XXVIIIth Rencontres de Moriond
QCD and Hadronic Interactions at High Energy

March 23rd-29th 2003

Measurements of Structure Functions, α_s and Parton Distribution Functions at HERA

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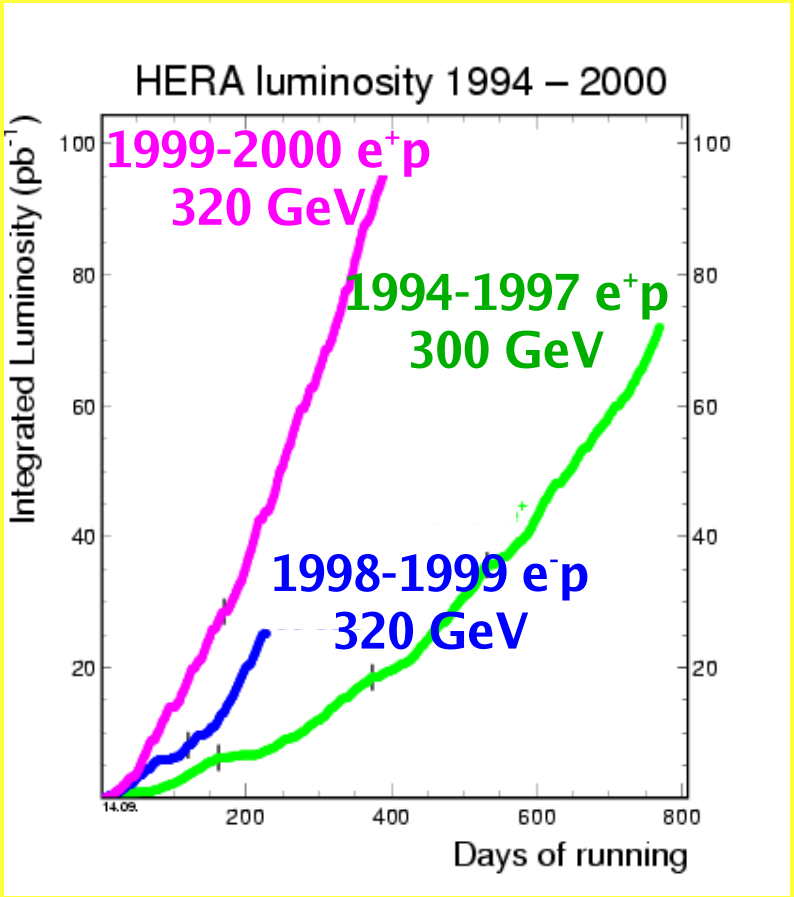
on behalf of the
H1 and ZEUS Collaborations

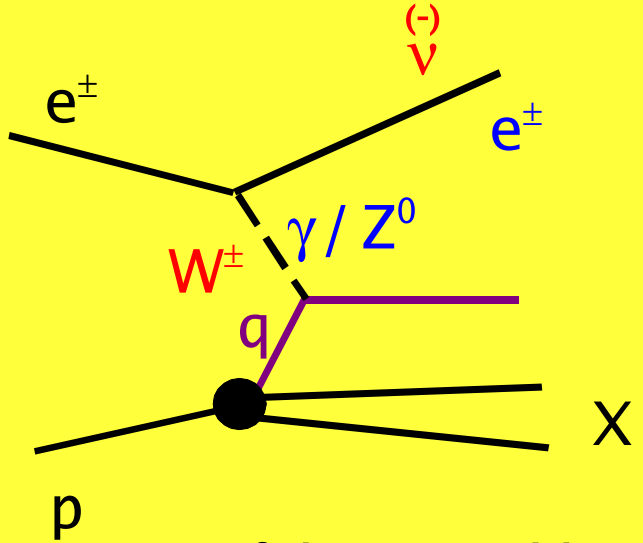
- Data Sets and HERA Kinematics
- Measurements at High & Medium Q^2
- H1 & ZEUS NLO QCD Fits
- Low Q^2 Data
- Summary

HERA Data and Kinematics

Most important data samples analysed since 1994:



Neutral and Charged Current processes at HERA:



resolution power of the virtual boson:

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

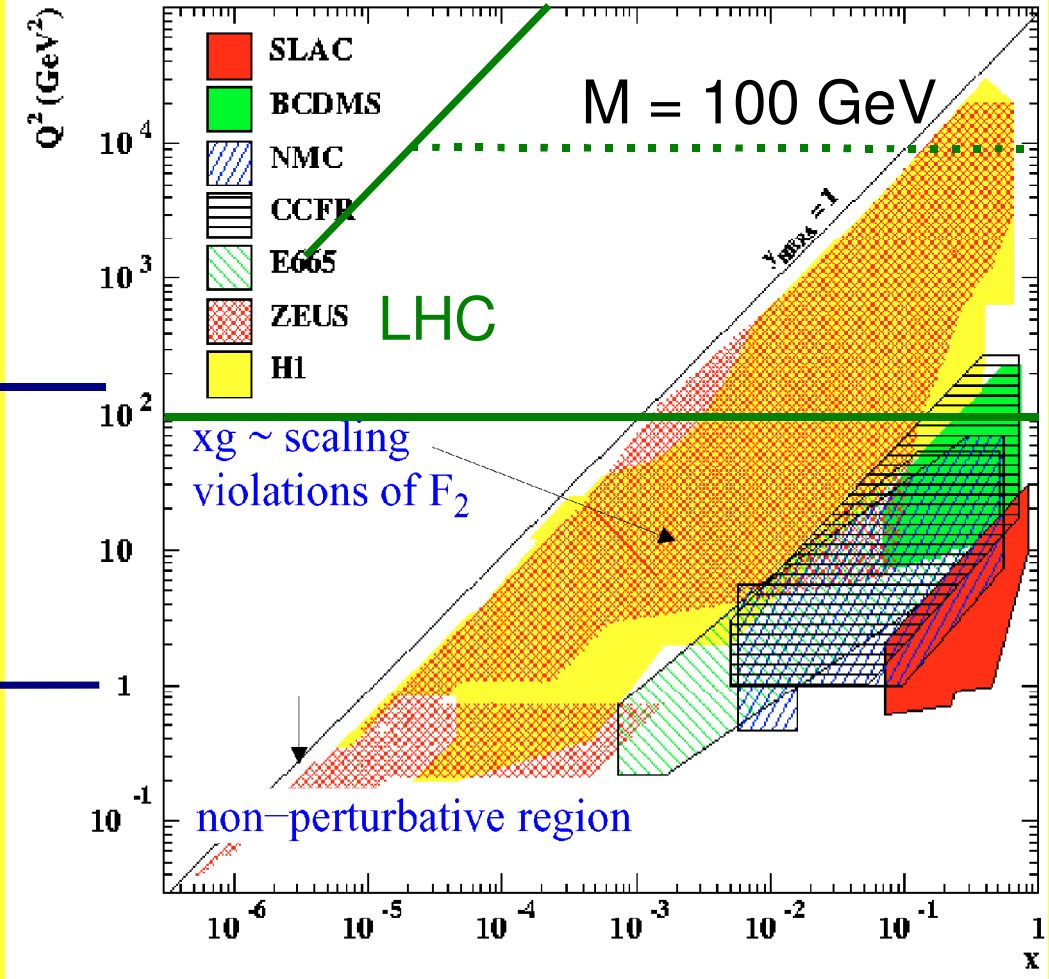
HERA is a unique facility to probe parton content of the proton

