Physics

at

HERA/DESY

Pheno 2001 Symposium

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The HERA COLLIDER and DETECTORS

First ep collider: 27.5 GeV $e^{\pm}$ on 820/920 GeV p

Detectors: H1, ZEUS, HERMES, HERA-B

Commissioned in:

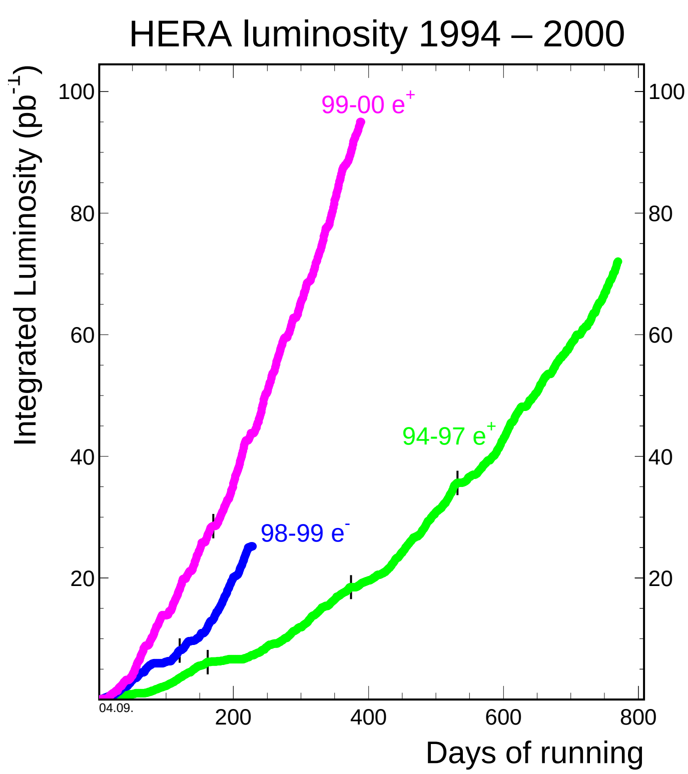
1992

Delivered so far:

$$\int \mathcal{L}dt = 27(e^-) + 166(e^+) = 193 \text{ pb}^{-1}$$

Compare Tevatron:

$$\int \mathcal{L}dt \sim 120 \text{ pb}^{-1} \text{ since } 1987$$



Selection of Recent Results

HERA experiments already produced $\mathcal{O}(200)$ physics papers

Update of $F_2(x, Q^2)$ Measurements

- $F_2(x, Q^2)$ at $Q^2 > 1$ GeV^2
- NLO QCD fits (DGLAP)
- Measurement of $xF_3(x, Q^2)$

Jet Production and α_s Determinations

- Inclusive jets and dijets
- Uncertainties of α_s determinations

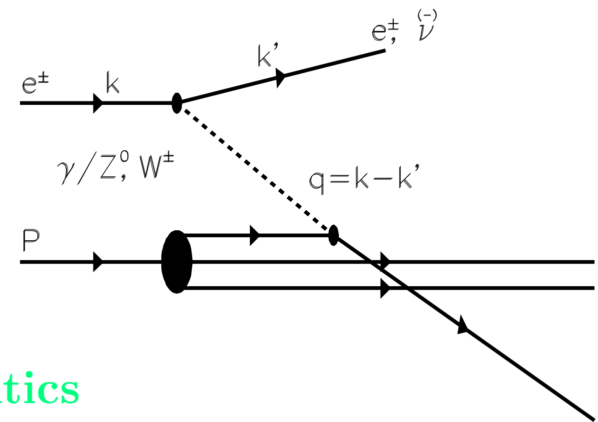
Polarized structure functions

- Measurements of g_1
- Flavor decomposition

Conclusions: Look into the future

Structure of the Proton

- **Experiment: Deep inelastic Scattering**



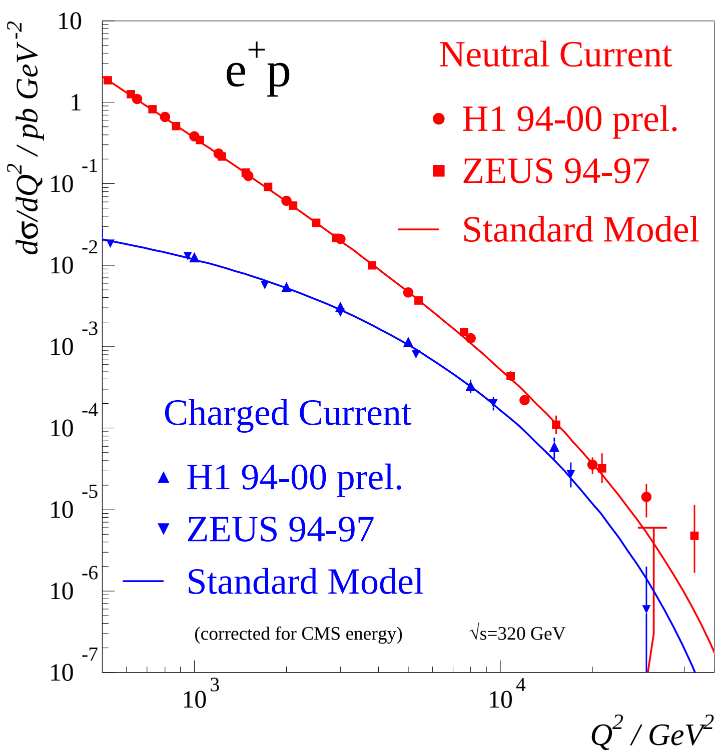
→ **Kinematics**

$Q^2 = -q^2 = (k - k')^2$ ... invariant mass of exchanged boson

$x = Q^2/(p \cdot q)$ ... momentum fraction of struck quark

$y = Q^2/(xs)$ ... inelasticity

→ **Measure** $\frac{d\sigma}{dQ^2}, \frac{d^2\sigma}{dxdQ^2}$



High precision data: Errors of 2 - 3 % !!!

EM and weak forces unified at large Q^2

- **Extract $\mathbf{F_2^{em}(x, Q^2)}$**

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^2}[Y_+F_2(x,Q^2) - F_L(x,Q^2) \mp Y_- xF_3(x,Q^2)]$$

→ **Structure functions of the proton**

$F_2(x,Q^2)$, $F_L(x,Q^2)$, $xF_3(x,Q^2)$

→ **$\mathbf{F_L(x, Q^2)}$ small: important only at large y**

taken from QCD predictions

→ **$\mathbf{xF_3(x, Q^2)}$ negligible for $Q^2 \ll M_Z^2$**

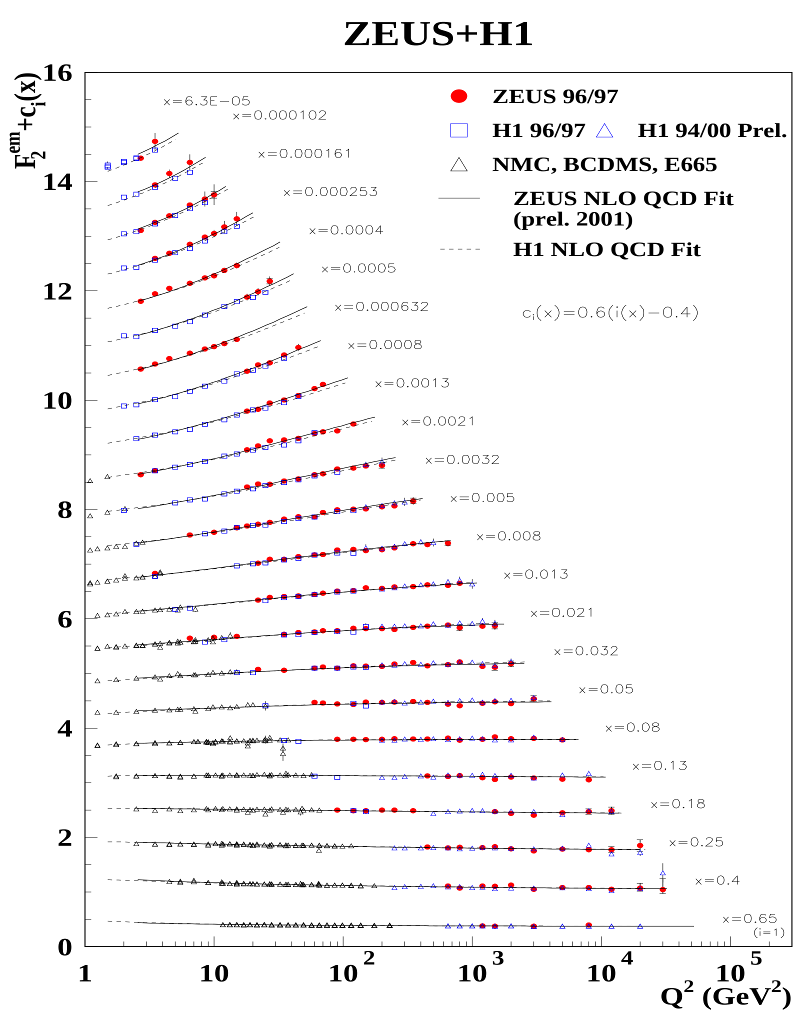
taken from QCD predictions (or measured)

