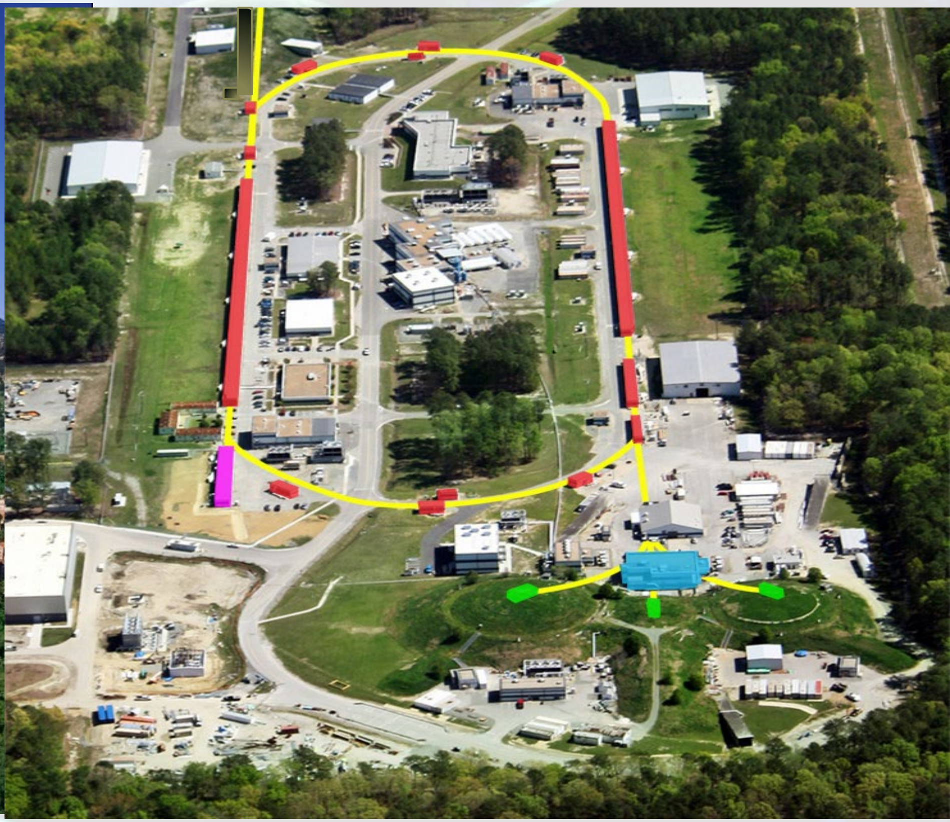
Nuclear Physics at Jefferson Lab

Thia Keppel

National Nuclear Physics Summer School



University of Colorado at Boulder

July 2017

Jefferson Lab

Thomas Jefferson National Accelerator Facility

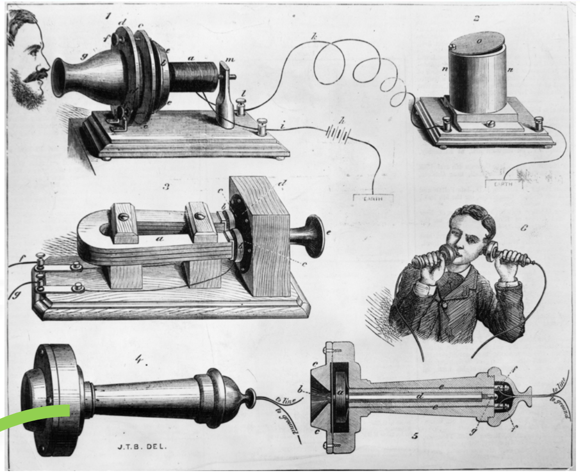
Lecture Scheme

DAYS 1 - 2

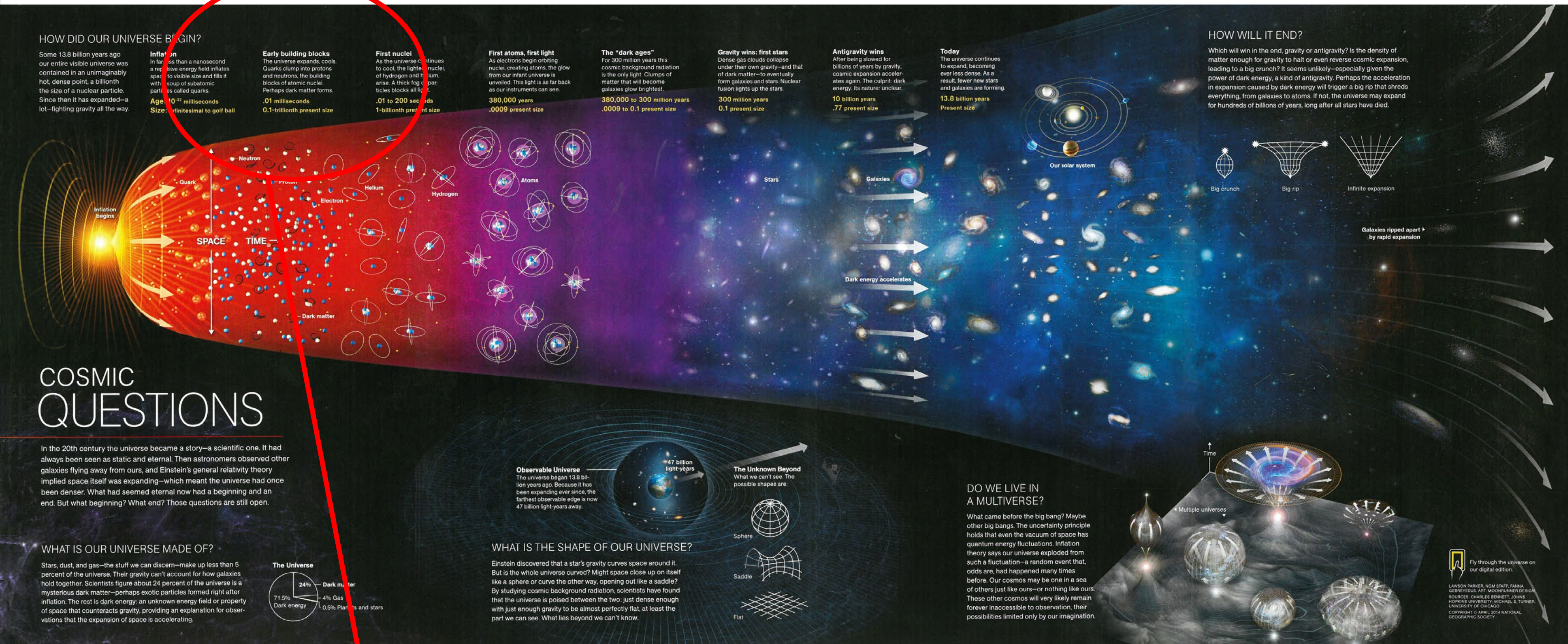
- Introduction
- History and Basics of Electron Scattering
- Jefferson Lab
- 1D Nucleon Structure

DAYS 2 - 3

- 3D Nucleon Structure
- Nucleons in the Nuclear Medium
- *Other topics*



What is the goal?

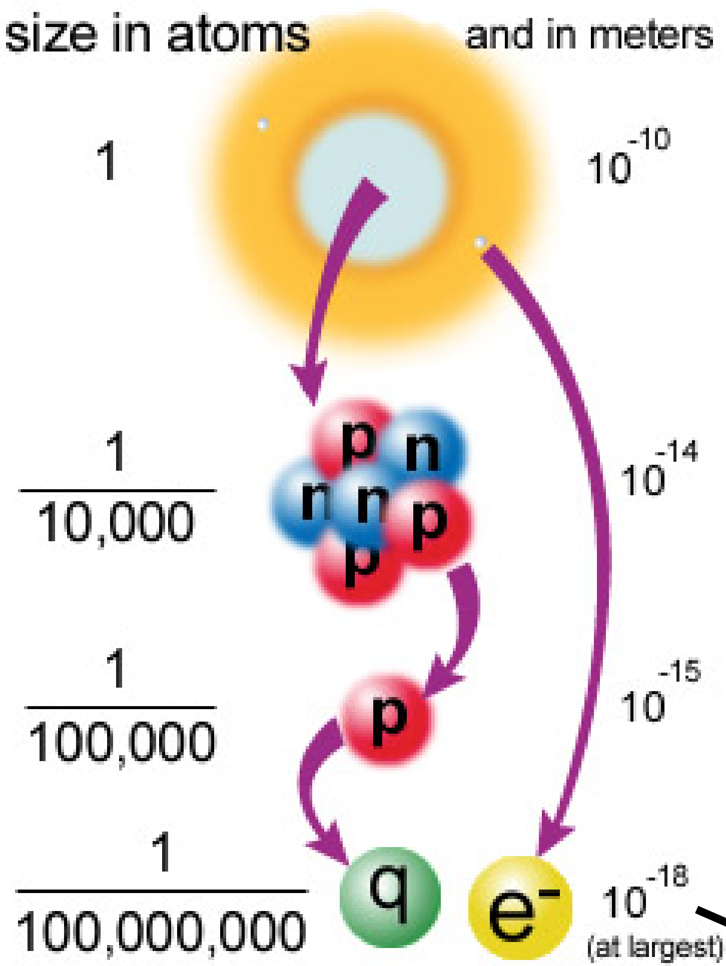


NATIONAL GEOGRAPHIC

Seek to:

- Understand the fundamental structure of visible matter (quarks, gluons,..)
- Understand how hadrons (mesons, nucleons,..) and nuclei are formed

How to probe the nucleons / quarks?



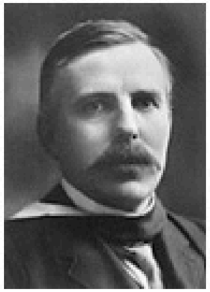
- Electron scattering experiments employ high momentum point-like leptons, + electromagnetic interactions, which are well understood, to probe hadronic structure (which isn't).

High energy electrons are a great tool for the job!

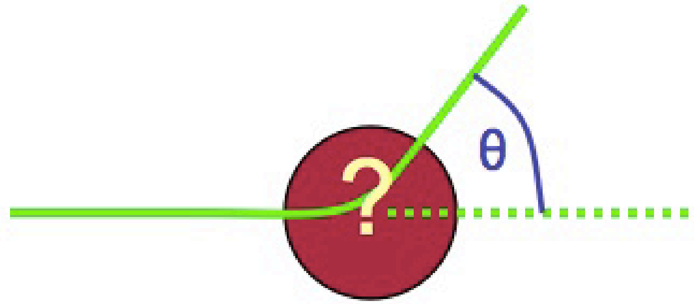
$$d_{probed} \propto \lambda\!\!\!^{-} = \frac{\hbar}{p} \approx 10^{-18}\ \mathrm{m}$$

short distance -> large momentum
(Uncertainty Principle!)

Rutherford Scattering



Rutherford taught us the most important lesson: use a scattering process to learn about the structure of matter



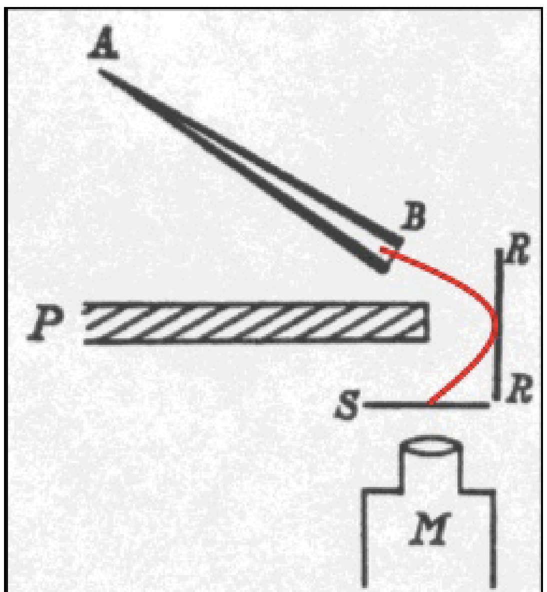


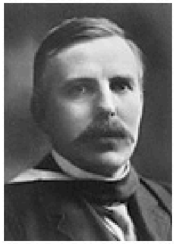
Fig. 1.