HERA Kinematic Plane

High Q^2:
Determination of PDFs,
Constraints on valence quark distribution

Medium Q^2:
Measurement of xg and α_s

Low and very low Q^2:
Testing transition region between perturbative and non-perturbative QCD



HERA has unique access to the low x region

Probing the Proton Structure

NC and CC cross sections are sensitive to the parton distribution functions via the proton structure functions:

NC: $F_2 = \frac{4}{9}\left(xU + x\bar{U}\right) + \frac{1}{9}\left(xD + x\bar{D}\right)$ $\quad xF_3^{\gamma Z} \propto x\left[2(U-\bar{U}) + (D-\bar{D})\right]$ $\quad F_L \sim x\,g$

more statistics needed

CC: $\phi_{CC}^{-} = xU + (1-y)^2 x\bar{D}$ $\quad \phi_{CC}^{+} = x\bar{U} + (1-y)^2 xD$

U = u+c
D = d+s

What DGLAP evolution tells us: $\left[\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2}\right]_x$ related to PDFs(x)

What we measure: Cross sections => structure functions
access to $[\text{PDFs}(x)]_{Q_0^2}$ at a certain Q_0^2

=> Evolution in Q^2 predicted by DGLAP
=> HERA: measure x & test the predicted Q^2 dependence

Parametrisation of the PDFs

Parton distribution functions are parametrised depending on x:

$$x f_q(x, Q_0) = A_q x^{B_q} (1-x)^{C_q} (1 + D_q \sqrt{x} + E_q x + F_q x^2)$$

normalisation

low x

high x

correction terms
(D and F only H1)

H1

parametrisation of combinations:
xg, xU, xD, xŪ, xD̄

=> **13 free parameters** (α_s fixed, fixed target data included)

ZEUS

'classical' parametrisation:
xg, xSea, u_v, d_v, ($\bar{u}$-$\bar{d}$)

=> **11 free parameters** (α_s fixed, fixed target data included)

sum-rules,
several assumptions e.g. on sea distribution

Fitting F_2

Two approaches with different ingredients:

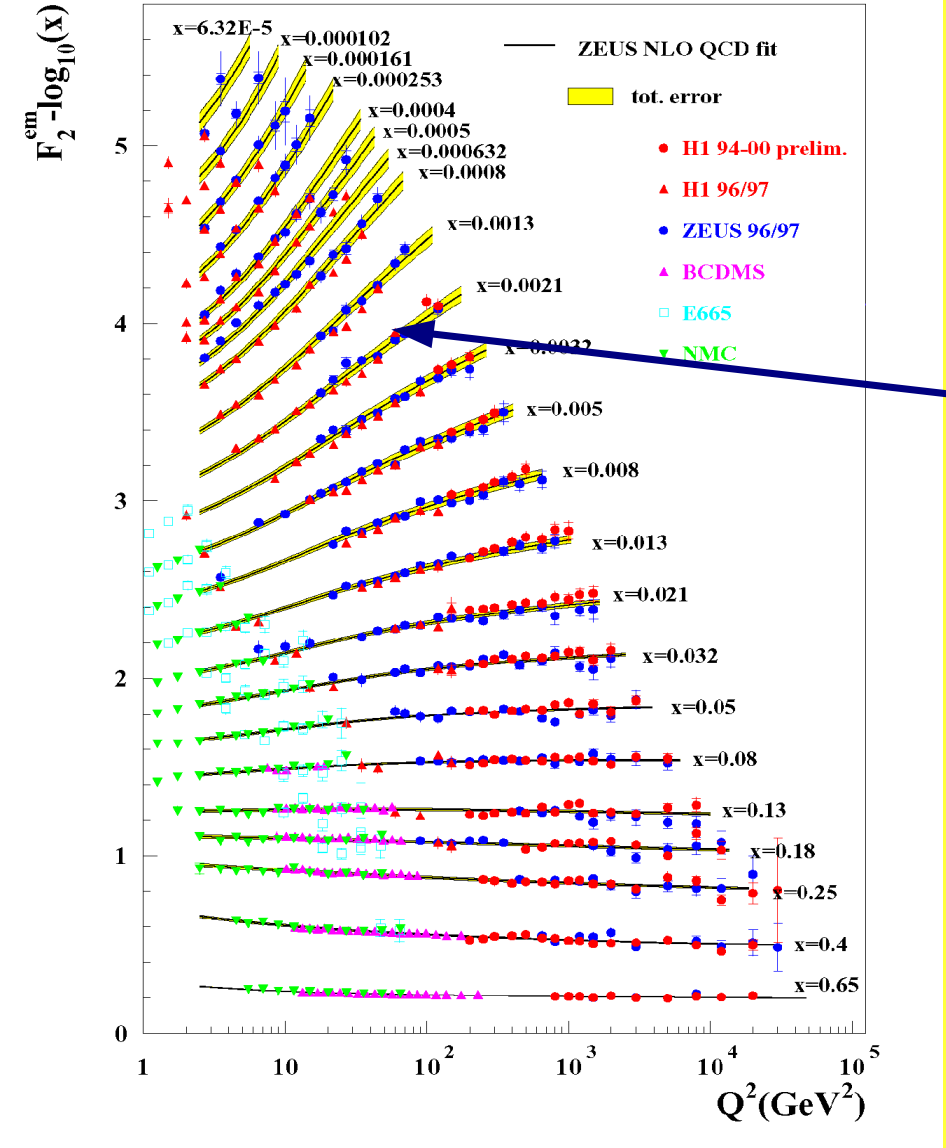
H1 (ICHEP02,978)

