Proton Structure at 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

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HERA collides e and p

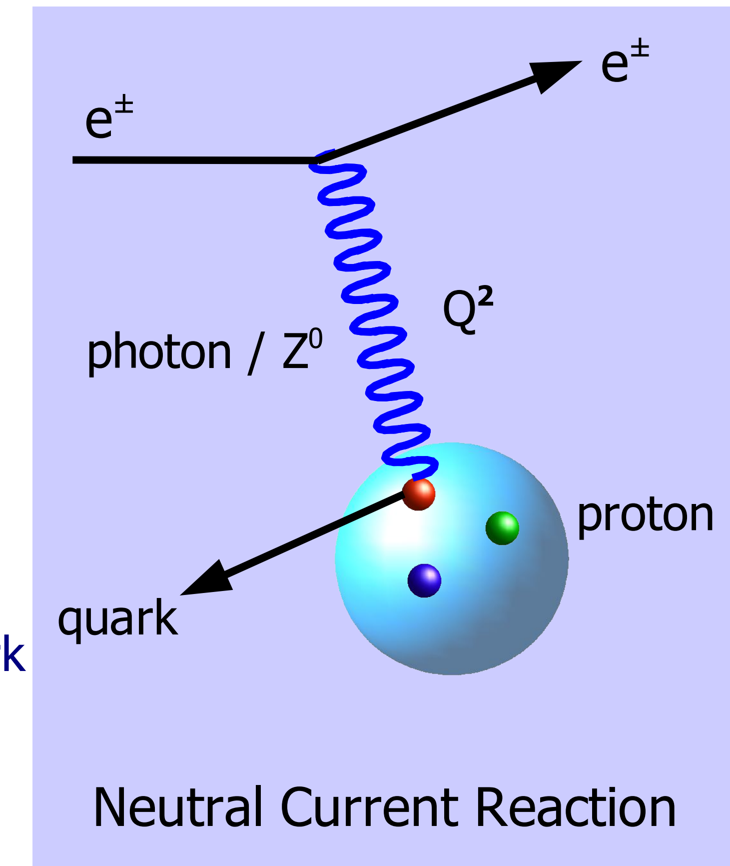
study strong, electromagnetic & weak forces through Deep Inelastic Scattering

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

$Q^2 = s \; x \; y$

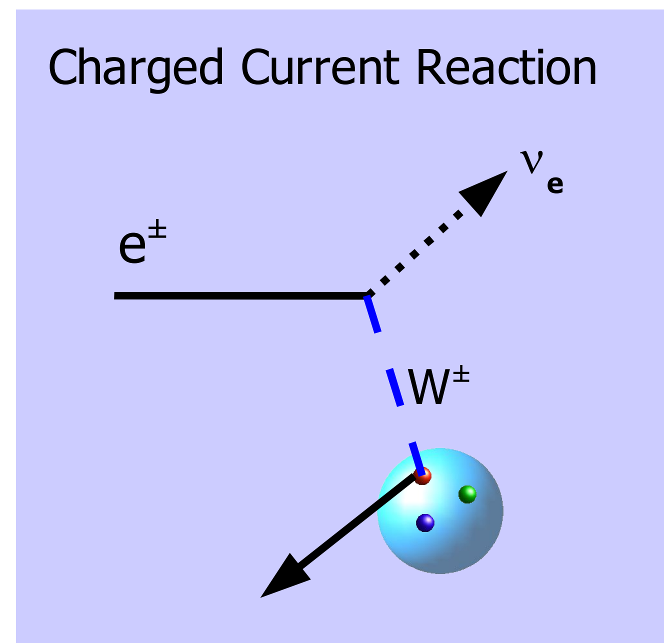
Q^2 = "resolving power" of probe

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



x = momentum fraction of proton carried by quark

HERA: $\sim 10^{-6}$ - 1

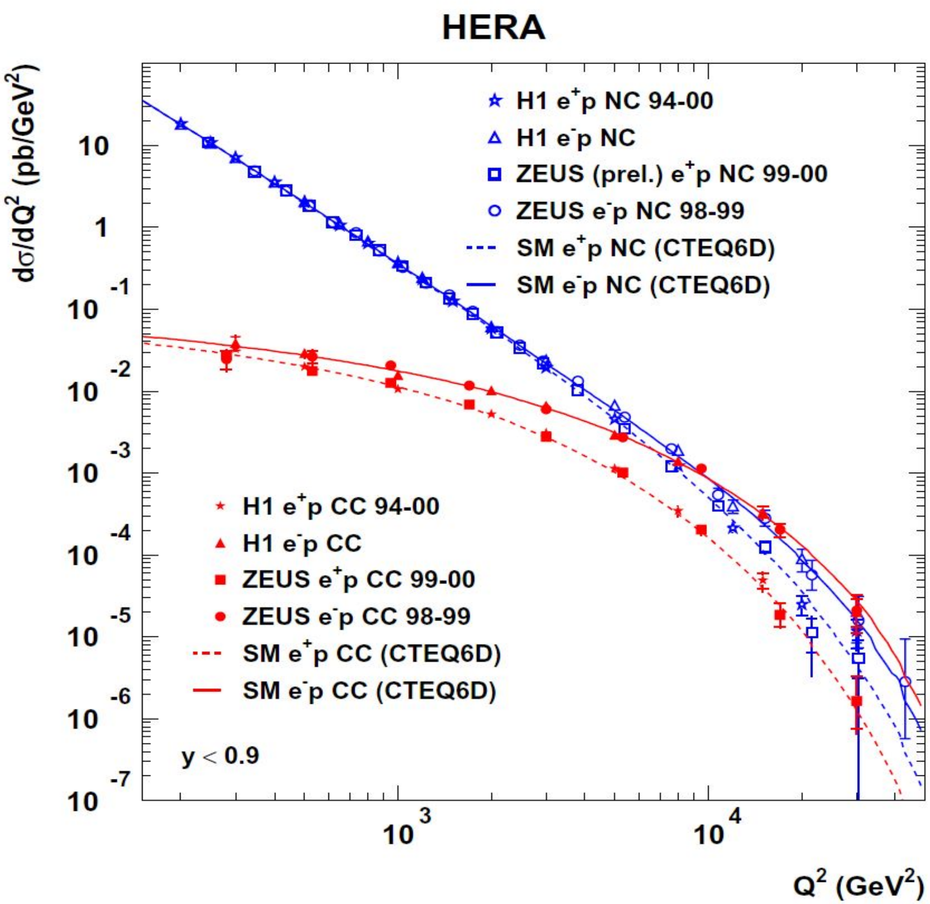


$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} \approx \frac{e^4}{8\pi\, x}\left[\frac{1}{Q^2}\right]^2\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

