Proton Structure and Simulating Cosmic Ray Interactions

T.Sloan

For H1 and ZEUS

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Overview

Brief review of our knowledge of the structure of the nucleon.

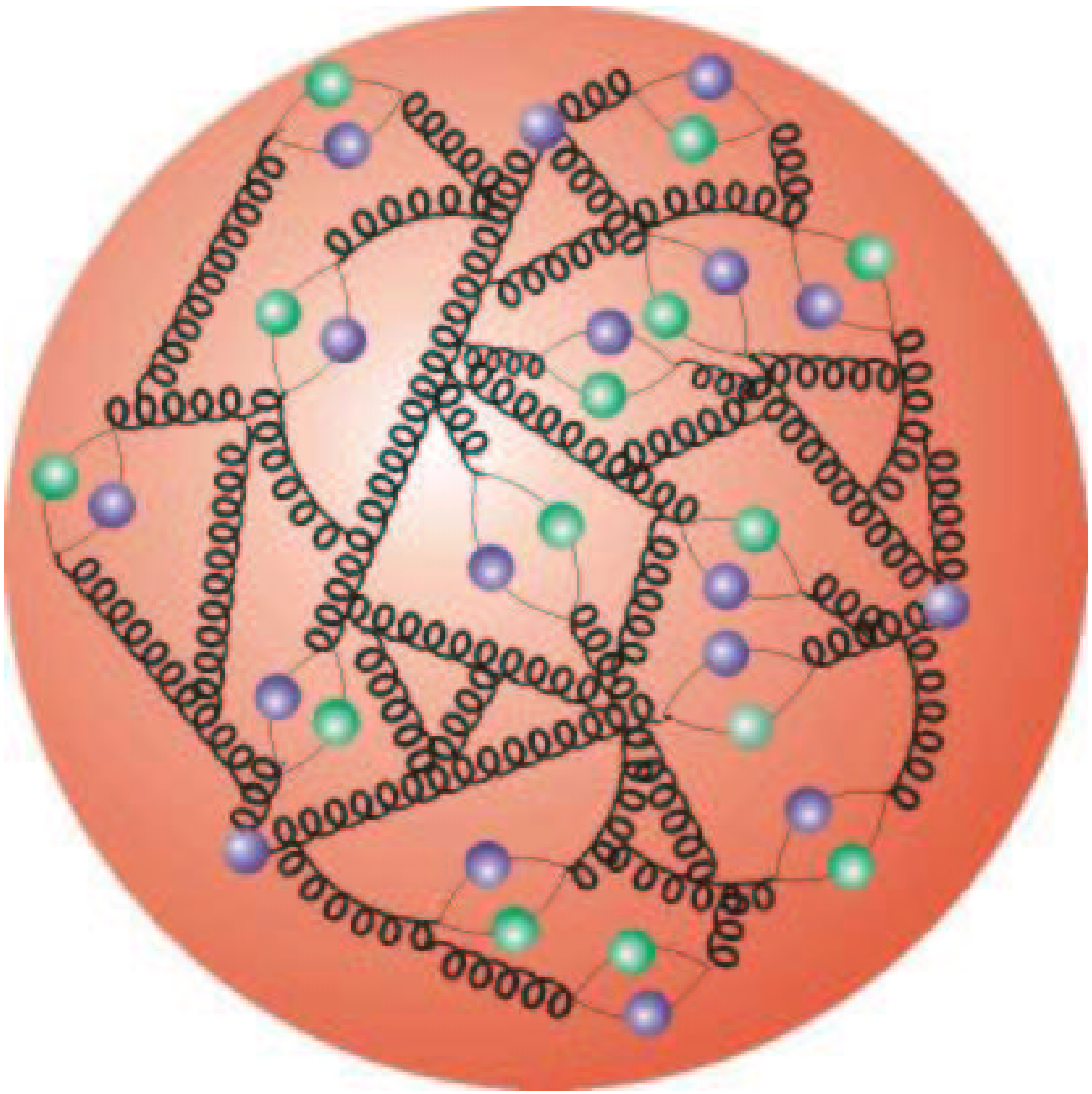
Structure function measurements from HERA.

Diffraction and the diffractive structure functions.

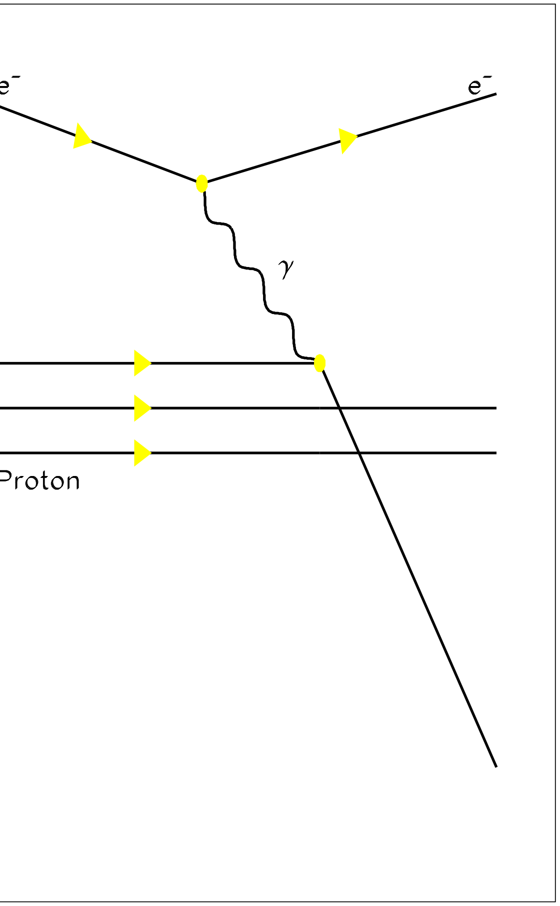
Nuclear effects.

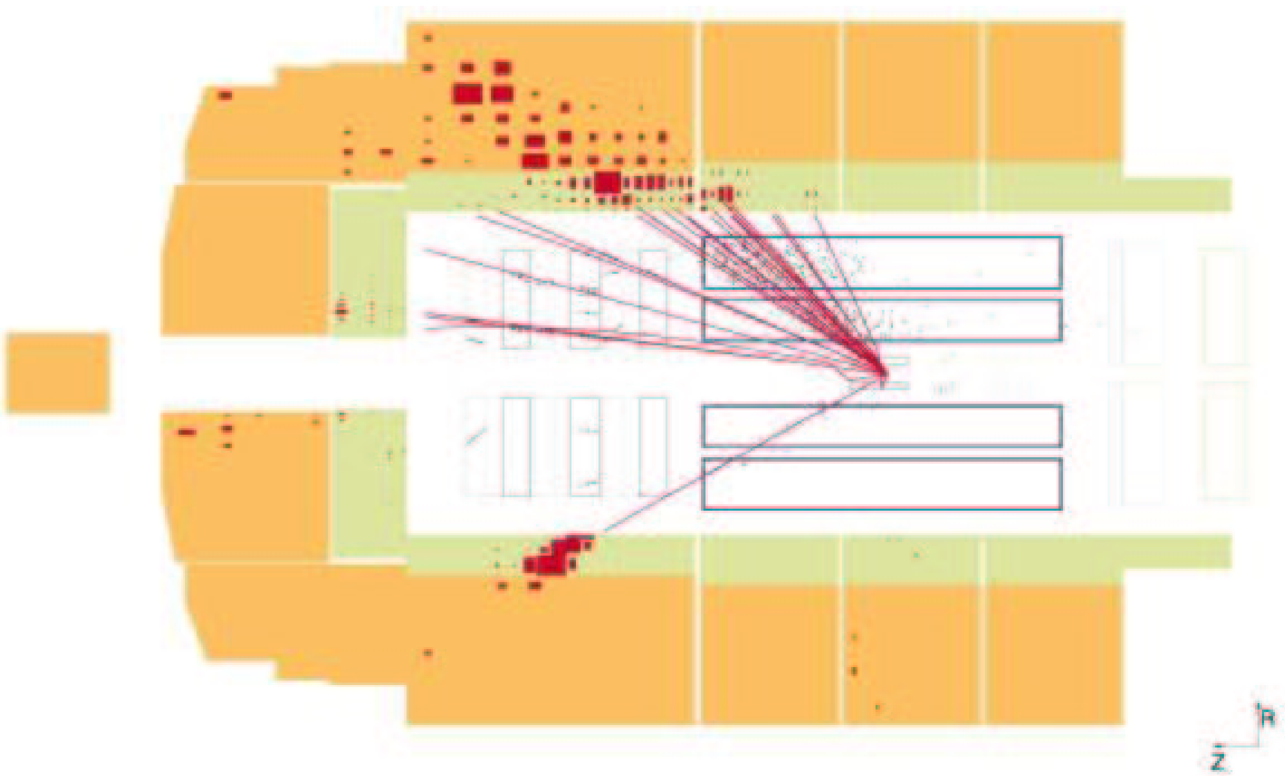
Modelling cosmic ray interactions.

