Structure Functions and Parton Distribution Functions at the HERA ep Collider

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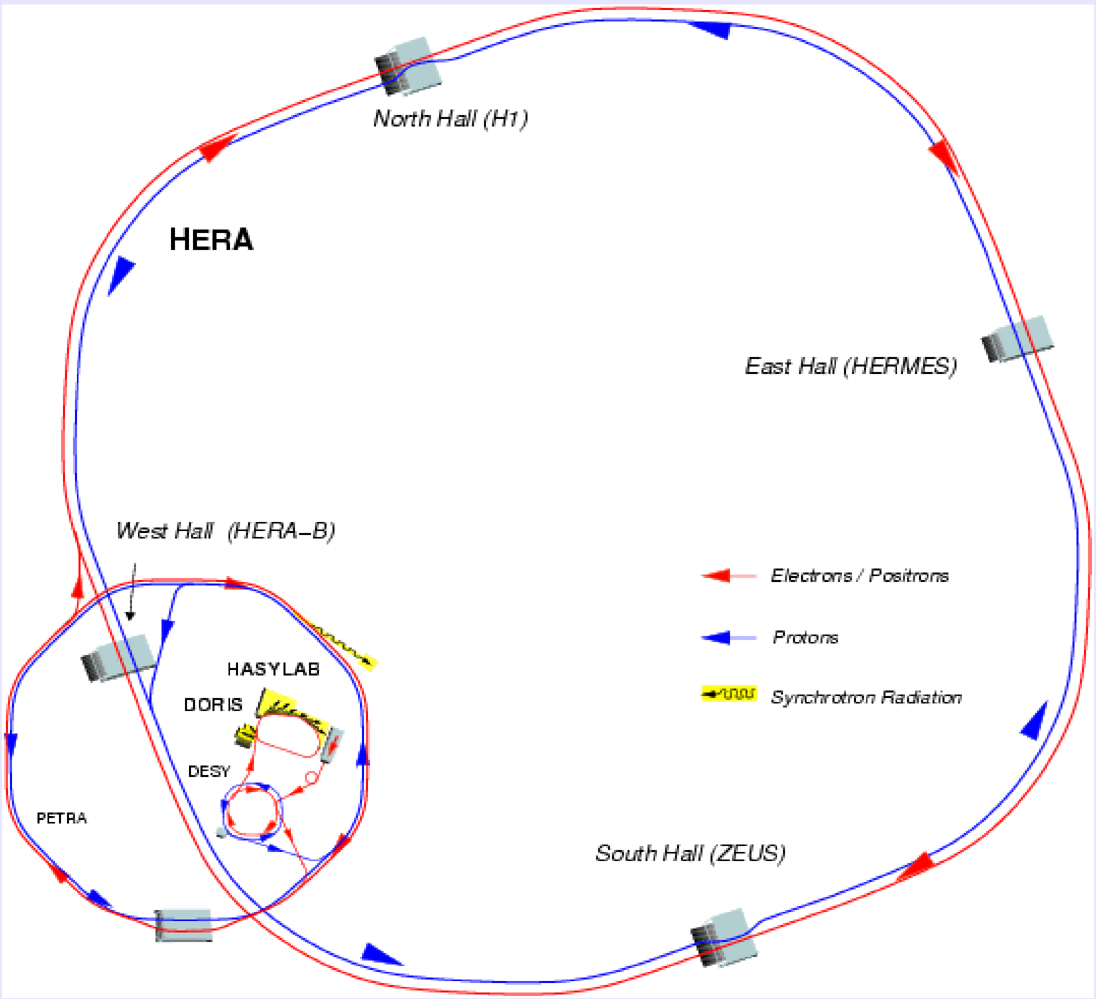
Moriond QCD, 16/03/2005

Contents

Today we'll be covering the following topics

- Introduction to HERA physics & kinematics
- ep cross-sections and structure functions
- Applications of HERA structure function data
- Measurements of F_2, xF_3 and F_L
- HERA QCD fits
- Summary

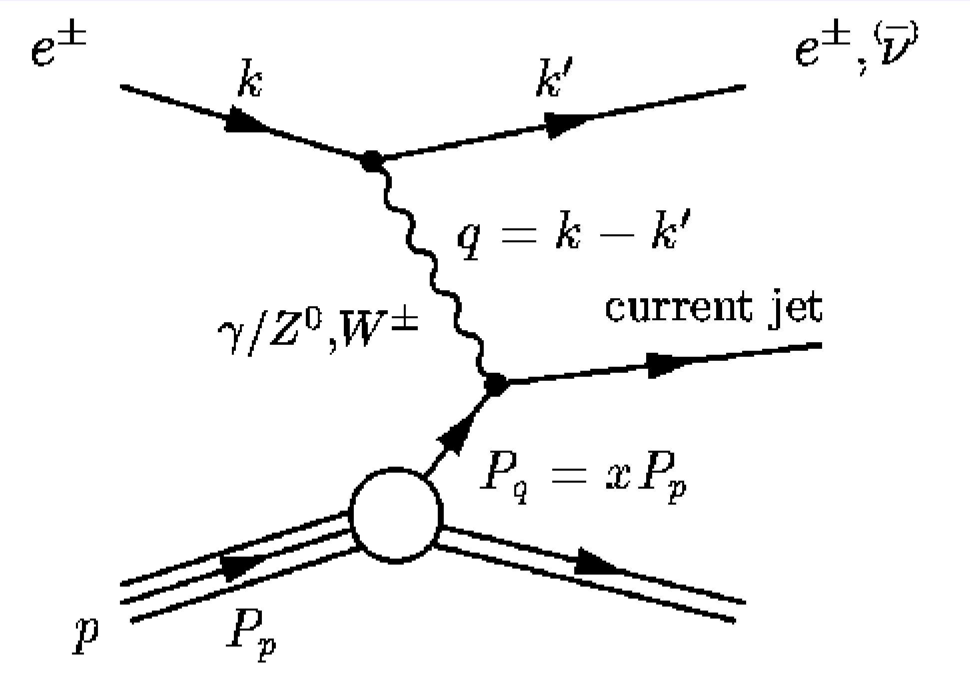
Introduction to HERA Physics



- HERA is the largest of the particle accelerator rings operated by DESY (Hamburg,Germany)
- The world's only ep collider.
- 90% of the delivered luminosity between 93-04 has been with e^+
- Currently delivering e^- luminosity
- ZEUS and H1 are two general purpose experiments located on the HERA ring

27.5GeV $e^{-/+}$ → ← 920(820)GeV p

Introduction to HERA Kinematics



γ / Z^0 exchange *Neutral Current (NC)*

$W^\pm$ exchange *Charged Current (CC)*

$\sqrt{s} = 320(300)\,GeV$ *CMS energy*

$Q^2 \equiv -q^2 = -(k-k')^2$ *γ virtuality*

$Q^2 > 1\,GeV^2$ *Deep Inelastic Scattering (DIS)*

$Q^2 < 1\,GeV^2$ *Photoproduction*

$$x = \frac{Q^2}{2P_p \cdot q}$$ *Fraction of proton's momentum carried by the struck parton*

$$y = \frac{P_p \cdot q}{P_p \cdot k'}$$ *Fraction of lepton's energy transferred to the proton*

$Q^2 = sxy$ $\qquad Y_\pm = 1 \pm (1-y)^2$

ep Cross-Sections and Structure Functions

$$\frac{d^2\sigma_{NC}(e^{\pm}p)}{dxdQ^2}=\frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2(x,Q^2)-y^2F_L(x,Q^2)\mp Y_-F_3(x,Q^2)\right]$$

Modified at high Q^2 by Z^0 propagator.

$$\frac{d^2\sigma_{CC}(e^{\pm}p)}{dxdQ^2}=\frac{G_F^2M_W^2}{2\pi x(M_W^2+Q^2)^2}\left[Y_+W_2^{\pm}(x,Q^2)-y^2W_L^{\pm}(x,Q^2)\mp Y_-W_3^{\pm}(x,Q^2)\right]$$

