Proton Structure Functions at HERA

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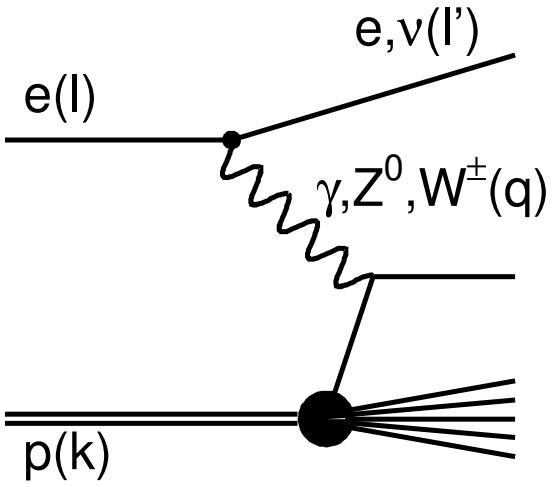
- Introduction
- NC and CC cross sections at high Q^2
- NLO QCD fits $\Rightarrow$ pdf's and α_s
- low x behaviour of F_2
- Conclusion

Presentation of HERMES results by M. Bouwhuis

Introduction

- Studies of differential cross sections and structure functions in lepton nucleon scattering played a crucial role in the understanding of hadronic structures
- Testing ground of the SM in the electroweak and strong interactions sector
- Parton density functions (pdf's) and strong coupling constant α_S are not predicted by theory
  $\Longrightarrow$ determination of pdf's and α_s by fitting to measured cross section
- Important knowledge for pp machines: Tevatron and LHC
  $\Longrightarrow$ predictions depend on accurate pdf's
- The H1 and ZEUS experiments of the HERA ep collider provide precise measurements of inclusive cross sections over a large kinematic region

HERA kinematics

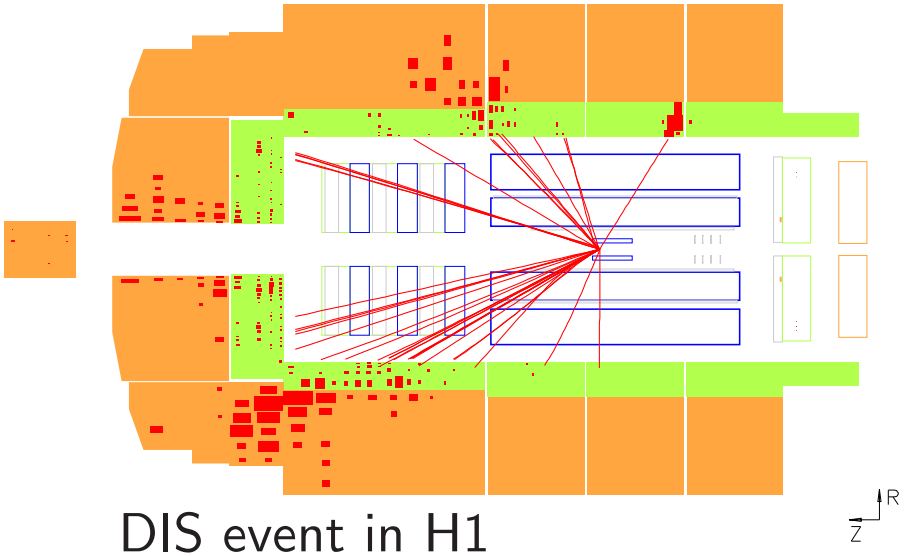


$$Q^2 = -q^2 \qquad \text{4-momentum transfer squared}$$

$$x = \frac{Q^2}{2k \cdot q} \qquad \text{momentum fraction of parton}$$

$$y = \frac{k \cdot q}{k \cdot l} \qquad \text{inelasticity}$$

$$W^2 = Q^2 \frac{1-x}{x} \qquad \text{square of inv. mass of had.f.s.}$$



DIS event in H1

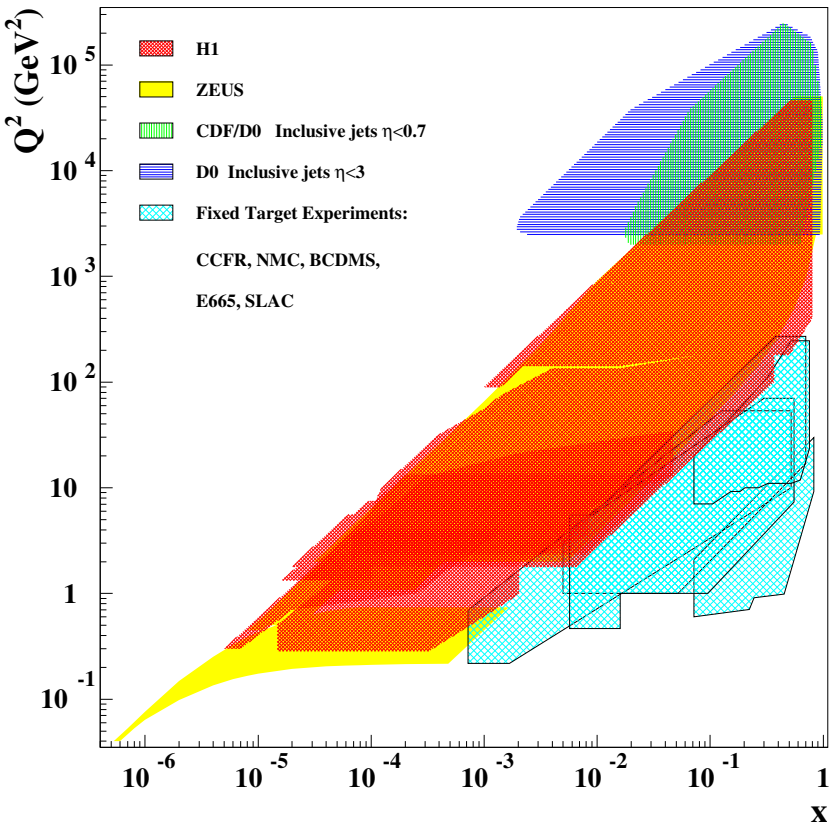
$$\Longrightarrow Q^2 = sxy \qquad \text{with}$$

ep center of mass energy
$\sqrt{s} = 300 - 318\ \mathrm{GeV}$

Kinematical coverage

- Access high Q^2 and low x region compared to fixed target experiments
- $Q^2 > 1$ GeV^2: DIS, perturbative QCD applicable

  electroweak sector accessed at $Q^2 > 10^4$ GeV^2
- $Q^2 \approx 0$ GeV^2: Photoproduction, phenomenological concepts e.g. soft interactions in Regge theory
- $Q^2 \approx 0.1$ GeV^2: transition region between photoproduction and DIS, validity of perturbative concepts?



- Luminosity analyzed by experiments:
  e^-p: $\approx$ 16 pb^{-1} (98-99)
  e^+p: $\approx$ 100 pb^{-1} (93-97 & 99-00)
- Precision of experiments on few % level

Structure functions

Inc. cross section: $\frac{d^2\sigma}{dxdQ^2} \sim$ coupling const $\cdot$ propagator term $\cdot\, \tilde{\sigma}(x, Q^2)$

Neutral Current

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dxdQ^2} = \frac{2\pi}{x}\cdot\alpha^2\cdot\left[\frac{1}{Q^2}\right]^2\cdot\tilde{\sigma}_{NC}^{\pm}(x, Q^2)$$

with reduced cross section

$\tilde{\sigma}_{NC}^{\pm}(x, Q^2) = Y_+\cdot\tilde{F}_2 \mp Y_-\cdot x\tilde{F}_3 - y^2\cdot\tilde{F}_L$

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

Structure functions related to quark densities $q(x, Q^2)$:

$\tilde{F}_2 \sim x\sum_q e_q^2\,(q + \bar{q})$

$x\tilde{F}_3 \sim x\sum_q (q - \bar{q})$ rel. at $Q^2 \gtrsim M_Z^2$

$\Leftrightarrow$ main contribution from γZ interference

$\tilde{F}_L \sim \alpha_S g(x)$ approx. in NLO

Charged Current

$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dxdQ^2} = \frac{1}{2\pi x}\cdot G_F^2\cdot\left[\frac{M_W^2}{Q^2 + M_W^2}\right]^2\cdot\tilde{\sigma}_{CC}^{\pm}$$

