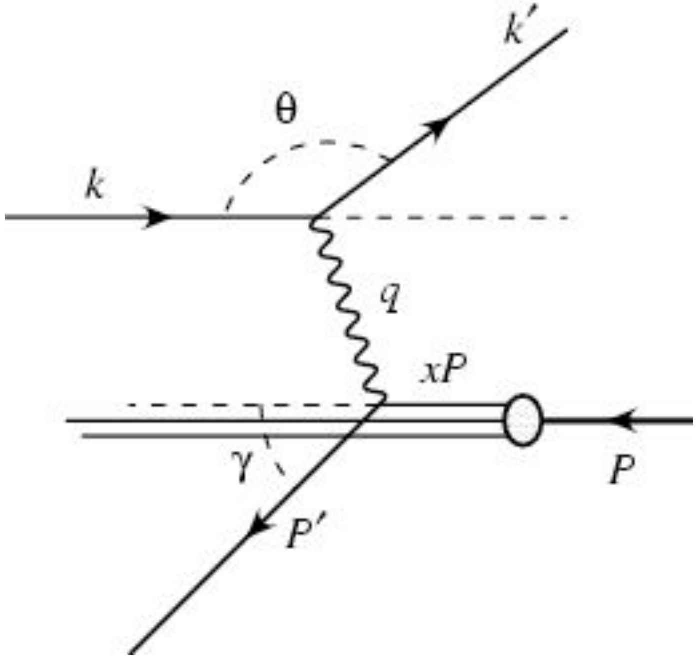
Probing proton structure in high-energy ep collisions

Alex Tapper
Imperial College London
For the H1 & ZEUS Collaborations

Deep inelastic scattering at HERA



- Probing the proton at small distance scales

$$Q^2 = -q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2p\cdot q} \qquad y = \frac{p\cdot q}{p\cdot k}$$

$$s = (p + k)^2 \qquad Q^2 = x\cdot y\cdot s$$

- Q^2 is the “probing power”
- x is the Bjorken scaling variable
- y is related to the scattering angle in CMS ($=\sin^2(\theta^*/2)$)

HERA I operation

e^+/e^-

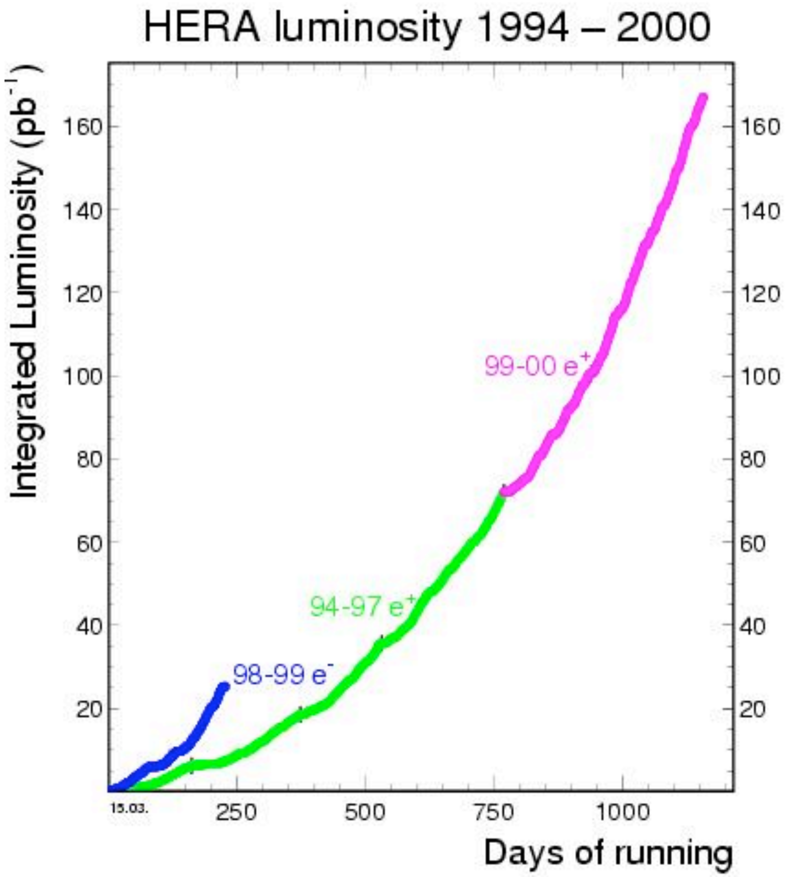
27.5 GeV

p

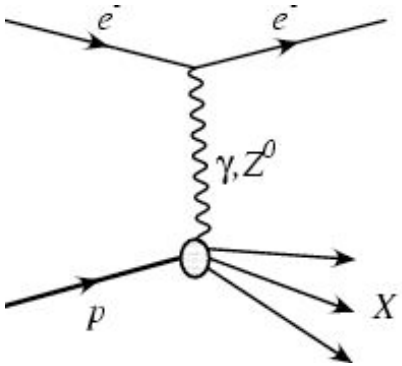
820 GeV 1994-97

920 GeV 1998-00

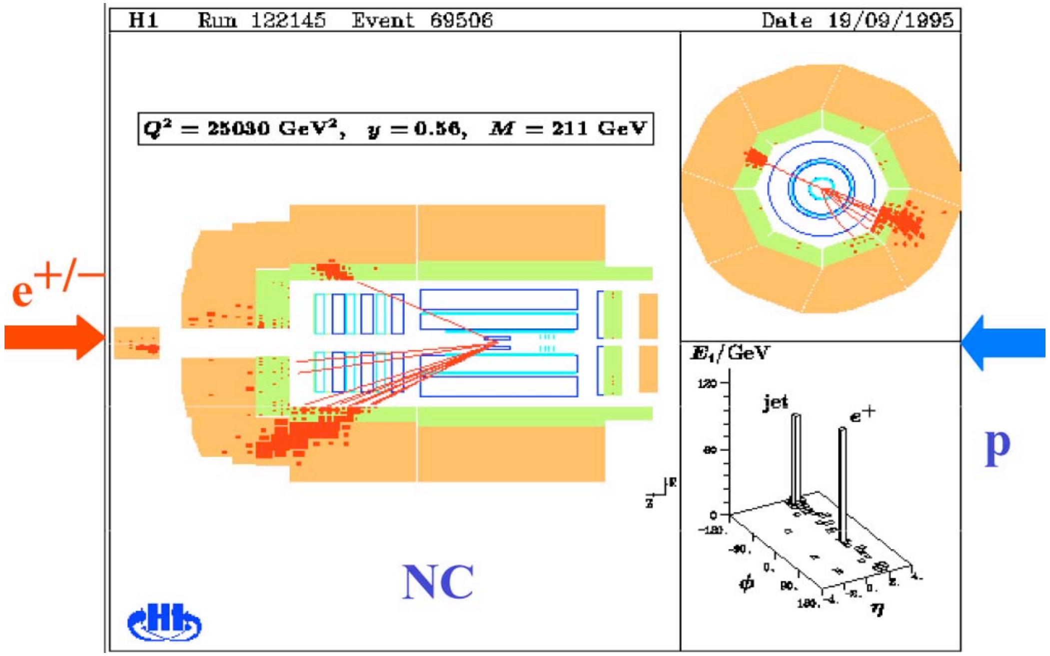
	e^+p	e^-p
H1	~100 pb^{-1}	~16 pb^{-1}
ZEUS	~110 pb^{-1}	~16 pb^{-1}



