New Trends
in
High Energy Physics
Jalta, Crimea
22-29 September, 2001

QCD Studies at HERA (selected topics)

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On behalf of the
H1 and ZEUS Collaborations

- Introduction
- Proton Structure Functions
- Jet Production in DIS
  - ▷ Inclusive Jets and Dijets
  - ▷ Jet Substructure
  - ▷ 3-Jets
- Conclusions

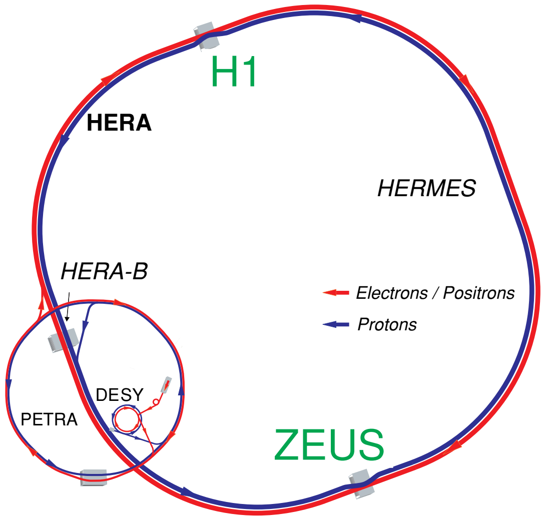
The HERA ep collider

H E R A I

$$e^{\pm} \quad \Longrightarrow \quad \Longleftarrow \quad p$$

27.5 GeV   820 – 920 GeV

$$\sqrt{s} = 300 - 319 \text{ GeV}$$



1993-1994

e^-p at $\sqrt{s} = 300$ GeV

H1 (ZEUS) 0.92 (0.82) pb^{-1}

1994-1997

e^+p at $\sqrt{s} = 300$ GeV

H1 (ZEUS) 36.6 (47.7) pb^{-1}

1998-1999

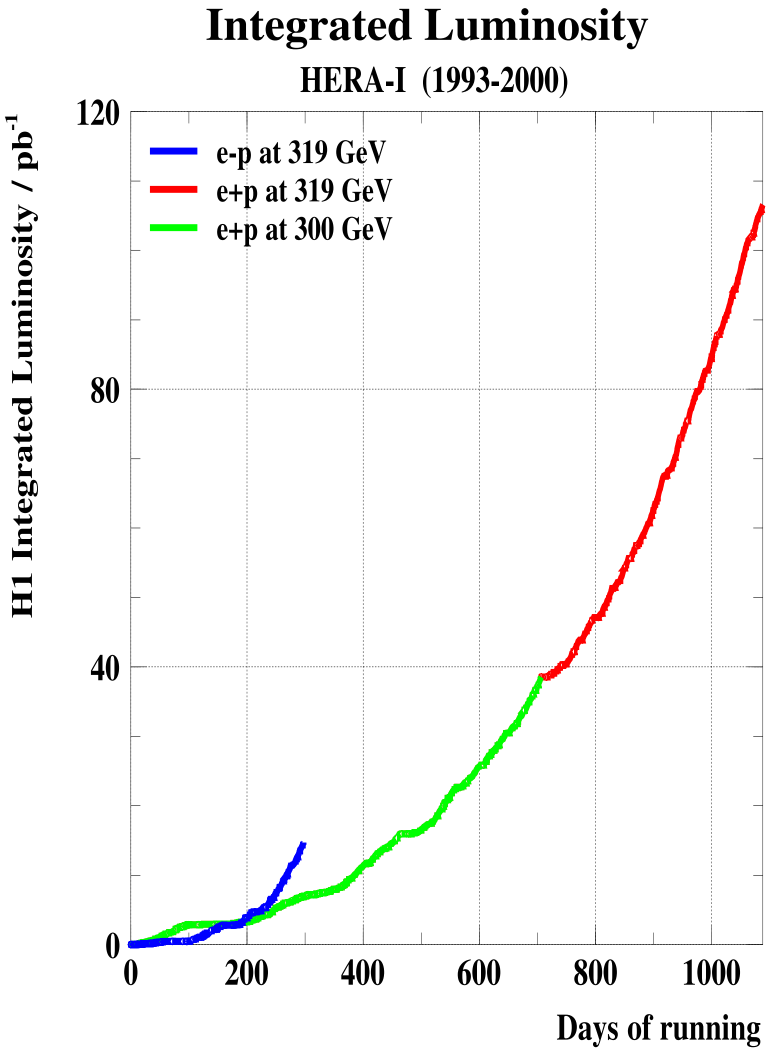
e^-p at $\sqrt{s} = 319$ GeV

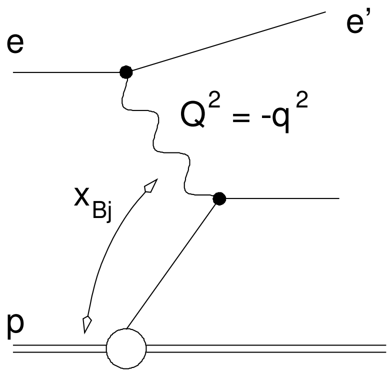
H1 (ZEUS) 16.4 (17) pb^{-1}

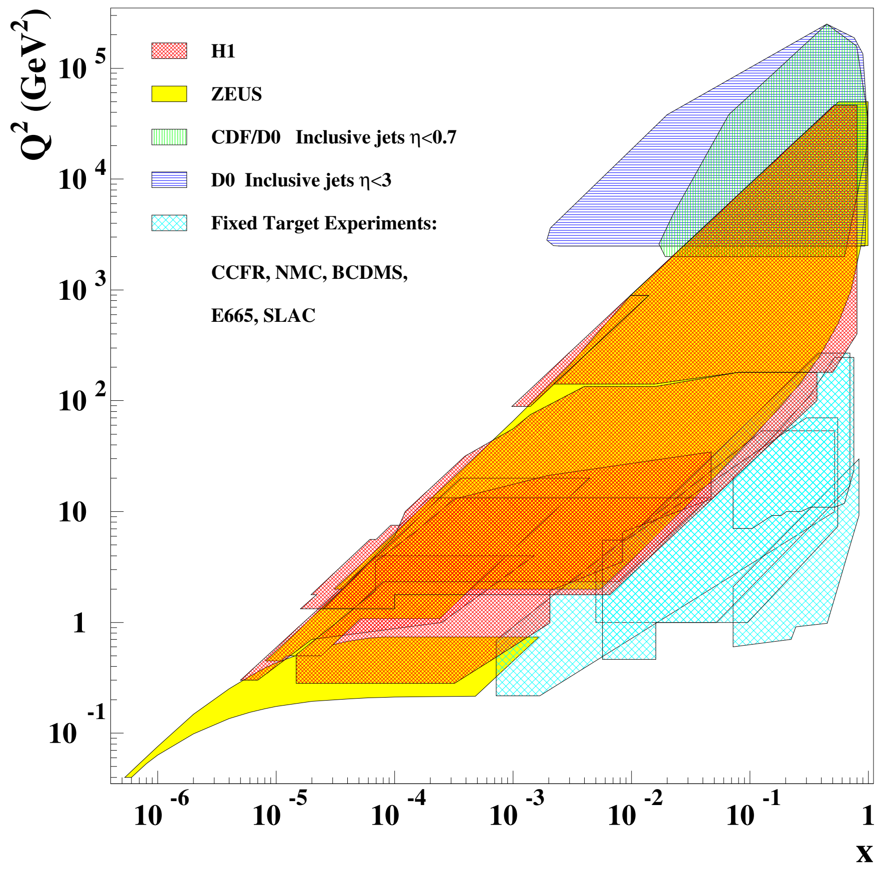
1999-2000

e^+p at $\sqrt{s} = 319$ GeV

H1 (ZEUS) 65 (70) pb^{-1}







NC Inclusive Cross Section $\quad (Q^2 \ll M_Z^2)$

$$\frac{d^2\sigma^{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}[Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2)]$$

$$Y_+ = 1 + (1-y)^2$$

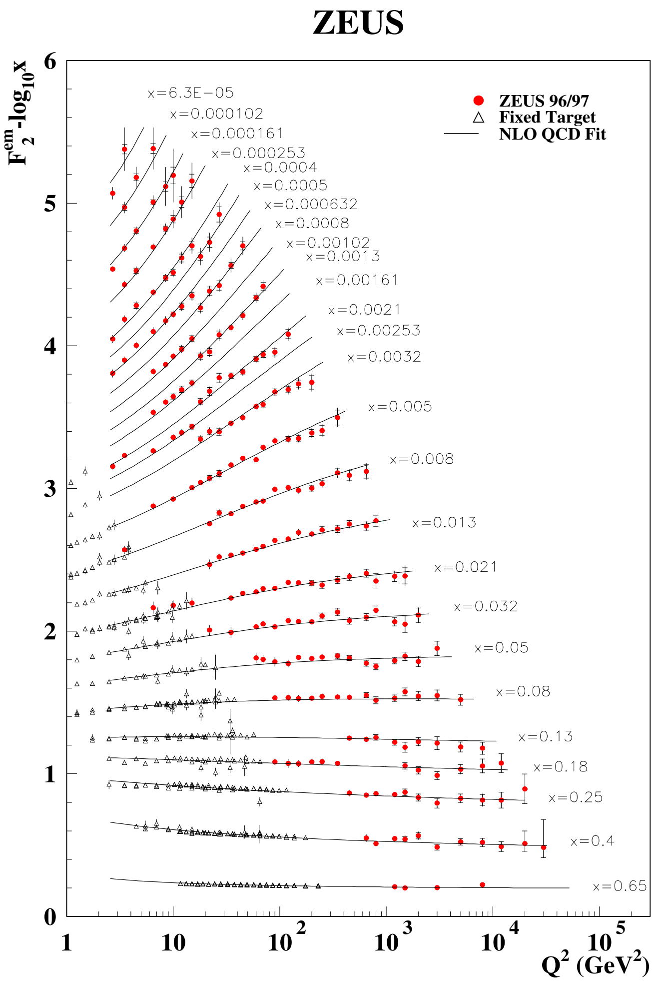
Reduced Cross Section

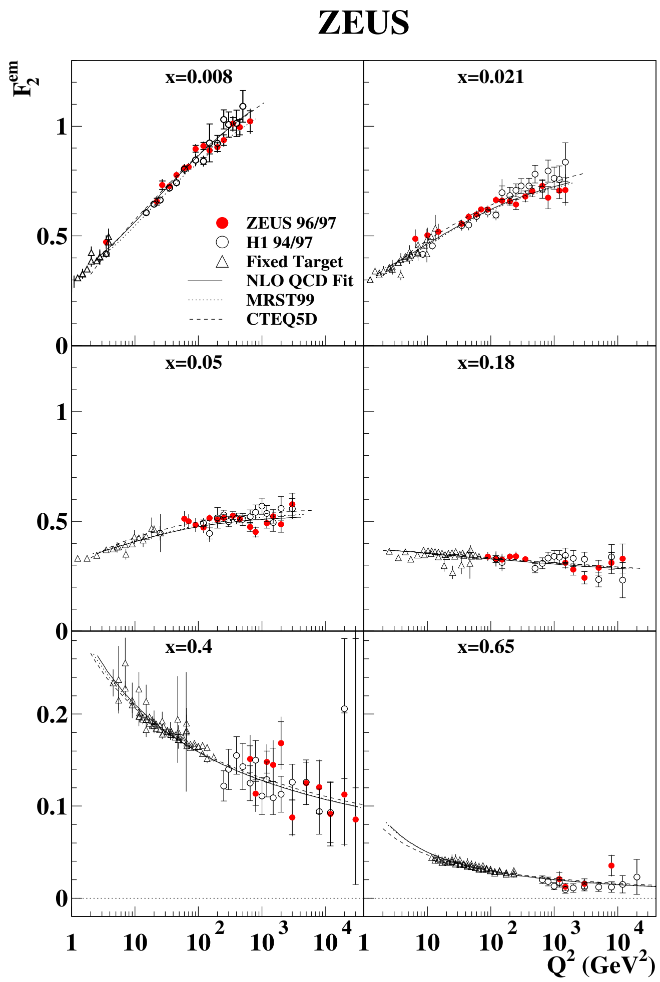
$$\sigma_r = \frac{d^2\sigma}{dx dQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

F_L contributes sizeably to cross section only at large y $\qquad 0 \le F_L \le F_2$

