Jets, Event Shapes, and Determination of α_s in DIS at HERA

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On Behalf of the H1 and ZEUS Collaborations

Outlook:
- Inclusive jets (ZEUS/H1)
- Dijets (ZEUS)
- Multijets (H1/ZEUS)
- Event shapes (H1/ZEUS)
- Summary

Jets: Motivation and basic concepts

Jet cross section in pQCD: Series expansion in powers of α_s

$$d\sigma = \sum_{m=0}^{\infty \text{ or } 2} \alpha_s^m(\mu_R) \sum_{a=q,\bar{q},g} f_a(\eta,\mu_F) \otimes d\hat{\sigma}(x_{Bj}/\eta,\mu_R,\mu_F)(1+\delta_{had})$$

pQCD factorization

Coefficients are convolutions of: $f_a(\eta,\mu_F)$...PDFs (proton structure) and $d\hat{\sigma}(x_{Bj}/\eta,\mu_R,\mu_F)$...hard scattering ME

Measurement:

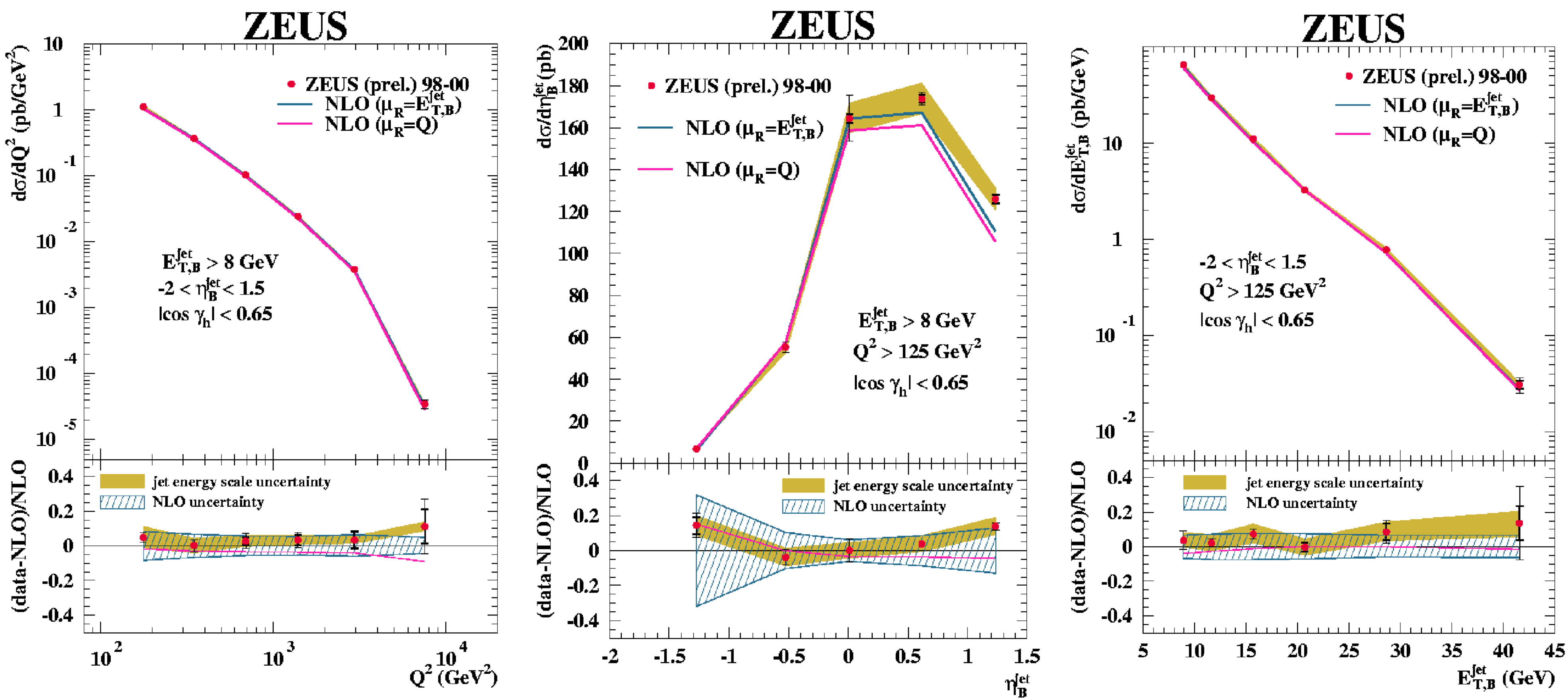
- Test concept of pQCD, factorization, universality of strong coupling and PDFs
- Assume factorization, pQCD ➡ **get α_s**, PDFs (important for LHC)
- Also access to underlying gauge group, effect of exchanged bosons, parton dynamics in the proton,...

Tools:

- k_T cluster algorithm on cells or energy flow objects (DIS: in the Breit reference frame)
- Data corrected for detector and QED effects with LO MC models
- NLO corrected to hadron level with LO MC + parton shower +hadronisation models
- Latest PDFs like CTEQ6...
- Excellent understanding of jet energy scale (1-3%) (typically 10 % effect in xsection)

Inclusive Jets (ZEUS)

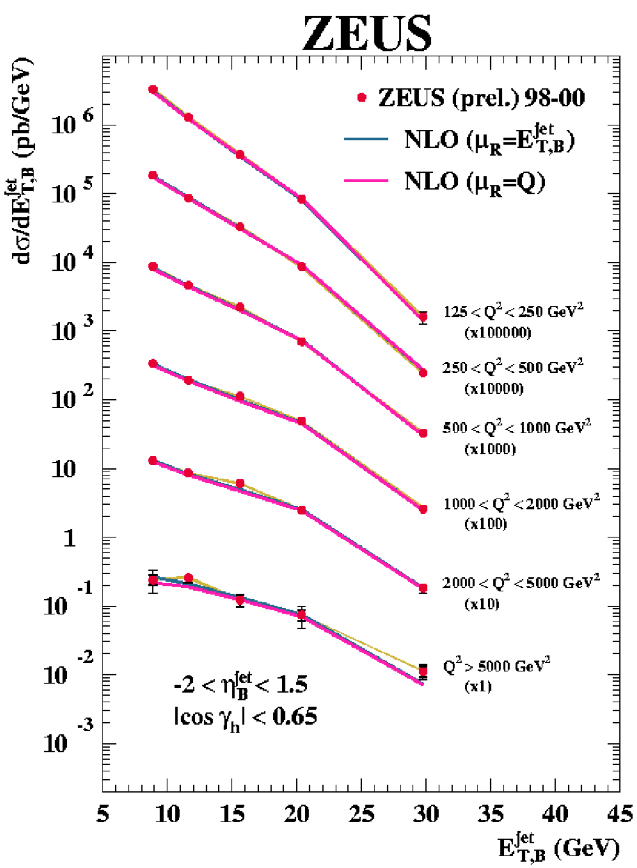
Data: 82 pb^{-1}(98-00) **Selection:** $Q^2 > 125$ GeV^2, $|\cos(\gamma_{had})| < 0.65$, $E_{T,B} > 8$ GeV, $-2 < \eta_B < 1.5$

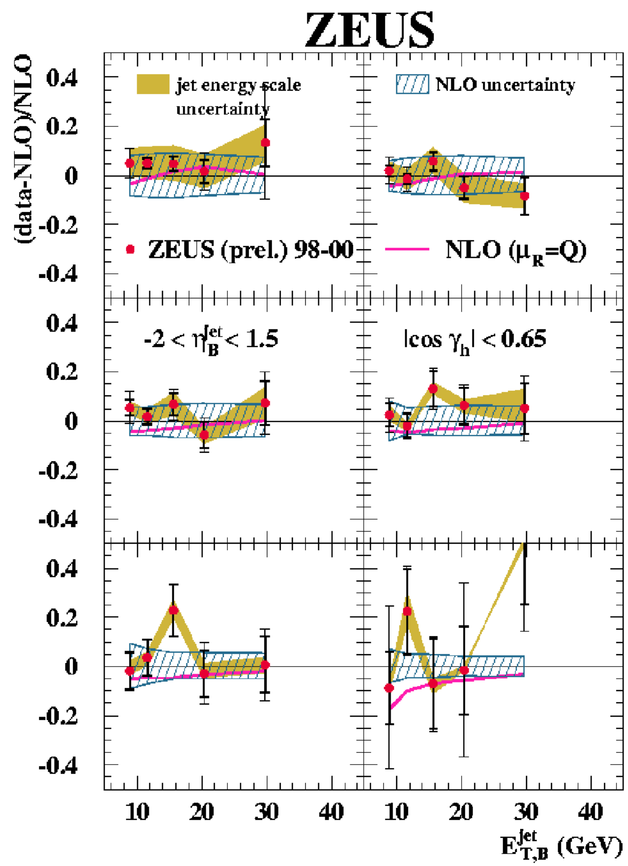


Data well described by the NLO (DISENT);
Experimental errors dominated by uncertainty on jet energy scale
Theoretical errors dominated by scale variation effect (missing higher orders ?)

