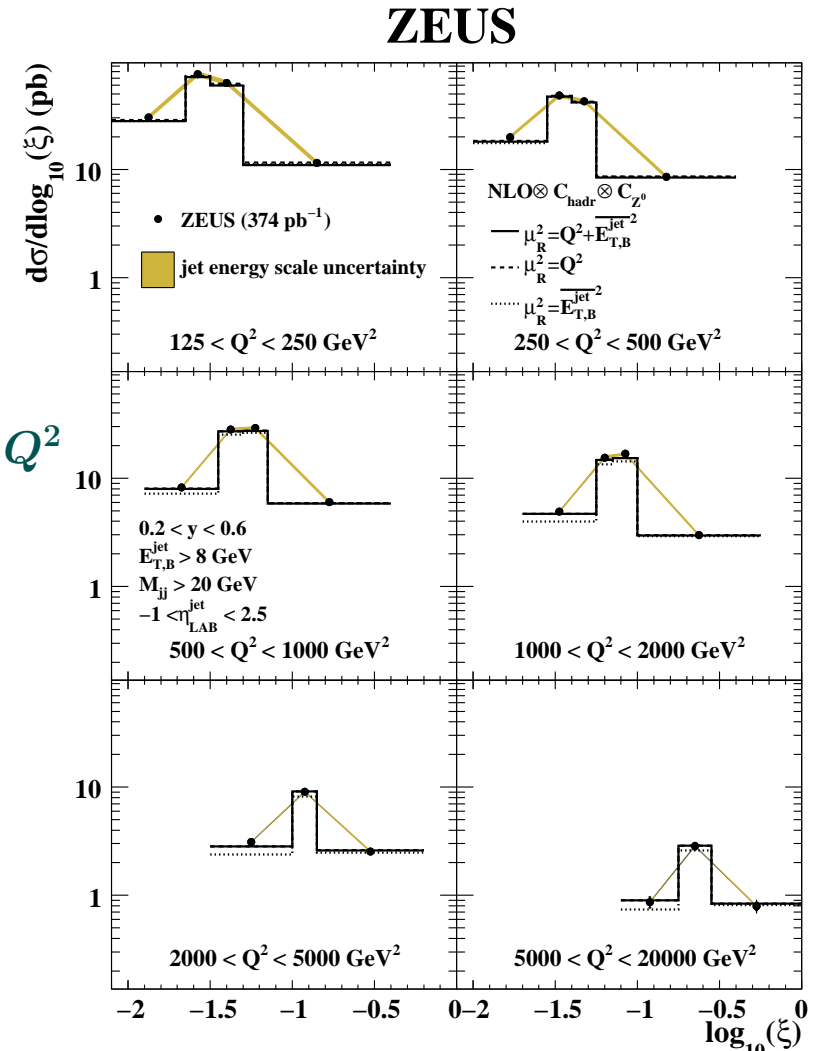
→ **correlated uncertainties (energy scale $\pm 1\%$ (!) for $E_T^{\text{jet}} > 10 \text{ GeV}$):** $\sim \pm 5$ (2)% at low (high) Q^2

- **Comparison to NLO predictions (NLOJET++):**

→ $\mu_R^2 = Q^2 + (E_{T,B}^{\text{jet}})^2$, $\mu_F = Q$; pPDFs: CTEQ6.6;

$\alpha_s(M_Z) = 0.118$; corrected for hadronisation and Z^0

- **The measured dijet cross sections are very well described by the NLO predictions in the whole measured range**



ZEUS Collab, ZEUS-pub-10-005

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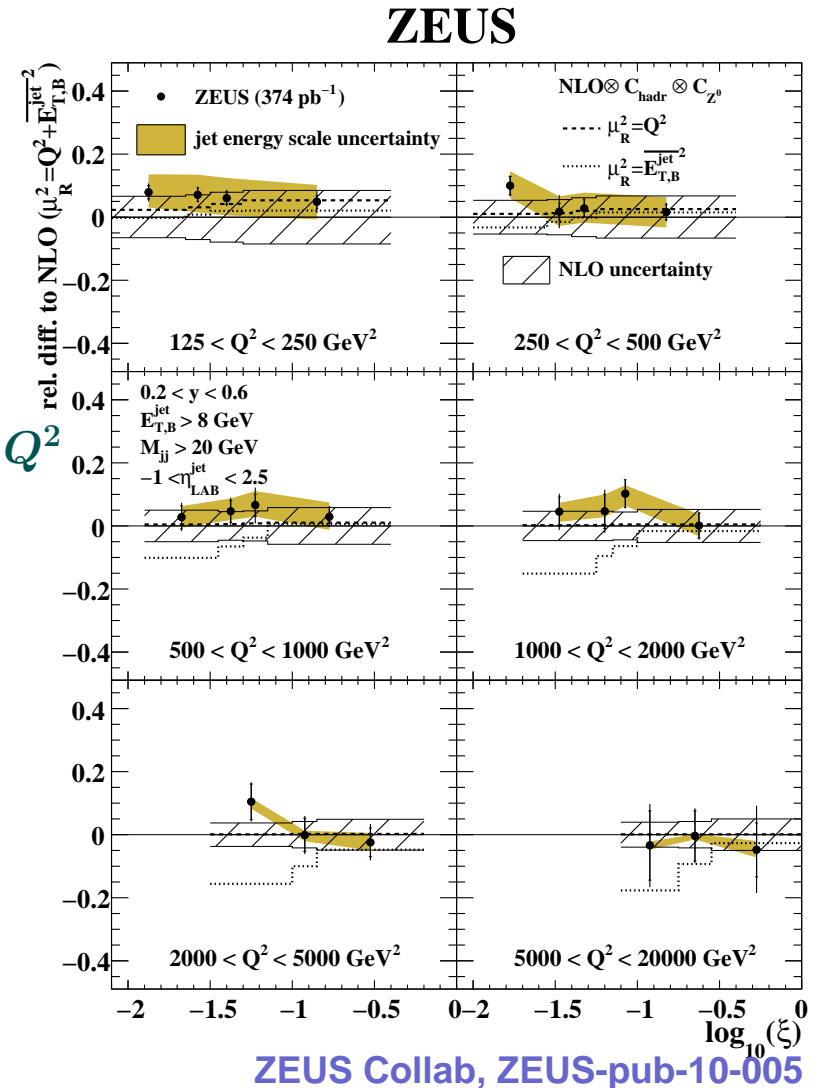
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- $\overline{E_{T,B}^{\text{jet}}}$ mean transverse energy of the two jets
→ well suited for precise tests of pQCD