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

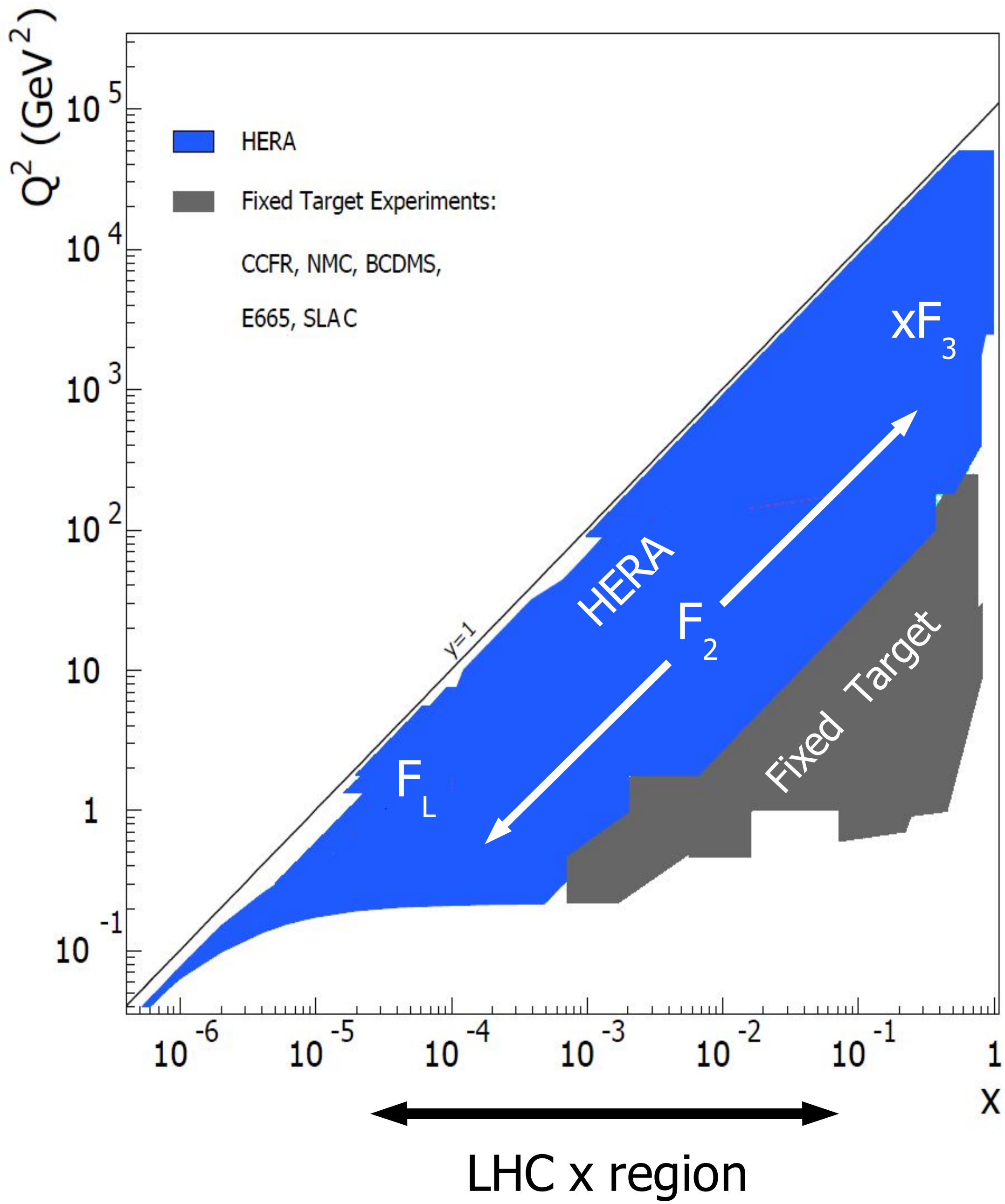
$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$ — only sensitive at high Q^2

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

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

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

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



Conventional QCD evolution only tells us Q^2 dependence

x dependence must come from data

Method:

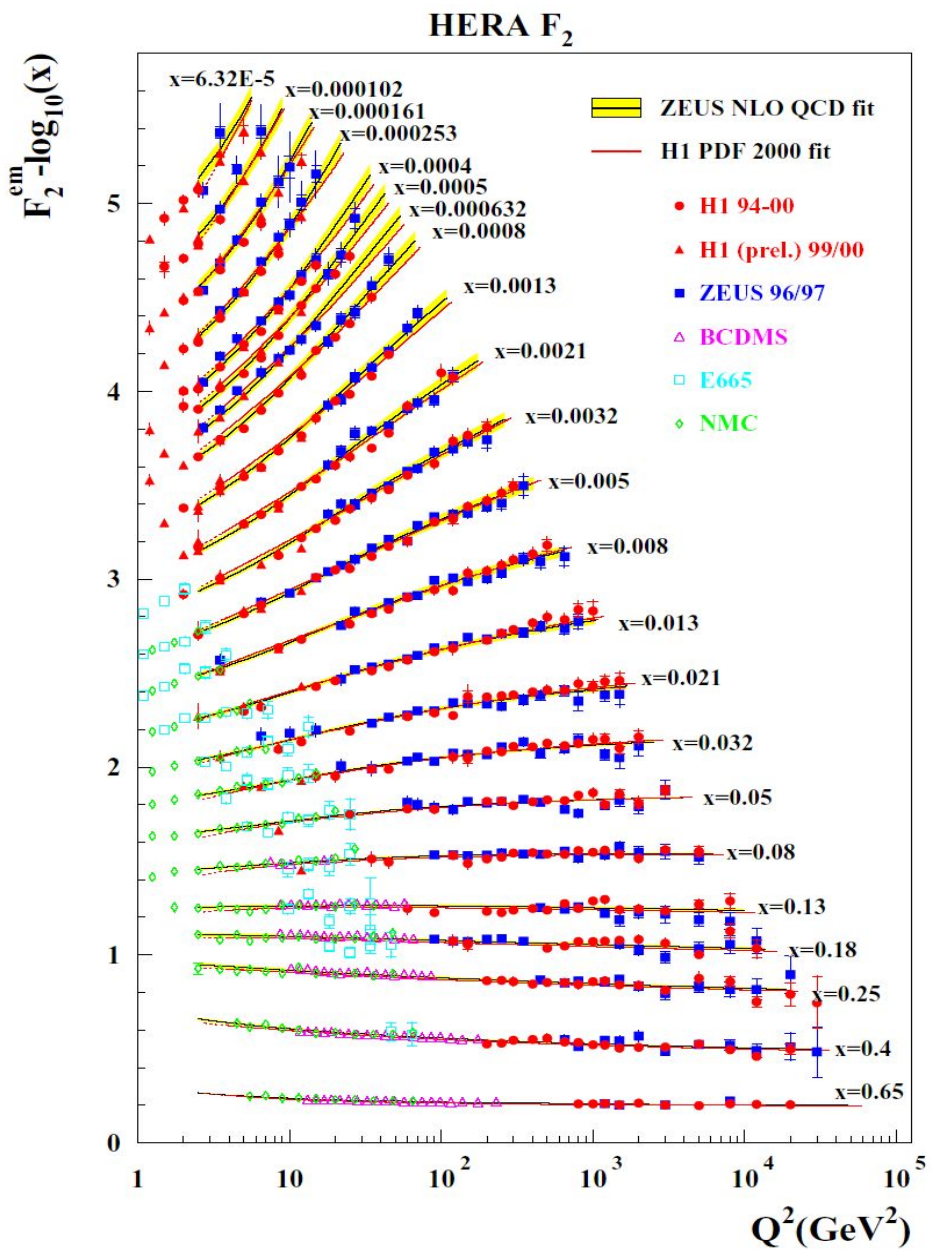
Measure cross sections

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

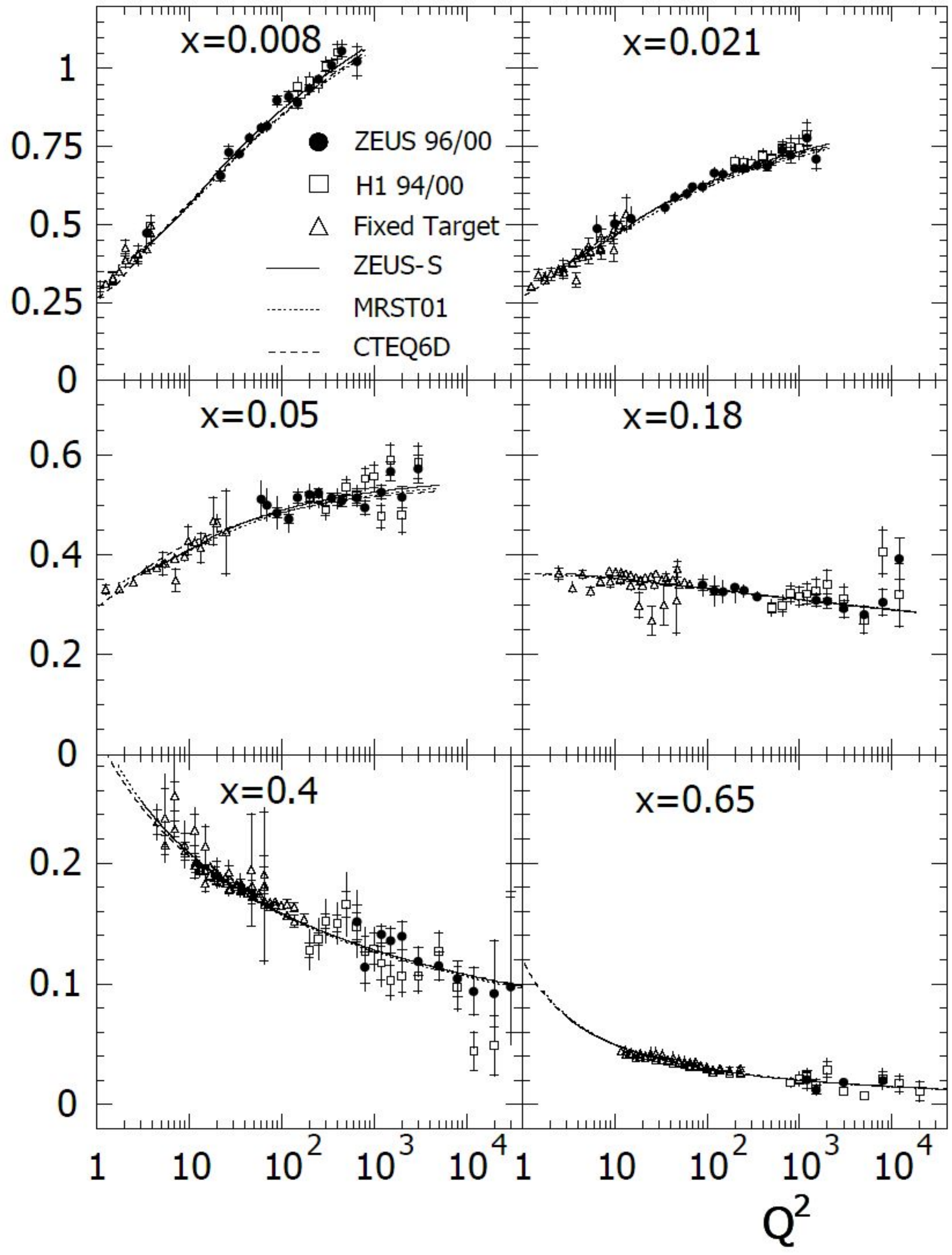
Range in x: 0.00001 – 1

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

Measured with ~2-3% precision

Directly sensitive to sum of all quarks and anti-quarks

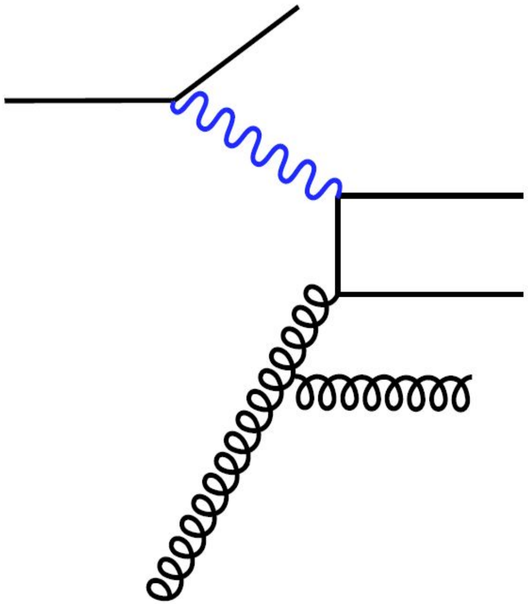
Indirectly sensitive to gluons via QCD radiation - scaling violations