H. Geiger and E. Marsden observed that α-particles were sometimes scattered through very large angles.

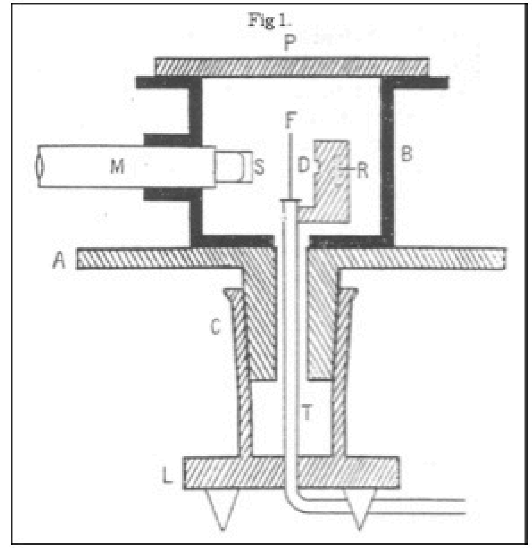
Rutherford interpreted these results as due to the coulomb scattering of the α-particles with the atomic nucleus:

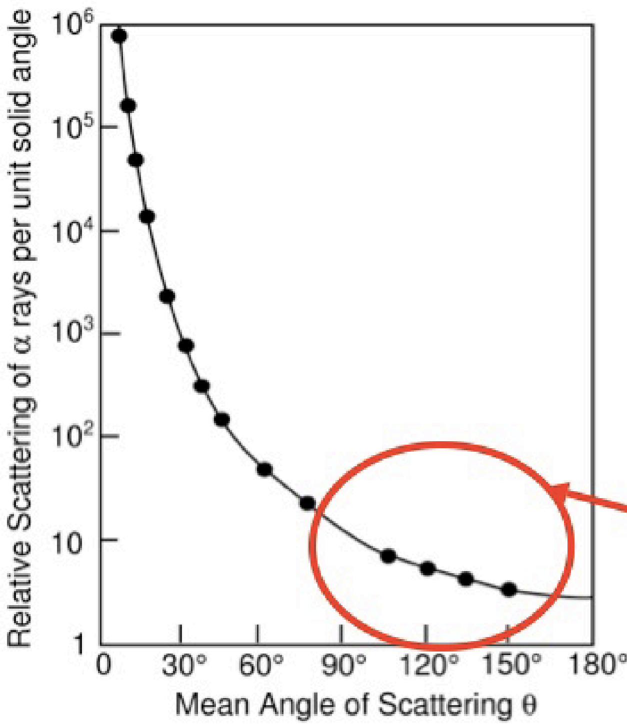
$$\sigma(\theta) = \frac{z^2 Z^2 e^4}{16 E^2} \frac{1}{\sin^4 \frac{1}{2}\theta}$$

Rutherford Scattering

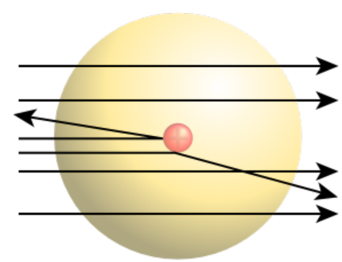


In a subsequent experiment Geiger and Marsden verified Rutherford's prediction





Discovery of atomic nucleus



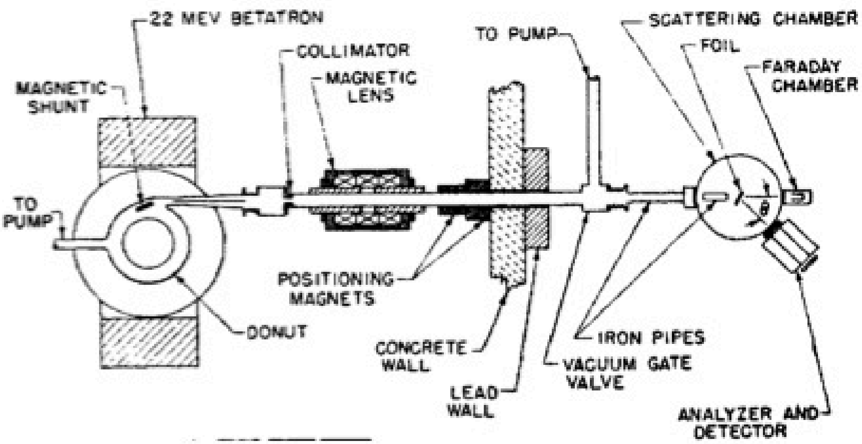
The atom consists of a charged nucleus (< 10^{-14} m) surrounded by a compensating distribution of electrons (10^{-10} m)

1st elastic electron-nucleus scattering

Scattering of 15.7-Mev Electrons by Nuclei*

E. M. Lyman, A. O. Hanson, and M. B. Scott†
Department of Physics, University of Illinois, Urbana, Illinois

(Received July 3, 1951)



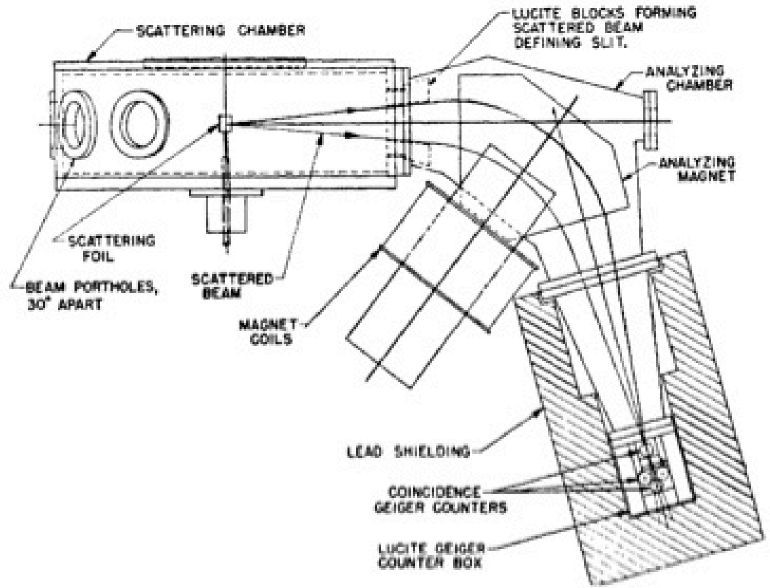
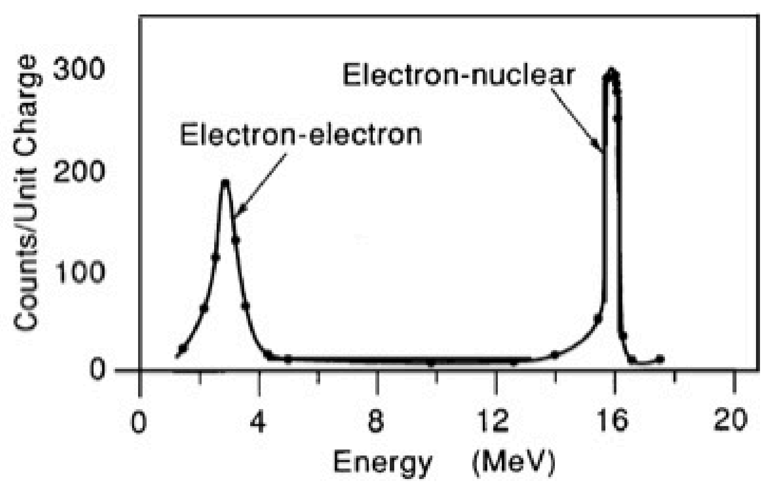


Fig. 2. Scattering chamber.

Point-like electron probe better than Rutherford's α-particles

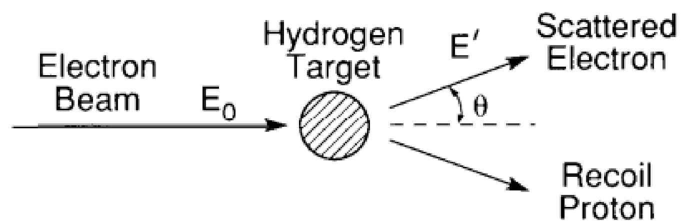
Probing power: $\lambda \propto 1/E$



Simplest Nucleus: Is the Proton Point-Like?

- Do protons have size?

1948-50 – Schiff, Rosenbluth: suggest use of **elastic electron-proton scattering** to probe the proton



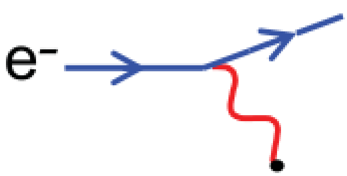
$$q = (E_0 - E', \vec{q}\,)$$

$$E' = \frac{E_0}{1 + \frac{2E_0}{M}\sin^2\frac{\theta}{2}}$$

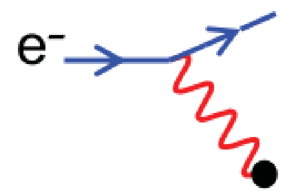
electron is left with less energy after meeting the proton

$$\boxed{Q^2 = 4E_0E'\sin^2\frac{\theta}{2}}$$

square of four-momentum transfer: connected to the probe's ability of resolving the structure of the proton



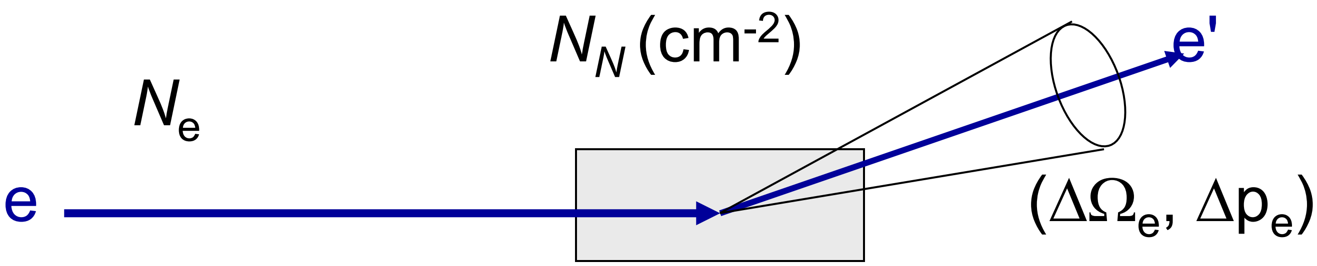
probe's ability of resolving structure $\sim \frac{\hbar}{Q}$



proton when $\frac{\hbar}{Q}$ >> than its size

same proton when $\frac{\hbar}{Q}$ $\sim$ its size

Extracting the (e,e') cross section



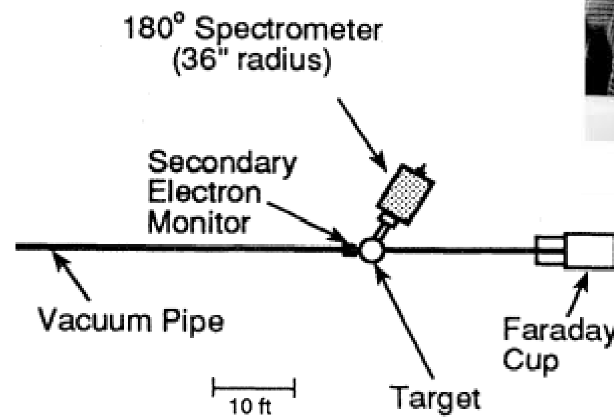
Scattering *probability* or cross section

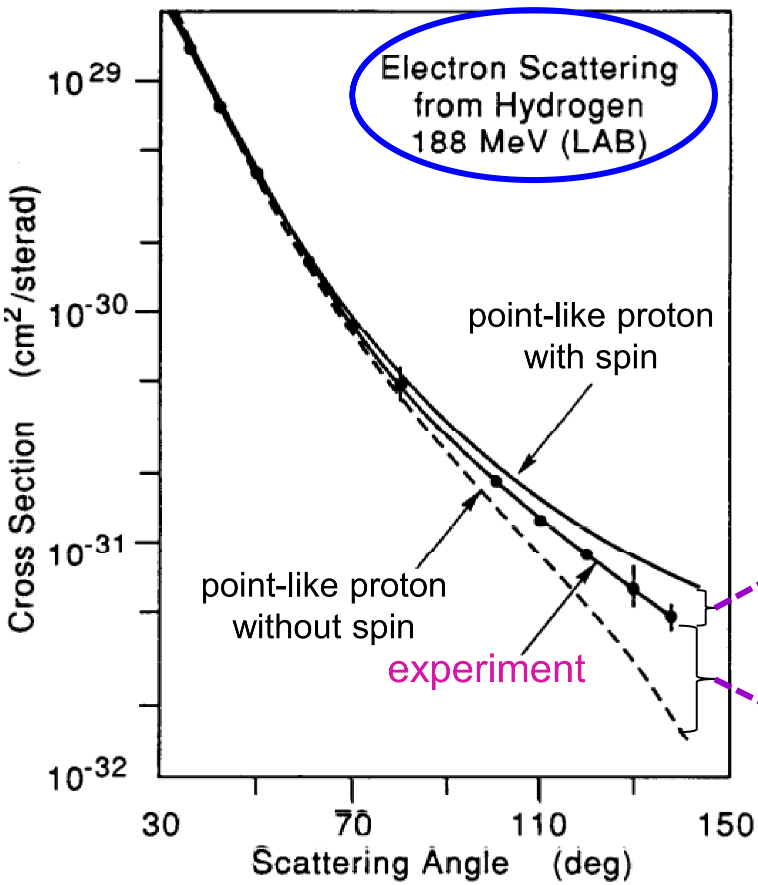
$$\boxed{\left\langle \frac{d^3\sigma}{d\Omega_e dp_e} \right\rangle = \frac{\text{Counts}}{N_e N_N \Delta\Omega_e \Delta p_e}}$$

Simplest Nucleus: Is the Proton Point-Like?

- Do protons have size? Electromagnetic interaction calculable...

