Sructure Functions and polarised cross section measurements from HERA

Measurements of Proton Structure at Low Q^2

The High Q^2 regime Neutral and Charged Current Processes

QCD: Partons in the Proton and α_s

First polarised measurements from HERA

Heavy quark structure functions

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HERA collides e and p

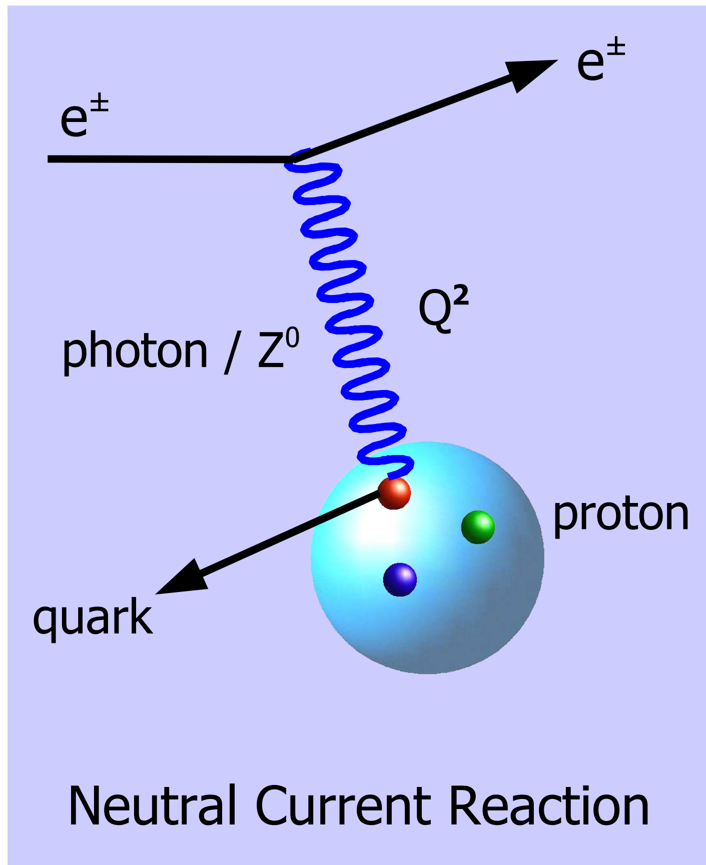
study strong, electromagnetic & weak forces through Deep Inelastic Scattering

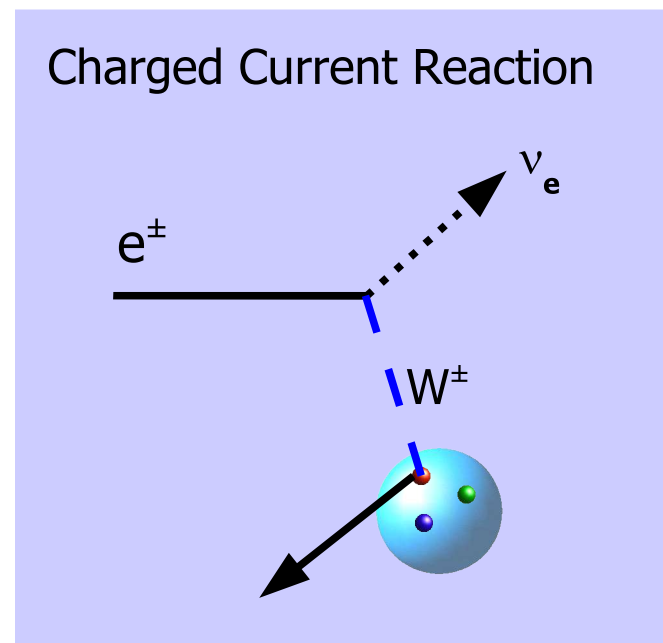
At fixed $\sqrt{s}$: two kinematic variables: x & Q^2

$Q^2 = s\ x\ y$

Q^2 = "resolving power" of probe

High Q^2 **:** resolve 1/1000th size of proton





x = momentum fraction of proton carried by quark

HERA: ~10^{-6} - 1

$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} \approx \frac{e^4}{8\pi x}\left[\frac{1}{Q^2}\right]^2 \left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

Modified at high Q^2 by Z propagator

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} \approx \frac{g^4}{64\pi x}\left[\frac{1}{M_W^2+Q^2}\right]^2 \left[Y_+\tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right]$$

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

$\tilde{F}_2 \propto \sum(xq_i + x\bar{q}_i)$ Dominant Contribution

$x\tilde{F}_3 \propto \sum(xq_i - x\bar{q}_i)$ Contributes when $Q^2 \simeq M^2_Z$

$\tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2)$ Contributes only at high y

similarly for $W_2^{\pm}$, $xW_3^{\pm}$ and $W_L^{\pm}$

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

$$\tilde{\sigma} = \tilde{F}_2 \quad \text{when} \quad \tilde{F}_L \equiv x\tilde{F}_3 \equiv 0$$

NC/CC with Lepton Polarisation

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = 2\pi\alpha^2\left[\frac{1}{Q^2}\right]^2\left[Y_+F_2^P \mp Y_- xF_3^P - y^2F_L\right]$$

$$F_2^P = \sum_q x\left[q(x,Q^2) + \bar{q}(x,Q^2)\right]\left(A_q^0 + PA_q^P\right), \quad Y_\pm = \tfrac{1}{2}\left(1 \pm (1-y^2)\right)$$

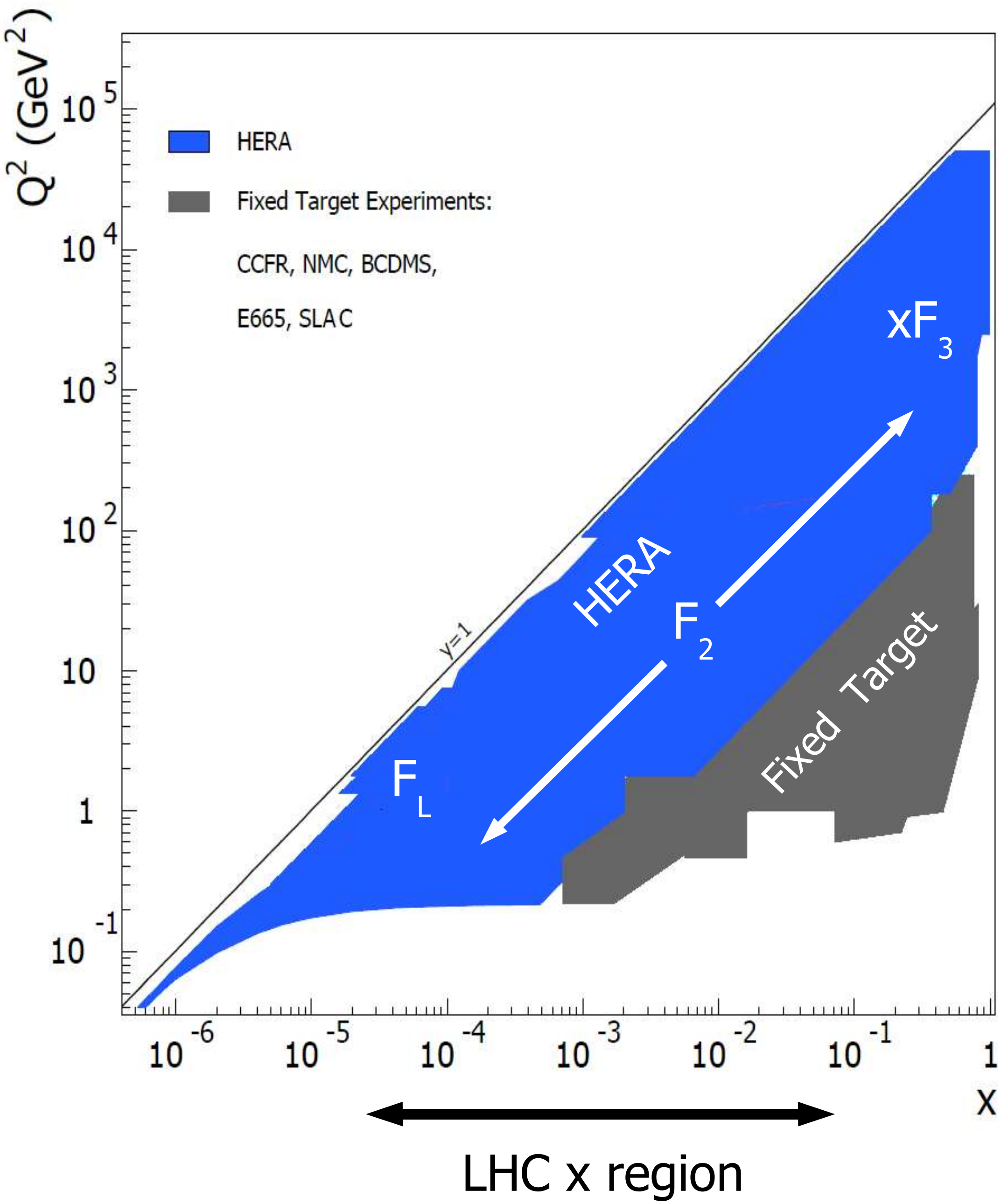
$$A_q^0 = e_q^2 + 2e_q v_q v_e \chi_Z + \left(v_q^2+a_q^2\right)\left(v_e^2+a_e^2\right)\chi^2$$

$$A_q^P = 2e_q v_q a_e \chi_Z + \left(v_q^2+a_q^2\right) v_e a_e \chi^2$$

$$\chi_Z \propto \left[\frac{Q^2}{Q^2+M_Z^2}\right]^2$$

$$\frac{d^2\sigma^{+}_{CC}}{dxdQ^2} = \left[1+P\right]\frac{G_\mu}{\pi}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2\left[\bar{u}+\bar{c}+(1-y)^2(d+s+b)\right]$$

$$\frac{d^2\sigma^{-}_{CC}}{dxdQ^2} = \left[1-P\right]\frac{G_\mu}{\pi}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2\left[u+c+(1-y)^2(\bar{d}+\bar{s}+\bar{b})\right]$$



Conventional QCD evolution only tells us Q^2 dependence

x dependence must come from data

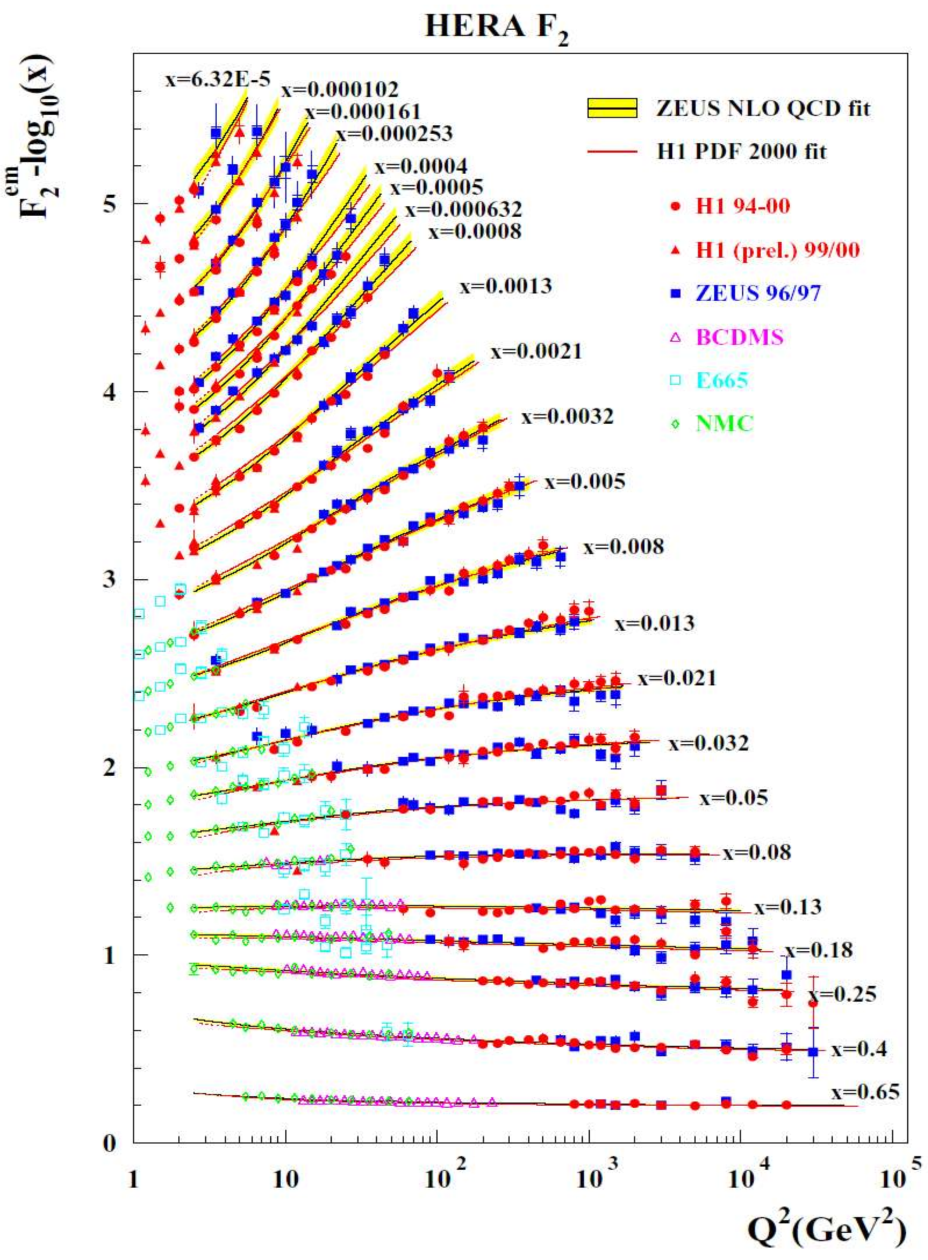
Method:

- Measure cross sections
- Fit data – extract x dep. of partons

HERA PDFs extrapolate into LHC region

LHC probes proton structure where gluon dominates (gluon collider)

HERA data crucial in calculations of new physics & measurements at LHC



F_2 dominates cross-section

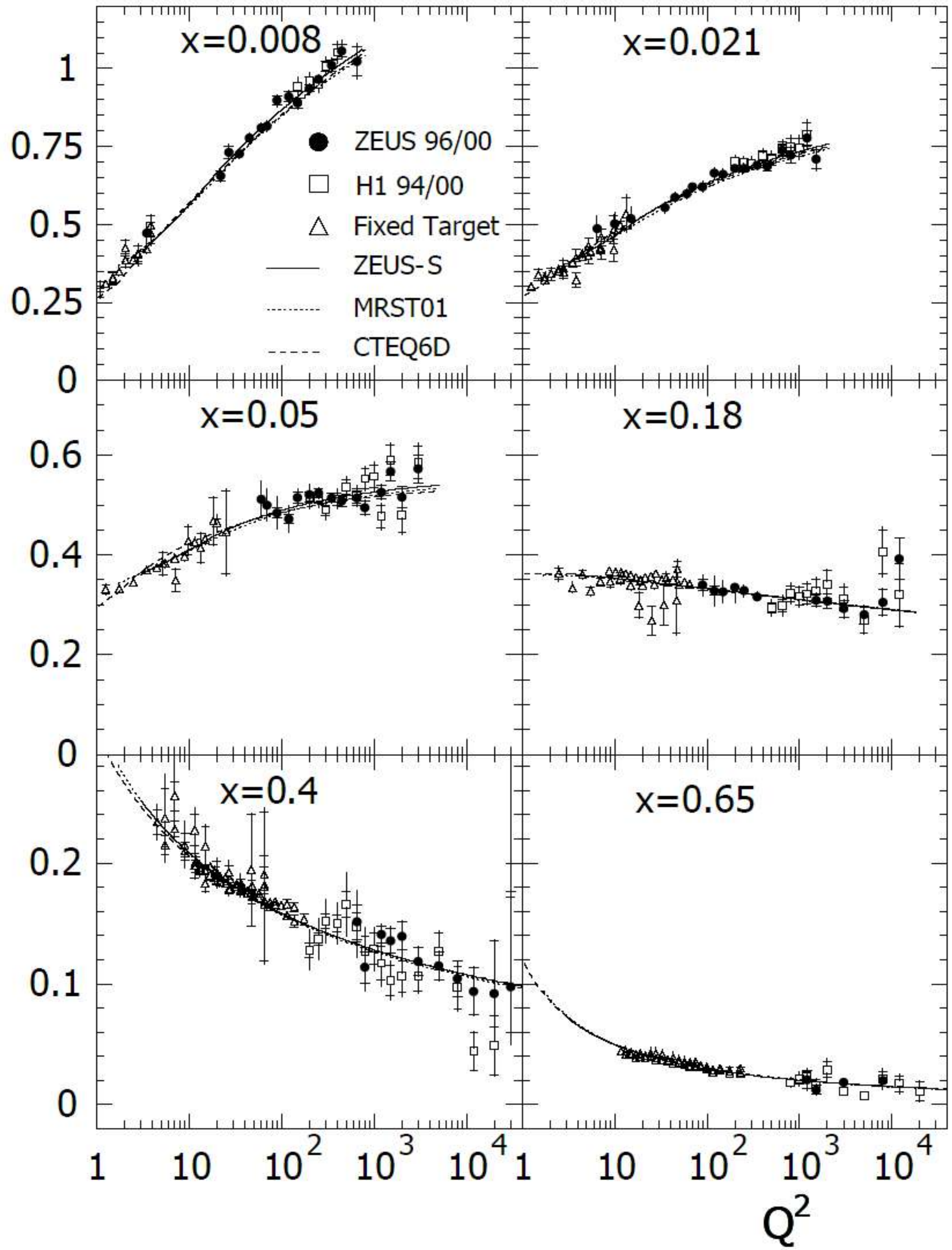
Range in x: 0.00001 – 1

Range in Q^2 ~1 - 30000 GeV^2

Measured with ~2-3% precision

Directly sensitive to sum of all quarks and anti-quarks

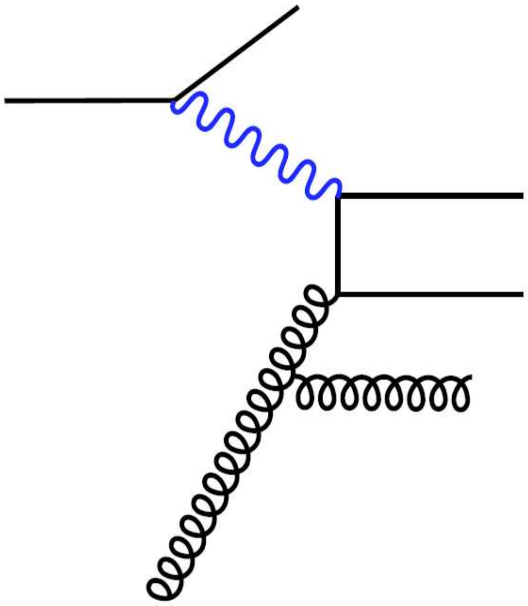
Indirectly sensitive to gluons via QCD radiation - scaling violations



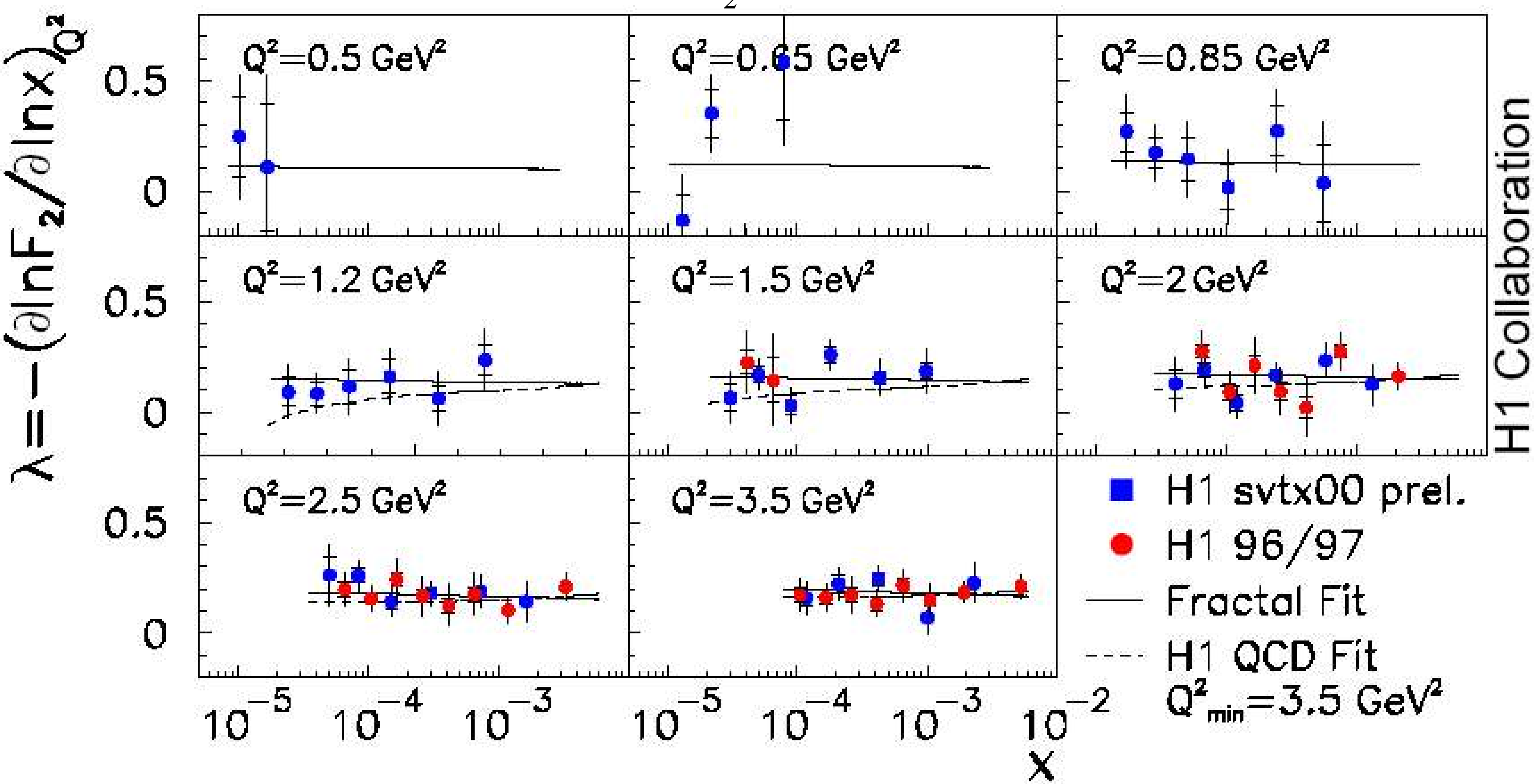
Dramatic scaling violations at low x

driven by gluon

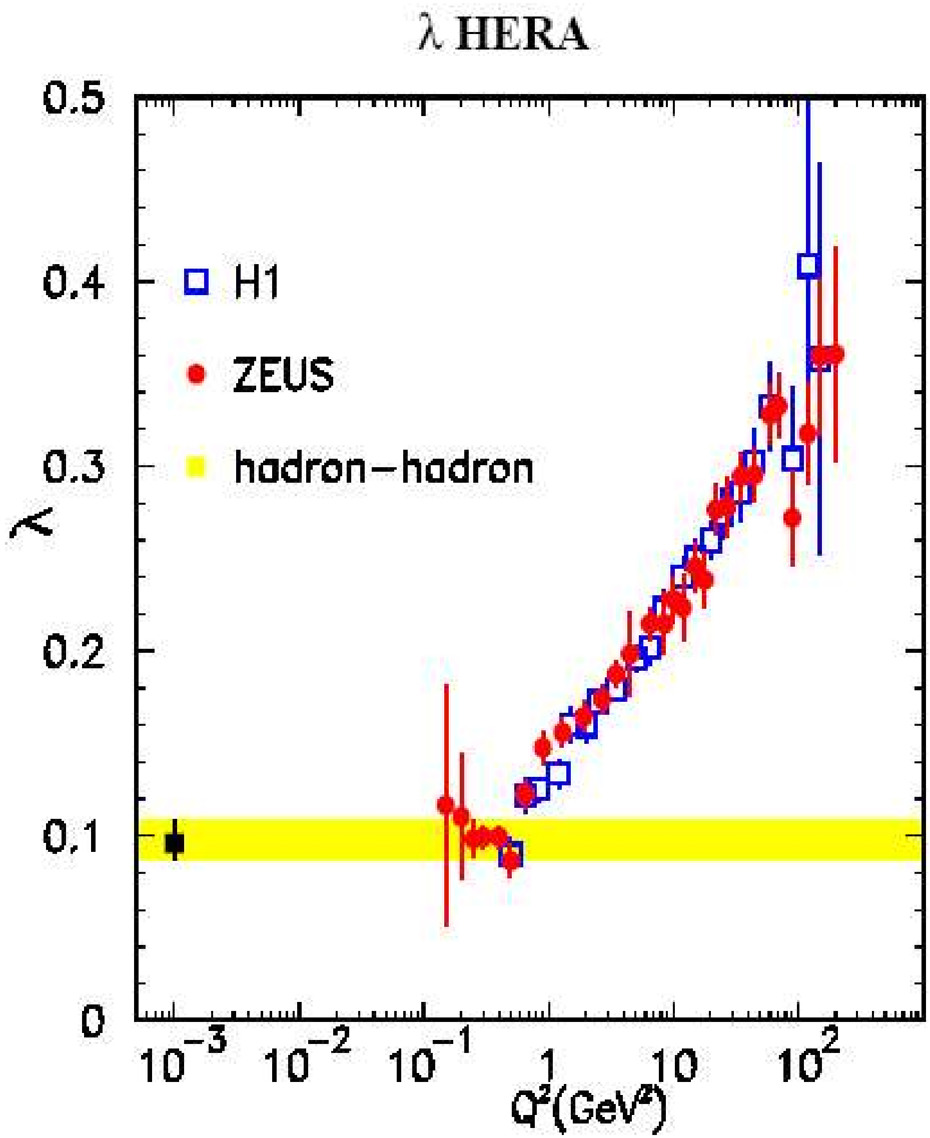
described by QCD



Look at derivative of F_2



- Find derivative of F_2 is constant with x (true at higher Q^2 too)
- No turn over found within HERA range
- Look at dependence with Q^2