Measure cross section at low y, extract F_2

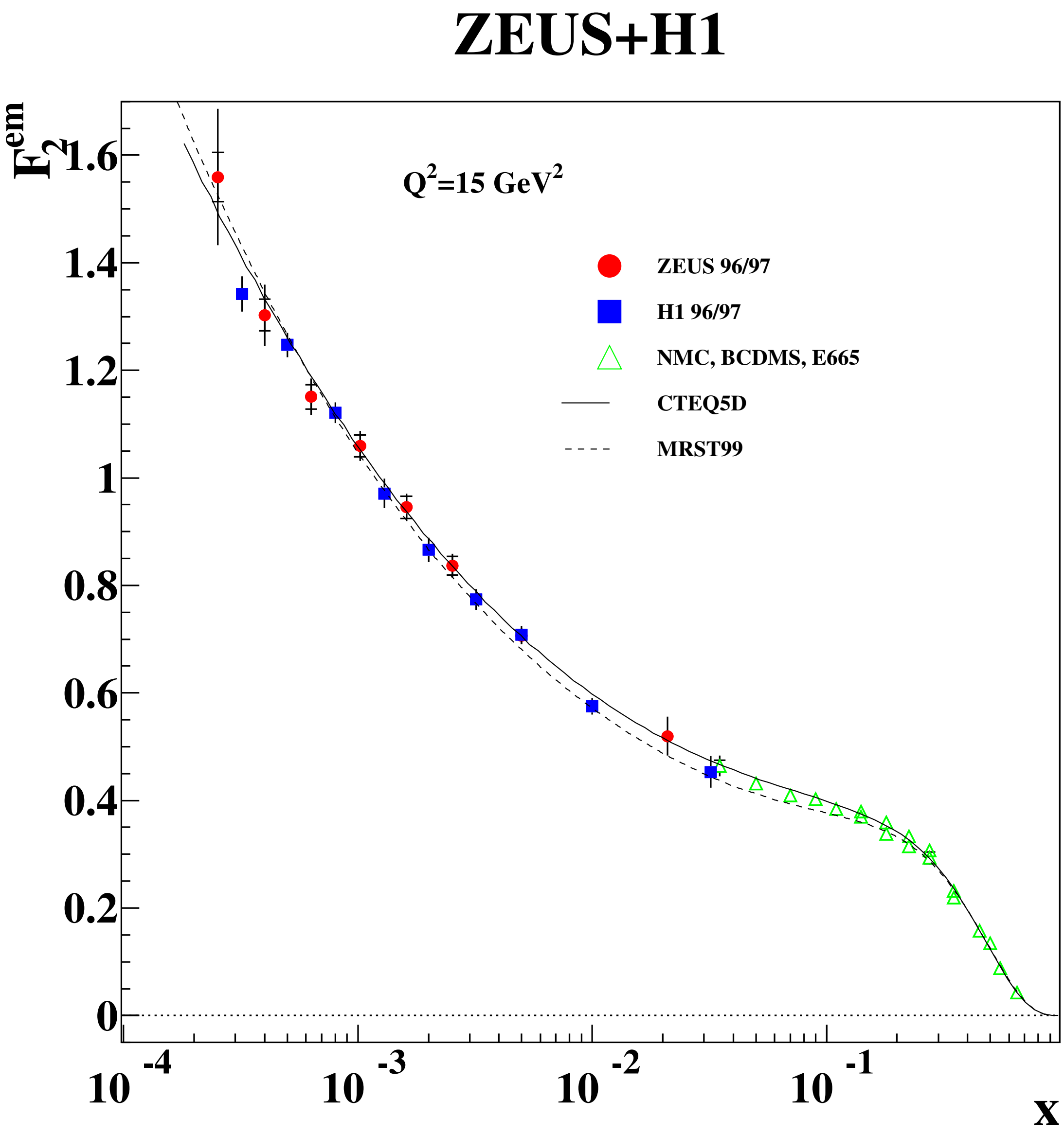
PROTON STRUCTURE FUNCTIONS





- **Bjorken scaling at $x \sim 0.1$**
- **Scaling violations:**
  - ▷ **positive at low x** $\qquad \dfrac{\partial F_2}{\partial \log Q^2} \sim \alpha_s x g$

    strong increase of gluons at low x
  - ▷ **negative at high x** $\qquad \dfrac{\partial F_2}{\partial \log Q^2} \sim \alpha_s F_2$
- **NLO QCD fits describe the data well**
  - ▷ **over 4 orders of magnitude**
  - ▷ **down to surprisingly low Q^2 (~ 1 GeV^2)**



Good Agreement

Between H1 and ZEUS

Between HERA and Fixed Target Experiments

H1 and ZEUS: NLO QCD Fits

Differences in Strategies and Methods:

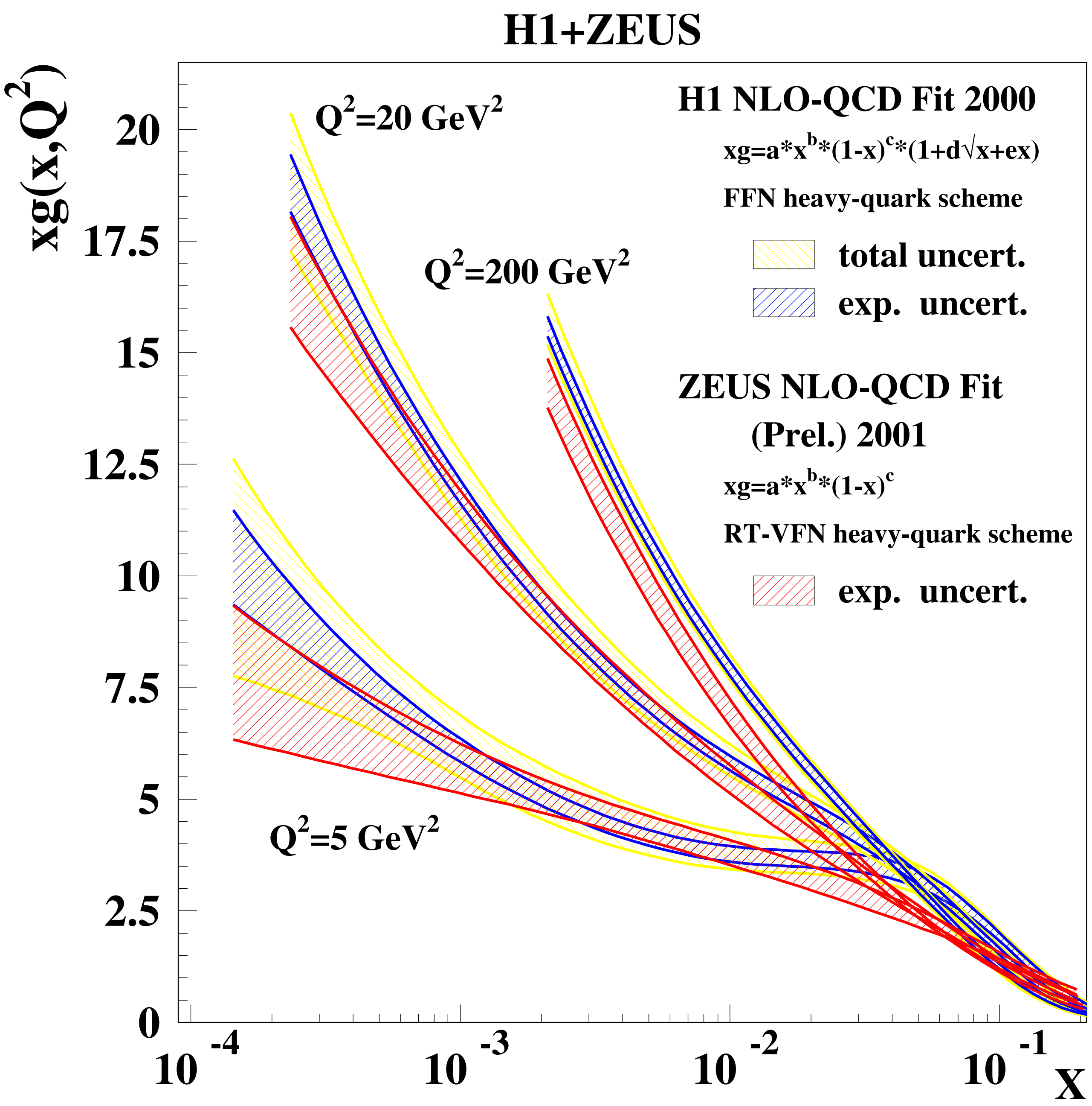
- **H1 :**
  - ▷ Lepton - proton data only (H1 + BCDMS)
  - ▷ Parameterise effective valence and sea PDF's, at $Q_0^2 = 4GeV^2$
  - ▷ Number of parameters in gluon and sea PDF's chosen so that χ^2 saturates
  - ▷ FFN massive heavy quark scheme
  - ▷ Treatment* of point-to-point correlated systematic errors
  - ▷ Systematic offsets determined by the fit

- **ZEUS :**
  - ▷ Use all data: ZEUS, BCDMS, E665, NMC, CCFR
  - ▷ Standard flavour decomposition $u_v, d_v, xg, xS, x(d-u)$ at $Q_0^2 = 7GeV^2$
  - ▷ RT-VFN heavy quark scheme
  - ▷ Treatment* of point-to-point correlated systematic errors
  - ▷ Systematic offsets not modified by the fit

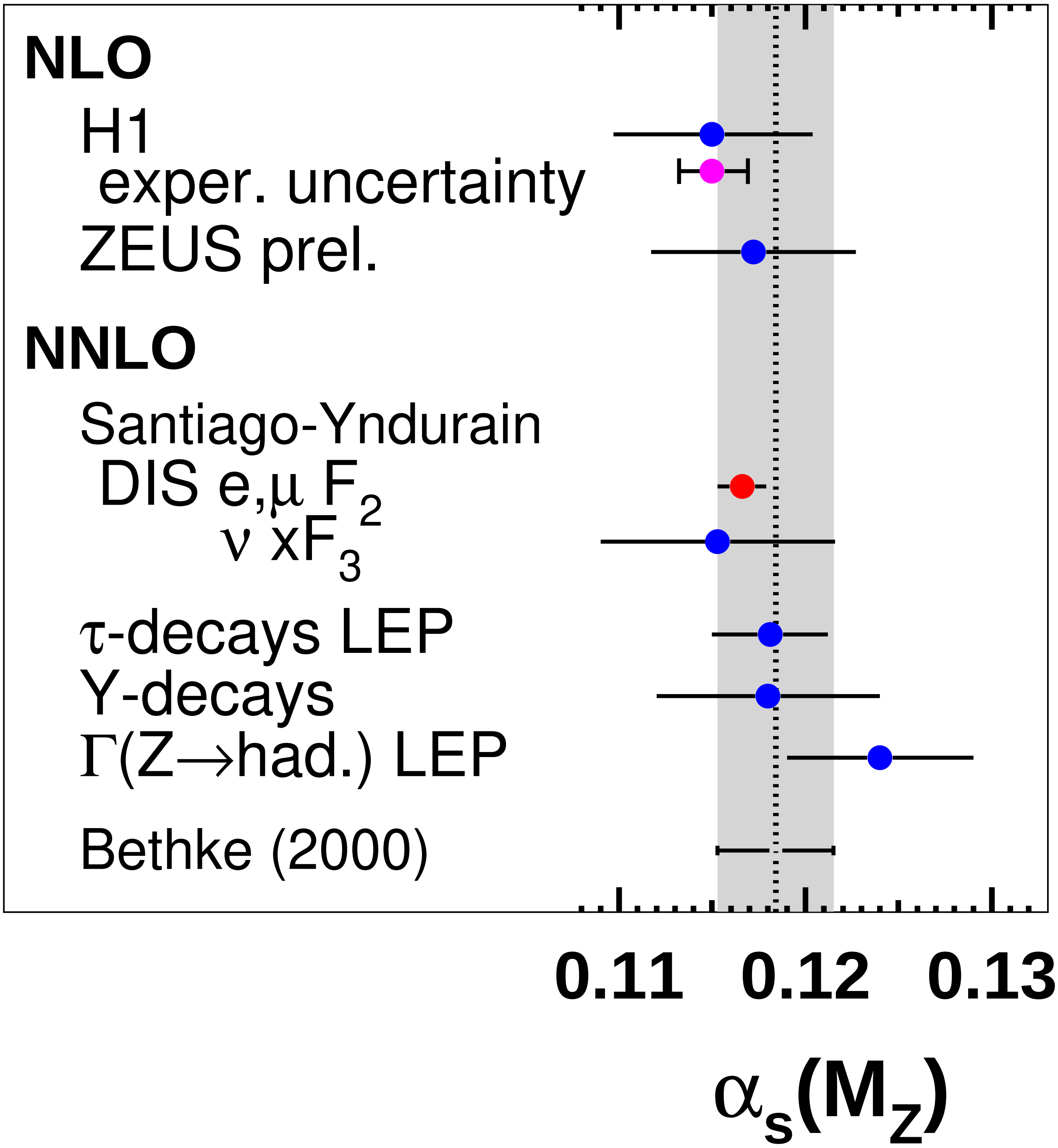
Excellent fits are obtained $\Longrightarrow$

* Both collaborations use the prescription of Pascaud & Zomer (LAL−95 − 05)

Simultaneous fit to Gluon and α_s



Gluon Density rises towards low x

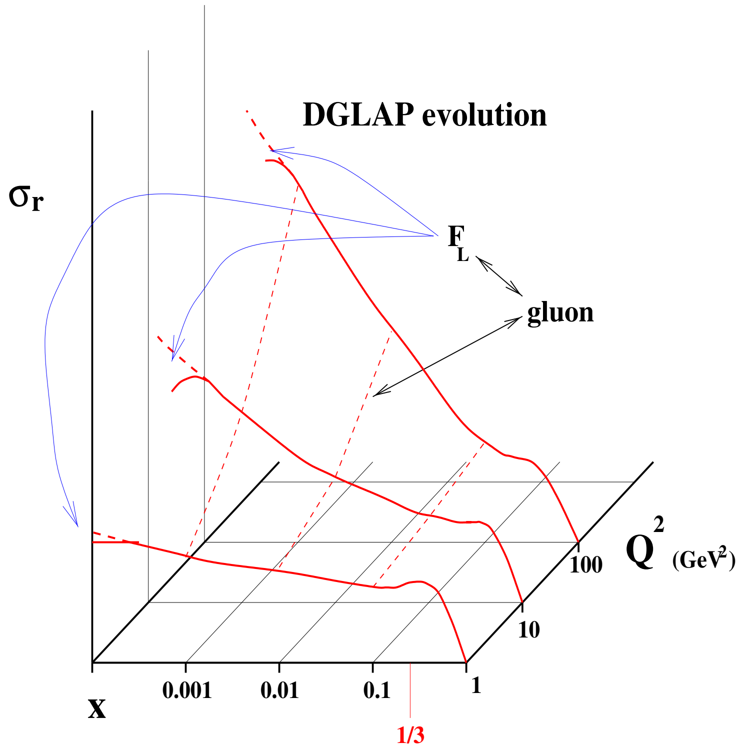


Theory developments: **NNLO calculations**

$\Longrightarrow$ **Even more precise α_s from DIS data**

Can experimental errors be further reduced?