Inclusive Jets (ZEUS)

Double differential: inclusive jet cross sections in ET in different regions of Q^2





Reminder: 96/97 inclusive jet measurement has been used in QCD fits and helped to reduce the error on gluon density at high x

→ gain from new analysis with higher statistic and higher $\sqrt{s}$

- Data well described by NLO;
- E_T and Q^2 dependence (E_T dependence gets less steep as Q^2 increases) indicates sensitivity to PDFs

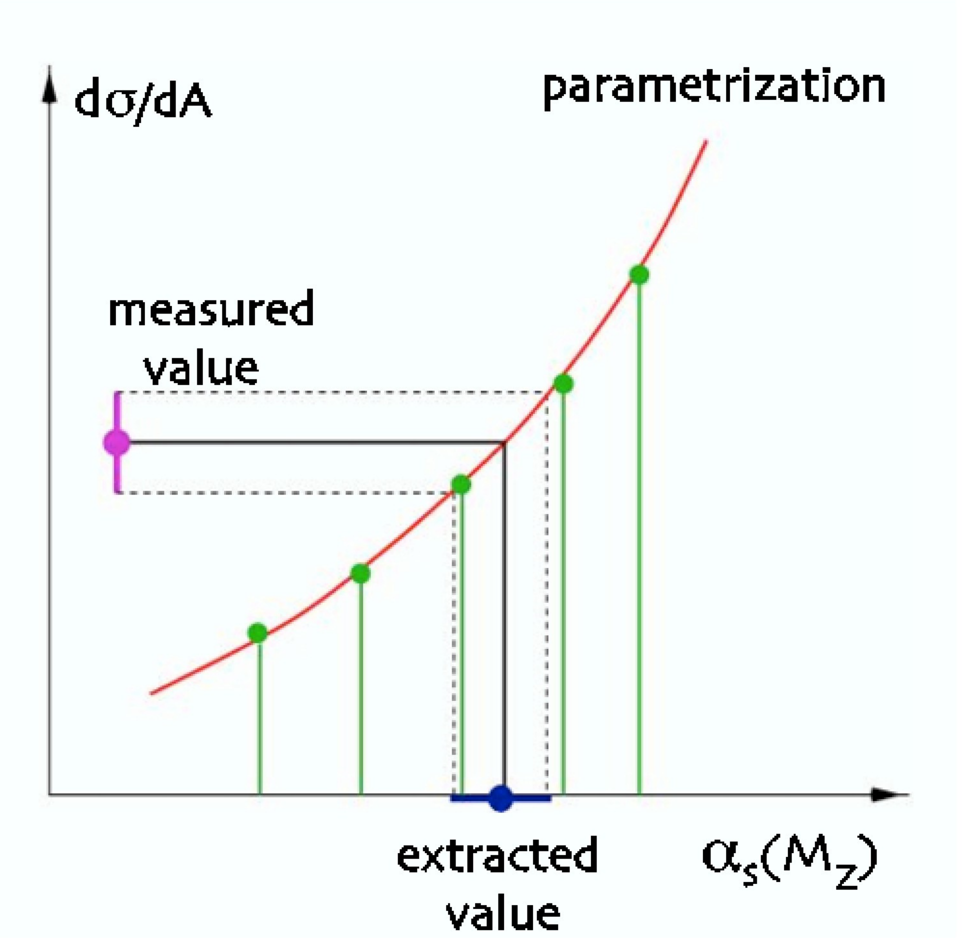
Extraction of α_s

- Perform NLO calculation with different values of $\alpha_s(M_Z)$

(The values of α_s used correspond to those used in the different PDFs sets available (incl. jets: MRST99; multijets: CTEQ4A))

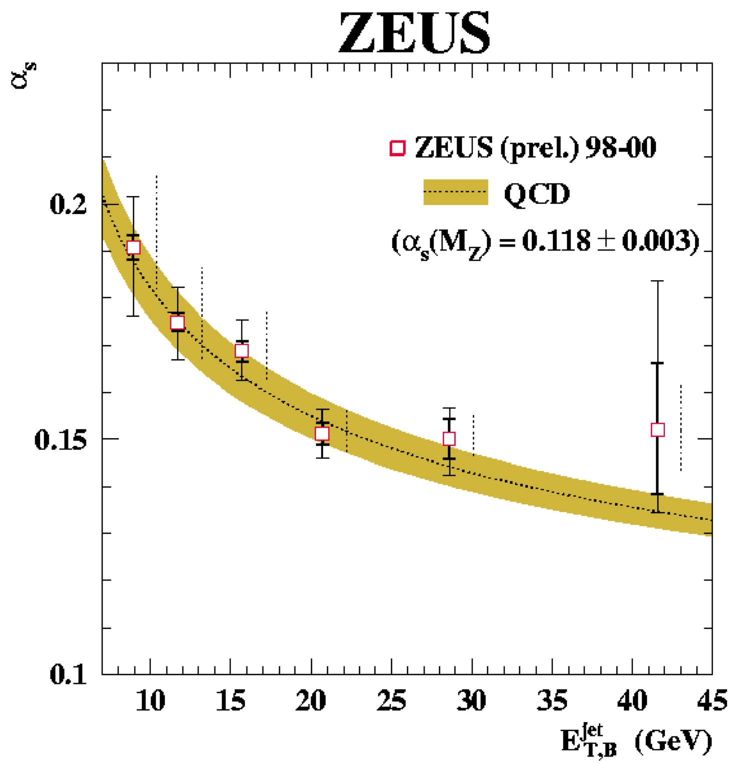
- Parametrize $\alpha_s(M_Z)$ dependence of observable ($d\sigma/dA$) in bin i according to

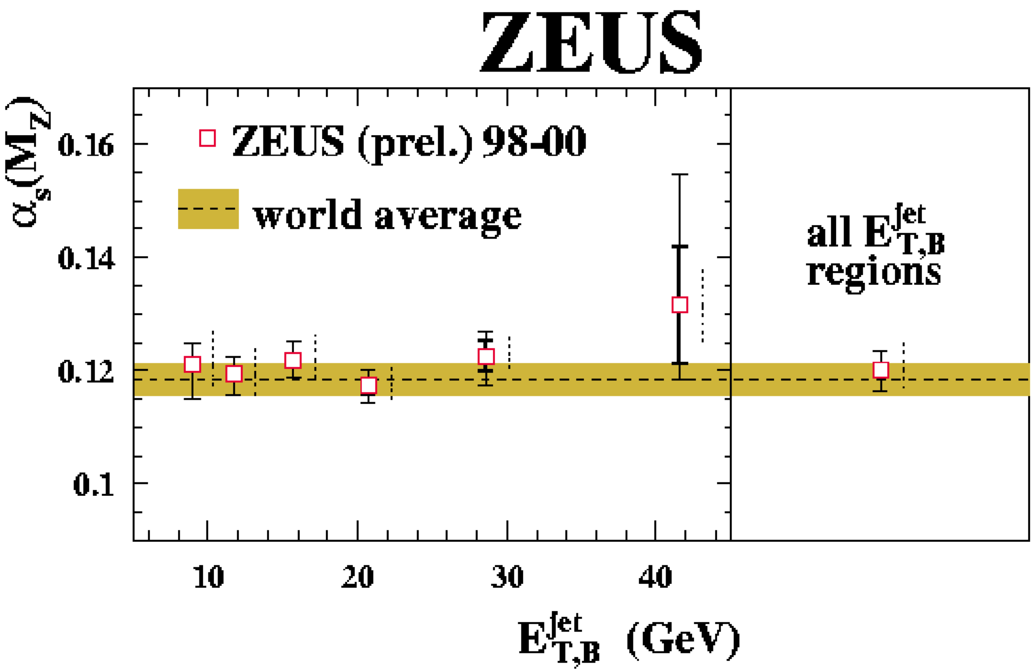
$$\frac{d\sigma_i}{dA} = C_1 \cdot \alpha_s(M_Z) + C_2 \cdot \alpha_s^2(M_Z)$$



- Map measured $d\sigma/dA$ to x-axis and extract $\alpha_s(M_Z)$

Inclusive Jets (ZEUS)





