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Jet physics at HERA

from

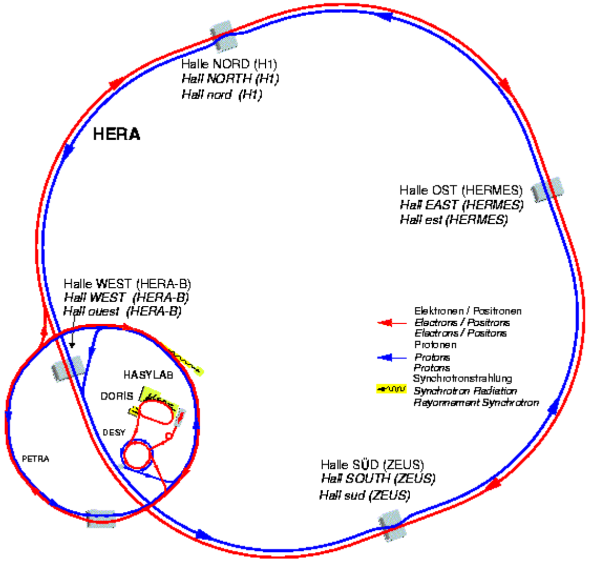
ZEUS Collab.

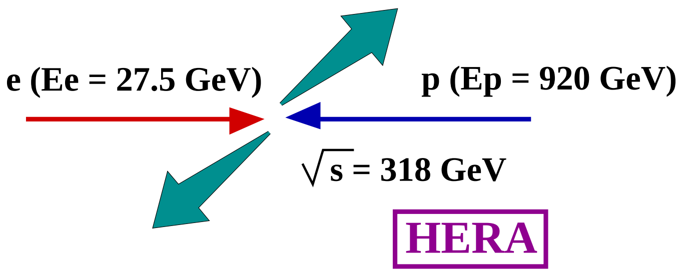
H1 Collab.

Claudia Glasman

Universidad Autónoma de Madrid

at





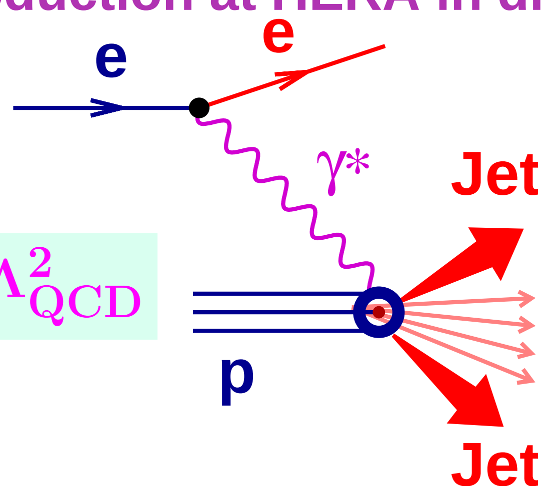
Jet physics at HERA

- ep collider HERA: very suitable environment to do precision studies of QCD
  - $\longrightarrow$ tests of QCD in hadronic-induced reactions (as opposed to e^+e^- at LEP)
  - $\longrightarrow$ but cleaner than $p\bar{p}$ at TeVatron or pp at LHC
- Jet physics at HERA
  - — tests of pQCD and precision measurements of QCD parameters
  - — constraints on PDFs

$\longrightarrow$ input to understand QCD background and make cross-section predictions at LHC

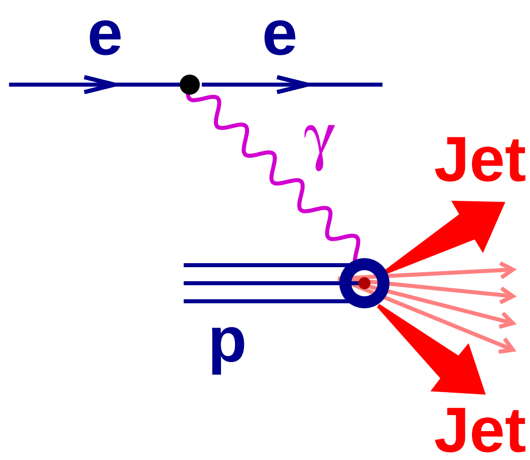
- Jet production at HERA in different kinematic regimes:

$Q^2 \gg \Lambda^2_{\rm QCD}$



NC deep inelastic scattering (DIS)

$ep \longrightarrow e + {\rm Jet}\ (+{\rm Jets}) + X$



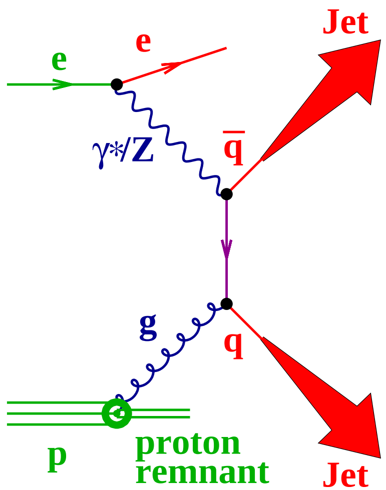
$Q^2 \approx 0$ GeV^2

Photoproduction (PHP)

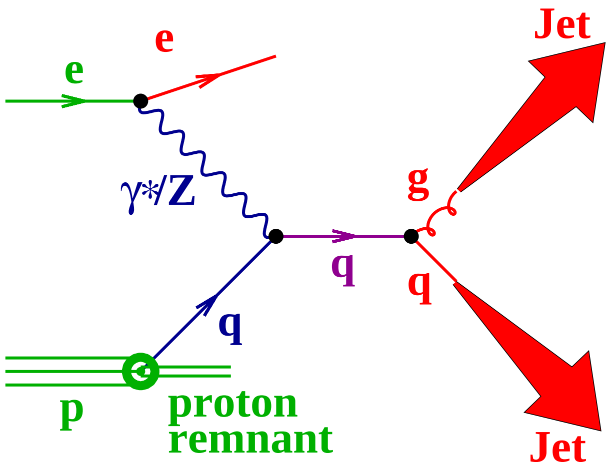
$ep \longrightarrow e + {\rm Jet}\ (+{\rm Jets}) + X$

Jets in NC DIS at HERA

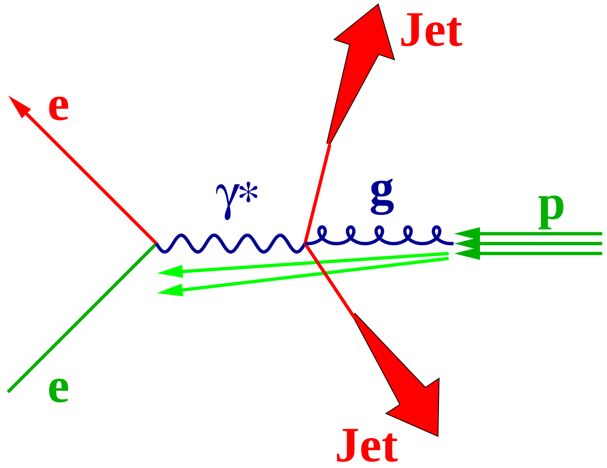
- Jet production in neutral current deep inelastic ep scattering at $\mathcal{O}(\alpha_s)$ in the Breit frame:



Boson-gluon fusion



QCD Compton



Breit frame

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

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

– 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

Kinematics:

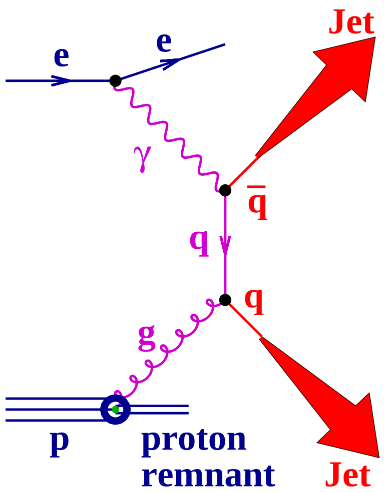
– momentum transfer: $Q^2 = -q^2 = -(k-k')^2$

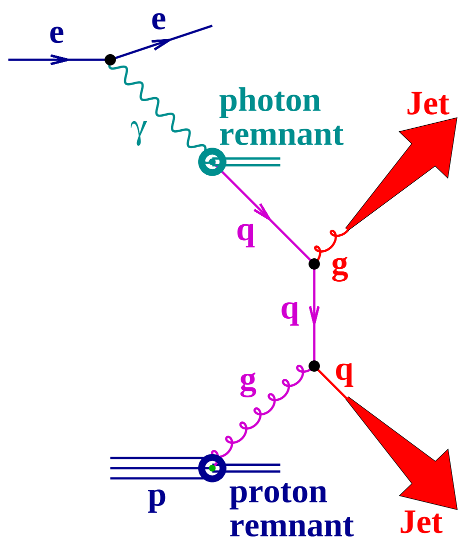
– Bjorken x: $x = \frac{Q^2}{2P\cdot q}$

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

Jets in PHP at HERA

- **Jet production in photoproduction at $\mathcal{O}(\alpha_s)$:**





Q^2: γ virtuality
W: γp cms energy
y: inelasticity
$x_{\gamma(p)}$: parton momentum fraction from $\gamma(p)$

direct photoproduction **resolved photoproduction**

- **Jet production cross section in photoproduction is given in pQCD by:**

$$d\sigma_{\rm jet} = \sum_{i,j} \int dy\, f_{\gamma/e}(y) \int dx_p\, f_{j/p}(x_p, \mu_{F_p}) \int dx_\gamma\, f_{i/\gamma}(x_\gamma, \mu_{F_\gamma})\, d\hat{\sigma}_{i(\gamma)j}$$

$\longrightarrow$ **Measurements of jet cross sections in photoproduction allow tests of:**

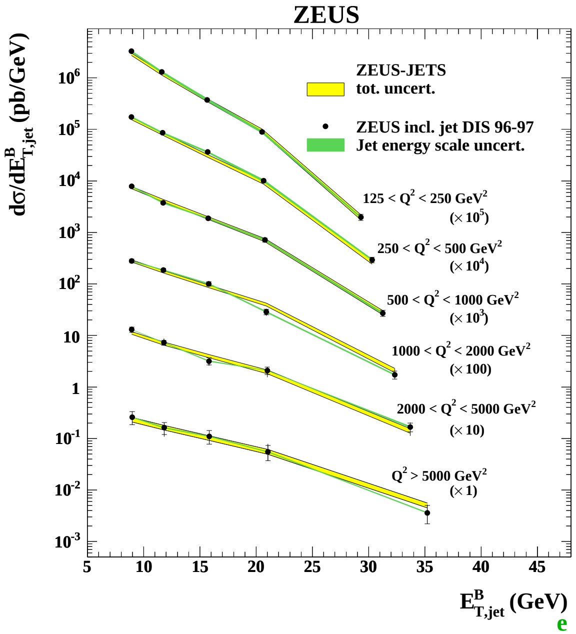
structure of the photon **pQCD, α_s** **structure of the proton**

Jets and PDFs at HERA

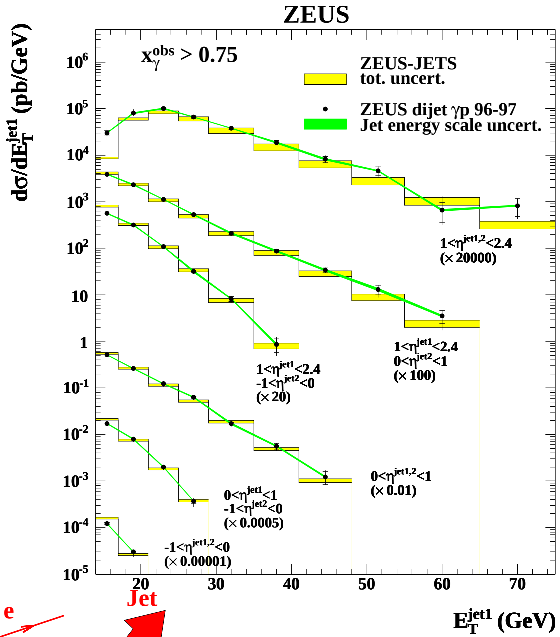
Jets and PDFs at HERA

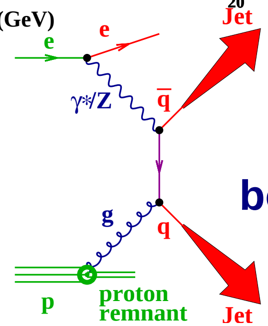
- **Very precise jet cross sections in NC DIS and photoproduction (directly sensitive to the gluon content of proton): constraints on gluon density**
- **The measurements were incorporated in a QCD fit (together with structure function data from ZEUS) to determine the PDFs:**

NC DIS



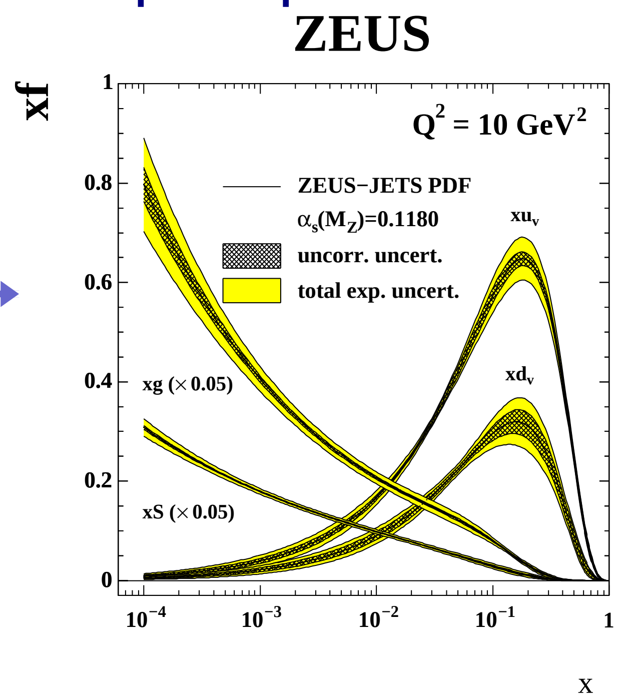
photoproduction





boson-gluon fusion

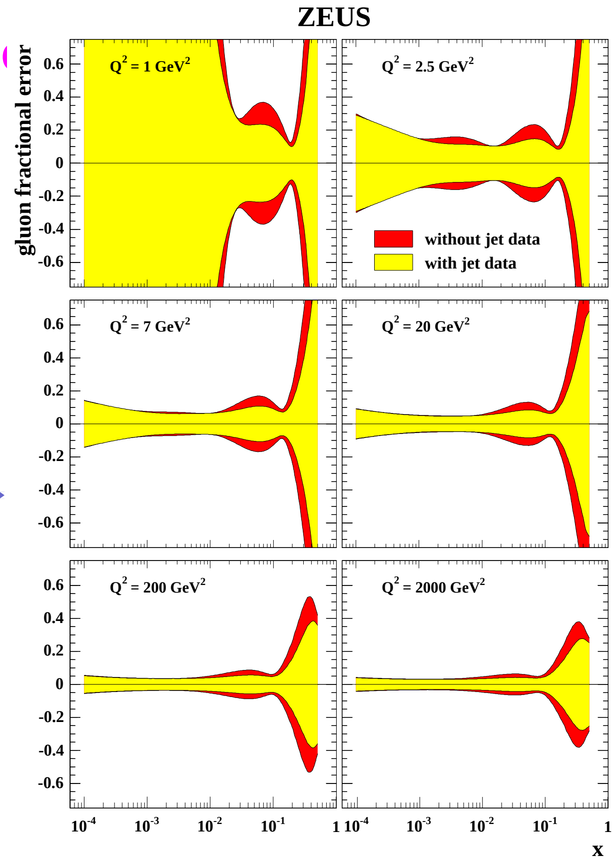
proton parton densities



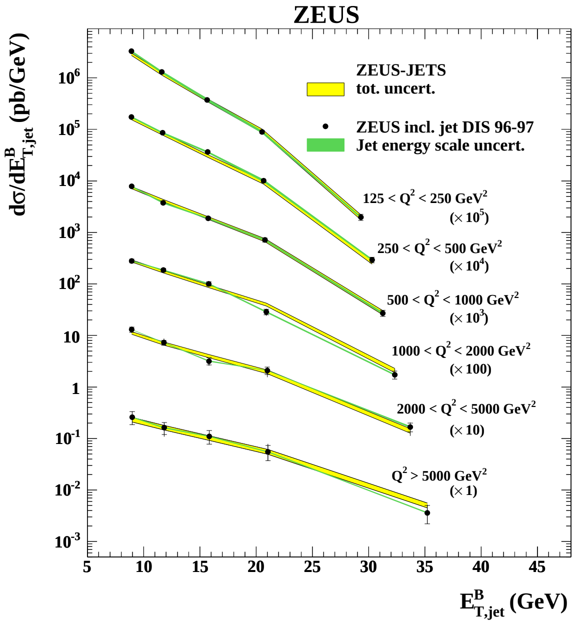
ZEUS Collab, EPJ C 42 (2005) 1

Jets and PDFs at HERA

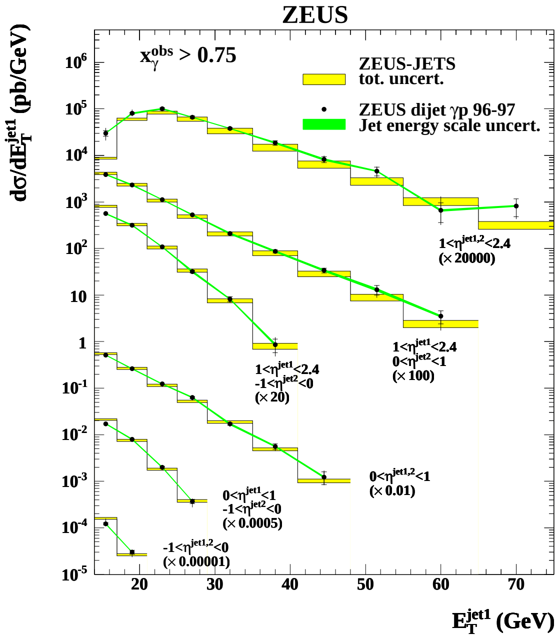
- **Very precise jet cross sections in NC DIS and photoproduction (directly sensitive to the gluon content of proton): constraints on gluon density**
- **The measurements were incorporated in a QCD fit (t function data from ZEUS) to determine the PDFs:**



