Introduction to Deep Inelastic Scattering: past and present

Outlook

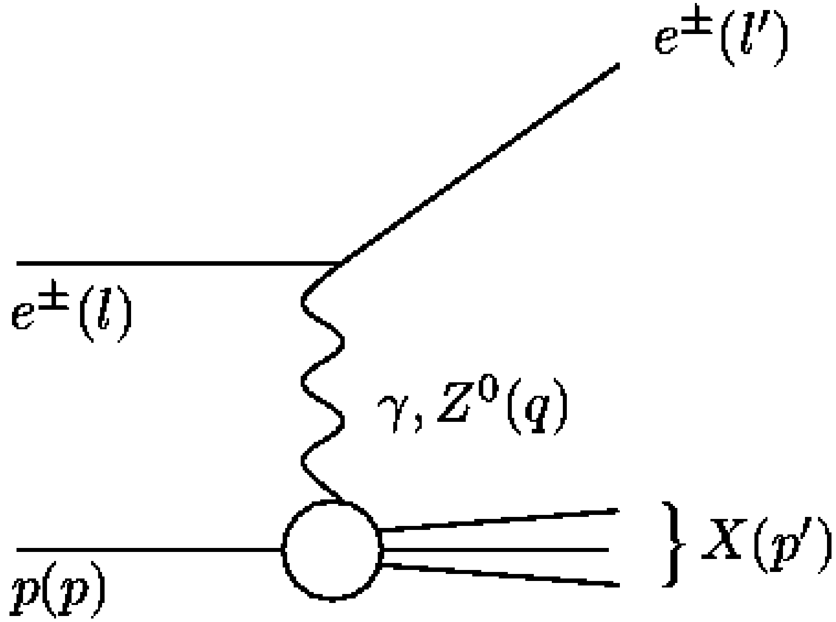
- Glorious surprises at SLAC
- High precision fixed target data and new themes (Spin and Nuclear effects)
- Discoveries from HERA
- High precision and extension of the field
- Conclusions

Deep Inelastic Scattering

Lepton-Nucleon **Scattering**

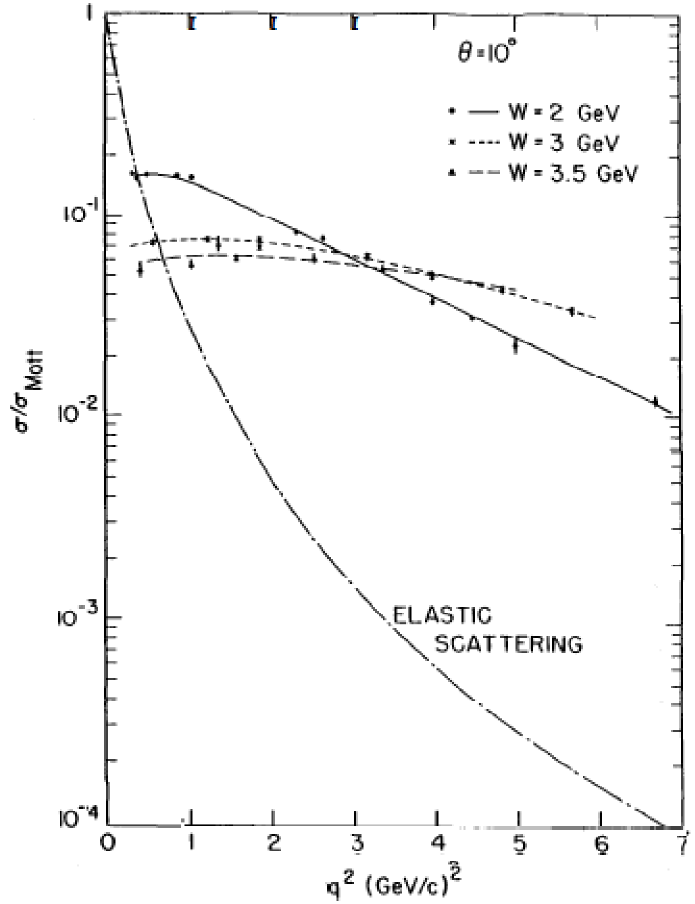
Large M_X = **Inelastic**

Large Q^2 = **Deep**

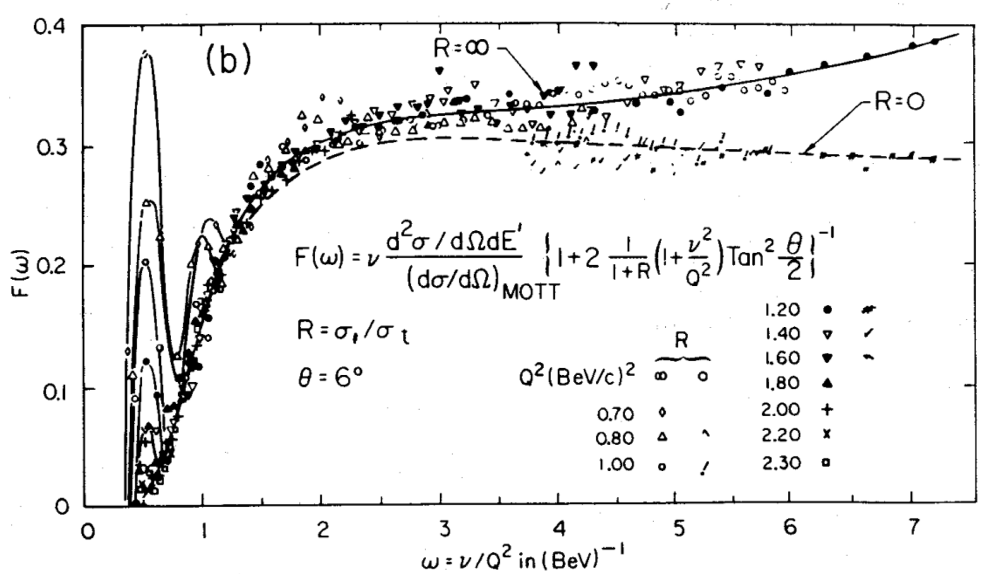


Two major surprises observed in late 1967 at SLAC

Very weak Q^2 dependence



Scaling at non asymptotic low Q^2 values



$$F(\omega) = \nu \frac{d^2\sigma / d\Omega dE'}{(d\sigma/d\Omega)_{MOTT}} \left\{ 1 + 2 \frac{1}{1+R}\left(1+\frac{\nu^2}{Q^2}\right) \mathrm{Tan}^2 \frac{\theta}{2} \right\}^{-1}$$

> the apparent success of the parametrization of the cross-sections in the variable ν/q^2 in addition to the large cross-section itself is at least indicative that point-like interactions are becoming involved.

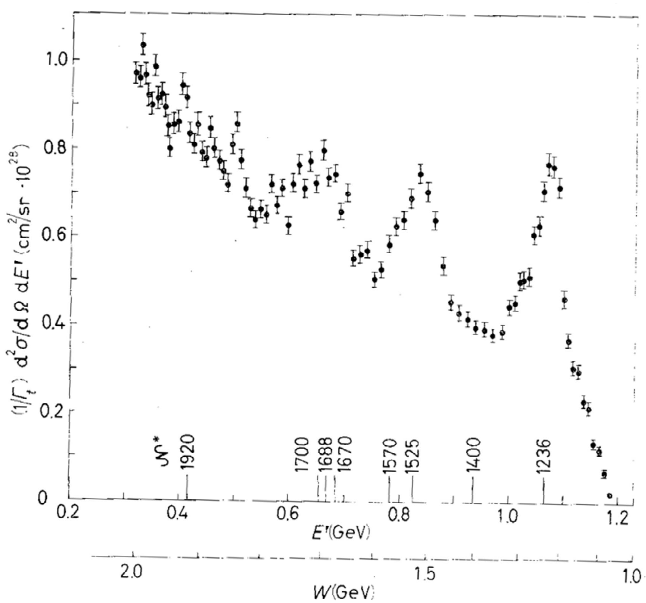
[W.K.H.Panovsky, HEP Vienna,1968]

Why was it such a surprise?

Before 1967 elastic scattering experiments (Hofstater) had demonstrated that the proton is not a point but an extensive structure

> It is clear from the proposal that the elastic experiment was the focus of interest at this juncture: "We expect that most members of the groups in the collaboration will be involved in the *e-p* elastic scattering experiment, and that the other experiments will be done by subgroups."

(Dick Taylor, Nobel Prize Lecture)



– Inelastic spectrum taken at $E = 2.231$ GeV and $\theta = 47.4°$, corresponding to $q^2 = 40\ \mathrm{fm}^{-2}$ at $W = 1236$ MeV.

(almost) Nobody expected that the study of the continuum at high W would be so crucial in the history of high energy physics.

At DESY, Brasse et al. did notice in june 1967 a surprising slow Q^2 dependence at high W that they tentatively attributed to resonances of high angular momentum.

Bjorken as lone prophet

Formal desciption of **scaling** but « a more physical description is without question needed » (Bjorken, 1966)

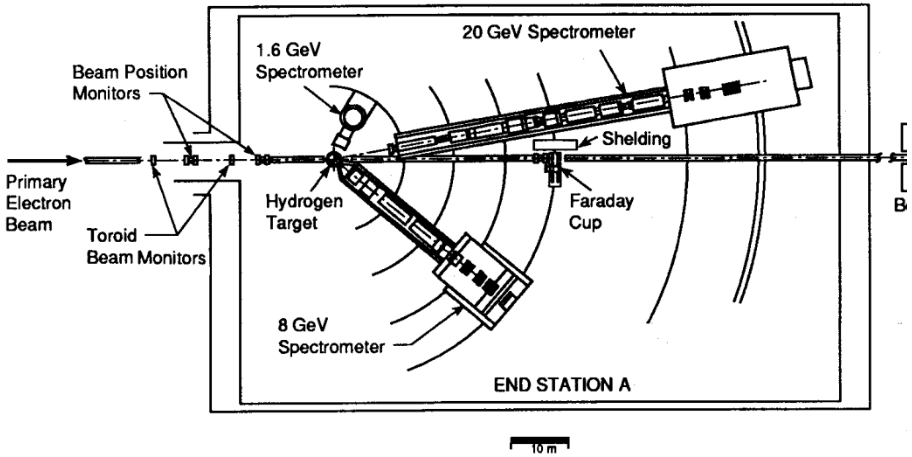
We can understand the **sum rules** in a very simple way (Bjorken, 1967).
We suppose that the nucleon consists of a certain number of '**elementary constituents**'