The H1 detector



Isolated electromagnetic cluster with matching track



- Liquid argon calorimeter
- 45000 cells
- EM:

$$\frac{\sigma(E)}{E} = \frac{12\%}{\sqrt{E}} \oplus 1\%$$

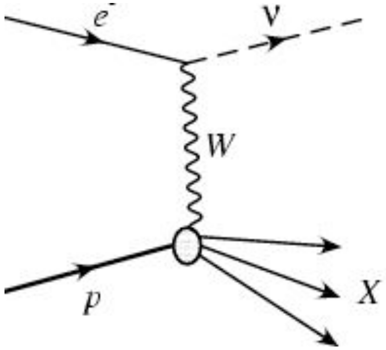
- Systematic 0.3-3%

- HAD:

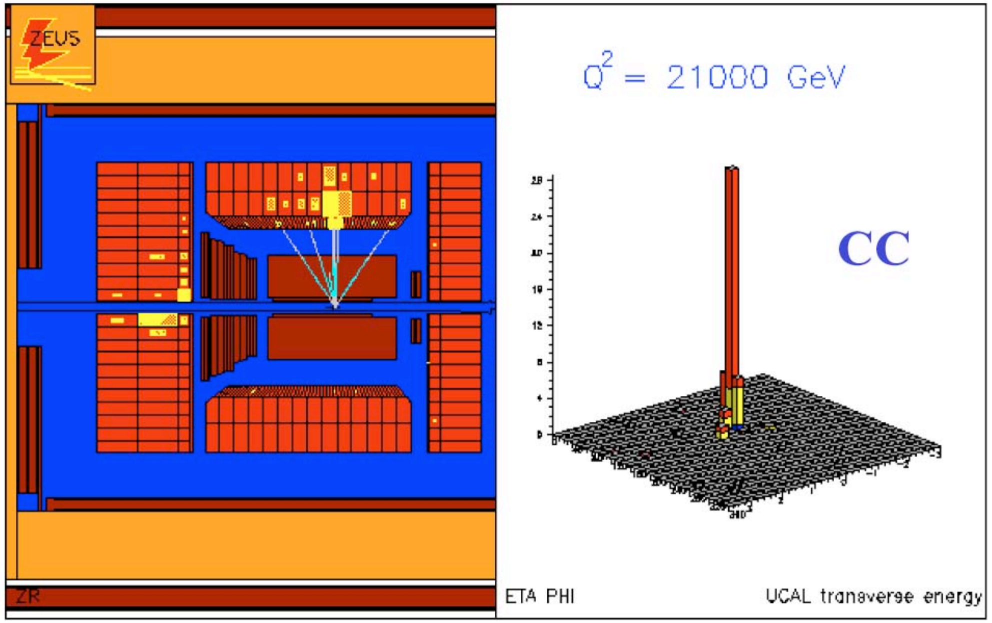
$$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 1\%$$

- Systematic 1.4-2%

The ZEUS detector



Missing transverse momentum from the neutrino



- Compensating depleted uranium calorimeter
- 6000 cells
- EM:

$$\frac{\sigma(E)}{E} = \frac{18\%}{\sqrt{E}}$$

- Systematic 1-2%

- HAD:

$$\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E}}$$

- Systematic 1%

DIS cross sections

NC Cross Section:

NC Reduced cross section: $\tilde{\sigma}_{NC}(x,Q^2)$

$$\frac{d^2\sigma^{NC}(e^\pm p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}Y_+\Big[\overbrace{F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3}\Big] \qquad Y_\pm = 1 \pm (1-y)^2$$

Dominant contribution

Sizeable only at high y

Contribution only important at high Q^2

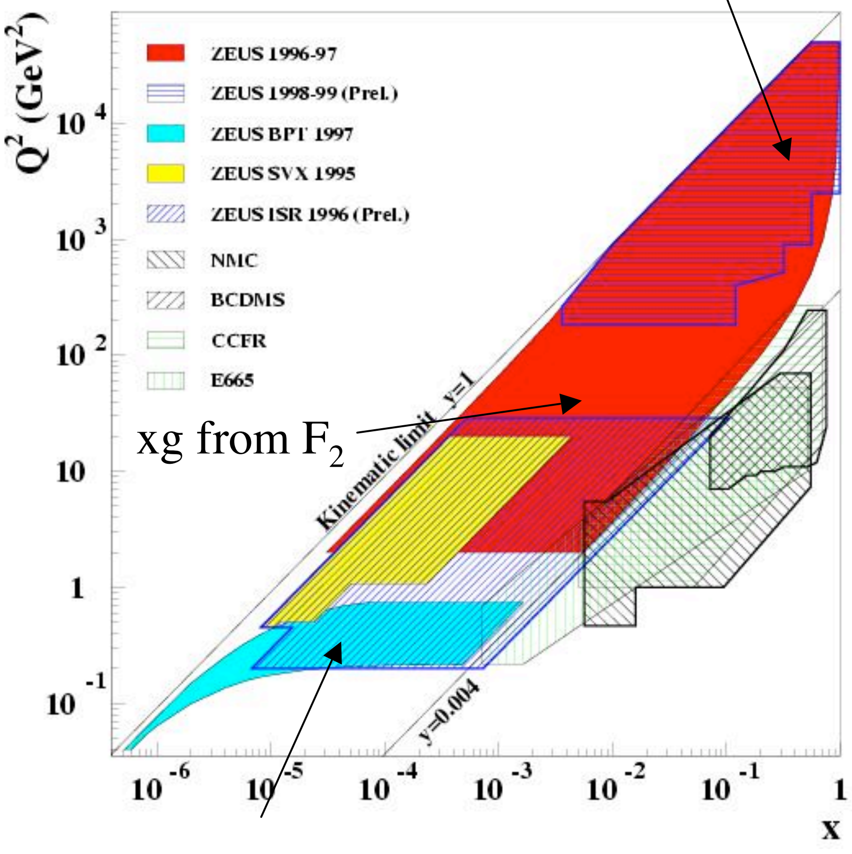
CC Cross Section:

$$\frac{d^2\sigma^{CC}(e^\pm p)}{dx\,dQ^2} = \frac{G_F^2}{4\pi x}\frac{M_W^4}{(Q^2+M_W^2)^2}\Big[\underbrace{Y_+F_2^{CC} - y^2F_L^{CC} \mp Y_-xF_3^{CC}}\Big]$$

CC Reduced cross section: $\tilde{\sigma}_{CC}(x,Q^2)$

Kinematic range of HERA data

- Overlap with fixed target data at low Q^2 and high x
- Gluon distn at low x
- Valence quarks at high x
- Access to non-peturbative region
- Measurements extend fixed target data to higher Q^2 and higher y
- Probe distances down to 1/1000 proton