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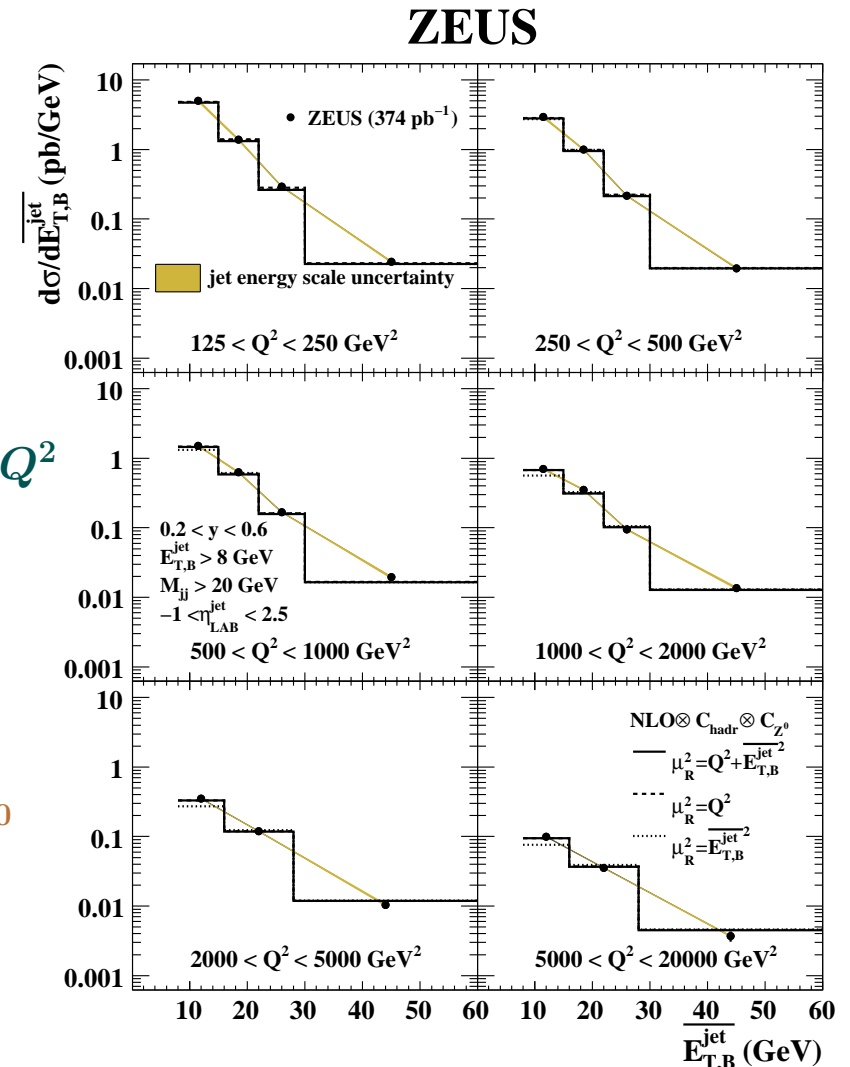
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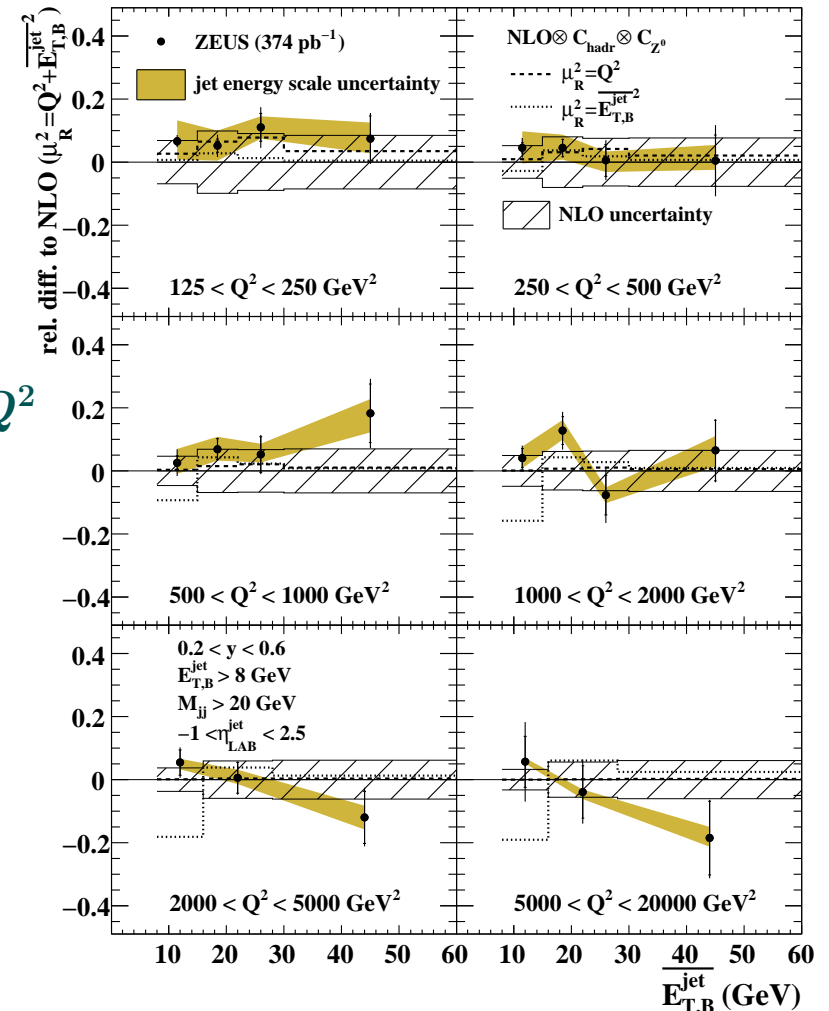
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ZEUS Collab, ZEUS-pub-10-005

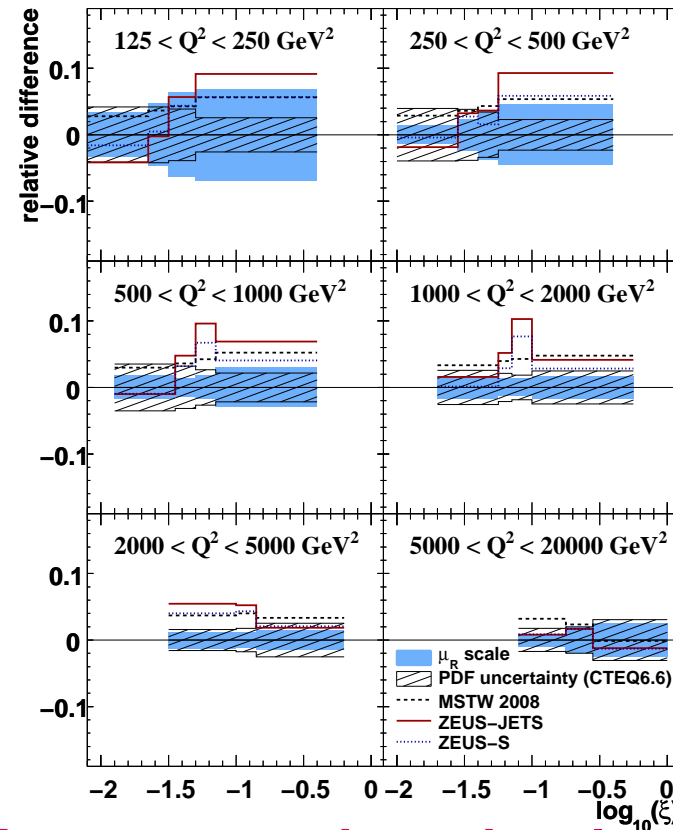
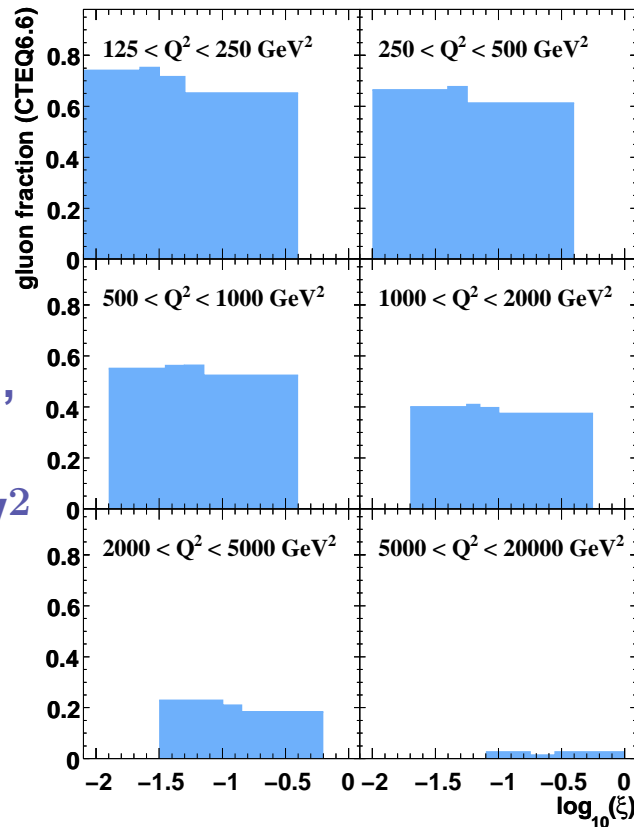
Dijet cross sections: constraints on pPDFs



- Gluon fraction and theoretical uncertainties in the phase-space region of the measurements:

**Predicted
Gluon
fraction:**

75% at low Q^2 ,
> 60% at
 $Q^2 \sim 500 \text{ GeV}^2$



**Theoretical
uncertainties**

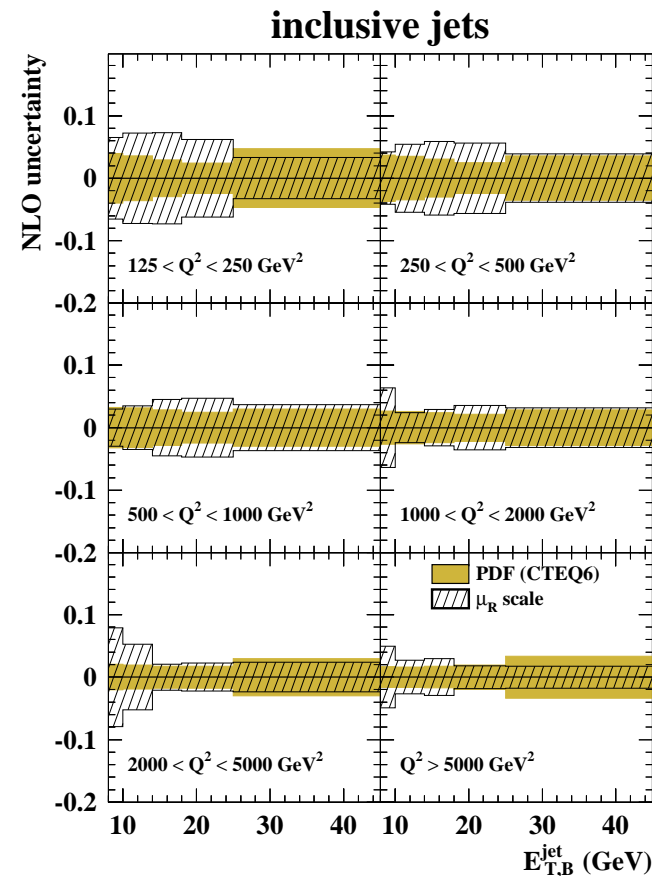
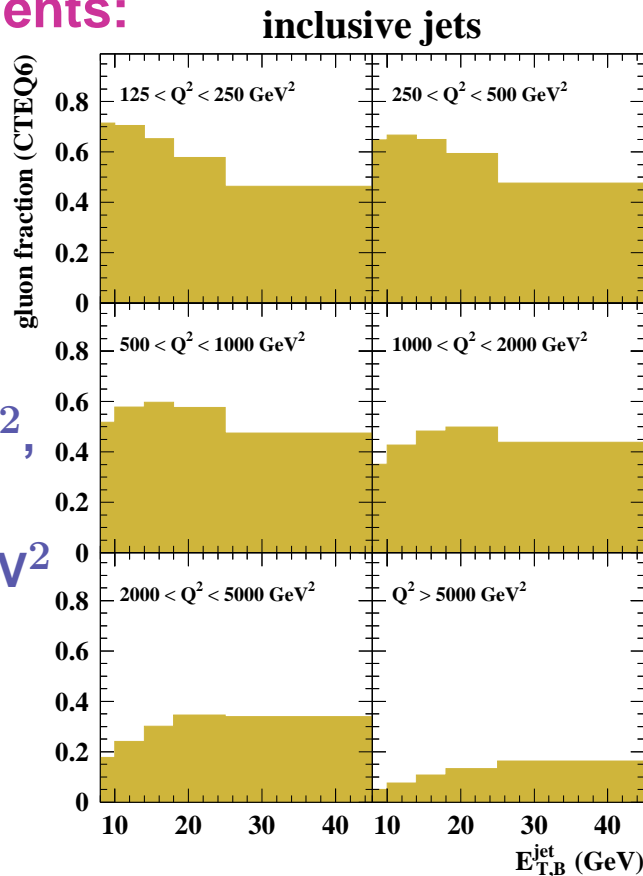
- PDF uncertainty large in regions of phase space where the gluon fraction is still sizeable
- high precision dijet data have the potential to constrain further the proton PDFs when included in the global fits

Inclusive-jet cross sections: constraints on pPDFs



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Inclusive-jet cross sections: constraints on pPDFs



$$e^\pm p \rightarrow e^\pm + \text{jet} + X \text{ (inclusive jets)}$$

- Jets searched using the k_T cluster algorithm in Breit frame
- Kinematic region: $Q^2 > 125 \text{ GeV}^2$ and $|\cos \gamma_h| < 0.65$
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- no cuts in LAB frame

- Small experimental uncertainties:

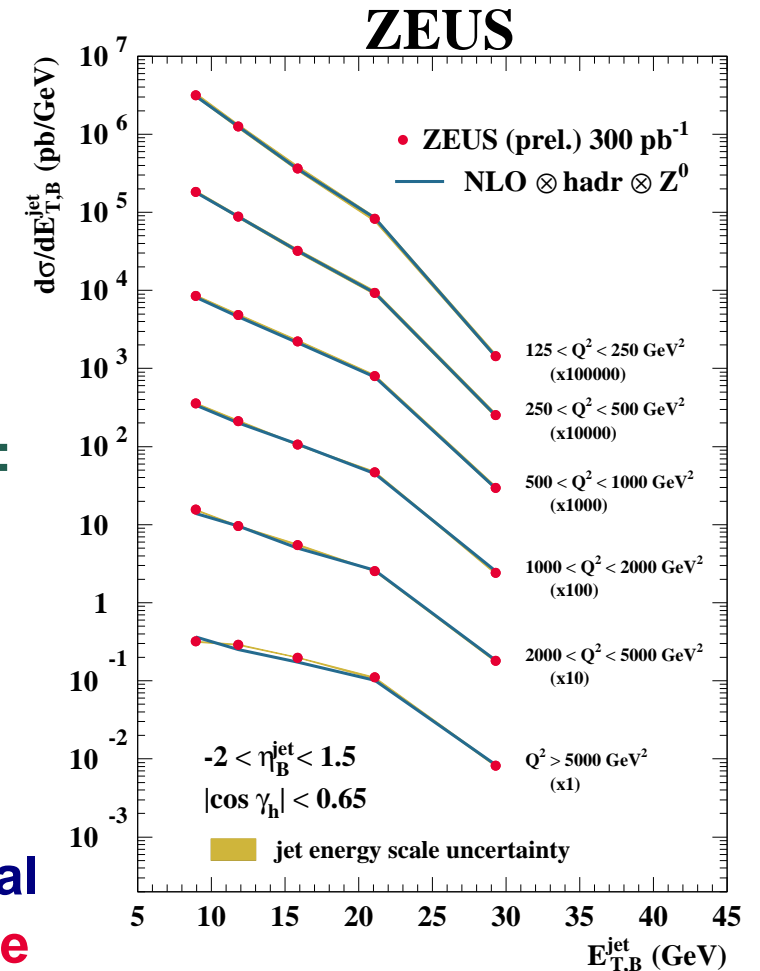
- uncorrelated: $\sim \pm 3$ (10)% at low (high) $Q^2/E_{T,B}^{\text{jet}}$
- correlated (energy scale $\pm 1\%$ (!) for $E_T^{\text{jet}} > 10 \text{ GeV}$):
 $\sim \pm 5$ (2)% at low (high) $Q^2/E_{T,B}^{\text{jet}}$

- Comparison to NLO ($\mathcal{O}(\alpha_s^2)$) predictions (DISENT):

- $\mu_R = E_{T,B}^{\text{jet}}$, $\mu_F = Q$; pPDFs: ZEUS-S; $\alpha_s(M_Z) = 0.118$
- corrected for hadronisation and Z^0 effects

- The measured inclusive-jet cross sections are very well described by the NLO predictions in the whole measured range
- High precision inclusive-jet data have the potential to constrain further the pPDFs in regions of phase space relevant for new physics searches at LHC

$$\mathcal{L} = 300 \text{ pb}^{-1} \text{ !!!}$$



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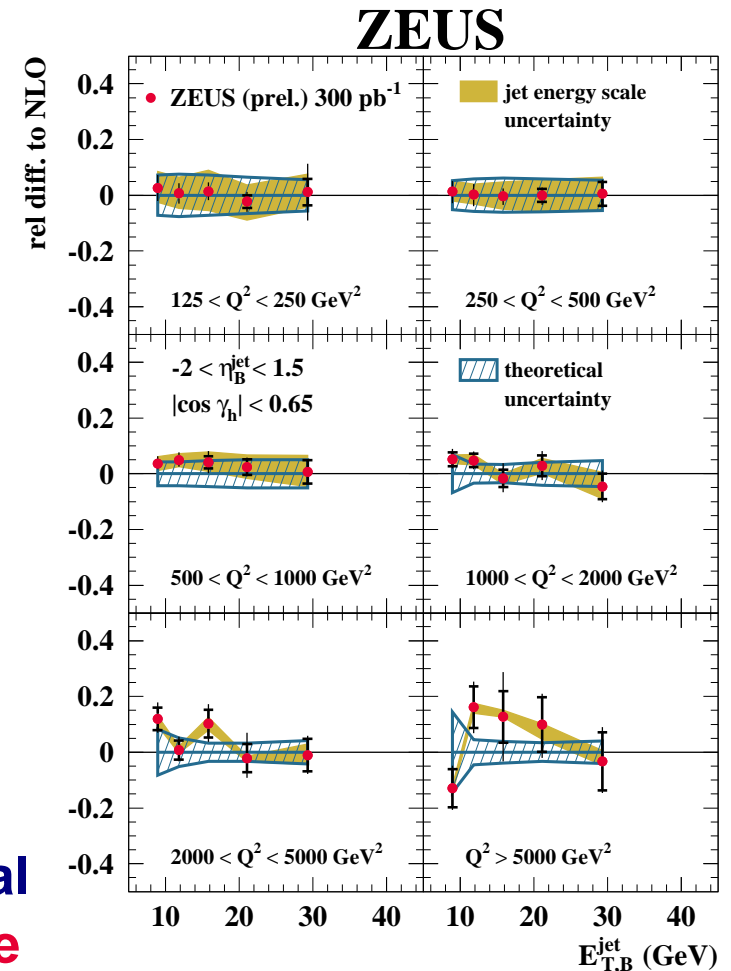
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Inclusive-jet cross sections: test of pQCD