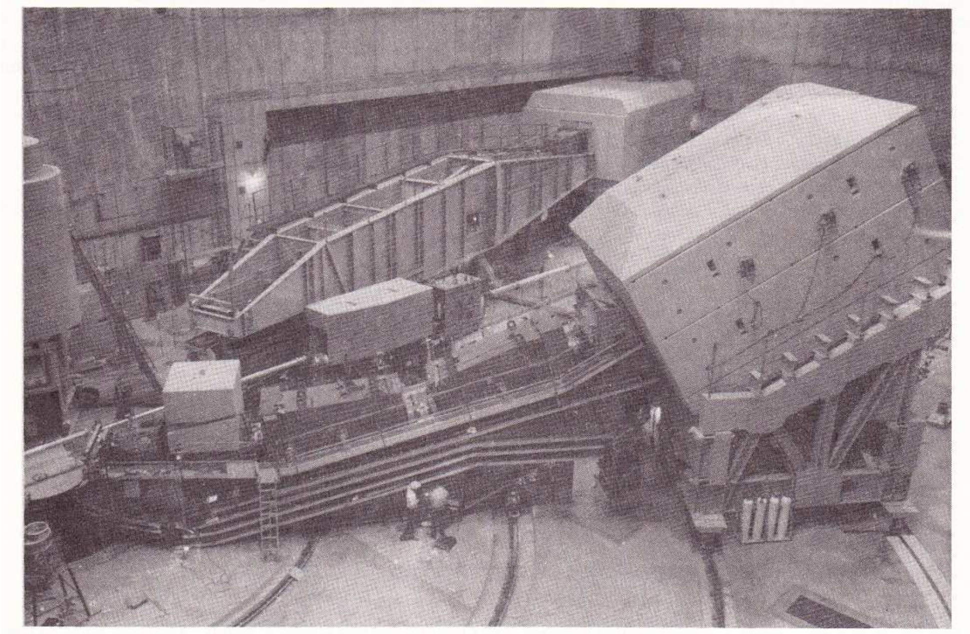
« It will be of interest to look at very large inelasticity » (Bjorken, 1967)

« Bjorken's results were based on current algebra, which we found as highly esoteric »
(J.Friedman, Nobel lecture)

Break through thanks to:

- A new accelerator : a two-mile SLAC of 20 GeV
- A very performant magnetic spectrometer





Momentum resolution : Δp/p = 0.1 %
Angular resolution : 0.3 mrad

- An outstanding team of physicists (Friedmann, Kendal, Taylor)

Despite the perspicacious remark of Panovsky in August 1968, **it took many years** before the Quark Parton Model emerges and becomes widely accepted (≈ 1974). The fashionable theories were based on :

- Bootstrap theories, nuclear democraty (all in all)
- Resonances models
- Regge Theory (trajectories)
- VDM (successful in photoproduction))
- …

In a visit to SLAC in summer 1968 Feynman immediately saw in partons an explanation of SLAC data. But **the theory waited for decisive tests**

Evidence for spin ½ of the elementary constituents (1969)

$$\frac{d^2\sigma}{d\Omega\, dE'}(E, E', \theta) = \Gamma\left[\sigma_T(\nu, q^2) + \epsilon\, \sigma_L(\nu, q^2)\right]$$

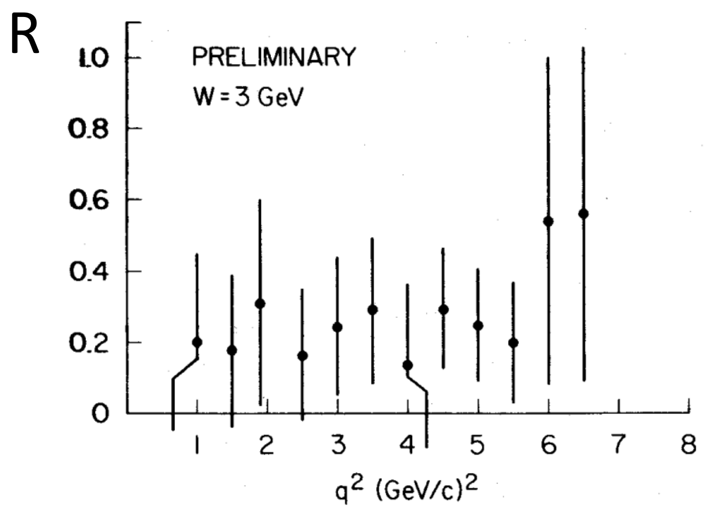
$$R(\nu, q^2) = \sigma_L \,/\, \sigma_T$$

Combining DESY and SLAC data

In Nov. 1968 Callan and Gross showed :

if $\sigma_L \to 0$ as $Q^2 \to \infty$

it would be an elegant indication that the em current is made only out of spin ½ constituents



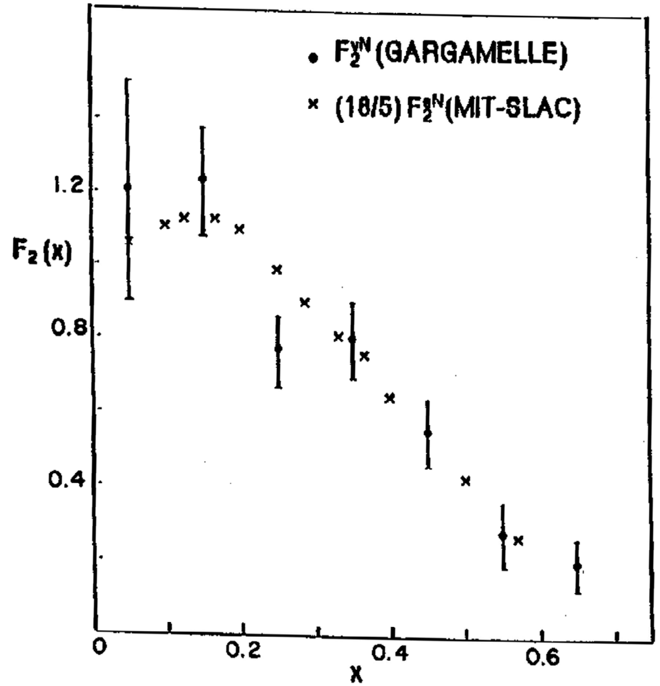
15. R against q^2 for fixed W = 3 GeV. Most of the data points have been obtained by interpolating between the measured data.

Stringent tests of the QPM from neutrino DIS (Gargamelle,CERN,1972)

1) **Fractional charge** of constituents
On isoscalar target, QPM preciction :

$$\frac{\frac{1}{2}\int[F_2^{ep}(x)+F_2^{en}(x)]\,dx}{\frac{1}{2}\int[F_2^{\nu p}(x)+F_2^{\nu n}(x)]\,dx}=\frac{e_u^2+e_d^2}{2}=\frac{5}{18}$$

(neglecting strange quarks)



2) **Linearity of the neutrino (antineutrino) total cross sections** as a function of beam energy predicted for point like constituents.

3) **Gross-Llewellyn Smith Sum Rule**

$\int F_3^{\nu N}(x)\,dx$ = (number of quarks) - (number of antiquarks) $= 3.2 \pm 0.6$

An intriguing result : quarks and antiquarks carry only half of the nucleon's momentum

$$\frac{1}{2}\int [F_2^{\nu p}(x) + F_2^{\nu n}(x)]\, dx$$

$$= \int x\, [u_p(x) + \bar{u}_p(x) + d_p(x) + \bar{d}_p(x) + s_p(x) + \bar{s}_p(x)]\, dx$$

$$= 0.49 \pm 0.07$$

[Gargamelle 1972]

(1968-1973) QPM emerges against strong oppositions, but still many vital problems

- Why the partons are free during the collisions?
- What are the partons which carry 50% of the momentum and do not have em or weak interactions ?
- Why no free quarks ?

Paradoxes solved by QCD (1973) which is a theory whch has drastically improved the QPM.

QPM has appeared as a zero approx of pert. QCD

First observation in 1974 of the clear pattern of scaling violation at low x and at large x with increasing Q^2.

Beam : muon at FNAL
Energy : 150 GeV and 56 GeV
Detector : iron toroid
Target : iron

Rise at low x
Fall at large x

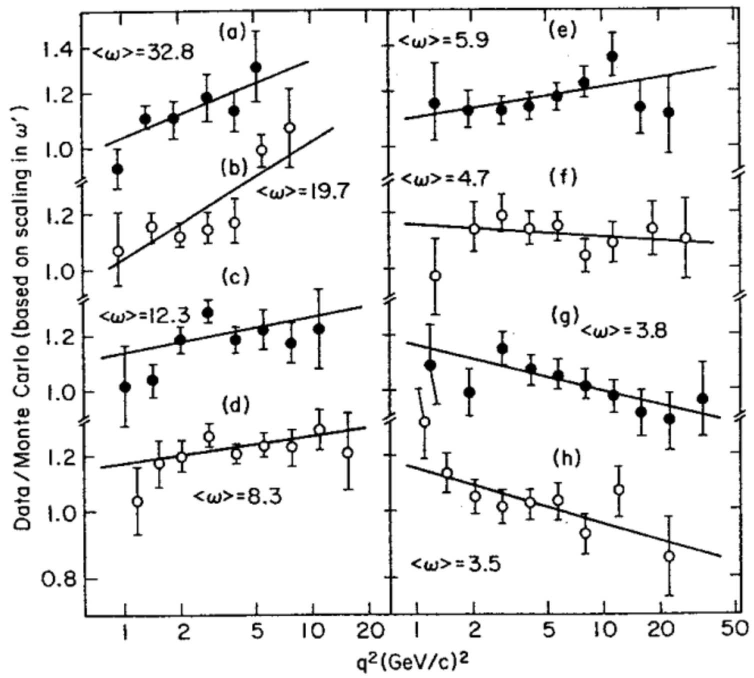


FIG. 1. Ratio of observed to simulated event rate versus q^2 for eight ranges of ω. Widths of these ranges and parameters of the straight-line fits are detailed in Table I. Errors are statistical.

A striking prediction of QCD due to radiation of gluons. Logarithmic violation predicted particurlary large at small x.

In 1978 a DIS experiment also crucial in support of the EW theory

Parity non-conservation in DIS of longitudinally polarised electrons (Prescott et al., SLAC,1978)

