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Jet cross sections in NC DIS at HERA

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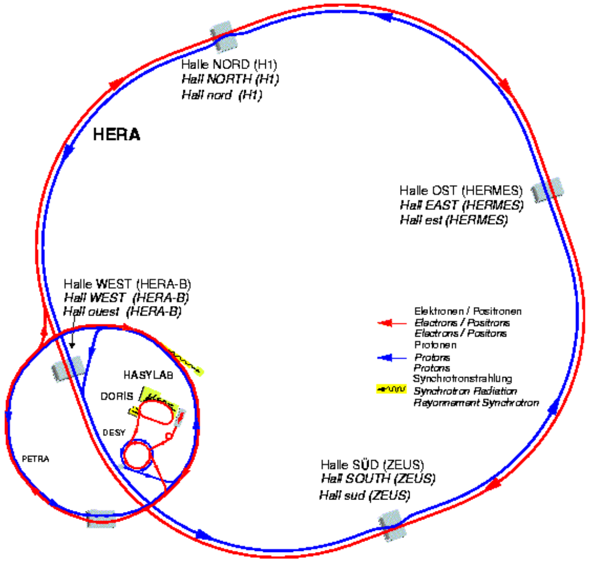
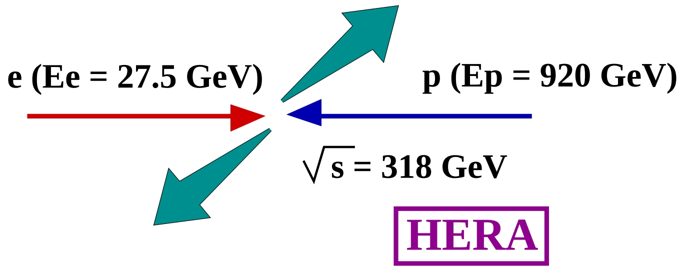
ZEUS

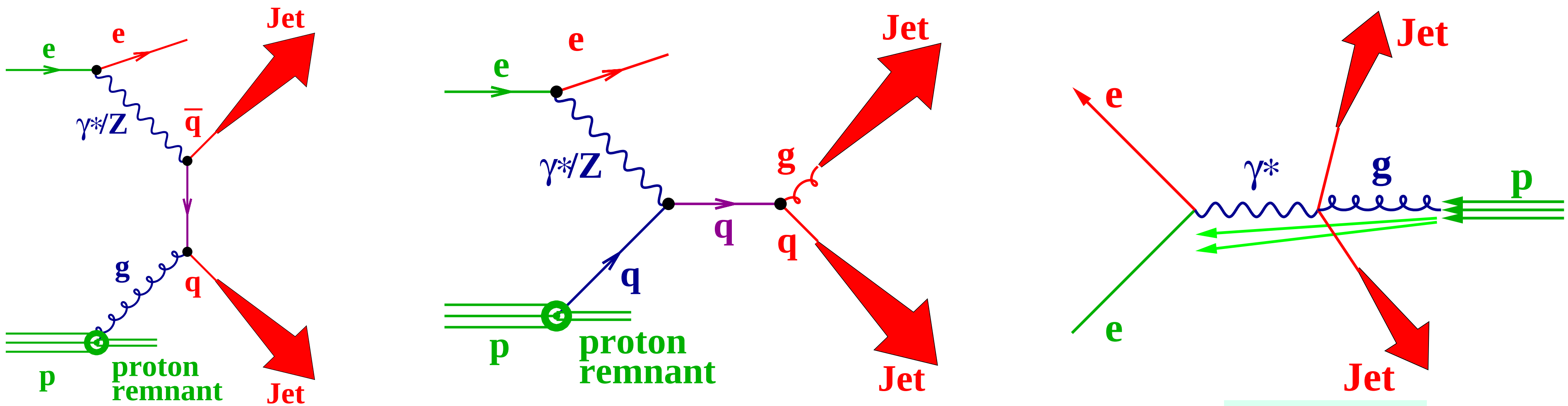
ZEUS Collaboration





Jet production in NC DIS at HERA

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



Boson-gluon fusion QCD Compton Breit frame

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

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

– f_a: parton a density, determined from experiment
  $\longrightarrow$ long-distance structure of the target

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

Kinematics:

– momentum transfer:
$Q^2 = -q^2 = -(k-k')^2$

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

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

Jets in NC DIS at HERA

- QCD processes dominant at hadron colliders
  - $\longrightarrow$ background to new physics searches (eg at LHC)
  - $\longrightarrow$ need good understanding of QCD processes

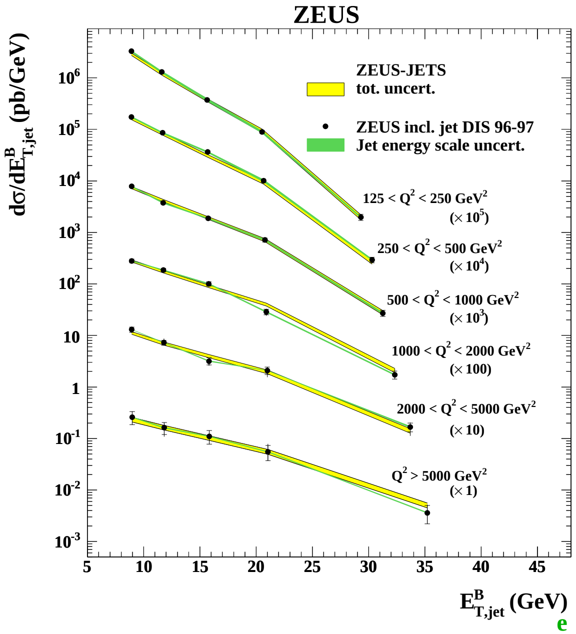
- Measurements of jet production in NC DIS at HERA provide a clean hadron-induced reaction and are a powerful tool
  - $\longrightarrow$ to test perturbative QCD calculations
  - $\longrightarrow$ to extract $\alpha_s(M_Z)$
  - $\longrightarrow$ to determine the energy dependence (running) of $\alpha_s(\mu)$
  - $\longrightarrow$ to constrain the proton PDFs (particularly the gluon)

- NEW MEASUREMENTS FROM ZEUS:
  - $\longrightarrow$ Inclusive-jet and dijet cross sections with more than three-fold increase in statistics wrt previous analyses:
    - $\longrightarrow$ further constrains on proton PDFs
  - $\longrightarrow$ Inclusive-jet cross sections with more than three-fold increase in statistics:
    - $\longrightarrow$ precise test of pQCD and extraction of α_s
  - $\longrightarrow$ Inclusive-jet cross sections with different jet algorithms:
    - $\longrightarrow$ test performance of new jet algorithms in a well-understood environment

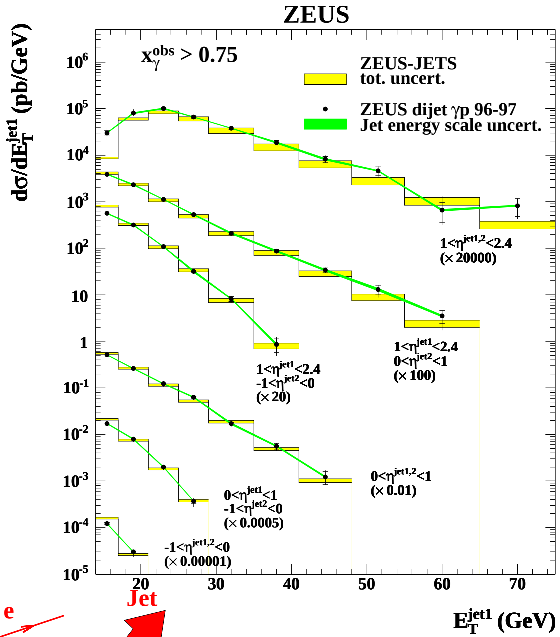
Jets and PDFs at HERA

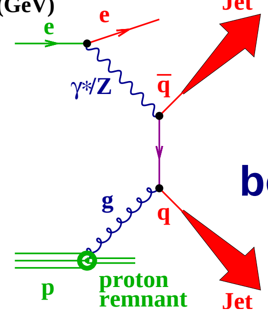
- **Very precise jet cross sections in NC DIS and photoproduction (directly sensitive to the gluon content of proton): constraints on gluon density**
- **Measurements incorporated in a QCD fit (together with structure function data from ZEUS) to determine PDFs parametrisations:**

NC DIS



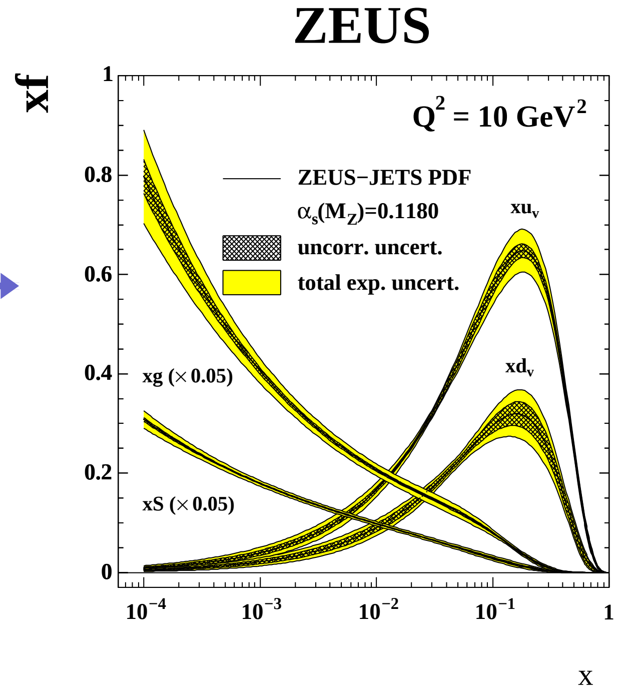
photoproduction





boson-gluon fusion

proton parton densities



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Jets and PDFs at HERA

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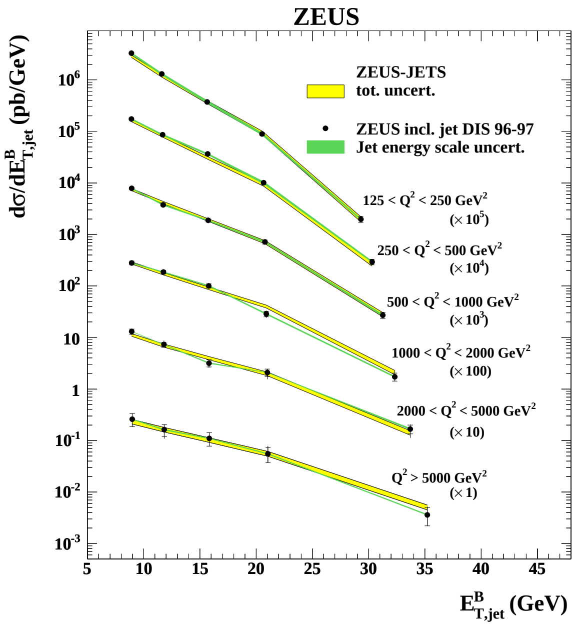
NC DIS



