Proton structure functions and and parton distribution functions at the HERA ep collider

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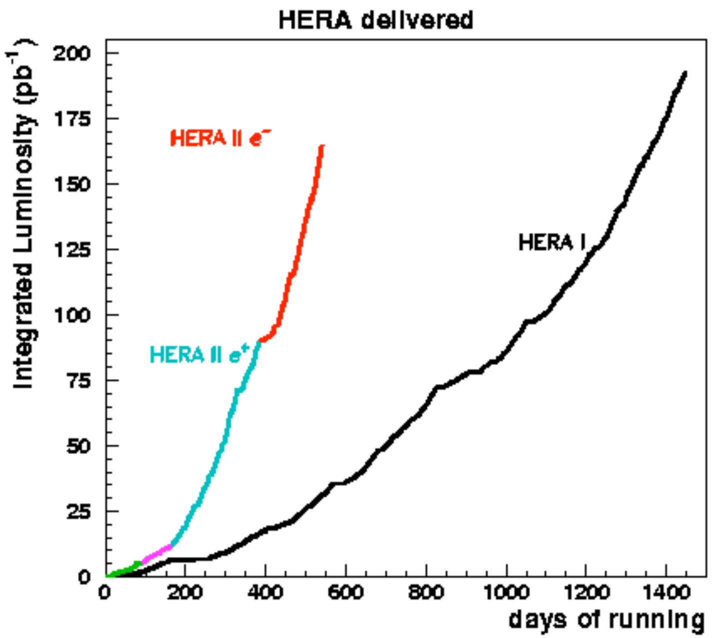
Outline

- HERA luminosities and kinematics
- The ZEUS and H1 detectors
- Deep inelastic scattering
- F_2, xF_3 and F_L structure functions and high Q^2 cross sections
- Parton distributions from QCD fits
- High Q^2 cross sections with polarised leptons
- Summary and future prospects

HERA

- ep collider in Hamburg, Germany
- Centre of mass energy of 320 (300) GeV
- In 2000-2002 HERA I upgraded to HERA II
  - Increased luminosity
  - Polarised leptons

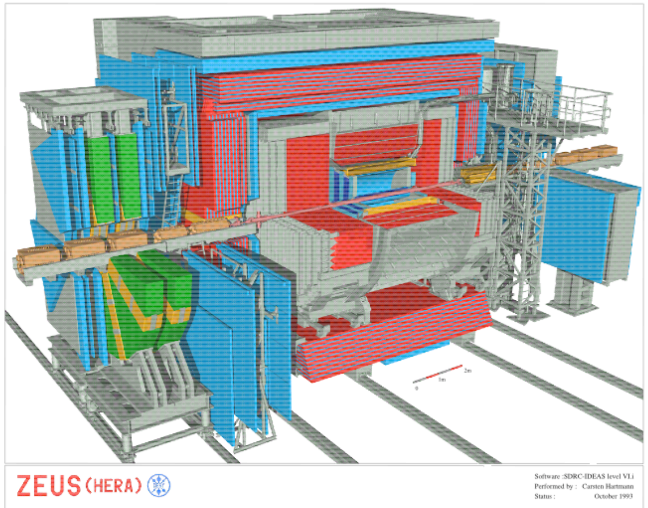


HERA luminosity (pb^{-1})	HERA I (92-00)	HERA II (02-)
e^-p	27	> 80
e^+p	165	90

The ZEUS and H1 detectors

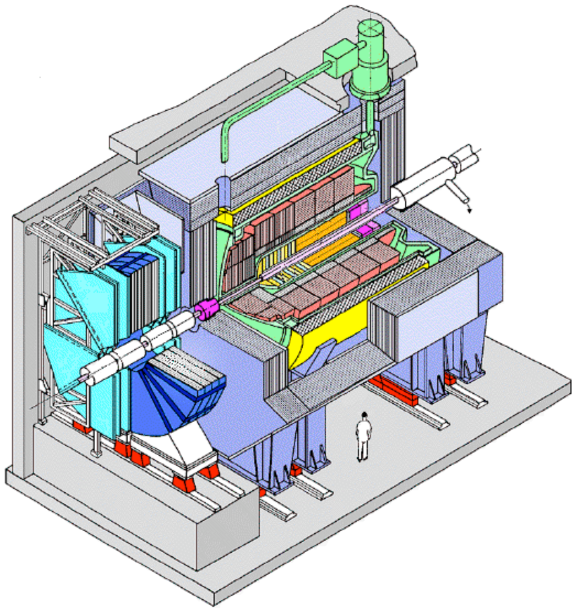
ZEUS

- General-purpose detector
- Depleted uranium calorimeter
  - $\sigma(E_{EM})/E_{EM} = 0.18/\sqrt{E_{EM}}$
  - $\sigma(E_{HAD})/E_{HAD} = 0.35/\sqrt{E_{HAD}}$
  - Systematics 1-2 %

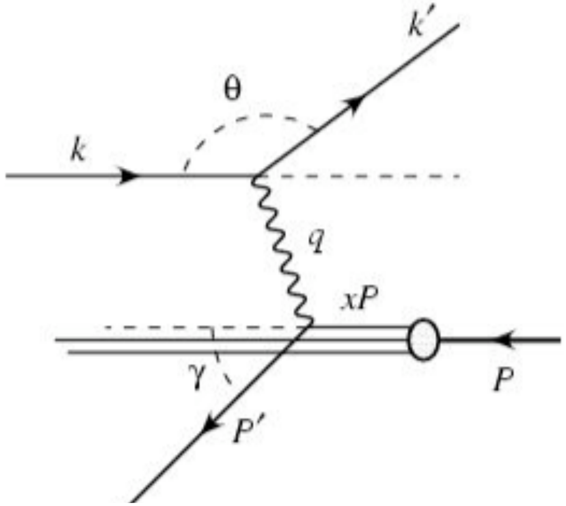


H1

- General-purpose detector
- Liquid argon calorimeter
  - $\sigma(E_{EM})/E_{EM} = 0.12/\sqrt{E_{EM}} \oplus 0.01$
  - $\sigma(E_{HAD})/E_{HAD} = 0.50/\sqrt{E_{HAD}} \oplus 0.01$
  - Systematics 0.3-3 %



Deep inelastic scattering kinematics



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

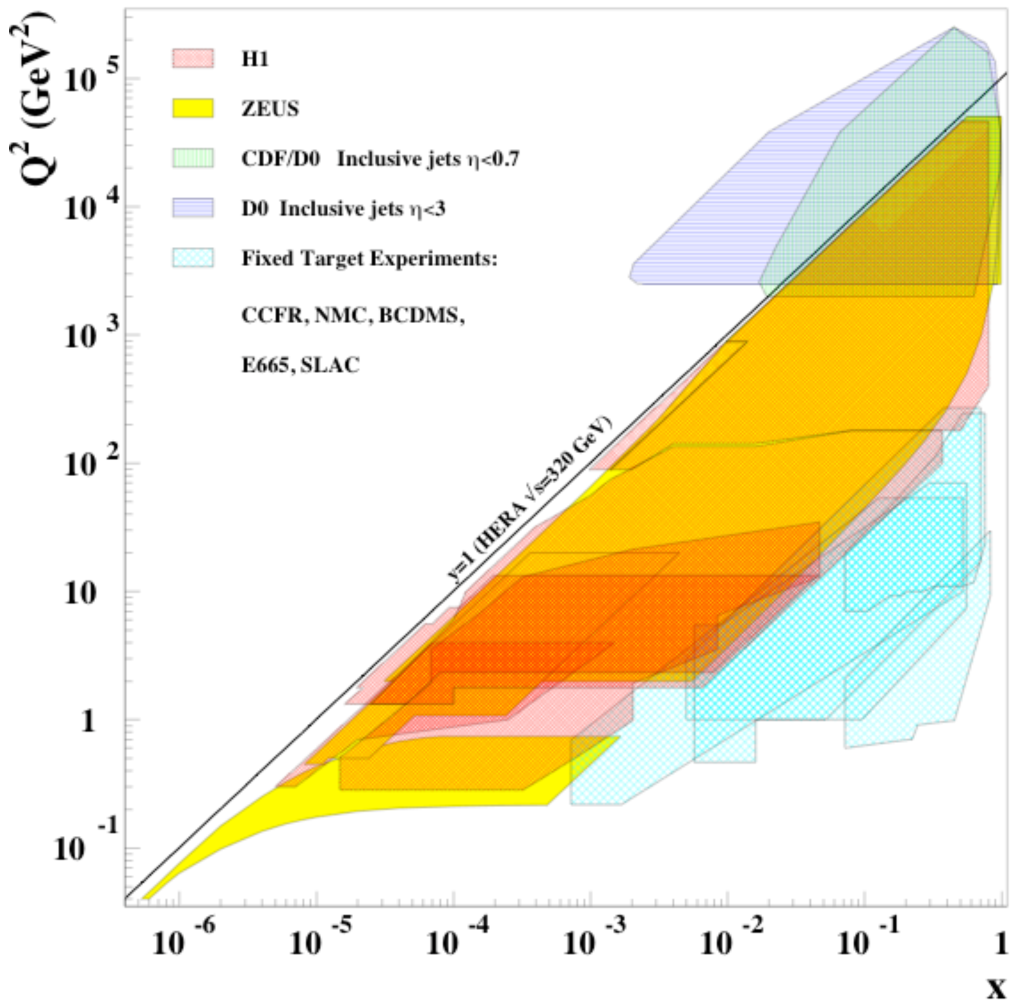
$$x = \frac{Q^2}{2p \cdot q} \qquad y = \frac{p \cdot q}{p \cdot k}$$

$$s = (p + k)^2 \qquad Q^2 = xys$$

- Q^2 is a measure of the probing power
  - High Q^2 ➔ small distance scale
  - Can probe 1/1000 proton
- x is Bjorken scaling variable
  - Fraction of proton's momentum carried by struck parton
- y related to θ in CoM frame
  - Fraction of lepton's energy transferred to the proton

