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Precision measurements of α_s at HERA

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ZEUS Collab.

H1 Collab.

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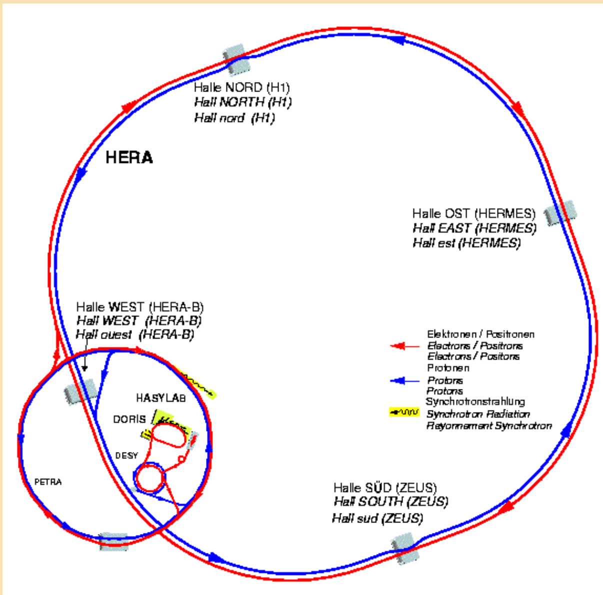
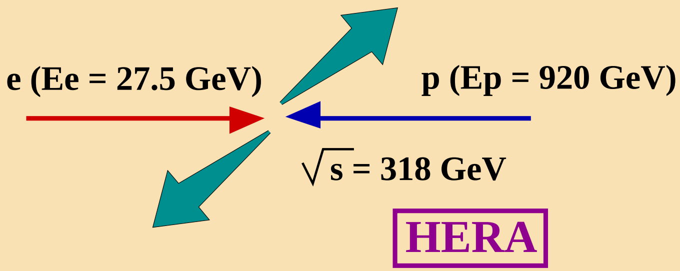




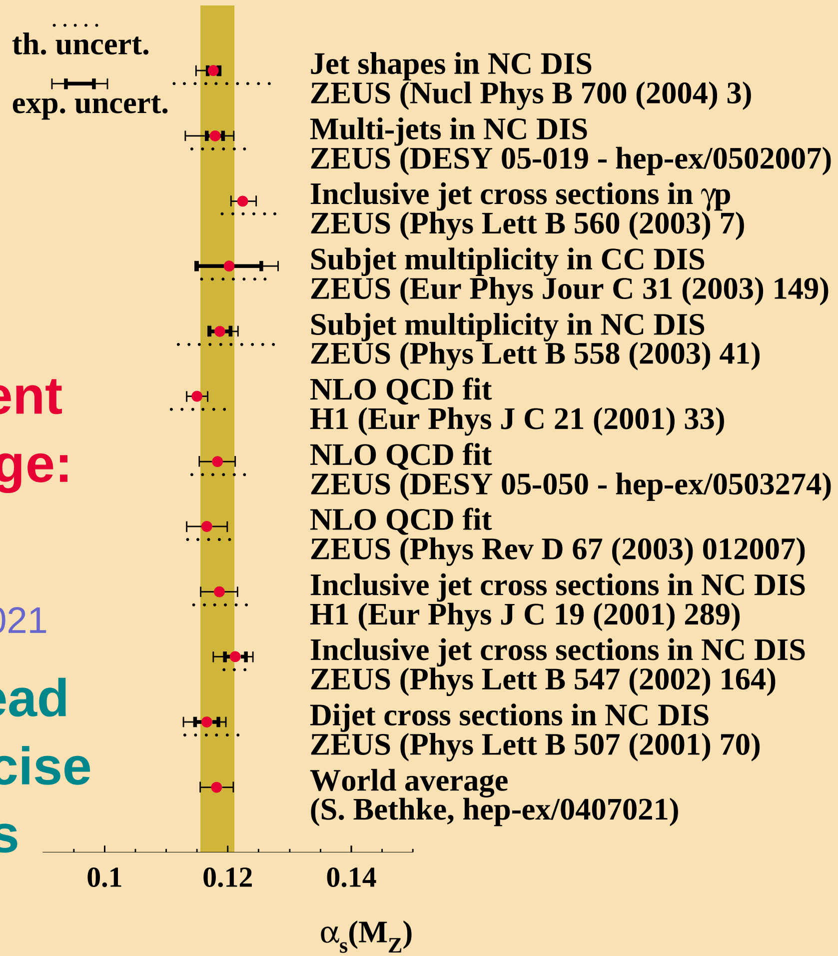
The strong coupling constant α_s

- The strong coupling constant, α_s, is one of the fundamental parameters of QCD
- However, its value is **not** predicted by the theory and must be determined from experiment
- The success of perturbative QCD lies on precise and consistent determinations of α_s from diverse phenomena
- There is a wealth of determinations of α_s at HERA from a variety of observables (jets, structure functions,...)
- The $\alpha_s(M_Z)$ values are all in good agreement and consistent with the current world average:

$$0.1182 \pm 0.0027$$

S Bethke, hep-ex/0407021

- Observables resulting from jet algorithms lead now to determinations of α_s that are as precise as those from more inclusive measurements (eg τ decays)



