Workshop on precision measurements of α_s

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Max Planck Institut für Physik, Munich, Germany

Review of α_s determinations from jets at HERA

from

ZEUS Collab.

H1 Collab.

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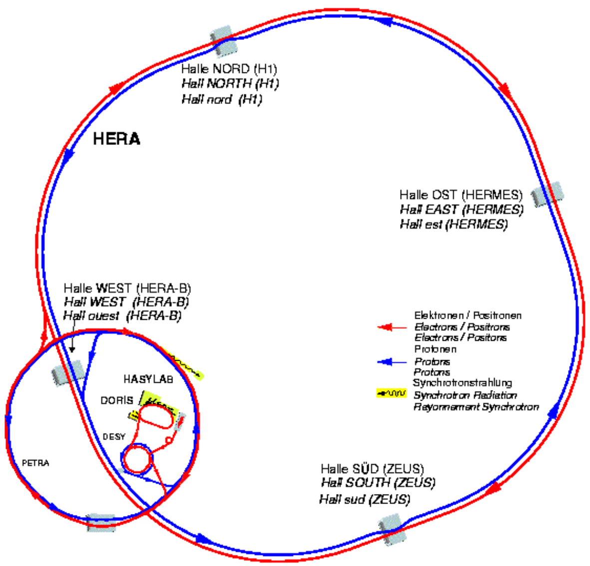
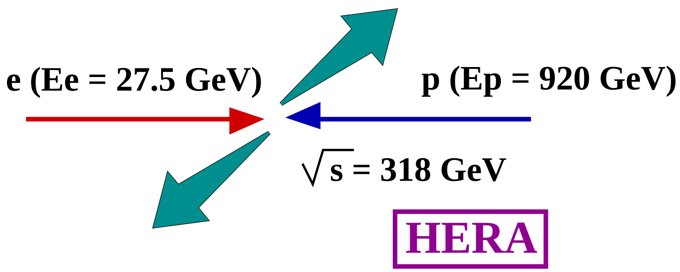
at





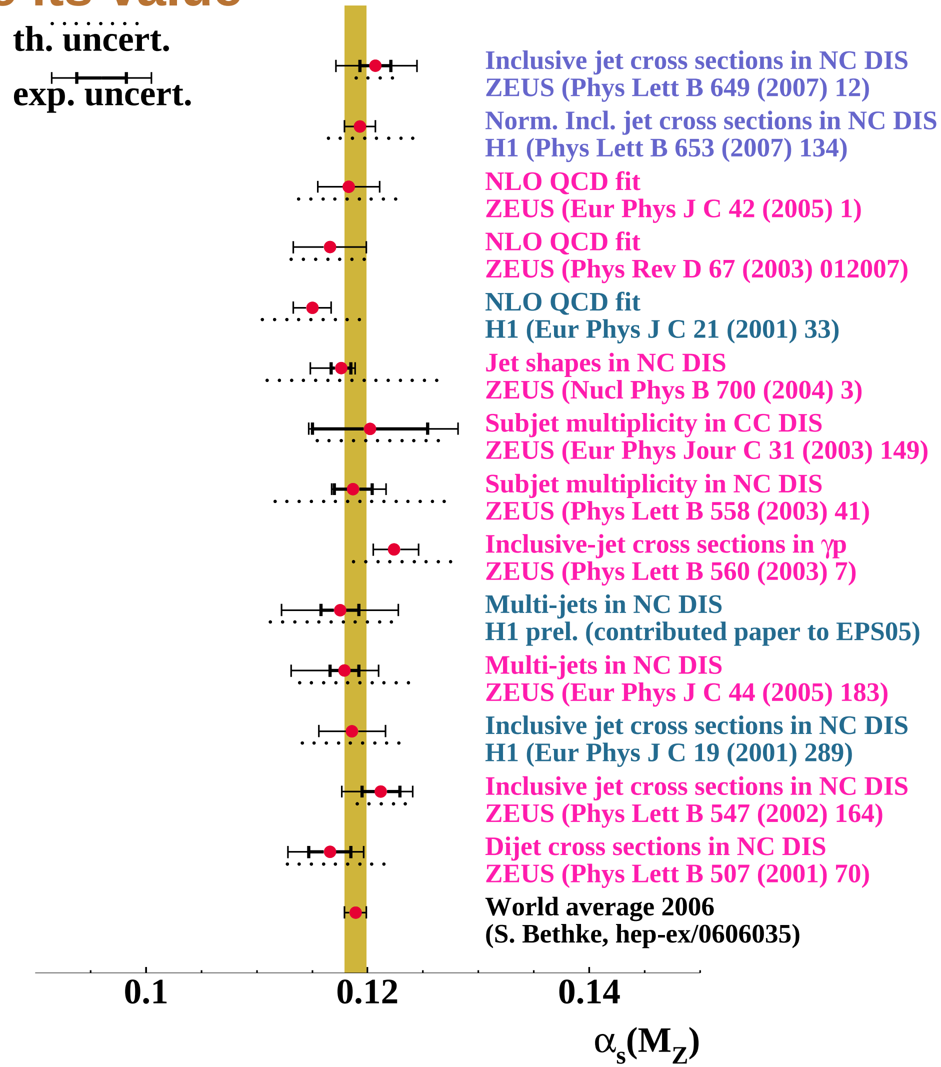
The strong coupling constant α_s in ep collisions

- The strong coupling constant, α_s, participates in any observable involving jets in ep collisions
  $\Rightarrow$ jet observables can be used to determine its value

- A wealth of α_s determinations are available from HERA data
  $\longrightarrow$ observables such as
  - jet cross sections
  - ratios of jet cross sections
  - internal structure of jets

  $\longrightarrow$ are sensitive to the value of α_s and were used to determine its value

- The $\alpha_s(M_Z)$ values from H1 and ZEUS are all in good agreement and consistent with the world average



Determination of α_s at HERA

- The predictions for jet cross sections at HERA can be written in QCD as

$$d\sigma(ep \rightarrow e + \text{Jet}(+\text{Jets}) + X) = \sum_{a=q,\bar{q},g} \int dx\ f_a(x, \mu_F)\ d\hat{\sigma}_a(x, \alpha_s(\mu_R), \mu_R, \mu_F)$$

$\Rightarrow$ to determine α_s from a jet observable at HERA, the correlation between
$\rightsquigarrow$ explicit dependence on α_s from the matrix elements
$\rightsquigarrow$ implicit dependence on α_s from the pPDFs
has to be taken into account properly

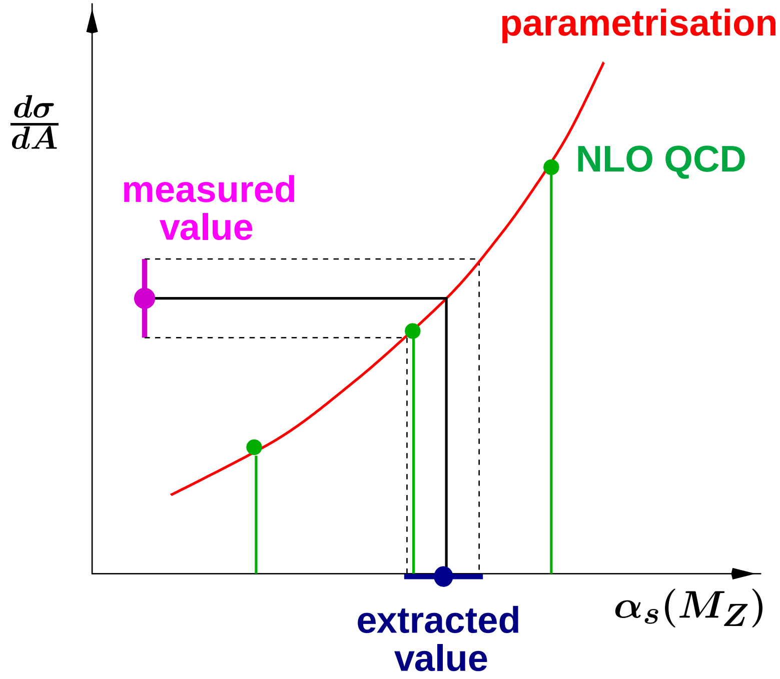
- Solutions:
  - $\longrightarrow$ determine α_s from observables with small dependence on the pPDFs (eg, determination from ratios of observables)
  - $\longrightarrow$ determine α_s by taking properly into account the correlation (eg. using pPDF sets extracted assuming different values of α_s $\longrightarrow$)
  - $\longrightarrow$ or perform simultaneous determination of α_s and the pPDFs (not treated in this talk)

A method to determine α_s from jet observables

- The method 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 pPDFs:
  - perform NLO calculations using different sets of pPDFs
  - use as input in each calculation the value of $\alpha_s(M_Z)$ assumed in each pPDF 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



- 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 pPDFs) in the fit, while preserving the correlation between α_s and the pPDFs

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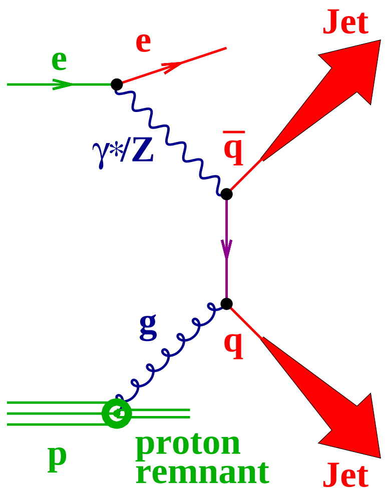
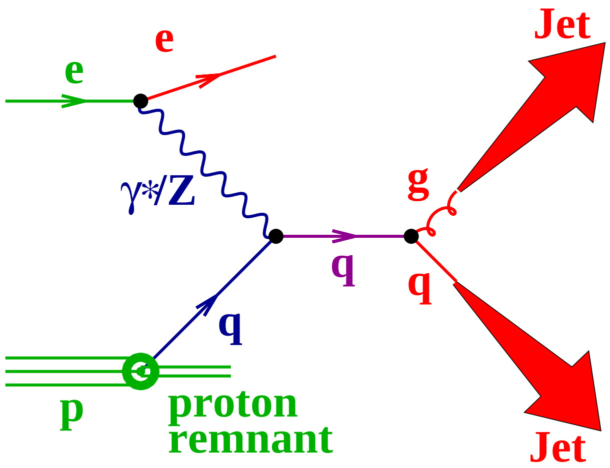
Jets in NC DIS at HERA

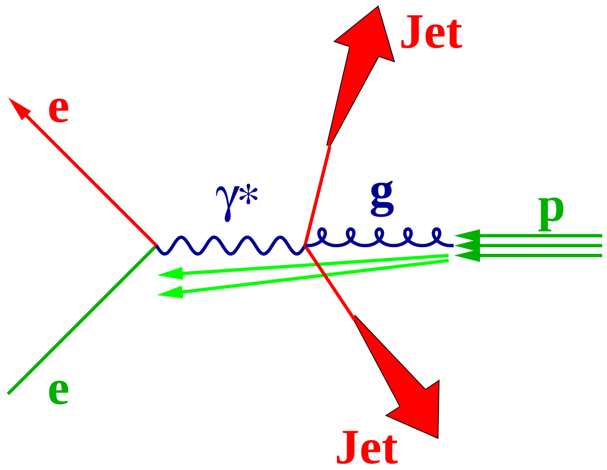
- **Jet production in neutral current deep inelastic ep scattering at $\mathcal{O}(\alpha_s)$ in the Breit frame:**



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

Jet cross sections in NC DIS at low Q^2

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

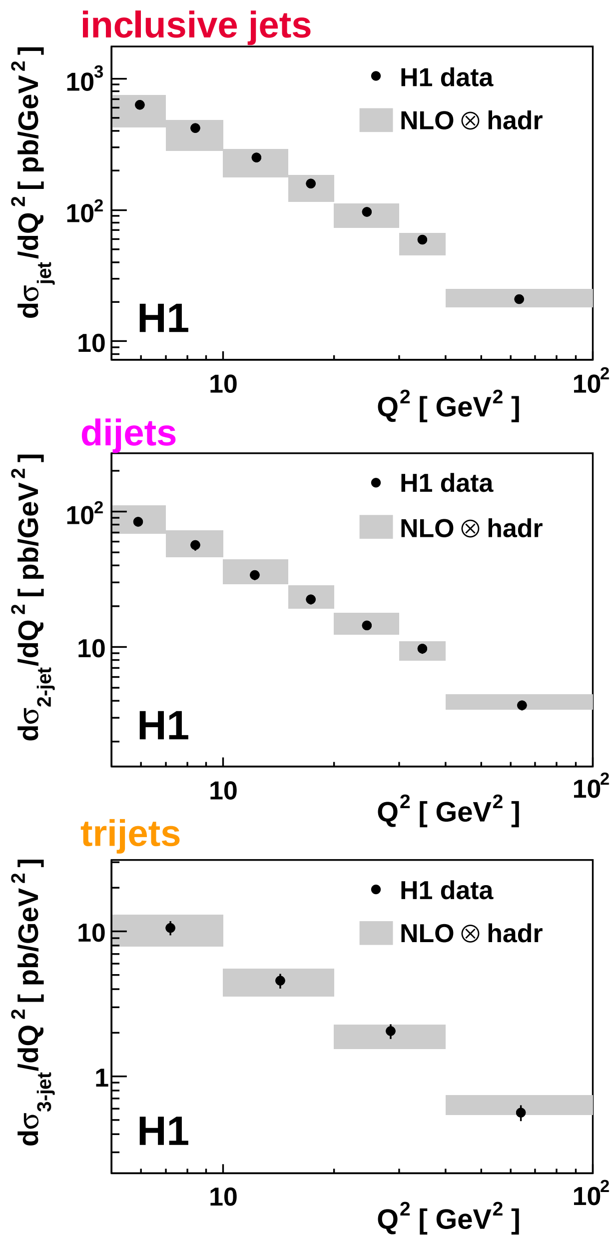
- Jets searched using the k_T cluster algorithm in Breit frame
- Kinematic region: $5 < Q^2 < 100$ GeV^2 and $0.2 < y < 0.7$
- Jets with $P_T > 5$ GeV and $-1 < \eta^{\text{jet}}_{\text{LAB}} < 2.5$
- ($M^{\text{jj}} > 18$ GeV)

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

- **Small experimental uncertainties**
  - $\rightarrow$ uncorrelated: $< \pm 5$, $\sim \pm 5$, $\sim \pm 8\%$
  - $\rightarrow$ correlated: $\sim \pm 5$, $\sim \pm 5$, $< \pm 8\%$
- **NLO predictions using NLOJET++**
  - $\rightarrow$ $\mu_R^2 = \mu_F^2 = (Q^2 + \langle P_T \rangle^2)/2$; pPDFs: CTEQ6.5M; corrected for hadronisation effects
- **Theoretical uncertainties:** dominated by terms beyond NLO
  - $\rightarrow$ higher orders (± 30 $(10)\%$ at low (high) Q^2)
  - $\rightarrow$ proton PDFs (± 6 $(2)\%$ at low (high) Q^2)
  - $\rightarrow$ parton-to-hadron corrections ($\pm 1 - 2.5$, $\pm 1 - 2$, $\pm 5\%$)

$\rightarrow$ **The measured jet cross sections are well described by the NLO predictions in the whole measured range**

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



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α_s from jet cross sections and ratios: NC DIS at low Q^2

$ep \rightarrow e + \text{jets} + \text{X}$: inclusive jets, dijets and trijets at low Q^2