- Proton & Deuteron Data:
  H1 (1994-2000 NC+CC)
  fixed target: BCDMS
- $3.5\ \text{GeV}^2 < Q^2 < 30.000\ \text{GeV}^2$
- $Q_0^2 = 4\ \text{GeV}^2$
- Fixed flavour scheme

ZEUS (PHYS.REV. D67:012007,03)

- Proton, Deuteron & Iron Data:
  ZEUS (1994-1997 NC)
  fixed target: NMC, BCDMS, E665, CCFR
- $2.5\ \text{GeV}^2 < Q^2 < 30.000\ \text{GeV}^2$
  $W^2 > 20\ \text{GeV}^2$
- $Q_0^2 = 7\ \text{GeV}^2$
- Variable flavour scheme (Thorne&Roberts)

F_2 and Scaling Violations



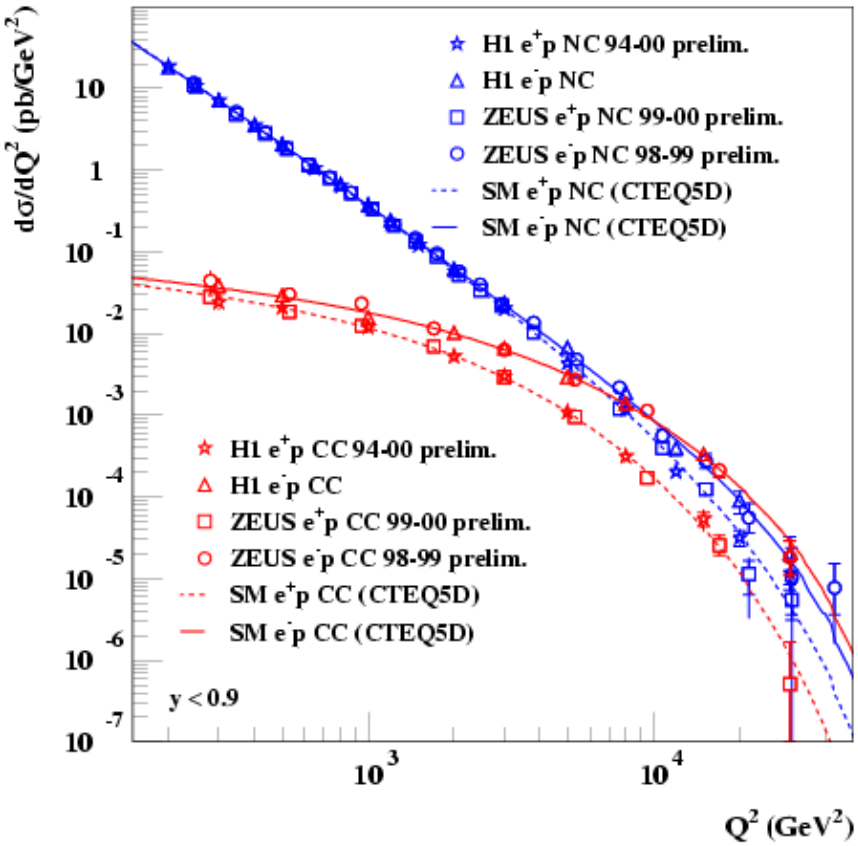
HERA data described by QCD/DGLAP over 4 orders of magnitude in x and Q^2!!

strong scaling violations driven by gluons

Further questions:

- What happens at very low Q^2?
  $\alpha_s \uparrow$, transition from pQCD to non-pert. QCD
- What happens at very low x in terms of PDFs?
- Do we see electro-weak unification?

High & Medium Q^2 Cross Sections



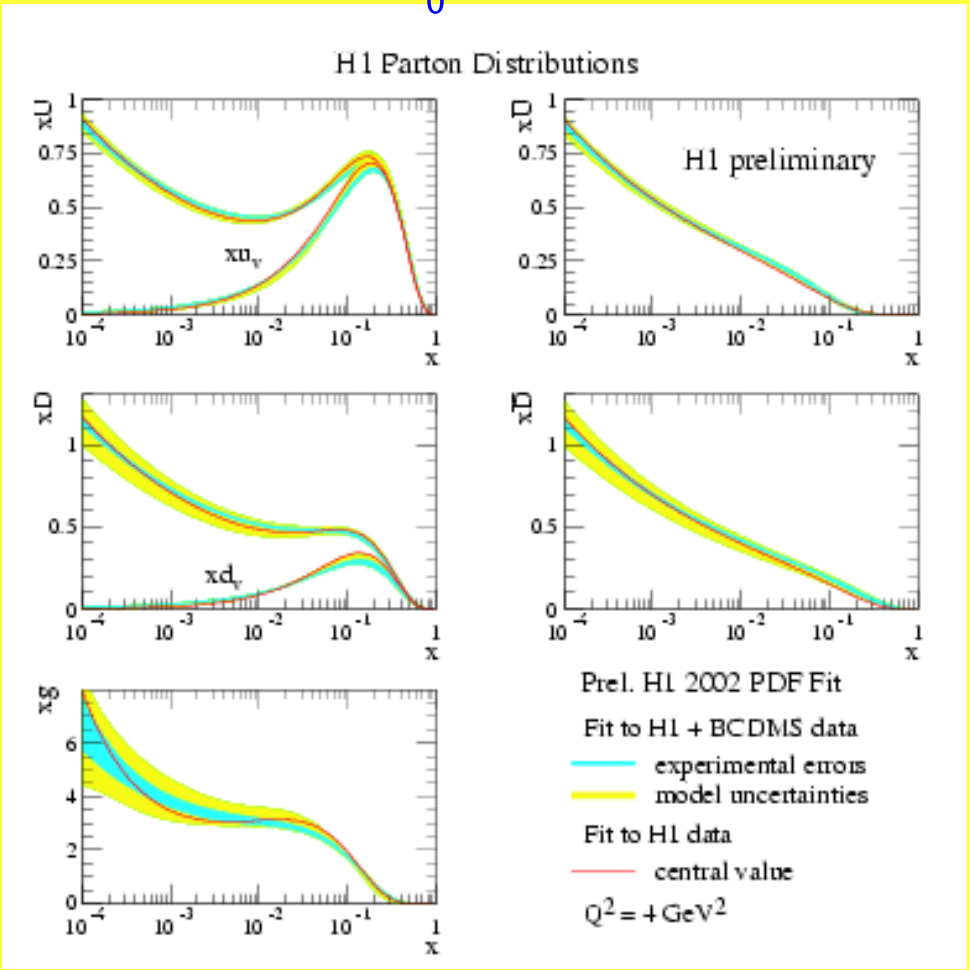
- H1 and ZEUS data consistent
- NC: $\sigma(e^-p) > \sigma(e^+p)$
  γZ interference
- CC: $\sigma(e^-p) > \sigma(e^+p)$
  $xu(x)$ $(1-y)^2xd(x)$
- high precision even at high Q^2