Comparison of α_s determinations at HERA

- **Determinations of $\alpha_s(M_Z)$ from ZEUS and H1 from jet cross sections, internal structure of jets and NLO QCD fits of structure functions:**

Process	Coll.	Value	Stat.	Experim.	Theory	Total
Dijet NC DIS	ZEUS	0.1166	0.0019	$^{+0.0024}_{-0.0033}$	$^{+0.0057}_{-0.0044}$	$^{+0.0065}_{-0.0058}$
Inc. Jet NC DIS	ZEUS	0.1212	0.0017	$^{+0.0023}_{-0.0031}$	$^{+0.0028}_{-0.0027}$	$^{+0.0040}_{-0.0044}$
Inc. Jet NC DIS	H1	0.1186	$\rightarrow$	$^{+0.0030}_{-0.0030}$	$^{+0.0051}_{-0.0051}$	$^{+0.0059}_{-0.0059}$
3/2 Jet NC DIS	ZEUS	0.1179	0.0013	$^{+0.0028}_{-0.0046}$	$^{+0.0064}_{-0.0046}$	$^{+0.0071}_{-0.0066}$
3/2 Jet NC DIS	H1	0.1175	0.0017	$^{+0.0050}_{-0.0050}$	$^{+0.0054}_{-0.0068}$	$^{+0.0076}_{-0.0086}$
Subjet NC DIS	ZEUS	0.1187	0.0017	$^{+0.0024}_{-0.0009}$	$^{+0.0093}_{-0.0076}$	$^{+0.0097}_{-0.0078}$
Jet Shape NC DIS	ZEUS	0.1176	0.0009	$^{+0.0009}_{-0.0026}$	$^{+0.0091}_{-0.0072}$	$^{+0.0092}_{-0.0077}$
Subjet CC DIS	ZEUS	0.1202	0.0052	$^{+0.0060}_{-0.0019}$	$^{+0.0065}_{-0.0053}$	$^{+0.0103}_{-0.0077}$
NLO QCD Fit	ZEUS	0.1183	$\rightarrow$	$^{+0.0028}_{-0.0028}$	$^{+0.0051}_{-0.0051}$	$^{+0.0058}_{-0.0058}$
NLO QCD Fit	H1	0.1150	$\rightarrow$	$^{+0.0017}_{-0.0017}$	$^{+0.0051}_{-0.0050}$	$^{+0.0054}_{-0.0053}$
Inc. Jet γp	ZEUS	0.1224	0.0001	$^{+0.0022}_{-0.0019}$	$^{+0.0054}_{-0.0042}$	$^{+0.0058}_{-0.0046}$

$\rightarrow$ experimental uncertainties: $\sim 3\%$
$\rightarrow$ theoretical uncertainties: $\sim 4\%$ (jet cross sections and NLO QCD fits)
$\sim 8\%$ (internal structure of jets)

Jet cross sections

- **Inclusive-jet cross sections in NC DIS (ZEUS):**

$\longrightarrow$ **α_s from $d\sigma/dQ^2$ for $Q^2 > 500$ GeV^2 and $E_{T,\mathrm{B}}^{\mathrm{jet}} > 8$ GeV:**

$$\alpha_s(M_Z) = 0.1212 \pm 0.0017\ (\mathrm{stat.})\ ^{+0.0023}_{-0.0031}\ (\mathrm{exp.})\ ^{+0.0028}_{-0.0027}\ (\mathrm{th.})$$