- From the measured double-differential cross sections for $5 < Q^2 < 100$ GeV^2, values of $\alpha_s(M_Z)$ were extracted:

$$\alpha_s(M_Z) = 0.1180 \pm 0.0018\ (\text{exp.})^{+0.0124}_{-0.0093}\ (\text{th.})$$ inclusive jets

$$\alpha_s(M_Z) = 0.1155 \pm 0.0018\ (\text{exp.})^{+0.0124}_{-0.0093}\ (\text{th.})$$ dijets

$$\alpha_s(M_Z) = 0.1170 \pm 0.0017\ (\text{exp.})^{+0.0091}_{-0.0073}\ (\text{th.})$$ trijets

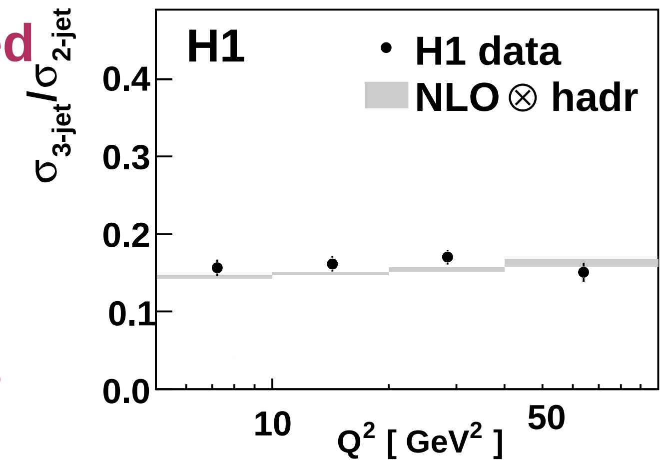
$$\alpha_s(M_Z) = 0.1160 \pm 0.0014\ (\text{exp.})^{+0.0094}_{-0.0079}\ (\text{th.})$$ combined

- Experimental uncertainty: $\pm 1.2\%$
- Theoretical uncertainty: $^{+8.1}_{-6.8}\%$, dominated by terms beyond NLO (offset method)

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

$$\alpha_s(M_Z) = 0.1215 \pm 0.0032\ (\text{exp.})^{+0.0067}_{-0.0059}\ (\text{th.})$$

experimental uncertainty: $\pm 2.6\%$; theoretical uncertainty: $^{+5.5}_{-4.9}\%$



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Normalised jet cross sections in NC DIS at medium Q^2

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

- Jets searched using the k_T cluster algorithm in BF
- Kinematic region: $150 < Q^2 < 15000$ GeV^2
- 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)

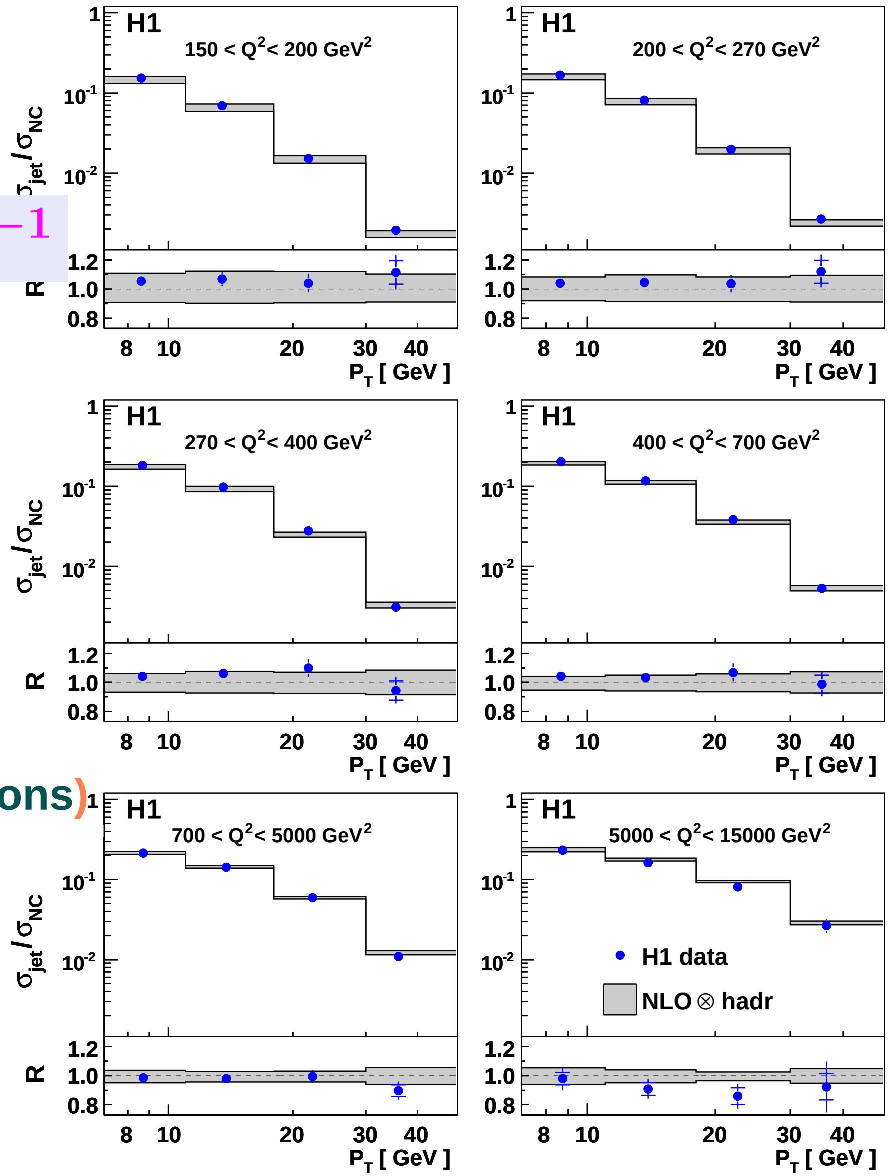
$\mathcal{L} = 395$ pb^{-1}

- **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
- **NLO predictions using NLOJET++**
  - $\rightarrow$ $\mu_R^2 = \mu_F^2 = (Q^2 + \langle P_T \rangle^2)/2$; pPDFs: CTEQ6.5M; corrected for hadronisation effects
- **Theoretical uncertainties:**
  - $\rightarrow$ dominated by terms beyond NLO, but smaller than at lower Q^2 (higher Q^2 and normalised cross sections)

$\rightarrow$ **The measured jet cross sections are well described by the NLO predictions**

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

Normalised Inclusive Jet Cross Section



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α_s from jet cross sections and ratios: NC DIS at medium Q^2

$ep \to e + \text{jets} + \text{X}$: normalised inclusive jets, dijets and trijets at medium Q^2

- From the measured normalised double-differential cross sections for $150 < Q^2 < 15000$ GeV^2, values of $\alpha_s(M_Z)$ were extracted:

$\alpha_s(M_Z) = 0.1195 \pm 0.0010\ (\text{exp.})^{+0.0052}_{-0.0040}\ (\text{th.})$	inclusive jets
$\alpha_s(M_Z) = 0.1155 \pm 0.0009\ (\text{exp.})^{+0.0045}_{-0.0035}\ (\text{th.})$	dijets
$\alpha_s(M_Z) = 0.1172 \pm 0.0013\ (\text{exp.})^{+0.0053}_{-0.0032}\ (\text{th.})$	trijets
$\alpha_s(M_Z) = 0.1168 \pm 0.0007\ (\text{exp.})^{+0.0049}_{-0.0034}\ (\text{th.})$	combined

- Experimental uncertainty:
  — $\pm 0.6\%$, equally shared by correlated/uncorrelated sources
- Theoretical uncertainty (offset method): $^{+4.2}_{-2.9}\%$ ($^{+8.1}_{-6.8}\%$ at low Q^2) ($^{+5.5}_{-4.9}\%$ ratio at low Q^2)
  — factorisation scale: $\pm 0.5\%$
  — hadronisation corrections: $\pm 0.4 - 1\%$
  — pPDFs: $\pm 1.5\%$
  — terms beyond NLO: $\pm 3 - 4\%$

∗ Reduction of theoretical uncertainties achieved by using normalised cross sections and higher Q^2

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Jet cross sections in NC DIS at high Q^2

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

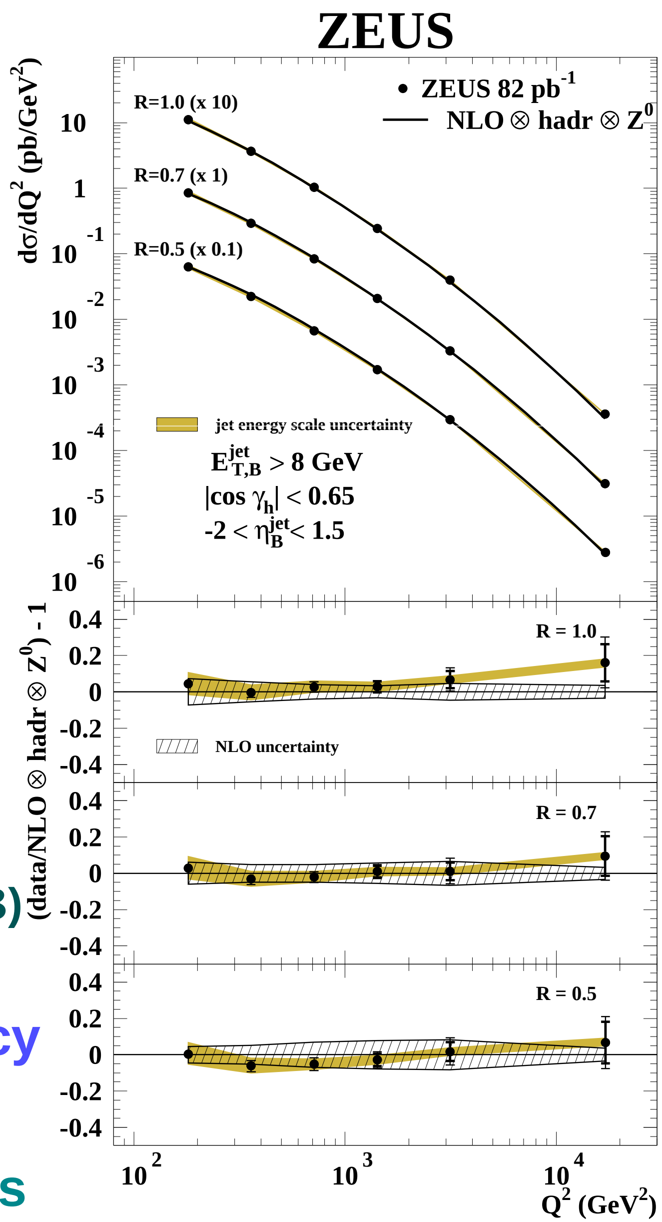
- Jets searched with k_T algorithm in the Breit frame
- different R values were used: 0.5, 0.7 and 1
- At least one jet with $E_{T,\text{B}}^{\text{jet}} > 8$ GeV and $-2 < \eta_{\text{B}}^{\text{jet}} < 1.5$
- Kinematic range: $Q^2 > 125$ GeV^2 and $|\cos\gamma| < 0.65$

$\mathcal{L} = 82$ pb^{-1}

- Small experimental uncertainties
  - $\rightarrow$ uncorrelated: $\sim \pm 5\%$
  - $\rightarrow$ correlated: $\sim \pm 5\%$
- NLO predictions using DISENT
  - $\rightarrow$ $\mu_R = E_{T,\text{B}}^{\text{jet}}$; $\mu_F = Q$; pPDFs: ZEUS-S; corrected for hadronisation and Z^0 effects
- Theoretical uncertainties:
  - $\rightarrow$ higher orders ($7(5)\%$ at low (high) Q^2, $> 10\%$ for $R = 1.2$)
  - $\rightarrow$ proton PDFs (below $\pm 3\ (4.4)\%$ at low (high) $E_{T,\text{B}}^{\text{jet}}$)
  - $\rightarrow$ hadronisation (below 25, 15, $\pm 5\%$; much bigger for $R = 0.3$)

$\rightarrow$ The measured jet cross sections are well described by NLO QCD for $R = 1, 0.7, 0.5$ with similar accuracy

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



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Jet cross sections in NC DIS at high Q^2

- 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 anti-k_T and SIScone (M Cacciari, G Salam & G Soyez)

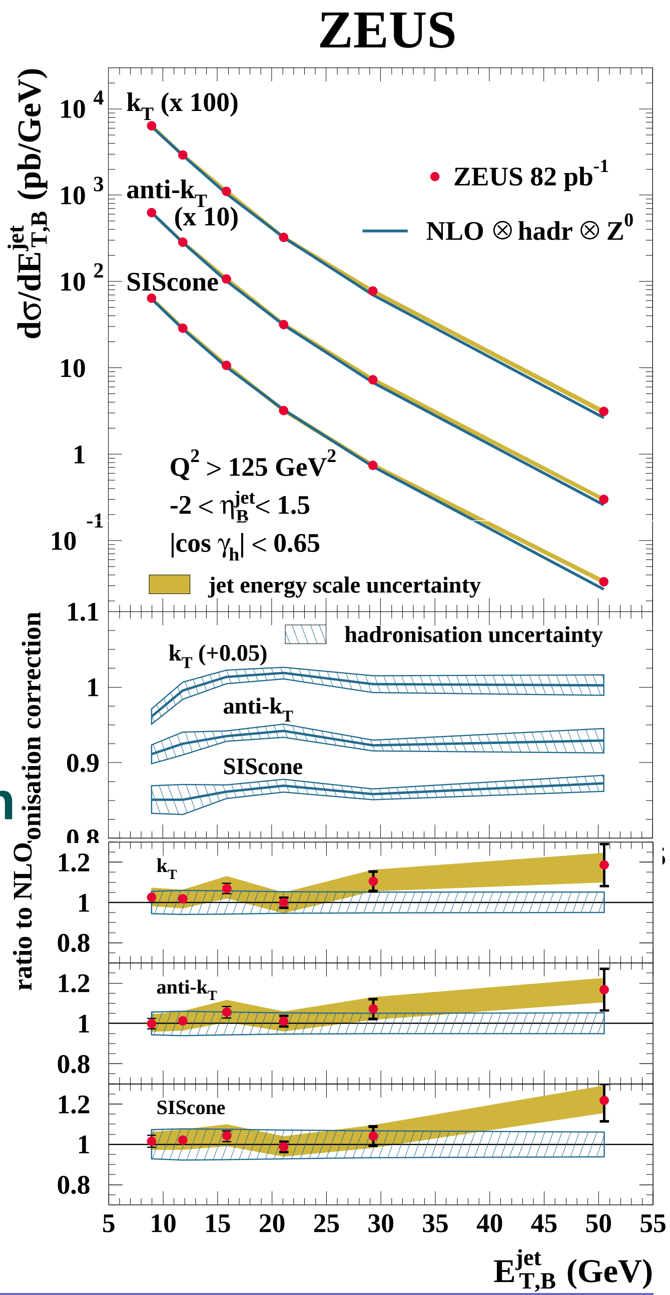
$\longrightarrow$ Good description of data in shape and normalisation by NLO QCD

$\longrightarrow$ Bigger hadronisation corrections and theoretical uncertainty for SIScone than anti-k_T (similar to k_T)

$\longrightarrow$ Similar shape and normalisation in data and theory for the three jet algorithms

$\longrightarrow$ Similar experimental uncertainties

$\mathcal{L} = 82$ pb^{-1}



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α_s from jet cross sections: NC DIS at high Q^2