Challenge to the Experiments . . .



$$F_L(x, Q^2) \sim \frac{\alpha_s}{\pi}\beta_2 \otimes xg(x, Q^2)$$

Measuring F_L is a powerful cross-check of $xg(x, Q^2)$

Test of QCD at low x

How can F_L be measured at HERA ?

Only possible by varying beam energies $s = Q^2 / xy$

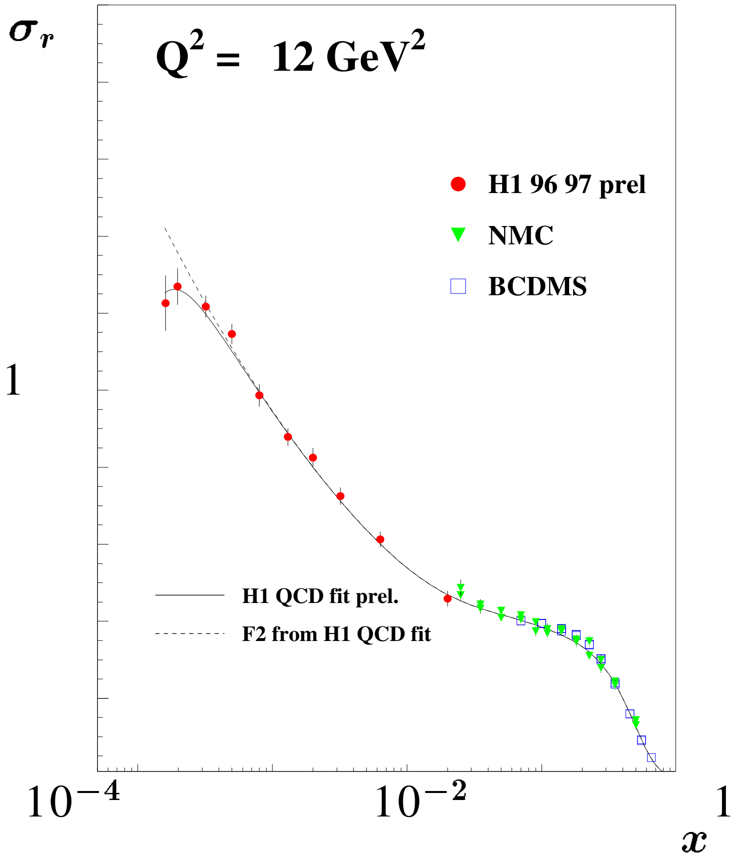
$$\sigma_1 - \sigma_2 = [(y^2/Y_+)_1 - (y^2/Y_+)_2] \cdot F_L$$

H1 tried several Methods of Extraction $\Longrightarrow$

MEASUREMENT OF F_L: METHOD I

- MEASURE REDUCED CROSS SECTION σ_r
- QCD FIT TO F_2 IN THE REGION WHERE F_L CONTRIBUTION IS NEGLIGIBLE $(y < 0.35)$
- EXTRAPOLATE F_2^{QCD} TO HIGH y
- SUBTRACT σ_r:

$$F_L = F_2^{QCD} - \frac{Y_+}{y^2}\sigma_r$$



USE THIS METHOD FOR $Q^2 > 10\ GeV^2$

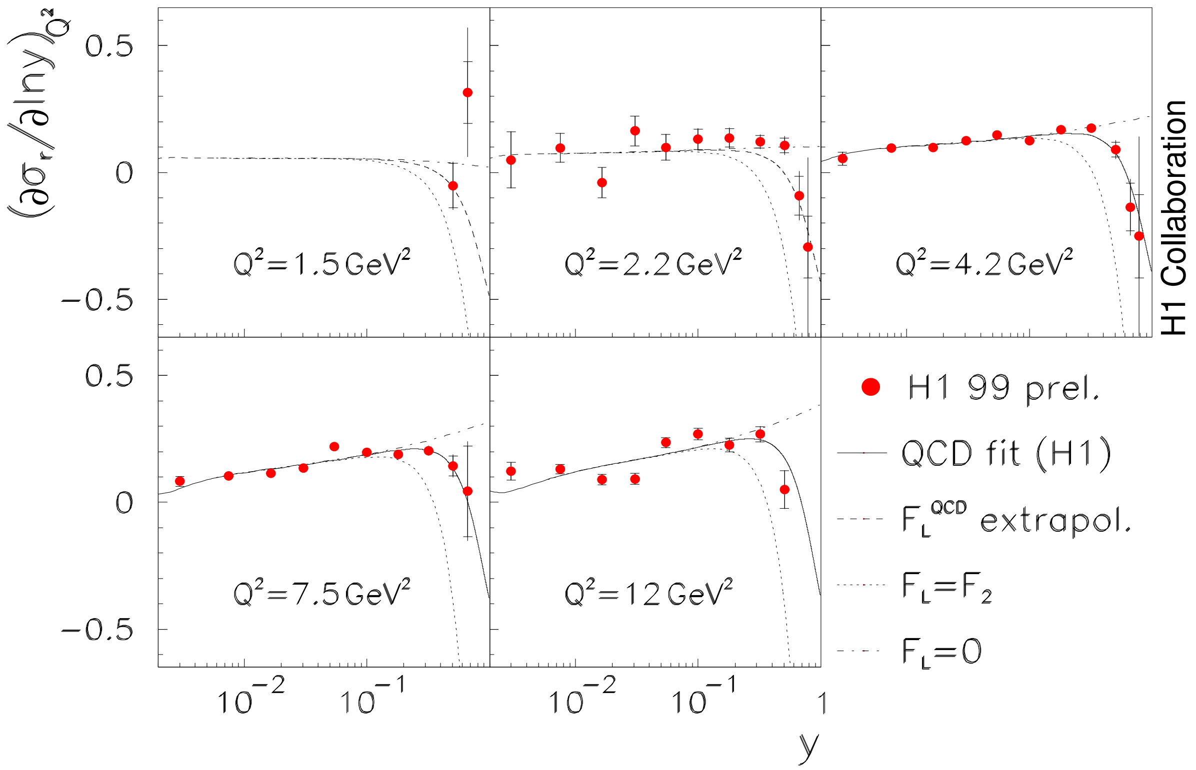
FIRST MEASUREMENT OF F_L AT HERA WITH H1 94 DATA:
PHYS.LETT. 393B (1997) 452

MEASUREMENT OF F_L: METHOD II

- FORM DERIVATIVES W.R.T. $\ln y$ FROM σ_r IN BINS OF Q^2 AND y:

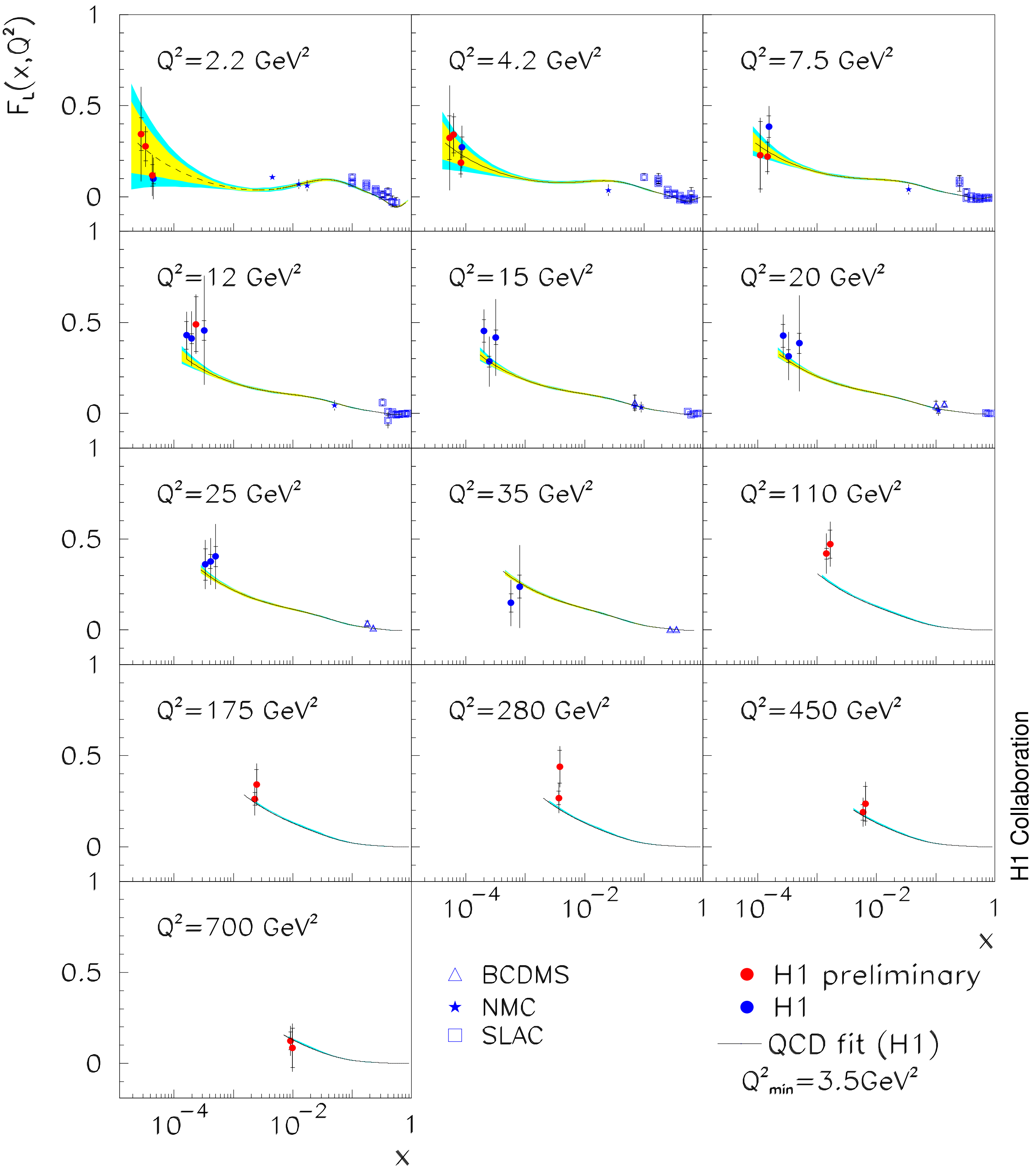
$$\frac{\partial \sigma_r}{\partial \ln y} = \frac{\partial F_2}{\partial \ln y} - F_L \cdot 2y^2 \cdot \frac{(2-y)}{Y_+^2} - \frac{\partial F_L}{\partial \ln y} \cdot \frac{y^2}{Y_+^2}$$

- $y \to 1 \quad \Rightarrow \quad \partial \sigma_r / \partial \ln y \approx \partial F_2 / \partial \ln y - 2 \cdot F_L$
  ($\partial F_L / \partial \ln y$ NEGLECTED, UNCERTAINTY INCLUDED IN ERROR)
- FOR GIVEN $Q^2 \quad \Rightarrow \quad F_2 \sim x^{-\lambda} \sim e^{\lambda \ln y}$
  LOW $Q^2 \Rightarrow$ SMALL λ : $\frac{\partial F_2}{\partial \ln y}$ LINEAR IN $\ln y$ TO GOOD APPROXIMATION
  $\Rightarrow$ CONFIRMED WITH QCD FIT AND DEVIATIONS INCLUDED IN ERROR
- STRAIGHT-LINE FIT TO $\partial \sigma_r / \partial \ln y$ IN BINS OF Q^2 FOR $y < 0.2$
- EXTRAPOLATE THE FITTED LINE TO HIGH y
- SUBTRACT $\frac{\partial \sigma_r}{\partial \ln y} \quad \Rightarrow \quad F_L$