→ **Correction for QED I/FSR: $\mathbf{F_2^{em}(x, Q^2)}$**

→ **Quark-Parton Model (QCD DIS scheme)**

$F_2^{em}(x,Q^2) = \sum_i e_i^2[xq_i(x,Q^2) + x\overline{q_i}(x,Q^2)]$

Measurements in large kinematic region



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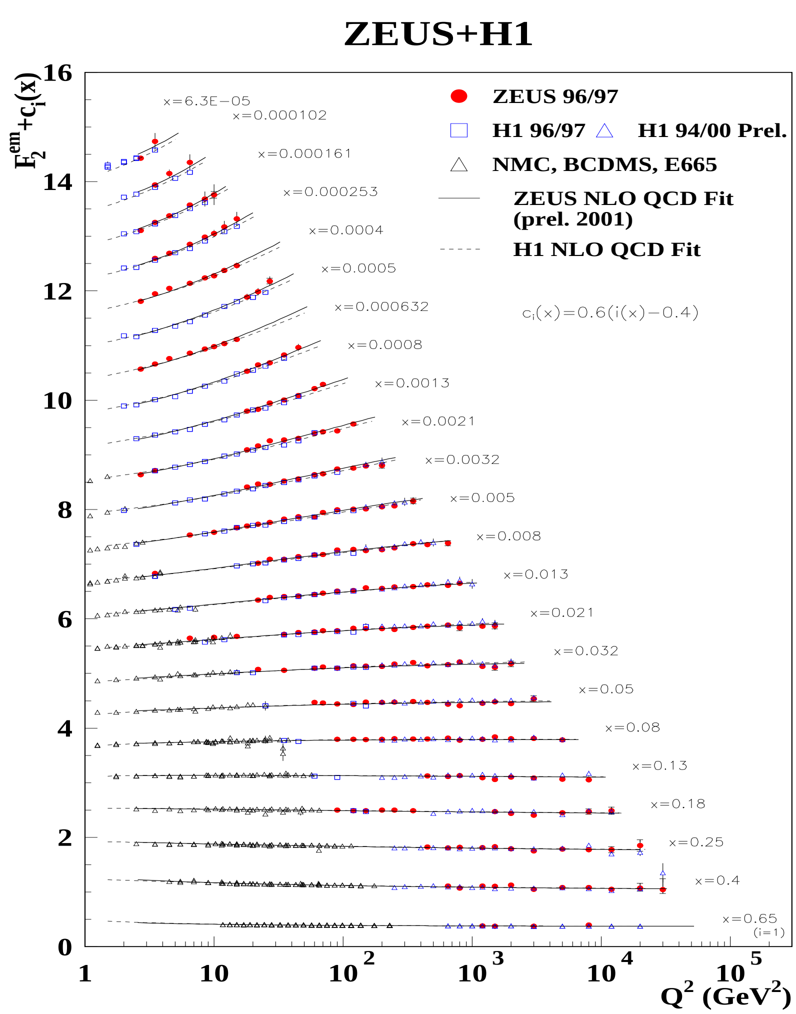
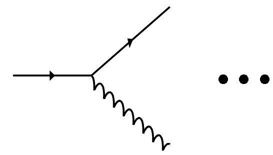


- **Fit to DGLAP evolution equations**

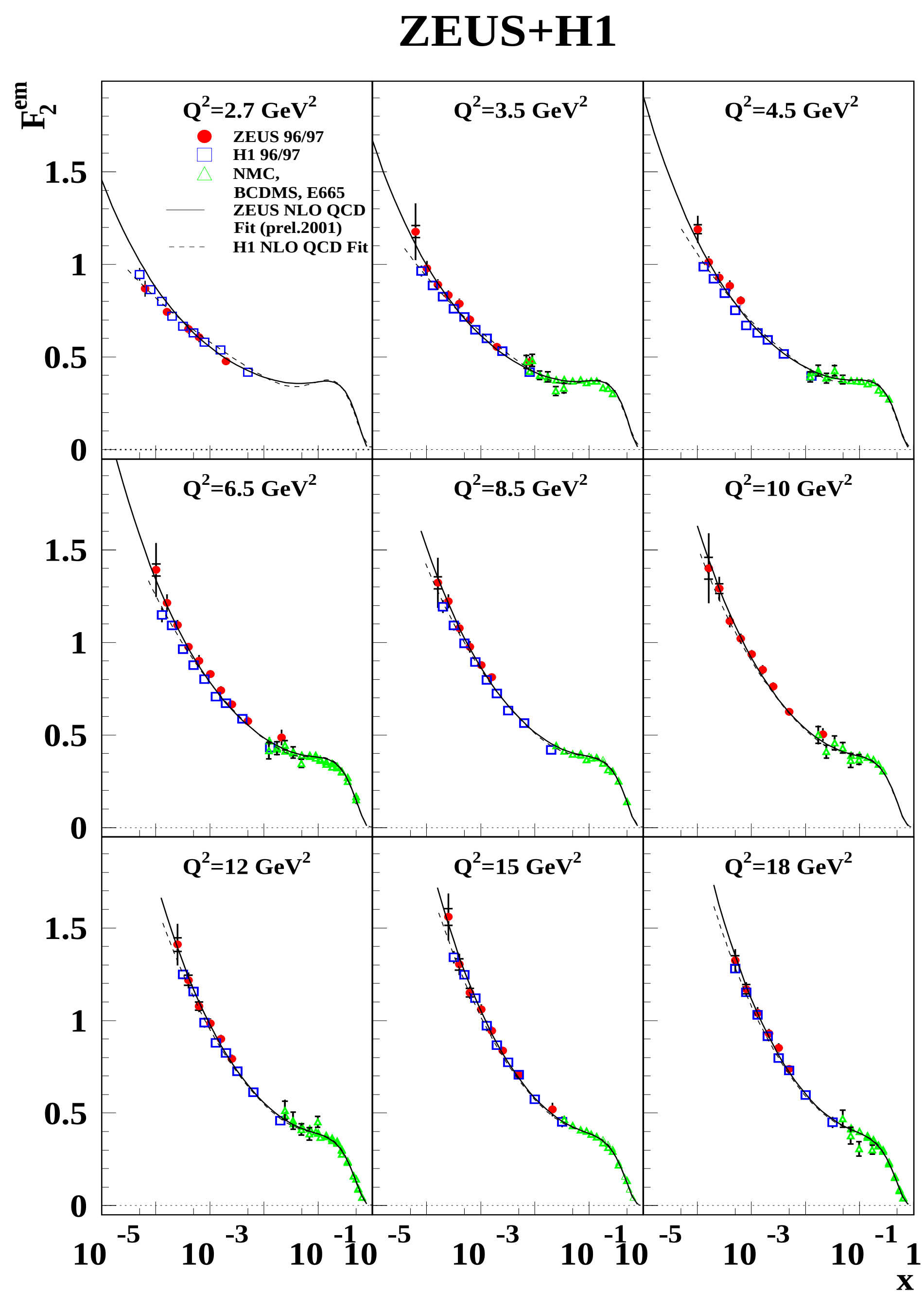
  → **Predicts evolution with Q^2:** $\partial \mathbf{q_i}/\partial \mathbf{Q^2} \sim \mathbf{q_i} \otimes \mathbf{P}$

  P ... splitting functions



  → **Parton densities:** $u_v,\ \overline{u}, d_v,\ \overline{d},\ s,\ c,\ b,\ g$

  → **Look for deviations from fit** (test of QCD)



Results of DGLAP fits

- **OK at low x**

  $\rightarrow$ No resummation of $\ln(1/x)$ terms necessary (BFKL)

- **OK at large Q^2**

  $\rightarrow$ No breakdown of pQCD observed at high scales

  $\rightarrow$ No evidence of new physics: CI, LQs...

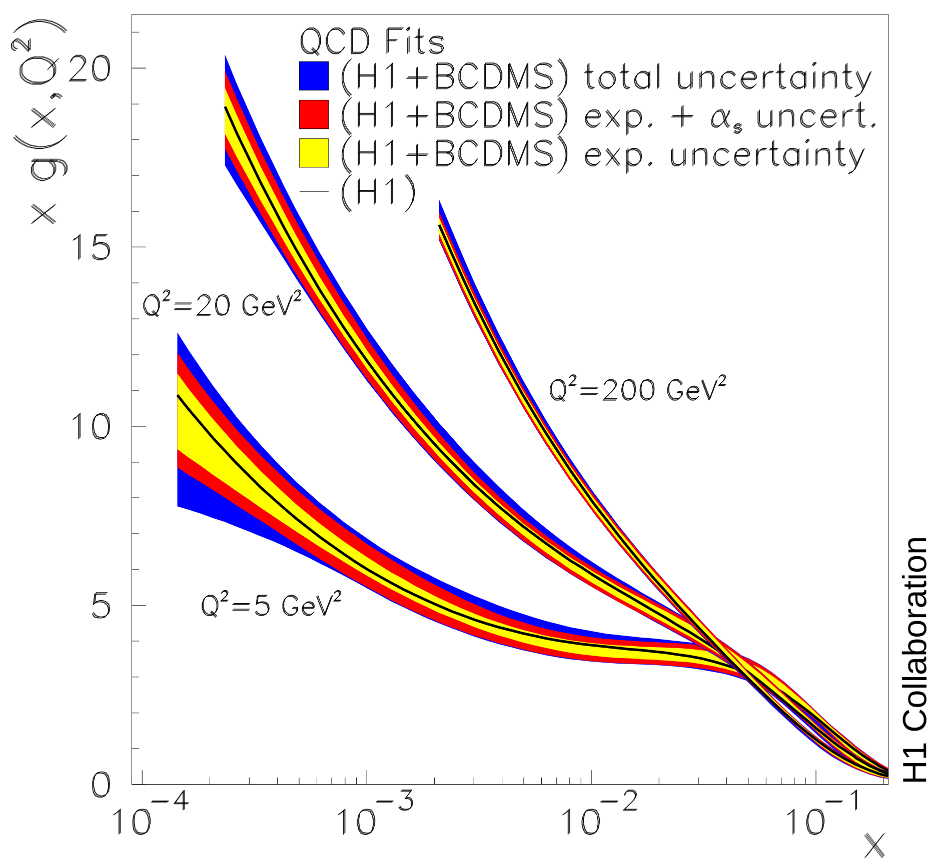
- **OK at low Q^2**

  $\rightarrow$ Fit down to $Q^2 = 1$ GeV^2 Surprise!