HERA kinematic range

- x dependence must be determined empirically from fits to cross sections
- HERA covers very large x range
- At low x measure gluon PDFs
- At high x measure xF_3 and valence quark PDFs
- Then extrapolate using pQCD to other Q^2 values
- LHC requires precise knowledge of PDFs from HERA to extrapolate into region of LHC new physics



Deep inelastic scattering cross sections

- Neutral current - exchange Z^0 / γ

$$\frac{d^2\sigma^{\pm}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \underbrace{\left(F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} x F_3 \right)}_{\tilde{\sigma}_{NC}\left(x, Q^2\right)} \qquad Y_{\pm} = 1 \pm (1-y)^2$$

- Charged current - exchange $W^{\pm}$

$$\frac{d^2\sigma^{\pm}}{dxdQ^2} = \frac{G_F^2}{4\pi x} \frac{M_W^4}{\left(Q^2 + M_W^2\right)} \underbrace{\left(Y_+ F_2^{CC} - y^2 F_L^{CC} \mp Y_- x F_3^{CC} \right)}_{\tilde{\sigma}_{CC}\left(x, Q^2\right)}$$

The structure functions

$$F_2 \propto \sum x\left(q+\bar{q}\right)$$

$$xF_3 \propto \sum x\left(q-\bar{q}\right)$$

$$F_L \propto \alpha_s x g\left(x, Q^2\right)$$

- F_2 is dominant contribution to cross sections
- xF_3 becomes significant at high Q^2
- F_L is only important at low Q^2 and high y
- At HERA can study sea and valence quarks
- Also gluons via scaling violations and jet data
- CC with e^-p (e^+p) most sensitive to u (d) valence quark

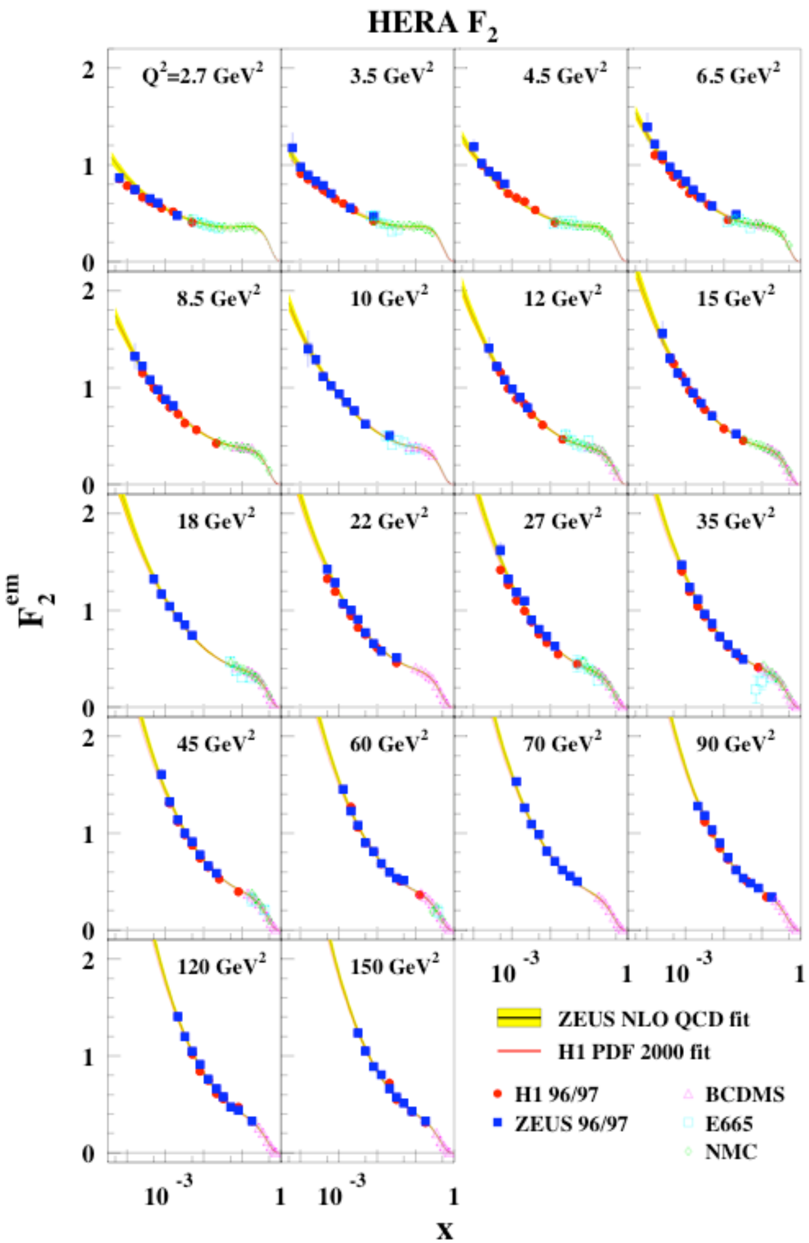
$$\frac{d^2\sigma^-_{CC}}{dx dQ^2} \propto \left(\left(u+c\right)+\left(1-y\right)^2\left(\bar{d}+\bar{s}\right)\right)$$

$$\frac{d^2\sigma^+_{CC}}{dx dQ^2} \propto \left(\left(\bar{u}+\bar{c}\right)+\left(1-y\right)^2\left(d+s\right)\right)$$

F_2 measurement

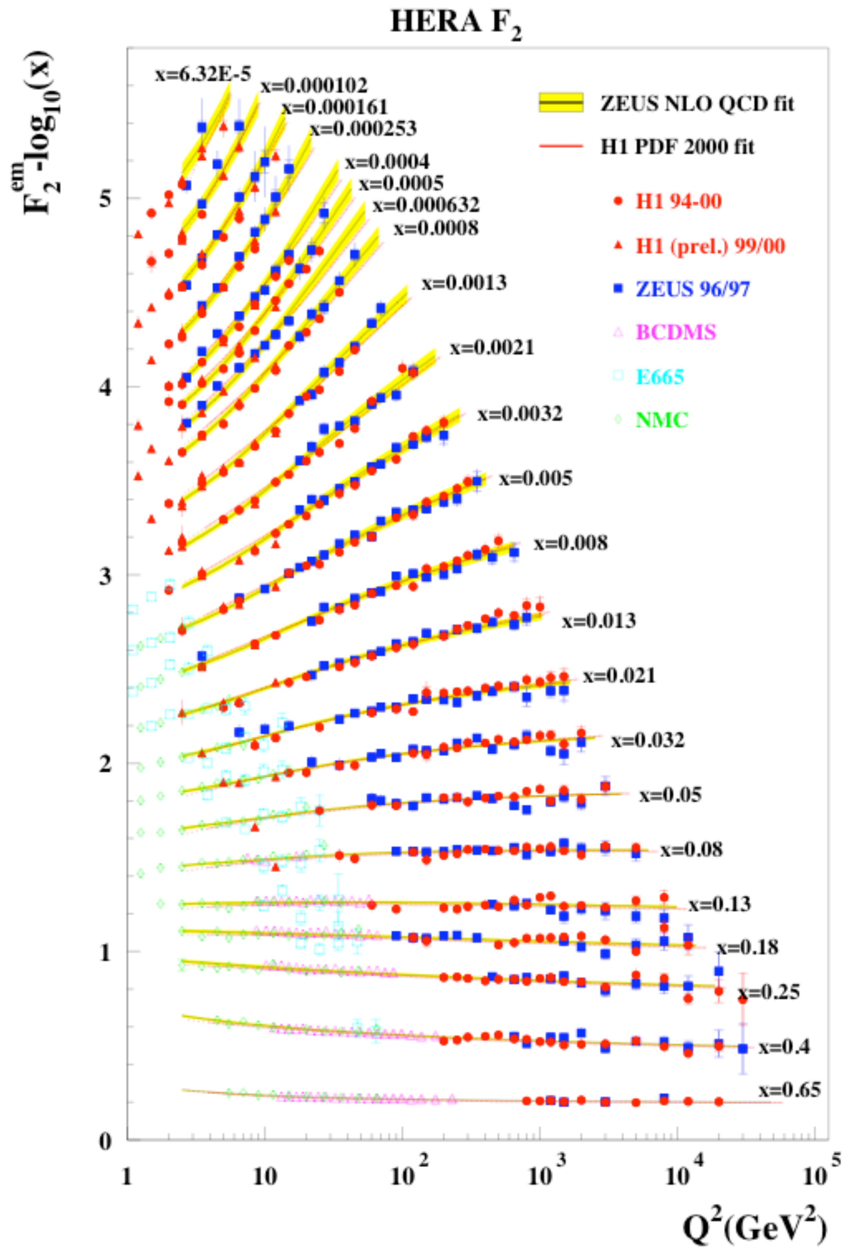
$$F_2 \propto \sum x\left(q+\bar{q}\right)$$