Dramatic scaling violations at low x

driven by gluon

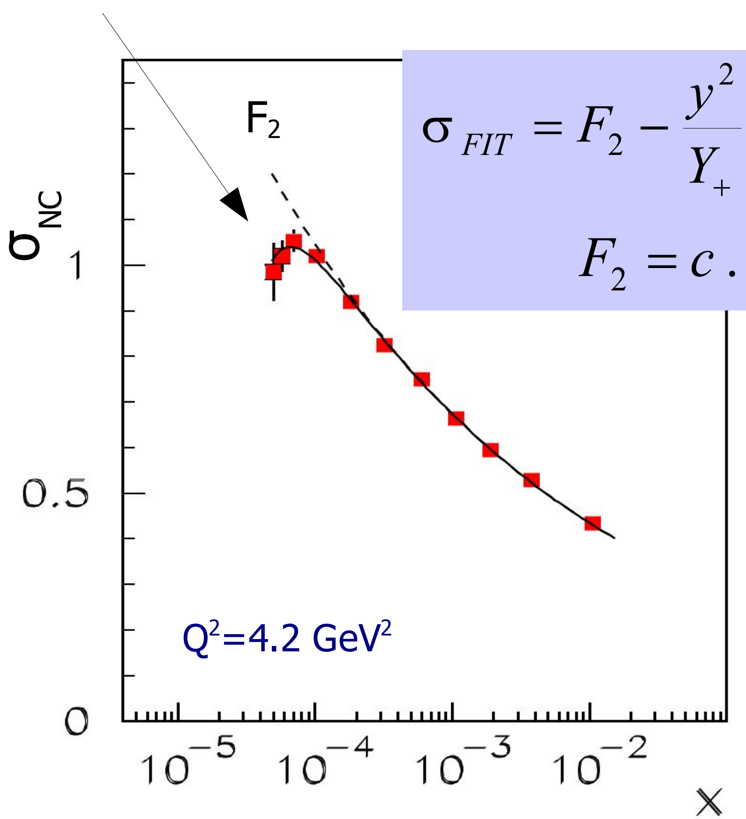
described by QCD



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

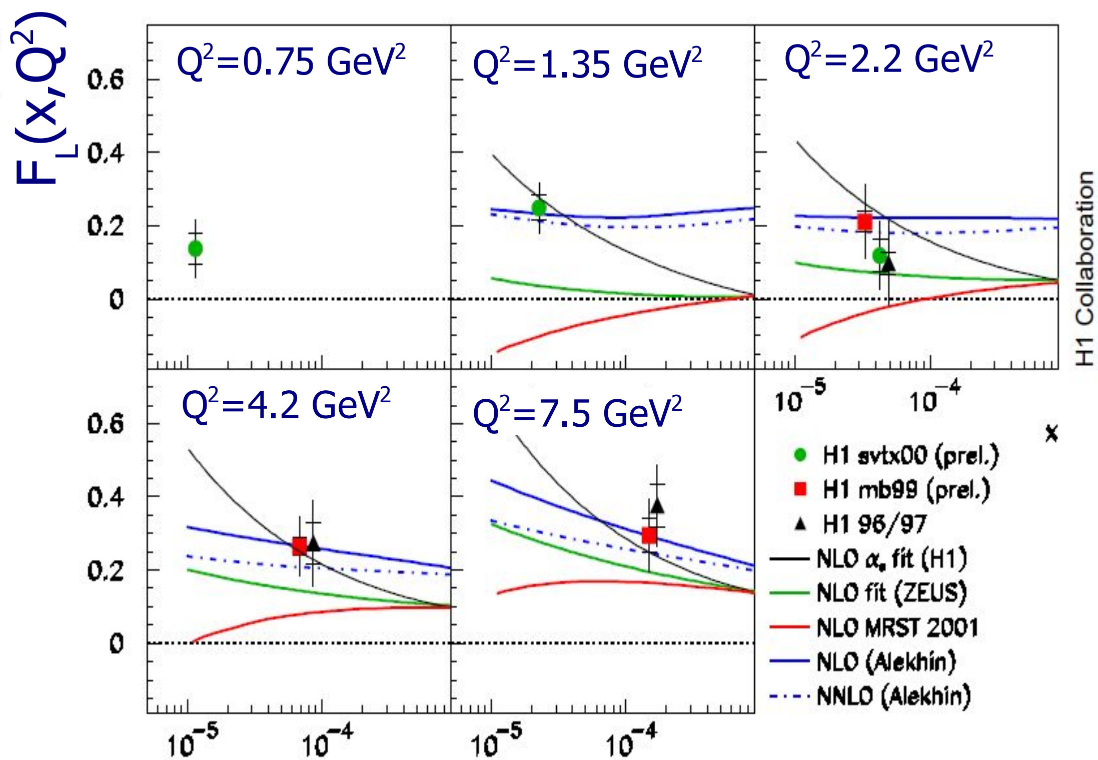
F_L is directly sensitive to gluon

σ_{NC} sensitive to F_L only at high y



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

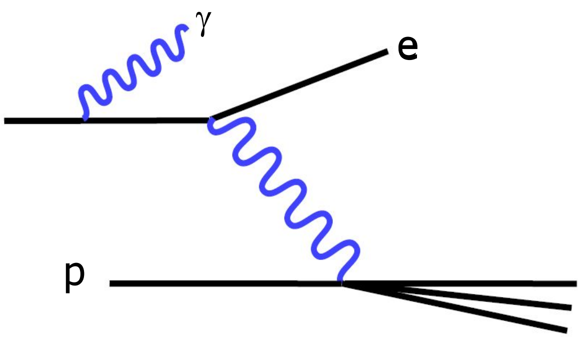
$$F_2 = c \, . \, x^{-\lambda}$$



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

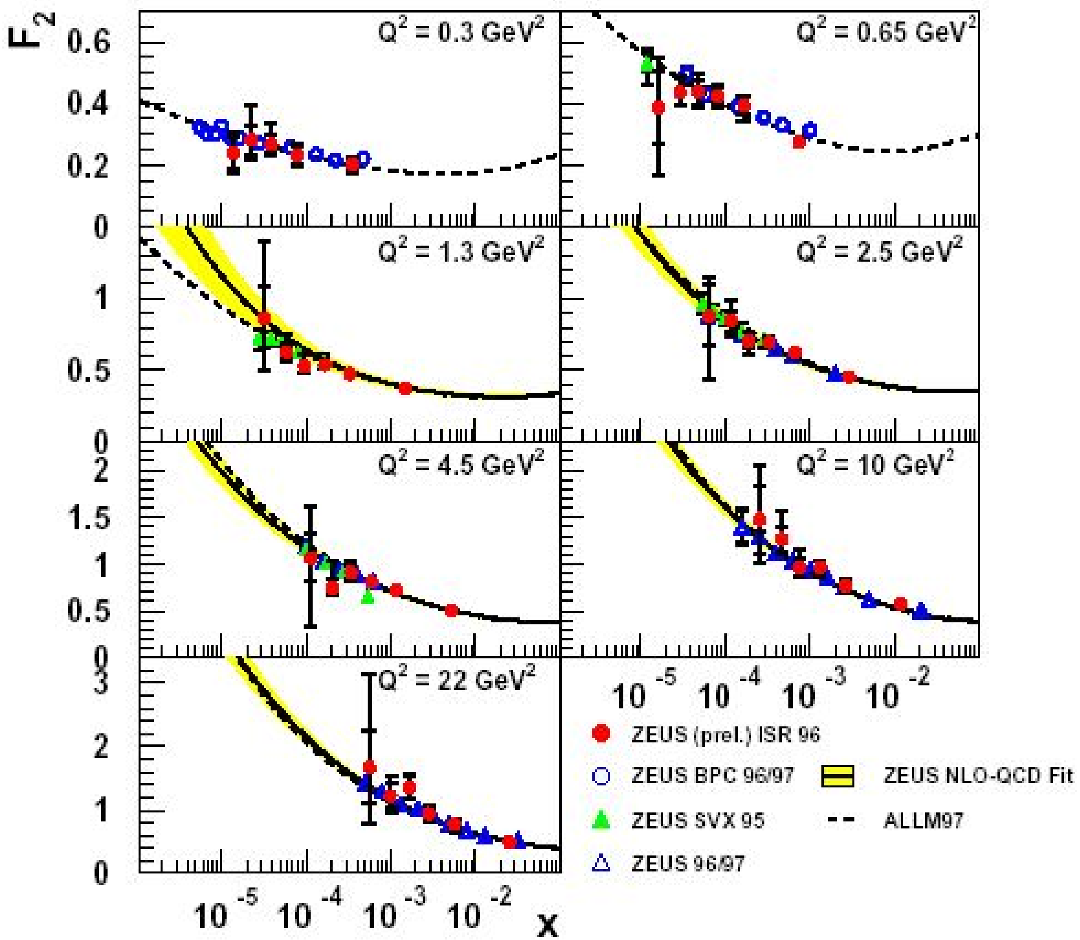
Whole x-range of measured data used to fit F_2 and F_L