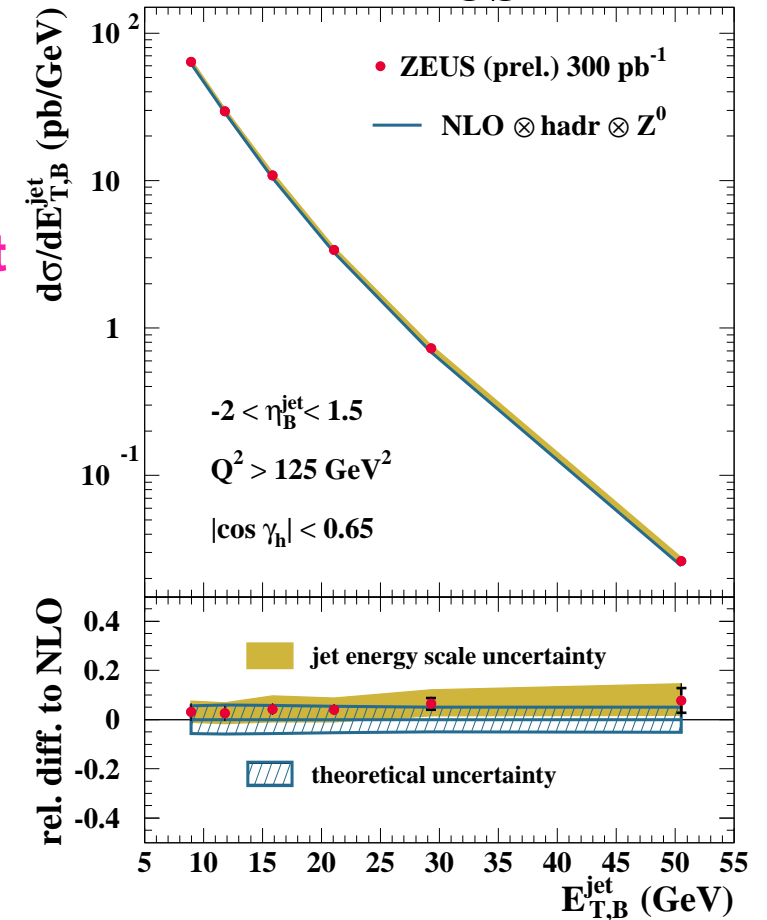


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- At least one jet with $E_{T,B}^{\text{jet}} > 8 \text{ GeV}$ and $-2 < \eta_B^{\text{jet}} < 1.5$
- no cuts in LAB frame
- Advantages of inclusive-jet cross sections:
 - infrared insensitivity (no dijet asymmetric/ M^{jj} cuts needed) \rightarrow wider phase-space than in dijet
 - suited to test resummed calculations
 - smaller theoretical uncertainties than in dijet cross sections
- Small experimental uncertainties:
 - \rightarrow uncorrelated: $\sim \pm 3$ (7)% at low (high) $Q^2/E_{T,B}^{\text{jet}}$
 - \rightarrow correlated (energy scale $\pm 1\%$ (!) for $E_T^{\text{jet}} > 10 \text{ GeV}$): $\sim \pm 5$ (2)% at low (high) $Q^2/E_{T,B}^{\text{jet}}$
- Small theoretical uncertainties:
 - \rightarrow higher orders (below $\pm 5\%$ for $Q^2 > 250 \text{ GeV}^2$)
 - \rightarrow proton PDFs (below $\pm 3\%$)
 - \rightarrow $\alpha_s(M_Z)$ (below ± 1 (2)% at low (high) $Q^2/E_{T,B}^{\text{jet}}$)
 - \rightarrow parton-to-hadron corrections (below $\pm 2\%$)

$$\mathcal{L} = 300 \text{ pb}^{-1} \text{ !!!}$$

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ZEUS Collab, ZEUS-prel-10-002

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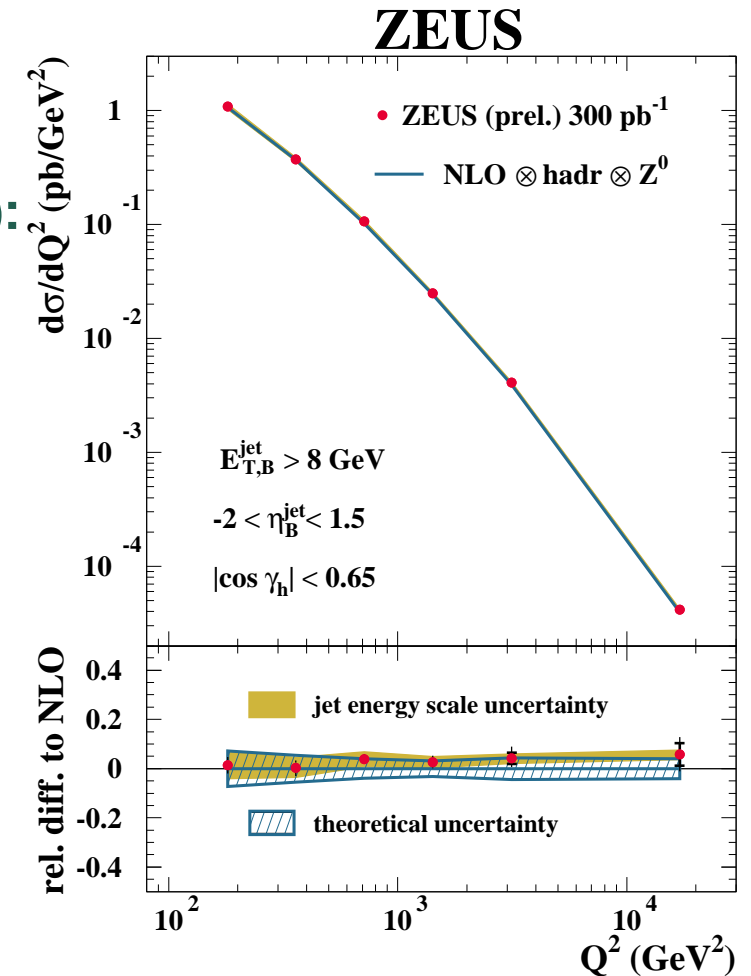
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→ The measured inclusive-jet cross sections are very well described by the NLO predictions in the whole measured range

→ Validity of the description of the dynamics of inclusive-jet production by pQCD at $\mathcal{O}(\alpha_s^2)$

→ Inclusive-jet cross sections in NC DIS provide direct sensitivity to $\alpha_s(M_Z)$ with small experimental and theoretical uncertainties

$$\mathcal{L} = 300 \text{ pb}^{-1} \text{ !!!}$$



Inclusive-jet cross sections: extraction of $\alpha_s(M_Z)$



- From the measured $d\sigma/dQ^2$ for $Q^2 > 500 \text{ GeV}^2$ a value of $\alpha_s(M_Z)$ has been extracted:

$$\alpha_s(M_Z) = 0.1208^{+0.0037}_{-0.0032} \text{ (exp.) } \pm 0.0022 \text{ (th.)}$$

(assuming predicted running of α_s)

- Experimental uncertainties:

→ dominated by jet energy scale uncertainty:

$$\Delta\alpha_s/\alpha_s = \pm 1.9\%$$

- Theoretical uncertainties:

→ terms beyond NLO: $\Delta\alpha_s/\alpha_s = \pm 1.5\%$

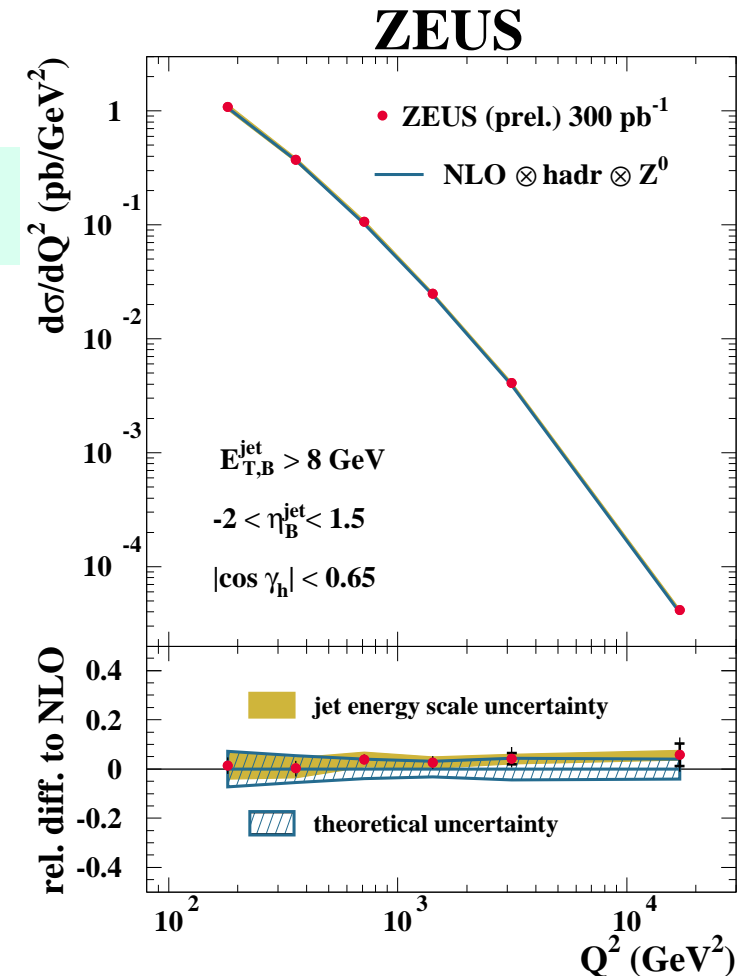
→ uncertainties from pPDFs: $\Delta\alpha_s/\alpha_s = \pm 0.7\%$