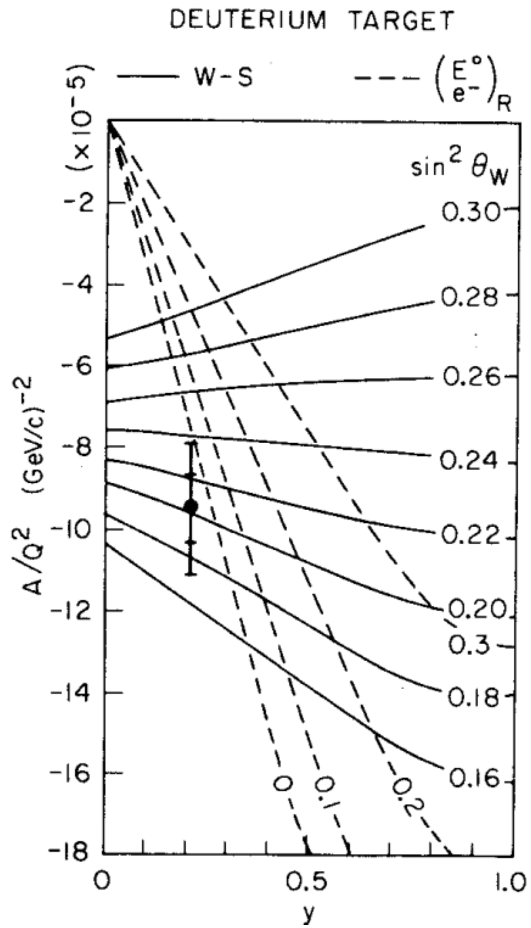
$$\vec{e} + d \longrightarrow e + X$$

20 GeV polarised beam from GaAs source.
Polarisation reversed 120 times per second.

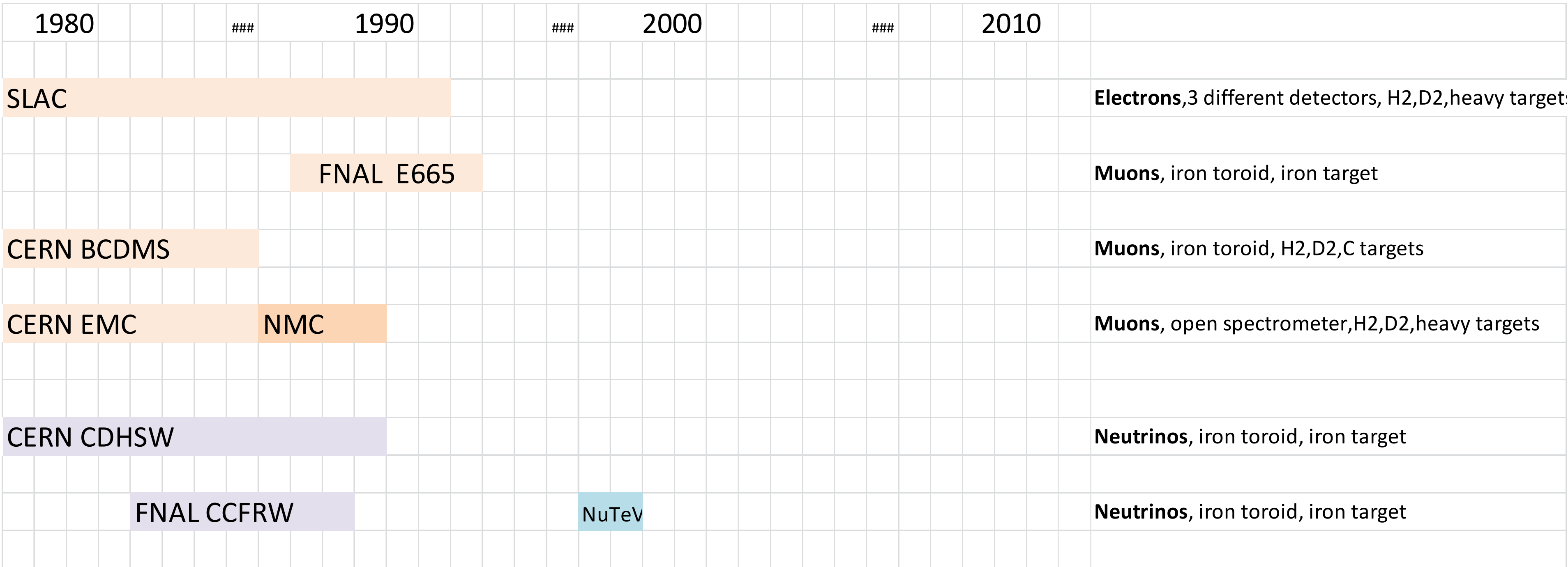
$$A = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$$

$$A\,/\,Q^2 = (-9.5 \pm 1.6)\,10^{-5}\,(GeV/c)^{-2}$$

Modest precision on $\sin^2\theta_W$ but this SLAC experiment was crucial in support of the EW theory in 1978

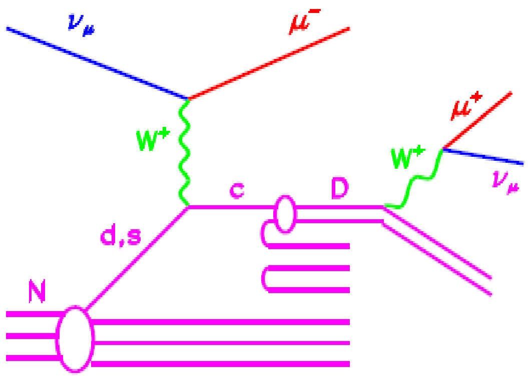


In the eighties, higher energy muon and neutrino DIS experiments at FNAL and CERN have been central to prove the quantitative correctness of perturbative QCD resting on DGLAP evolution equation, but the **high accuracy has been painful to be obtained**.



High statistic Fixed Target experiments in the eighties

Direct measurement of strange density in the nucleon :



CDHS (1982) ,CCFR(1995) and NuTeV (2001)
+ CHORUS and NOMAD at CERN)

$$\kappa = \int_0^1 \mathrm{d}x\, 2xs(x) \Big/ \int_0^1 \mathrm{d}x\, (x\bar{u}(x) + x\bar{d}(x)) \approx 0.5$$

at present, full x distributions in PDFs fits

Surprising flavour asymmetry of the sea

$$\int_0^1 (\bar{u}(x) - \bar{d}(x))dx = -0.147 \pm 0.039$$

(NMC (1994) from $F_2^p - F_2^n$,
also from DY and W production)

A few unexpected results :

Spin crisis first observed by EMC (1982) → next slides

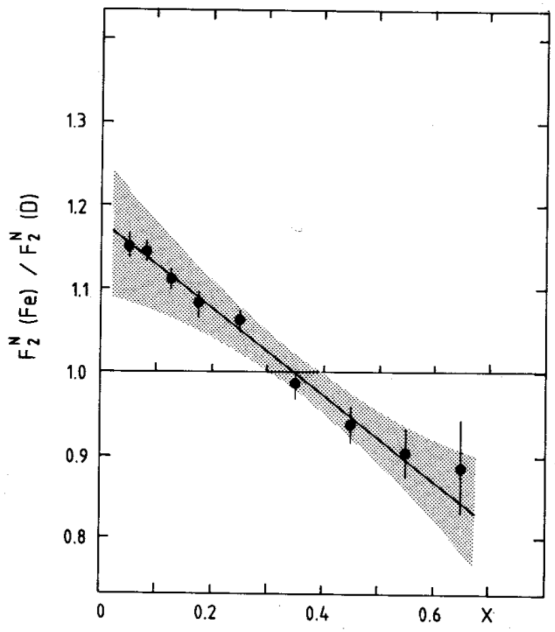
Nuclear effects first observed by EMC (1988) → next slides

EMC effect (1982)

Expected that parton distributions in a nucleon imbedded in a nucleus would only differ from distributions in a free nucleon:
-at large x (well known Fermi motion, x can be greater than 1)
-at very low Q^2 (shadowing)

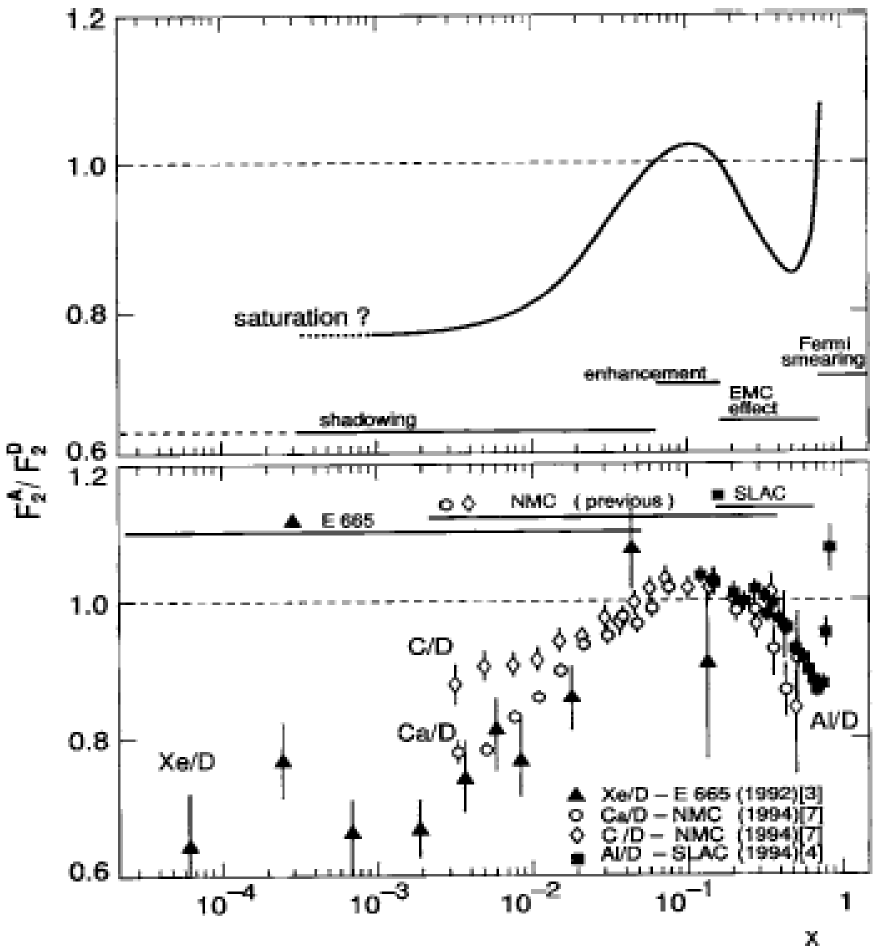
A large negative effect at $x \sim 0.6$ and very short distantce (high Q^2) was a big surprise.

Partons have lower $<x>$ in a nucleus!!!!



Discovered by EMC

EMC effect : many models but not yet fully understood



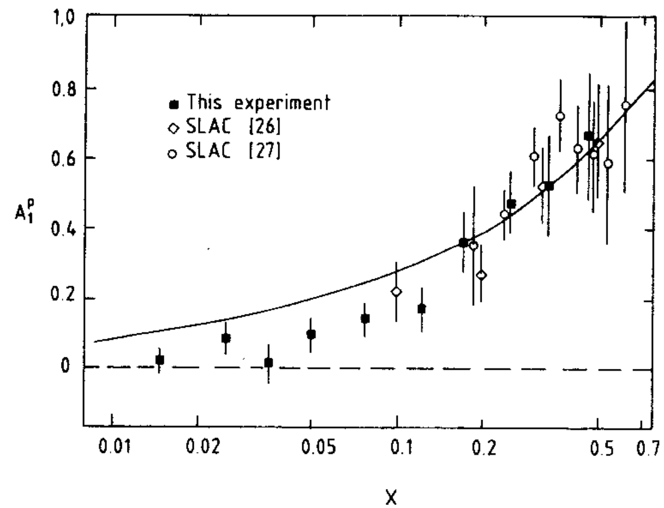
Important message :
Caution when using heavy nuclei data to extract PDFs of free nucleons!
Model dependance !!
Also true for the deuterium !!!

Spin crisis in 1988

Measure asymmetries from longitudinally polarised beams

on polarised targets :
$$A = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}}$$

Combining asymmetries measured at
SLAC (Yale SLAC) and CERN (EMC) :
High x data from 23 GeV polarised
electron beams (SLAC) and
Low x data from 100 , 120 and 200 GeV
muon beams (CERN)



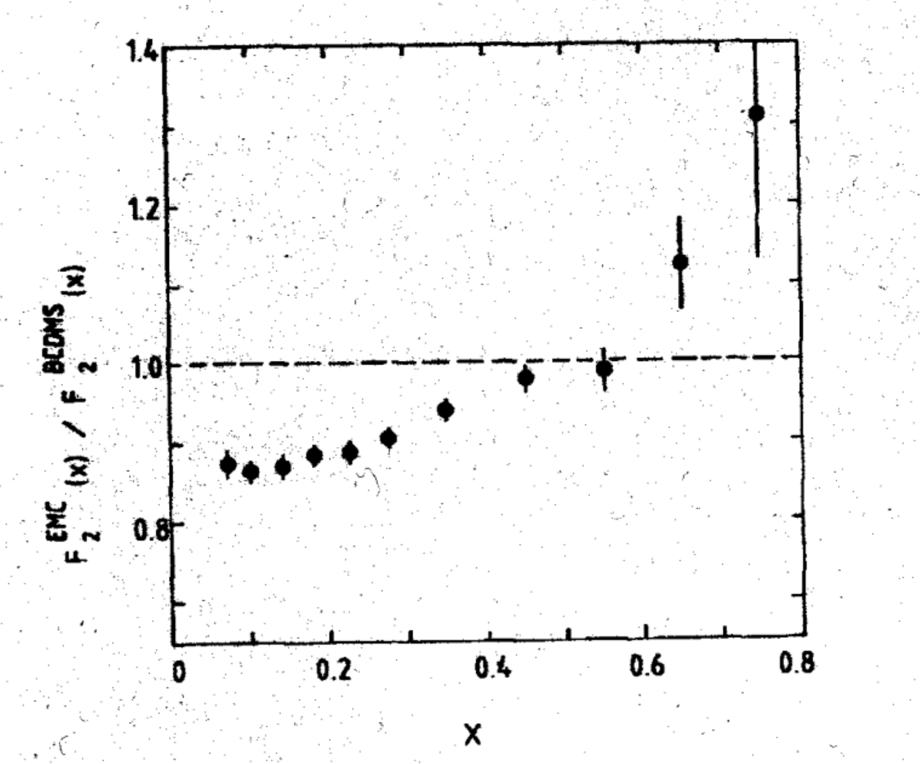
Extract **ΔΣ** the fraction of the proton spin carried by the quarks

ΔΣ = 12 ± 9 ± 14 % , Compatible with zero !!!