Current picture of the proton



This picture emerges mainly from Deep Inelastic Scattering.

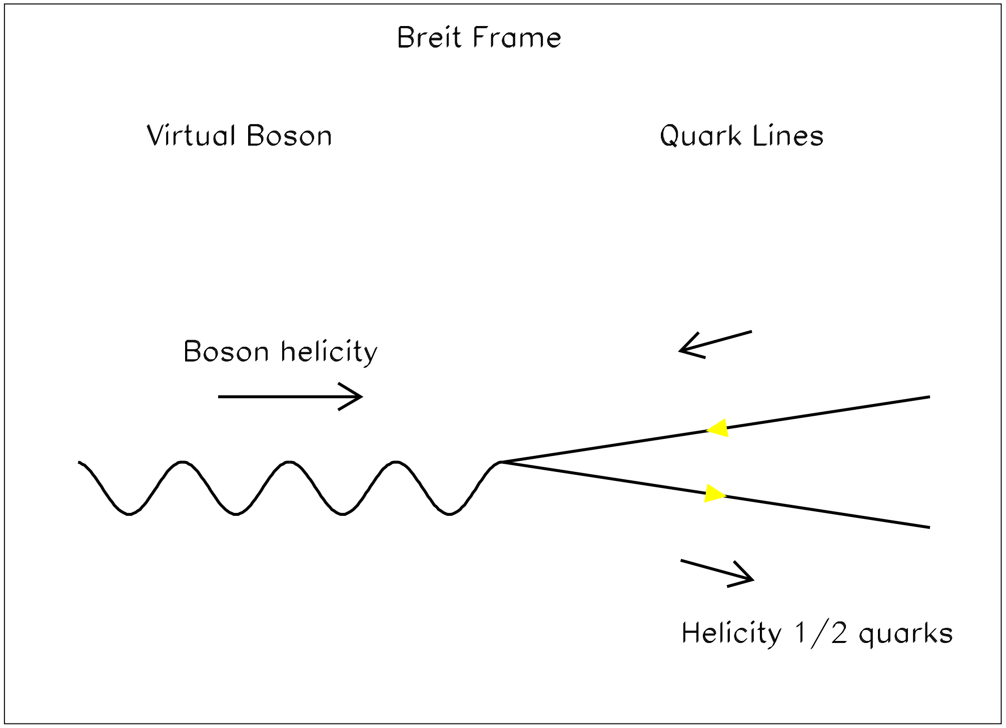




Exchanged boson kicks a quark from target which materialises (i.e. fragments) into hadrons.

x = fraction of momentum of proton carried by struck quark; $Q^2 \propto 1/\lambda$.

Quarks have half integral spins.



Boson helicity zero (longitudinal bosons) has zero absorption cross section on helicity 1/2 (i.e. spin 1/2) quarks by angular momentum conservation.

Longitudinal boson cross section observed to be small. Acquires a small finite value from quark transverse momenta.

More formally - for unpolarised scattering

$$\frac{d\sigma}{dxdy} = AF_2(x,Q^2) + BF_1(x,Q^2) \pm CxF_3(x,Q^2)$$

here A,B,C are factors from electoweak theory and F_2, F_1, xF_3 are structure functions

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

NB Constant of proportionality is quark charged squared when boson = photon

F_L is related to the cross section for absorption by longitudinal bosons

$$R = \sigma_L/\sigma_T = (F_2 - 2xF_1)/2xF_1 = F_L/2xF_1$$

and

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

How does this confirm the Quark model of the nucleon ?

Ratio of $F_2^{\nu N}/F_2^{eN}$ expected to be 5/18

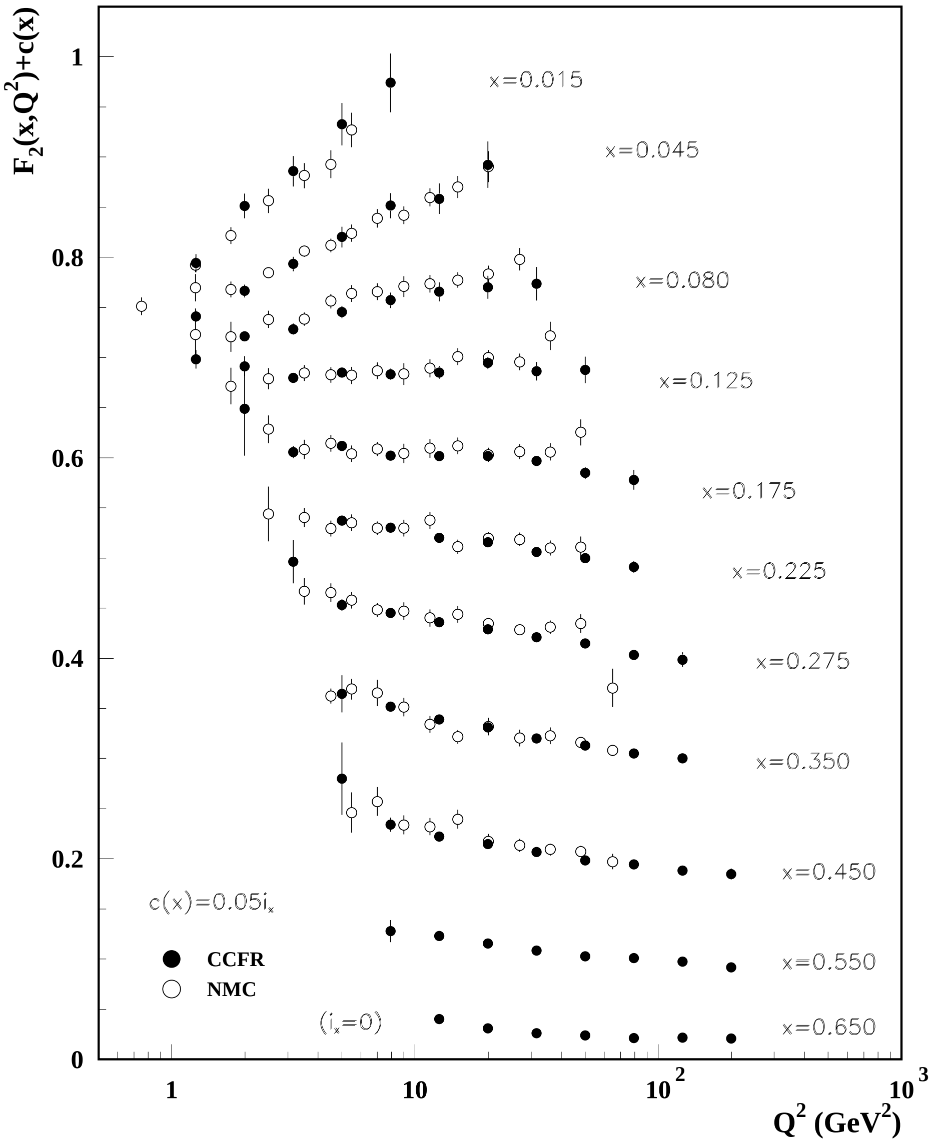
$$\frac{F_2^{eN}}{F_2^{\nu N}} = \frac{1}{2}\frac{4/9u + 1/9d + 1/9u + 4/9d}{d+u} = \frac{5}{18}$$

Here F_2^{eN} is the average of F_2^{ep} and F_2^{en} measured in deuterium. NB u quarks distribution in proton is the same as the d quark distribution in the neutron (isospin invariance).