- **Experimental uncertainties:**

$\longrightarrow$ **dominated by jet energy scale uncertainty:**

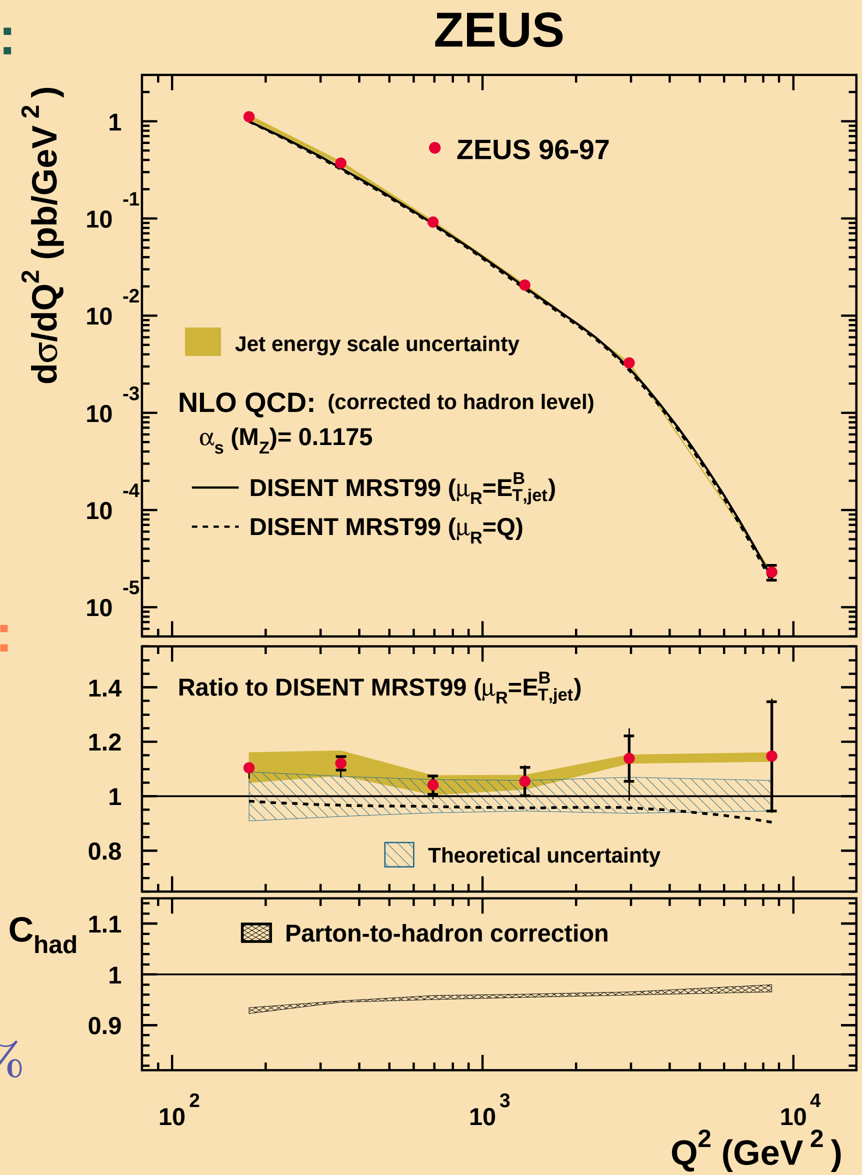
$$\Delta\alpha_s/\alpha_s = ^{+1.6}_{-1.7}\%$$

- **Theoretical uncertainties:**

$\longrightarrow$ **terms beyond NLO:** $\Delta\alpha_s/\alpha_s = \pm 2\%$

$\longrightarrow$ **uncertainties from pPDFs:** $\Delta\alpha_s/\alpha_s = \pm 1\%$

$\longrightarrow$ **hadronisation corrections:** $\Delta\alpha_s/\alpha_s = \pm 0.2\%$



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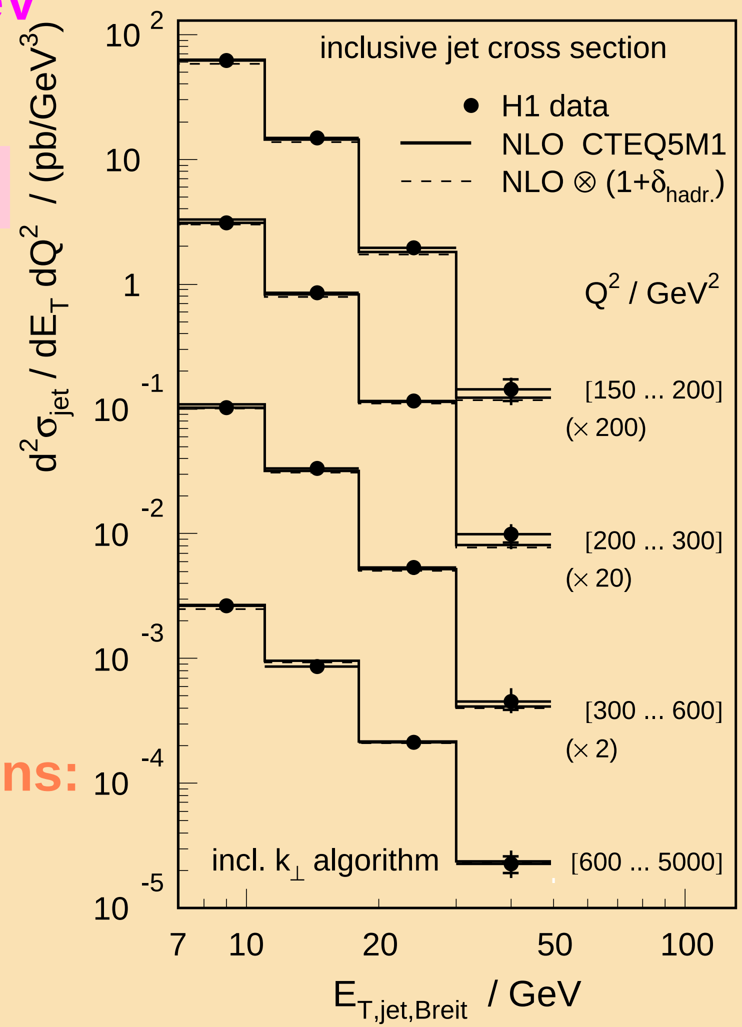
Jet cross sections