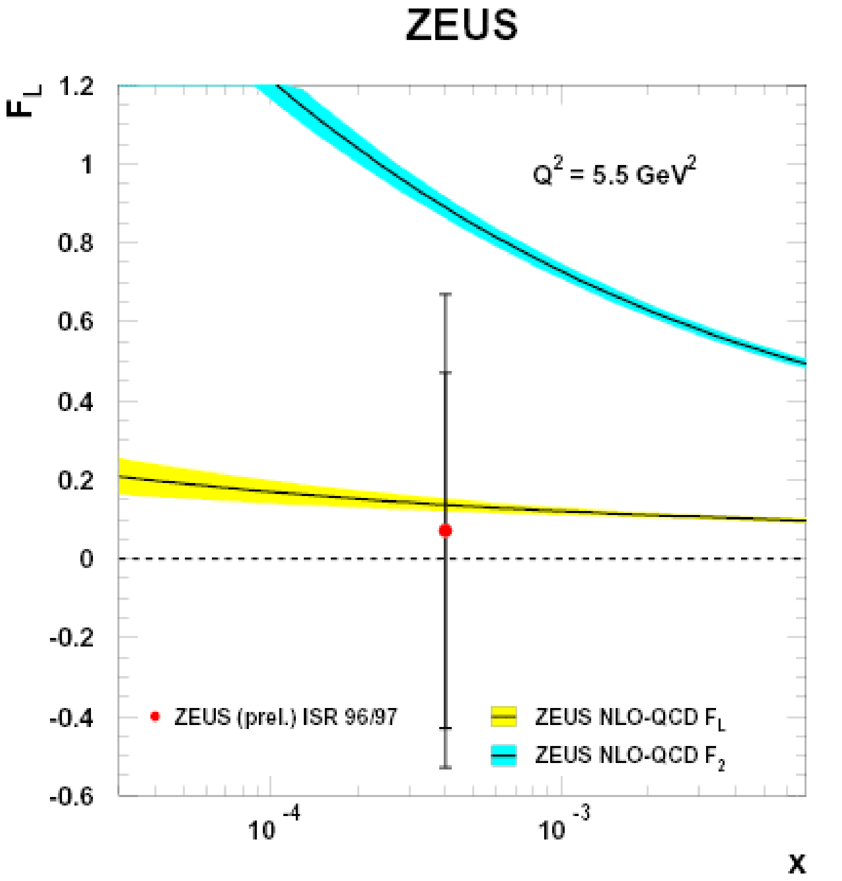
no extrapolation of F_2 - smaller errors

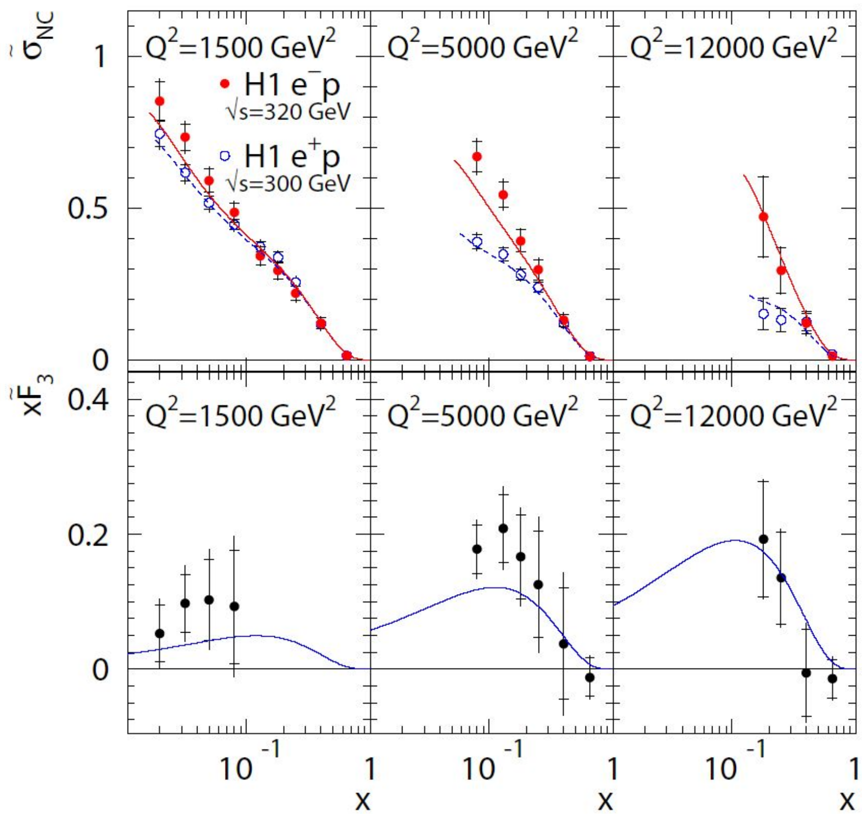


- Initial state radiation reduces $\sqrt{s}$
- At fixed x, Q^2 then y is different
- Changes contribution of F_2 and F_L
- Measure σ_{NC} vs y: fit for F_L