Yes! Experiments at High Energy Physics Laboratory Stanford, 1955





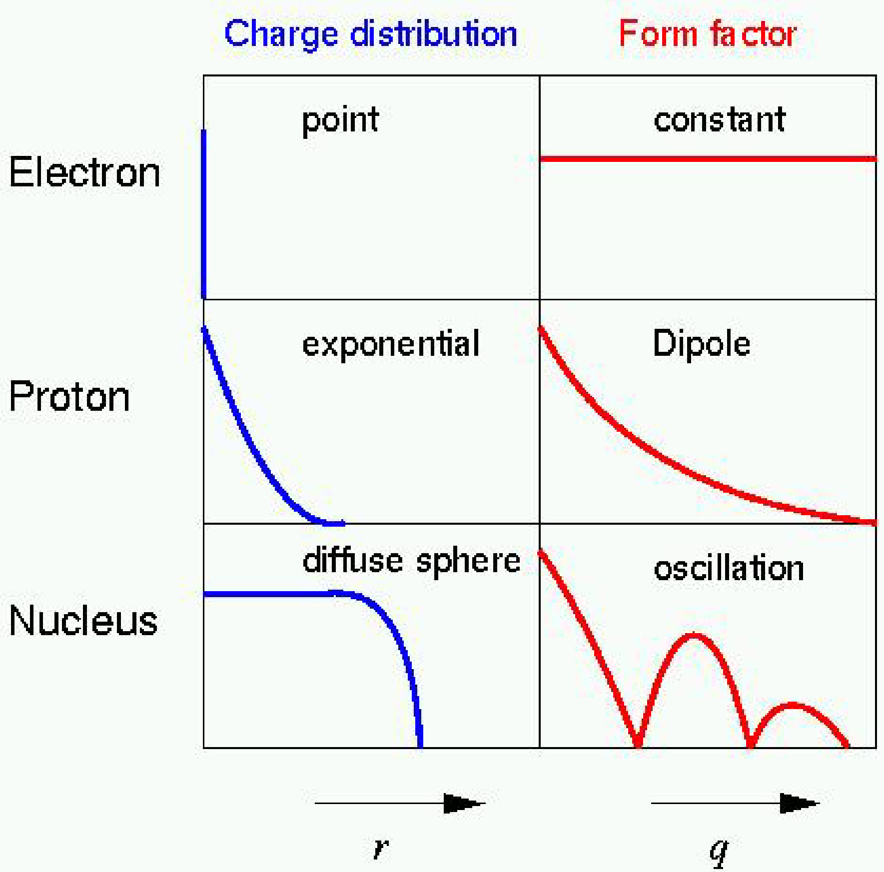
Probability of interaction less than expected from point-like proton with spin

Probability of interaction more than expected from point-like proton without spin

How Do the Charge and Magnetic Moment Distribute?

Probability of elastic interaction: $$\frac{d\sigma}{d\Omega} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{point} = \left[\frac{G^2{}_E(Q^2) + \tau G^2{}_M(Q^2)}{1+\tau} + 2\tau G^2{}_M(Q^2)\tan^2\frac{\theta}{2}\right] \qquad \tau = \frac{Q^2}{4M^2}$$

- Form Factors are (in some limit) Fourier transforms of charge and magnetic moment distributions



- Elastic cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm exp} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Mott} \left|F(q^2)\right|^2$$

- Form factor

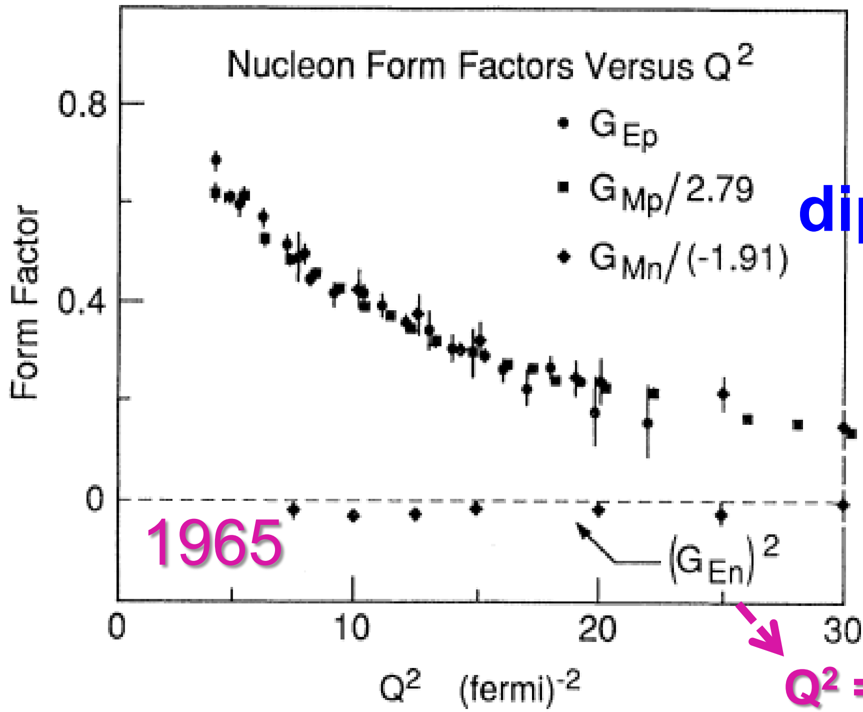
$$F(q^2) = \int e^{iqx/\hbar}\rho(x)d^3x$$

How Do the Charge and Magnetic Moment Distribute?

Probability of elastic interaction:

$$\frac{d\sigma}{d\Omega} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{point} = \left[\frac{G^2{}_E(Q^2) + \tau G^2{}_M(Q^2)}{1+\tau} + 2\tau G^2{}_M(Q^2)\tan^2\frac{\theta}{2}\right] \qquad \tau = \frac{Q^2}{4M^2}$$

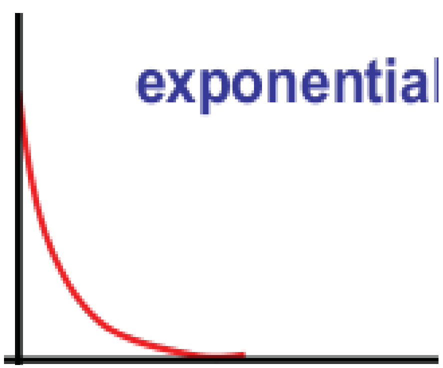
- The Q^2 dependence of form factors was measured…



dipole

Q² = 1 GeV²

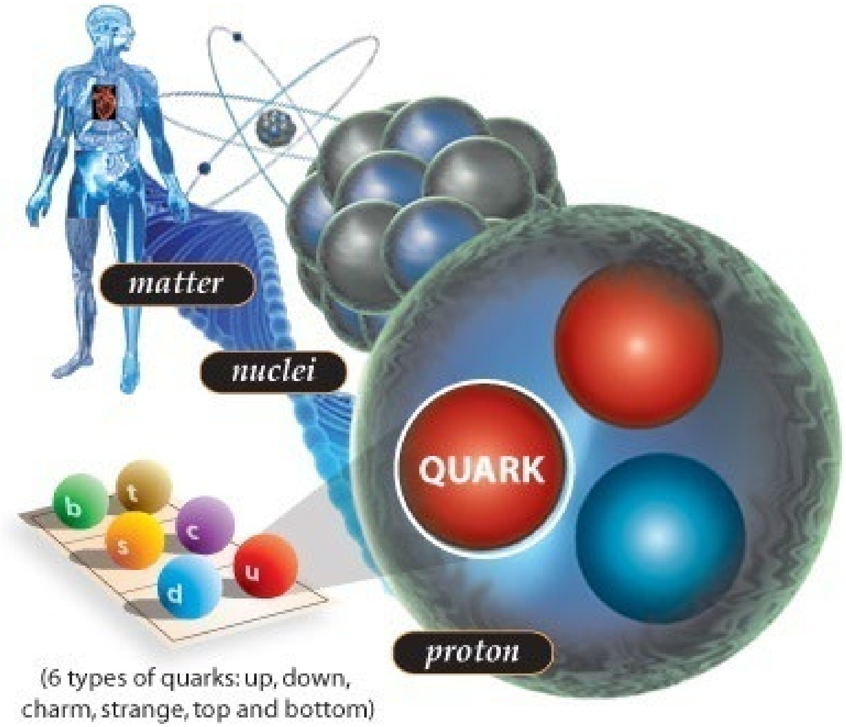
Distribution of Charge or Magnetic Moment

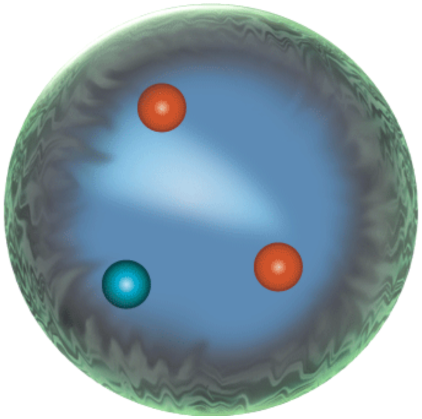


Caveat: The Form Factor as the Fourier transformation of a charge distribution is a non-relativistic concept.

Actually, highly relativistic…

• Protons and neutrons swirl in a heavy atomic nucleus with speeds of up to some ¾ c. More commonly, their speed is some ¼ the speed of light. They are "strong-forced" to reside in a small space.





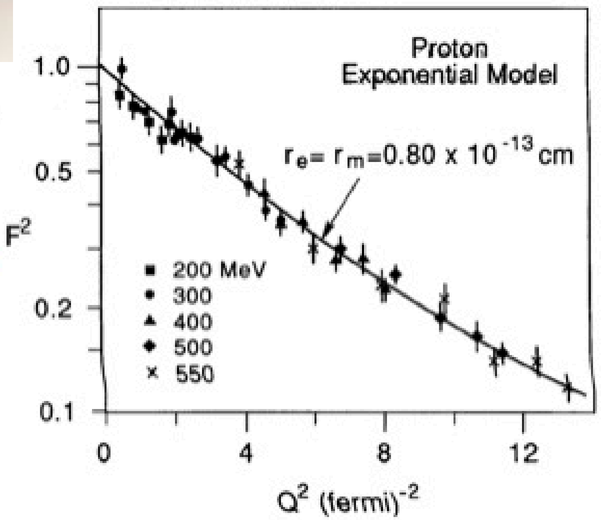
• Quarks (and gluons) are "confined" to the even smaller space inside protons and neutrons. Because of this, they swirl around with the speed of light.

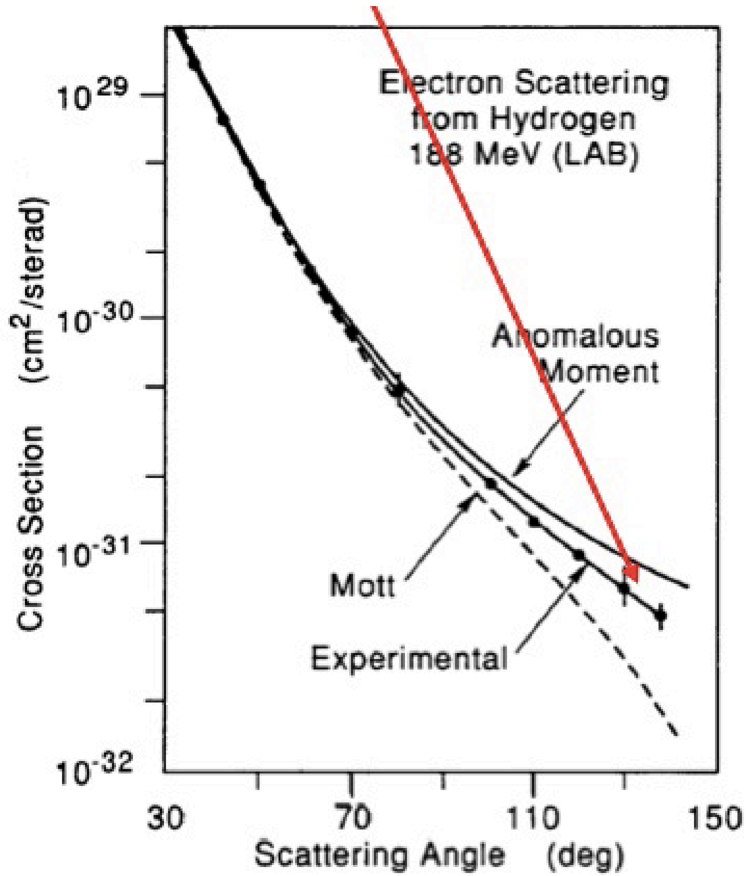
e-p and e-d elastic scattering

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_0^2 \sin^4 \theta/2} \cdot \cos^2 \theta/2 \cdot \frac{E'}{E_0} \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2 \theta/2 \right]$$

