DIS Experimental Review
PPP-II Lecture 4 (FS 2012)

Michael Dittmar (ETH-Zürich/CMS)
13.3.2012

- What we (do not?) know today
  (Proton PDF's, Quarks, Leptons and their Interactions).
- Scattering experiments: from Rutherford to Hofstadter et al to SLAC (DIS) and HERA (DIS)
  (and LHC... $\rightarrow$ more details in a few weeks from now).
- Reminder: experimental observables and the theoretical DIS picture.
- The most important experimental ep DIS scattering results.

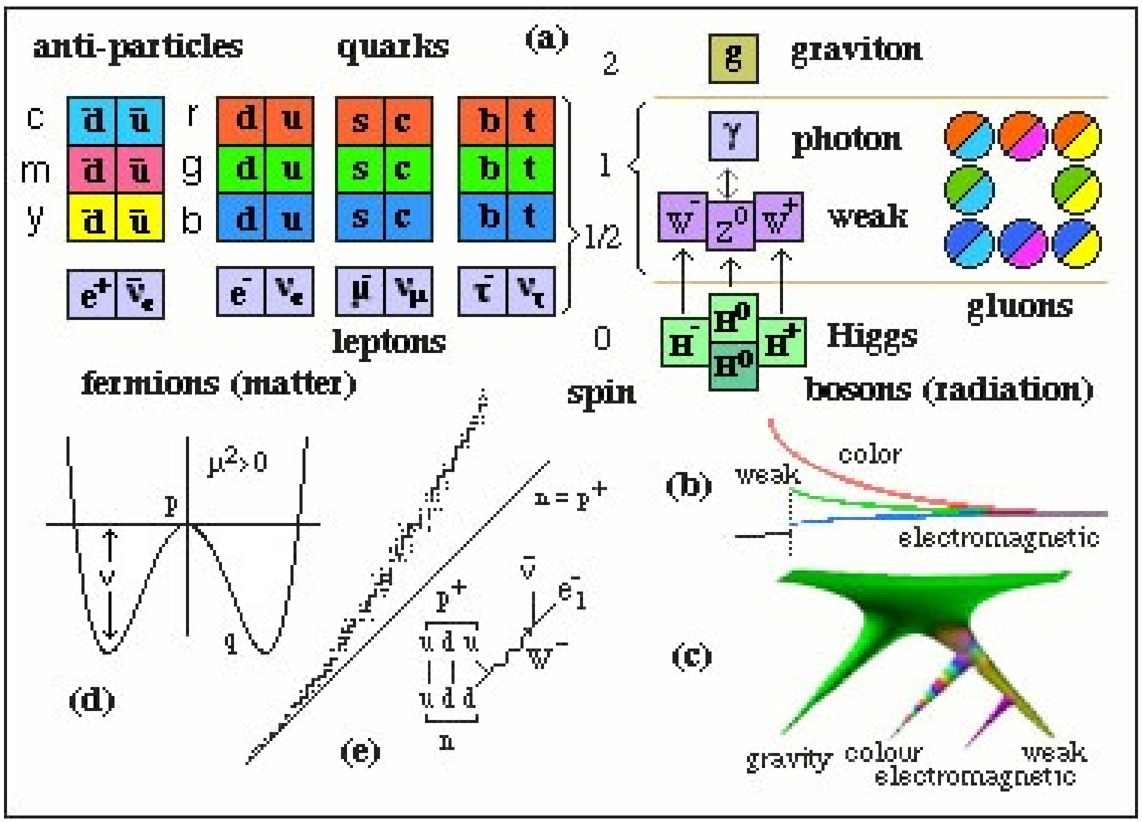
What we (do not?) know today (I) (Proton PDF's, Quarks, Leptons and their Interactions).

SM of particle physics (electroweak and QCD):

- Point like spin 1/2 fermions: the "Matter" particles
  6 Quarks and 6 Leptons (http://www.youtube.com/watch?v=TGrDj5vFefQ)

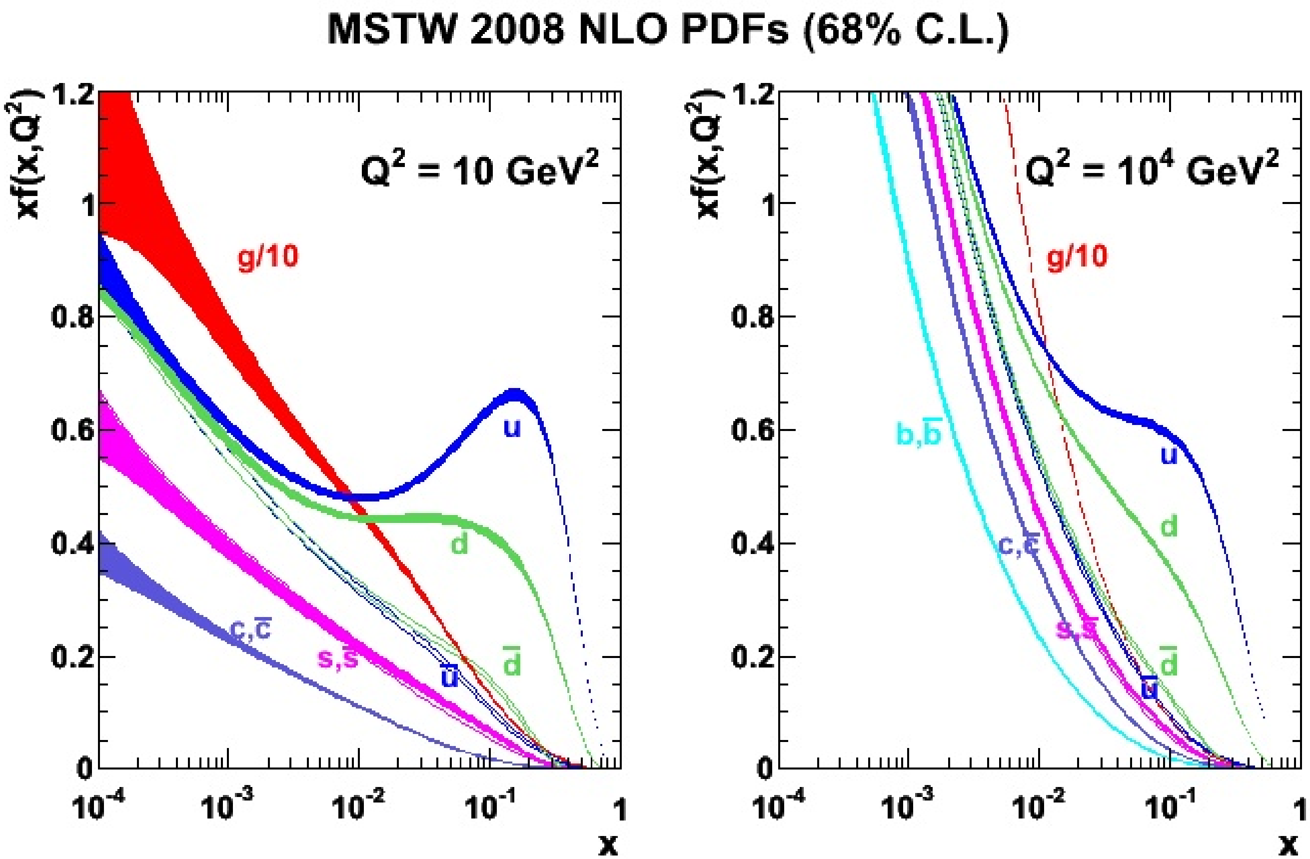
- Interactions described with point like spin 1 bosons (γ, W, Z and gluons)

- Higgs particle (or Higgs field(?)) gives "mass" to W, Z bosons and to the fermions



What we (do not?) know today (II) (Proton PDF's, quarks, ...).

Protons (all hadrons) made of valence quarks (antiquarks) and a sea of gluons, quarks and antiquarks!
The proton structure depends on the Q^2 of the reaction!