Demonstration of running coupling

Points compatible with each other and with world average

ZEUS inclusive jets: $\alpha_s(M_Z) = 0.1196 \pm 0.0025(\exp) \pm 0.0023(theo)$

World average $\alpha_s(M_Z) = 0.1187 \pm 0.0020$

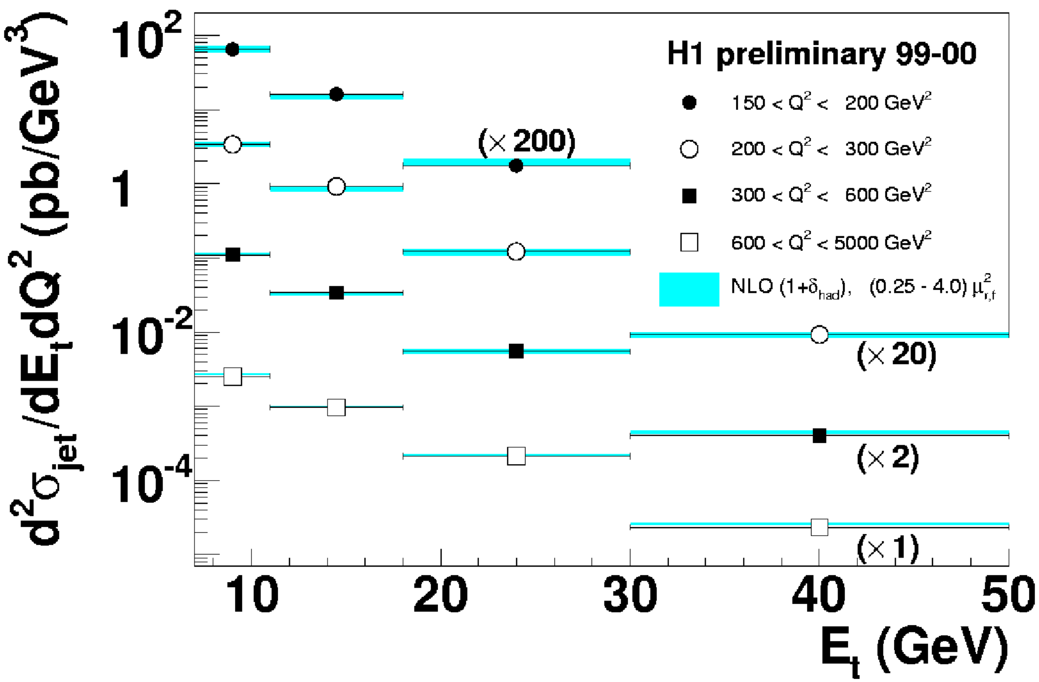
H1 inclusive jets: $\alpha_s(M_Z) = 0.1197 \pm 0.0016(\exp) \pm 0.0047(theo)$

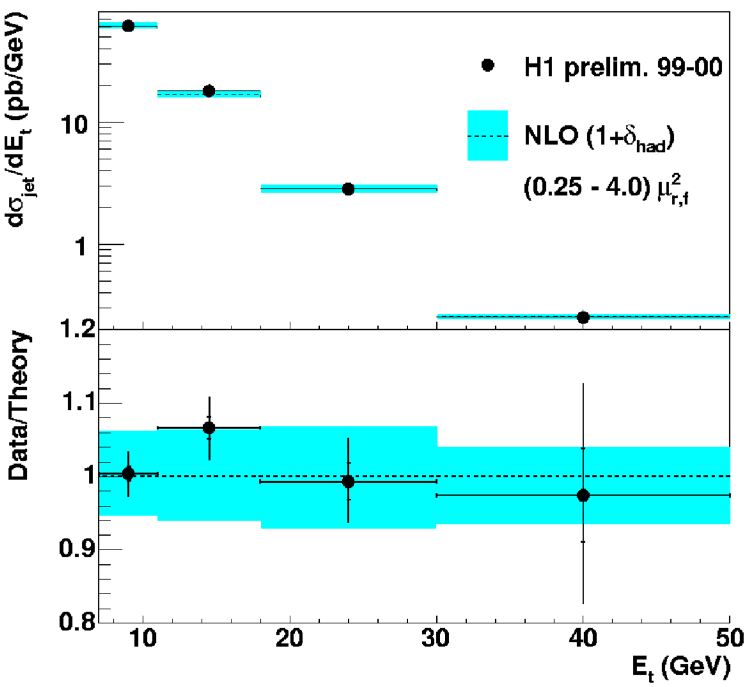
Inclusive Jets (H1)

Data:
61 pb^{-1} (99-00)

Selection:
$125 < Q^2 < 5000$ GeV^2
$0.2 < y < 0.6$
$E_{T,B} > 7$ GeV , $-1 < \eta_L < 2.5$

Similar phase space as ZEUS analysis; similar precision

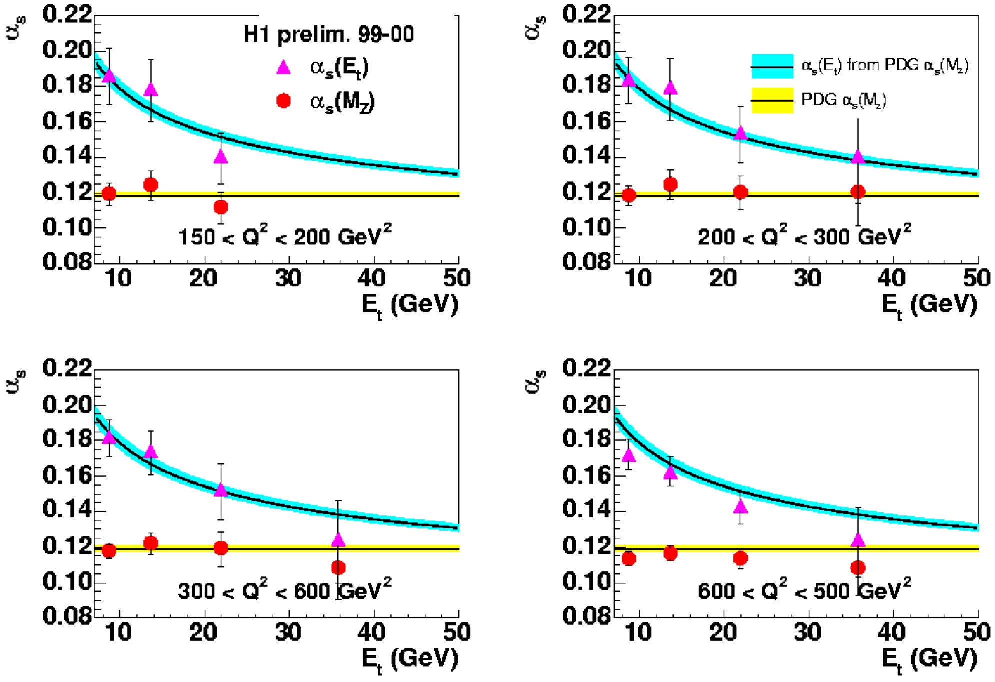




Very good agreement of data and theory (NLOJET++/ CTEQ5M1) within all errors
Uncertainty dominated by theory (scale variation effect; missing higher orders!)

Inclusive Jets (H1)

$\alpha_s(M_Z)$ extracted from double diff. xsections:



- $\alpha_s(M_Z)$ extracted from 15 data points
- All single measurements are consistent
- Combination of all points in one value
- Result consistent with world average and ZEUS inclusive jets
- Small experimental uncertainty
- Theory error dominates (missing higher orders) but remember: $Q^2 < 5000$ GeV^2; theoretical errors get smaller at high values of Q^2

H1 inclusive jets: $\alpha_s(M_Z) = 0.1197 \pm 0.0016(\exp) \pm 0.0047(theo)$

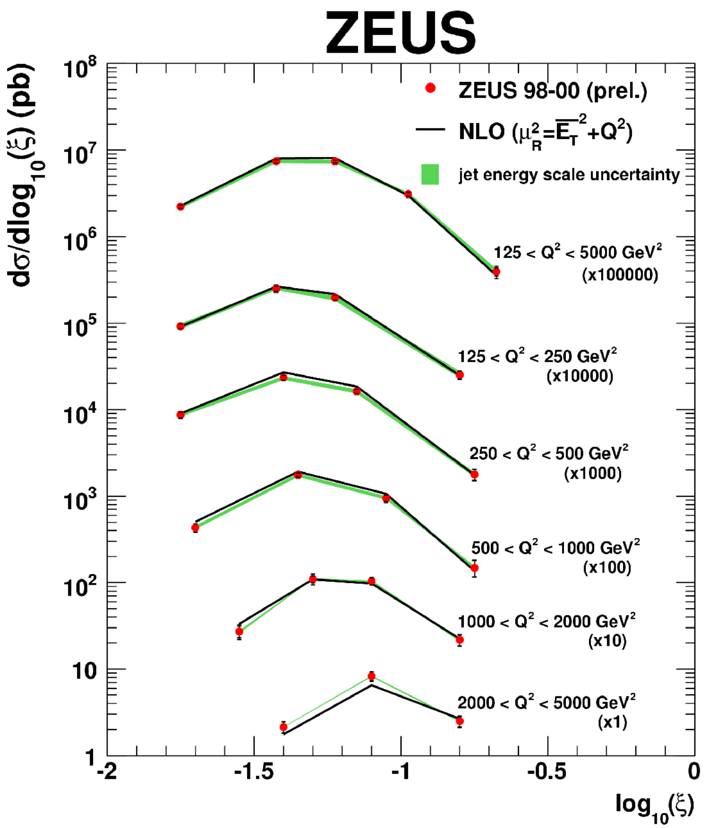
World average $\alpha_s(M_Z) = 0.1187 \pm 0.0020$