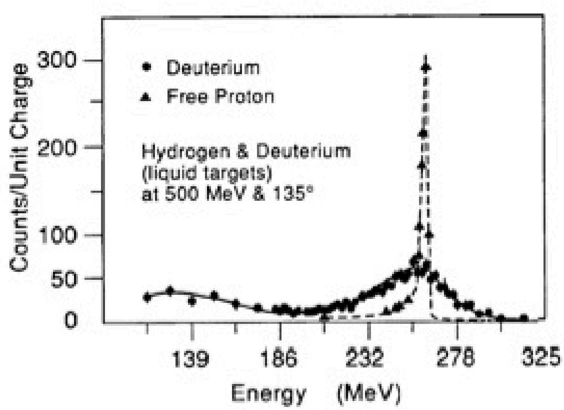
Protons have charge distribution

First determination of the proton form factor



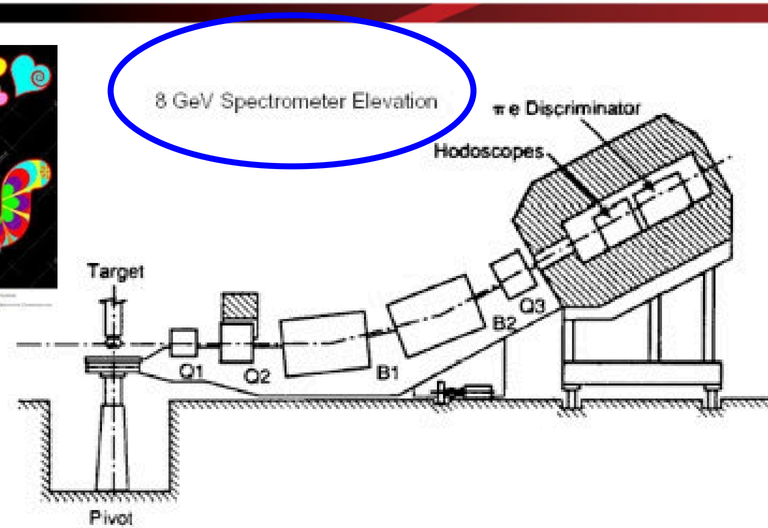


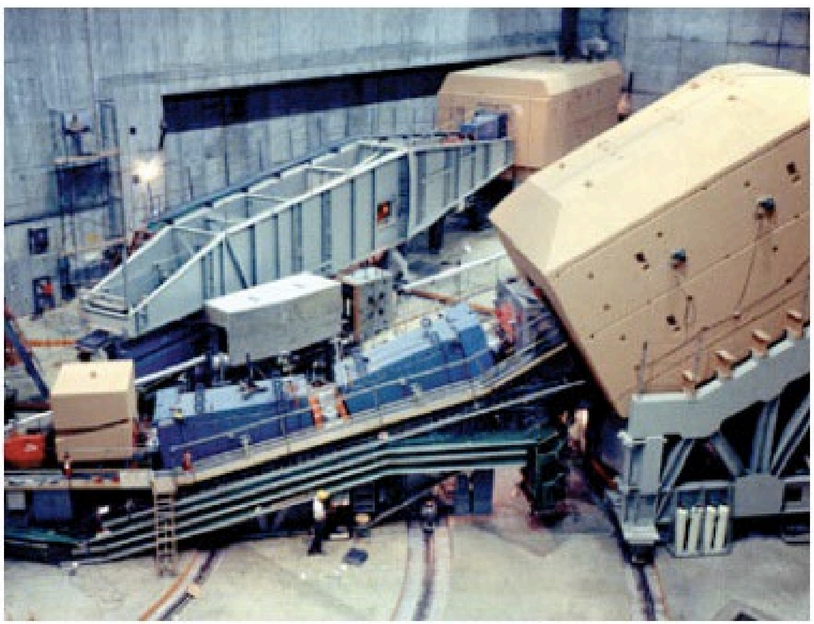
Deuterium smeared out by Fermi energy

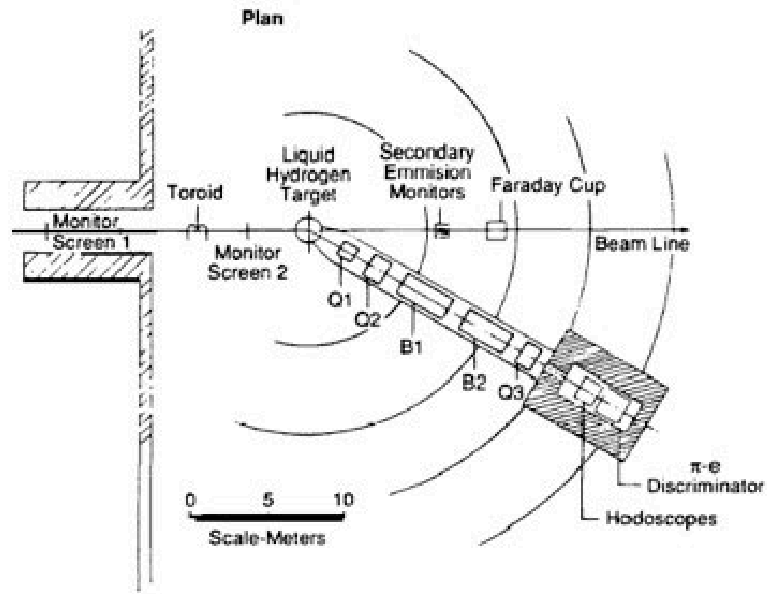


Higher energy e-p and e-d elastic scattering at SLAC

J. Friedman, H.Kendall, R.Taylor
Nobel Prize 1990



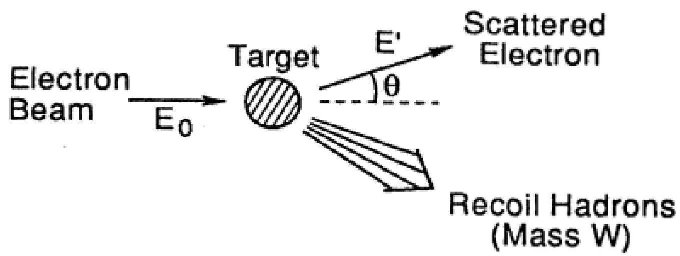




Matter Puzzle: What's Inside the Proton?

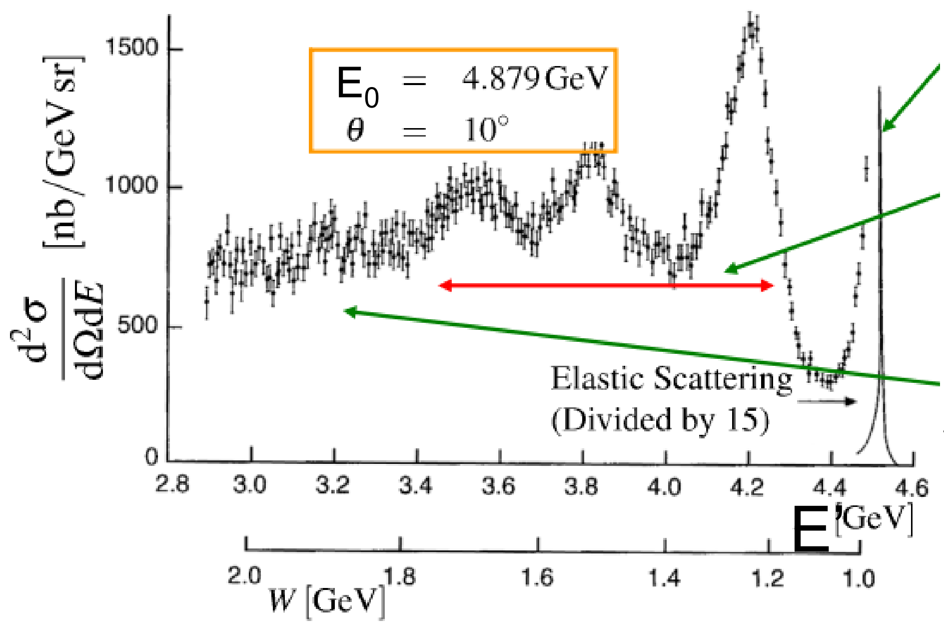
- Is the proton elementary?

To find out increase the probe's ability of resolving structure (decrease $\frac{\hbar}{Q}$)



$$E' = \frac{E_0 - \frac{W^2 - M^2}{2M}}{1 + \frac{2E_0}{M}\sin^2\frac{\theta}{2}} \qquad \nu = E_0 - E' \qquad y = \frac{\nu}{E_0} \qquad x = \frac{Q^2}{2M\upsilon}$$

$$W^2 = M^2 + 2M\upsilon - Q^2$$



Elastic scattering: proton stays intact, $W = M$

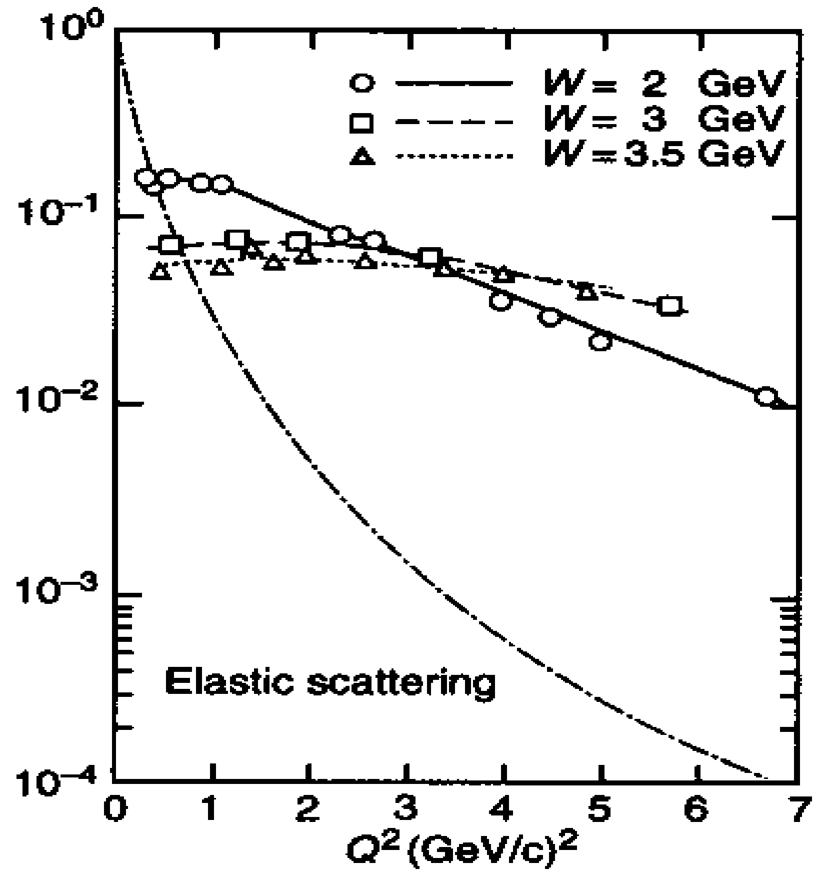
Inelastic scattering: proton gets excited, produce excited states or proton's resonances, $W = M_{resonance}$

Deep inelastic scattering: proton breaks up and we end up with a many particle final state, W = *large*

- Q^2 = four-momentum transfer in electron scattering process
- First SLAC experiment (‘69):
  - expected from proton form factor:

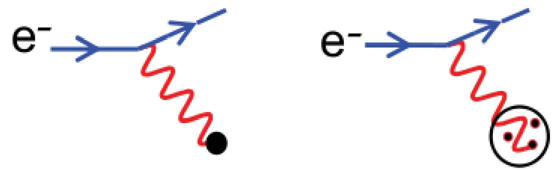
$$\frac{d\sigma / dE' d\Omega}{(d\sigma / d\Omega)_{\mathrm{Mott}}} = \left(\frac{1}{(1+Q^2/0.71)^2} \right)^2 \propto Q^{-8}$$

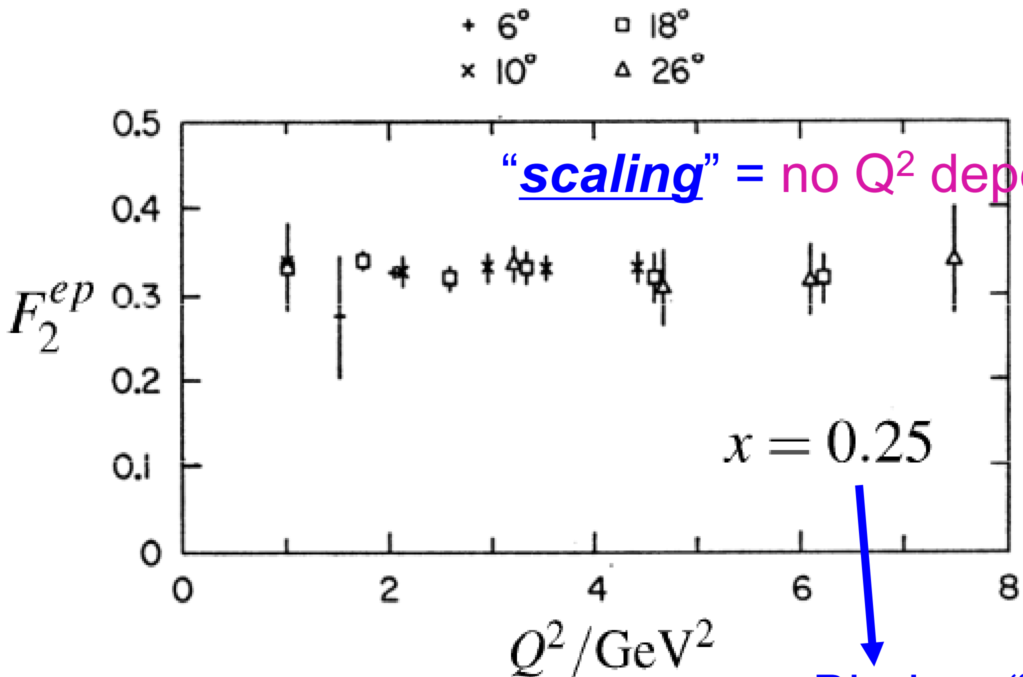
- First data show big surprise:
  - very weak Q^2-dependence
  - scattering off point-like objects?
  - *quark structure of the proton!*