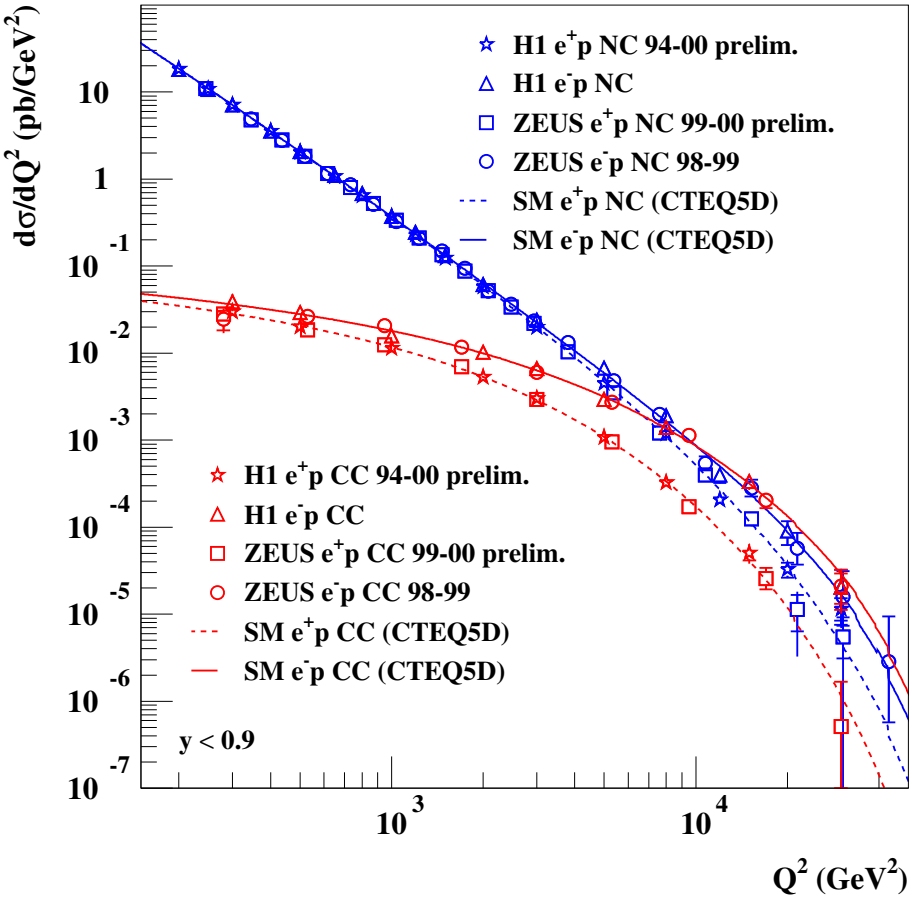
with:

$\tilde{\sigma}_{CC}^{+} = x[(\bar{u} + \bar{c}) + (1-y)^2(d + s)]$

$\tilde{\sigma}_{CC}^{-} = x[(u + c) + (1-y)^2(\bar{d} + \bar{s})]$

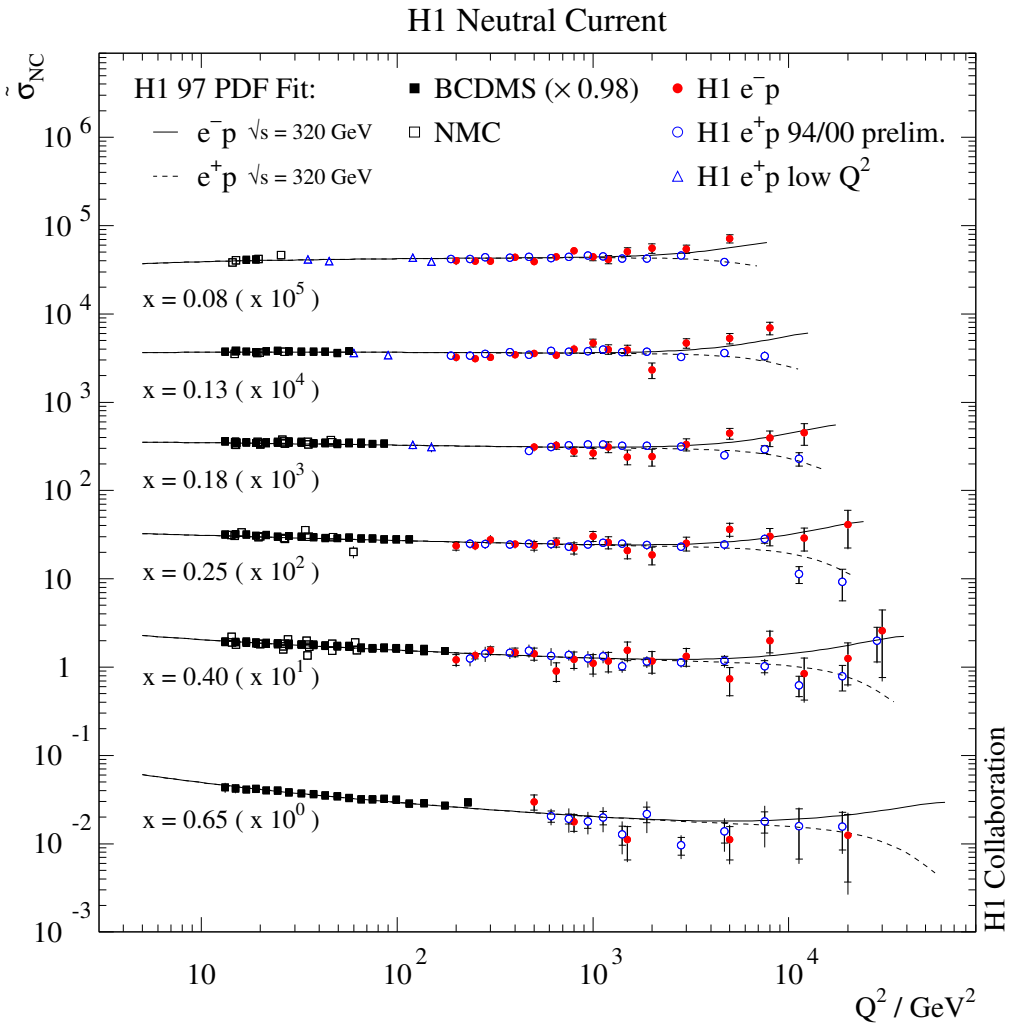
Inclusive cross section at high Q^2

- $\sigma_{CC} \ll \sigma_{NC}$ at $Q^2 \ll M_W^2$
  due to propagator term in cross section
- $\sigma_{CC} \approx \sigma_{NC}$ at $Q^2 \gtrsim M_W^2$
  $\Rightarrow$ electroweak unification
- NC: $\sigma_{NC}^{e^-p} > \sigma_{NC}^{e^+p}$
  due to γZ interference term
- CC: $\sigma_{CC}^{e^-p} > \sigma_{CC}^{e^+p}$
  sensitivity to quark densities
- H1 and ZEUS data consistent
- description of data by SM (QCD & EW) over 6 orders of magnitude
  $\Rightarrow$ SM by NLO QCD global fits



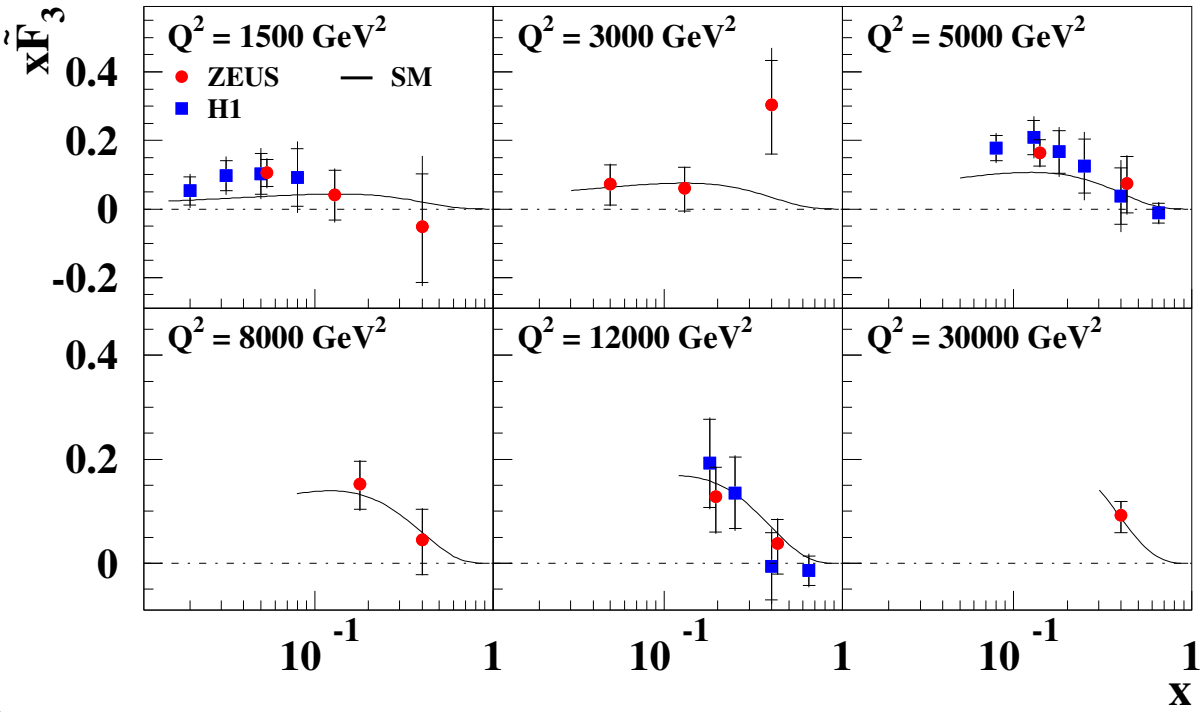
NC reduced cross section $\tilde{\sigma}$