→ hadronisation corrections: $\Delta\alpha_s/\alpha_s = \pm 0.8\%$

→ μ_F uncertainty: negligible

→ $\alpha_s(M_Z)$ from inclusive jet cross sections: precise determination at HERA

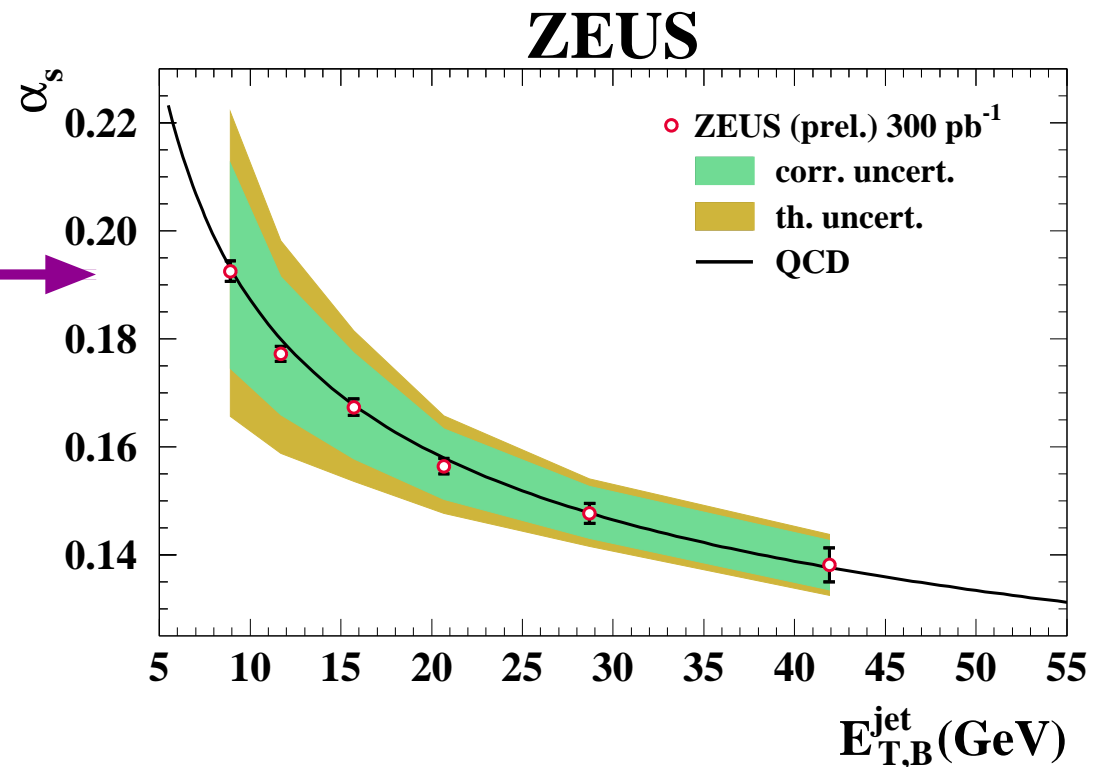
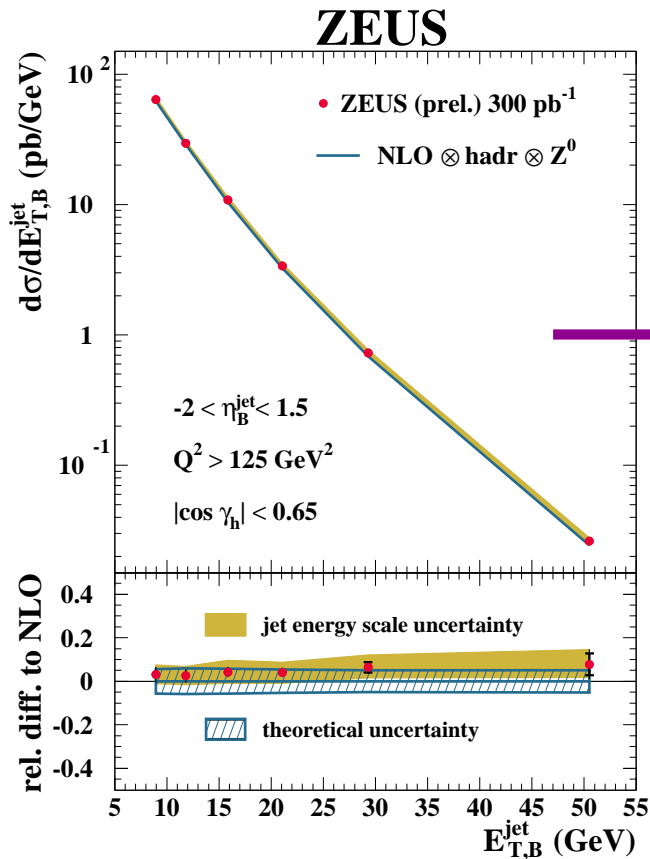
→ (total uncertainty: $\sim \pm 3.5\%$; theoretical uncertainty: $\sim 1.9\%$)



Determination of the energy-scale dependence of α_s



- The energy-scale dependence of the coupling was determined by extracting α_s from the measured $d\sigma/dE_{T,B}^{\text{jet}}$ at different $E_{T,B}^{\text{jet}}$ values:
 - in this procedure α_s is **NOT** assumed to run!



- The results are in good agreement with the predicted running of α_s over a large range in $E_{T,B}^{\text{jet}}$

Inclusive-jet cross sections: jet algorithms



● Tests of pQCD with jets require infrared- and collinear-safe jet algorithms:

→ k_T cluster algorithm in the longitudinally invariant inclusive mode (S Catani, S Ellis & D Soper)

● Performance of k_T algorithm tested extensively

→ **stringent tests of pQCD:** good description of data for all jet radii with similar precision

→ **good performance of k_T algorithm:** small theoretical uncertainties and small hadronisation corrections

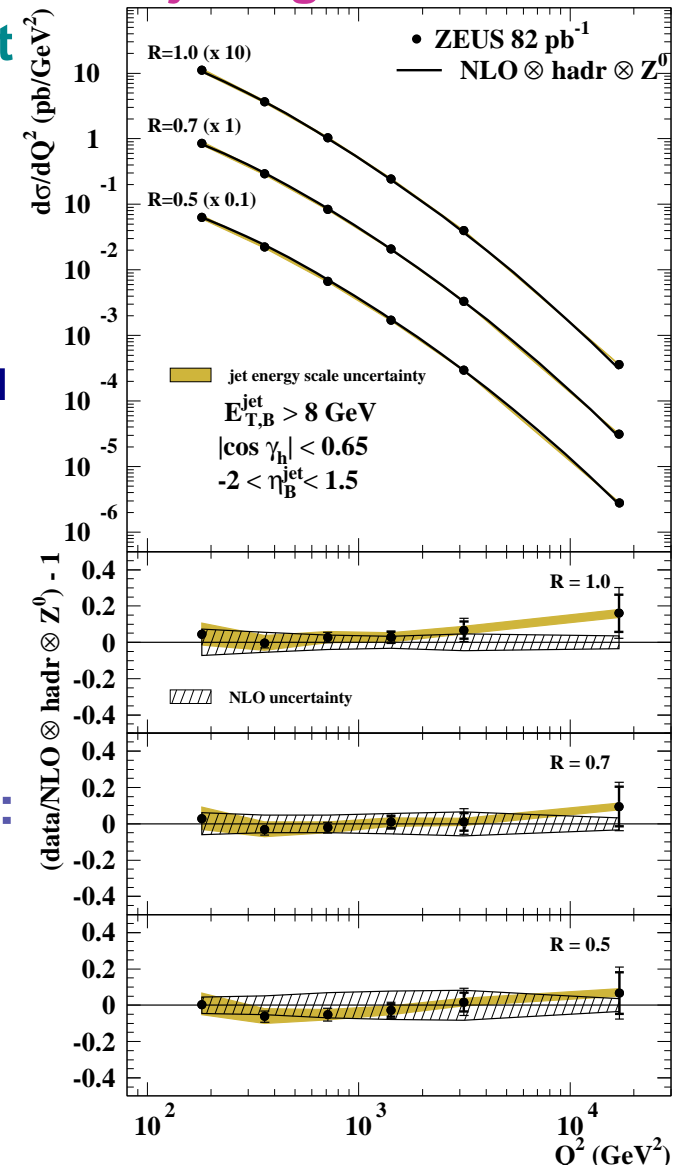
● New jet algorithms being used at LHC

→ **need validation**

● NEW STUDIES AT ZEUS:

→ test of performance of **anti- k_T and SIScone** in a hadron-induced but well-understood reaction:

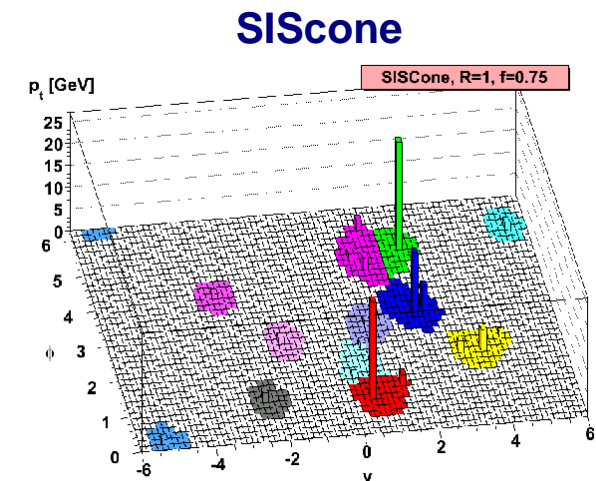
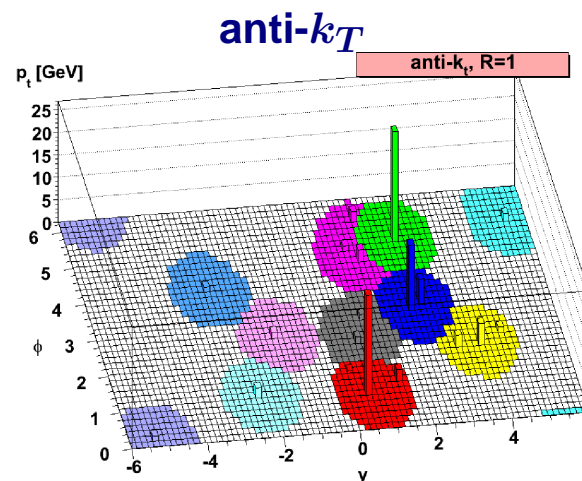
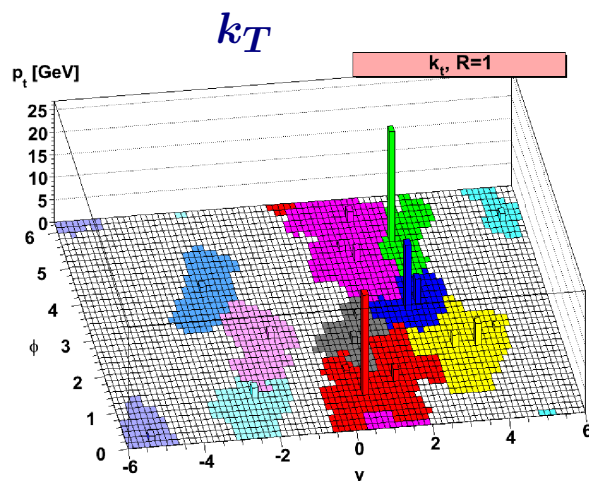
- * comparison to measurements based on k_T
- * comparison of measurements and NLO QCD calculations
- * study of theoretical uncertainties and hadronisation corrections



ZEUS Collab, Phys Lett B 649 (2007) 12

Inclusive-jet cross sections: k_T vs anti- k_T vs SiScone

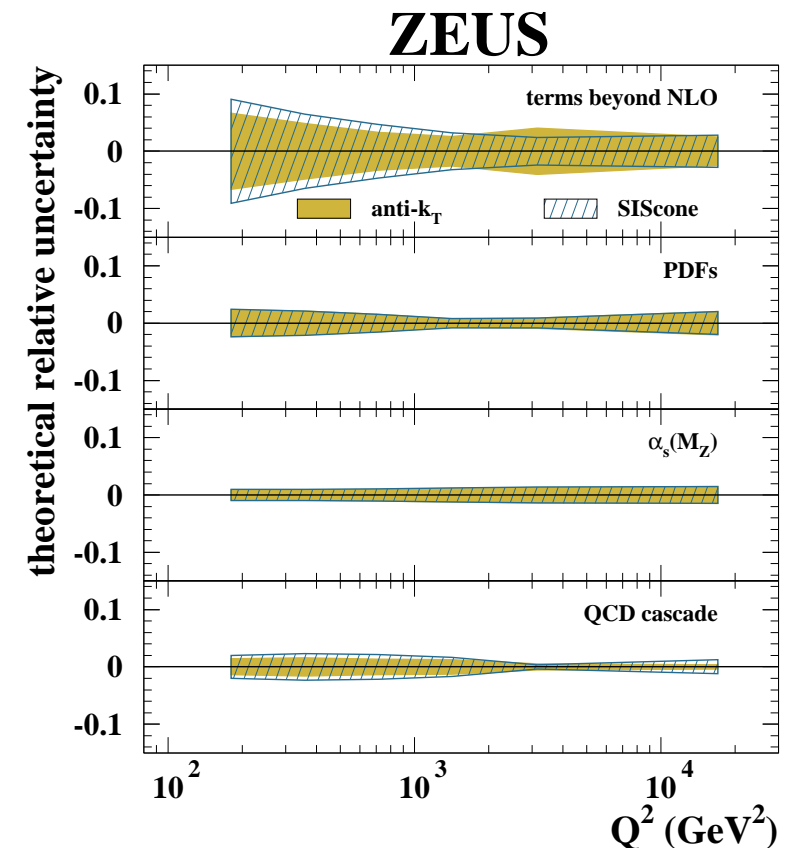
- **New infrared- and collinear-safe jet algorithms:**
 - **anti- k_T** (M Cacciari, G Salam & G Soyez) and **SiScone** (G Salam & G Soyez)
- **Cluster algorithms:**
 - $d_{ij} = \min((E_{T,B}^i)^{2p}, (E_{T,B}^j)^{2p}) \cdot \Delta R^2 / R^2$ with $p = 1$ (-1) for k_T (anti- k_T)
 - **anti- k_T keeps infrared and collinear safety and provides \approx circular jets (experimentally desirable)**
- **Cone algorithms:**
 - **seedless cone algorithm produces also jets with well-defined area and is infrared and collinear safe (theoretically desirable)**



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- **Cone algorithms:**
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- **Theoretical uncertainties:**
 - **proton PDFs and value of $\alpha_s(M_Z)$:**
 - **very similar for all three jet algorithms**
 - **terms beyond NLO and parton-shower modelling:**
 - **very similar for k_T and anti- k_T**
 - **somewhat larger for SiScone**

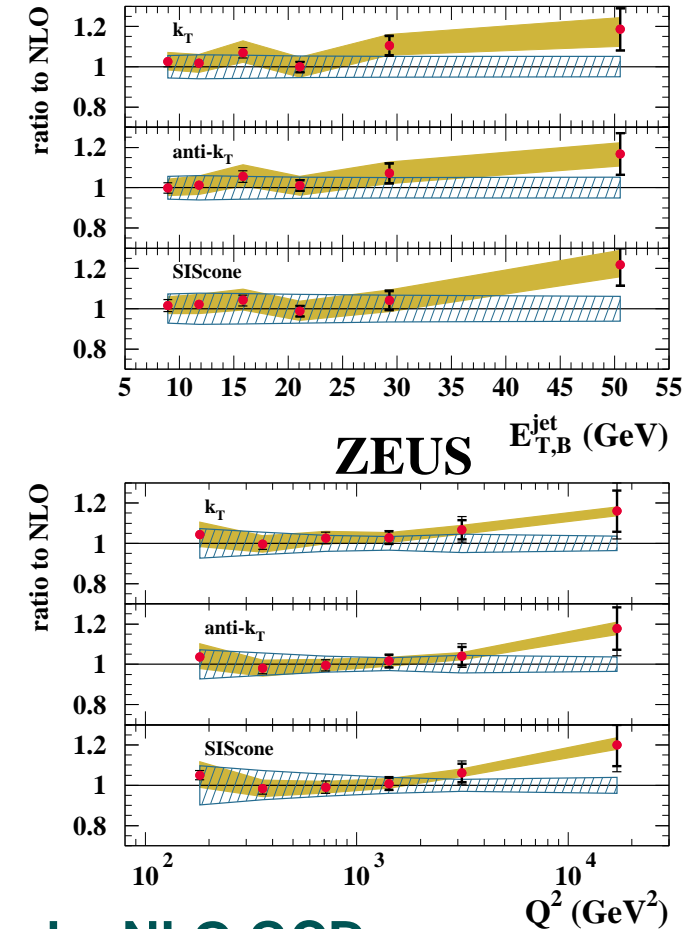
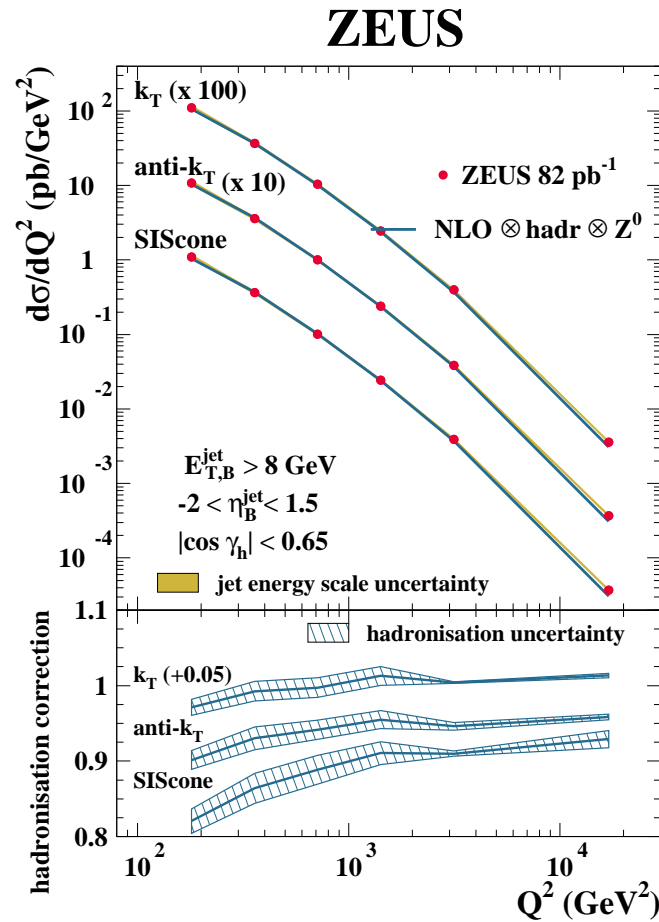
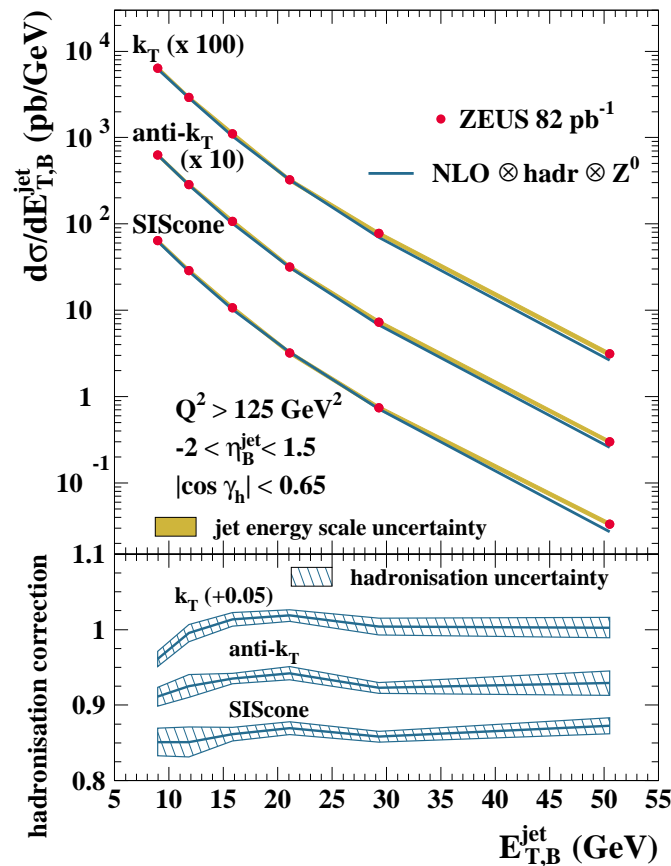