  $\rightarrow$ Need larger lever arm in Q^2 ?

- **Gluon density**

  $\rightarrow$ High precision: $\sim \pm$ 7 % for $\mu^2 = 20$ GeV^2

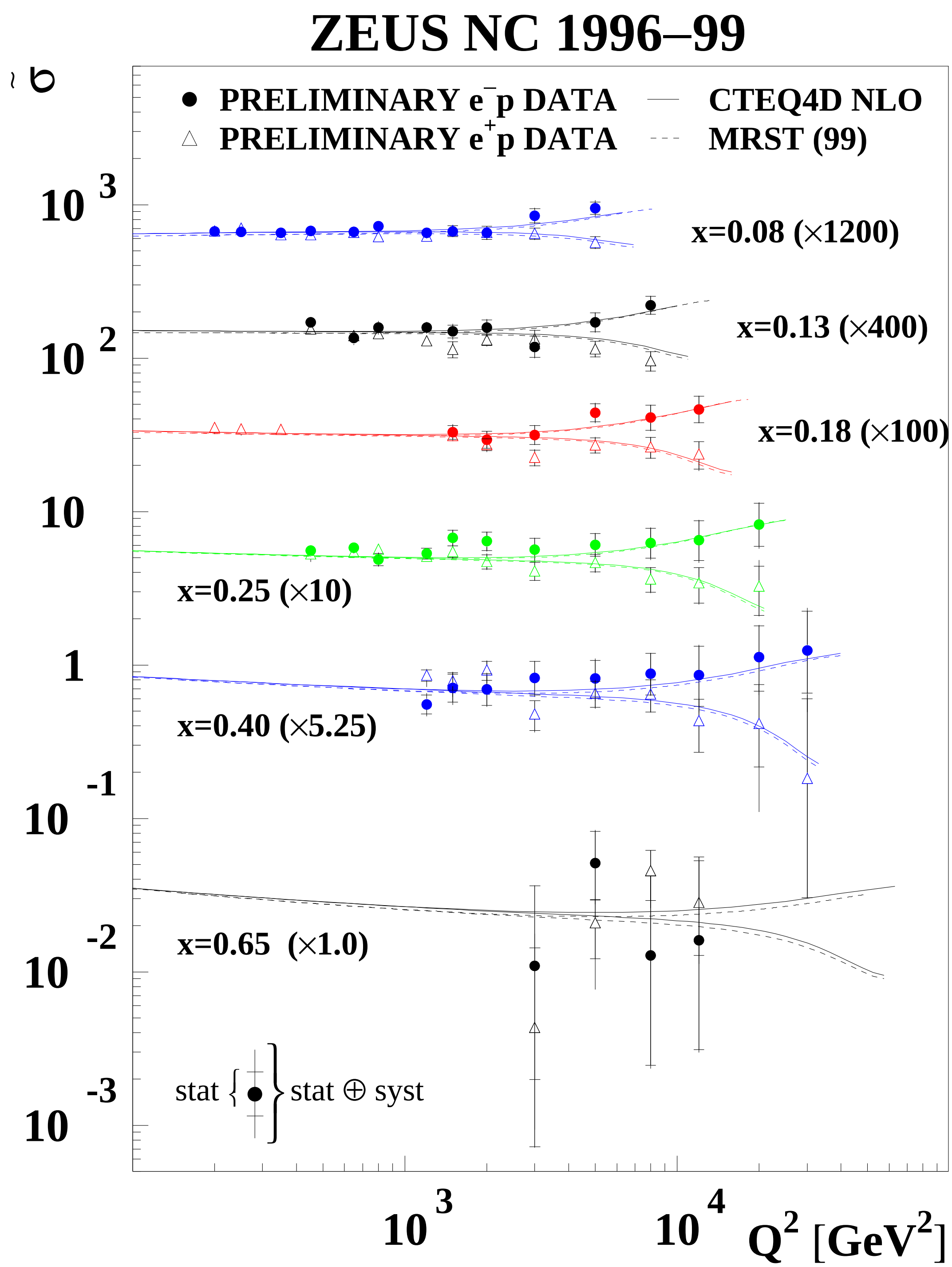


Extraction of $xF_3(x, Q^2)$

Neutral Current DIS cross sections

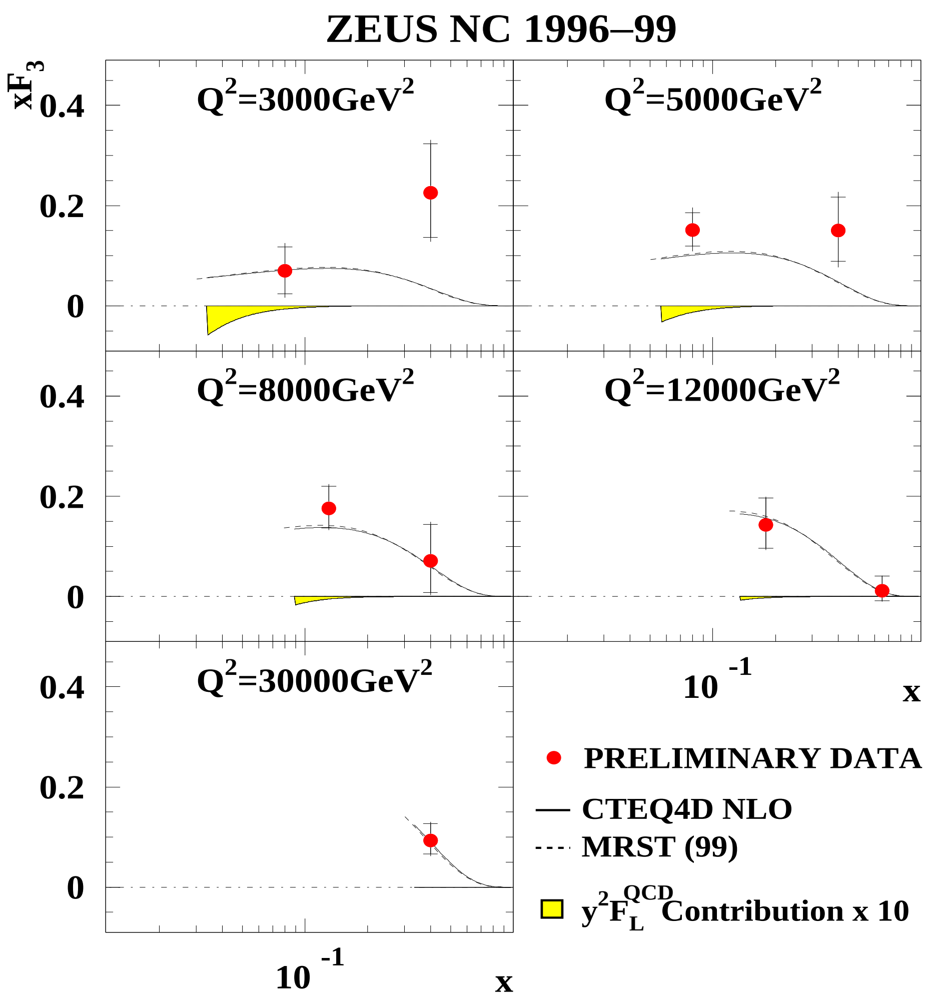
$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^2}[Y_+F_2(x,Q^2) - F_L(x,Q^2) \mp Y_-xF_3(x,Q^2)]$$

where $Y_{\pm} = 1 \pm (1-y)^2$



Use difference between e^- and e^+ data

$$xF_3(x,Q^2) = \frac{xQ^4}{4\pi\alpha}\frac{1}{Y_-}\left[\frac{d^2\sigma^{e^-p}}{dxdQ^2} - \frac{d^2\sigma^{e^+p}}{dxdQ^2}\right]$$



First measurement of xF_3 on proton

No correction for nuclear effects

Need more statistics

Quark - Parton Model

$$xF_3(x,Q^2) = x\,\Sigma_f\, B_f(Q^2)[q_f(x,Q^2) - \overline{q}_f(x,Q^2)]$$

Sum over valence quark distribution

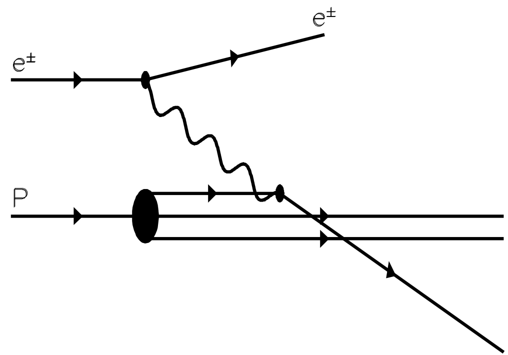
$B_f(Q^2)$ ... Electroweak coupling factors

Agreement with CTEQ4D/MRST(99)