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

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

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

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

- Experimental uncertainties:
  - → dominated by jet energy scale: $\Delta\alpha_s/\alpha_s =\sim \pm 2\%$
- Theoretical uncertainties: (Jones et al method)

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

→ $\alpha_s(M_Z)$ from inclusive-jet cross sections in NC DIS at high Q^2:

→ 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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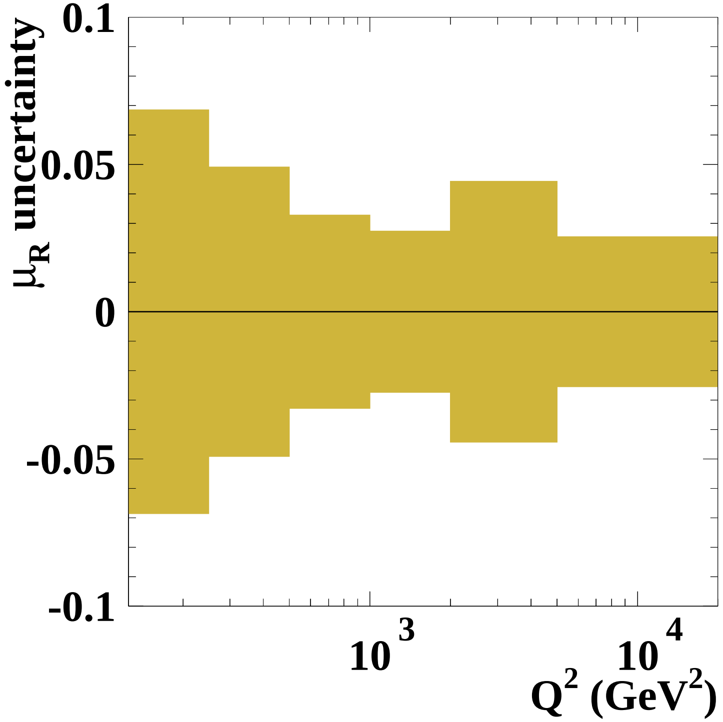
Precision of $\alpha_s(M_Z)$



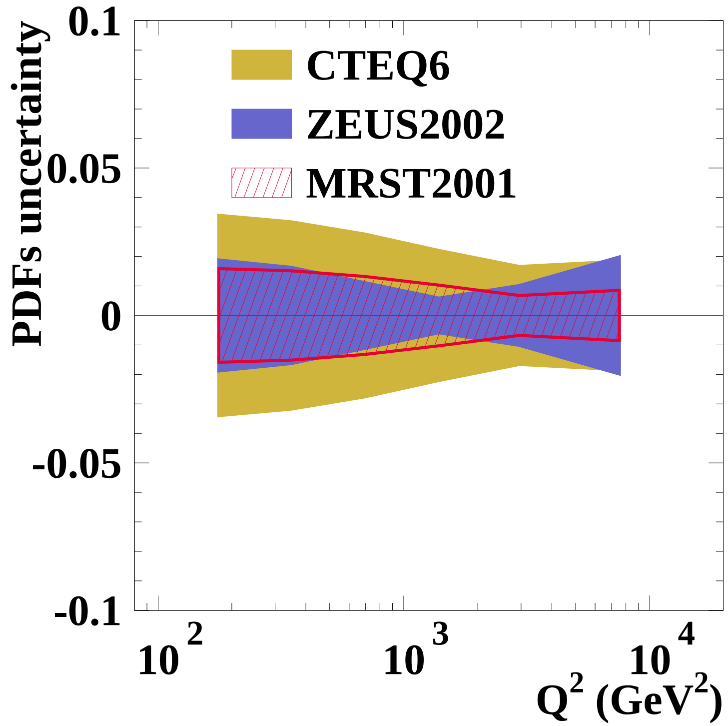
- Theoretical uncertainties on $\alpha_s(M_Z)$:

$\longrightarrow$ Uncertainty of inclusive-jet cross section from terms beyond NLO as a function of Q^2 estimated by varying μ_R by factors 2 and 0.5

$\longrightarrow$ decreases with increasing Q^2

$\longrightarrow$ partially cancels in ratios of cross sections

- PDF uncertainty of inclusive-jet cross section as a function of Q^2 for various PDF sets $\longrightarrow$



- PDF uncertainty on $\alpha_s(M_Z)$:

ZEUS-S	$\longrightarrow$	/ $\pm 0.7\%$
MRST-2008	$\longrightarrow$	0.4-0.7% / $\pm 0.7\%$
CTEQ6	$\longrightarrow$	0.8-1.5% / $\pm 1.5\%$

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Jet cross sections in NC DIS at high Q^2: update

$ep \rightarrow e + \text{jet} + X$: 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 $-2 < \eta_{\text{B}}^{\text{jet}} < 1.5$

- **Smaller experimental uncertainties**
  - $\rightarrow$ uncorrelated: $\sim \pm 3\ (7)\%$ at low (high) $Q^2/E_{T,\text{B}}^{\text{jet}}$
  - $\rightarrow$ correlated: $\sim \pm 5\ (2)\%$ at low (high) $Q^2/E_{T,\text{B}}^{\text{jet}}$

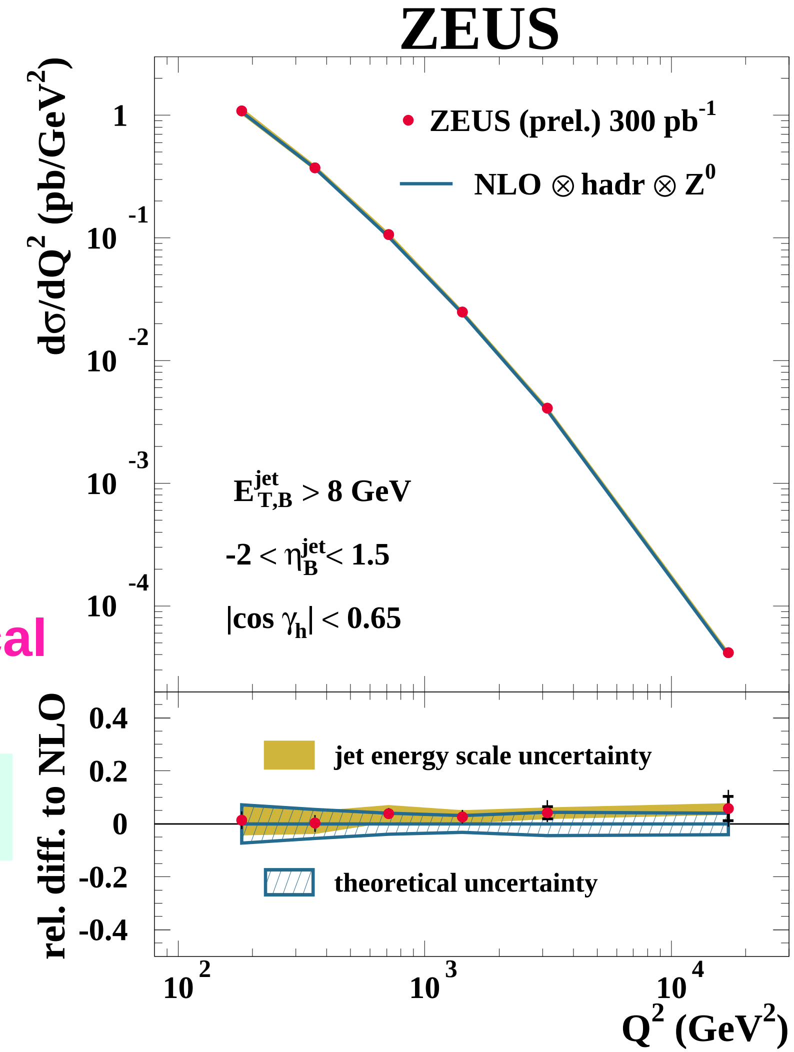
$\rightarrow$ The measured jet cross sections are well described by NLO QCD

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

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

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

theoretical uncertainty: $\pm 1.9\%$



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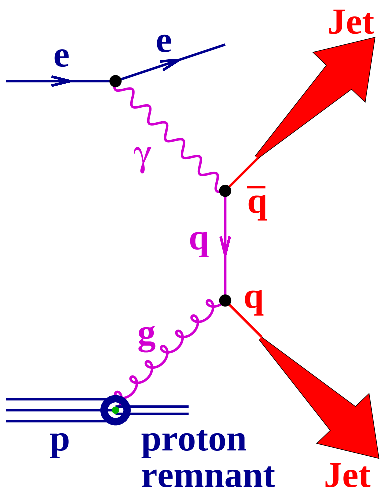
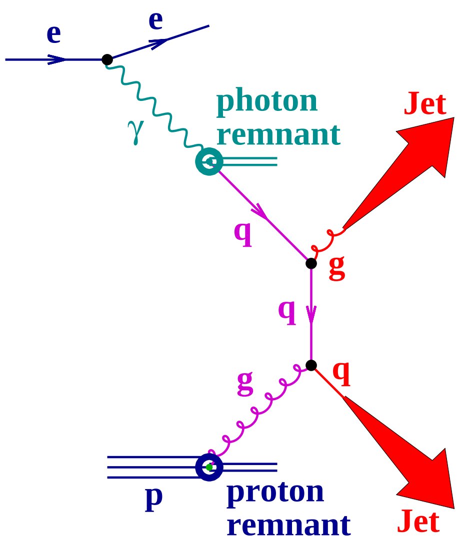
Jets in PHP at HERA

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



direct photoproduction



resolved photoproduction

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

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

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

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

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

Jet cross sections in PHP at high $E_T^{\rm jet}$

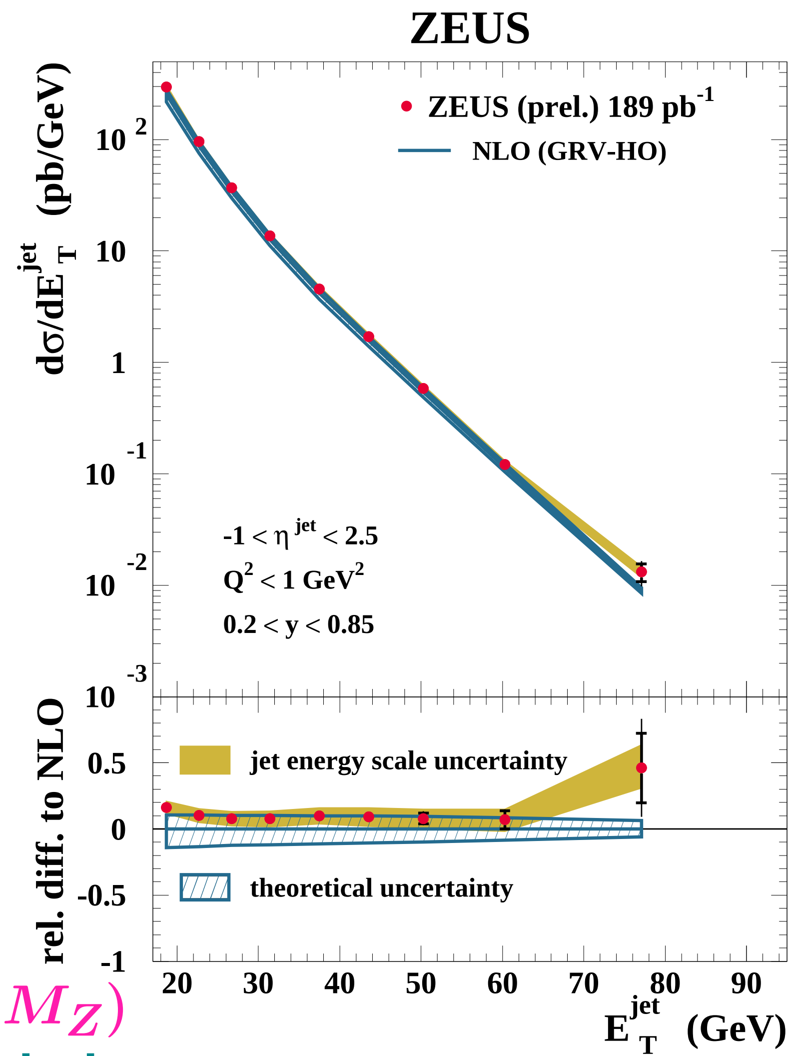
$ep \rightarrow e + \text{jet} + X$: inclusive jets at high $E_T^{\rm jet}$

$\mathcal{L} = 189$ 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 $E_T^{\rm jet} > 17$ GeV and $-1 < \eta^{\rm jet} < 2.5$
- Small experimental uncertainties
  - $\rightarrow$ uncorrelated: typically $< \pm 4\%$
  - $\rightarrow$ correlated: $\sim \pm 5\%$
- NLO predictions using Klasen et al
  - $\rightarrow$ $\mu_R = \mu_F = E_T^{\rm jet}$; pPDFs: ZEUS-S; γPDFs: GRV-HO corrected for hadronisation effects
- Theoretical uncertainties:
  - $\rightarrow$ higher orders ($\pm 10\ (7)\%$ at low (high) $E_T^{\rm jet}$)
  - $\rightarrow$ proton PDFs ($\pm 1\ (5)\%$ at low (high) $E_T^{\rm jet}$)
  - $\rightarrow$ photon PDFs ($-10\ (-2)\%$ at low (high) $E_T^{\rm jet}$)
  - $\rightarrow$ parton-to-hadron corrections (below $\pm 3\%$)

$\rightarrow$ **The measured jet cross sections are well described by NLO QCD**

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



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α_s from jet cross sections: PHP at high $E_T^{\rm jet}$

- From the measured $d\sigma/dE_T^{\rm jet}$ for $21 < E_T^{\rm jet} < 71$ GeV values of $\alpha_s(M_Z)$ were extracted:

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

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

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

- Experimental uncertainties:
  $\longrightarrow$ dominated by jet energy scale uncertainty: $\Delta\alpha_s/\alpha_s = \pm 1.7\%$
- Theoretical uncertainties:

		k_T	anti-k_T	SIScone
$\longrightarrow$ terms beyond NLO:	$\Delta\alpha_s/\alpha_s(\%) =$	$^{+2.4}_{-2.5}$	$^{+2.3}_{-2.4}$	$^{+3.2}_{-3.4}$
$\longrightarrow$ uncertainties from pPDFs:	$\Delta\alpha_s/\alpha_s(\%) =$	± 1.0	± 0.9	± 0.9
$\longrightarrow$ uncertainties from γPDFs:	$\Delta\alpha_s/\alpha_s(\%) =$	$+2.4$	$+2.4$	$+2.1$
$\longrightarrow$ hadronisation corrections:	$\Delta\alpha_s/\alpha_s(\%) =$	± 0.5	± 0.4	± 0.2

$\longrightarrow$ $\alpha_s(M_Z)$ from inclusive-jet cross sections in PHP at high $E_T^{\rm jet}$:

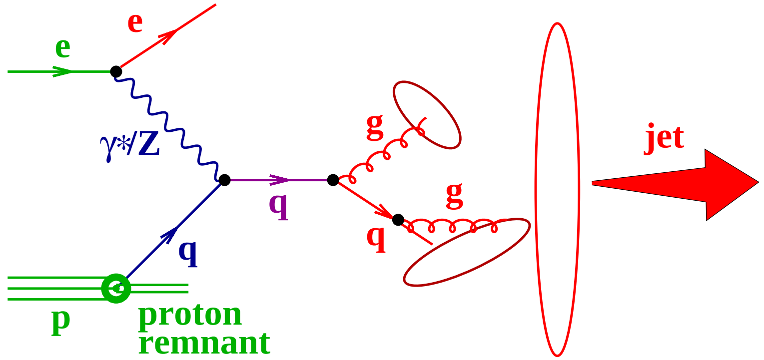
$\longrightarrow$ precise determination using	k_T	anti-k_T	SIScone
$\longrightarrow$ total uncertainty (%):	$^{+4.1}_{-3.3}$	$^{+4.1}_{-3.2}$	$^{+4.4}_{-3.9}$
$\longrightarrow$ theoretical uncertainty (%):	$^{+3.6}_{-2.7}$	$^{+3.5}_{-2.6}$	$^{+3.9}_{-3.5}$