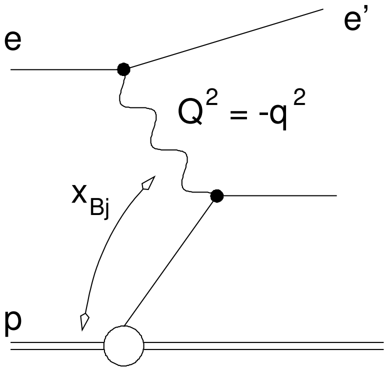


USE THIS METHOD FOR $Q^2 < 10\ GeV^2$

H1 Measurements of F_L



ALL Measurements consistent with NLO QCD Fit

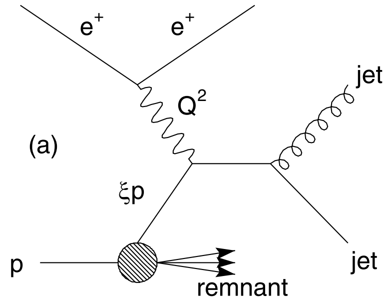


Born Process $O(\alpha_s^0)$

Leading Contribution to F_2

Direct Sensitivity

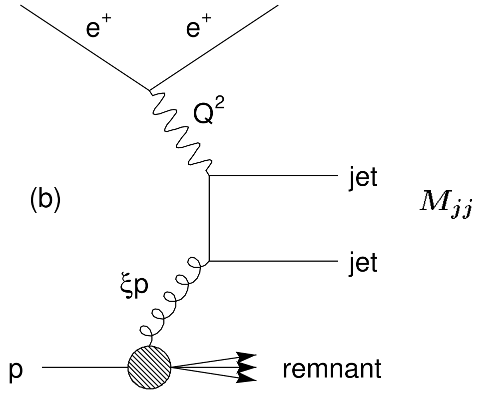
only to the quark PDF's



QCDC, BGF processes $O(\alpha_s)$

Direct Sensitivity to $g(x)$, α_s

2 scales: $E_{T,jet}$ Q^2

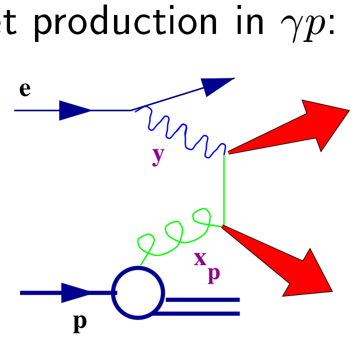


$$\xi = x_{Bj}(1 + M_{jj}^2/Q^2)$$

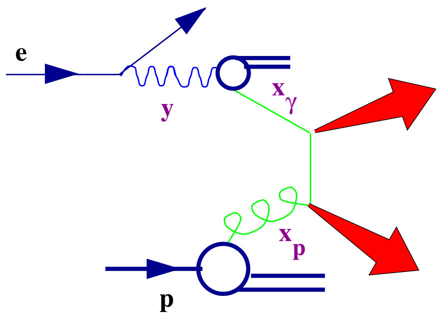
Parton momentum fraction in LO directly sensitive to parton density at $x = \xi$

At low values of Q^2 the "Resolved Photon" contributes

Jet production in γp:

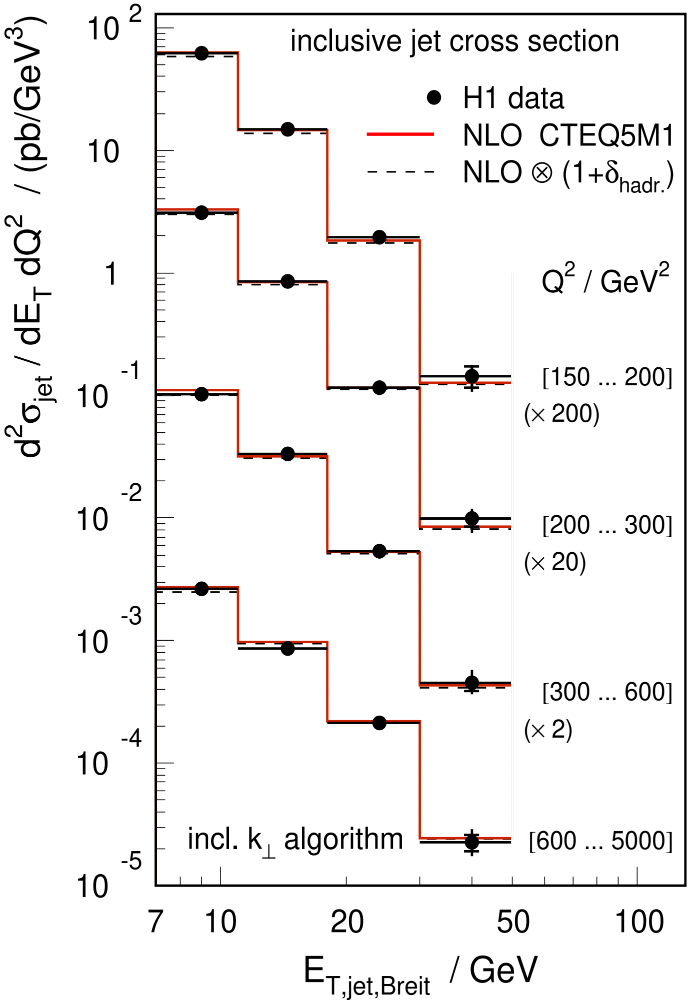


DIRECT ($x_\gamma = 1$)



RESOLVED ($x_\gamma < 1$)

Need large scale values for study of proton PDF's

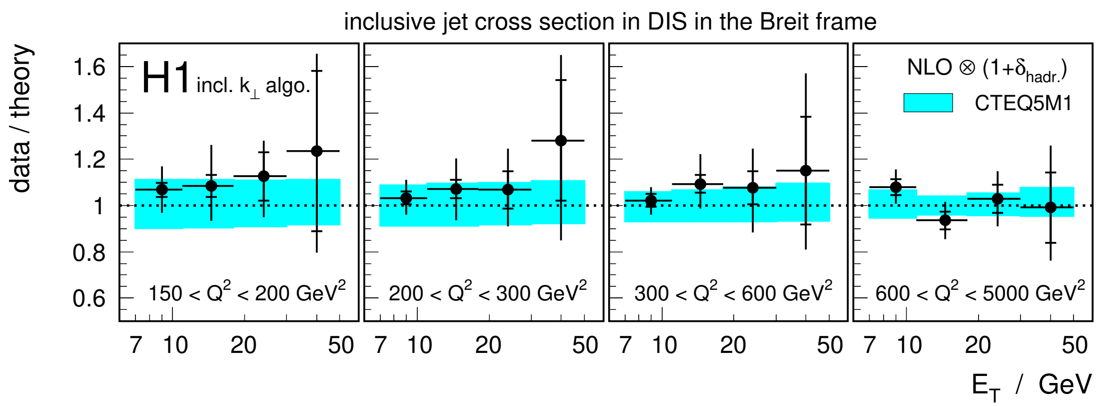


Inclusive, Differential Jet Cross Section

$150 < Q^2 < 5000\ \mathrm{GeV}^2$
$7 < E_{T,jet,Breit} < 50$ GeV

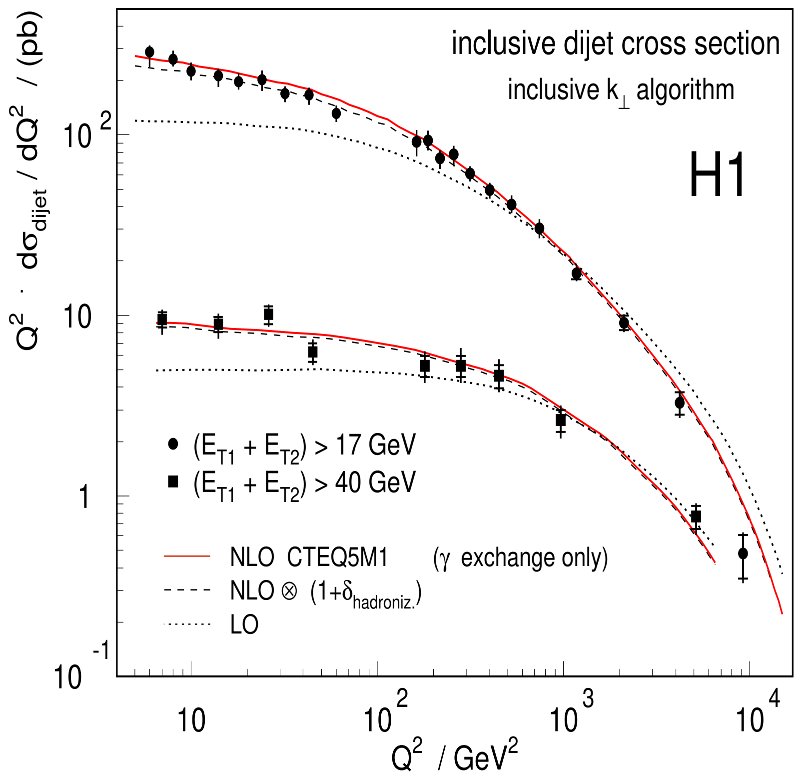
Jets defined in the Breit Frame
Inclusive $k_\perp$ Jet Search Algorithm

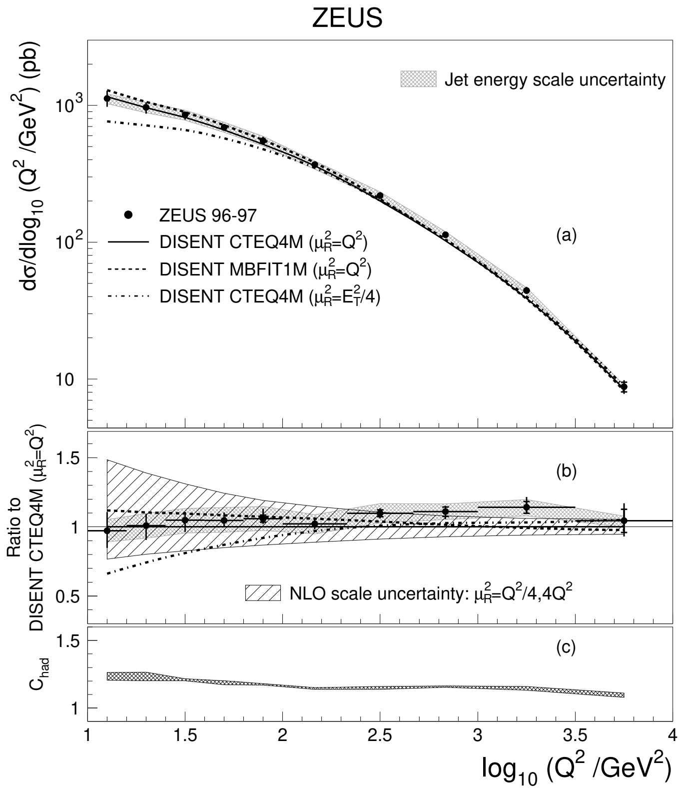
NLO QCD Calculations
Renormalization scale $\mu_r = E_{T,jet,Breit}$
Hadronization corrections small



Very good agreement between Data and NLO QCD
in whole kinematic range of Q^2 AND $E_{T,jet}$

Inclusive Dijet Cross Section

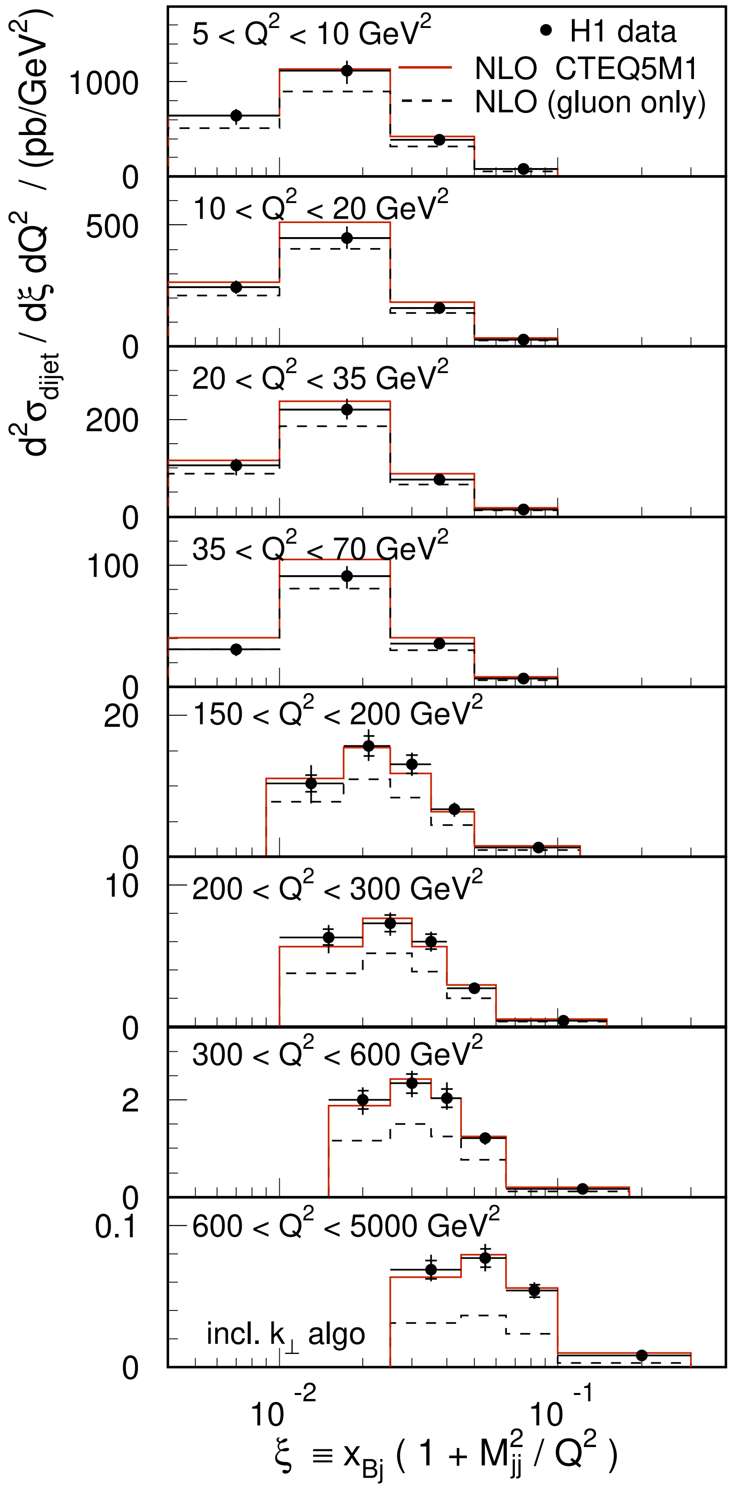




NLO QCD predictions describe the data well, over large range of Q^2 and $E_{T,jet}$