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







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

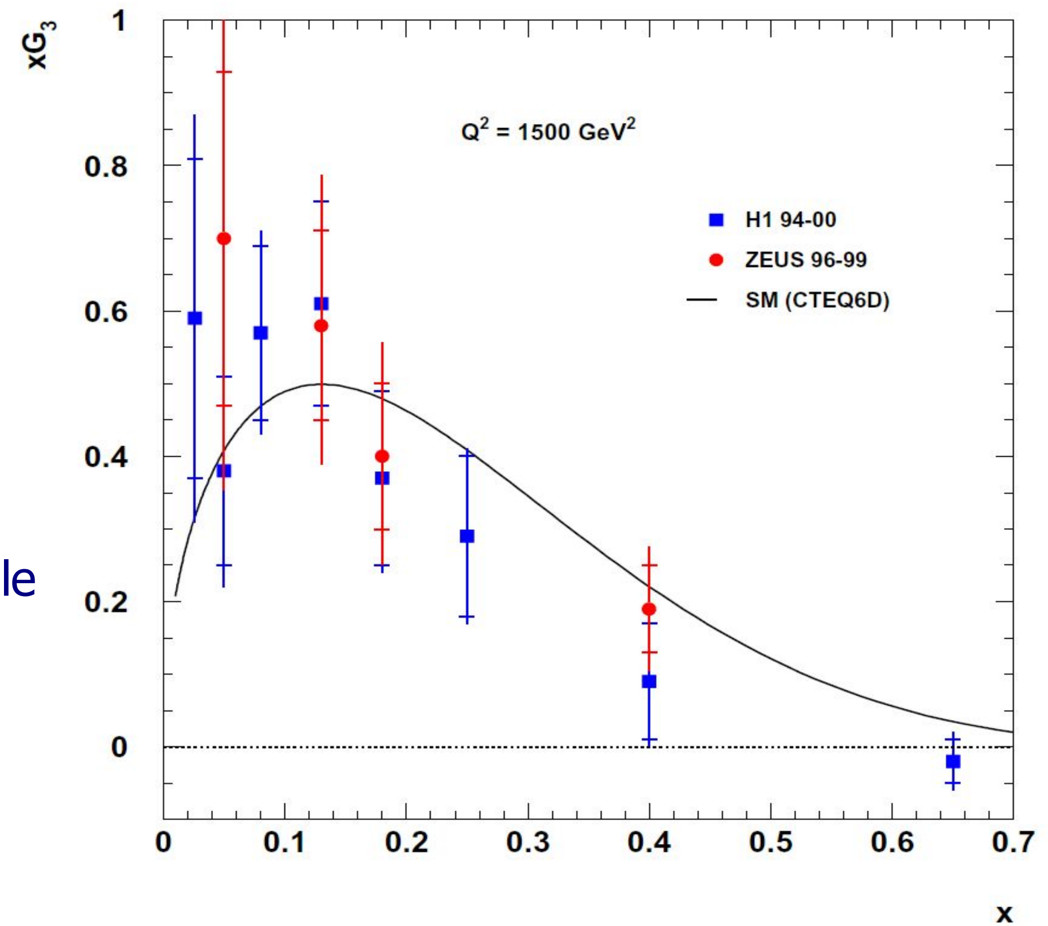
$$\tilde{\sigma}^{\pm}_{NC} \sim \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

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



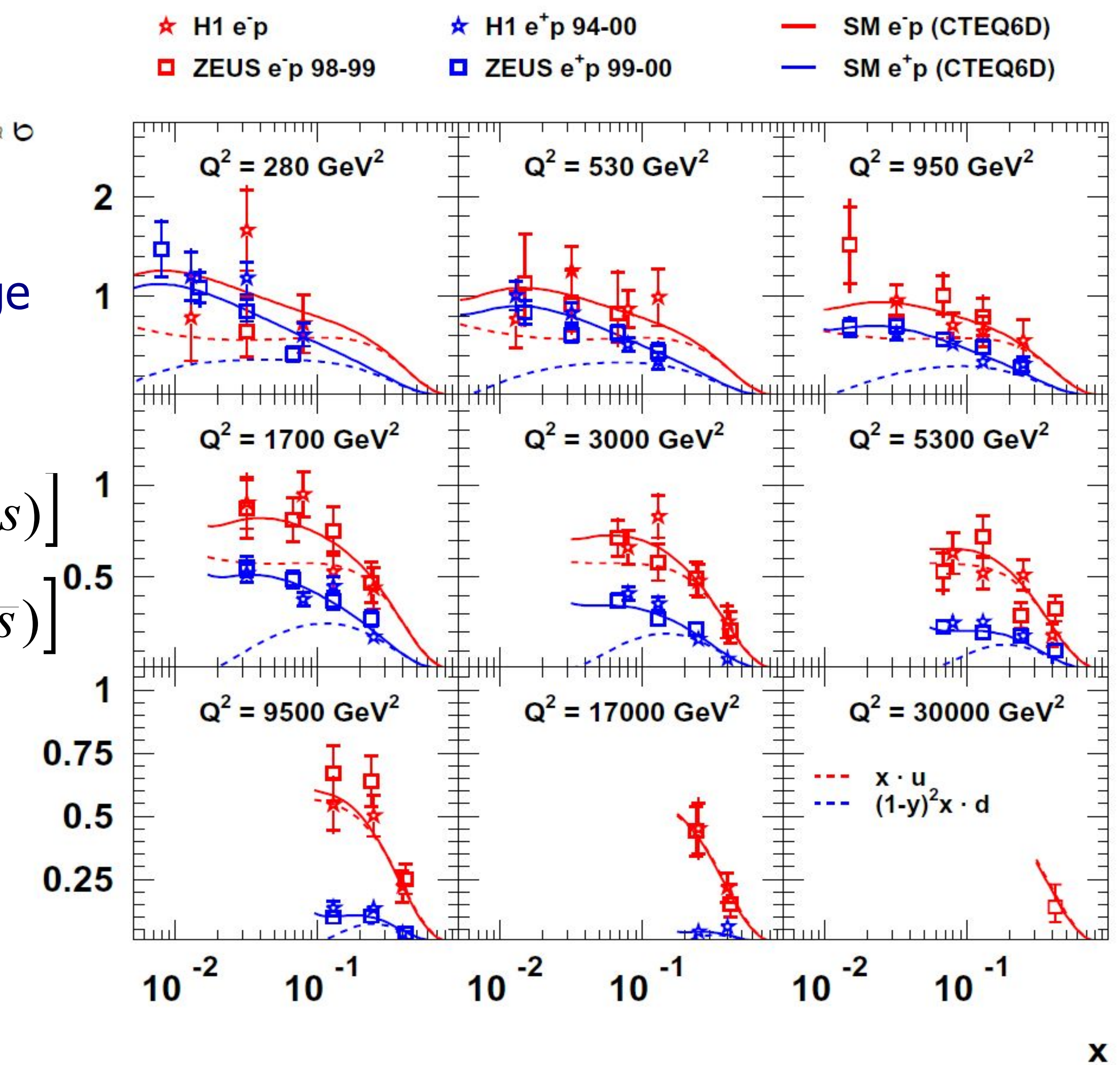
Charged current process provides sensitivity to quark flavour

