Jet production in deep inelastic scattering at HERA

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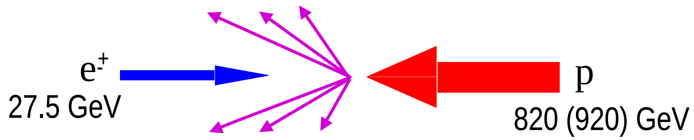
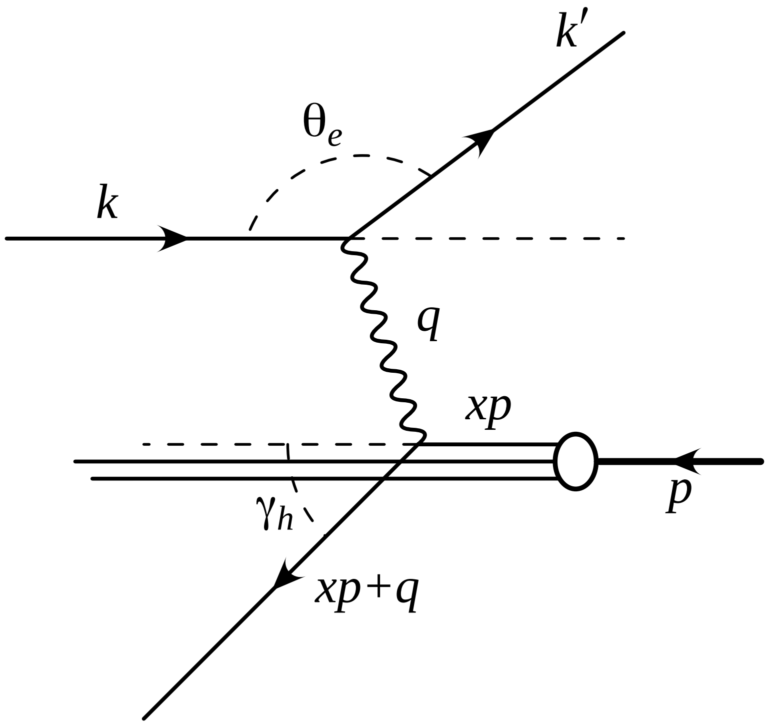
By way of introduction...

- The HERA collider provides a unique laboratory for the study of the hadronic final state.
- High transverse energy jet data are now very precise, typically experimental systematic uncertainties are below 5% and non-perturbative effects are small...
  - ▷ Precision tests of our understanding of QCD.
  - ▷ Study where theoretical uncertainties are small, and where large.
  - ▷ Where small, allows extraction of QCD parameters.
  - ▷ Constraints on proton parton distribution functions.
- Study sub-processes directly proportional to α_s or higher powers.
- Explore low Q^2 transition region ➡ see talk by Kamil Sedlák.

HERA kinematics

- HERA: an ep collider, 27.5 GeV positrons (or electrons) with:
  - ▷ 1994-1997: 820 GeV protons, $\sqrt{s} = 300$ GeV
  - ▷ 1998-2000: 920 GeV protons, $\sqrt{s} = 318$ GeV





- (Negative) squared 4-momentum transfer

$$Q^2 = -(k - k')^2.$$

- Bjorken scaling variable

$$x \equiv \frac{Q^2}{2p.q}.$$

- Inelasticity

$$y \equiv \frac{p.q}{p.k}.$$

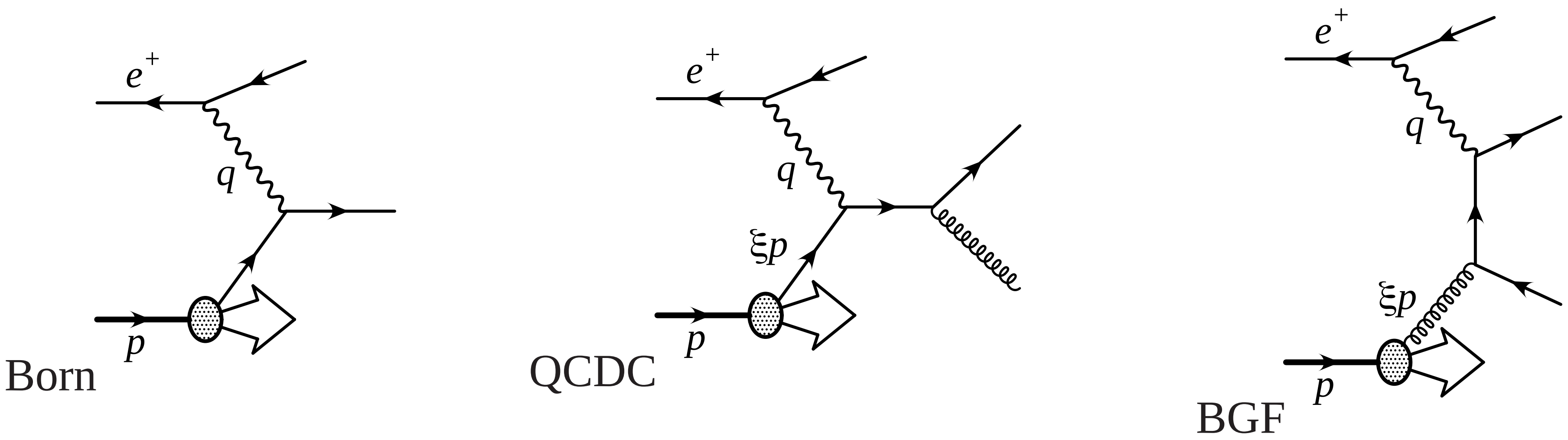
- Total hadronic centre-of-mass energy squared

$$W^2 = (q + p)^2 = ys - Q^2$$

Jets in deep inelastic scattering

- Factorise jet cross-section into a convolution of PDF's in the proton, f_a, with short distance subprocess, $\mathrm{d}\hat{\sigma}_a$....

$$d\sigma_{\rm jet} = \sum_{a=q,\bar{q},g} \int \mathrm{d}x \; f_a(x,\mu_F^2) \;\times\; \mathrm{d}\hat{\sigma}_a(x,\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2) \times (1+\delta_{\rm had})$$

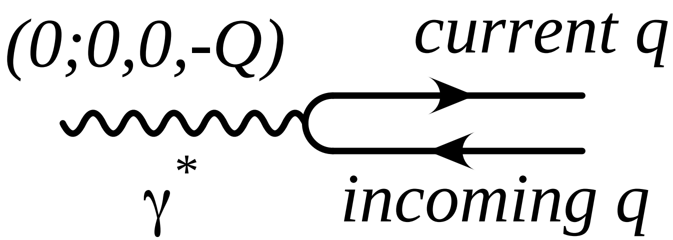


- Longitudinally invariant k_T algorithm (Catani et al).
  ➡ At high E_T hadronisation effects are small ➡ more reliable QCD predictions.

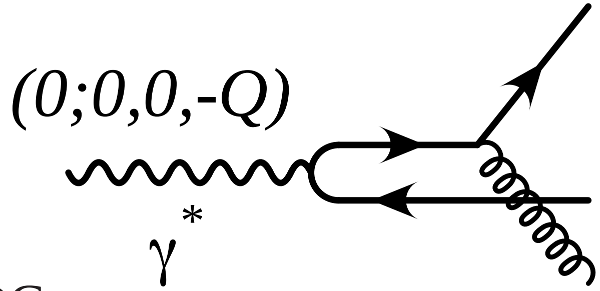
- Large scale variation possible in both Q^2 and E_T.

Jet production in the Breit frame

- Breit frame ➡ purely space-like photon.



Born



QCDC

- Inclusive jet production in LAB frame $\mathcal{O}(\alpha\alpha_s^0)$ at lowest order.
- Inclusive jets with high E_T in the Breit frame, $\mathcal{O}(\alpha\alpha_s)$ at lowest order.
  - ▷ Suppresses Born contribution (in Breit frame current quark has no E_T).
  - ▷ No cuts on sub-leading jet (can be unobserved)
    ➡ Theory has better infrared behaviour, smaller renormalisation scale uncertainty.
  - ▷ Leading order contributions from $\gamma^* g \to q\bar{q}$ and $\gamma^* q \to qg$ ➡ Directly sensitive to the gluon distribution within the proton and to QCD subprocess at $\mathcal{O}(\alpha\alpha_s)$.

NLO QCD calculations of jet production in DIS

- Many calculations available, virtual and collinear singluarities cancelled using subtraction or phase space slicing methods, Those used here,
  - ▷ Dijet production
    DISENT (Catani and Seymour): $A\alpha_s + B{\alpha_s}^2$ – subtraction method
  - ▷ Two and Three jet producution
    NLOJET (Nagy and Trocsanyi): $C{\alpha_s}^2 + D{\alpha_s}^3$ – subtraction method.
- Two "natural" scales in jet production, Q and $E_T^{\rm jet}$, renormalisation and factorisation scales, μ_R, $\mu_F = Q$ or $E_T^{\rm jet}$.
- Calculations at parton level ➡ correct calculations for hadronisation effects.
- Theoretical uncertainties...
  - ▷ Terms beyond NLO, usually estimated by varying scale, μ_R by factor of 2.
  - ▷ Uncertainty on α_s and the proton parton distribution functions.
  - ▷ Hadronisation corrections.

