Measurement of Jet Cross Sections and α_S at HERA

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on behalf of the H1 and ZEUS collaborations

QCD “Metrology” in Deep Inelastic Scattering(DIS)

- QCD is a one-parameter theory (neglecting m_q, θ_{QCD}): $\Lambda_{QCD} \longleftrightarrow \alpha_S(m_Z)$
- α_S measurements in Deep Inelastic Scattering (DIS):
  - scaling violations (QCD fits of structure functions)
  - event and jet shapes
  - **Jet cross-sections**

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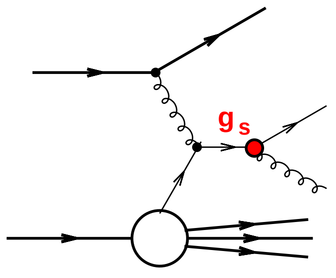
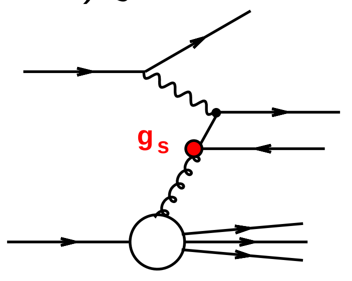
- production of $n + 1$(remnant) jets in leading order proportional to $\alpha_S{}^{n-1}$





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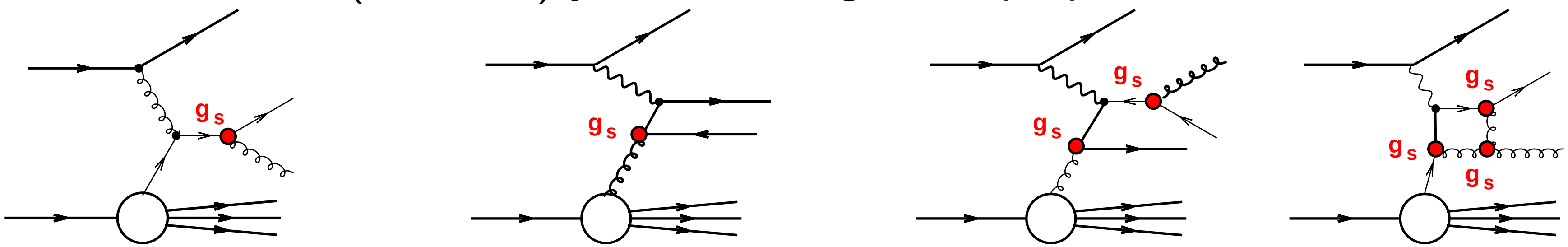

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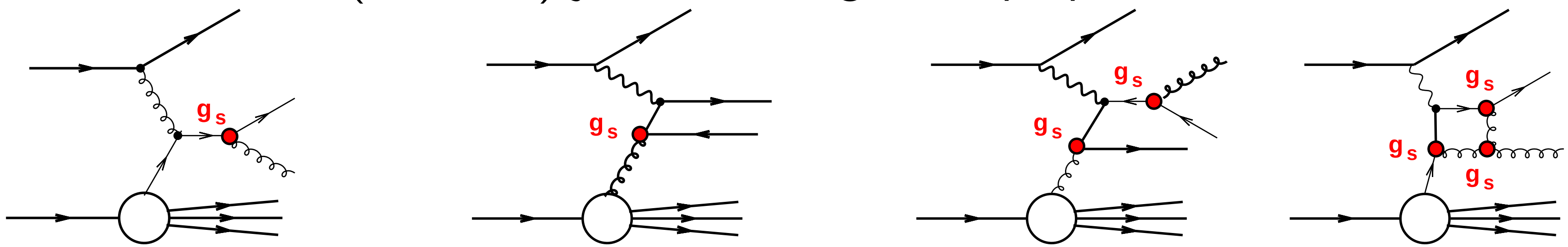
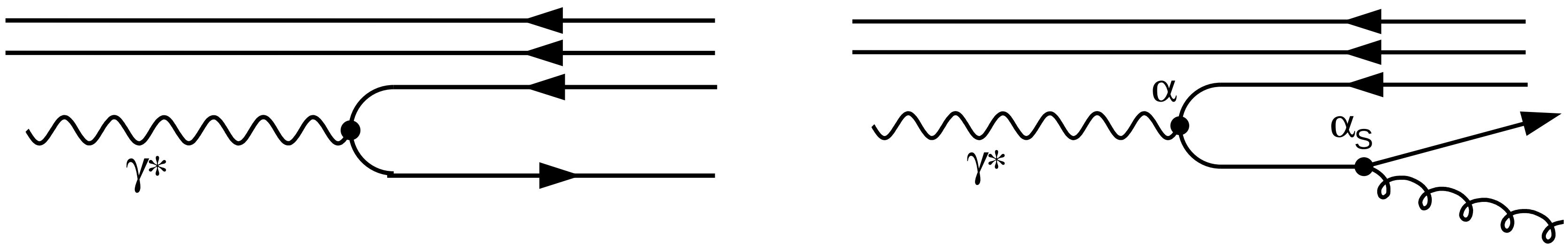


"QCD Compton" "Boson-Gluon-Fusion" "2 jet production at NLO"

- **inclusive jet cross-section**: high statistics, infrared safe (no asymmetric cuts)
- **ratio tri-jet / di-jet cross-section**: lower statistics, partial cancellation of syst. errors (luminosity, hadronic energy scale, parton distribution functions)

Jet Observables in the Breit Frame

- Definition of Breit frame in naive quark-parton model (and no intrinsic p_T):
  γ and q collide head on, $\vec{p}_q^{\,out} = -\vec{p}_q^{\,in}$



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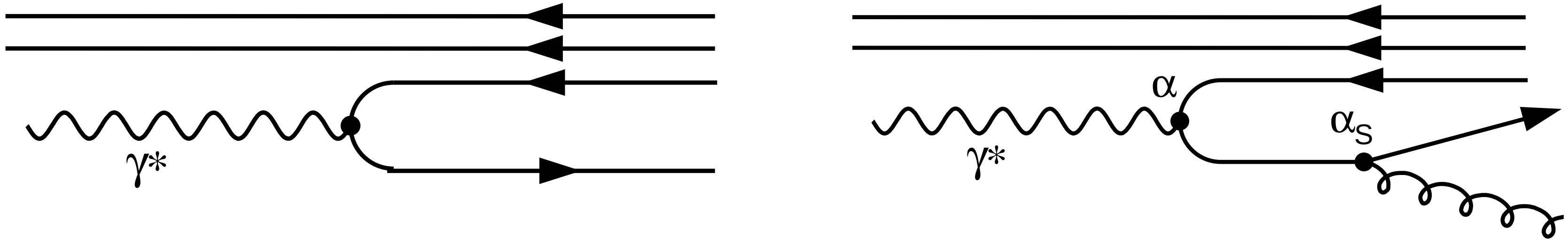

- transverse momentum in Breit frame stems mainly from QCD process
- longitudinally invariant k_T jet-algorithm in the Breit Frame
  - collinear and infrared safe
  - iterative clustering $d_{i,j} = \min(E_{T,i}^2, E_{T,j}^2) \cdot \left((\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2\right)$
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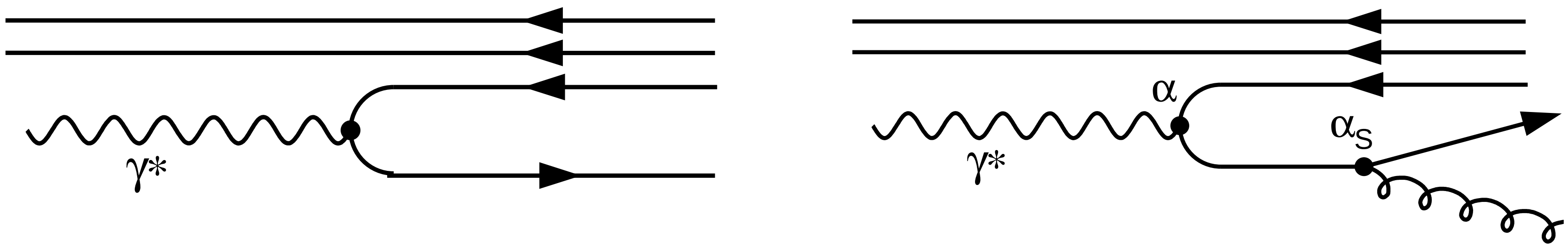

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  - result: n jets with $d_{i,j} > R_0$ where $R_0 = 1$
- Sources of experimental systematic uncertainties:
  - electron kinematics $\longrightarrow$ Lorentz transformation
  - model dependence for data correction (detector, hadronization, parton showers, QED)
  - **absolute hadronic energy scale**

Jet Production Cross-Sections in perturbative QCD

- jet cross-sections calculated in perturbative QCD at fixed order of α_S:

$$\sigma_{\rm jet} = \sum_{\rm i=q,\bar{q},g} \int {\rm dx}\, {\rm f_i}({\rm x}, \mu_{\rm F}, \alpha_{\rm S})\hat{\sigma}_{\rm QCD}({\rm x}, \mu_{\rm F}, \mu_{\rm R}, \alpha_{\rm S}(\mu_{\rm R})) \cdot (1 + \delta_{\rm had})$$

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- possible choices of μ_R and μ_F : $Q, E_T, f(Q, E_T)$
  assess theoretical uncertainty due to missing higher orders through μ_R-dependence of σ_{jet} and measured α_S by varying μ_R $\longrightarrow$ convention: $\mu_R \nearrow 2\mu_R$ and $\mu_R \searrow 0.5\mu_R$