- Sensitive to sum of quark and anti-quark
- Measured to 2-3 % precision
- Low Q^2 ➔ systematic error dominates
- High Q^2 (beyond 1000 GeV^2) ➔ statistical error dominates



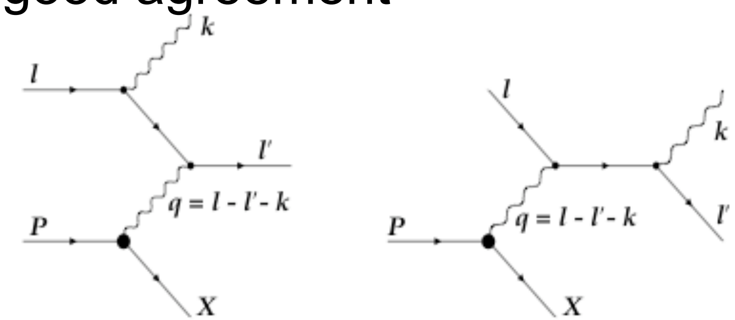
F_2 measurement

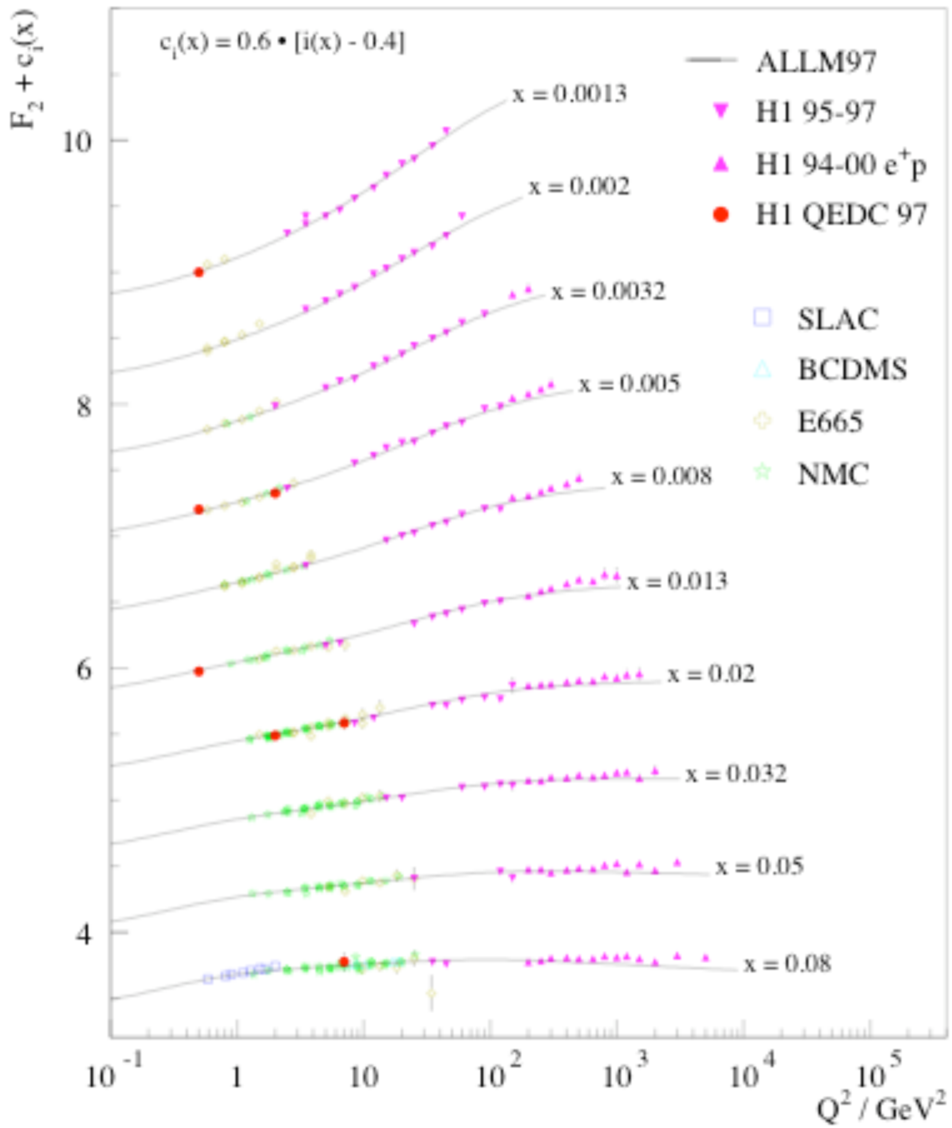
- Measure over huge range
  - $1 < Q^2 < 30{,}000\ GeV^2$
  - $10^{-5} < x < 1$
- F_2 sensitive to gluon density by QCD radiation
  - scaling violation
  - F_2 not constant with Q^2
- ZEUS and H1 data in agreement and well-described by QCD



Low Q^2 F_2 measurement

- F_2 well measured in bulk region
- Now extend HERA's range
  - $0.5 < Q^2 < 7$ GeV^2
  - $0.001 < x < 0.06$
- Based on analysis of QED Compton events
  - Cross section depends on F_2 and F_L, but y small so $F_L \sim 0$
- Overlap with fixed target data in good agreement