$\lambda(Q^2)$ from the fit to

$$F_2(x,Q^2) = c(Q^2)\, x^{-\lambda(Q^2)}$$

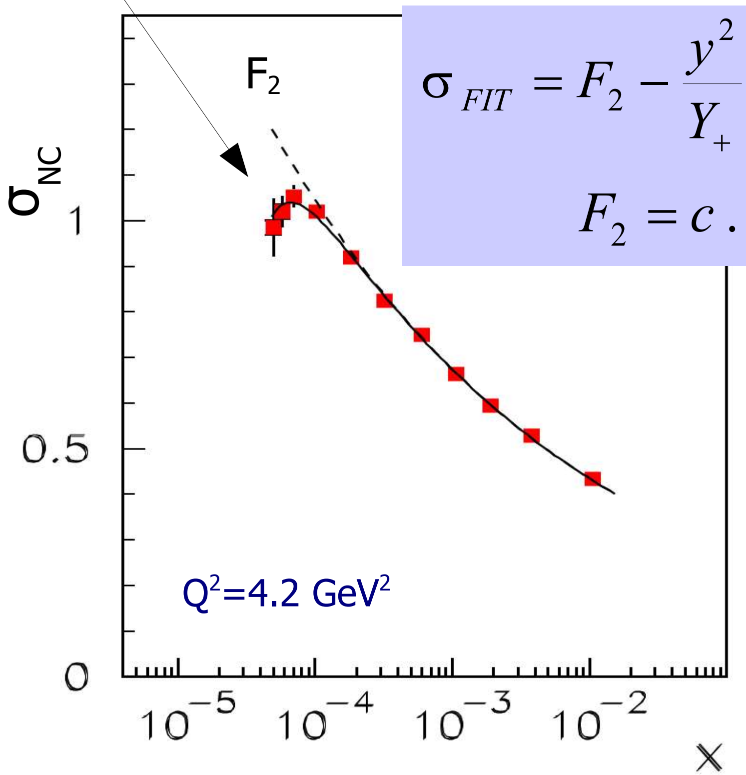
$$\lambda(Q^2) \propto \ln Q^2$$

- Rises with Q^2
- Change in slope at low Q^2
- Reaches soft pomeron limit (taken from total hadron-hadron cross sections)

At low Q^2 cannot measure $xg(x,Q^2)$ via scaling violations of F_2

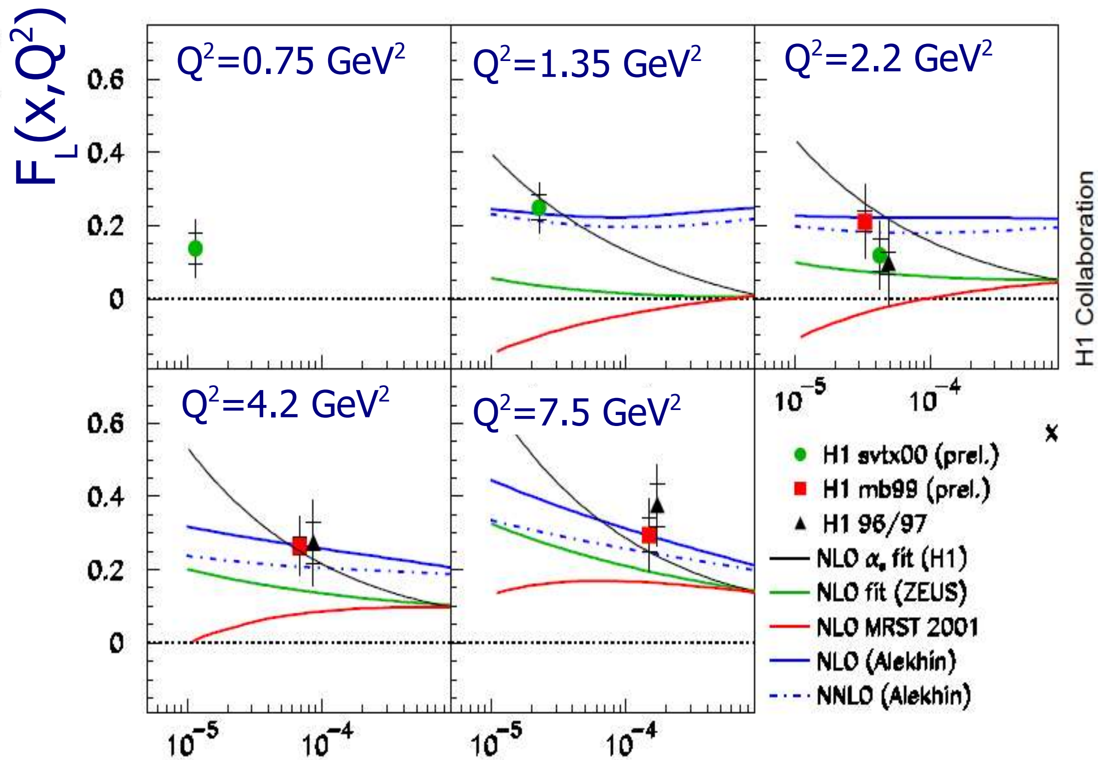
F_L is directly sensitive to gluon

σ_{NC} sensitive to F_L only at high y



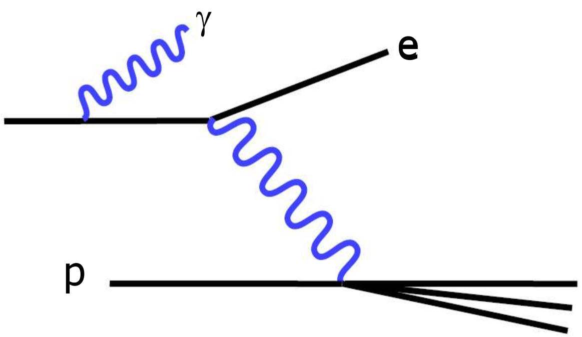
$$\sigma_{FIT} = F_2 - \frac{y^2}{Y_+} F_L$$

$$F_2 = c \, . \, x^{-\lambda}$$



Shape of σ_r at high y driven by kinematic factor y^2/Y_+ not F_L behaviour

Whole x-range of measured data used to fit F_2 and F_L



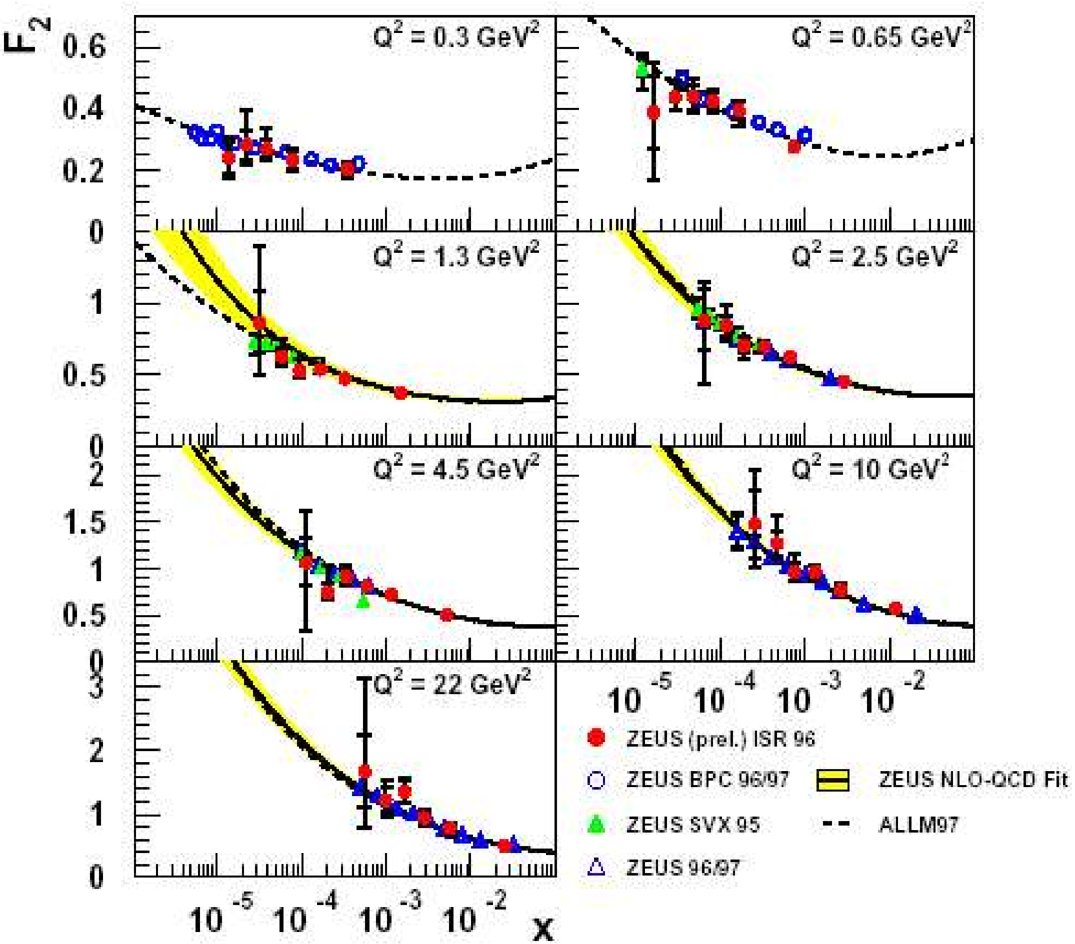
Initial state radiation reduces $\sqrt{s}$