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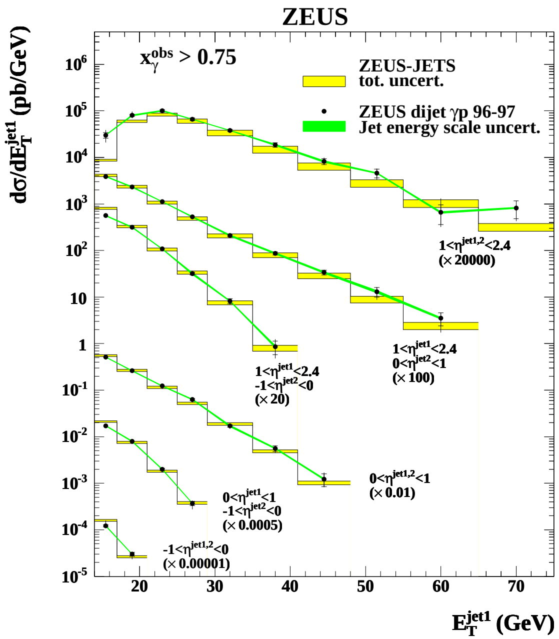

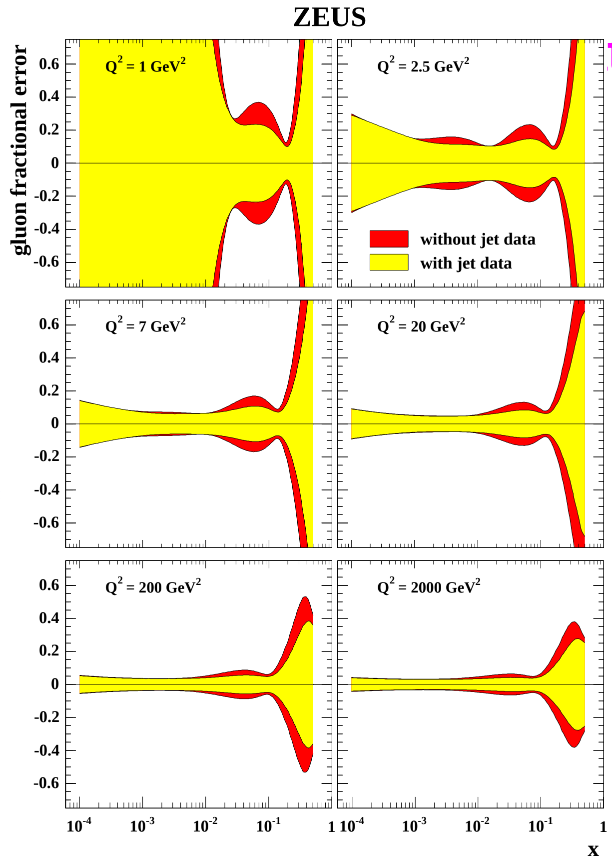

- The result was an improvement of the determination of the gluon density
  - ⟶ the uncertainty in the gluon density decreased up to a factor of two for mid- to high-x
  - ⟶ relevant for new physics searches at LHC

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Dijet cross sections: constraints on pPDFs

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

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

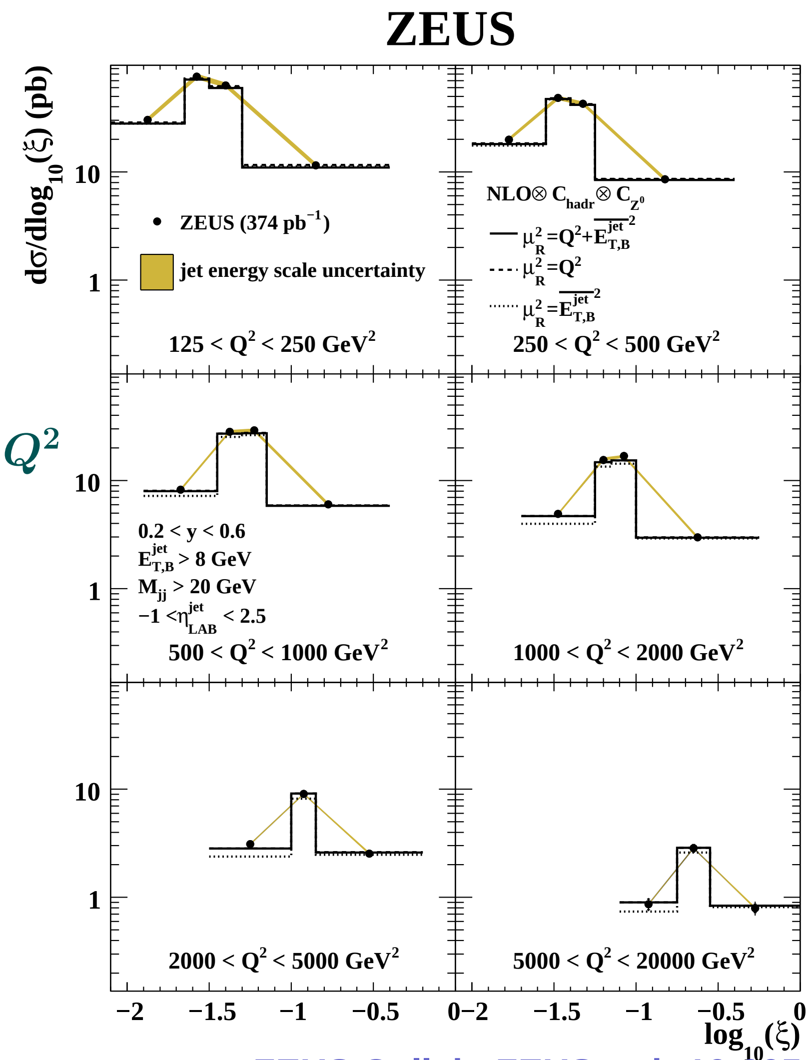
- Jets searched using the k_T cluster algorithm in Breit frame
- Kinematic region: $125 < Q^2 < 20000$ GeV^2 and $0.2 < y < 0.6$
- Two jets with $E_{T,\rm B}^{\rm jet} > 8$ GeV and $-1 < \eta_{\rm LAB}^{\rm jet} < 2.5$
- $M^{\rm jj} > 20$ GeV

- $\xi = x_{\rm Bj}(1 + (M^{\rm jj})^2/Q^2)$ 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 $E_T^{\rm jet} > 10$ GeV): $\sim \pm 5\ (2)\%$ at low (high) Q^2

- Comparison to NLO predictions (NLOJET++):
  - → $\mu_R^2 = Q^2 + (E_{T,\rm B}^{\rm jet})^2$, $\mu_F = Q$; 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



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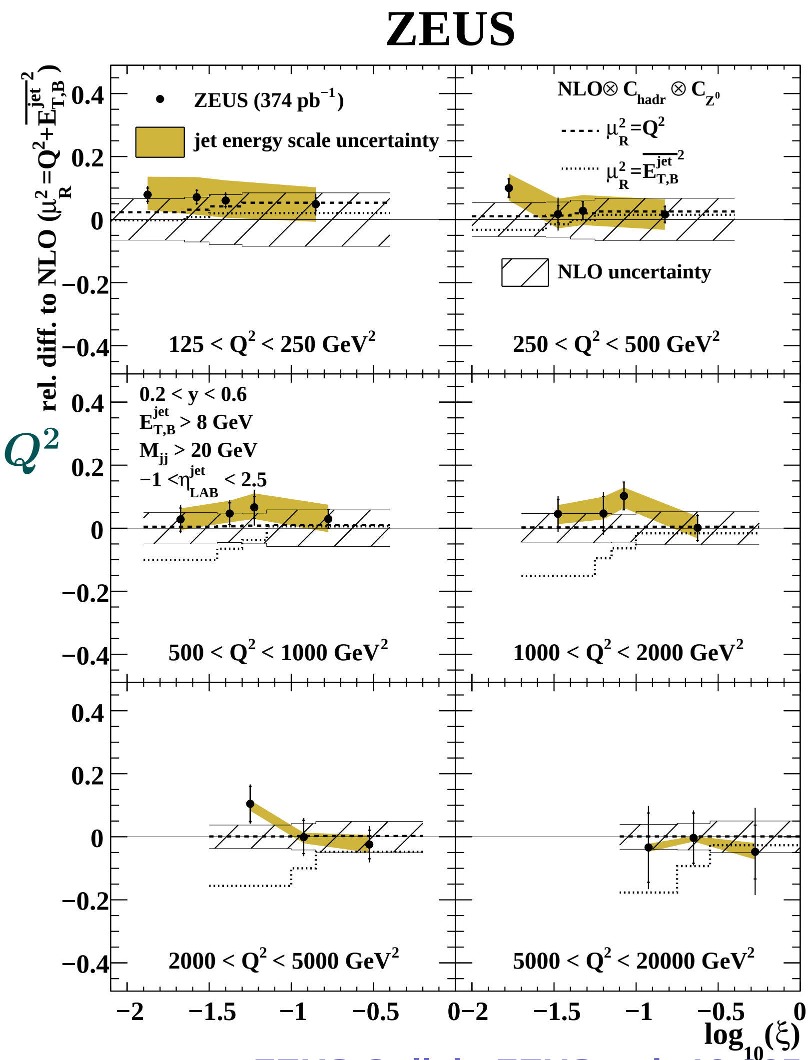

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- $\overline{E_{T,\rm B}^{\rm jet}}$ mean transverse energy of the two jets
  $\longrightarrow$ well suited for precise tests of pQCD