- Scaling behaviour at $x \approx 0.1$ over 3 orders of magnitude in Q^2
- Scaling violation at high $x = 0.65$
- $\sigma_{NC}^{e^-p} > \sigma_{NC}^{e^+p}$ at high Q^2
  constructive γZ interf. for e^-p
  destructive γZ interf. for e^+p
- consistency between HERA data and fixed target results
- compatible with NLO QCD fits



xF_3 determination

- $x\tilde{F}_3 \sim x\sum_q(q-\bar{q})$
  $\sim 2u_v + d_v$
  sensitive to valence quarks
- determined from:
  $xF_3 \sim \sigma^{e^-p}_{NC} - \sigma^{e^+p}_{NC}$
- H1 and ZEUS data consistent with SM
- first measurement of $x\tilde{F}_3$ at high Q^2



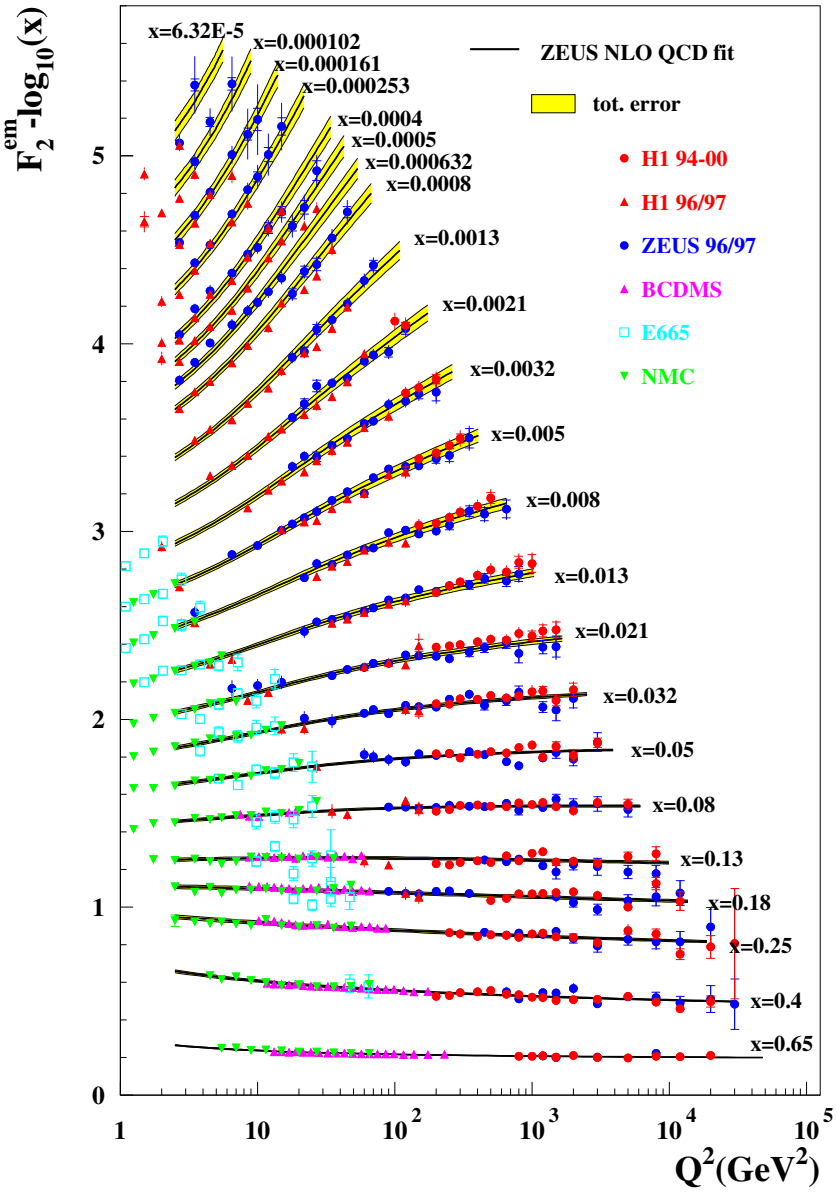
QCD Analyses

- ZEUS NLO QCD analysis (2002):
  - fit to ZEUS and fixed target data (BCDMS, NMC, E665 and CCFR)
  - $Q^2_{min} = 2.5$ GeV^2, variable heavy flavour scheme (Thorne and Roberts)
  - simultaneous fit of $u_v,\ d_v,\ S,\ \bar{d} - \bar{u},\ xg$ and α_S
- H1 α_S fit (2000):
  - fit to H1 and BCDMS μp data
  - $Q^2_{min} = 3.5$ GeV^2, fixed heavy flavour
  - fit of ep valence, $xg(x)$ and α_S
- H1 pdf fit (2002):
  - fit to H1 and BCDMS μp, μd data
  - $Q^2_{min} = 3.5$ GeV^2, massless quarks
  - fit of $u + c,\ \bar{u} + \bar{c},\ d + s,\ \bar{d} + \bar{s},\ xg$
- procedure:
  - parameterization of pdf's at Q^2_0
  - Q^2 dependence of pdf's by DGLAP evolution in NLO
    $\Rightarrow$ neglection of $\ln(1/x)$ terms

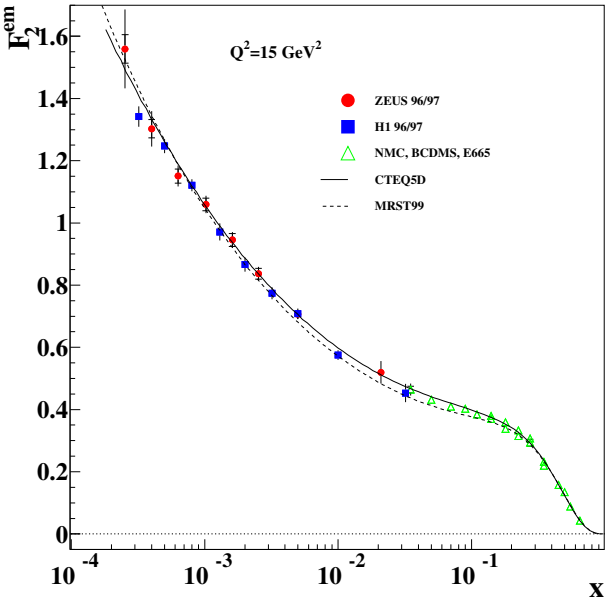
Global fits e.g. CTEQ, MRST
NLO QCD fits to various data sets:
H1, ZEUS, D0, CDF, CCFR, E866,
BCDMS, NMC, E605, NuTeV, E665,
SLAC

- main differences:
  - input data sets
  - parameterizations at Q^2_0
  - treatment of heavy quarks
  - treatment of systematics