Evolved from low Q^2 data

Jets and α_s Determinations

Inclusive DIS

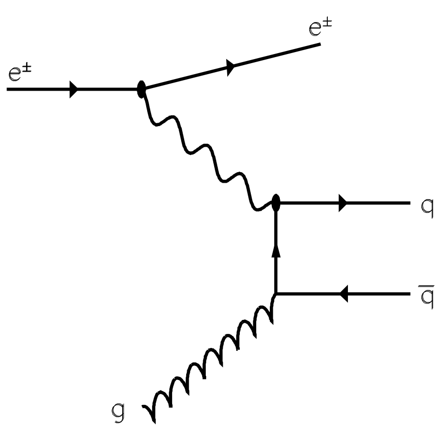


Described by x, Q^2 (measured at the lepton vertex)

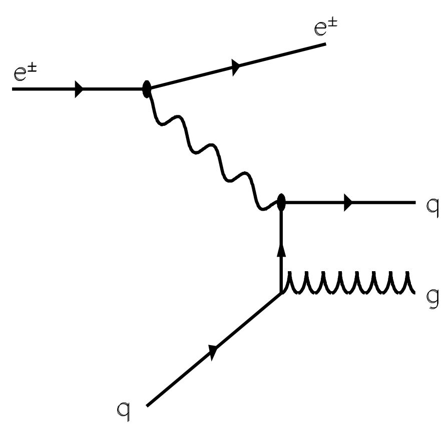
Directly sensitive to q, $\overline{q}$ densities of the proton

Multijet production: $N_{jet} \geq 2$

Two contributions to LO in α_s



Photon−Gluon Fusion



QCD Compton

Described by x, Q^2, M_{jj}, ξ, E_T, N_{jet}...

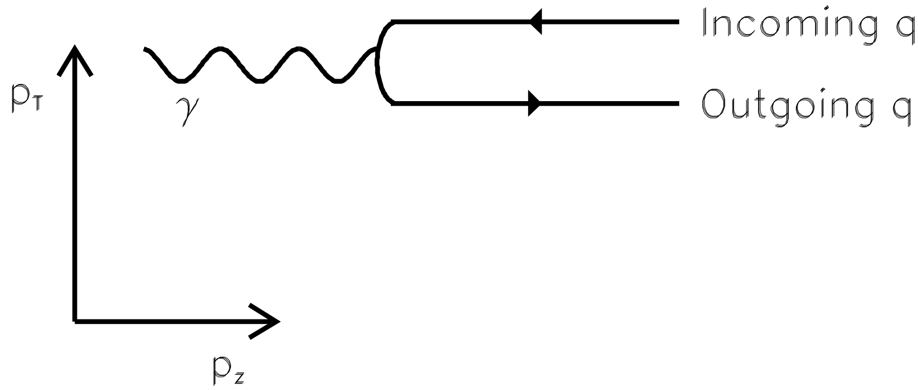
Directly sensitive to q, $\overline{q}$, and g densities

Production cross sections depend on α_s

Jet Finding

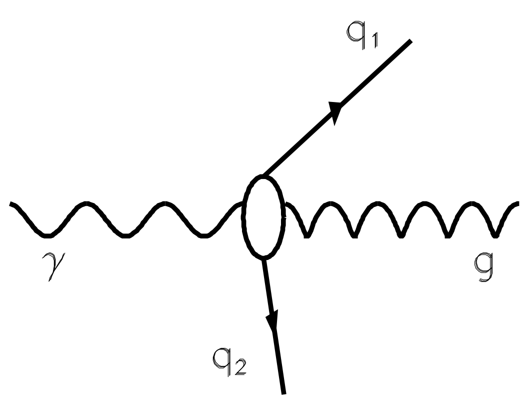
Breit Frame: Collinear to γ^* and p: $2x\vec{P} + \vec{q} = 0$

Quark-Parton Model type events ($\mathcal{O}(\alpha_s^0)$)



→ Low E_T in HFS

PGF and QCDC events ($\mathcal{O}(\alpha_s^n)$)



→ High E_T in HFS

Jet Search

Inclusive k_T Algorithm

→ Smaller hadronization corrections

Results at the Hadron Level

Experiment

Correct results for detector effects

Theory

Parton level calculations at NLO ($\mathcal{O}(\alpha_s^2)$)

Calculation requires choice of two scales

Factorization scale: μ_F separates σ_{hard} from PDF
Renormalization scale: μ_R for evaluation of $\alpha_s(\mu_R)$

(Arbitrary) choice of scales

Generally use 'hard scale' of process: $f \cdot E_T/2$ or $f \cdot Q$

Result ideally independent of scale choice

Reality: Largest theoretical uncertainty
Measure of uncertainty due to missing HOs
Typically estimated by varying f between 1/2 and 2

Correction to hadron level

Based on leading order Monte Carlo programs

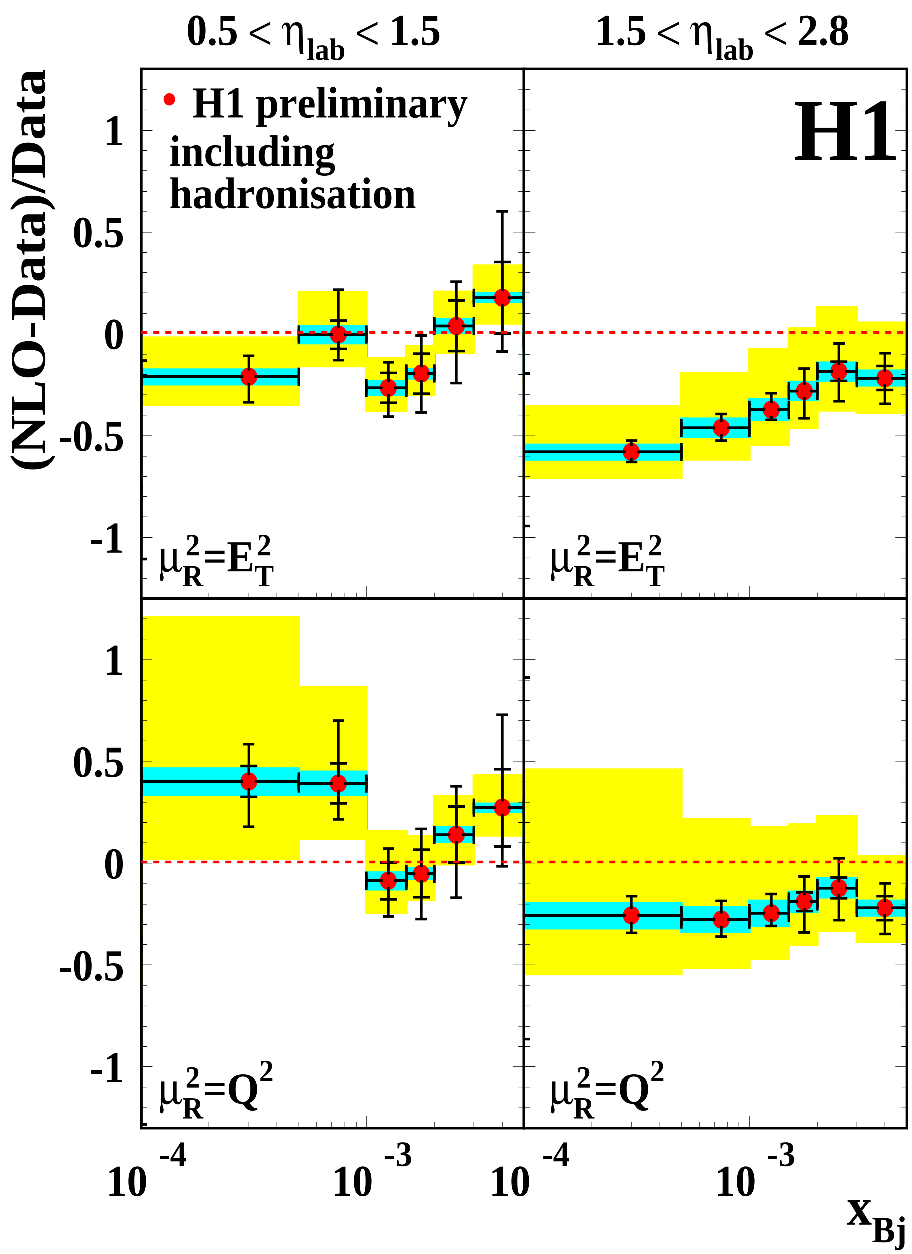
Direct comparison Exp/Th possible

Inclusive Jet Cross Sections

Measurements at low Q^2, E_T

$5 < Q^2 < 100$ GeV^2

$E_T^{jet} > 5$ GeV



Uncertainties

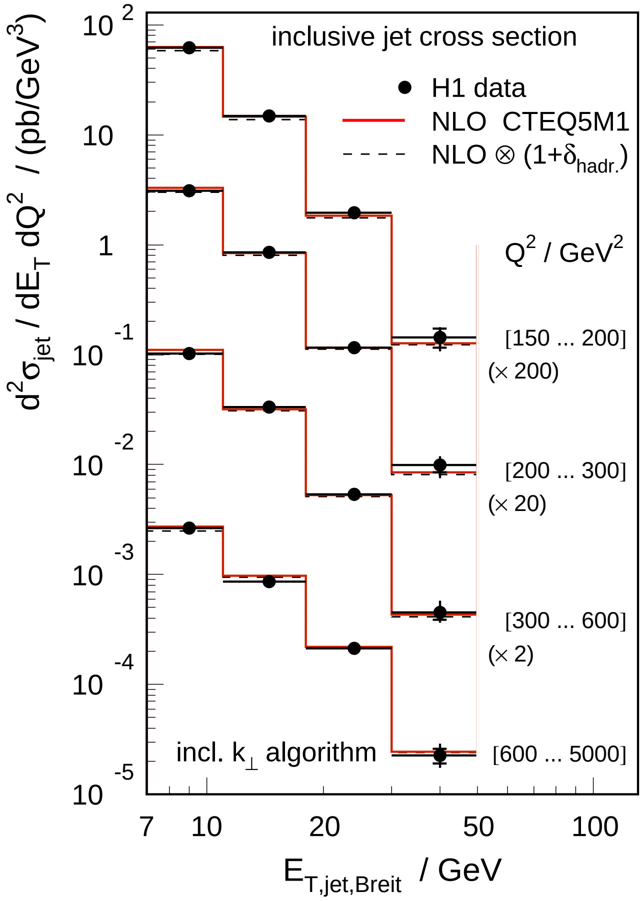
Measurement	$\sim \pm 20$ %	$\sim \pm$ 7 %
Theory (yellow band)	$\sim \pm 40$ %	$\sim \pm$ 35%