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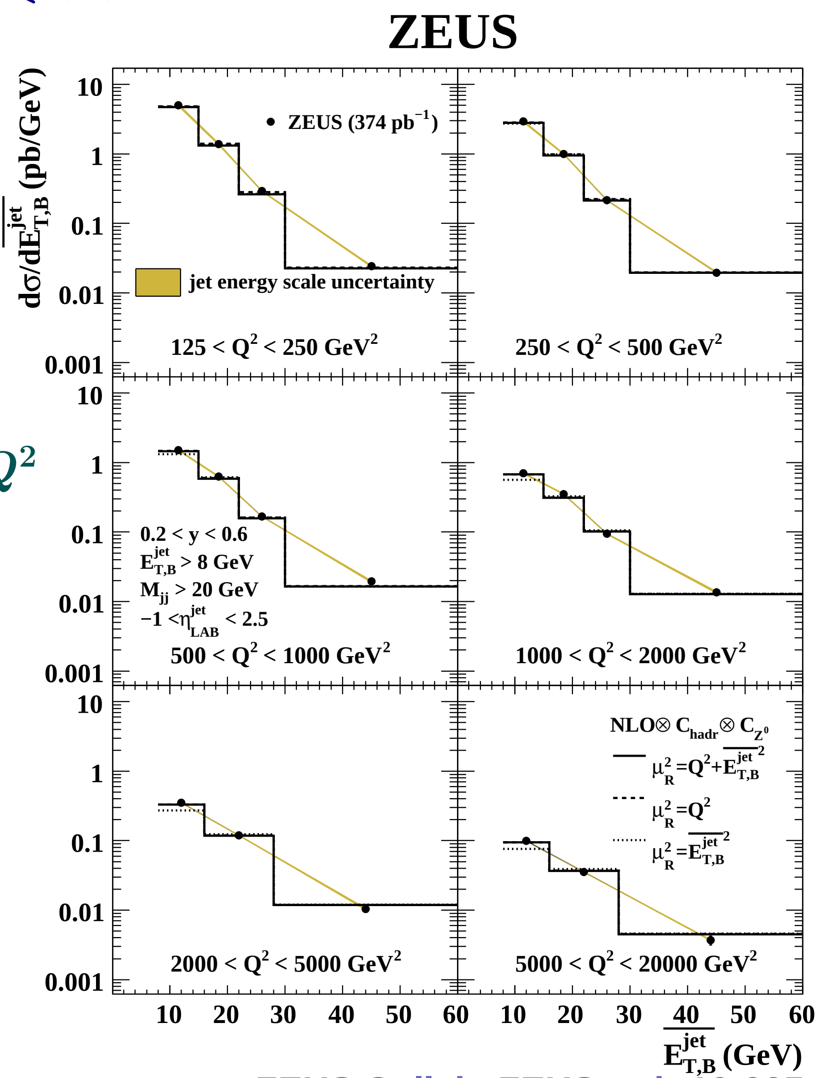

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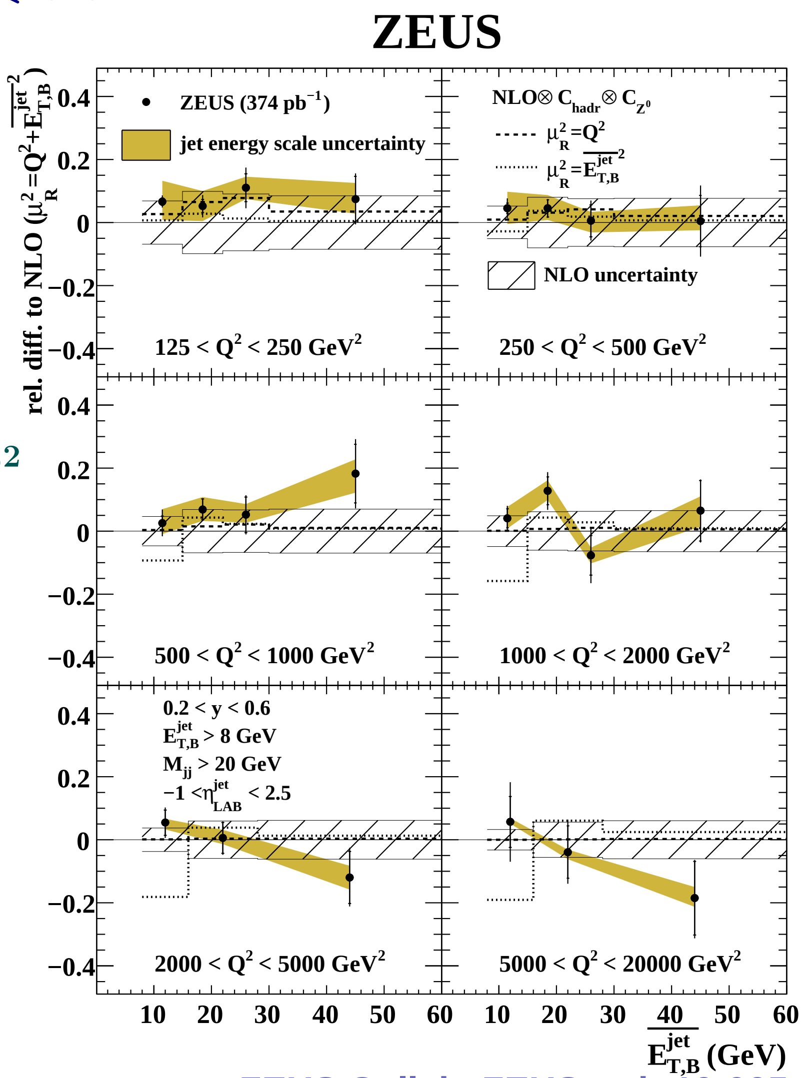

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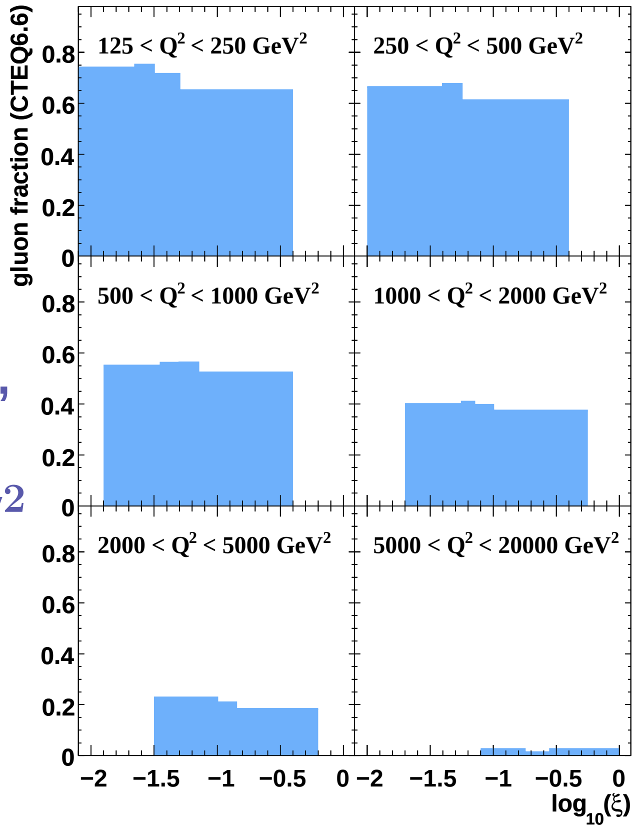
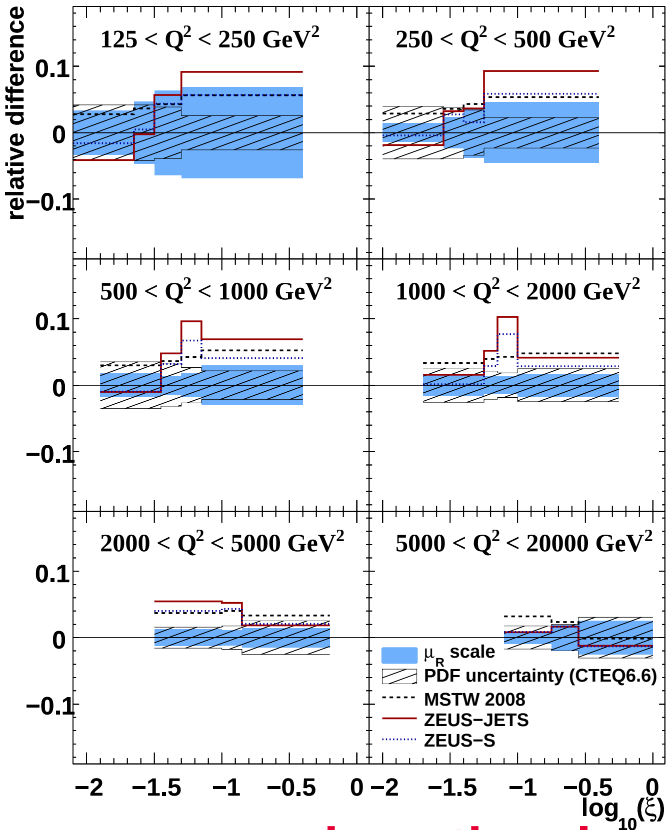
Dijet cross sections: constraints on pPDFs

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

Predicted Gluon fraction:
75% at low Q^2,
$> 60\%$ at
$Q^2 \sim 500$ GeV^2





Theoretical uncertainties

$\longrightarrow$ PDF uncertainty large in regions of phase space where the gluon fraction is still sizeable

$\longrightarrow$ high precision dijet data have the potential to constrain further the proton PDFs when included in the global fits

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Inclusive-jet 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,
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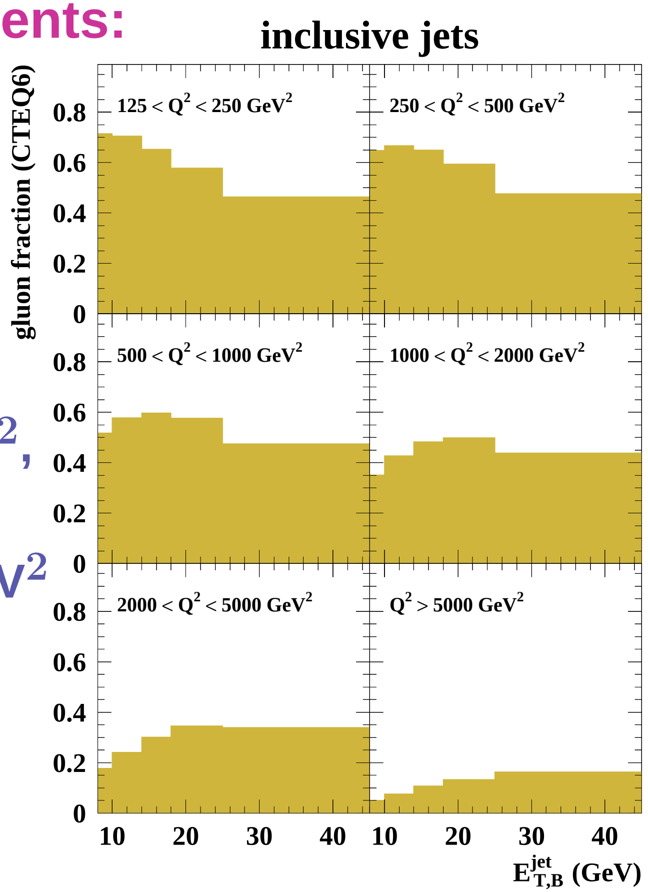