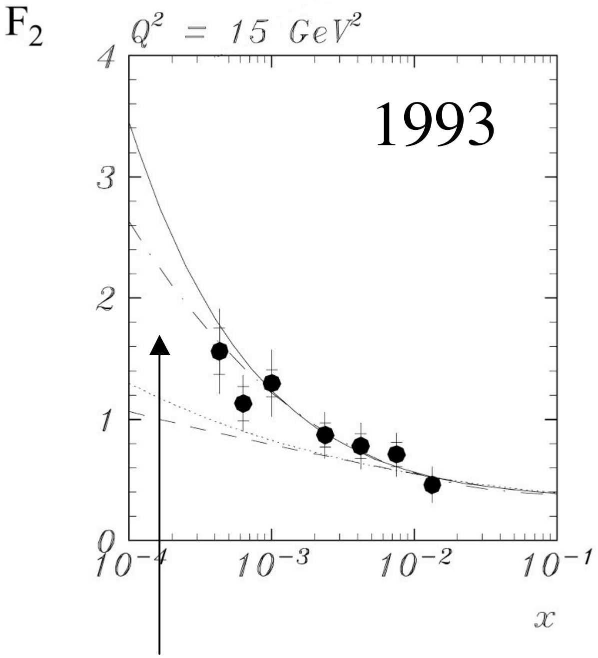


xF_3 & valence quarks

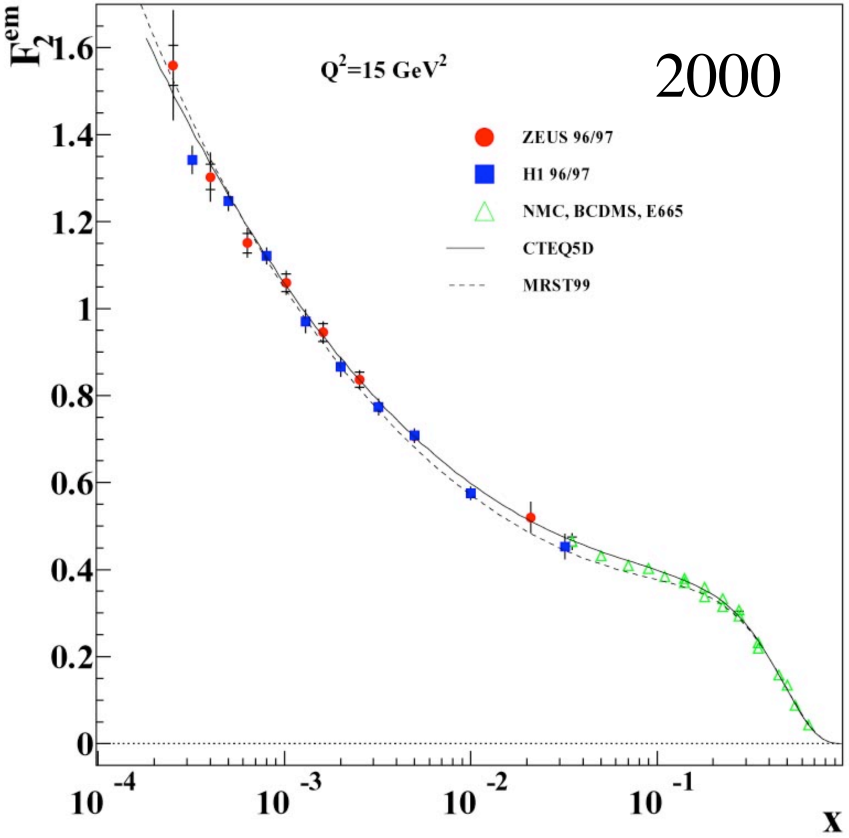
xg from F_2

Non-peturbative region

The structure function F_2

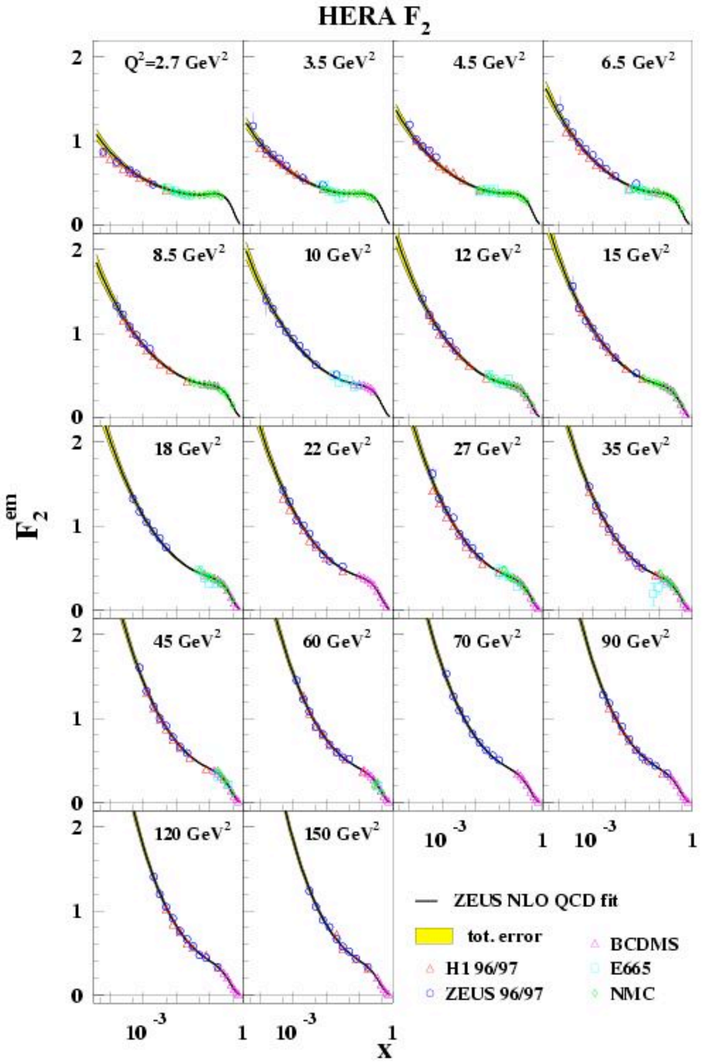


Wide range of predictions before HERA



Vast progress since since the beginning of HERA

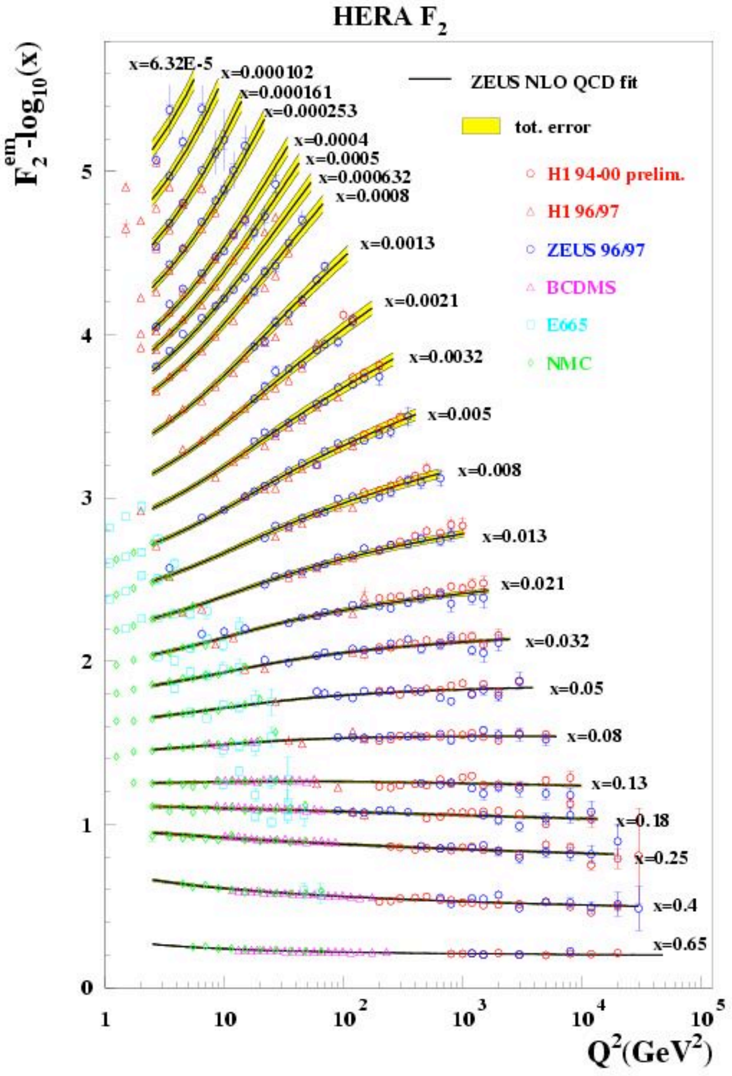
The structure function F_2



$$F_2 \propto \sum_q e_q^2 x(q + \overline{q})$$

- F_2 dominates cross section
- Measured with precision of ~2-3%
- Systematics limited at low Q^2
- Statistics limited above Q^2 ~ 1000 GeV^2
- Directly senstive to sum of quarks and antiquarks

