Quantum Chromo Dynamics at HERA

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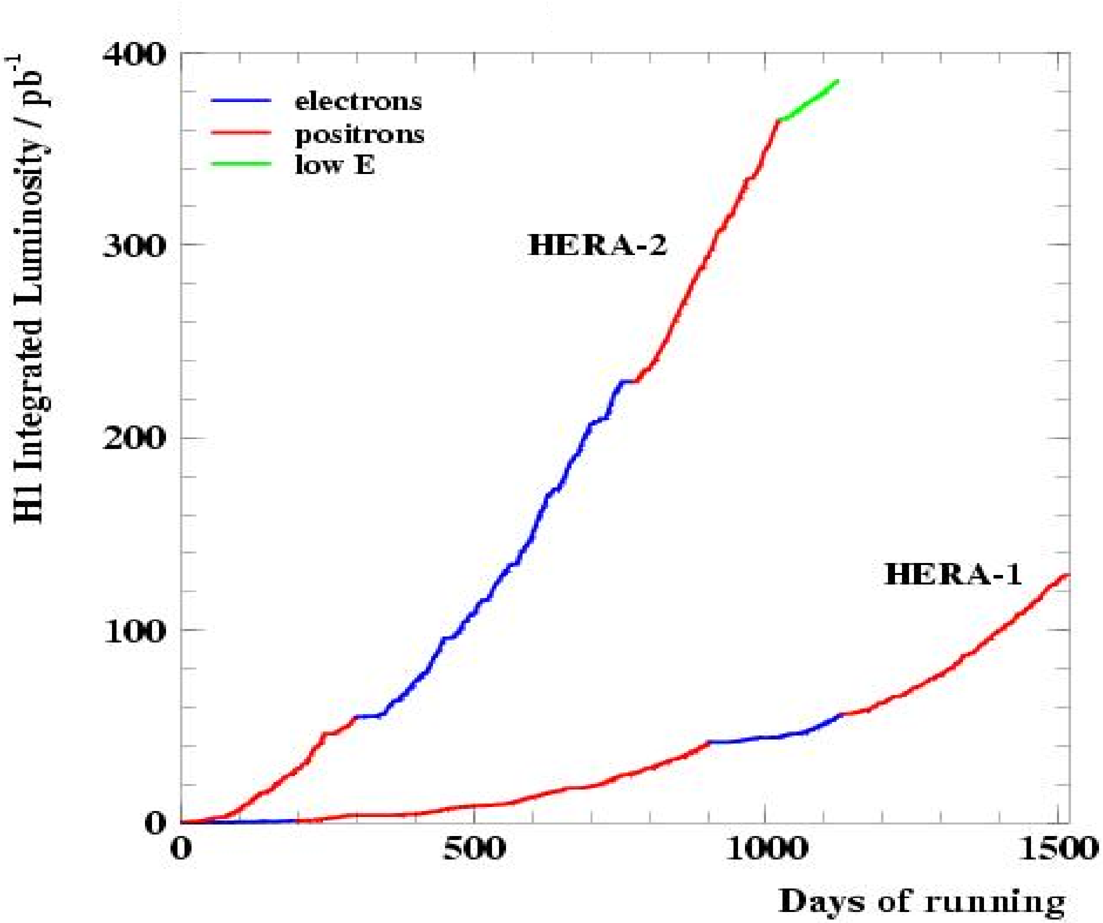
- **H1 and ZEUS at HERA**
- **Proton Structure Functions**
- **α_s determination**
- **(total photon cross section)**
- **Outlook**

HERA Luminosities

HERA: $e^{\pm}p$ collider 1992-2007

HERA I: unpolarised $e^{\pm}$ beams

HERA II: polarised $e^{\pm}$ beams



Gated luminosities

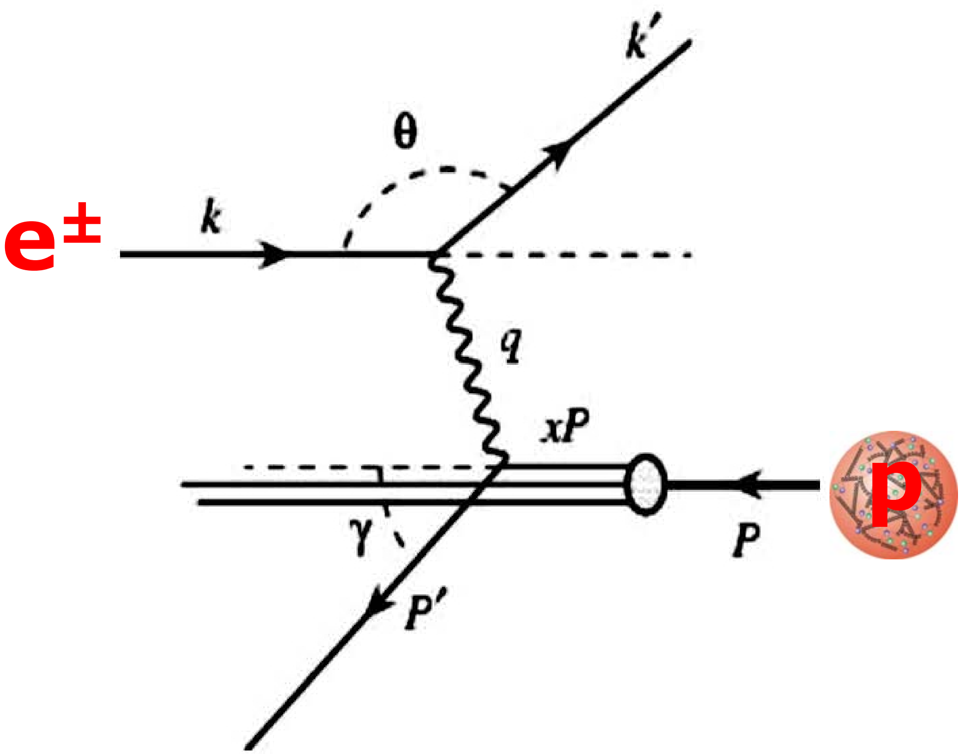
$e^{\pm}p$	H1	ZEUS
HERA I	128 pb^{-1}	143 pb^{-1}
HERA II	385 pb^{-1}	407 pb^{-1}

~ 0.5 fb^{-1} per experiment

$e^{\pm}p$ – Kinematics at HERA

27.6 GeV electrons/positrons on 920(820) GeV protons

equivalent to a 50 TeV $e^{\pm}$ on fixed proton
or probing the proton at the 10^{-18} m scale



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

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

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

Q^2 = exchanged momentum (squared)
x = Bjorken scaling variable
y = inelasticity scaling variable
$\sqrt{s}$ = center of mass energy (~318 GeV)
W = photon-proton center of mass energy

Deep Inelastic Scattering (DIS)

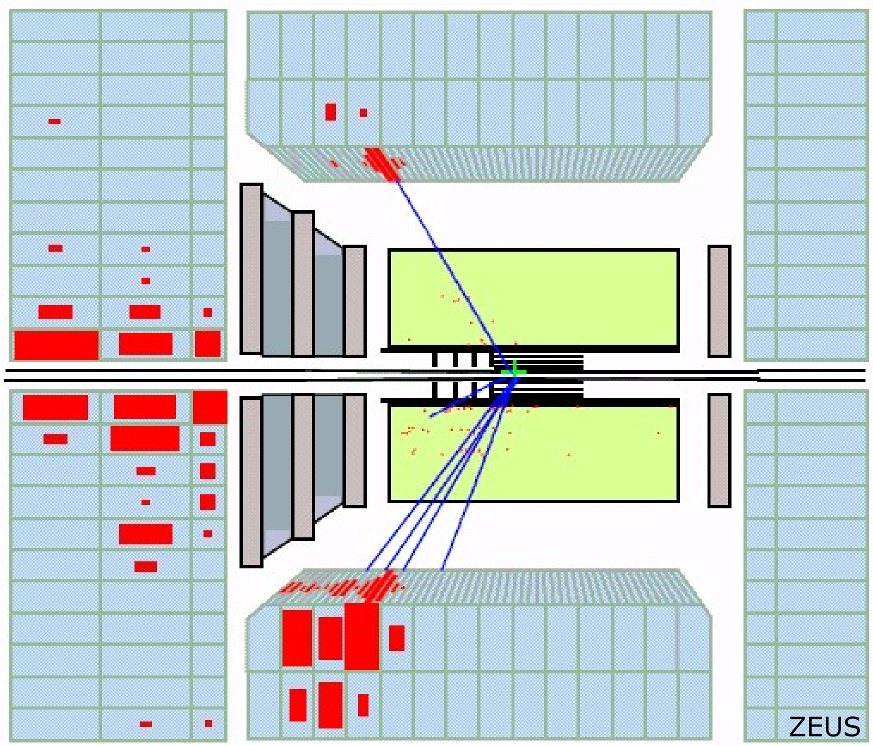
Neutral current (NC) via γ/Z^0 exchange

Charged current (CC) via $W^{\pm}$ exchange

Photoproduction (γp): $Q^2 \approx 0$ → the photon is almost real

Neutral Current DIS

mediated by exchange of γ/Z^0



The inclusive cross section can be written in terms of three structure functions F_i:

$$F_2 = x \sum e_q^2 (q(x) + \overline{q}(x))$$

dominant, representing valence quarks, sea quarks and gluons

F_L = "longitudinal", contributing at high y and sensitive to gluon distribution

$$xF_3 = x \sum e_q^2 a_q (q(x) - \overline{q}(x))$$

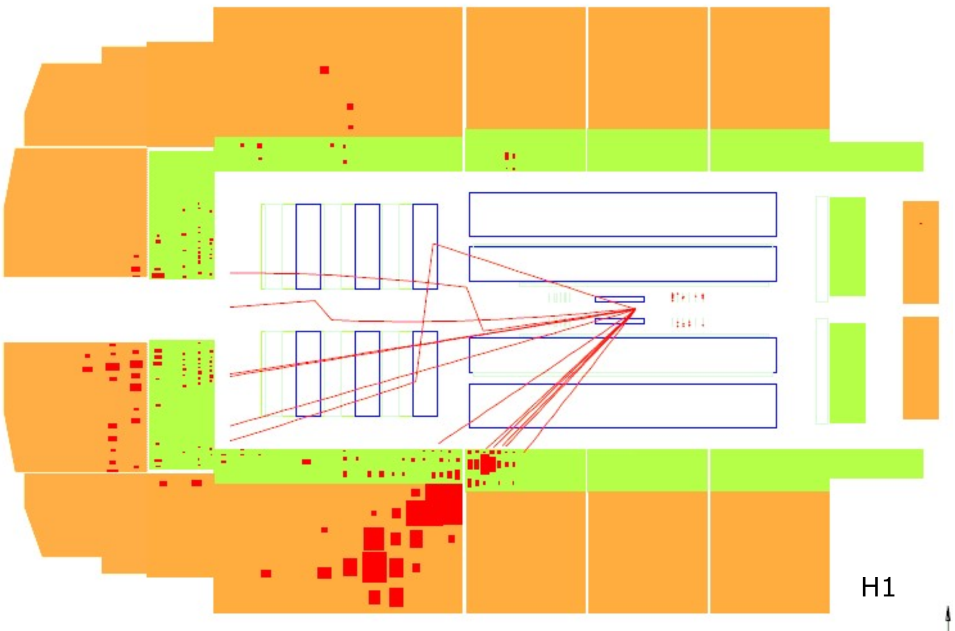
describes valence quarks at high Q^2

$$\frac{d^2\sigma_{NC}^{(e^\mp p)}}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \pm \frac{Y_-}{Y_+}xF_3(x,Q^2)\right)$$