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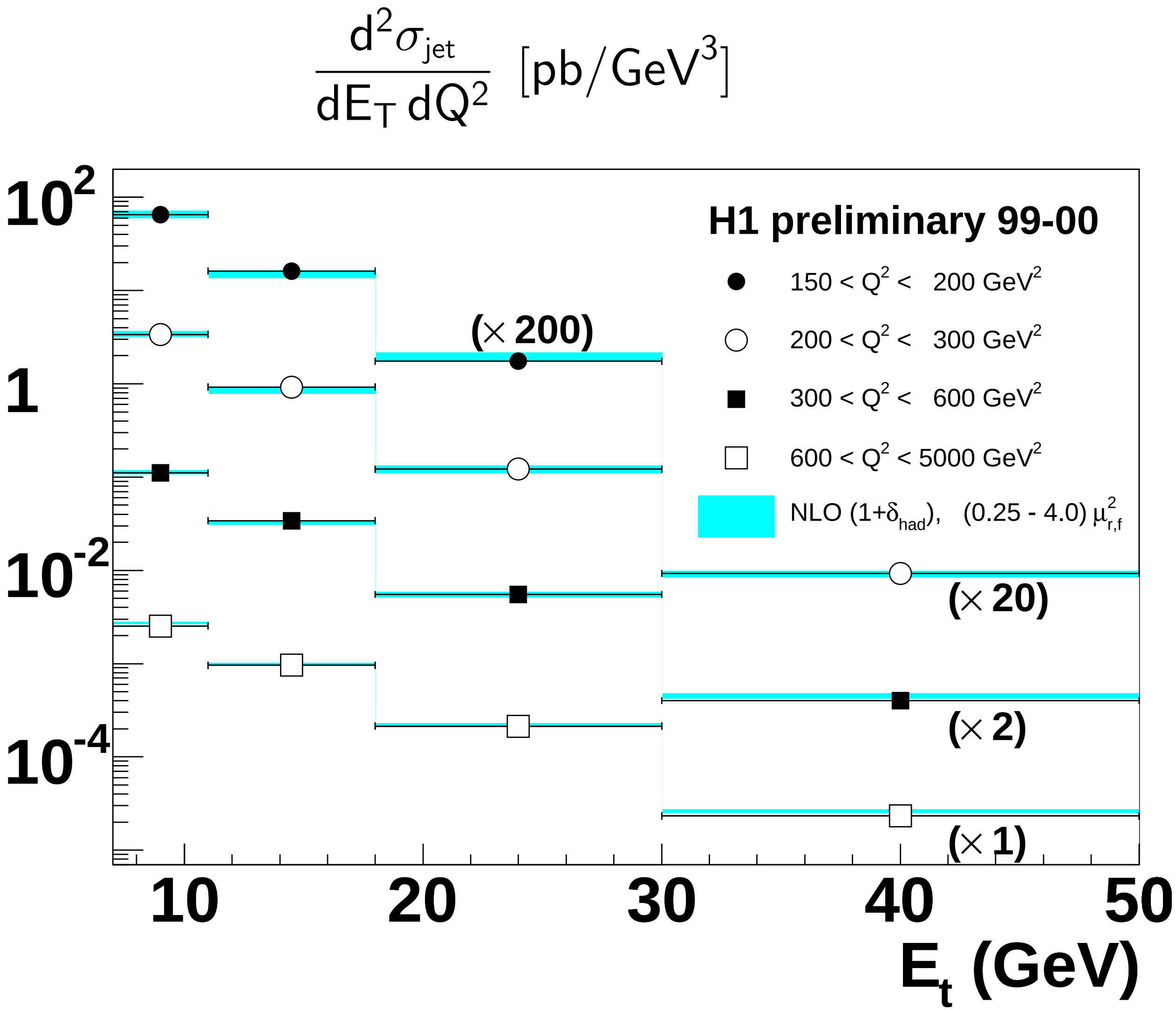
- pQCD calculation programs $\longrightarrow$ implementation of user jet algorihm
  - `DISENT`: 2+1 jets NLO (α_S^2)
  - `NLOJET++`: 3+1 jets NLO(α_S^3)

Measurement of Inclusive Jet Cross-Sections (H1)

- DIS phase space:
  $150 < Q^2 < 5000\,\mathrm{GeV}^2,\ 0.2 < y < 0.6$
- inclusive jets phase space:
  $E^{jet}_{T,Breit} > 7\,\mathrm{GeV},\ -1.0 < \eta_{Lab} < 2.5$
- Data correction (det.&QED):
  (CDM[DJANGO]+MEPS[RAPGAP])/2
- dominating exp. uncertainty:
  abs. hadronic energy scale
  $\longrightarrow$ vary E in HCAL by $\pm 2\%$
- NLO pQCD (NLOJET):
  - scales: $\mu_R = E_T,\ \mu_F = Q$
  - PDFs: CTEQ5M1
  - hadronization corrections:
    (CDM[DJANGO]+MEPS[RAPGAP])/2



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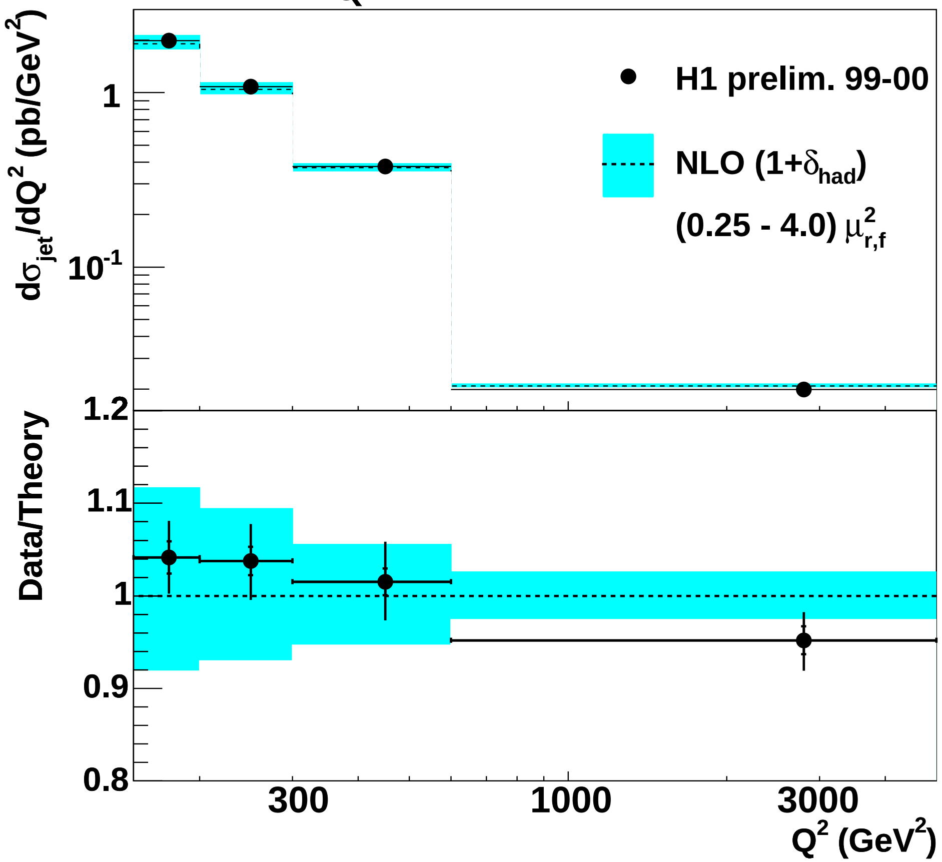
$$\frac{d\sigma_{jet}}{dQ^2}\ [pb/GeV^2]$$



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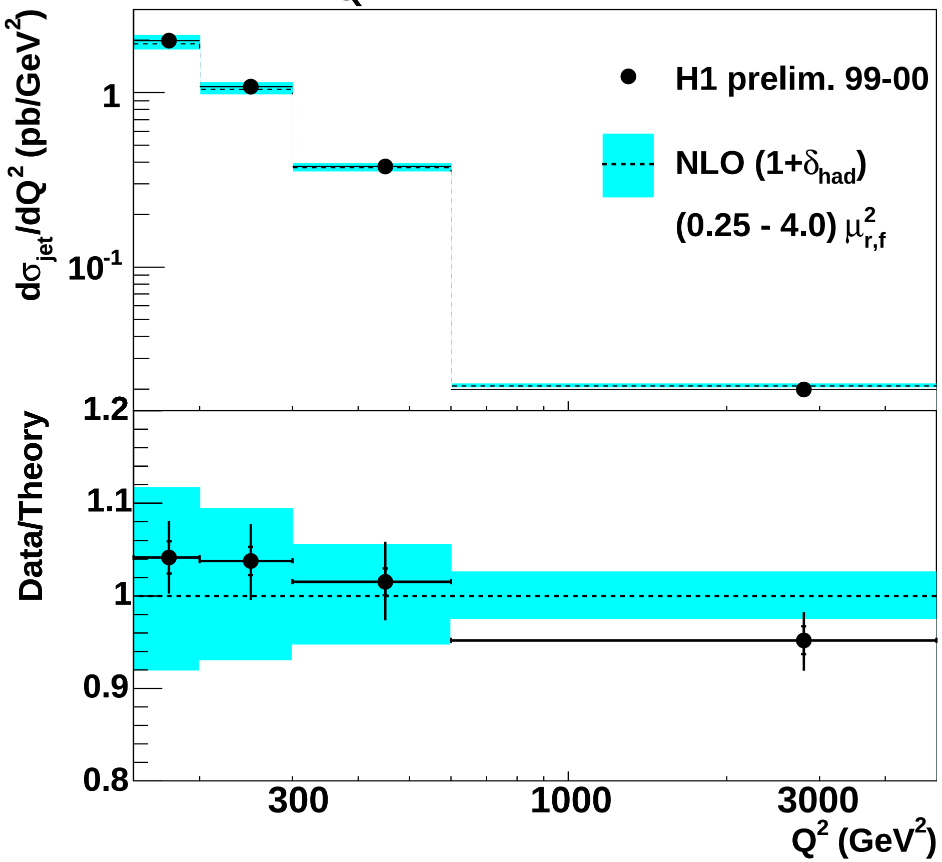
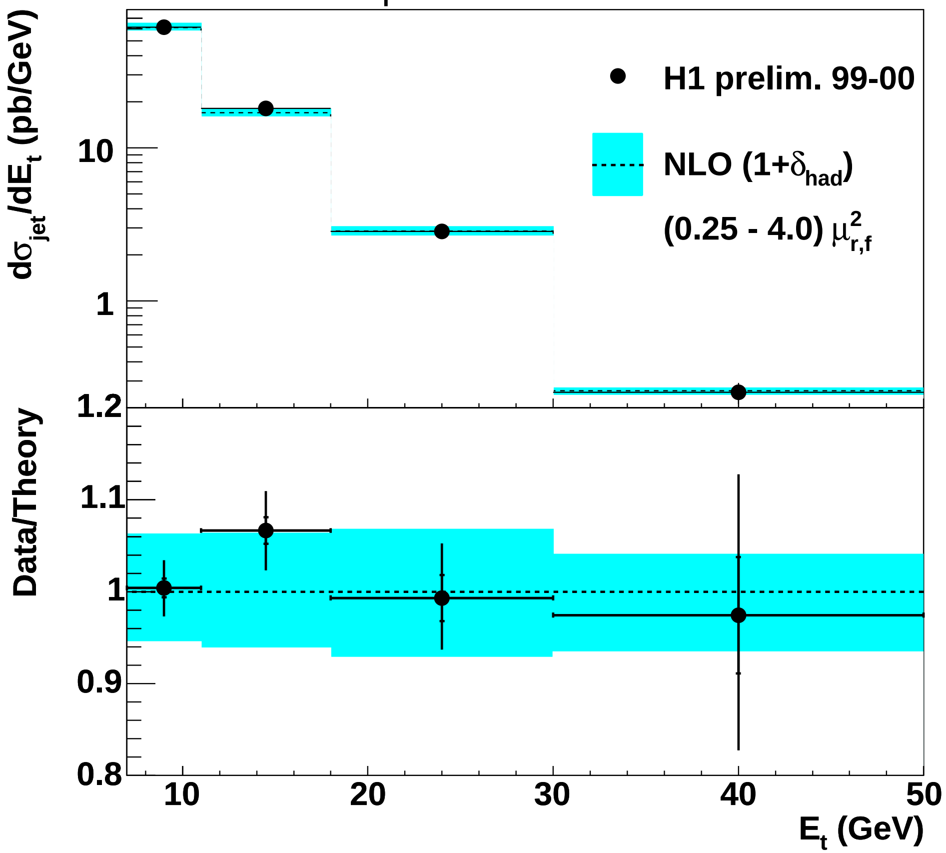