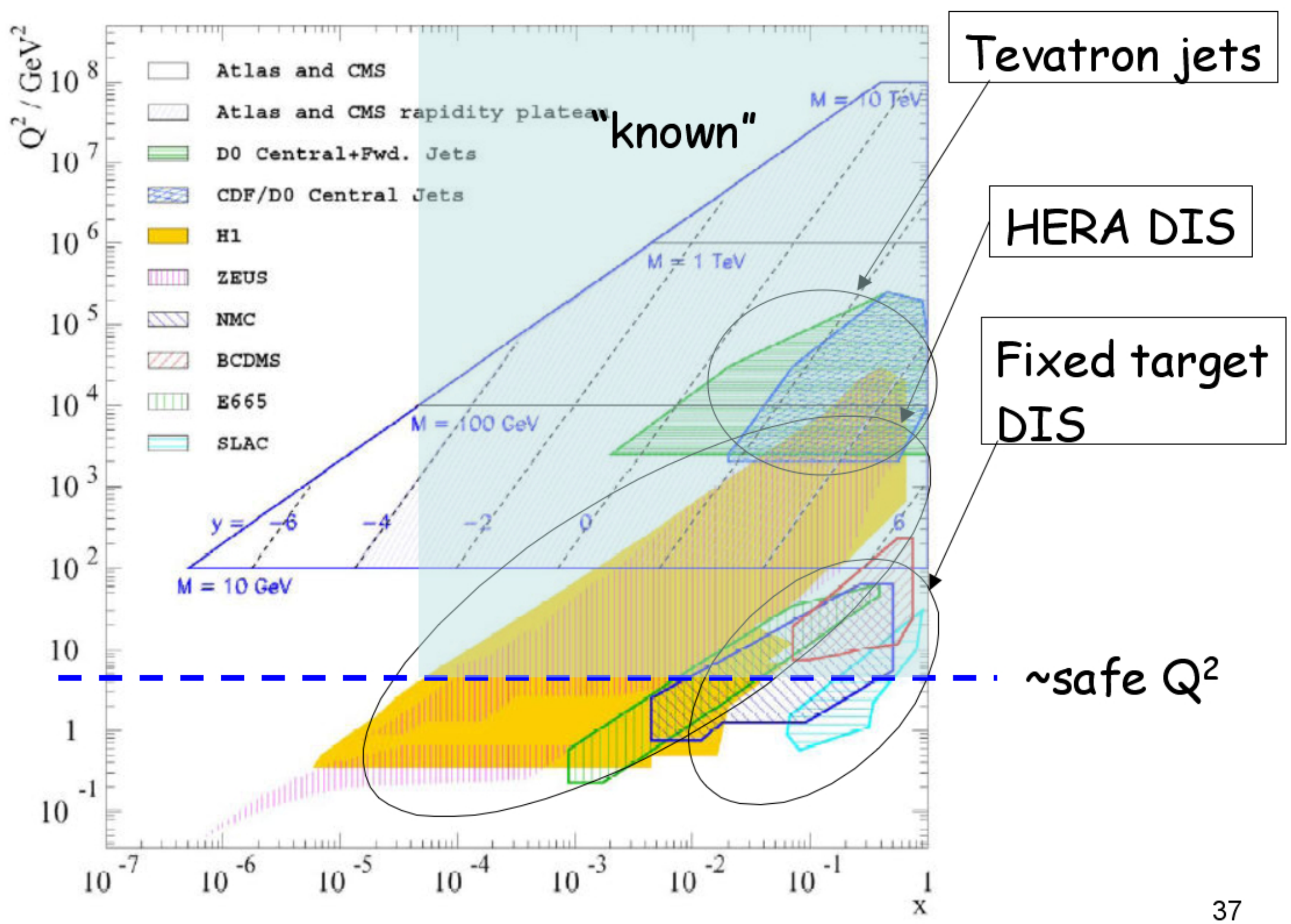


What we (do not?) know today (III) (Proton PDF's, quarks, ...).

Experimental access: the proton structure, Q^2 and new physics(?)

plot from R. Yoshida http://www.ppt2txt.com/r/6b7daa5e/

attention: the "known" x range in the diagram is understood and SM cross sections up to the highest Q^2 can thus be calculated. We are hoping to measure deviations from the "known".



What we (do not?) know today (IVa) (Proton PDF's, quarks, ...).

Experiments: from the Nucleous (Proton) size (188 MeV electrons) to SLAC ep DIS and HERA/LHC

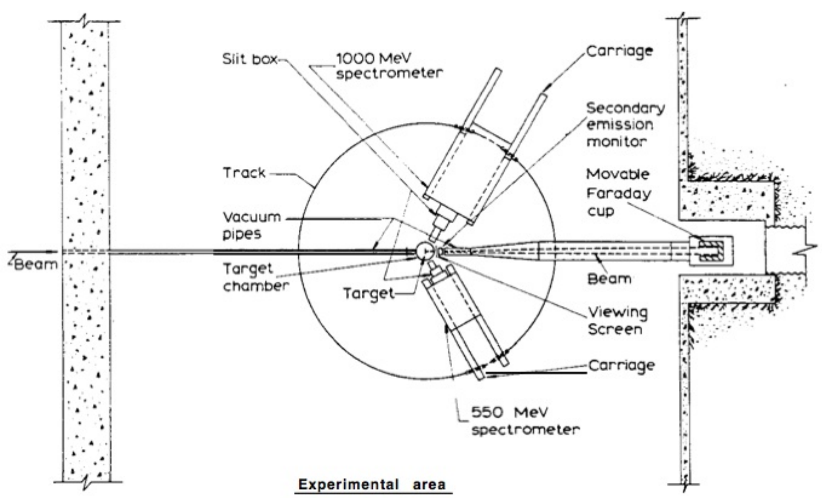


Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

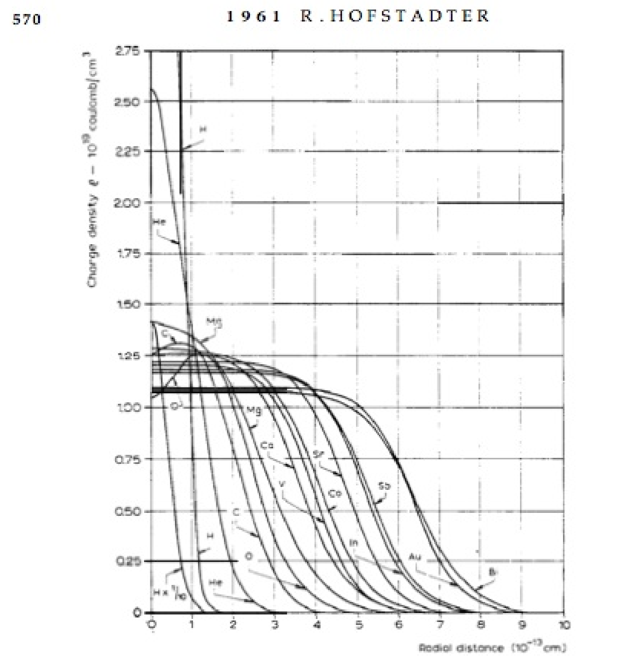
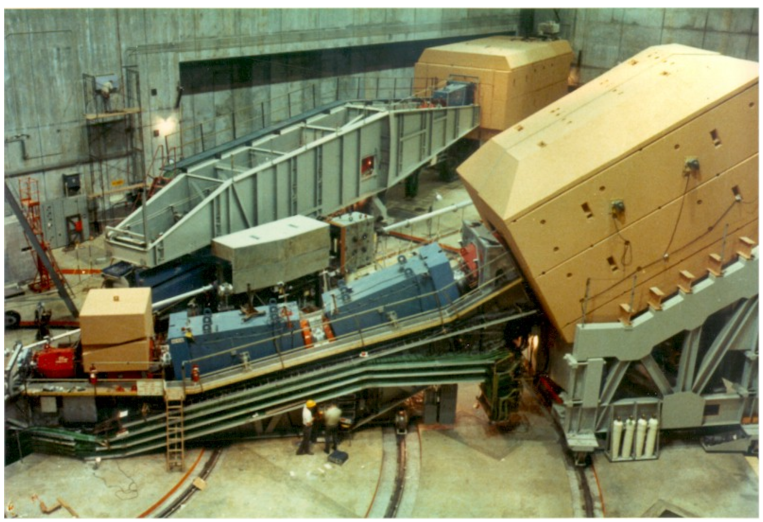


Fig. 8. This figure gives a summary of the approximate charge density distributions found for various nuclei studied by electron-scattering methods. The central densities are the least well determined positions of the curves. Note, however, the large disparity between the *average* central densities of the proton and all other nuclei. The alpha particle (^{4}He) is also a unique case and exhibits a much larger central density than all heavier nuclei.

What we (do not?) know today (IVb) (Proton PDF's, quarks, ...).

Measurements: from 188 MeV ep to **21 GeV ep (SLAC DIS scattering)** to the "4π" TeV HERA/LHC collider experiments