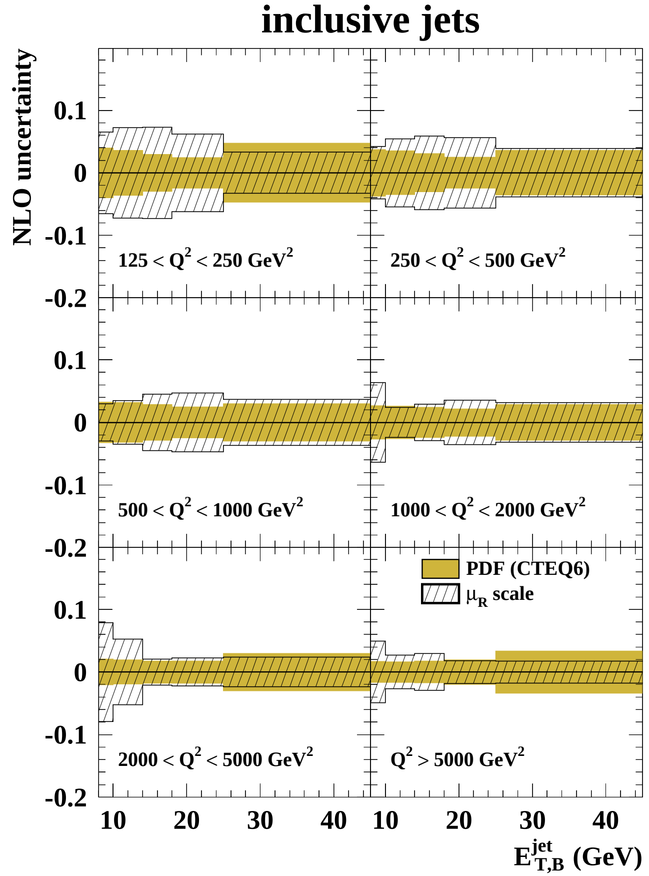

Theoretical uncertainties

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ZEUS Collab, Nucl Phys B 765 (2007) 1

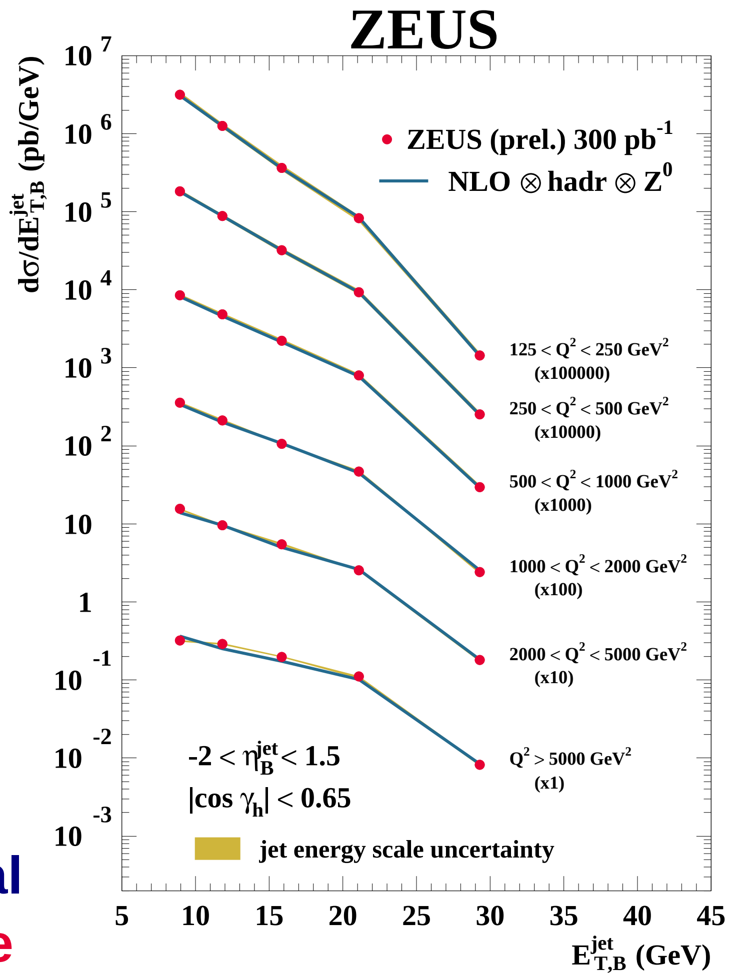
Inclusive-jet cross sections: constraints on pPDFs

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

- Jets searched using the k_T cluster algorithm in Breit frame
- Kinematic region: $Q^2 > 125$ GeV^2 and $|\cos\gamma_h| < 0.65$
- At least one jet with $E_{T,\text{B}}^{\text{jet}} > 8$ GeV and $-2 < \eta_{\text{B}}^{\text{jet}} < 1.5$
- no cuts in LAB frame

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

- Small experimental uncertainties:
  - → uncorrelated: $\sim \pm 3\ (10)\%$ at low (high) $Q^2/E_{T,\text{B}}^{\text{jet}}$
  - → correlated (energy scale $\pm 1\%$ (!) for $E_T^{\text{jet}} > 10$ GeV): $\sim \pm 5\ (2)\%$ at low (high) $Q^2/E_{T,\text{B}}^{\text{jet}}$
- Comparison to NLO ($\mathcal{O}(\alpha_s^2)$) predictions (DISENT):
  - → $\mu_R = E_{T,\text{B}}^{\text{jet}}$, $\mu_F = Q$; 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

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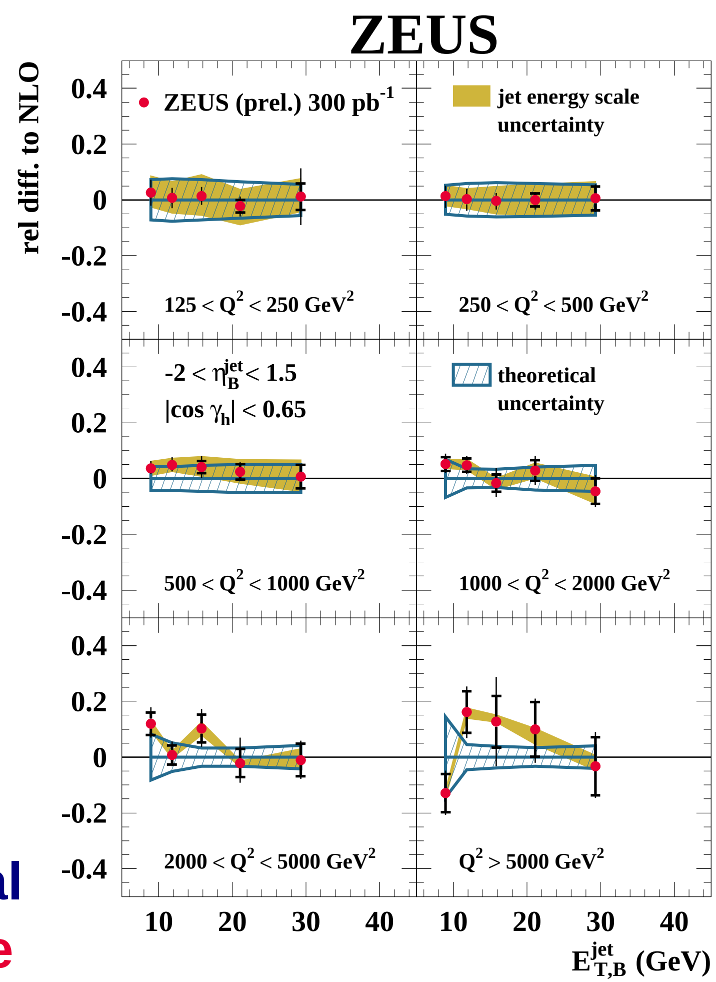

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Inclusive-jet cross sections: test of pQCD

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

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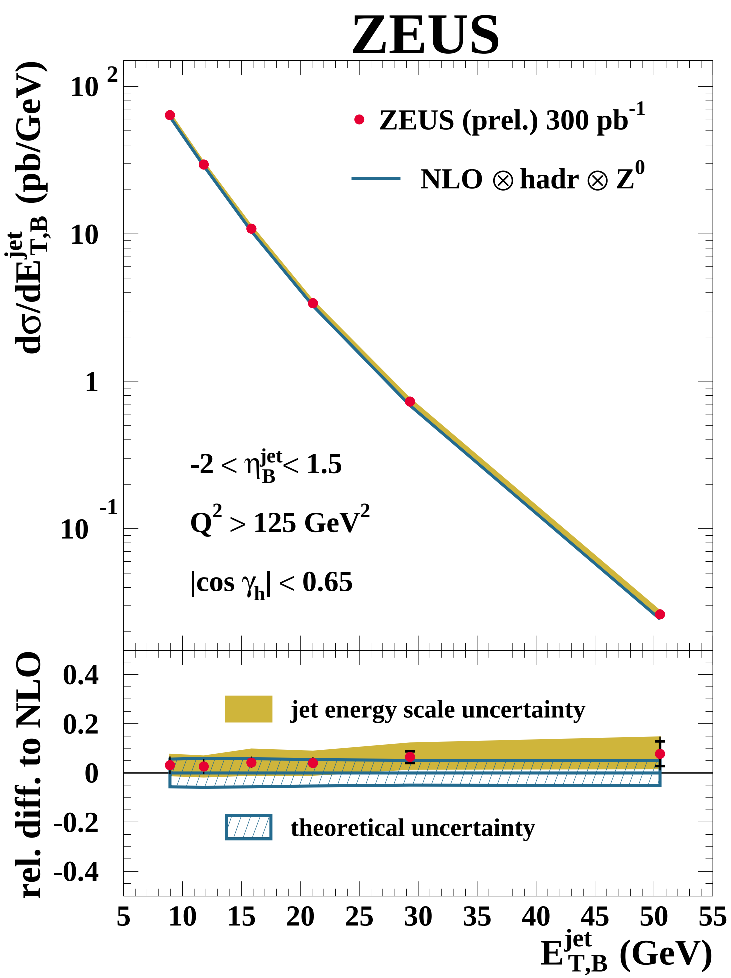
- no cuts in LAB frame