Hadronization Corrections are small

The Scale Uncertainty is large $(10 - 50\ \%)$ in the whole kinematic range



NLO QCD describes the data also at low Q^2

Gluon induced contributions in the cross section vary:

- **80 % at low Q^2**
- **40 % at high Q^2**

Strategy of QCD Analysis

Several Steps:

- **Fit Jet data to the NLO QCD predictions**

  Use PDF's from global, external fits

  Only 1 free parameter: $\Longrightarrow$ α_s

  H1: Inclusive, differential Jet cross sections
  CTEQ5M1 PDF's

  ZEUS: Dijet Rate MBFIT PDF's

- **α_s value consistent with other measurements?**
  (not dependent on hadrons in the initial state)

  Fix α_s to external value !

  Fit the Jet data $\Longrightarrow$ proton PDF's
  In particular the Gluon Density

- **Perform a Global, Simultaneous fit,**
  using both Jet data and Inclusive DIS data

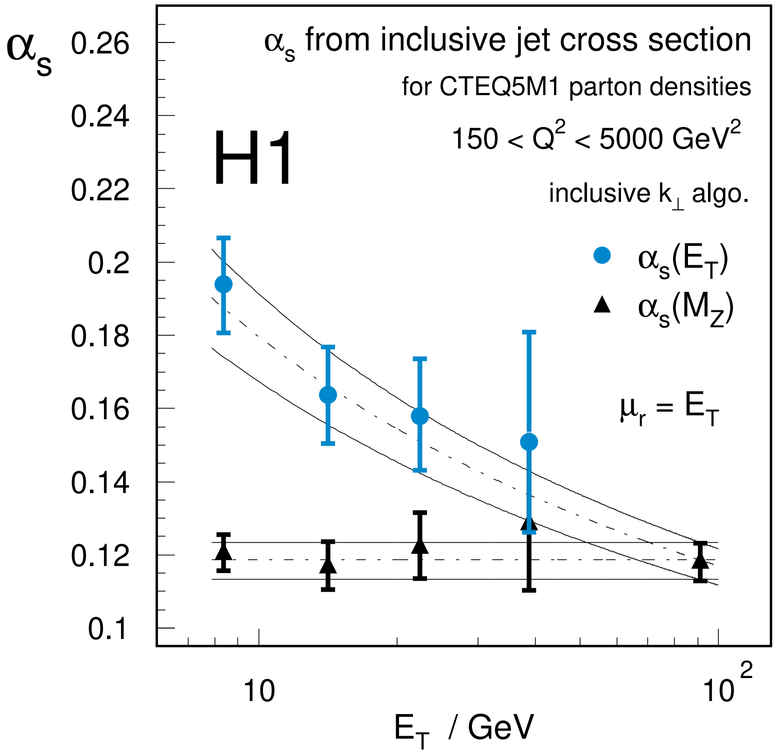
  $\Longrightarrow$ Gluon Density AND α_s

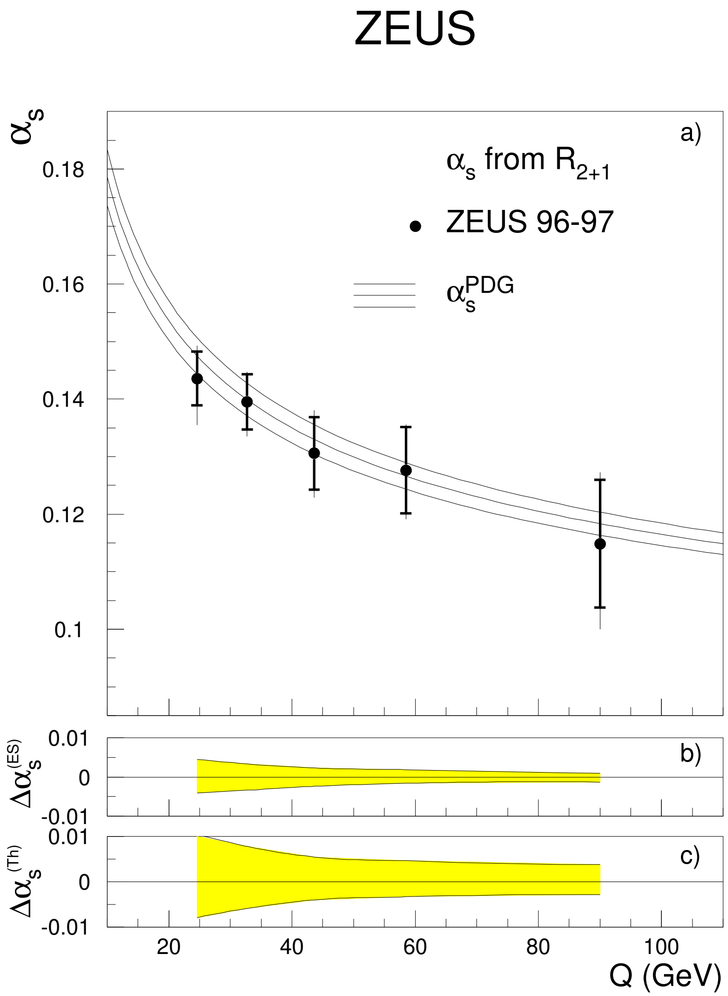
  This does NOT work !
  Strong anti-correlation between $g(x)$ and α_s
  No useful information with present data

INCLUSIVE JET PRODUCTION IN DIS

α_s using external proton PDF's

Running in both scales, $E_{T,jet}$ and Q

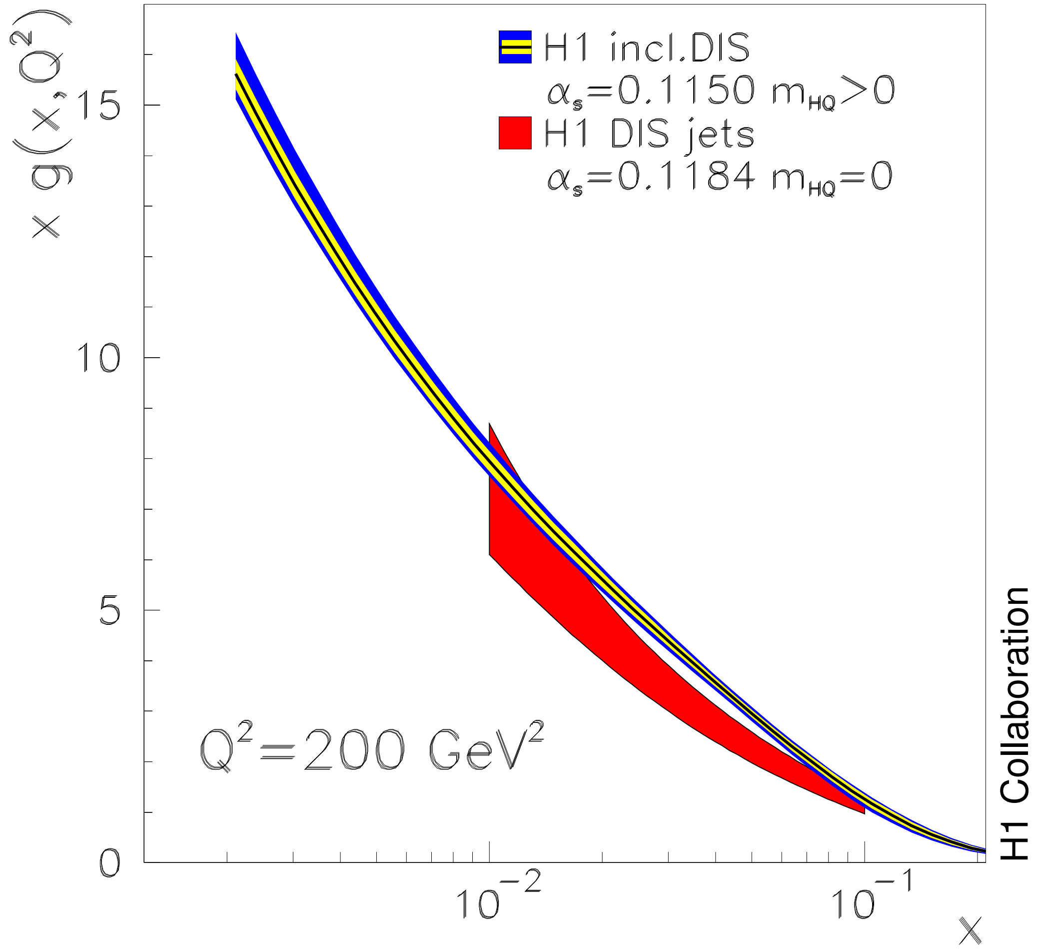




Largest Experimental uncertainty: **The Calorimeter Energy Scale**

Largest Theoretical uncertainties: **Renormalization Scale, Hadronization**

Gluon PDF from Jet Data



Fix α_s to external value

Global fit of proton PDF's, using Jet Data and Inclusive Jet Data

Bands give the total error

$$\mu_F = \sqrt{200}\ \text{GeV}$$

Integration over $0.01 < x < 0.1$ $\Longrightarrow$ Gluons carry 23 % of proton momentum in this range