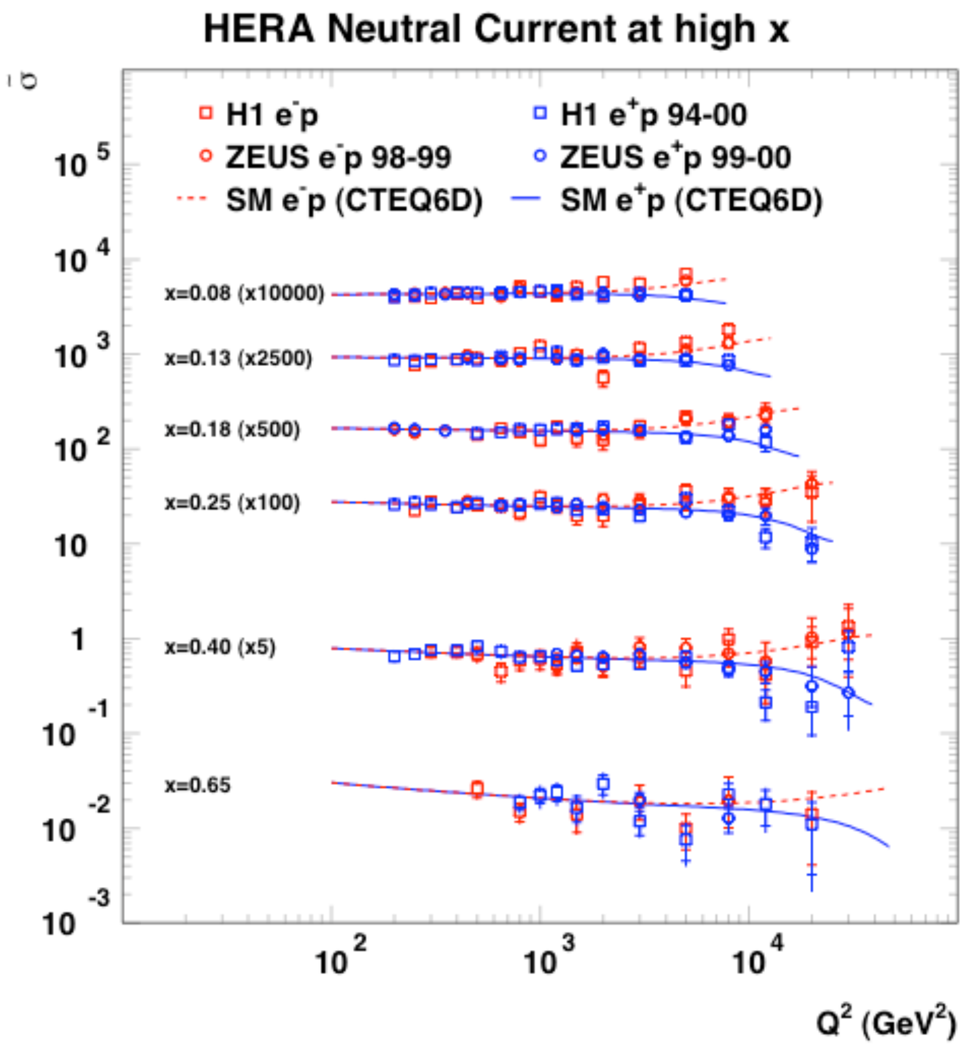




High Q^2 neutral current cross sections

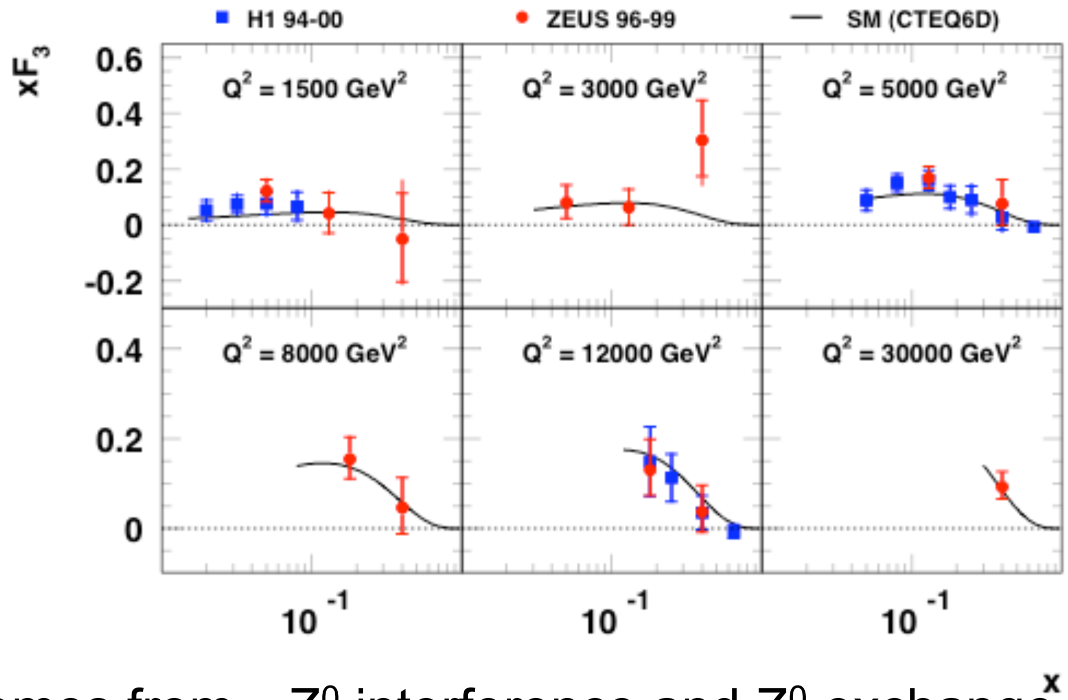
$$\tilde{\sigma}^{\pm}_{NC} \simeq F_2 \mp \frac{Y_-}{Y_+} xF_3$$

$$xF_3 \propto \sum x(q - \bar{q})$$



- At high Q^2 σ_{NC} different for e^- and e^+
- Small cross sections so need high luminosity
- Can measure difference between cross sections and extract xF_3

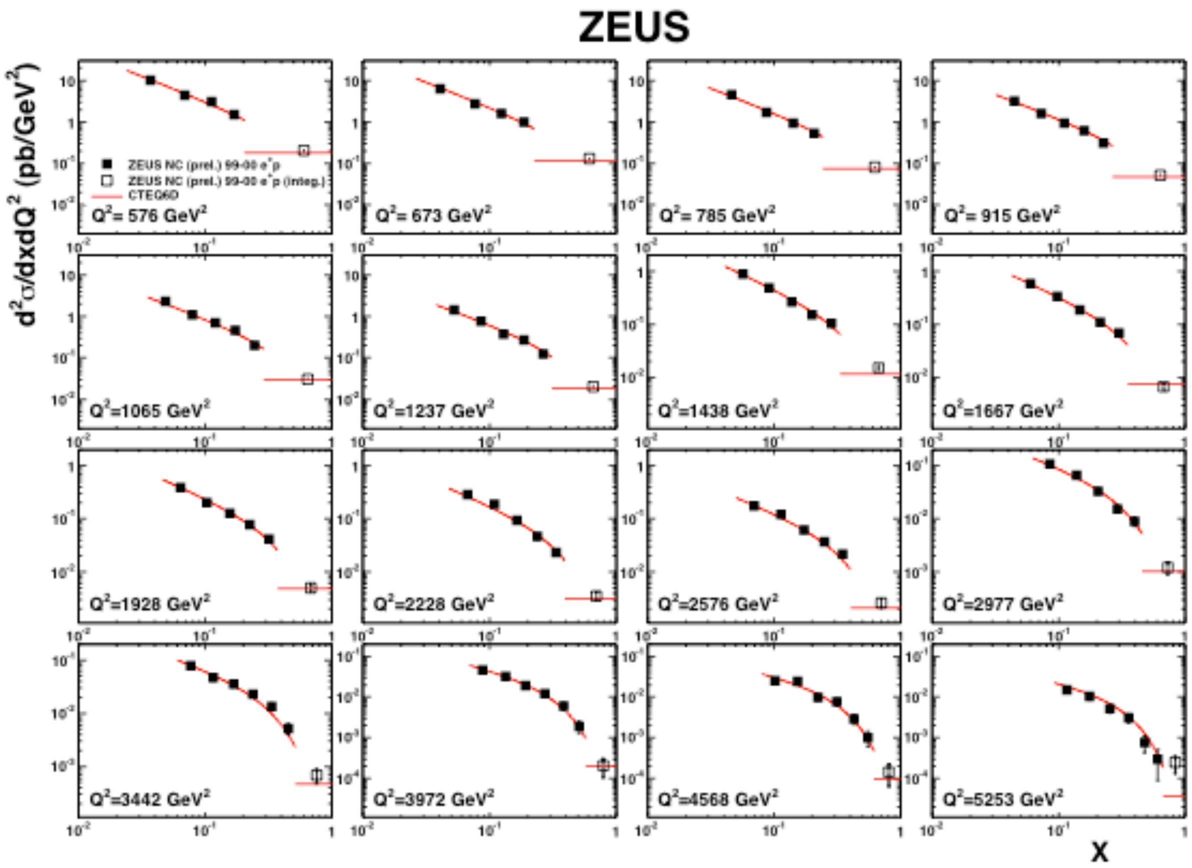
xF_3 measurements



- xF_3 comes from γ-Z^0 interference and Z^0 exchange
- Confirm valence quark structure of proton
- Large statistical uncertainty
  - Using small HERA I e^-p sample
  - Now collecting more e^-p data at HERA II…

High x neutral current cross sections

- Hard to measure PDFs at high x
  - Low statistics
  - High migration
- New reconstruction method at high x
  - Use E_{jet} and θ_{jet}
  - Better x resolution at high x
- Cross section measurements in good agreement with theory
- Will be used as input to fits to measure PDFs at high x more accurately



The longitudinal structure function F_L

$$F_L \propto \alpha_s x g\left(x, Q^2\right)$$

- Important only at high y and low Q^2
- Zero in LO QCD
- Appears in NLO QCD
  - directly sensitive to gluon distribution
- Test QCD
- ZEUS and H1 use different methods to measure F_L
  - ZEUS - events with initial state radiation for varying $\sqrt{s}$
  - H1 - ‘shape method’

F_L measurement: ZEUS

- NC with initial state radiation
- For fixed x and Q^2 can measure at range of y values by varying √s
- Measure