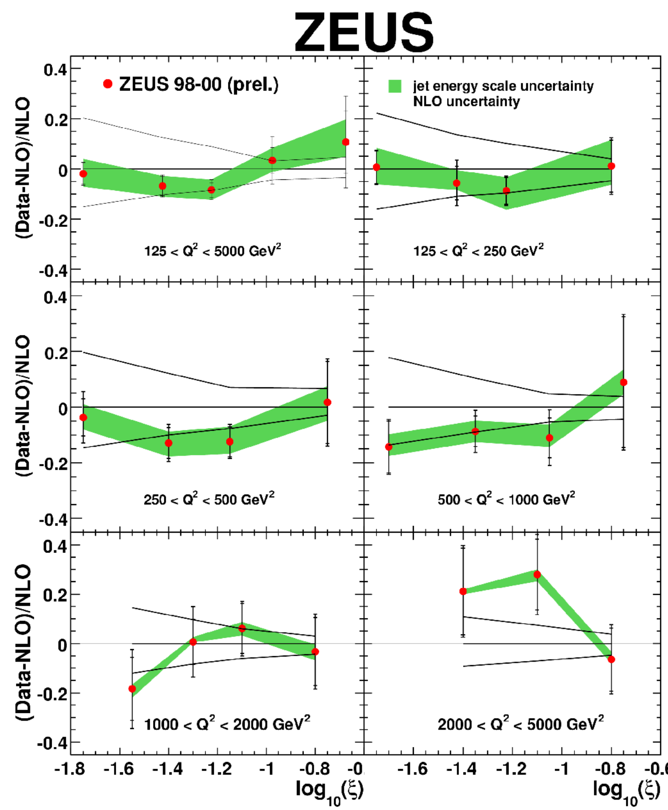
ZEUS inclusive jets: $\alpha_s(M_Z) = 0.1196 \pm 0.0025(\exp) \pm 0.0023(theo)$

Dijets (ZEUS)

Data: 82 pb^{-1}(98-00)

Selection: $Q^2 > 125\ GeV^2$, $|\cos(\gamma_{had})| < 0.65$, $E_{T,B}^{jet1(2)} > 12(8)$ GeV, $-2 < \eta_B < 1.5$





Idea: PDFs characterized by Q^2 and ξ ➡ use double diff. Xsections for QCD fits (g at high ξ)

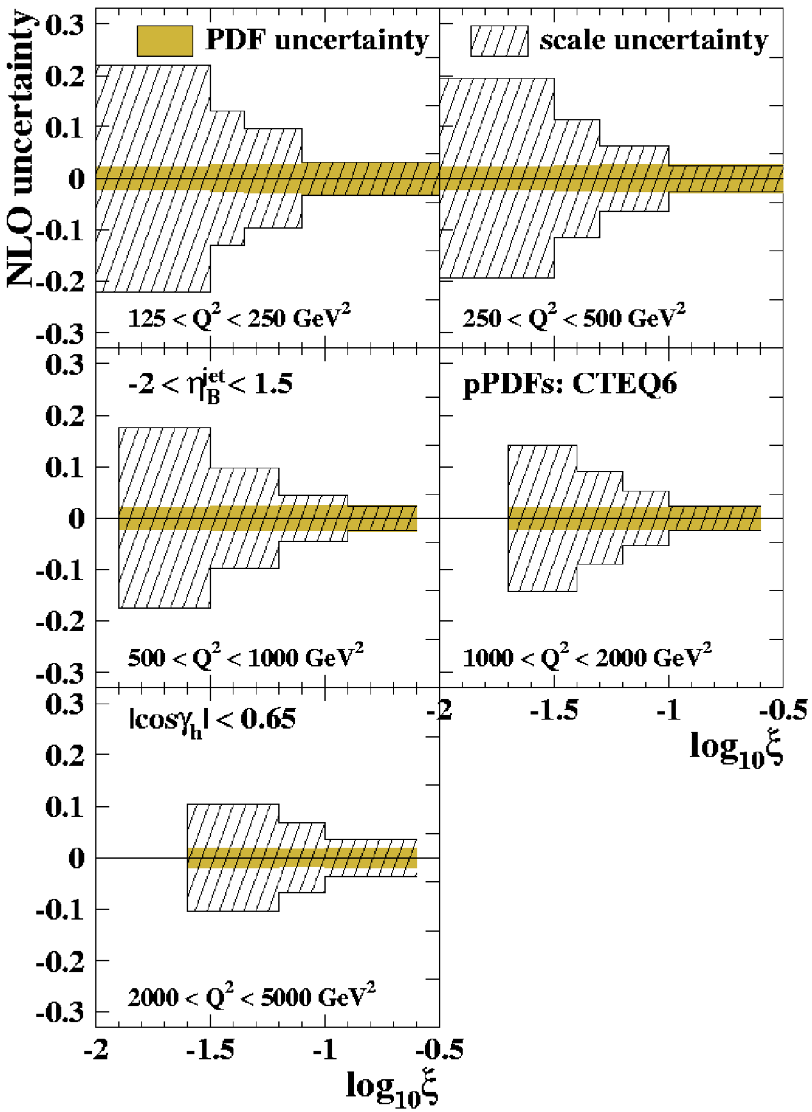
In dijet events:

$$\xi = x_{Bj}\left(1+\frac{M_{jj}}{Q^2}\right)$$

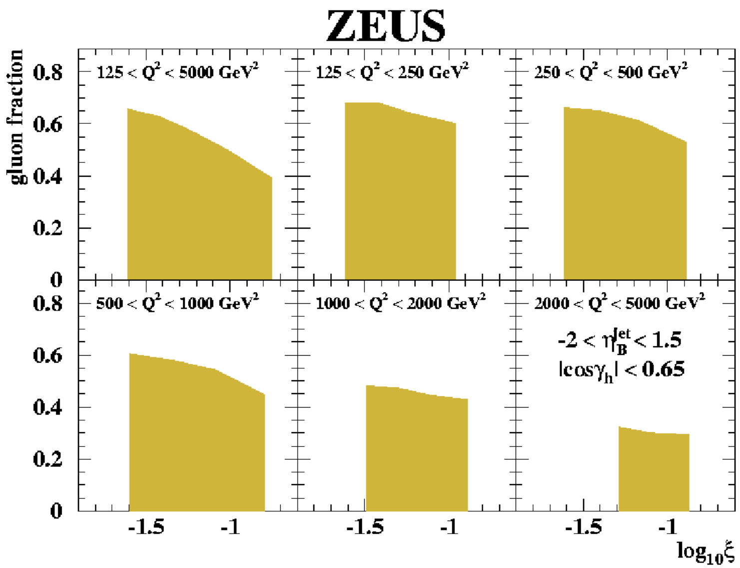
- Data well described by NLO (DISENT/CTEQ6);
- Theoretical errors are dominating in most regions
- At high Q^2 statistic is getting low (important to look at HERA II data!)

Dijets (ZEUS)

NLO uncertainty:



Gluon fraction:



Theoretical errors:

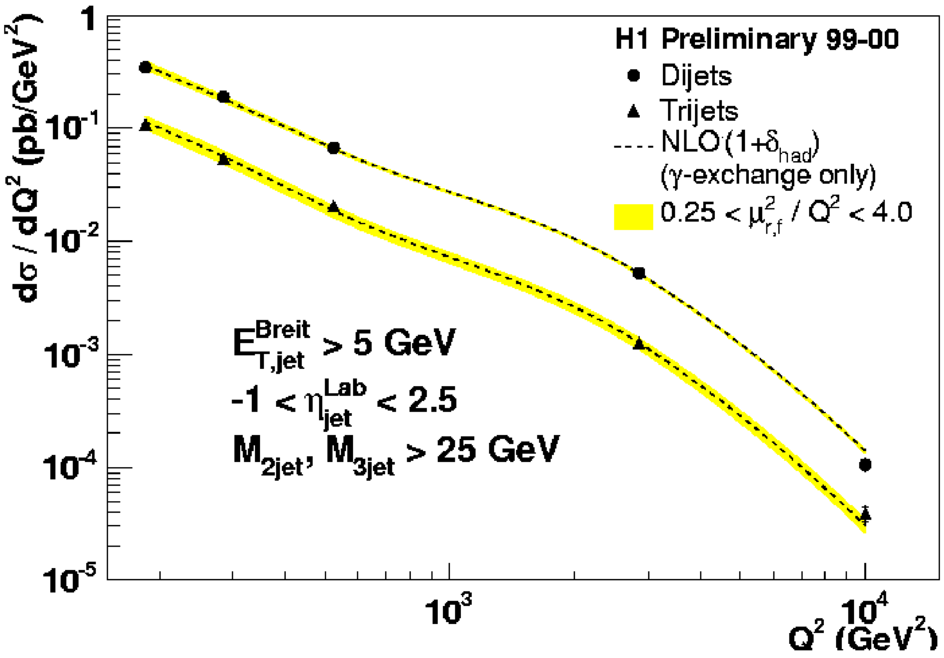
- Scale uncertainty 5-20 %, large at small ξ, Q^2
- PDF uncertainties ≈ 3 %, significant at high ξ
- Gluon fraction decreases with increasing ξ and Q^2 but still substantial gluon contribution (> 30 %)
- Also gluon uncertainty sizable (not shown)