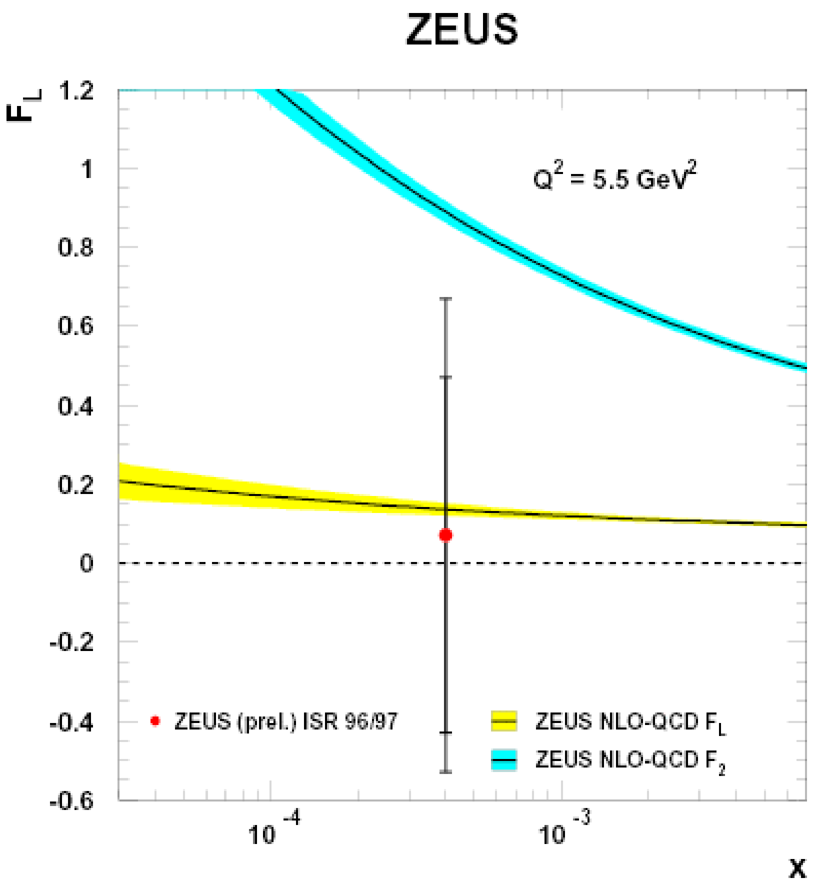
At fixed x,Q^2 then y is different

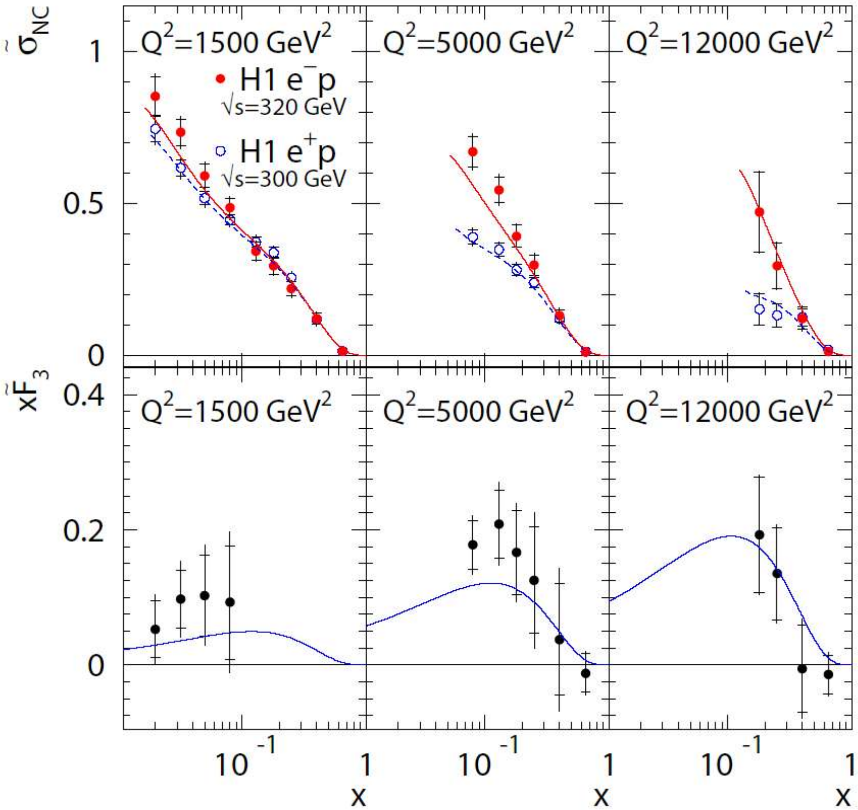
Changes contribution of F_2 and F_L

Measure σ_{NC} vs y: fit for F_L

$$\sigma_{NC} = F_2 - \frac{y^2}{Y_+} F_L$$



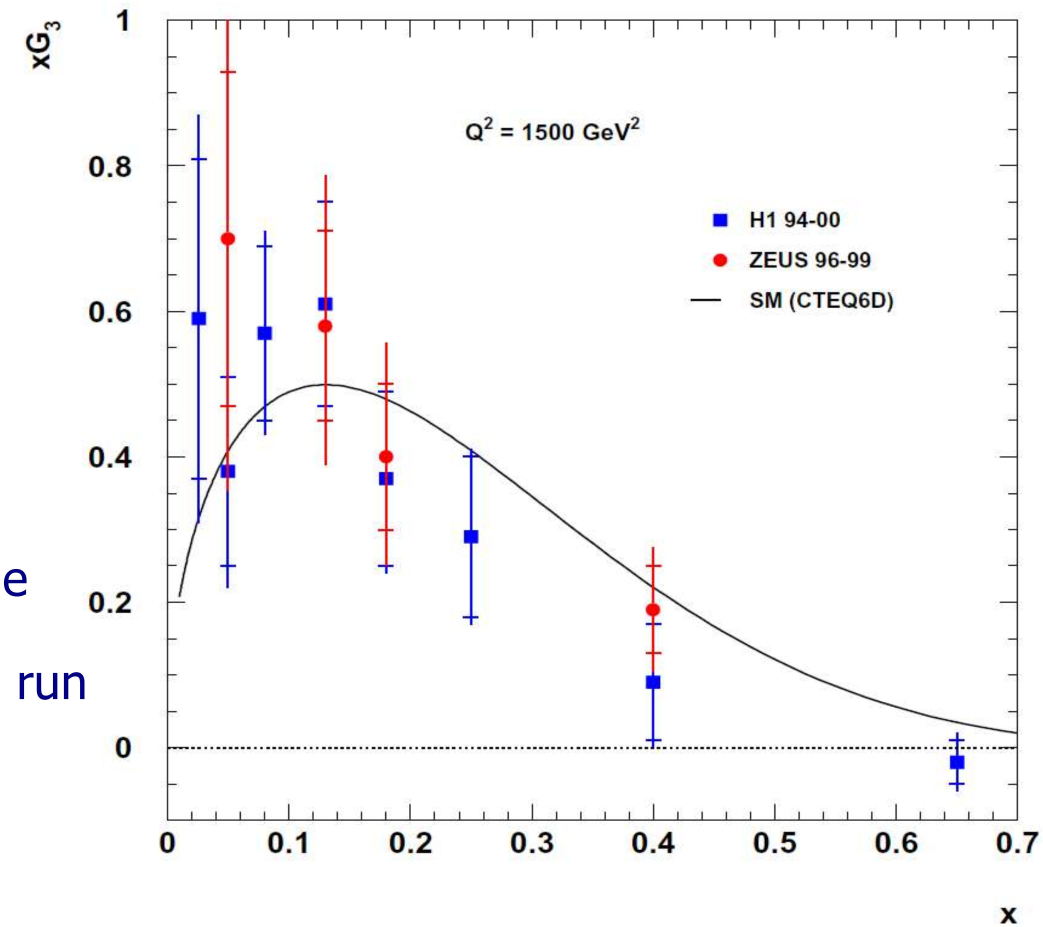




At high Q2 NC cross sections for e^+ and e^- deviate

$$\tilde{\sigma}_{NC}^{\pm} \sim \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

Subtract NC positron from electron cross section



HERA confirm valence quark structure

Errors dominated by stat. error of e- sample

Clear need for high luminosity - HERA II e- run planned for fall 2004

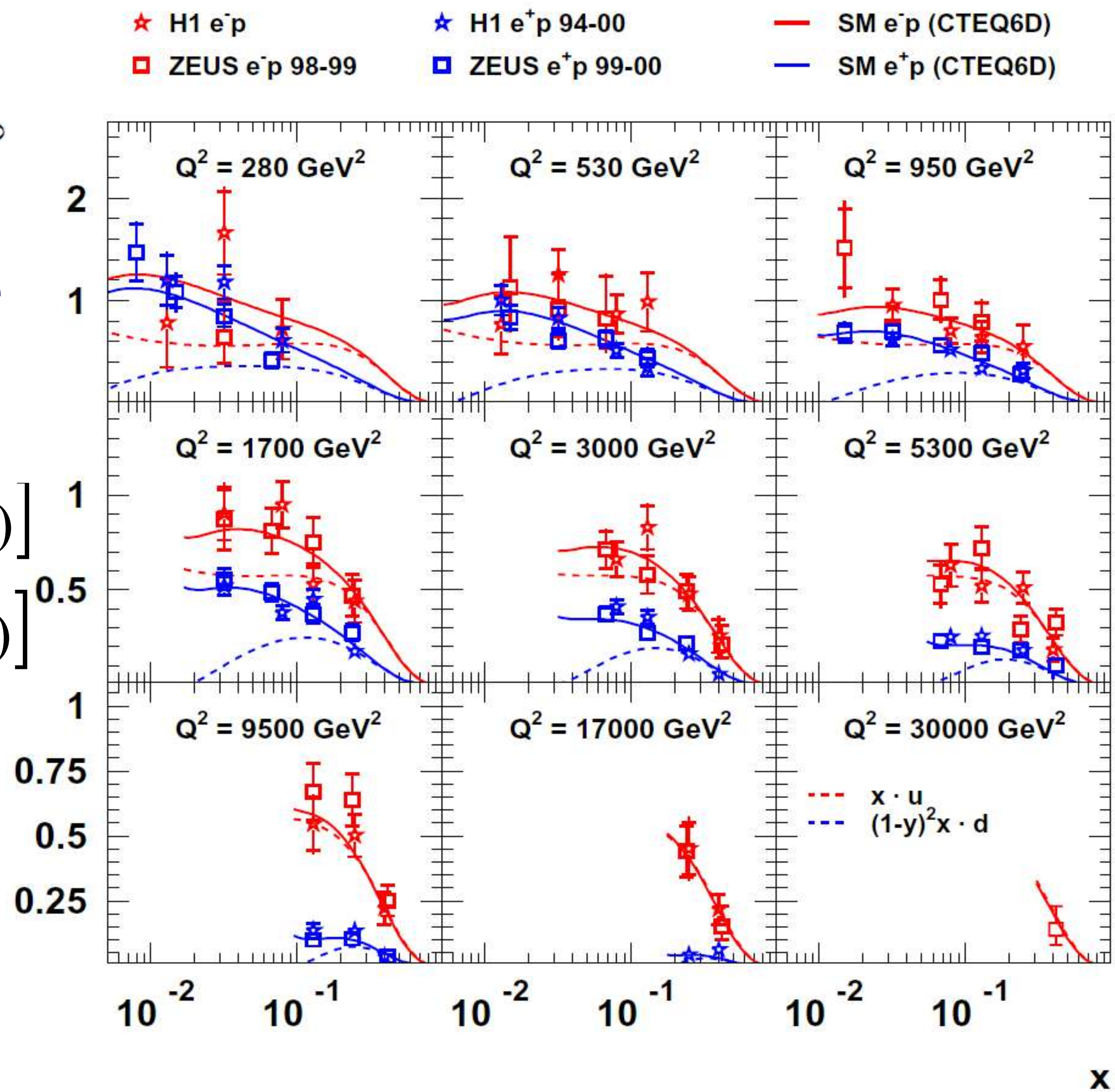
Charged current process provides sensitivity to quark flavour

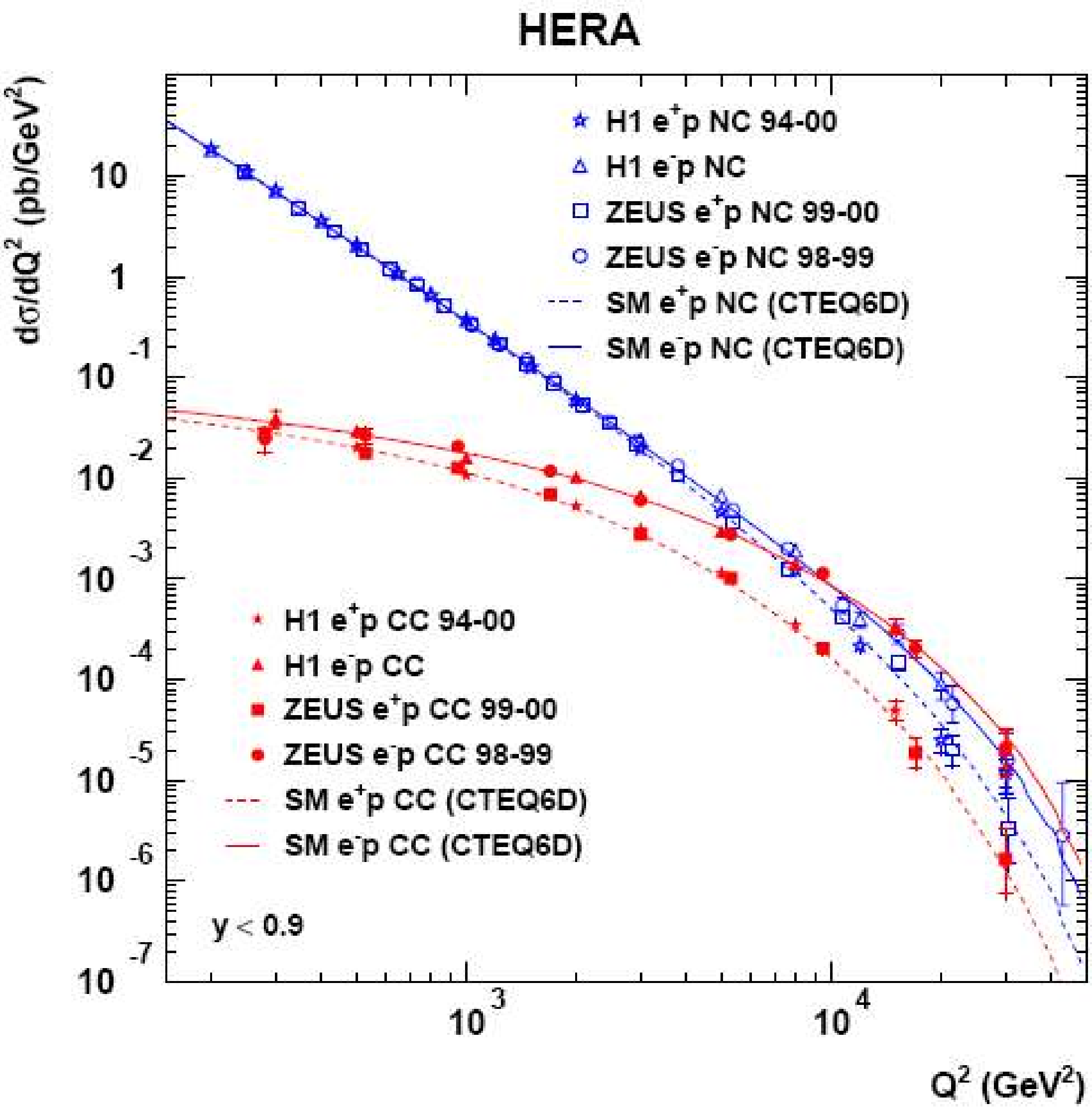
Cross sections small due to large W mass in propagator