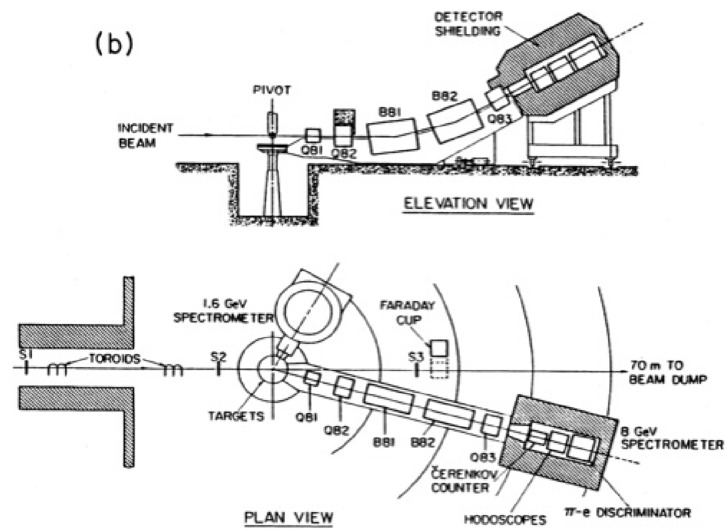
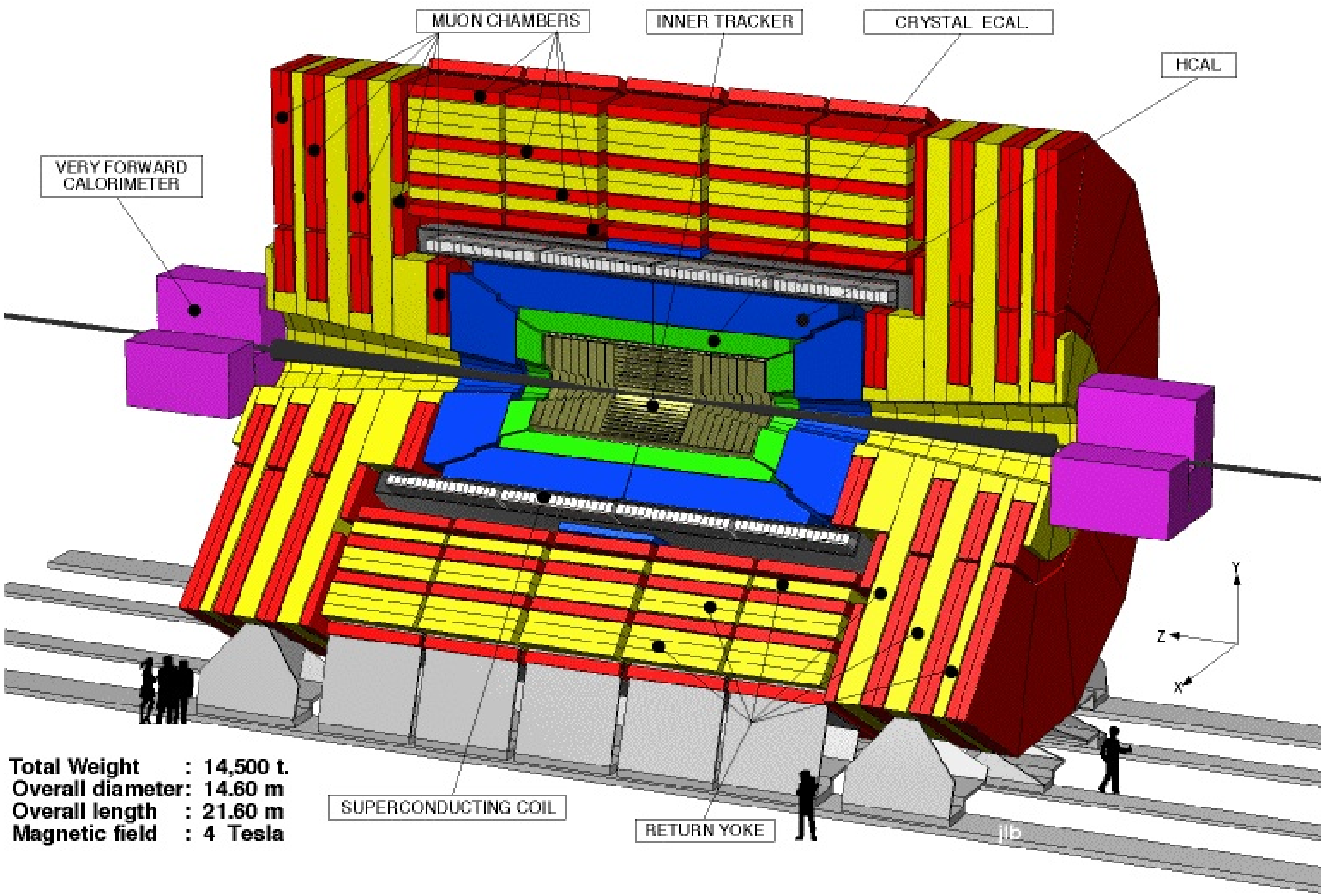


FIG. 2. (a) Plan view of End Station A and the two principal magnetic spectrometers employed for analysis of scattered electrons. (b) Configuration of the 8 GeV spectrometer, employed at scattering angles greater than 12°.

Rev. Mod. Phys., Vol. 63, No. 3, July 1991

What we (do not?) know today (IVc) (Proton PDF's, quarks, ...).

Experiments: to the "4π" HERA/LHC collider experiments

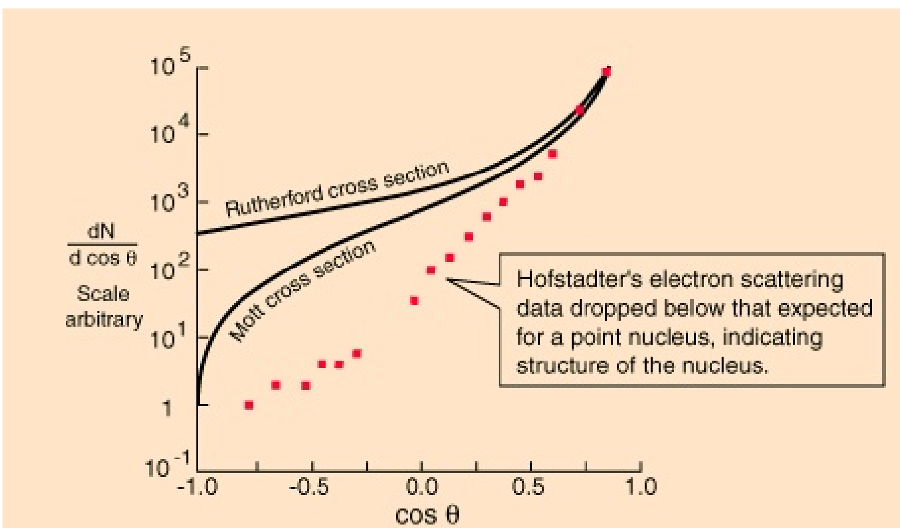


From Rutherford's αN scattering

(few MeV Energy) to Hofstadter et al (from the Atom model to the proton size)

- Reminder 1: the Rutherford experiment (http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/elescat.html) http://www.youtube.com/watch?v=hJs6PcgqMPA&feature=related

- Reminder 2: the Hofstadter et al experiments (few hundred MeV e beam) http://www.youtube.com/watch?v=8HsFF23RiJU&feature=endscreen&NR=1 http://www.youtube.com/watch?v=pZqkaJDaz2A



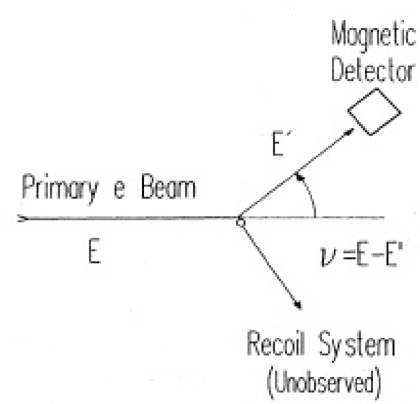


FIG. 3. Scattering kinematics.

Rev. Mod. Phys., Vol. 63, No. 3, July 1991

ep scattering: from Hofstadter et al to the SLAC DIS experiments ($E_e = 21$ GeV)

From the size of the proton to quarks and gluons:
Deep inelastic scattering: Experiments on the proton and the observation of scaling (1967-1973) (Noble lectures R.E.Taylor, H.W. Kendall and J.I. Friedman 1990)
http://www-hep2.fzu.cz/~chyla/talks/others/taylor.pdf
http://www-hep2.fzu.cz/~chyla/talks/others/kendall.pdf
http://www-hep2.fzu.cz/~chyla/talks/others/friedman.pdf

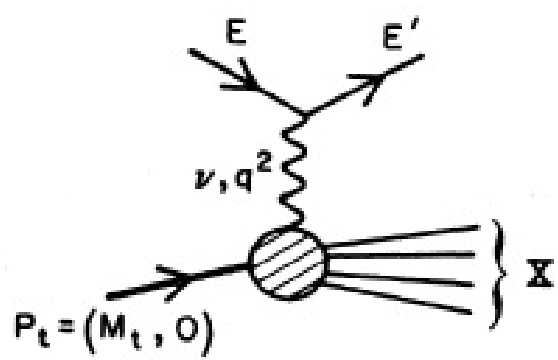
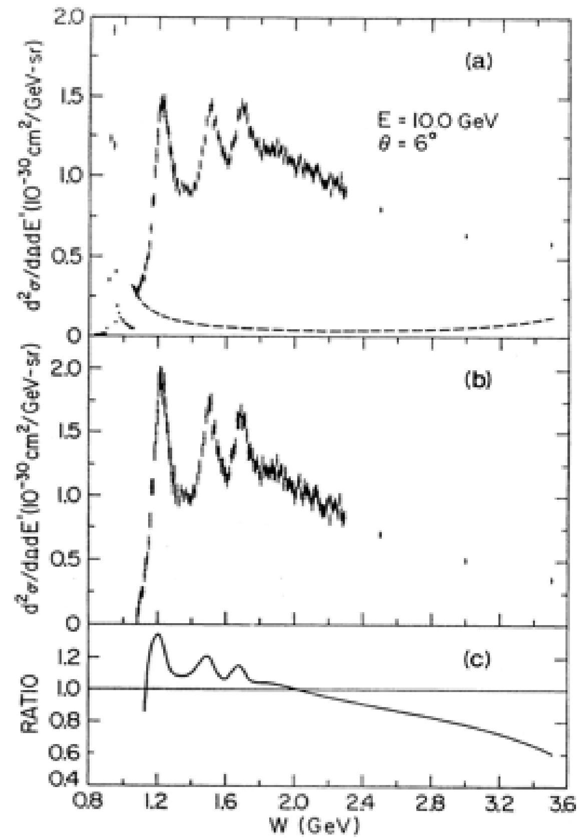


FIG. 5. Feynman diagram for inelastic electron scattering.