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

where

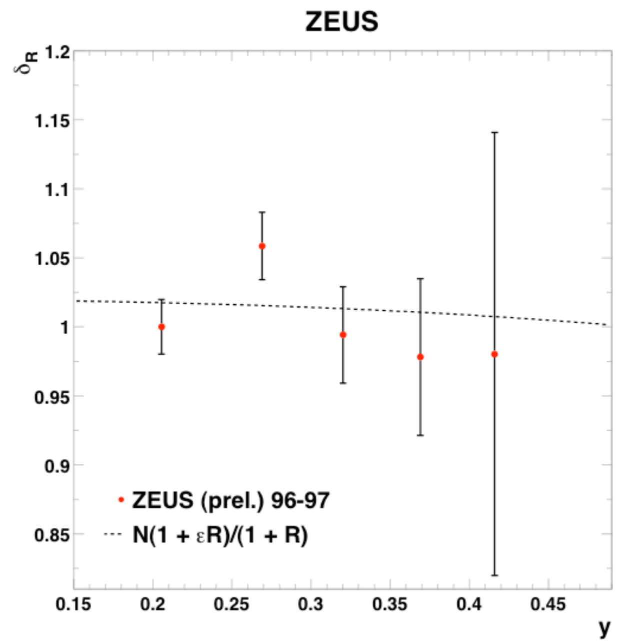
$$\epsilon = \frac{2(1-y)}{1+(1-y)^2}$$

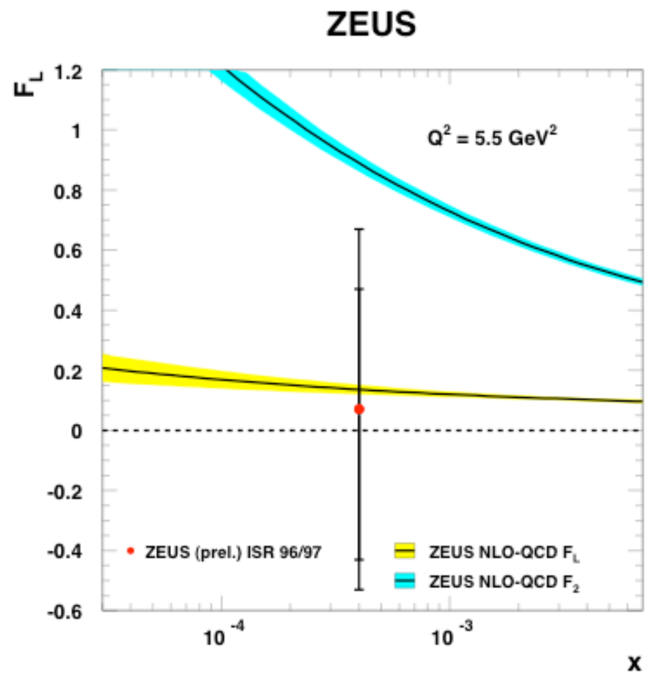
- Fit

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

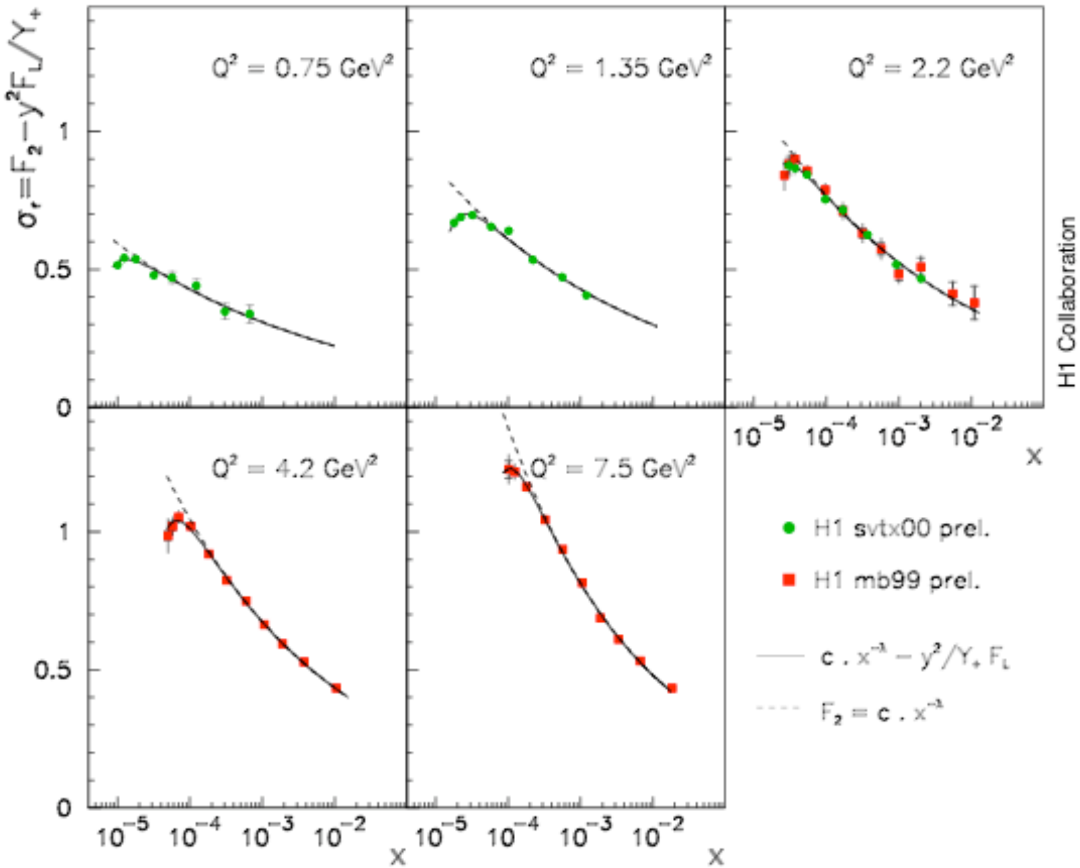
with N and F_L as free parameters

- Consistent with NLO QCD ➔ method works
- Would have to vary beam energy for greater precision





F_L measurement: H1



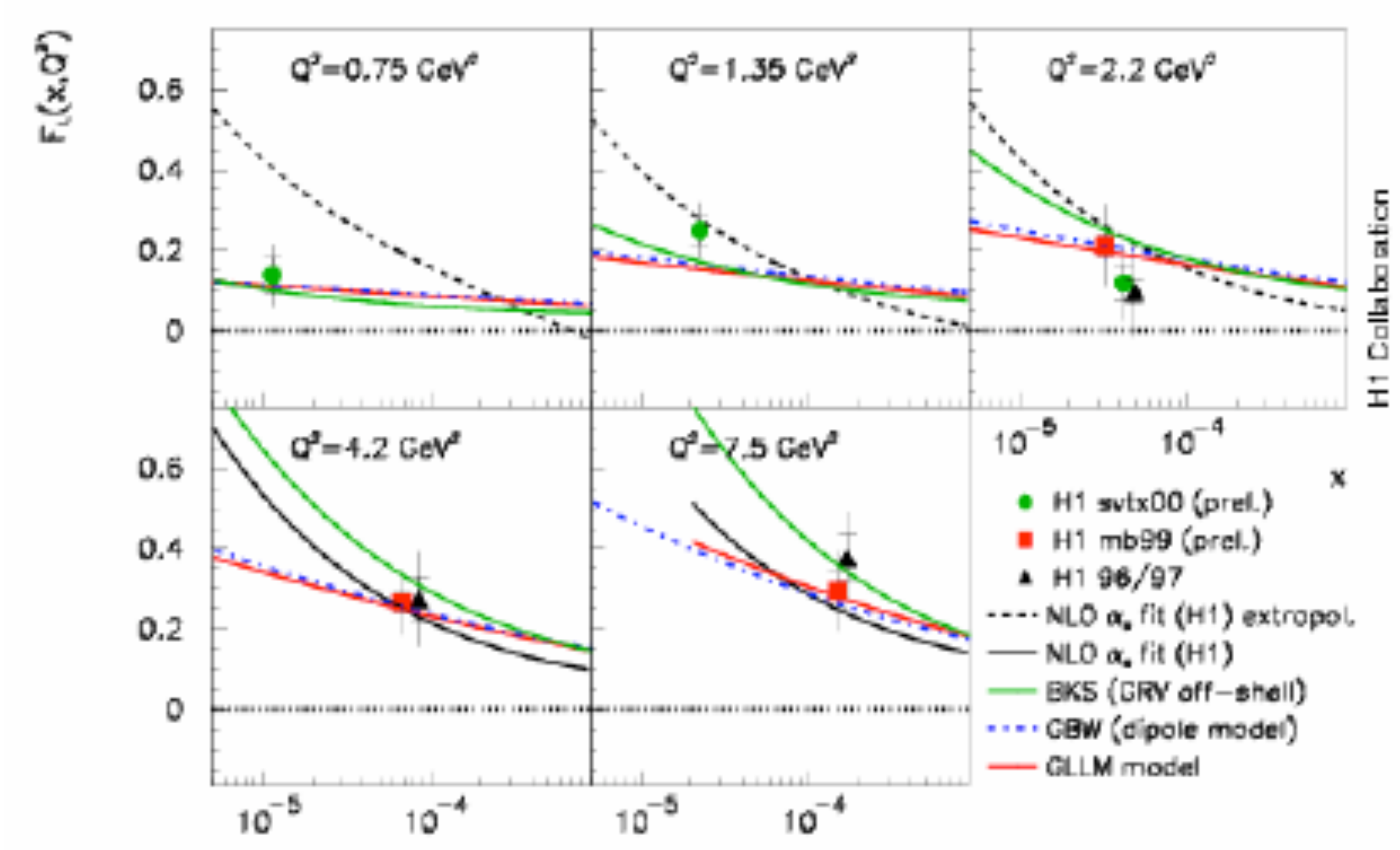
- Fit $$\tilde{\sigma} = F_2 - \frac{y^2}{Y_+} F_L$$

  with $F_2 = cx^{-\lambda}$

  and $F_L\left(x, Q^2\right) = F_L\left(Q^2\right)$

  in bins of Q^2 at <y>
- c, λ and F_L free
- F_L constant over small x range
- Fits match data well