Cross sections small due to large W mass in propagator

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

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

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

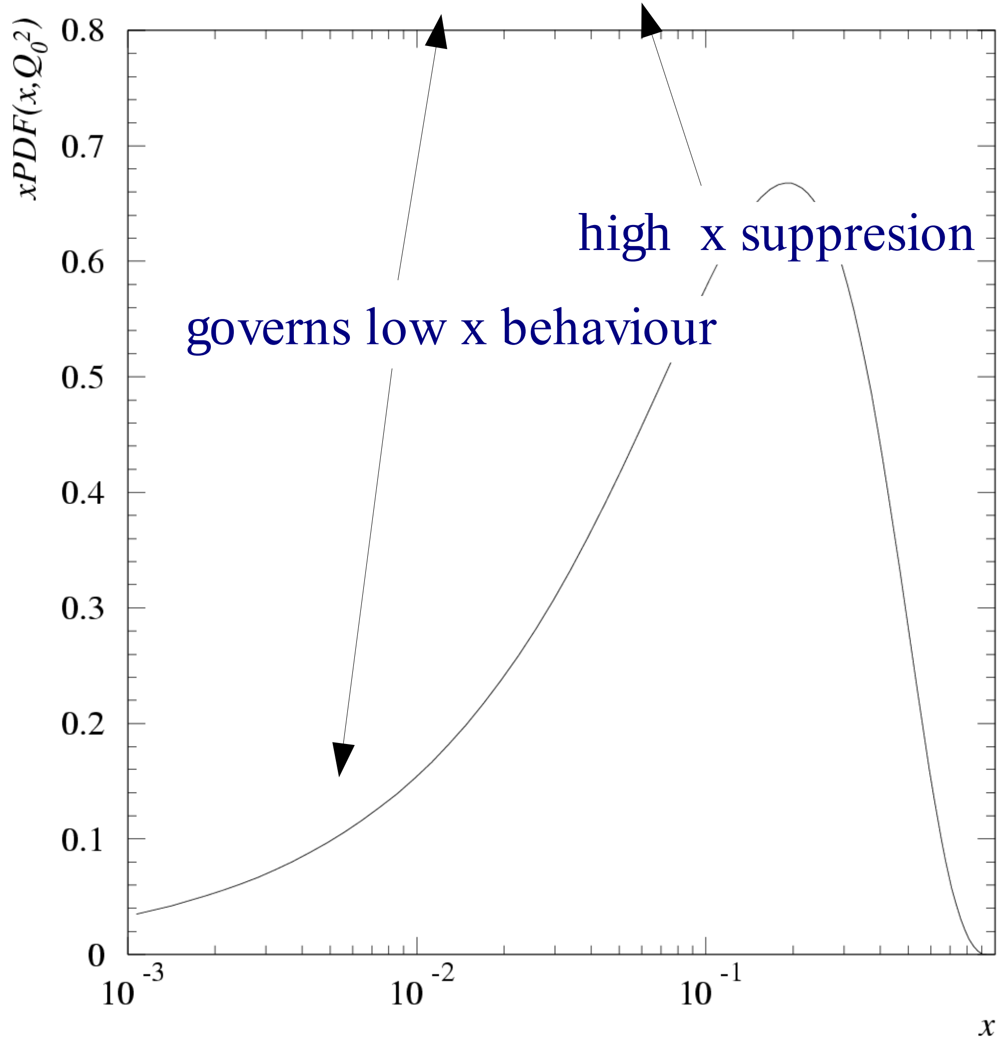


QCD analyses require many choices to be made
Should be reflected in PDF uncertainty:

- Q_0^2 starting scale
- Choice of data sets used
- Cuts to limit analysis to perturbative phase space (Q^2_{min})
- Choice of densities to parameterise (e.g. u_v, d_v, xg, xS)
- Treatment of heavy quarks
- Allowed functional form of PDF parameterisation
- Treatment of experimental systematic uncertainties
- Renormalisation / factorisation scales
- Choice of α_s
- etc...

PDFs parameterised at starting scale Q_0^2

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



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

Choosing parameterisation is something of an art!

Unclear how to include choice of parameterisation in PDF uncertainty

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 world structure function data

ZEUS 96/97 NC e^+ reduced cross sections	gluon / quarks at low x / Q^2
F_2 NMC p &D and ratio F_2 D/p	quarks at medium x
F_2 E665 p & D	quarks at medium x
F_2 BCDMS p only	u quarks at high x / low Q^2
xF_3 CCFR (0.1 < x < 0.65)	valence quarks at high x / low Q^2

- 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 = $A \,.\, x^b \cdot (1-x)^c \cdot (1 + dx + ex)$
- 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

Careful choice of parameterisations search for χ^2 saturation

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

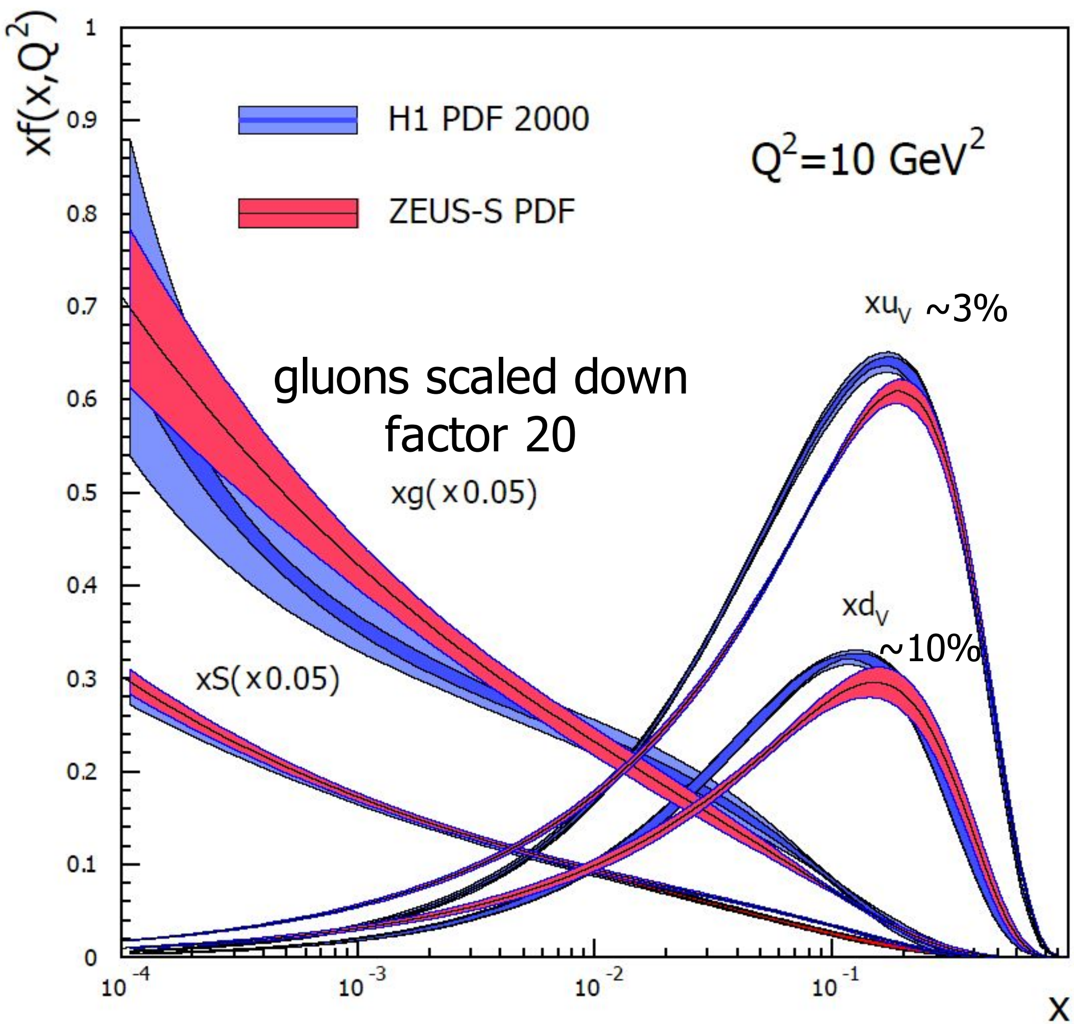
Use BCDMS p and D data as cross check only

Similar technique used for dedicated H1+BCDMS fit for gluon + α_s

Check for consistency of H1 & BCDMS datasets first

H1: χ^2 / ndf = 0.88 (621 data points, 10 pars.)