$$\frac{d\sigma_{jet}}{dE_T}\ [pb/GeV]$$



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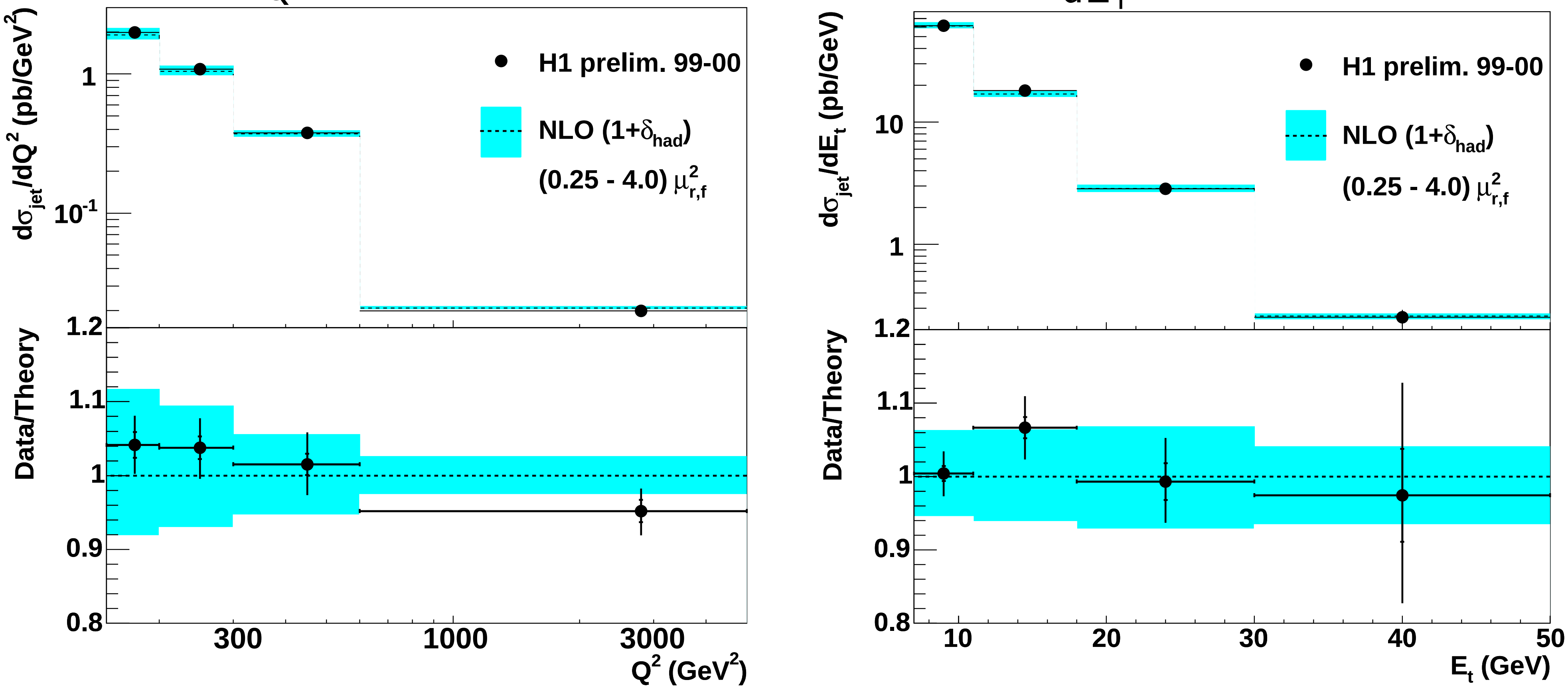
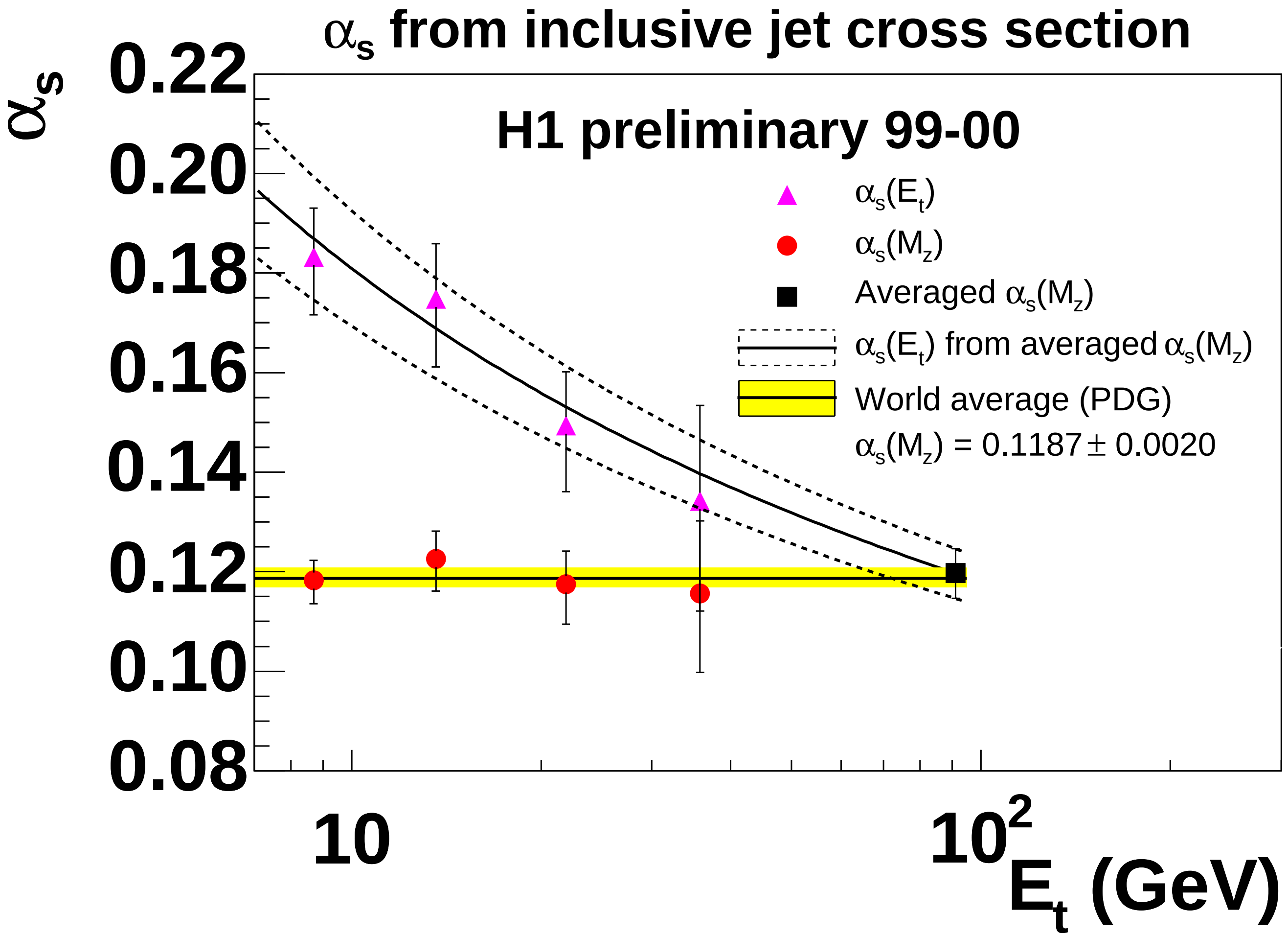


good agreement between pQCD (NLOJET) prediction and data over full phase space

α_S Measurement from Inclusive Jets (H1)

- parametrize pQCD prediction for cross-section in bin (i): $\sigma_{\text{jet}}^{(\text{i})}(\alpha_S) = \text{A}_\text{i} \cdot \alpha_S + \text{B}_\text{i} \cdot \alpha_S{}^2$
- fit α_S in each bin of double-diff. cross-section
- consider exp. syst. errors partially correlated
- scales: $\mu_R = E_T, \mu_F = Q$
- $\chi^2/\text{ndf} = 20.14/14$