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

- Advantages of inclusive-jet cross sections:
  - infrared insensitivity (no dijet asymmetric/$M^{\rm jj}$ 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) $Q^2/E_{T,\rm B}^{\rm jet}$
  - $\rightarrow$ correlated (energy scale $\pm 1\%$ (!) for $E_T^{\rm jet} > 10$ GeV): $\sim \pm 5\ (2)\%$ at low (high) $Q^2/E_{T,\rm B}^{\rm jet}$
- Small theoretical uncertainties:
  - $\rightarrow$ higher orders (below $\pm 5\%$ for $Q^2 > 250$ GeV^2)
  - $\rightarrow$ proton PDFs (below $\pm 3\%$)
  - $\rightarrow$ $\alpha_s(M_Z)$ (below $\pm 1\ (2)\%$ at low (high) $Q^2/E_{T,\rm B}^{\rm jet}$)
  - $\rightarrow$ parton-to-hadron corrections (below $\pm 2\%$)

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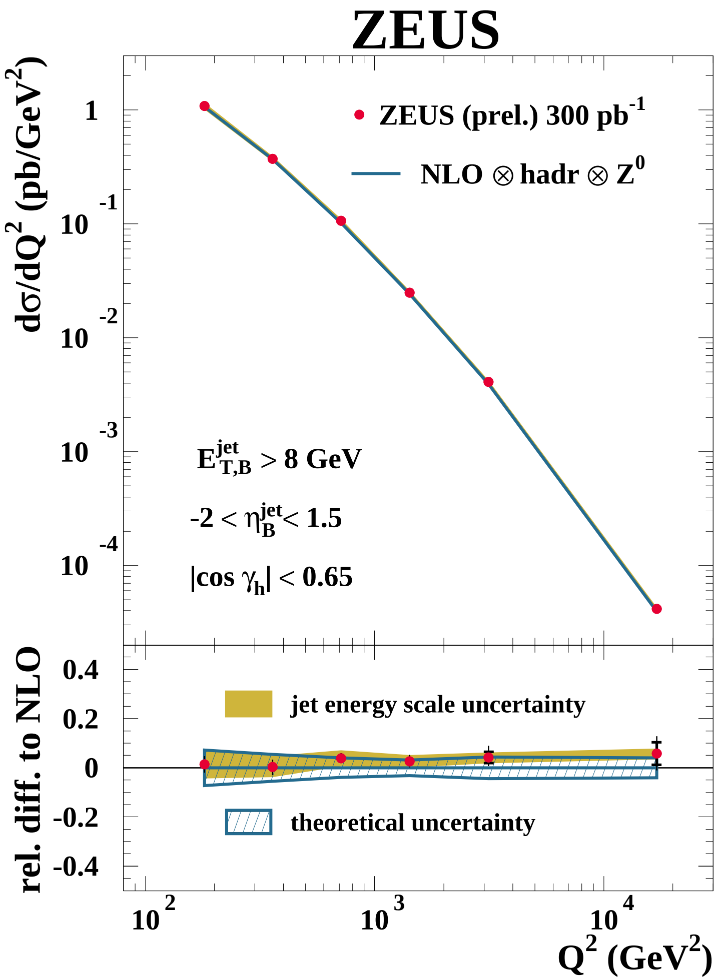
- Comparison to NLO ($\mathcal{O}(\alpha_s^2)$) predictions (DISENT):
  - $\longrightarrow$ $\mu_R = E_{T,\text{B}}^{\text{jet}}$, $\mu_F = Q$; pPDFs: ZEUS-S; $\alpha_s(M_Z) = 0.118$
  - $\longrightarrow$ corrected for hadronisation and Z^0 effects



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

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

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

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

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

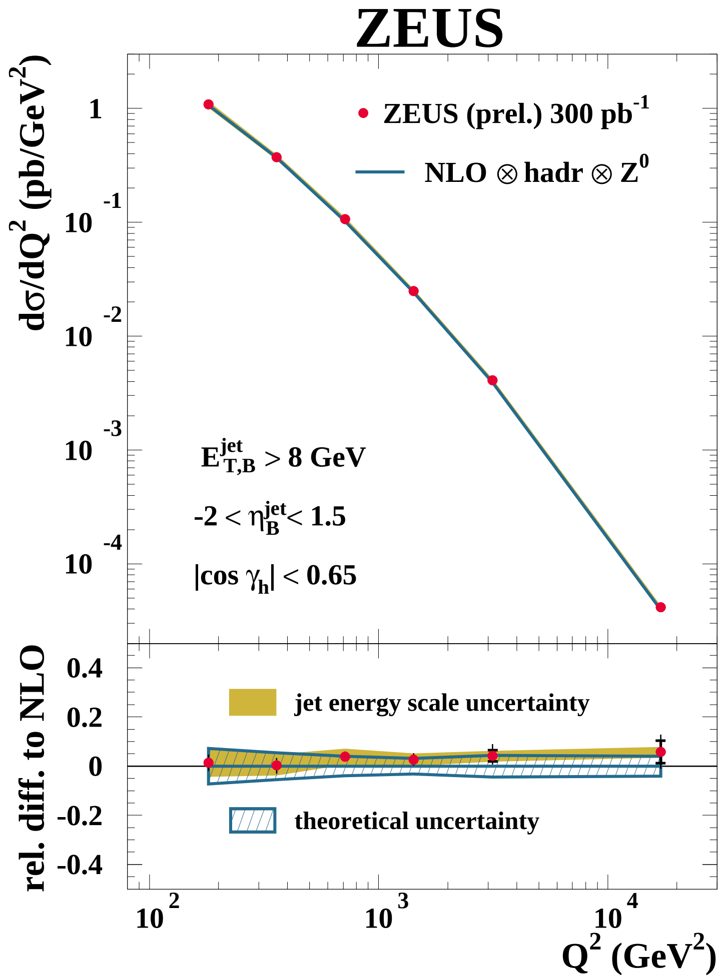
$$\alpha_s(M_Z) = 0.1208^{+0.0037}_{-0.0032}\ (\text{exp.})\ ^{+0.0022}_{-0.0022}\ (\text{th.})$$

(assuming predicted running of α_s)

- Experimental uncertainties:
  - $\longrightarrow$ dominated by jet energy scale uncertainty:

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

- Theoretical uncertainties:
  - $\longrightarrow$ terms beyond NLO: $\Delta\alpha_s/\alpha_s = \pm 1.5\%$
  - $\longrightarrow$ uncertainties from pPDFs: $\Delta\alpha_s/\alpha_s = \pm 0.7\%$
  - $\longrightarrow$ hadronisation corrections: $\Delta\alpha_s/\alpha_s = \pm 0.8\%$
  - $\longrightarrow$ μ_F uncertainty: negligible



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

$\longrightarrow$ (total uncertainty: $\sim^{+3.5}_{-3.2}$ %; theoretical uncertainty: $\sim 1.9\%$)

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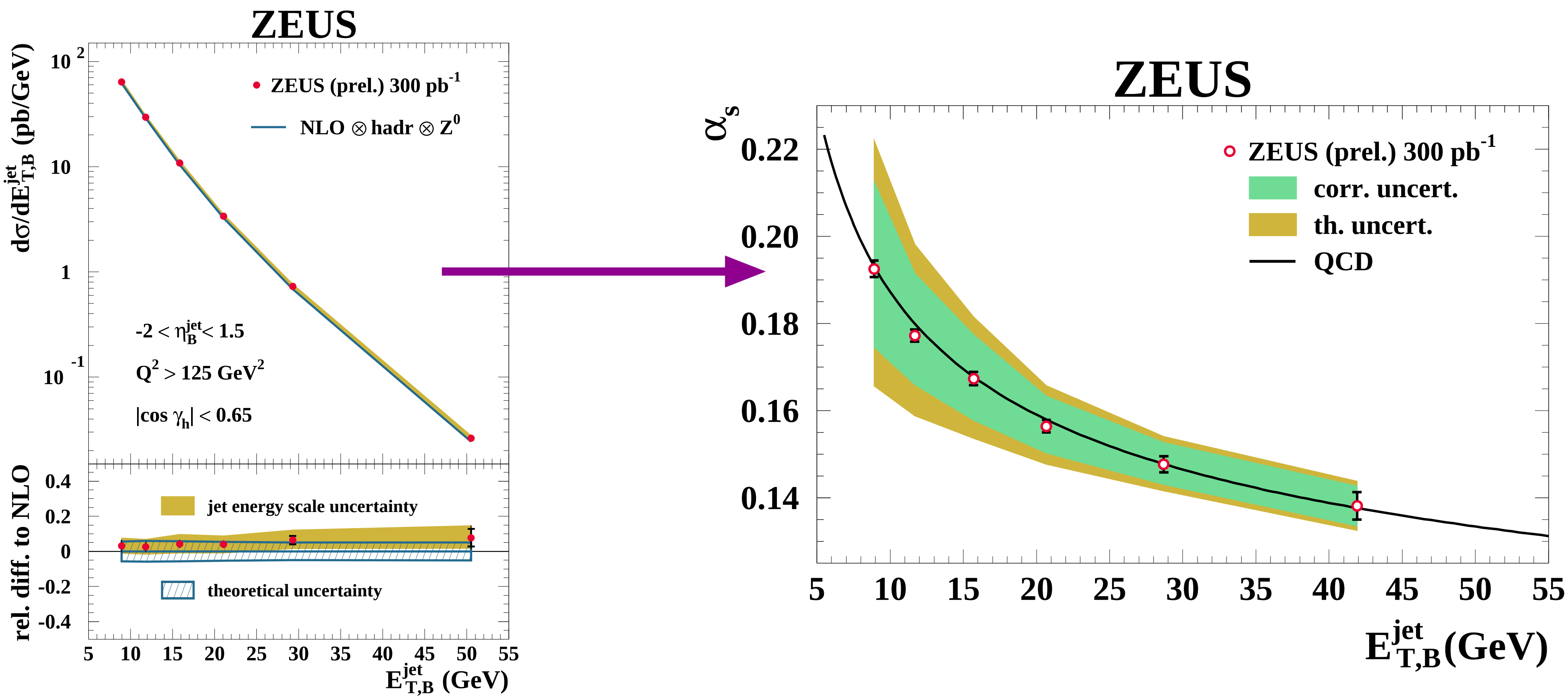
Determination of the energy-scale dependence of α_s