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

Charged Current DIS

mediated by exchange of $W^{\pm}$

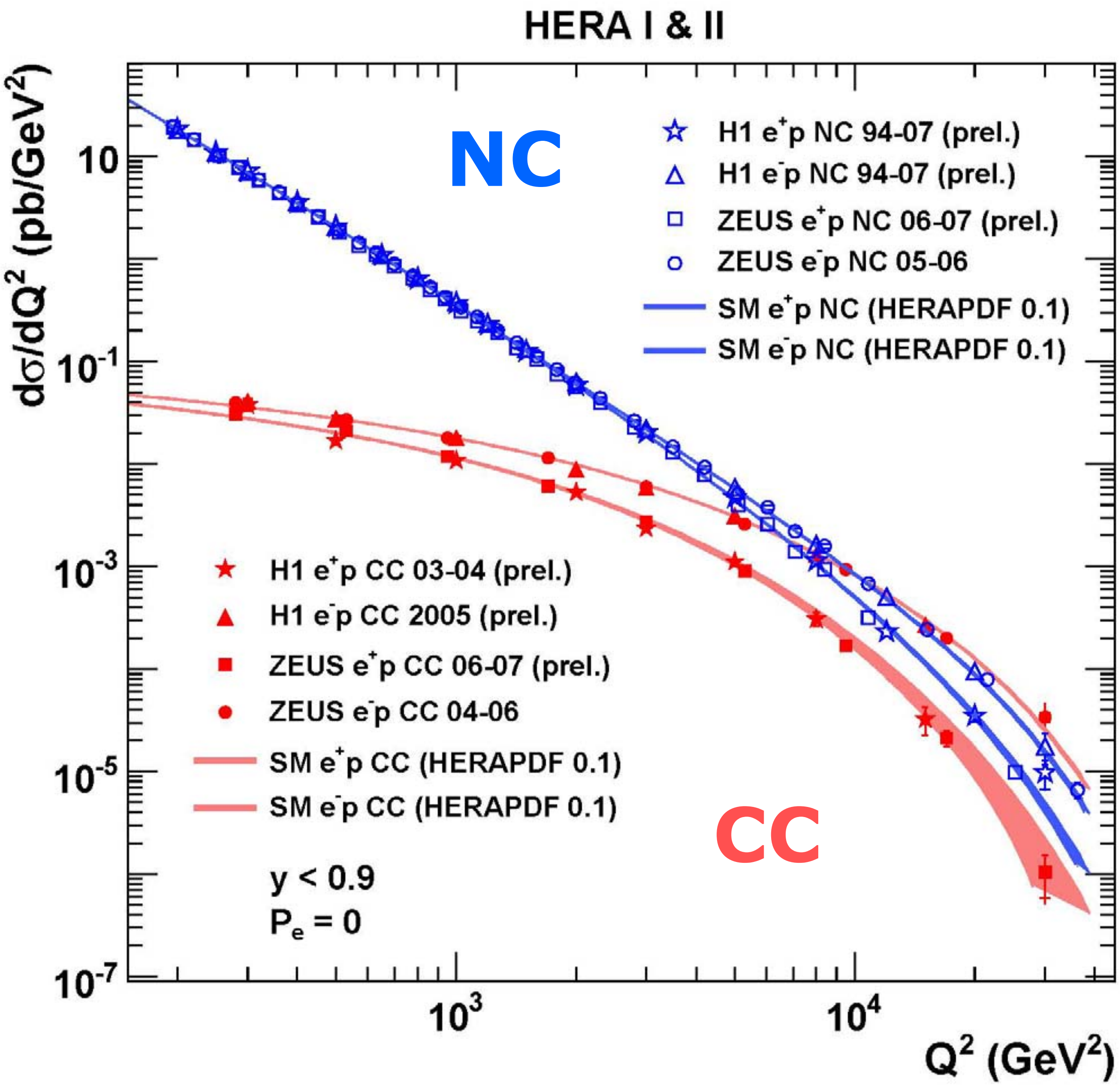


Similarily to the NC case, the cross section can be written in terms of structure functions F_i

$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dx dQ^2} = (1 \pm P_e)\frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \left[Y_+ F_2^{CC}(x,Q^2) \mp Y_- x F_3^{CC}(x,Q^2)\right]$$

P_e is the lepton polarisation (HERA II only, =0 for HERA I)

Electroweak Unification



γ-exchange clearly dominates at low Q^2

However, both **NC** and **CC** cross sections meet at $Q^2 \geq M^2_{Z/W}$: unification.

Agreements between both experiments and with the Standard Model

NC DIS Measurements

Reduced cross sections:

$$\tilde{\sigma}(e^{\mp}p) = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \pm \frac{Y_-}{Y_+}xF_3(x,Q^2)$$

F_2 is the main term and measured directly

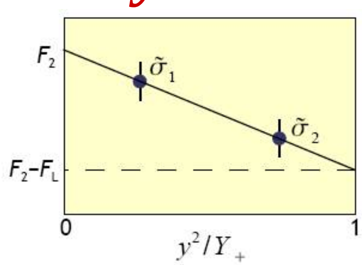
(with small corrections/assumptions from other terms)

xF_3 can be determined from the difference between e^+p and e^-p data

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}^{e^-p} - \tilde{\sigma}^{e^+p}) \quad \sim \sigma(2u_\nu + d_\nu)$$

F_L can only be extracted from masurements at same x and Q^2 but different y values → different c.o.m. energies → lower proton beam energies

Q^2=sxy



$$\tilde{\sigma}_{NC}(e^{\pm}p) = \tilde{F}_2(Q^2,x) - \frac{y^2}{1+(1-y)^2}\tilde{F}_L(Q^2,x)$$

Combining H1+ZEUS Data

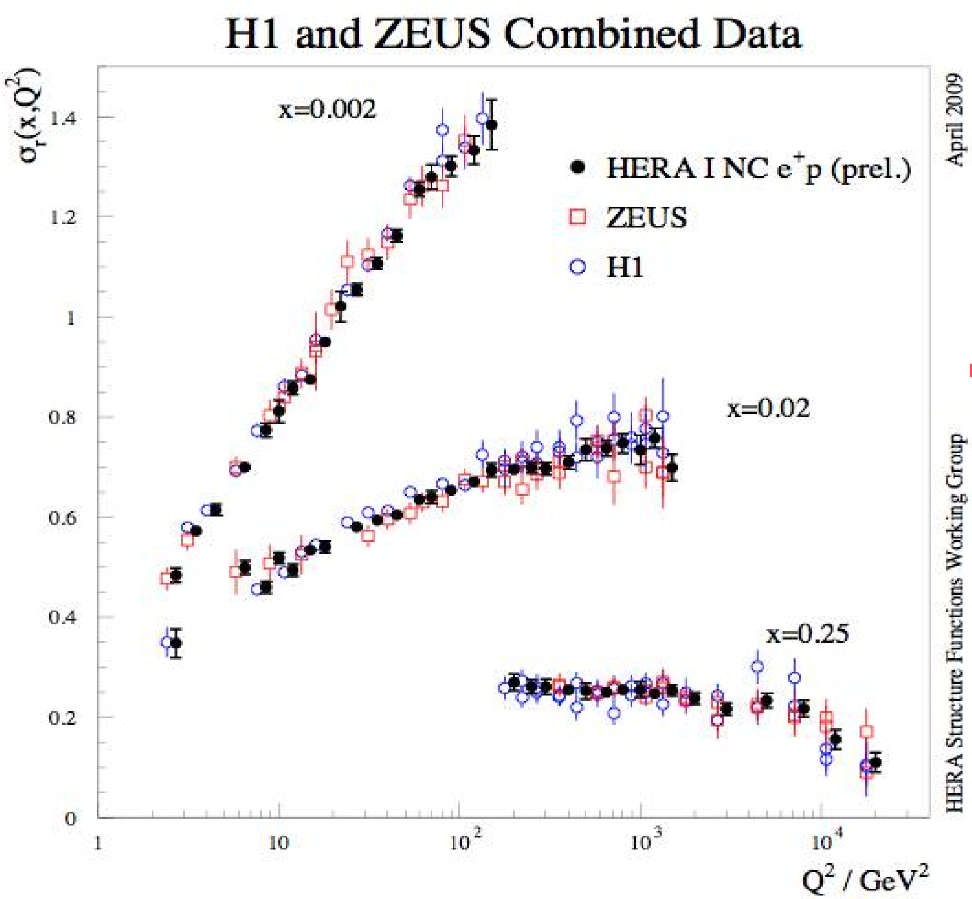
- check the consistency of the data
- reduce the stat./systematic errors
- extract new protons PDF's for HERA

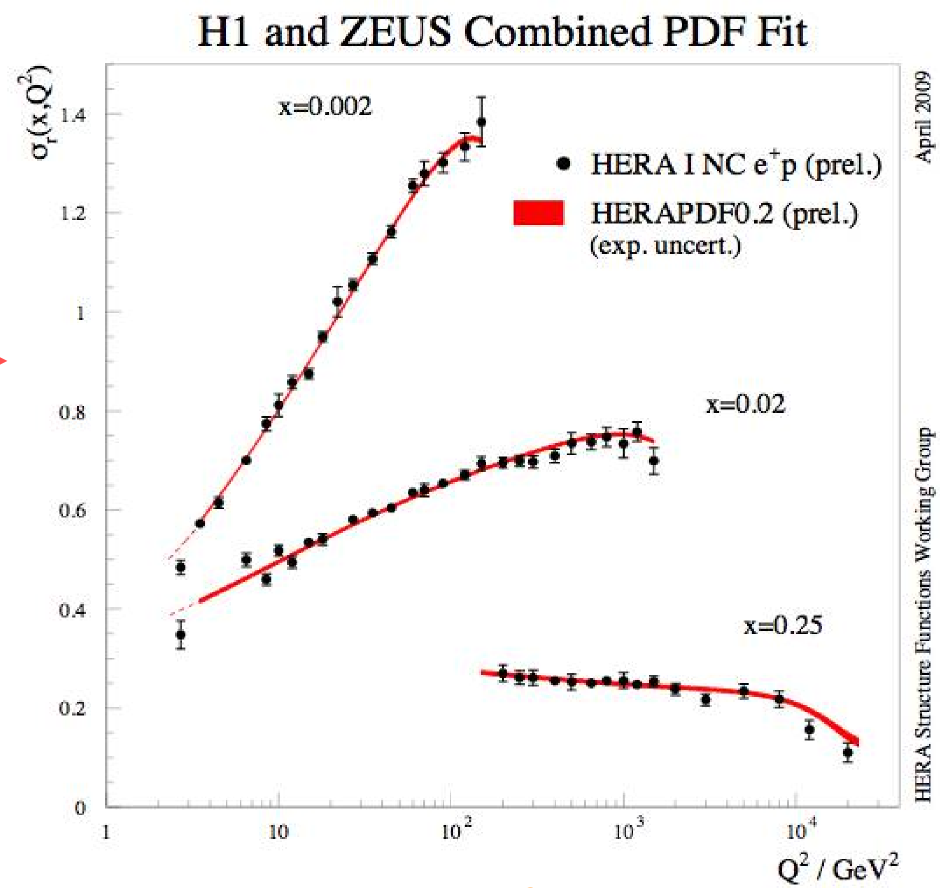
all of NC and CC data from HERA I

full error correlations (e.g. γp or E-scale)

averaging procedure uncertainties

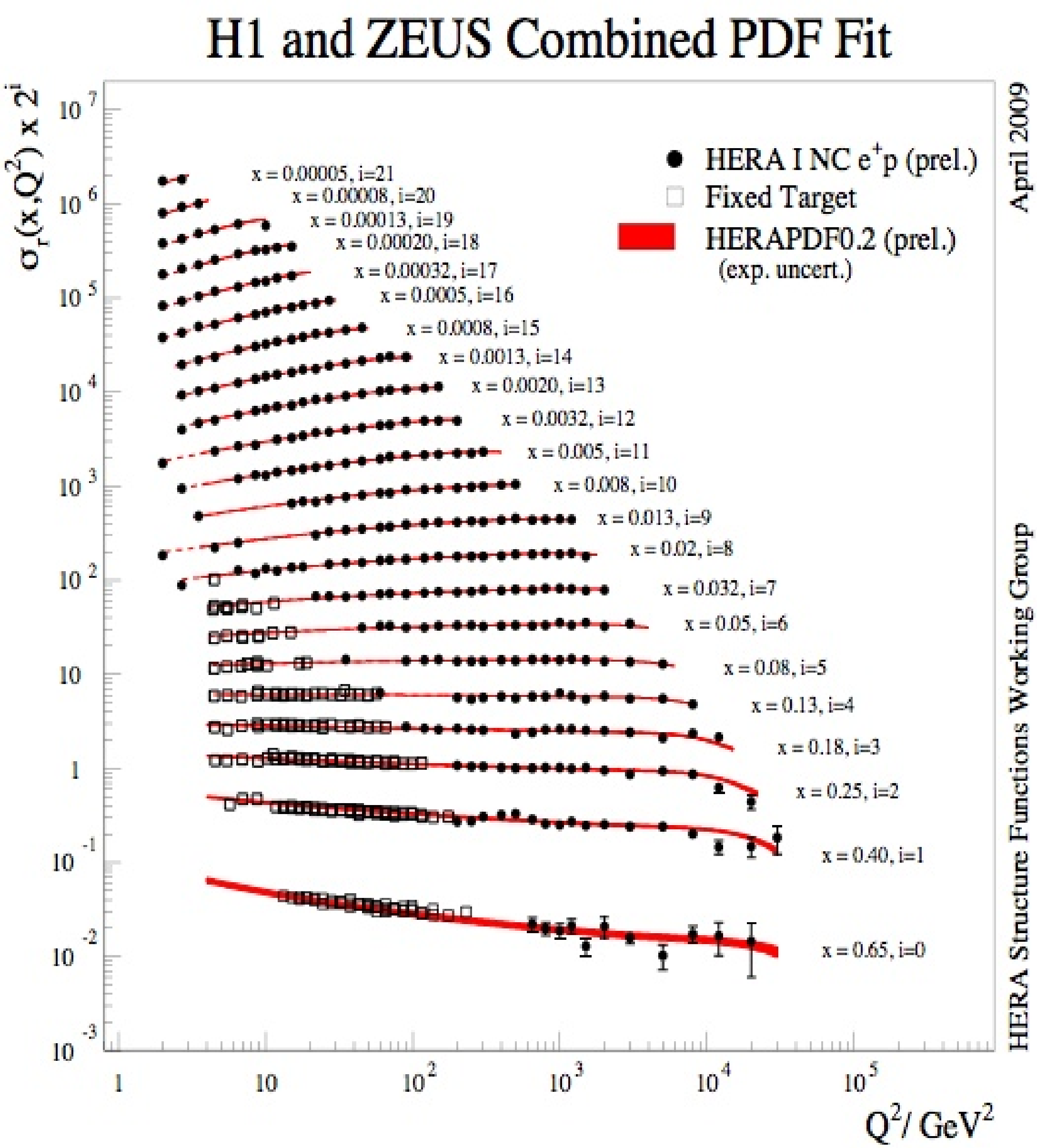
global QCD fits excellent





huge data sets, e.g. NC with Q^2 from 0.05 to 30000 GeV^2

F_2



Large kinematic domain available at HERA:

$0.00005 < \mathbf{x} < 0.65$

$0.05\ \mathrm{GeV}^2 < \mathbf{Q^2} < 30000\ \mathrm{GeV}^2$

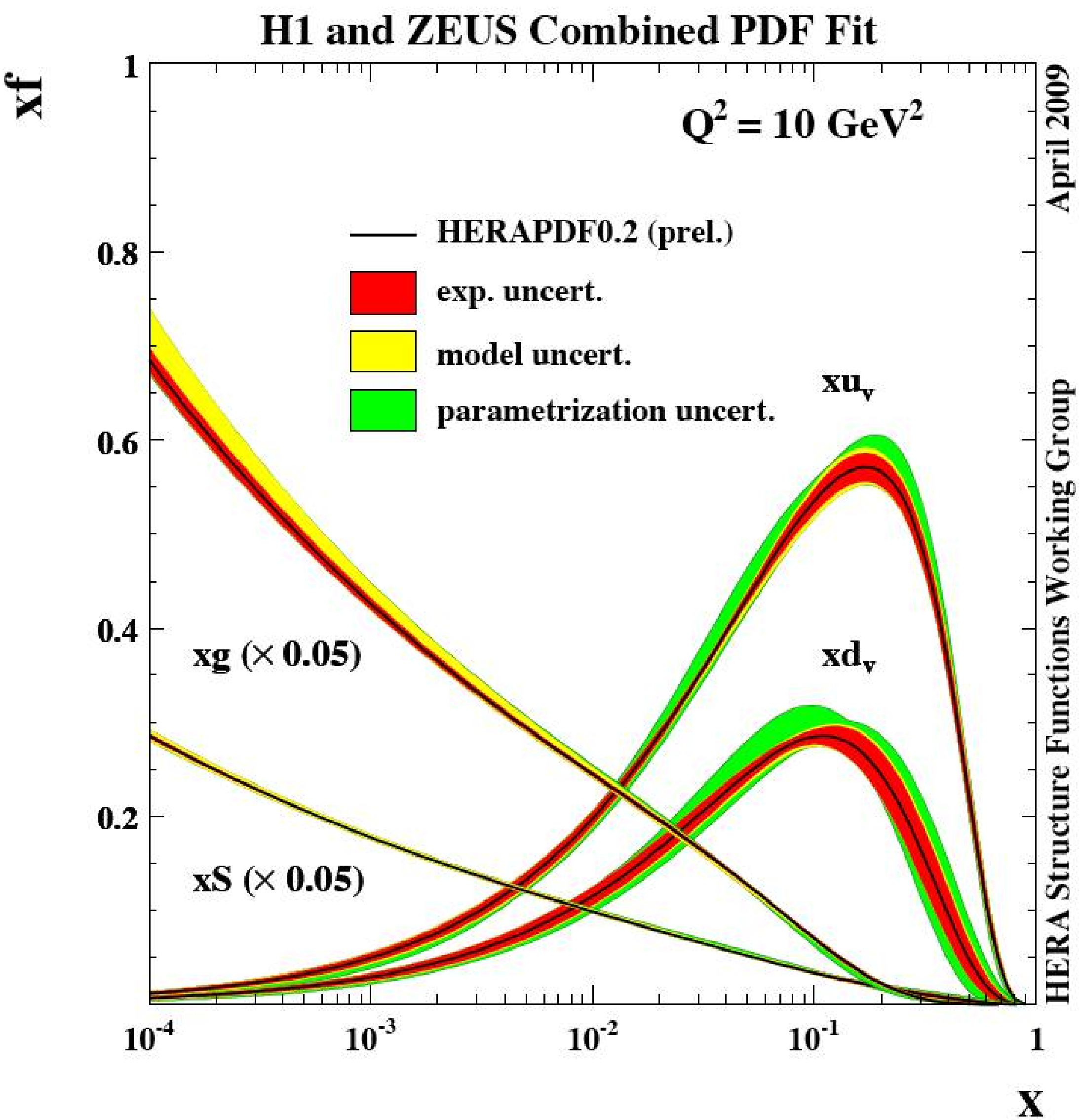
Experimental uncertainties shown in both data and fit

Comparison with the fixed target measurements

Scaling violations (gluons) clearly seen, especially at low *x* values

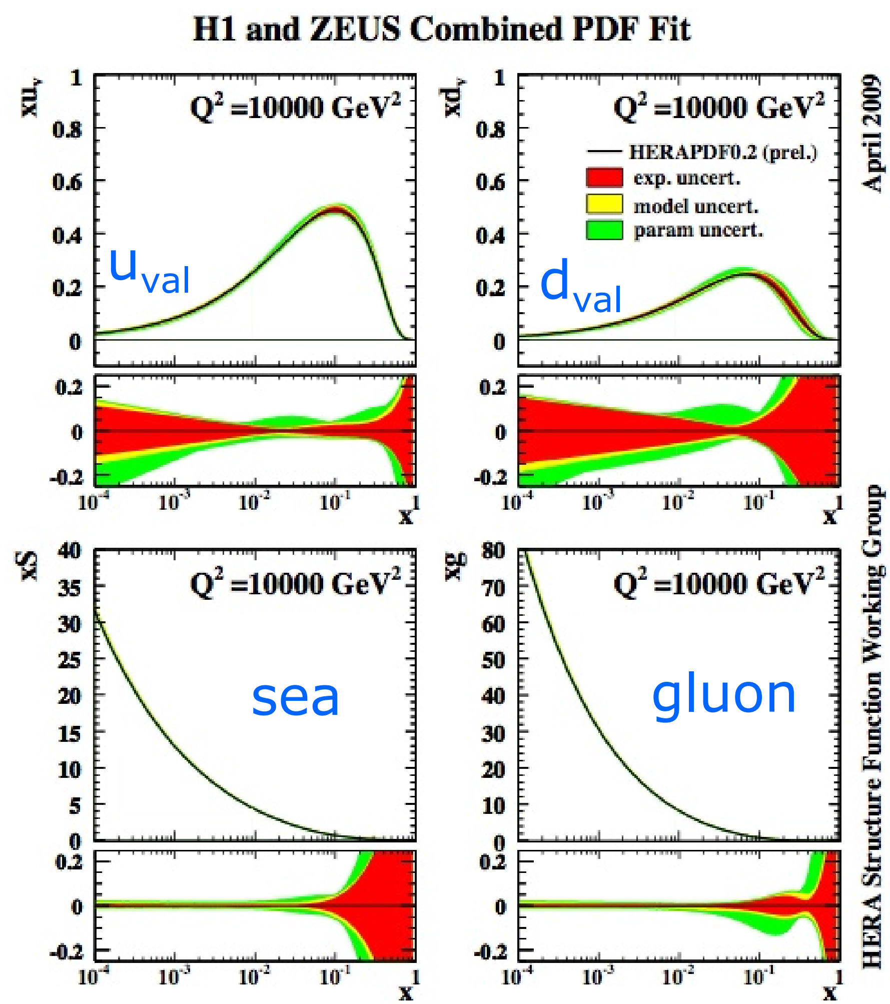
Parton Density Functions

Results from the QCD NLO fit



e.g. Sensitivity at LHC Q^2 scale

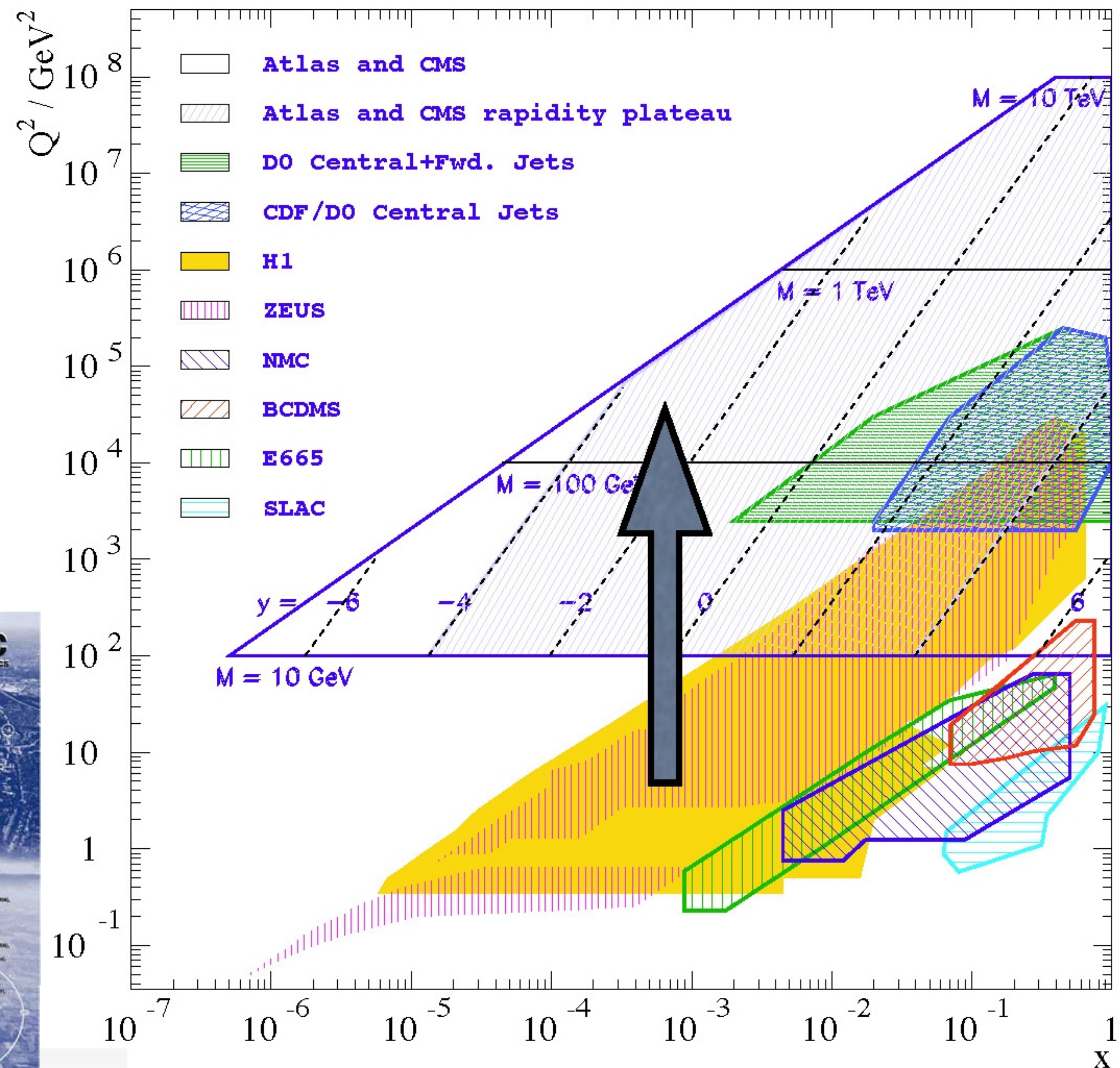
PDF's very precise (parametrisation uncertainty dominates at high *x*)



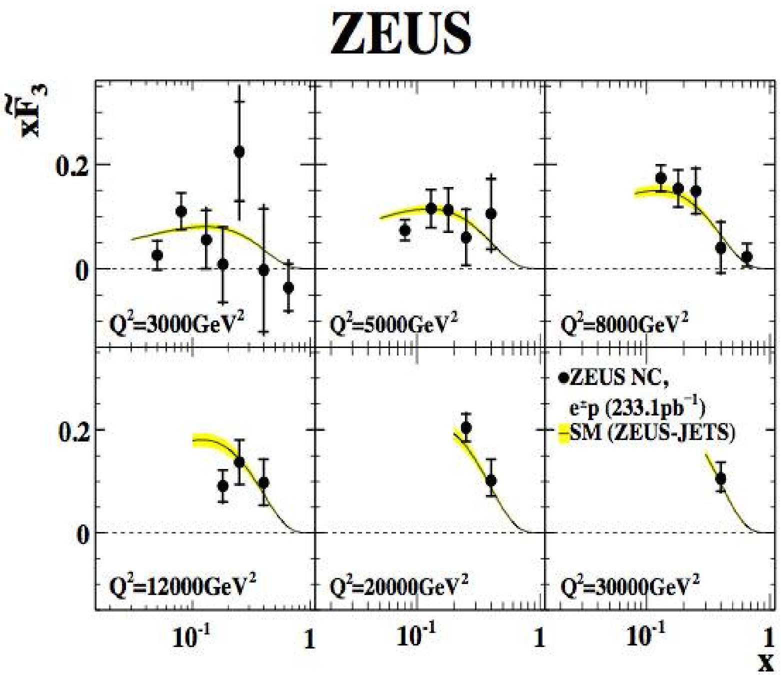
LHC

Knowledge of the proton structure is necessary to calculate cross sections at the LHC