Inclusive jet production at high E_T - H1

- DIS event selection

$$150 < Q^2 < 5000\mathrm{GeV}^2$$

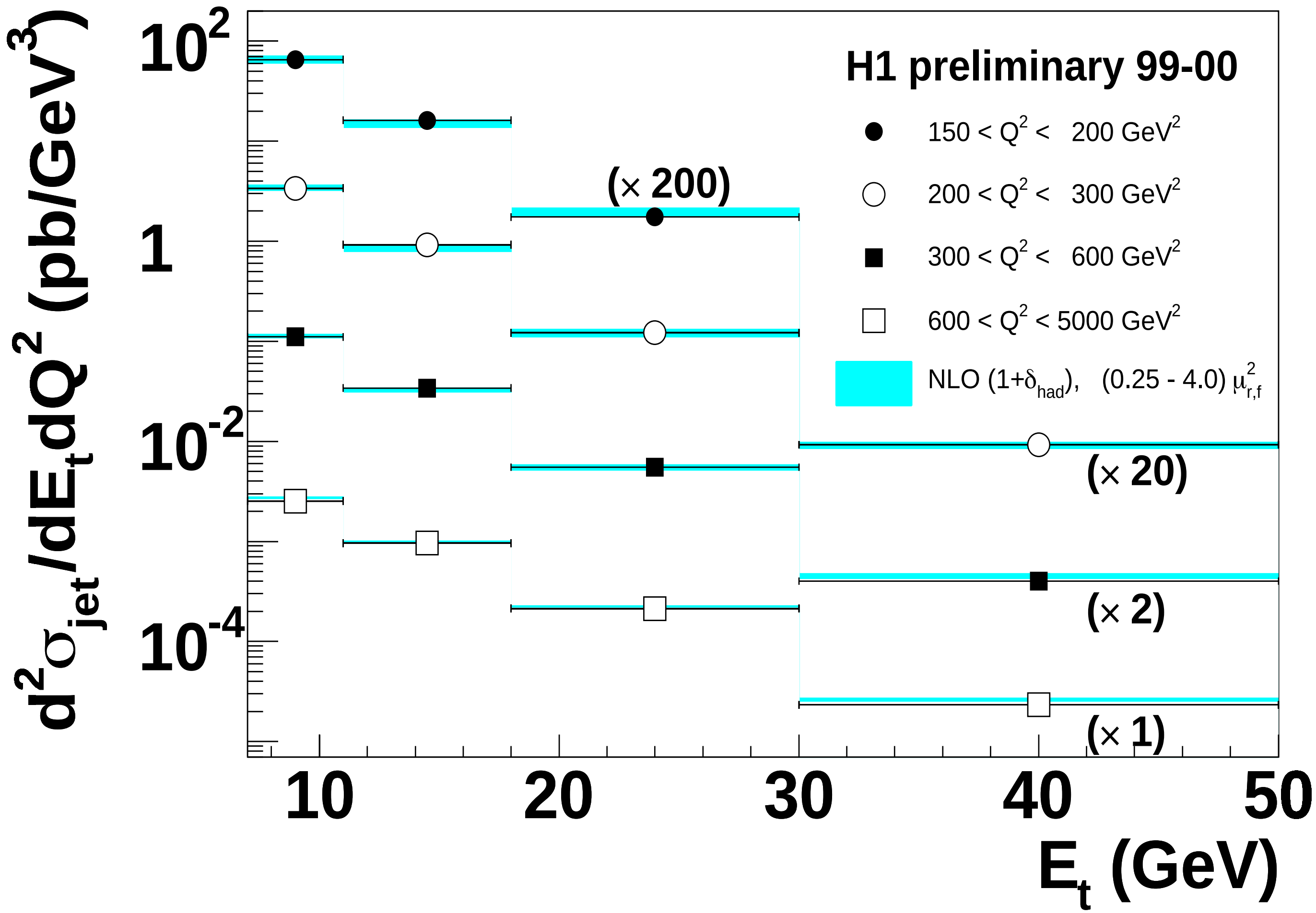
$$0.2 < y < 0.6$$

- Inclusive jet selection in the Breit frame

$$E^{\mathrm{jet}}_{\mathrm{T,Breit}} > 7.1\ \mathrm{GeV}$$

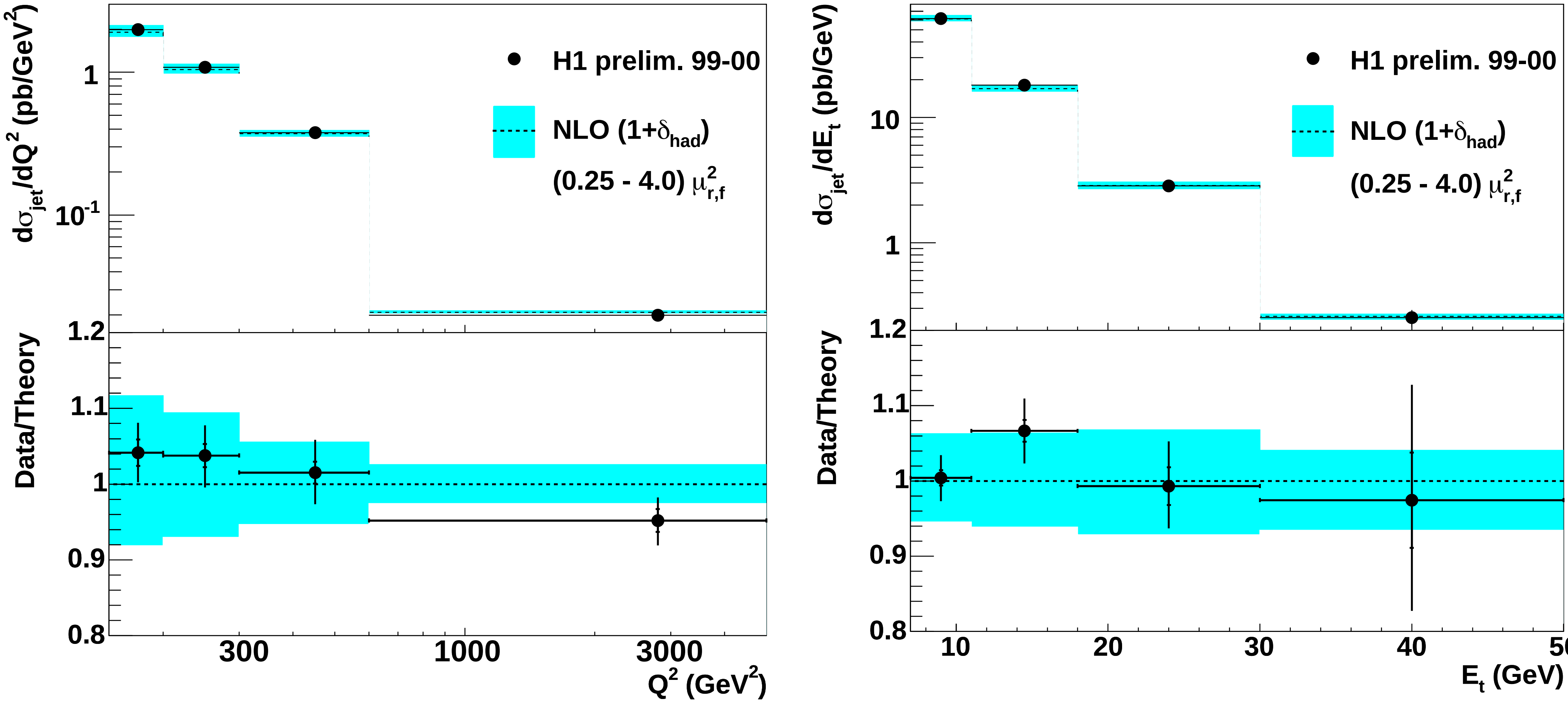
$$-1 < \eta^{\mathrm{jet}}_{\mathrm{Breit}} < 2.5$$

- Sub-leading jet can be unobserved.



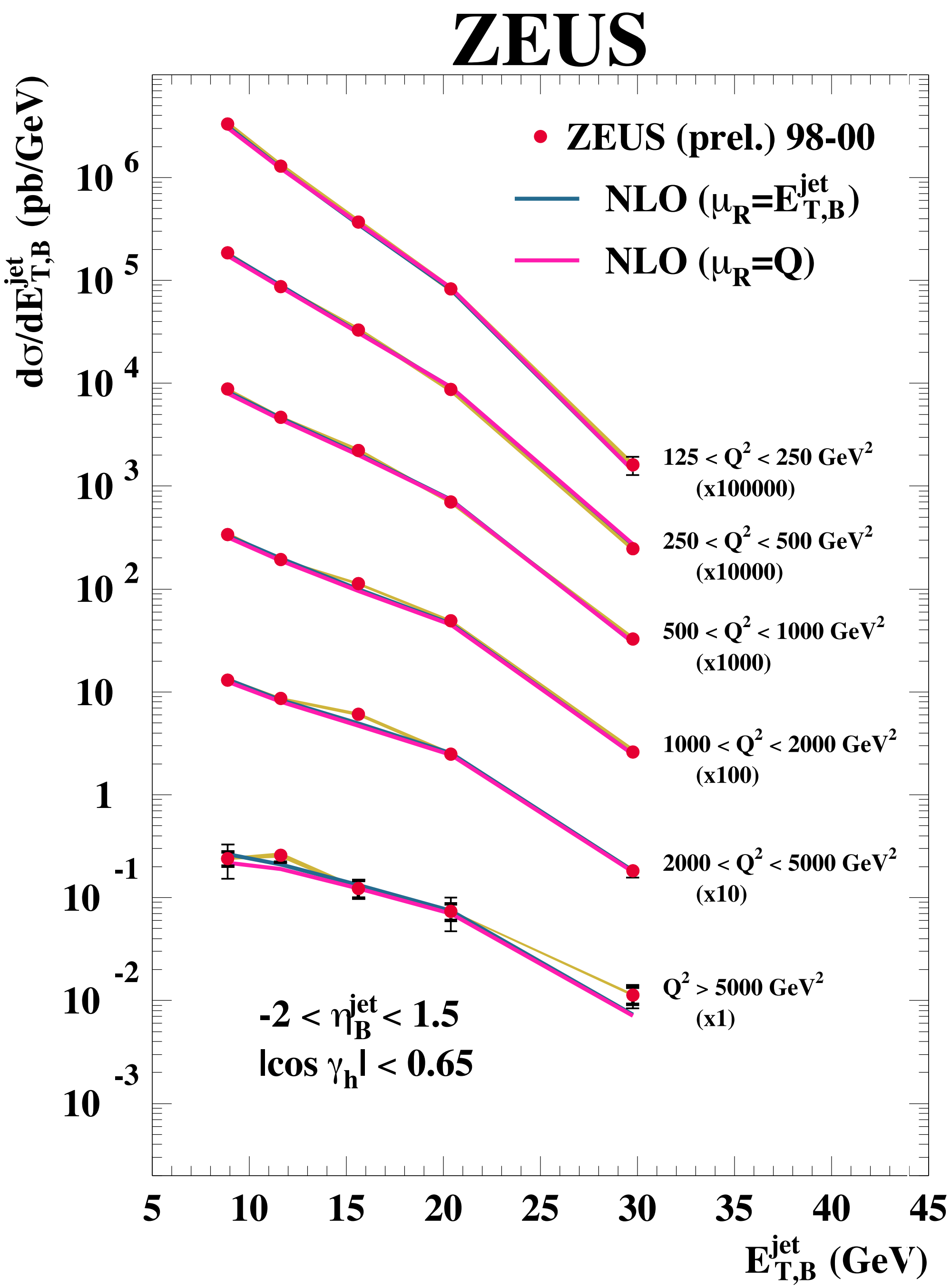
- NLO theory (NLOJET), CTEQ5M1 proton pdf.
- Reasonably description of data over several orders of magnitude in both Q^2 and $E^{\mathrm{B}}_{T,\mathrm{jet}}$.