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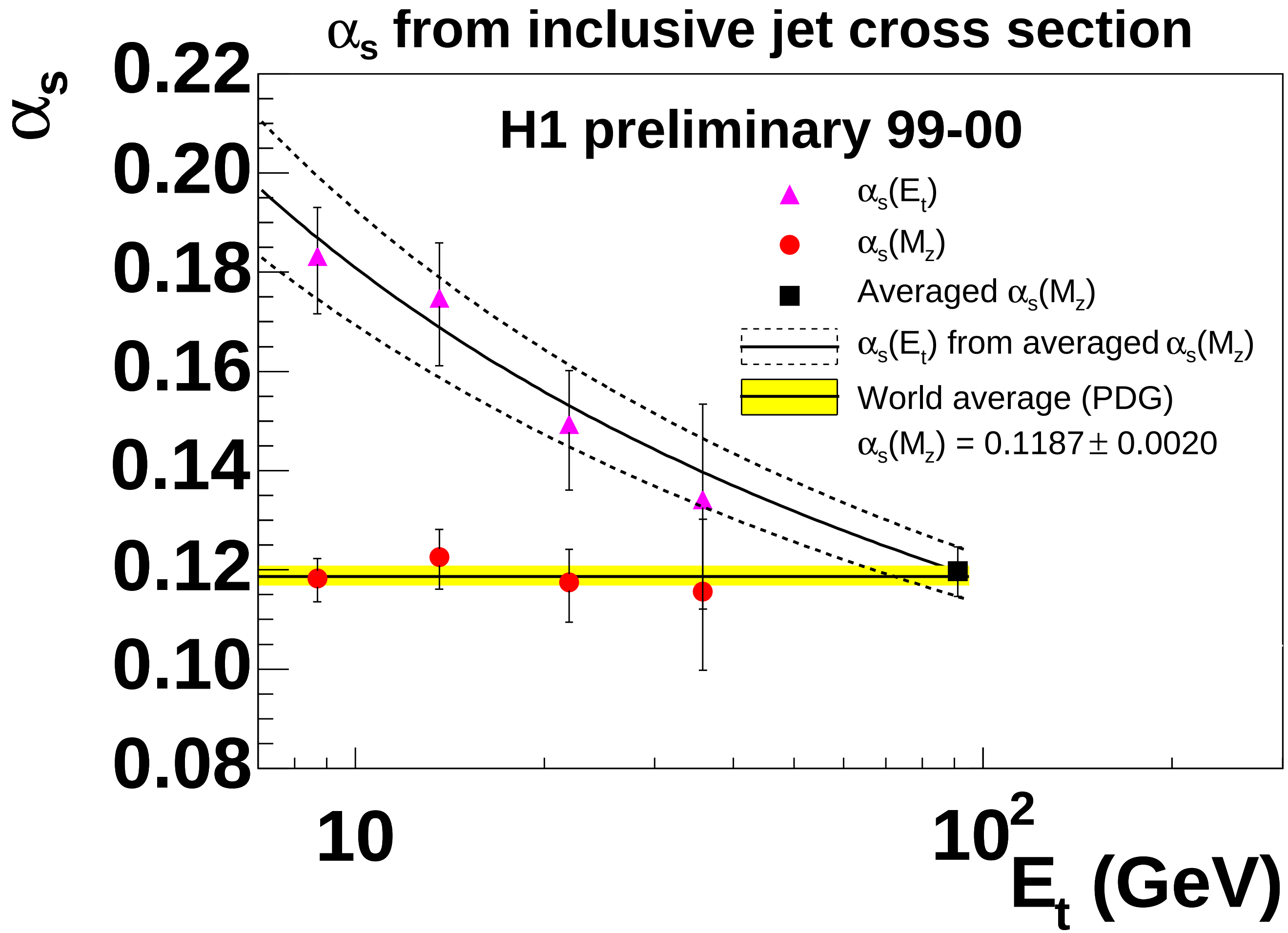
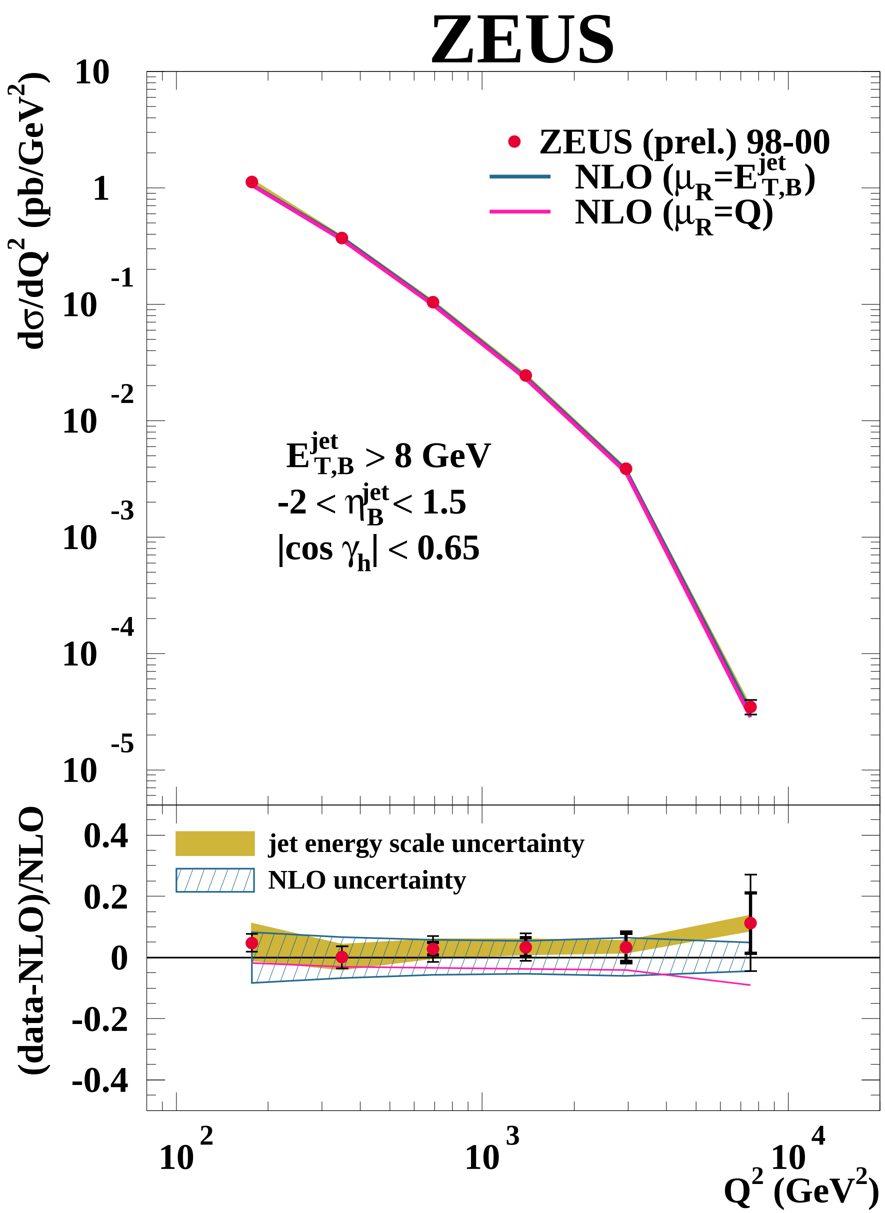


$$\alpha_S(m_Z) = 0.1197 \pm 0.0016(\text{exp.}) \begin{array}{l} +0.0046 \\ -0.0048 \end{array} (\text{th.})$$

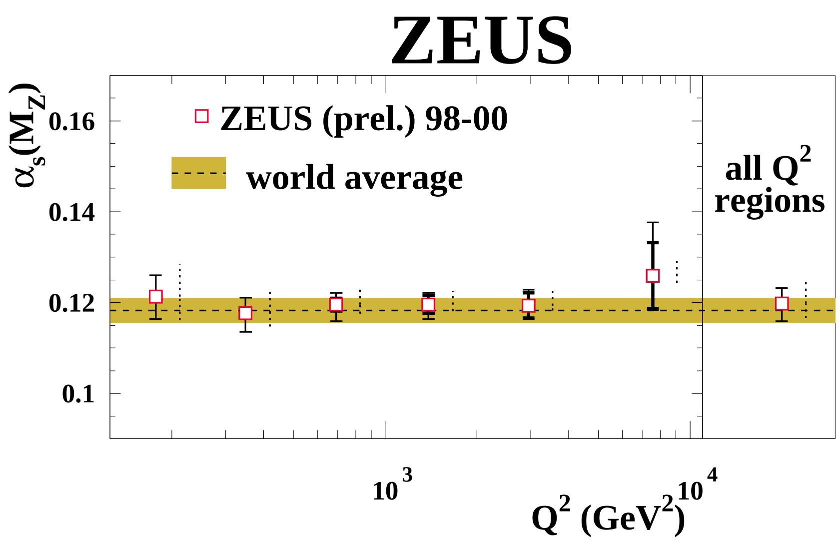
Measurement of Inclusive Jet Cross-sections (ZEUS)

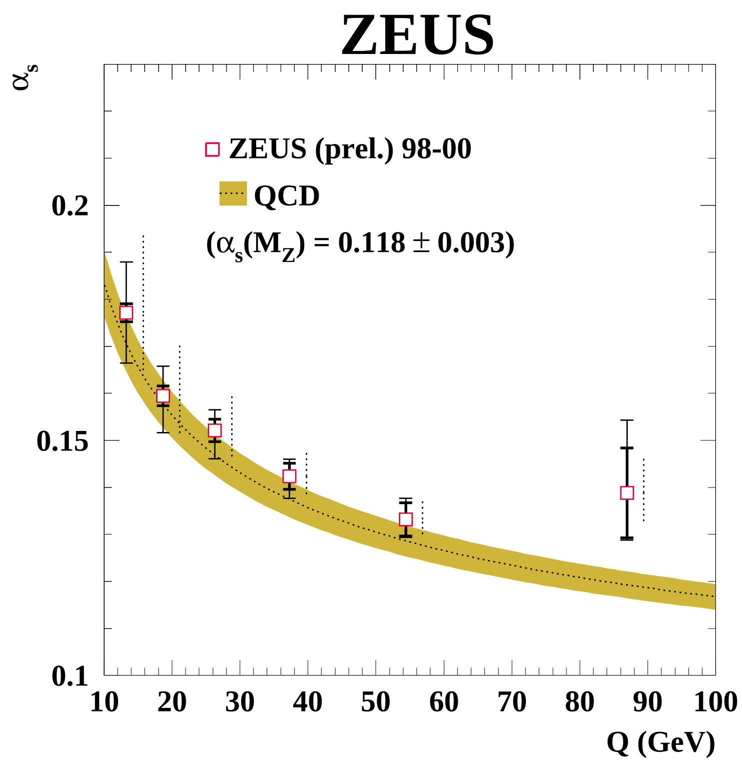
- DIS phase space:
  $Q^2 > 125\,\mathrm{GeV}^2$, $|\cos\gamma_{\mathrm{HAD}}| < 0.65$
- inclusive jets phase space:
  $E^{\mathrm{jet}}_{T,\mathrm{Breit}} > 8\,\mathrm{GeV}$, $-2.0 < \eta^{\mathrm{jet}}_{\mathrm{Breit}} < 1.5$
- Measure: $\frac{d\sigma_{\mathrm{jet}}}{dQ^2}$, $\frac{d\sigma_{\mathrm{jet}}}{dE_T}$, and $\frac{d\sigma_{\mathrm{jet}}}{d\eta^{\mathrm{jet}}_{\mathrm{Breit}}}$
- dominating exp. error: hadr. E-scale
  - vary $E^{\mathrm{jet}}_{T,\mathrm{Breit}}$ by $\pm$ 1% ($\pm$3% if $E^{\mathrm{jet}}_{T,\mathrm{Lab}} < 10\,\mathrm{GeV}^2$)
  - typical effect ob σ_{jet} : $\pm$5%
- Comparison with pQCD (DISENT):
  - scales: $\mu_R = E_T$(or Q), $\mu_F = Q$
  - PDFs: MRST99
  - hadr. and Z^0 exchange corrs: ARIADNE
- **good description of data**
  (slightly better with $\mu_R = E_T$)