The HERA PDF's must therefore be evolved into the LHC phase space (using DGLAP)



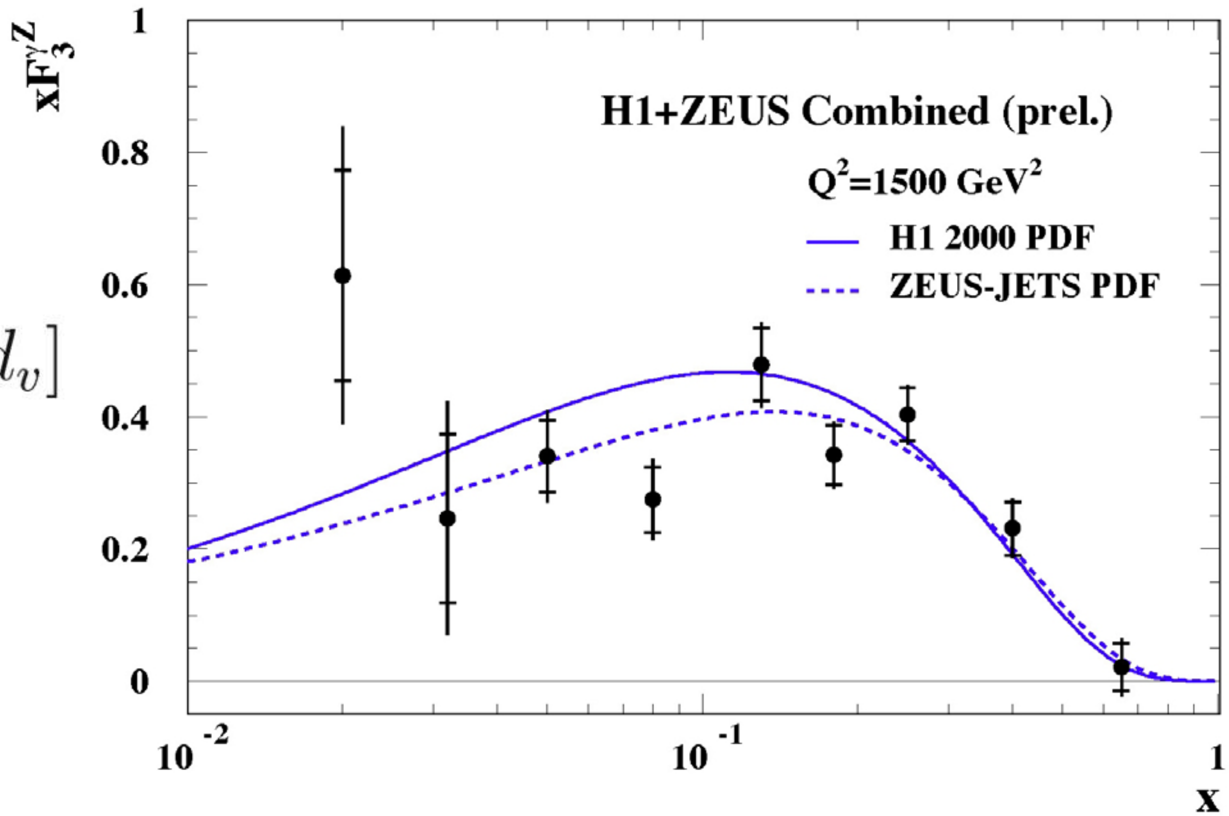
xF_3



From high Q^2 NC cross sections

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}^{e^-p} - \tilde{\sigma}^{e^+p})$$

$$xF_3^{\gamma Z} = 2x[e_u a_u u_v + e_d a_d d_v] = \frac{x}{3}(2u_v + d_v)$$



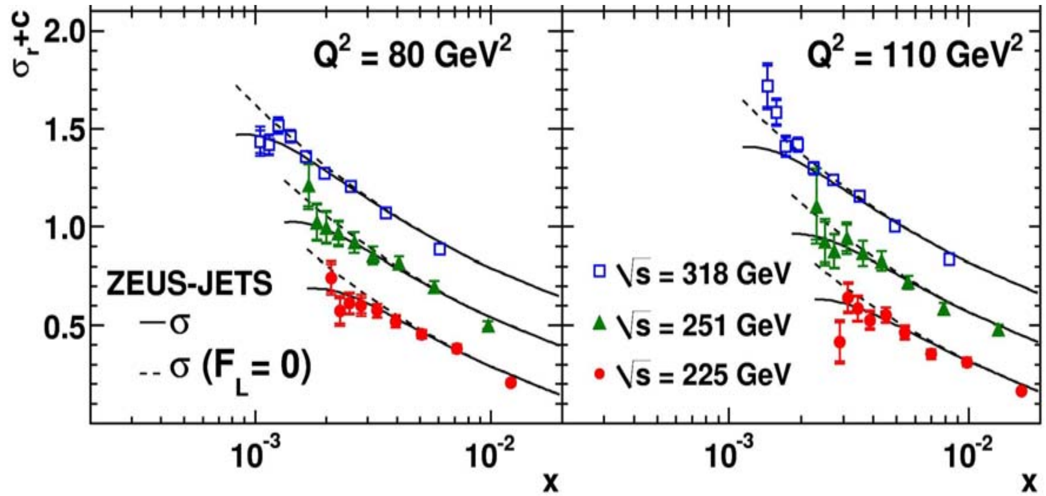
→ improve the valence quark PDF's at high *x*

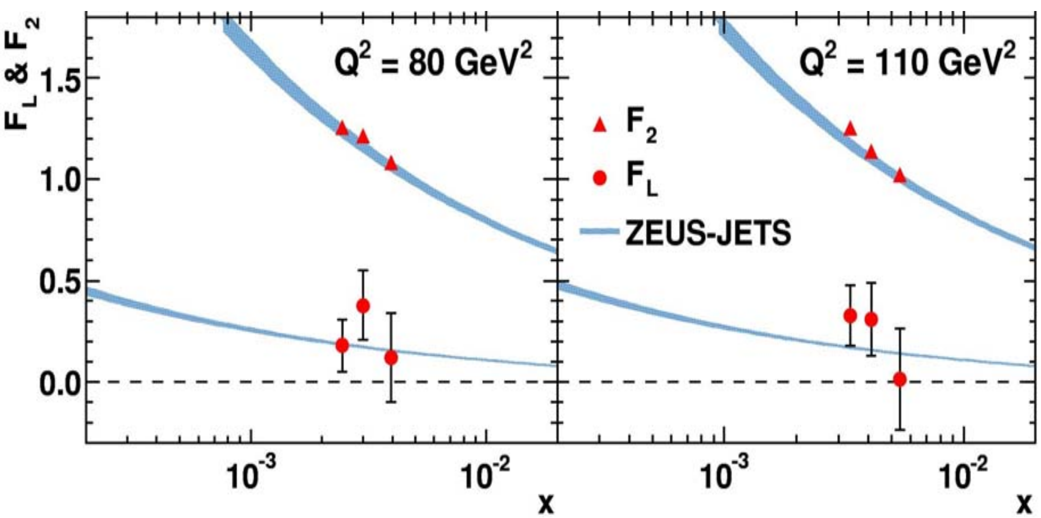
F_L

Reduced cross sections

20 GeV^2 < Q^2 < 130 GeV^2 and 0.0005 < x < 0.007

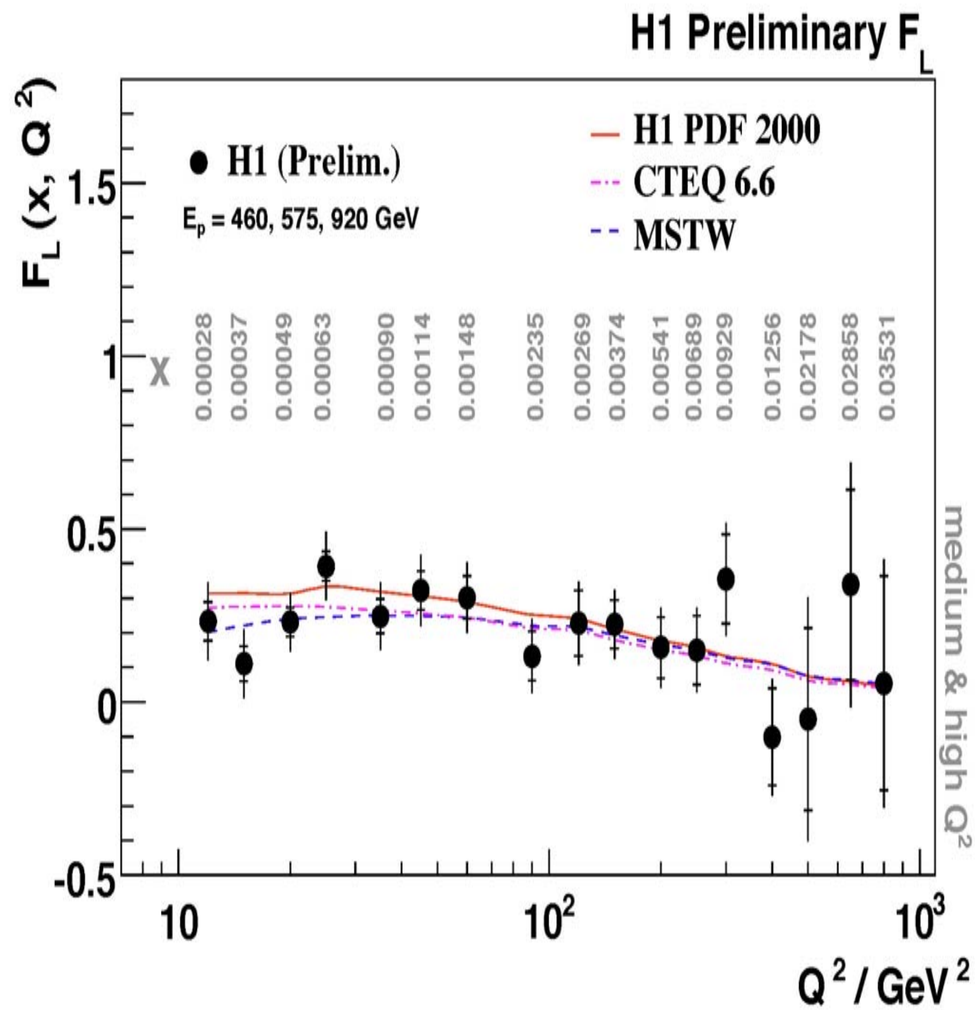
small deviations observed at low x



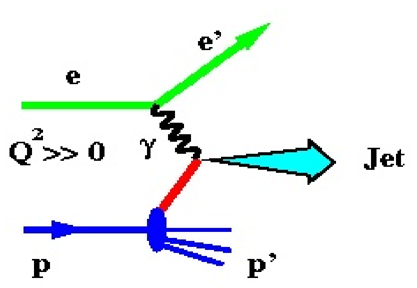


Extract F2 and FL simultaneously

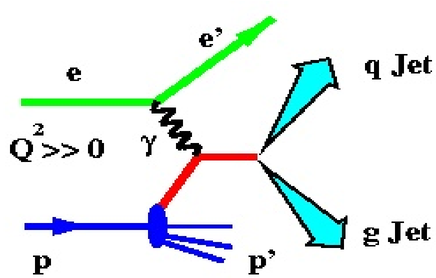
Averaged values consistent with non-zero F_L and with predictions