The structure function F_2



- F_2 sensitive to gluon density via QCD radiation
- Scaling violations
  - Largest at low x
  - Driven by gluon density
- Well described by QCD

The longitudinal structure function F_L

- At leading order in QCD $F_L=0$
- Appears in NLO QCD
- Direct access to gluon distribution
- Important test of QCD

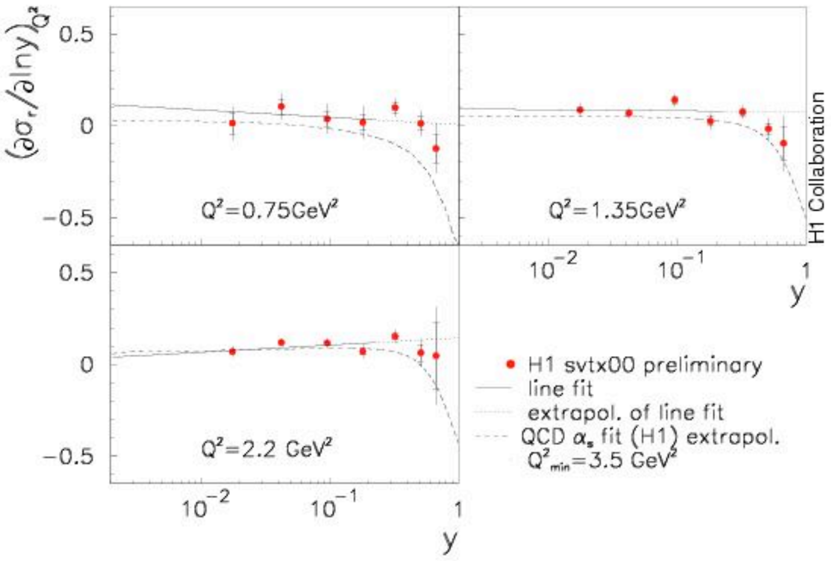
- Two methods from H1
  - “Derivative” method
  - “Shape” method
  - Will discuss new low Q^2 extractions

- ZEUS
  - ISR events to vary CMS energy

F_L from the derivative method

$$\left(\frac{\partial\sigma}{\partial \ln y}\right)_{Q^2} = \left(\frac{\partial F_2}{\partial \ln y}\right)_{Q^2} - F_L \cdot y^2 \cdot \frac{2-y}{Y_+^2} - \frac{\partial F_L}{\partial \ln y} \cdot \frac{y^2}{Y_+}$$

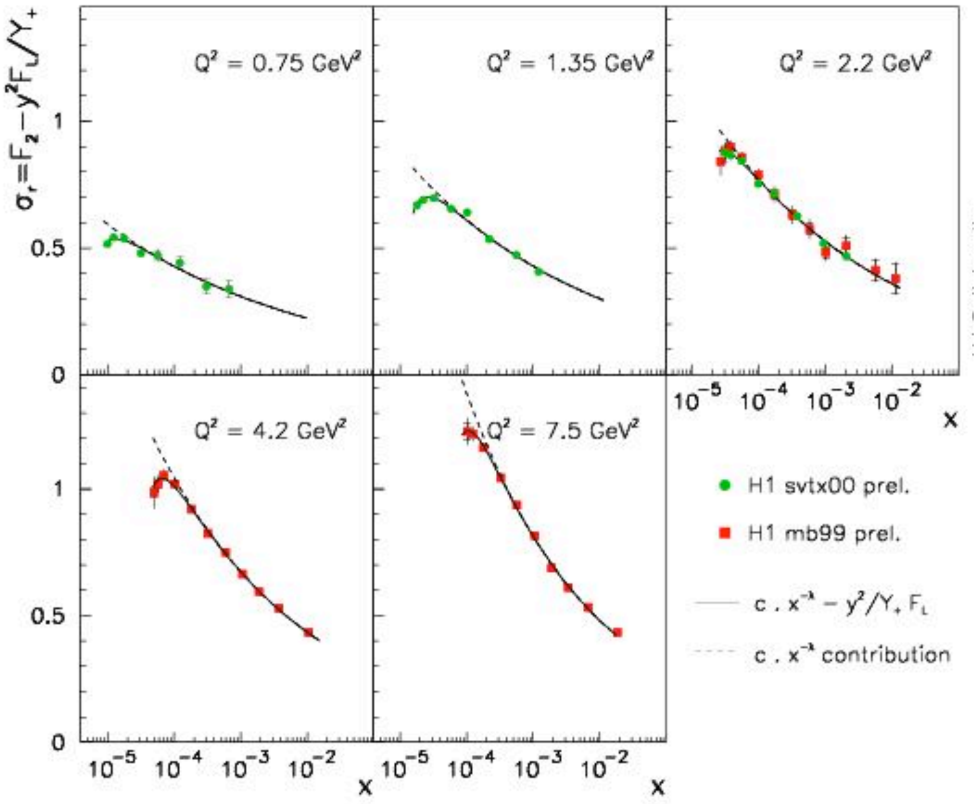
- At a fixed Q^2
  - $F_2 \sim x^{-\lambda} \sim e^{\lambda \ln y} \sim 1 + \lambda \ln y + \ldots$
- Fit $\partial\sigma/\partial \ln y$ with a straight line at low y (<0.2)
- Extrapolate line to high y
- Difference between extrapolated line and measured points gives FL (y>0.4)
- Assumption that $\partial F2/\partial \ln y$ linear in lny