HERA inclusive data provides valuable information on sea and valence quarks. Gluons probed indirectly via scaling violations and directly via jet data.

$$F_2\propto\sum(xq_i+x\bar{q}_i)$$ *Dominant contribution*

$$xF_3\propto\sum(xq_i-x\bar{q}_i)$$ *Sensitive at high Q^2*

$$F_L\propto\alpha_s\,xg(x,Q^2)$$ *Sensitive at high Q^2 & high y*

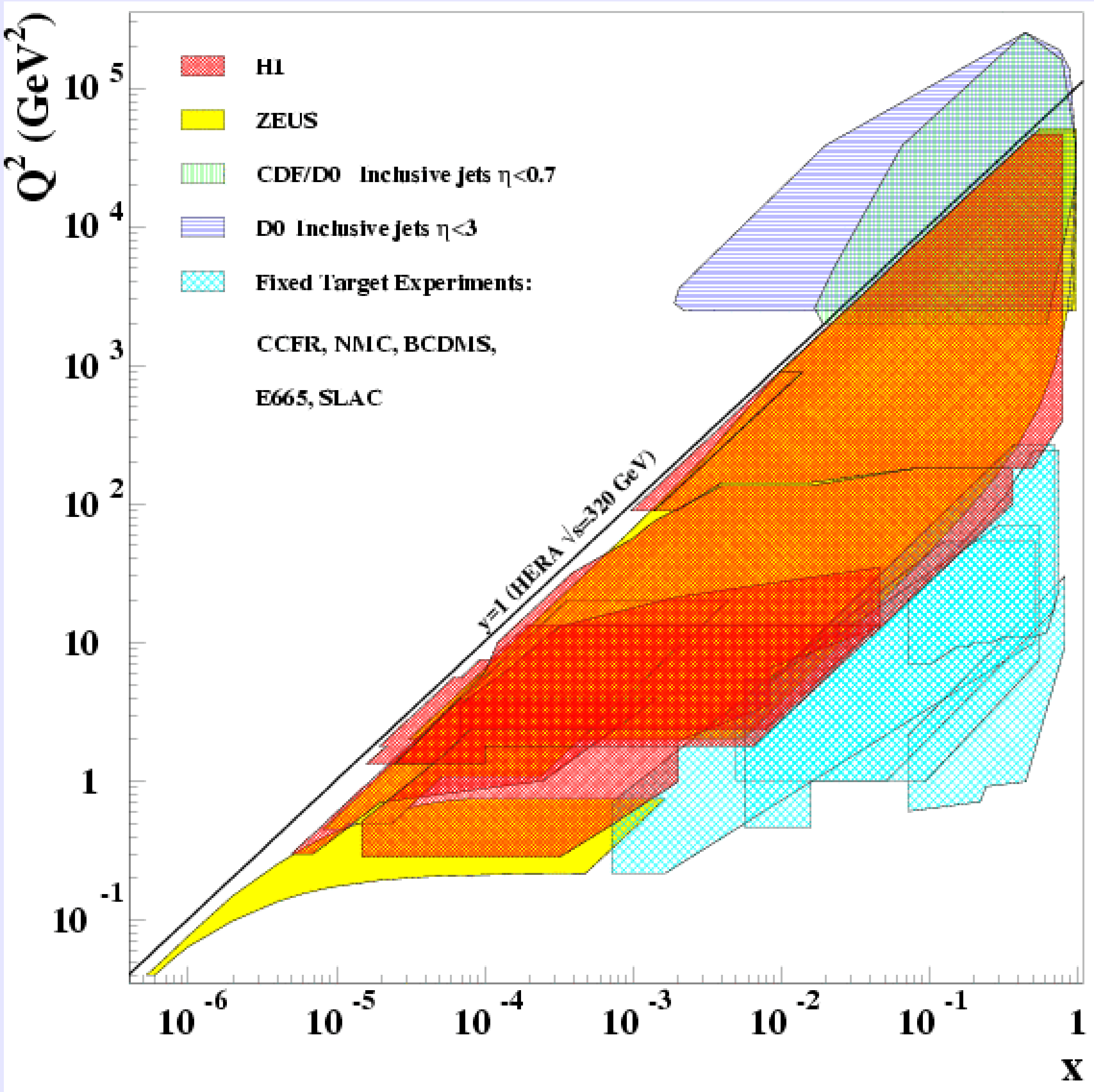
similarly for $W^{\pm}_2$, $xW^{\pm}_3$ and $W^{\pm}_L$.

$$\frac{d^2\sigma_{CC}(e^+p)}{dxdQ^2}\propto\left[(\bar{u}+\bar{c})+(1-y)^2(d+s)\right]$$

$$\frac{d^2\sigma_{CC}(e^-p)}{dxdQ^2}\propto\left[(u+c)+(1-y)^2(\bar{d}+\bar{s})\right]$$

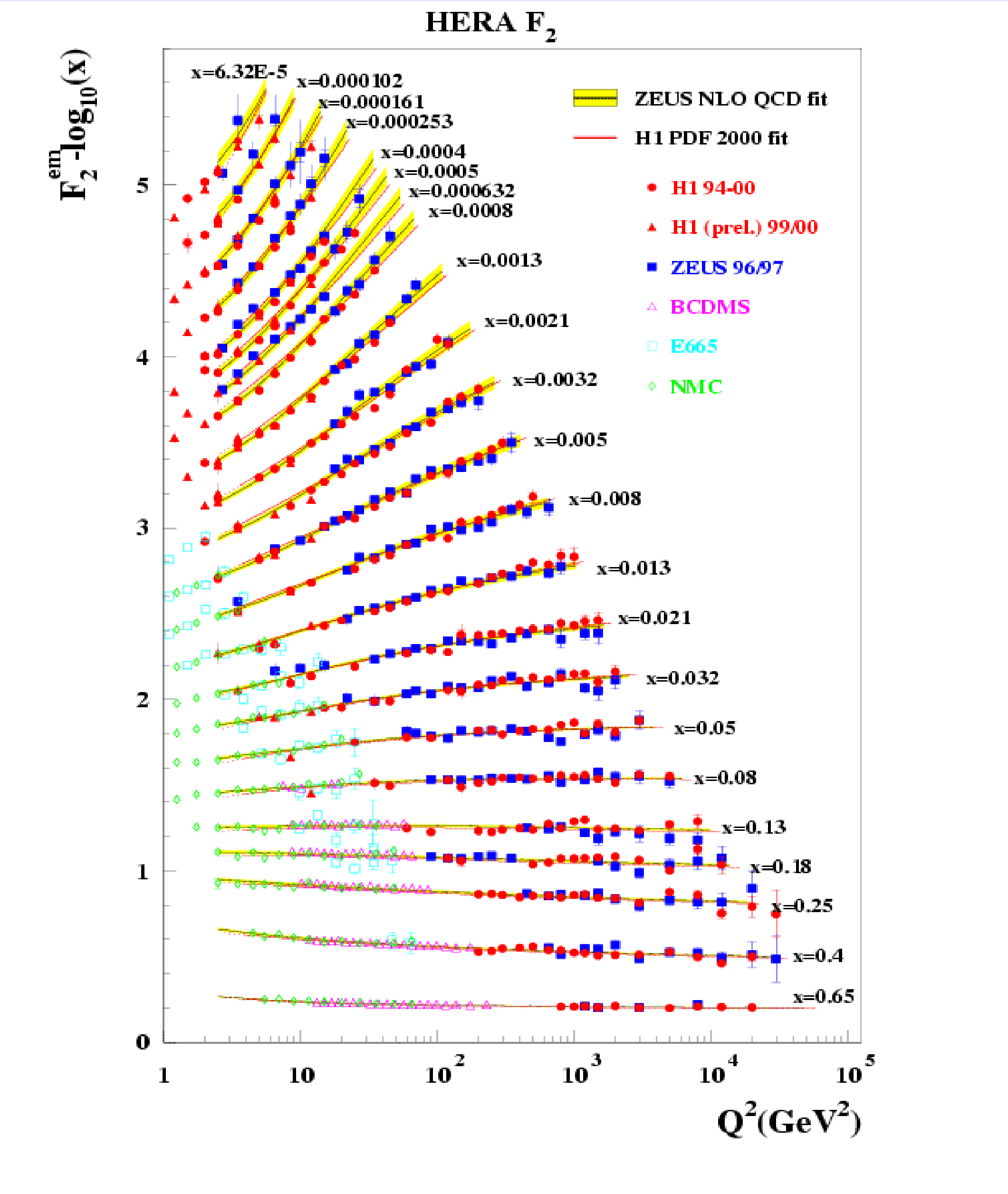
Sensitive to u and d valence quarks at LO