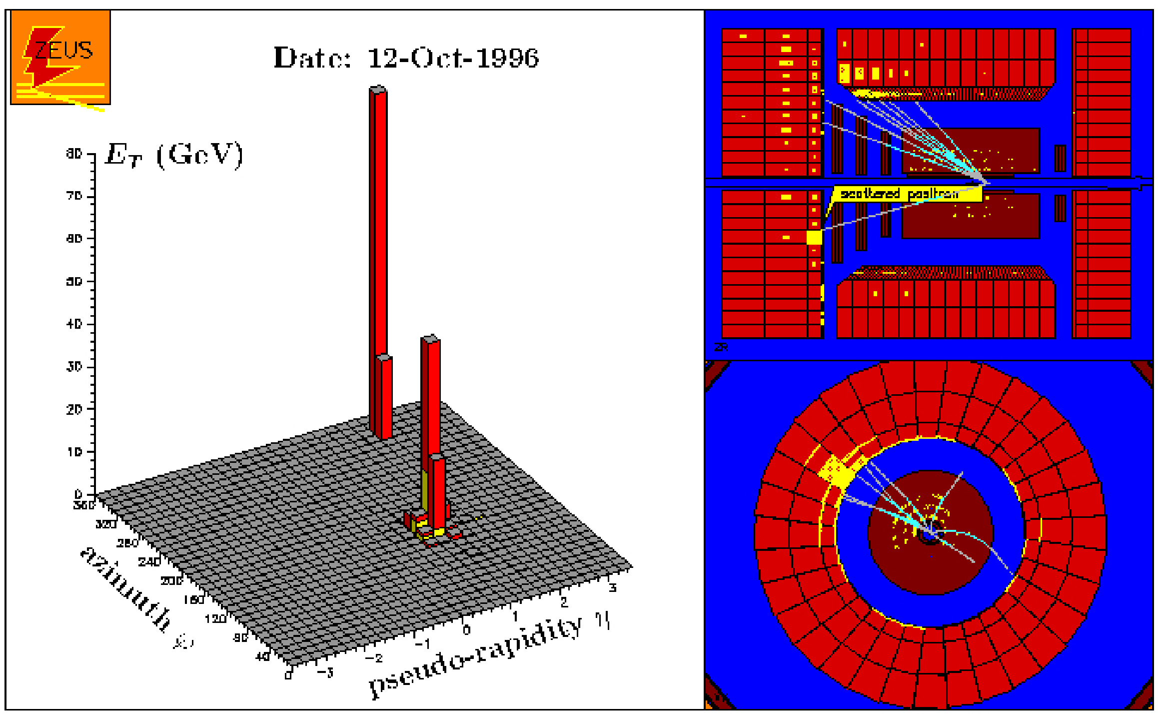
From fixed target $e(\mu,\nu)p$ DIS scattering to colliding beam DIS experiments (HERA)

The "ultimate" DIS ep scattering experiments H1 and ZEUS at HERA:

From $\sqrt{s} = \sqrt{2E_b \times m_p}$ to colliding beams $\sqrt{4 \times 30 \times 820}$ GeV$\approx$ 300 GeV)

$$E_t = 204\ GeV \quad E - p_Z = 50.2\ GeV \quad \gamma = 38.6^\circ$$
$$p_t = 2.2\ GeV \quad E'_e = 380\ GeV \quad \theta_e = 15.4^\circ$$

$$x_{DA} = 0.709 \pm 0.034 \qquad x_e = 0.605 \pm 0.060$$
$$y_{DA} = 0.721 \pm 0.008 \qquad y_e = 0.752 \pm 0.021$$
$$Q^2_{DA} = 46100 \pm 1600\ GeV^2 \qquad Q^2_e = 41000 \pm 3000\ GeV^2$$



About the theoretical picture of the proton substructure, ep scattering and deep inelastic scattering (I)

Elastic versus inelastic ep scattering:

- Low energies (Hofstadter et al): elastic(!) electron-proton scattering! **"No" extra particles were created and at most nucleus was left in an "excited" state!**

- When the beam energy increases, some hadrons (pions) can be produced and the reaction becomes more and more inelastic!

- Kinematics of the scattered electron allow to distinguish between elastic and inelastic reactions!

  Elastic scattering: $E' = E\frac{M_p}{M_p+E(1-\cos\Theta)}$

  if the observed E' is smaller than in the formula: $\rightarrow$ we have an inelastic scattering reaction!

- The "magic" comes when the ep inelastic scattering is replaced by elastic e-quark (parton) scattering!
  Elastic e-quark scattering "looks" like ep inelastic scattering!

About the theoretical picture of the proton substructure, ep scattering and deep inelastic scattering (II)

Some very early ep scattering measurements

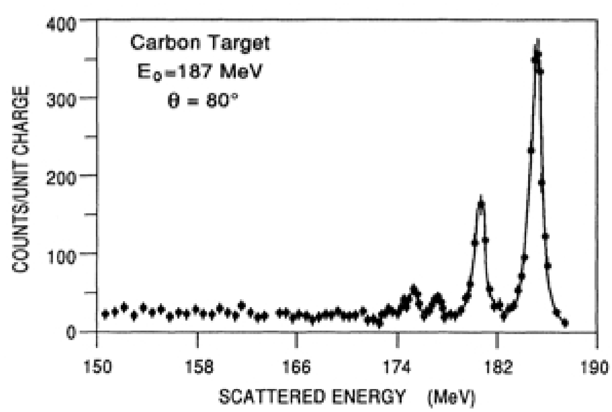


FIG. 3. Energy spectrum of 187 MeV electrons scattered through 80° by a carbon target, using the apparatus in Fig. 2.

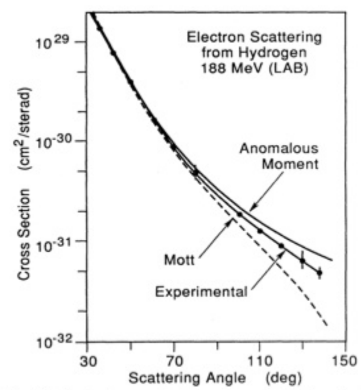


FIG. 5. Elastic electron scattering cross sections from hydrogen compared with the Mott scattering formula (electrons scattered from a particle with unit charge and no magnetic moment) and with the Rosenbluth cross section for a point proton with an anomalous magnetic moment. The data falls between the curves, showing that magnetic scattering is occurring but also indicating that the scattering is less than would be expected from a point proton.

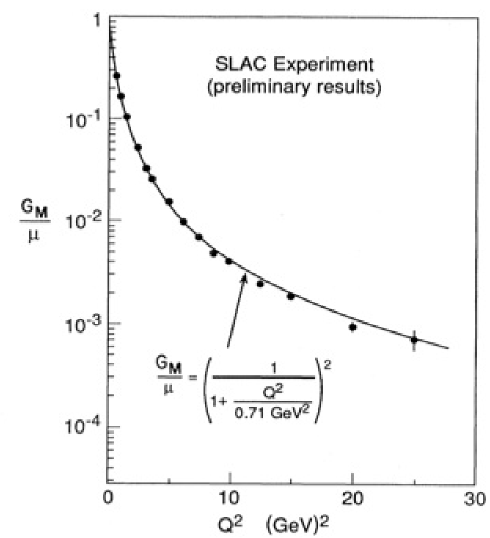


FIG. 36. Magnetic form-factor measurement at SLAC in 1967. The dipole curve is the same as in Fig. 25, here extended to $Q^2=25$ GeV^2. Again, the agreement is imperfect, but the curve describes the general behavior of the data quite well.

About the theoretical picture of the proton substructure, ep scattering and deep inelastic scattering (III)

Some early ep scattering measurements (DESY)
(Bartel et al, 1968 the inelastic cross section becomes more interesting, but was inconclusive and interpreted as "quasi-elastic scattering")
http://www.sciencedirect.com/science/article/pii/037026936890155X