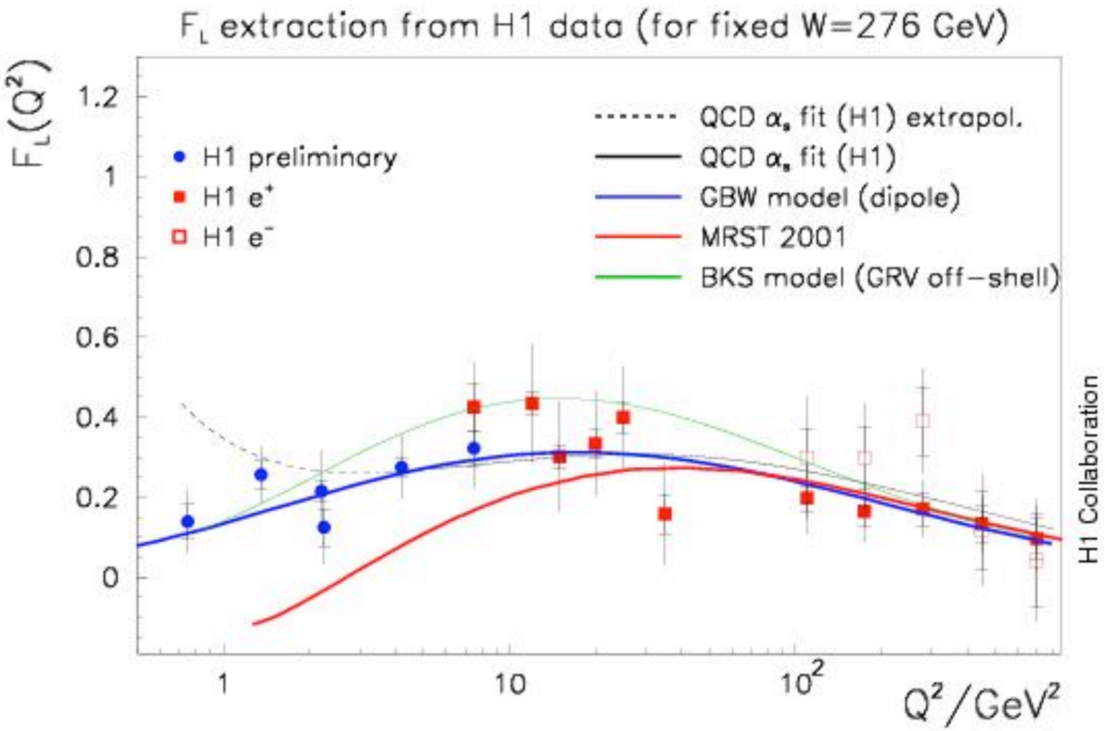
FL from the shape method

$$\sigma_{FIT} = c \cdot x^{-\lambda} - \frac{y^2}{1+(1-y)^2} F_L$$

- Fit for one F_L point per Q^2 bin at <y>
- c, λ and F_L free parameters
- Shape driven by y^2/Y_+ factor
- Constant F_L over small x range
- Fits describe the data well



The structure function F_L



- Extractions consistent
- Shape method gives smaller uncertainties

FL from ISR events

- NC events with initial state radiation
- Hard photon detected in tagger
- Variation in √s gives access to a range of y values at a fixed x and Q^2
- Use shape of cross section as a function of y to measure F_L

F_L from ISR events

- Define:

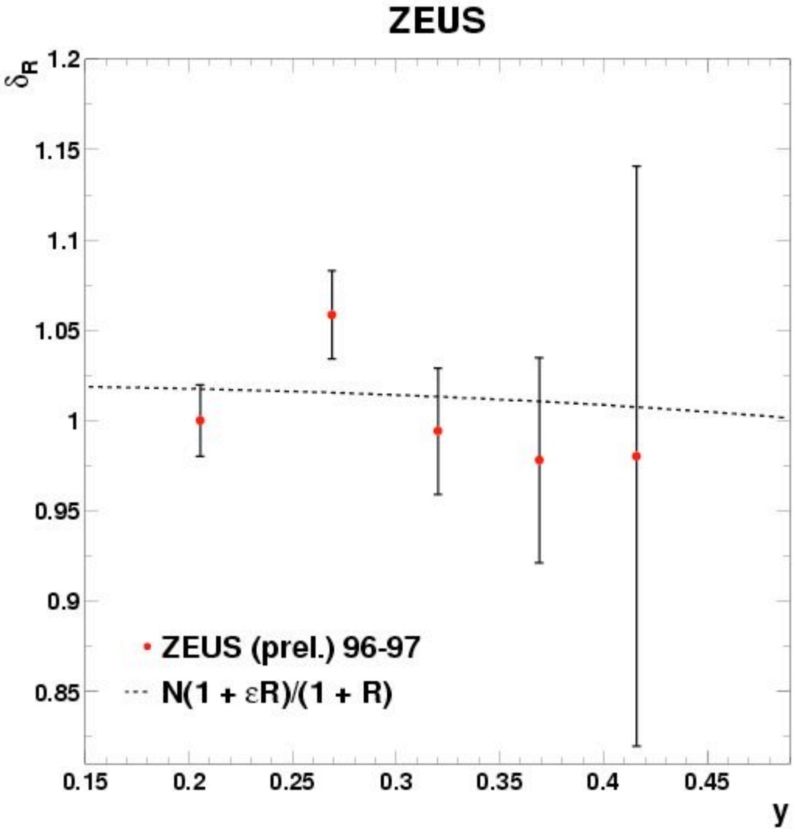
$$\delta_{F_L} = \frac{\sigma(F_L \neq 0)}{\sigma(F_L = 0)} = \frac{F_2 - (1-\varepsilon)F_L}{F_2}$$

$$\varepsilon = \frac{2(1-y)}{1+(1-y)^2}$$

- Fit:

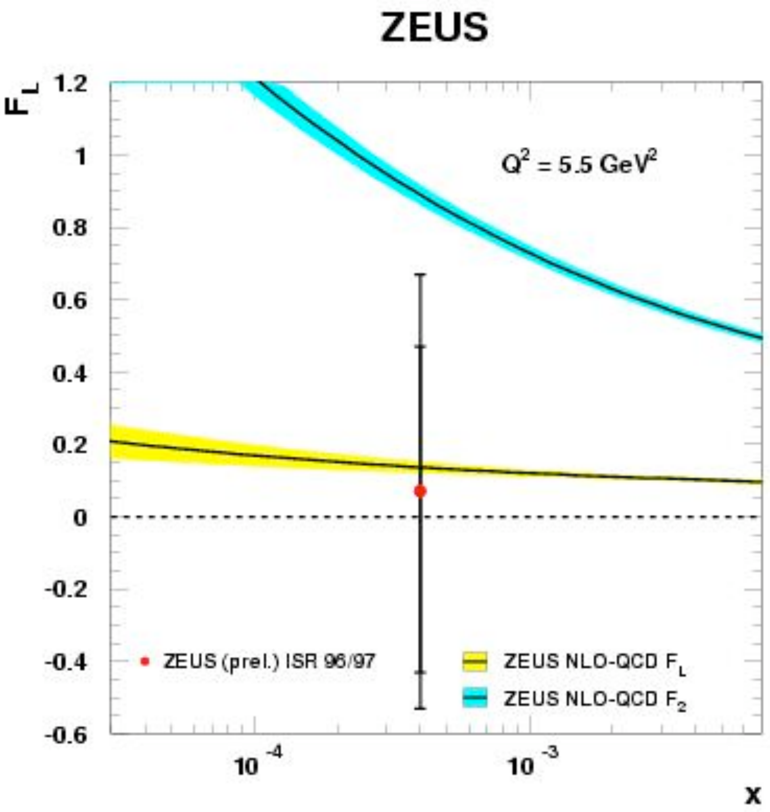
$$\frac{N_{data}}{N_{MC}(F_{L=0})} = N \cdot \delta_{F_L}$$

- Fit as a function of y
- N and F_L free paramters
- F_2 measured



The structure function F_L

- Direct measurement of F_L
- Currently not statistically precise, but…
  - Consistent with NLO QCD
  - Proof that ISR method can work
- For precise measurement of F_L at HERA in the future need to vary beam energy