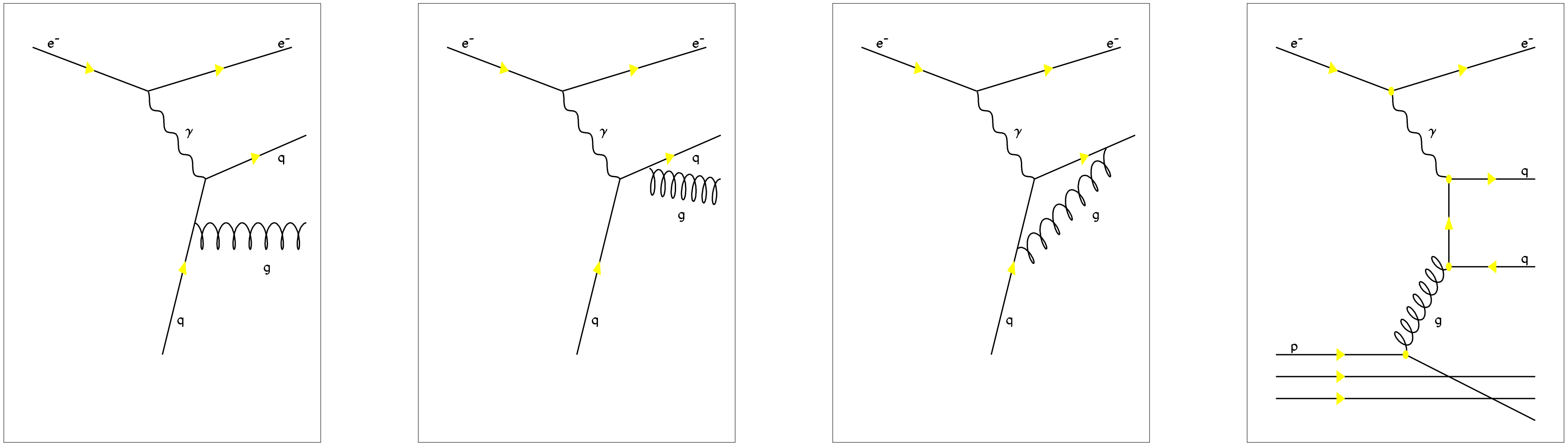
Next figure shows F_2^{eN} compared to $5/18F_2^{\nu N}$

Notice scaling i.e. independence of Q^2 i.e. wavelength of virtual boson.

Comparison of eN Structure Functions with νN times 5/18 .



Scaling violations i.e. deviations from flatness with Q^2 arise from QCD effects.

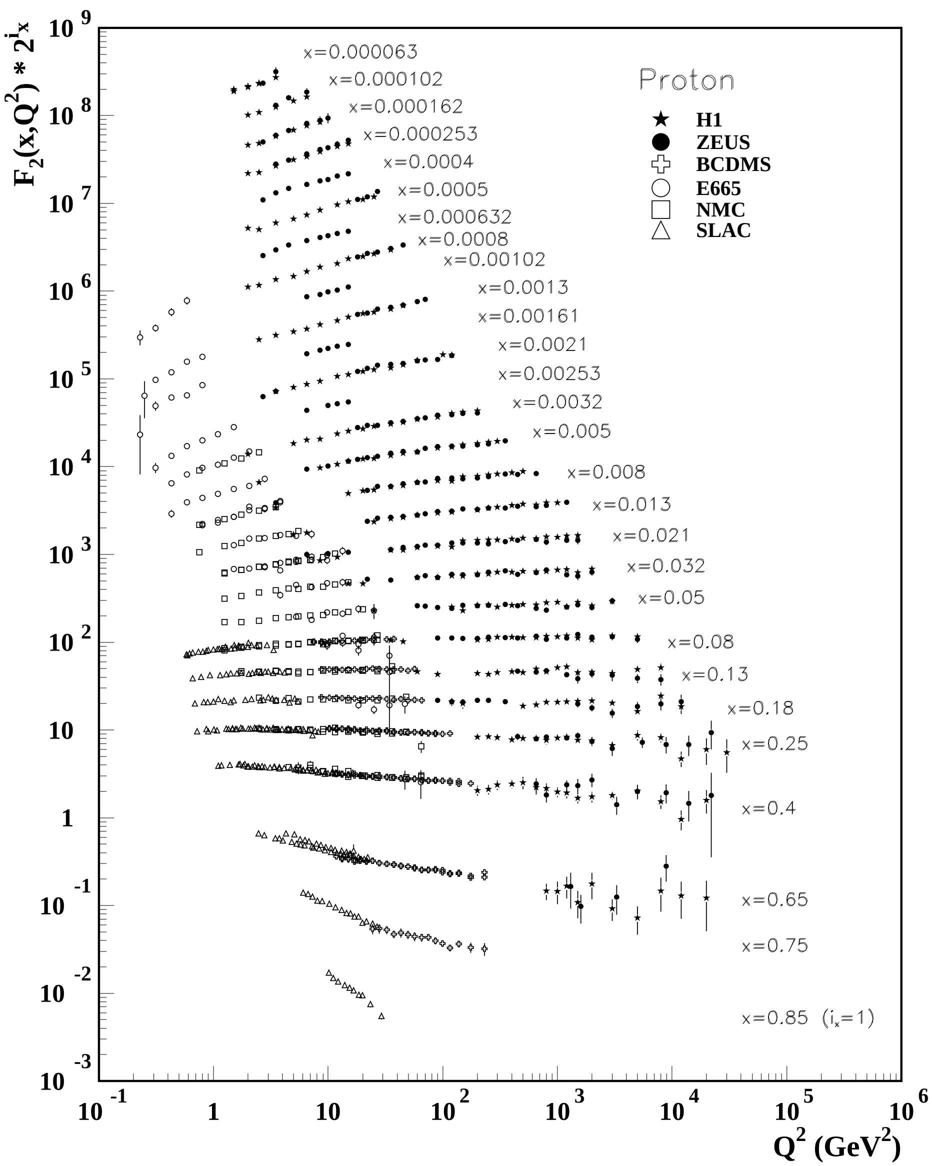


Scaling violations caused (at LO) by 4 graphs which can be calculated.

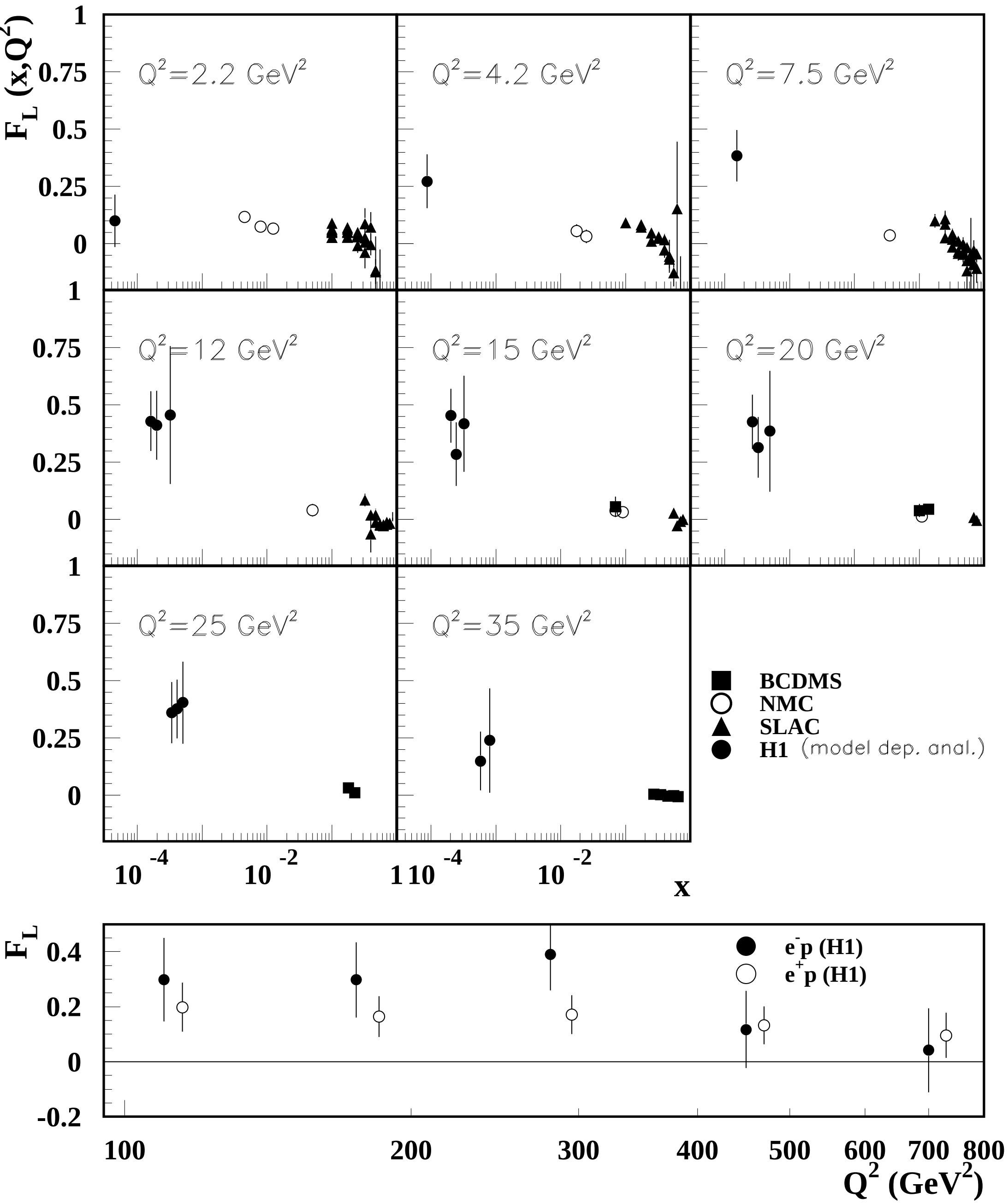
These allow rate of change of quark and gluon distributions with Q^2 to be calculated.