ZEUS Collab, ZEUS-prel-10-003 ZEUS Collab, ZEUS-prel-10-015

Jet substructure and QCD predictions

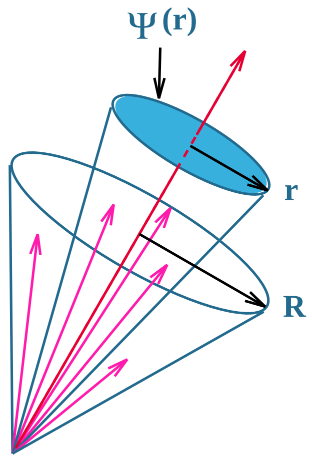
- The investigation of the internal structure of jets gives insight into the transition between a parton produced in a hard process and the experimentally observable jet of hadrons

- QCD predictions:
  - → jet substructure driven by gluon emission off primary partons (at sufficiently high $E_T^{\rm jet}$, fragmentation effects negligible)
  - → gluon jets are broader than quark jets (larger colour charge of the gluon)
  - → jet substructure depends mainly on flavour of primary parton from which the jet originated and to a lesser extent on the hard scattering process



Jet substructure: integrated jet shape

- $\psi(r)$: fraction of the jet transverse energy that lies inside a cone in the $\eta - \phi$ plane of radius r, concentric with the jet axis



$$\psi(r) = \frac{E_T(r)}{E_T^{\rm jet}} \longrightarrow \langle\psi(r)\rangle = \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_T(r)}{E_T^{\rm jet}}$$

mean integrated jet shape

Jet substructure: subjet multiplicity

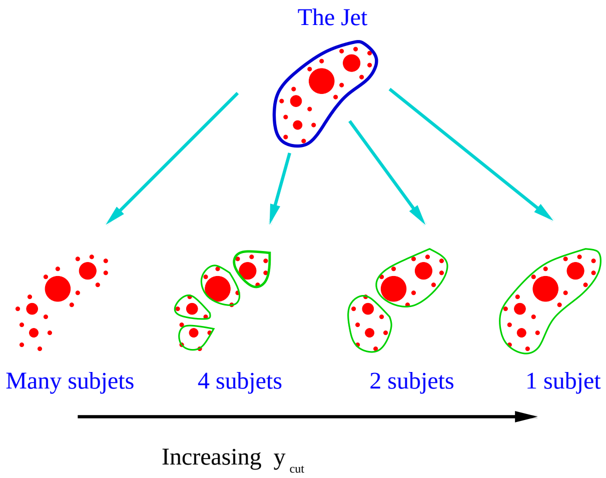
- **subjets:** are resolved within a jet by reapplying the k_T cluster algorithm until for every pair of particles i, j

$$d_{ij} = \min(E_{Ti}, E_{Tj})^2[(\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2]$$

is above $y_{\rm cut} \cdot (E_T^{\rm jet})^2$

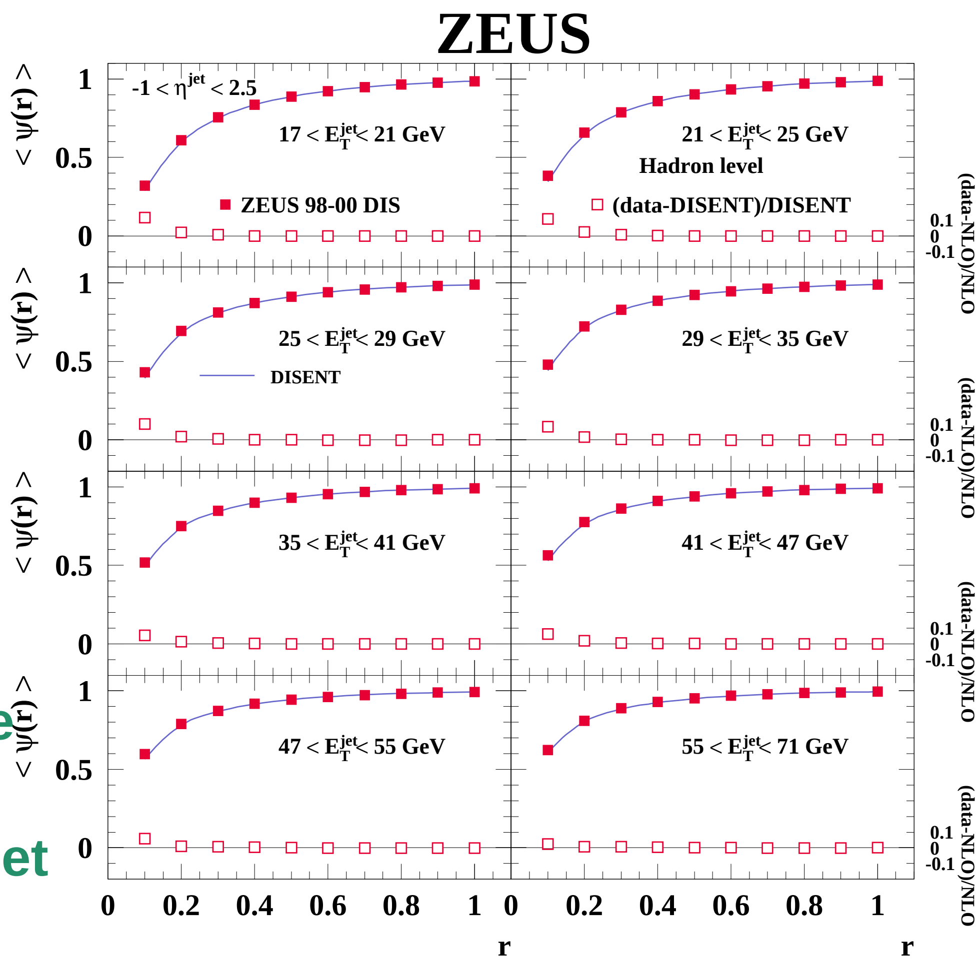
$$\longrightarrow \langle n_{\rm subjet}(y_{\rm cut})\rangle = \frac{1}{N_{\rm jets}} \sum_{i=1}^{N_{\rm jets}} n_{\rm subjet}^i(y_{\rm cut})$$

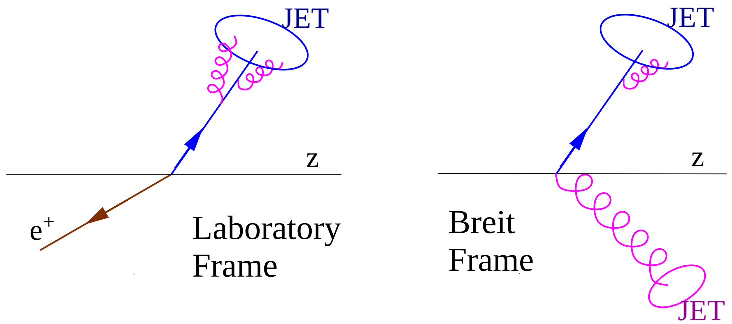
mean subjet multiplicity



Jet shapes in NC DIS at high E_T^{jet}

- E_T^{jet} dependence of $\langle\psi(r)\rangle$ in NC DIS
  - Jets searched using the k_T cluster algorithm in Laboratory frame
  - Kinematic region: $Q^2 > 125$ GeV^2
  - At least one jet with $E_T^{jet} > 17$ GeV and $-1 < \eta^{jet} < 2.5$
- $\langle\psi(r)\rangle$ vs r in different E_T^{jet} regions:
  → the jets become narrower as E_T^{jet} increases
- Comparison to QCD predictions:
  → NLO predictions in NC DIS are possible in LAB frame from $\mathcal{O}(\alpha_s^2)$ calculations since three partons can be inside one jet





→ the data are well described by the NLO QCD calculations for $r > 0.1$

ZEUS Collab, Nucl Phys B 700 (2004) 3

α_s from internal structure of jets: NC DIS at high $E_T^{\rm jet}$

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

- From the measured $\langle\psi(r = 0.5)\rangle$ for $E_T^{\rm jet} > 21$ GeV a value of $\alpha_s(M_Z)$ was extracted:

$$\alpha_s(M_Z) = 0.1176\ ^{+0.0013}_{-0.0028}\ (\text{exp.})\ ^{+0.0091}_{-0.0072}\ (\text{th.})$$

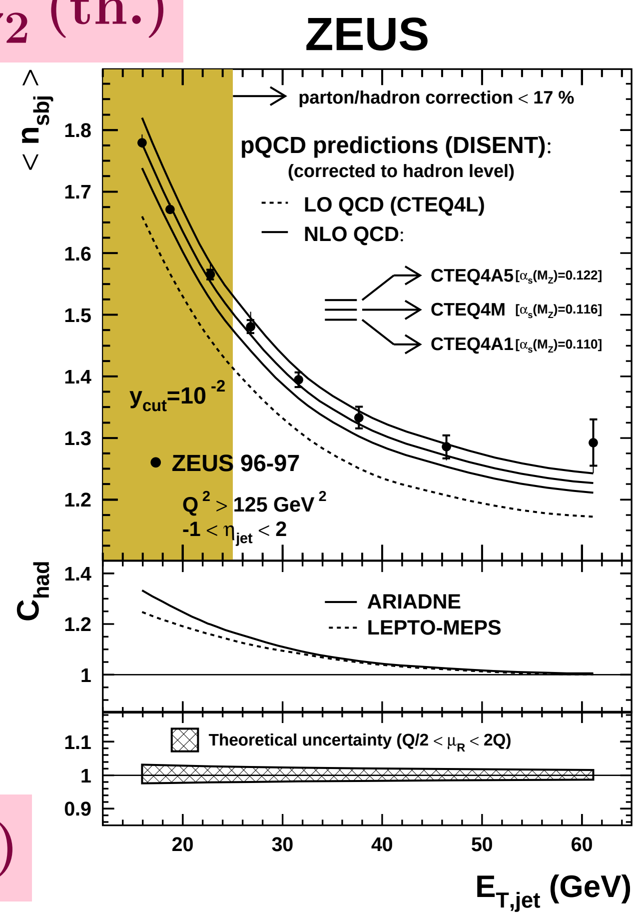
- Experimental uncertainties:

$$\Delta\alpha_s/\alpha_s = ^{+0.8}_{-2.2}\%$$

- Theoretical uncertainties:
  - $\longrightarrow$ terms beyond NLO: $\Delta\alpha_s/\alpha_s = ^{+7.6}_{-6.0}\%$
  - $\longrightarrow$ uncertainties from pPDFs: negligible
  - $\longrightarrow$ hadronisation corrections: $\Delta\alpha_s/\alpha_s = \pm 1.5\%$

- From the measured $\langle n_{\rm subjet}(y_{\rm cut} = 10^{-2})\rangle$ for $25 < E_T^{\rm jet} < 71$ GeV a value of $\alpha_s(M_Z)$ was extracted:

$$\alpha_s(M_Z) = 0.1187\ ^{+0.0029}_{-0.0019}\ (\text{exp.})\ ^{+0.0093}_{-0.0076}\ (\text{th.})$$