➡ use in NLO QCD fits of PDFs

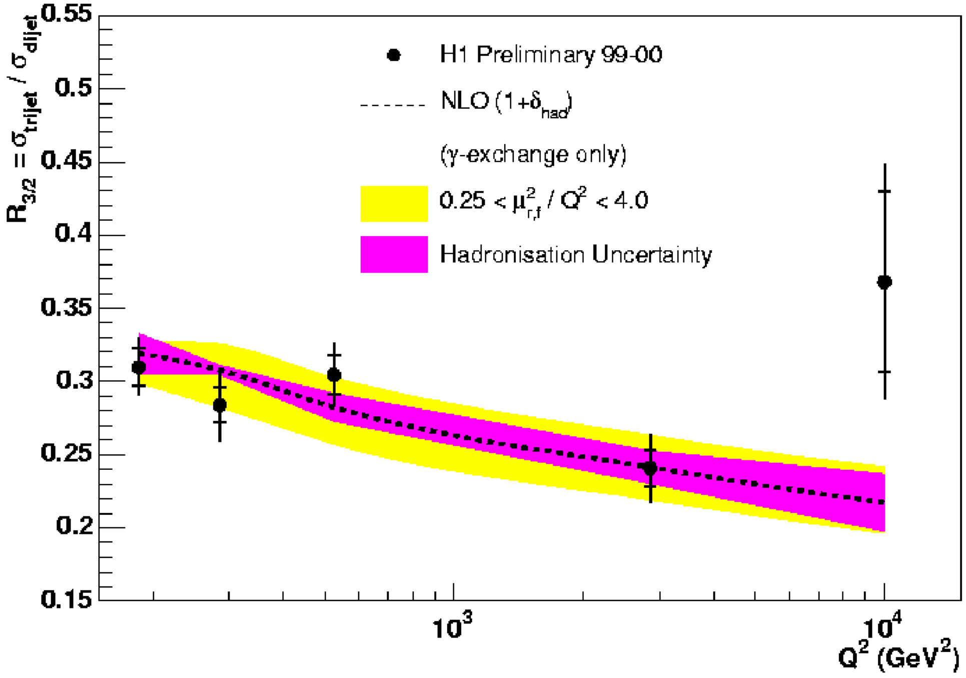
Multijets (H1)

Data: 65 pb^{-1} (99-00) **Selection:** $Q^2 > 125\ GeV^2$, $0.2 < y < 0.6$,
$E_{T,B} > 5$ GeV, $M_{jj} > 25$ GeV, $-1 < \eta_L < 2.5$

Di -and trijets:



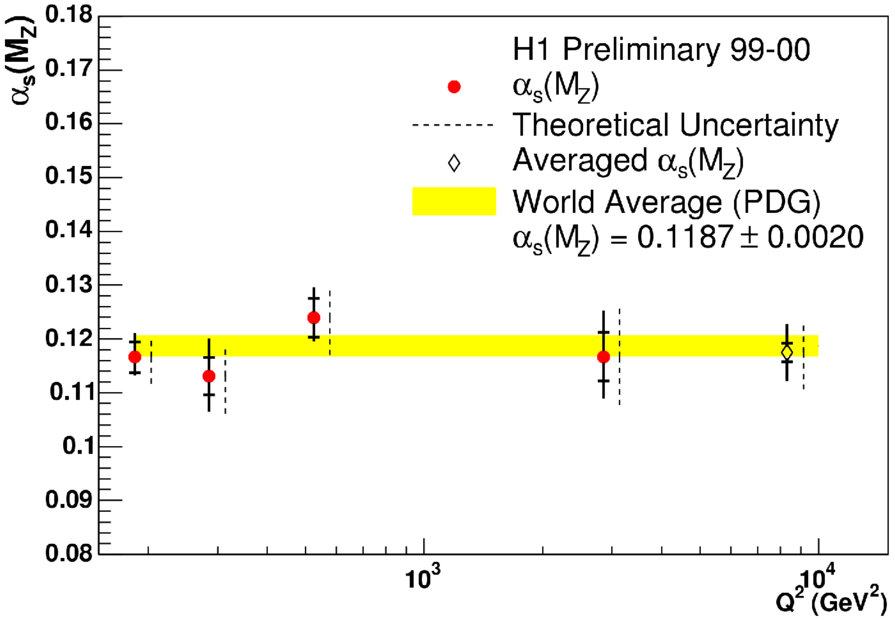
Ratios:

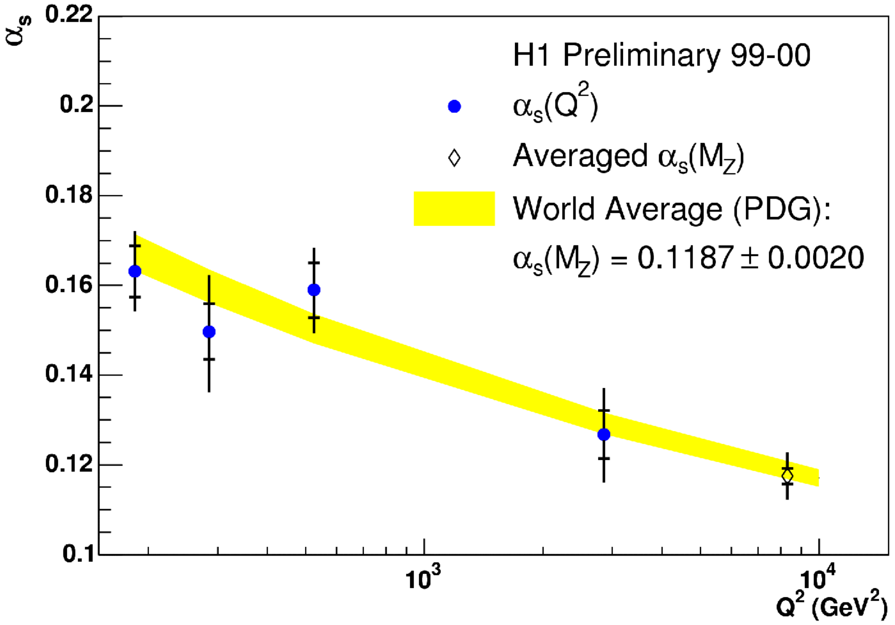


- NLO QCD (NLOJET++ / CTEQ5M) provides excellent description of di-and trijet data
- Last data point in ratio not described; Z^0 exchange not included in NLO calculation
- In the 3/2-jet ratio some theo. and exp. errors cancel ➡ use this quantity for α_s

Multijets (H1)

Strong coupling from 3/2-jet ratio:





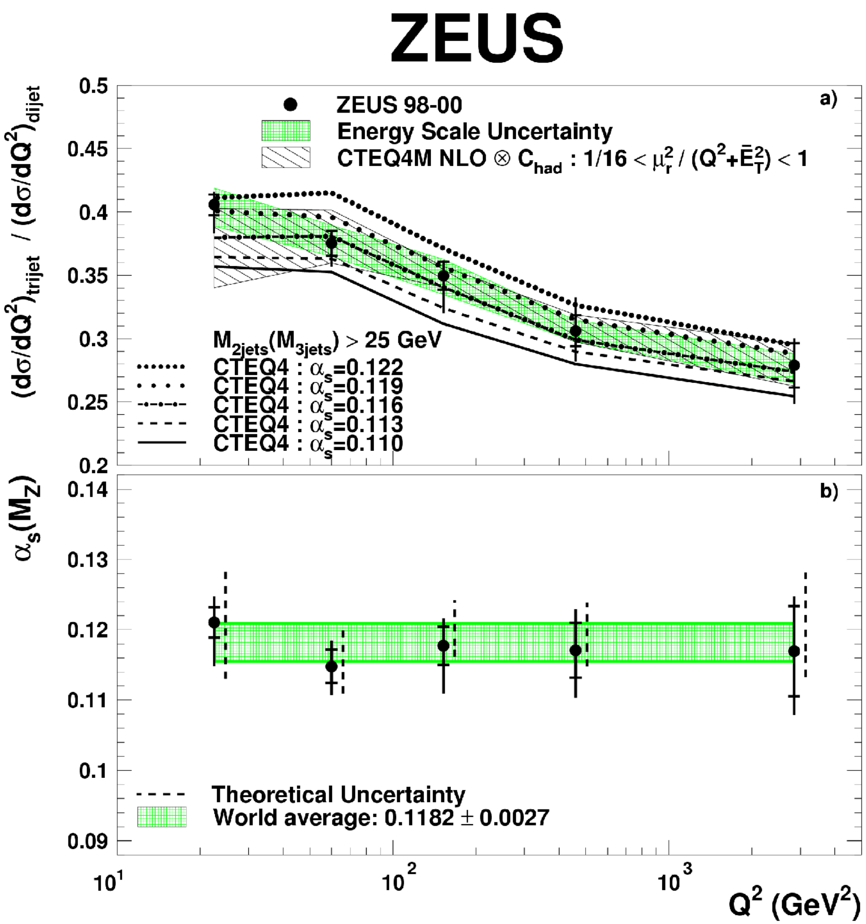
- Values are compatible with each other and world average
- Nice demonstration of running coupling