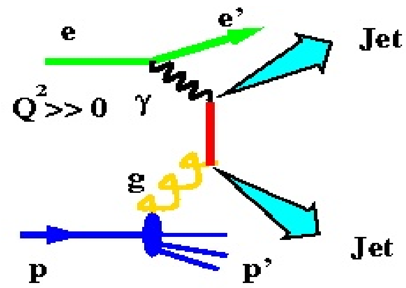
Jet Production in DIS



LO



QCD-COMPTON



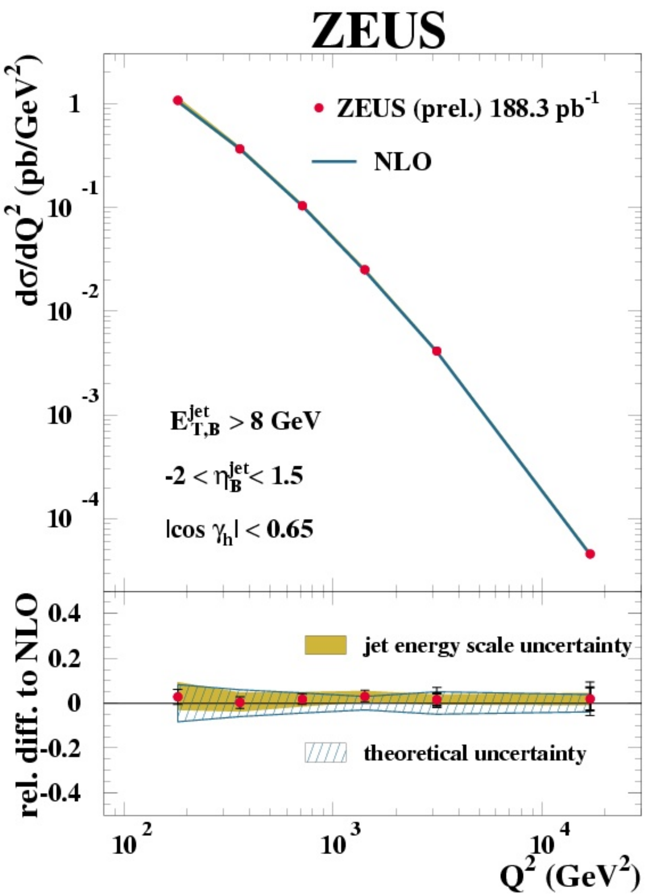
BGF (Boson-Gluon Fusion)

Entering the theory:

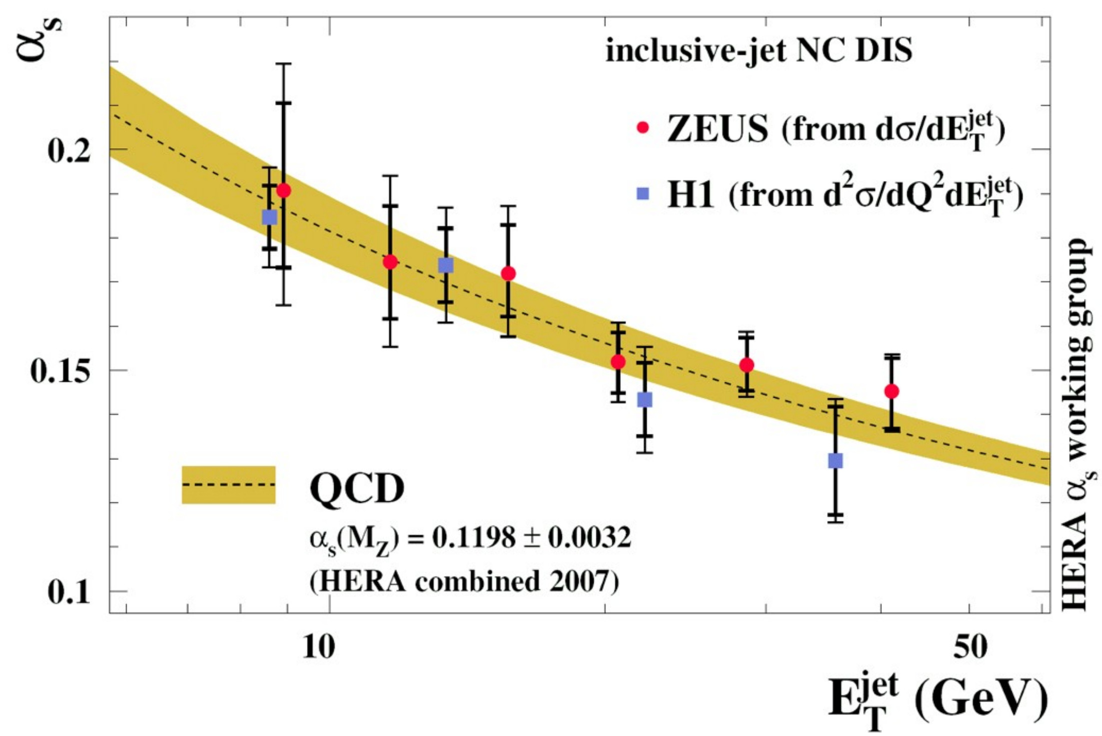
Matrix elements

PDF's

α_s



Measure e.g. the jet rate and fit for α_s

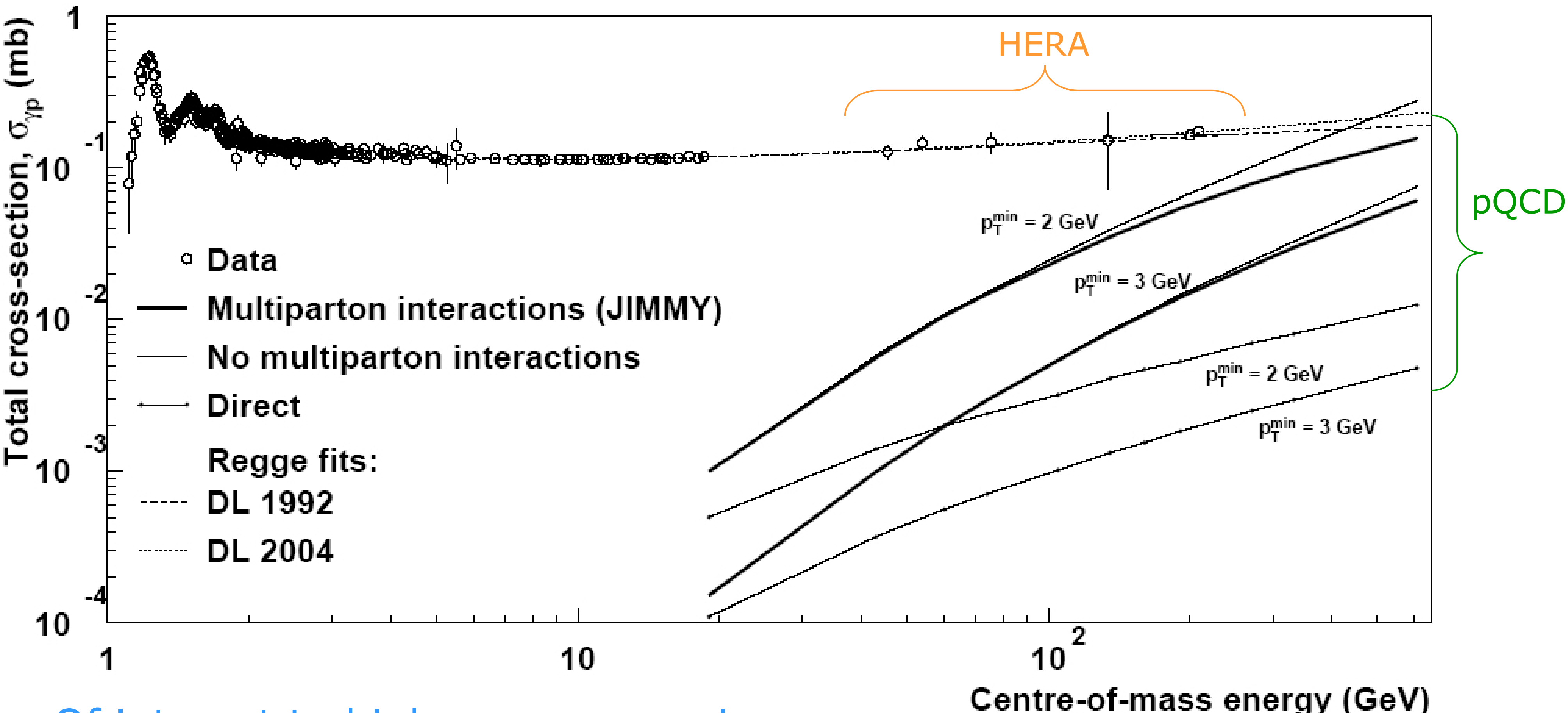


Total Cross Section

In photoproduction (γp) at HERA, the photon is almost real.

At 200 GeV center-of-mass energy, equivalent to a 40 TeV γ on target

Photon splitting γ→qq̄ means large hadron-hadron-like cross sections

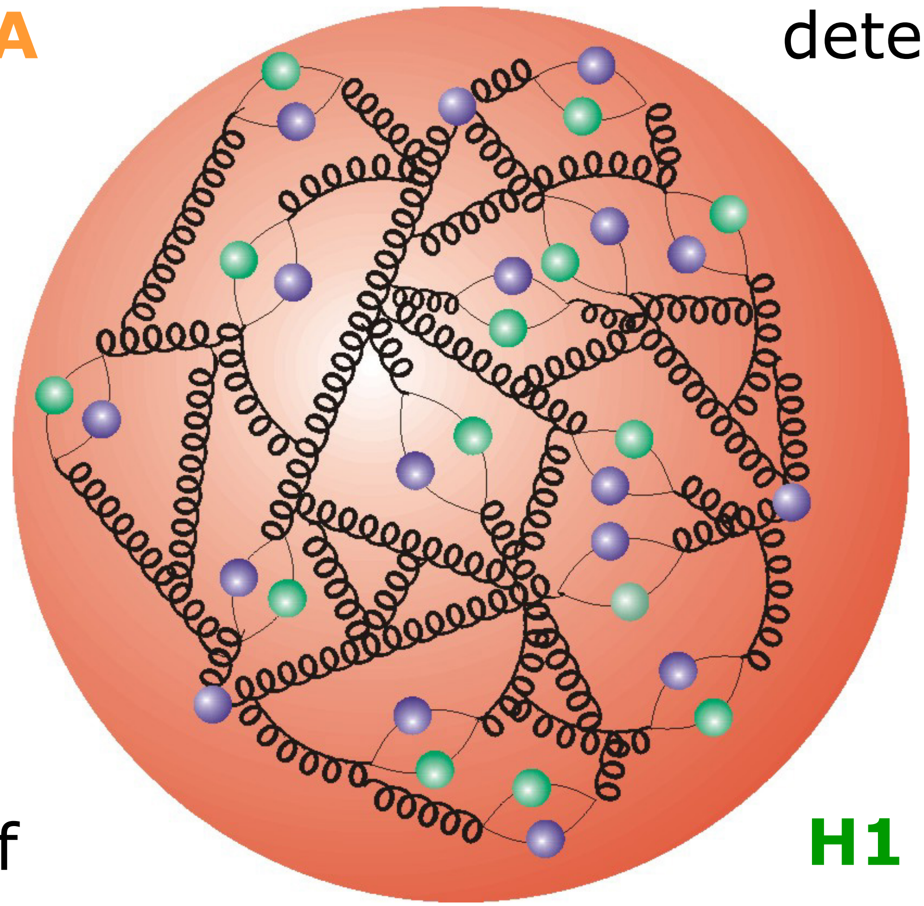


Of interest to high energy cosmic rays

Summary and Outlook

Large number of **QCD** studies were made possible at **HERA**

All proton structure functions could be determined from **ep**



HERA talk by Katerina Lipka for the heavy flavour studies

Impact on **pp** cross section measurements at the **LHC**

Determination of α_s, total photon cross section, etc..