α_S Measurement from Inclusive Jets (ZEUS)

- fit α_S-parametrized pQCD prediction to $\frac{d\sigma_{jet}}{dE_T}$ and $\frac{d\sigma_{jet}}{dQ^2}$
- alternatively: running $\alpha_S \longrightarrow$ fit $\alpha_S(\langle E_T \rangle)$- or $\alpha_S(\langle Q \rangle)$-parametrized pQCD



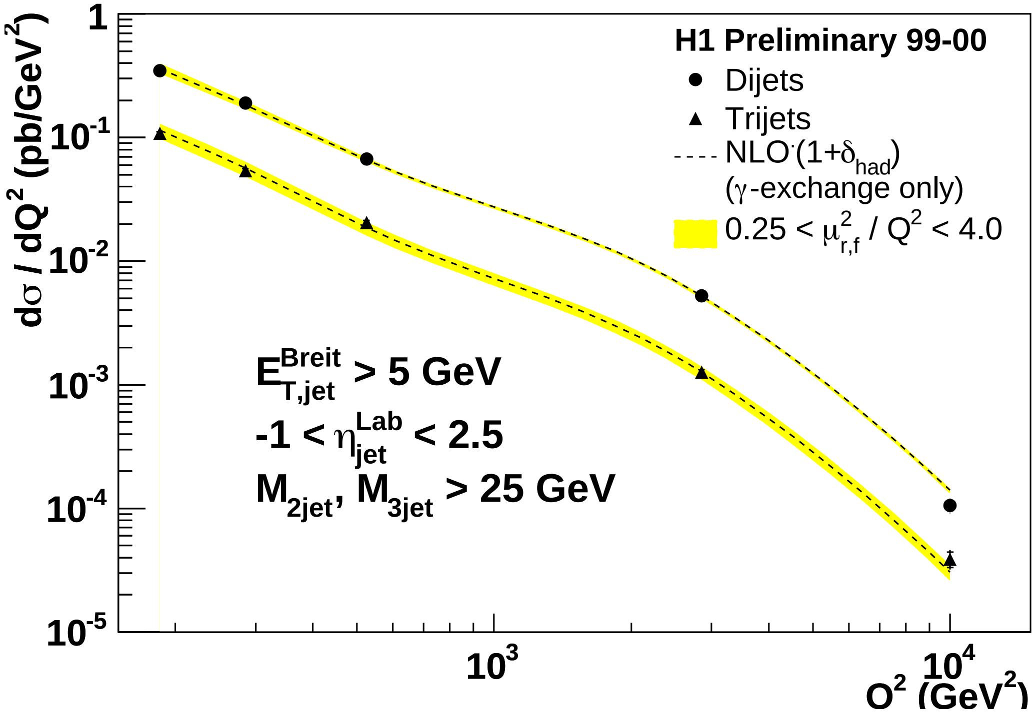


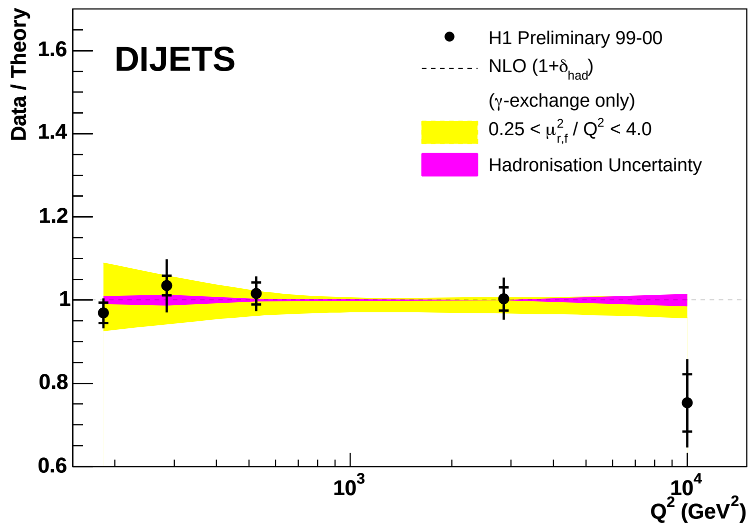
- best for $\frac{d\sigma_{jet}}{dQ^2}$, $Q^2 > 500 \mathrm{GeV}^2$:

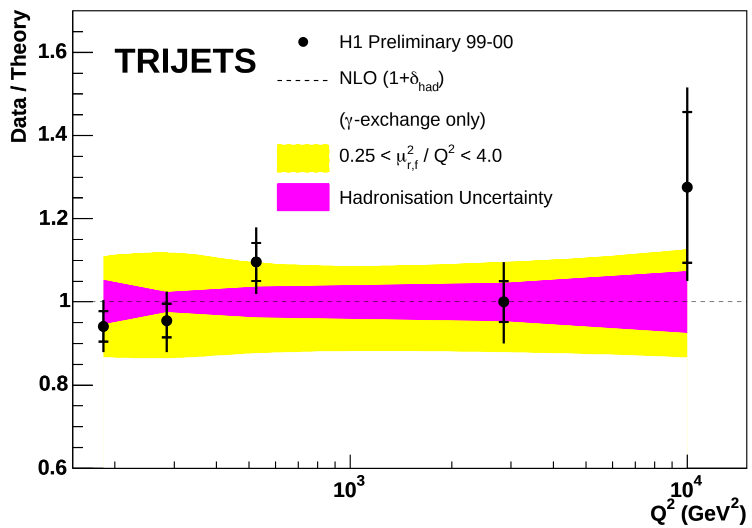
$$\alpha_S(m_Z) = 0.1196 \pm 0.0011(\text{stat.})\ {}^{+0.0019}_{-0.0025}\ (\text{exp.})\ {}^{+0.0029}_{-0.0017}\ (\text{th.})$$

Measurement of 2-jet and 3-Jet Cross-Sections (H1)

- data correction(detector & QED, but no EW):
  (DJANGO+RAPGAP)/2 ⟶ Dijets: $\times 1.10$, Trijets: $\times 0.95$
- Comparison with NLOJET:
  - scales: $\mu_R = \mu_F = Q$
  - PDFs: CTEQ5M (CTEQ4A for α_S fits)
  - had. corrs: Dijets: $\times 0.93$, Trijets: $\times 0.75$

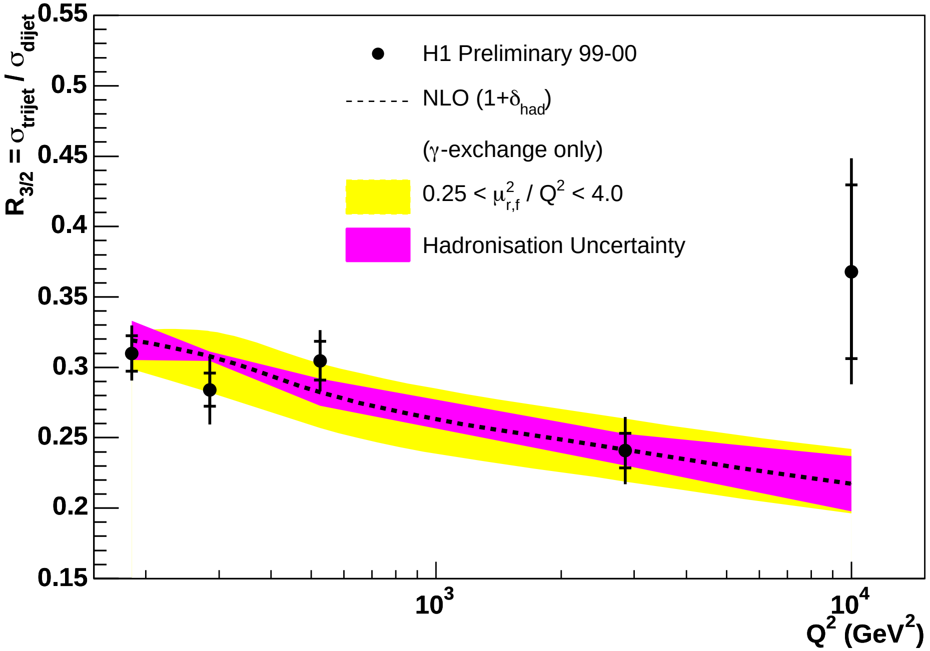






Good agreement for $Q^2 < m^2_{Z^0}$

α_S Measurement from 3-jet / 2-jet Cross-Section Ratio (H1)



- $R_{3/2}$ well described by pQCD where EW effects negligable $\longrightarrow$ exclude highest Q^2 bin
- fit α_S parametrized NLO pQCD prediction (NLOJET) for $R_{3/2}$

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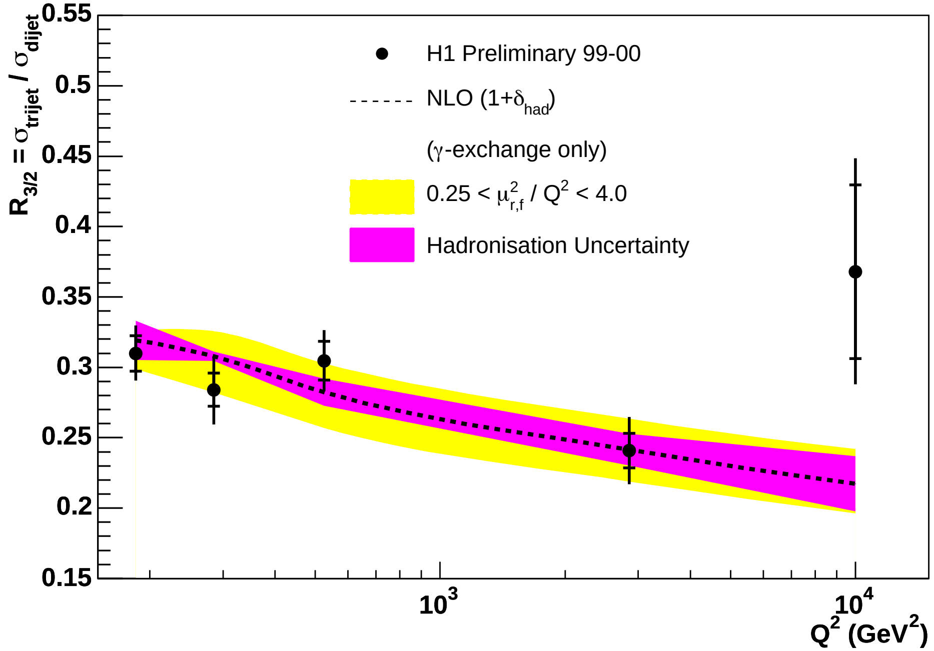