F_L measurement: H1

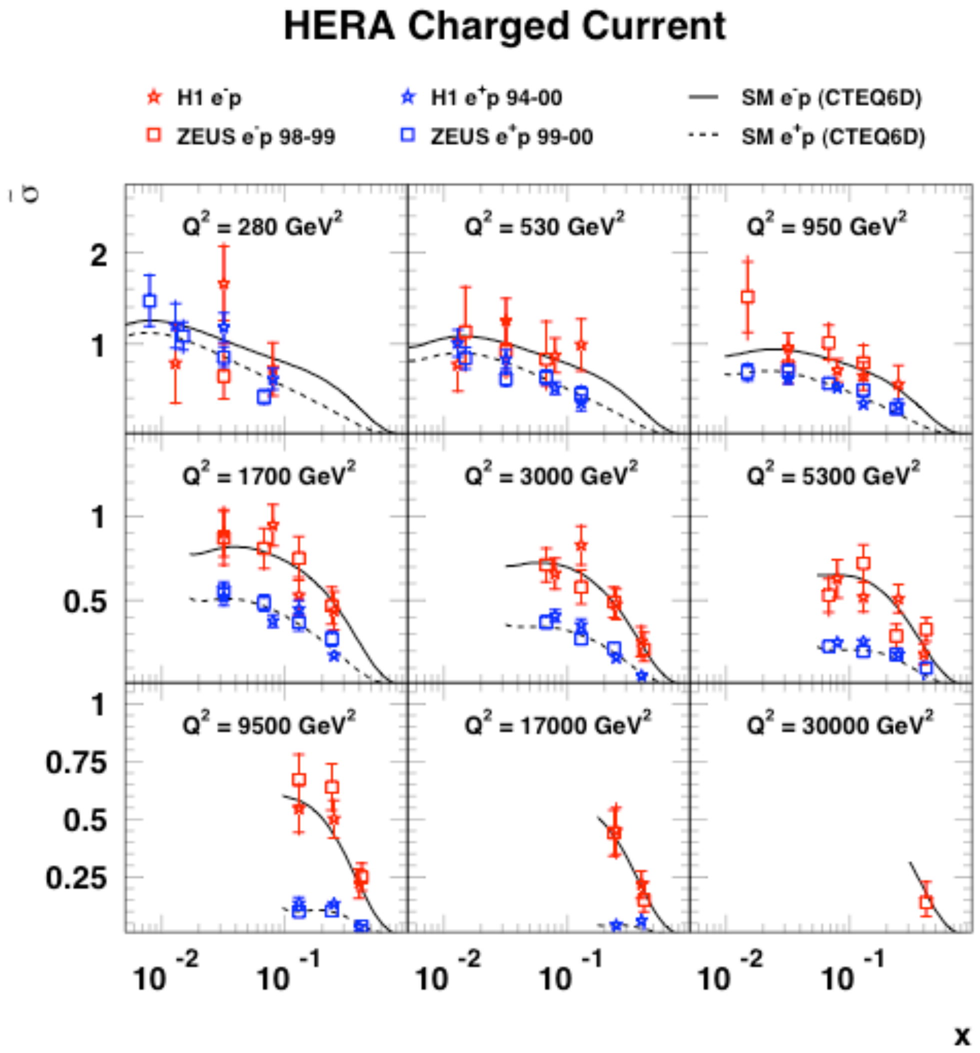


- F_L measurement and predictions consistent

Charged current cross sections

$$\frac{d^2\sigma^-_{CC}}{dxdQ^2} \propto \left((u+c) + (1-y)^2 \left(\bar{d}+\bar{s}\right)\right)$$

$$\frac{d^2\sigma^+_{CC}}{dxdQ^2} \propto \left((\bar{u}+\bar{c}) + (1-y)^2 \left(d+s\right)\right)$$

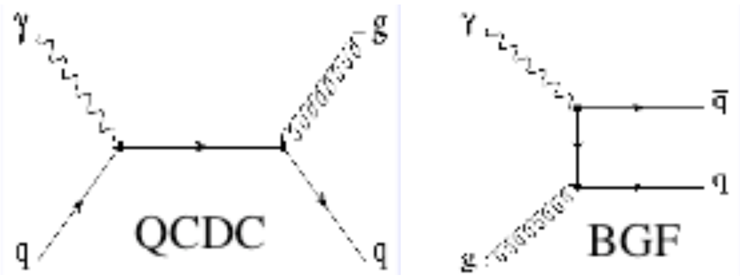


- e^-p most sensitive to $u(x,Q^2)$
- e^+p most sensitive to $d(x,Q^2)$
- e^+p cross section suppressed by factor $(1-y)^2$
- Small cross sections
  - Large statistical errors
- H1 and ZEUS agree
- Agree with global PDFs

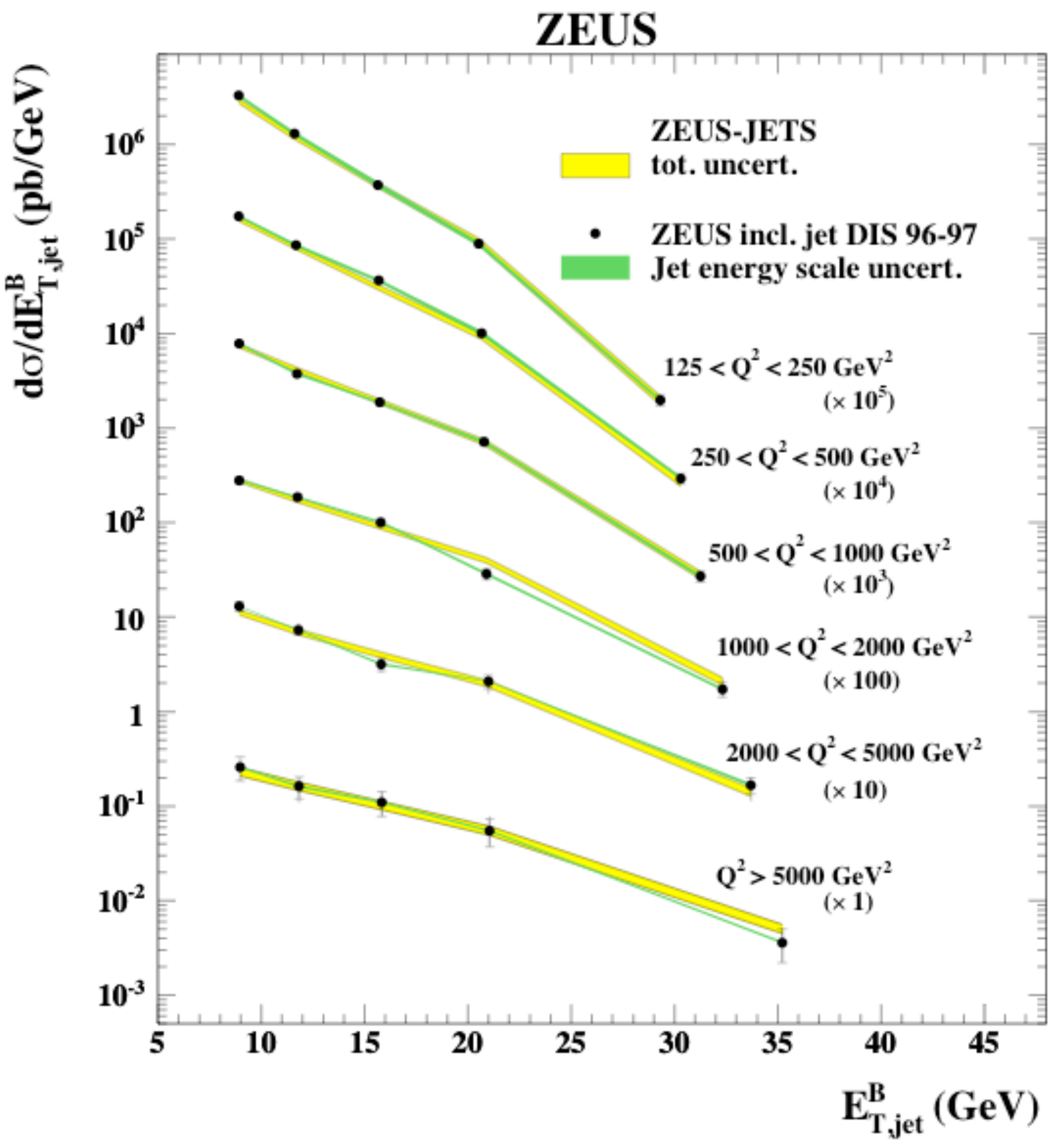
Parton distributions

- Want high precision e.g. for high-x gluon PDFs at LHC
- Perturbative QCD (pQCD) cannot calculate PDFs
- Measure them at some Q^2 and fit as a function of x
- Evolve to higher Q^2 with pQCD
- HERA fits previously used
  - Heavy target data to constrain valence quarks
  - World F_2 data
  - Inclusive cross sections to parameterise gluon by scaling violations
- Many experiments, each with own systematics
- Now use HERA-only data
  - High Q^2 CC and NC constrain valence and low-x sea and gluon
  - Jet data to constrain mid to high-x gluon directly