At high x (low y) lepton charge separates u from d

$$\sigma^{+}_{cc} \approx x\left[\bar{u} + \bar{c} + (1-y)^2(d+s)\right]$$

$$\sigma^{-}_{cc} \approx x\left[u + c + (1-y)^2(\bar{d} + \bar{s})\right]$$



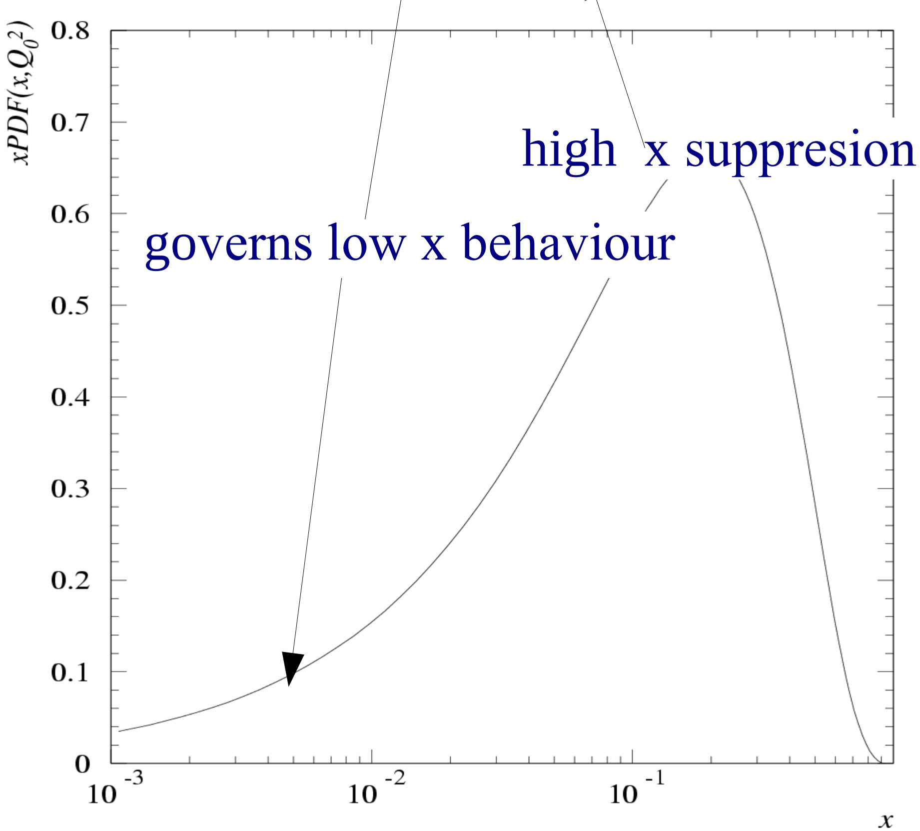


- Cross sections measured over 3 orders of magnitude in Q^2
- CC cross section supressed at low Q^2 by W propagator
- At high Q^2 NC+CC cross sections comparable
- electroweak unification

NLO QCD Fits

PDFs parameterised at starting scale Q_0^2 and use DGLAP to evolve to higher Q^2

$$xPDF(x,Q_0^2) = Ax^b(1-x)^c(1+dx+e\sqrt{x}+fx^2+gx^3)$$



parameters A,b,c,d,e,f optimised in fit for each PDF

some parameters constrained by sum rules e.g. momentum sum = 1

$$\int u_v\,dx = 2 \qquad \int d_v\,dx = 1$$

- ZEUS perform a new global analysis - use zeus inclusive data+DIS+γp jets
- Standard xg, xu_v, xd_v, Sea, $x(\bar{d} - \bar{u})$ decomposition of proton
- $Q^2_0 = 7$ GeV^2 / $Q^2_{min} = 2.5$ GeV^2
- Use functional form = $A \,.\, x^b \cdot (1-x)^c \cdot (1 + dx + e\sqrt{x})$
- Additional constraints on valence quark parameters ($b_{uv} = b_{dv} = 0.5$)
- Experimental systematic uncertainties are propagated onto final PDF uncertainty
- Use Thorne/Roberts variable flavour number scheme.
- $x(\bar{d} - \bar{u})$ params taken from MRST - only normalisation free in fit

Use only H1 inclusive NC & CC x-sections (e^+p and e^-p)

H1 dedicated fit: tune fitted PDFs to HERA NC/CC cross section sensitivity:

$$xU = xu + xc$$

$$xD = xd + xs$$

$$x\overline{U} = x\overline{u} + x\overline{c}$$

$$x\overline{D} = x\overline{d} + x\overline{s}$$

$$xg$$

$$u_v = U - \overline{U}$$

$$d_v = D - \overline{D}$$

$$F_2 = \frac{4}{9}(xU + x\overline{U}) + \frac{1}{9}(xD + x\overline{D})$$

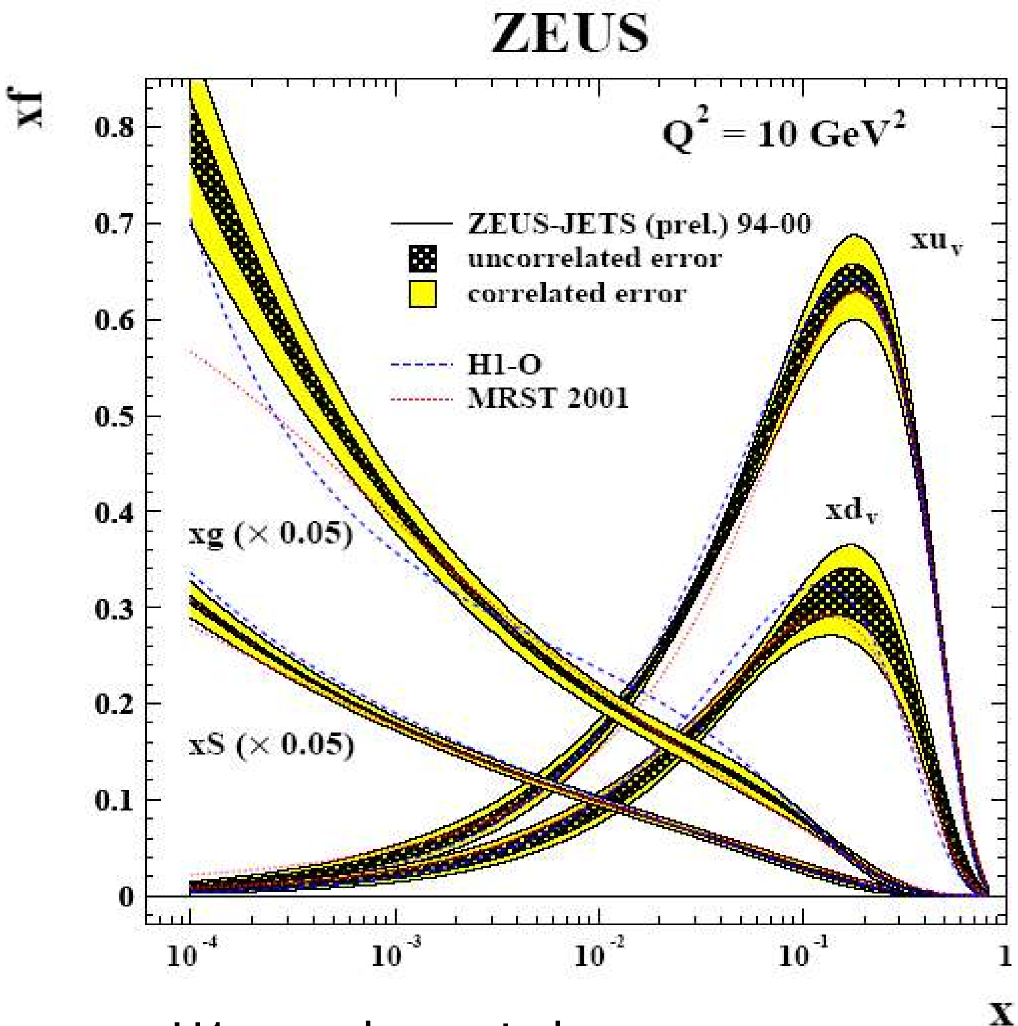
$$\sigma_{cc}^{+} = x\overline{U} + (1-y)^2 xD$$

$$\sigma_{cc}^{+} = xU + (1-y)^2 x\overline{D}$$

Perform fit in massless scheme - appropriate for high Q^2

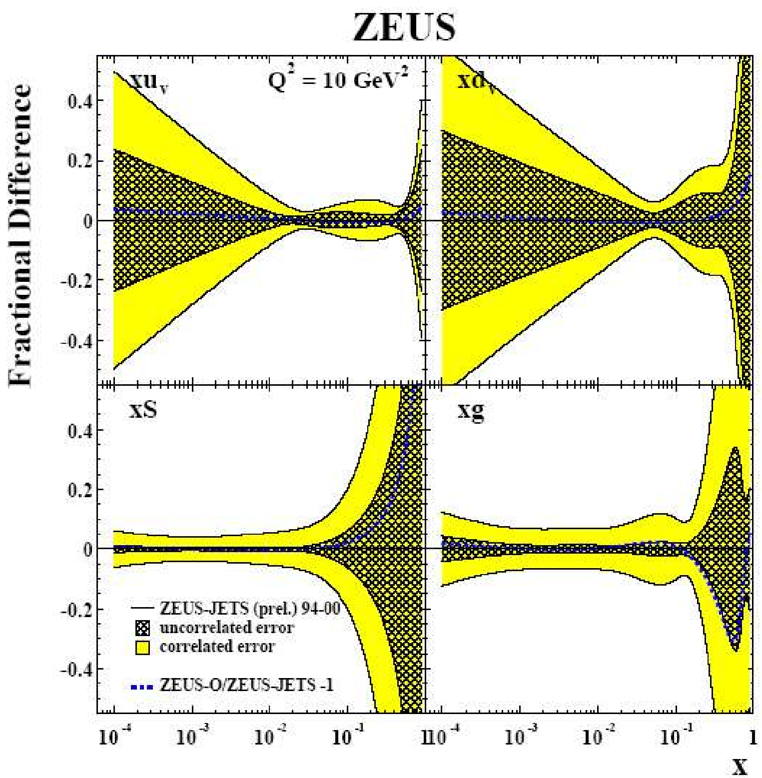
$Q^2_0 = 4$ GeV^2 / $Q^2_{min} = 3.5$ GeV^2

Use BCDMS p and D data in addition to measure α_s



- Hera able to extract PDFs w/o external input
- H1/ZEUS broadly agree but some differences at medium *x*
- Reasonable agreement with MRST global fit
- Errors still large on *d* and *g* at high *x*