Inclusive jet production at high E_T



- Theoretical uncertainty largest at low Q^2, experimental uncertainty $\sim 5\%$.
- Reasonable agreement over complete phase space.

Inclusive jet production at high E_T

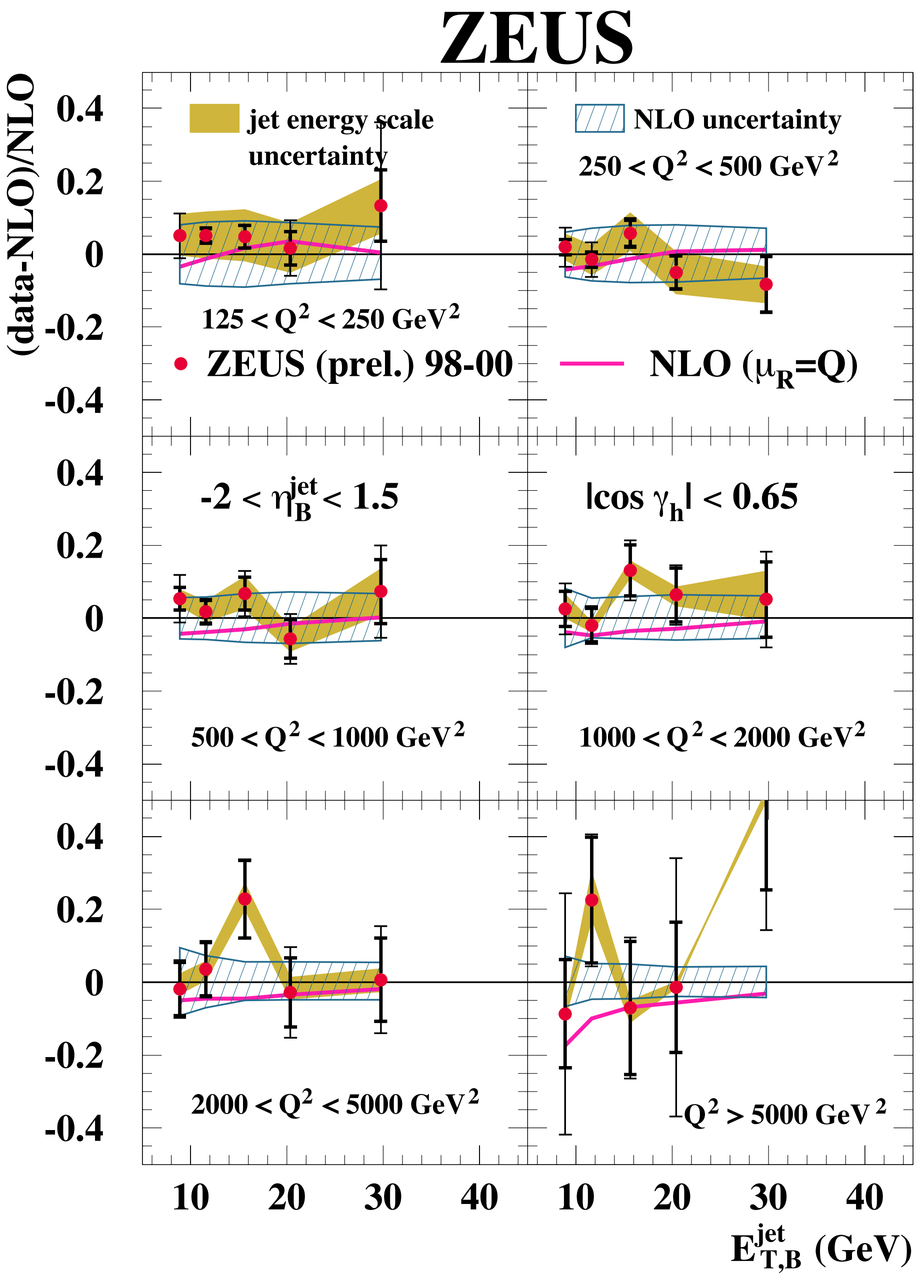


- High $Q^2 > 125\ \mathrm{GeV}^2$
- Inclusive jet cross sections measured in the Breit frame

$$E^{\mathrm{B}}_{T,\mathrm{jet}} > 8\mathrm{GeV}, \quad -2 < \eta^{\mathrm{B}}_{\mathrm{jet}} < 1.5$$

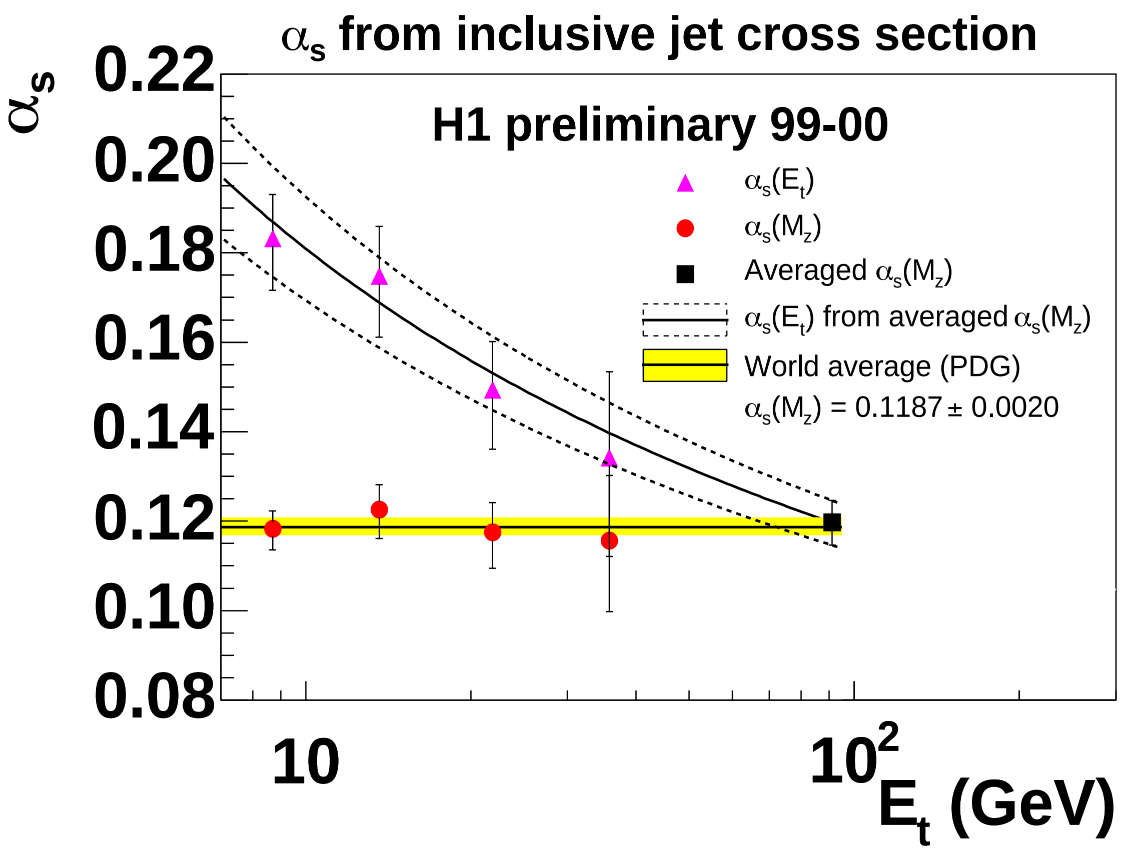
- Again, reasonable agreement with NLO (DISENT) over both Q^2 and $E^{\mathrm{B}}_{T,\mathrm{jet}}$.

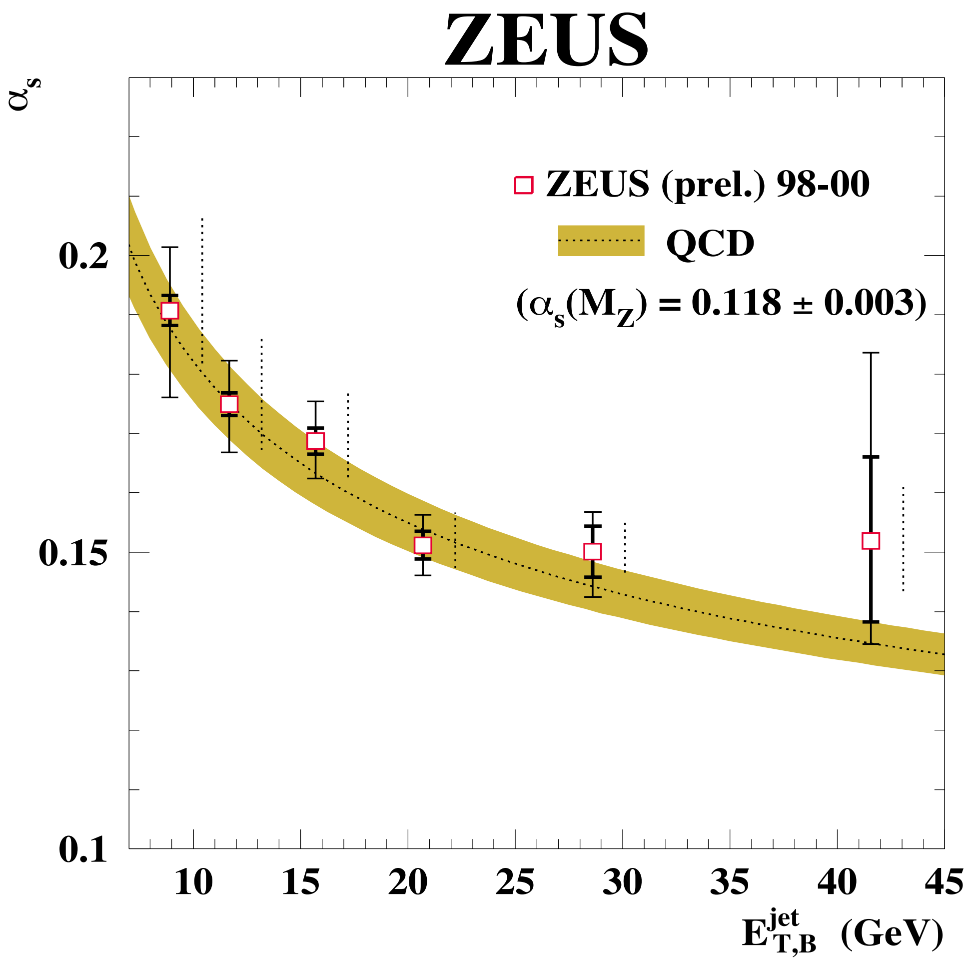
Inclusive jet production at high E_T



- Hatched band: NLO scale uncertainty for, $E^{\mathrm{B}}_{T,\mathrm{jet}}/2 < \mu_R < 2E^{\mathrm{B}}_{T,\mathrm{jet}}$.
- Better agreement with $\mu_R = E^{\mathrm{B}}_{T,\mathrm{jet}}$.
- NLO scale uncertainty $\pm 5\%$.
- Hadronisation uncertainty $< 1\%$.
- Overall, reasonable agreement within the experimental and theoretical uncertainties ➡ extraction of the QCD coupling α_s.