Fit the structure functions and the variation with Q^2 by a parameterisations of quark and gluon distributions at a fixed Q_0^2 and α_s, the strong coupling constant of QCD - solving a set of integral-differential equations.

Gluon distribution is difficult to obtain - better constrained by ZEUS by using jet information.

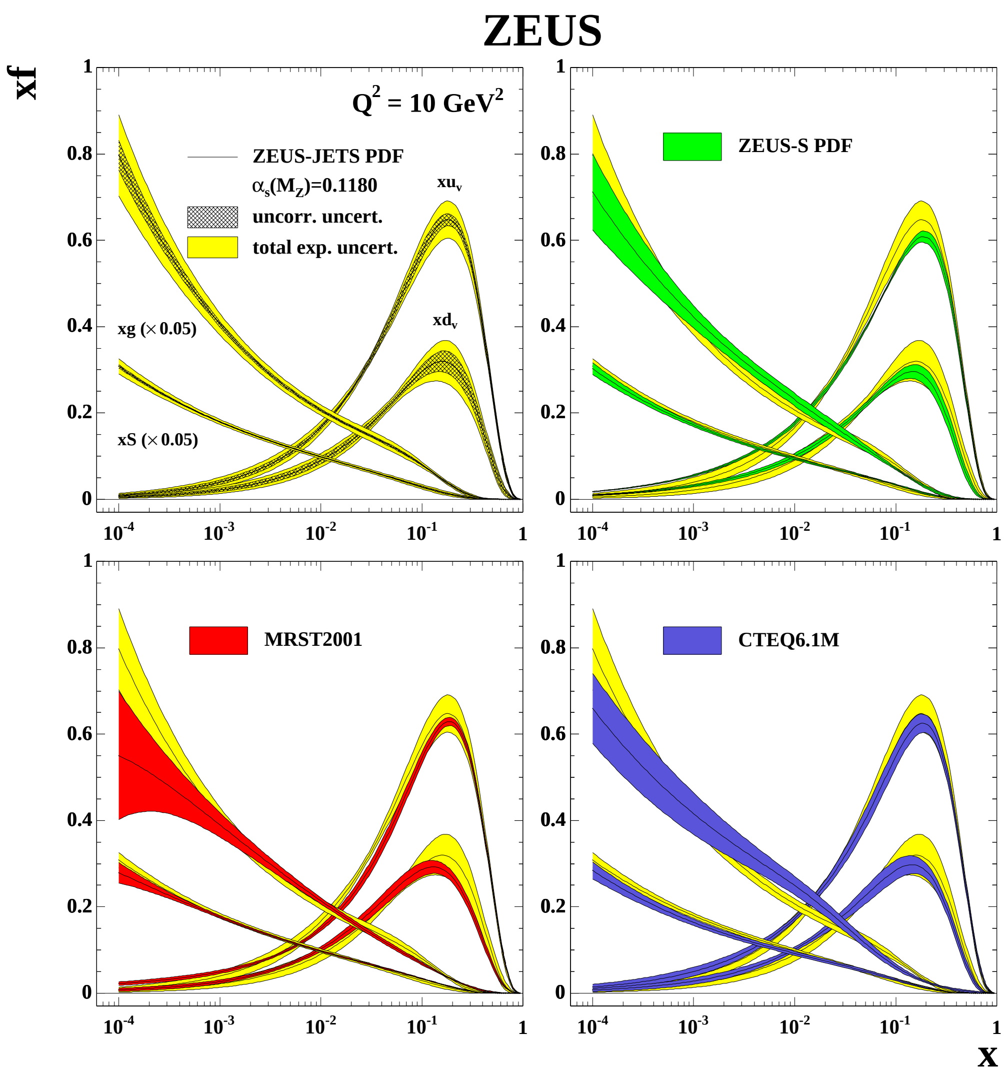


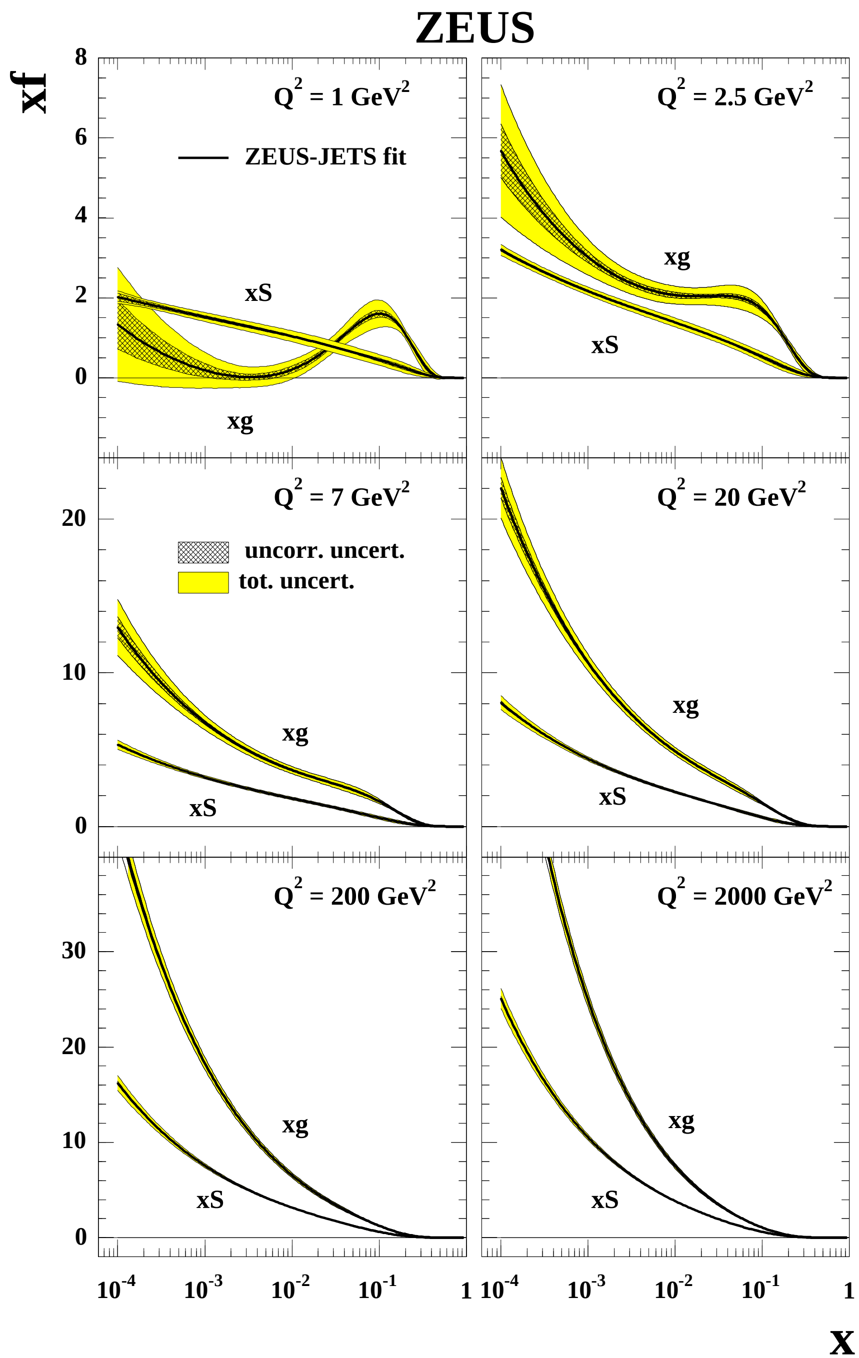
Proton
H1
ZEUS
BCDMS
E665
NMC
SLAC
x=0.000063
x=0.000102
x=0.000162
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.00102
x=0.0013
x=0.00161
x=0.0021
x=0.00253
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
x=0.75
x=0.85 (i_x=1)
F_2(x,Q^2) * 2^i_x
Q^2 (GeV^2)