H1 and **ZEUS** have an active program to combine all **HERA** data

Extra Slides

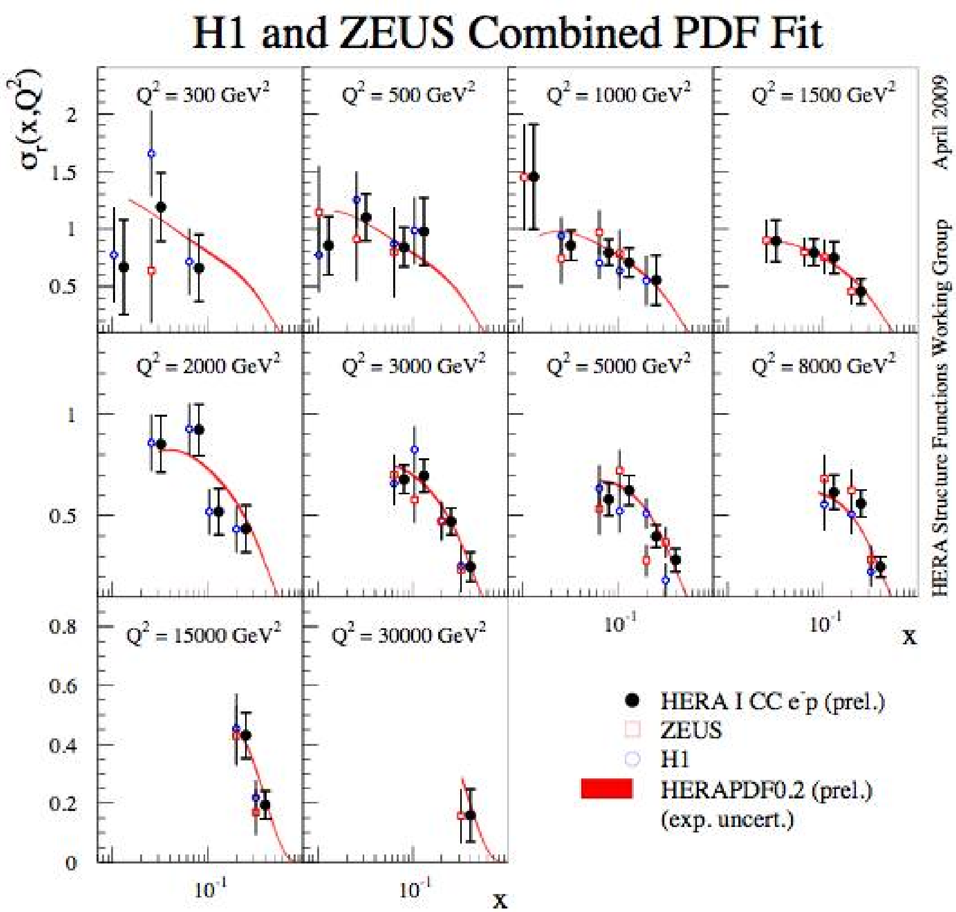
Abstract

QCD at HERA

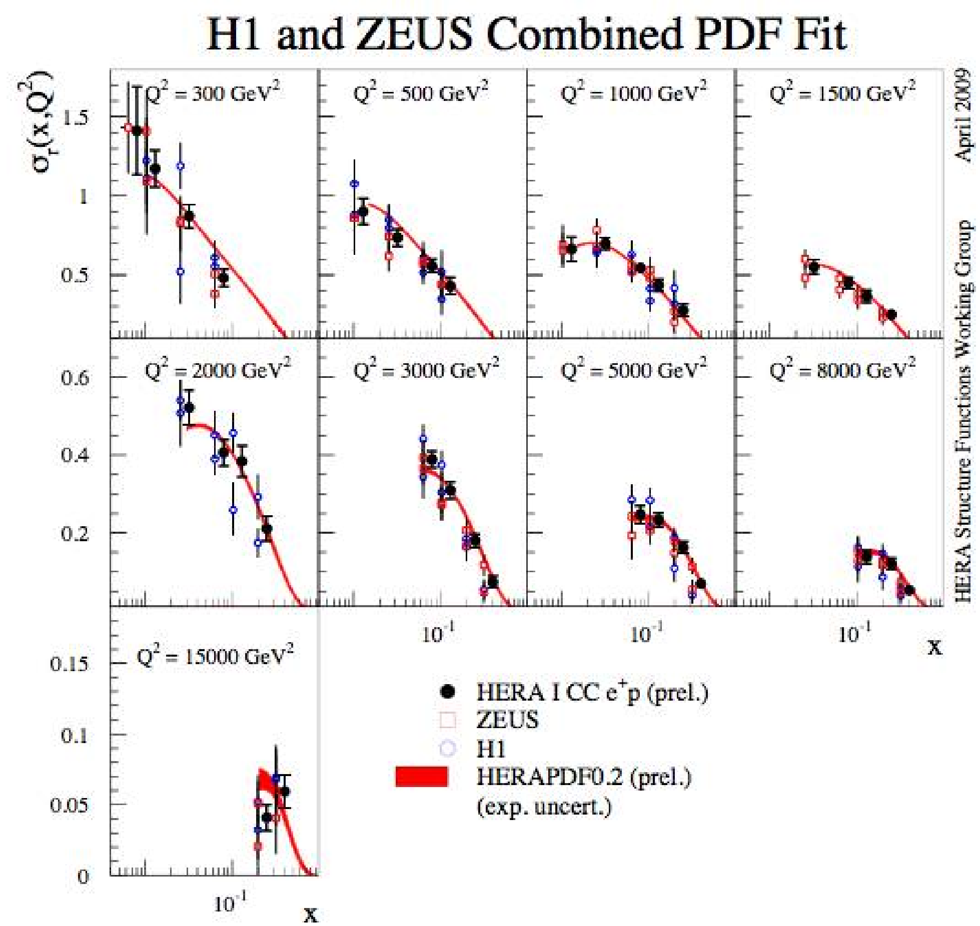
HERA is a unique electron-proton collider which has terminated its operations in 2007. Large amounts of experimental data are currently being analyzed. A brief review of the highlights of the QCD studies performed by the ZEUS and H1 detectors will be presented, followed by the latest results on the proton structure functions and on α_s, the coupling constant of the strong interaction.