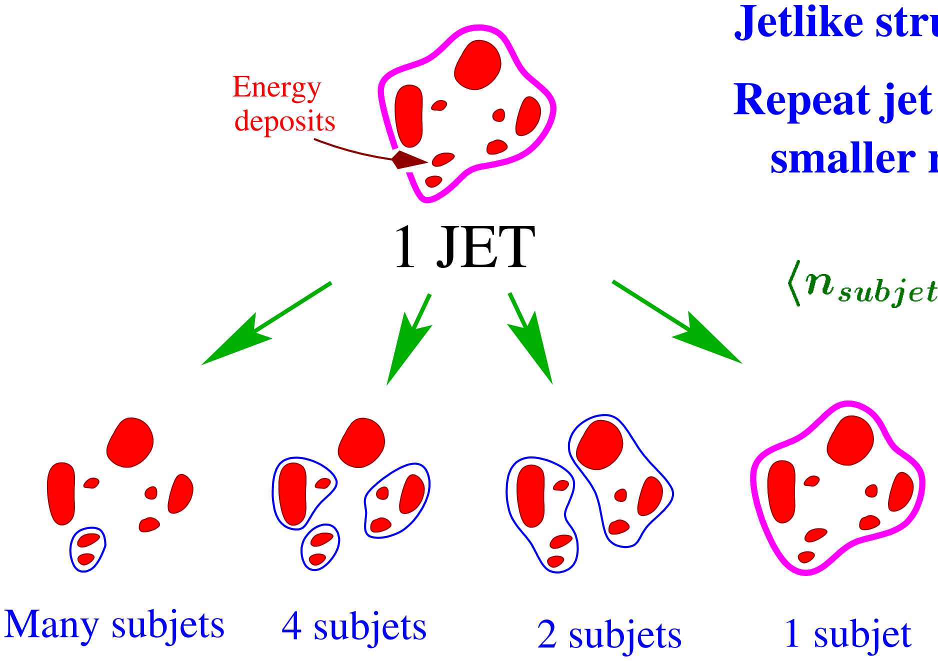
Good agreement with external PDF sets

Subjet Multiplicity

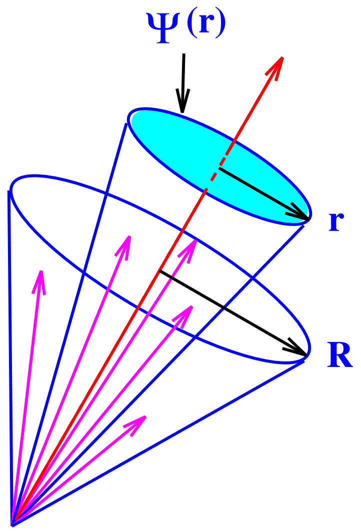
Jetlike structures within a jet

Repeat jet algorithm with smaller resolution scale

$$\langle n_{subjet} \rangle = \frac{1}{N_{jet}} \sum_{1}^{N_{jet}} n_{subjet}$$



Jet Shape



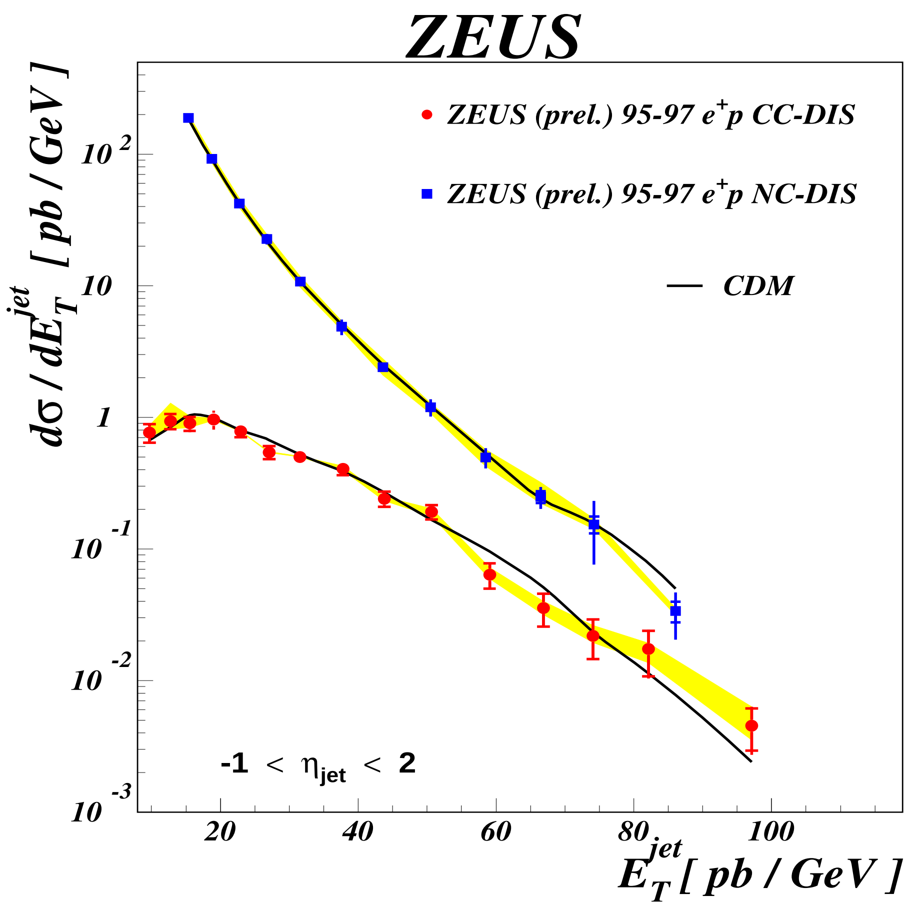
$$\Psi(r) = \frac{1}{N_{jet}} \sum_{1}^{N_{jet}} \frac{E_T^{jet}(r)}{E_T^{jet}(r = R)}$$

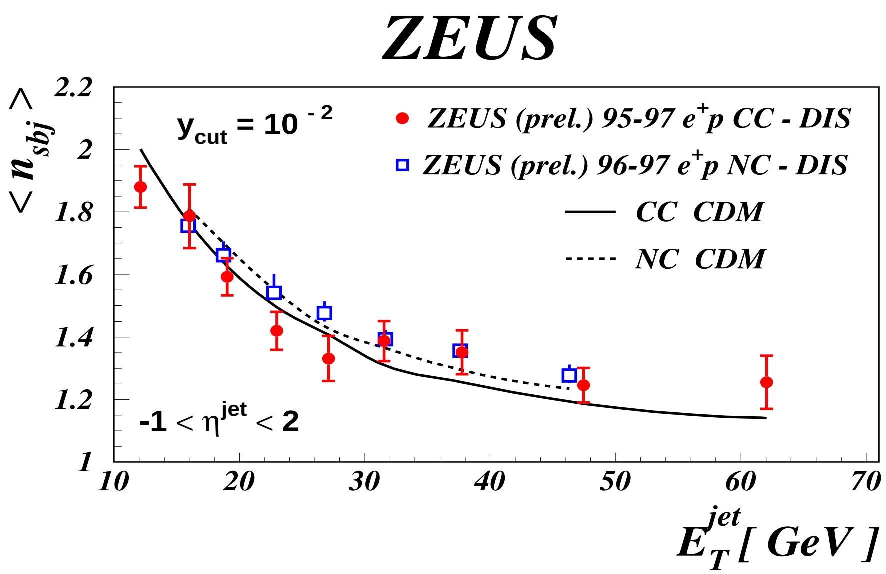
Jet Substructure

- **Independent of original hard scattering process ?** **Yes**
- **Dependent on original parton nature (quark / gluon) ?** **Yes**
- **Sensitive to α_s ?** **Yes**

Jet Substructure is a useful tool for testing QCD !

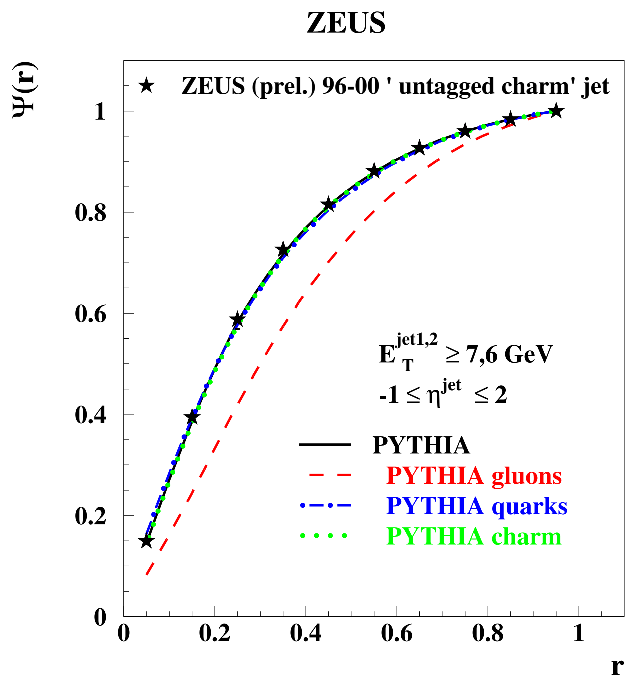
Jets in Charged Current and Neutral Current Events $Q^2 > 200\ \mathrm{GeV}^2$

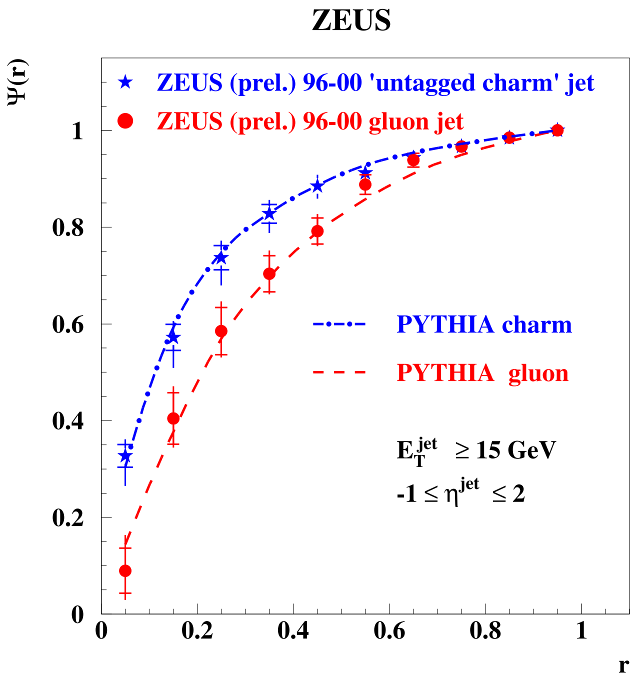




- CC and NC jets look alike
- Pattern of QCD radiation close to a primary quark is independent of the hard scattering process

Dijet Events



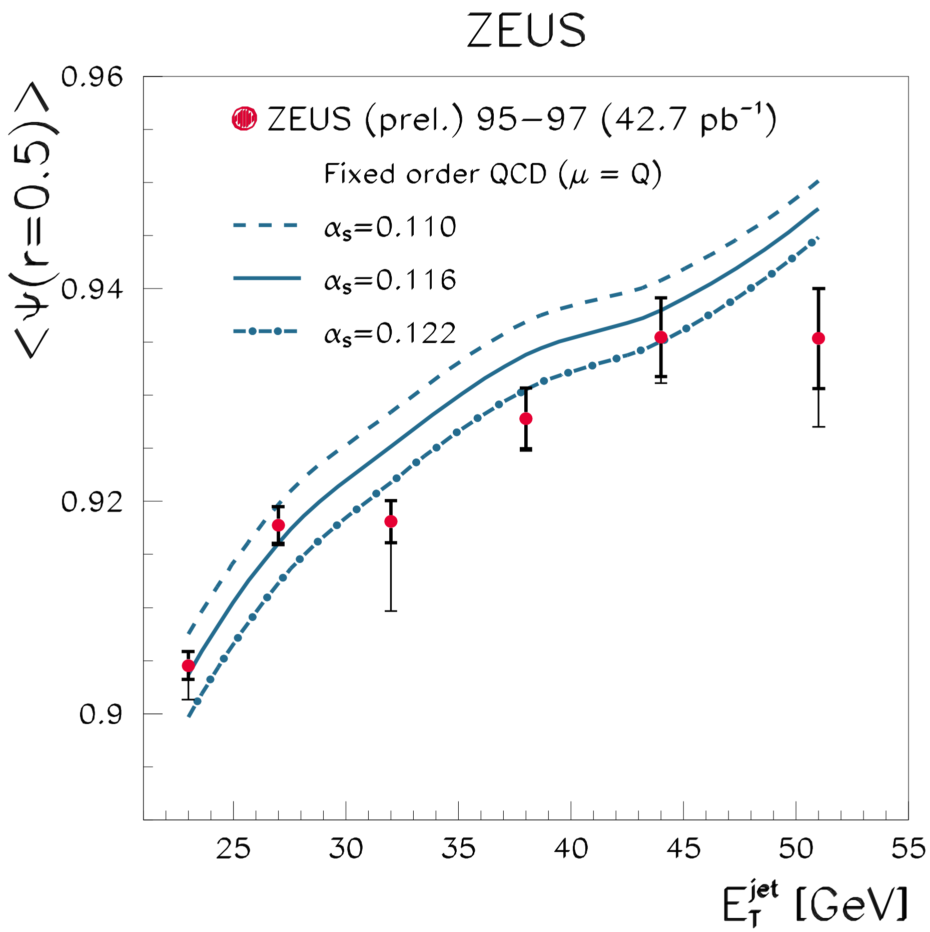


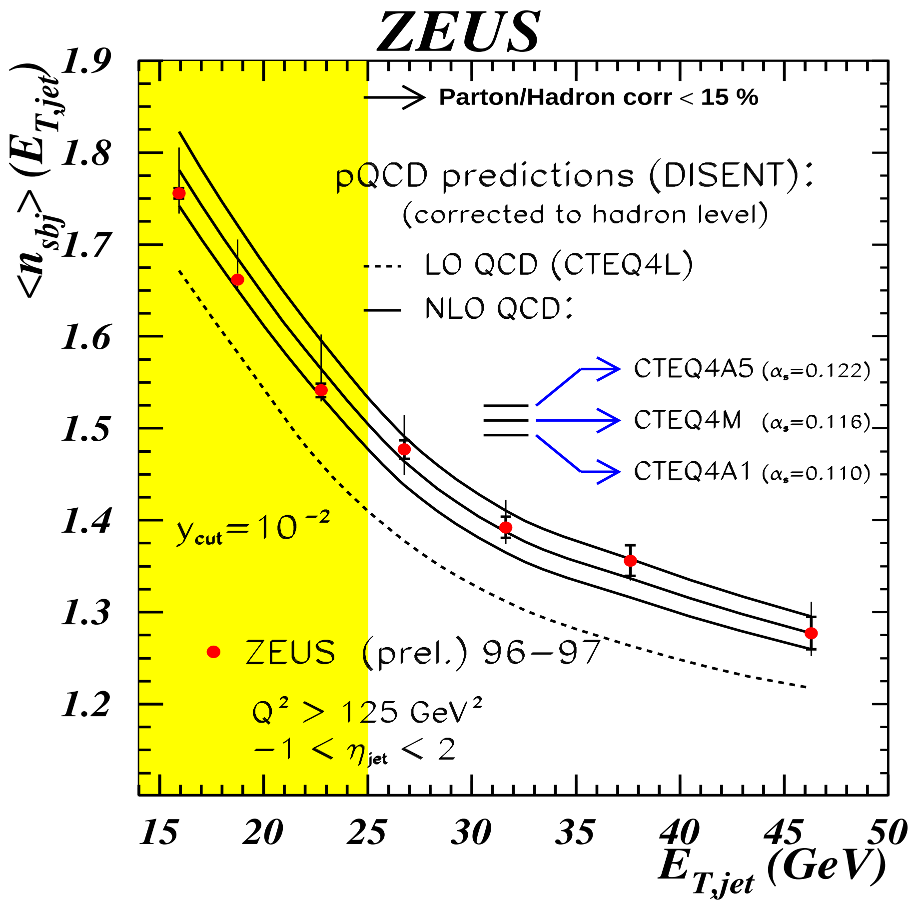
- **Select events with D^* candidate (using ΔM technique)**
  $\Longrightarrow$ **Tagged Charm Jet**
  $\Longrightarrow$ **Untagged Charm Jet**
- **PYTHIA predictions for charm / quark jets agree well with Untagged Charm Jet**