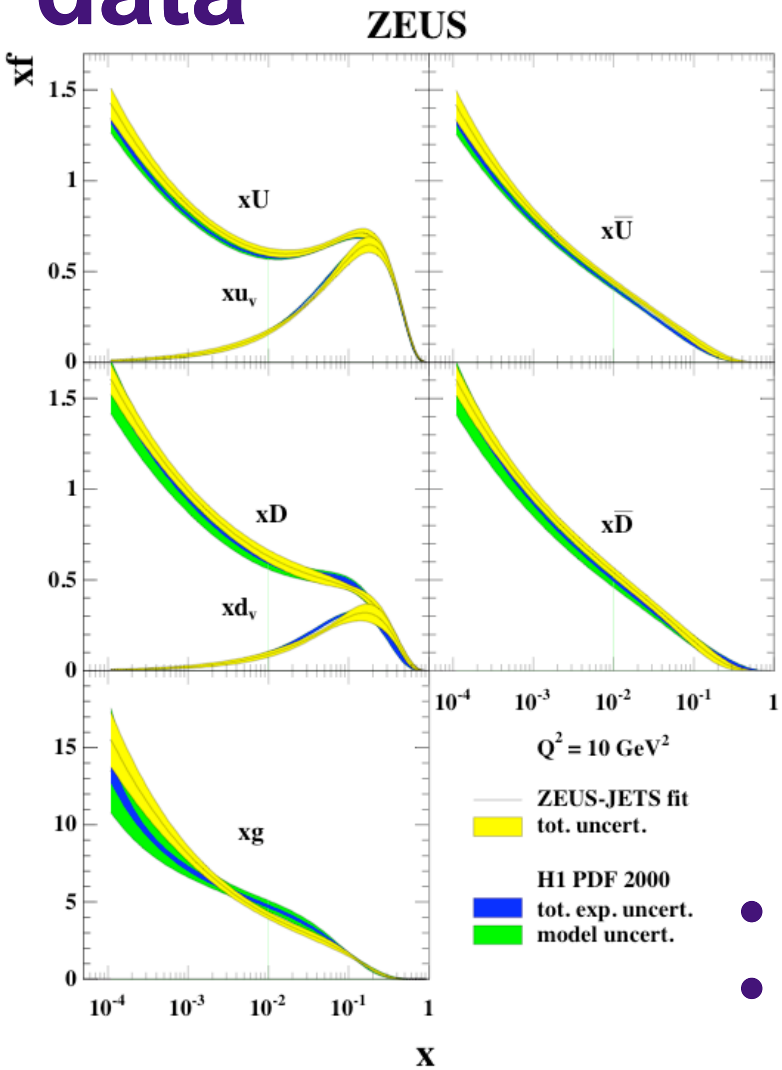
Jet data

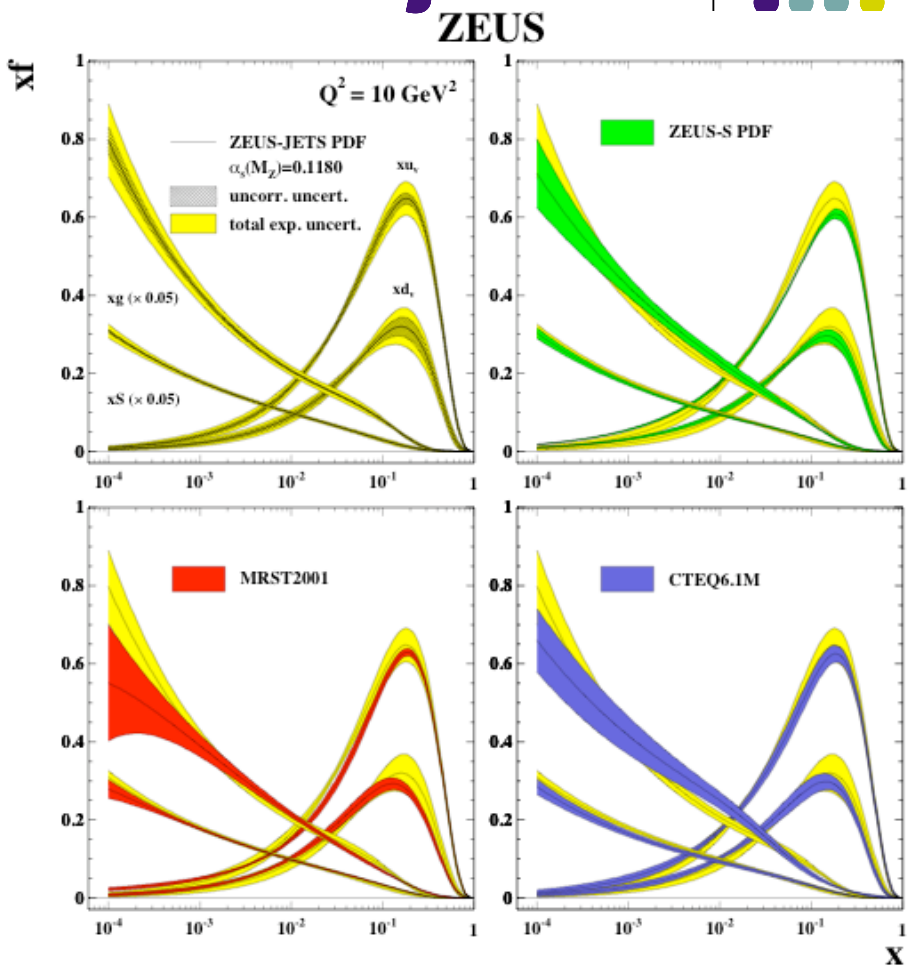


- QCD Compton and boson-gluon fusion processes
  - Distinct jets in final state
- QCDC depends on α_s and $q_i(x,Q^2)$
- Constrain q_i with NC and CC data
- BGF depends on $g(x,Q^2)$
  - Constrain gluon directly



Parton distributions with jet data

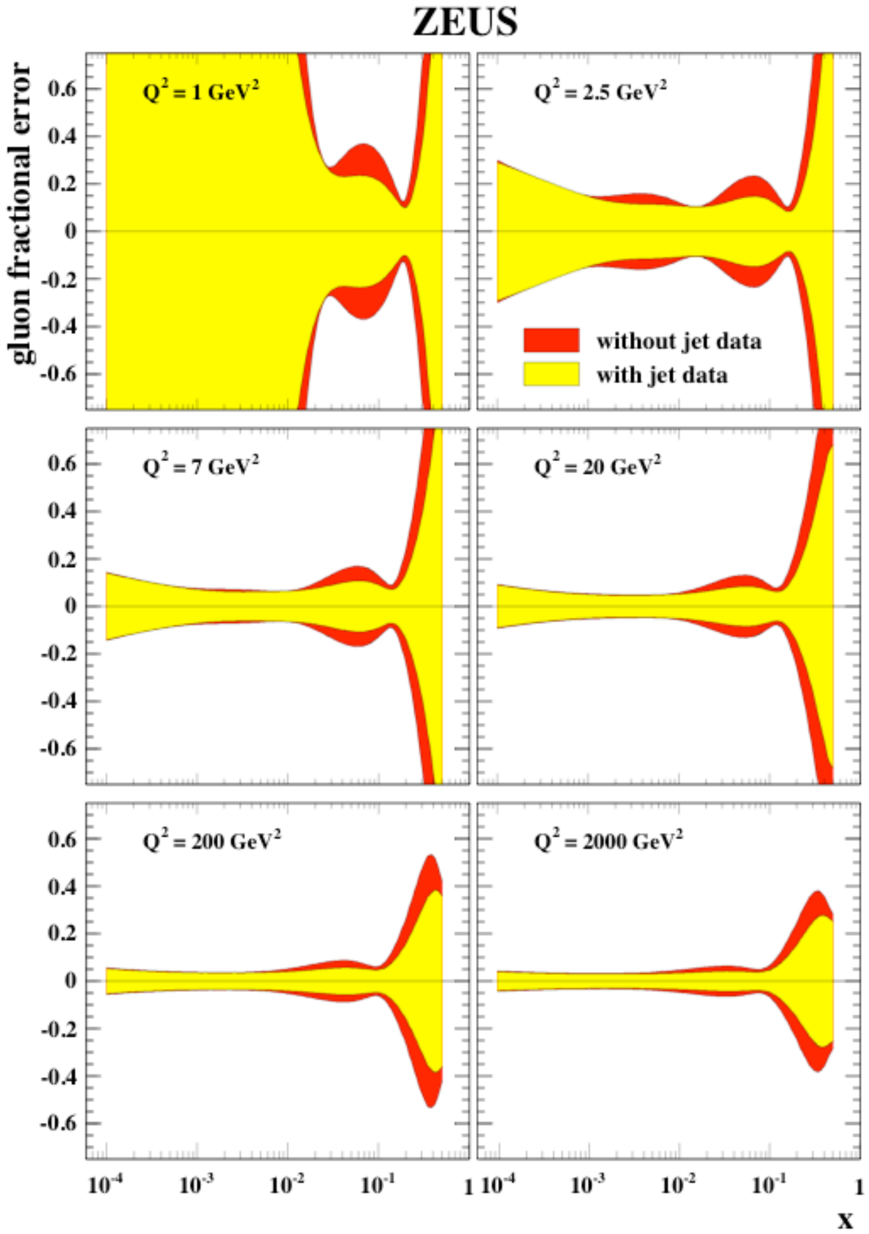




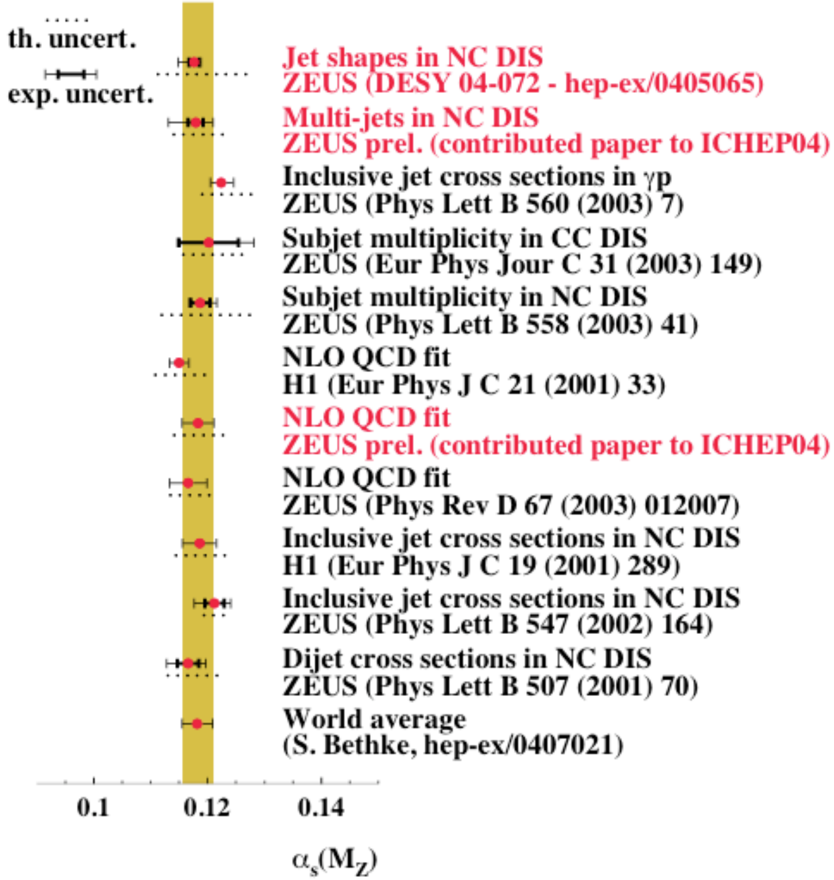
- ZEUS and H1 PDFs consistent
- PDFs with jet data consistent with MRST and CTEQ