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



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

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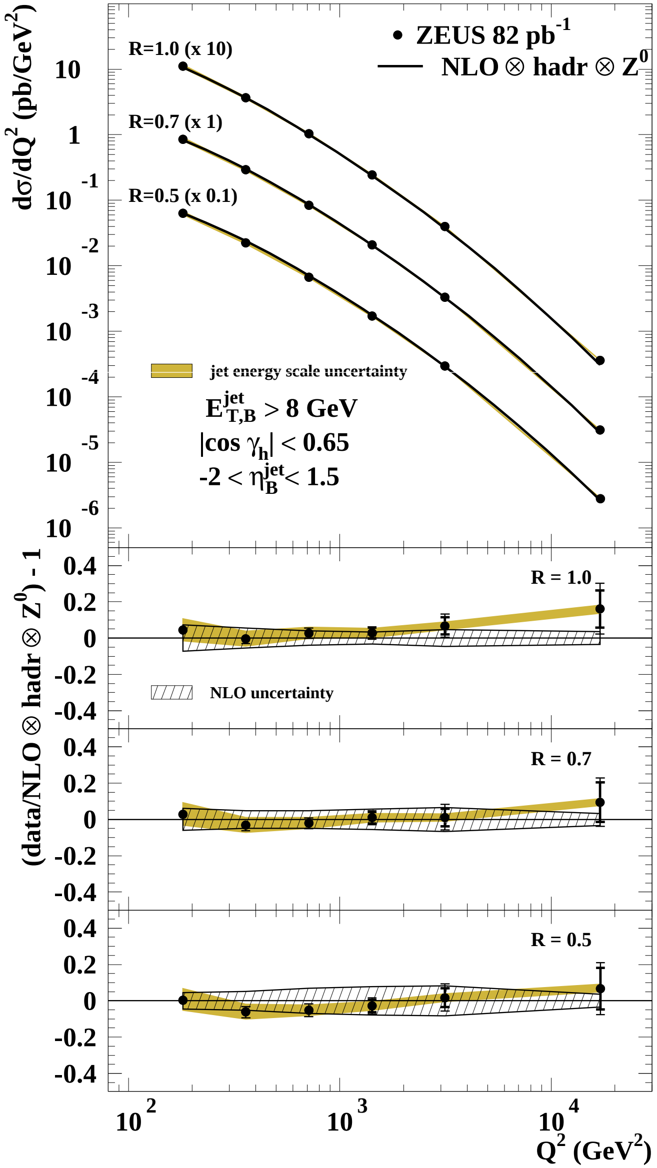
Inclusive-jet cross sections: jet algorithms

- Tests of pQCD with jets require infrared- and collinear-safe jet algorithms:
  - $\longrightarrow$ k_T cluster algorithm in the longitudinally invariant inclusive mode (S Catani, S Ellis & D Soper)
- Performance of k_T algorithm tested extensively
  - $\longrightarrow$ stringent tests of pQCD: good description of data for all jet radii with similar precision
  - $\longrightarrow$ good performance of k_T algorithm: small theoretical uncertainties and small hadronisation corrections
- New jet algorithms being used at LHC
  - $\longrightarrow$ need validation
- NEW STUDIES AT ZEUS:
  - $\longrightarrow$ test of performance of anti-k_T and SIScone in a hadron-induced but well-understood reaction:
    - $\ast$ comparison to measurements based on k_T
    - $\ast$ comparison of measurements and NLO QCD calculations
    - $\ast$ study of theoretical uncertainties and hadronisation corrections



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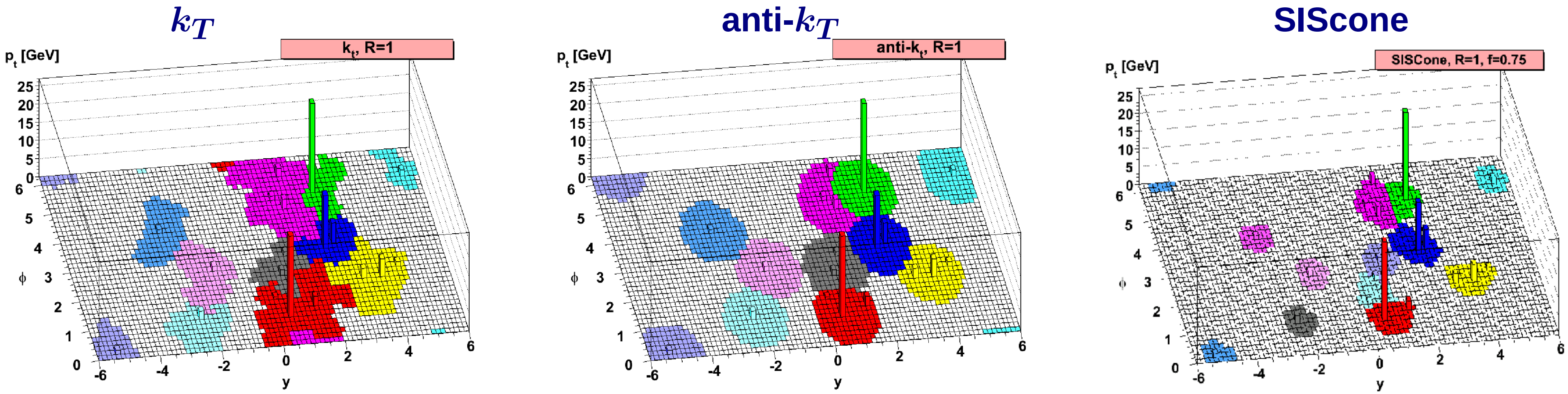
Inclusive-jet cross sections: k_T vs anti-k_T vs SIScone

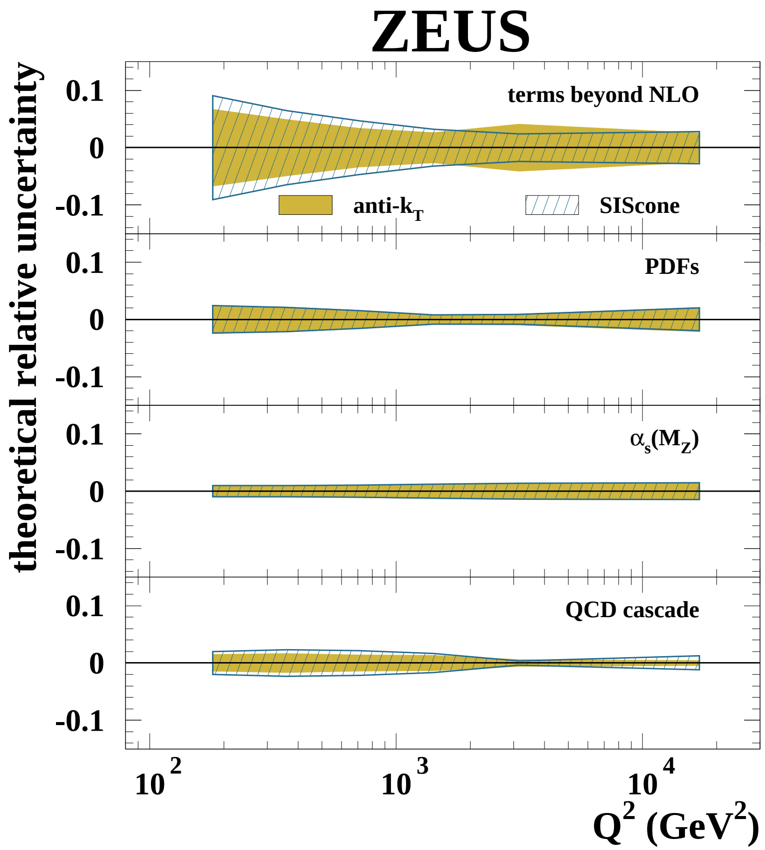
- New infrared- and collinear-safe jet algorithms:
  $\longrightarrow$ anti-k_T (M Cacciari, G Salam & G Soyez) and SiScone (G Salam & G Soyez)
- Cluster algorithms:
  $\longrightarrow$ $d_{ij} = \min((E^i_{T,\mathrm{B}})^{2p}, (E^j_{T,\mathrm{B}})^{2p}) \cdot \Delta R^2/R^2$ with $p=1$ (-1) for k_T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



M Cacciari, G P Salam and Soyez, JHEP 0804 (2008) 063

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

- New infrared- and collinear-safe jet algorithms:
  - $\longrightarrow$ anti-k_T (M Cacciari, G Salam & G Soyez) and SiScone (G Salam & G Soyez)
- Cluster algorithms:
  - $\longrightarrow$ $d_{ij} = \min((E^i_{T,\text{B}})^{2p}, (E^j_{T,\text{B}})^{2p}) \cdot \Delta R^2/R^2$ with $p = 1$ (-1) for k_T (anti-k_T)
  - $\longrightarrow$ anti-k_T keeps infrared and collinear safety and provides $\approx$ circular jets (experimentally desirable)
- Cone algorithms:
  - $\longrightarrow$ seedless cone algorithm produces also jets with well-defined area and is infrared and collinear safe (theoretically desirable)
- Theoretical uncertainties:
  - $\longrightarrow$ proton PDFs and value of $\alpha_s(M_Z)$:
    - $\longrightarrow$ very similar for all three jet algorithms
  - $\longrightarrow$ terms beyond NLO and parton-shower modelling:
    - $\longrightarrow$ very similar for k_T and anti-k_T
    - $\longrightarrow$ somewhat larger for SIScone