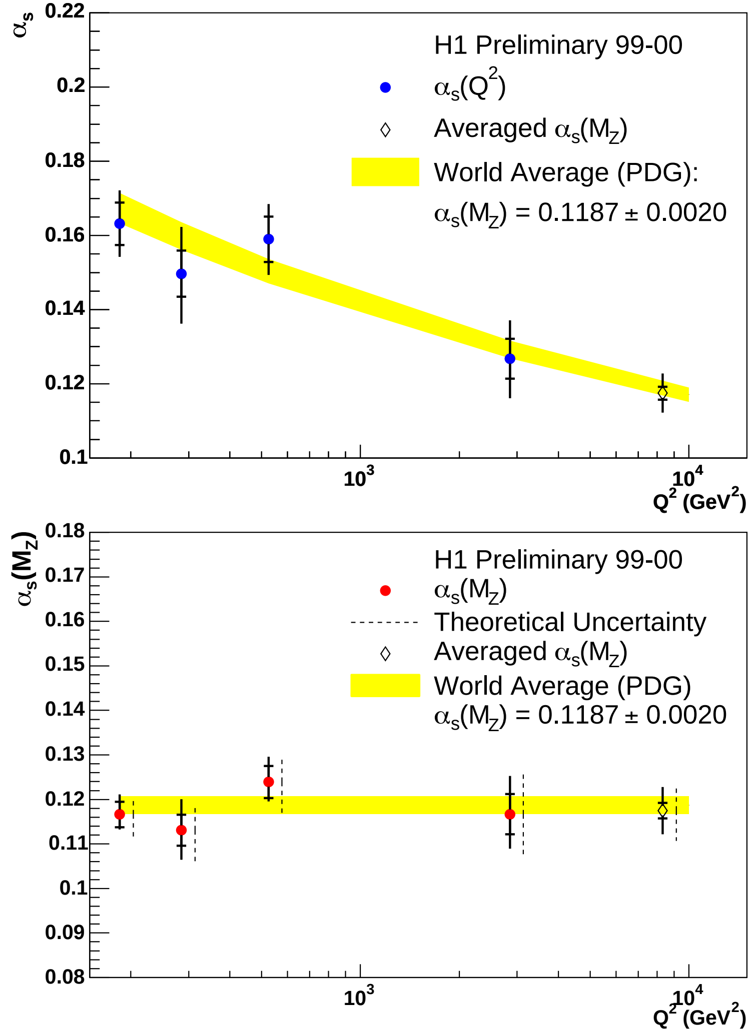

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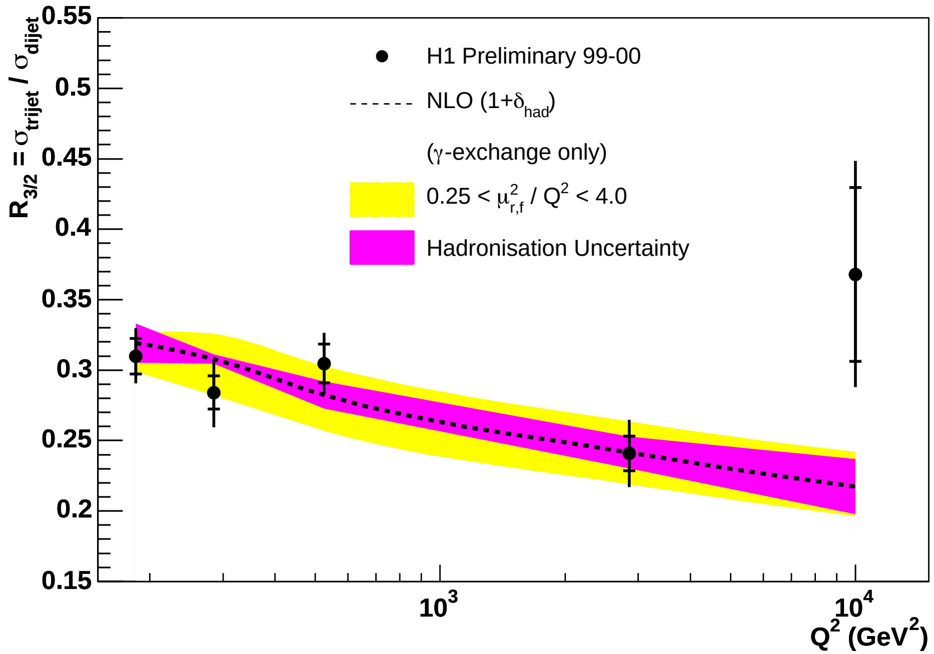

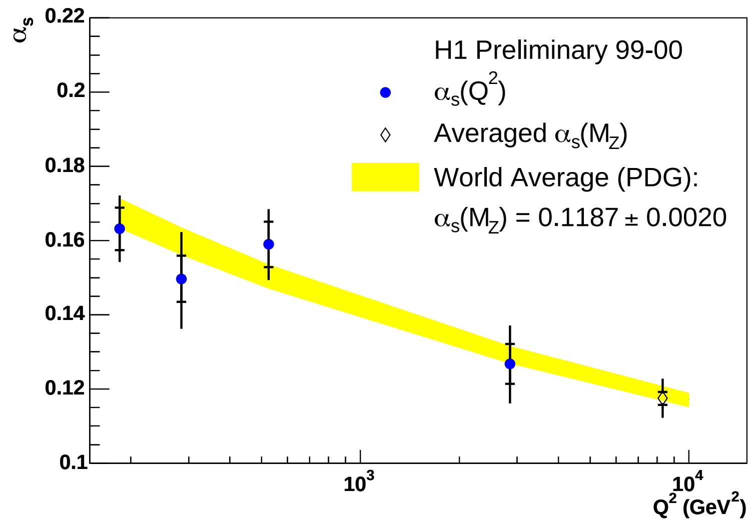

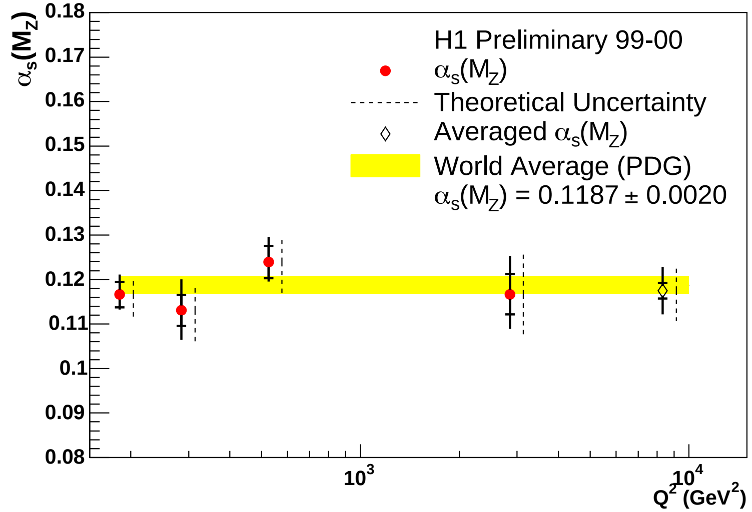

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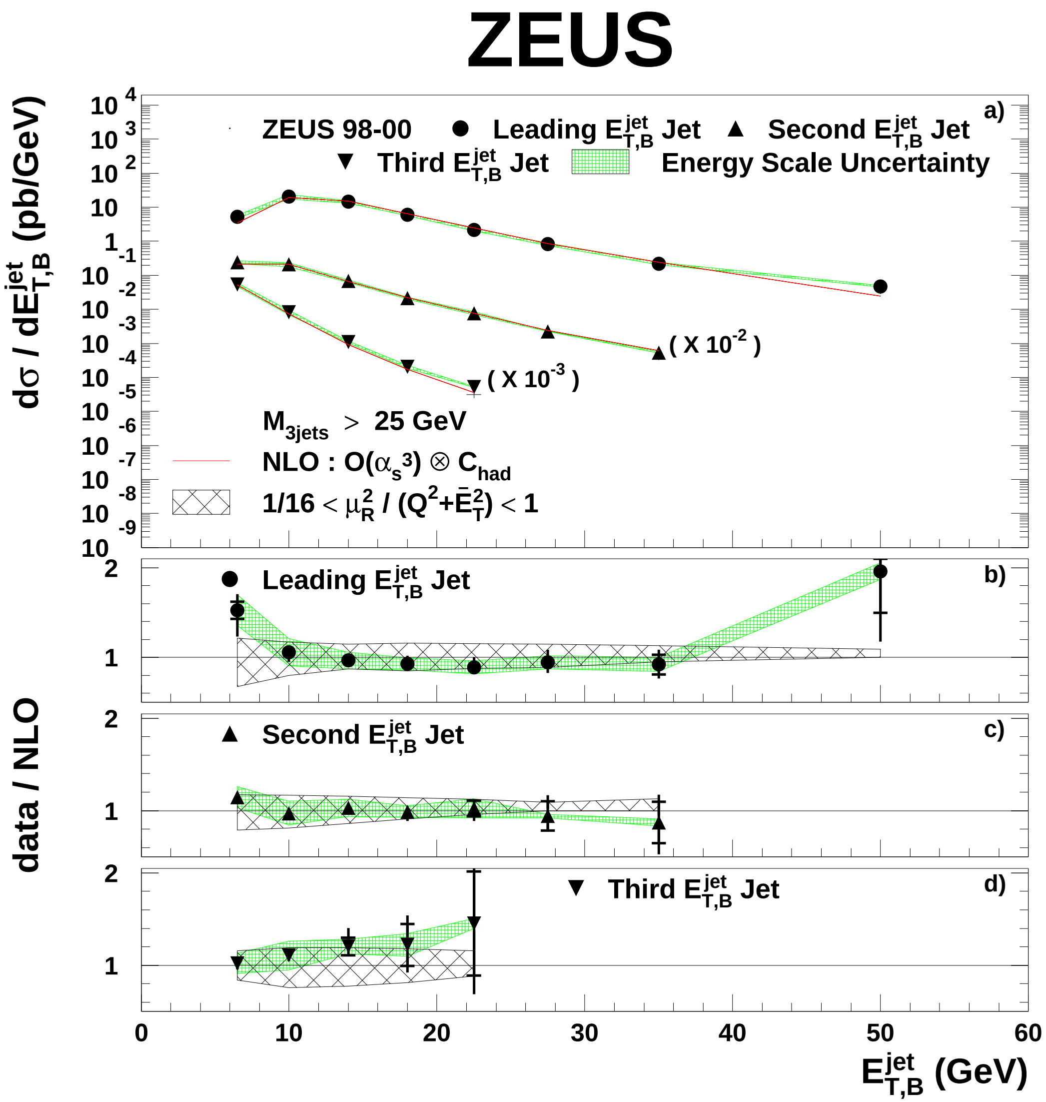
- fit α_S parametrized NLO pQCD prediction (NLOJET) for $R_{3/2}$

$$\alpha_S(m_Z) = 0.1175 \pm 0.0017(\text{stat.}) \pm 0.0050(\text{exp.}) \begin{matrix} +0.0054 \\ -0.0068 \end{matrix} (\text{th.})$$