NLO fit in comparison to data

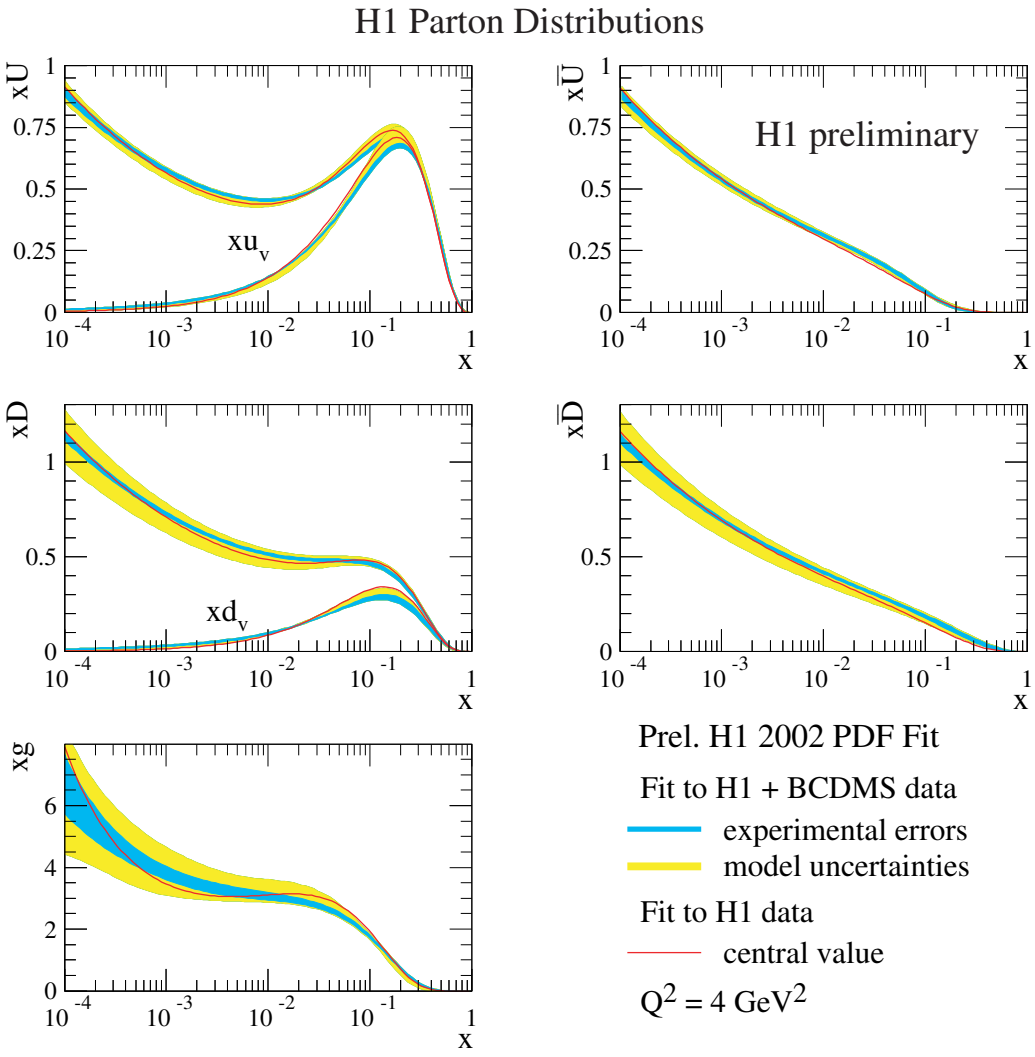


- ZEUS NLO fit describes HERA and fixed target data well over 4 orders of magnitude
- Strong scaling violation at low x due to gluon radiation
- neglection of $\ln \frac{1}{x}$ terms in DGLAP $\Rightarrow$ applicability in the low x region?

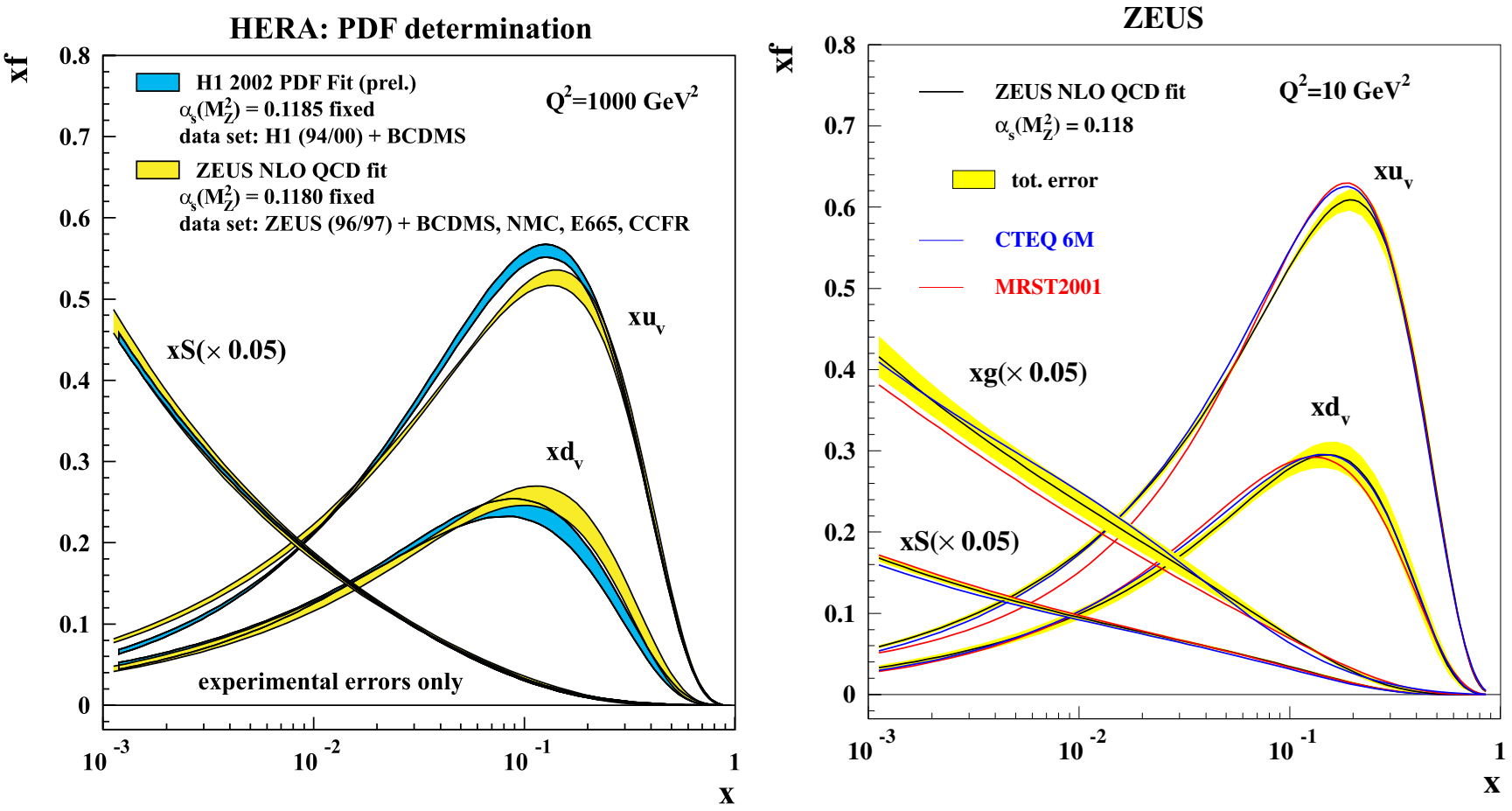


Parton distributions from QCD fits

- fit to H1 (NC+CC) and BCDMS (μp,μd) data
- determine: g
  $U = u + c \qquad \bar{U} = \bar{u} + \bar{c}$
  $D = d + s \qquad \bar{D} = \bar{d} + \bar{s}$
  $\Rightarrow u_v = U - \bar{U}$
  $d_v = D - \bar{D}$
- 13 free parameters
  $\alpha_S = 0.1185$ fixed
  massless quarks
- consistent result with H1 data only
- $xg(x, Q^2)$ consistent with α_S-fit considering heavy flavour treatment



Parton distributions from QCD fits

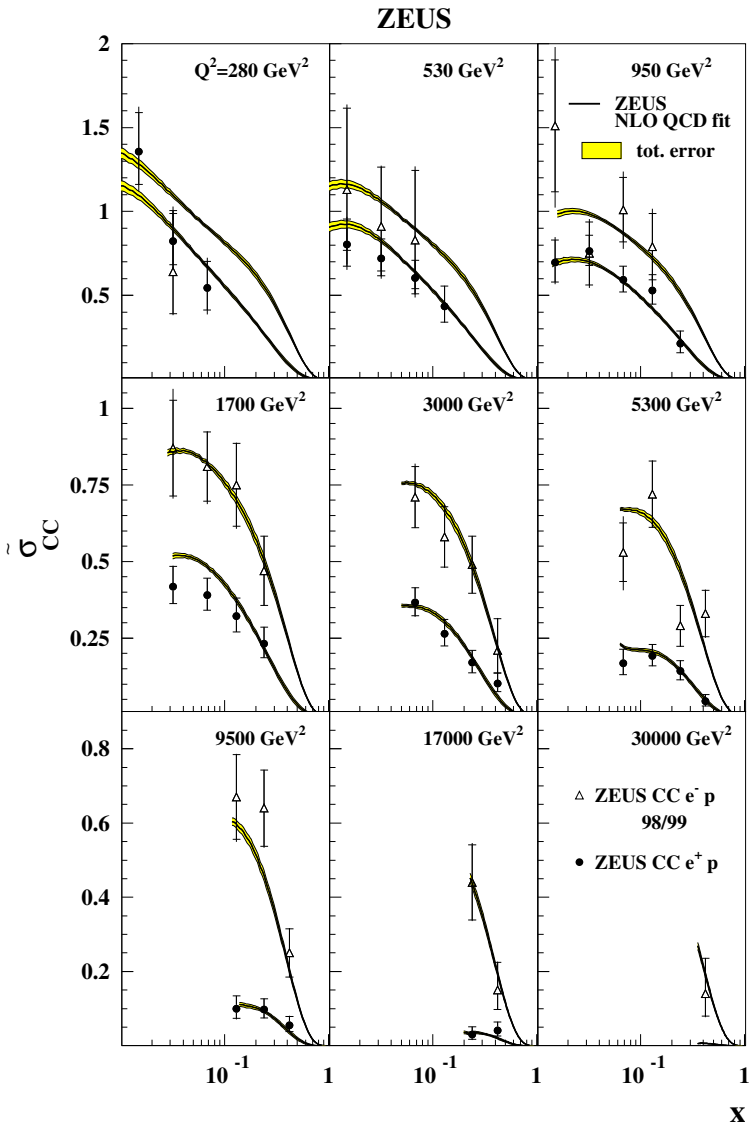


$\Longrightarrow$ good agreement between H1 and ZEUS, considering different approaches