$\Rightarrow$ **Theoretical uncertainties dominant**

$\Rightarrow$ **Test ground for: Resummations, NNLO...**

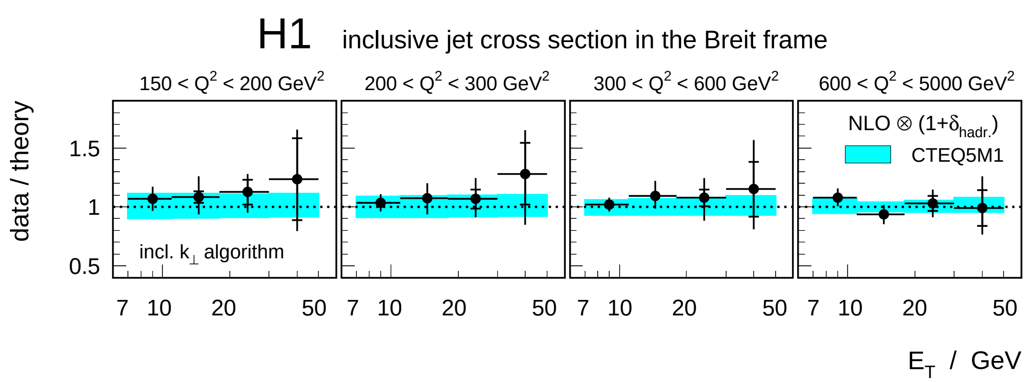
Inclusive Jet Cross Sections at High Q^2

Large Kinematic Region



$150 < Q^2 < 5000$ GeV^2

$7 < E_T < 50$ GeV



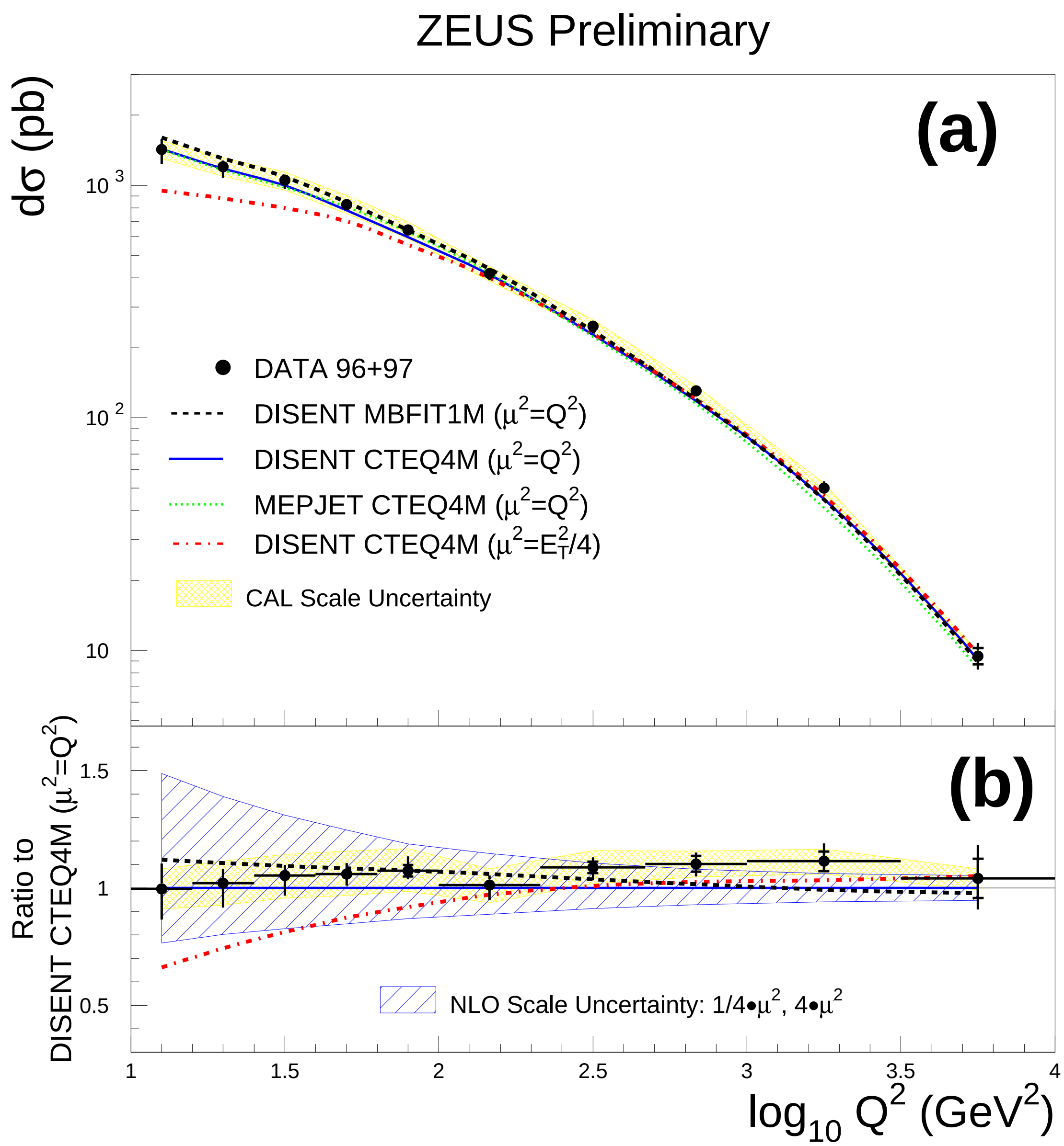
Smaller experimental and theoretical errors: $\sim \pm 10$ %

Agreement satisfactory (using $\mu_R = E_T$)

Extraction of α_s possible (see later)

Jet selection: Delta cut: $(E_{T_1} > E_{T_0} + \Delta) \oplus (E_{T_2} > E_{T_0})$

$\Delta = 3$ GeV: $E_{T_1} > 8$ GeV, $E_{T_2} > 5$ GeV



⇒ Agreement with theory at $\sim 10\%$ level

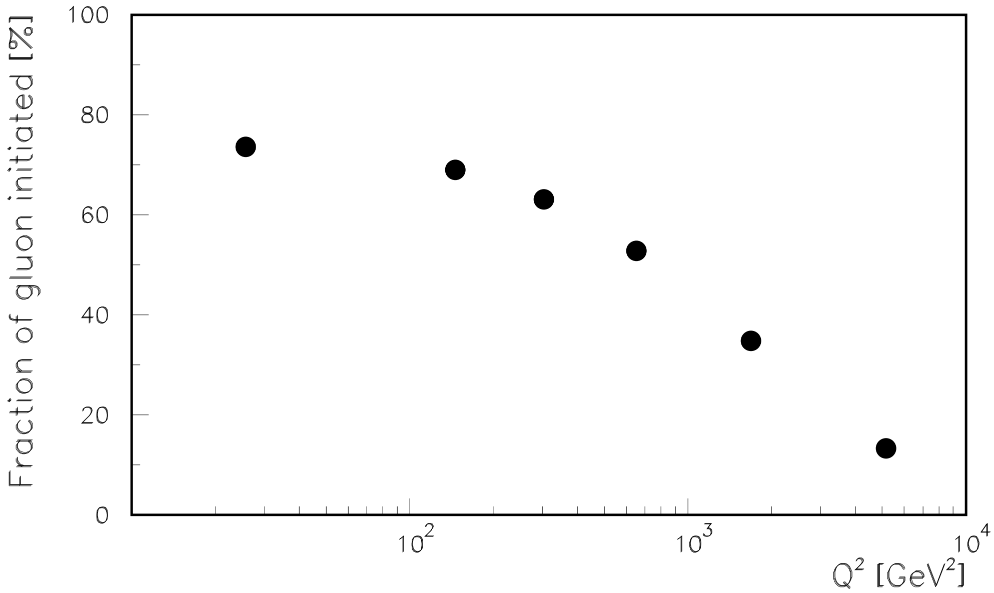
⇒ Experimental uncertainties at $\sim \pm\, 5\%$ level

⇒ Theoretical uncertainties at $\pm(45 - 10)\ \%$ level

Dijet Cross Sections and the Gluon Density

At low Q^2:

Large faction of gluon induced events

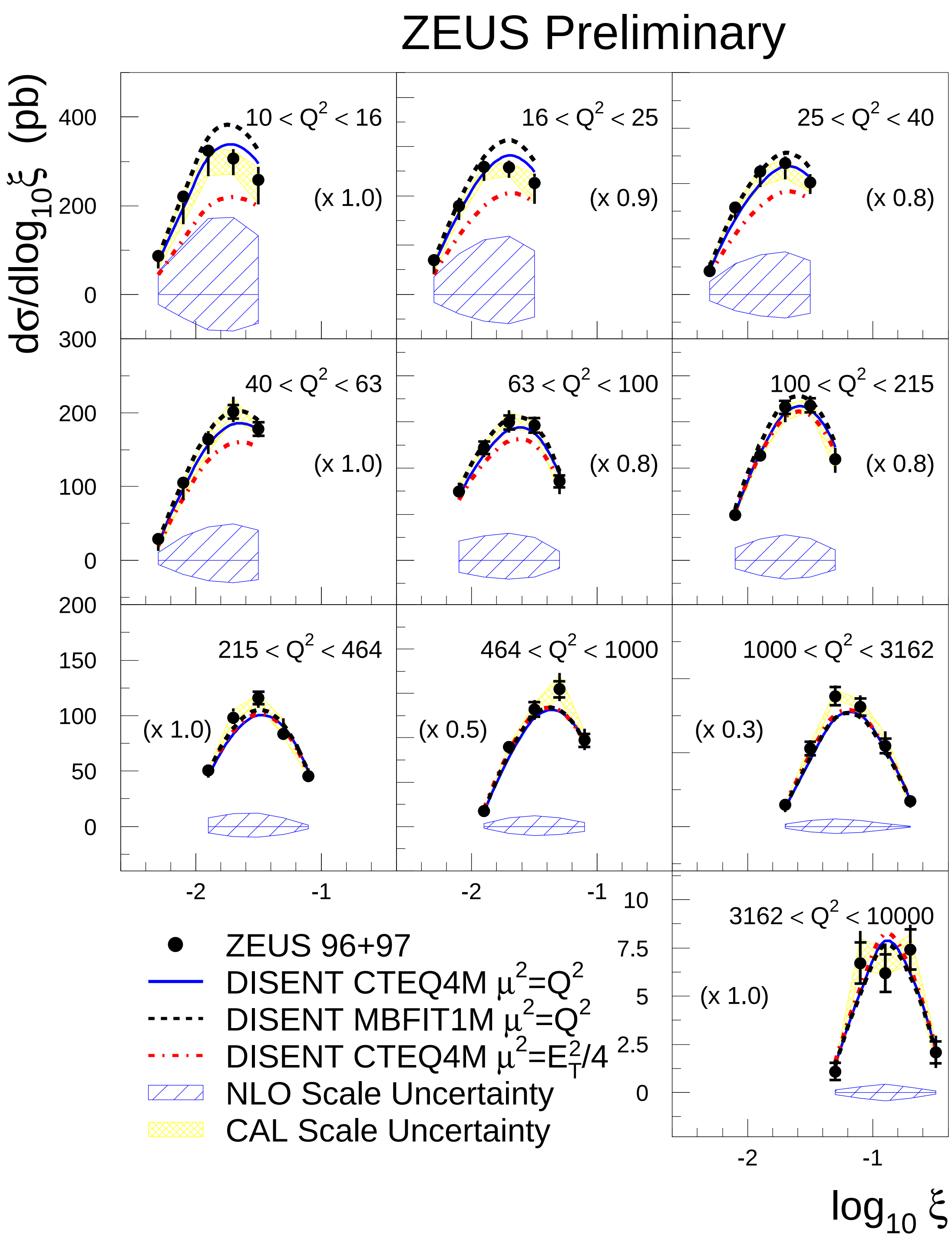


$\Rightarrow$ **Direct sensitivity to $xg(x)$ at low Q^2**

$\Rightarrow$ **At high Q^2: quark induced events dominating**

Reconstruct momentum fraction of gluon

$$\xi = x(1 + (m_{JJ}/Q)^2)$$



Scale uncertainty:

Prevents meaningful determination of $xg(x)$ at low Q^2

Better at high Q^2: but reduced sensitivity

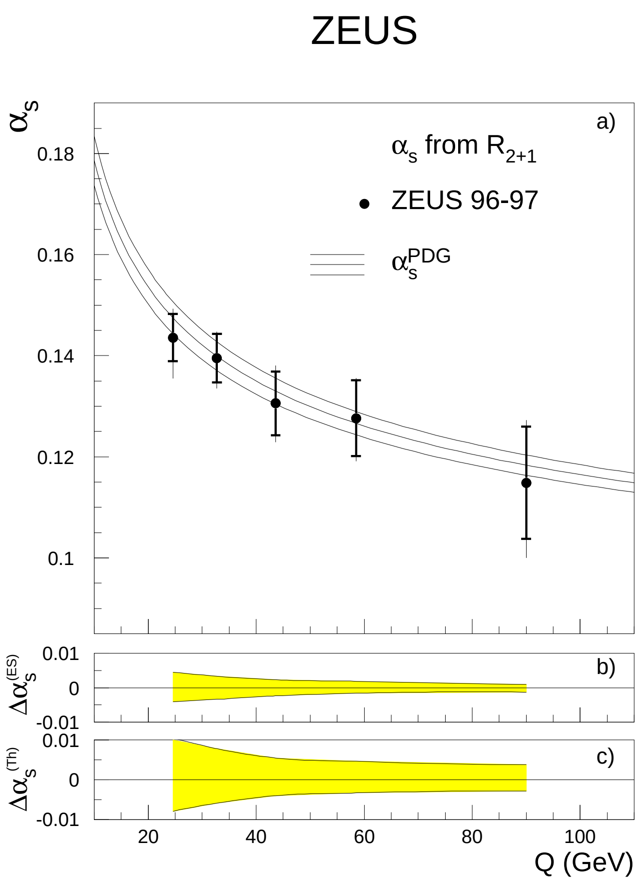
Data consistent with current parameterizations of $xg(x)$

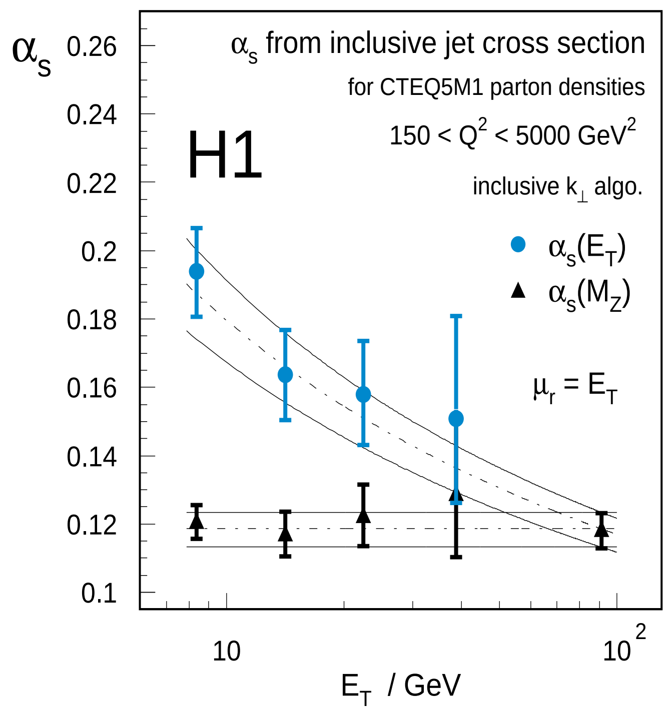
Extraction of α_s

Extraction using high Q^2 data

Reduced scale uncertainty

PDFs better known (q and $\bar{q}$ dominated)