NC DIS



photoproduction



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

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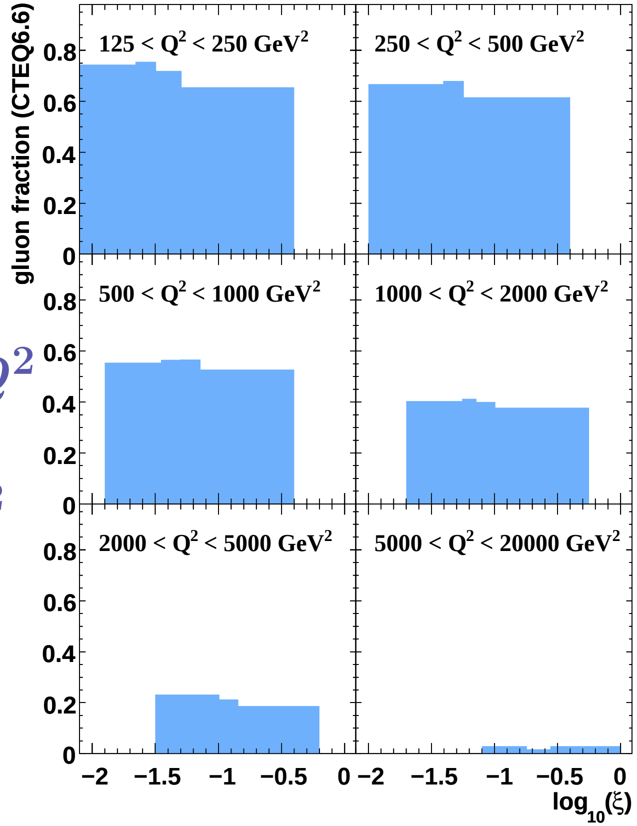
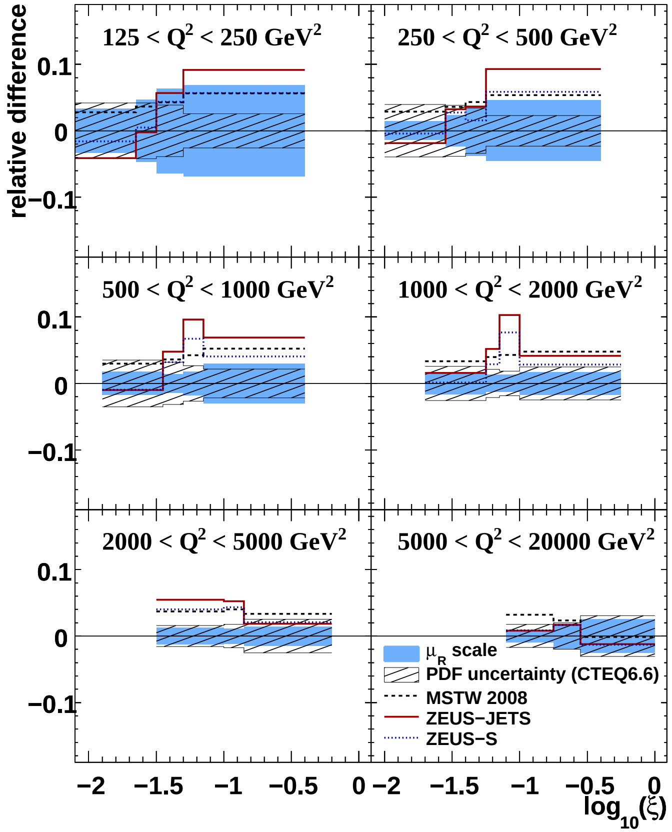
Constraints on the proton PDFs

- Gluon fraction and theoretical uncertainties for dijet cross sections for $125 < Q^2 < 20000$ GeV^2:

Predicted gluon fraction:
$> 75\%$ at low Q^2
$> 50\%$ at $Q^2 \sim 500$ GeV^2





Theoretical uncertainties

$\longrightarrow$ PDF uncertainty large and uncertainty from higher orders small in regions of phase space where the gluon fraction is still sizeable
$\longrightarrow$ potential to constrain PDFs with jet data

ZEUS Collab, ZEUS-pub-10-005

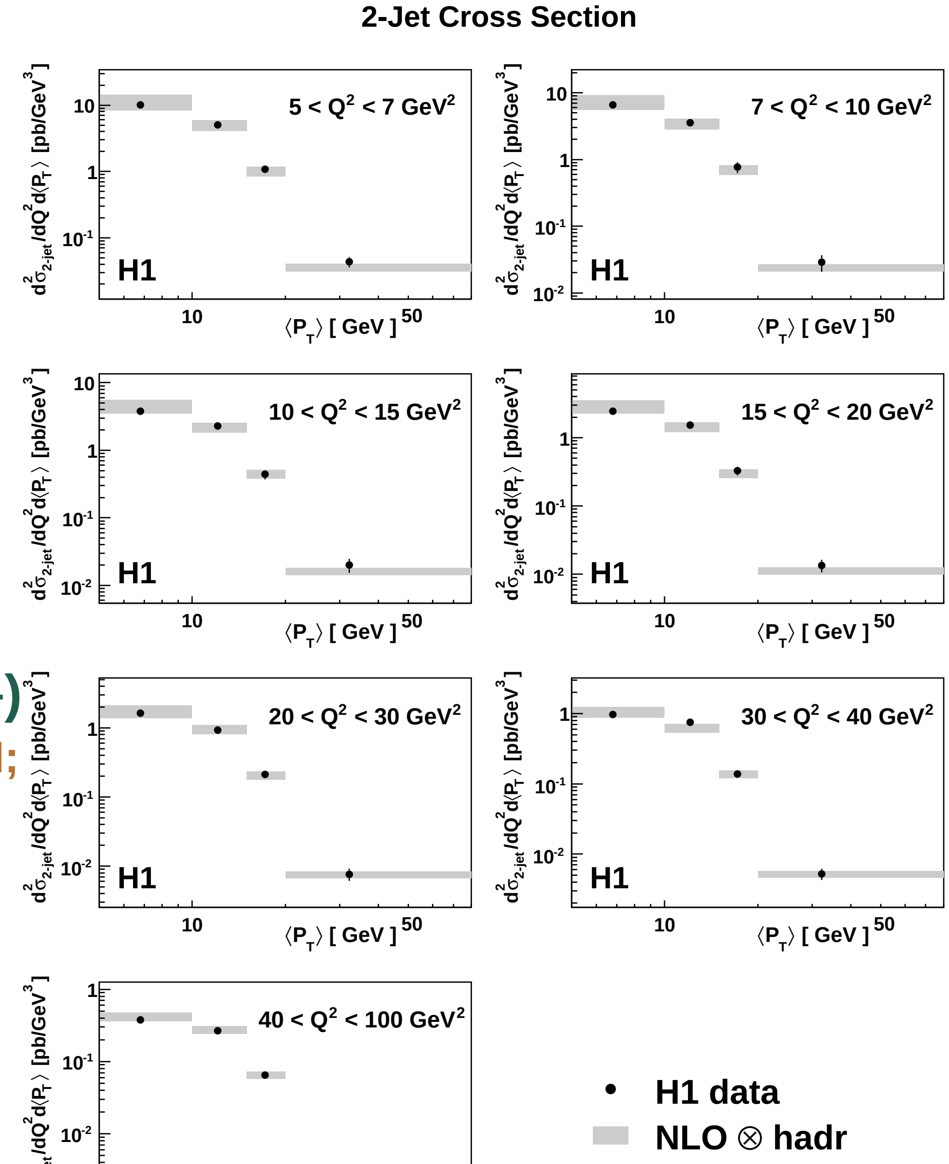
Constraints on pPDFs: dijet cross sections in NC DIS

$ep \to e + \text{jet} + \text{jet} + \text{X}$: dijets at low Q^2

- Jets searched using the k_T cluster algorithm in BF
- Kinematic region: $5 < Q^2 < 100$ GeV^2 and $0.2 < y < 0.7$
- Two jets with $P_T > 5$ GeV and $-1 < \eta^{\text{jet}}_{\text{LAB}} < 2.5$
- $M^{\text{jj}} > 18$ GeV

- **Small experimental uncertainties**
  - $\to$ uncorrelated: $\sim \pm 5\ (15)\%$ at low (high) $\langle P_T \rangle$
  - $\to$ correlated (energy scale $\pm 2\%$ (!)): $\sim \pm 5\ (15)\%$ at low (high) $\langle P_T \rangle$

- **Comparison to NLO predictions (NLOJET++)**
  - $\to$ $\mu_R^2 = \mu_F^2 = (Q^2 + \langle P_T \rangle^2)/2$; pPDFs: CTEQ6.5M; $\alpha_s(M_Z) = 0.118$; corrected for hadronisation
  - $\to$ **The measured dijet cross sections are well described by the NLO predictions in the whole measured range**



$\mathcal{L} = 43.5$ pb^{-1}

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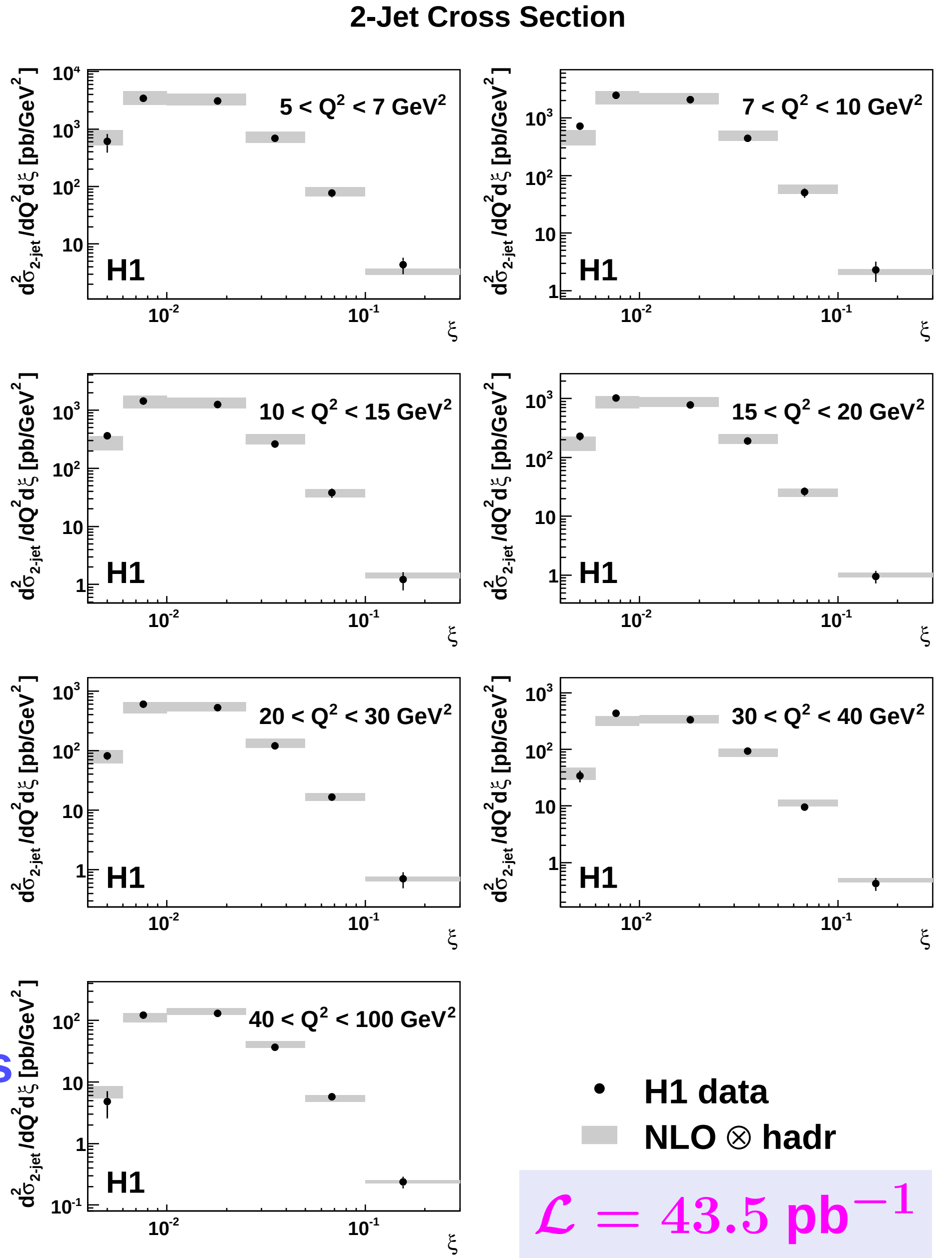
Constraints on pPDFs: dijet cross sections in NC DIS

$ep \longrightarrow e + \text{jet} + \text{jet} + \text{X}$: dijets at low Q^2

- Jets searched using the k_T cluster algorithm in BF
- Kinematic region: $5 < Q^2 < 100$ GeV^2 and $0.2 < y < 0.7$
- Two jets with $P_T > 5$ GeV and $-1 < \eta^{\text{jet}}_{\text{LAB}} < 2.5$
- $M^{\text{jj}} > 18$ GeV
- $\xi = x_{\text{Bj}}(1 + (M^{\text{jj}})^2/Q^2)$ estimator of the fractional momentum carried by the struck parton
- **Small experimental uncertainties**
  - $\longrightarrow$ uncorrelated: $\sim \pm 6\%$
  - $\longrightarrow$ correlated: $\sim \pm 5\%$
  - $\longrightarrow$ **The measured dijet cross sections are well described by the NLO predictions in the whole measured range**
- **Large gluon fraction at low Q^2**
- **Theoretical uncertainty dominated by terms beyond NLO: NNLO predictions needed to take full advantage of high-precision data**



$\mathcal{L} = 43.5$ pb^{-1}

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Constraints on pPDFs: dijet cross sections in NC DIS

$ep \rightarrow e + \text{jet} + \text{jet} + X$: **dijets at high Q^2**

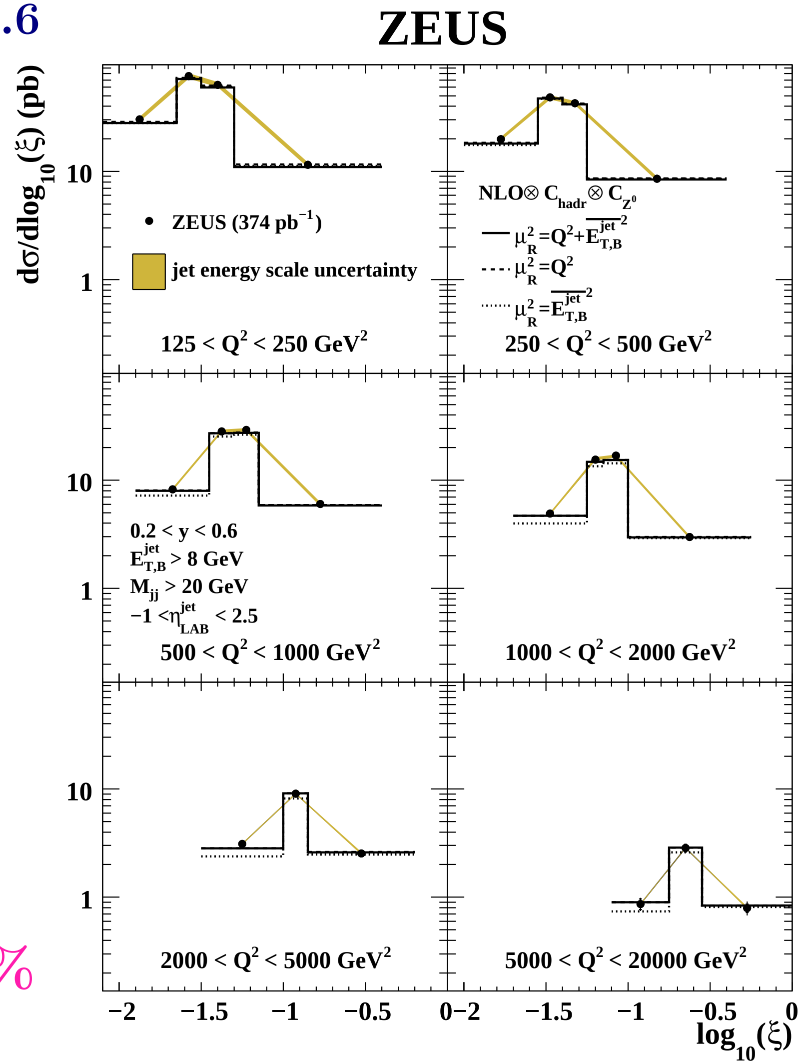
$\mathcal{L} = 374$ pb^{-1}

- 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 $E_{T,\mathrm{B}}^{\mathrm{jet}} > 8$ GeV and $-1 < \eta_{\mathrm{LAB}}^{\mathrm{jet}} < 2.5$
- $M^{\mathrm{jj}} > 20$ GeV

- **Small experimental uncertainties:**
  - $\rightarrow$ uncorrelated: $\sim \pm 2\ (10)\%$ at low (high) Q^2
  - $\rightarrow$ correlated (energy scale $\pm 1\%$ (!) for $E_T^{\mathrm{jet}} > 10$ GeV: $\sim \pm 5\ (2)\%$ at low (high) Q^2