The Importance of HERA Data



- Q^2 dependence is directly calculable using pQCD (DGLAP)
- x dependence has to be determined empirically
- Measure cross sections -> perform fits
- HERA PDFs extrapolate into LHC region
- Crucial in calculations of new physics and measurements at LHC

Precision F_2 Data



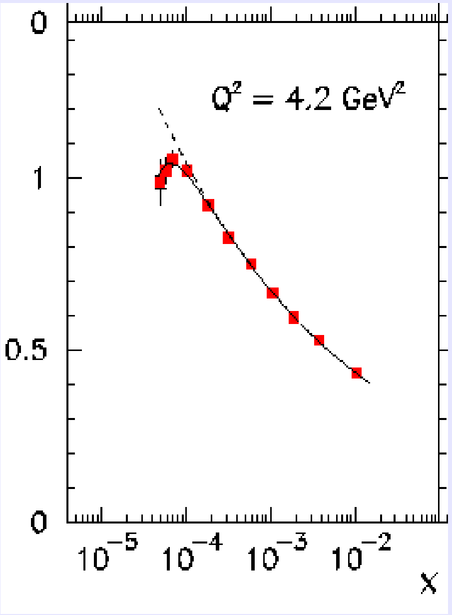
$$\tilde{\sigma}_{NC} = \frac{Q^2 x}{2\alpha\pi^2}\frac{1}{Y_+}\frac{d^2\sigma}{dxdQ^2}$$ *Reduced cross section*

$$\tilde{\sigma} = F_2 \text{ when } F_L \equiv xF_3 \equiv 0$$

- Range in x : 0.00001 -1
- Range in Q^2 ~ 1-30000GeV^2
- Measured with ~2-3% precision
- Directly sensitive to sum of all quarks and anti-quarks
- Indirectly sensitive to gluons via scaling violations.

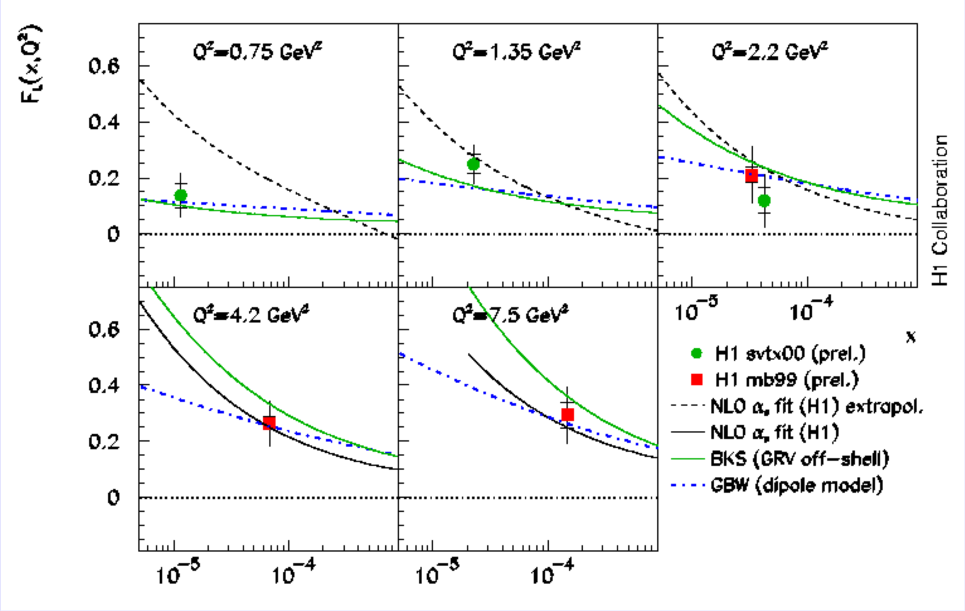
H1 Measurement of F_L

- Here we discuss the 'Shape method'.



$$\sigma_r = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

- For fixed s and Q^2 very distinct overlap in σ_r observed at low x, or high y (Q^2=sxy).
- At fixed Q^2, F_2 parameterised as $cx^{-\lambda}$ and F_L assumed to be constant across the region of overturn i.e.