$\Longrightarrow$ good agreement with global fits

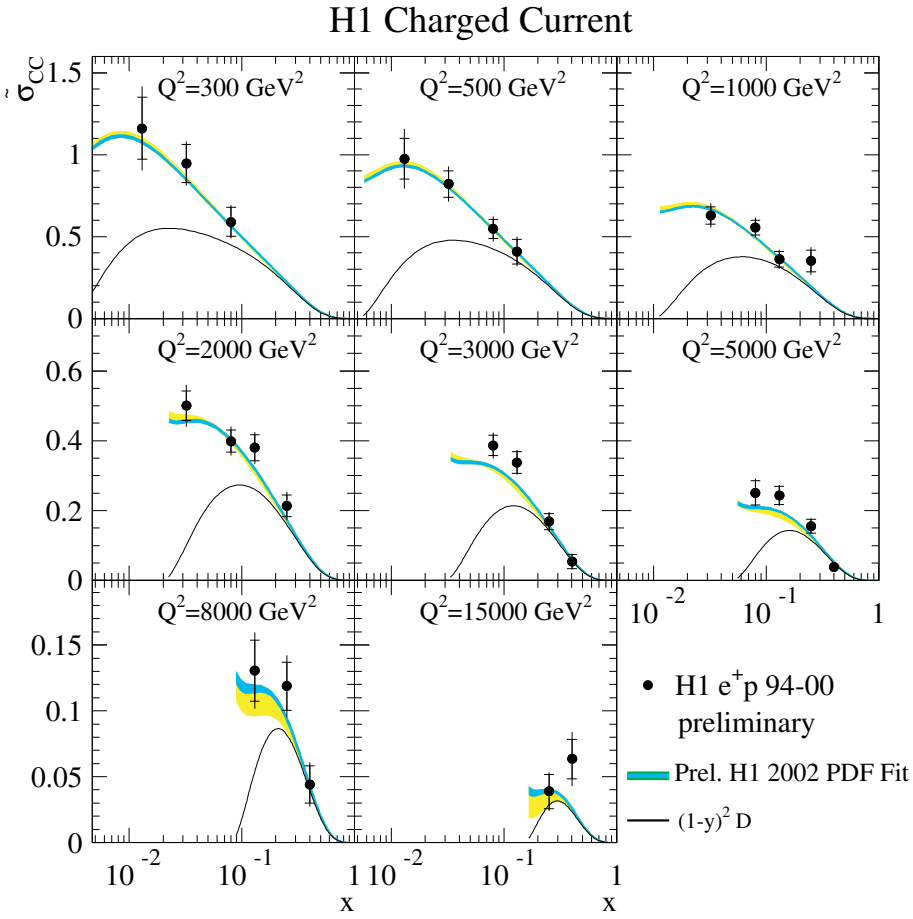
CC cross section

- $\sigma_{CC}^{e^{\pm}p}$ not included in fit procedure



- $\sigma_{CC}^{e^-p} > \sigma_{CC}^{e^+p}$ due to quark content

$$\tilde{\sigma}_{CC}^{-} = x[(u+c) + (1-y)^2(\bar{d}+\bar{s})]$$
$$\tilde{\sigma}_{CC}^{+} = x[(\bar{u}+\bar{c}) + (1-y)^2(d+s)]$$
$$\Longrightarrow \text{constrain } d \text{ quark contribution}$$



Results on α_S

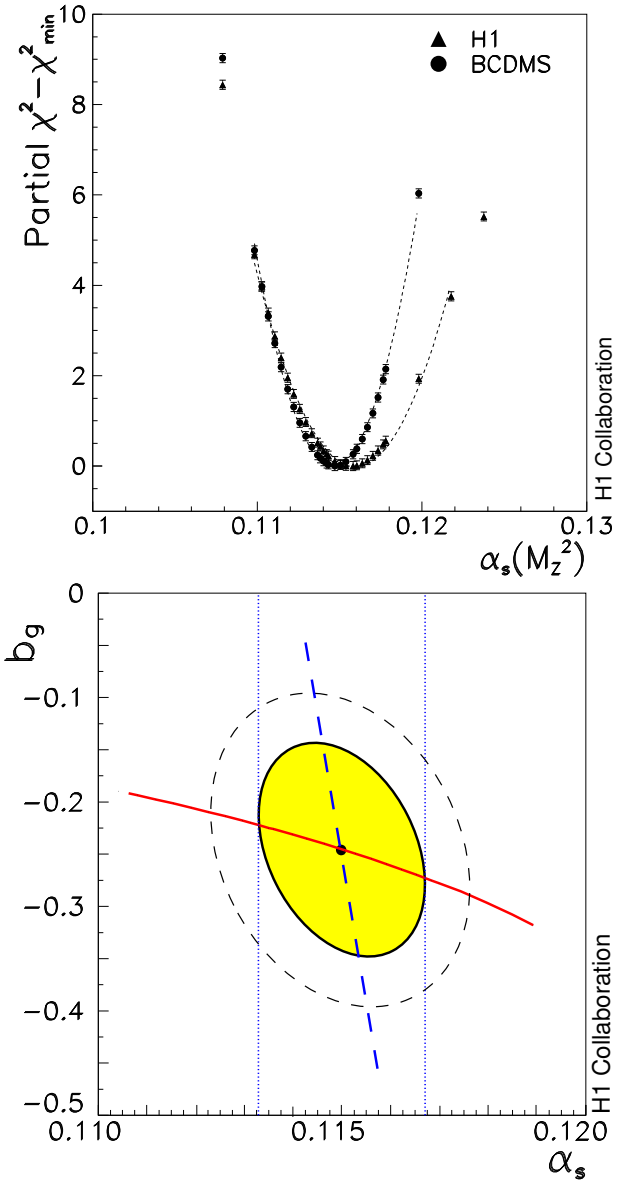
- H1:
  $\alpha_S(M_Z^2) = 0.115 \pm 0.0017(\text{exp})^{+0.0009}_{-0.0005}(\text{model})$

  includes (μp) data from BCDMS
  BCDMS deuteron data added: 0.1158±0.0016(exp)
  NMC replaces BCDMS: 0.116±0.003(exp)
  consistent contribution from H1 and BCDMS to χ^2
  correlation between α_s and $xg(x) \sim x^{bg}$

- ZEUS:
  $\alpha_S(M_Z^2) = 0.1166 \pm 0.0008(\text{unc}) \pm 0.0032(\text{corr})$
  $\pm 0.0036(\text{norm}) \pm 0.0018(\text{mod})$

  includes data from BCDMS, NMC, E665 and CCFR

- Variation of renorm. scale leads to add. theo. uncertainty:
  H1: $\pm$ 0.005 if $\mu_r = (\frac{1}{4}..4) \cdot Q^2$
  ZEUS: $\pm$ 0.004 if $\mu_r = (\frac{1}{2}..2) \cdot Q^2$
- World average (PDG 2000): $\alpha_S = 0.1185 \pm 0.0020$
- α_S error dominated by theoretical uncertainties
  $\Longrightarrow$ NNLO will provide improvement



Intermission

- H1 and ZEUS provide precise measurements on the few % level of NC and CC cross sections over a large kinematic region

- NLO QCD fits to HERA data in combination with fixed target data:

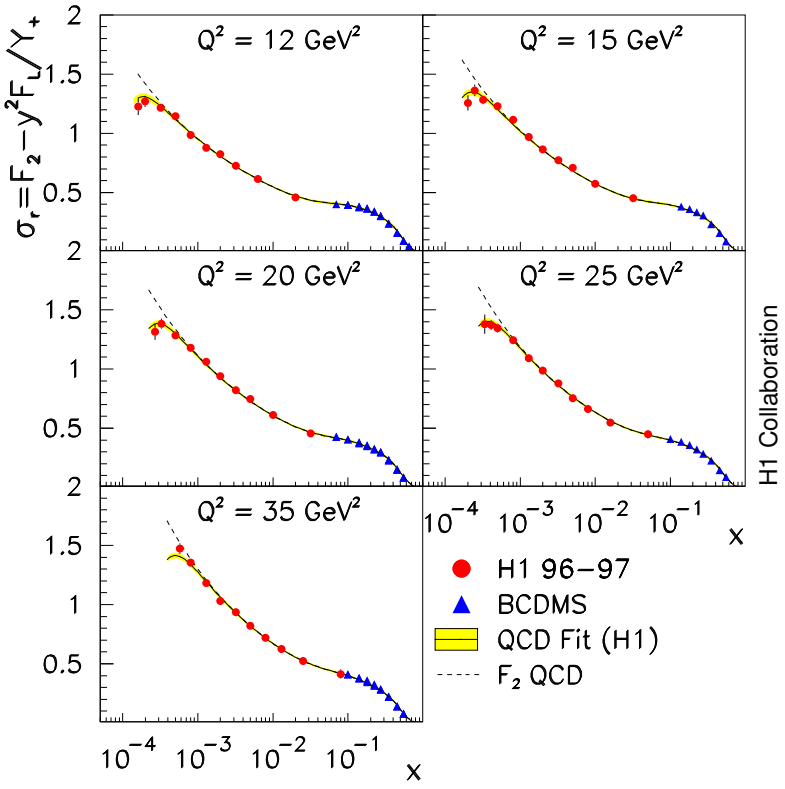
  determination of pdf's (5-10%) $\Rightarrow$ compatible with global fits

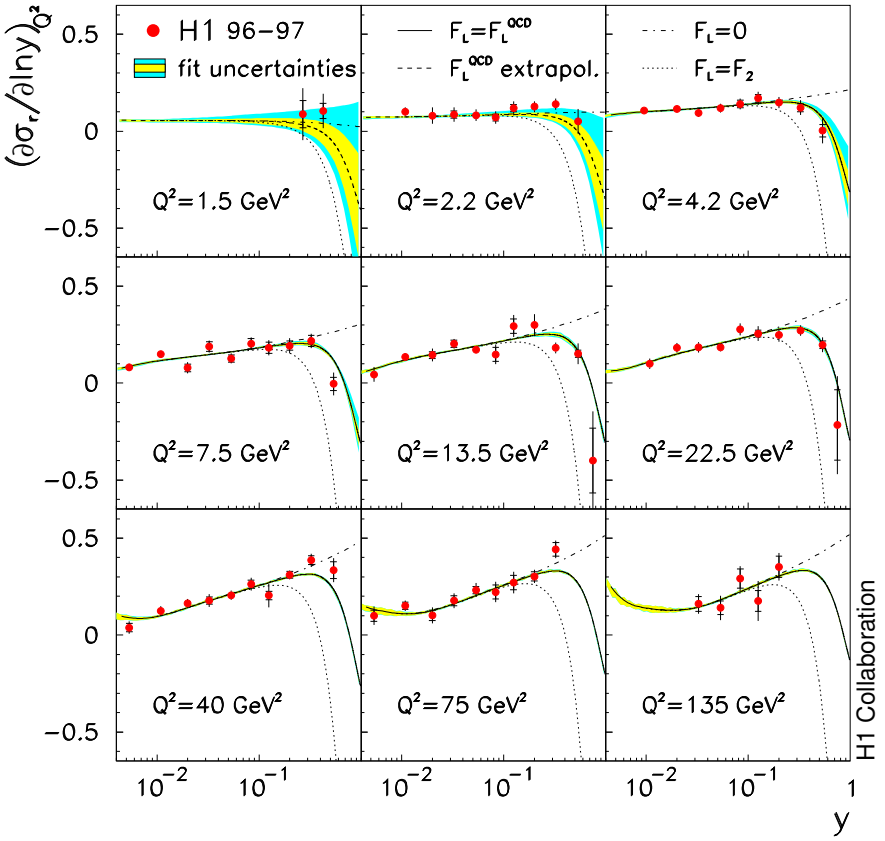
  determination of α_S with competitive experimental accuracy
  need NNLO for inclusive DIS to decrease theoretical uncertainties

- H1 and ZEUS measurements and QCD fits show a consistent picture of the SM

Determination of F_L

- $F_L \sim \alpha_S g \Leftrightarrow$ direct test for $xg(x)$
- F_L contributes at high y (low x)
- 2 methods for F_L determination:
  - derivative - extrapolation

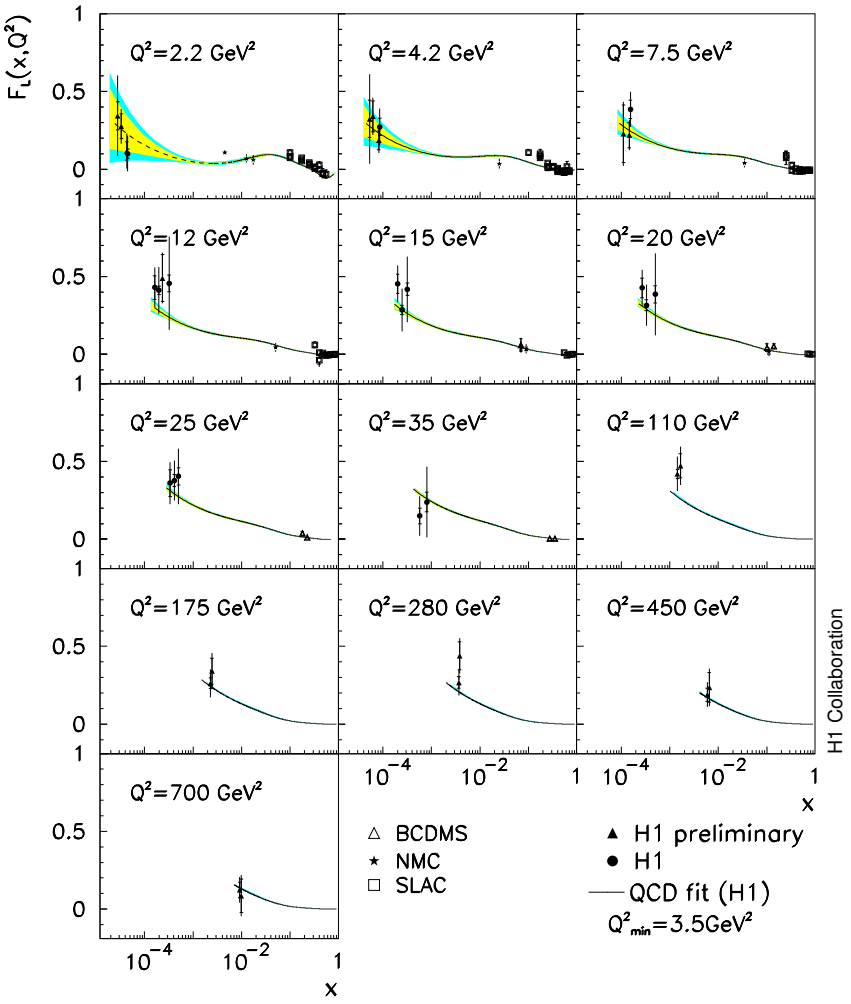




- Estimate derivative of reduced cross section for $Q^2 < 10$ GeV^2:

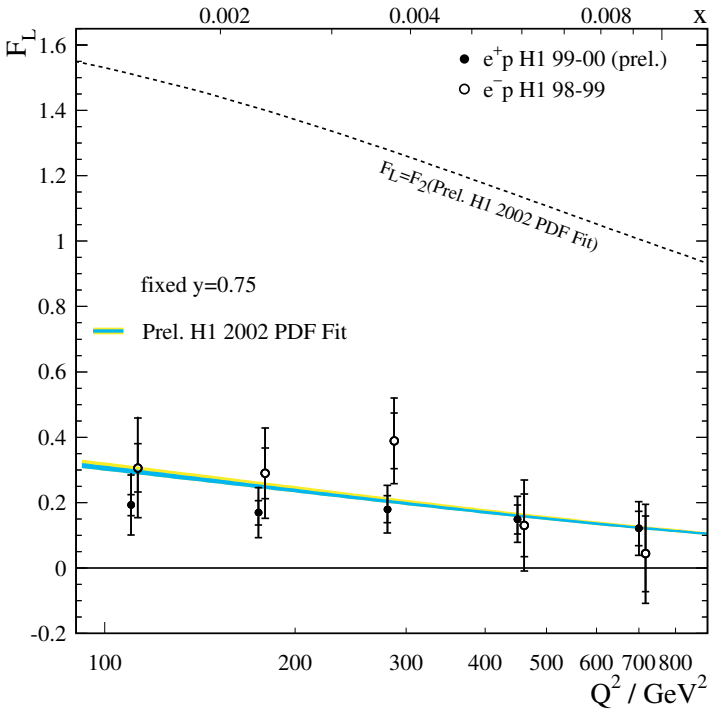
$$\left(\frac{\partial \sigma_r}{\partial \ln y}\right)_{Q^2} = \left(\frac{\partial F_2}{\partial \ln y}\right)_{Q^2} - F_L \cdot 2y^2 \cdot \frac{2-y}{Y_+^2}$$