from dijet rate

$\mu_R = Q$

$\alpha_s(M_Z) = 0.1166 \pm^{0.0031}_{0.0038} \pm^{0.0056}_{0.0044}$

from inclusive jet σ

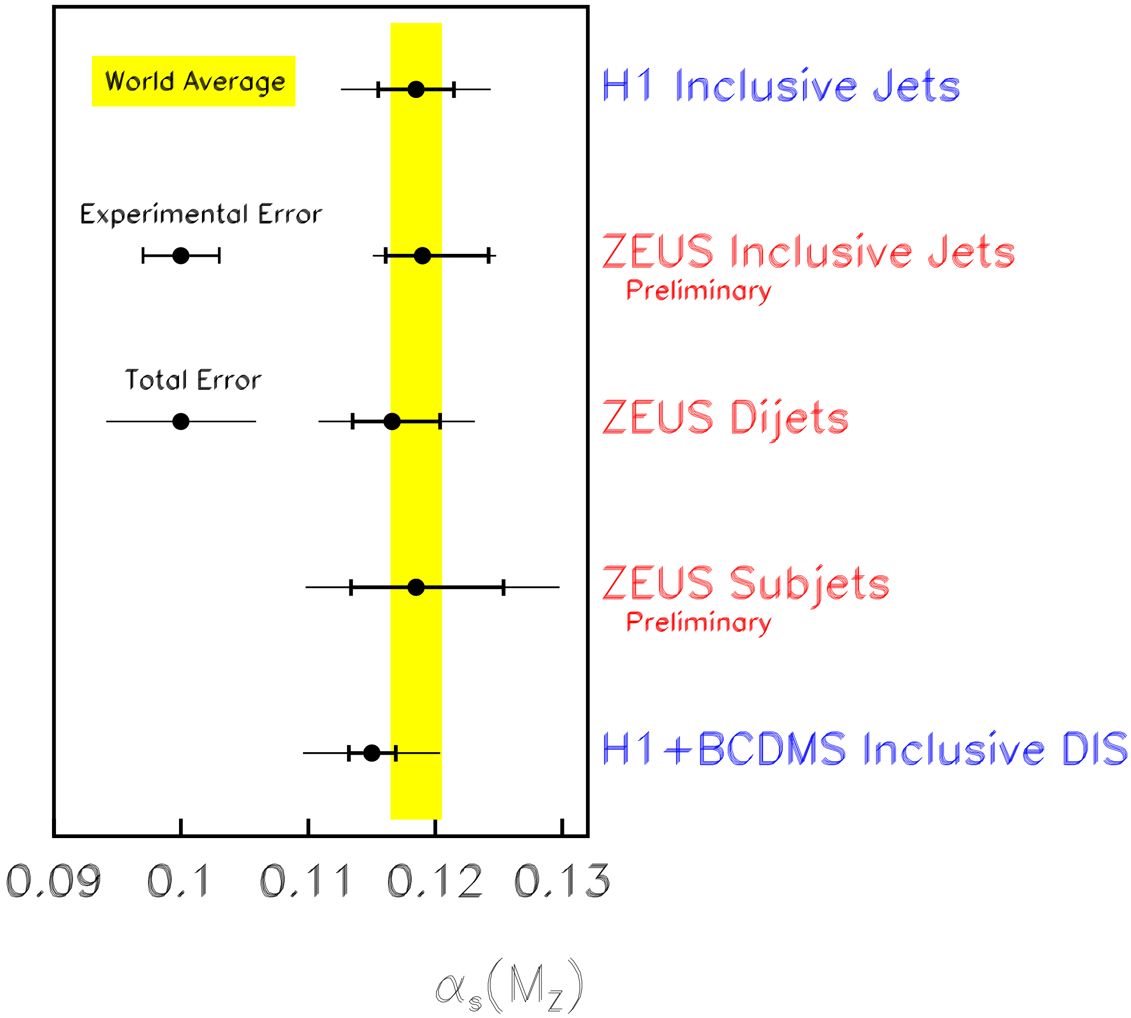
$\mu_R = E_T$

$\alpha_s(M_Z) = 0.1186 \pm 0.0030 \pm 0.0051$

$\Rightarrow$ **Consistent with renormalization group equation**

$\Rightarrow$ **Dominating error: theoretical scale uncertainty**

Summary of α_s Determinations



Experimental errors

Systematic dominated

HERA II $\rightarrow$ further reduced

Theoretical error

Dominant

Need to reduce scale uncertainties
$\rightarrow$ Resummations, higher oder corrections...

Competitive measurements

Polarized Deep Inelastic Scattering

Understanding the proton spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$\Delta\Sigma = \Sigma_q(\Delta q + \Delta\overline{q})$ ... helicity distribution of q and $\overline{q}$

ΔG ... helicity distribution of gluons

L_q ... angular momentum of q's

L_g ... angular momentum of g's

where $\Delta q(x) \equiv q^{\uparrow}(x) - q^{\downarrow}(x)$ wrt p spin

Non-relativistic quark model

$\Delta\Sigma = 1$

First measurement: EMC 1988

$\Delta\Sigma = 0.12 \pm 0.17$

$\Rightarrow$ **Spin crisis**

Since: many measurements: SMC, SLAC, HERMES

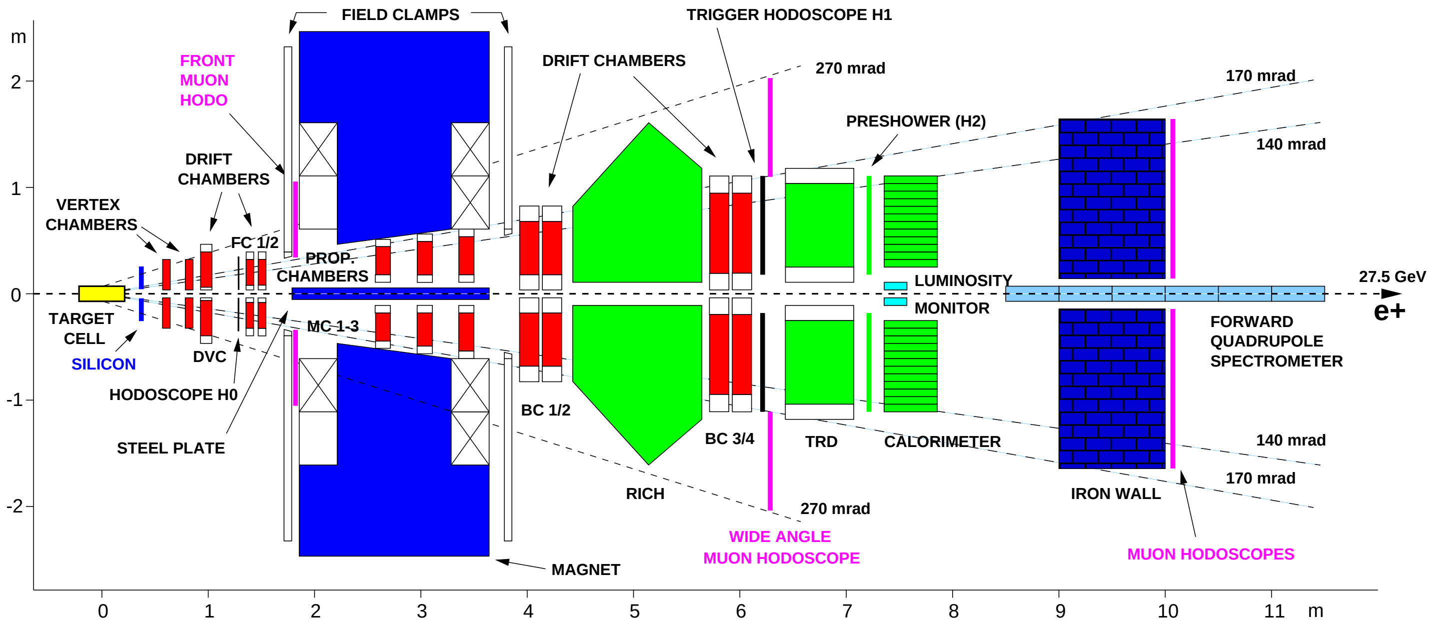
$\Delta\Sigma = 0.2 - 0.3$

Since: refined predictions:

e.g. Relativistic bag model: $\Delta\Sigma = 0.6 - 0.75$

Other approaches: other predictions

The HERMES Spectrometer



Uses longitudinally polarized $e^{\pm}$ of 27.5 GeV

$\Rightarrow$ Average beam polarization 55 % (Sokolov-Ternov)

Internal polarized gas target

$\Rightarrow$ H, D, ^{3}He

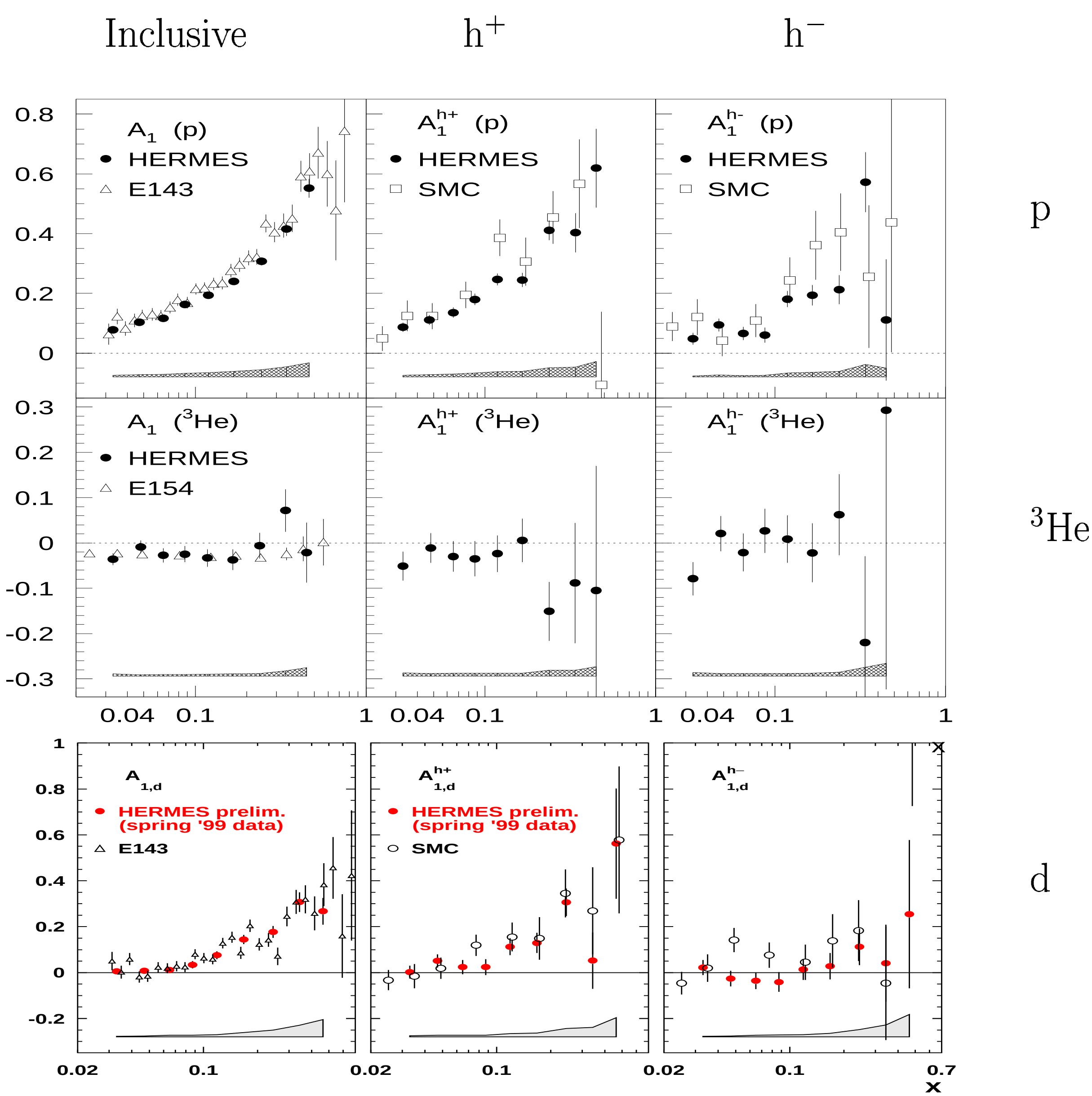
$\Rightarrow$ Average polarization $\sim$ 90 %