- **Comparison to NLO predictions (NLOJET++):**
  - $\rightarrow$ $\mu_R^2 = Q^2 + (\overline{E_{T,\mathrm{B}}^{\mathrm{jet}}})^2$; $\mu_F = Q$; pPDFs: CTEQ6.6; $\alpha_s(M_Z) = 0.118$; corrected for hadronisation and Z^0
  - $\rightarrow$ **The measured dijet cross sections are well described by the NLO predictions in the whole measured range**

- **Gluon fraction still sizeable at $Q^2 \sim 500$ GeV^2**
- **Theoretical uncertainty from higher orders: $\pm 6\%$**
  - $\rightarrow$ **more sensitivity to PDFs**

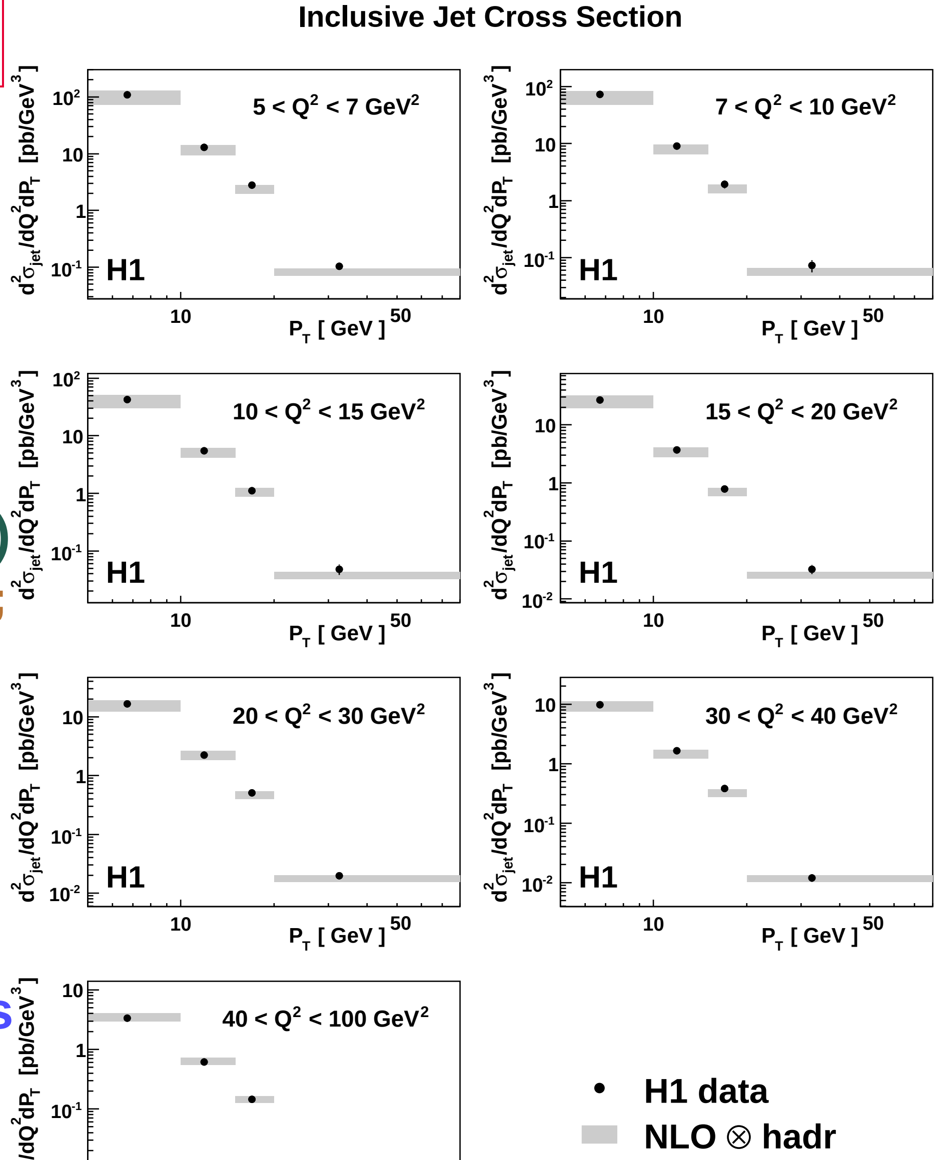


ZEUS Collab, ZEUS-pub-10-005

Constraints on pPDFs: inclusive-jet cross sections in NC DIS

$ep \longrightarrow e + \text{jet} + X$: inclusive jets at low Q^2

- Jets searched using the k_T cluster algorithm in BF
- Kinematic region: $5 < Q^2 < 100$ GeV^2 and $0.2 < y < 0.7$
- Jets with $P_T > 5$ GeV and $-1 < \eta_{\rm LAB}^{\rm jet} < 2.5$
- **Small experimental uncertainties**
  - $\longrightarrow$ uncorrelated: $\sim \pm 5\ (10)\%$ at low (high) P_T
  - $\longrightarrow$ correlated: $\sim \pm 5\ (10)\%$ at low (high) P_T
- **Comparison to NLO predictions (NLOJET++)**
  - $\longrightarrow$ $\mu_R^2 = \mu_F^2 = (Q^2 + (P_T)^2)/2$; pPDFs: CTEQ6.5M; $\alpha_s(M_Z) = 0.118$; corrected for hadronisation
  - $\longrightarrow$ **The measured jet cross sections are well described by the NLO predictions in the whole measured range**
- **Large gluon fraction at low Q^2**
- **Theoretical uncertainty dominated by terms beyond NLO: $\pm 30\%$ (PDF uncertainty: $\pm 6\%$)**
  - $\longrightarrow$ **NNLO predictions needed to take full advantage of high-precision data**



$\mathcal{L} = 43.5$ pb^{-1}

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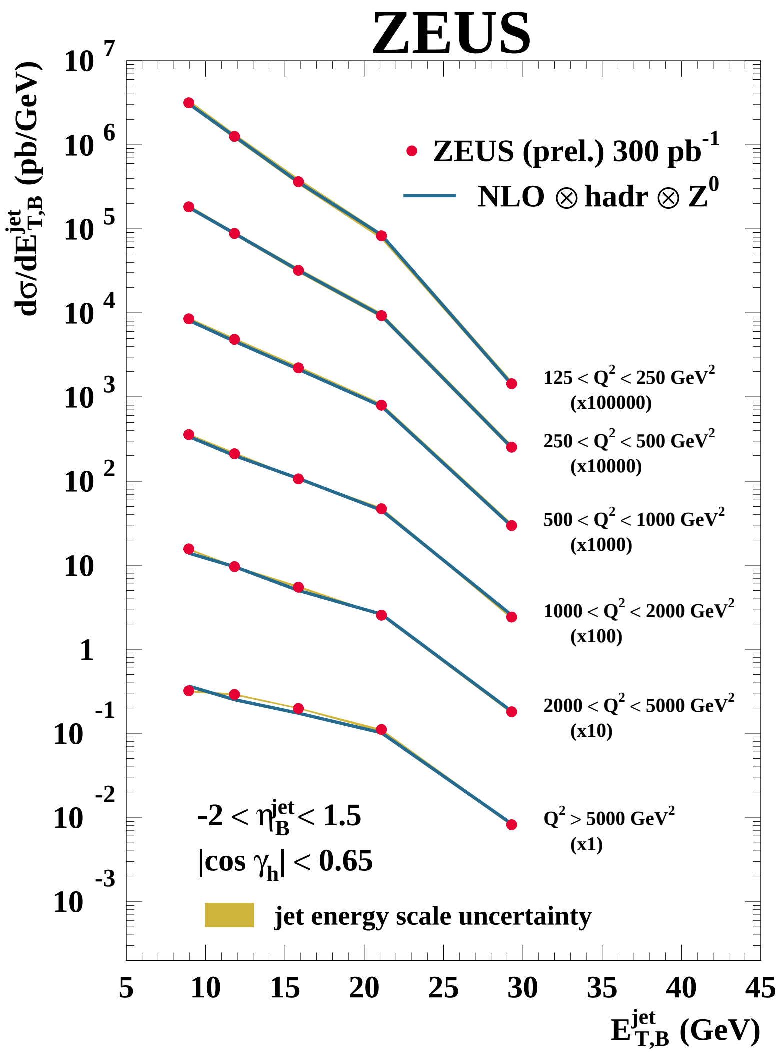
Constraints on pPDFs: inclusive-jet cross sections in NC DIS

$ep \to e + \text{jet} + X$: inclusive jets at high Q^2

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

- 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 $E_{T,\rm B}^{\rm jet} > 8$ GeV and $-2 < \eta_{\rm B}^{\rm jet} < 1.5$

- **Small experimental uncertainties:**
  - $\to$ uncorrelated: $\sim \pm 3\ (10)\%$ at low (high) $Q^2/E_{T,\rm B}^{\rm jet}$
  - $\to$ correlated: $\sim \pm 5\ (2)\%$ at low (high) $Q^2/E_{T,\rm B}^{\rm jet}$
- **Comparison to NLO predictions (DISENT):**
  - $\to$ $\mu_R = E_{T,\rm B}^{\rm jet}$; $\mu_F = Q$; pPDFs: ZEUS-S; $\alpha_s(M_Z) = 0.118$; corrected for hadronisation and Z^0 effects
  - $\to$ **The measured inclusive-jet cross sections are well described by the NLO predictions in the whole measured range**



ZEUS Collab, ZEUS-prel-10-002

Constraints on pPDFs: inclusive-jet cross sections in NC DIS

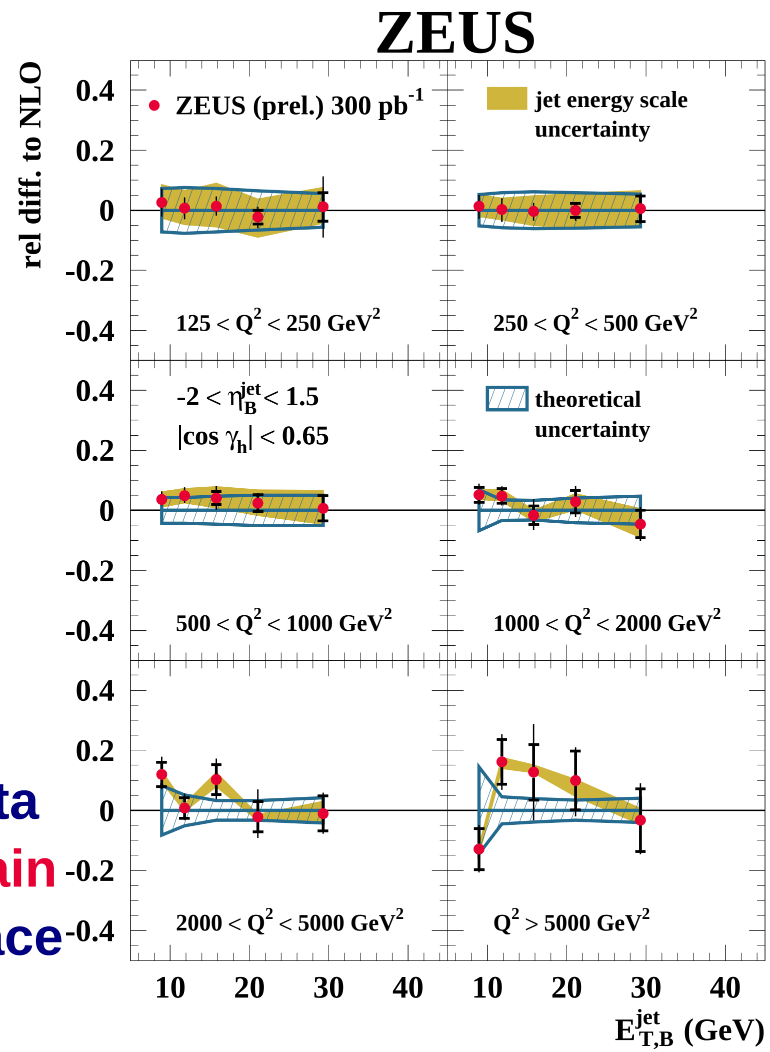
$ep \rightarrow e + \text{jet} + X$: inclusive jets at high Q^2

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

- 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 $-2 < \eta_{\text{B}}^{\text{jet}} < 1.5$

- **Small experimental uncertainties:**
  - → uncorrelated: $\sim \pm 3\ (10)\%$ at low (high) $Q^2/E_{T,\text{B}}^{\text{jet}}$
  - → correlated: $\sim \pm 5\ (2)\%$ at low (high) $Q^2/E_{T,\text{B}}^{\text{jet}}$
- **Comparison to NLO 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 well described by the NLO predictions in the whole measured range

→ **High precision NC DIS inclusive-jet and dijet data at low and high Q^2 have the potential to constrain further the proton PDFs in regions of phase space relevant for new physics searches at LHC**



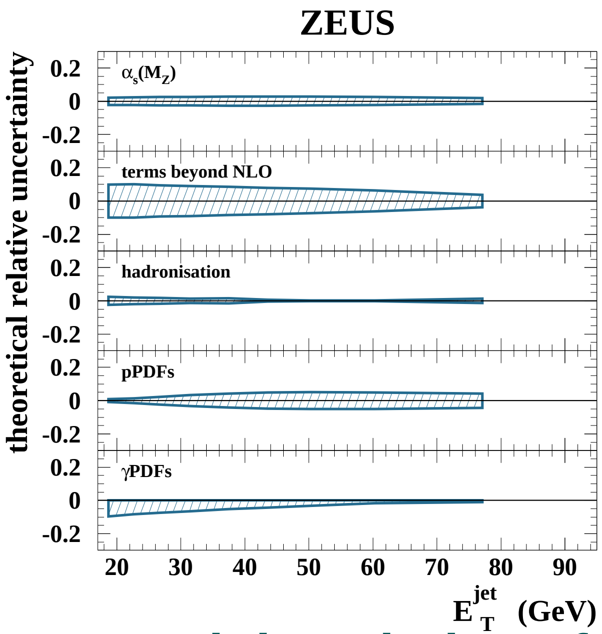
ZEUS Collab, ZEUS-prel-10-002

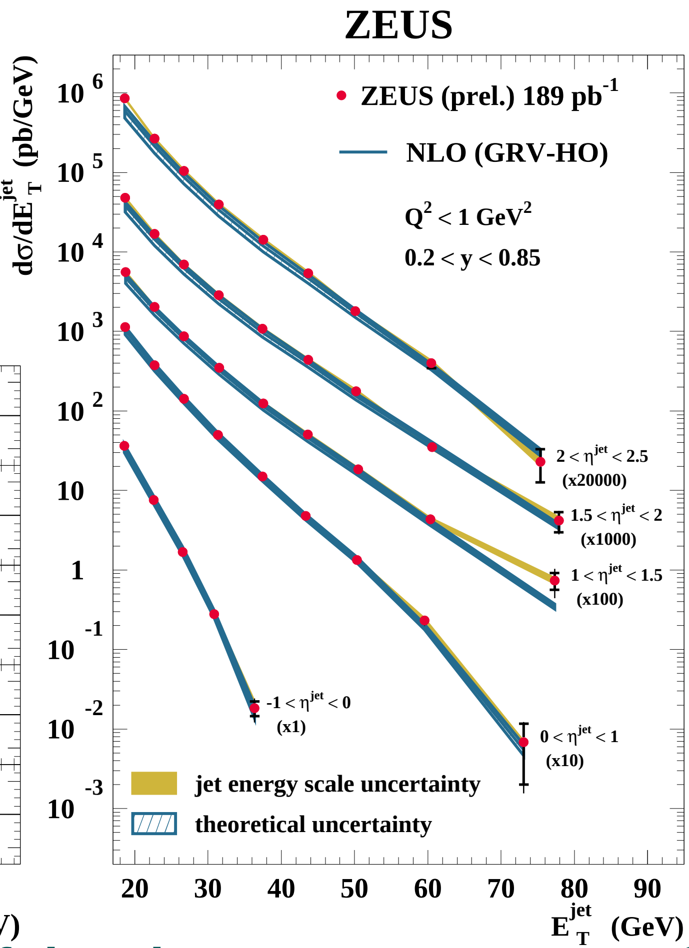
Constraints on p/γPDFs: inclusive-jet cross sections in PHP

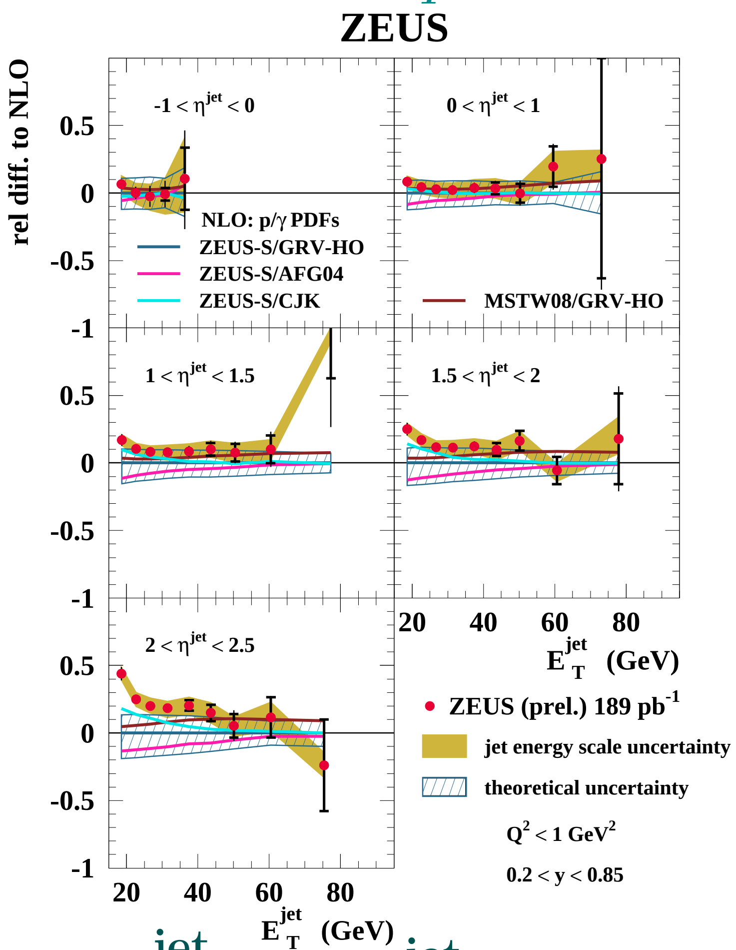
$ep \rightarrow e + \text{jet} + X$: inclusive jets at high E_T^{jet}