ZEUS Collab, DESY-10-034

Inclusive-jet cross sections: k_T vs anti- k_T vs SIScone



- Inclusive-jet cross sections as functions of $E_{T,B}^{\text{jet}}$ and Q^2 for k_T , anti- k_T and SIScone



- Good description of data in shape and normalisation by NLO QCD
- Bigger hadronisation corrections for SIScone than anti- k_T (similar to k_T)
- Similar shape and normalisation in data and theory for the three jet algorithms

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Inclusive-jet cross sections: k_T vs anti- k_T vs SIScone

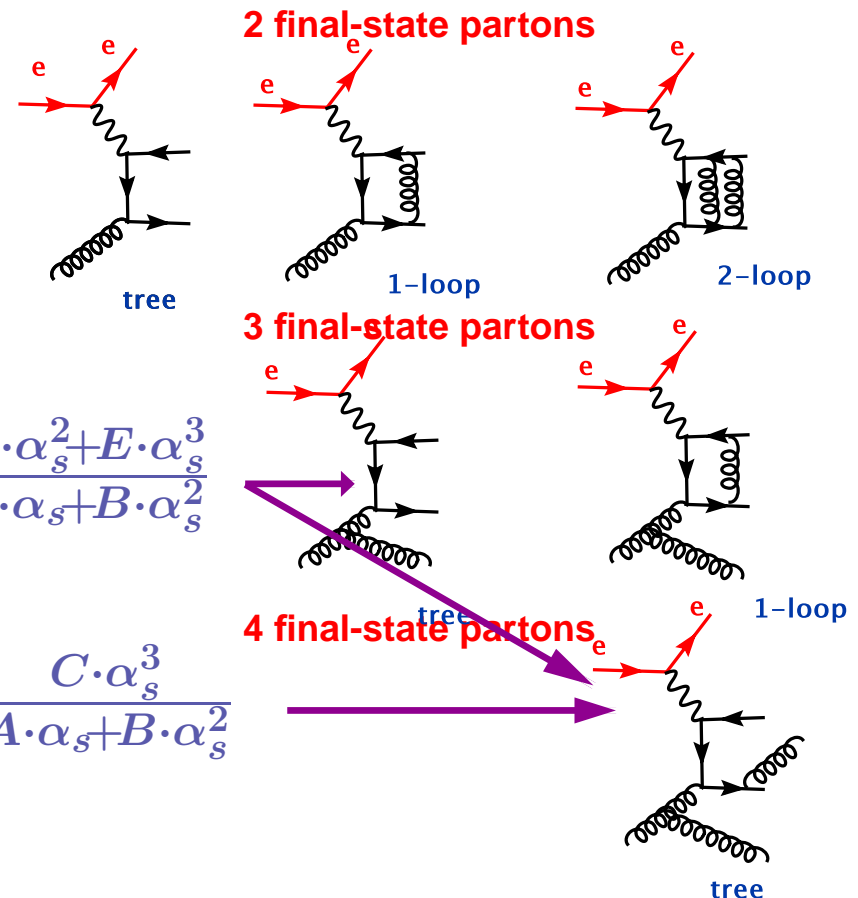


- Inclusive-jet cross sections can be calculated only up to $\mathcal{O}(\alpha_s^2)$ (DISENT or NLOJET++)
- Differences of cross sections using different algorithms can be calculated up to $\mathcal{O}(\alpha_s^3)$ with NLOJET++

- Ratios of cross sections for different algorithms can be calculated using the differences up to $\mathcal{O}(\alpha_s^3)$ as:

$$\frac{d\sigma_{\text{SIScone}}/dX}{d\sigma_{k_T}/dX} = 1 + \frac{d\sigma_{\text{SIScone}}/dX - d\sigma_{k_T}/dX}{d\sigma_{k_T}/dX} \simeq 1 + \frac{D \cdot \alpha_s^2 + E \cdot \alpha_s^3}{A \cdot \alpha_s + B \cdot \alpha_s^2}$$

$$\frac{d\sigma_{\text{anti-}k_T}/dX}{d\sigma_{k_T}/dX} = 1 + \frac{d\sigma_{\text{anti-}k_T}/dX - d\sigma_{k_T}/dX}{d\sigma_{k_T}/dX} \simeq 1 + \frac{C \cdot \alpha_s^3}{A \cdot \alpha_s + B \cdot \alpha_s^2}$$

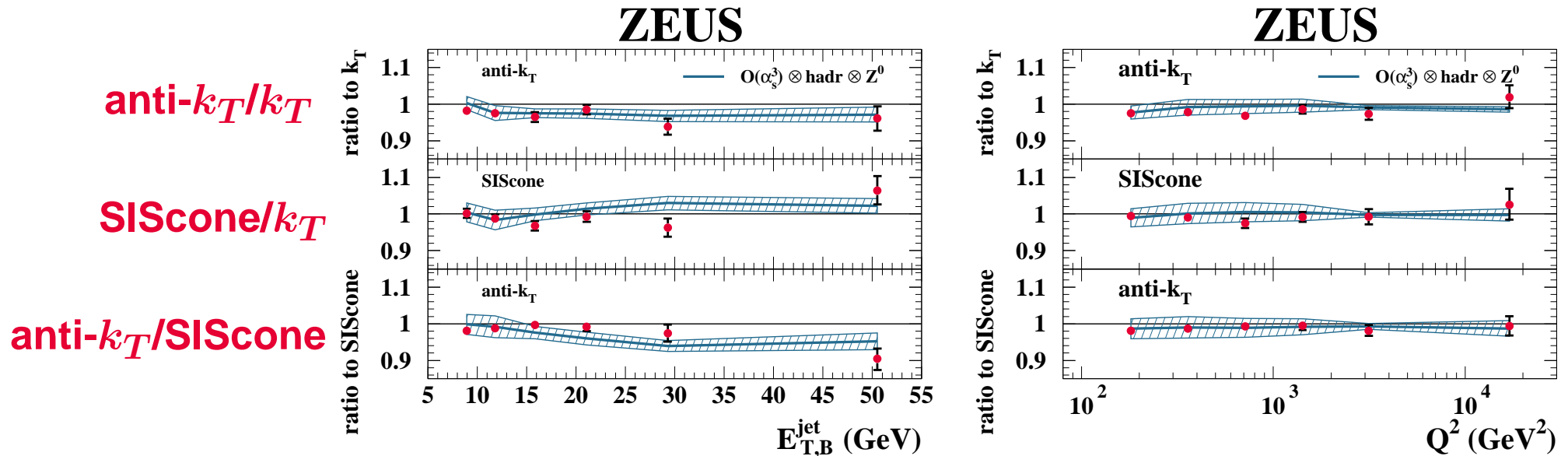


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Inclusive-jet cross sections: k_T vs anti- k_T vs SIScone