Extract Shape of Gluon Jet

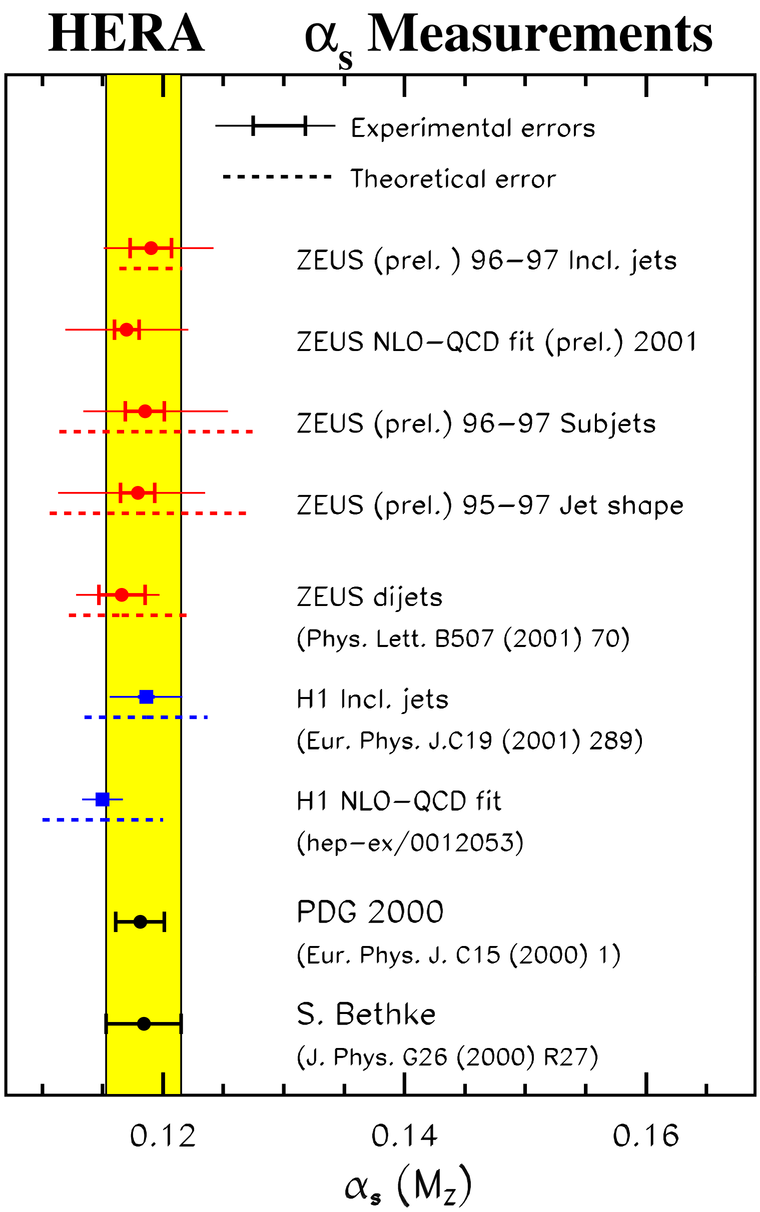
- $\Psi(r)_{all} = f_q\Psi(r)_{quark} + f_g\Psi(r)_{gluon}$
  - ▷ $\Psi(r)_{quark}$ **given by Charm jets**
  - ▷ $f_q,\ f_g$ **given by MC**

  $\Longrightarrow \quad \Psi(r)_{gluon}$
- **Extracted Gluon Jet agrees well with MC predictions (and with LEP Data)**





Sensitivity to α_s $\Longrightarrow$ Fit α_s from Jet Substructure !

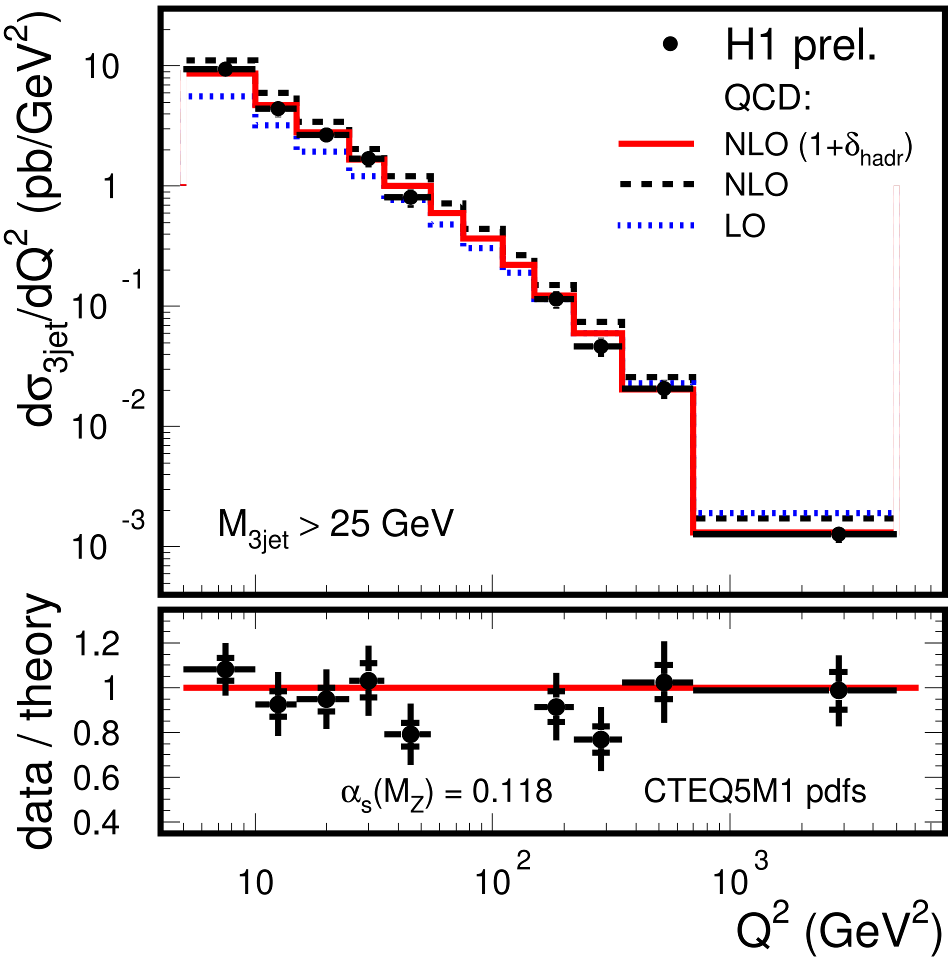


Consistent, New Measurements of α_s

from HERA DIS Jet Data and Inclusive DIS Data

Small errors: Impact on the World Average

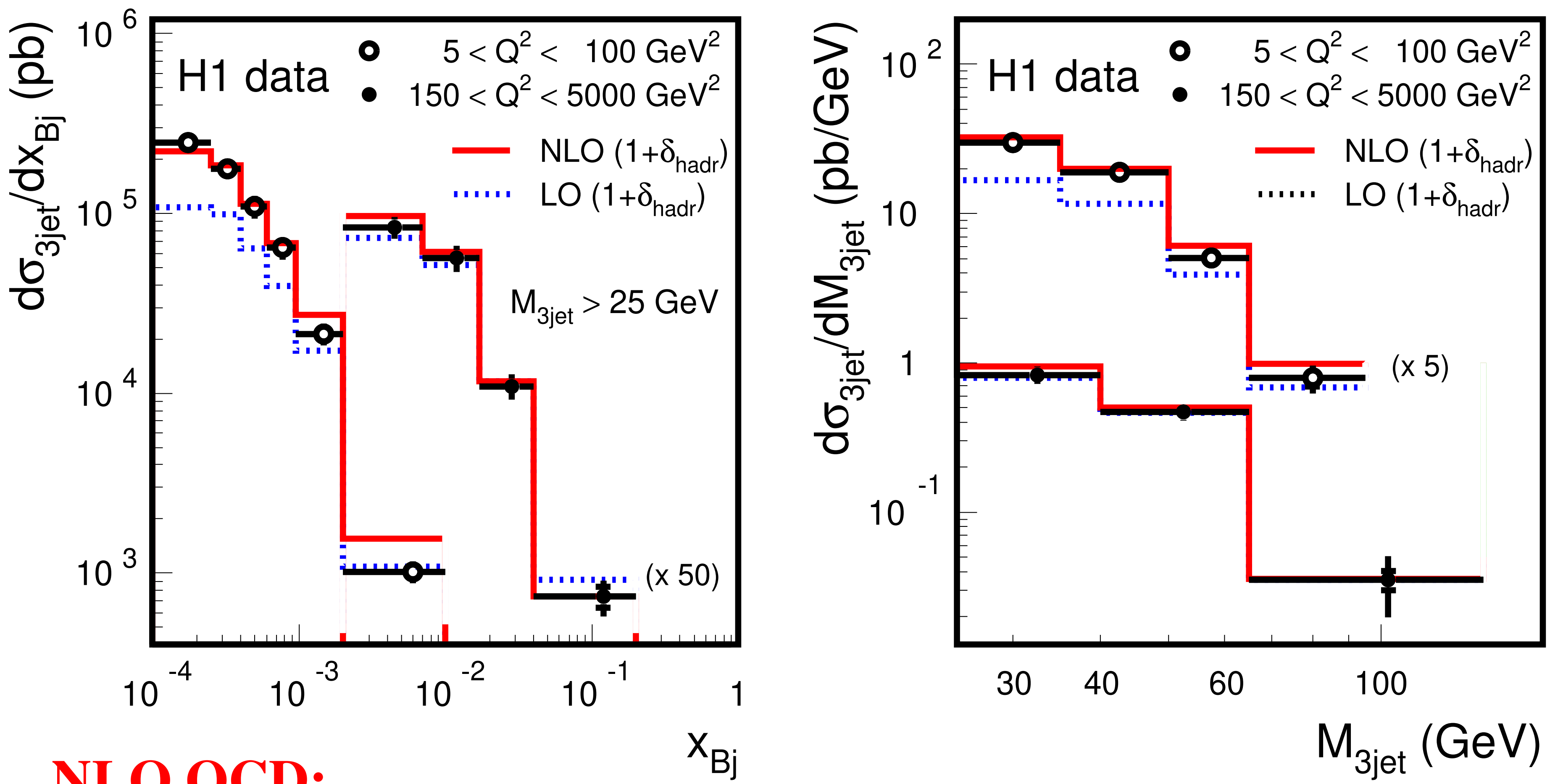
3 Jets in Hadronic Final State



H1 e^+p data 1995−97
$5 < Q^2 < 5000$ GeV^2
3 Jets
Breit Frame
Inclusive $k_\perp$ algorithm)
$E_{T,jet} > 5$ GeV
$M_{3jet} > 25$ GeV
$-1 < \eta_{jet,lab} < 2.5$

New NLO QCD calculation
"NLOJET"
Nagy, Trocsányi

Good agreement
Data − NLO QCD

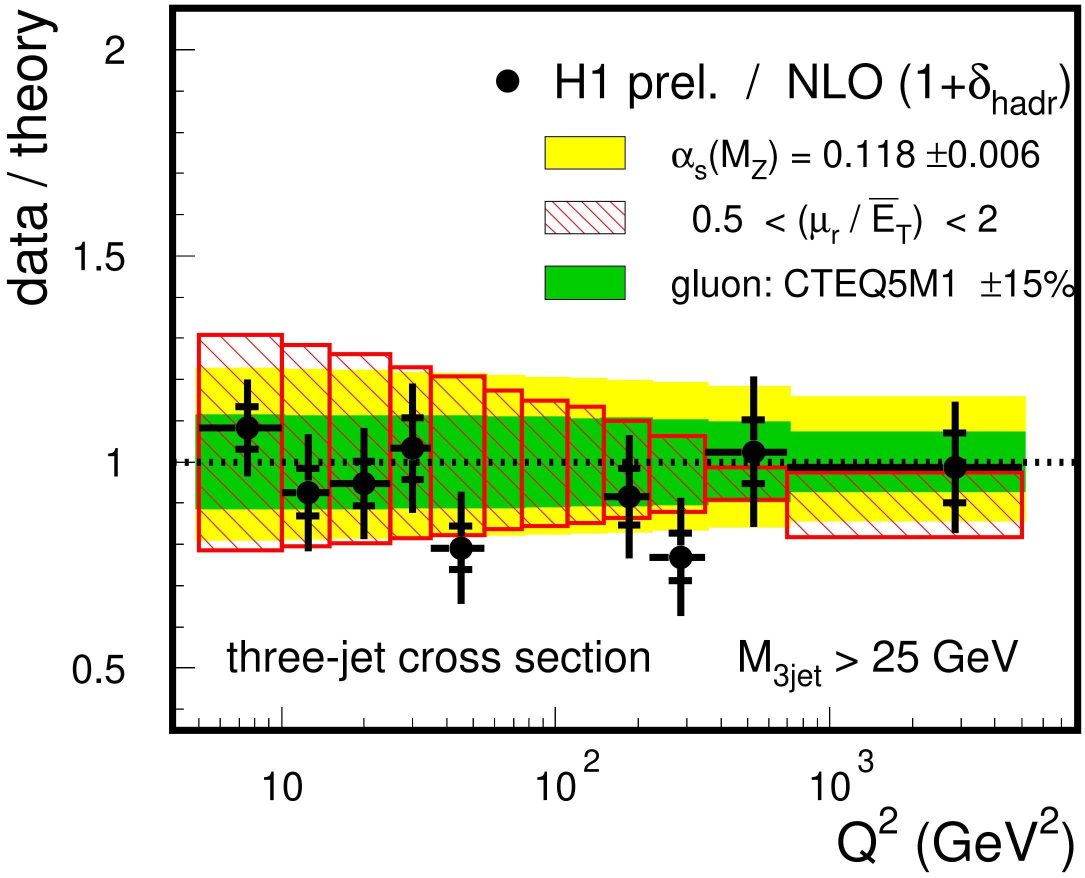


NLO QCD:

Good agreement with Data over the whole kinematic range

$10^{-4} < x_{Bj} < 0.15$ $\quad$ $25 < M_{3jet} < 140$ **GeV**

Ratio Data / Theory



Quantitative Tests ?