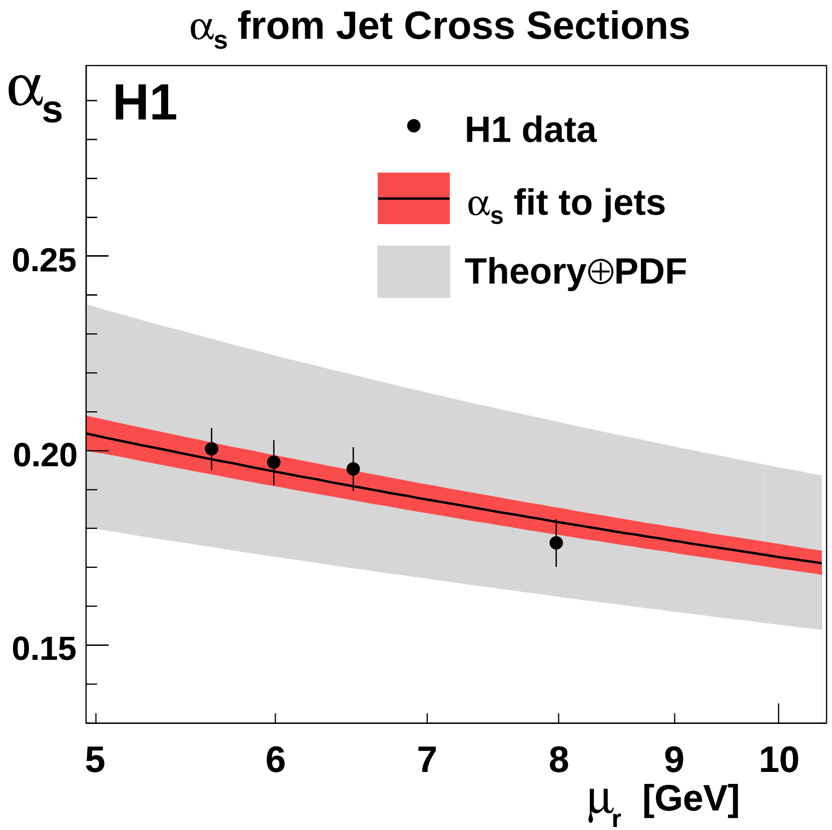


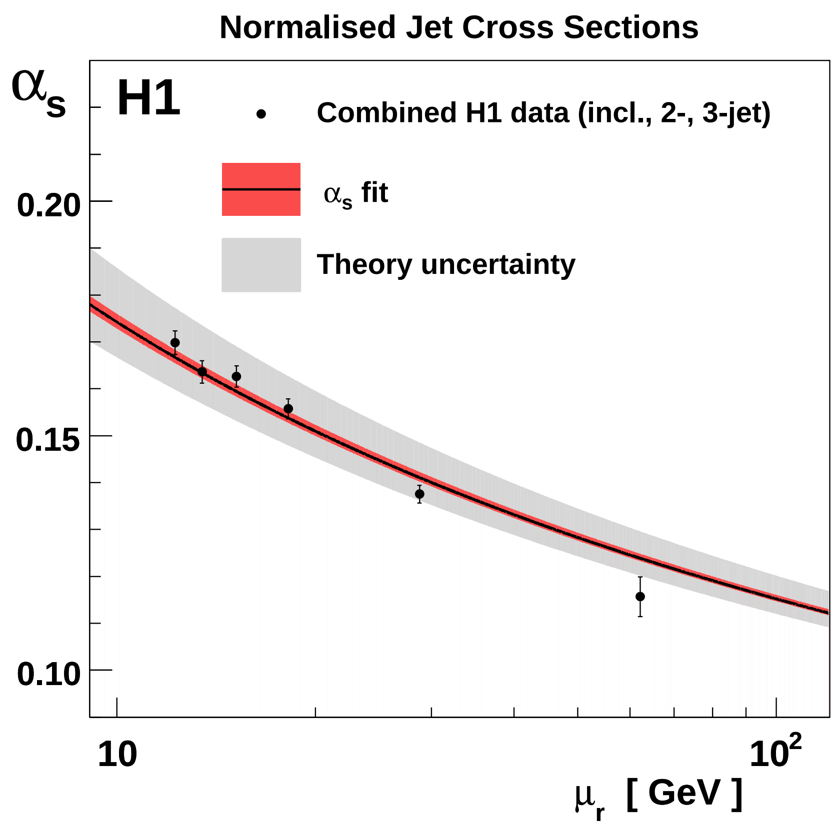
ZEUS Collab, Nucl Phys B 700 (2004) 3

ZEUS Collab, Phys Lett B 558 (2003) 41

α_s running: NC DIS from low to medium Q^2

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





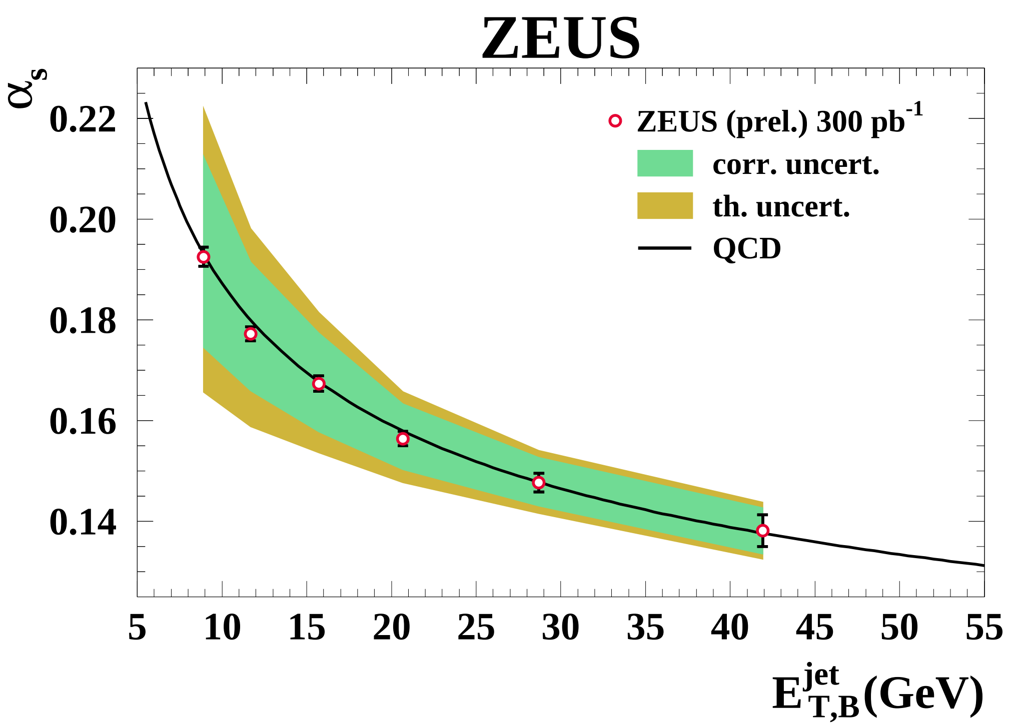
→ The results are in good agreement with the predicted running of α_s with small experimental uncertainties in a wide range of the scale

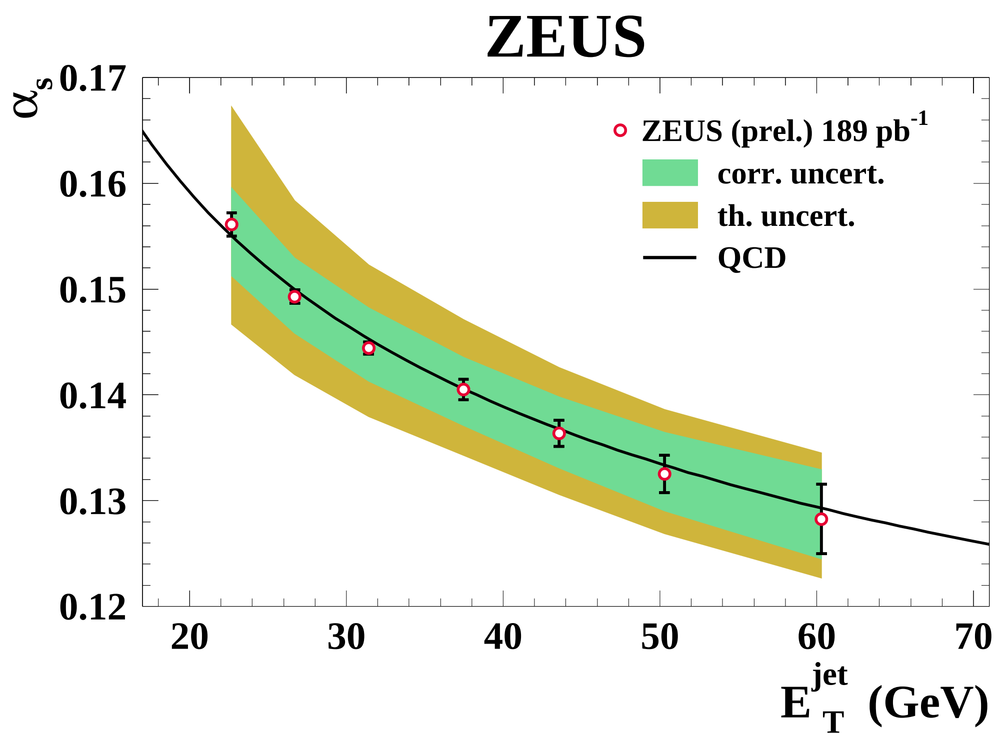
H1 Collab, Eur Phys J C 67 (2010) 1

H1 Collab, EPJ C 65 (2010) 363

α_s running: NC DIS and PHP at high $E_T^{\rm jet}$

- The energy-scale dependence of the coupling was determined by extracting α_s from the measured jet cross sections from low to high $E_T^{\rm jet}$:





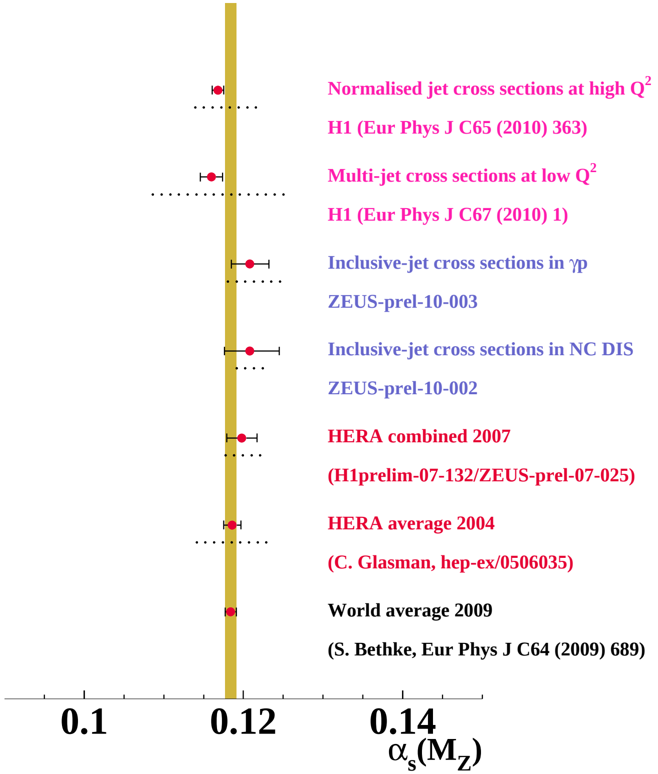
→ The results are in good agreement with the predicted running of α_s with small experimental uncertainties in a wide range of the scale

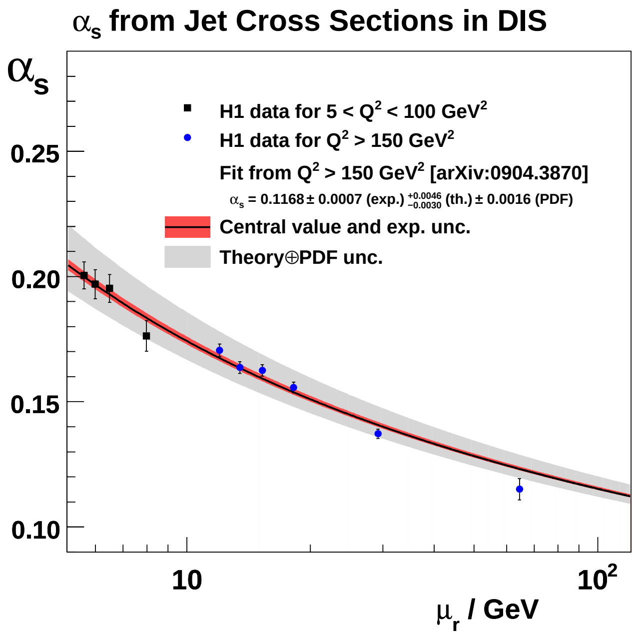
ZEUS Collab, ZEUS-prel-10-002 ZEUS Collab, ZEUS-prel-10-003

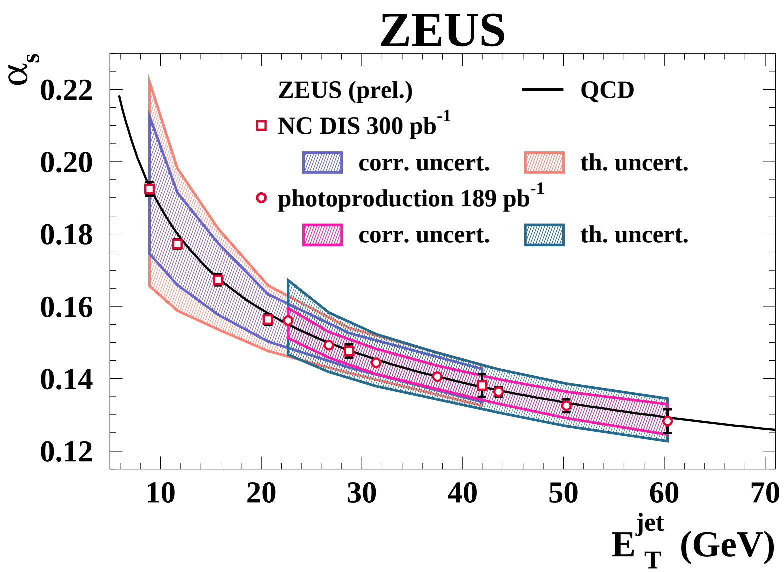
Summary and Conclusions

- **Jet physics at HERA provides**
  - → precise values of $\alpha_s(M_Z)$ in different regimes
  - → precise determinations of the running of α_s over a wide range of the scale
- **Room for improvement?**
  - → all HERA data analysed: experimental uncertainties in α_s small
  - → theoretical uncertainties dominant (terms beyond NLO)

⇒ NNLO calculations for jet cross sections at HERA needed to improve precision on α_s further



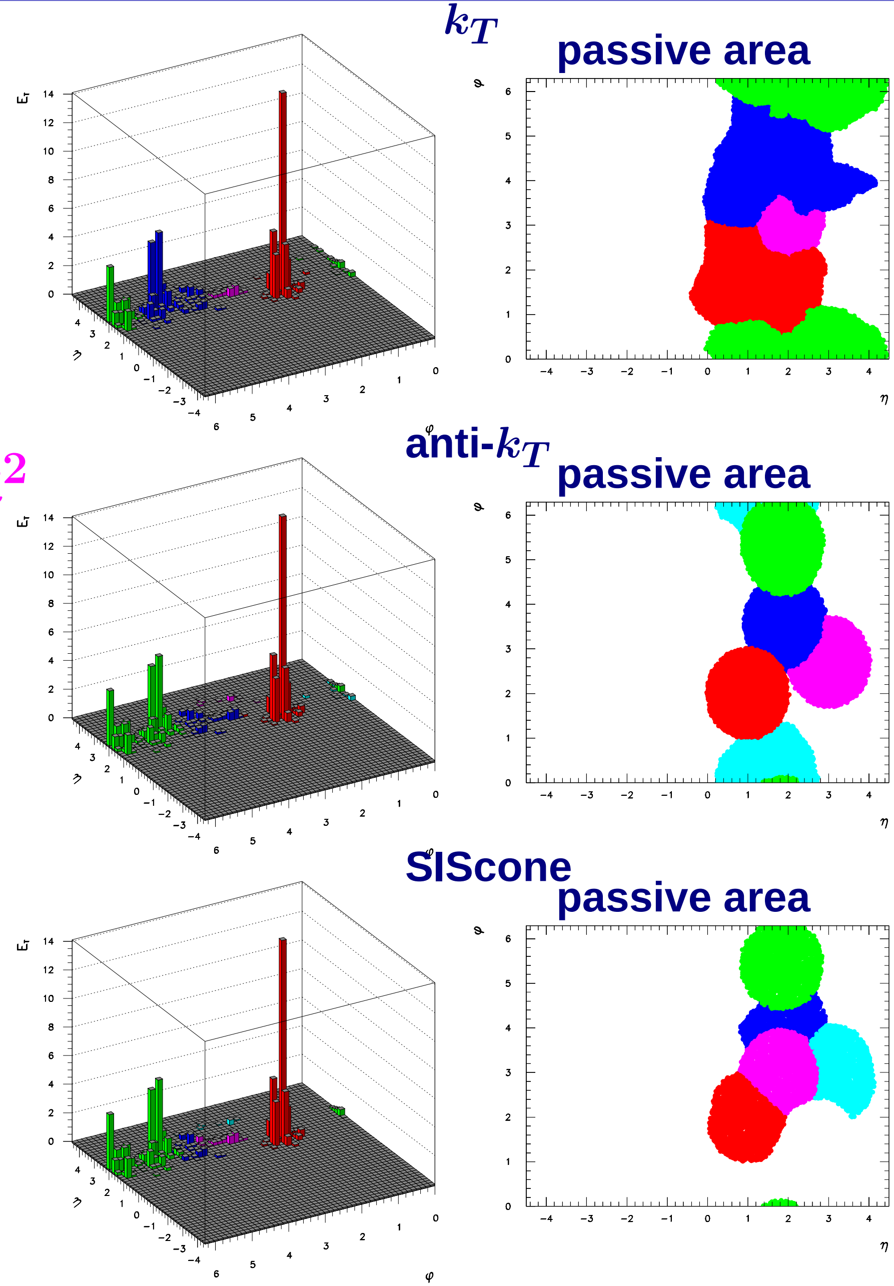




Back-up slides

Tests of pQCD: k_T vs anti-k_T vs SIScone

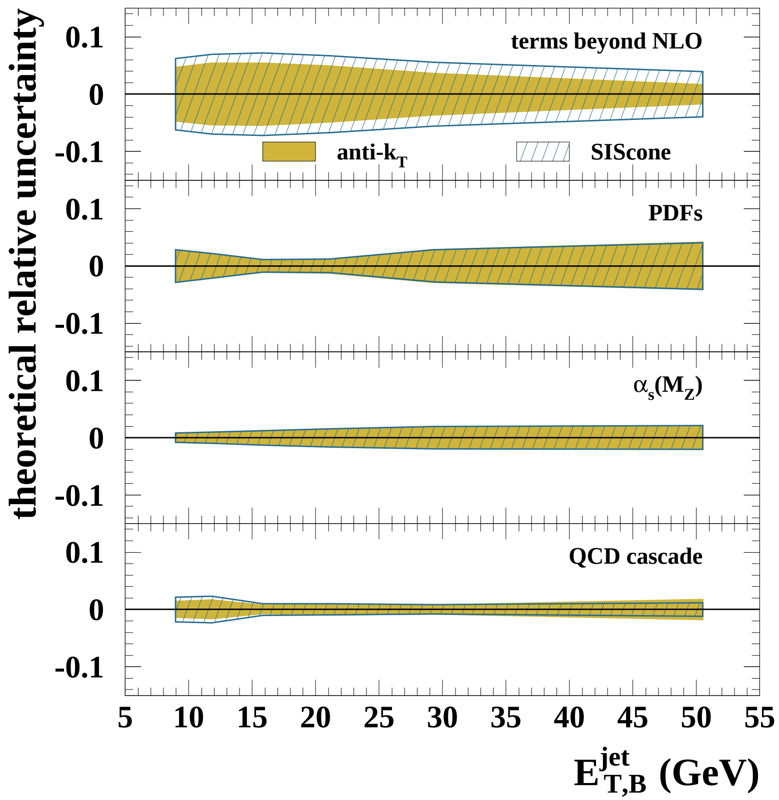
- New infrared- and collinear-safe jet algorithms:
  - $\longrightarrow$ anti-k_T (M Cacciari, G Salam & G Soyez) and SIScone (G Salam & G Soyez)
- Cluster algorithms:
  - $\longrightarrow$ $d_{ij} = \min[(E^i_{T,\mathrm{B}})^{2p}, (E^j_{T,\mathrm{B}})^{2p}] \cdot \Delta R^2/R^2$ with $p = 1$ (-1) for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