$Q^2 \geq M_Z^2, M_W^2 \Rightarrow \sigma_{CC} \approx \sigma_{NC}$

illustrates electro-weak unification

PDFs from NLO QCD Fits

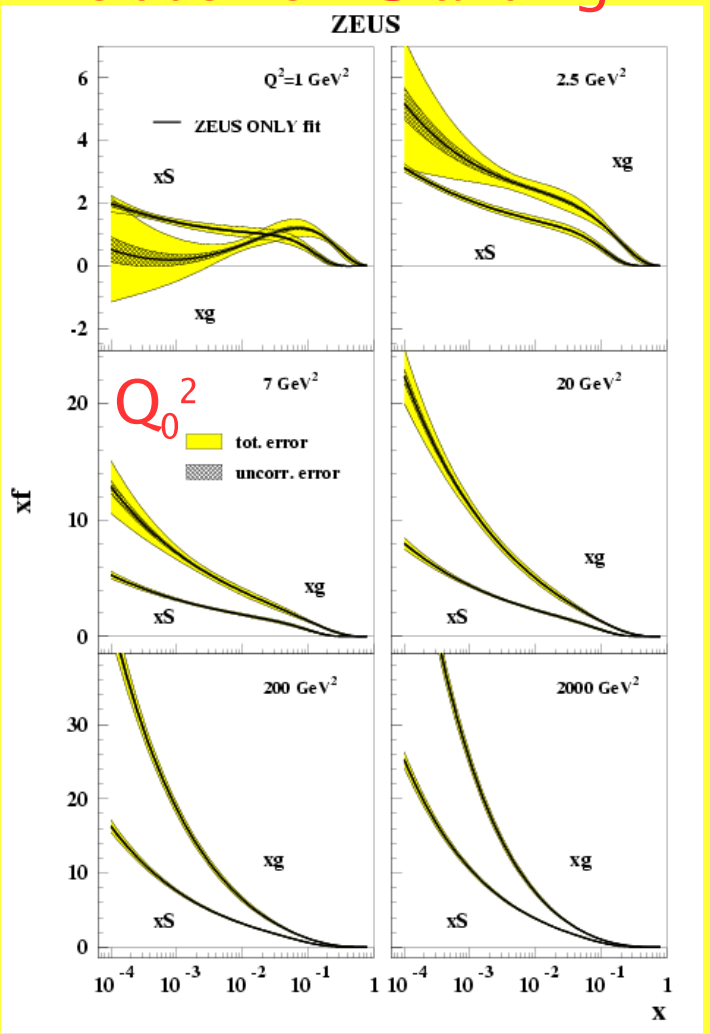
PDFs at Q_0^2=4 GeV^2



Evolution of xS and xg:

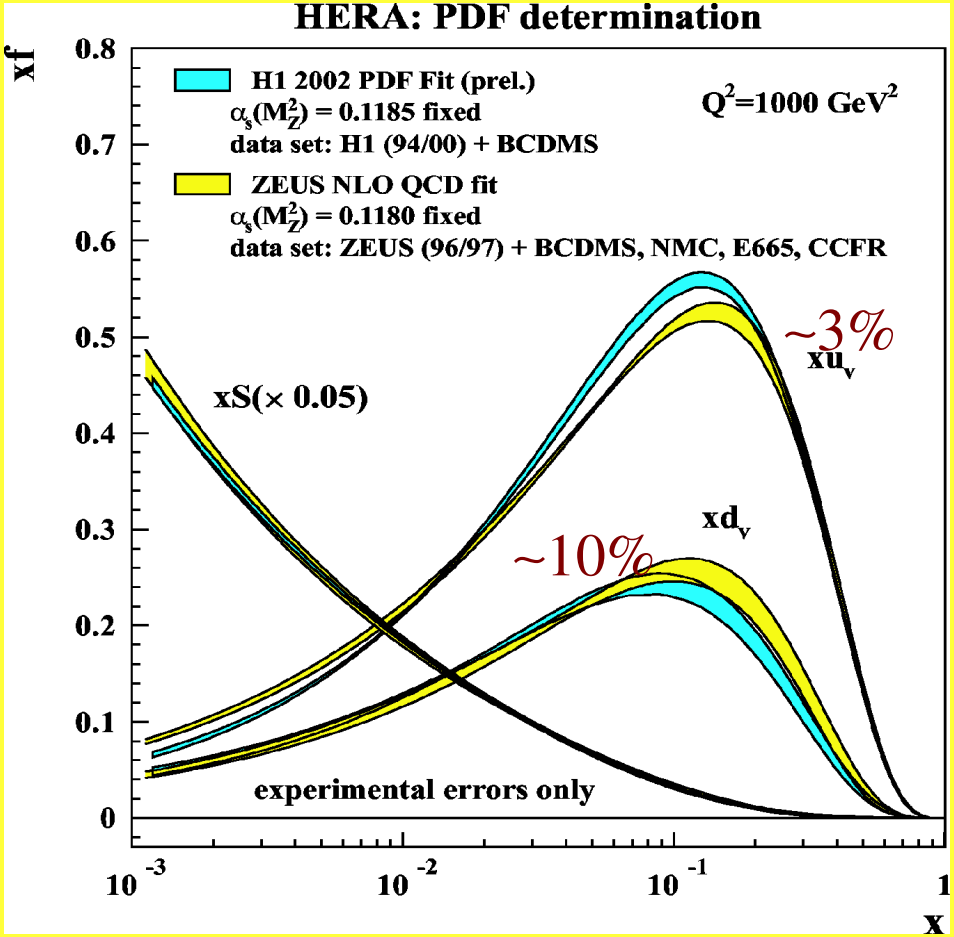
backward

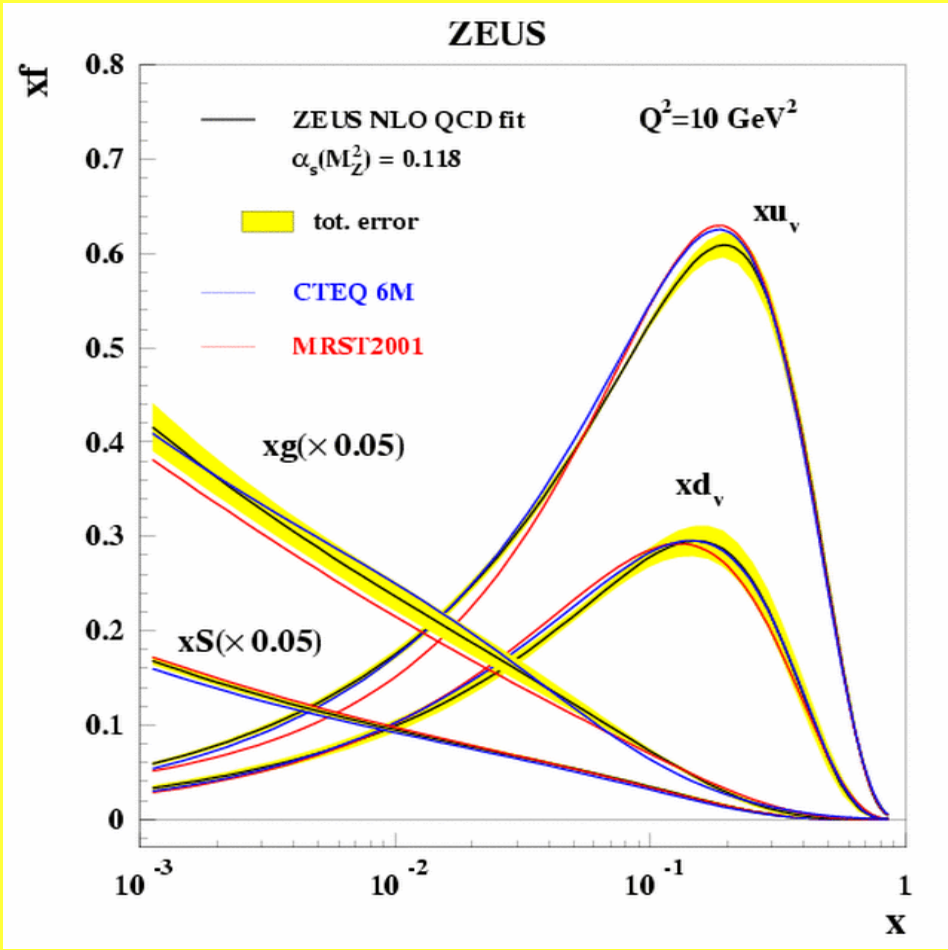
forward



Fits to HERA data only are consistent with fits including fixed target data

PDFs: H1 vs. ZEUS





NLO QCD fits by H1 and ZEUS

ZEUS fit compared to global fits

=> good overall agreement!

xu and xd at large x

H1 local extraction of data points:

Ingredients:

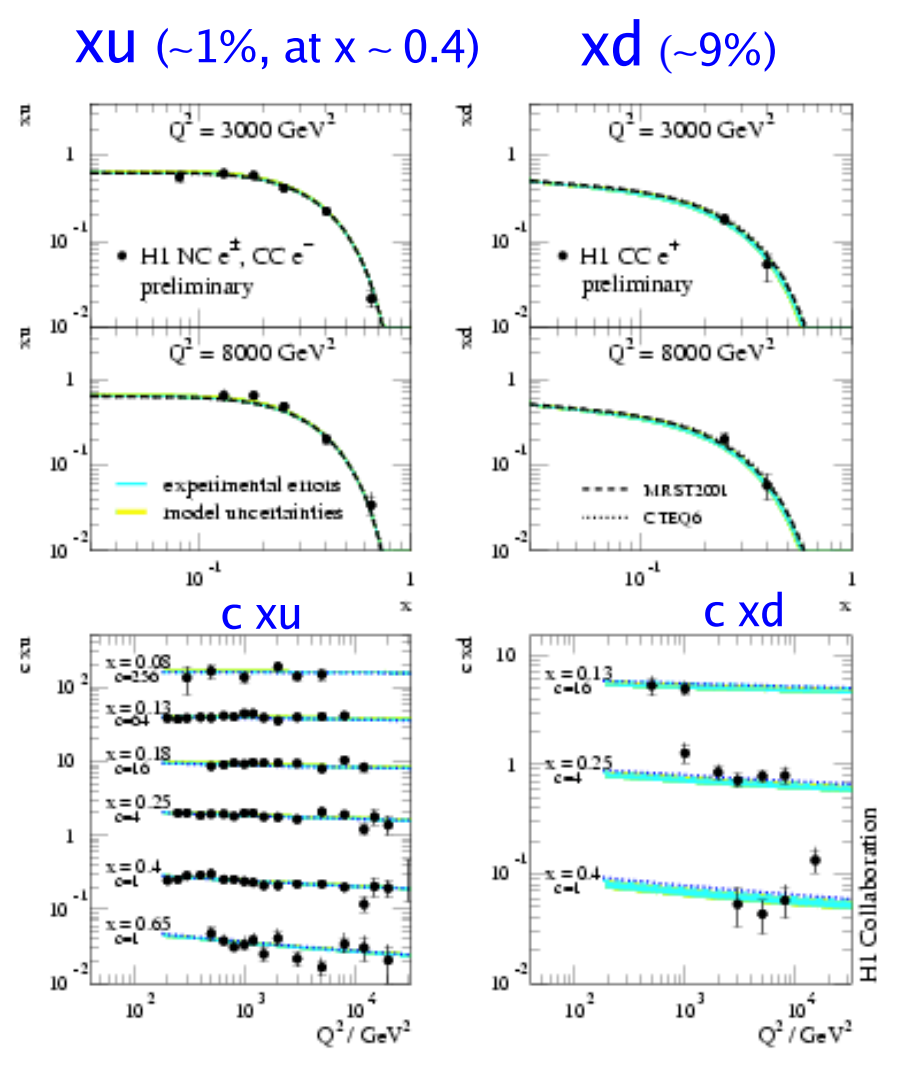
-QCD assumptions on u and d
(70% at high x)