Volume 28B, number 2 PHYSICS LETTERS 11 November 1968

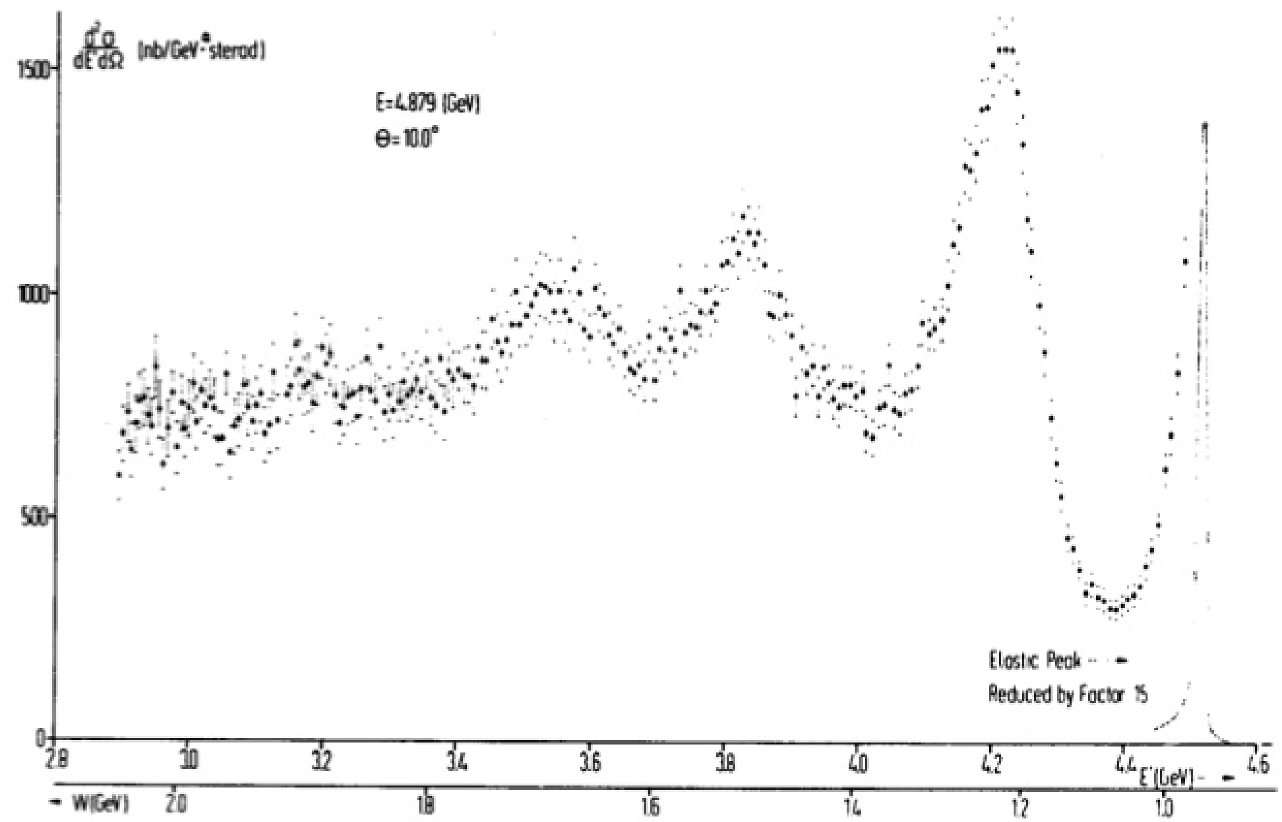


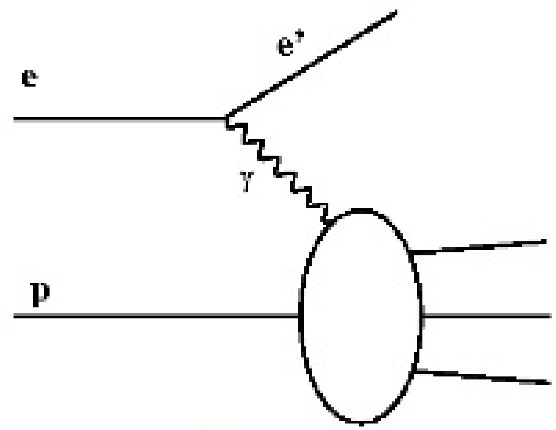
Fig. 1. Inelastic cross section before application of radiative corrections. The momentum transfer at the peak of the $\Delta(1236)$ isobar was $q^2 = 0.63\ (\mathrm{GeV}/c)^2$.

About the theoretical picture of the proton substructure, ep scattering and deep inelastic scattering (IV)

Probing the structure of matter

- virtual photons (in analogy to optics)
- BUT also:
  - ➔ Z/W exchange
  - ➔ Jet production
  - ➔ Heavy quarks
- Example Deep Inelastic Scattering:
  - Kinematics:

$$
\begin{aligned}
s &= (e+p)^2 \\
q &= e - e' \\
Q^2 &= -q^2 \\
y &= \frac{q.p}{e.p} \\
W^2 &= (q+p)^2 \\
x &= \frac{Q^2}{2p.q}
\end{aligned}
$$



- in p-rest frame:

$$p = (M, 0)$$

$$\nu = \frac{p.q}{M} = \frac{M q_0}{M} = E - E'$$

- using

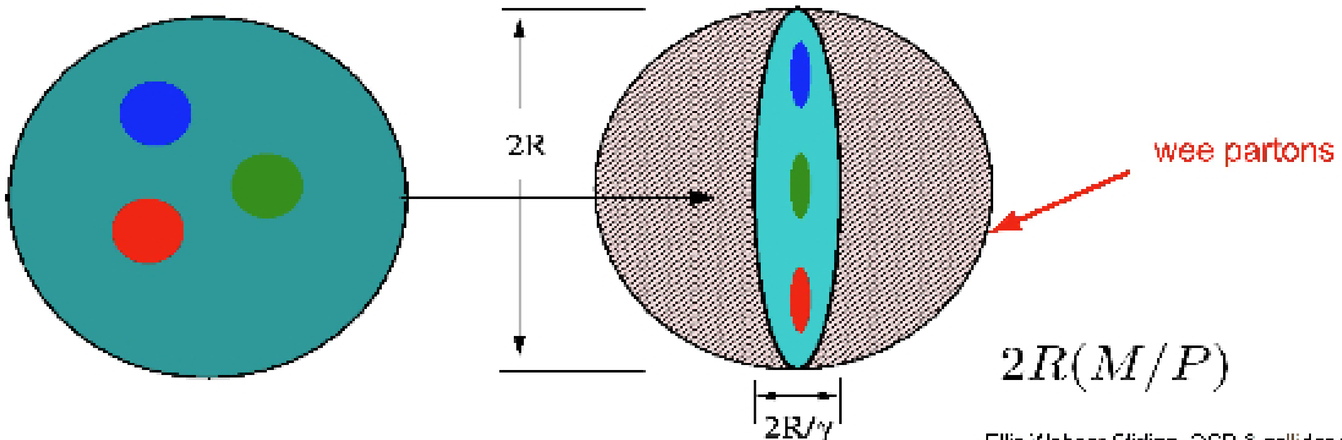
$$
\begin{aligned}
W^2 &= (q+p)^2 \\
&= M^2 + 2q.p - Q^2
\end{aligned}
$$

$$\nu = \frac{Q^2 + W^2 - M^2}{2M}$$

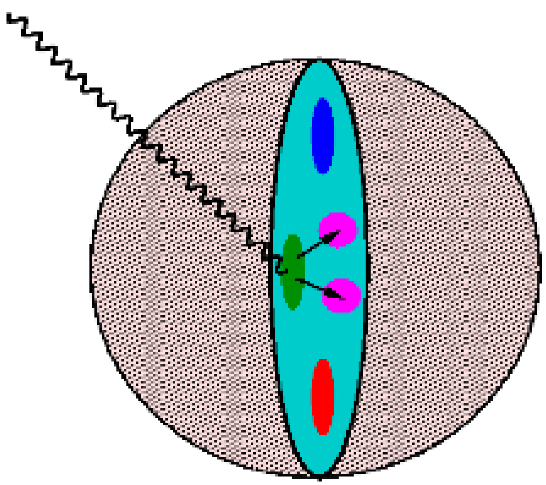
H. Jung, QCD & MC, Lecture 1, University Antwerp, Oct 2011

About the theoretical picture of the proton substructure, ep scattering and deep inelastic scattering (V)

Space time picture of DIS



Ellis,Webber Stirling, QCD & collider physics, p 07



- Partons with finite x and fixed transverse size are distributed on the Lorentz contracted disc and the number of partons per unit of long. Phase space dx/x is rather small.
- Partons with very small x (x˜ 1GeV/P), so called wee partons are not confined to the Lorentz contracted disc, but acc. to uncertainty principle: $\Delta z \sim 1/(xP)$

Space time picture: free partons ?

- Compare lifetime of proton fluctuation τ_0 with time of interaction τ
- In CM frame P splits into q1=xP and q2=(1-x)P, with k_t.

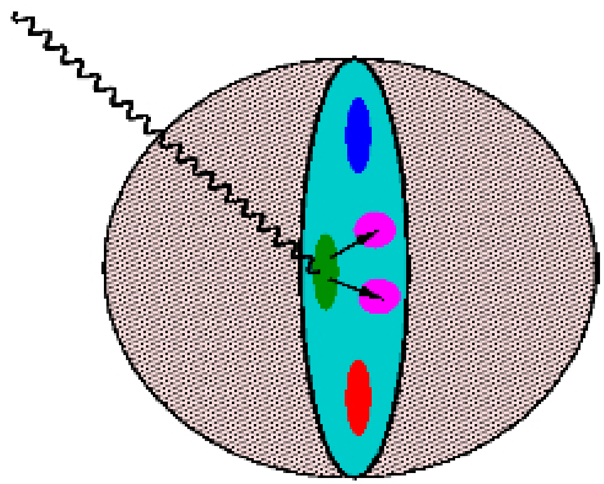
$$\tau = \frac{1}{\Delta E}$$

$$\Delta E = E_1 + E_2 - E_0 = \frac{k_t^2}{2x(1-x)P} \sim \frac{k_t^2}{2xP}$$

γ^* four-vector $q = (E_\gamma, \mathrm{q_t}, 0)$

with $x = \frac{Q^2}{2q.p}$ obtain $E_\gamma = \frac{Q^2(1-x)}{4xP}$

$$\tau_0 = \frac{1}{E_\gamma}$$



$$\frac{\tau}{\tau_0} \sim \frac{2k_t^2}{Q^2}$$

- Lifetime of proton fluctuation long compared to interaction time

Some more experimental details and results (0)

Around 1965 theorists didn't believe their own models:

". . . we know that. . . [mesons and baryons] are mostly, if not entirely, make up out of one another. . . . The probability that a meson consists of a real quark pair rather than two mesons or a baryon and antibaryon must be quite small.
M. Gell-Mann Proc. XIIIth International Conference on High Energy Physics, Berkeley, California 1967.