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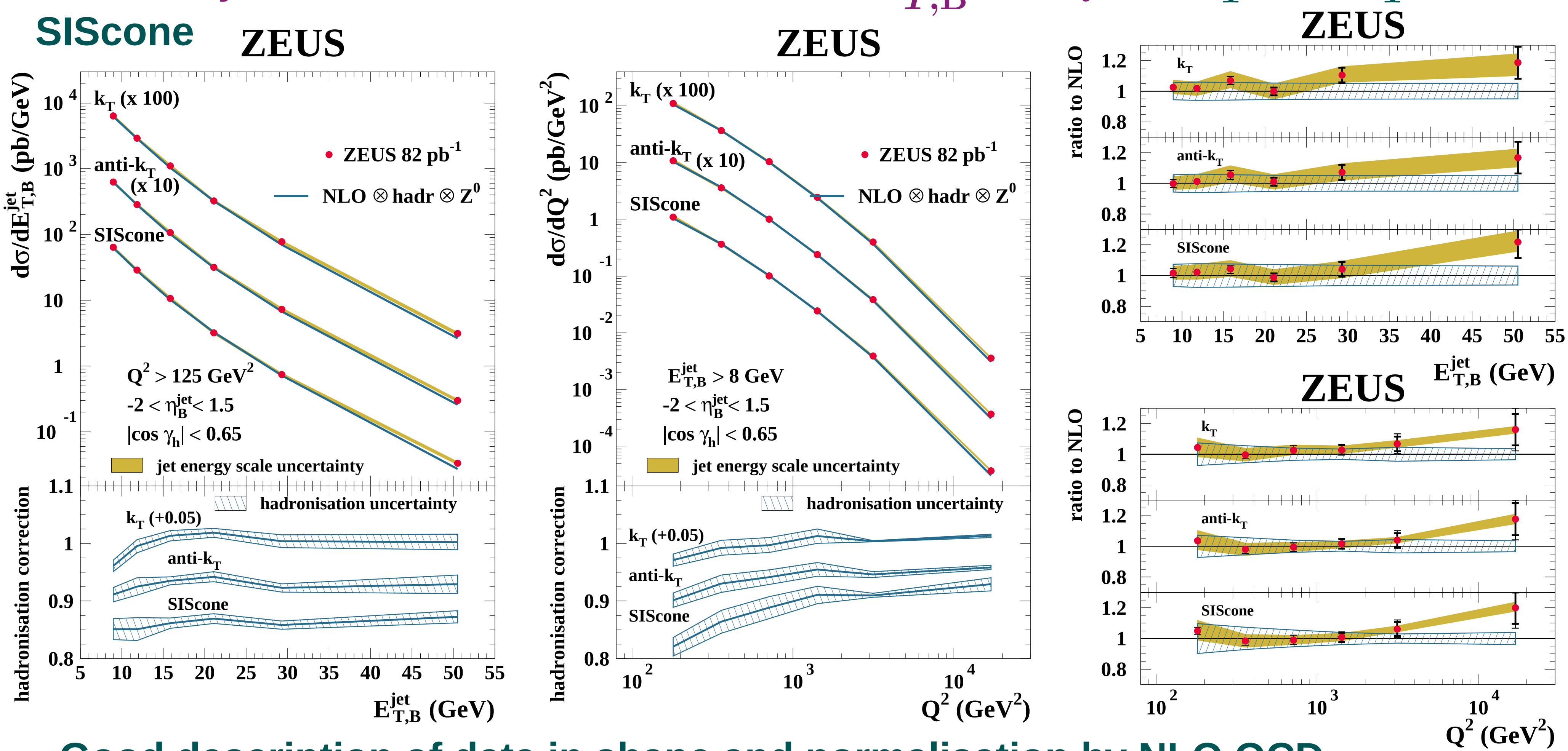
Inclusive-jet cross sections: k_T vs anti-k_T vs SIScone

- Inclusive-jet cross sections as functions of $E_{T,\mathrm{B}}^{\mathrm{jet}}$ 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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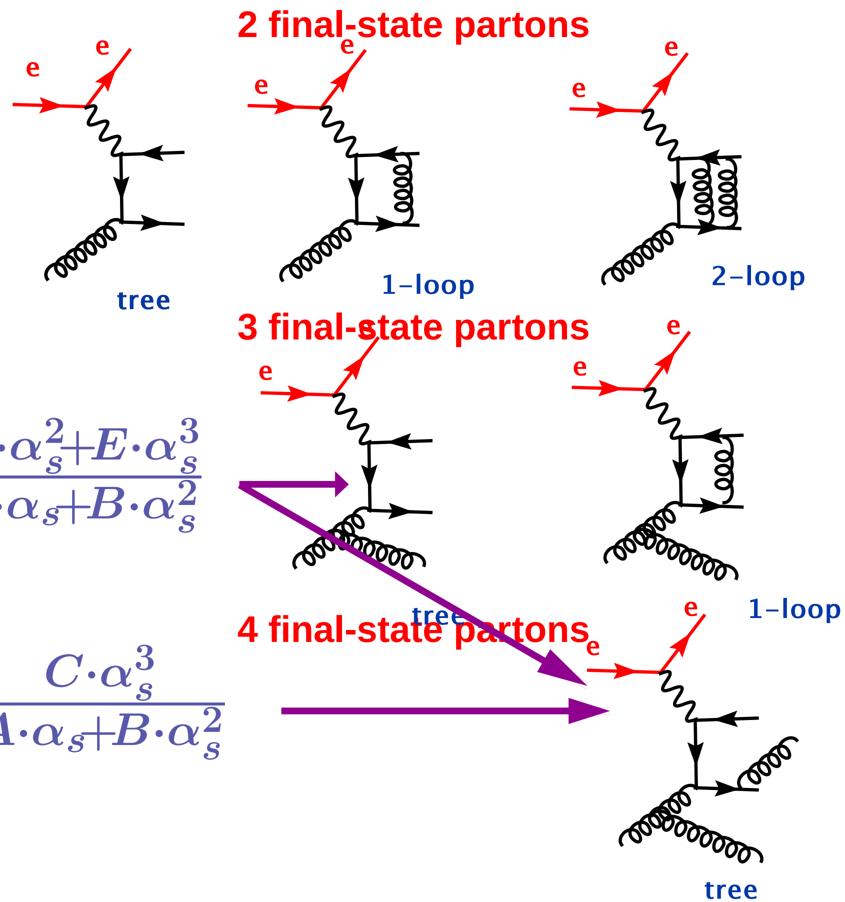
Inclusive-jet cross sections: k_T vs anti-k_T vs SIScone

- 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:

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

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



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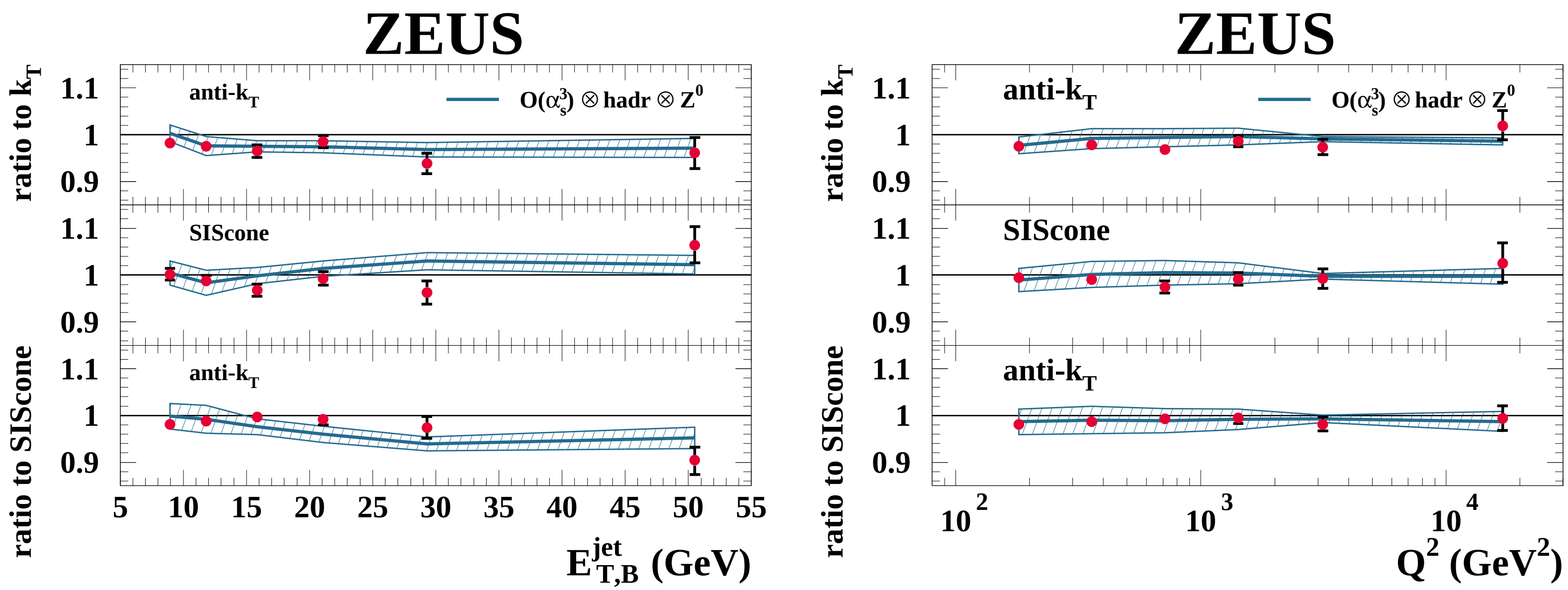
Inclusive-jet cross sections: k_T vs anti-k_T vs SIScone

- Ratio of cross sections based on different jet algorithms:

anti-k_T/k_T

SIScone/k_T

anti-k_T/SIScone



$\longrightarrow$ the measured cross sections with the three jet algorithms are similar

$\longrightarrow$ $< 3.2\%$ for Q^2 and $< 3.6\%$ for $E_{T,\mathrm{B}}^{\mathrm{jet}}$ (except at high $E_{T,\mathrm{B}}^{\mathrm{jet}}$: 10%)

$\longrightarrow$ the uncertainty due to higher orders in the $\mathcal{O}(\alpha_s^3)$ calculation is reduced

$\longrightarrow$ theoretical uncertainty now dominated by that on the QCD-cascade modelling

$\Rightarrow$ **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**

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

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

$$\alpha_s(M_Z) = 0.1188^{+0.0036}_{-0.0035}\,(\mathrm{exp.})\;^{+0.0022}_{-0.0022}\,(\mathrm{th.})\ \textbf{(anti-}k_T\textbf{)}$$

$$\alpha_s(M_Z) = 0.1186^{+0.0037}_{-0.0035}\,(\mathrm{exp.})\;^{+0.0026}_{-0.0026}\,(\mathrm{th.})\ \textbf{(SIScone)}$$

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

- Experimental uncertainties:

  $\longrightarrow$ dominated by jet energy scale uncertainty:

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

- Theoretical uncertainties:

		anti-k_T	SIScone	k_T
$\longrightarrow$ terms beyond NLO:	$\Delta\alpha_s/\alpha_s(\%) =$	$^{+1.4}_{-1.5}$	$^{+1.6}_{-1.7}$	$^{+1.5}_{-1.5}$
$\longrightarrow$ uncertainties from pPDFs:	$\Delta\alpha_s/\alpha_s(\%) =$	± 0.8	± 0.8	± 0.7
$\longrightarrow$ hadronisation corrections:	$\Delta\alpha_s/\alpha_s(\%) =$	± 0.9	± 1.3	± 0.8