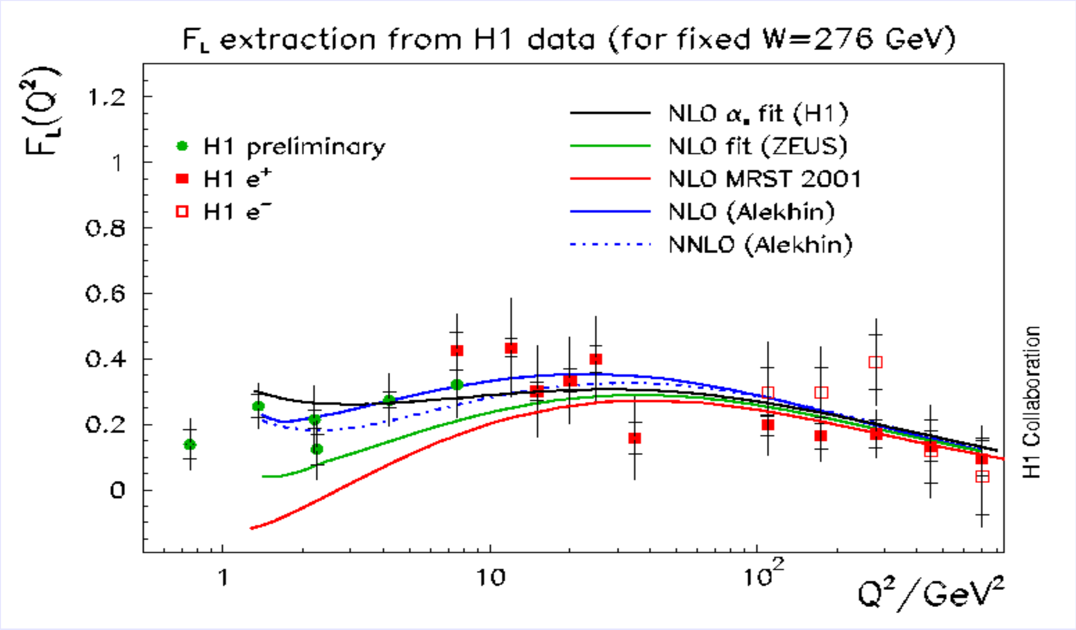


$$F_2 = cx^{-\lambda} \text{ and } F_L(x,Q^2) \equiv F_L(Q^2)$$

Therefore, fit

$$f(y) = cx^{-\lambda} - \frac{y^2}{Y_+} F_L(Q^2)$$

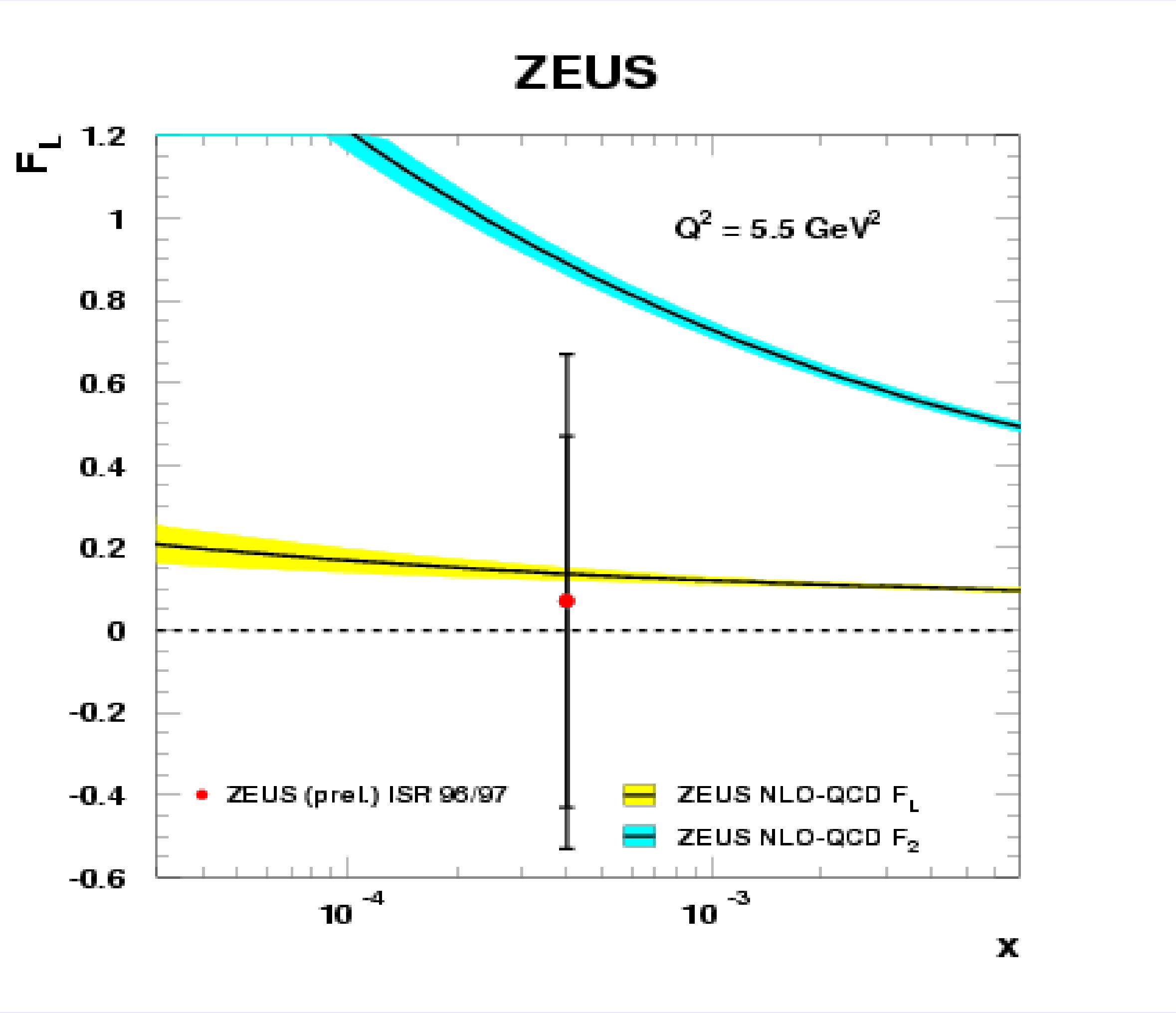
with measured $\sigma_r(y)$ to find $F_L(Q^2)$



- At presently reached accuracy F_L data is reasonably well described by NLO QCD in which the gluon distribution is determined from the scaling violations of F_2

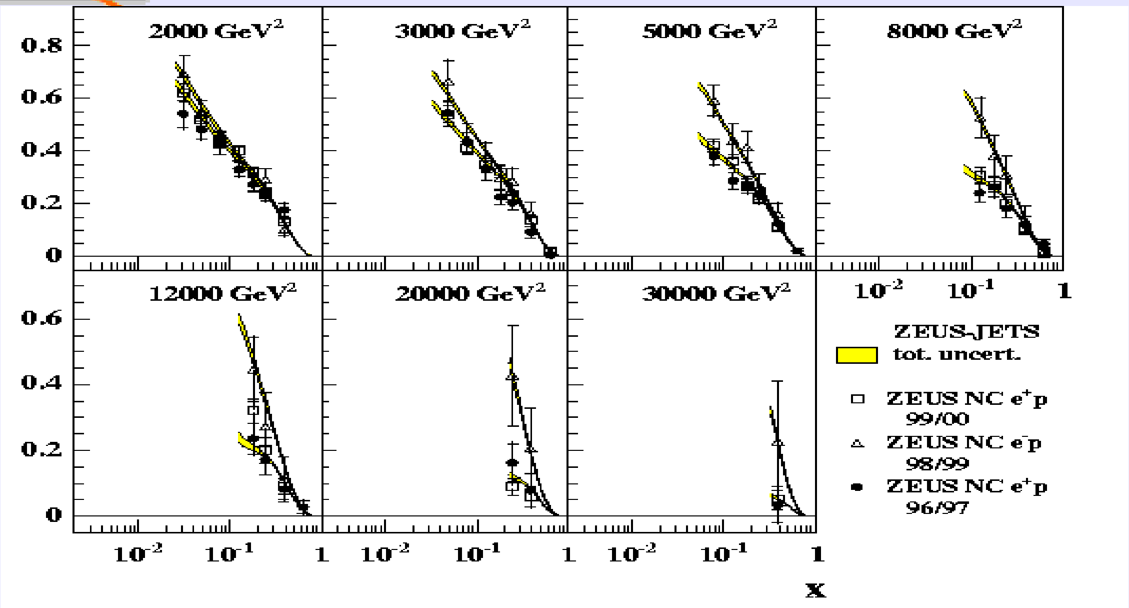
ZEUS Measurement of F_L

- The only way to measure F_L directly is to make measurements of σ_r at fixed x and Q^2 but differing values of y.
- F_L can then be disentangled from F_2 $\sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$



- ISR reduces s
- At fixed x and Q^2, y is different
- Changes contribution of F_2 and F_L.
- Measure σ_r vs y and fit for F_L.
- Measurement only made in one Q^2 bin.
- Measurement is not very precise but is clearly consistent with the expectations of pQCD.

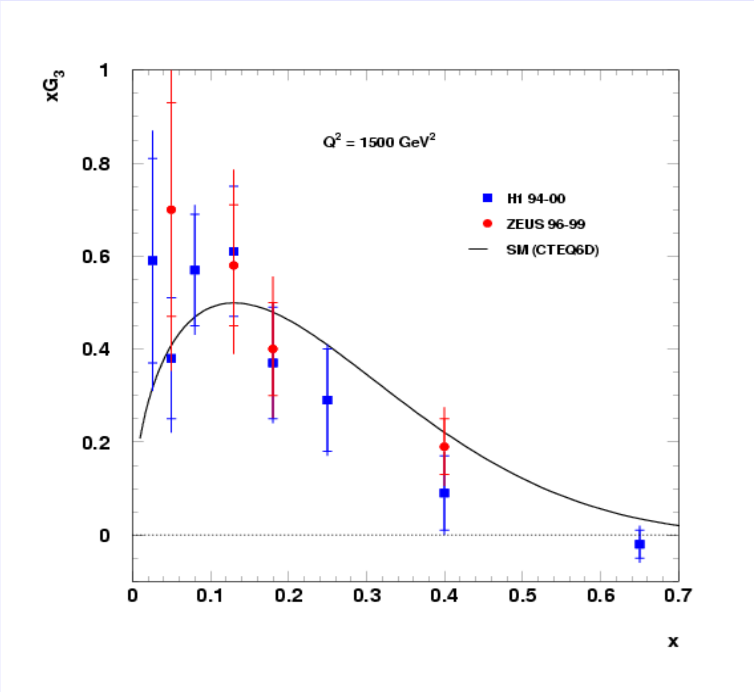
High Q^2 NC Cross Sections



- At high Q^2 NC cross sections for e^+ and e^- deviate

$$\tilde{\sigma}^{\pm}_{NC} \simeq F_2 \mp \frac{Y_-}{Y_+} xF_3$$

- Subtract NC positron from electron cross section



- High Q^2 NC cross sections directly sensitive to different species of valence quark
- Errors dominated by statistical error of the e^- sample
- Need greater luminosity
- Currently running with e^-