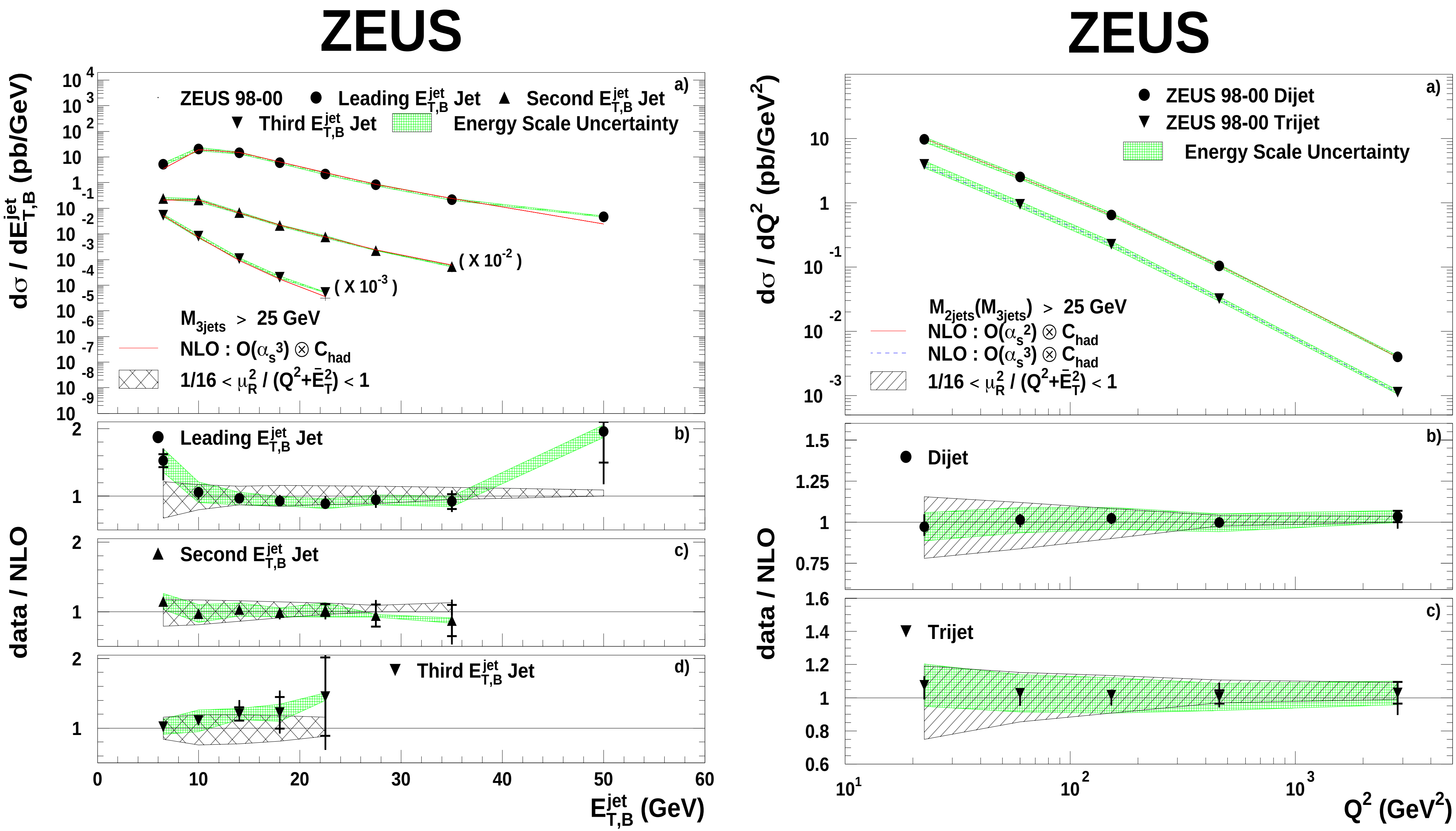
Extraction of the strong coupling constant





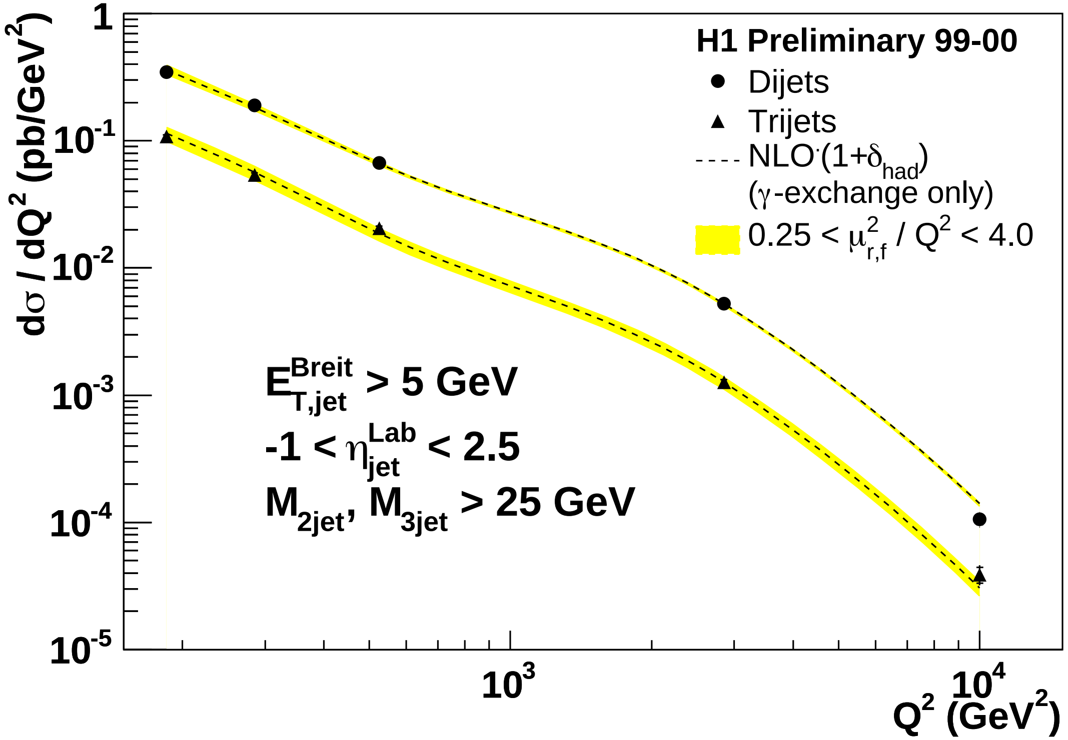
- H1 value $\alpha_s(M_Z) = 0.1197 \pm 0.0016(\mathrm{exp})^{+0.0046}_{-0.0048}(\mathrm{th})$
- ZEUS value $\alpha_s(M_Z) = 0.1196 \pm 0.0011(\mathrm{stat})^{+0.0019}_{-0.0025}(\mathrm{exp})^{+0.0029}_{-0.0017}(\mathrm{th.})$

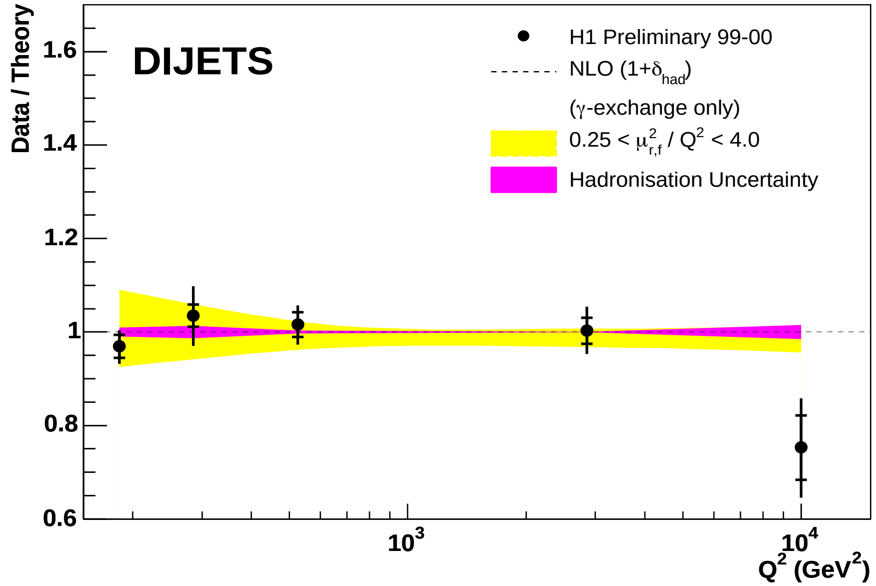
Two and three jet production - ZEUS

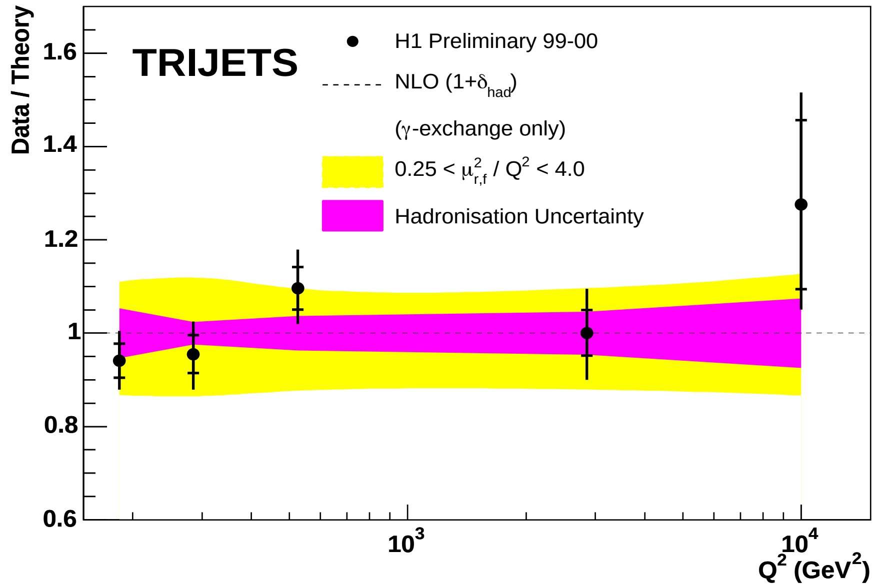


- Three jet dynamics reasonably well described by NLO calculation (NLOJET).