ZEUS: χ^2 / ndf = 0.95 (1263 data points, 11 pars.)



HERA able to extract PDFs w/o external input

PDFs broadly agree at low x (HERA data)

Discrepancies in med-high x region

CTEQ6 lies between the two fits

Some uncertainties unaccounted?

- data sets inconsistent?
- missing theory
- PDF parametric forms?
- different assumptions

H1: 0.1150 +-0.0017(exp)
+0.0009 -0.0007(model)

if: systematic errors are not fitted: +0.0005

NMC replaces BCDMS 0.116±0.003 (exp)

4 light flavours: +0.0003

BCDMS deuteron data added: 0.1158 ± 0.0016 (exp)

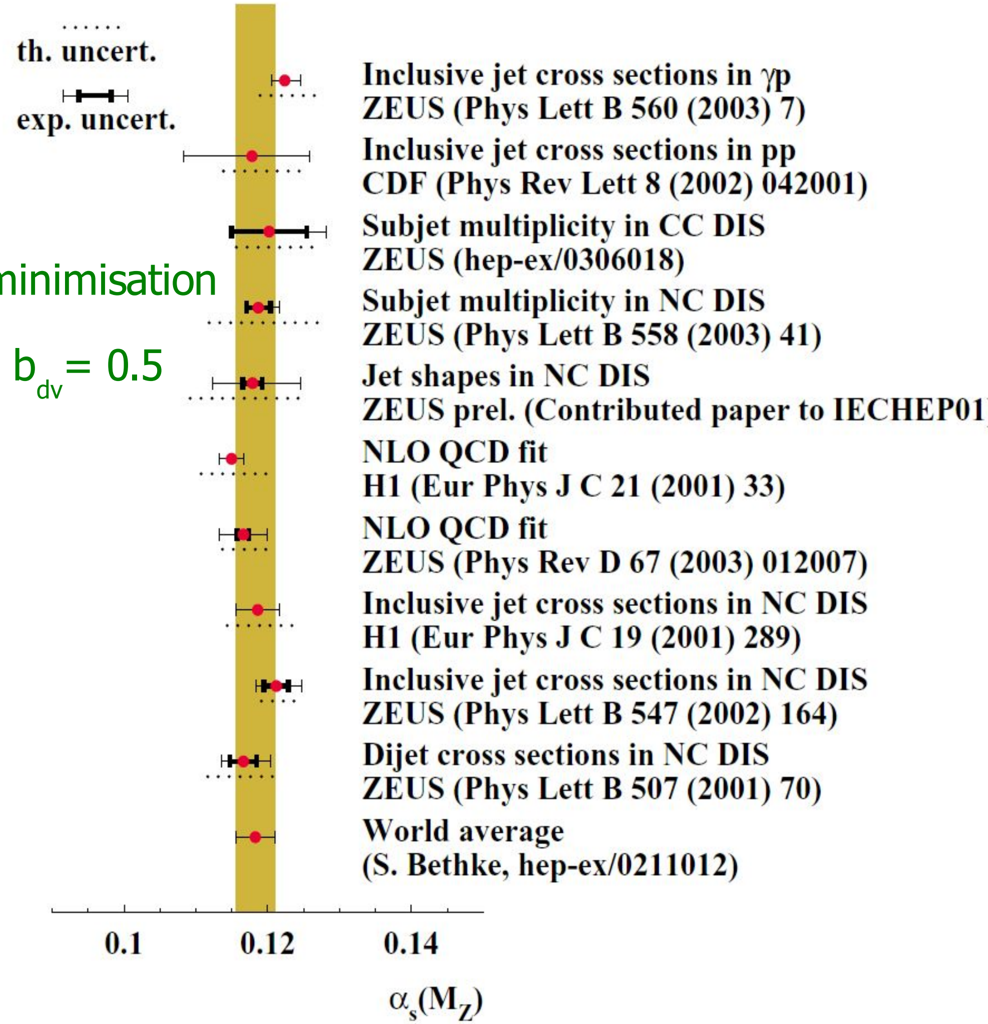
ZEUS: 0.1166 ±0.0008(unc) ±0.0032(corr)
±0.0036(norm) ±0.0018(model)

systematic errors are not allowed to vary in chi2 minimisation

$Q^2 > 2.5\ GeV^2$, $W^2 > 20 GeV^2$, RT-VFNS, $b_{uv} = b_{dv} = 0.5$

fit α_s, xg, uv, dv, sea, dbar-ubar (MRST)

if fixed flavour scheme is used: +0.0010



Large χ^2 variations if renormalisation scale is varied: ±20 units !

→ (¼ .. 4) : ± 0.005 (H1)

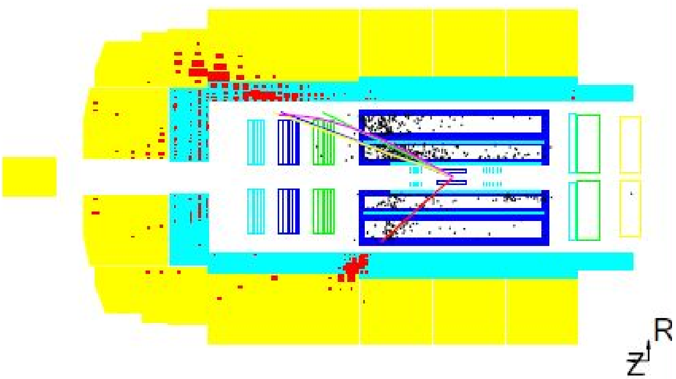
→ (½ .. 2) : ± 0.004 (ZEUS)

Variations of factors 2 or 4 are ad hoc

Largest single uncertainty in determination of α_s

Expected to be reduced in a NNLO analysis

NC: Q^2=13500 GeV^2



HERA-II now in production Lumi mode

Experiments no longer limited by background

Machine routinely delivering almost 2 pb^{-1} per week

Analysis of new data in progress...

High Q^2 events recorded recently in new data

CC: Q^2=6000 GeV^2