$\mathcal{L} = 189$ pb^{-1}

- Jets searched using the k_T cluster algorithm in Laboratory frame
- Kinematic region: $Q^2 < 1$ GeV^2 and $0.2 < y < 0.85$ and $-1 < \eta^{\text{jet}} < 2.5$
- At least one jet with $E_T^{\text{jet}} > 17$ GeV
- Comparison to NLO predictions (Klasen et al.): $\rightarrow \mu_R = \mu_F = E_T^{\text{jet}}$







$\rightarrow$ Good description of data by NLO QCD, except for low E_T^{jet}, high η^{jet} (see page 21)

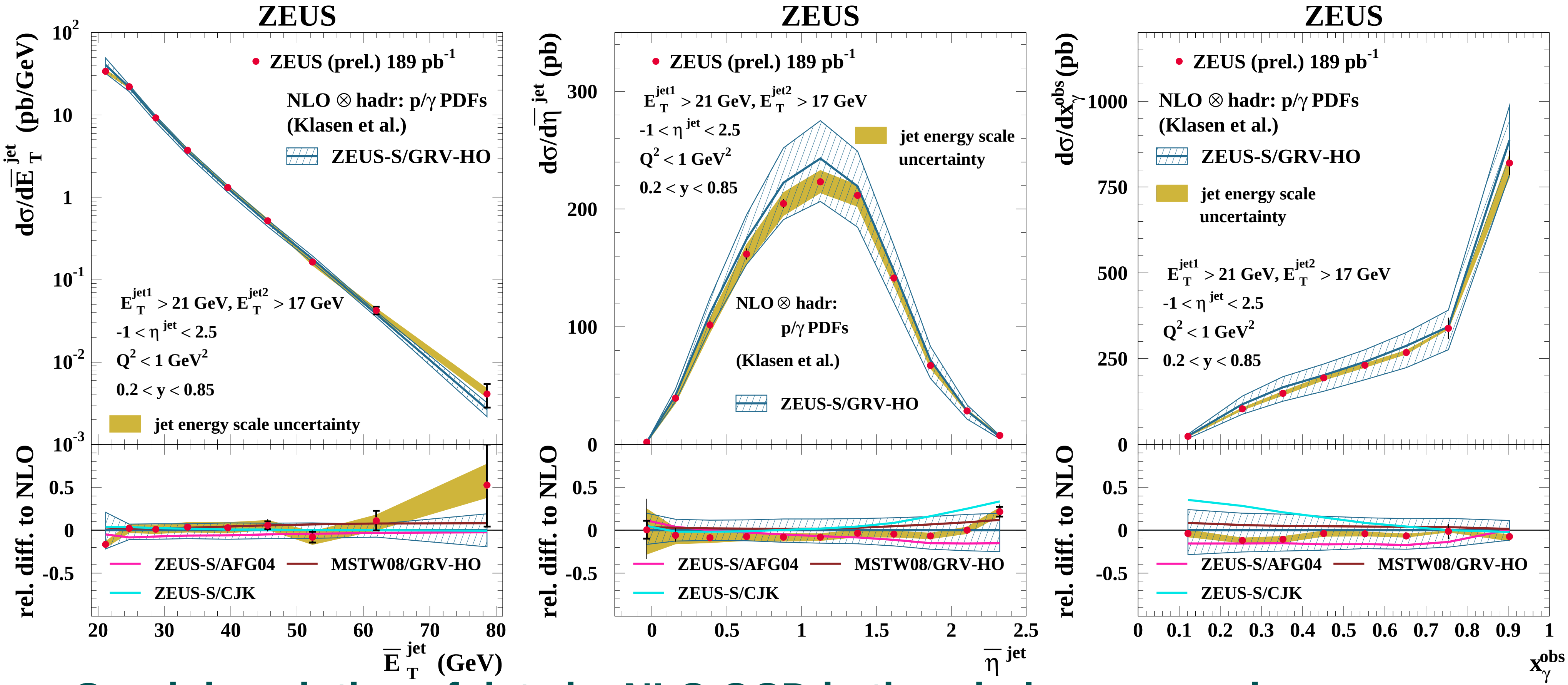
$\rightarrow$ Sensitivity to proton (high E_T^{jet}, low η^{jet}) and photon (low E_T^{jet}, high η^{jet}) PDFs

Constraints on p/γPDFs: dijet cross sections in PHP

$ep \rightarrow e + \mathrm{jet} + \mathrm{jet} + X$: dijets at high E_T^{jet}

$\mathcal{L} = 189\ \mathrm{pb}^{-1}$

- Jets searched using the k_T cluster algorithm in Laboratory frame
- Kinematic region: $Q^2 < 1$ GeV^2 and $0.2 < y < 0.85$
- Two jets with $E_T^{\mathrm{jet1}} > 21$ GeV, $E_T^{\mathrm{jet2}} > 17$ GeV and $-1 < \eta^{\mathrm{jet}} < 2.5$



→ Good description of data by NLO QCD in the whole measured range

→ Sensitivity to proton (high E_T^{jet}) and photon (high η^{jet}, low x_γ^{obs}) PDFs

Tests of pQCD at HERA

and

determination of α_s

Tests of pQCD: jet cross sections in NC DIS

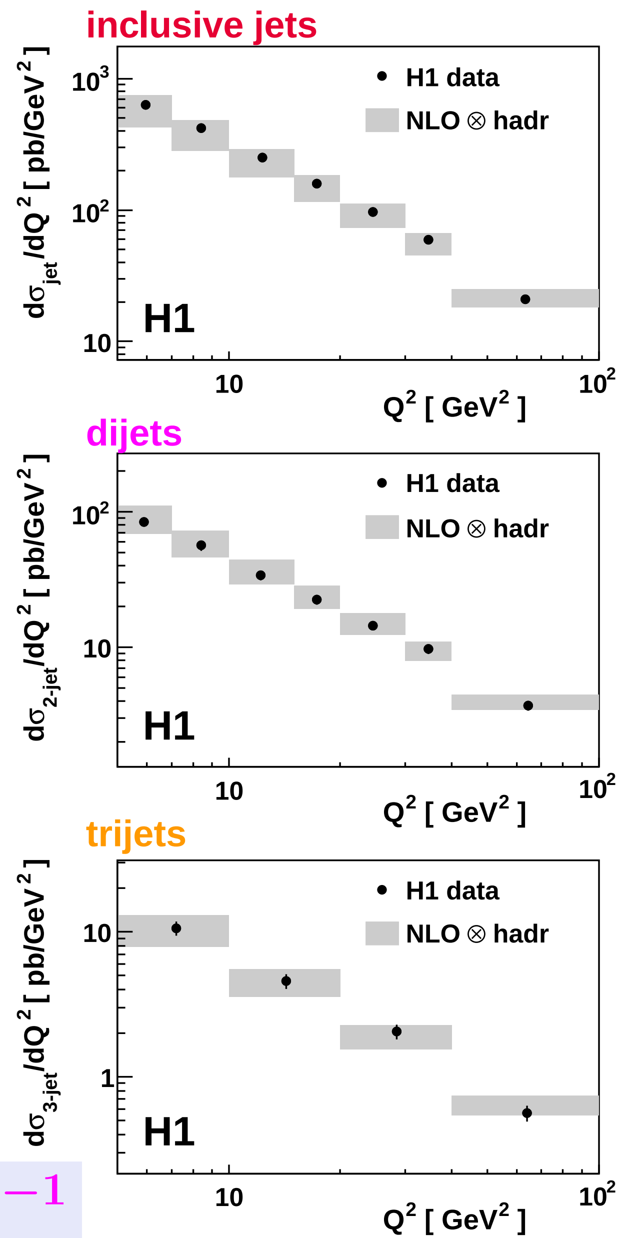
$ep \longrightarrow e + \text{jet(s)} + \text{X}$: **jets at low Q^2**

- Jets searched using the k_T cluster algorithm in Breit frame
- Kinematic region: $5 < Q^2 < 100$ GeV^2 and $0.2 < y < 0.7$
- Jets with $P_T > 5$ GeV and $-1 < \eta^{\text{jet}}_{\text{LAB}} < 2.5$
- ($M^{\text{jj}} > 18$ GeV)

- **Small experimental uncertainties**
  - $\longrightarrow$ uncorrelated: $< \pm 5$, $\sim \pm 5$, $\sim \pm 8\%$
  - $\longrightarrow$ correlated: $\sim \pm 5$, $\sim \pm 5$, $< \pm 8\%$
- **Theoretical uncertainties:**
  - $\longrightarrow$ higher orders (± 30 $(10)\%$ at low (high) Q^2)
  - $\longrightarrow$ proton PDFs (± 6 $(2)\%$ at low (high) Q^2)
  - $\longrightarrow$ parton-to-hadron corrections ($\pm 1 - 2.5$, $\pm 1 - 2$, $\pm 5\%$)

$\longrightarrow$ **Good description of data by NLO predictions**
$\longrightarrow$ **validity of the description of the dynamics of jet production at $\mathcal{O}(\alpha_s^2)$**

$\longrightarrow$ **Measurements provide direct sensitivity to $\alpha_s(M_Z)$ with small experimental uncertainties**



$\mathcal{L} = 43.5$ pb^{-1}

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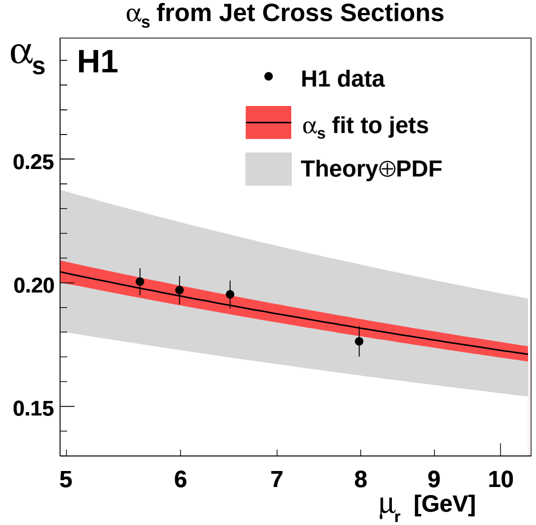
Tests of pQCD: determination of α_s

- The energy-scale dependence of the coupling was determined by extracting α_s from the measured jet cross sections at low Q^2:



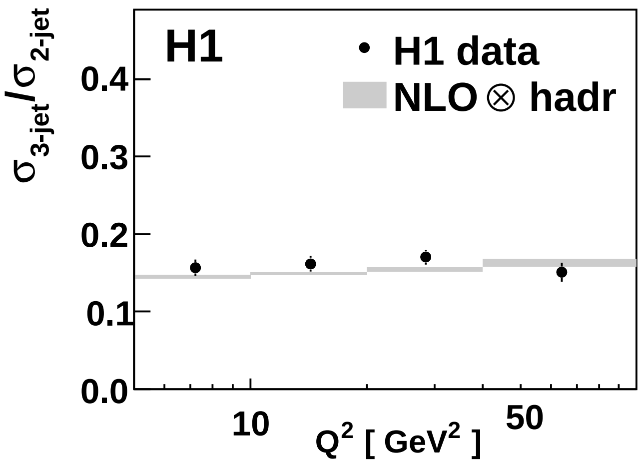
→ Results in good agreement with the predicted running of α_s within the measured range with small experimental uncertainties

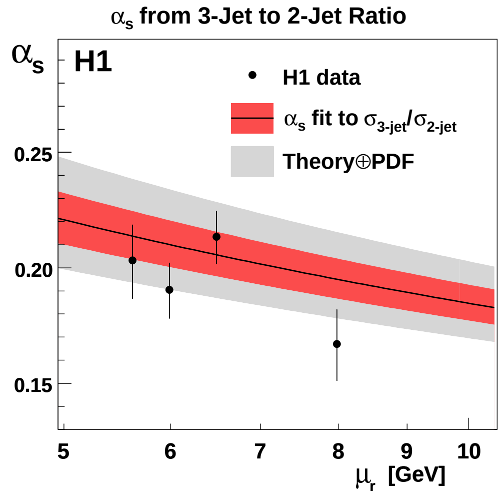
- A value of $\alpha_s(M_Z)$ was determined from a simultaneous fit to the inclusive-jet, dijet and trijet measurements:

$$\alpha_s(M_Z) = 0.1160 \pm 0.0014\ (\text{exp.})^{+0.0094}_{-0.0079}\ (\text{th.})$$

experimental uncertainty: $\pm 1.2\%$
theoretical uncertainty: $^{+8.1}_{-6.8}\%$

∗ Reduction of theoretical uncertainties can be achieved by determining α_s from the measured trijet to dijet ratio:





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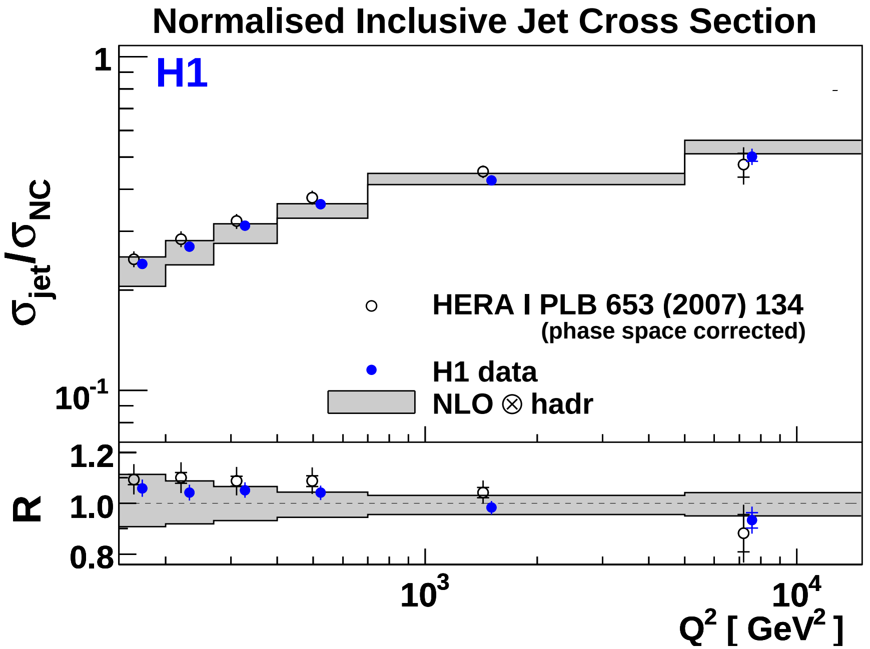
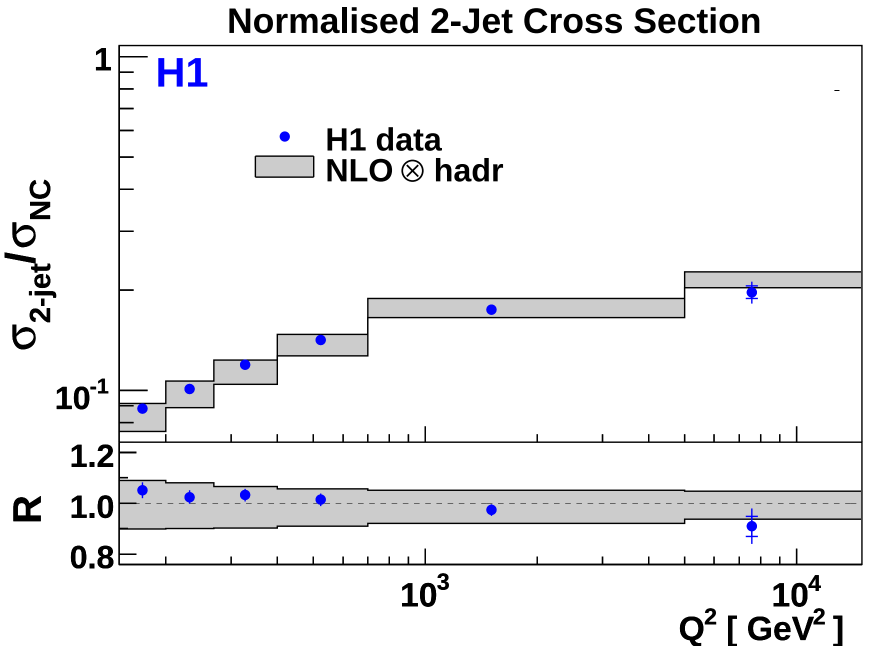
Tests of pQCD: normalised jet cross sections in NC DIS

$ep \longrightarrow e + \mathrm{jet(s)} + \mathrm{X}$: jets at high Q^2

$\mathcal{L} = 395$ pb^{-1}

- Jets searched using the k_T cluster algorithm in Breit frame
- Kinematic region: $150 < Q^2 < 15000$ GeV^2 and $0.2 < y < 0.7$
- Jets with $P_{T,1} > 7$ GeV, ($P_{T,2}, P_{T,3} > 5$ GeV) and $-0.8 < \eta^{\mathrm{jet}}_{\mathrm{LAB}} < 2$
- ($M^{\mathrm{jj}} > 16$ GeV)