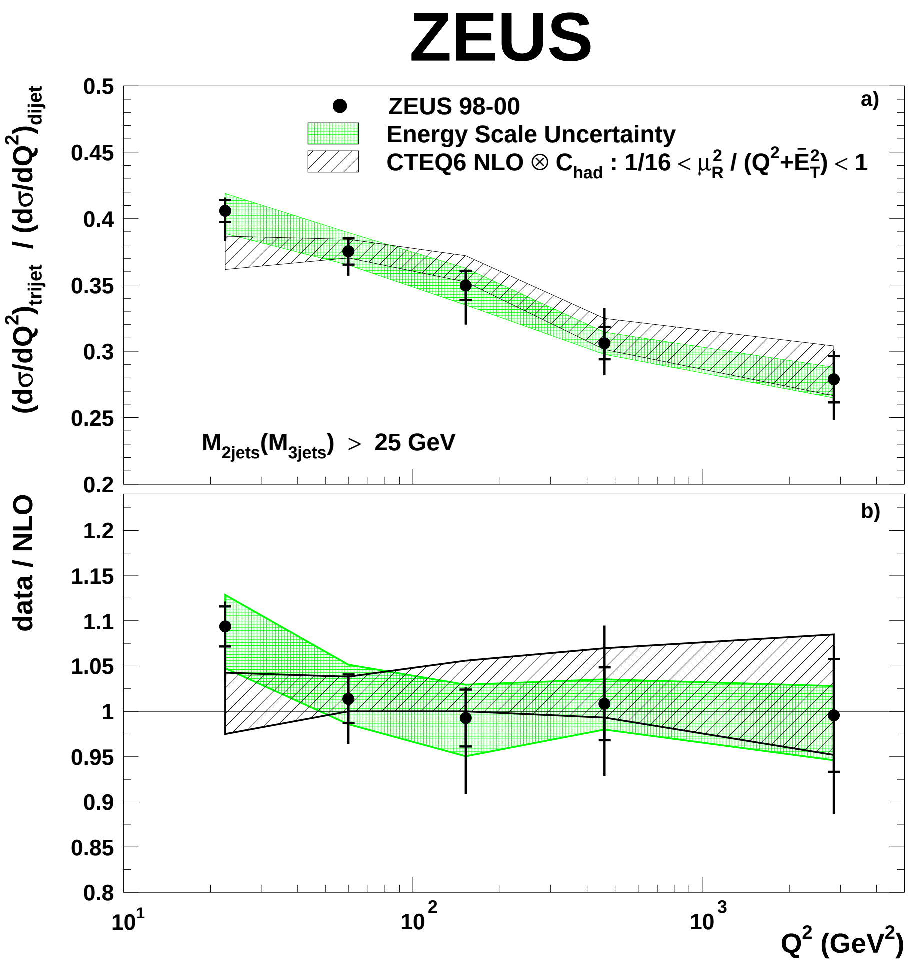
Measurement Multi-jet Cross-Sections (ZEUS)

- DIS phase space:
  $10 < Q^2 < 5000\,\mathrm{GeV}^2,\ 0.04 < y < 0.6$
- inclusive jets phase space:
  $E^{jet}_{T,Breit} > 5\,\mathrm{GeV},\ -1.0 < \eta^{jet}_{Lab} < 2.5$
  $M_{2jet},\ M_{3jet} > 25\,\mathrm{GeV}$
- Measure: $\frac{d\sigma_{3jet}}{dQ^2}$, $\frac{d\sigma_{3jet}}{dE_T}$, and $\frac{d\sigma_{3jet}}{d\eta^{jet}_{Breit}}$
- dominating exp. uncertainty: hadronic energy scale
  - ▶ vary $E^{jet}_{T,Breit}$ by $\pm 1\%$ ($\pm 3\%$ if $E^{jet}_{T,Lab} < 10\,\mathrm{GeV}^2$)
  - ▶ typ. effect on σ_{3jet} : $\pm 6\%$ ($\pm 3\%$ on $R_{3/2}$)
- Comparison with NLOJET:
  - ▶ scales: $\mu_R = \mu_F = \sqrt{(\bar{E}^2_{T,B} + Q^2)/4}$
  - ▶ PDFs: CTEQ6
  - ▶ hadr. corrs: LEPTO $\longrightarrow$ $\times 1.15$–1.35



good agreement data ↔ NLO pQCD

α_S Measurement from 3-jet / 2-jet Cross-Section ratio (ZEUS)



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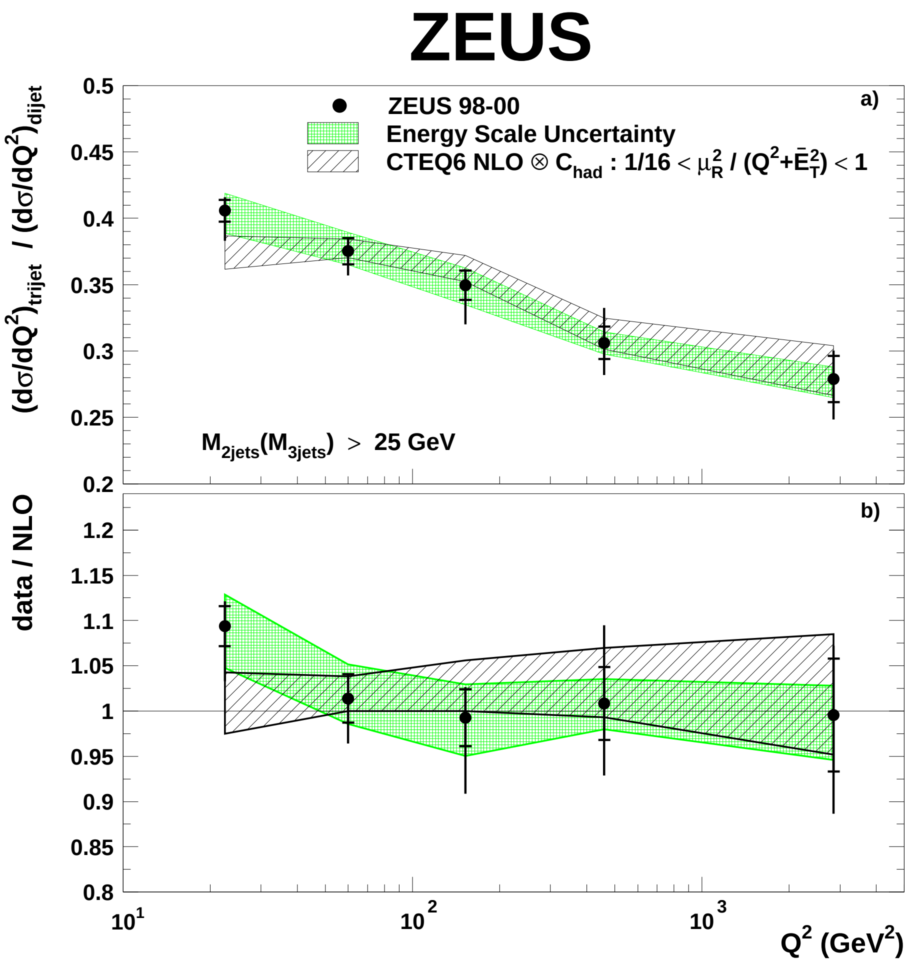