"Additional data is necessary and very welcome in order to destroy the picture of elementary constituents."
J. D. Bjorken.
"I think Prof. Bjorken and I constructed the sum rules in the hope of destroying the quark model."
Kurt Gottfried. Both quotations from Proc. 1967 International Symposium on Electron and Photon Interactions at High Energy, Stanford, California, September 5 9 1967.

Difficult times at the end of the 60ies when you want to perform DIS experiments!

Some more experimental details and results (I)

(Kendall's review): Fig 9: cross section at fixed angles, increasing q^2 and as a function of the recoil mass: with larger q^2 the cross section is "rising" cross section as a function of the recoil mass!
Fig 11: unexpected weak q^2 dependence at constant W

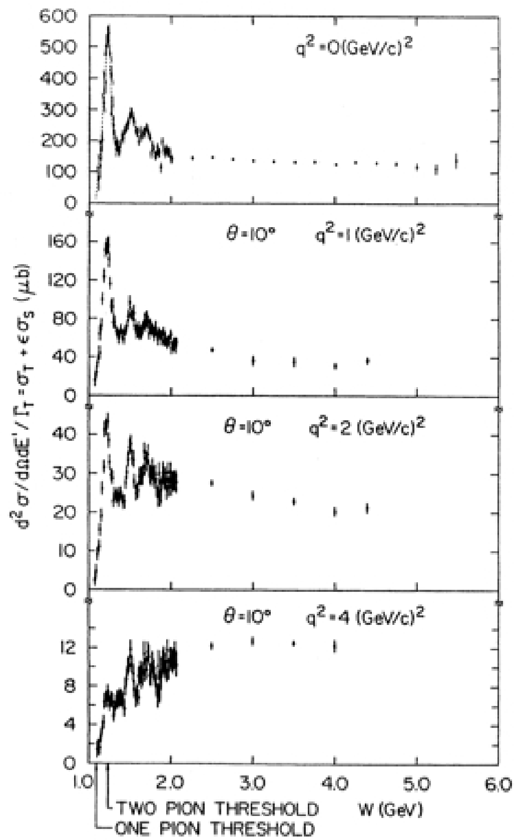


FIG. 9. Spectra of electrons scattered from hydrogen at q^2 up to 4 $(GeV/c)^2$. The curve for $q^2=0$ represents an extrapolation to $q^2=0$ of electron scattering data acquired at $\theta=1.5°$. Elastic peaks have been subtracted and radiative corrections have been applied.

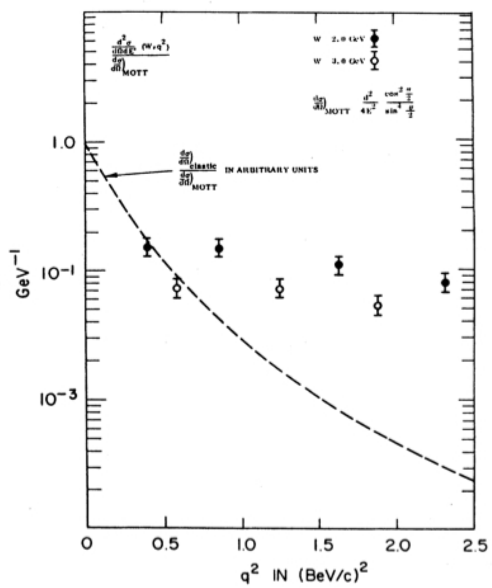


FIG. 11. Inelastic data for $W=2$ and 3 GeV as a function of q^2. This was one of the earliest examples of the relatively large cross sections and weak q^2 dependence that were later found to characterize the deep inelastic scattering and which suggested point-like nucleon constituents. The q^2 dependence of elastic scattering is shown also; these cross sections have been divided by σ_M.

Some more experimental details and results (II)

(Kendall's review): "During the analysis of the inelastic data, J. D. Bjorken suggested a study to determine if $F_2 = \nu W_2$ was a function of $\omega = \nu/Q^2$ alone." (Fig 12b)
for elastic scattering $\nu = E - E' = q^2/(2M)$ and $q^2 = 2EE'(1 - \cos(\theta))$
for inelastic scattering $W^2 = 2M\nu + M^2 - q^2$ = missing mass (mass of the hadronic system)

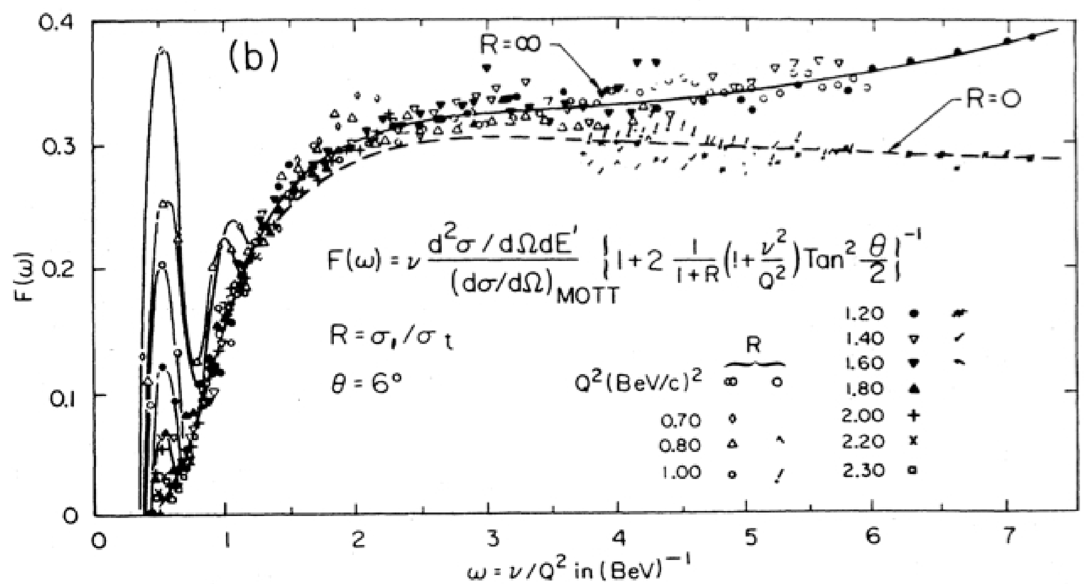


FIG. 12. (a) The inelastic structure function $W_2(\nu, q^2)$ plotted against the electron energy loss ν. (b) The quantity $F_1 = \nu W_2(\omega)$. The "nesting" of the data observed here was the first evidence of scaling. The figure is discussed further in the text.

Rev. Mod. Phys., Vol. 63, No. 3, July 1991

Some more experimental details and results (III)

The SLAC DIS results were an unexpected "Eldorado" for theorists. Feynman explained the weak q^2 dependence and the scaling with the pointlike (almost free) partons (= quarks) in the proton. This opened the way to asymptotic freedom and QCD!

the variable $K_0 = F_2/xF_1 - 1$

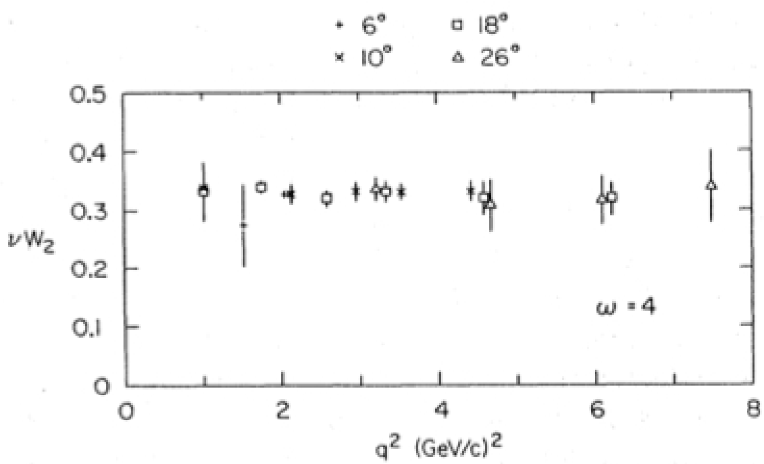


FIG. 13. An early observation of scaling: νW_2 for the proton as a function of q^2 for $W > 2$ GeV, at $\omega=4$.

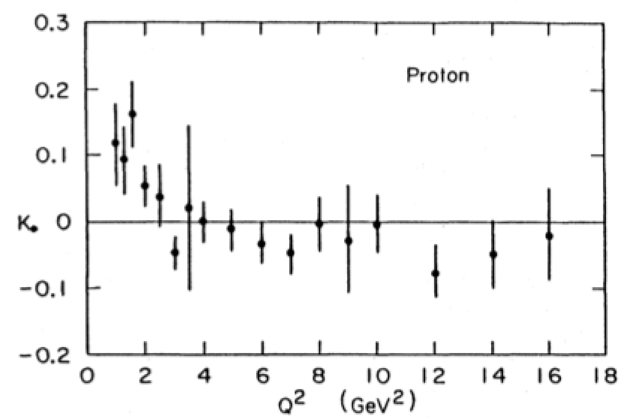


FIG. 18. The Callan-Gross relation: K_0 vs q^2, where K_0 is defined in the text. These results established the spin of the partons as 1/2.

Some more experimental details and results (IV)

in the following years the fixed target experiments completed the picture!
$e - Neutron$ PDF's and the νp PDF's were measured!