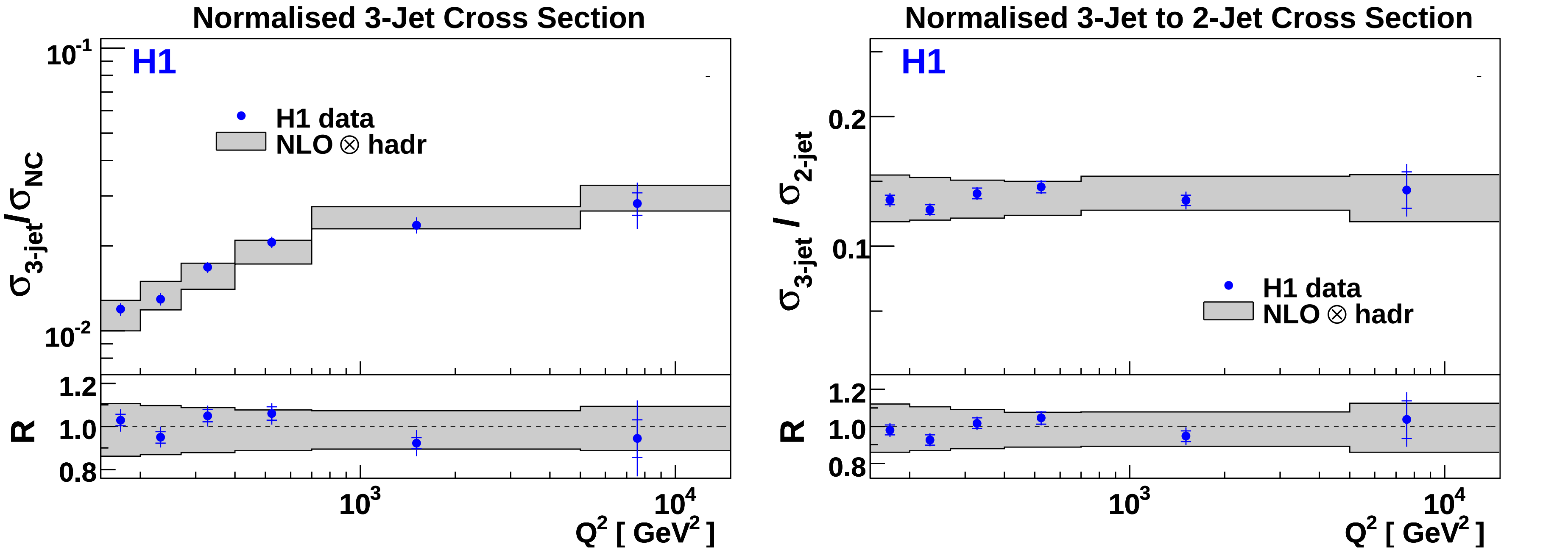
H1 Collab, Eur Phys J C 65 (2010) 363

Tests of pQCD: normalised jet cross sections in NC DIS

$ep \longrightarrow e + \text{jet(s)} + \text{X}$: jets at high Q^2

$\mathcal{L} = 395$ pb^{-1}

- Jets searched using the k_T cluster algorithm in Breit frame
- Kinematic region: $150 < Q^2 < 15000$ GeV^2 and $0.2 < y < 0.7$
- Jets with $P_{T,1} > 7$ GeV, ($P_{T,2}, P_{T,3} > 5$ GeV) and $-0.8 < \eta^{\text{jet}}_{\text{LAB}} < 2$
- ($M^{\text{jj}} > 16$ GeV)



$\longrightarrow$ Good description of data by NLO predictions

$\longrightarrow$ validity of the description of the dynamics of jet production at $\mathcal{O}(\alpha_s^2)$

$\longrightarrow$ Measurements provide direct sensitivity to $\alpha_s(M_Z)$ with small experimental and theoretical uncertainties

H1 Collab, Eur Phys J C 65 (2010) 363

Tests of pQCD: normalised jet cross sections in NC DIS

$ep \to e + \text{jet} + X$: inclusive jets at high Q^2

- Jets searched using the k_T cluster algorithm in BF
- Kinematic region: $150 < Q^2 < 15000$ GeV^2 and $0.2 < y < 0.7$
- At least one jet with $P_T > 7$ GeV and $-0.8 < \eta^{\rm jet}_{\rm LAB} < 2$
- Small experimental uncertainties
  - $\rightarrow$ uncorrelated: $\sim \pm 3\ (10)\%$ at low (high) Q^2/P_T
  - $\rightarrow$ correlated: $\sim \pm 2\ (4)\%$ at low (high) Q^2/P_T
- Theoretical uncertainties:
  - $\rightarrow$ higher orders
  - $\rightarrow$ proton PDFs
  - $\rightarrow$ parton-to-hadron corrections

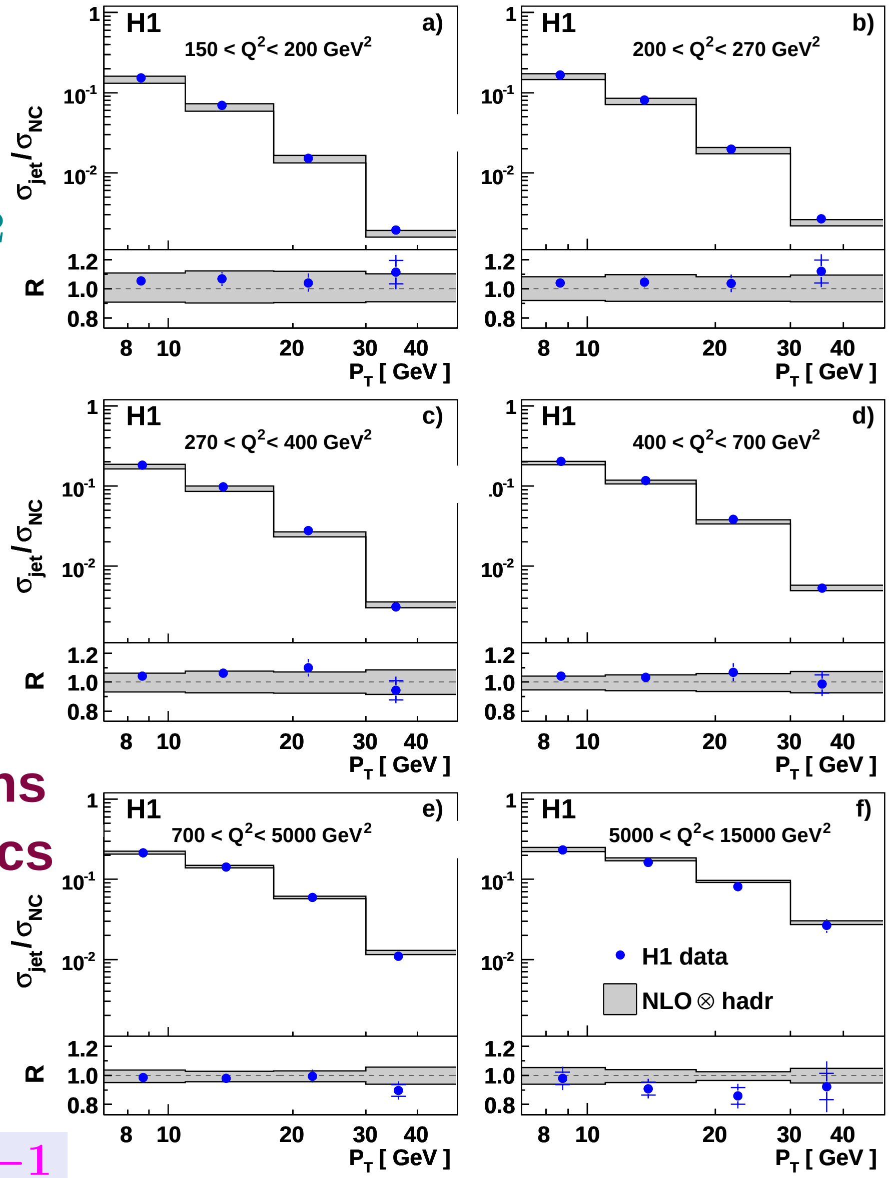
$\longrightarrow$ Good description of data by NLO predictions
$\longrightarrow$ validity of the description of the dynamics of jet production at $\mathcal{O}(\alpha_s^2)$

$\longrightarrow$ Measurements provide direct sensitivity to $\alpha_s(M_Z)$ with small experimental and theoretical uncertainties

H1 Collab, Eur Phys J C 67 (2010) 1

$\mathcal{L} = 395$ pb^{-1}

Normalised Inclusive Jet Cross Section

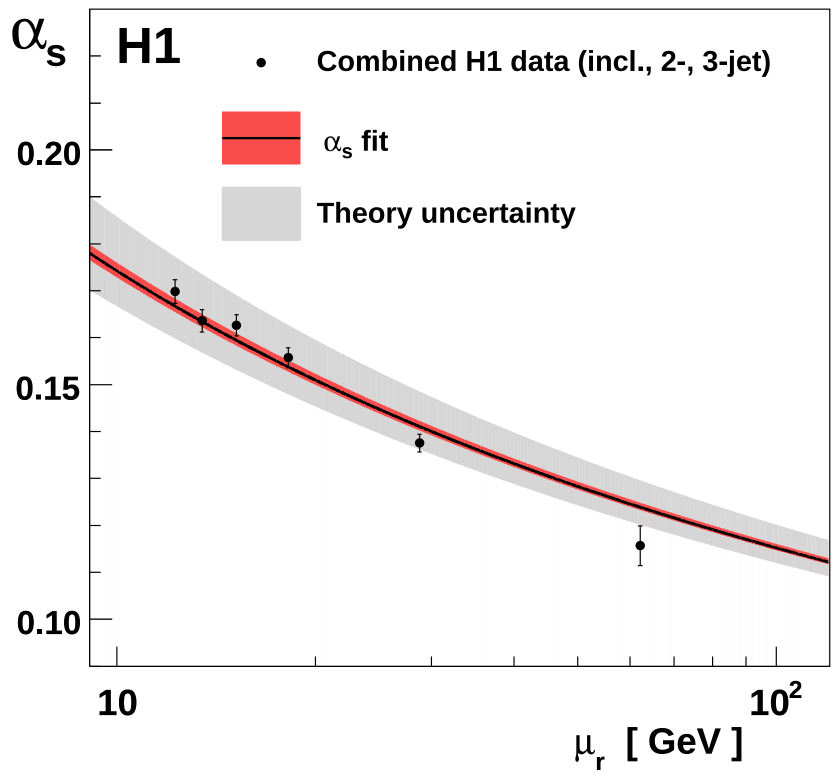


Tests of pQCD: determination of α_s

- The energy-scale dependence of the coupling was determined by extracting α_s from the measured normalised jet cross sections at high Q^2:

→ Results are in good agreement with the predicted running of α_s with small experimental and theoretical uncertainties in a wide range of the scale

∗ Reduction of experimental (extraction from normalised cross sections) and theoretical (extraction at higher Q^2) uncertainties



- A value of $\alpha_s(M_Z)$ was determined from a simultaneous fit to the normalised inclusive-jet, dijet and trijet cross-section measurements:

$$\alpha_s(M_Z) = 0.1168 \pm 0.0007\ (\text{exp.})^{+0.0049}_{-0.0034}\ (\text{th.})$$

experimental uncertainty: $\pm 0.6\%$

theoretical uncertainty: $^{+4.2}_{-2.9}\%$

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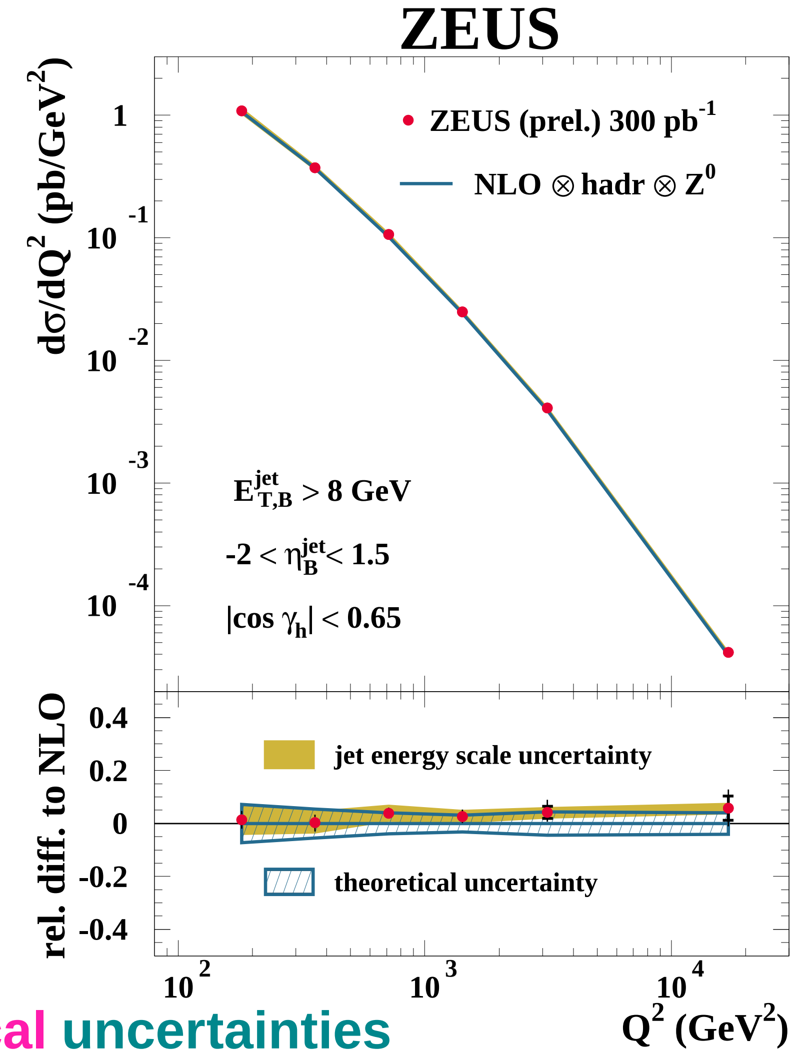
Tests of pQCD: inclusive-jet cross sections in NC DIS

$ep \to e + \text{jet} + \text{X}$: inclusive jets at high Q^2

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

- 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 $-2 < \eta_{\text{B}}^{\text{jet}} < 1.5$



- **Small experimental uncertainties**
  - → uncorrelated: $\sim \pm 3\ (7)\%$ at low (high) $Q^2/E_{T,\text{B}}^{\text{jet}}$
  - → correlated: $\sim \pm 5\ (2)\%$ at low (high) $Q^2/E_{T,\text{B}}^{\text{jet}}$
- **Small theoretical uncertainties**
  - → higher orders (below $\pm 5\%$ for $Q^2 > 250$ GeV^2)
  - → proton PDFs (below $\pm 3\%$)
  - → $\alpha_s(M_Z)$ (below $\pm 1\ (2)\%$ at low (high) $Q^2/E_{T,\text{B}}^{\text{jet}}$)
  - → parton-to-hadron corrections (below $\pm 2\%$)

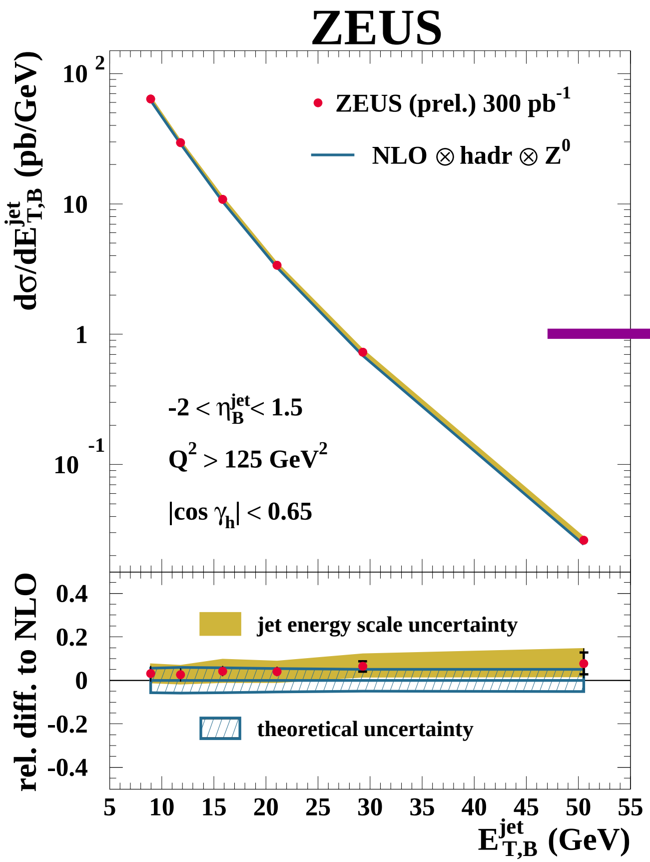
→ **Good description of data by NLO prediction**
→ validity of the description of the dynamics of jet production at $\mathcal{O}(\alpha_s^2)$