-local NC and CC cross section measurements for quark separation

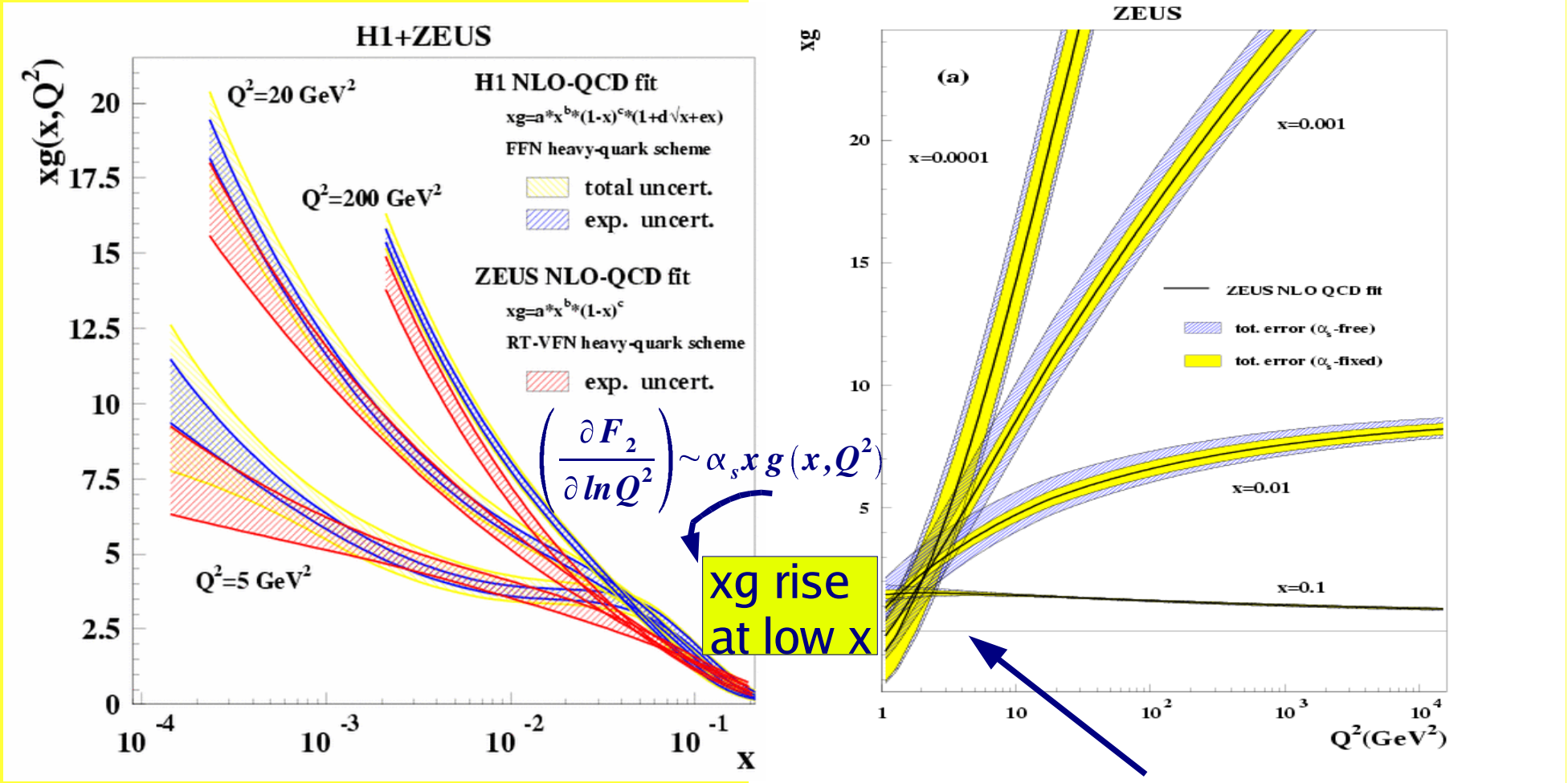
=> insensitive to assumptions in other regions of phase space

BUT: separation depends fully on Z^0 exchange of NC and helicity structure of CC

=> **Need more lumi for better precision and extension of x region**



The Gluon Density



Need to look at low Q^2 data

α_s

At small x weakened correlation between xg and α_s (F_2 gluon driven)

=> simultaneous fit possible

H1: + proton data from BCDMS (dedicated fit)

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017(\text{exp.})^{+0.0009}_{-0.0007}(\text{model})$$

Eur.Phys.J.C21(01)33-61

ZEUS: + proton and deuteron data from BCDMS, NMC, E665, CCFR

$$\alpha_s(M_Z^2) = 0.1166 \pm 0.0008(\text{uncorr.}) \pm 0.0032(\text{corr.}) \pm 0.0036(\text{norm.}) \pm 0.0018(\text{model})$$

PHYS.REV. D**67**:012007(03)