$F_L(x,Q^2)$
Q^2=2.2 GeV^2
Q^2=4.2 GeV^2
Q^2=7.5 GeV^2
Q^2=12 GeV^2
Q^2=15 GeV^2
Q^2=20 GeV^2
Q^2=25 GeV^2
Q^2=35 GeV^2
BCDMS
NMC
SLAC
H1 (model dep. anal.)
x
F_L
e^-p (H1)
e^+p (H1)
Q^2 (GeV^2)

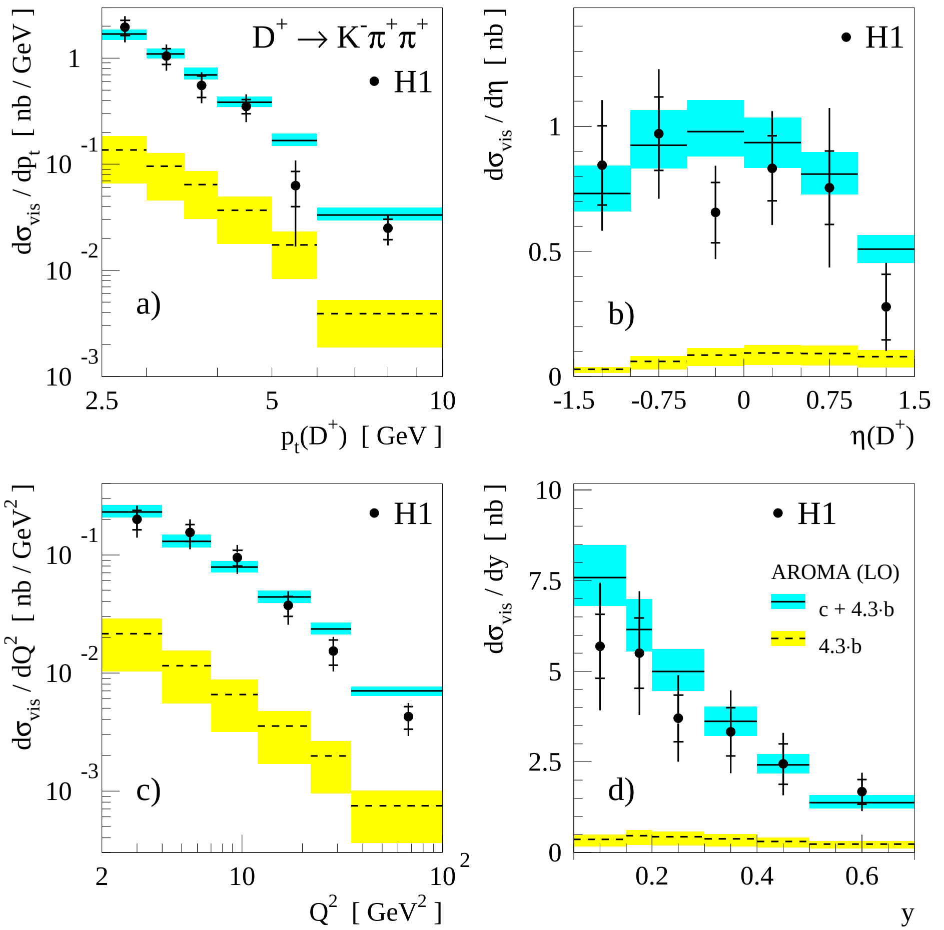
Each Collaboration does its own fit. ZEUS includes NC, CC and they use jet information to constrain gluon distribution.

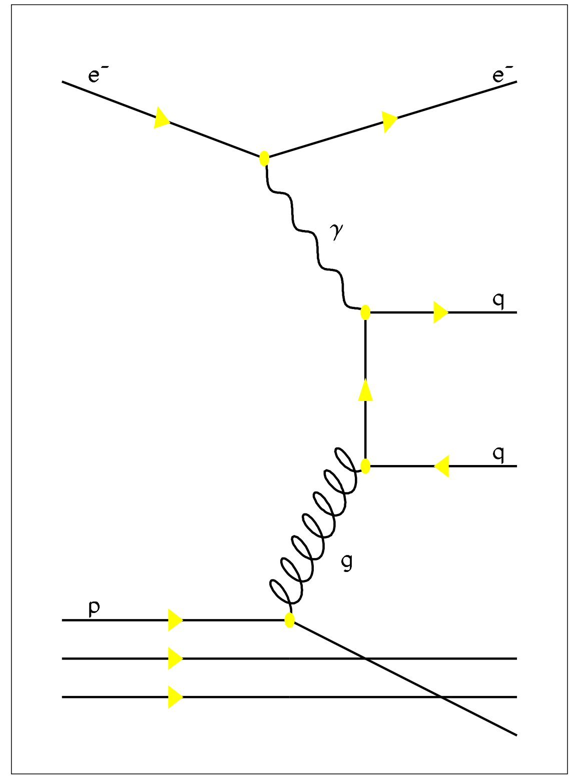




ZEUS
xf
Q^2 = 1 GeV^2
ZEUS-JETS fit
xS
xg
Q^2 = 2.5 GeV^2
xg
xS
Q^2 = 7 GeV^2
uncorr. uncert.
tot. uncert.
xg
xS
Q^2 = 20 GeV^2
xg
xS
Q^2 = 200 GeV^2
xg
xS
Q^2 = 2000 GeV^2
xg
xS
x

This picture working.



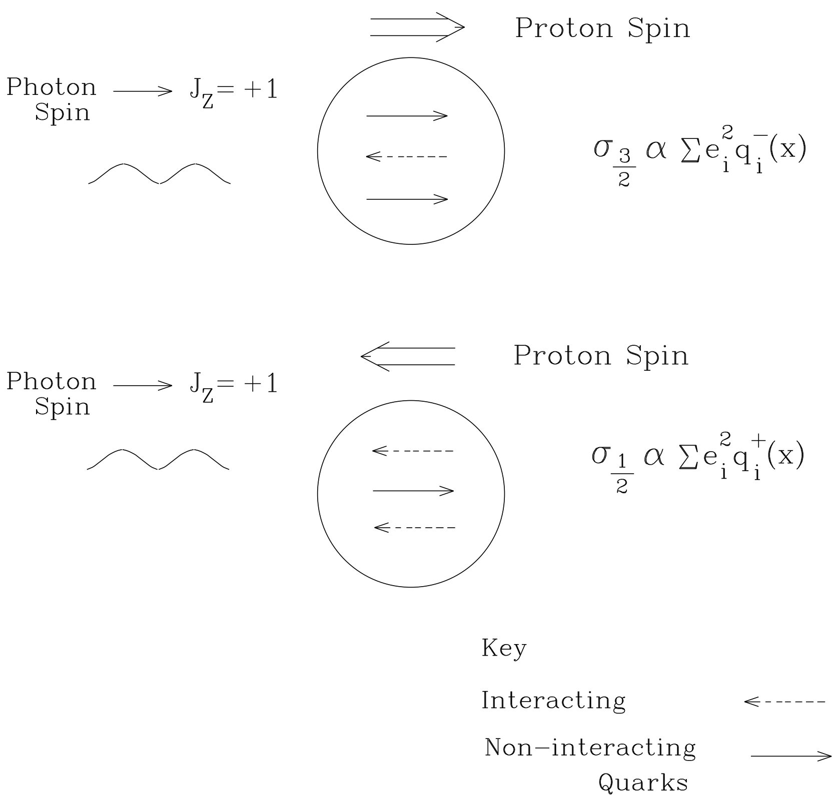


Blue histogram is photon-gluon fusion model calculated from measured gluon distribution.