Point-Like Constituents Inside Proton

Scattering from point-like, charged objects in the proton



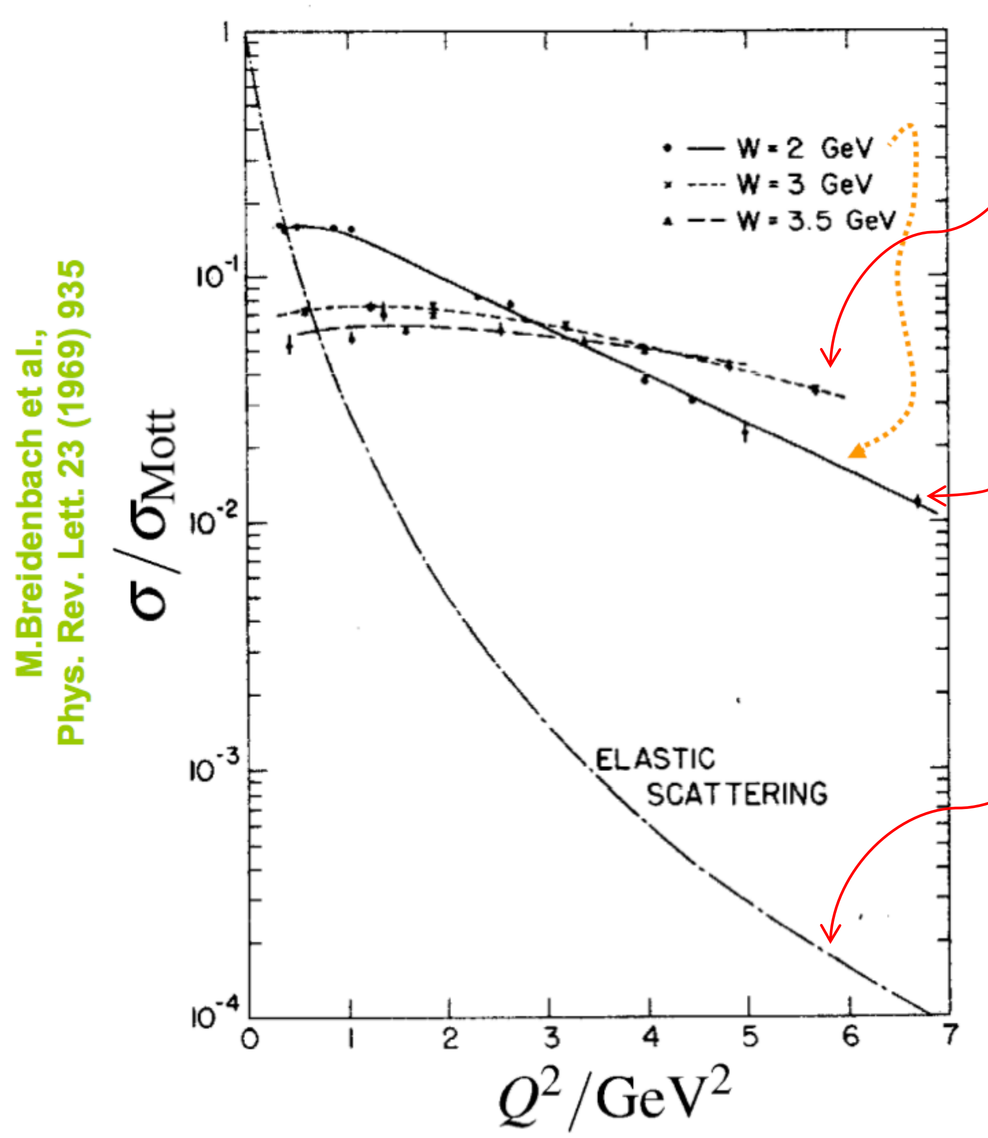


"***scaling***" = no Q^2 dependence

x : Bjorken "scaling" variable ($= Q^2/2M\nu$), *momentum fraction of struck quark*

Structure "looks the same" even as the probe's resolution is increased more and more

Looking deep inside the Proton



- **Deep Inelastic scattering** cross sections almost independent of Q^2!
  i.e. "Form factor" ➔1

Scattering off point-like objects within the proton

- **Inelastic scattering** cross sections only weakly dependent on Q^2

- **Elastic scattering** falls of rapidly with Q^2 due to the proton not being point-like (i.e. form factors)

$$\frac{\sigma}{\sigma_{\mathrm{Mott}}} = \left(\frac{1}{(1+Q^2/0.71)^2}\right)^2 \propto Q^{-8}$$

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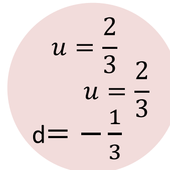
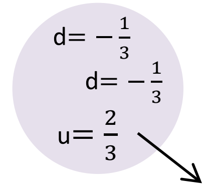
Hypothesis: Quarks/Partons Inside the Proton…

- Gell-Mann, Zweig: Three quarks – u, d, s – combine following well defined rules to make the observed hadrons

static proton 

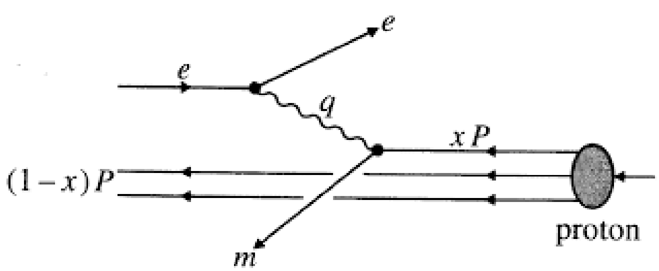


static neutron

valence quark

- Feynman: Quark-Parton model – large Q^2 scattering from quasi-free, point-like, partons

Infinite Momentum Frame: time it takes for virtual photon to couple to partons much smaller than interaction time between partons



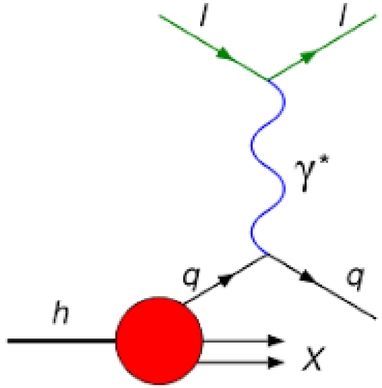
virtual photon couples to a parton carrying momentum fraction x of proton's total momentum

$$F_2(x) = x \sum_q e^2{}_q f_q(x) = 2xF_1(x)$$

longitudinal momentum distribution of partons inside proton: parton distribution functions

towards a dynamical proton and neutron

Structure Functions in Deep Inelastic Electron-Nucleon Scattering



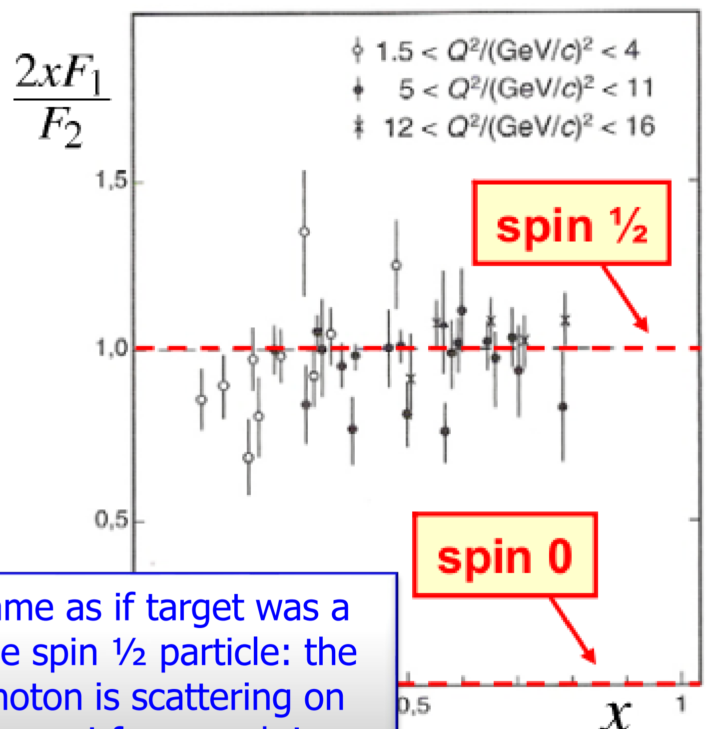
Probability of inelastic interaction:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2{}_0 \sin^4\frac{\theta}{2}} \cos^2\frac{\theta}{2}\left[\frac{1}{\nu} F_2(x,Q^2) + \frac{2}{M} F_1(x,Q^2) \tan^2\frac{\theta}{2}\right]$$

Unpolarized *"Structure Functions"* $F_1(x,Q^2)$ and $F_2(x,Q^2)$:

- Account for the sub-structure of the protons and neutrons
- Give access to *partonic structure* of the nucleon, i.e.

$$F_2^p = x\left[\tfrac{4}{9}(u+\overline{u}) + \tfrac{1}{9}(d+\overline{d}) + \tfrac{1}{9}(s+\overline{s})\right]$$

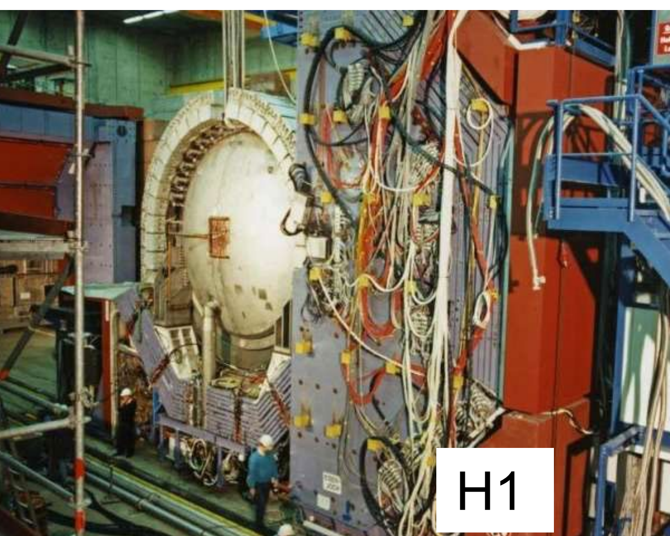


Same as if target was a free spin ½ particle: the photon is scattering on quasi-free quark !

- Comparing the DIS cross section formula with the Mott and Dirac elastic cross sections for particles of mass m = xM and spin 1/2
- *If point-like constituents were spin zero particles, we would expect F_1 to be zero*

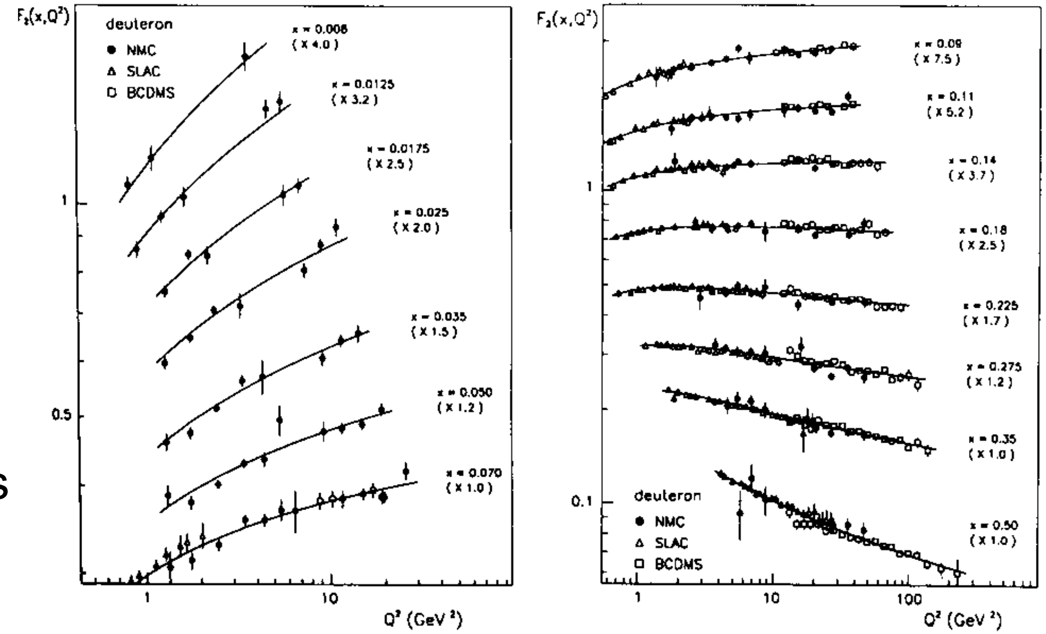
Fast forward….

30+ years of charged lepton Deep Inelastic Scattering at *multiple* laboratories including SLAC (to ~2000), CERN 80-90s EMC, NMC, BCDMS..), DESY (90s – 21st century H1, ZEUS,...), and ***more!***



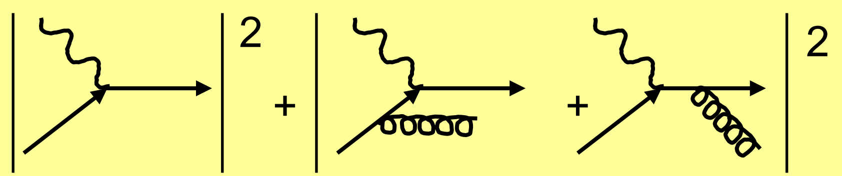
QuantumChromoDynamics prediction: scaling *violations*

- Originally: $F_2 = F_2(x)$
  - but also Q^2-dependence
- Why scaling *violations*?
  - if Q^2 increases:
    - $\Rightarrow$ more resolution ($\sim 1/\,Q^2$)
    - $\Rightarrow$ more sea quarks +gluons



- QCD improved QPM:

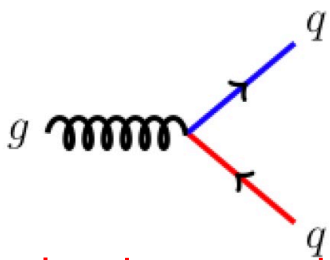
$$\frac{F_2(x,Q^2)}{x} =$$



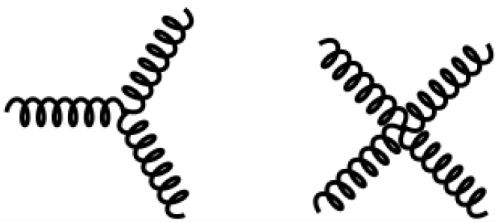
- Dokshitzer-Gribov-Lipatov-Altarelli-Parisi ("DGLAP") Evolution…

Quantum Chromo Dynamics

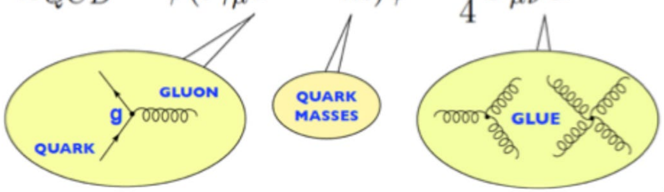
Gluons are the messengers for the quark-quark interactions
Quantum Chromo Dynamics (QCD) is the theory that governs their behaviour