H1 multijets: $\alpha_s(M_Z) = 0.1175 \pm 0.0017(stat) \pm 0.0050(syst) \pm 0.0061(theo)$

H1 incl. jets: $\alpha_s(M_Z) = 0.1197 \pm 0.0016(\exp) \pm 0.0047(theo)$

- Errors significantly larger than for inclusive jets
- Systematic and theoretical errors are of the same size

Multijets (ZEUS)



Data:

82 pb^{-1} (98-00)

Selection:

10 **<** $Q^2 < 5000\ GeV^2$, $0.04 < y < 0.6$,

$E_{T,B} > 5$ GeV, $M_{jj} > 25$ GeV, $-1 < \eta_L < 2.5$

Using 3/2-jet ratio ➡ cancellation of errors (theo.) allows extraction of α_s with good precision down to very low Q^2 ($Q^2 = 10\ GeV^2$)

ZEUS multijets: $\alpha_s(M_Z) = 0.1179 \pm 0.0013(stat) \pm 0.0037(\exp) \pm 0.0055(theo)$

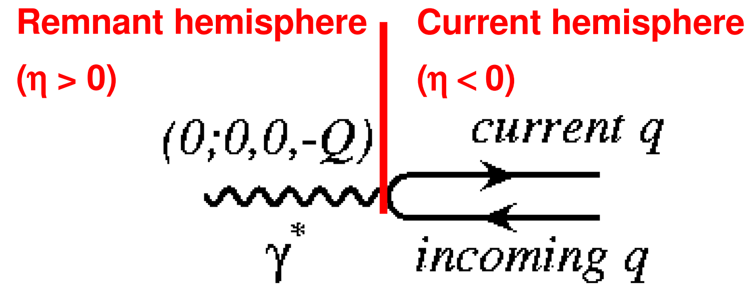
H1 multijets: $\alpha_s(M_Z) = 0.1175 \pm 0.0017(stat) \pm 0.0050(syst) \pm 0.0061(theo)$

Event Shapes: Motivation and basic concepts

Alternative approach to non-perturbative hadronisation effects: Power Corrections (PC)
PC calculable for inclusive quantities: event shapes

$$\tau = 1 - \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|} \qquad B = \frac{\sum_i |\vec{p}_i \times \vec{n}|}{\sum_i |\vec{p}_i|} \qquad M = \frac{\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{p}_i\right|^2}{\left(2\sum_i |E_i|\right)^2}$$

Thrust — Jet broadening — Jet invariant mass



PC introduces new parameter: $\alpha_0(\mu_I) = \frac{1}{\mu_I}\int_0^{\mu_I} \alpha_{eff}(\mu)\, d\mu$ ... supposed to be universal for all variables

Mean values (NLO + PC):	$\hat{V}(\alpha_s, \alpha_0) = \hat{V}_{PT}(\alpha_s) + \hat{V}_{pow}(\alpha_s, \alpha_0)$
Differential cross sections (NLO+NLL + PC):	$\frac{d\sigma}{dV}(V) = \frac{d\sigma}{dV_{PT}}(V - \hat{V}_{pow})$

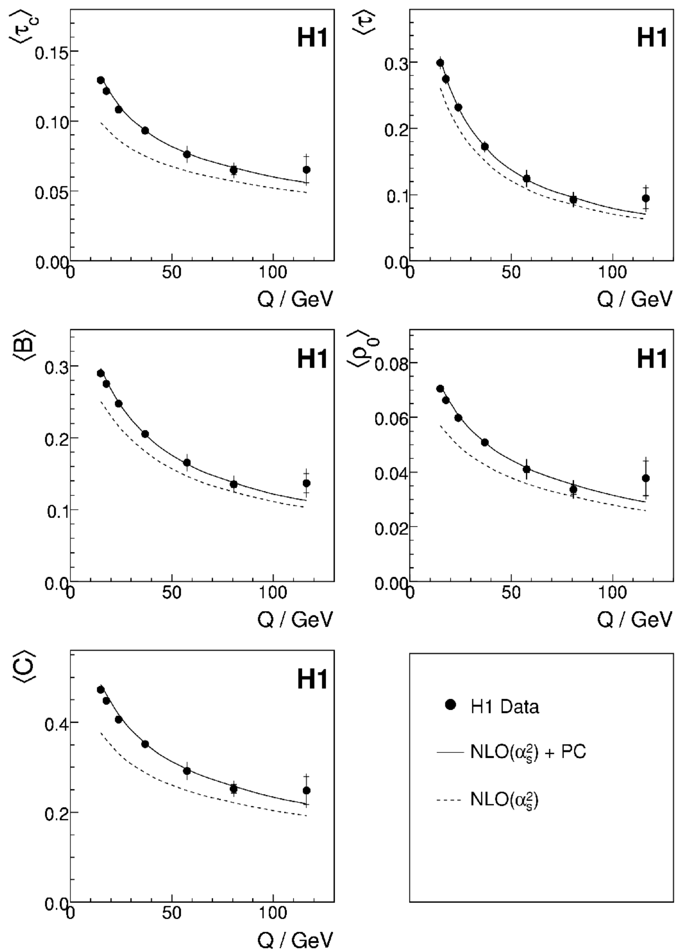
NLO+NLL: different matching schemes
Avoid double counting!

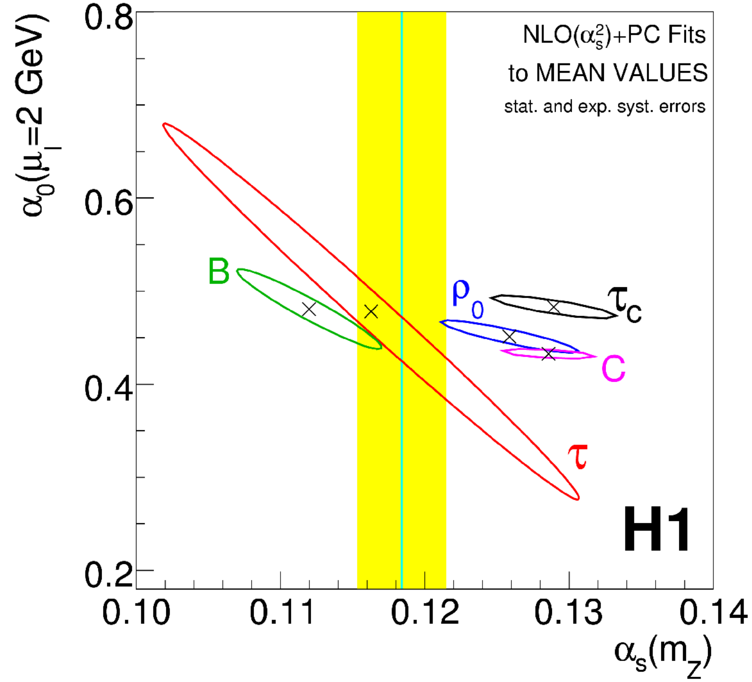
Measurement:
- Test Power Correction ansatz
- Extract α_s and α_0

Event Shapes (H1)

Data: 106 pb^{-1} (95-00)   **Selection:** $196 < Q^2 < 40000$ GeV^2, $0.1 < y < 0.7$