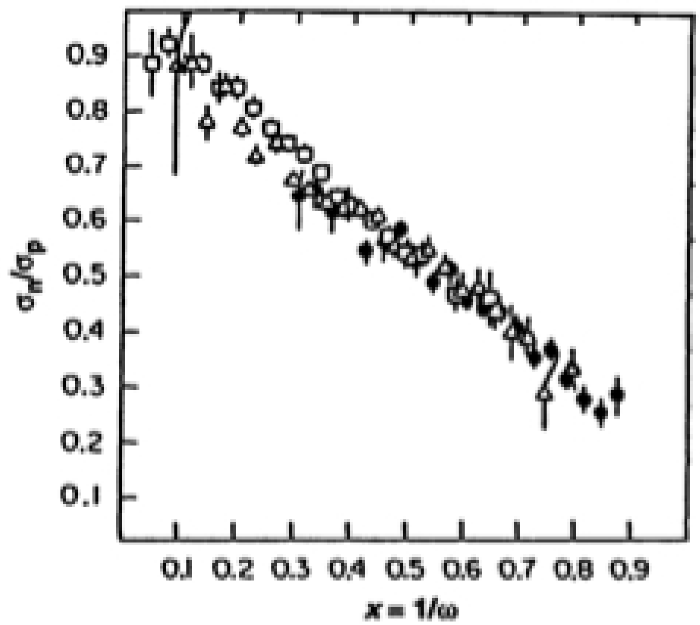


Fig. 7. The ratio of neutron to proton cross sections, as measured in three separate MIT-SLAC experiments (*28*) [(●), 15°, 19°, 26°, and 34°; (△), 18°, 26°, and 34°; and (□), 6° and 10°]. These data appeared to be a single function of $x = 1/\omega$ that decreased from unity at $x = 0$ to about 0.3 at the highest values of x measured.

SCIENCE • VOL. 256 • 29 MAY 1992

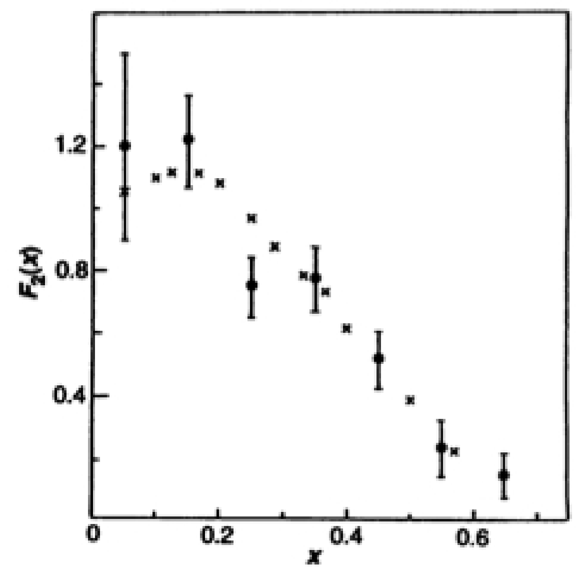
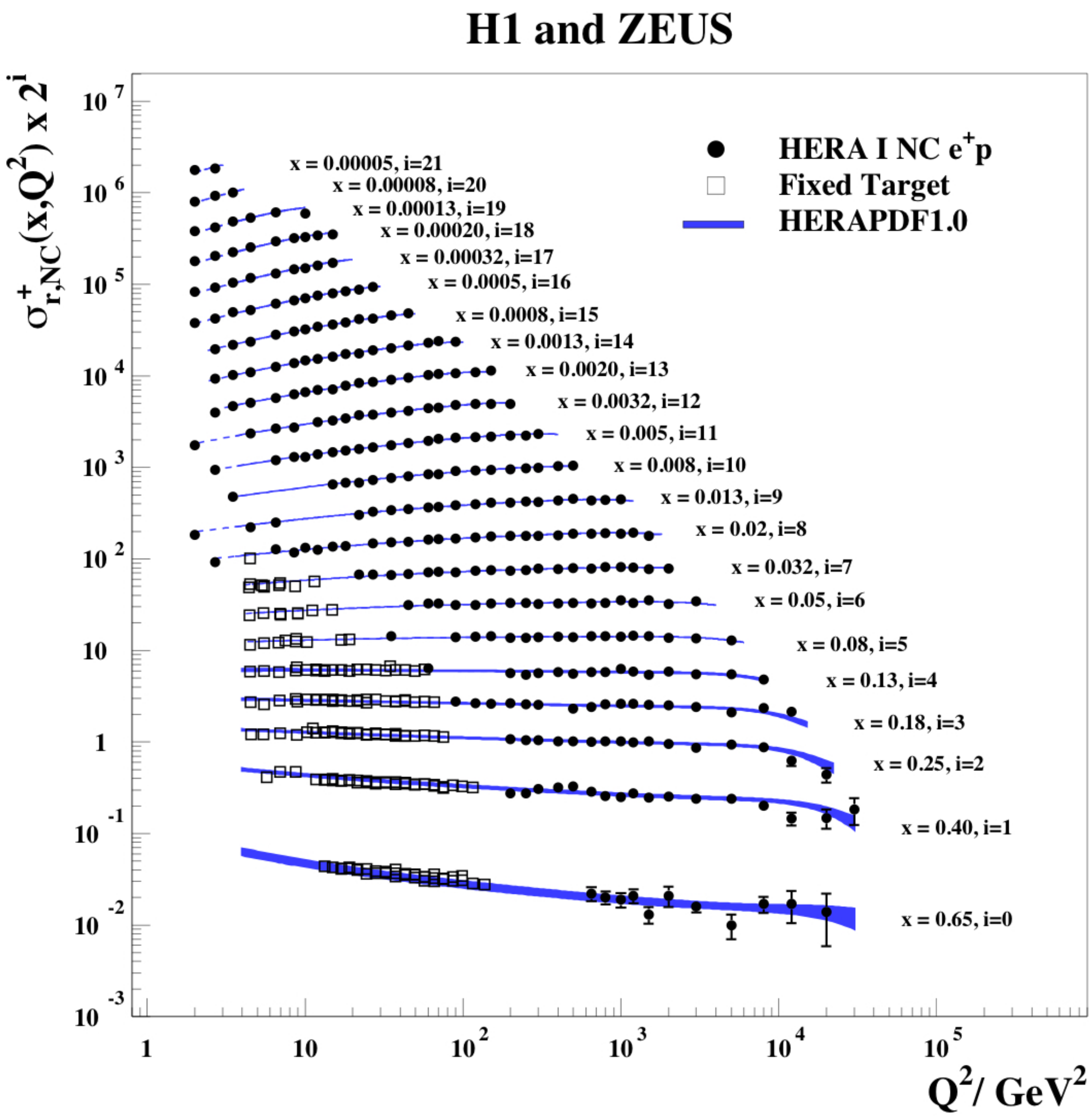


Fig. 8. Comparison of structure functions measured in deep inelastic neutrino-nucleon scattering experiments on the Gargamelle heavy-liquid bubble chamber with the MIT-SLAC data [(●), Gargamelle, $F_2^{\nu N}$; (×), MIT-SLAC, (18/5)F_2^{eN}]. When multiplied by 18/5, a number specified by the quark-parton model, the electron scattering data coincide with the neutrino data.

SCIENCE • VOL. 256 • 29 MAY 1992

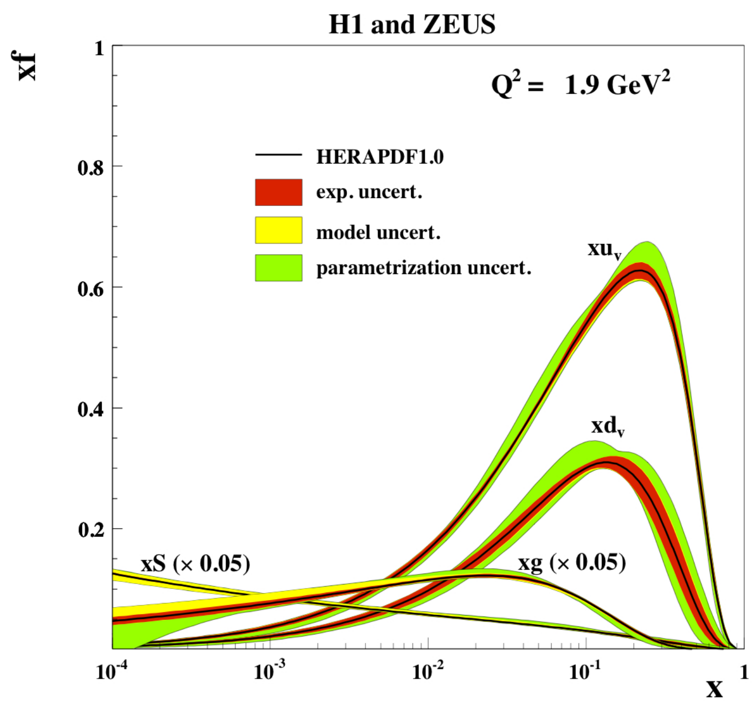
Some more experimental details and results (V)