Change of renorm. + fact. scale:
=> large χ^2 variations
=> NNLO calculations needed

H1: $(1/4\text{-}4)Q^2 \rightarrow \pm 0.005$
ZEUS: $(1/2\text{-}2)Q^2 \rightarrow \pm 0.004$

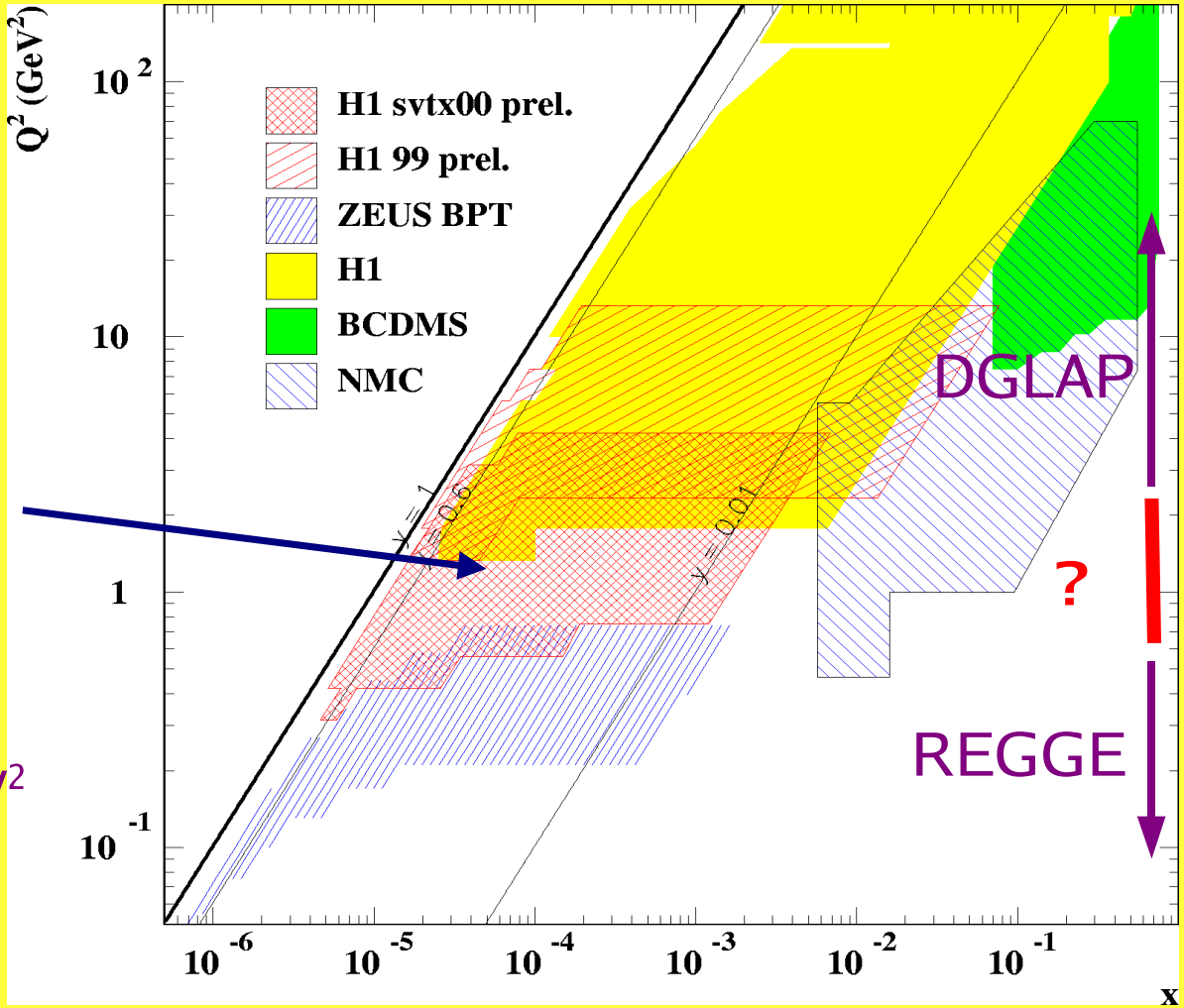
=> Results consistent and compatitive with world average (PDG 2002): 0.1172(20)

New Measurements at low Q^2

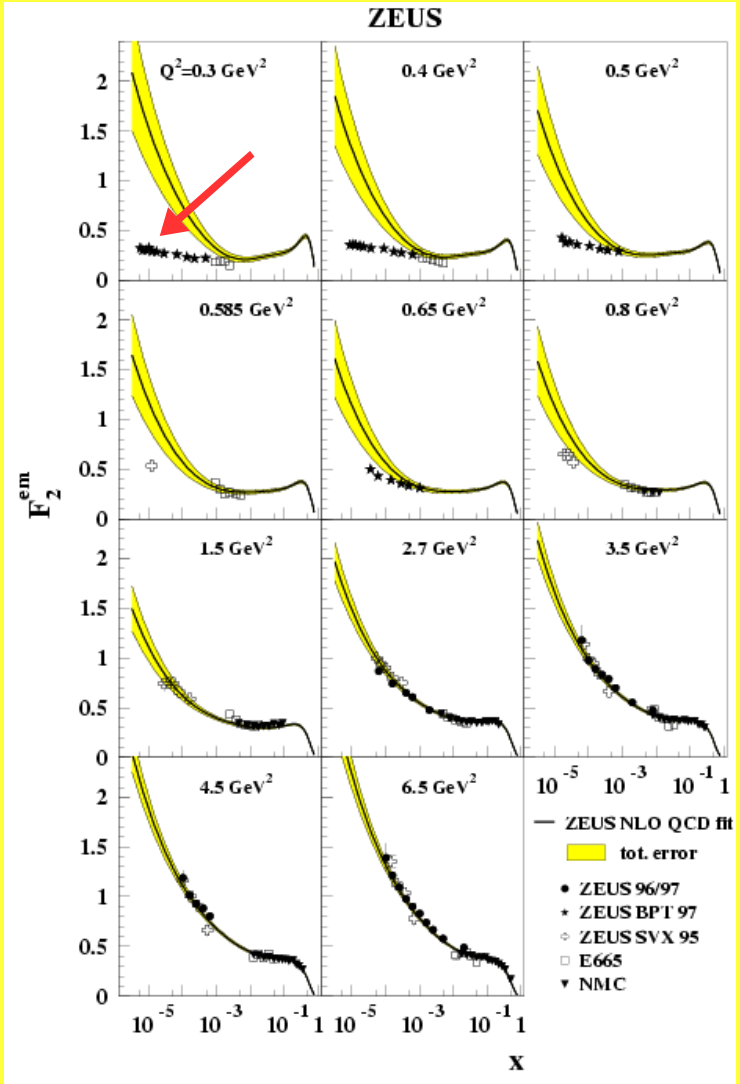
- What happens for $Q^2 < Q_0^2$?
- How low in Q^2 does pQCD work?
- Parton saturation at very low x?