QCD fits

General method

- Parameterize PDFs at some starting scale Q_0^2
- Evolve to arbitrary Q^2 using DGLAP
- Calculate cross sections and compare to data
- Iteratively change the starting parameters until best fit is found

HERA QCD fits – A brief history

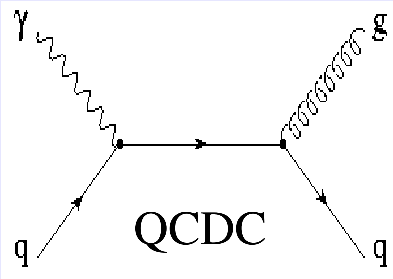
- Performed by both H1 and ZEUS, broadly compatible
- Valence quarks constrained by heavy target data (υFe and μD)
- World F_2 data used -> Many different experiments, not just HERA
- Inclusive cross sections indirectly sensitive to gluon (scaling violations)
- α_s and gluon strongly correlated via DGLAP -> poor α_s and gluon extraction

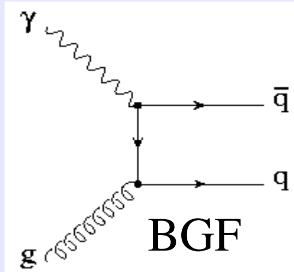
$$\frac{dq_i(x,Q^2)}{dlnQ^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j q_j(y,Q^2)P_{q_i q_j}\left(\frac{x}{y}\right) + g(y,Q^2)P_{q_i g}\left(\frac{x}{y}\right)\right]$$

HERA QCD fits – New developments

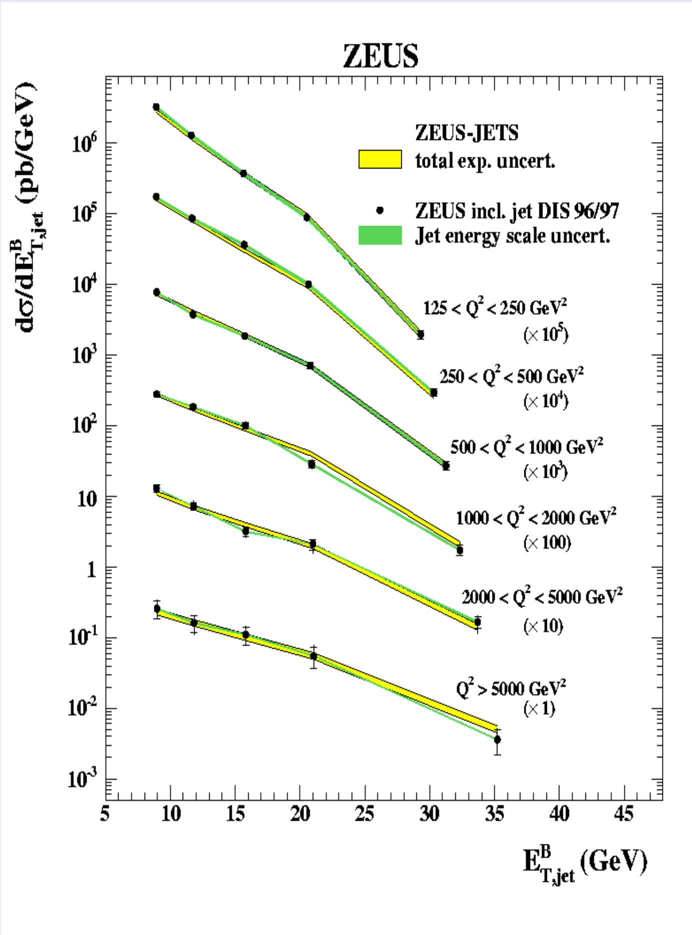
- High Q^2 NC and CC data constrain valence quarks -> No fixed target data
- Exclusive (Jet) cross sections tie down the gluon, accurate determination of α_s.
- *Fits done entirely with HERA data, no external experiments*

ZEUS QCD fits – Jet Data

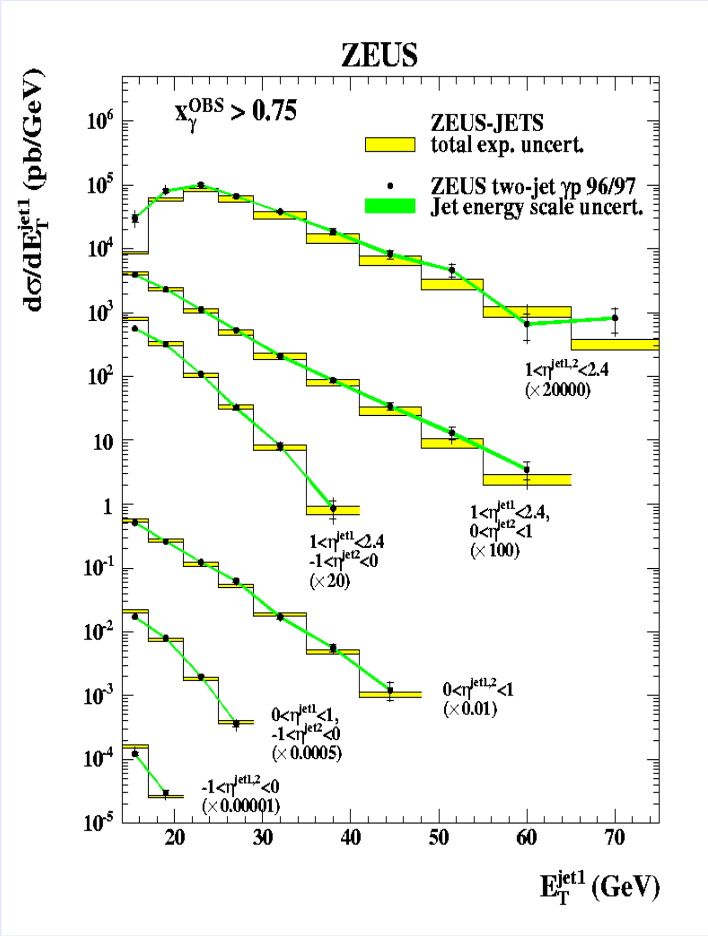




- QCD Compton and Boson-Gluon fusion processes give rise to events with distinct jets in the final state.
- QCDC depends on α_S & $q_i(x,Q^2)$, dominates at hard scales.