Determination of F_L



- Extrapolate F_2 from QCD fit to high y for $Q^2 > 10$ GeV^2:

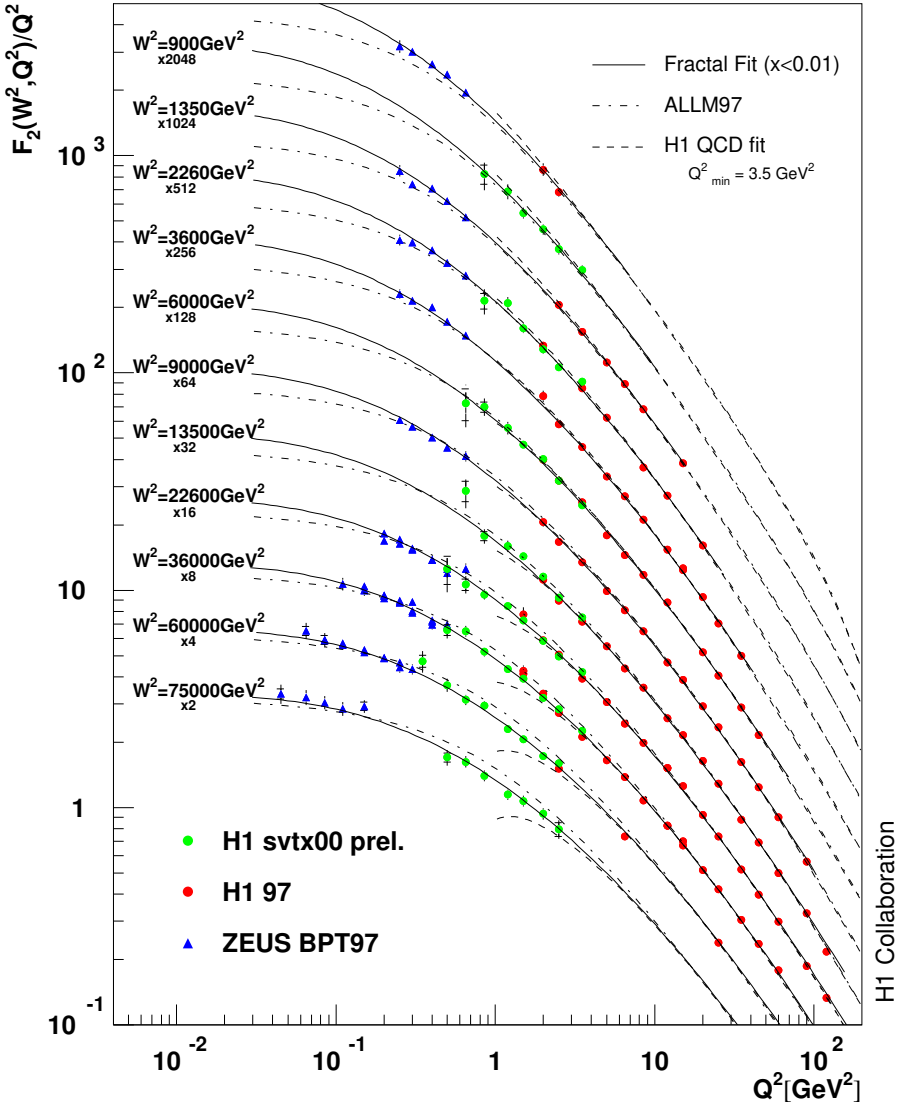
$$F_L = \frac{Y_+}{y^2}\left[F_2 - \sigma_r\right]$$



$\Longrightarrow$ Good agreement between data and NLO QCD fit
successfull consistency check of QCD fit procedure

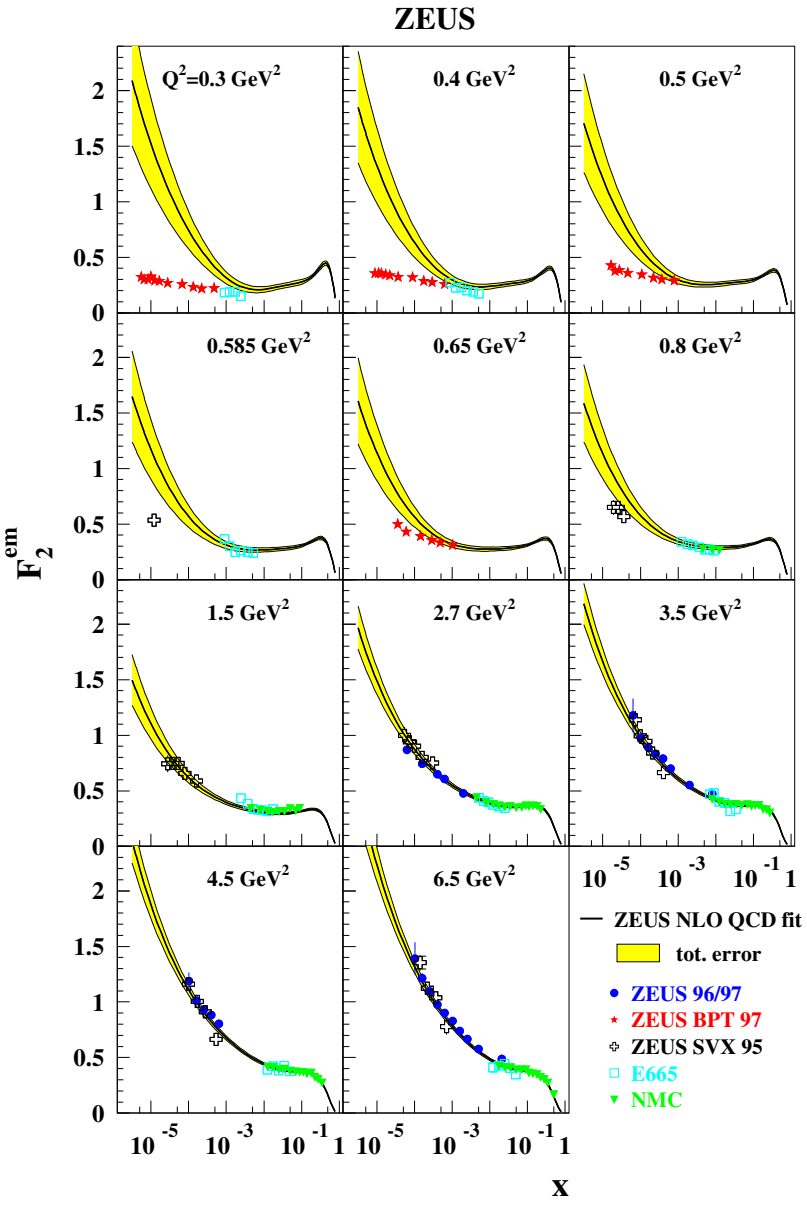
Transition to low Q^2

- $\gamma^* p$ cross section: $\sigma_{\gamma^* p} \sim F_2/Q^2$ at fixed $W^2 \simeq ys$ (at low x)
- good agreement between H1 and ZEUS data
  $\Rightarrow$ continuous coverage to $Q^2 = 0.045$ GeV^2
- backward extrapolation of H1 QCD fit ($Q^2_{min} = 3.5$ GeV^2) undershoots data
- fractal fit is based on self-similar structure of gluon emissions and splittings at low x
  hep-ph/0203260