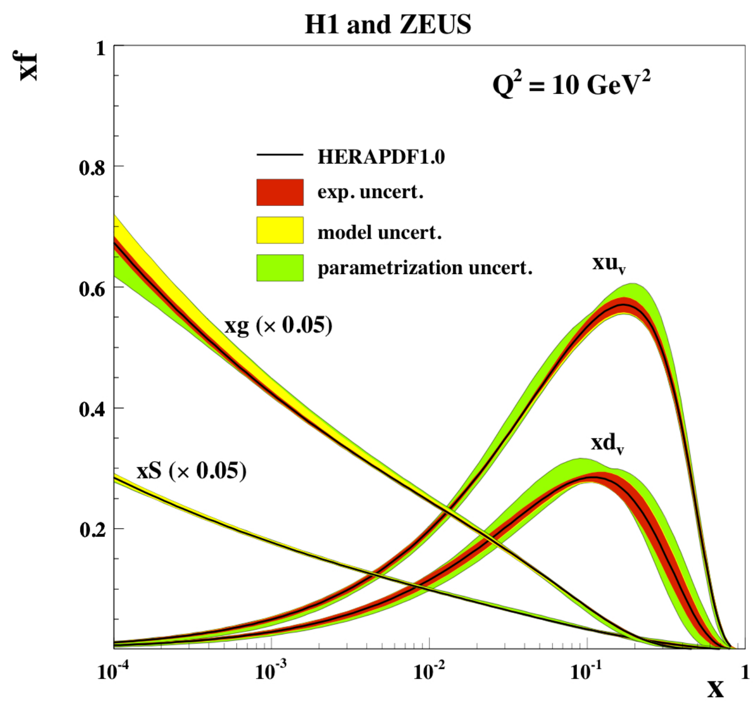
Today's picture: HERA results (I)



Some more experimental details and results (VI)

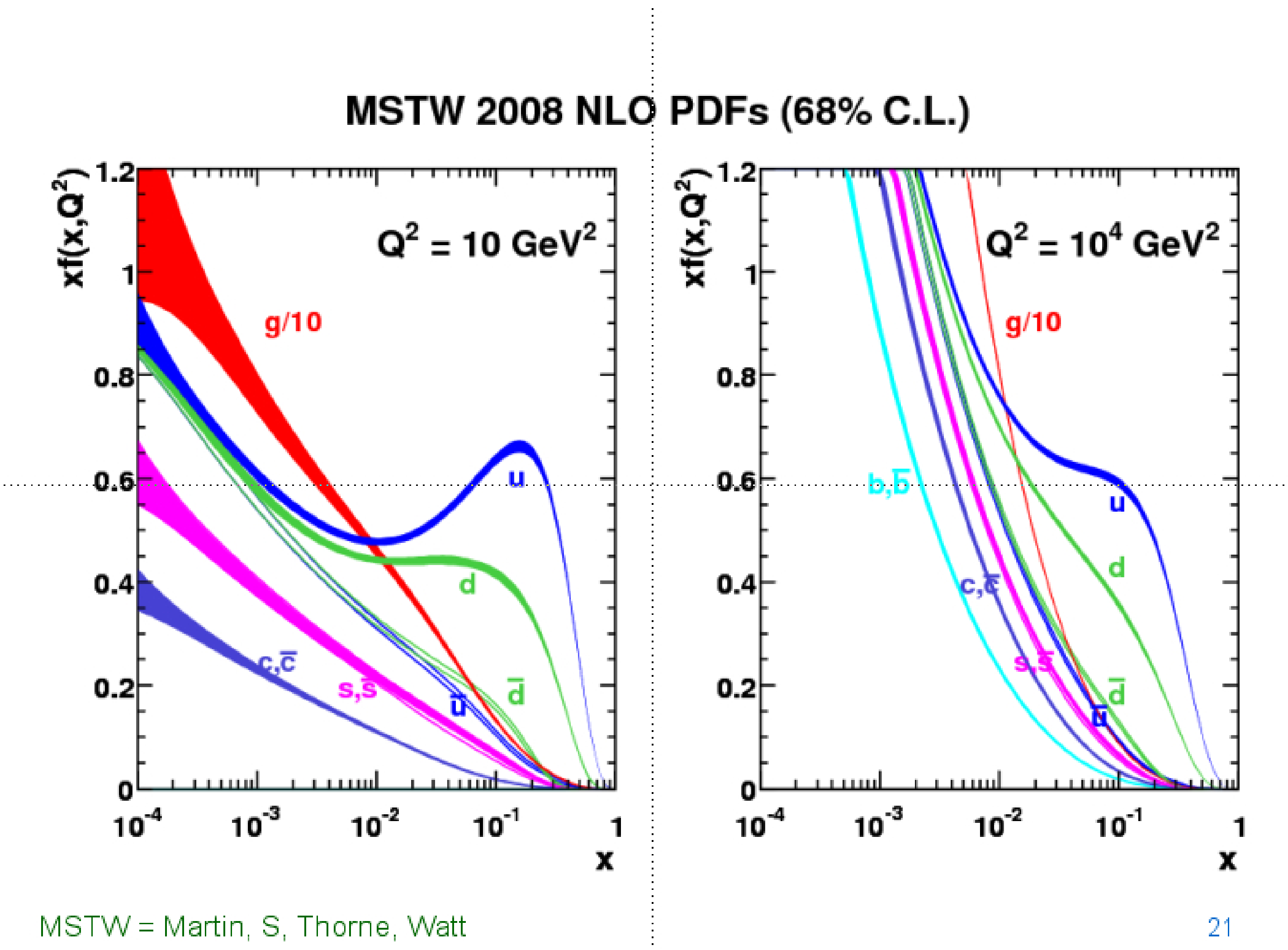
Today's picture: HERA results (II)





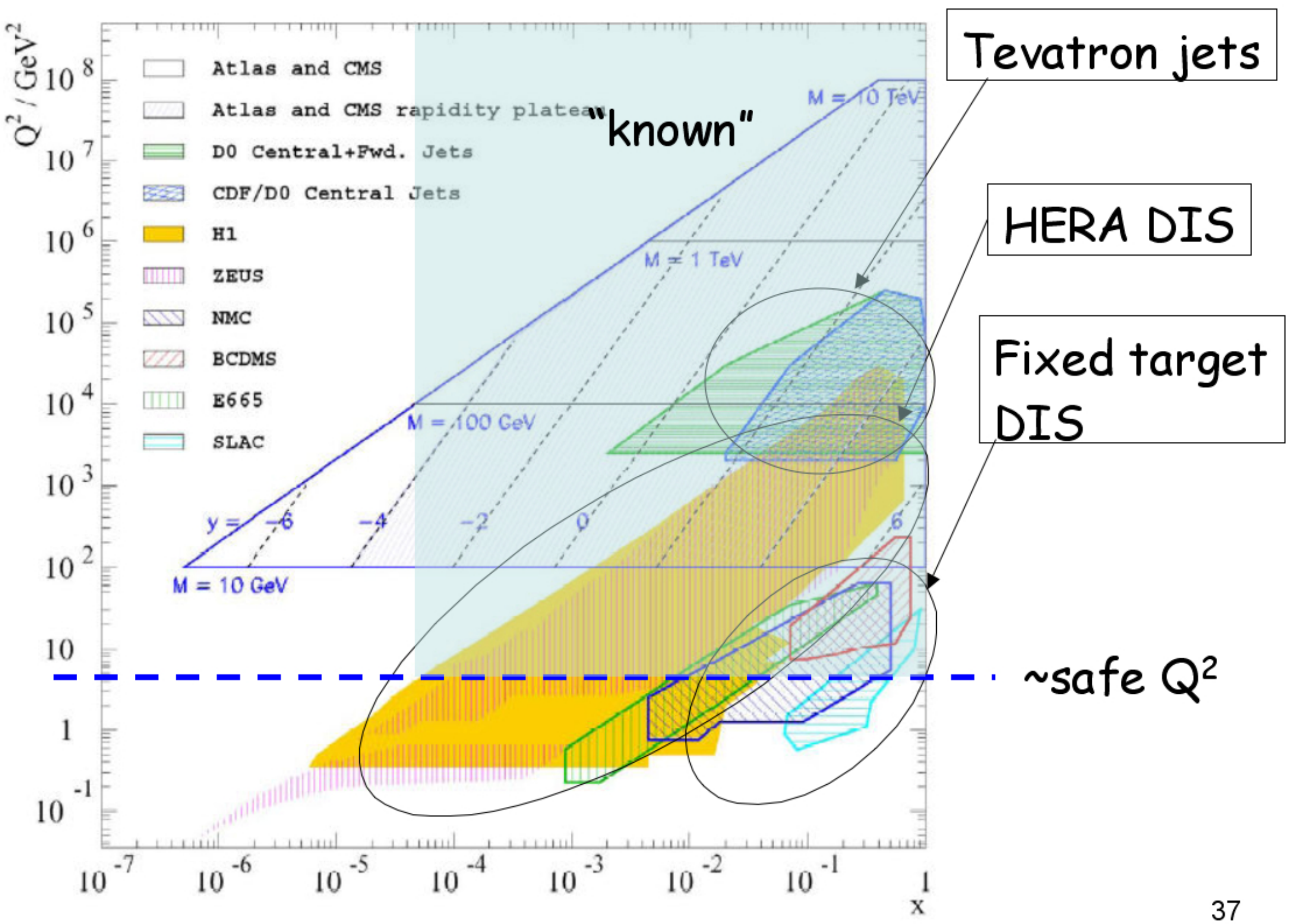
Some more experimental details and results (VII)

Today's picture: PDF's for the LHC (I)



Some more experimental details and results (VIII)

Today's picture: PDF's for the LHC (II)



http://www.youtube.com/watch?v=8HsFF23RiJU&feature=endscreen&NR=1
http://www.youtube.com/watch?v=71nURVXXeaM&feature=related