But there are problems e.g. spin

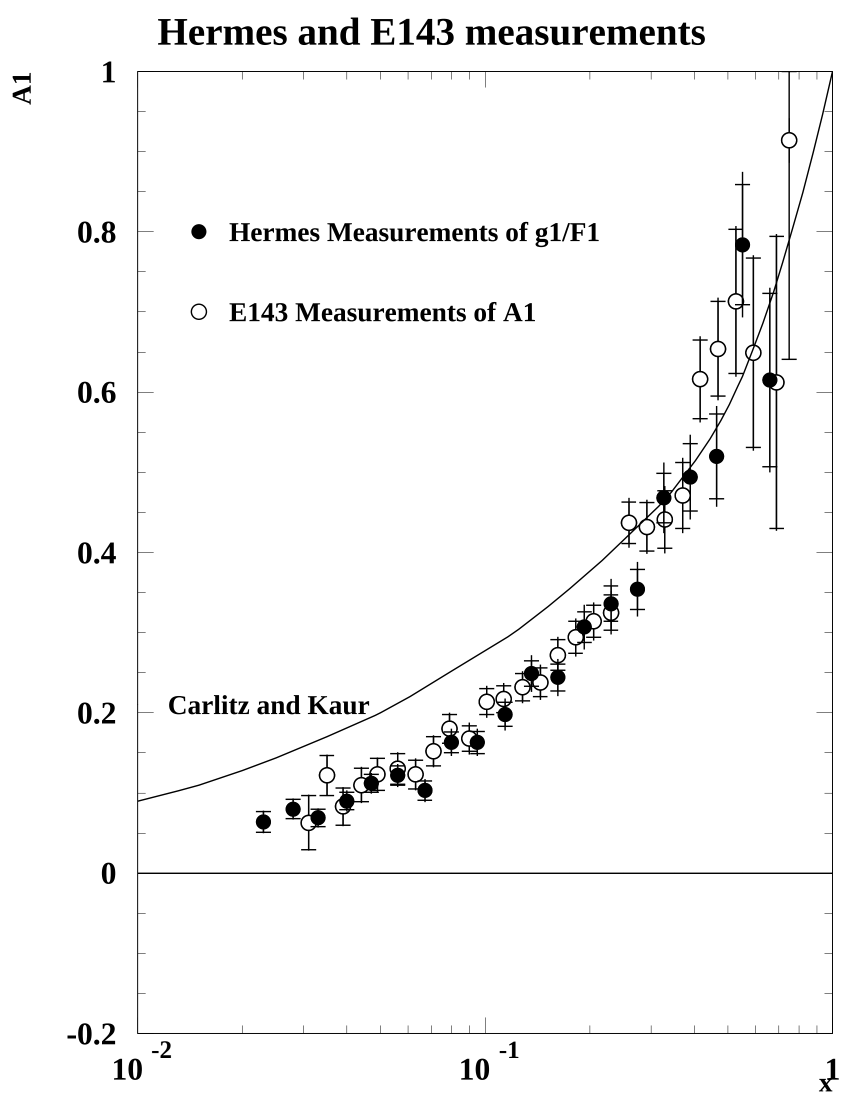
For polarised scattering

$$\frac{d\sigma\uparrow\uparrow}{dxdy} - \frac{d\sigma\uparrow\downarrow}{dxdy} \propto C g_1(x,Q^2)$$



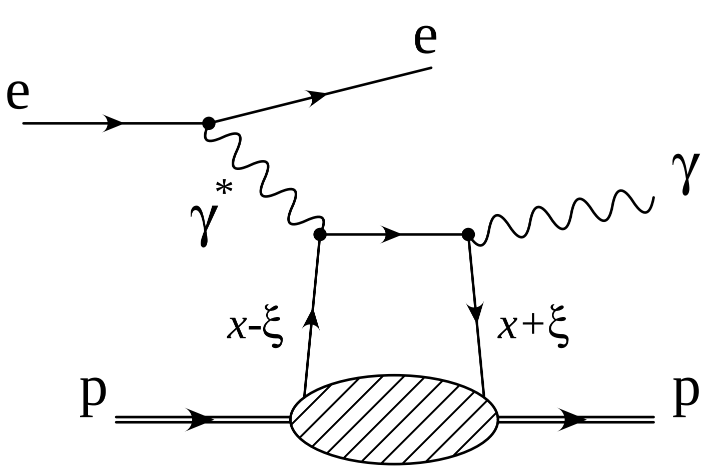
$$g_1 = q\uparrow - q\downarrow$$

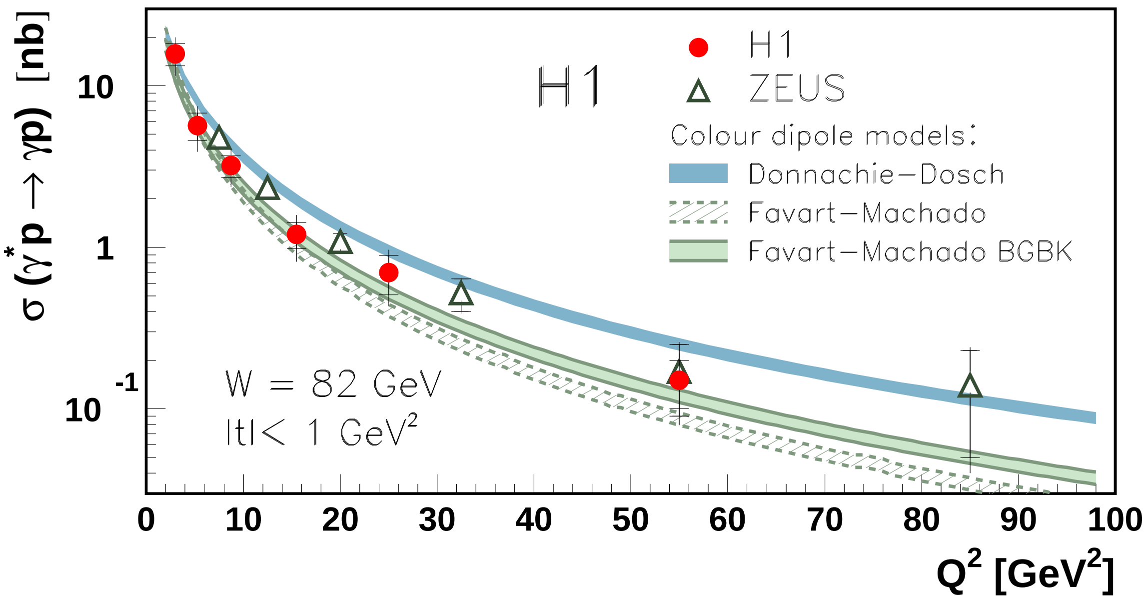
Smooth curve shows quark parton model prediction.



Small x discrepancy implies only $\sim 30\%$ of proton spin at high Q^2 carried by quarks.

Correlations between quarks - coming under experimental study through Deep Virtual Compton Scattering (DVCS) i.e. scatter with a highly virtual photon but detect a real photon (NB e,γ and proton in final state).