Mean values compared to NLO QCD fits +PC : nice description of the data

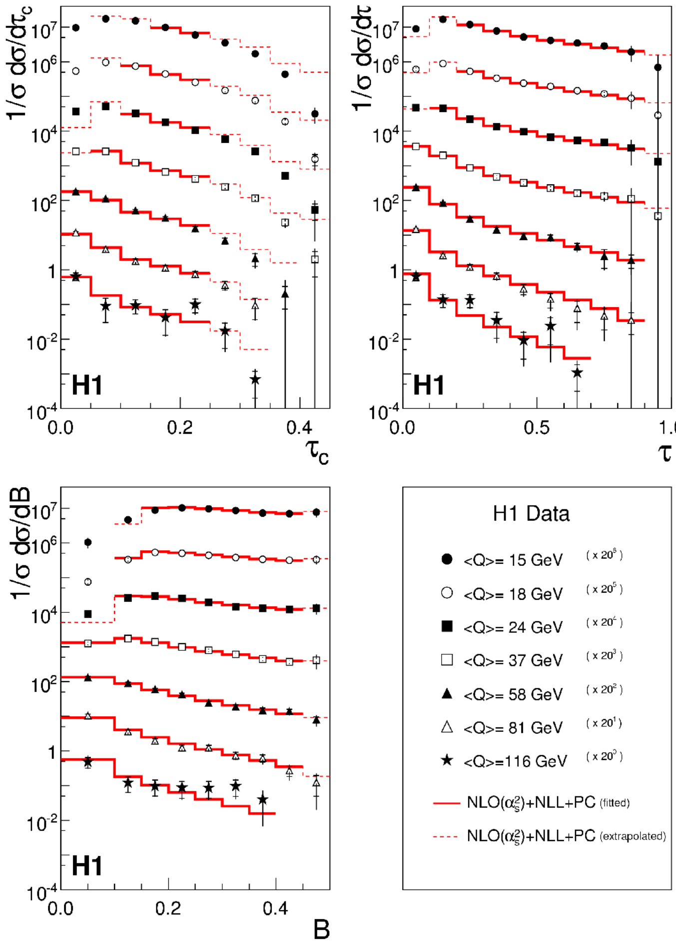




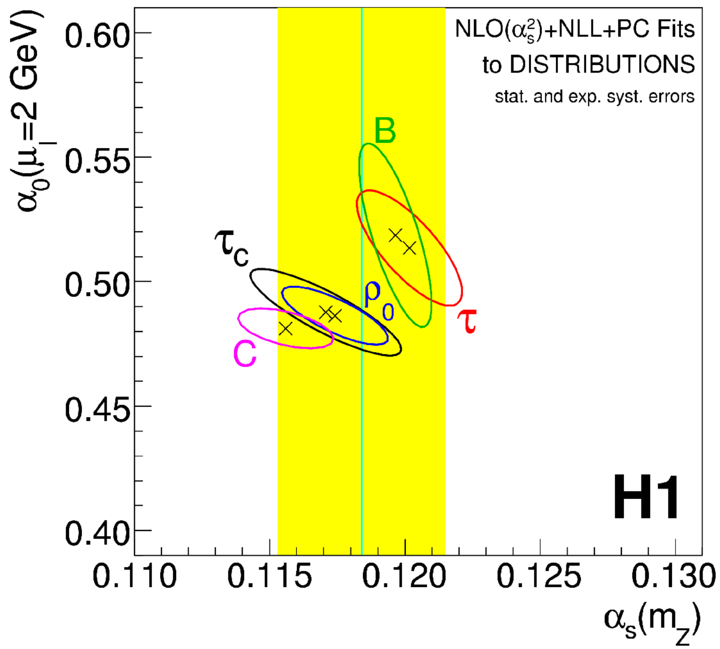
- Extracted α_0 values $\approx 0.45 - 0.5$ (universality at 10% level)
- Extracted values of α_s show a rather large spread

Event Shapes (H1)

Differential cross sections:



Extracted α_0 and α_s values:



- Consistent values for α_0 and α_s (maximal difference: two STDV)
- α_s in good agreement with world average
- $\alpha_0 \approx 0.5$ universal within 10%

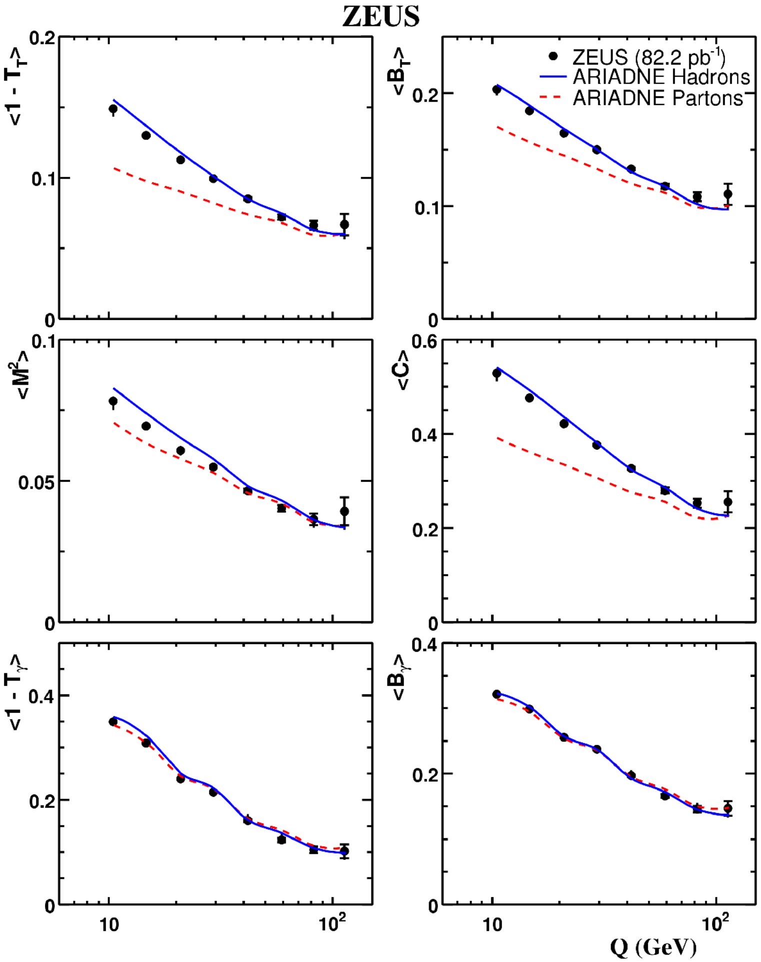
$\alpha_s(M_Z) = 0.1198 \pm 0.0013(\text{exp}) \pm 0.0050(\text{theo})$ (in good agreement with H1. incl jets)

$\alpha_0 = 0.476 \pm 0.008(\text{exp}) \pm 0.039(\text{theo})$

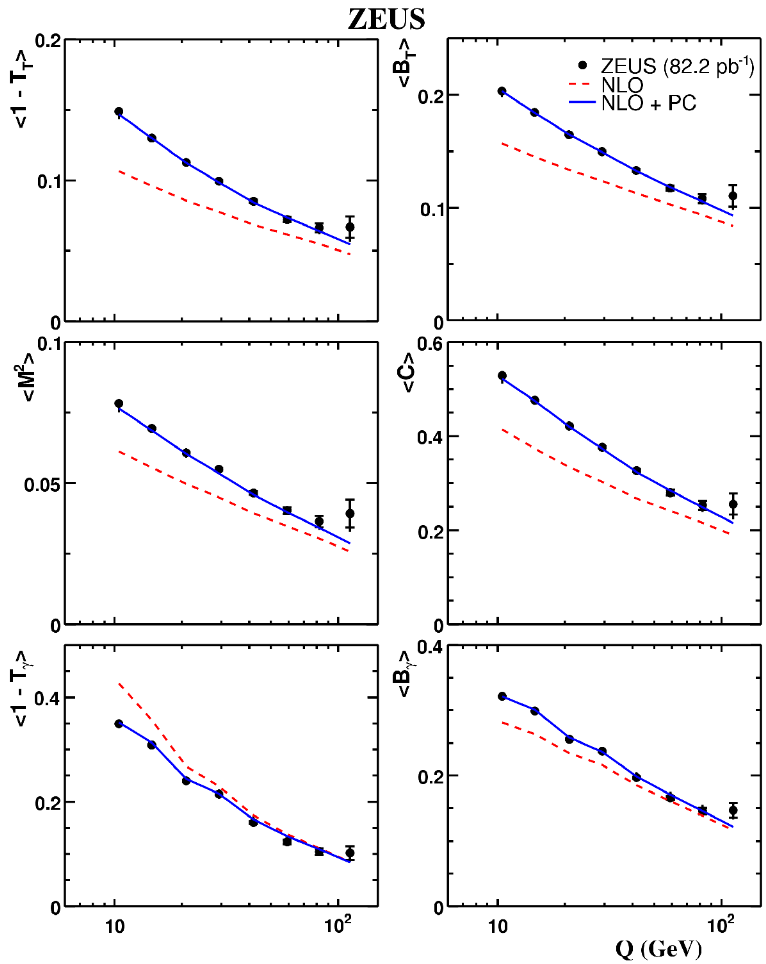
Event Shapes (ZEUS)

Data: 82 pb^{-1} (98-00) **Selection:** $80 < Q^2 < 20480$ GeV^2, $0.0024 < x < 0.6$, $0.04 < y < 0.9$