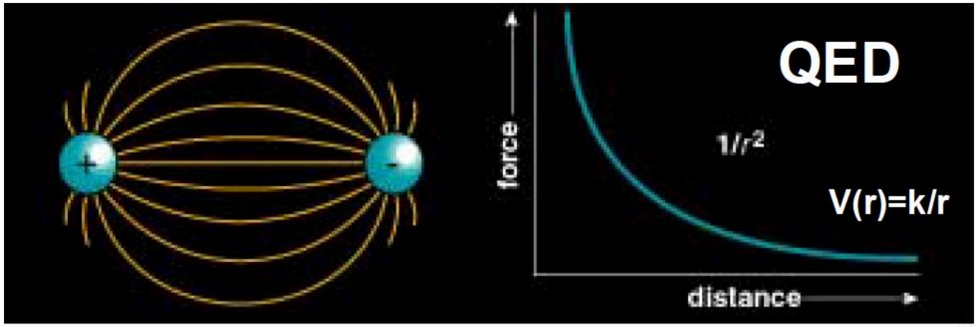
Gluons carry color charge, and we can draw 3- and 4- gluon diagrams *(self-interaction)*

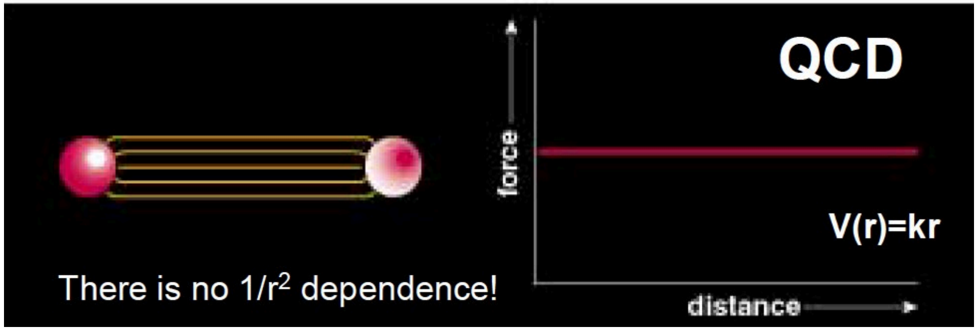


$$\mathcal{L}_{QCD} = \bar{\psi}(i\gamma_\mu D^\mu - m)\psi - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$$

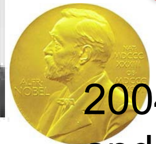


The strong force does not get weaker with large distances (opposite to the EM force) and blows up at distances around 10^{-15} m (the radius of the nucleon)

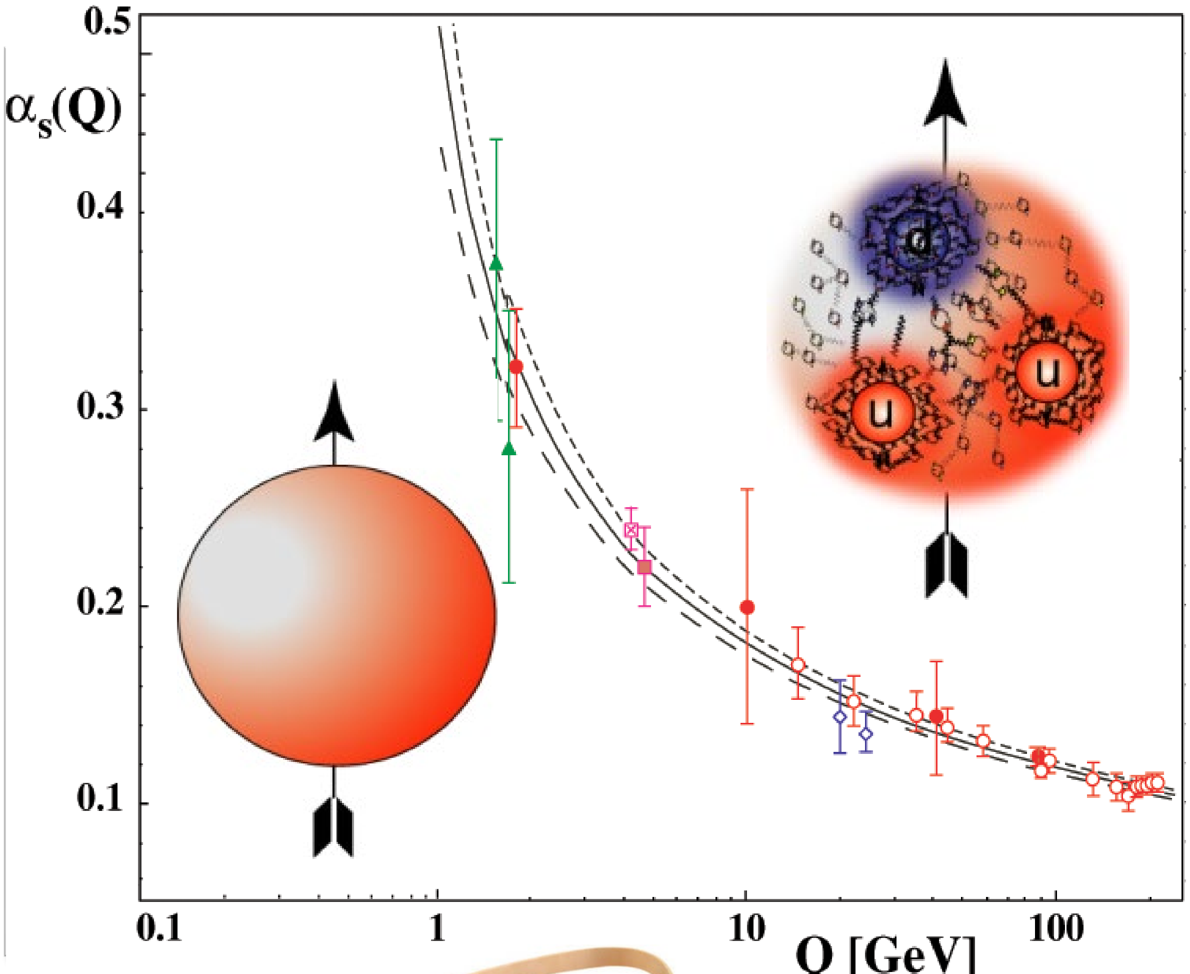




Quantum ChromoDynamics



2004 David Gross, David Politzer and Frank Wilczek



At short distances

quarks move as though they are free → **Asymptotic freedom**

Physics at short distance is understood through perturbation theory - $\alpha_s(m_Z)$= 0.1189(10)

Perturbative QCD tested up to 1% level

At longer distances

Confinement ensures that only hadronic final states are observed

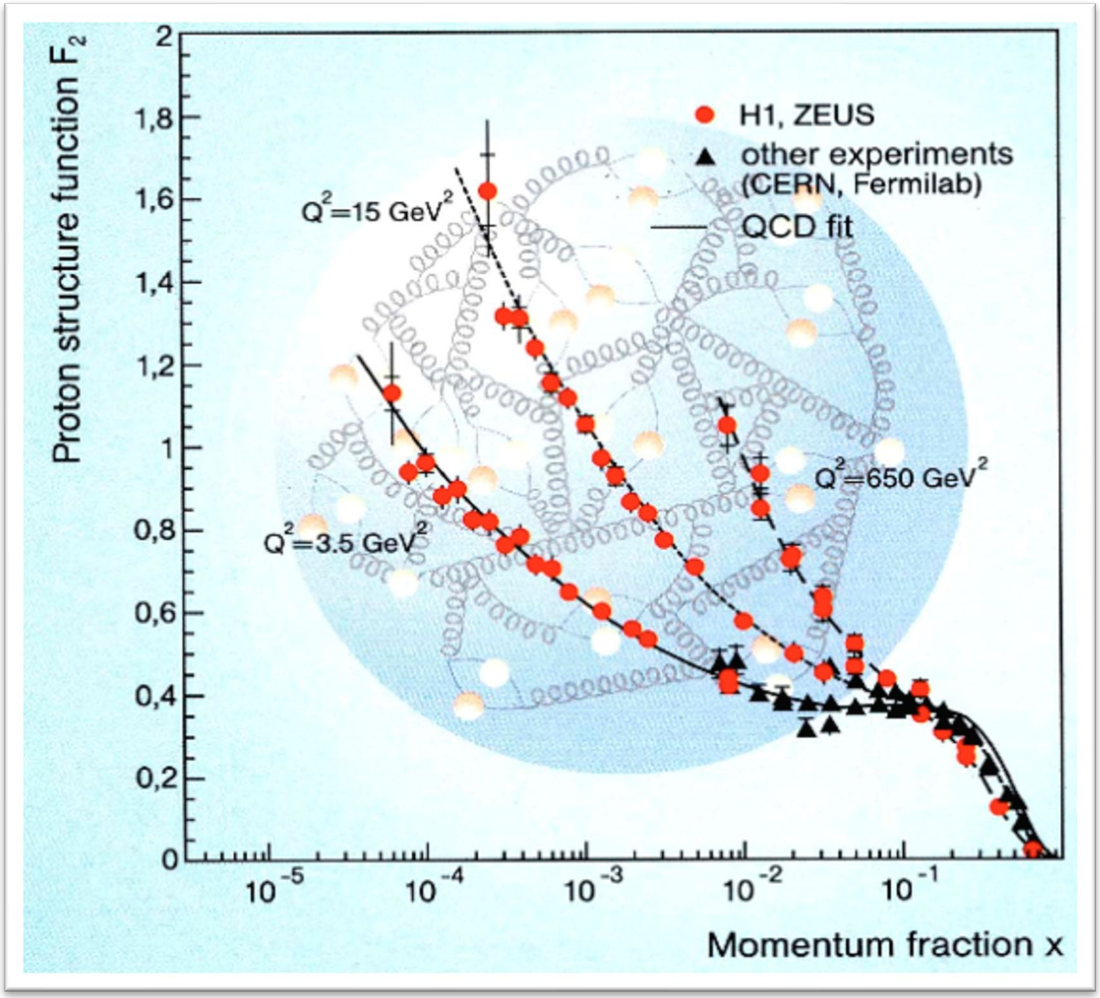
Quarks can be removed from the proton, but cannot be isolated!!!

We never see a free quark

<u>QCD still unsolved in non-perturbative region</u>

Insights into soft phenomena exist through qualitative models and quantitative numerical (lattice) calculations