Two and three jet production - H1

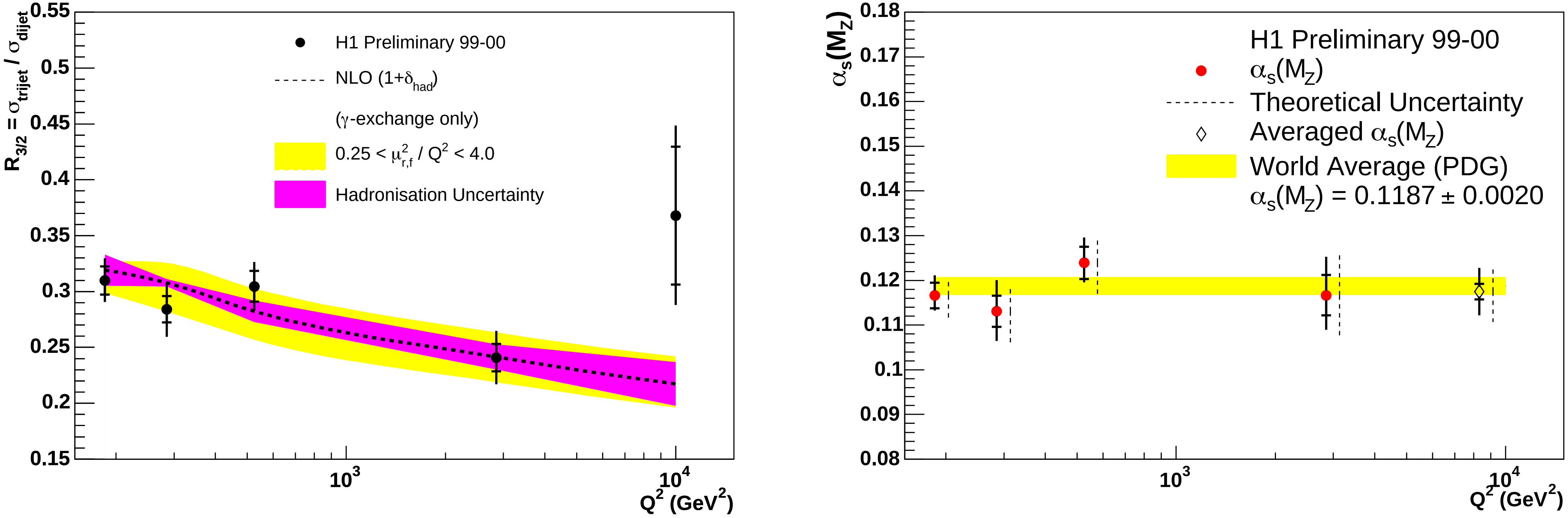






- Three jet production in the Breit frame - $\mathcal{O}(\alpha\alpha_s^2)$ at lowest order.
- Scales, $\mu_F = \mu_R = Q$, reasonable agreement for
  - ▷ Dijet cross section, $\mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_s^2)$.
  - ▷ Trijet cross section, $\mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_s^3)$.

Extracting the strong coupling constant

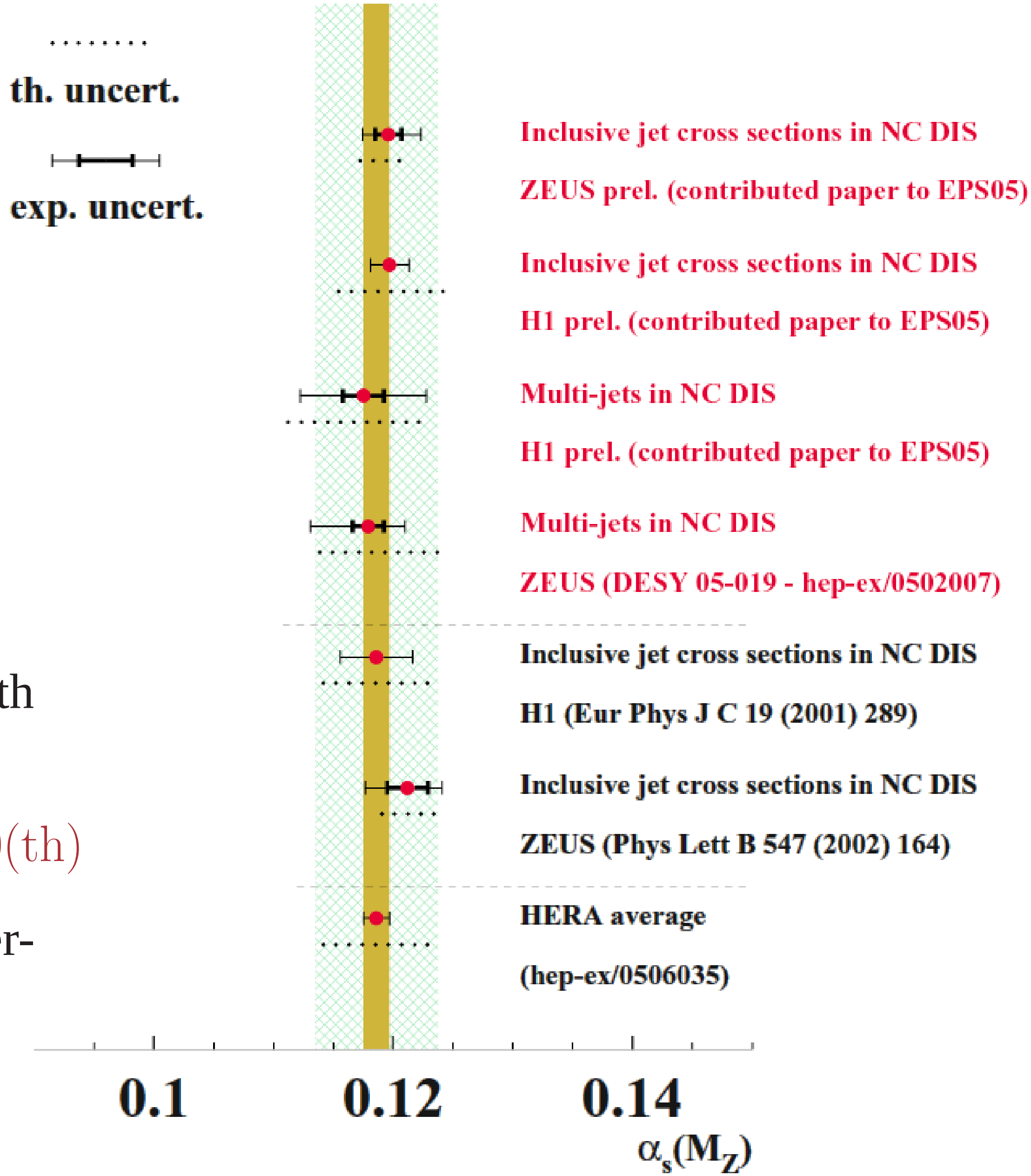


- The two-to-three jet ratio $R_{3/2}$ is directly sensitive to α_s.
  - ▷ Reduces renormalisation scale uncertainty.
  - ▷ PDF uncertainty partially cancels.

- H1 value $\alpha_s(M_Z) = 0.1175 \pm 0.0017(\text{stat}) \pm 0.0050(\text{exp})^{+0.0054}_{-0.0068}(\text{th.})$

- ZEUS value $\alpha_s(M_Z) = 0.1179 \pm 0.0013(\text{stat})^{+0.0028}_{-0.0046}(\text{exp})^{+0.0064}_{-0.0046}(\text{th})$

Selected $\alpha_s(M_Z)$ values from HERA jet data



- Inclusive and (two)three jet data...
- Compare with existing HERA average with published data (hep-ex/0506035)

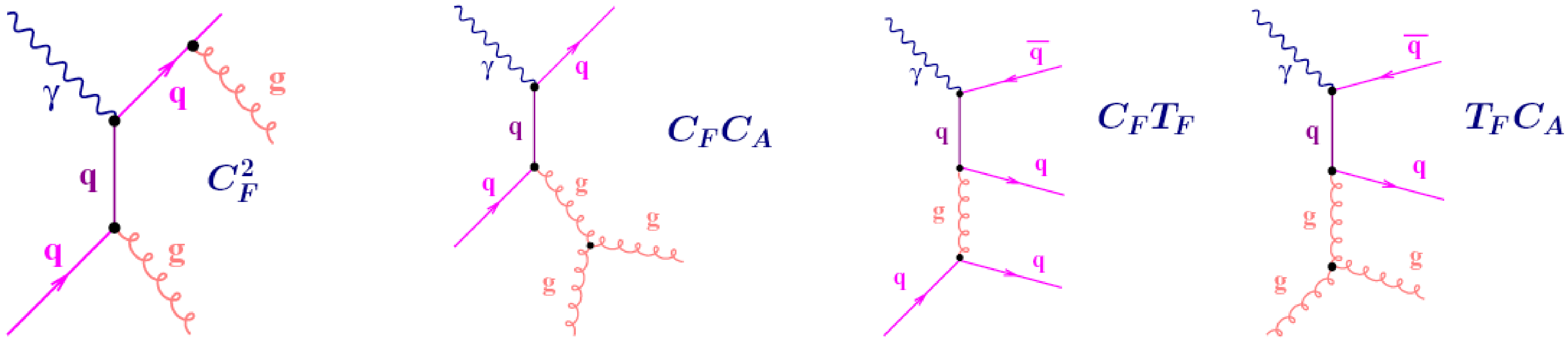
  $\alpha_s(M_Z) = 0.1188 \pm 0.0011(\mathrm{exp}) \pm 0.0050(\mathrm{th})$

- Competitively small experimental uncertainties!