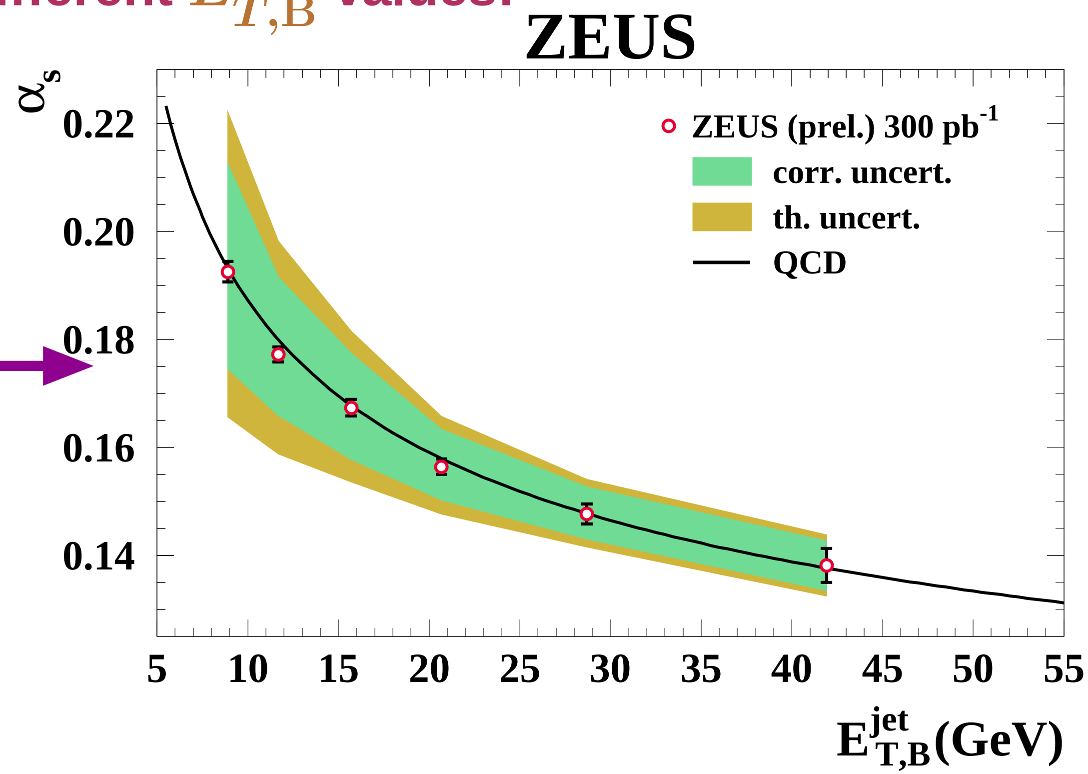
→ **Measurements provide direct sensitivity to $\alpha_s(M_Z)$ with small experimental and theoretical uncertainties**

ZEUS Collab, ZEUS-prel-10-002

Tests of pQCD: determination of α_s

- The energy-scale dependence of the coupling was determined by extracting α_s from the measured $d\sigma/dE_{T,\mathrm{B}}^{\mathrm{jet}}$ at different $E_{T,\mathrm{B}}^{\mathrm{jet}}$ values:





→ Results in good agreement with the predicted running of α_s over a large range in $E_{T,\mathrm{B}}^{\mathrm{jet}}$

- A value of $\alpha_s(M_Z)$ was determined from $Q^2 > 500$ GeV^2:

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

experimental uncertainty: $^{+3.1}_{-2.6}\%$

theoretical uncertainty: $\pm 1.9\%$

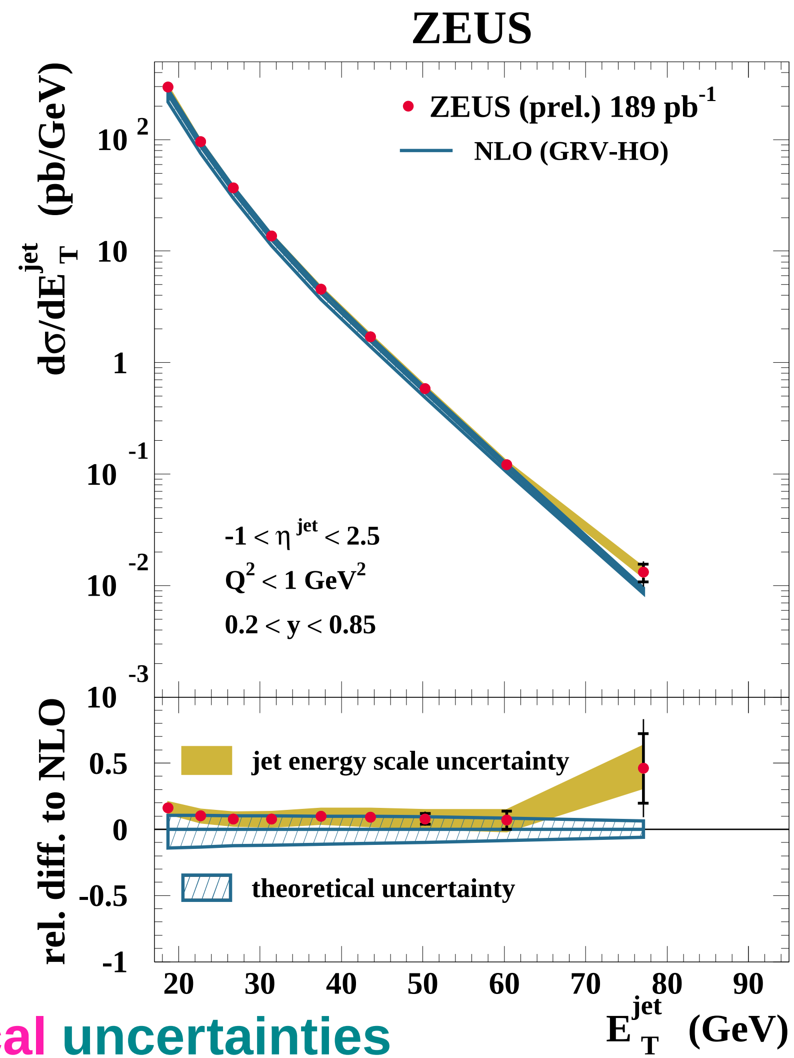
ZEUS Collab, ZEUS-prel-10-002

Tests of pQCD: inclusive-jet cross sections in PHP

$ep \rightarrow e + \text{jet} + X$: inclusive jets at high E_T^{jet}

$\mathcal{L} = 189$ pb^{-1}

- Jets searched using the k_T cluster algorithm in Laboratory frame
- Kinematic region: $Q^2 < 1$ GeV^2 and $0.2 < y < 0.85$
- At least one jet with $E_T^{\text{jet}} > 17$ GeV and $-1 < \eta^{\text{jet}} < 2.5$
- **Small experimental uncertainties**
  - $\rightarrow$ uncorrelated: typically $< \pm 4\%$
  - $\rightarrow$ correlated: $\sim \pm 5\%$
- **Small theoretical uncertainties**
  - $\rightarrow$ higher orders (± 10 $(7)\%$ at low (high) E_T^{jet})
  - $\rightarrow$ proton PDFs (± 1 $(5)\%$ at low (high) E_T^{jet})
  - $\rightarrow$ photon PDFs (-10 $(-2)\%$ at low (high) E_T^{jet})
  - $\rightarrow$ $\alpha_s(M_Z)$ (below $\pm 3\%$)
  - $\rightarrow$ parton-to-hadron corrections (below $\pm 3\%$)



$\rightarrow$ **Good description of data by NLO prediction**

$\rightarrow$ validity of the description of the dynamics of jet production at $\mathcal{O}(\alpha_s^2)$

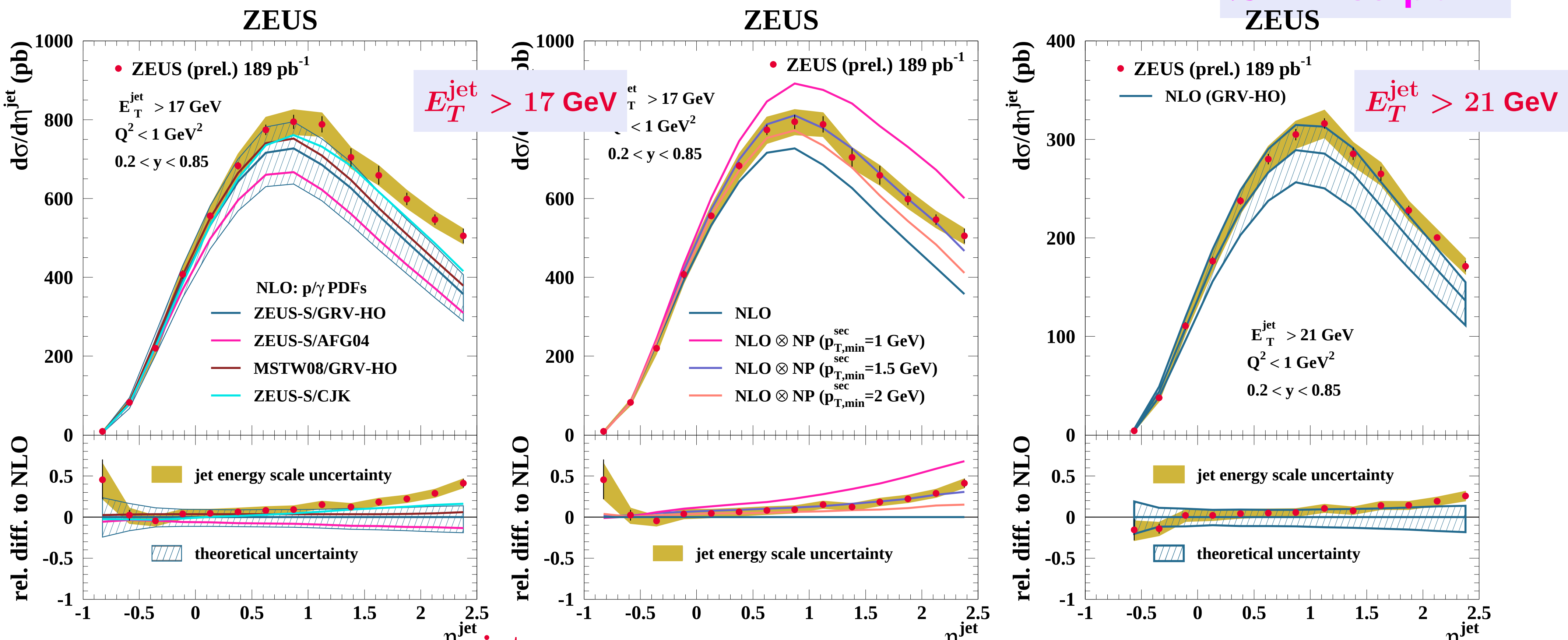
$\rightarrow$ **Measurements provide direct sensitivity to $\alpha_s(M_Z)$ with small experimental and theoretical uncertainties**

ZEUS Collab, ZEUS-prel-10-003

Tests of pQCD: inclusive-jet cross sections in PHP

$ep \rightarrow e + \text{jet} + X$: inclusive jets at high E_T^{jet}

$\mathcal{L} = 189$ pb^{-1}



- **Discrepancies at high η^{jet} might be due to γPDFs or non-perturbative effects**
  - $\rightarrow$ γPDFs: AFG04 (CJK) gives lower (higher) prediction than GRV-HO
  - $\rightarrow$ Non-perturbative contribution increases jet rate at high η^{jet}
  - $\rightarrow$ Disagreement between data and NLO disappears when increasing E_T^{jet}

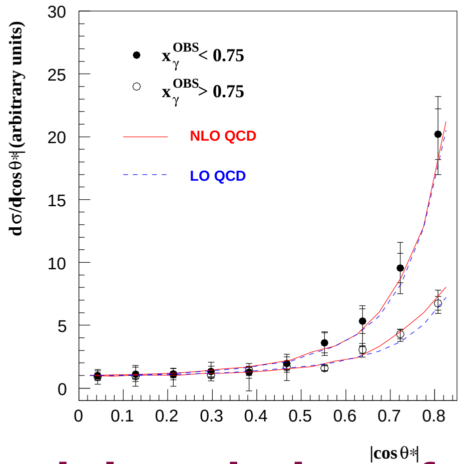
ZEUS Collab, ZEUS-prel-10-003

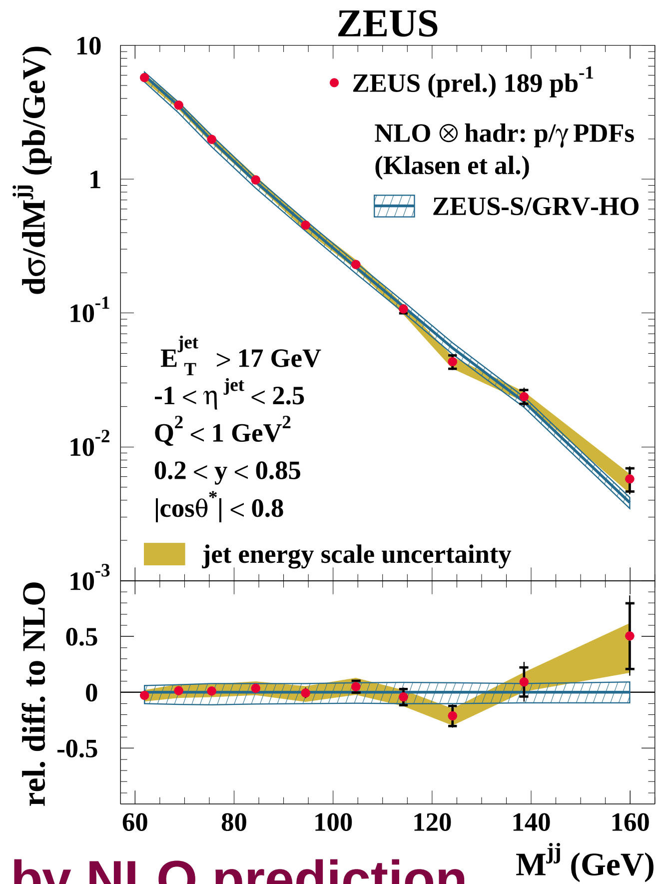
Tests of pQCD: dijet cross sections in PHP

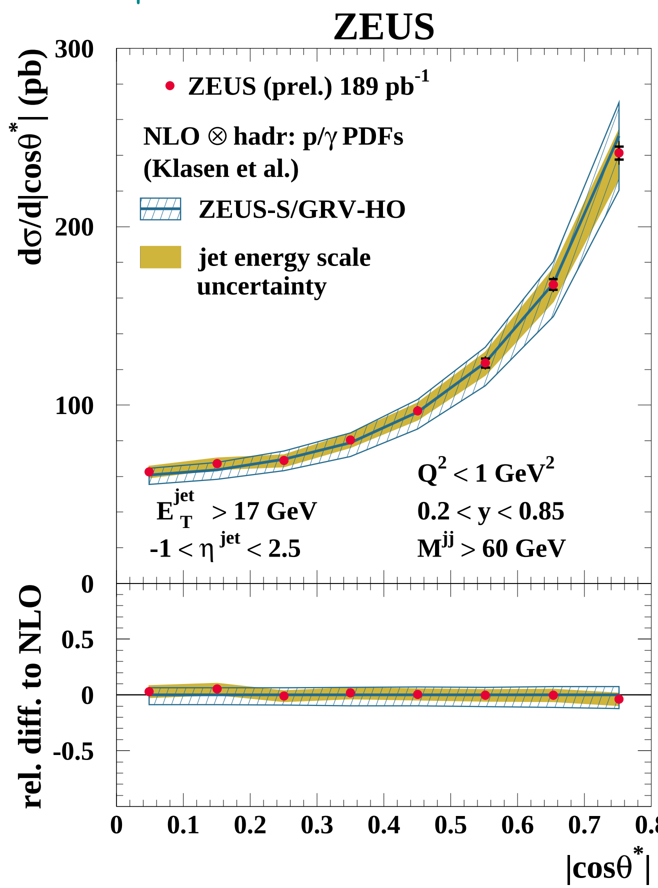
$ep \rightarrow e + \text{jet} + \text{jet} + X$: dijets at high E_T^{jet}

$\mathcal{L} = 189$ pb^{-1}

- Jets searched using the k_T cluster algorithm in Laboratory frame
- Kinematic region: $Q^2 < 1$ GeV^2 and $0.2 < y < 0.85$
- Two jets with $E_T^{\text{jet}} > 17$ GeV, $-1 < \eta^{\text{jet}} < 2.5$, $M^{\text{jj}} > 60$ GeV and $|\cos\theta^*| < 0.8$
- M^{jj} and $|\cos\theta^*|$:
  - $\rightarrow$ well suited to test underlying dynamics
  - $\rightarrow$ M^{jj} sensitive to form of matrix elements
  - $\rightarrow$ θ^* sensitive to spin of exchanged particle







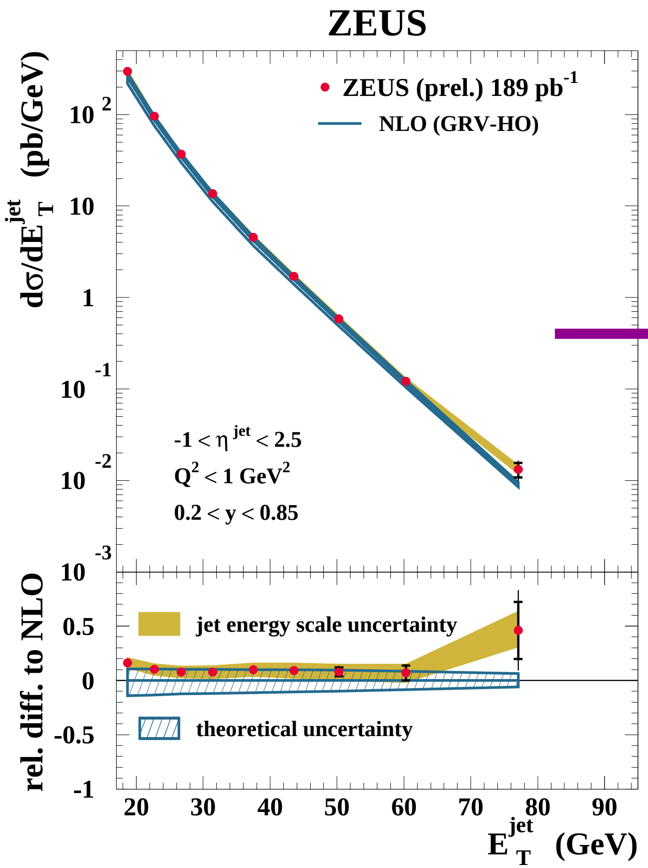
$\rightarrow$ **Good description of data by NLO prediction**