- **Inclusive-jet cross sections in NC DIS (H1):**

- **α_s from $d^2\sigma/dE_{T,\mathrm{B}}^{\mathrm{jet}}dQ^2$ for $150 < Q^2 < 5000$ GeV^2 and $E_{T,\mathrm{B}}^{\mathrm{jet}} > 7$ GeV:**

$$\alpha_s(M_Z) = 0.1186 \pm 0.0030\ (\mathrm{exp.}) \pm 0.0051\ (\mathrm{th.})$$



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

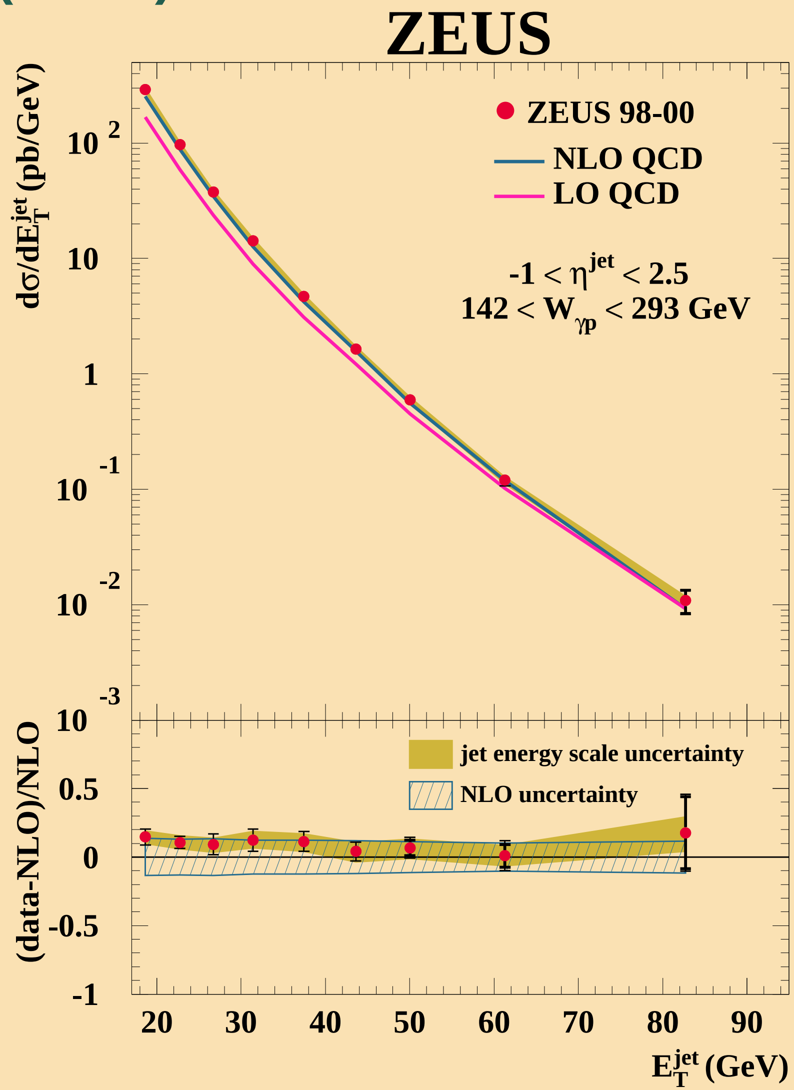
- **Theoretical uncertainties:**
  $\longrightarrow$ **terms beyond NLO and hadronisation corrections:**
  equal contribution to $\Delta\alpha_s/\alpha_s$
  $\longrightarrow$ **uncertainties from pPDFs: $\Delta\alpha_s/\alpha_s =^{+2.8}_{-1.9}$ %**

Jet cross sections

- **Inclusive-jet cross sections in photoproduction (ZEUS):**

→ α_s **from** $d\sigma/dE_T^{\rm jet}$ **for** $E_T^{\rm jet} > 17$ **GeV:**

$$\alpha_s(M_Z) = 0.1224 \pm 0.0001\ ({\rm stat.})\ ^{+0.0022}_{-0.0019}\ ({\rm exp.})\ ^{+0.0054}_{-0.0042}\ ({\rm th.})$$



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

$$\Delta\alpha_s/\alpha_s = \pm 1.5\%$$

- **Theoretical uncertainties:**
  → **terms beyond NLO:** $\Delta\alpha_s/\alpha_s = ^{+4.2}_{-3.3}\ \%$
  → **uncertainties from pPDFs:** $\Delta\alpha_s/\alpha_s = \pm 0.9\%$
  → **hadronisation corrections:** $\Delta\alpha_s/\alpha_s = +0.8\%$
  → **uncertainties from γPDFs:** $\Delta\alpha_s/\alpha_s = +0.7\%$