CC Combined Data

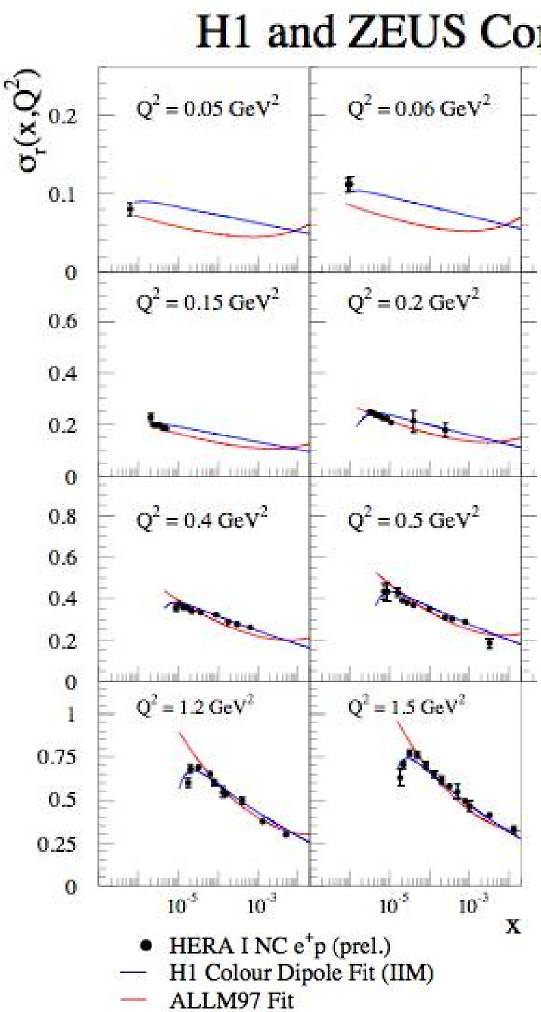
CC e^-p

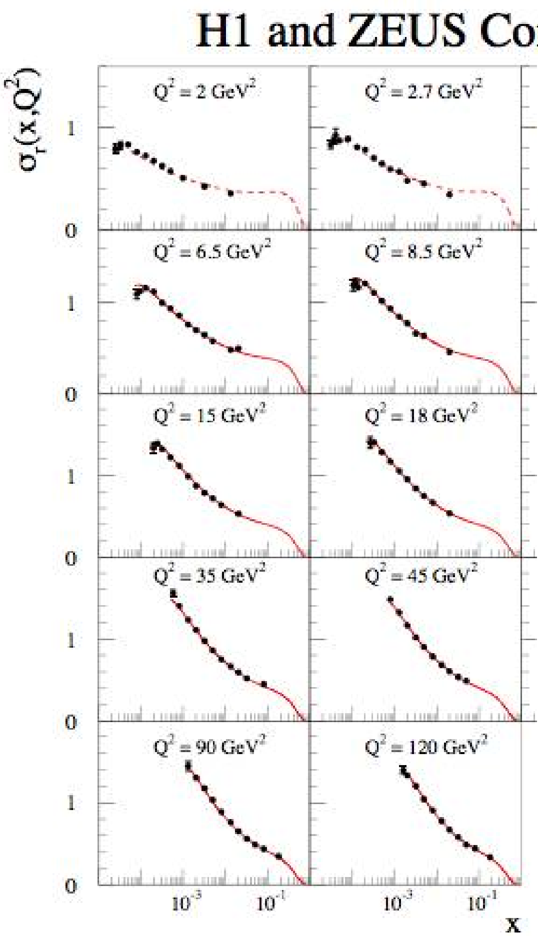


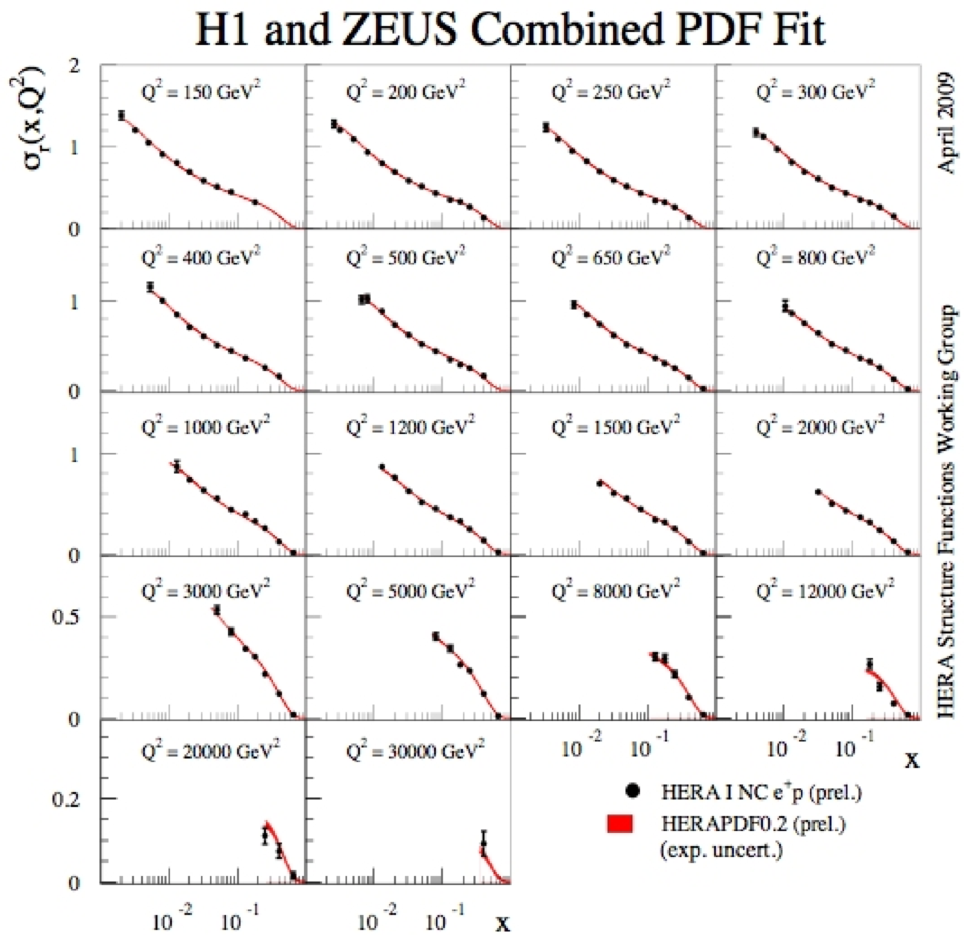
CC e^+p



NC Combined e^+p Data

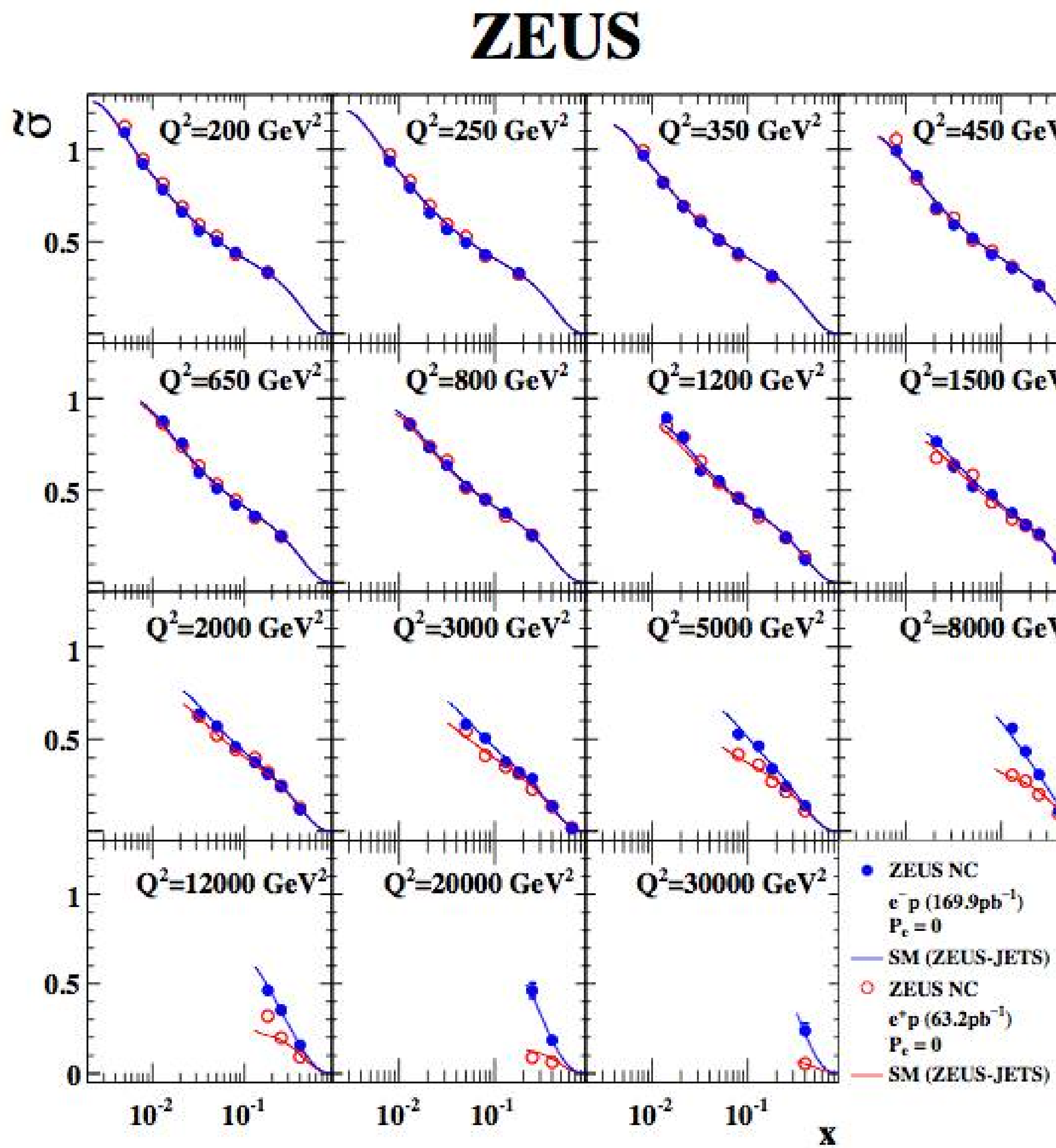






Q^2 range: 0.05 — 30000 GeV^2

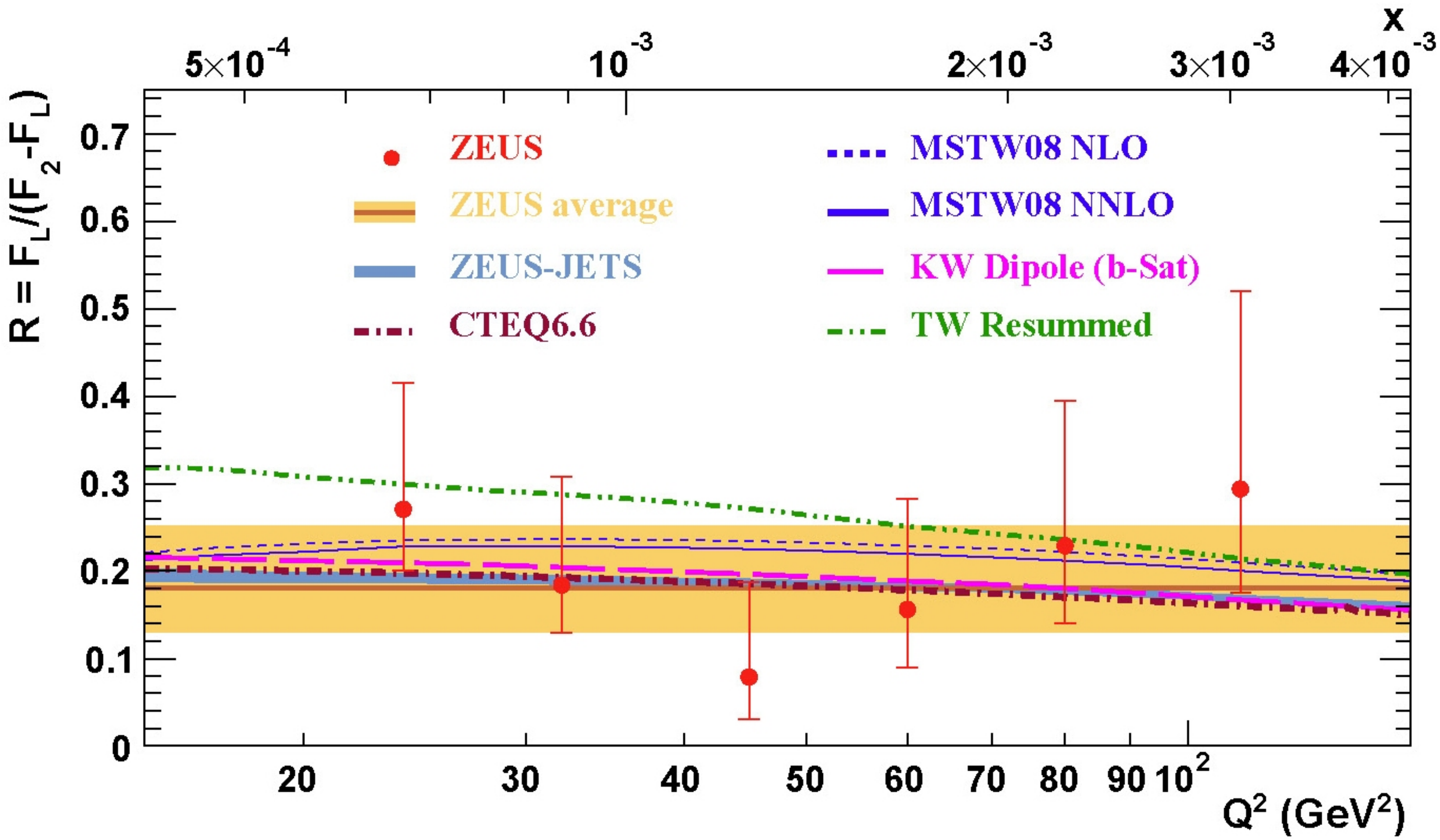
xF_3


ZEUS
$x\tilde{F}_3$
Q^2=200 GeV^2
Q^2=250 GeV^2
Q^2=350 GeV^2
Q^2=450 GeV^2
Q^2=650 GeV^2
Q^2=800 GeV^2
Q^2=1200 GeV^2
Q^2=1500 GeV^2
Q^2=2000 GeV^2
Q^2=3000 GeV^2
Q^2=5000 GeV^2
Q^2=8000 GeV^2
Q^2=12000 GeV^2
Q^2=20000 GeV^2
Q^2=30000 GeV^2
ZEUS NC
e^-p (169.9pb^{-1})
$P_e = 0$
SM (ZEUS-JETS)
ZEUS NC
e^+p (63.2pb^{-1})
$P_e = 0$
SM (ZEUS-JETS)
x

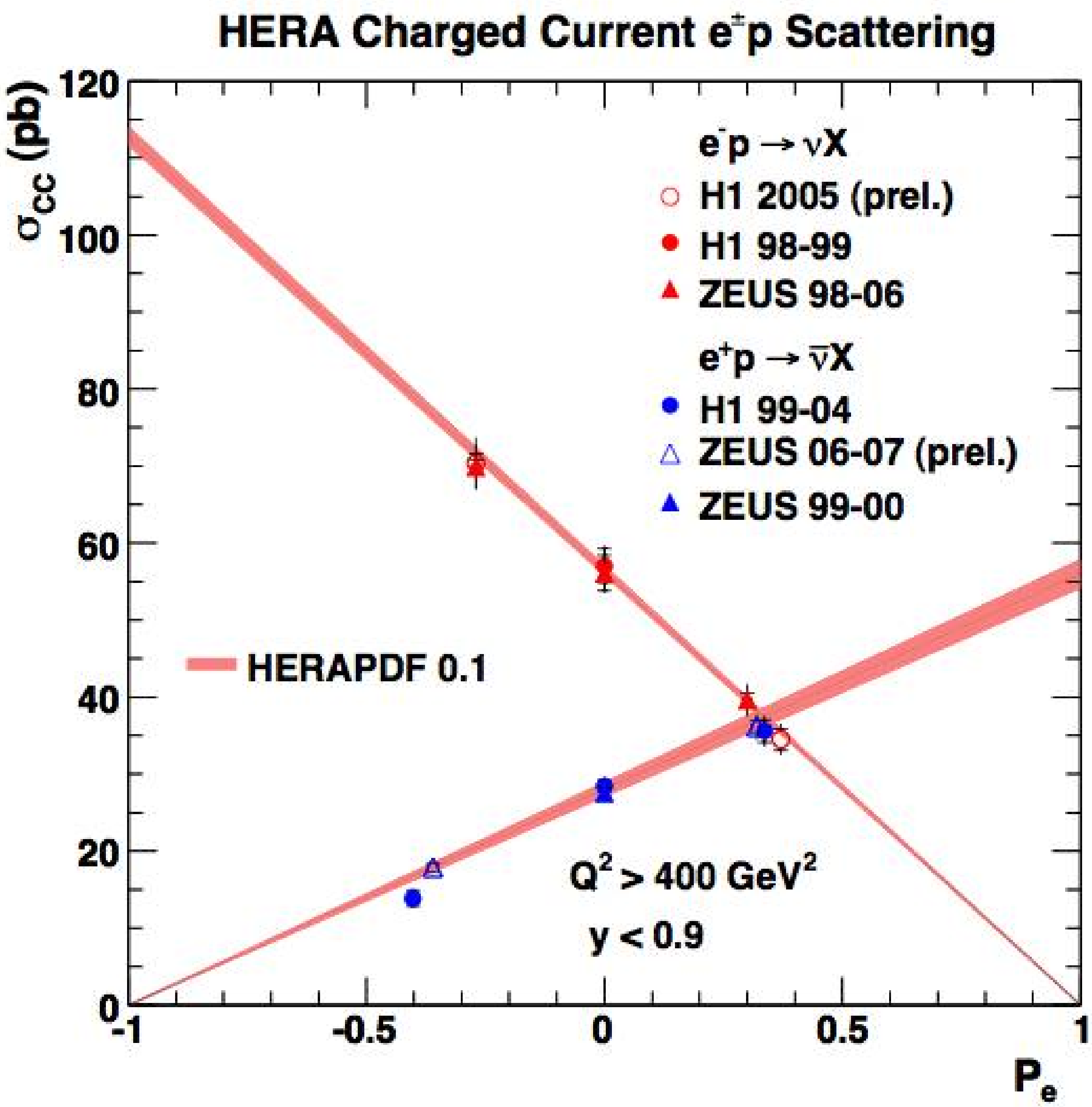
R

$$R = \frac{F_L}{F_2 - F_L}$$

$$\mathrm{R} = 0.18^{+0.07}_{-0.05}$$



Polarization at HERA II



$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dx dQ^2} = (1 \pm P_e)\frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 ..$$

The linear polarization dependence of the **CC** cross section demonstrates the V-A chiral structure of the weak current.

Extrapolations to small cross sections at high polarizations indicate no right-handed coupling.

H1 limit: $\mathbf{W_R > 208\ GeV}$

Parity Violation in NC

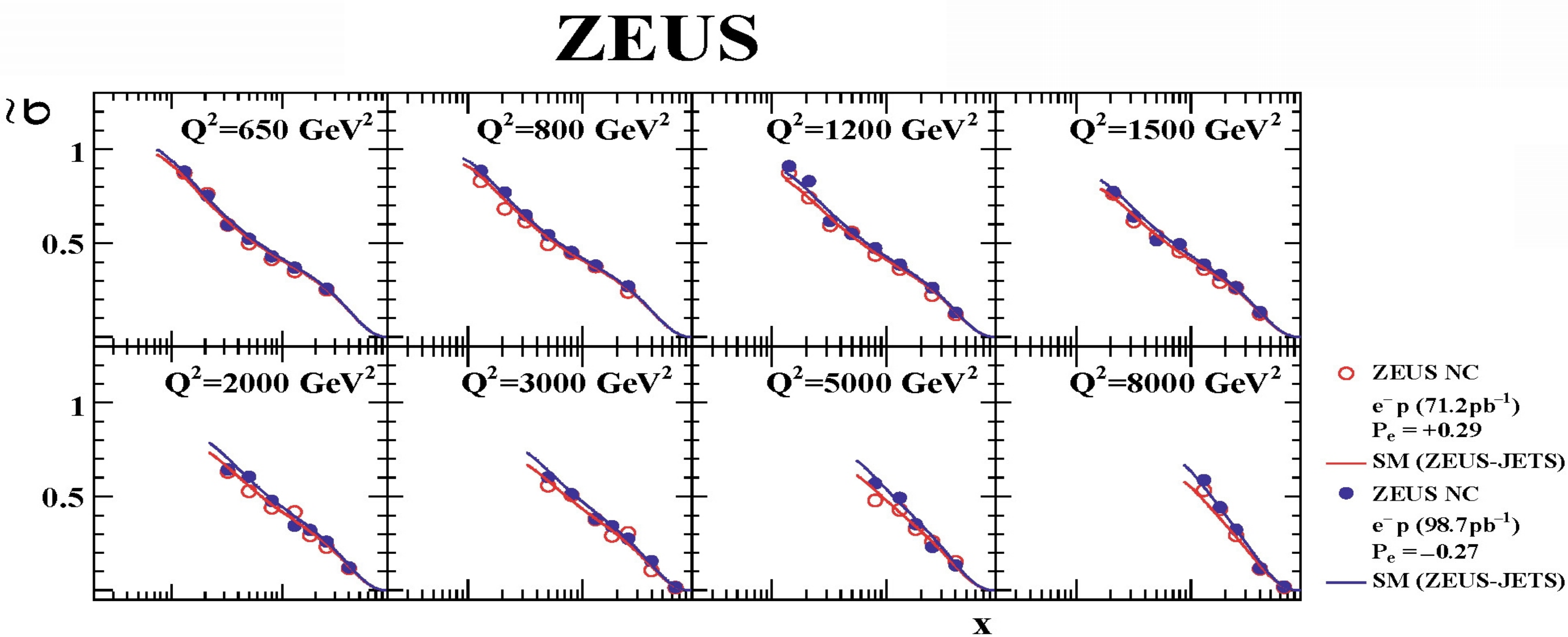
through Z⁰ exchange and γZ⁰ interference

$$F_2 \simeq \sum_i \left[e_i^2 + P_e(2\chi_Z a_e e_i v_i)\right] \times x(q_i + \bar{q}_i)$$