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

	anti-k_T	SIScone	k_T
$\longrightarrow$ precise determination using			
$\longrightarrow$ total uncertainty (%):	~ 3.5	3.7	3.7
$\longrightarrow$ theoretical uncertainty (%):	~ 1.9	2.2	1.9

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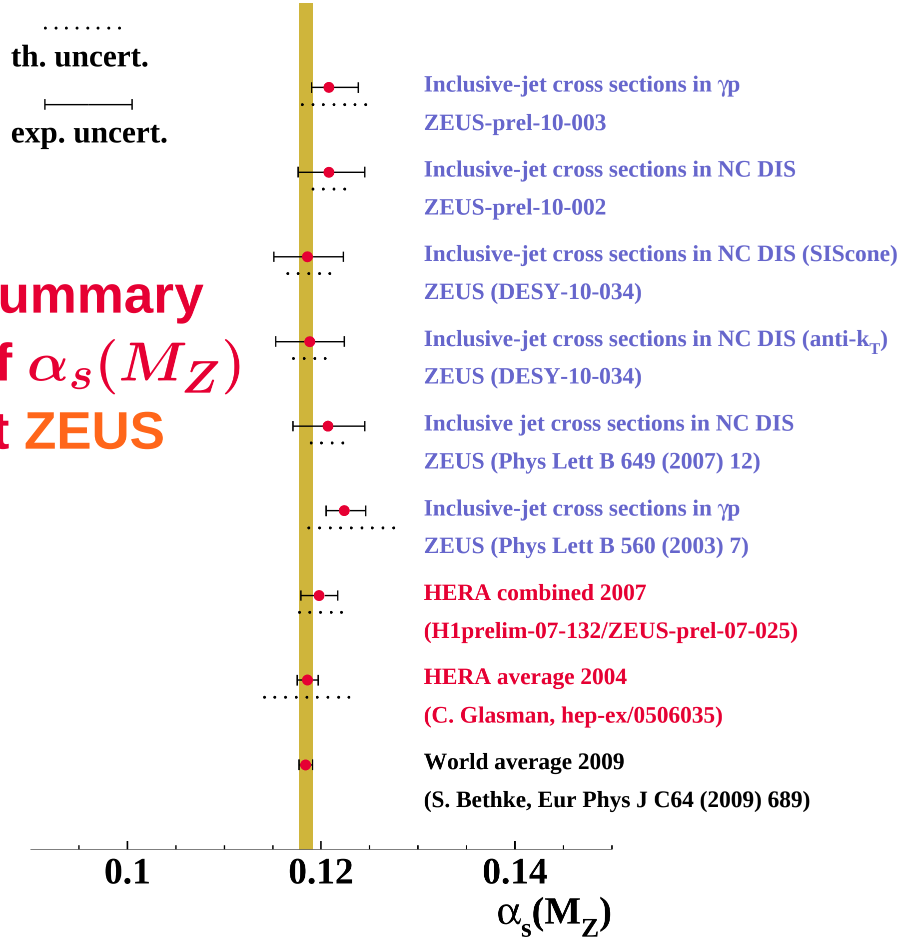
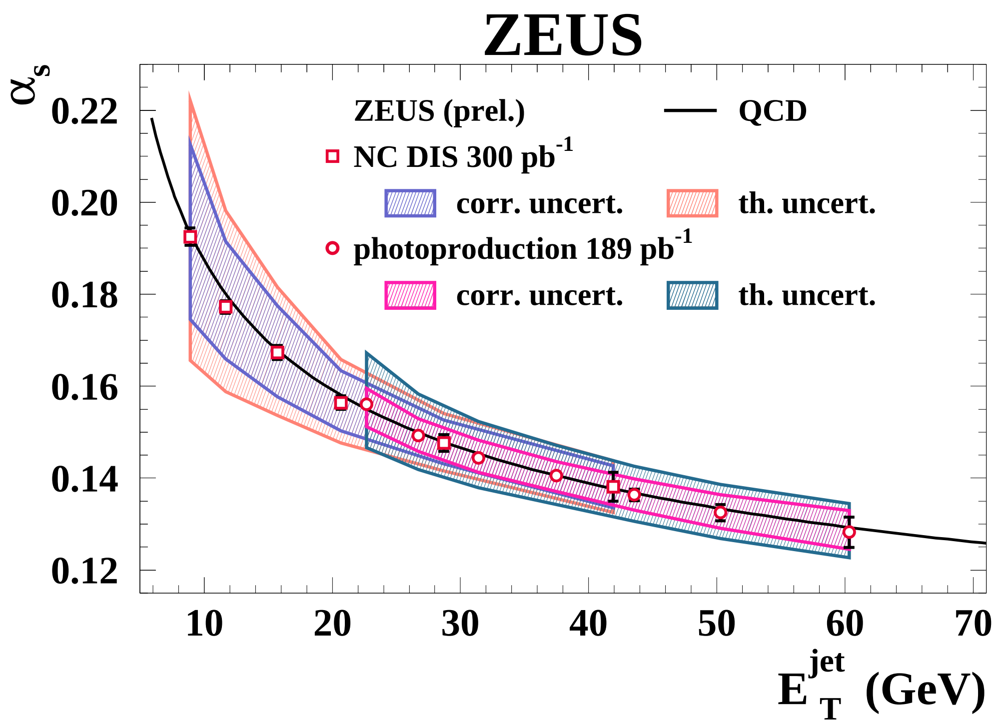
Summary of α_s extraction at ZEUS

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

Summary of $\alpha_s(M_Z)$ at ZEUS



Summary of α_s running at ZEUS

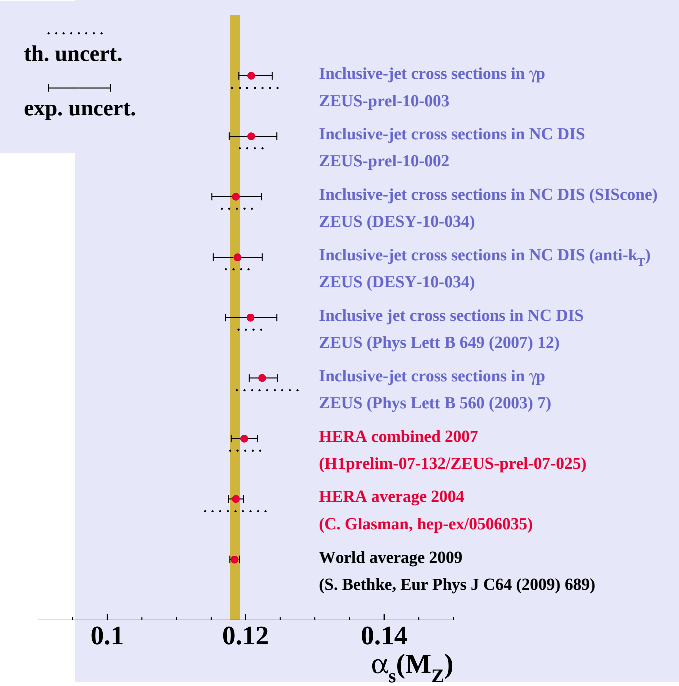


Measurements consistent with each other and the world average

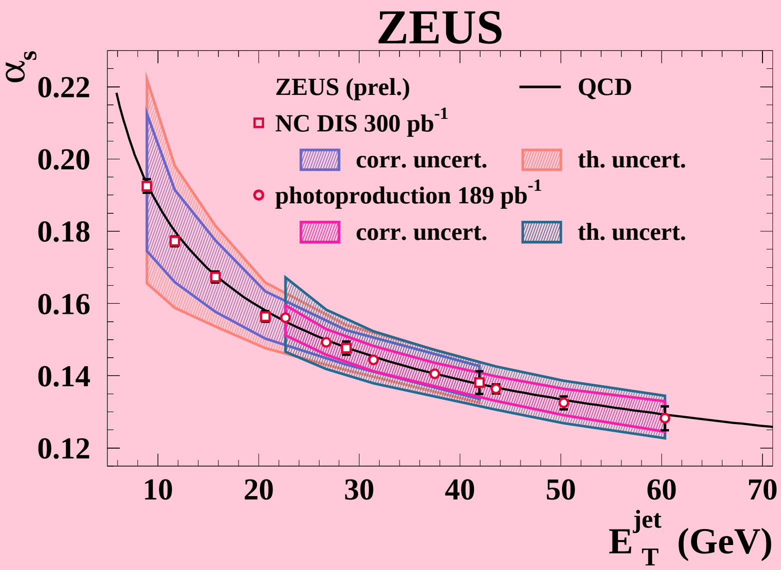
Measurements consistent with the predicted running of α_s over a wide range of $E_T^{\rm jet}$

Conclusions

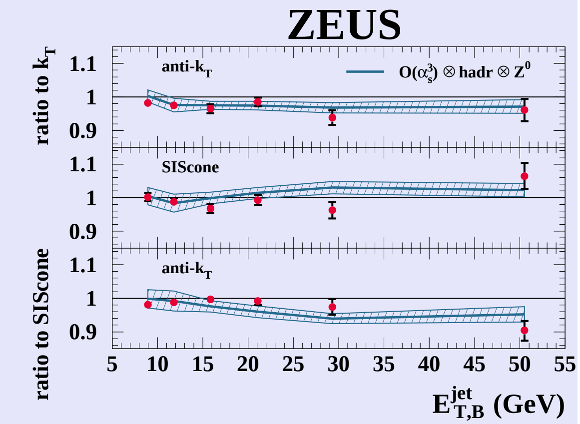
∗ Precise values of $\alpha_s(M_Z)$ extracted from jet production

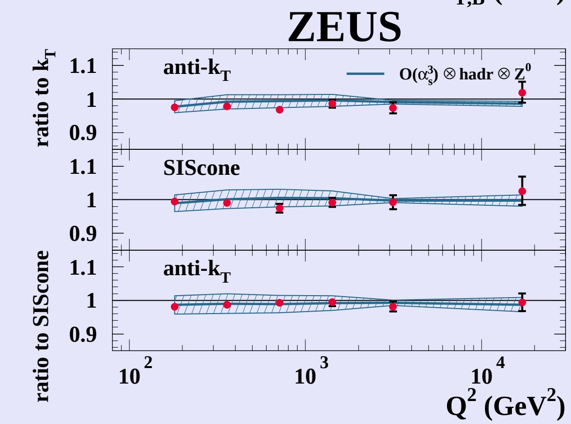


⇝ Precise determination of the running of α_s over a wide range in the scale



★ Precise test of the performance of the k_T, anti-k_T and SIScone algorithms





↬ Precise new jet measurements will help to constrain further the proton PDFs