The QCD matrix element

- At tree level, the three-jet cross section can be expressed as

$$\sigma_{ep\rightarrow 3\text{jets}} = C_F^2\sigma_A + C_F C_A \sigma_B + C_F T_F \sigma_C + T_F C_A \sigma_D$$



- $SU(N)$: $C_F = (N^2-1)/2N,\ C_A = N,\ T_F = 1/2$
- The qqg and ggg couplings have different spin structures ➡ Angular correlations in three jet production sensitive to the underlying gauge structure of the QCD matrix elements.
- Kinematic region, (98-00 data - 920 GeV protons)

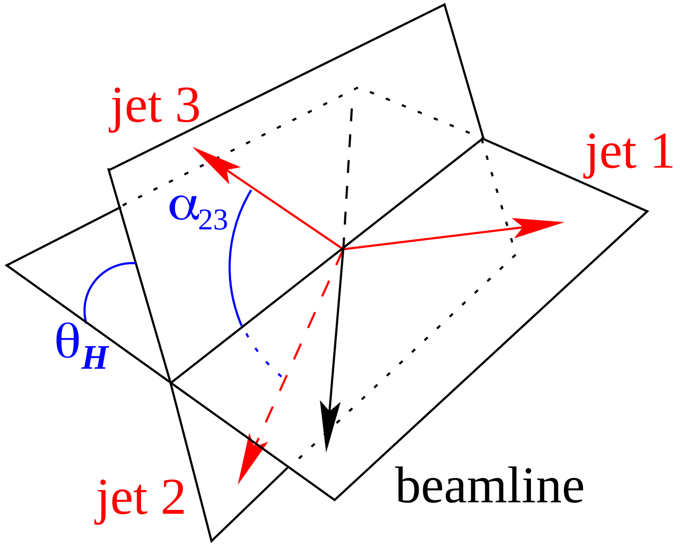
$$Q^2 > 125\text{GeV}$$

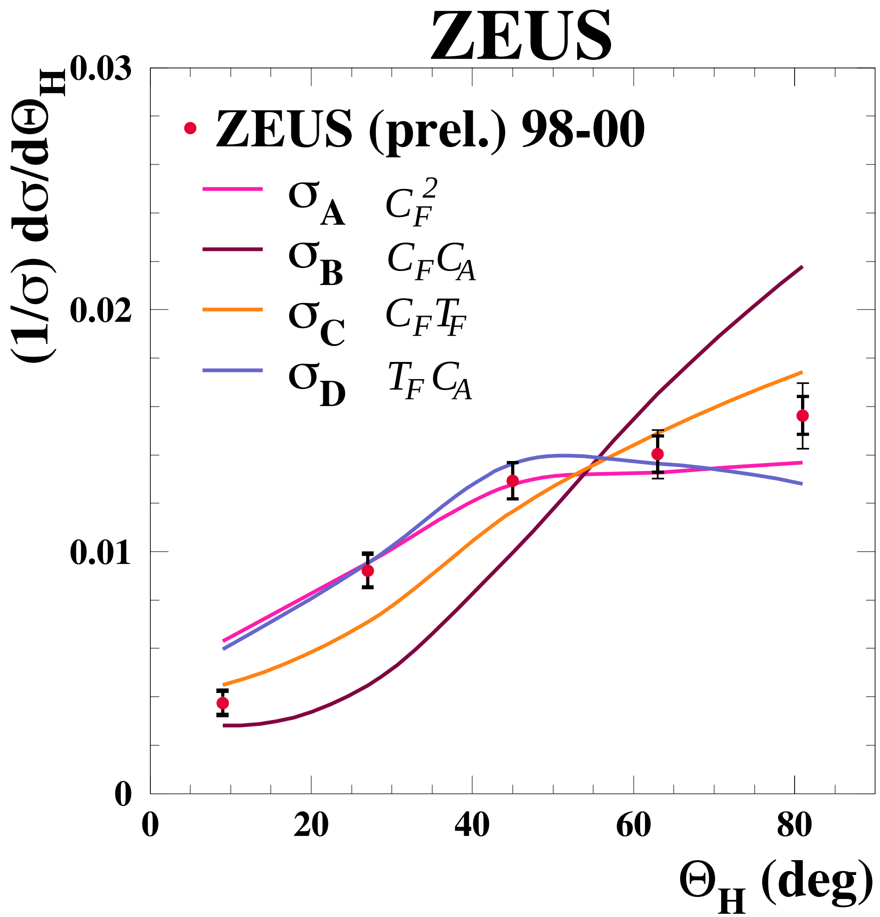
$$E_T^{\text{jet1}} > 8\text{GeV}, \quad E_T^{\text{jet2,3}} > 5\text{GeV} \quad -2 < \eta^{\text{jet}} < 1.5$$

QCD - SU(3) contributions (CTEQ6M1 PDF's),

$$\sigma_A : 23\%, \ \sigma_B : 13\%, \ \sigma_C : 39\%, \ \sigma_D : 25\%$$

Angular distributions





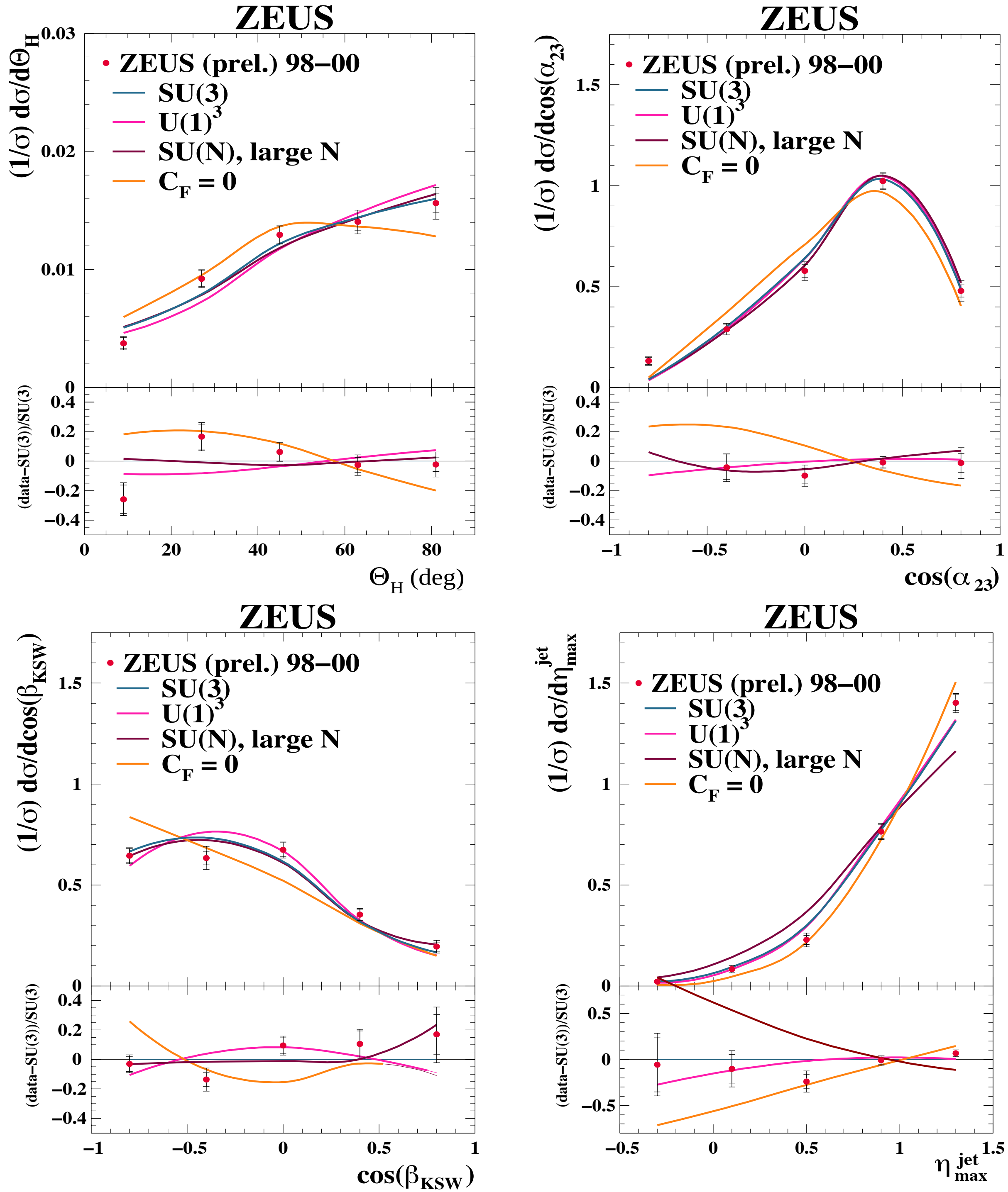
θ_H: the angle between plane containing the beamline and highest E_T jet and the plane containing the second and third highest E_T jets.

$\eta^{\rm jet}_{\rm max}$: Pseudo-rapidity in the Breit frame of the most forward of the three highest E_T jets.

α_{23}: the angle between the second and third highest E_T jets.

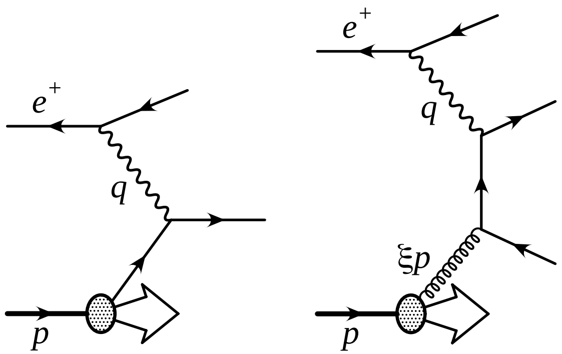
$$\cos(\beta_{\rm KSW}) := \cos\left(\tfrac{1}{2}\left[\angle[(\vec{p_1} \times \vec{p_3}), (\vec{p_2} \times \vec{p_B})] + \angle[(\vec{p_1} \times \vec{p_B}), (\vec{p_2} \times \vec{p_3})]\right]\right)$$

The subprocess gauge group



- Data disfavour $SU(N)$ in the limit of large N, and $C_F = 0$.
- Some difference between $SU(3)$ and $U(1)^3$ - discrimination, statistics limited.
- All distributions consistent with $SU(3)$.

Extracting the proton parton densities using jet data



- PDF fits using only inclusive DIS data sensitive only indirectly to the gluon density through higher-order term.
- Multijet data (and inclusive jet data in the Breit frame) directly sensitive to the gluon distribution and α_s at their leading order.