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NLO QCD fits of structure functions

- **H1:** inclusive lepton-proton data from low-x H1 data, high-Q^2 H1 data and large-x BCDMS data:

$$\alpha_s(M_Z) = 0.1150 \pm 0.0017\,(\mathrm{exp.})\,^{+0.0009}_{-0.0005}\,(\mathrm{model})\ \pm 0.0050\,(\mathrm{th.})$$

  - Experimental uncertainties: $\Delta\alpha_s/\alpha_s = \pm 1.5\%$
  - Model uncertainties: $\Delta\alpha_s/\alpha_s =^{+0.8}_{-0.4}\%$
  - Theoretical uncertainties: $\Delta\alpha_s/\alpha_s = \pm 4.3\%$

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- **ZEUS:** data from HERA-I on NC and CC inclusive cross sections and jet cross sections in NC DIS and photoproduction:

$$\alpha_s(M_Z) = 0.1183 \pm 0.0028\,(\mathrm{exp.}) \pm 0.0008\,(\mathrm{model}) \pm 0.0050\,(\mathrm{th.})$$

  - Experimental uncertainties:
    $\longrightarrow$ (un)correlated systematic sources: $\Delta\alpha_s/\alpha_s = \pm(0.6)1.9\%$
    $\longrightarrow$ normalisation: $\Delta\alpha_s/\alpha_s = \pm 1.4\%$
  - Model uncertainties: $\Delta\alpha_s/\alpha_s = \pm 0.7\%$
  - Theoretical uncertainties: $\Delta\alpha_s/\alpha_s = \pm 4.2\%$

DESY 05-050 - hep-ex/0503274

Averaging the determinations of α_s at HERA

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

  → Experimental uncertainties:
  - eg jet energy scale (correlated among the determinations from each experiment)

  → Theoretical uncertainties:
  - parton distribution functions of the proton (correlated)
  - hadronisation corrections (partially correlated)
  - terms beyond NLO (correlated?)

→ Since the theoretical uncertainties are dominant and the biggest contribution arises from the terms beyond NLO

→ 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

Averaging the determinations of α_s at HERA

- **Several methods have been used to obtain an average $\overline{\alpha_s(M_Z)}$ value and its uncertainty from the HERA measurements:**

$\longrightarrow$ **Naive approach: determinations assumed to be uncorrelated**

$$\overline{\alpha_s(M_Z)} = 0.1188 \pm 0.0020 \ (\mathrm{ZEUS} + \mathrm{H1})$$

$\longrightarrow$ **Schmelling's method: a procedure to average correlated data when correlations are present but hard to quantify (used by S. Bethke)**

$\longrightarrow$ **A more reliable (but conservative) approach:**

- **known correlations among the $\alpha_s(M_Z)$ determinations from the same experiment are taken into account**
- **the theoretical uncertainties arising from terms beyond NLO are assumed to be fully correlated (conservative!)**

Average of α_s from HERA I measurements

- **Method I. Error-weighted average and optimised-correlation error (M Schmelling, Phys. Scripta 51 (1995) 676):**

  - an optimised correlation error was calculated from the error covariance matrix, assuming an overall correlation factor between the total errors of all measurements → this factor is adjusted so that the overall $\chi^2/\mathrm{dof} = 1$
  - error-weighted average obtained separately for ZEUS and H1 and from the combination of all measurements:

$$\overline{\alpha_s(M_Z)} = 0.1196 \pm 0.0060 \ (\mathrm{ZEUS}) \quad \text{and} \quad \overline{\alpha_s(M_Z)} = 0.1166 \pm 0.0053 \ (\mathrm{H1})$$

$$\overline{\alpha_s(M_Z)} = 0.1188 \pm 0.0057 \ (\mathrm{ZEUS + H1})$$

→ This error estimation gives rise to larger errors than expected when some measurements have large correlations, as it is the case here → it is preferable to restrict to the most accurate measurements ($\Delta\alpha_s^i < 0.006$):

$$\overline{\alpha_s(M_Z)} = 0.1192 \pm 0.0047 \ (\Delta\alpha_s^i < 0.006) \ (\mathrm{ZEUS + H1})$$

Average of α_s from HERA I measurements

- **Method II. Average and uncertainty using correlated sources:**
  - error-weighted average obtained separately for ZEUS and H1 with:
    - uncorrelated experimental uncertainties
    - correlated experimental uncertainties (jet energy scale)
    - individual theoretical uncertainties (higher orders, PDFs and hadronisation)
  - estimation of overall uncertainty conservative, since theoretical uncertainty due to higher orders assumed to be fully correlated for all measurements:

$$\overline{\alpha_s(M_Z)} = 0.1200 \pm 0.0023\ (\mathrm{exp.})^{+0.0058}_{-0.0049}\ (\mathrm{th.})\ (\mathrm{ZEUS})$$

$$\overline{\alpha_s(M_Z)} = 0.1160 \pm 0.0016\ (\mathrm{exp.})^{+0.0048}_{-0.0049}\ (\mathrm{th.})\ (\mathrm{H1})$$