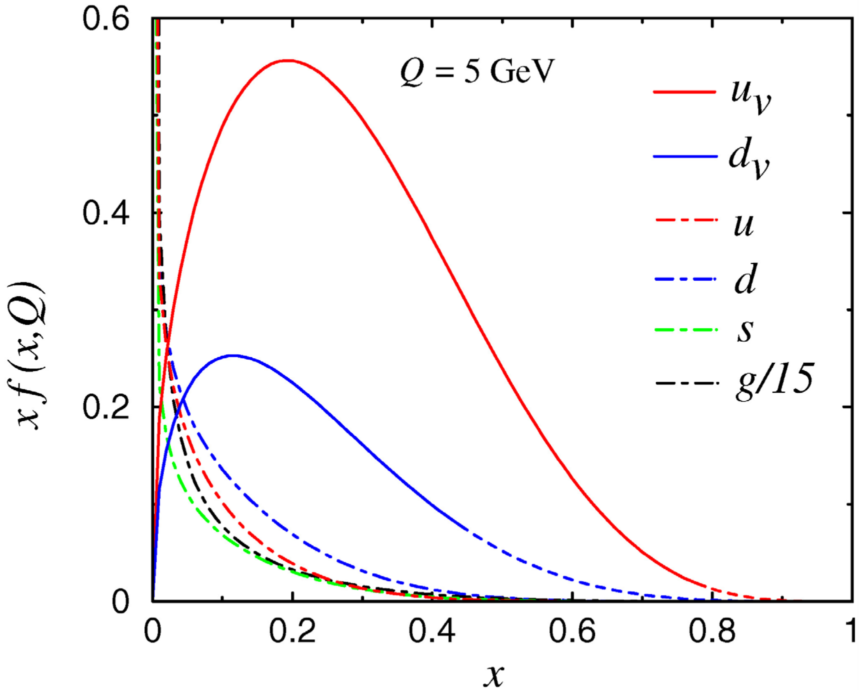
Scaling Violations

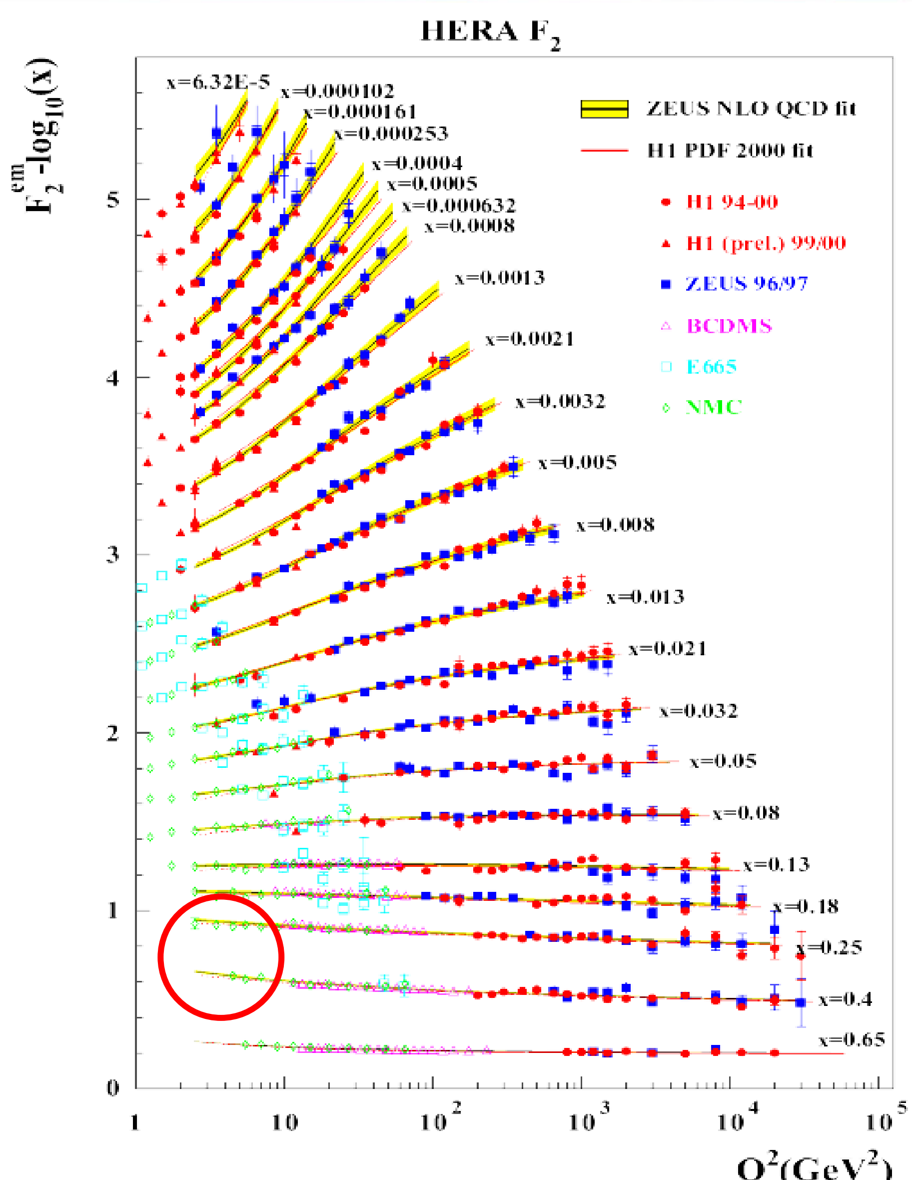


- Scaling violation is due to the fact that the quarks radiate gluons that can "materialize" as q-qbar pairs (sea quarks)
- Increasing Q^2 increases the resolution of the probe ($\sim\hbar/\sqrt{Q^2}$) and thus increases the number of partons that are "seen" bring a fraction x of the proton momentum
- The parton distribution functions (PDFs) can not be calculated from first principle of QCD but their Q^2 dependence is calculable in perturbative QCD using the DGLAP evolution equations

Q^2 Evolution of the F_2 *Proton* Structure Function

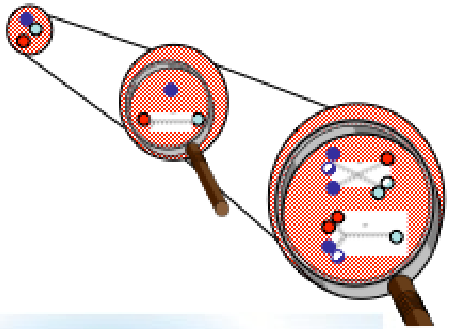
F_2^p Structure Function measured over impressive range of x and Q^2

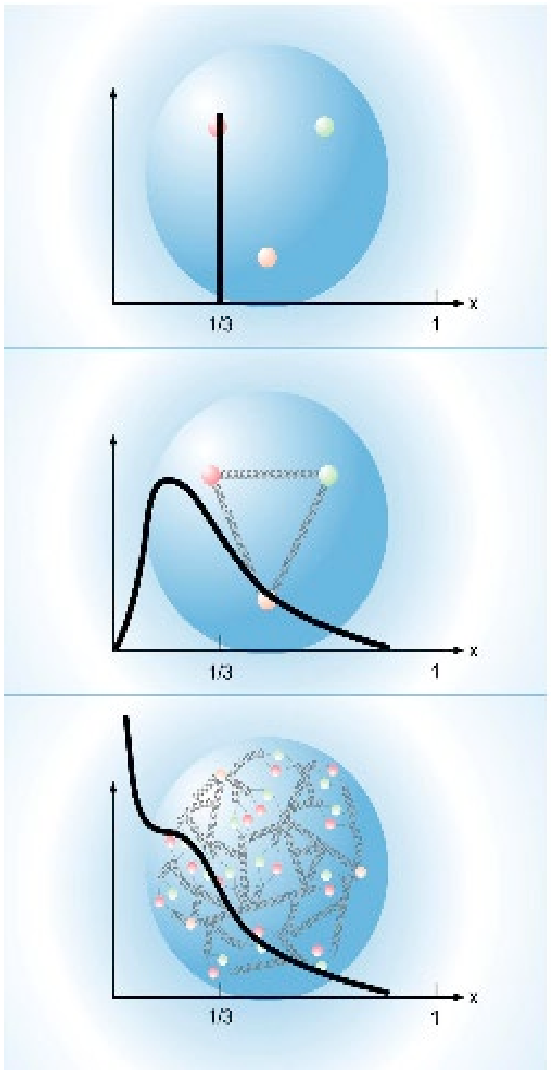


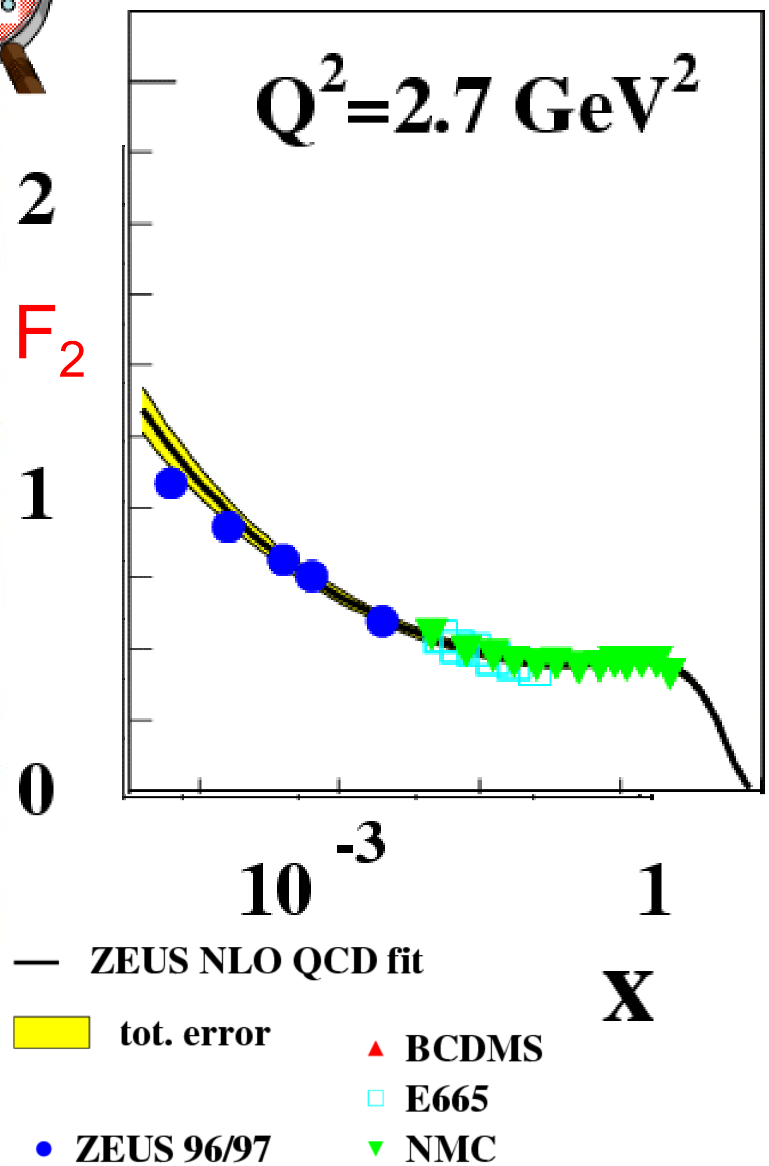


Allows extraction of "Parton Distribution Functions" f(x,Q^2) - think momentum distribution of quarks

Proton Structure Function F_2







Q^2 dependence described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations

Increasing Q^2:

- High x decrease
- Low x increase

Allows extraction of Parton Distribution Functions $f(x,Q^2)$ through Q^2 evolution From high x, low Q to high Q, low x

Factorization

The fundamental assumption of the Quark Parton Model is factorization:

The process of hadronization occurs on longer time scales compared to the elementary lepton - parton scattering , so it is possible to conclude that there is a factorization between hard scattering process lepton - parton and processes between soft partons , leading to their recombination to form colorless hadrons.

In other words the two phenomena , in good approximation, are decoupled. The former are calculable using perturbative QCD (pQCD), in principle, with arbitrary accuracy; the latter, instead, are parameterized in the form of phenomenological functions a priori unknown, e.g. Parton Distribution Functions.

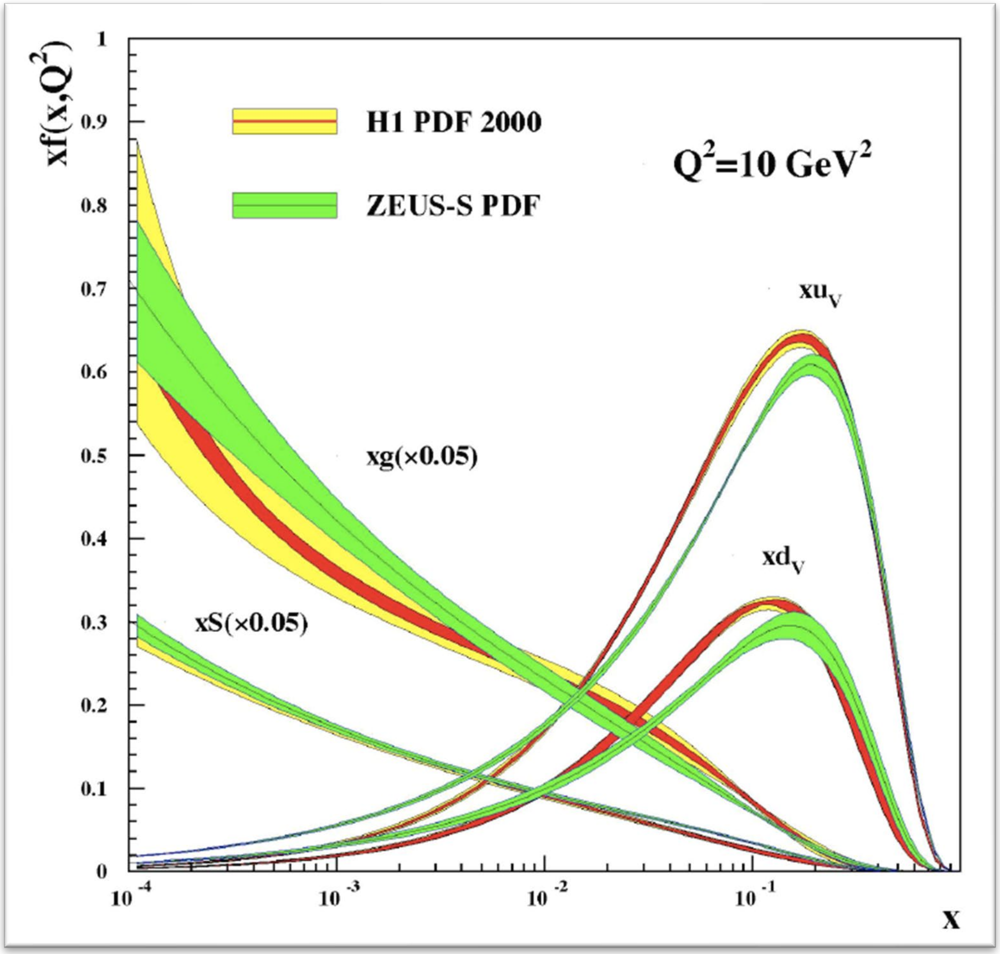
They can therefore be extracted from the comparison with the experimental data of a certain process, and to be reinserted in the calculation of the cross section of a another hard process to make predictions