PDF's

deviations are observed for non-zero polarization values

however the effect is small

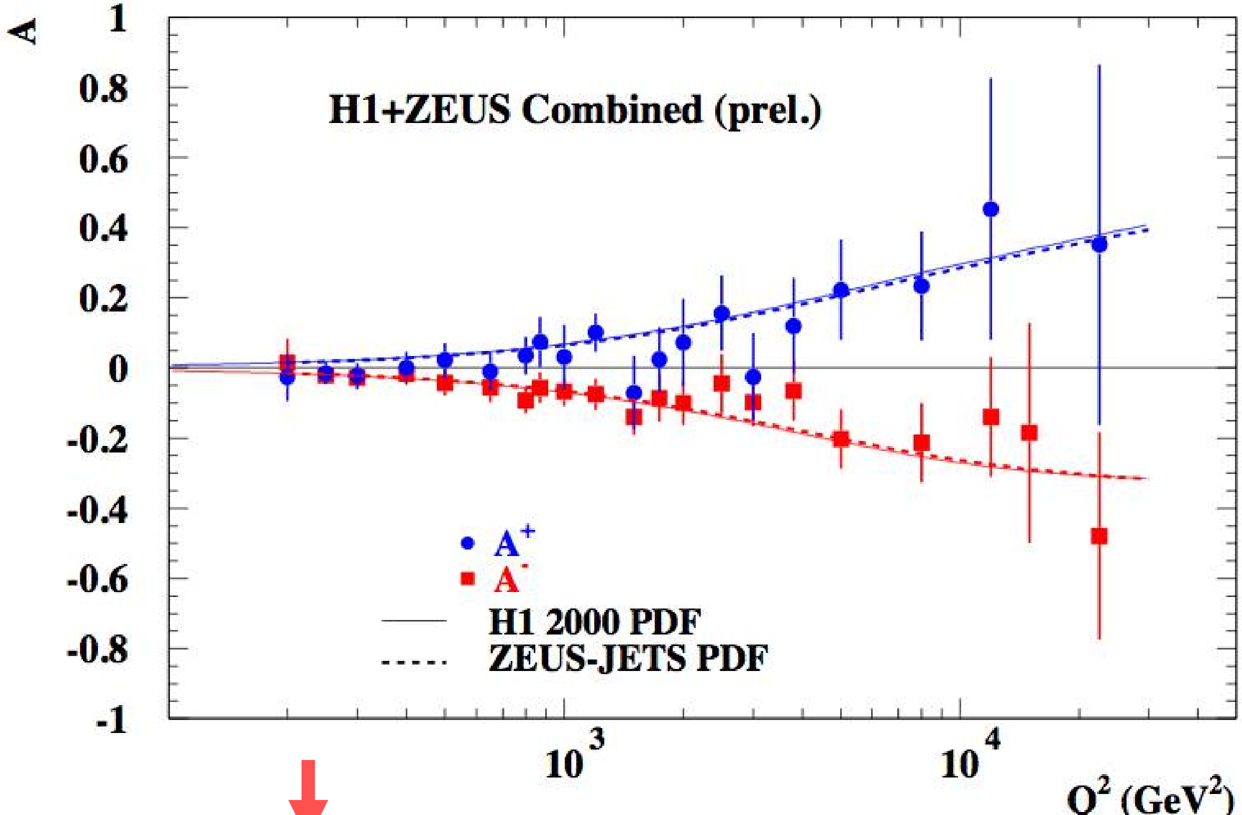


Asymmetry in NC

An asymmetry can be defined to estimate the strength of the parity violation:

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{e^{\pm}p}(P_R) - \sigma^{e^{\pm}p}(P_L)}{\sigma^{e^{\pm}p}(P_R) + \sigma^{e^{\pm}p}(P_L)}$$

$$A^{\pm} \simeq \chi_Z a_e \frac{2\mathrm{v_i}}{e_i}$$

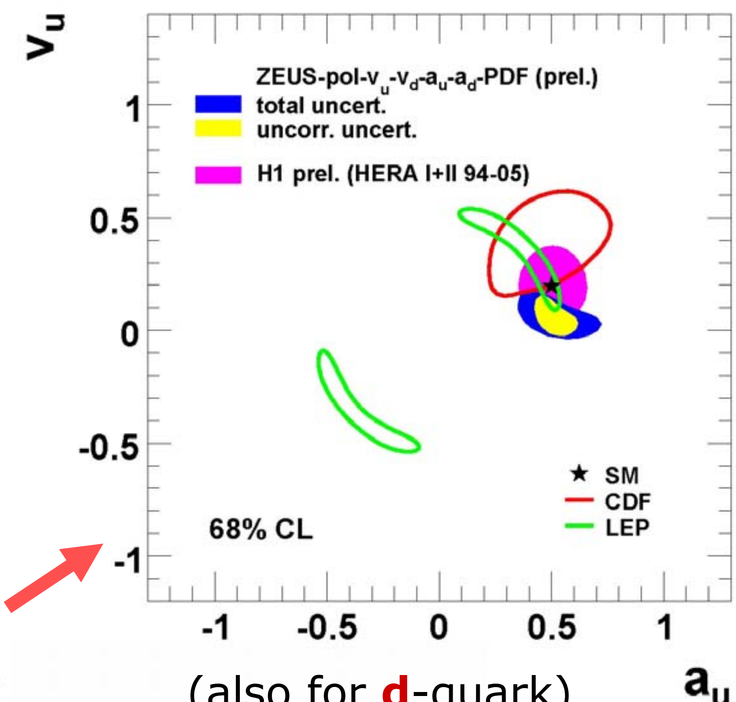


Parity violation at very small distances (~10^{-18}m)

from polarized F_2 and unpolarized xF_3 (NC):

$$xF_3 \sim \sum_i x(q_i - \bar{q}_i) \times (-2\chi_Z a_e e_i \mathrm{a_i})$$

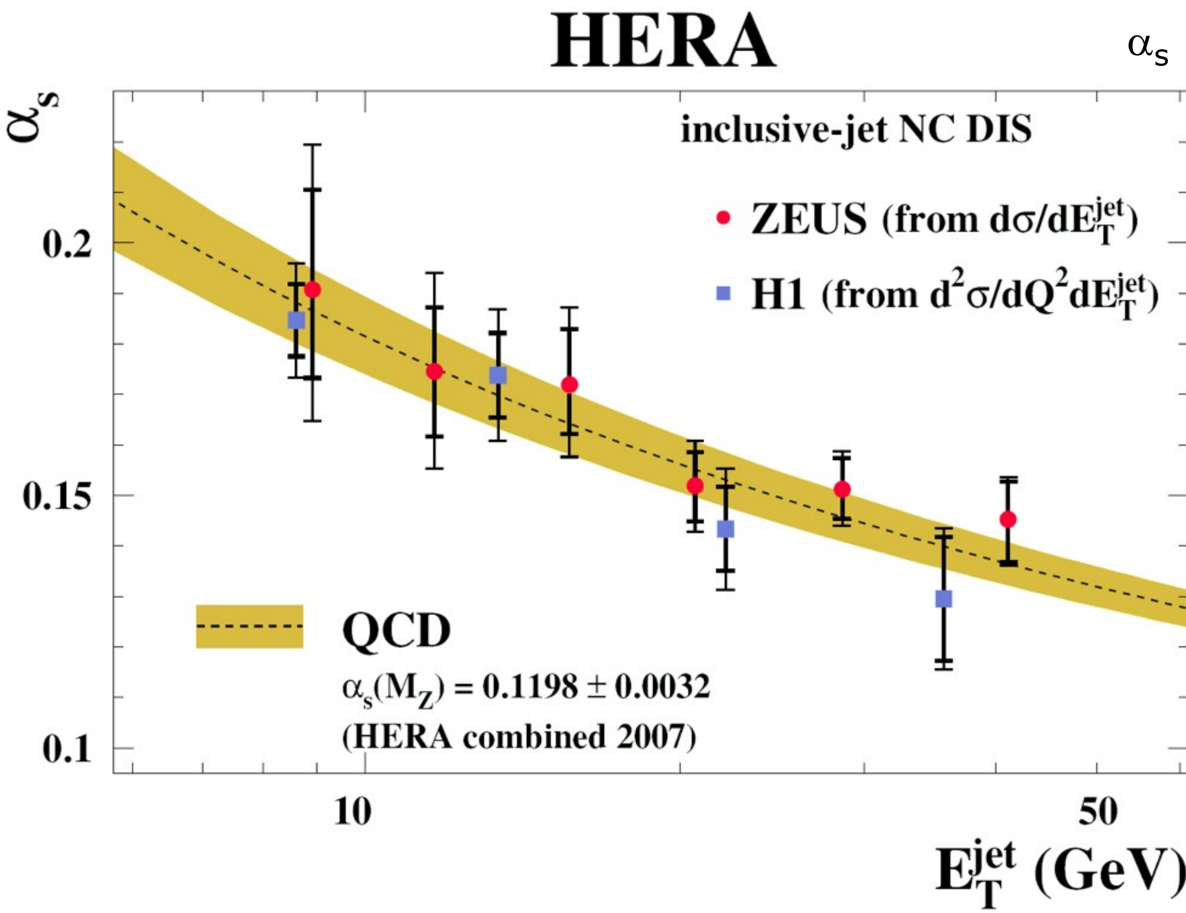
u-quark coupling to Z^0

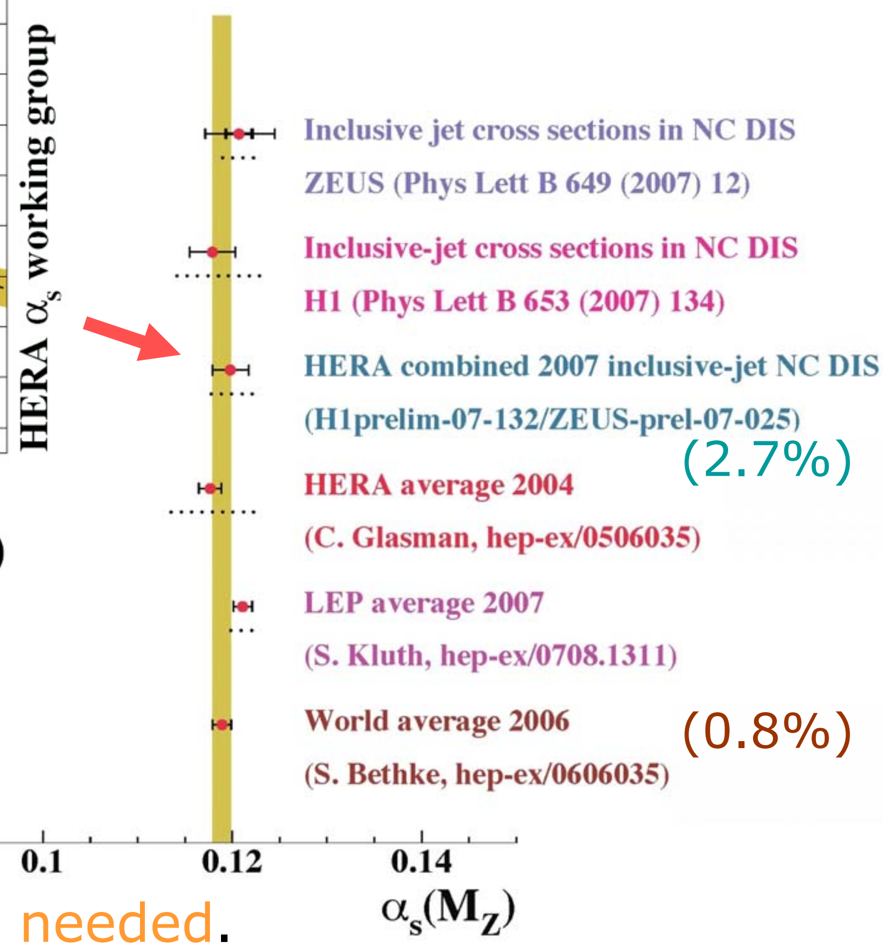


(also for **d**-quark)

Determination of α_s

$\alpha_s = 0.1198 \pm 0.0019(\text{exp.}) \pm 0.0026(\text{th.})$





New α_s measurement analyses underway using the full HERA data sets and extending the Q^2 range to cover two order of magnitudes. Limited by theory uncertainty → (NNLO) needed.