High statistic FT experiments : SF measurements

With the high statistics the systematics became by far the largest source of uncertainties for SF measurement.

Many glaring discrepancies have generated heavy discussions for many years…



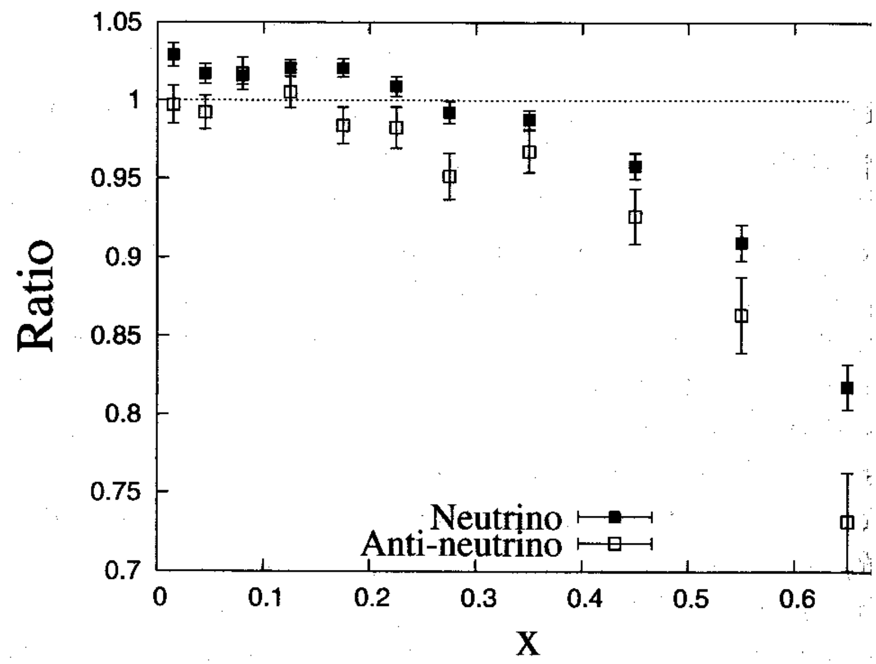
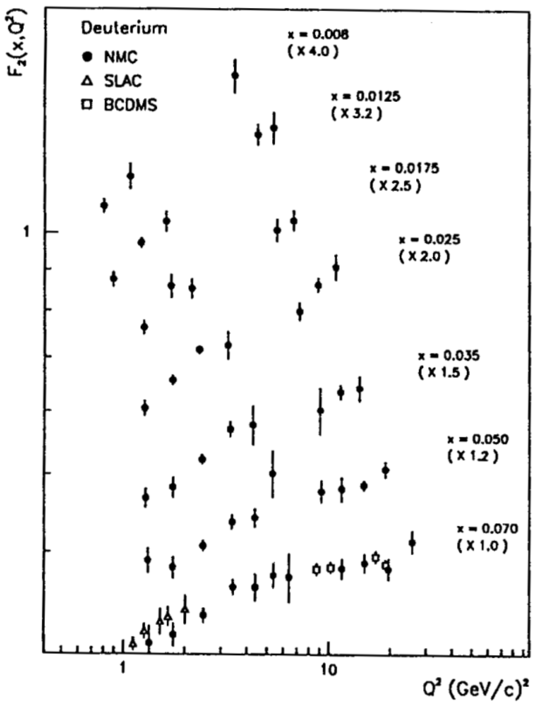


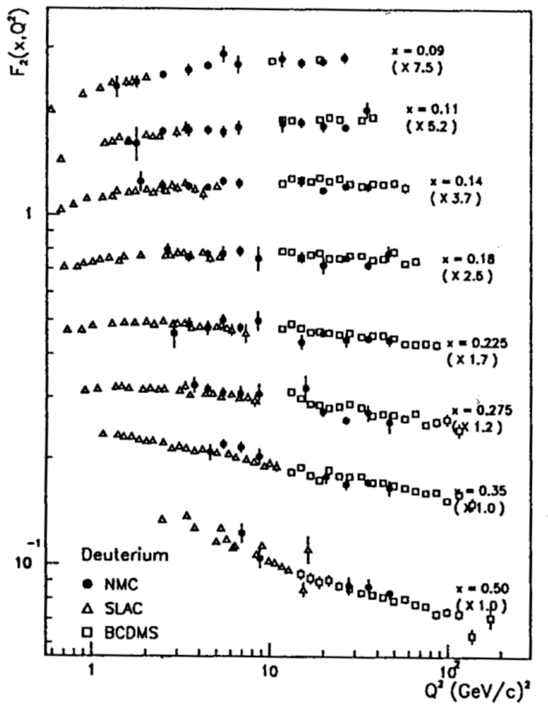
FIG. 12. Ratio of CCFR to NuTeV cross sections as a funct

High stat.FT experiments in the eighties, SF measurements : 30 years after (personal view)

Electron and muon beams

Almost* perfect agreement between SLAC, BCDMS and NMC (which has understood EMC pb and superseded EMC)



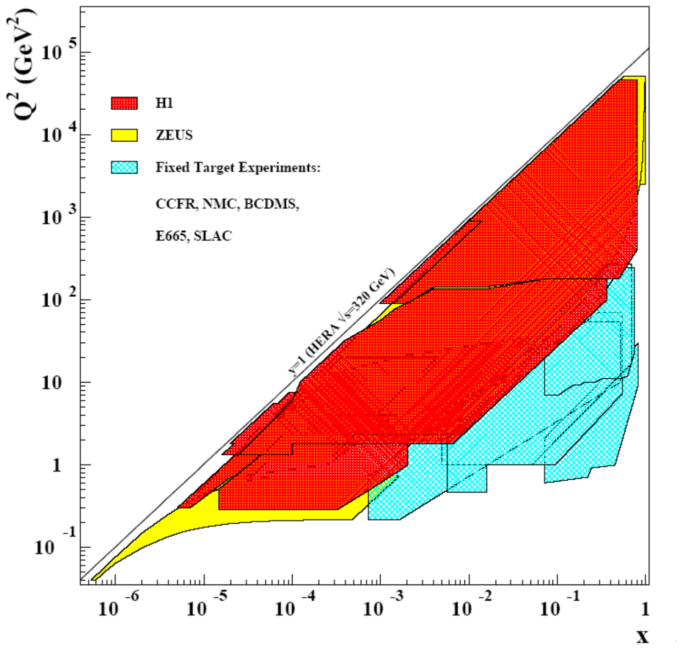


* Still likely that one correlated systematics of BCDMS is underevaluated

Neutrino beams

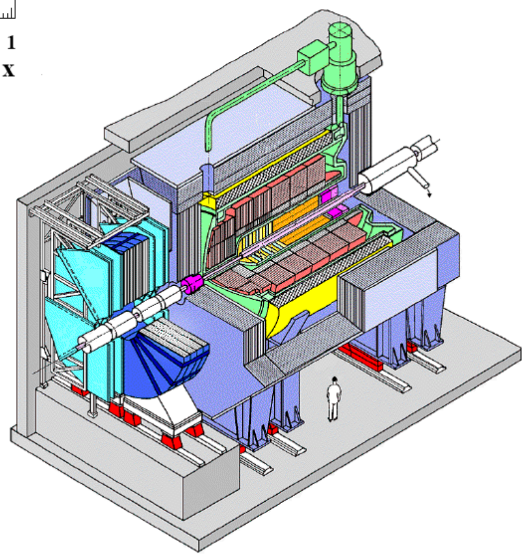
NuTeV on iron has understood CCFR pb and has superseded CCFR

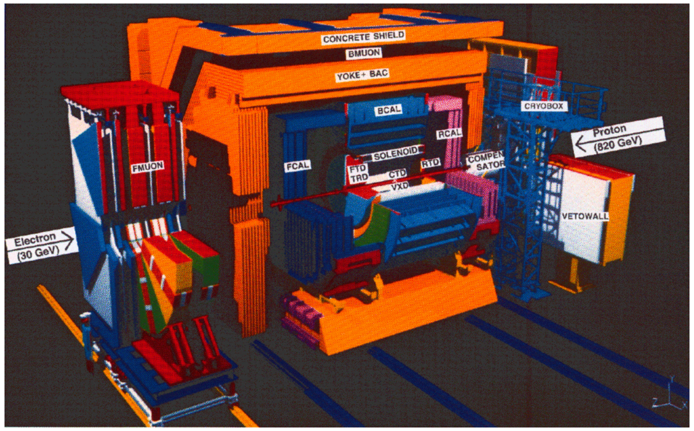
In 1992 HERA has opened up a new kinematic domain



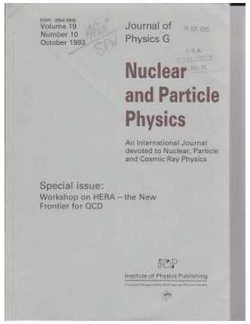
The physics interest in the early proposals of HERA was focused on large Q^2.
H1 and ZEUS detectors were not fully optimised for x < 10-2
or very forward DIS physics

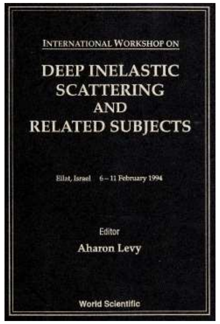
The discoveries were at small x

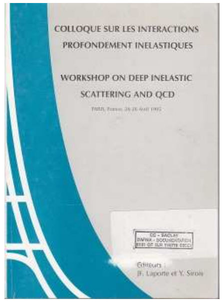


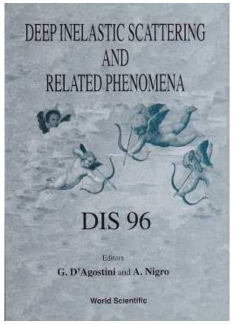


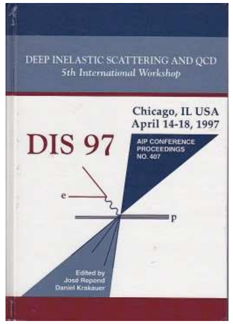
HERA Physics well documented in the 19 DIS Workshops since 1993 !!