  - combined ZEUS+H1 average obtained by using error-weighted average and
    - experimental uncertainties considered to be uncorrelated
    - overall theoretical uncertainty taken as linear average of uncertainties in each experiment, since values are very similar:

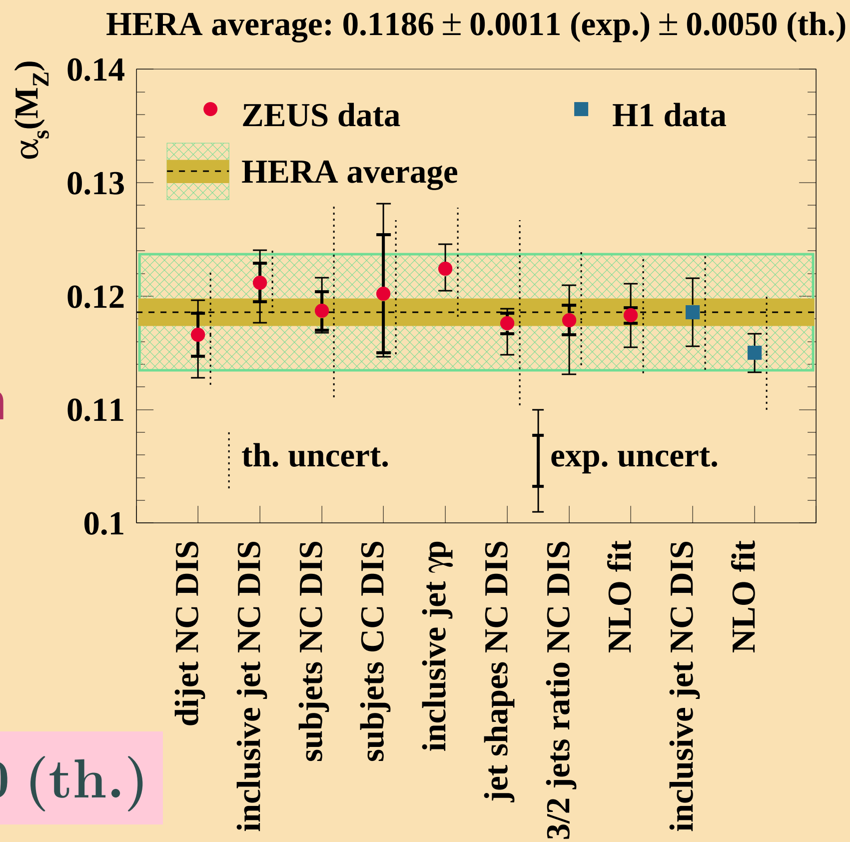
$$\rightarrow \overline{\alpha_s(M_Z)} = 0.1186 \pm 0.0011\ (\mathrm{exp.}) \pm 0.0050\ (\mathrm{th.})\ (\mathrm{ZEUS+H1})$$

Average of α_s from HERA I measurements: summary of $\alpha_s(M_Z)$

- 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



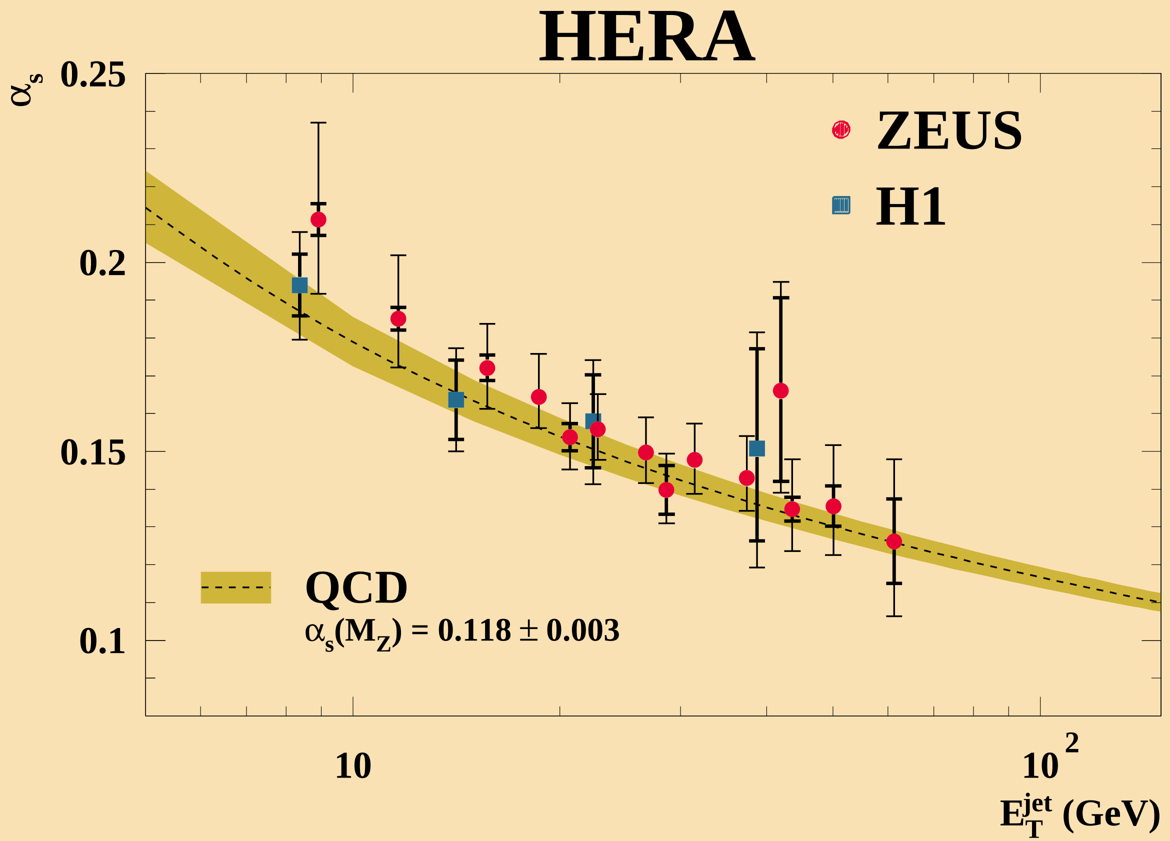
- The HERA average is:

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

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

Scale dependence of α_s

- The QCD prediction for the energy-scale dependence of α_s has been tested 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}

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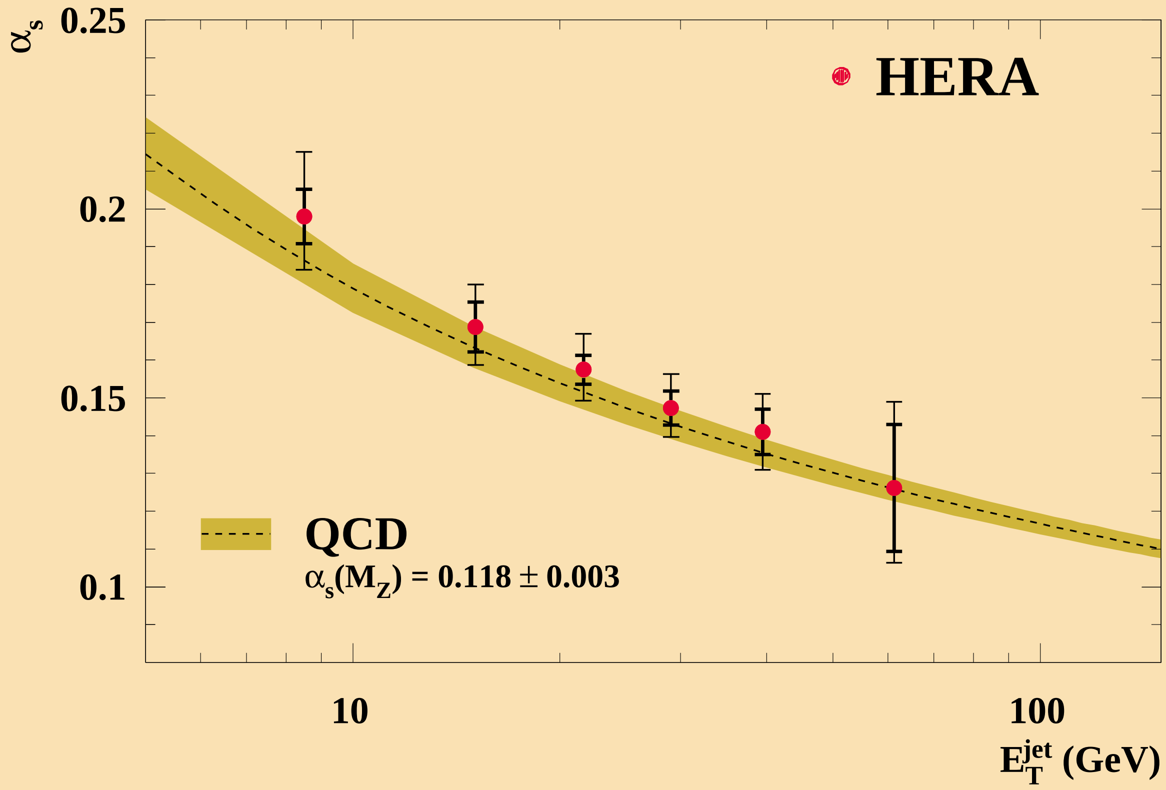
Scale dependence of α_s