- NLO jet calculations have existed for some time, but use in PDF fitting prohibative

  ➡ must perform convolution over x and Q^2

$$\mathrm{d}\sigma_{\mathrm{jet}} = \sum_{a=q,\bar{q},g} f_a(x, \mu_F^2) \otimes \mathrm{d}\hat{\sigma}_a(x, \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

  for each iteration through the PDF parameter space, where $d\hat{\sigma}$ involves non-analytic integration over the phase space including the jet algorithm to cancel the IR divergences.

- Deconvolute the PDF and α_s from the matrix elements in the calculation on a grid of ξ and Q^2

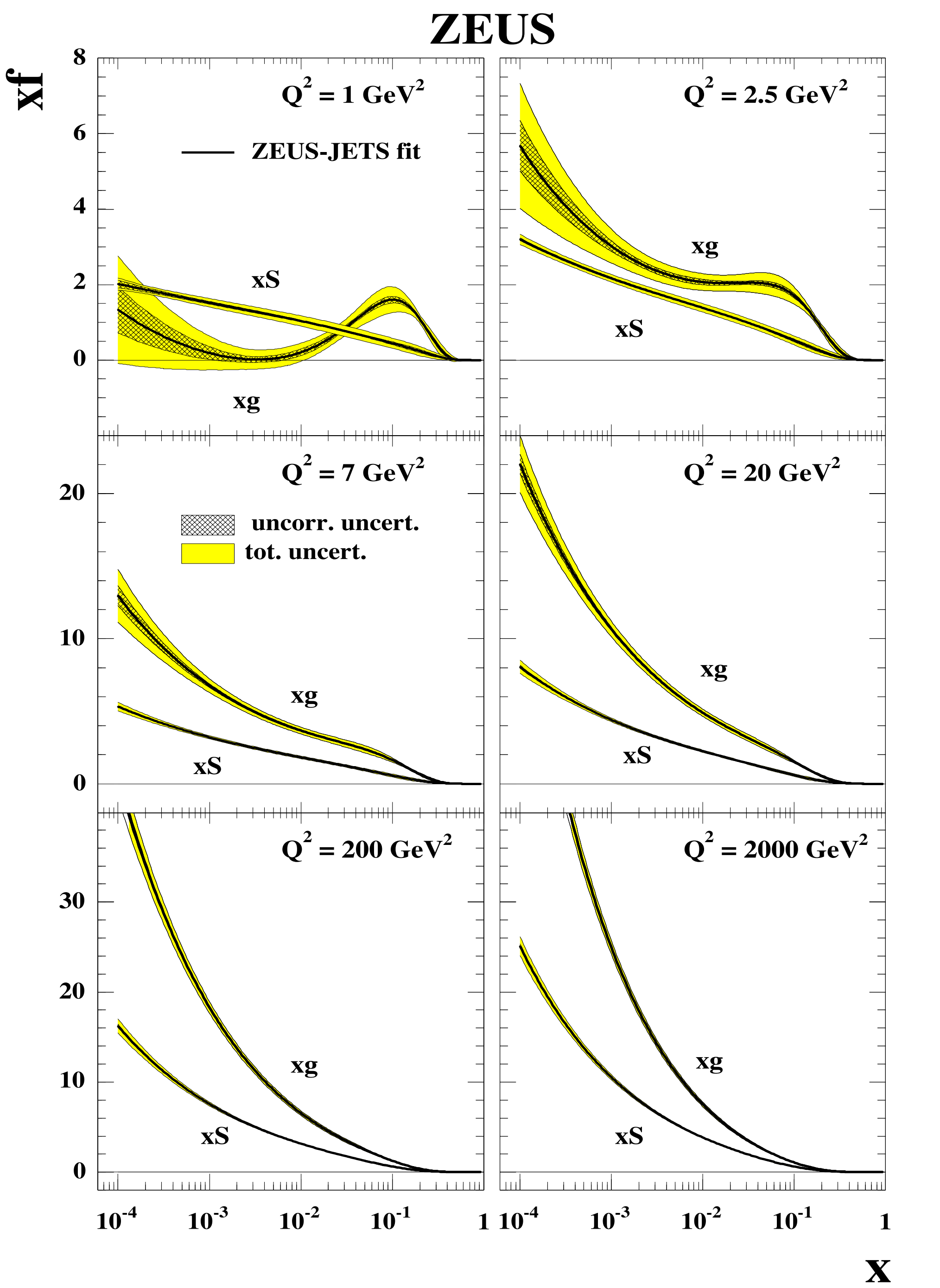
$$d\sigma_i^{\mathrm{jet}} = \sum_{n=1,2} \sum_{a=q,\bar{q},g} \sum_j \sum_k f_a(\xi_k, Q_j^2) \times \alpha_s^n(Q_j^2) \times G_{i,a,n,\xi_k,Q_j^2}$$

  - ▷ Allows NLO calculation to be done once,
  - ▷ Convolution to be done by fast summation ➡ suitable for iterative fit.

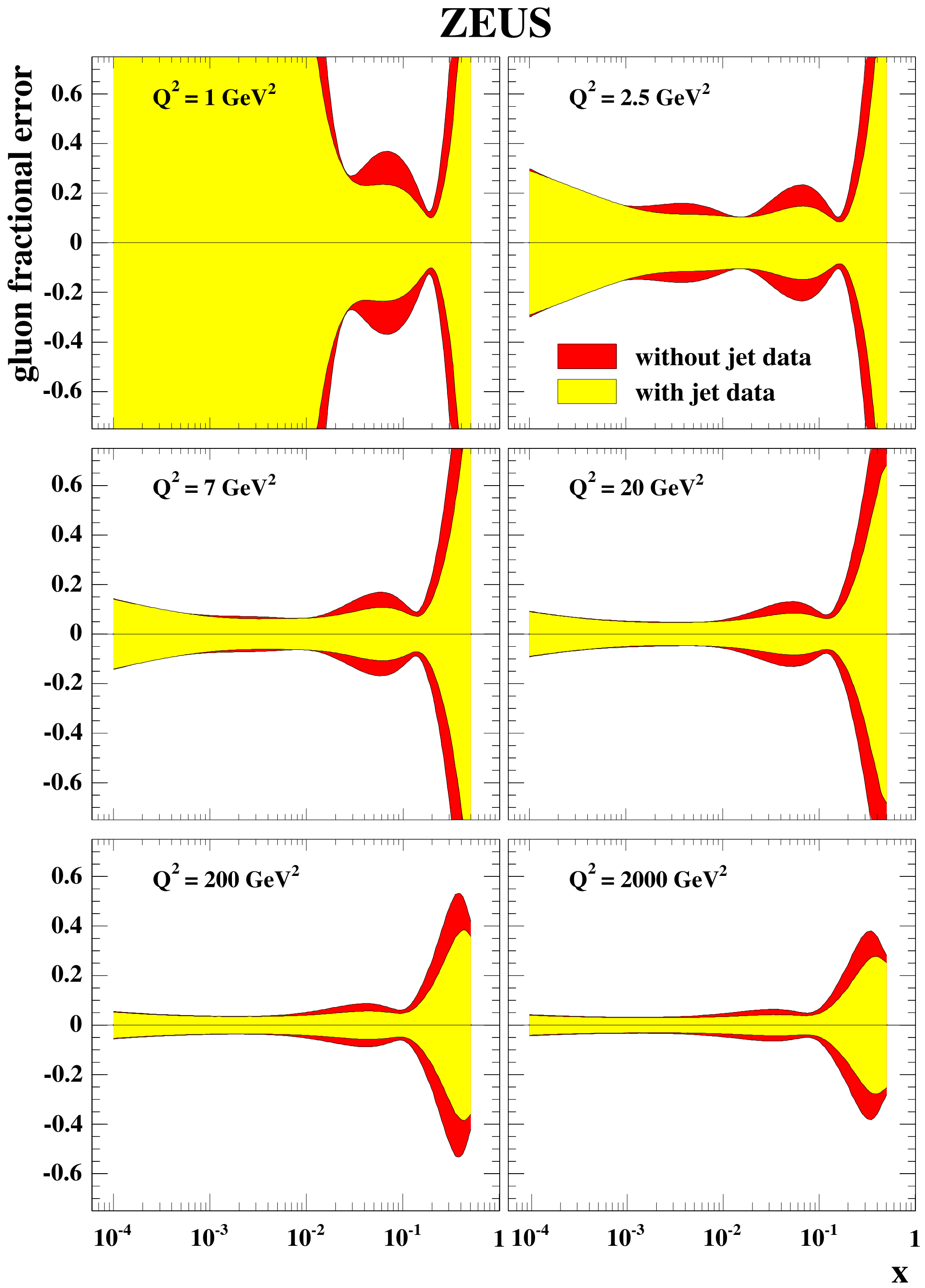
- Jet calculations can be done for any PDF set and any value of α_s to better than 0.5% accuracy!

The gluon distribution from jet data

- Principle data sets for the ZEUS-jets fit...
  - ▷ Published ZEUS Inclusive neutral and charged current DIS data.
  - ▷ Published ZEUS inclusive DIS jets (96-97 data) – (Preliminary 98-00 inclusive jets shown here)
  - ▷ Published ZEUS 96-97 Dijet photoproduction.
- NC and CC data constrain the quarks.
- Jet data constrain the medium x gluon (and α_s).
- No tension between inclusive and jet data ⇒ factorisation, see talk by Bruce Straub.