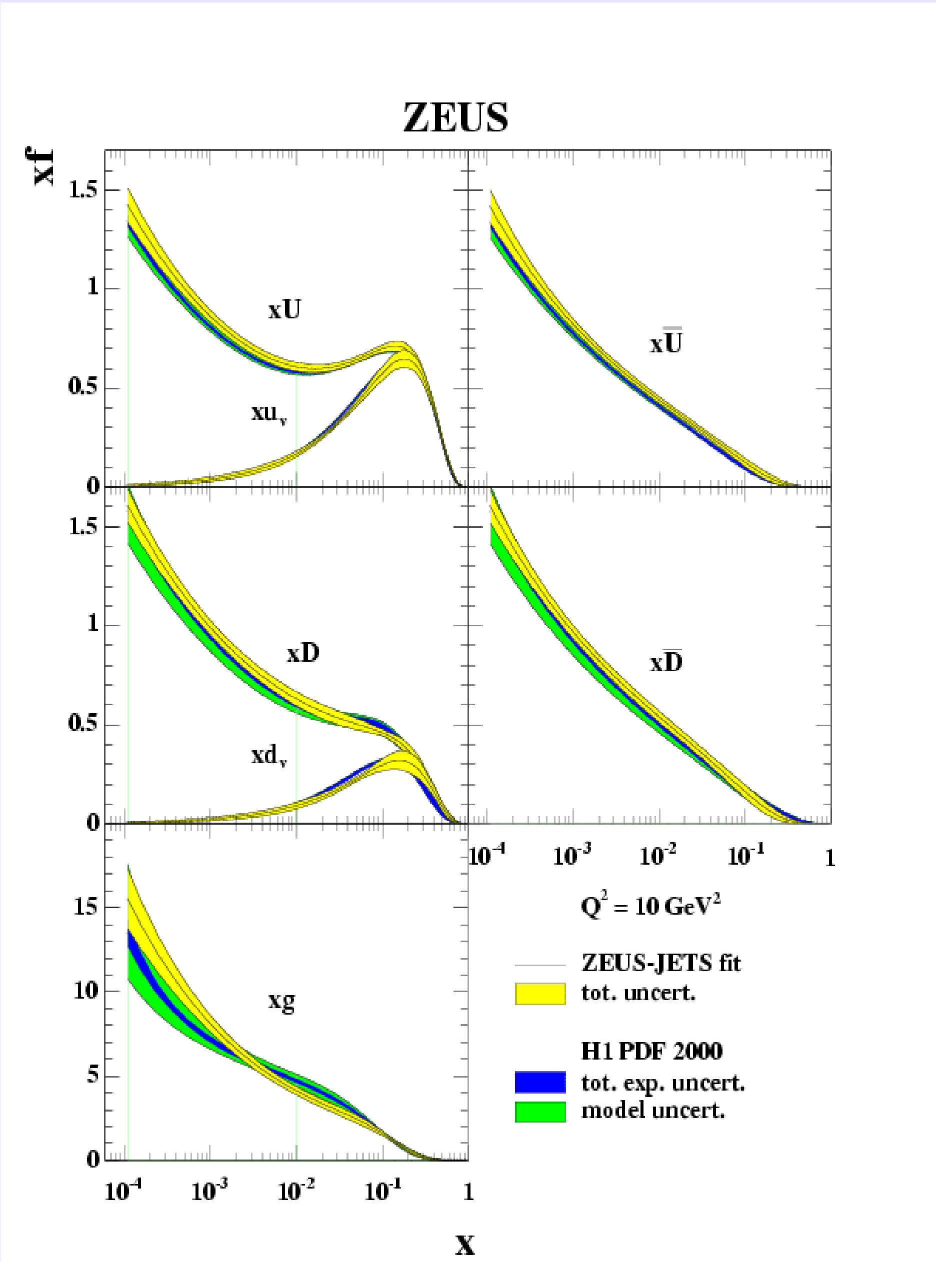
DIS inclusive jets

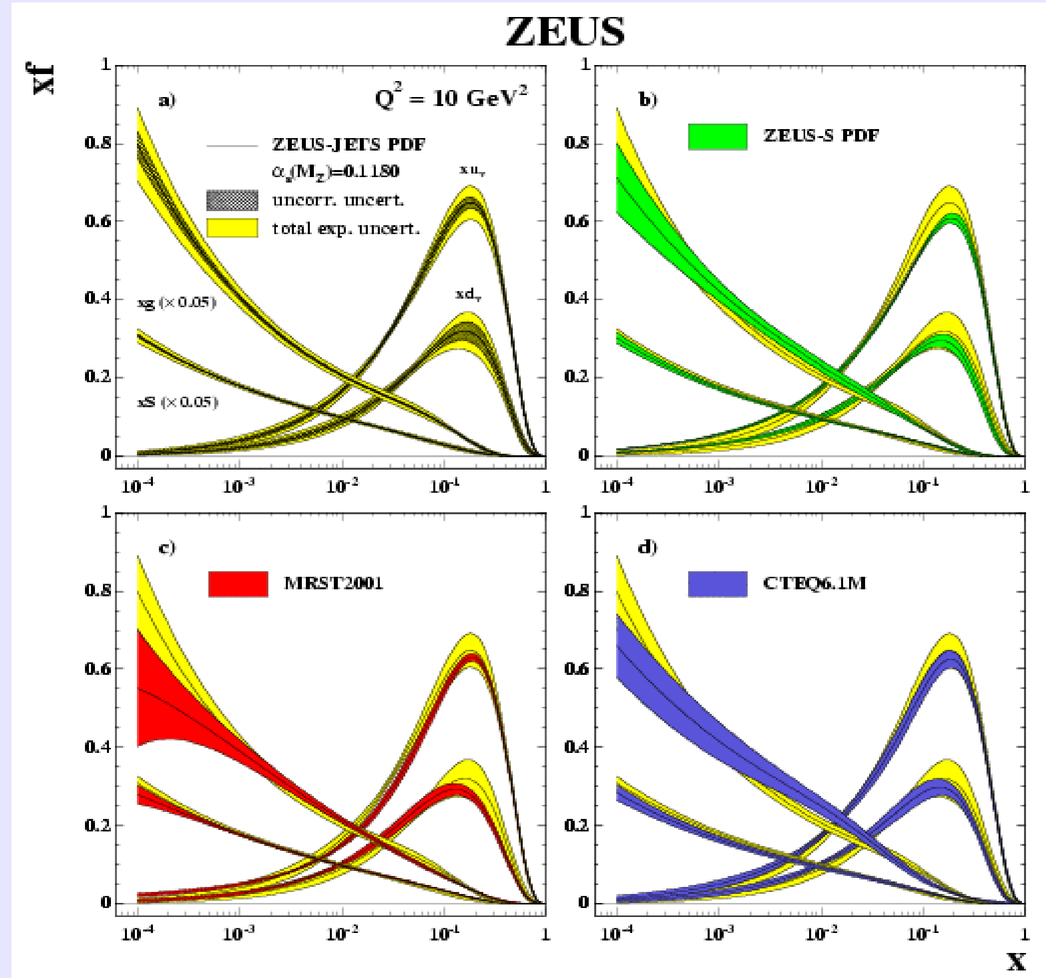


γp dijets

- $q_i(x,Q^2)$ well constrained from NC and CC data.
- Thus, at hard scales α_s may be extracted without strong correlation to $g(x,Q^2)$
- Further, BGF depends directly on $g(x,Q^2)$ and provides a means to constrain the gluon