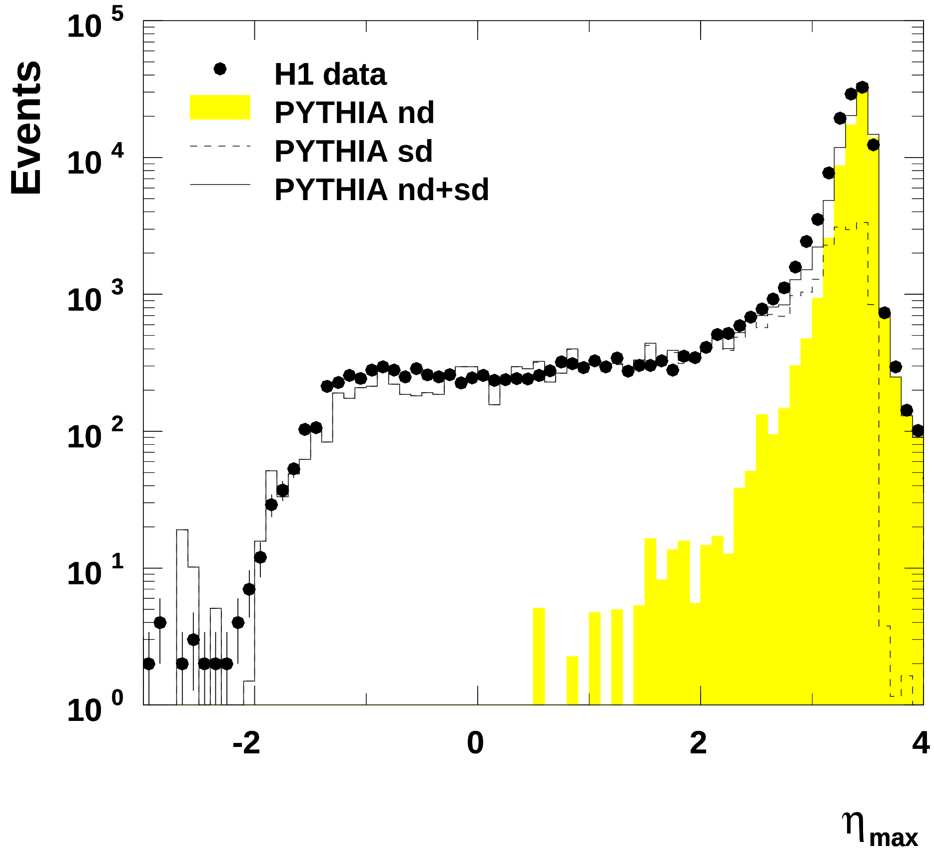


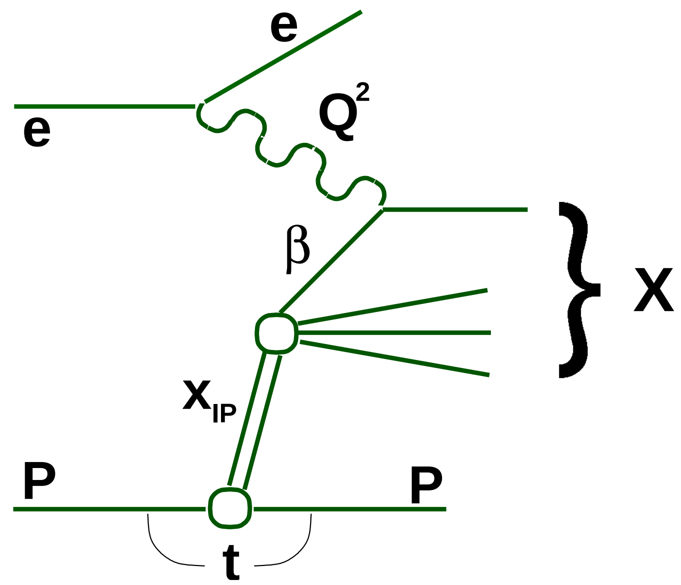


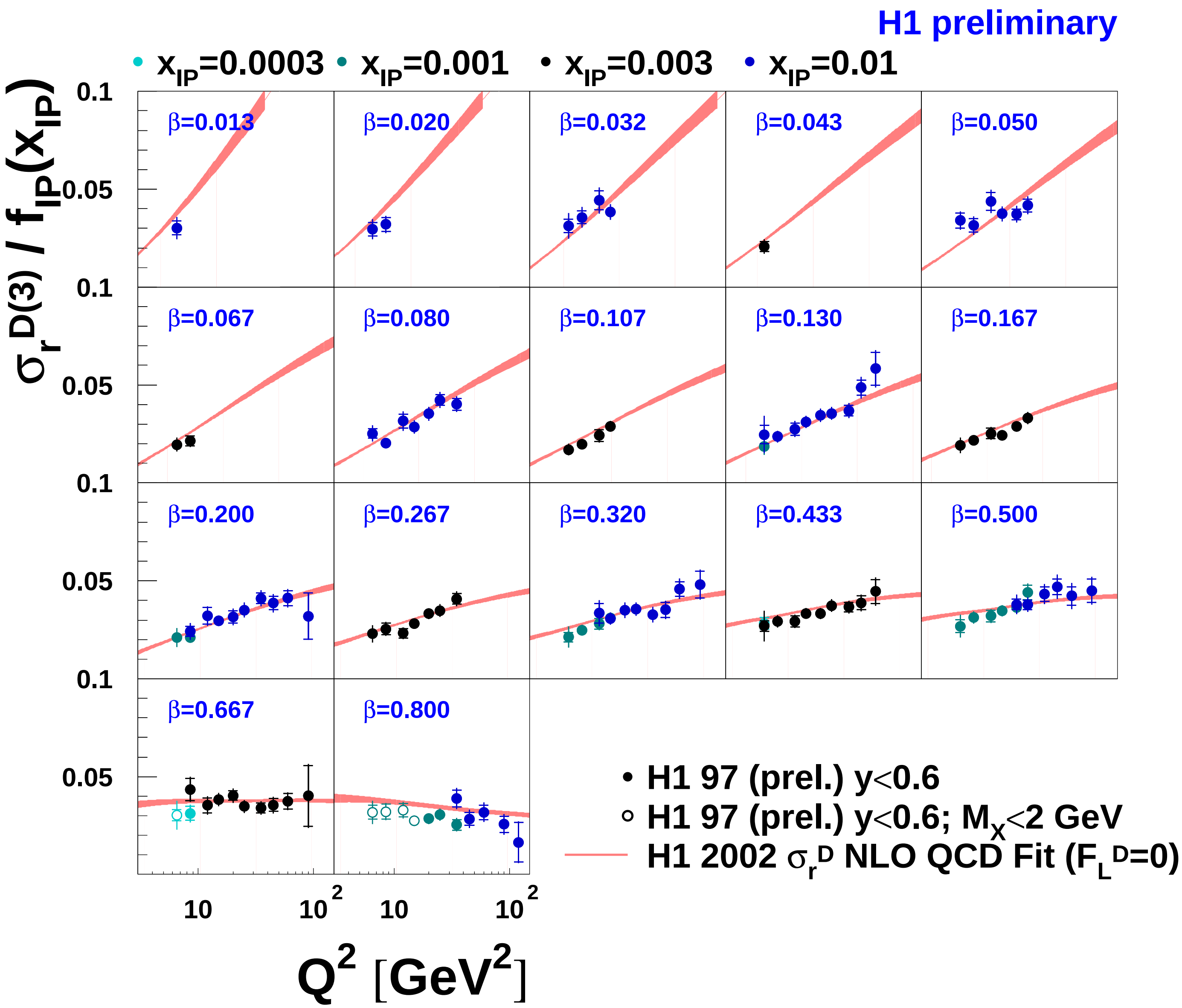
Several new structure functions are needed to describe such correlations. Not yet known how to measure them - hence can only compare with models of DVCS.

Diffraction observed at HERA - interpreted as interactions in the colourless clouds within the nucleon.

Events recognisable by their rapidity gap . Measure total cross section for such events i.e. the structure function.