H1 error bar not shown
gluon+sea scaled by X 20

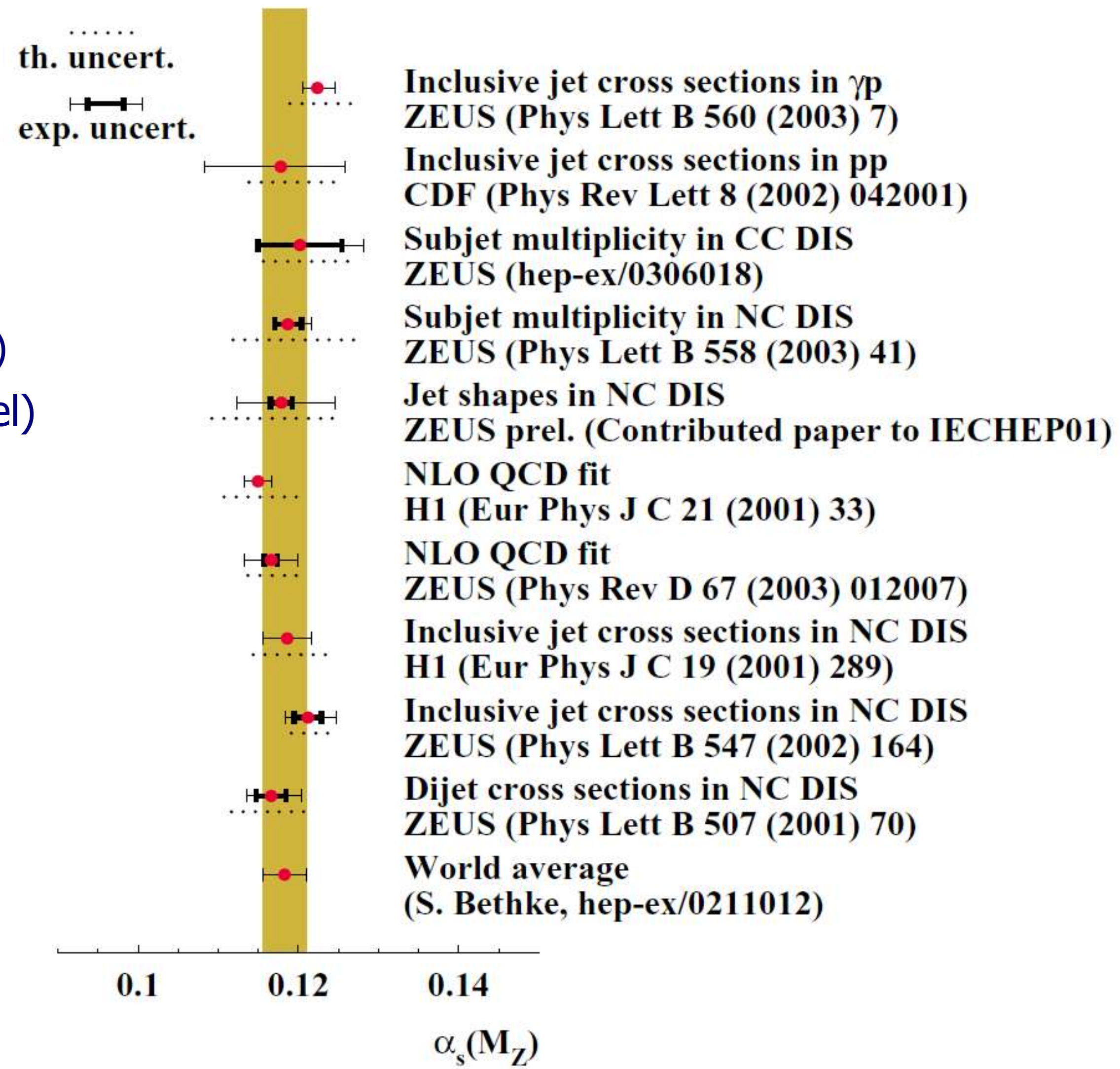


α_s from NLO QCD fits

H1: 0.1150 ±0.0017(exp) ±0.0008(model)
±0.005 (scale)

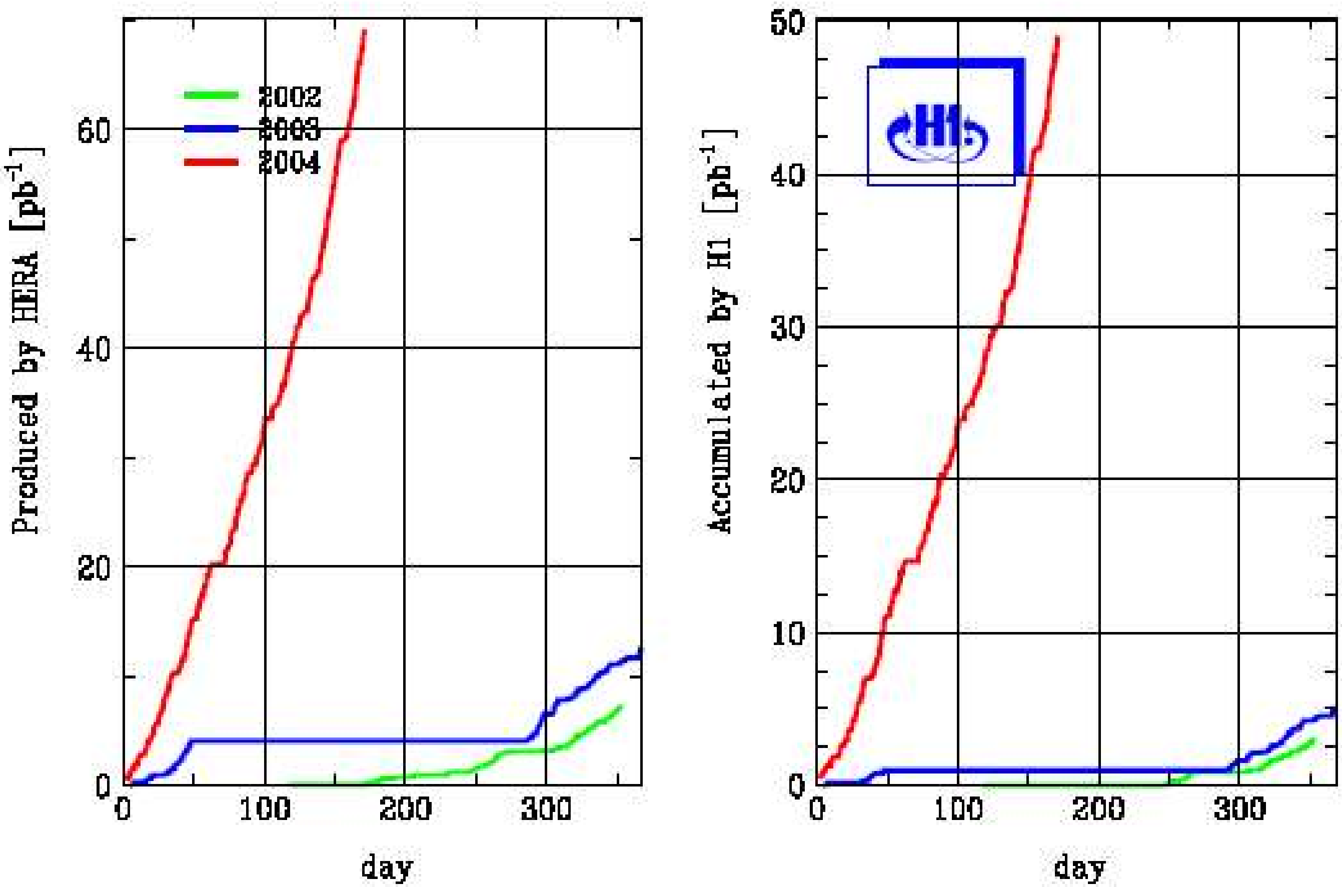
ZEUS: 0.1166 ±0.0008(unc) ±0.0032(corr)
±0.0036(norm) ±0.0018(model)
±0.004 (scale)

- Experimental errors competative with world average
- Largest error from renormalisation scale uncertainty (changed by factor 4 H1, 2 ZEUS)
- NNLO analysis should reduce the scale uncertainty by factor 2-4