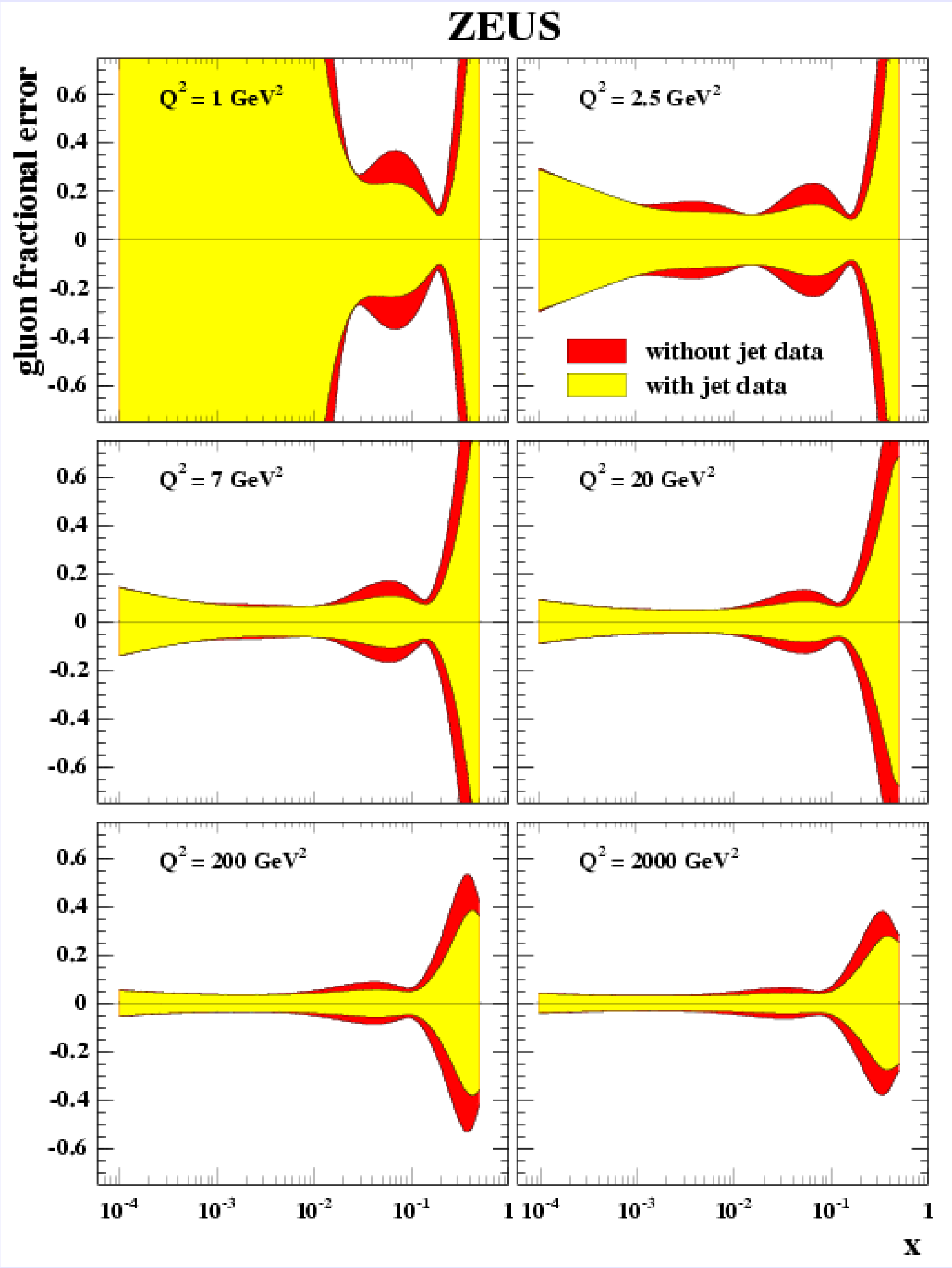
HERA QCD fits – Extracted PDFs





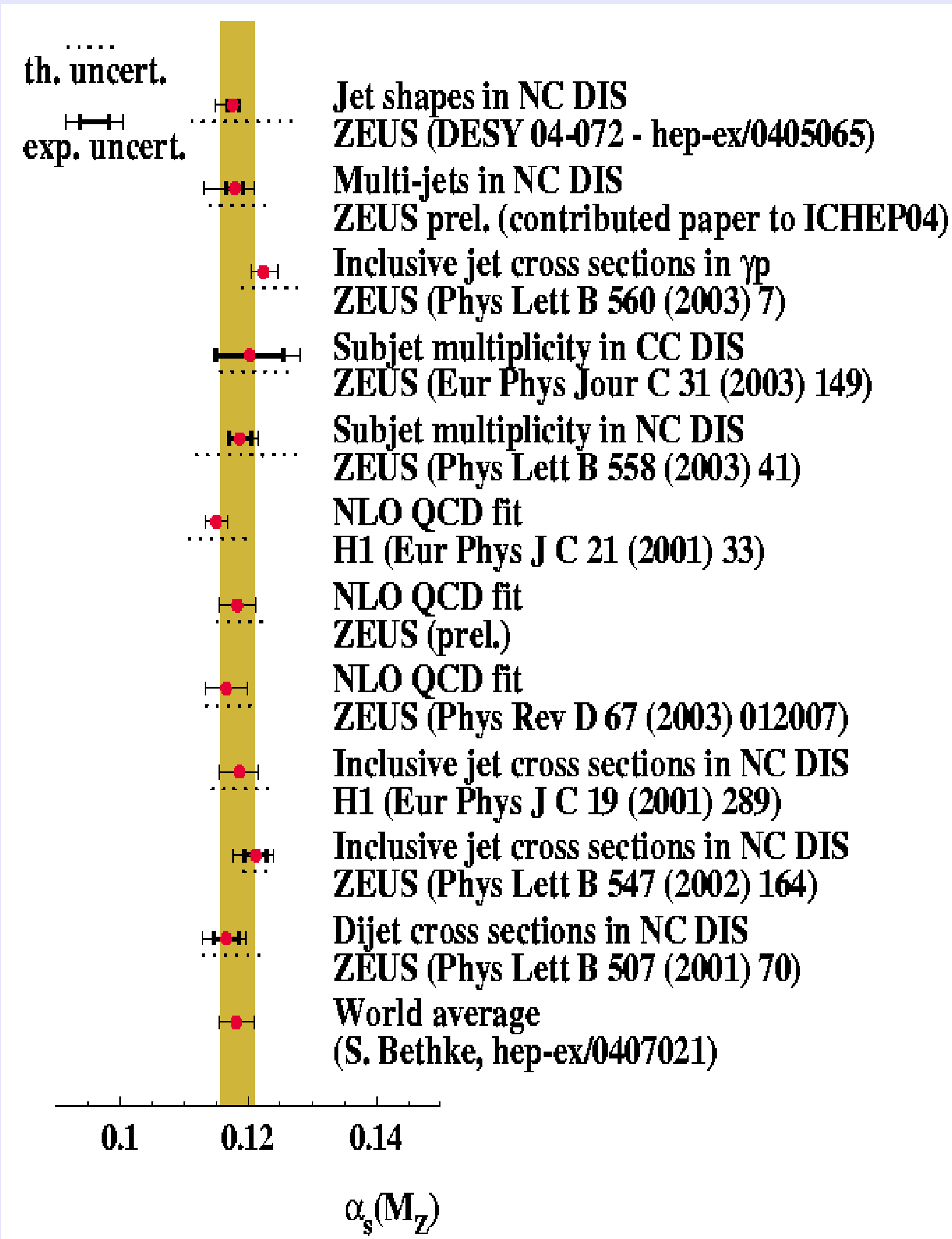
- ZEUS and H1 PDFs broadly consistent
- HERA PDFs consistent with those of MRST and CTEQ