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

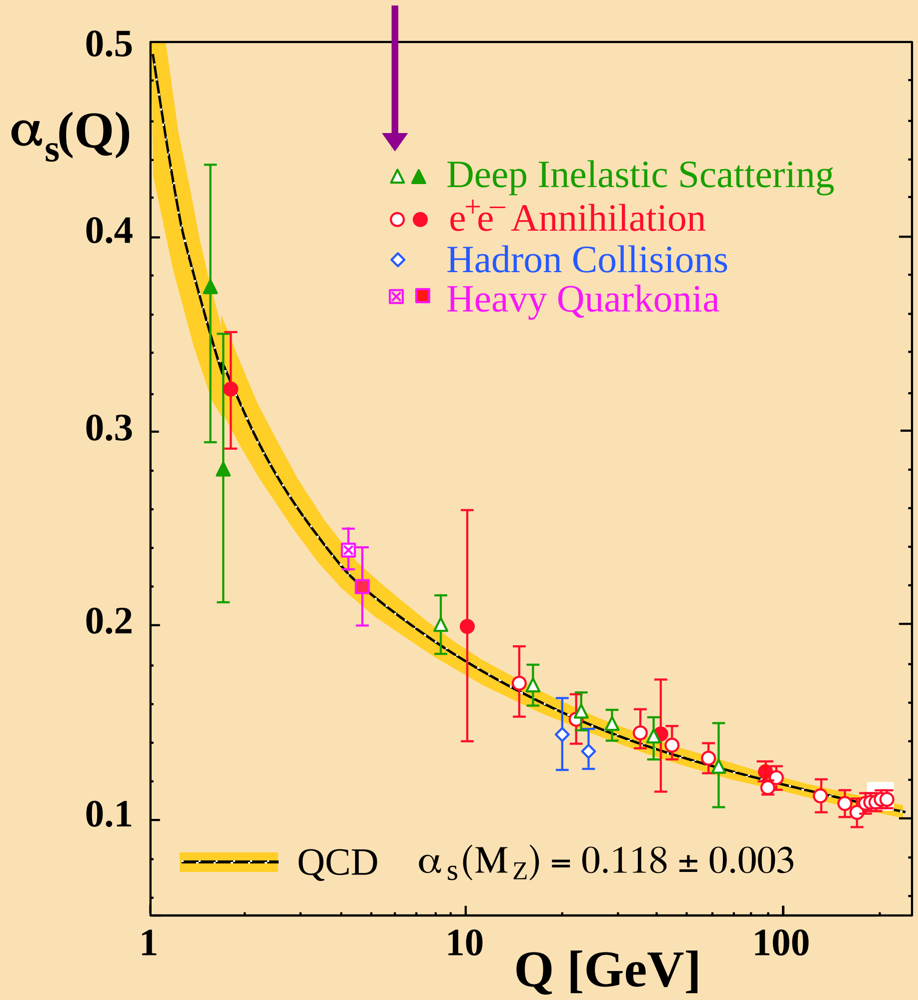


$\longrightarrow$ **Observation of the running of α_s from HERA jet data**

Scale dependence of α_s

- **Comparison of HERA results with other experiments:**

HERA jet data



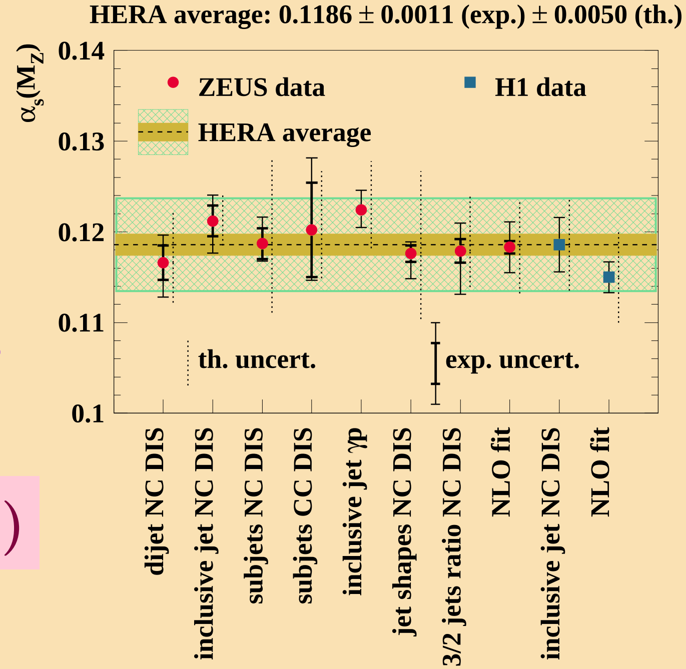
→ **HERA determinations consistent with other experiments**

→ **Uncertainties of HERA determinations very competitive**

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

Summary

- A comprehensive average of the $\alpha_s(M_Z)$ and its energy scale dependence at HERA has been performed taking into account the known correlations in each experiment and assuming (conservatively) that the theoretical uncertainties arising from higher orders are fully correlated:



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

- Room for improvement?
  - ⟶ NNLO calculations needed for determination of PDFs have recently been finished
  - ⟶ NNLO calculations needed for jet-based observables are well under way