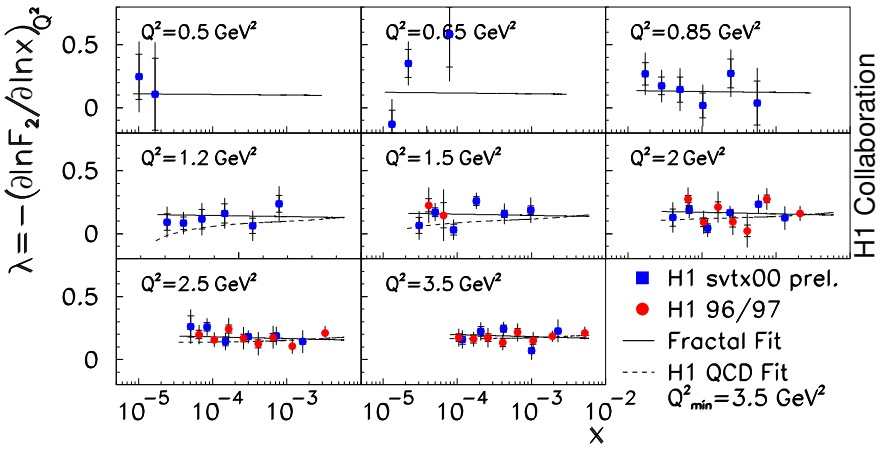
Applicabilty of QCD

- ZEUS NLO QCD fit: $Q^2_{min} = 2.5$ GeV^2
  $\ln(1/x)$ resummation terms and
  non-perturbative effects neglected
- backward extrapolation of fit
  overshoots data for $Q^2 < 0.8$ GeV^2
- transition to flat behaviour
  at $Q^2 \approx 1$ GeV^2 not predicted by fit

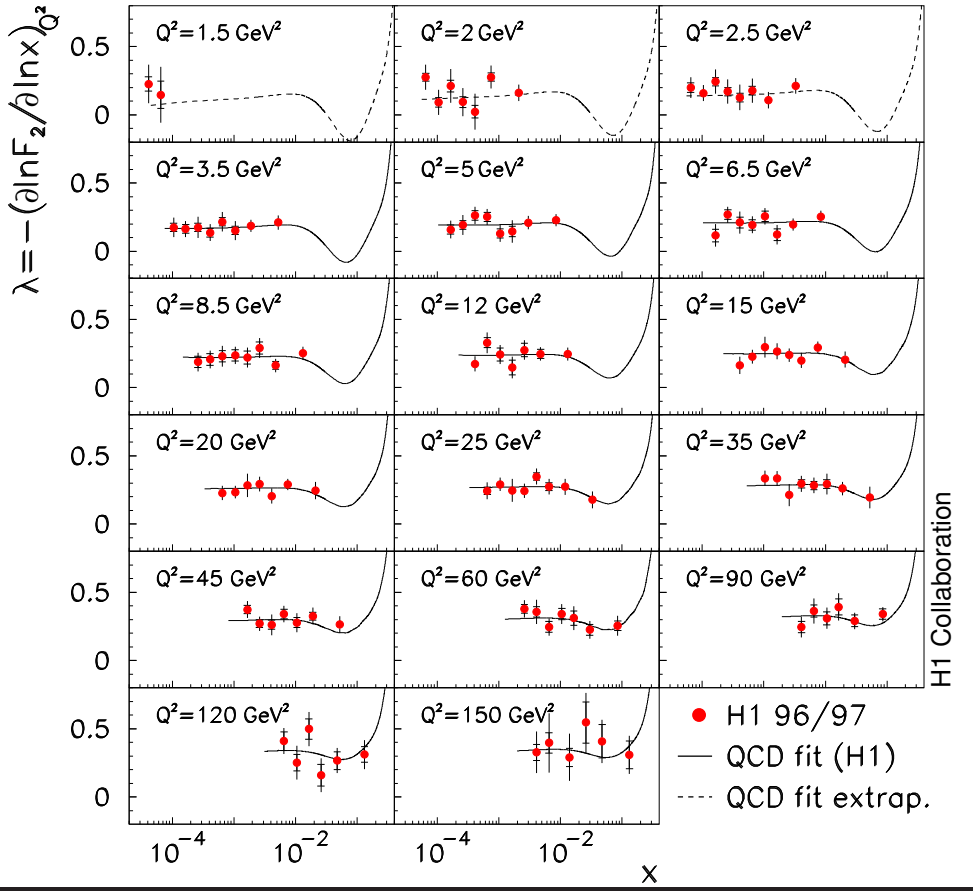


x dependence of F_2

- BFKL predicts:
  F_2 rises as power of x at low x
- $\lambda(x, Q^2) = \left(\frac{\partial \ln F_2(x,Q^2)}{\partial \ln x}\right)_{Q^2}$
- λ const. at fixed Q^2 for x <0.01
- $\Rightarrow F_2(x, Q^2) = c(Q^2)x^{-\lambda(Q^2)}$



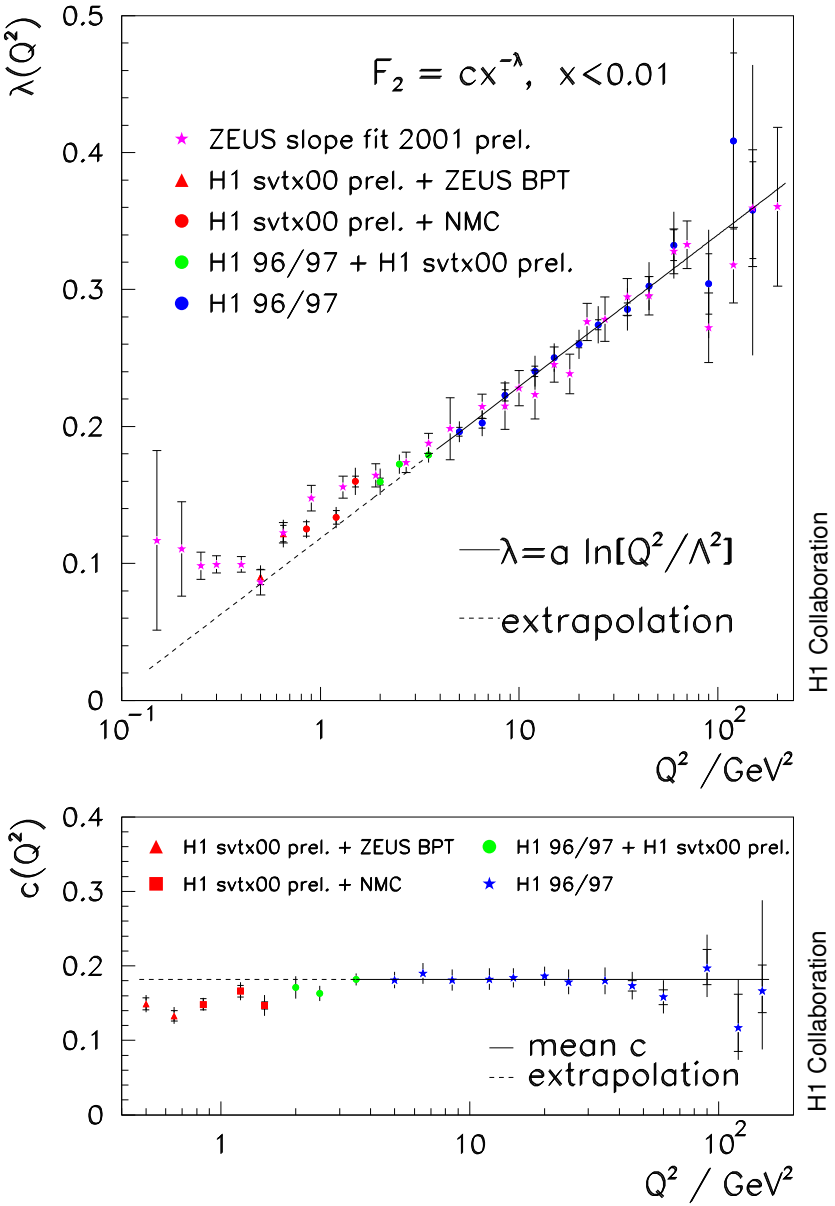
- transition to valence quark region at large x
- no taming of gluon rise towards low x



Behaviour at low Q^2

- at $Q^2 \lesssim 3$ GeV^2:
  - λ deviates from log-dependence
  - decrease of c
    expect $c \sim Q^2$ for $Q^2 \to 0$

- for fixed Q^2 Regge theory predicts:
  $F_2(x, Q^2) \sim x^{-(\alpha_{I\!P}(0)-1)}$ with
  $\alpha_{I\!P}(0) - 1 \approx 0.08$ (Donnachie Landshoff)
  $\Rightarrow \lambda \approx 0.08$



Conclusion

- H1 and ZEUS provide precise measurements of inclusive NC and CC cross sections over several orders of magnitude:
  $0.045 < Q^2 < 30000$ GeV^2 and $10^{-6} < x < 0.65$
- Good agreement between HERA I data and expectations from QCD and EW
- NLO QCD fits, based on DGLAP evolution, to HERA and fixed target data describe data well $\Longrightarrow$ extraction of pdf's and α_S with high precision
- Low Q^2 data reach limit of applicability of pQCD
  $\Longrightarrow$ need theoretical development
- HERA II will provide higher luminosity $\mathcal{L} \approx 1$ fb^{-1}, beam polarization and improved experimental conditions to extend kinemtical coverage to high Q^2 and high x
- Precise determination of α_S and $F_L(x, Q^2)$ with low E_p run