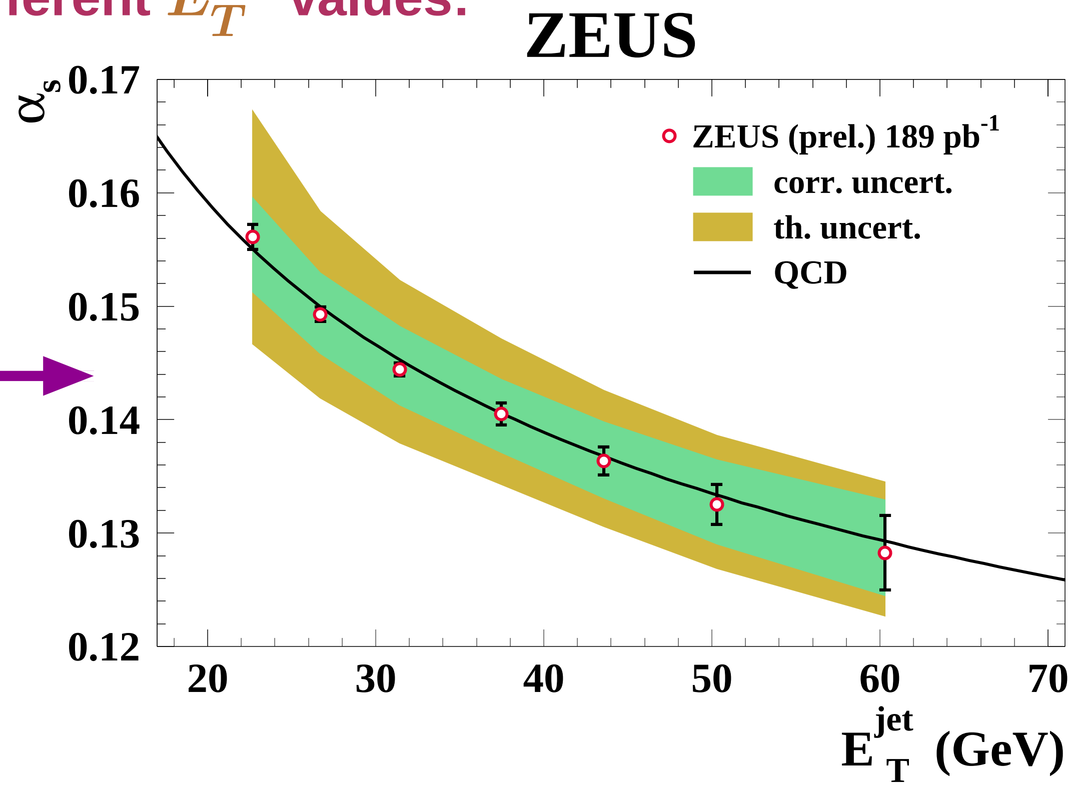
$\rightarrow$ validity of the description of the dynamics of jet production at $\mathcal{O}(\alpha_s^2)$

ZEUS Collab, ZEUS-prel-10-014

Tests of pQCD: determination of α_s

- The energy-scale dependence of the coupling was determined by extracting α_s from the measured $d\sigma/dE_T^{jet}$ at different E_T^{jet} values:





→ Results in good agreement with the predicted running of α_s over a large range in E_T^{jet}

- A value of $\alpha_s(M_Z)$ was determined from $21 < E_T^{jet} < 71$ GeV:

$$\alpha_s(M_Z) = 0.1208^{+0.0024}_{-0.0023}\,(\text{exp.})\,^{+0.0044}_{-0.0033}\,(\text{th.})$$

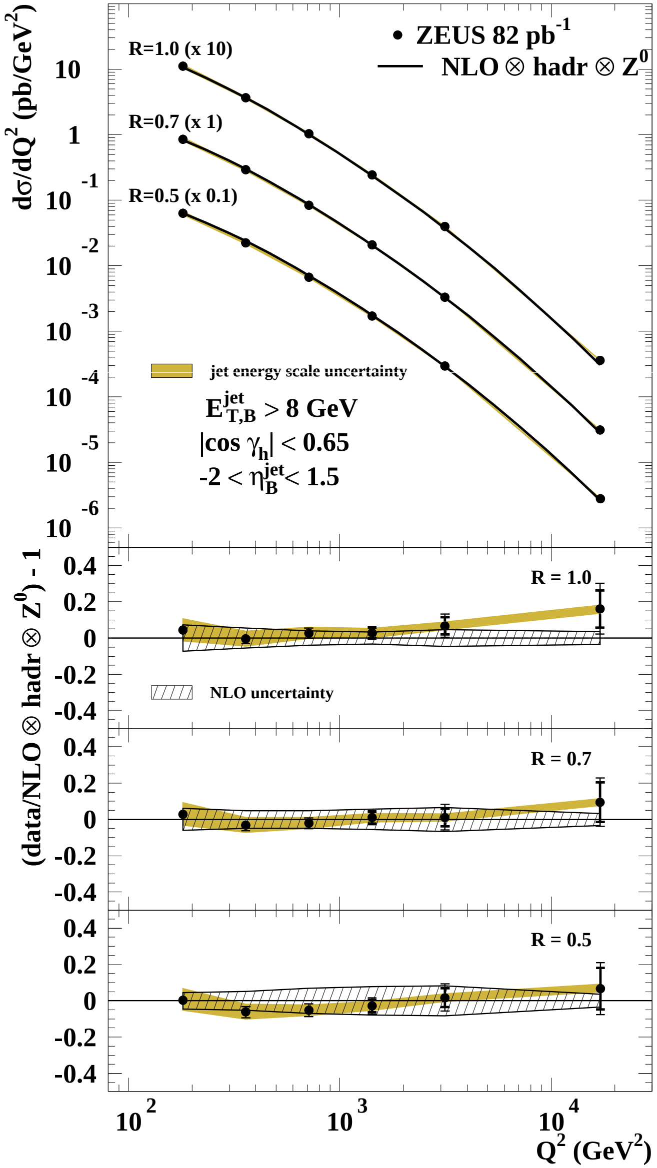
experimental uncertainty: $^{+2.0}_{-1.9}\%$

theoretical uncertainty: $^{+3.6}_{-2.7}\%$

ZEUS Collab, ZEUS-prel-10-003

Tests of pQCD: 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 test of performance
- NEW STUDIES in NC DIS and PHP:
  - → 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



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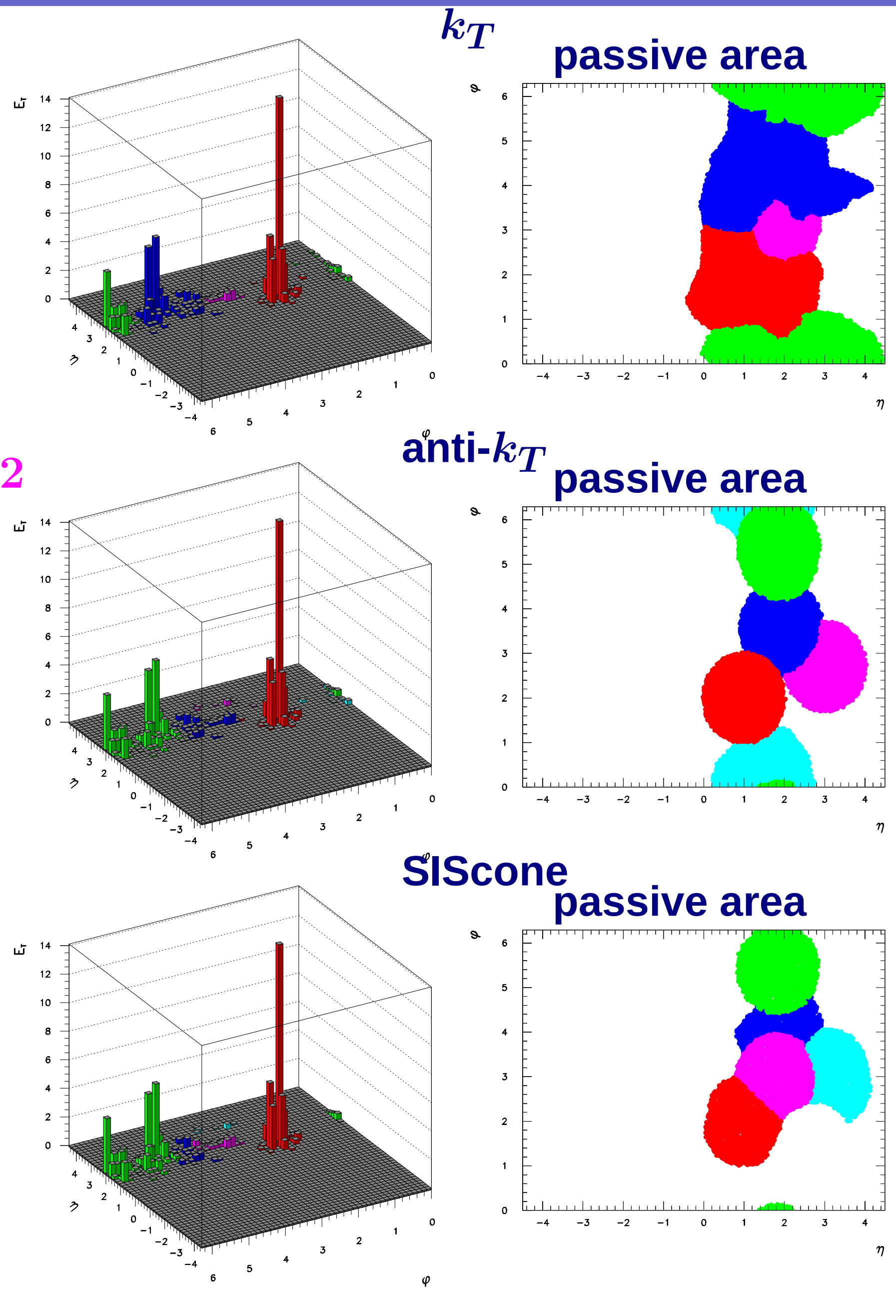
Tests of pQCD: k_T vs anti-k_T vs SIScone

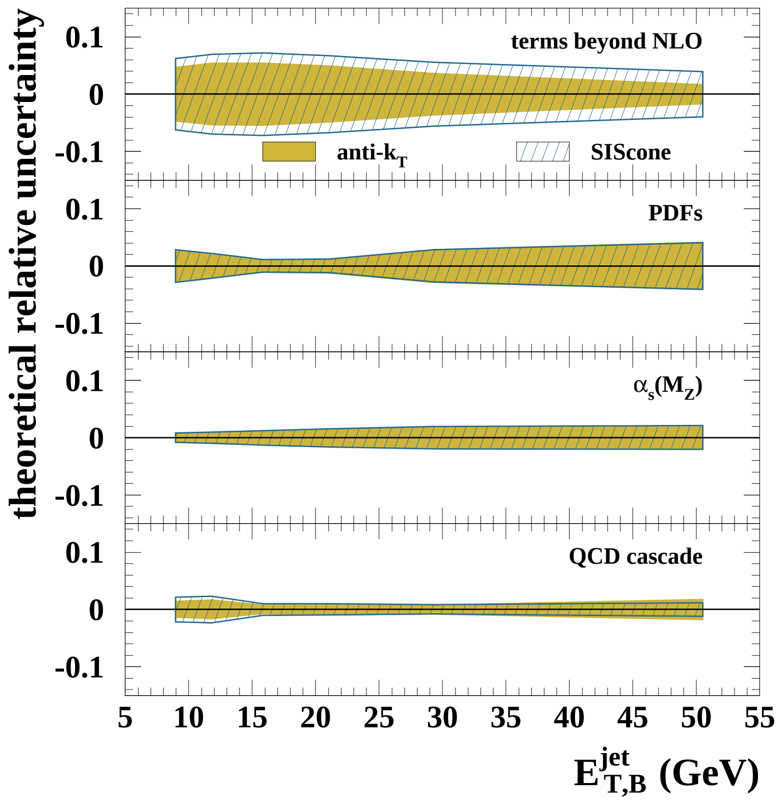
- **New infrared- and collinear-safe jet algorithms:**
  $\longrightarrow$ **anti-k_T (M Cacciari, G Salam & G Soyez) and SIScone (G Salam & G Soyez)**
- **Cluster algorithms:**
  $\longrightarrow$ $d_{ij} = \min[(E^i_{T,\mathrm{B}})^{2p}, (E^j_{T,\mathrm{B}})^{2p}] \cdot \Delta R^2/R^2$
  with $p = 1$ (-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)**



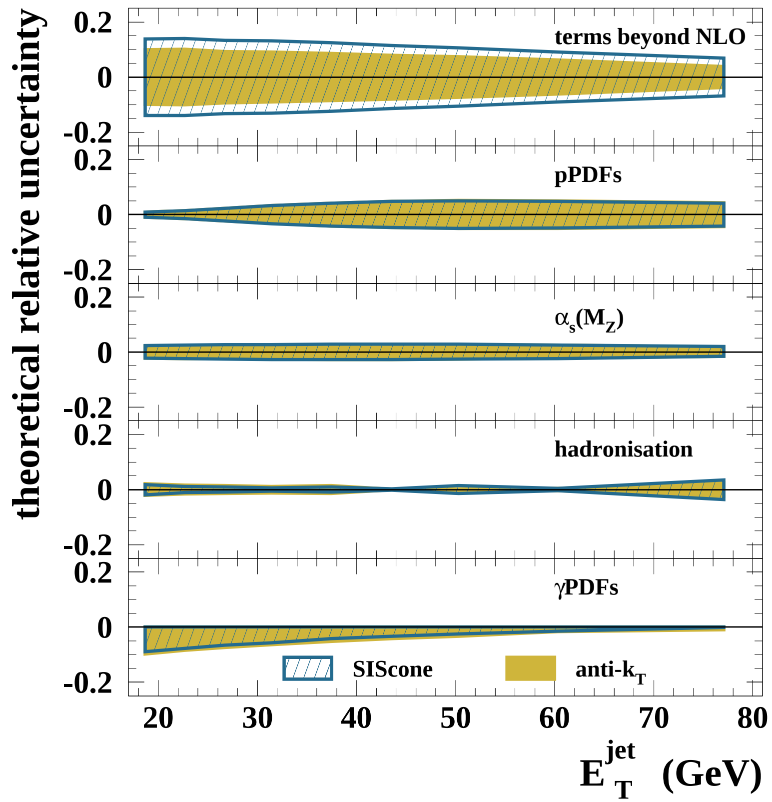
Tests of pQCD: k_T vs anti-k_T vs SIScone

- Theoretical uncertainties:
  - $\longrightarrow$ PDFs and value of $\alpha_s(M_Z)$:
    - $\longrightarrow$ very similar for all three jet algorithms
  - $\longrightarrow$ terms beyond NLO and QCD cascade/hadronisation modelling:
    - $\longrightarrow$ very similar for k_T and anti-k_T; somewhat larger for SIScone

NC DIS



PHP



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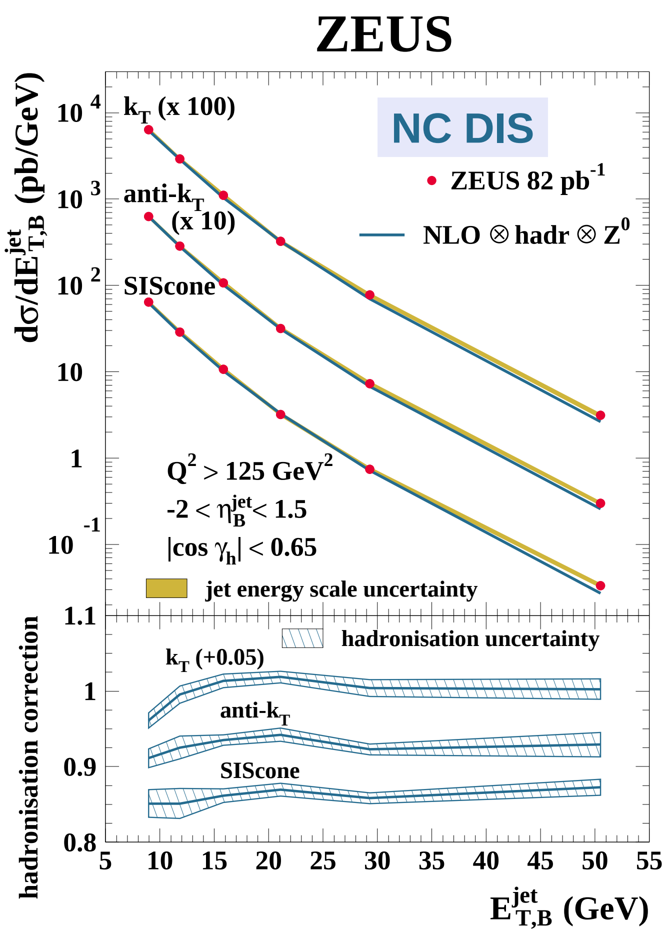
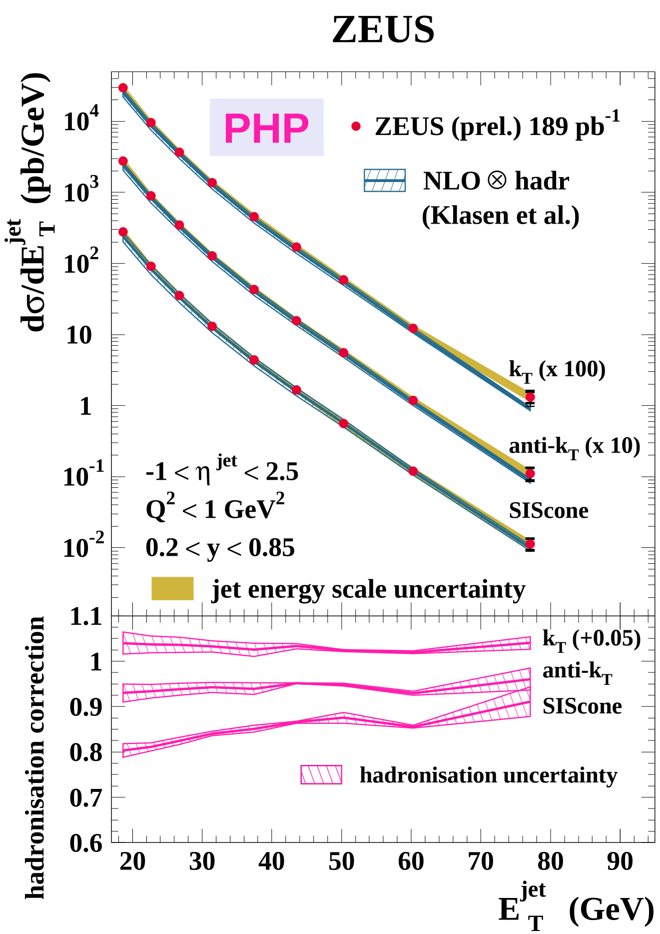
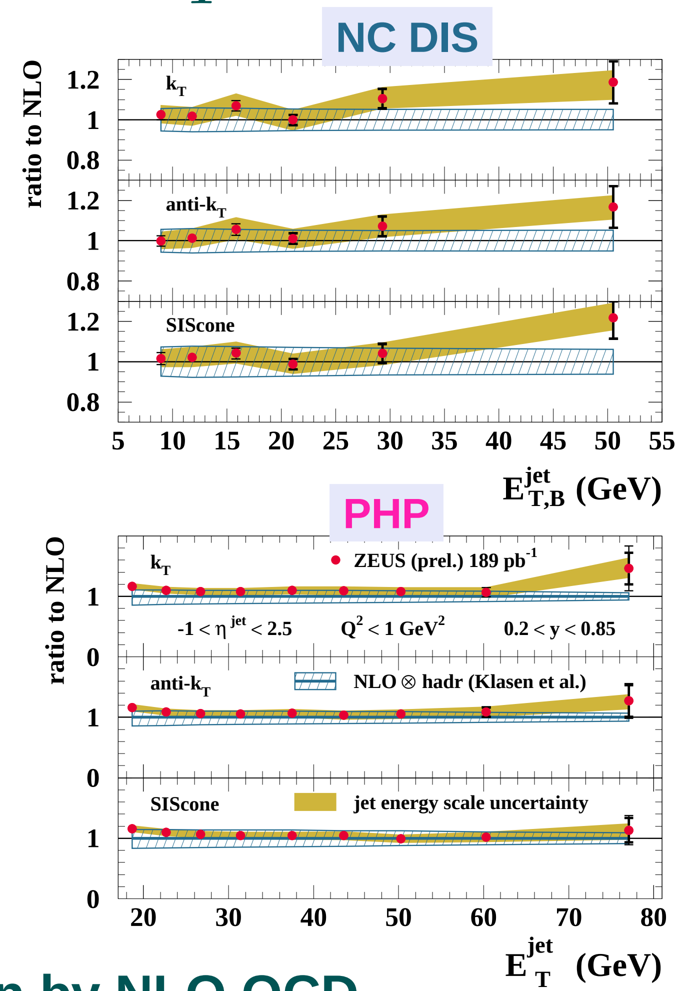
ZEUS Collab, ZEUS-prel-10-015