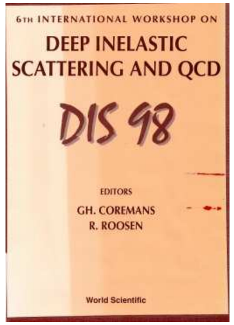


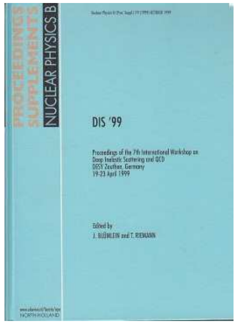


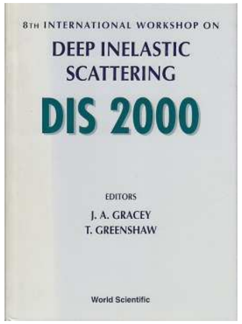


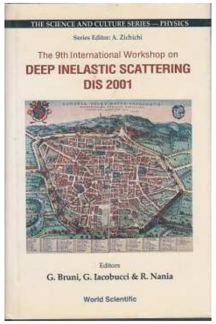


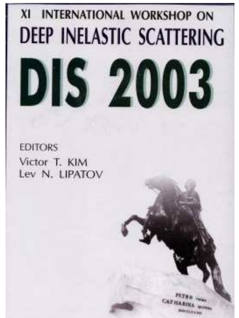


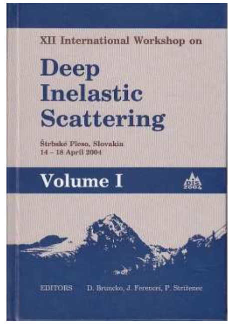


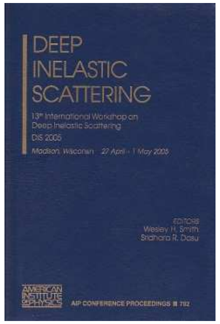


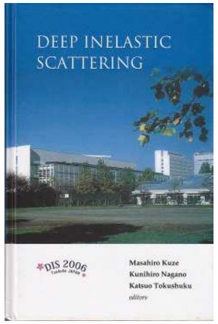


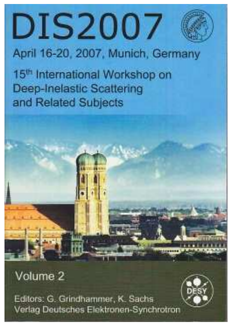












Early HERA DIS discovery. Lumi = 22.5 nb^{-1}. Rise of F_2 as $x \to 0$

Impressive and unexpected rise of F_2 as $x \to 0$

Rise of the sea quark and gluon densities.

The rise increases with Q^2

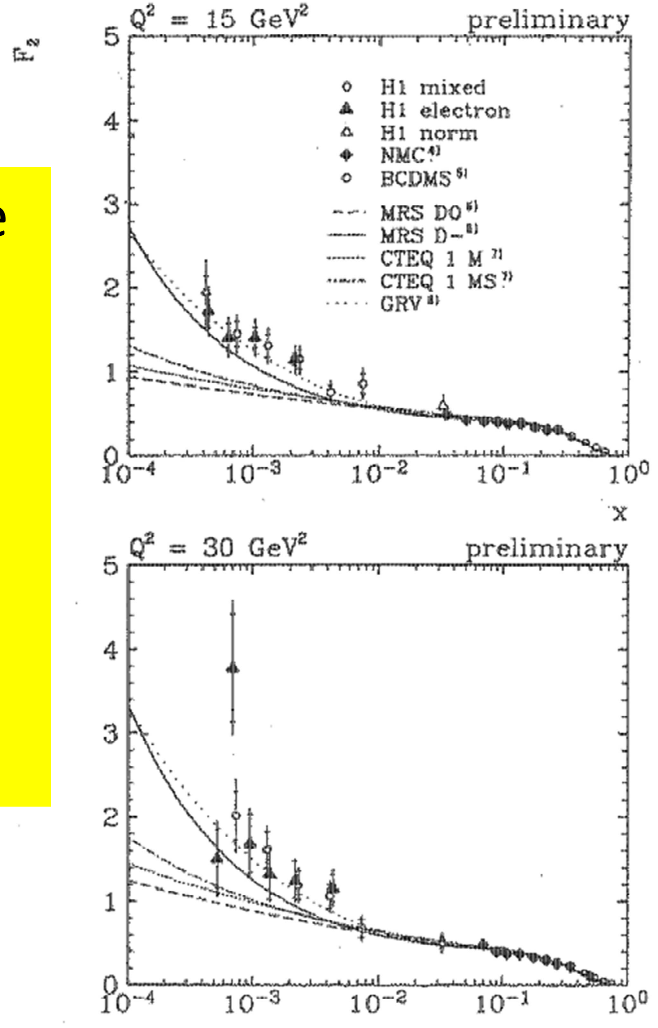


FIGURE 1

H1 preliminary F_2 compared to previous experimental results [4,5] and various parton parametrisations [6,7,8]

March 1993, Durham workshop and Moriond Conf.

Early HERA DIS discoveries , Rise of F_2 as $x \rightarrow 0$

Why was it a surprise ?

Large spread in the theoretical predictions.
Extrapolations from pre-HERA data indicated a « flattish » F_2 ,
that's also what came out from Regge-like arguments :

$$F_2 \sim x^{-\epsilon} \quad \text{as} \quad x \to 0 \quad \text{where} \quad \epsilon \approx 0.08$$

Was however predicted by the fathers of QCD (1974) but forgotten since. The gluon should rise at low x for Q^2 high enough and the rise should increase with Q^2.

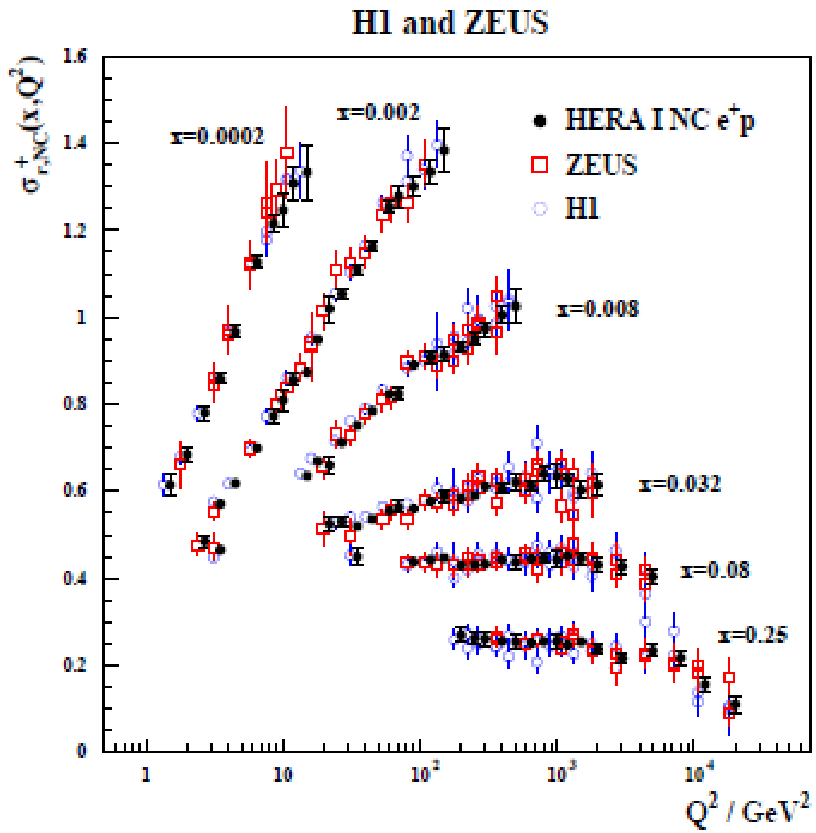
Important feature: the **Q^2 evolution is perfectly described by DGLAP** evolution equations down to $x \approx 10^{-4}$ and $Q^2 \approx 2\ \text{GeV}^2$

SF : where we are now

For ultimate precisions, an important step in the recent history of DIS :

Combinig H1 and ZEUS data with different detection techniques reduce systematics !!

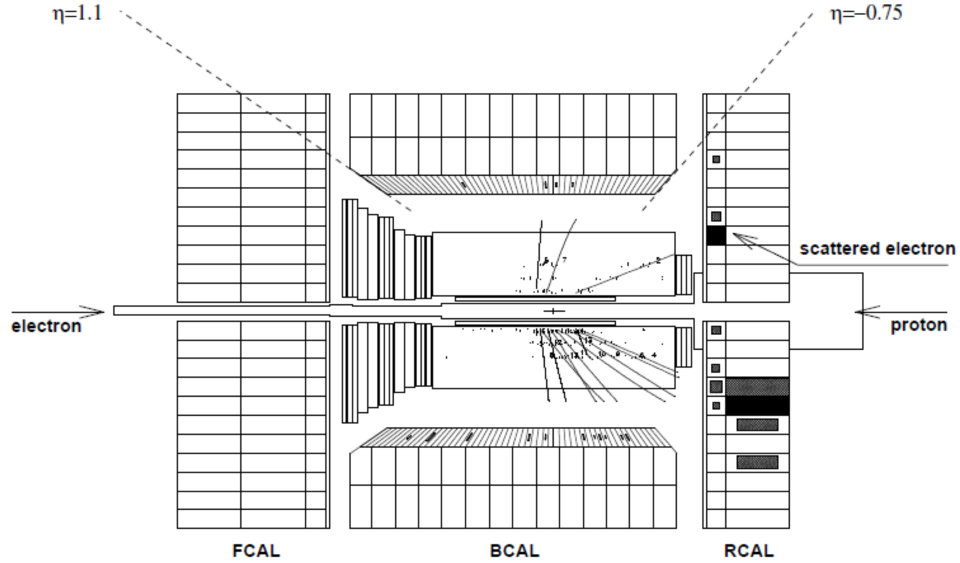
At present , active combination on progress on ~ all HERA processes.