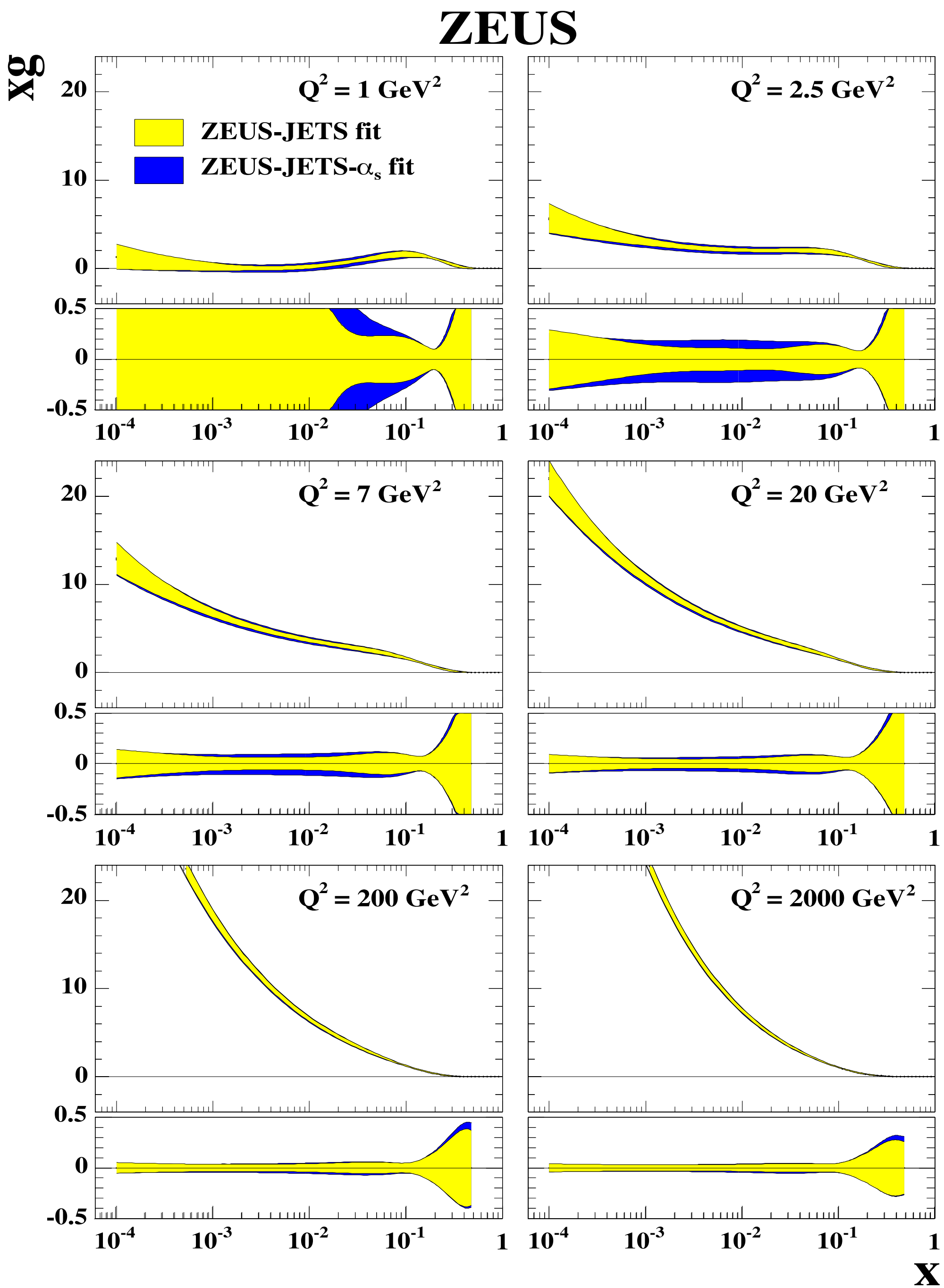


The gluon distribution from jet data



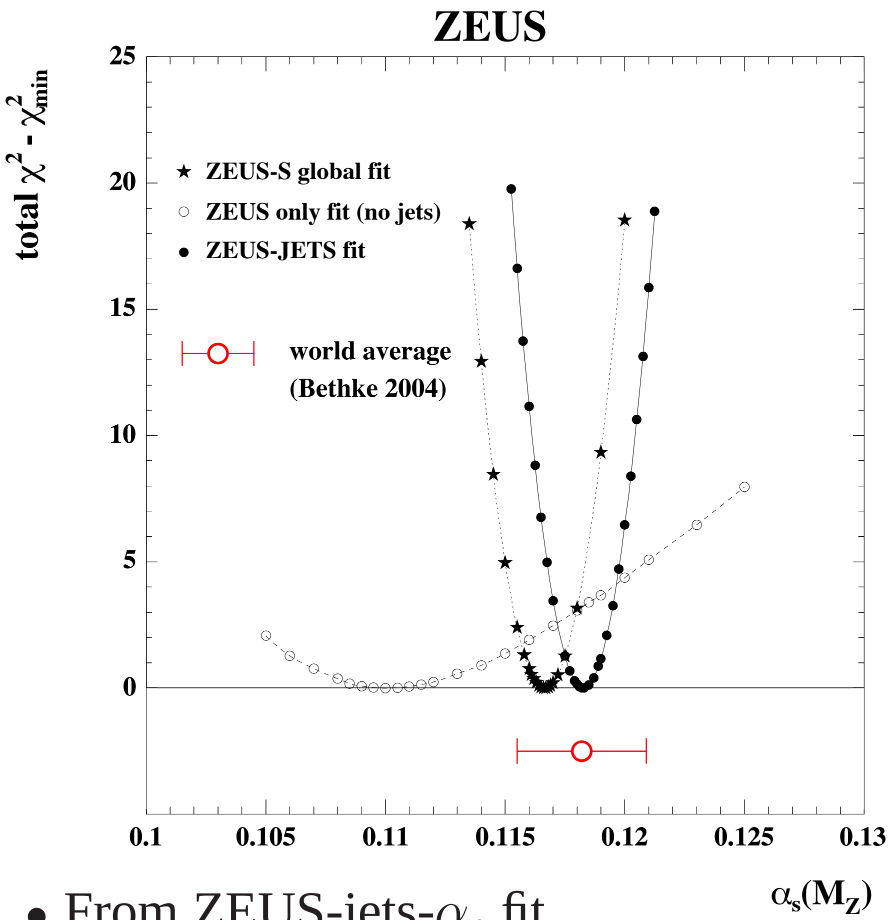
- Significant reduction in the gluon uncertainty ⇒ around factor of 2 for medium x, still significant improvement for high x.

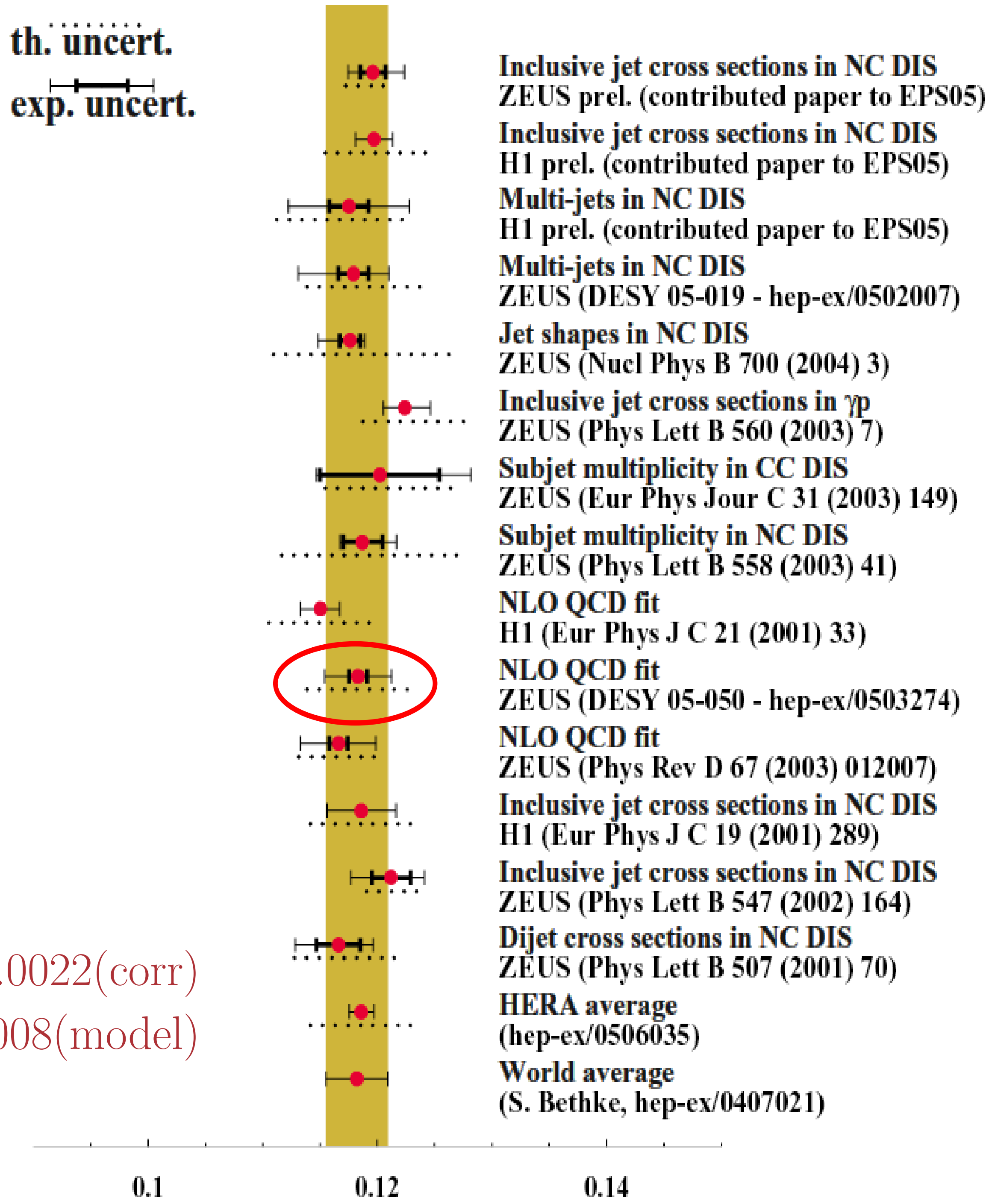
The strong coupling constant



- Jet cross sections sensitive to α_s through
  - ▷ quark density, $\gamma^* q \to qg$,
  - ▷ gluon density $\gamma^* g \to q\bar{q}$.
- Allows simultaneous determination of α_s and gluon density which are not strongly correlated. ➡ gluon does not become unconstrained when α_s is a free parameter in the fit.

The strong coupling constant





- From ZEUS-jets-α_s fit

$$\alpha_s(M_Z) = 0.1183 \pm 0.0007(\text{uncorr}) \pm 0.0022(\text{corr}) \pm 0.0016(\text{norm}) \pm 0.0008(\text{model})$$

- Estimated uncertainty from terms beyond NLO ± 0.0050

Summary and outlook

- ZEUS and H1 continue to produce many high precision measurements of the hadronic final states in DIS.
- Theoretical uncertainties continue to dominate over much of the phase space.
- First rigourous use of high precision HERA jet data to extract α_s and constrain the gluon in the proton.
  - ▷ Value from the QCD fit including jet data, using HERA data alone,

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

  consistent with the world average, $\alpha_s(M_Z) = 0.1182 \pm 0.0027$ (Bethke, 2004)

- Much more data is currently available and around 700 pb^{-1} is expected by the end of HERA-II running which will allow even better constraints on QCD and the structure of the proton.