Comparison of mean values to ARIADNE:

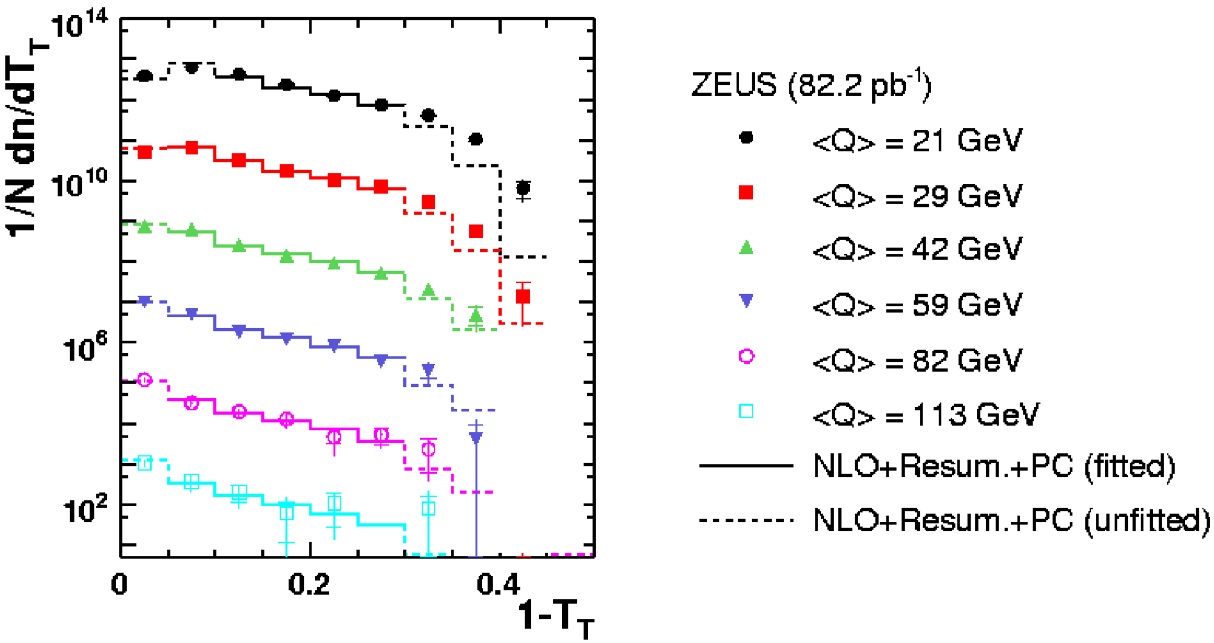


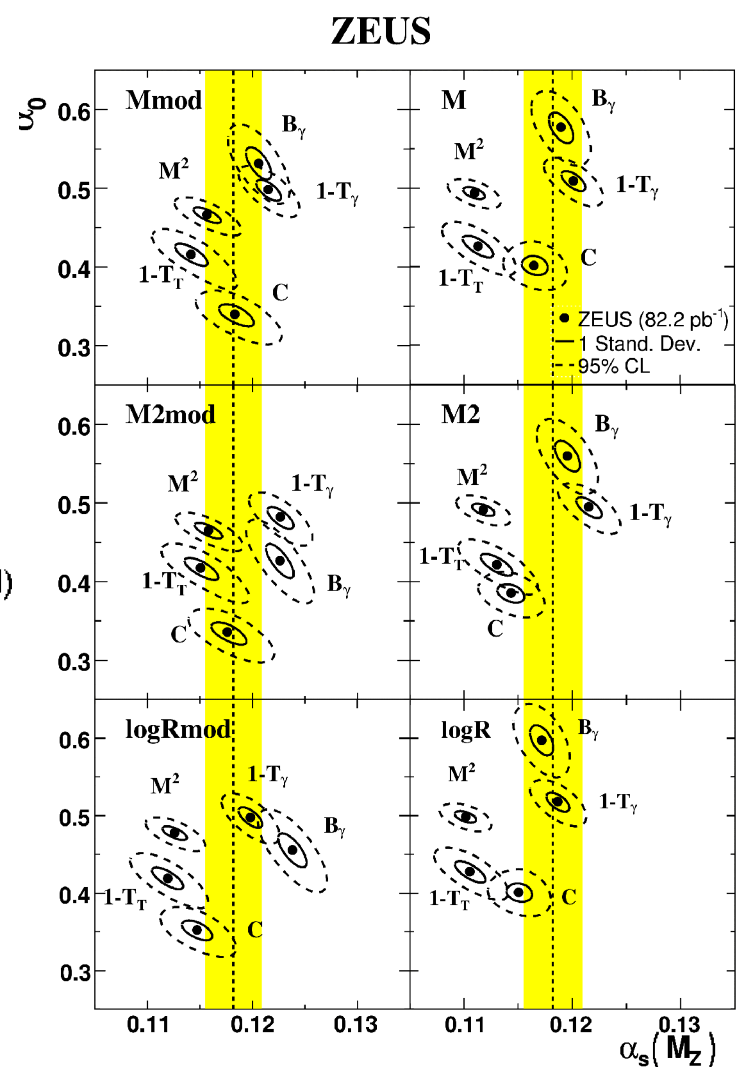
Comparison of mean values to NLO+PC:



Event Shapes (ZEUS)

Differential cross sections:



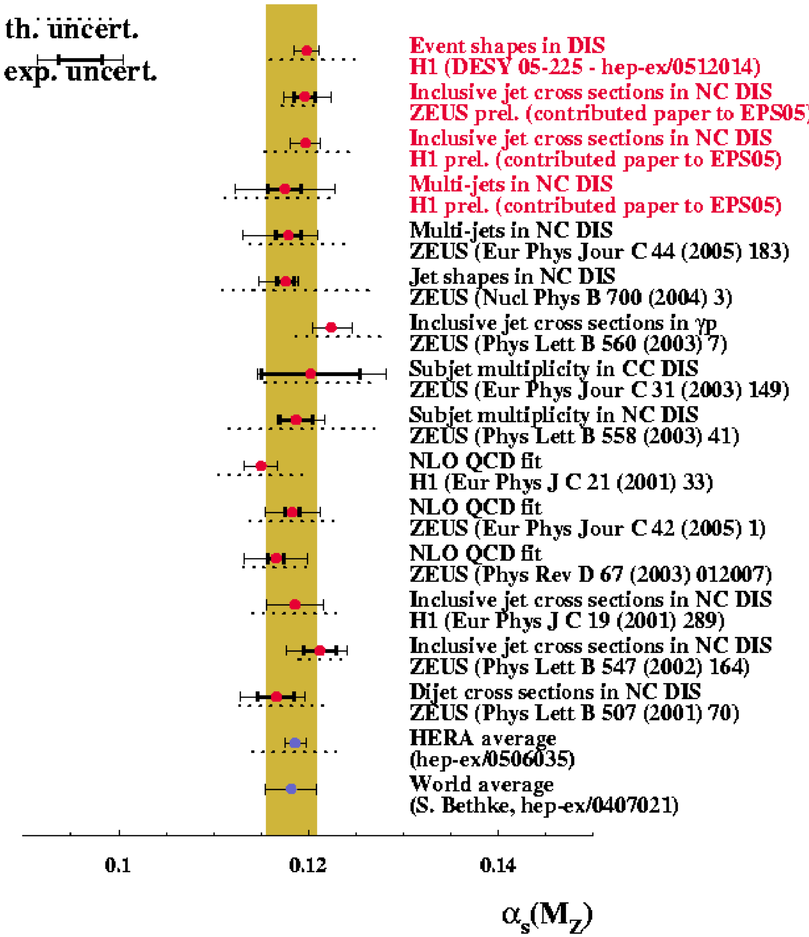


Extracted values of α_s and α_0 for different matching schemes (from differential xsections)

- Results depend on the scheme used.
- Large spread of extracted α_0 (universality?)
- Could indicate problems in theoretical description of the data.

Summary

- Measurements demonstrate excellent understanding of pQCD; concepts of factorization and PDF universality work very well.
- Power correction gives nice description of mean event shape variables but results depend on matching scheme (could indicate problems with PC)
- Very precise extraction of α_s; values are consistent with each other and world average.
- In many regions (low Q^2, E_T, M_{jj}) errors are dominated by scale variation effects; higher orders (NNLO) would really help.
- Correction of NLO is done with LO MC+PS; would be great to have NLO+PS for consistency.
- Analyses shown based on HERA I data: at high Q^2, E_T, M_{jj}, and ξ statistic is getting low (dominating error).
- HERA II already delivered more than 350 pb^{-1}: will allow even more precise measurements.



HERA average: $\alpha_s(M_Z) = 0.1186 \pm 0.0011(\mathrm{exp}) \pm 0.0050(\mathrm{theo})$ (June 2005)