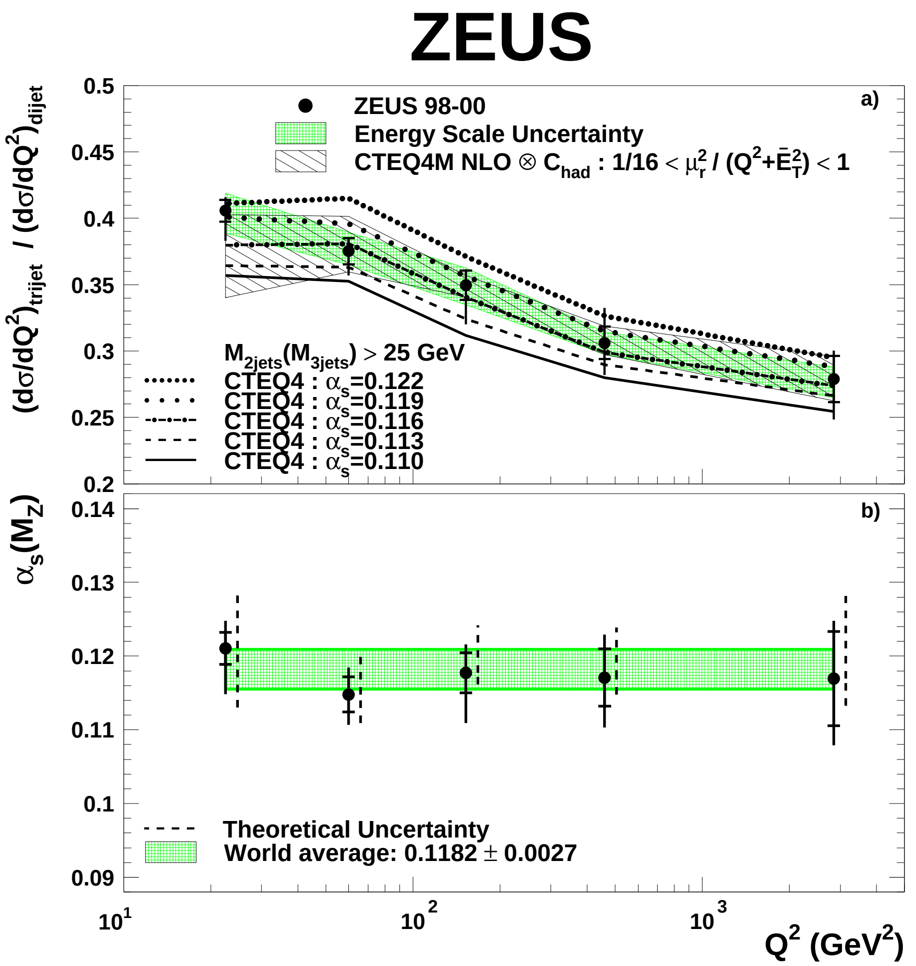

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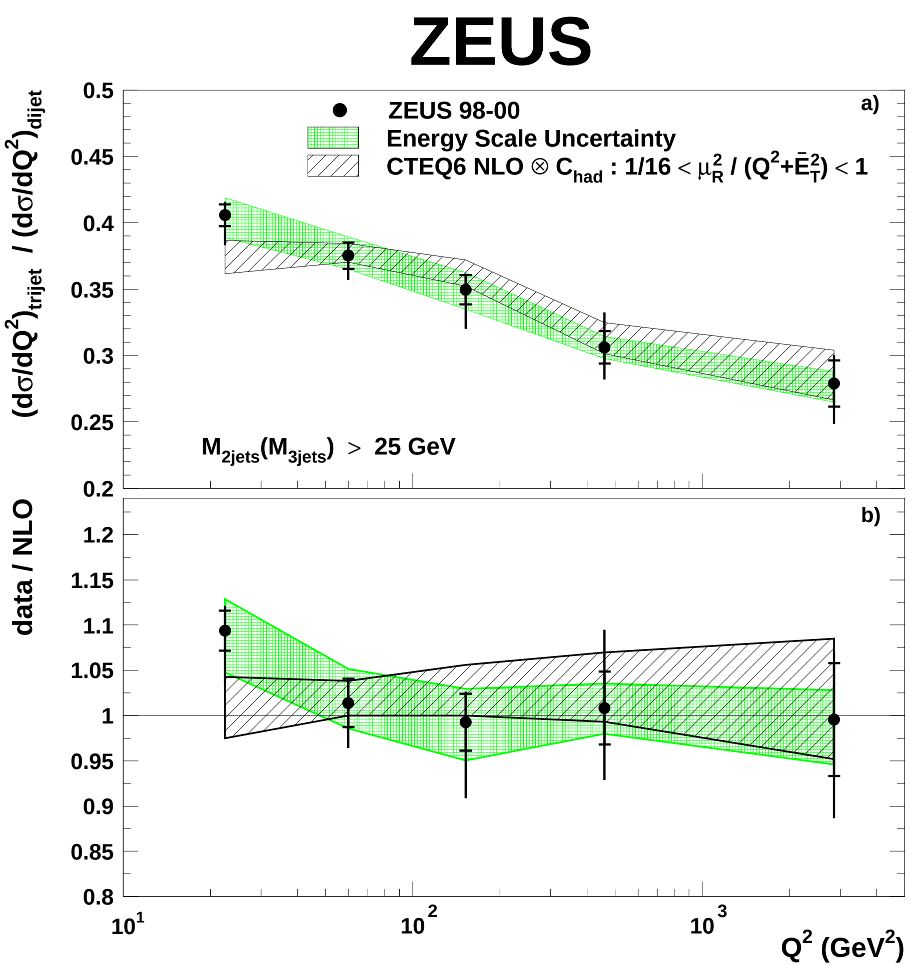
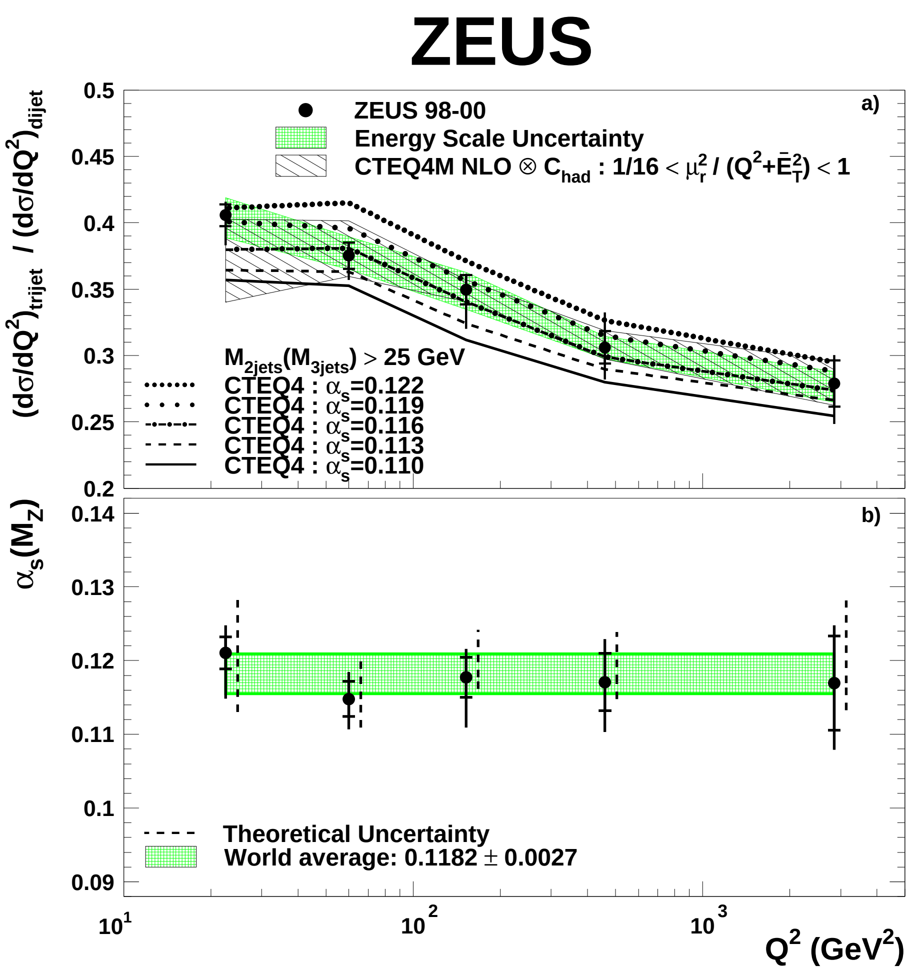


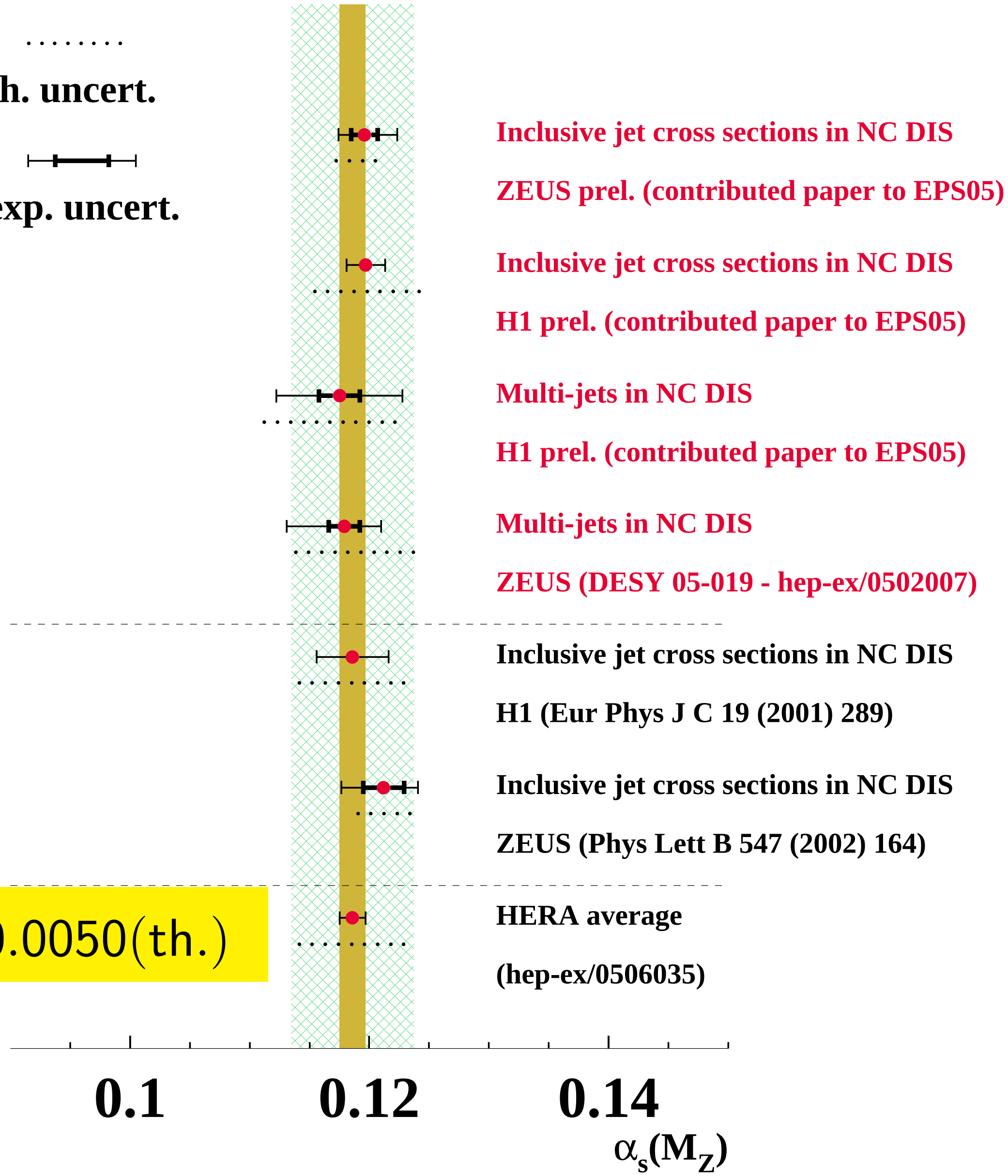


$$\alpha_S(m_Z) = 0.1179 \pm 0.0013(\text{stat.}) \,^{+0.0028}_{-0.0046}\,(\text{exp.}) \,^{+0.0064}_{-0.0046}\,(\text{th.})$$

Summary of α_S Measurements with Jets at HERA

- accurate measurements of α_S from jet production at HERA:
  - ▶ increased statistics (full HERA-1)
  - ▶ exp.syst. errors improved
- consistent measurements between H1 and ZEUS
  - ▶ combined fits (cf. C. Glasman, DIS2005)
  - ▶ conservative analysis of error correlation
- **HERA average:** (ZEUS & H1)

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



Conclusion and Perspectives

- α_S measurements from HERA are

... mutually consistent

... all consistent with world average

... competitive

- theory uncertainty > exp. error ($\gg$ for combined α_S)
- dominating theor. uncertainty: renormalization scale dependence $\Longrightarrow$ NNLO jet calculations needed
- dominating exp. uncertainty: hadronic energy scale (jet E) $\longrightarrow$ room for improvement with HERA2 data