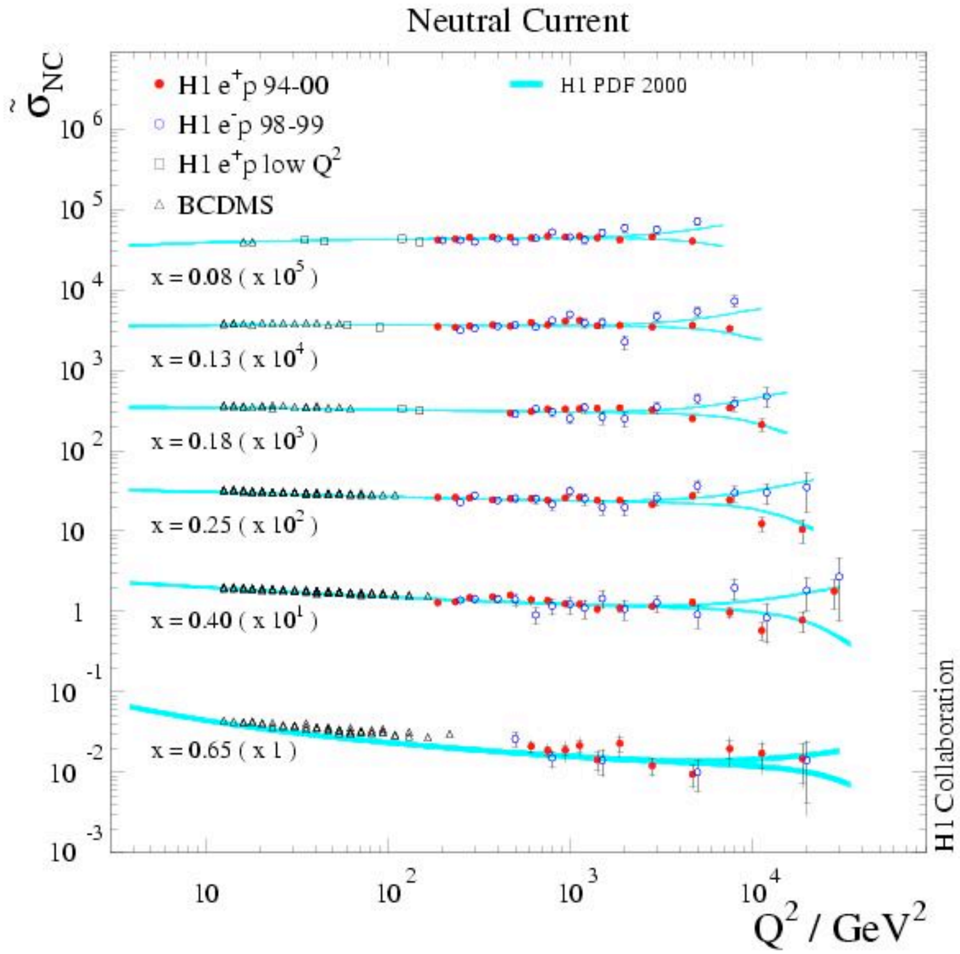


High Q^2 cross sections & xF_3

- Current knowledge comes from fixed target data
- Data very precise but subject to theoretical uncertainties
  - Nuclear binding effects
  - Non-peturbative effects at low Q^2

- HERA data free from these uncertainties
- Data at high Q^2 and high x constrain the valence quark distributions
- Low statistics
  - Cross sections are low
- Sensitive to EW effects through exchange of Z^0 in neutral current and W in charged current

High Q^2 cross sections & xF_3

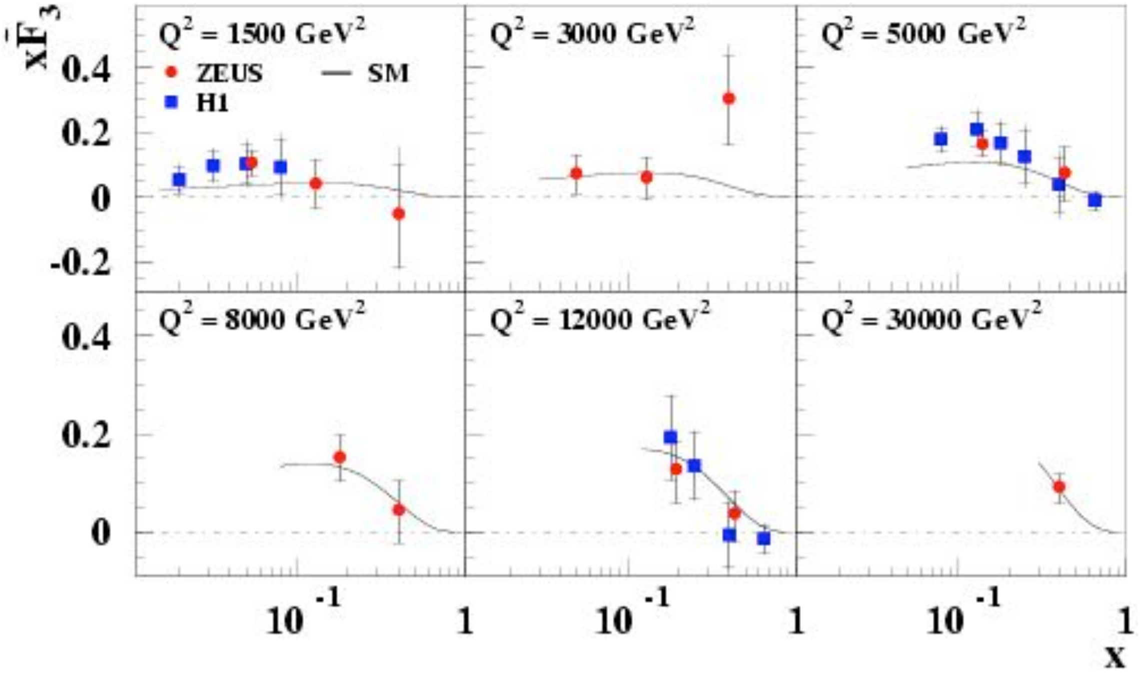


- Difference between e^+p and e^-p cross sections gives xF_3

$$xF_3 \propto \sum_q x(q-\overline{q})$$

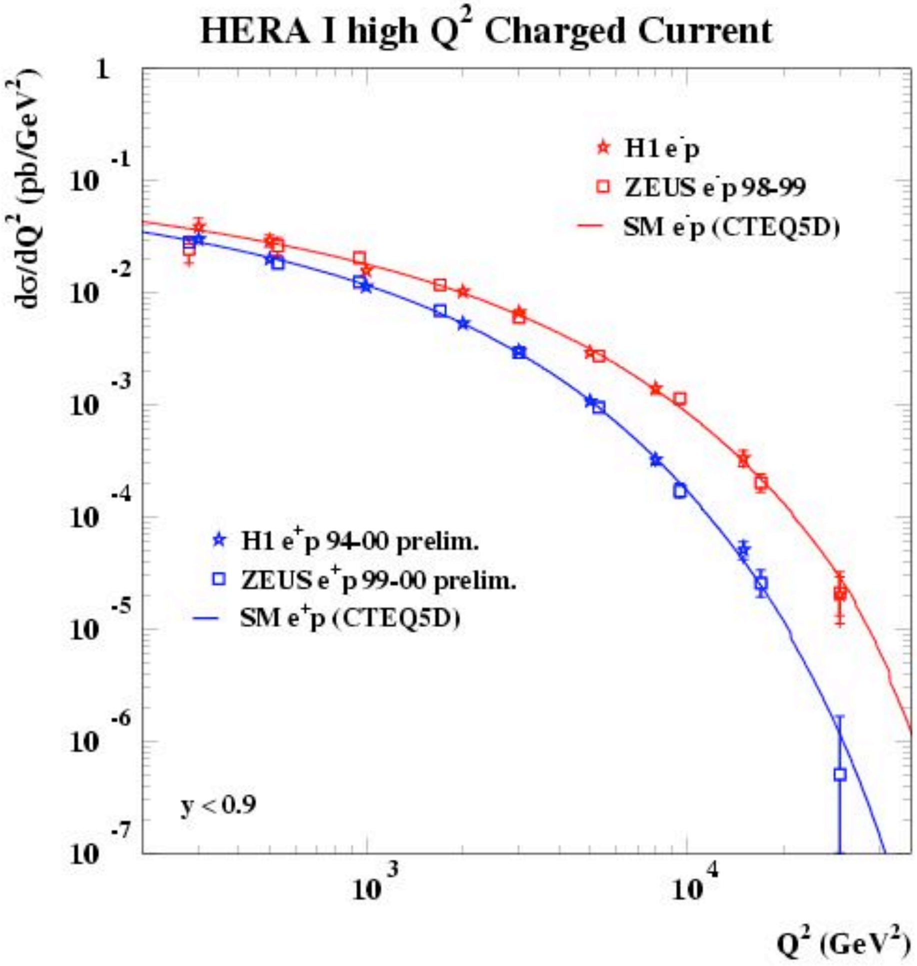
- F_L is small contribution
- xF_3 comes from interference between gamma and Z^0 exchange processes