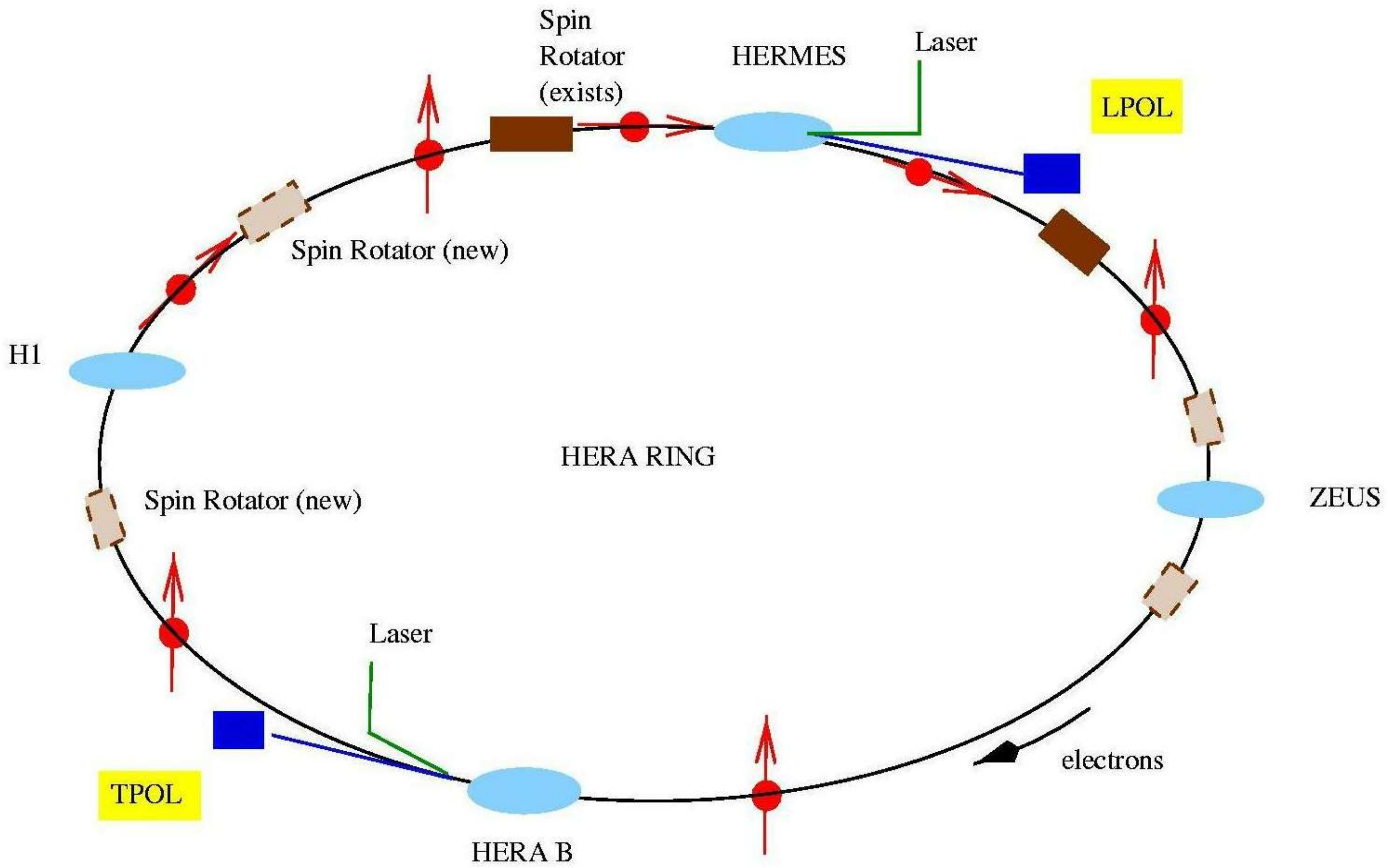


HERA II

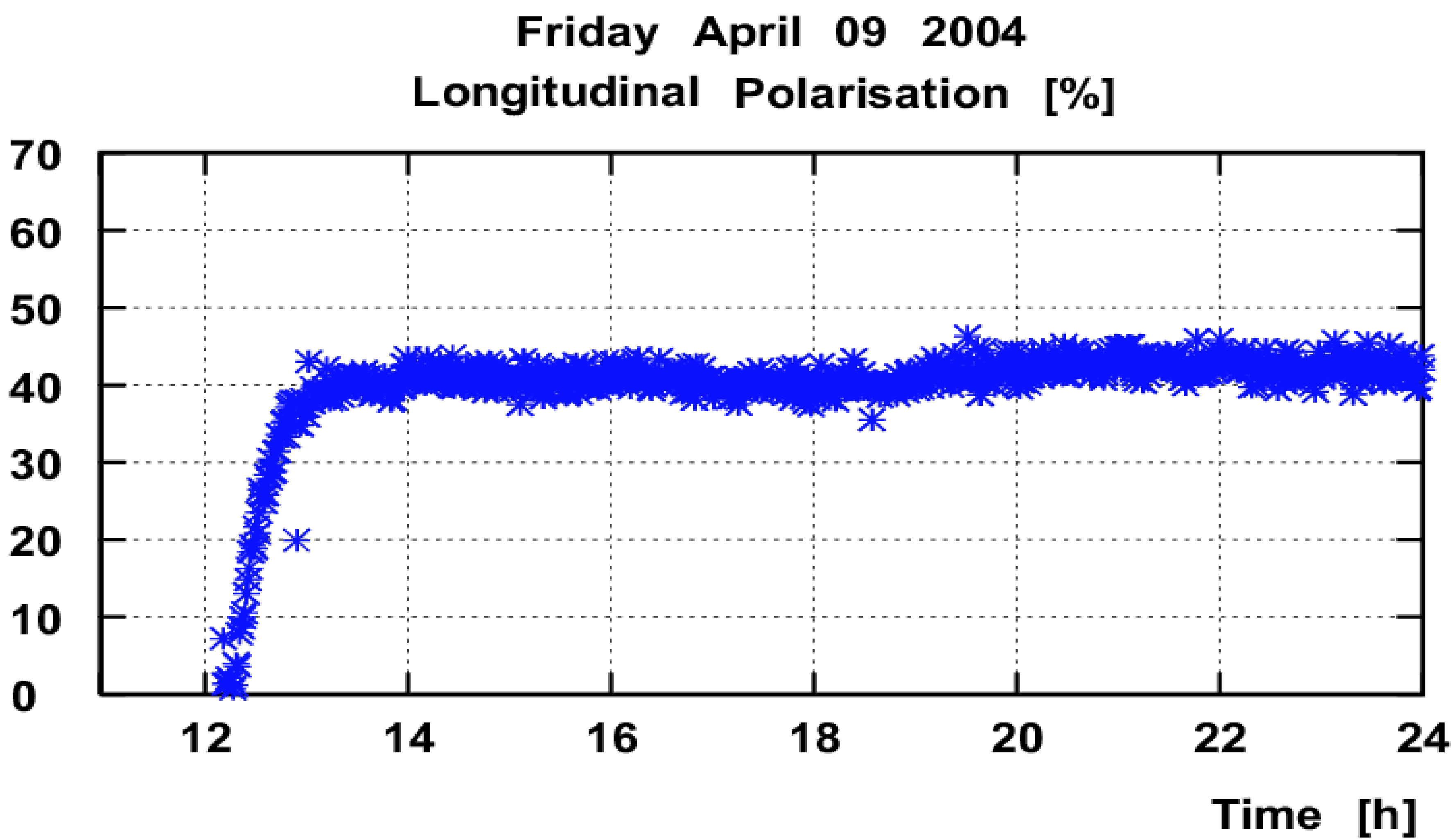
INTEGRATED LUMINOSITY (21.06.04)



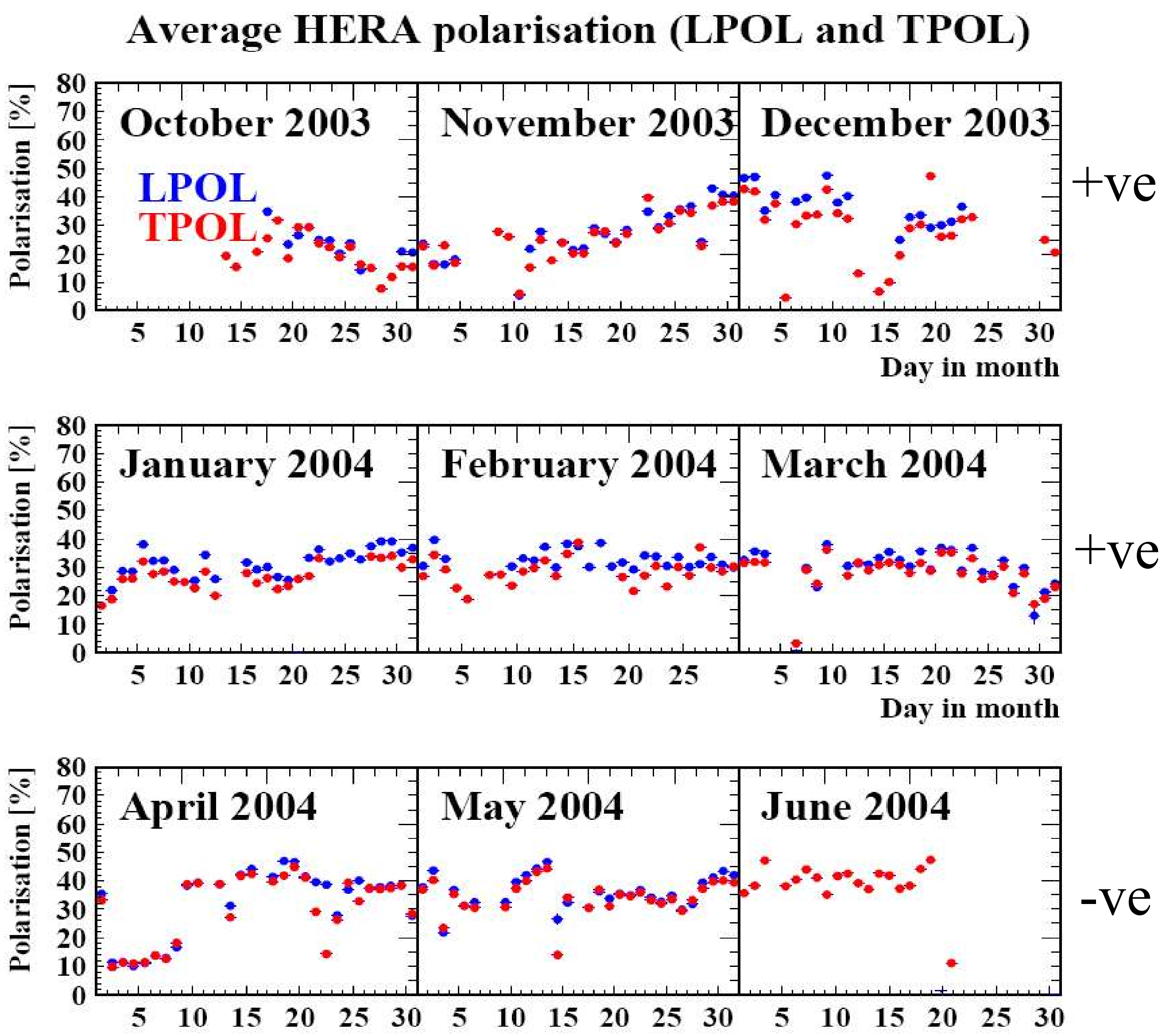
- 5 fold lumi increase achieved by focusing magnets and higher beam currents
- Slow start up 2002-03
- Problems with high beam related backgrounds
- Now solved. Best ever HERA performance

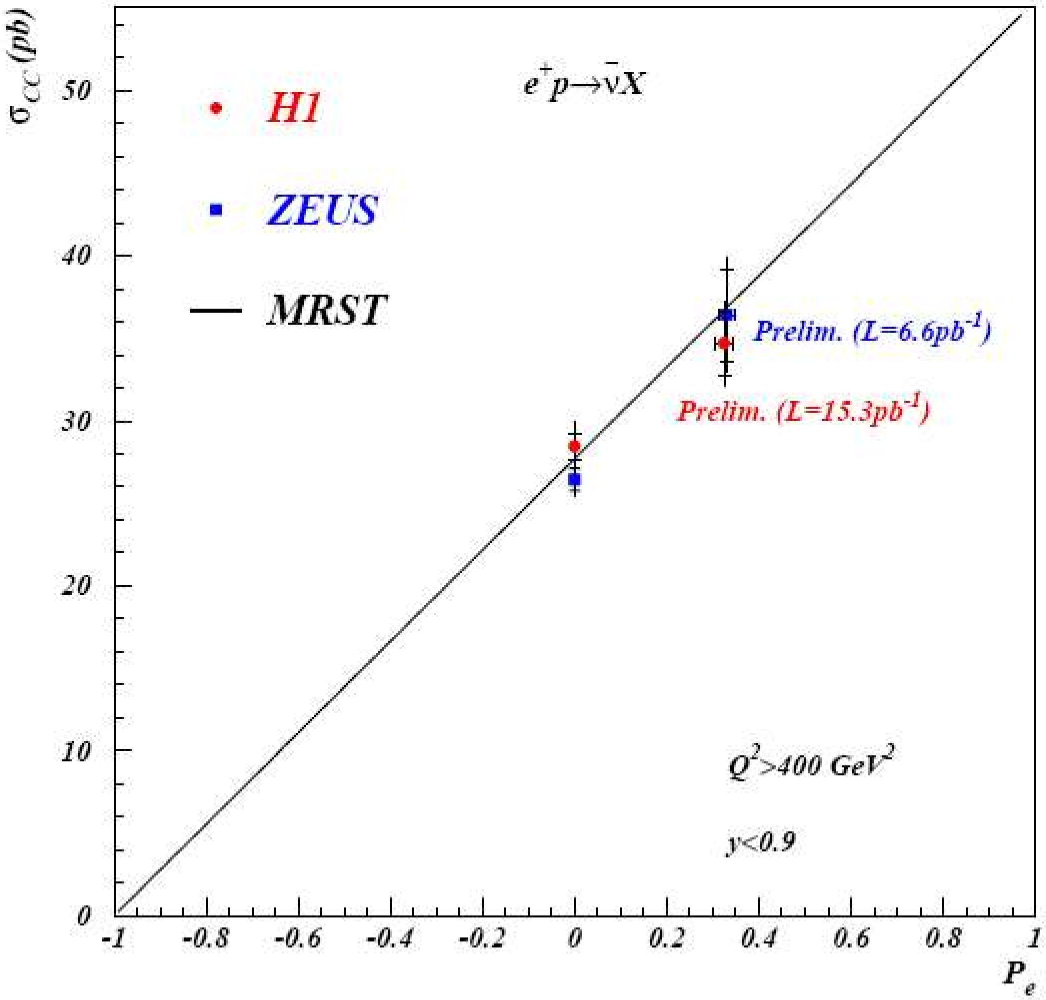


- Electron beam naturally transversely polarised
- Spin Rotators at IP give longitudinal polarisation
- Polarimeters provide independent polarisation measurements



Quick rise-time to a constant value

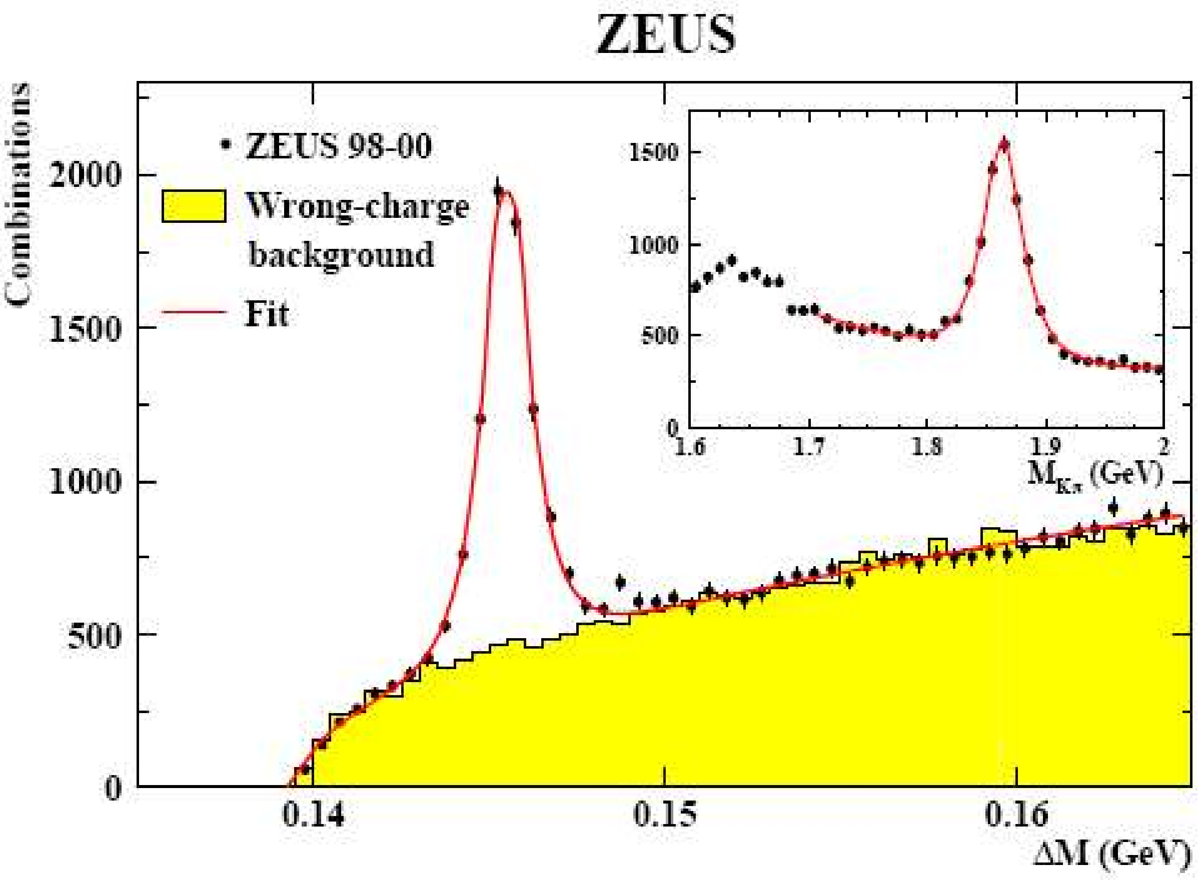

Average HERA polarisation (LPOL and TPOL)
October 2003
November 2003
December 2003
LPOL
TPOL
Polarisation [%]
Day in month
January 2004
February 2004
March 2004
April 2004
May 2004
June 2004
+ve
+ve
-ve