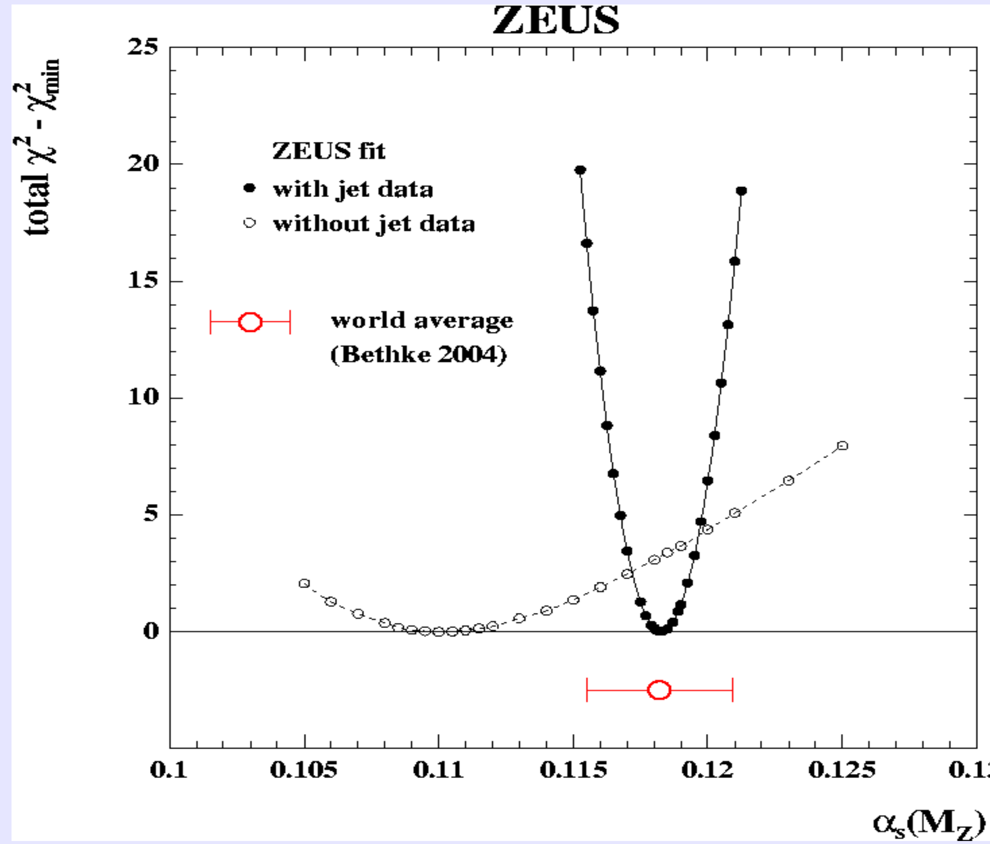
ZEUS QCD fits – Impact of Jet Data



- Jet data has a significant impact on the precision of the extracted gluon PDF.
- MRST and CTEQ also include jet data in their fits (High-E_T Tevatron jet data), however the cross sections are included using approximate techniques.
- ZEUS utilizes a rigorous method of including jet data in its fits.

HERA QCD fits – Determination of α_s





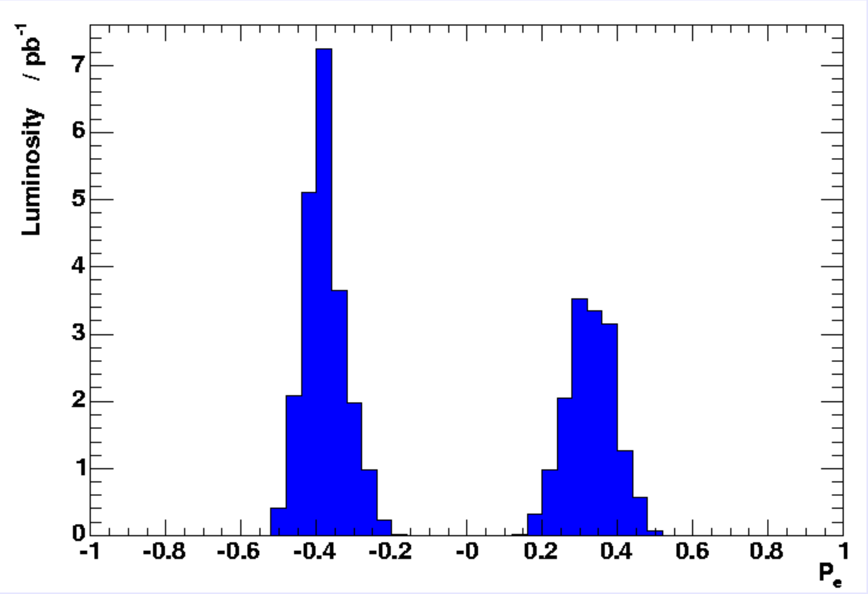
$$\alpha_s = 0.1150 \pm 0.0017(\exp) \pm 0.0007(model) \quad \textbf{H1}$$

$$\alpha_s = 0.1183 \pm 0.0028(\exp) \pm 0.0008(model) \quad \textbf{ZEUS}$$

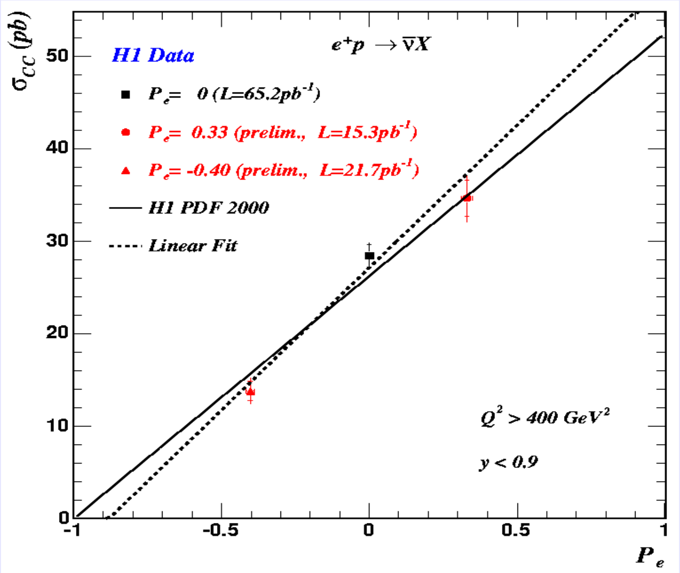
- Scale uncertainty = ± 0.005
- Quite large but would significantly improve with NNLO fits

Summary

- HERA continues to produce important research on proton structure and provide a stringent testing ground for QCD
- PDFs and α_s can be extracted with minimal data from external experiments
- Rigorous inclusion of jet data into the fitted data sets leads to a significantly more precise gluon PDF and α_s to be extracted from HERA data alone
- HERA II measurements already reaching publication stage



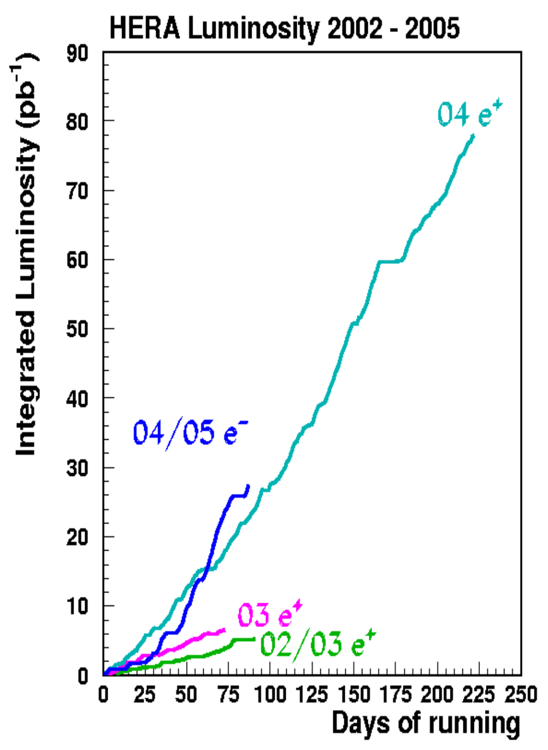
- Luminosity has now been collected with 0, (-) and (+) polarisation



- First measurement of the helicity structure of CC interactions with a space-like gauge boson

Future Plans

- HERA II program well underway -> Increased statistics -> even more precise cross section measurements
- Currently running with electrons -> More precise electron NC and CC cross sections -> More precise extraction of xF_3
- Combination of ZEUS and H1 data sets to produce Global HERA fits
- NNLO QCD fits
- Inclusion of more exclusive data in to the fitted data sets: heavy flavor cross sections, optimized jet cross sections etc
- Possible dedicated reduced E_p (still in the early stages of deliberation) running periods allowing a direct measurement of F_L



Thank you for paying attention! Any queries, please contact us target@mail.desy.de