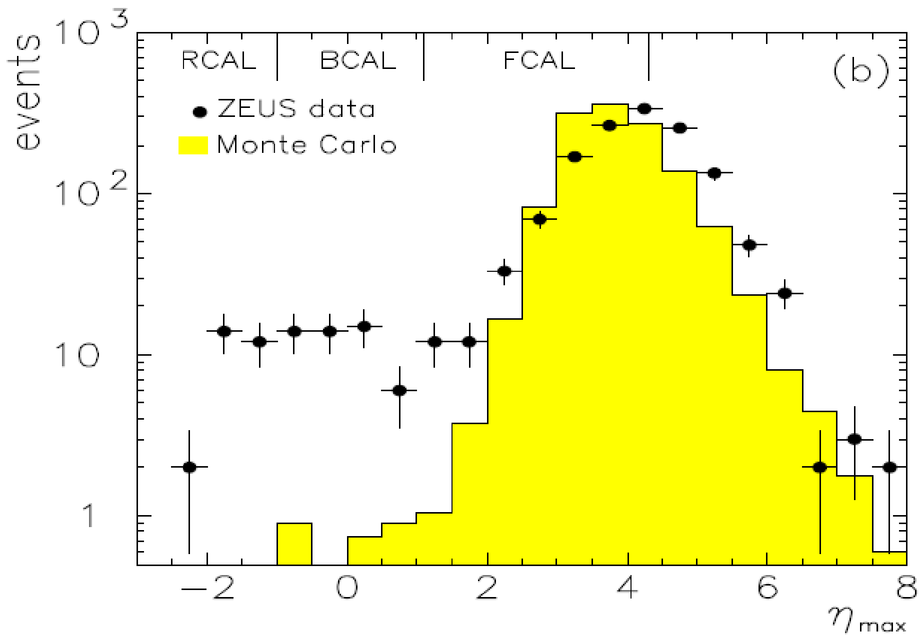


Early HERA discovery :
hard diffraction

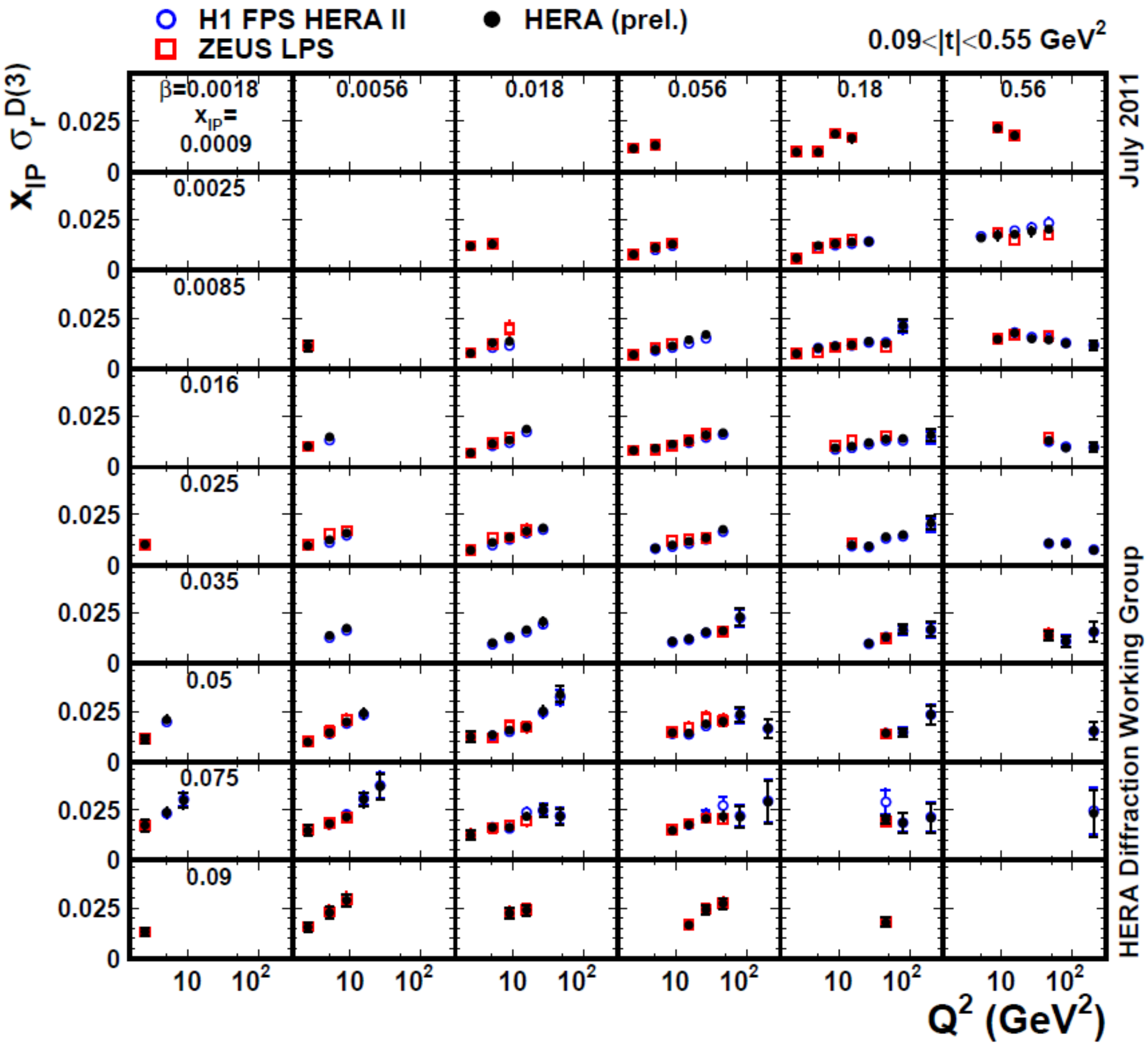
10% of NC DIS events have gap between forward proton and central activity.

The fraction of diffractive to standard DIS events is constant vs energy W.





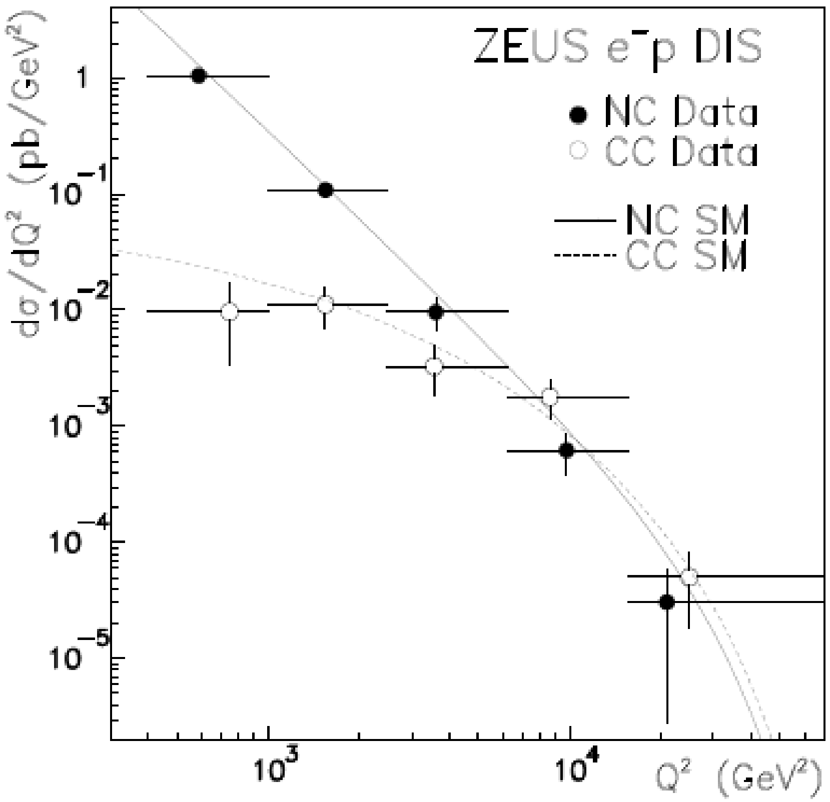
Hard diffraction : an example of where we are now



Beautiful data.
Physics not yet fully clarified

Early years from HERA

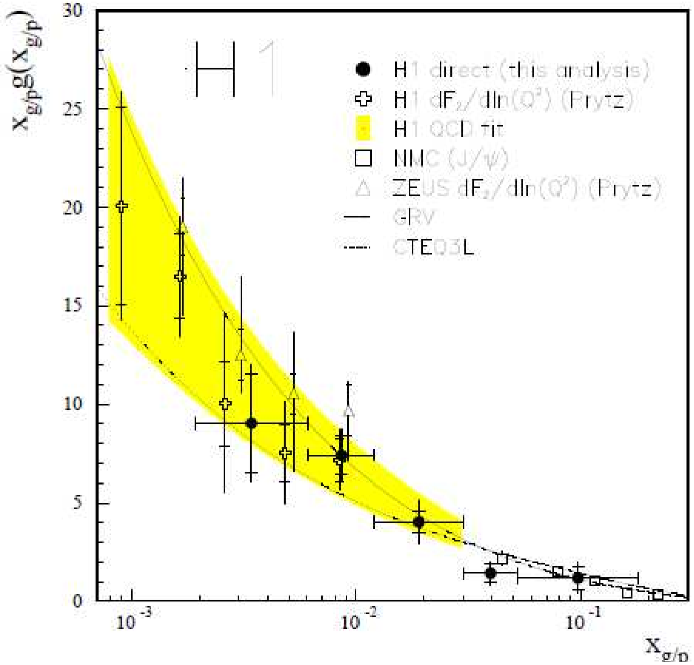
The most graphic and simple demonstration of EW unification (1995)

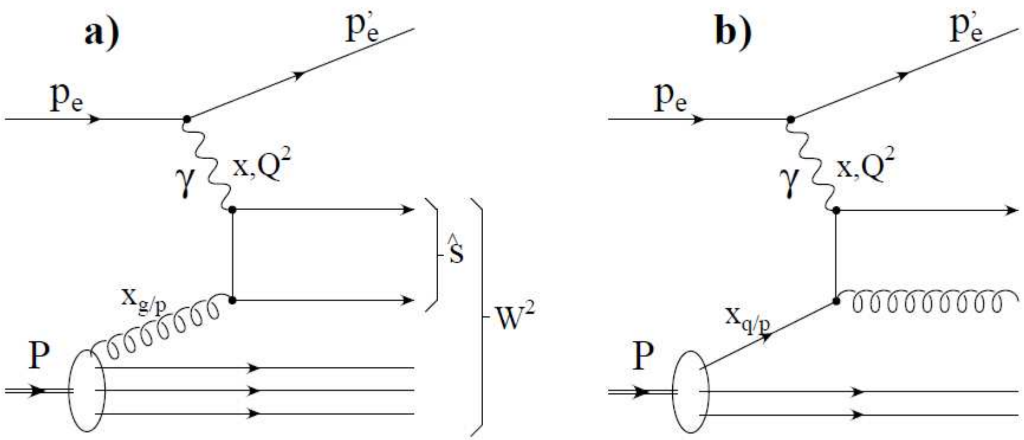


Early years from HERA

One of the many triumphs of QCD
and of the DGLAP evolution equations :

Gluon density from scaling violation is identical to the gluon density from photogluon fusion jets cross sections