- First Measurement of helicity dependence of ep →ν X
- Expect a linear dependence from SM
- ZEUS+H1 measurements in agreement + with SM
- Expect data with -ve P soon +NC

Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

Method 1: D^*



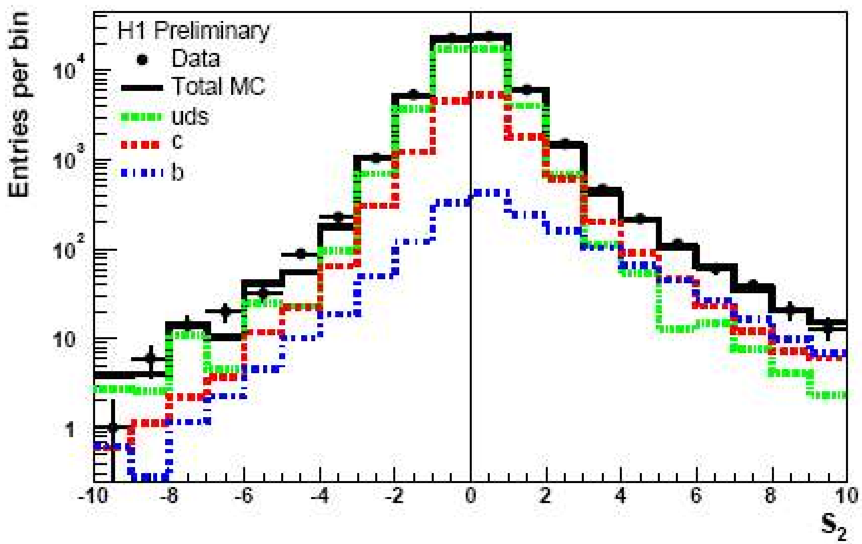
- Access charm by

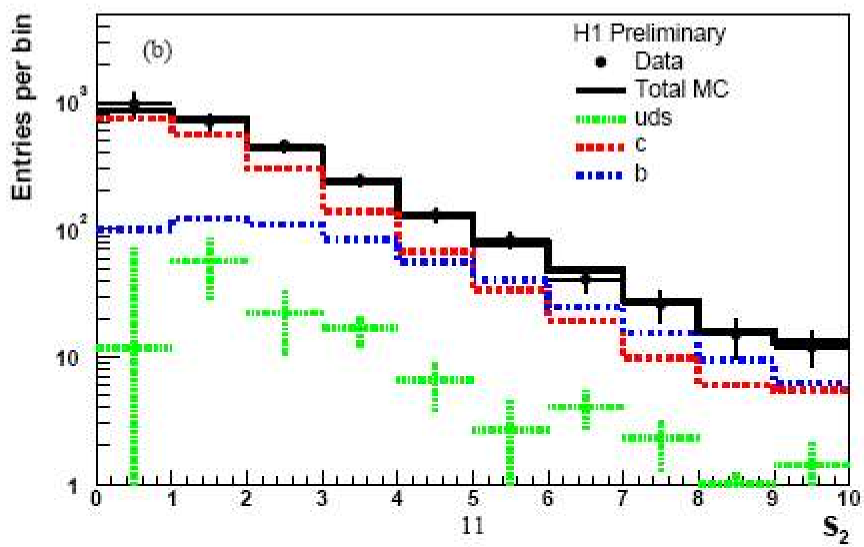
$$c \rightarrow D^{*\pm} \rightarrow K^{\pm}\pi^{\pm}\pi^{\mp}$$

- Correct for branching fractions and unseen phase space (low P_T of D^*)

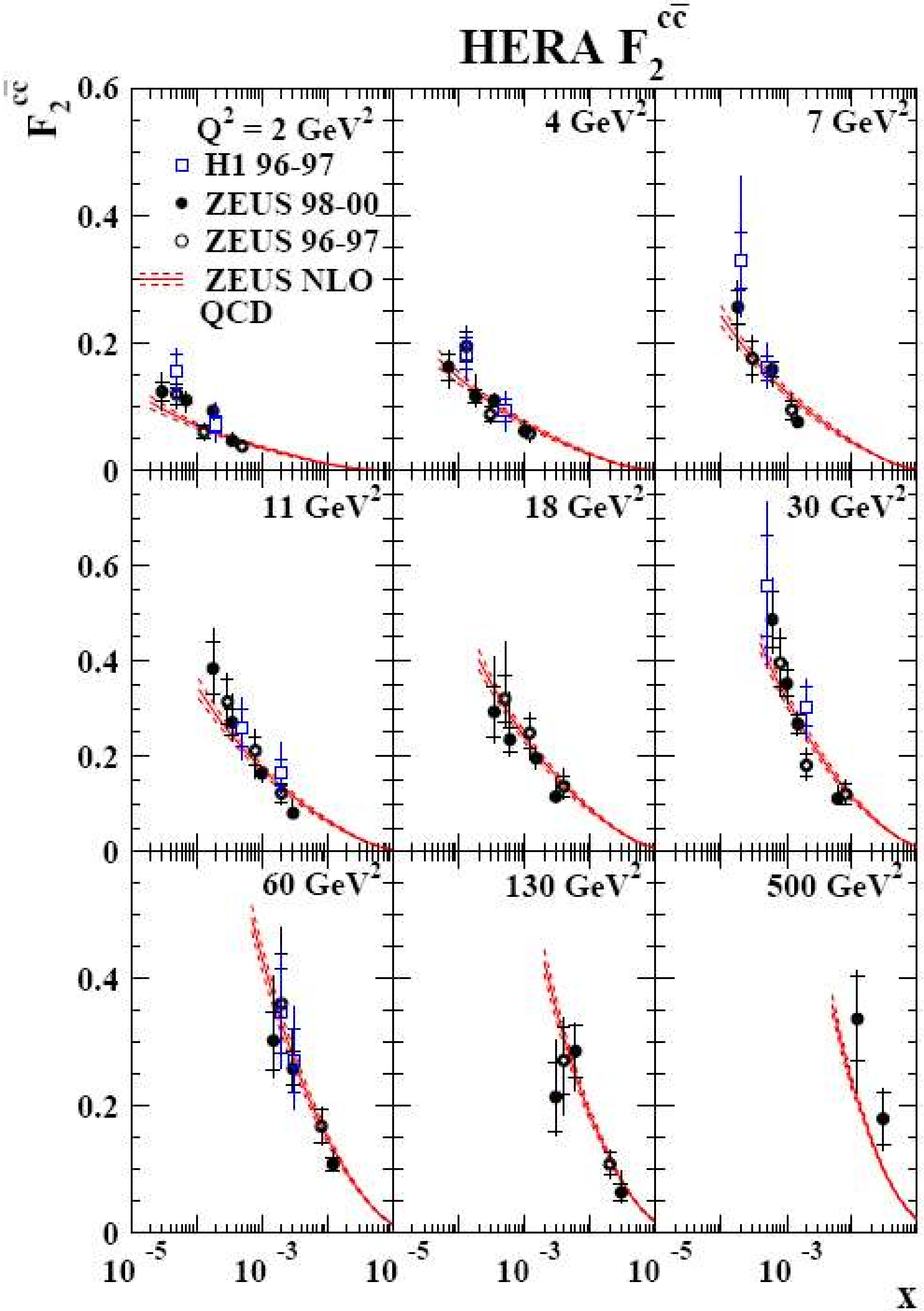
- Only used for $F_2^{c\bar{c}}$

Method 2: Displaced tracks



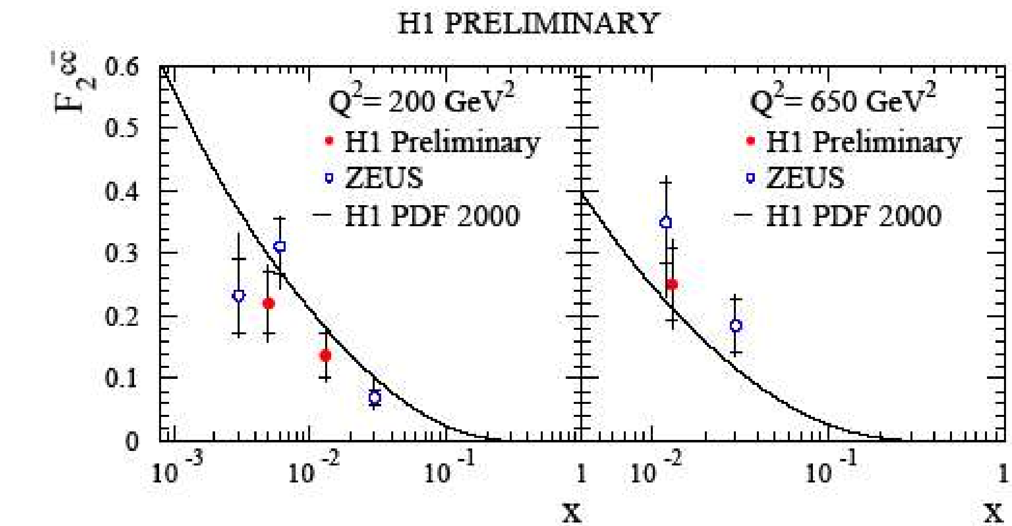


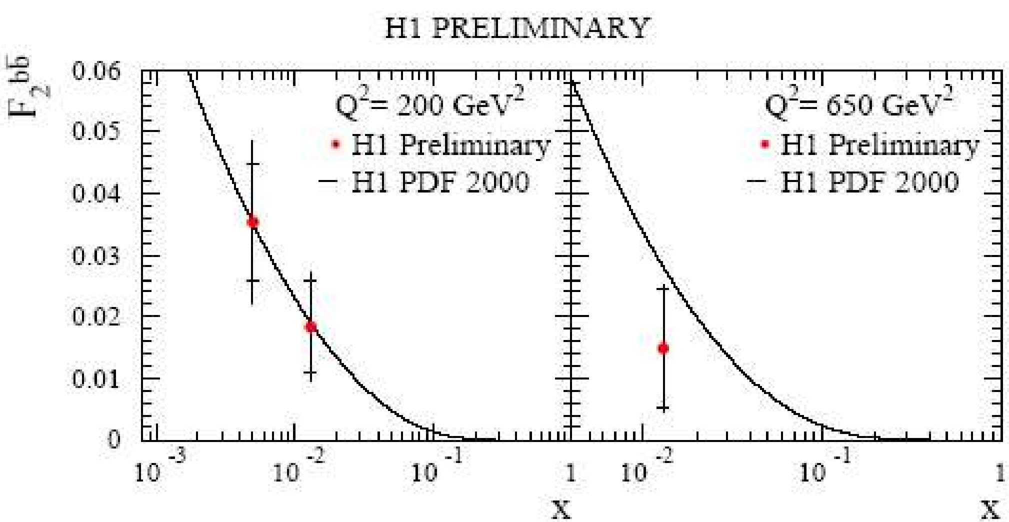
- Use S=DCA/σ(DCA) of track to vertex
- Take highest S for events with 1 reconstructed track
- Take 2nd highest S for events with 2 reconstructed tracks
- Subtract -ve bins from +ve
- Fit distributions for *c, b* and light quarks
- Minimal extrapolation needed to extract $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$
- Only done for high Q^2 so far



$F_2^{c\bar{c}}$ from D^*

- Measured over wide kinematic range
- Good agreement H1/ZEUS
- Good agreement with SM





$F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ from displaced tracks

- $F_2^{c\bar{c}}$ good agreement with D^* method + with SM
- First mesurement of $F_2^{b\bar{b}}$
- $F_2^{b\bar{b}}$ good agreement with SM
  - no evidence for excess
- Agreement also good with different QCD models (massive/massless/ VFNS) + PDFs

Summary

- Inclusive mesurements from HERA I have greatly added to our understanding of the structure of the proton
- Parton distribution functions have errors of a few % over most of the *x* range
- Inclusive measurements have achieved a very competative measurement of α_s
- First measurements of polarised CC cross section consistent with a linear dependence as in SM
- Semi-inclusive charm and bottom show we have a good understanding of QCD and the PDFs