High Q^2 cross sections & xF_3



- HERA data confirm valence quark structure
- Uncertainties dominated by statistical uncertainty of e^-p data sample
- Clear need for high luminosity

Charged current cross sections



- Different for e^+p and e^-p

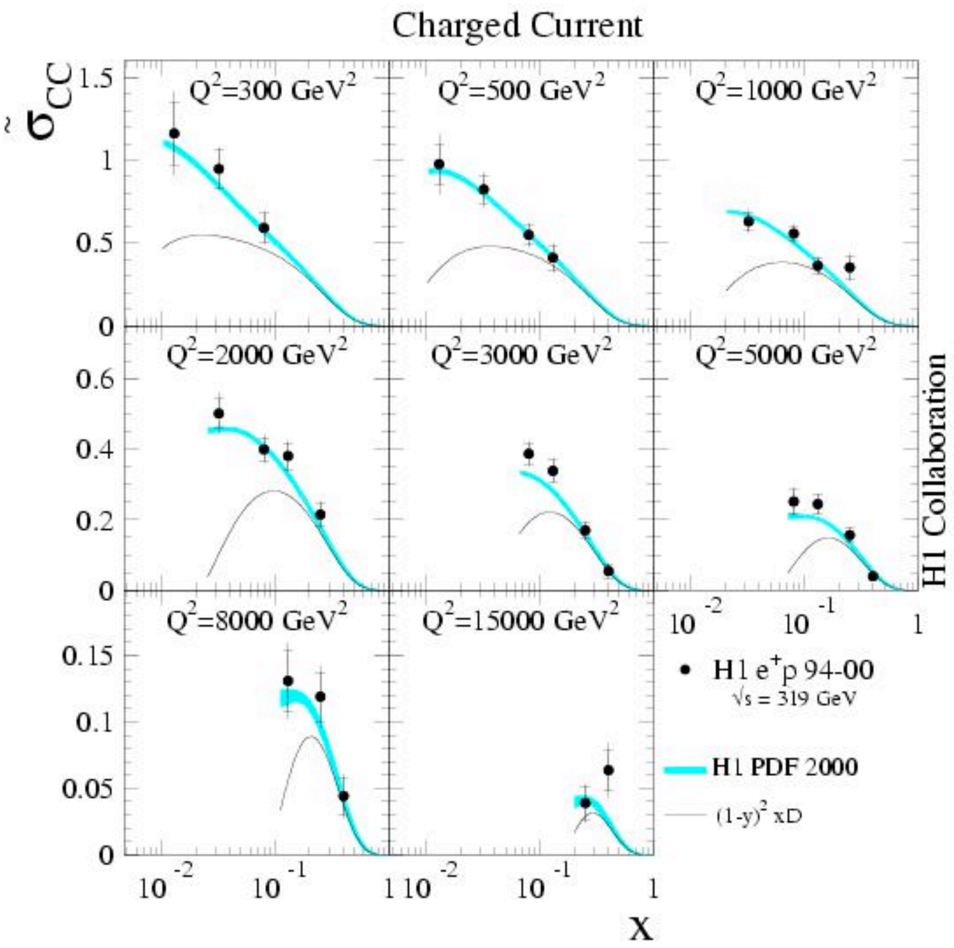
$$\sigma \propto [u + c + (1-y)^2(\bar{d} + \bar{s})]$$

  - e^-p sensitive to $u(x,Q^2)$

$$\sigma \propto [\bar{u} + \bar{c} + (1-y)^2(d + s)]$$

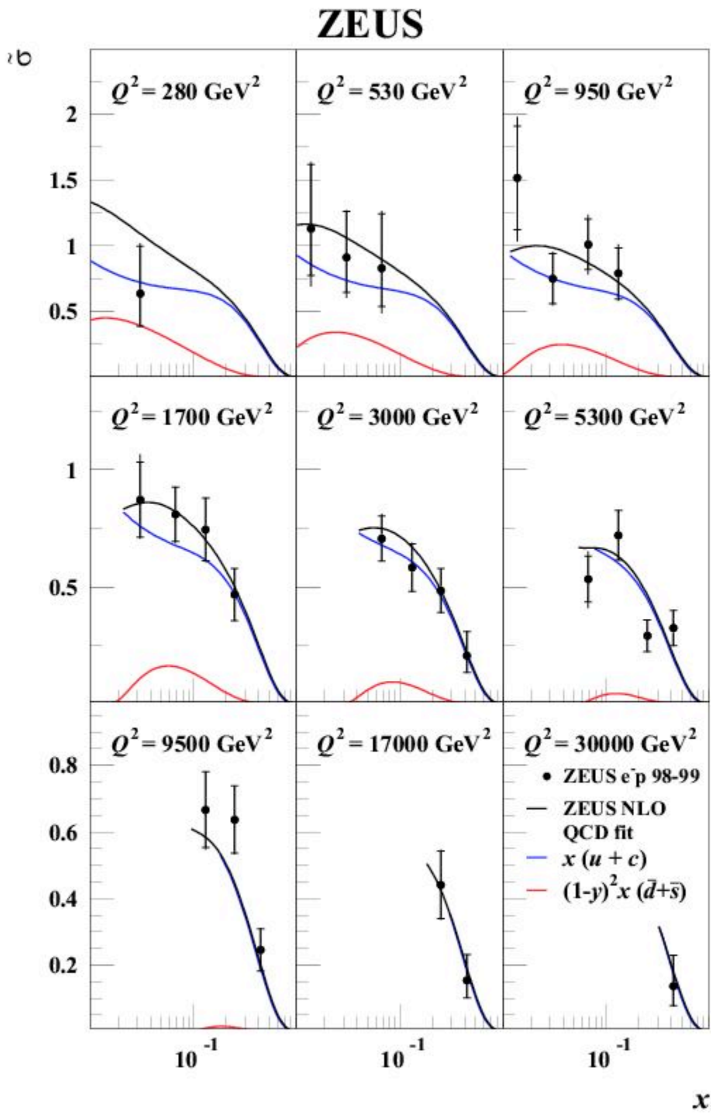
  - e^+p sensitve to $d(x,Q^2)$
  - e^+p suppressed by $(1-y)^2$ helicity factor
- Sensitive to M_W through propagator

Charged current cross sections



- e^+p scattering sensitive to $d(x,Q^2)$
- Current measurements limited by statistics
- In agreement with global PDFs

Charged current cross sections



- e^-p scattering sensitive to $u(x,Q^2)$
- Current measurements limited by statistics
- In agreement with global PDFs

Parton distributions

- PDFs cannot be calculated by pQCD
  - Measured at a Q^2 value
  - Parameterise as a function of x
  - Evolve using DGLAP to all Q^2 where pQCD is valid