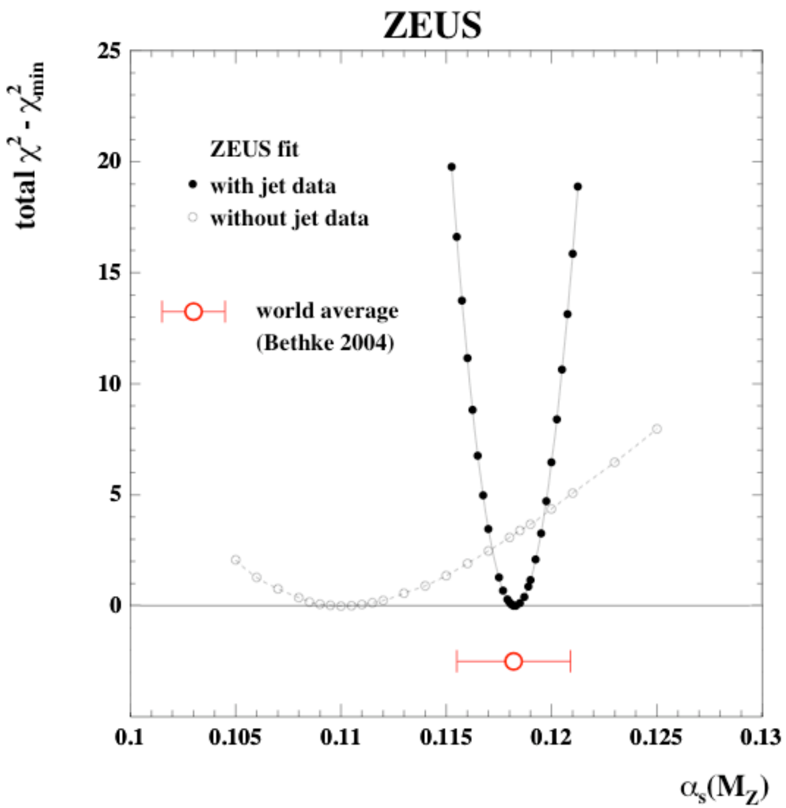
Gluon PDFs with jet data

- Precision of mid to high-x gluon PDF improves with inclusion of jet data



α_s determination from QCD fits

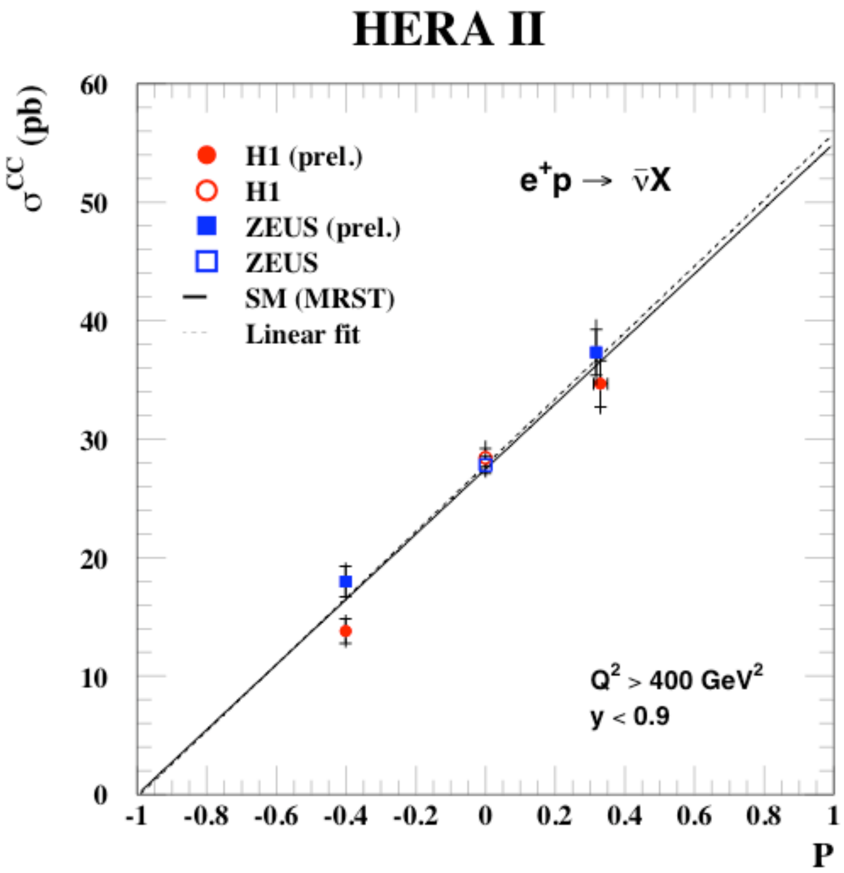




- Compatible with world average with competitive precision

- Jet data significantly improves precision of α_s determination
- $\alpha_s(M_Z) = 0.1183 \pm 0.0028(\text{exp}) \pm 0.0008(\text{model}) \pm 0.0030\ (\text{scale})$
- Large uncertainty from scale
  - Would improve with NNLO fits

Spin-dependent CC cross section



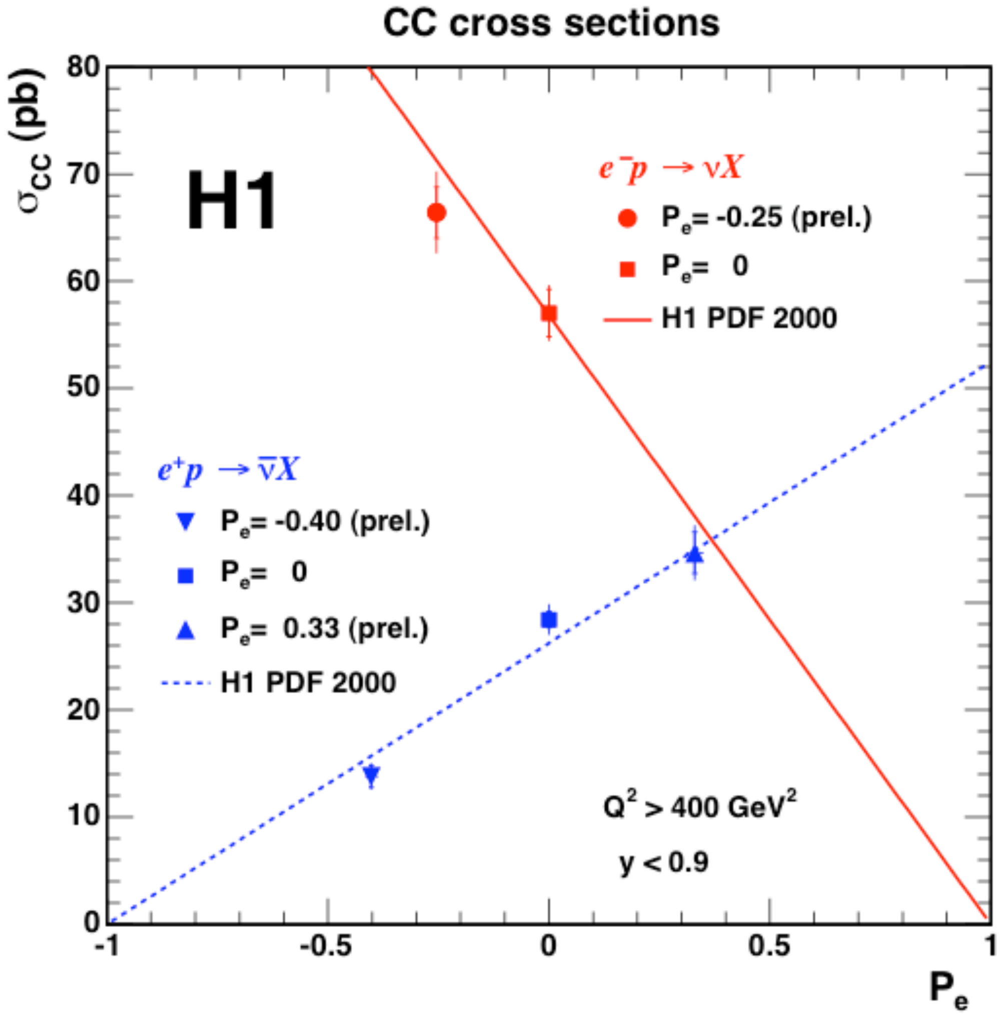
- HERA II is delivering polarised leptons
- Charged current cross section

$$\sigma^{\pm}(P) = (1 \pm P)\sigma_0^{\pm}$$

- No RH CC in SM
  - $\sigma(P=\pm1) = 0$
- Can test spin-dependent part of SM
- Higher cross sections increase statistics and improve precision of structure function and PDF measurements

Spin-dependent CC cross section

- Latest results from e^-p running
- Highest CC cross section from LH e^-
- Results in agreement with SM
- Data-taking is continuing with both lepton helicities



Summary and outlook

- HERA provides important measurements of structure functions and PDFs
- Inclusion of jet data in fits to measure PDFs has constrained gluon PDF - especially important for LHC
- HERA luminosity still increasing so will be able to provide even more accurate measurements of structure functions and PDFs
- Combine ZEUS and H1 data for global fits
- NNLO QCD fits