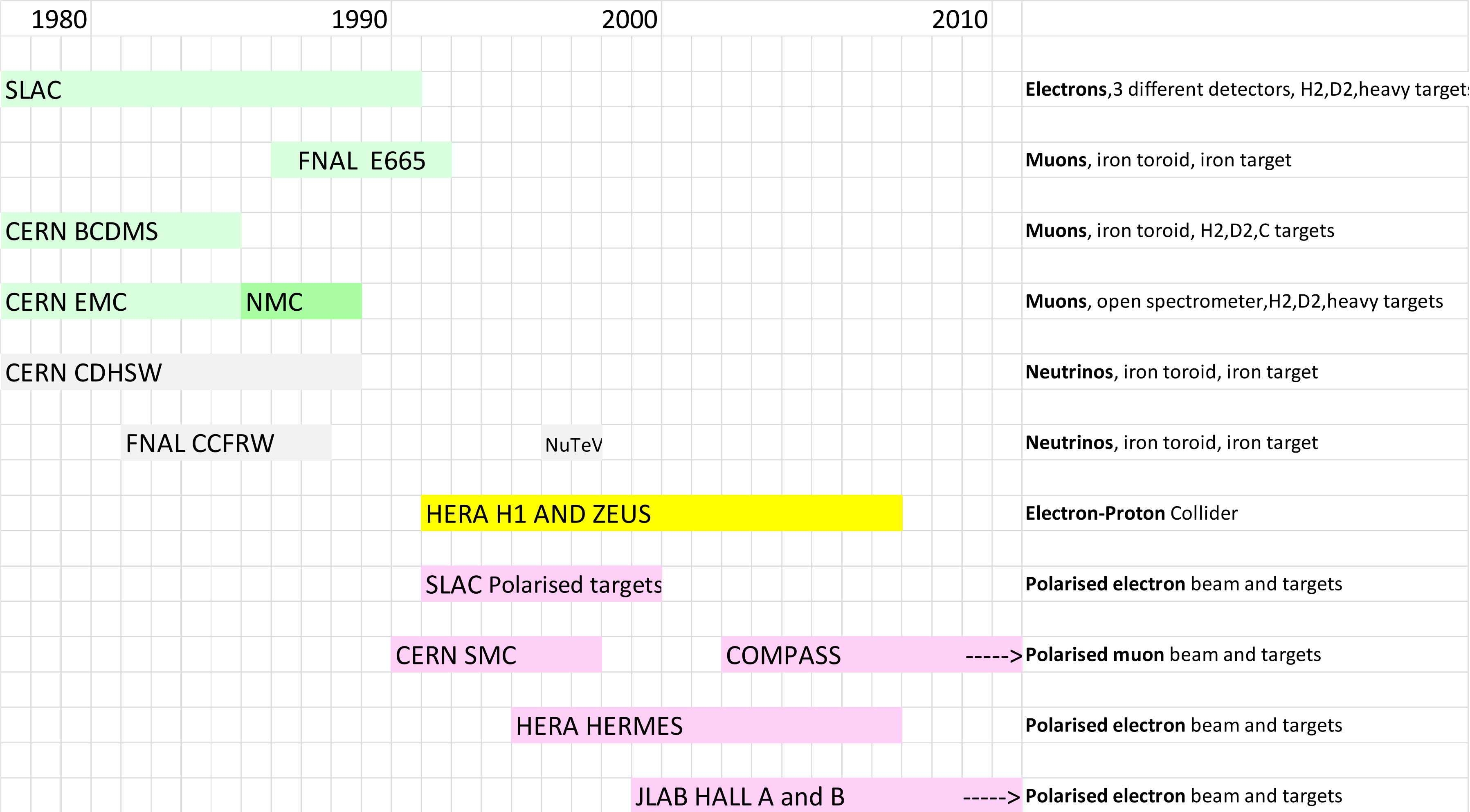




After the early discoveries, since 20 years, a permanent fight towards high precision (**fight against systematics)** and development of **new domains of DIS** physics beyond the simple measurement of inclusive cross sections.

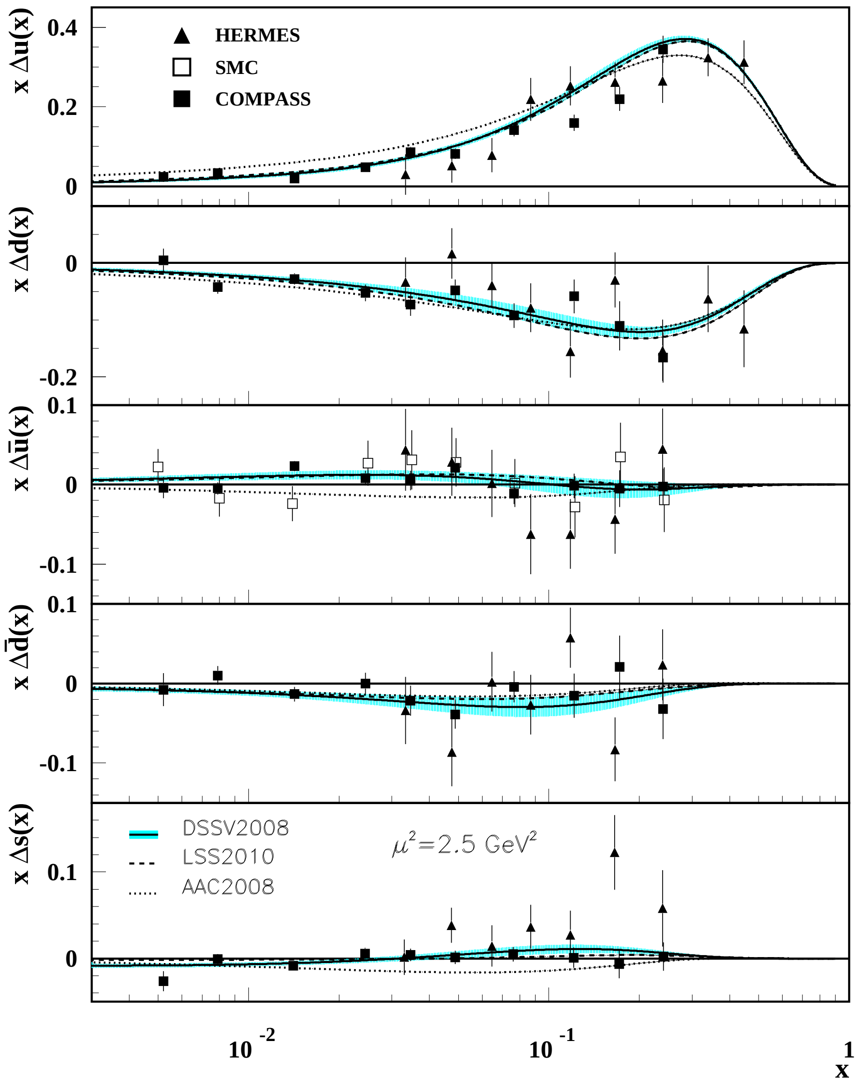
- Physics at low x : BFKL → CGC /forward jets
- Diffraction/ Production of VMs / DVCS/ ep vs pp/
- Jet physics / gluon density /α_s determination/NNLO ?
- Direct measurement of HQ densities : $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$
- QCD fits, PDFs extractions (only DIS vs global), predictions vs measurements at Tevatron and LHC
- Searches

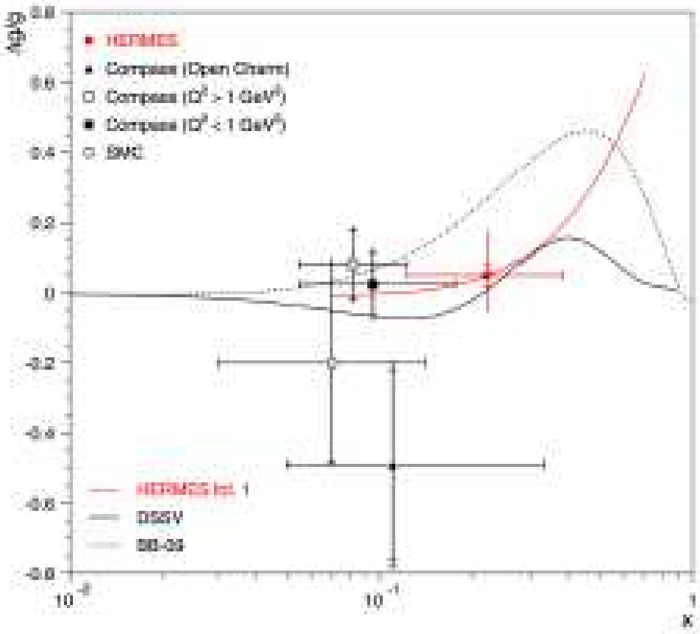
In the last 20 years DIS was not restricted to HERA physics



+ input from hadron-hadron collisions: TeVatron RHIC LHC

Impressive theoretical and experimental work on origin of proton helicity





Where the proton spin comes from ?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Answer in GPDs ?

→ Hermes, JLab, Compass

CONCLUSIONS : 45 YEARS OF TREMENDOUS PROGRESS

DIS processes have been crucial for establishing the **dynamical reality of quarks** and the impressive quantitative **correctness of perturbative QCD.**

DIS processes are central for the **extraction of PDFs** and calculation of all relevant hadronic hard processes.

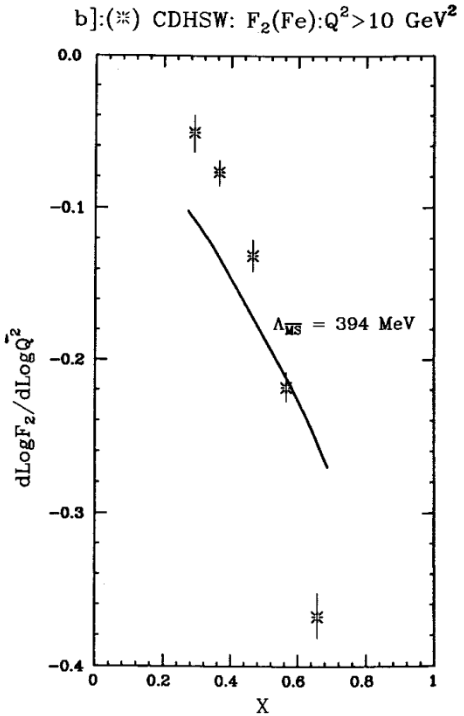
Open problems (a personal view) :

- Genuine uncertainties of PDFs (for searches at LHC ?)
- α_s determination
- Understanding of physics at small x and diffraction, unified description ?
- Proton helicity