Tests of pQCD: inclusive-jet cross sections

- Inclusive-jet cross sections in NC DIS and PHP 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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Tests of pQCD: inclusive-jet cross sections

- Ratio of cross sections based on different jet algorithms:

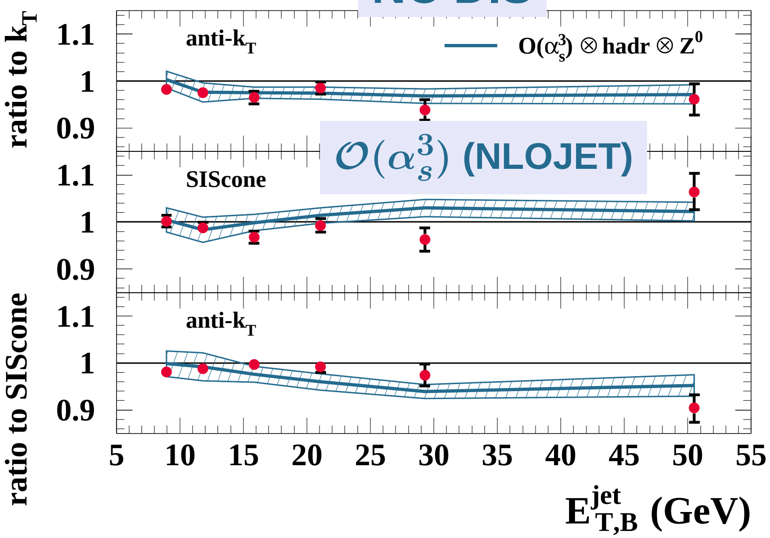
NC DIS

anti-k_T/k_T

SIScone/k_T

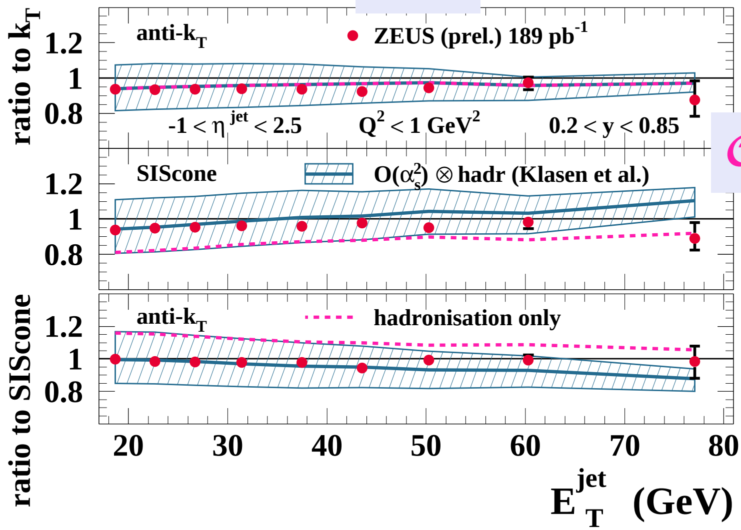
anti-k_T/SIScone

$\mathcal{O}(\alpha_s^3)$ (NLOJET)



PHP

$\mathcal{O}(\alpha_s^2)$



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

$\longrightarrow$ NC DIS: differences $< 3.6\%$ at low $E^{jet}_{T,B}$ and increase to 10% at high $E^{jet}_{T,B}$

$\longrightarrow$ PHP: anti-k_T same shape and $\approx 6\%$ smaller than k_T

SIScone slightly different shape than k_T and anti-k_T

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

$\longrightarrow$ theoretical uncertainty dominated by QCD-cascade modelling

$\Rightarrow$ Demonstration of ability of pQCD calculations with up to four (three) partons in final state to account adequately for the differences between jet algorithms

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Tests of pQCD: determination of $\alpha_s(M_Z)$

- Values of $\alpha_s(M_Z)$ were determined from the measured cross sections to quantify the performance of the jet algorithms:

NC DIS

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

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

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

PHP

$$\alpha_s(M_Z) = 0.1208^{+0.0024}_{-0.0023}\,(\text{exp.})\,^{+0.0044}_{-0.0033}\,(\text{th.})\ (k_T)$$

$$\alpha_s(M_Z) = 0.1200^{+0.0024}_{-0.0023}\,(\text{exp.})\,^{+0.0043}_{-0.0032}\,(\text{th.})\ (\text{anti-}k_T)$$

$$\alpha_s(M_Z) = 0.1199^{+0.0022}_{-0.0022}\,(\text{exp.})\,^{+0.0047}_{-0.0042}\,(\text{th.})\ (\text{SIScone})$$

→ $\alpha_s(M_Z)$ from inclusive-jet cross sections in NC DIS and PHP with different jet algorithms are consistent with each other and have similar precision

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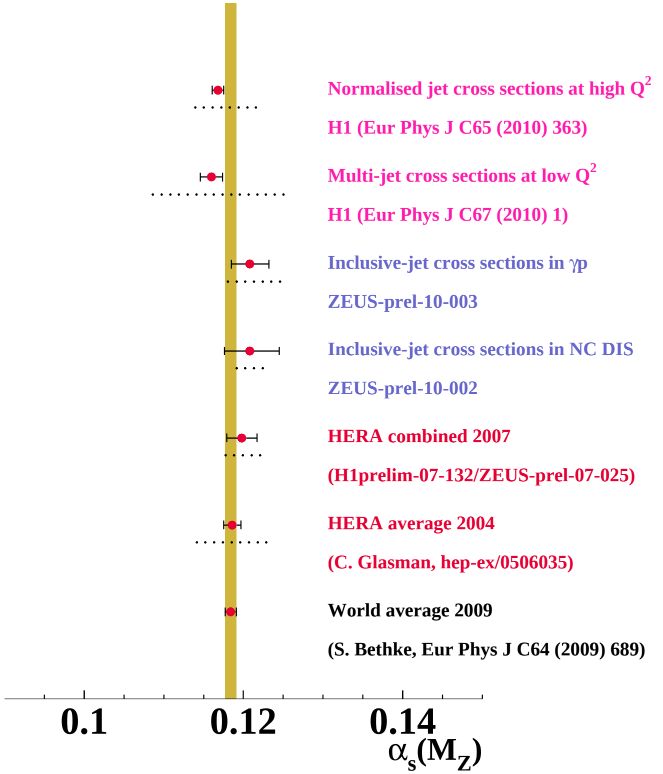
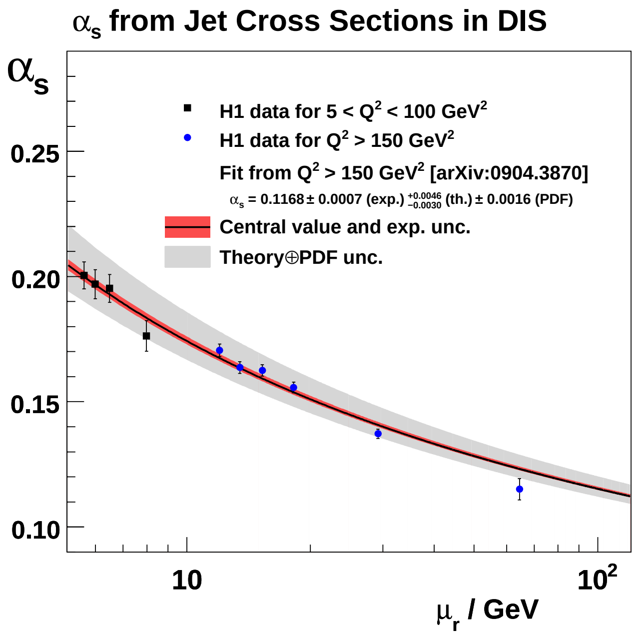
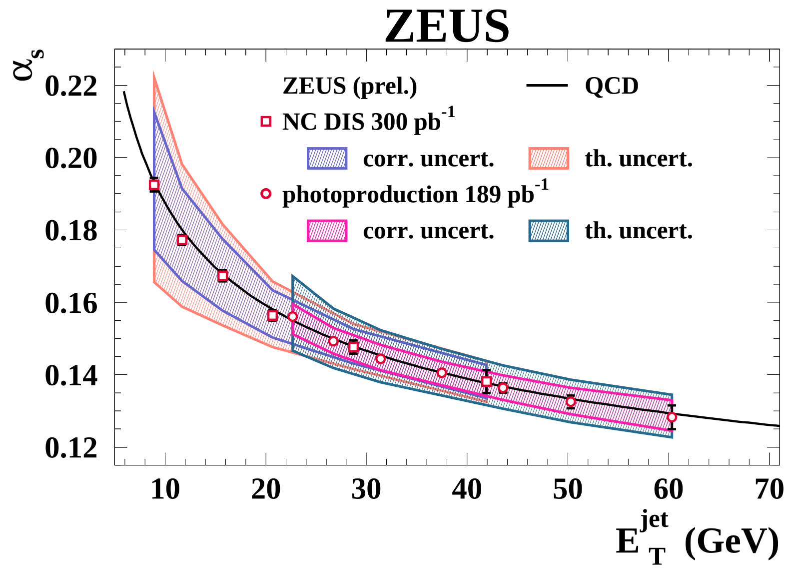
Conclusions

- **Jet physics at HERA continues providing precision measurements towards understanding QCD and improving the determination of the p/γPDFs**
  - $\longrightarrow$ **Precise new jet measurements will help to constrain further the proton and photon PDFs**
  - $\longrightarrow$ **Precise tests of the performance of new jet algorithms**
  - $\longrightarrow$ **Precise values of $\alpha_s(M_Z)$ extracted from jet production in different regimes**
  - $\longrightarrow$ **Precise determination of the running of α_s over a wide range of the scale**







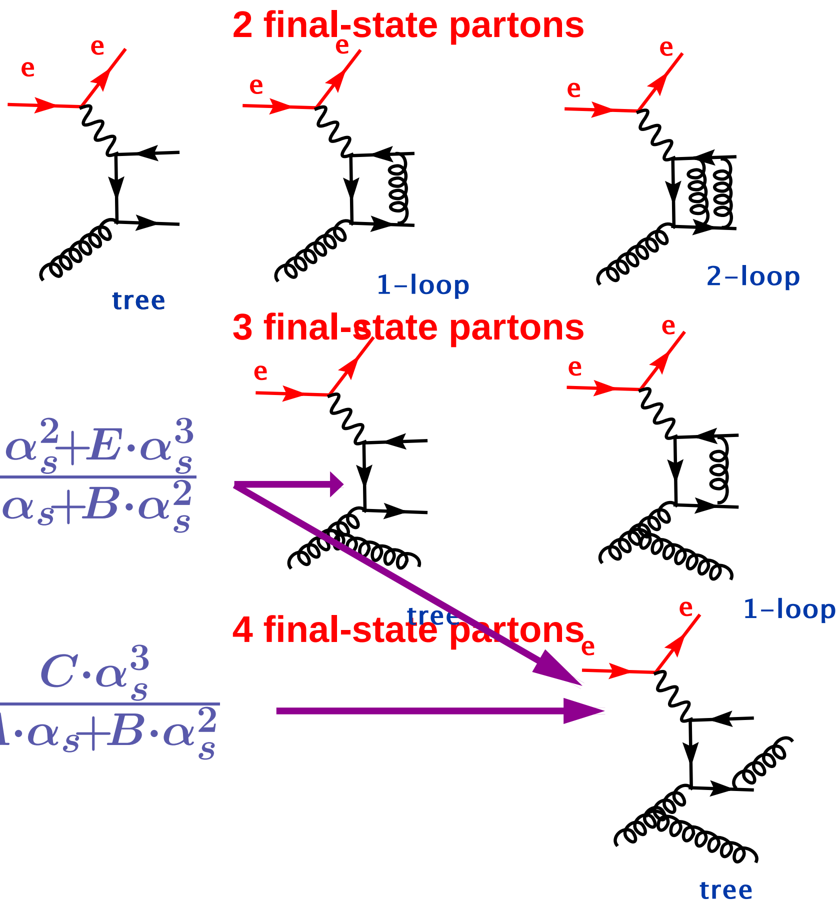
Back-up slides

Tests of pQCD: k_T vs anti-k_T vs SIScone

- Inclusive-jet cross sections in NC DIS can be calculated only up to $\mathcal{O}(\alpha_s^2)$ using the programs 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:

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

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

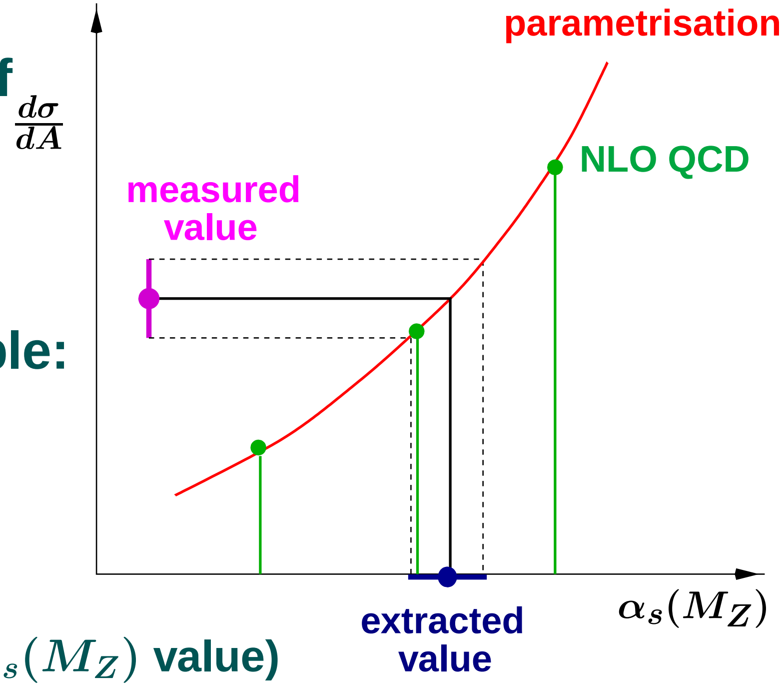


The method to determine α_s from jet observables

- The procedure to determine α_s from jet observables used by ZEUS is based on the α_s dependence of the pQCD calculations, taking into account the correlation with the PDFs:
  - perform NLO calculations using different sets of proton PDFs
  - use as input in each calculation the value of $\alpha_s(M_Z)$ assumed in each PDF set
  - parametrise the α_s dependence of the observable:

$$A^i(\alpha_s(M_Z)) = A_1^i\,\alpha_s(M_Z) + A_2^i\,\alpha_s(M_Z)^2$$

  - determine $\alpha_s(M_Z)$ from the measured value using the NLO parametrisation (MINUIT is used to determine $A_j^i,\ j=1,2$ and the final $\alpha_s(M_Z)$ value)



- This procedure handles correctly the complete α_s-dependence of the NLO calculations (explicit dependence in the partonic cross section and implicit dependence from the PDFs) in the fit, while preserving the correlation between α_s and the PDFs