(Semi)-inclusive Asymmetries

Measurement of

$$A_1^h(x) = \frac{\sigma^{\uparrow\downarrow}(x) - \sigma^{\uparrow\uparrow}(x)}{\sigma^{\uparrow\downarrow}(x) + \sigma^{\uparrow\uparrow}(x)}$$

$\uparrow\downarrow$ ... Spin of photon and proton: parallel
$\uparrow\uparrow$ ... Spin of photon and proton: antiparallel



Measurement of semi-inclusive asymmetries on different targets

⇒ Important for flavor decomposition of spin structure

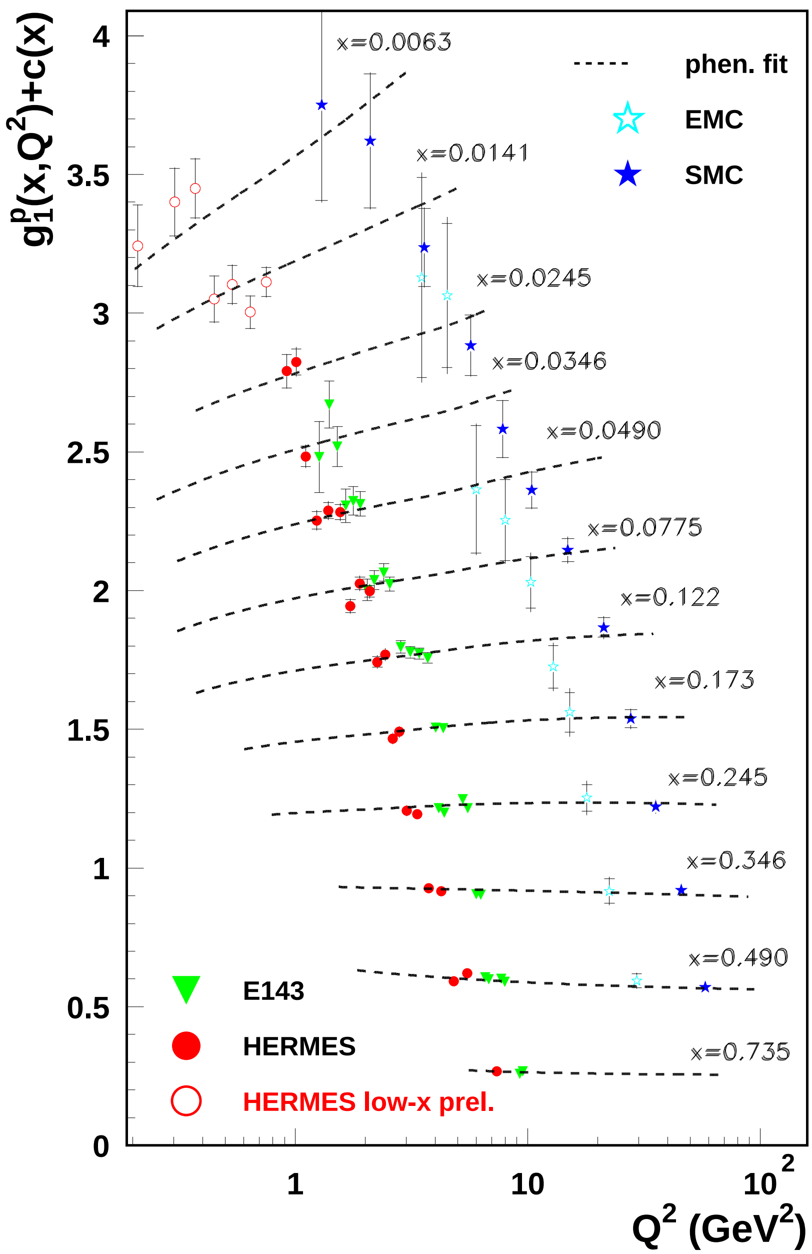
Extraction of spin S.F. $g_1^p(x, Q^2)$

$$A_1(x,Q^2) \approx \frac{g_1(x,Q^2)}{F_1(x,Q^2)} = 2x[1+R(x,Q^2)]\frac{g_1(x,Q^2)}{F_2(x,Q^2)}$$

where $F_1(x,Q^2) = \frac{1}{2}\Sigma_f e_f^2 q_f(x,Q^2)$ ... unpolarized

$g_1(x,Q^2) = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x,Q^2)$ ... polarized

$R = \sigma_L/\sigma_T$



⇒ **HERMES: contributions at low x/Q^2**

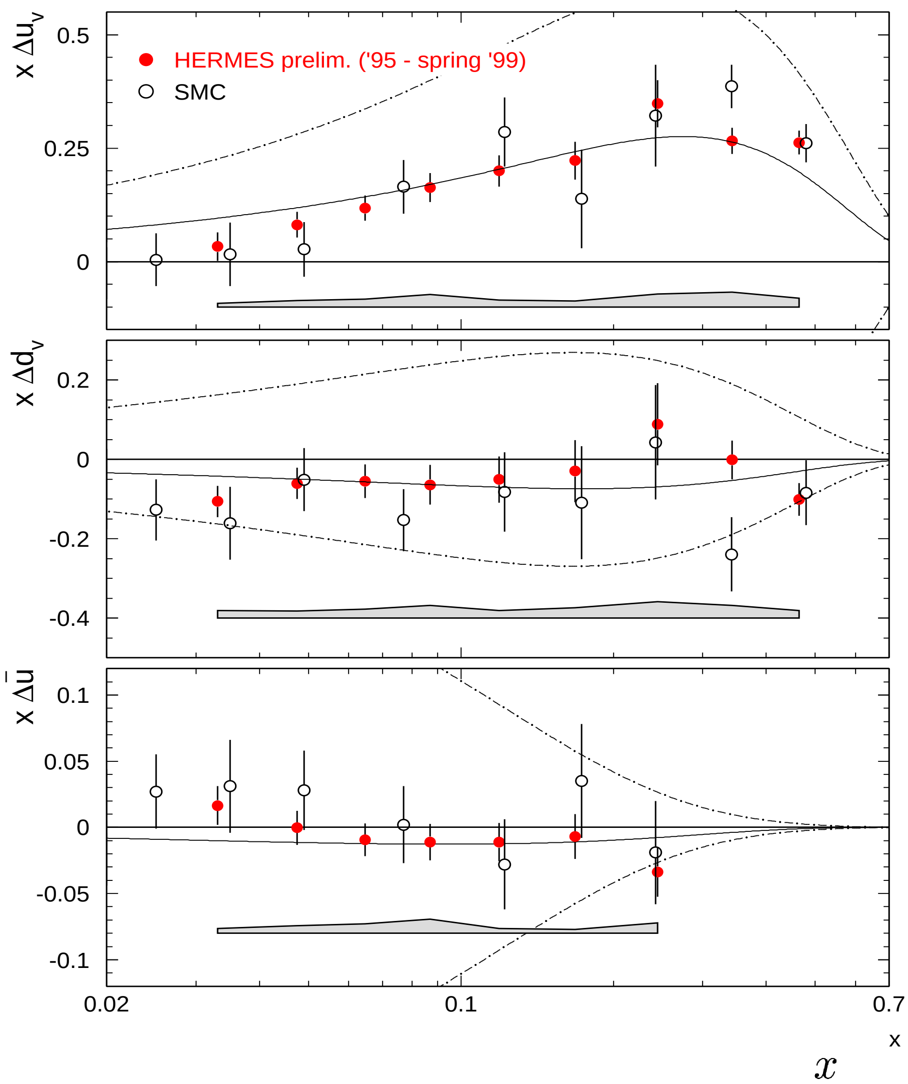
Flavor Dependent Δq

Double differential asymmetries

$$A_1^h(x,z) = \Sigma_q P_Q^h(x,z) \cdot \frac{\Delta q(x)}{q(x)}$$

h ... π, K, p ... Identified with RICH

$P_q^h(x,z)$ ... Probability of $q(x)$ given $h(z)$
... Spin independent quantities
... Obtained from PYTHIA



Compared to parameterization of Gehrmann and Stirling ('Gluon A', LO)

⇒ **Higher precision when all 95-00 data included**

Conclusions

High precision data emerging from HERA

S.F measurements at the 2% uncertainty level

Jet production measurements at the ∼5% level

Many topics not covered in this talk

Diffraction

Charm production

Photon structure

Search beyond S.M.

Other spin S.Fs

Luminosity upgrade: HERA II

Start-up summer 2001

Expect to collect 1 fb^{-1}/experiment by 2005/6

Polarized $e^{\pm}$ for collider experiments
→ Improved sensitivity to effects beyond S.M.

Measurements with unprecedented precision in QCD

Theory

Currently not matching precision of data

(Large) effort in

Resummation of (sub)-leading logs
Calculation of NNLO corrections
Matching NLO calculations to PS and hadronization