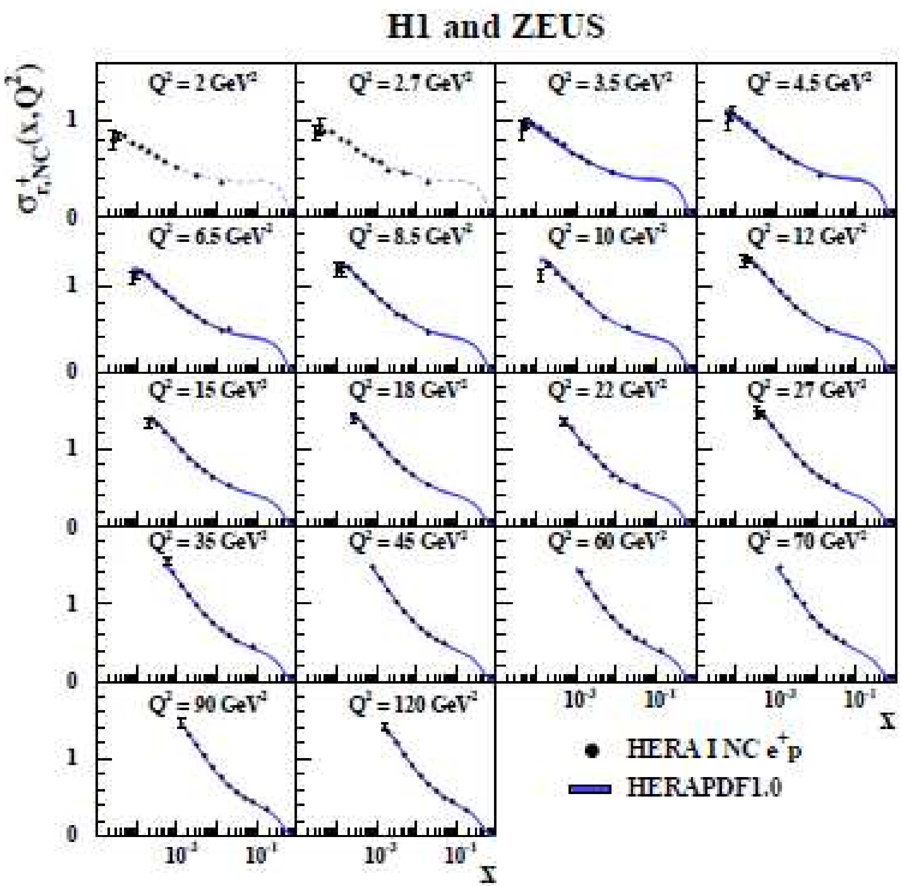
EXTRA

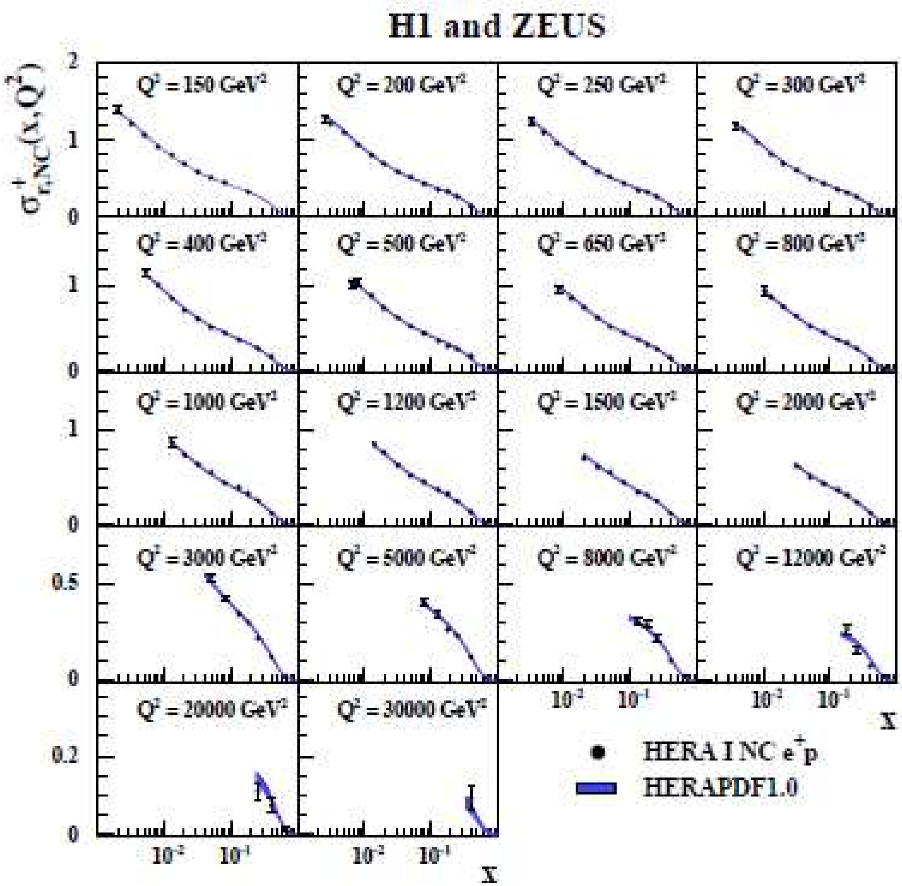
High statistic FT experiments in the eighties

With the high statistics the systematics became by far the largest source of uncertainties for SF measurement.



SF F2 : where we are now (not the last word !)





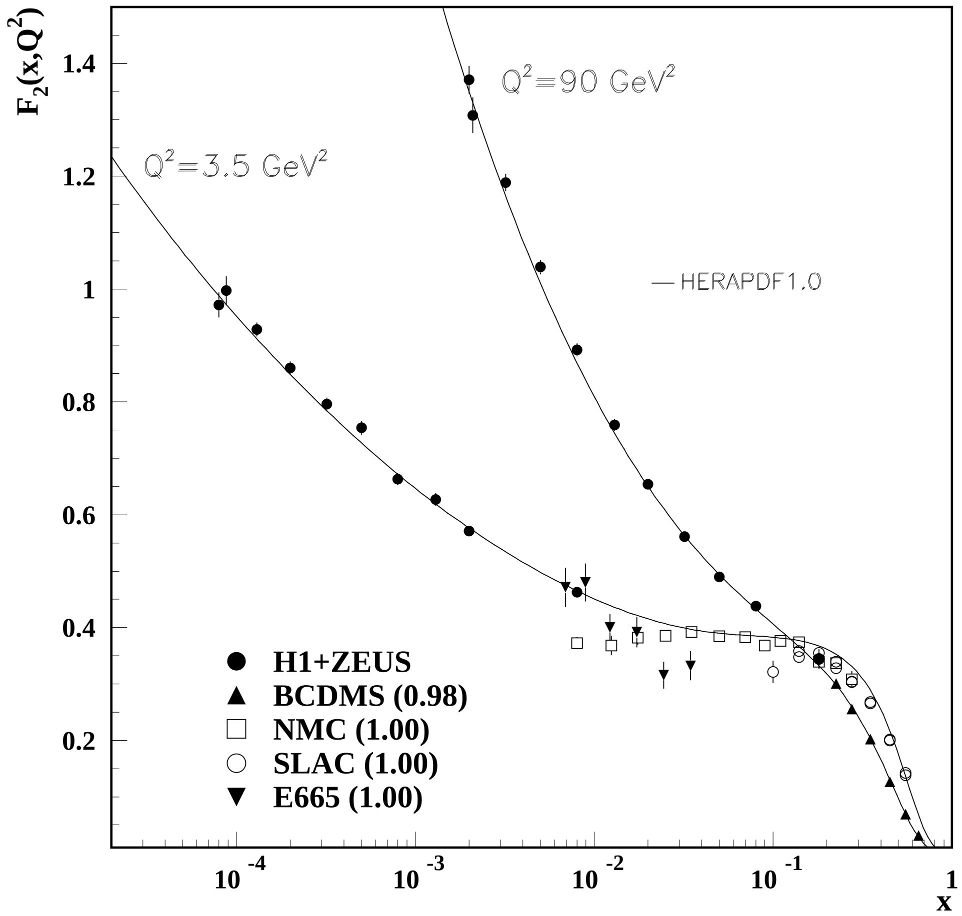
Early HERA DIS discoveries , Rise of F2 as $x \rightarrow 0$

Why was it a sur prise ?
Large spread in the theoretical predictions.
Extrapolations from pre-HERA data indicated a « flattish » F2 , that's also what came out from Regge-like arguments :
$F2 \sim x^{-\varepsilon}$ as $x \rightarrow 0$ where $\varepsilon \approx 0.08$

Was however predicted by the fathers of QCD (1974) but forgotten since. The gluon should rise at low x for Q2 high enough and the rise should increase with Q2.

The most dramatic of the QCD foundational papers that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later.
Frank Wilczek (QCD, Foundational papers)

Early HERA DIS discoveries , Rise of F2 as x → 0



The Q2 evolution is pefectly described by the DGLAP equ.
For Q2 > 2 GeV2 (tbc)

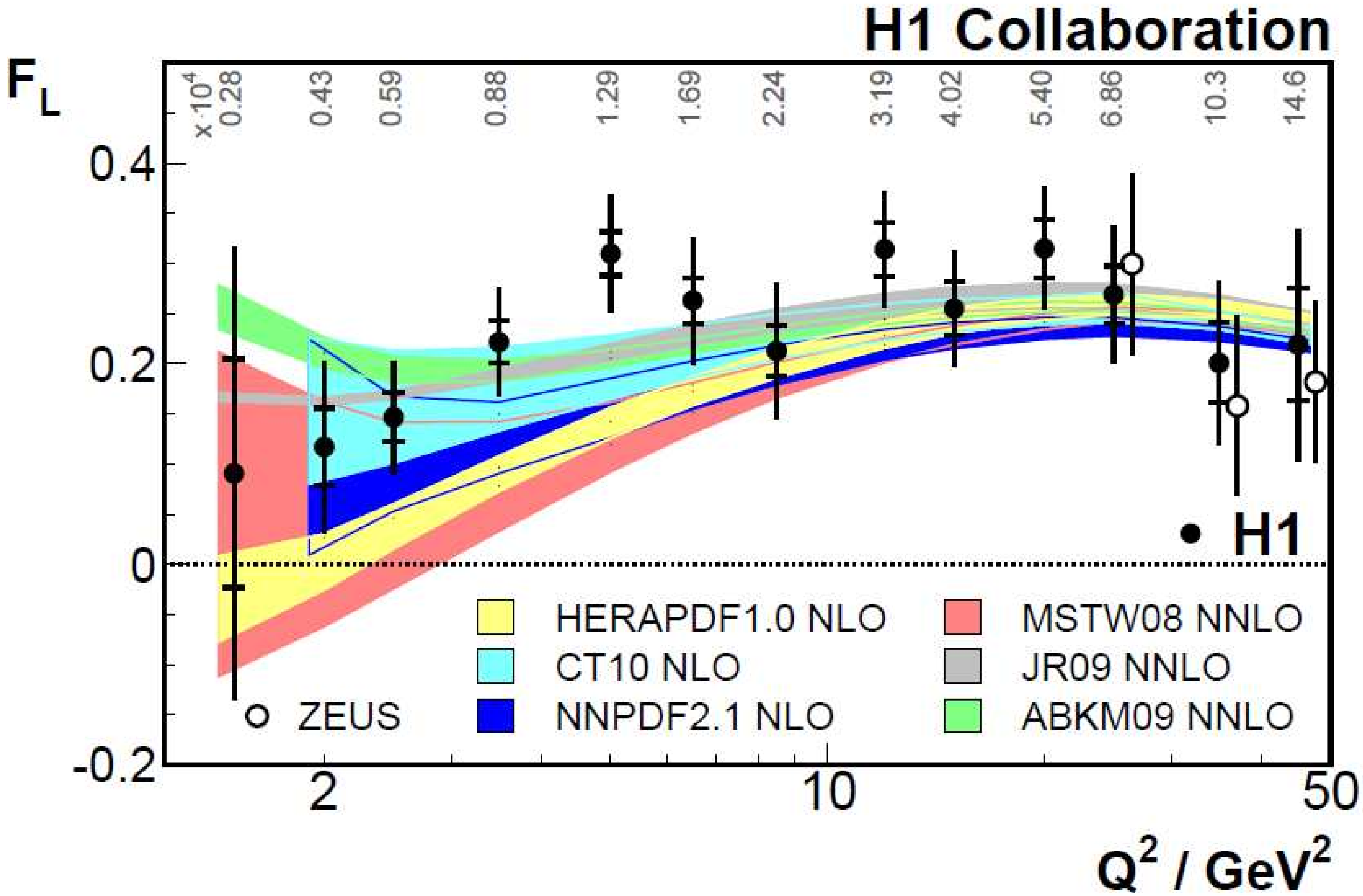
The differential cross section expressed in the usual dimensionless variables described above has the following form:

$$\frac{d^2\sigma^{l(\bar{l})N}}{dxdy} = A\left\{\frac{y^2}{2}2xF_1(x,Q^2) + (1-y)F_2(x,Q^2) + (-)(y-\frac{y^2}{2})xF_3\right\} \qquad (3)$$

where, for $Q^2 \ll M^2_{W,Z}$ (the mass squared of the intermediate vector bosons), $A = \frac{G^2 s}{2\pi}$ for neutrinos and antineutrinos, and $A = \frac{4\pi\alpha^2 s}{Q^4}$ for charged leptons.

SFs : where we are now.

Even F_L has finally been measured with a meaningful precision



It has taken 30 years to check the QCD behaviour of F_L
(G.Altarelli, DIS 2009)

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GPDs describe correlations between the momentum and the spatial distributions of quarks.

Four new distributions = "GPDs"

helicity conserving $\rightarrow$ $H(x,\xi,t), E(x,\xi,t)$
helicity flip $\rightarrow$ $\tilde{H}(x,\xi,t), \tilde{E}(x,\xi,t)$

"Femto-photography" of the proton

N.C.R. Makins, Workshop on QCD, Washington, DC, Dec 15-16, 2006

Ji sum rule:

$$J^q = \frac{1}{2}\int_{-1}^{1} x\,dx\,[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

$$J^q = \frac{1}{2}\Delta\Sigma + L^q$$

$\rightarrow$ ***model-independent* access to *L* !**

First data from HERMES and JLAB