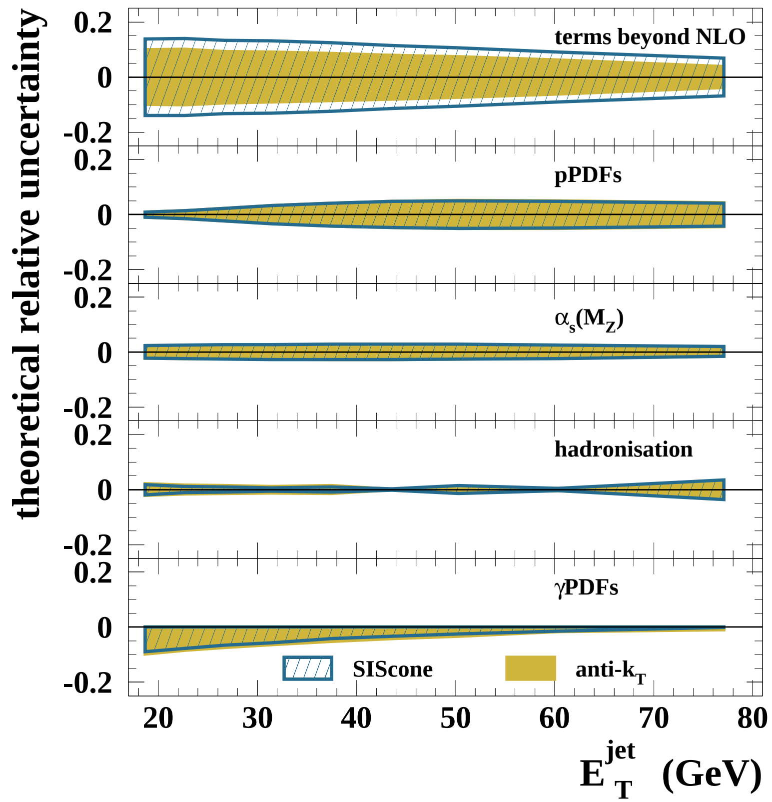
- **Theoretical uncertainties:**
  - → PDFs and value of $\alpha_s(M_Z)$:
    - → very similar for all three jet algorithms
  - → terms beyond NLO and QCD cascade/hadronisation modelling:
    - → very similar for k_T and anti-k_T; somewhat larger for SIScone

NC DIS



ZEUS Collab, Phys Lett B 691 (2010) 127

PHP



ZEUS Collab, ZEUS-prel-10-015

HERA averages

Comparison of $\alpha_s(M_Z)$ determinations at HERA

- Determinations of $\alpha_s(M_Z)$ by ZEUS and H1 from jet cross sections, ratios, internal structure of jets and structure functions:

Process	Collab.	Value	Stat.	Exp.	Th.	Total	(%)
Inc. Jet NC DIS	ZEUS	0.1212	0.0017	$^{+0.0023}_{-0.0031}$	$^{+0.0028}_{-0.0027}$	$^{+0.0040}_{-0.0044}$	~ 3.5
Inc. Jet NC DIS	H1	0.1186	$\rightarrow$	$^{+0.0030}_{-0.0030}$	$^{+0.0051}_{-0.0051}$	$^{+0.0059}_{-0.0059}$	~ 5
Inc. Jet γp	ZEUS	0.1224	0.0001	$^{+0.0022}_{-0.0019}$	$^{+0.0054}_{-0.0042}$	$^{+0.0058}_{-0.0046}$	~ 4
Dijet NC DIS	ZEUS	0.1166	0.0019	$^{+0.0024}_{-0.0033}$	$^{+0.0057}_{-0.0044}$	$^{+0.0065}_{-0.0058}$	~ 5
3/2 Jet NC DIS	ZEUS	0.1179	0.0013	$^{+0.0028}_{-0.0046}$	$^{+0.0064}_{-0.0046}$	$^{+0.0071}_{-0.0066}$	~ 6
Jet Shapes NC DIS	ZEUS	0.1176	0.0009	$^{+0.0009}_{-0.0026}$	$^{+0.0091}_{-0.0072}$	$^{+0.0092}_{-0.0077}$	~ 7
Subjets NC DIS	ZEUS	0.1187	0.0017	$^{+0.0024}_{-0.0009}$	$^{+0.0093}_{-0.0076}$	$^{+0.0097}_{-0.0078}$	~ 8
Subjets CC DIS	ZEUS	0.1202	0.0052	$^{+0.0060}_{-0.0019}$	$^{+0.0065}_{-0.0053}$	$^{+0.0103}_{-0.0077}$	~ 8
SF	H1	0.1150	$\rightarrow$	$^{+0.0017}_{-0.0017}$	$^{+0.0051}_{-0.0050}$	$^{+0.0054}_{-0.0053}$	~ 4.5
SF	ZEUS	0.1183	$\rightarrow$	$^{+0.0028}_{-0.0028}$	$^{+0.0051}_{-0.0051}$	$^{+0.0058}_{-0.0058}$	~ 5

$\rightarrow$ experimental uncertainties: $\sim 3\%$

$\rightarrow$ theoretical uncertainties: $\sim 4\%$ (jet cross sections and SF)

$\sim 8\%$ (internal structure of jets)

Averaging the determinations of $\alpha_s(M_Z)$ at HERA

- A proper average requires the inclusion of correlations among the different determinations:

$\longrightarrow$ Experimental uncertainties:

– eg jet energy scale (correlated among the determinations from each experiment)

$\longrightarrow$ Theoretical uncertainties:

– parton distribution functions of the proton (correlated)
– hadronisation corrections (partially correlated)
– terms beyond NLO (correlated?)

$\longrightarrow$ Since the theoretical uncertainties are dominant and the biggest contribution arises from the terms beyond NLO

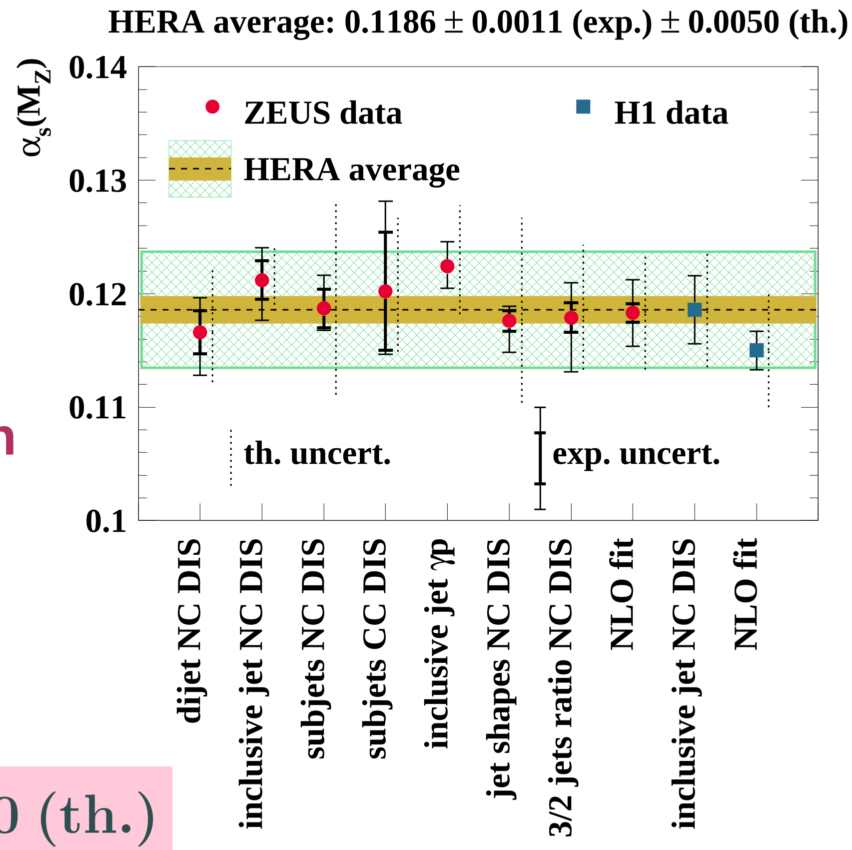
$\longrightarrow$ the difficulty of averaging the determinations of $\alpha_s(M_Z)$ at HERA lies on the treatment of the theoretical uncertainties arising from terms beyond NLO

HERA 2004 average: $\alpha_s(M_Z)$

- **Several methods have been used to obtain an average of $\alpha_s(M_Z)$ at HERA:**
  - $\longrightarrow$ **Naive method:** $\overline{\alpha_s(M_Z)} = 0.1188 \pm 0.0020$
  - $\longrightarrow$ **Schmelling's method:** $\overline{\alpha_s(M_Z)} = 0.1192 \pm 0.0047$
  - $\longrightarrow$ **Correlated sources:**

$$\overline{\alpha_s(M_Z)} = 0.1186 \pm 0.0011\ (\text{exp.}) \pm 0.0050\ (\text{th.})$$
$$= 0.1186 \pm 0.0051$$

- **The last two methods give comparable uncertainties $\longrightarrow$ confidence on the result**
- **The last method is considered to be the most realistic (though conservative) since the known correlations among determinations from the same experiment were taken into account**



- **The HERA average is:**

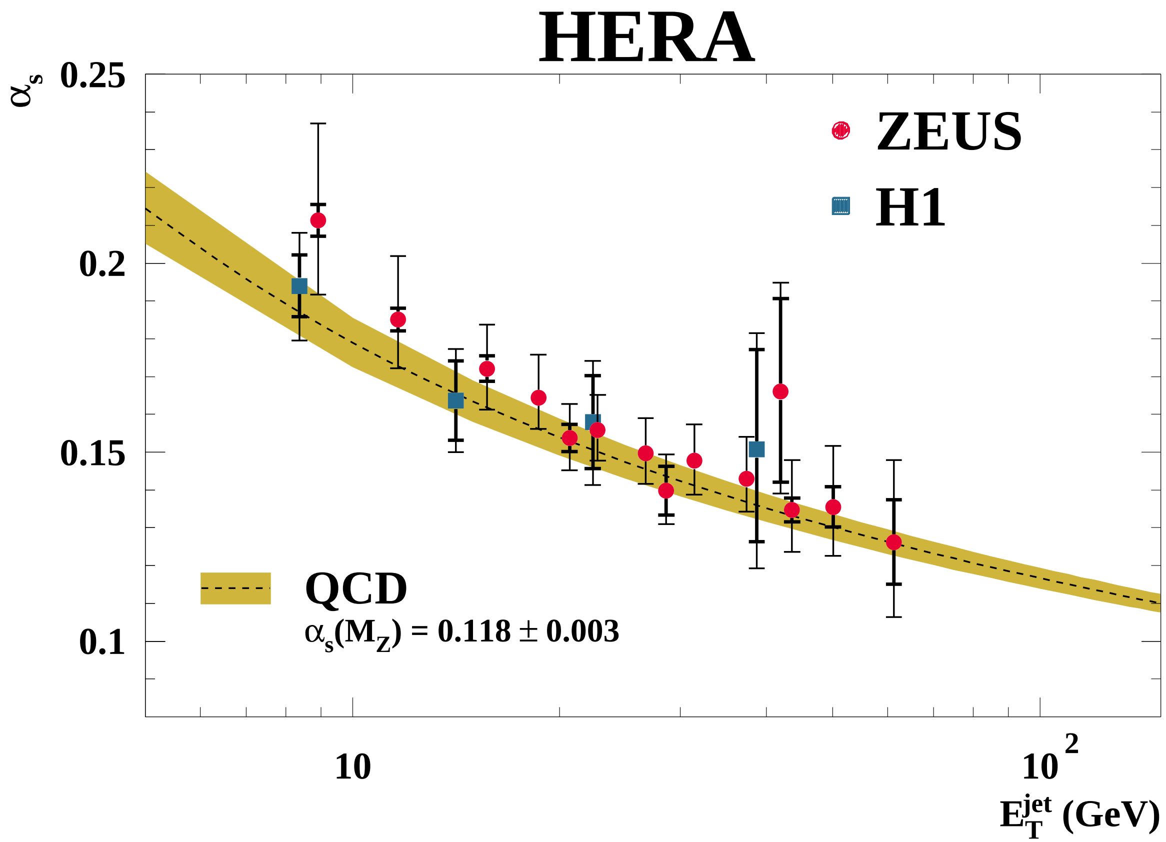
$\longrightarrow$ $\overline{\alpha_s(M_Z)} = 0.1186 \pm 0.0011\ (\text{exp.}) \pm 0.0050\ (\text{th.})$

experimental uncertainty: $\sim 0.9\%$; **theoretical uncertainty:** $\sim 4\%$

C Glasman, hep-ex/0506035

HERA 2004 average: scale dependence of α_s

- The QCD prediction for the energy-scale dependence of α_s was measured by determining α_s from the measured differential cross sections at different E_T^{jet}:

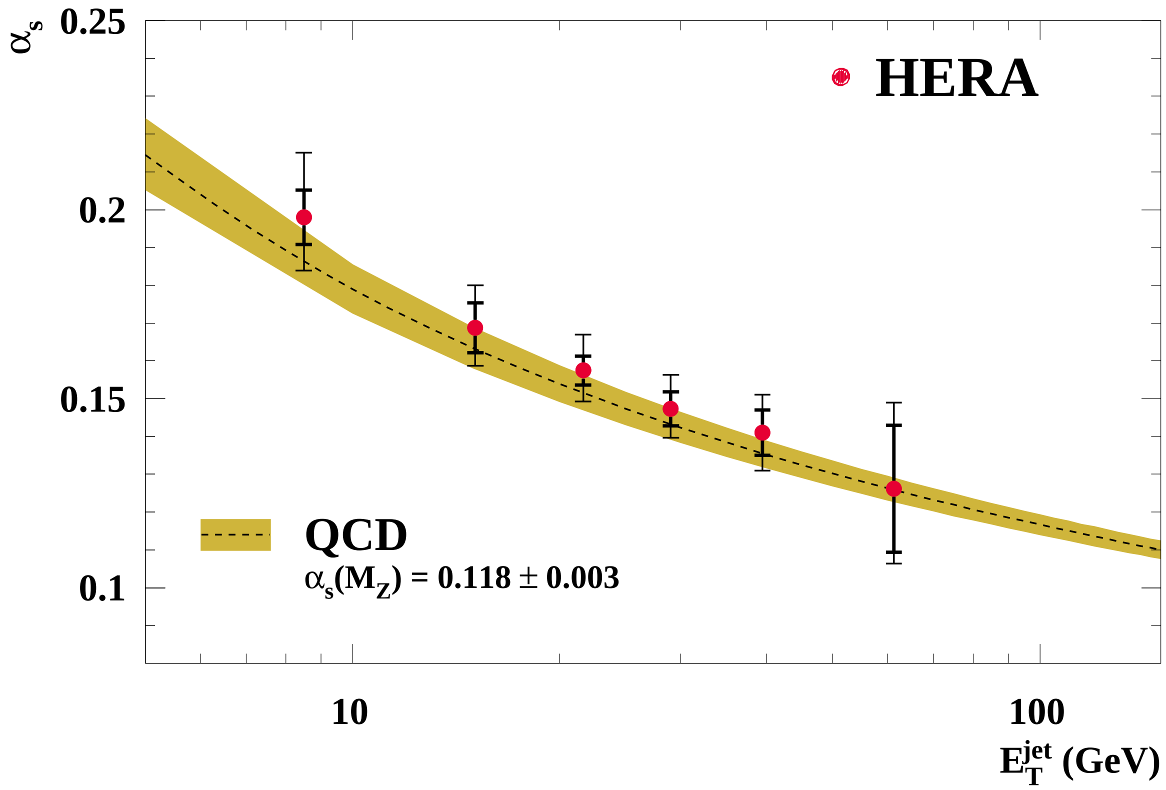


→ The determinations are consistent with the running of α_s predicted by QCD over a large range in E_T^{jet}

C Glasman, hep-ex/0506035

HERA 2004 average: scale dependence of α_s

- Determinations at similar $E_T^{\rm jet}$ were combined using the correlation method:



→ **Observation of the running of α_s over a wide range in the scale from HERA jet data alone**

C Glasman, hep-ex/0506035

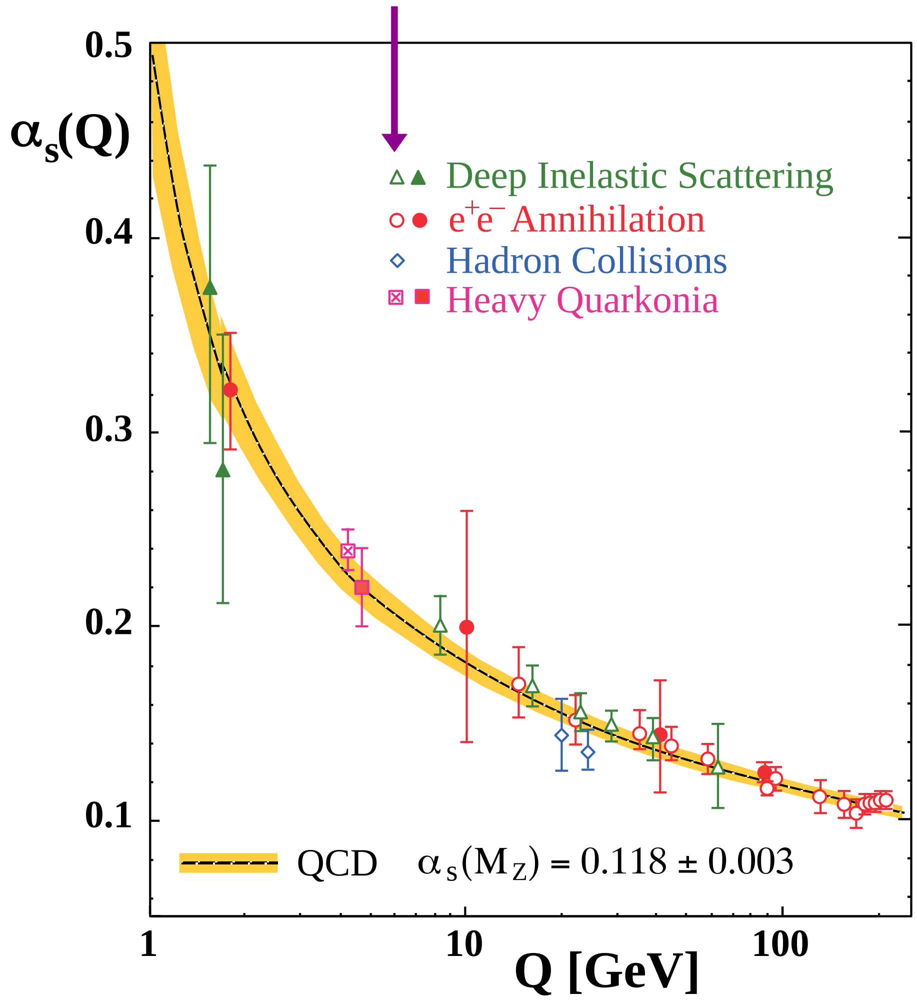
HERA 2004 average: scale dependence of α_s

- Comparison of HERA results with other experiments:

→ HERA determinations consistent with other experiments

→ Uncertainties of HERA determinations very competitive

HERA jet data

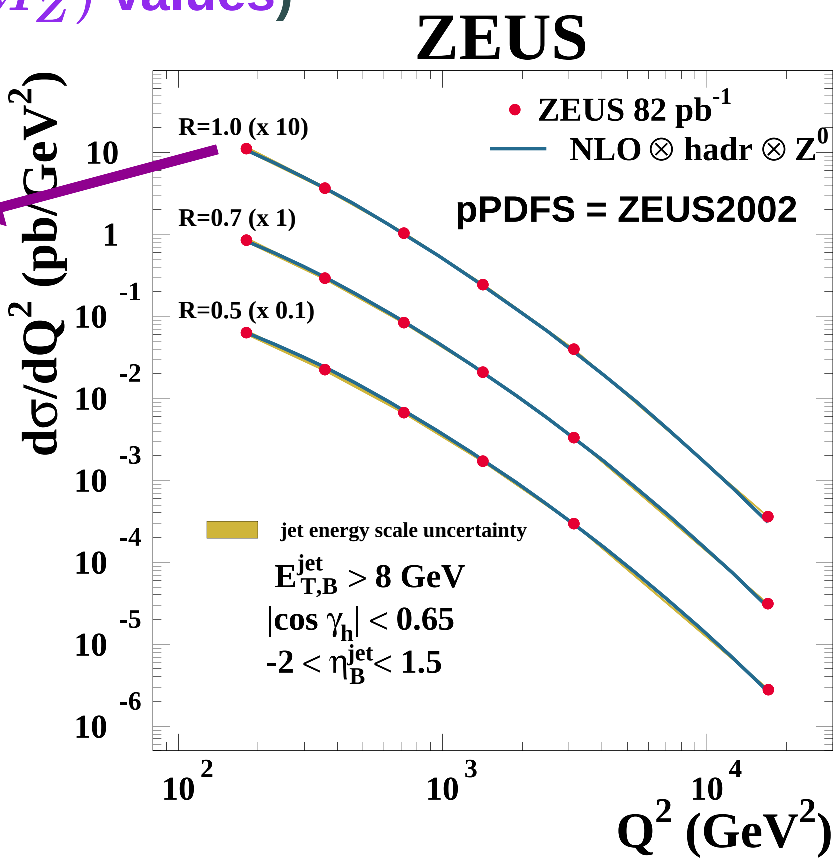


S Bethke and P Zerwas, Physik Journal 3 (2004) 31

HERA 2007 combination: $\alpha_s(M_Z)$

- New $\alpha_s(M_Z)$ combination from inclusive-jet cross sections in NC DIS
  - make a simultaneous fit to ZEUS and H1 data sets which yield the most precise $\alpha_s(M_Z)$ values (instead of combining $\alpha_s(M_Z)$ values)
- From measured $d\sigma/dQ^2$ ($Q^2 > 500$ GeV^2):

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



- Experimental uncertainties:
  - → dominated by jet energy scale uncertainty:

$$\Delta\alpha_s/\alpha_s = \pm 2\%$$

- 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 in the Breit frame: very precise determination at HERA (total uncertainty: $\sim 3.6\%$; theoretical uncertainty: $\sim 1.9\%$)

ZEUS Collab, Phys Lett B 649 (2007) 12

HERA 2007 combination: $\alpha_s(M_Z)$

- New $\alpha_s(M_Z)$ combination from inclusive-jet cross sections in NC DIS
  - make a simultaneous fit to ZEUS and H1 data sets which yield the most precise $\alpha_s(M_Z)$ values (instead of combining $\alpha_s(M_Z)$ values)
- From measured normalised $1/\sigma_{\rm NC}\, d^2\sigma_{\rm jets}/dE^{\rm jet}_{T,\rm B}dQ^2$ ($150 < Q^2 < 15000$):

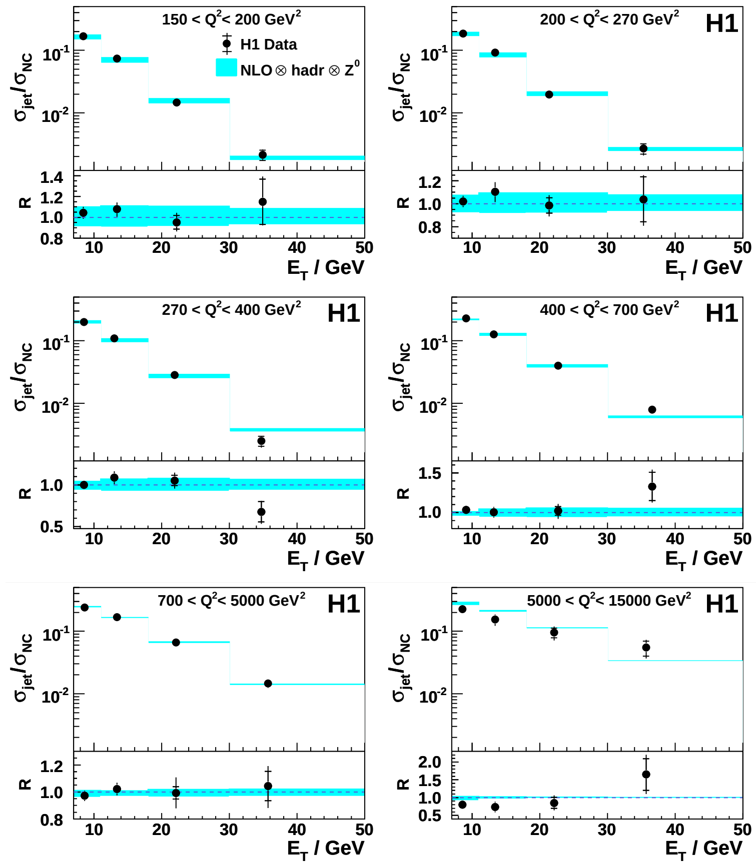
$$\alpha_s(M_Z) = 0.1193 \pm 0.0014\,(\text{exp.})^{+0.0049}_{-0.0034}\,(\text{th.})$$

- Experimental uncertainties:
  - $\longrightarrow$ dominated by jet energy scale uncertainty and model dependence
- Theoretical uncertainties:
  - $\longrightarrow$ terms beyond NLO: dominant
  - $\longrightarrow$ uncertainties from pPDFs: small
  - $\longrightarrow$ uncertainties from μ_F: small
  - $\longrightarrow$ hadronisation corrections: negligible

pPDFS = CTEQ6.5

$\longrightarrow$ $\alpha_s(M_Z)$ from normalised inclusive jet cross sections: very precise determination at HERA
total uncertainty: $\sim 4.3\%$
experimental uncertainty: $\sim 1.1\%$

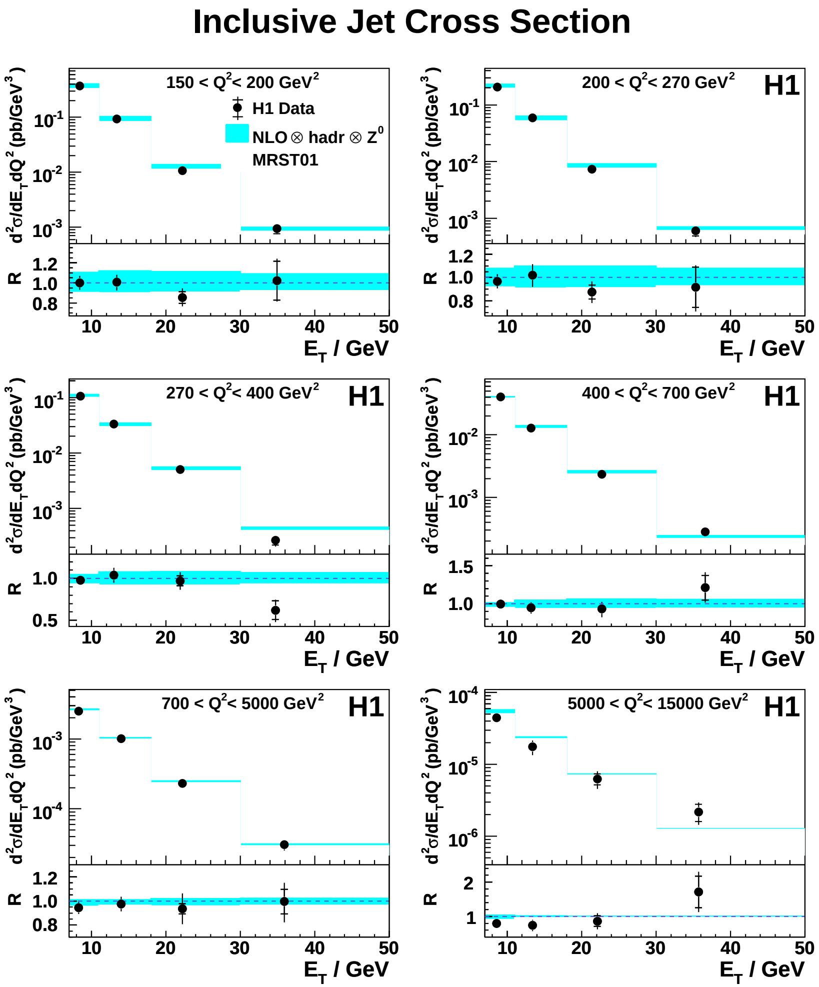
Normalised Inclusive Jet Cross Section



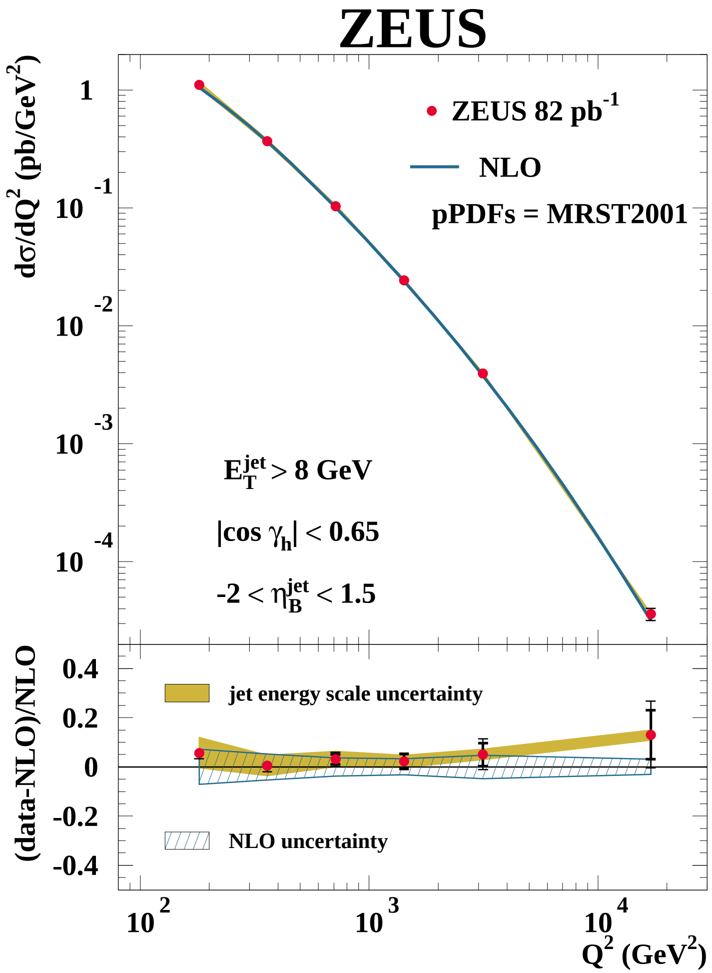
H1 Collab, Phys Lett B 653 (2007) 134

HERA 2007 combination: $\alpha_s(M_Z)$

- **New $\alpha_s(M_Z)$ combination from inclusive-jet cross sections in NC DIS**
  - **make a simultaneous fit to ZEUS and H1 data sets which yield the most precise $\alpha_s(M_Z)$ values (instead of combining $\alpha_s(M_Z)$ values)**