Theory Uncertainties, due to

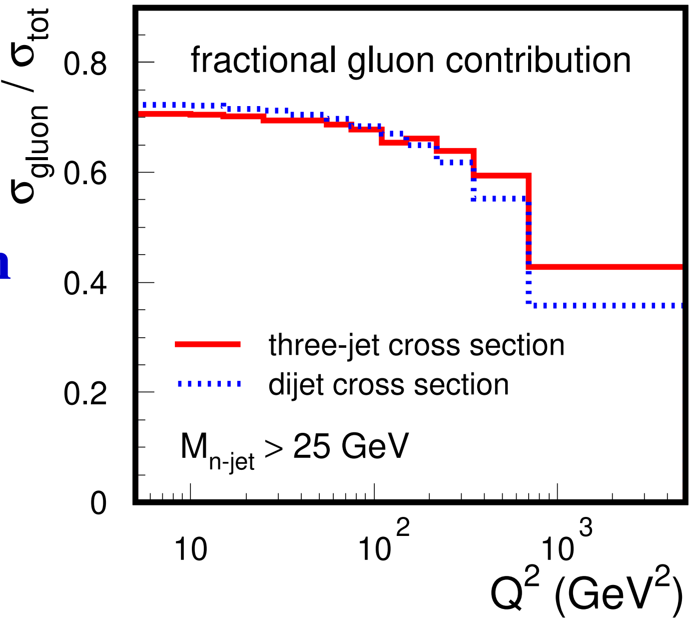
- **α_s: Large over whole Q^2 range**
- **μ_R: Large at low Q^2 values**
  Smaller at high Q^2 values
- **Gluon PDF: Smaller at high Q^2 values**

Need better statistics at high Q^2 $\cdots$

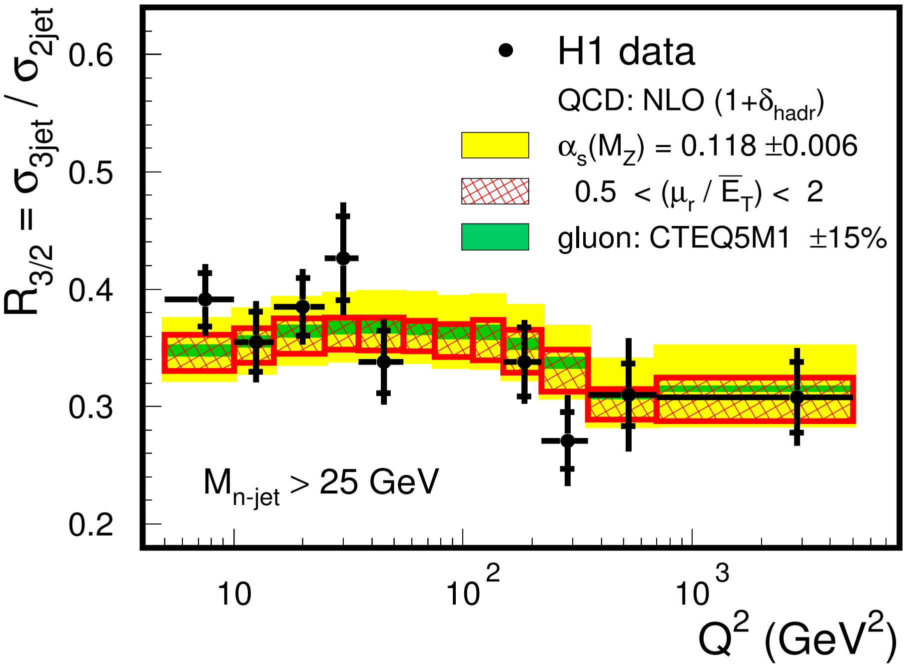
3-JET PRODUCTION IN DIS

At same Q^2,
Dijet and 3-jet production involves the same Gluon Fraction

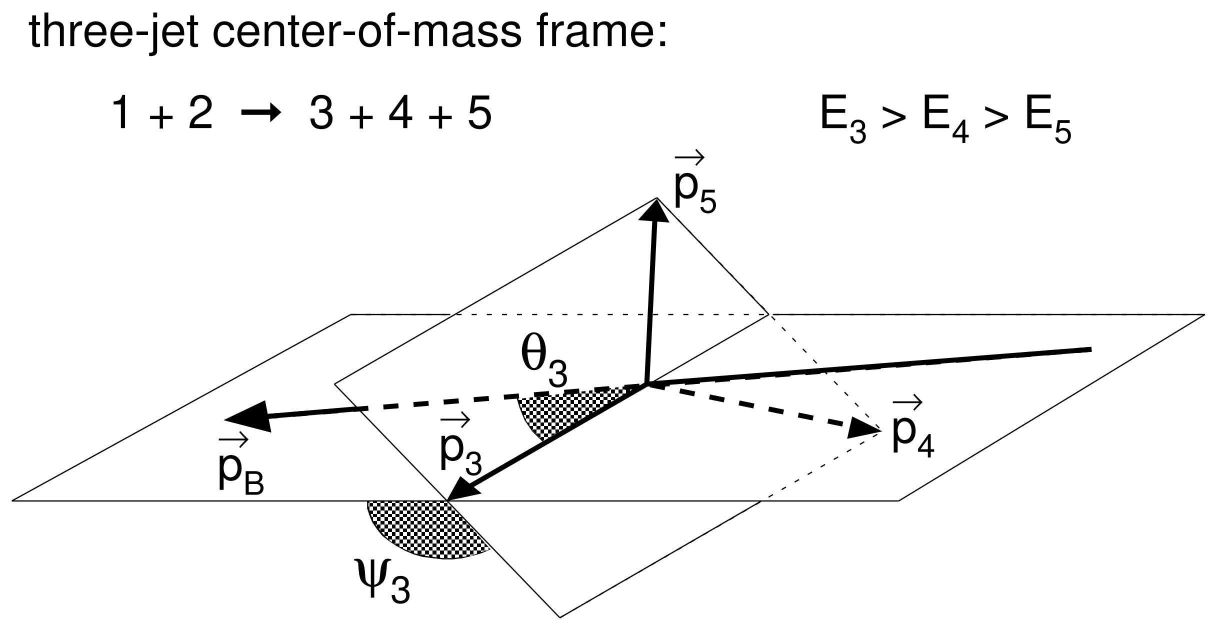
- **PDF uncertainties cancel in the ratio**
  $R_{3/2} = \sigma_{3jet}/\sigma_{2jet}$
- $R_{3/2} \propto \alpha_s$



- **Theory and Data agree very well**
- **μ_R dependence small over whole Q^2 range**



With smaller data errors (statistics !) very precise tests of QCD possible



3 Jets $\Longrightarrow$ **More Degrees of Freedom**
More Detailed Tests of QCD

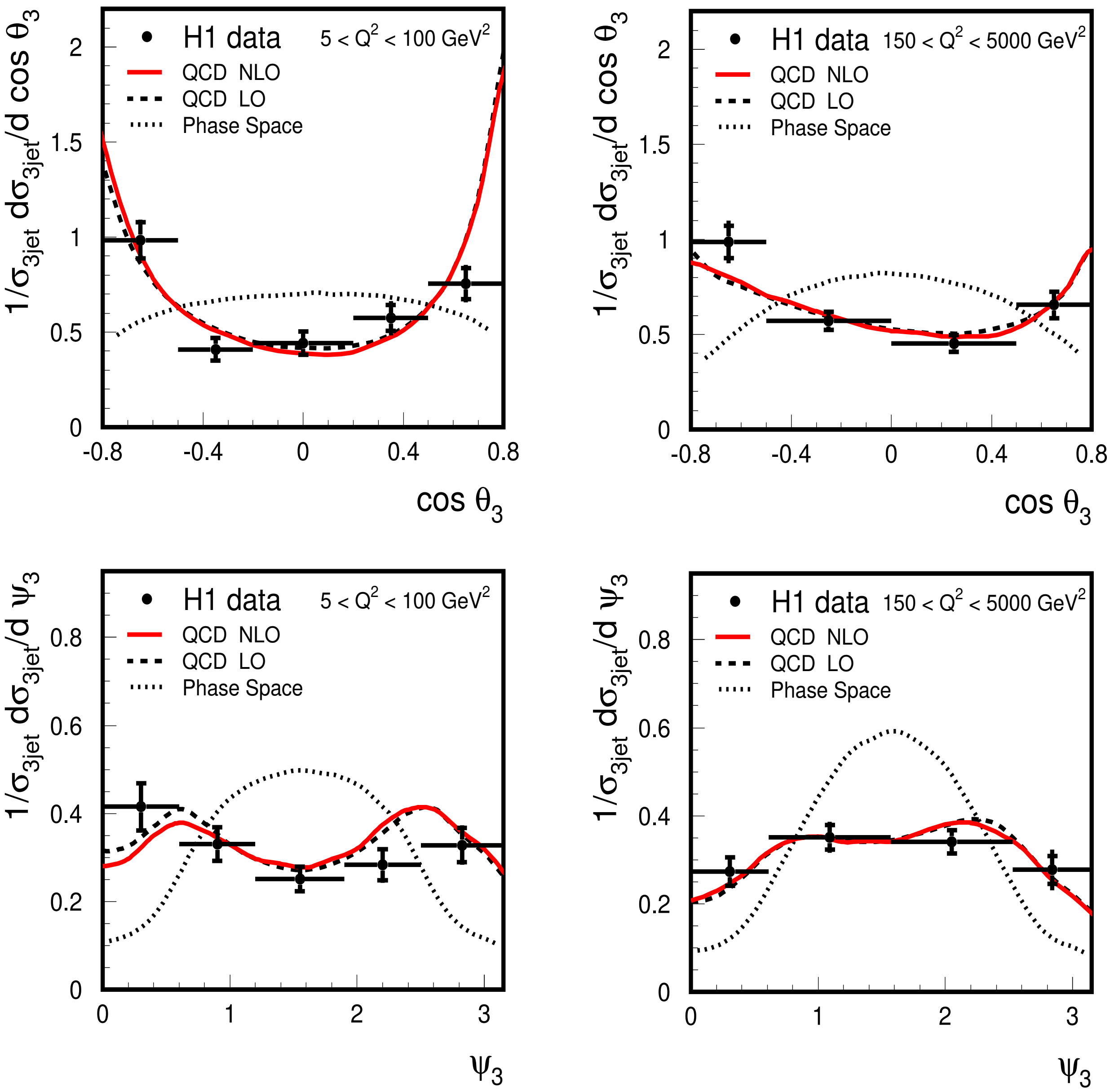
3 Jets described by 8 variables:

$$Q^2,\ x,\ \phi,\ M_{3jet},\ X_3,\ X_4,\ \Theta_3,\ \Psi_3$$

Energy Fractions:

$$X_3 = 2\,E_3/M_{3jet}$$
$$X_4 = 2\,E_4/M_{3jet}$$

Θ_3: **Angular orientation of strongest jet**
Ψ_3: **Angular orientation of weakest jet**



Angular Distributions follow QCD Predictions
Very different from Phase Space !

Bremsstrahlung Radiation Pattern
Jets tend to be aligned with Photon or Proton

Coherence Property of QCD

CONCLUSIONS

- H1 and ZEUS test QCD and measure the Proton Structure Functions F_2 and F_L in new kinematic region
- DIS Data well described by NLO QCD and DGLAP
- Jet Cross Sections in DIS are a powerful tool for measuring α_s and the Gluon Density in the Proton
- Jet Substructure is another Useful Tool for Testing QCD and for measuring α_s
- Consistent α_s Measurements
  Errors highly Competitive with the World Average
- Running of α_s tested within Single Experiment
  - ▷ over a large range of μ_R
  - ▷ with both scales, $E_{T,jet}$ and Q
- Consistent Gluon Density measurements
- 3-jet event distributions agree well with NLO QCD predictions and show a high potential for Future Precision Tests of perturbative QCD

Wait for the HERA I data (1999-2000) !
Wait for the HERA II data !