- Accurate determination of PDFs allow accurate SM predictions

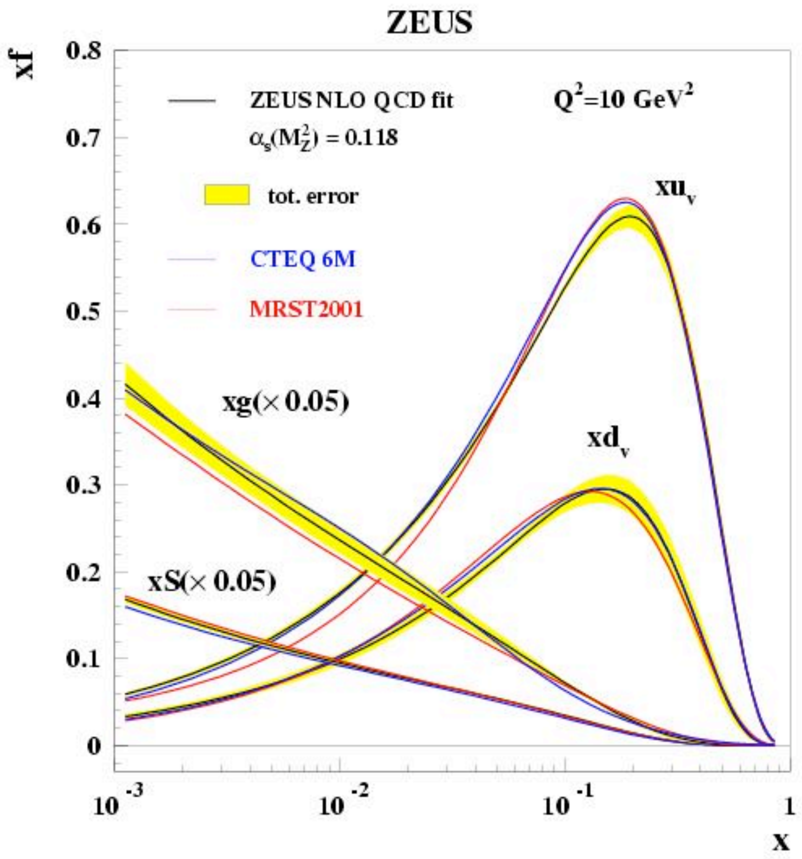
- QCD fits have many choices, should be reflected in the PDF uncertainty:
  - Starting scale, min Q^2, data sets, peturbative phase space? choice of densities to parameterise, treatment of heavy quarks, functional form of parameterisation, treatment of experimental systematic uncertainties,renorm/factorisation scale…

- H1 & ZEUS make different choices…

ZEUS 2002 fit

- Essentially a global analysis
  - ZEUS 96/97 NC e^+p
  - p and d F_2 NMC
  - p and d F_2 E665
  - F_2 p BCDMS
  - CCFR xF_3
- 2.5 $GeV^2 < Q^2 <30000\ GeV^2$
- $W^2>20\ GeV^2$
- $Q_o^2=7\ GeV^2$
- Fit xg, xu_v, xd_v, xSea, x(db-ub)
- Thorne-Roberts VFNS

ZEUS 2002 fit



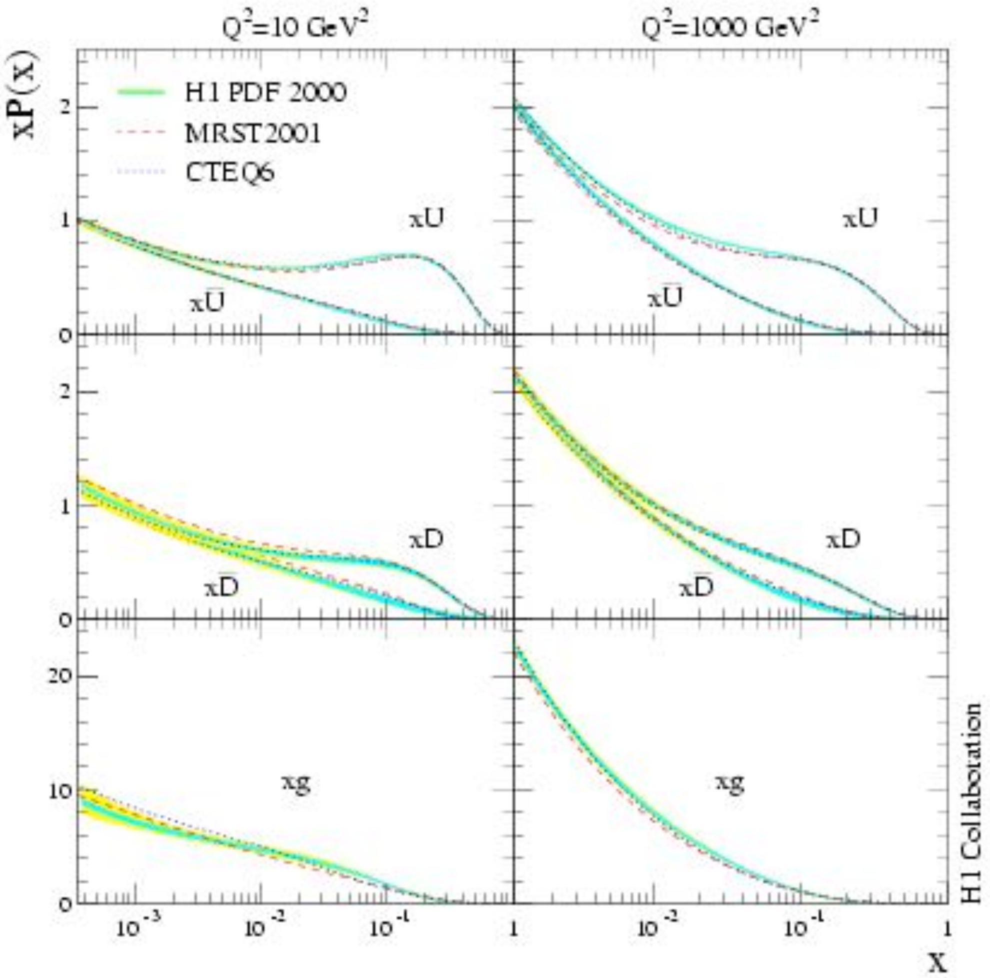
- Agreement with CTEQ and MRST
- Δg ~ 10% Q^2>20 GeV^2
- Gluon negative for Q^2~1 GeV^2
- Can free α_S

•α_S=0.1166 ±0.0008(uncorr.) ± 0.0032(corr.) ± 0.0036(norm.)± 0.0018(model)

H1 2000 fit

- Minimum number of data sets
  - H1 only
  - BCDMS F_2 p as a cross check
- 3.5 $GeV^2 < Q^2 <30000\ GeV^2$
- $Q_o^2=4\ GeV^2$
- Fit tuned combinations of PDFs to cross sections
  - xg,xU(=u+c),xD(=d+s),xUb,xDb
- Zero mass variable flavour number scheme

H1 2000 fit



- In agreement with CTEQ and MRST
- ΔxU~3% x=0.4
- ΔxD~10% x=0.4
- Uncertainties on valences PDFs factor ~2 larger with only HERA data

Summary

- Many interesting results from HERA I
- Analysis of structure function data is (almost) complete
- Precision of 2-3% for F_2
- HERA provide consistent picture of NC/CC/F_2/F_L/xF_3
- Measurements cover 5 orders of magnitude in Q^2 and x
- Probe structure of the proton at 10^{-18}m
- Fits allow HERA data to constrain PDFs

Future prospects for HERA II

- H1 and ZEUS detectors upgraded
  - New detector components comissioned
- Design specific luminosity achieved
- 50% e^+ longitudinal polarisation achieved
- Beam currents limited by backgrounds in detectors
  - Remedied during current shutdown

- Improved precision at high Q^2
- F_L measurement from lower beam energy runs
- Measure polarisation dependence of charged and neutral current cross sections

- HERA III?