MRST2001



H1 Collab, Phys Lett B 653 (2007) 134

ZEUS Collab, PLB 649 (2007) 12

HERA 2007 combination: $\alpha_s(M_Z)$

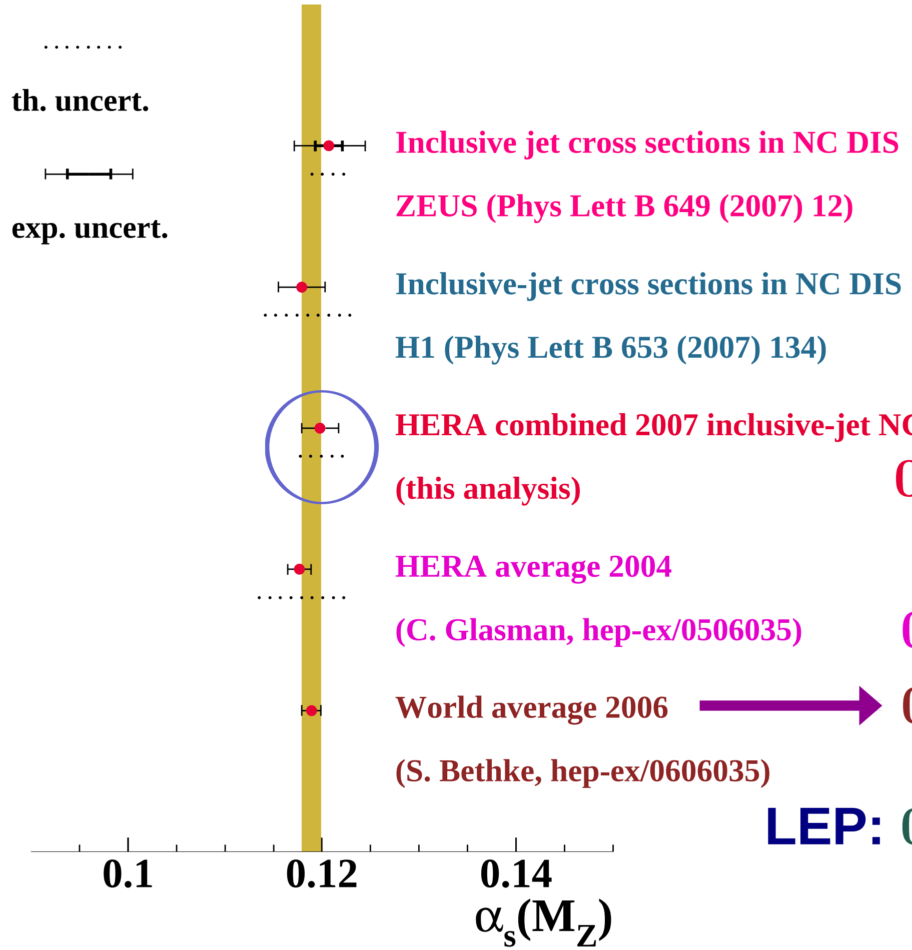
- **Fit to 30 measurements of inclusive-jet cross sections in NC DIS:**
  $\longrightarrow$ 24 H1 data points from double-differential cross section ($150 < Q^2 < 15000$ GeV^2)
  $\longrightarrow$ 6 ZEUS data points from single-differential Q^2 cross section ($125 < Q^2 < 10^5$ GeV^2)
- **NLO QCD calculations:**
  $\longrightarrow$ differential cross sections were calculated at NLO ($\mathcal{O}(\alpha_s^2)$) with:
  - pPDFs: MRST2001 sets
  - renormalisation scale: $\mu_R = E_{T,\mathrm{B}}^{\mathrm{jet}}$ of each jet
  - factorisation scale: $\mu_F = Q$
- **Experimental uncertainties on combined $\alpha_s(M_Z)$:**
  $\longrightarrow$ 0.0019 (obtained using Hessian method; fit sources of systematic uncertainties, eg energy scale, luminosity, model dependence)
- **Theoretical uncertainties on combined $\alpha_s(M_Z)$:**
  $\longrightarrow$ terms beyond NLO: 0.0021 (using Jones et al method, JHEP 122003007)
  $\longrightarrow$ factorisation scale: 0.0010 (obtained by varying μ_F by factors 2 and 0.5 in the calculations)
  $\longrightarrow$ pPDFs: 0.0010 (obtained by using 30 sets of MRST2001)
  $\longrightarrow$ hadronisation: 0.0004 (obtained from different parton-shower models)

H1 Collab (H1prelim-07-132) and ZEUS Collab (ZEUS-prel-07-025)

HERA 2007 combination: $\alpha_s(M_Z)$

- **HERA 2007 combination:**

$$\alpha_s(M_Z) = 0.1198 \pm 0.0019\ (\text{exp.}) \pm 0.0026\ (\text{th.})$$



Measurements consistent with each other and the world average

HERA combined 2007: $0.1198 \pm 0.0019(\text{exp}) \pm 0.0026(\text{th})$ (2.7%)

HERA average 2004: $0.1186 \pm 0.0011(\text{exp}) \pm 0.0050(\text{th})$ (4.3%)

World average 2006 → 0.1189 ± 0.0010 (0.8%)

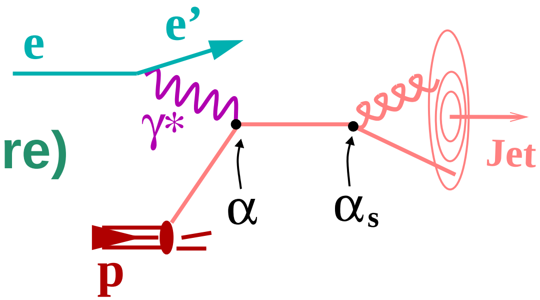
LEP: $0.1211 \pm 0.0010(\text{exp}) \pm 0.0018(\text{th})$ (1.7%)

HERA α_s Working Group

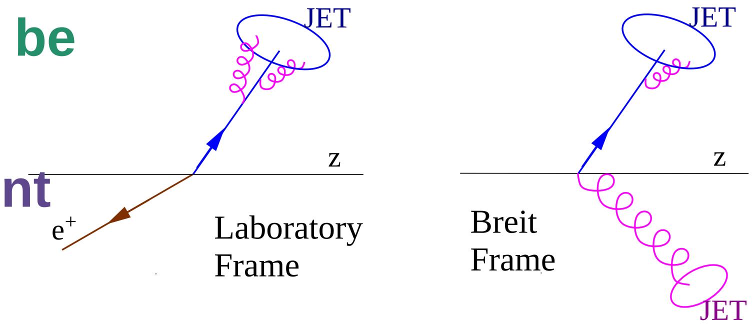
H1 Collab (H1prelim-07-132) and ZEUS Collab (ZEUS-prel-07-025)

QCD calculations of jet substructure

- **QCD-based Monte Carlo models:**
  - $\longrightarrow$ PYTHIA, HERWIG, ARIADNE, LEPTO **approximate the substructure of jets with parton showers**



- **Fixed-order QCD calculations:**
  - $\longrightarrow$ **at lowest order, a jet consists of one parton (no structure)**
  - $\longrightarrow$ **higher-order terms give the non-trivial contributions**
  - $\longrightarrow$ **NLO calculations in NC DIS are possible in LAB frame from $\mathcal{O}(\alpha_s^2)$ predictions since three partons can be inside one jet**



- **Measurements of jet substructure provide a stringent test of pQCD calculations directly beyond LO**
- **pQCD calculations of jet shapes:**

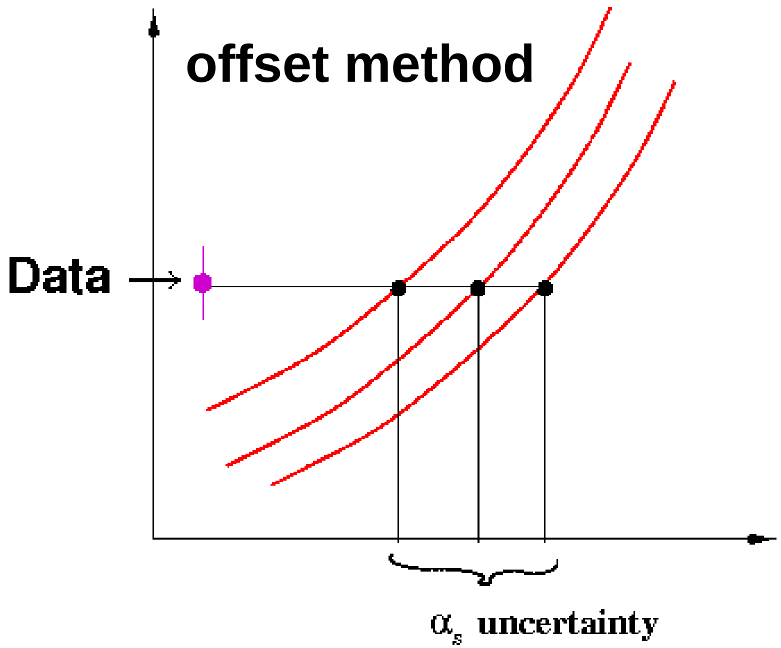
$$\langle 1-\psi(r)\rangle = \frac{\int_r^R dE_T\ (E_T/E_T^{\rm jet})[d\sigma(ep\rightarrow 2{\rm partons})/dE_T]}{\sigma_{\rm jet}(E_T^{\rm jet})}$$

- **pQCD calculations of subjet multiplicities:**

$$\langle n_{\rm subjet}(y_{\rm cut})\rangle = 1+\frac{1}{\sigma_{\rm jet}}\sum_{j=2}^{\infty}(j-1)\cdot\sigma_{{\rm sbj},j}(y_{\rm cut}) = 1 + C_1\,\alpha_s + C_2\,\alpha_s^2$$

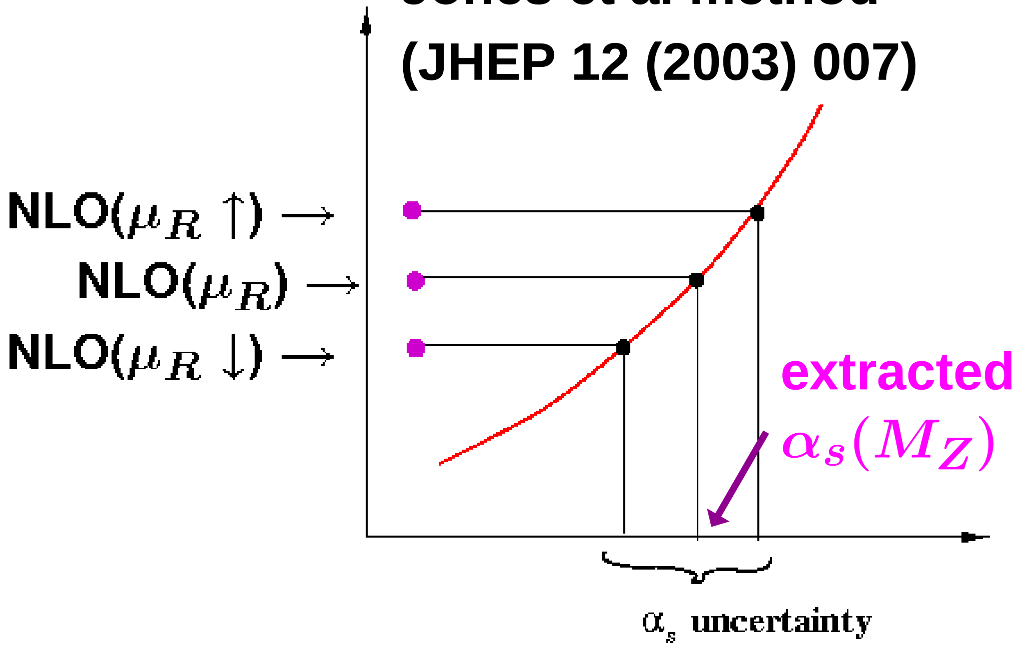
Theoretical uncertainties: offset method vs Jones et al method

subject to fluctuations in data



independent of data

Jones et al method (JHEP 12 (2003) 007)



terms beyond NLO

		anti-k_T	SIScone
→ **offset method:**	$\Delta\alpha_s/\alpha_s =$	$\pm 1.1\%$	$\pm 1.9\%$
→ **Jones et al method:**	$\Delta\alpha_s/\alpha_s =$	$^{+1.4}_{-1.5}\%$	$^{+1.6}_{-1.7}\%$

ZEUS Collab, Phys Lett B 691 (2010) 127

α_s from jet cross sections: NC DIS at medium Q^2

- $\alpha_s(M_Z)$ from the measured $d^2\sigma_{\rm jets}/dE^{\rm jet}_{T,{\rm B}}dQ^2$ for $150 < Q^2 < 15000$ GeV^2:

$$\alpha_s(M_Z) = 0.1179 \pm 0.0024\,({\rm exp.})^{+0.0052}_{-0.0032}\,({\rm th.}) \pm 0.0028\,({\rm pdf})$$

$\longrightarrow$ experimental, theoretical and PDFs uncertainties go up

$\alpha_s(M_Z)$ from the normalised $1/\sigma_{\rm NC}\, d^2\sigma_{\rm jets}/dE^{\rm jet}_{T,{\rm B}}dQ^2$ for $150 < Q^2 < 15000$ GeV^2:

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

- $\alpha_s(M_Z)$ from the measured normalised $1/\sigma_{\rm NC}\, d^2\sigma_{\rm jets}/dE^{\rm jet}_{T,{\rm B}}dQ^2$ for $700 < Q^2 < 5000$ GeV^2:

$$\alpha_s(M_Z) = 0.1171 \pm 0.0023\,({\rm exp.})^{+0.0032}_{-0.0010}\,({\rm th.}) \pm 0.0010\,({\rm pdf})$$

$\longrightarrow$ experimental uncertainty goes up, theoretical and PDFs uncertainties go down

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