shifted vertex run

Aim:
Cover gap around $Q^2 \approx 1$ GeV^2



Precise Very Low Q^2 Data



ZEUS
backward extrapolation of
DGLAP evolution:

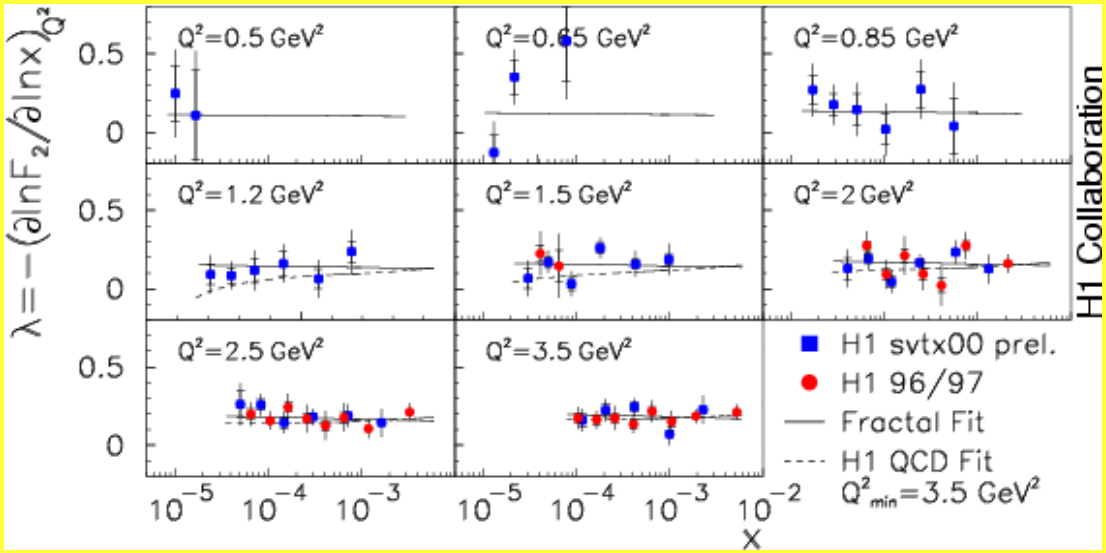
=>

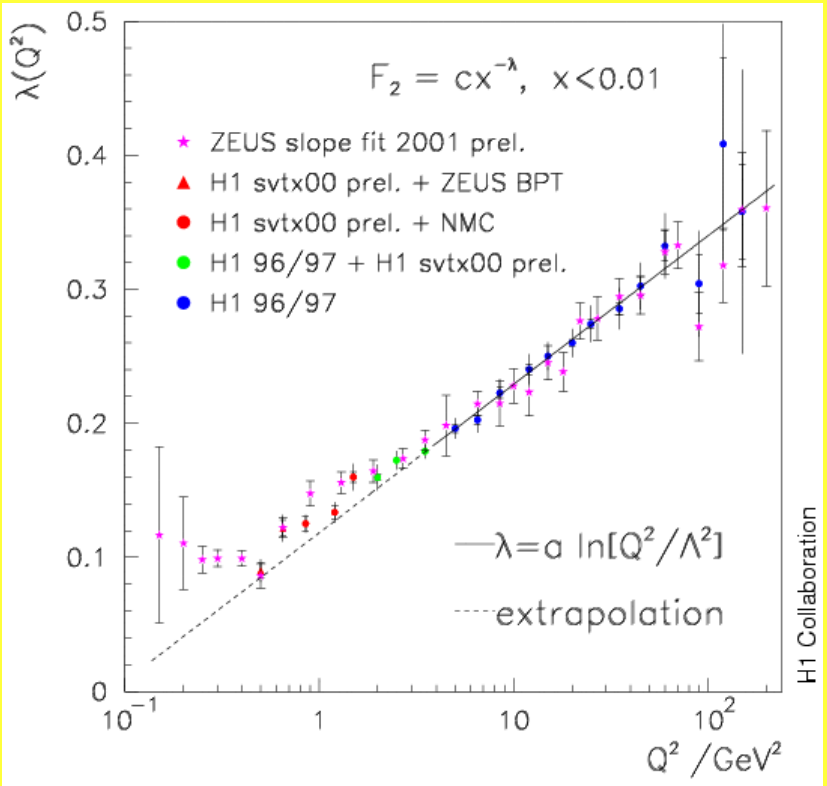
Fit works well down to $Q^2 \approx 0.8$ GeV^2

Rise of F_2 at Low x

Ansatz:

$$\lambda = -\left[\frac{\partial \ln(F_2)}{\partial \ln(x)}\right]_{Q^2}$$





λ constant at fixed Q^2 and x<0.01

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

from Regge theory expected for soft hadronic interactions: λ≈0.08

Q^2 < 1 GeV² : compatible with soft hadronic interactions

Summary

HERA data at high and medium Q^2:

- NC and CC interactions consistent with QCD and EW expectations
- pQCD fits based on DGLAP evolution of PDFs describe the data very well
- HERA data alone are able to constrain xu and xd
- NLO determination of α_s is competitive with world average

HERA data at low and very low Q^2:

- Rise of F_2 also at very low x
- Observe departure from DGLAP F_2 behaviour

=> Challenging for theorists

=> For better precision benefit from more statistics of HERA II