- Ratio of cross sections based on different jet algorithms:



- the measured cross sections with the three jet algorithms are similar
 - $< 3.2\%$ for Q^2 and $< 3.6\%$ for $E_{T,B}^{\text{jet}}$ (except at high $E_{T,B}^{\text{jet}}$: 10%)
- the uncertainty due to higher orders in the $\mathcal{O}(\alpha_s^3)$ calculation is reduced
 - theoretical uncertainty now dominated by that on the QCD-cascade modelling

⇒ Demonstration of the ability of pQCD calculations with up to four partons in the final state to account adequately for the differences between jet algorithms

Inclusive-jet cross sections: extraction of $\alpha_s(M_Z)$



- From the measured $d\sigma/dQ^2$ for $Q^2 > 500 \text{ GeV}^2$ values of $\alpha_s(M_Z)$ were extracted:

$$\alpha_s(M_Z) = 0.1188_{-0.0035}^{+0.0036} \text{ (exp.) } \pm_{-0.0022}^{+0.0022} \text{ (th.) (anti-}k_T\text{)}$$

$$\alpha_s(M_Z) = 0.1186_{-0.0035}^{+0.0037} \text{ (exp.) } \pm_{-0.0026}^{+0.0026} \text{ (th.) (SIScone)}$$

$$\alpha_s(M_Z) = 0.1207_{-0.0036}^{+0.0038} \text{ (exp.) } \pm_{-0.0023}^{+0.0022} \text{ (th.) (}k_T\text{)}$$

- Experimental uncertainties:

→ dominated by jet energy scale uncertainty:

$$\Delta\alpha_s/\alpha_s = \pm 1.9\% \text{ (anti-}k_T\text{), } \pm 1.9\% \text{ (SIScone), } \pm 2\% \text{ (}k_T\text{)}$$

- Theoretical uncertainties:

→ terms beyond NLO:

$$\Delta\alpha_s/\alpha_s(\%) = \begin{array}{ccc} \text{anti-}k_T & \text{SIScone} & k_T \\ +1.4 & +1.6 & +1.5 \\ -1.5 & -1.7 & -1.5 \end{array}$$

→ uncertainties from pPDFs:

$$\Delta\alpha_s/\alpha_s(\%) = \begin{array}{ccc} \text{anti-}k_T & \text{SIScone} & k_T \\ \pm 0.8 & \pm 0.8 & \pm 0.7 \end{array}$$

→ hadronisation corrections:

$$\Delta\alpha_s/\alpha_s(\%) = \begin{array}{ccc} \text{anti-}k_T & \text{SIScone} & k_T \\ \pm 0.9 & \pm 1.3 & \pm 0.8 \end{array}$$

→ $\alpha_s(M_Z)$ from inclusive-jet cross sections in NC DIS:

→ precise determination using **anti- k_T** **SIScone** **k_T**

→ total uncertainty (%): ~ 3.5 **3.7** **3.7**

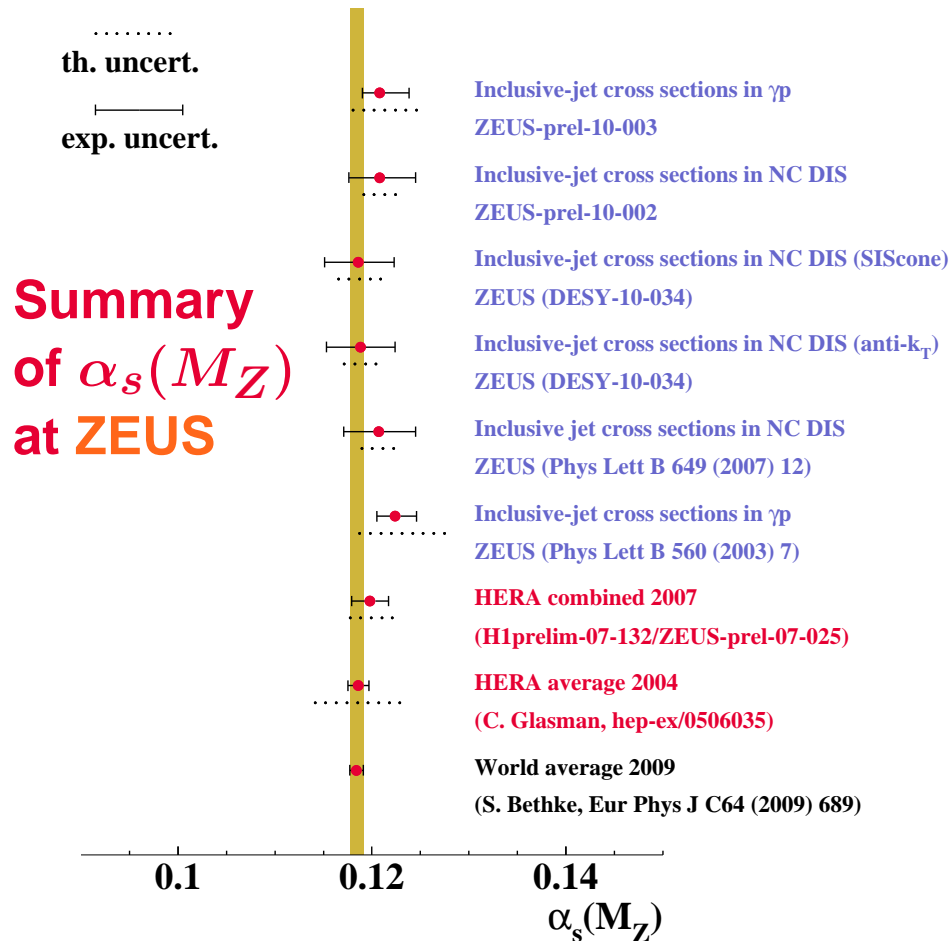
→ theoretical uncertainty (%): ~ 1.9 **2.2** **1.9**

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Summary of α_s extraction at ZEUS

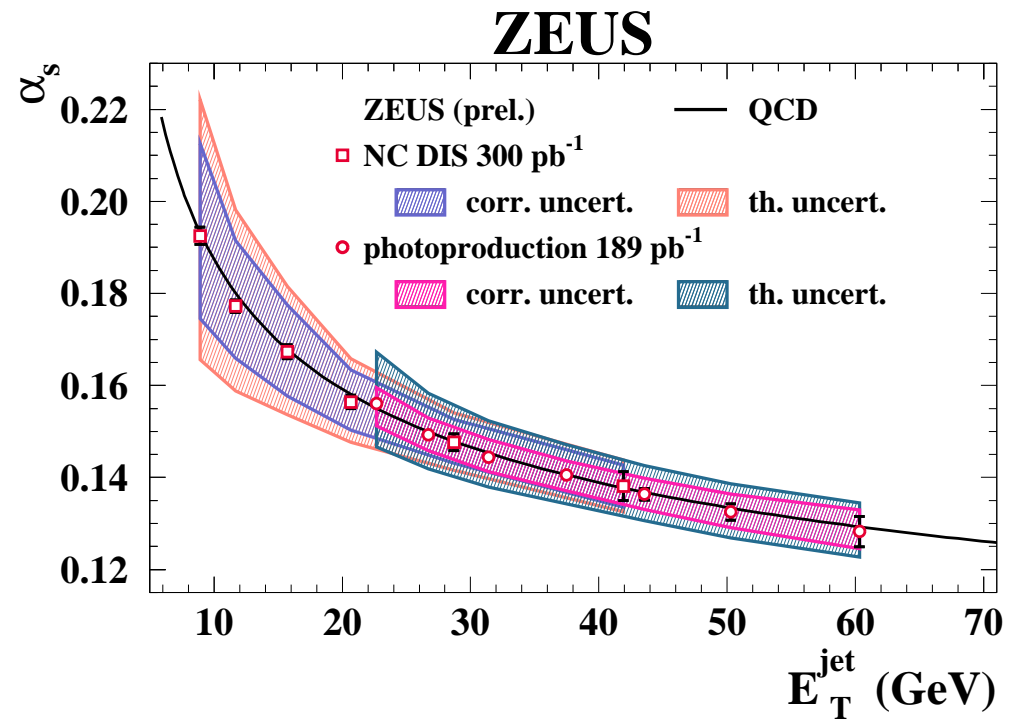


- **ZEUS latest $\alpha_s(M_Z)$ values and running of α_s from inclusive-jet cross sections in NC DIS and photoproduction:**



Measurements consistent with each other and the world average

Summary of α_s running at ZEUS



Measurements consistent with the predicted running of α_s over a wide range of E_T^{jet}