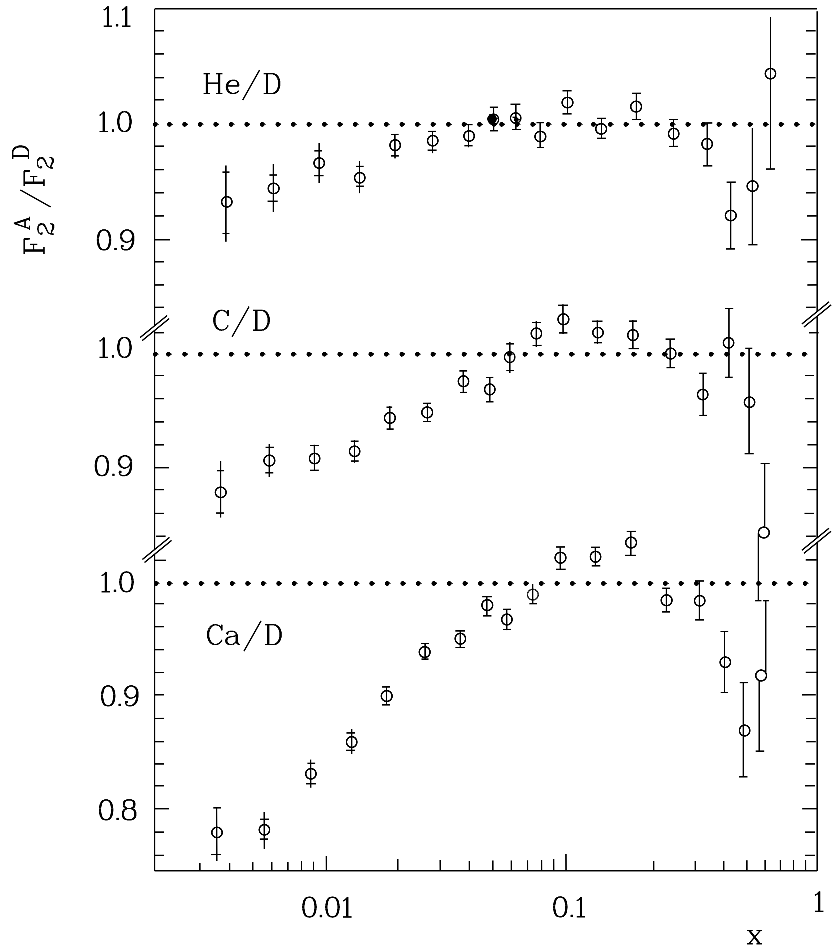






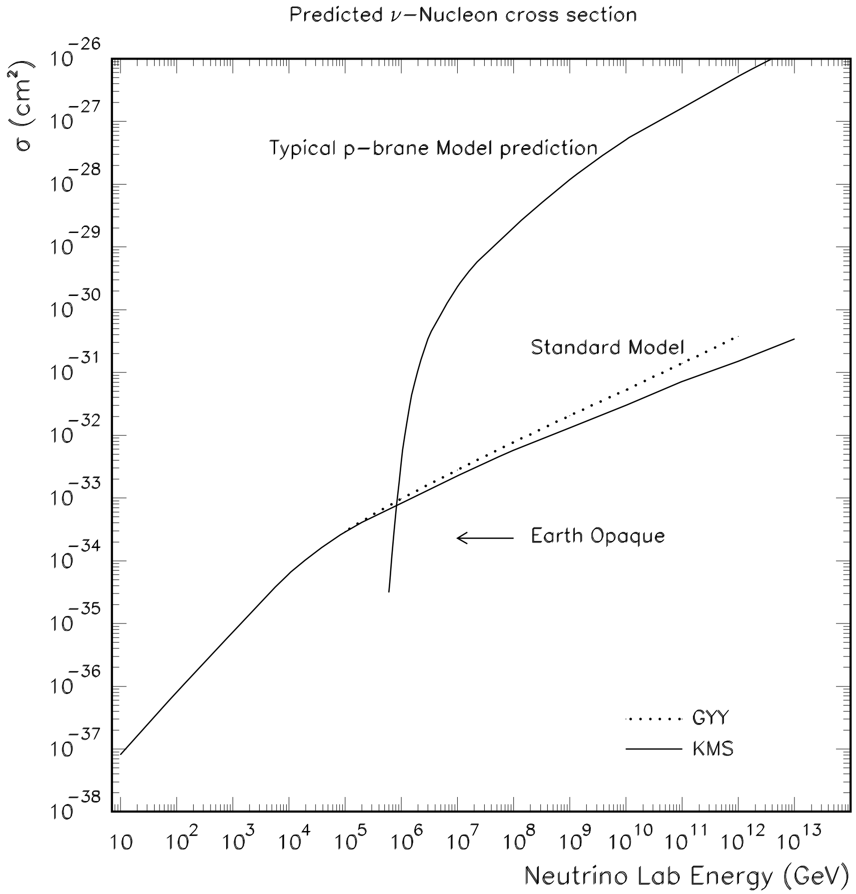
Diffractive Structure Functions. The Pomeron mainly gluons (small negative slope at high x).

Further complication - nuclear effects (NMC data).



Conclude - for A nucleons packed inside a nucleus, the quark and gluon structure is modified.

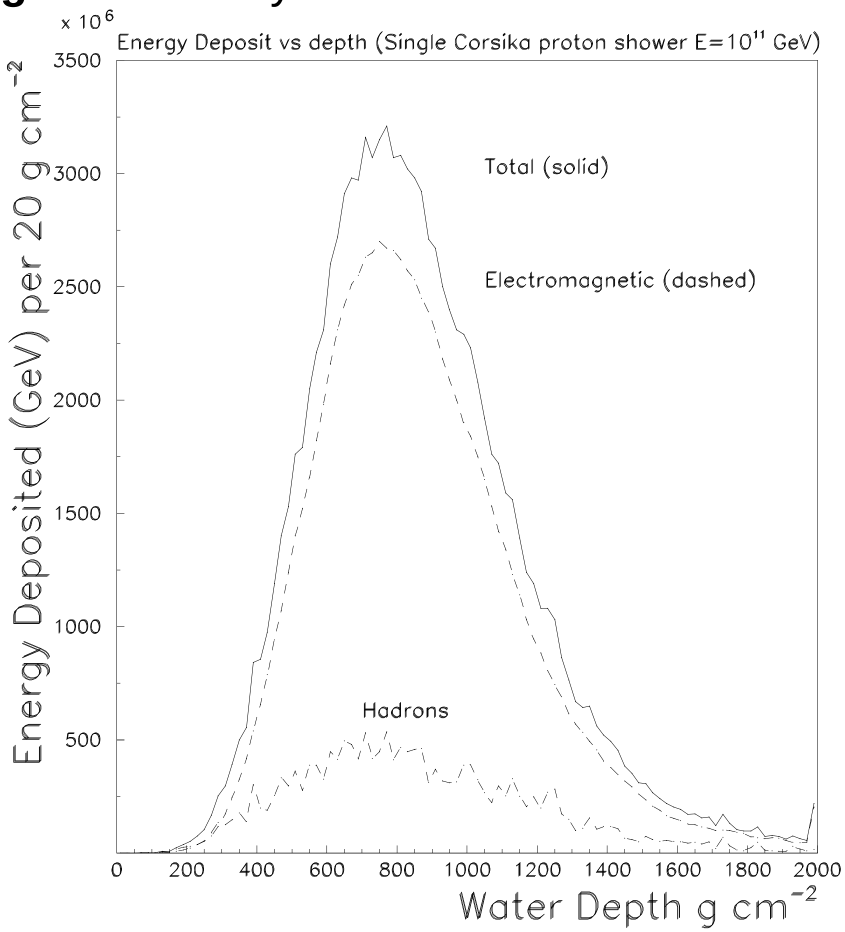
Sensitivity of neutrino cross section to nucleon structure via quark distribution functions.



This is derived by integrating the differential cross section

$$\frac{d^2\sigma}{dQ^2dy} \propto \frac{1}{sy}\Big(q(x,Q^2) + (1-y)^2\bar{q}(x,Q^2)\Big) \text{ where } Q^2 = sxy.$$

Modelling Cosmic Ray interactions - CORSIKA modified for water.



Shower mainly electromagnetic - similar effect is seen in hadron calorimeters.

Reason - $\sim 1/3$ of energy becomes neutral hadrons (decaying to photons) at each hadron-nucleus interaction. So at n^{th} interaction, energy fraction in charged hadrons $\sim (2/3)^n$ and $\sim 1-(2/3)^n$ is electromagnetic.

Sensitivity of cosmic ray experiments to modelling hadron-nucleus interactions.

All are sensitive to total hadron-nucleus cross section which is unknown above energies of 10^{18} eV (for protons). Total cross section determines the collision length i.e. rate at which the shower grows.

Muon detectors of high energy cosmic rays (eg large shower arrays) need to model charged hadron production accurately i.e. sensitive to the nucleon structure and quark fragmentation.

However, most other detectors of high energy cosmic rays are sensitive to total ionisation deposited i.e. are sensitive to the modelling of electromagnetic component (CORSIKA uses EGS) but are relatively insensitive to modelling the hadron development.

E.G. Fluorescent detectors (e.g. Fly's Eye), radio detection of air showers (geo-synchotron radiation), radio detection of cosmic ray neutrinos (FORTE, RICE, GLUE, ANITA), acoustic detection of ultra high energy (GZK region) cosmic ray neutrinos.

Conclusions

Structure of the Nucleon is getting to be well understood.

Allows us to predict various cross sections e.g. Higgs production at the LHC, high energy ν cross sections. Hence allows us to look for physics beyond the standard model.

Some problems still in understanding detailed spin structure at high Q^2.

Simulation of high energy cosmic ray interactions is not impaired too much by our lack of a complete knowledge of the nucleon structure.