➥ **Factorization and universality test**

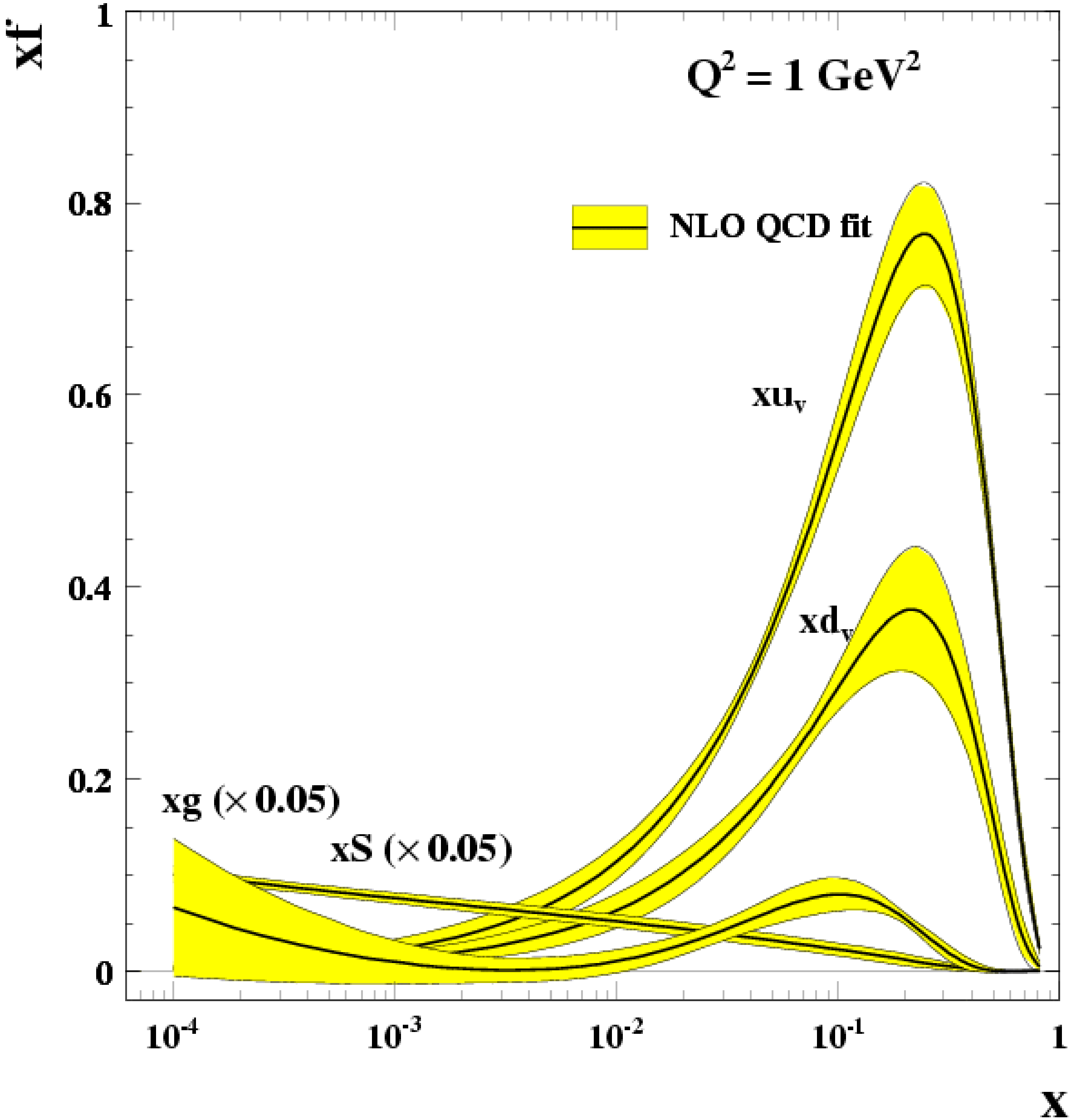
PDF Extractions

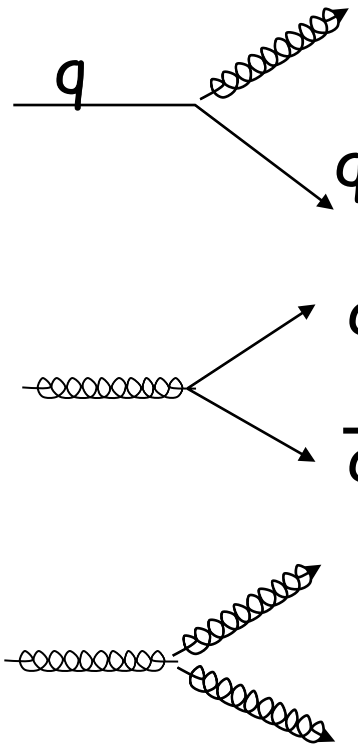
- A large range of available deep inelastic and related hard scattering data involving incoming protons (and antiprotons) are used to determine the parton densities, f_i of the proton.

- The procedure is to parametrize the x dependence of $f_i(x,Q^2_0)$ at some low, yet perturbative, scale Q^2_0. Then to use the DGLAP equations to evolve the f_i up in Q^2, and to fit to available data (DIS structure functions, Drell-Yan production, Tevatron jet and W production...) to determine the values of the input parameters



Parton Distribution Functions and QCD Evolution

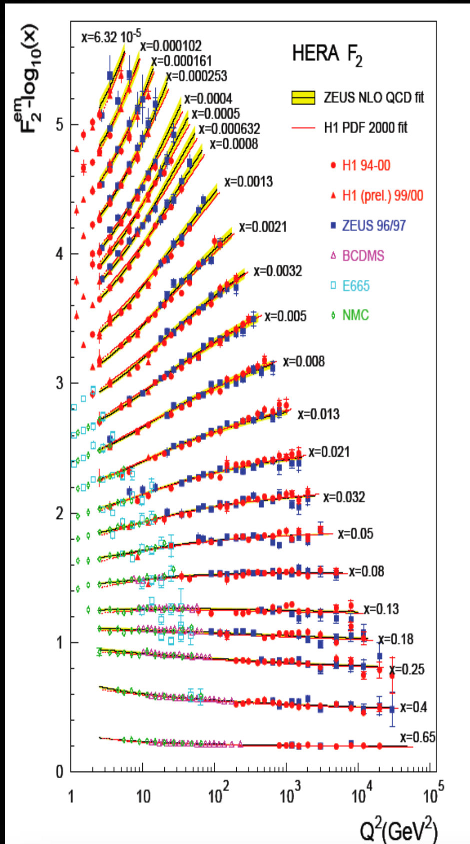




Valence quarks maximum around *x=0.2; f(x) →0* for x→1 and x→0

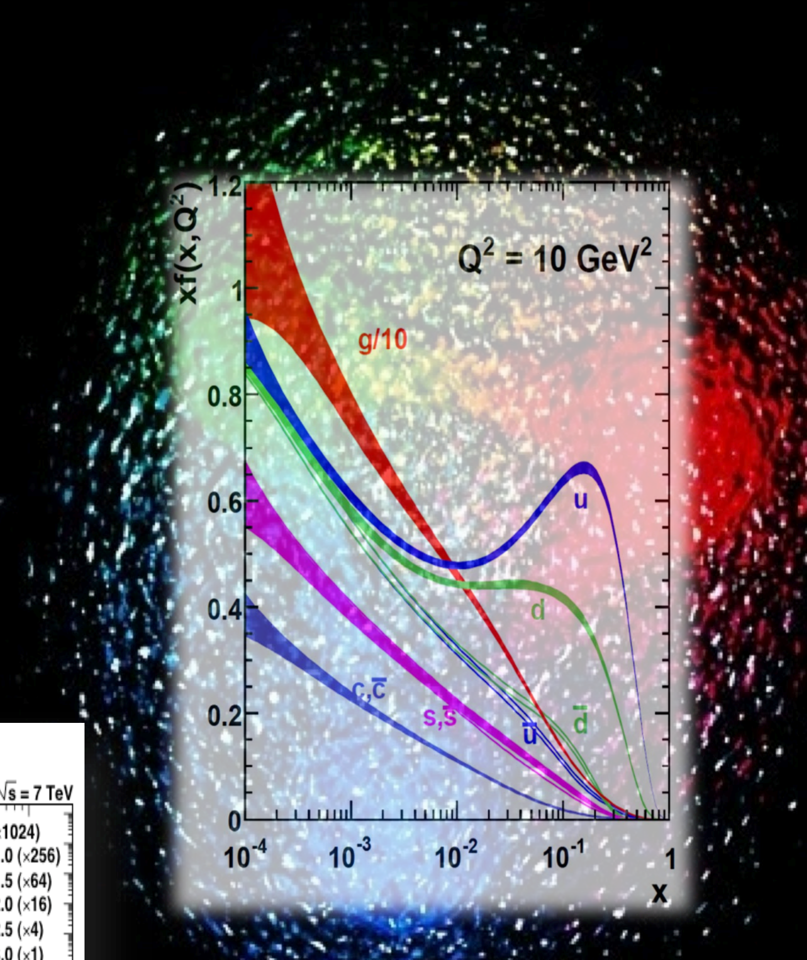
Sea quarks and gluons - contribute at low values of x

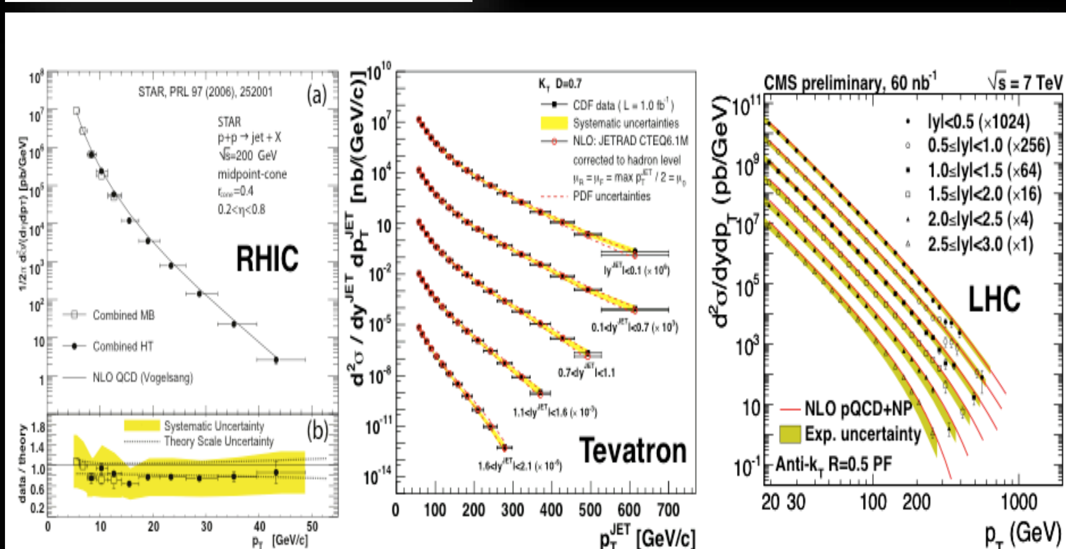
QCD Success !



Measure e-p @ 0.3 TeV (HERA)

p-p and p-$\bar{p}$ at 0.2, 1.96, and 7 TeV





Lepton Scattering: a Powerful Tool

The best evidence we have for what the nucleon looks like comes from electron scattering experiments

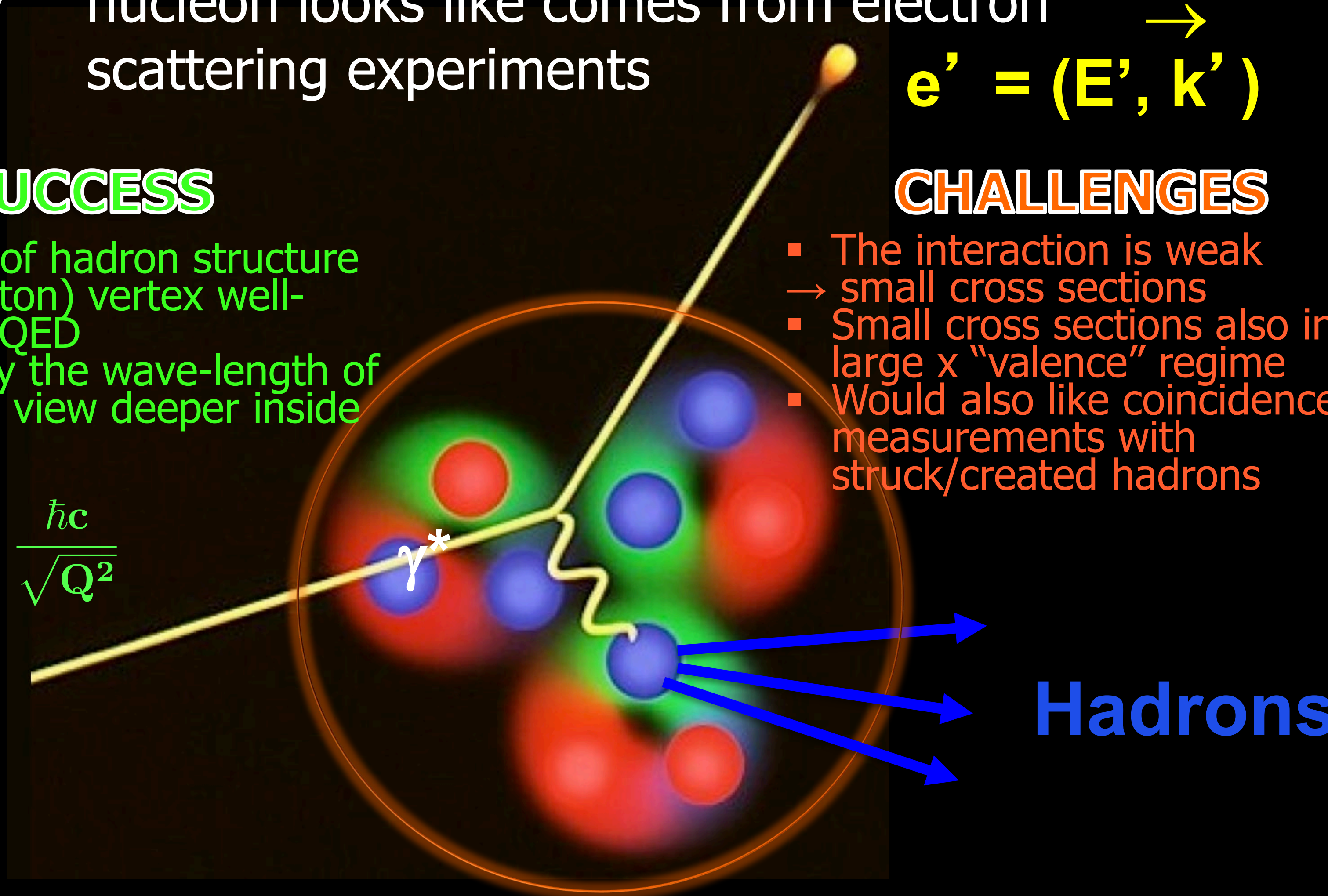
SUCCESS

- Clean probe of hadron structure
- Electron (lepton) vertex well-known from QED
- One can vary the wave-length of the probe to view deeper inside the hadron

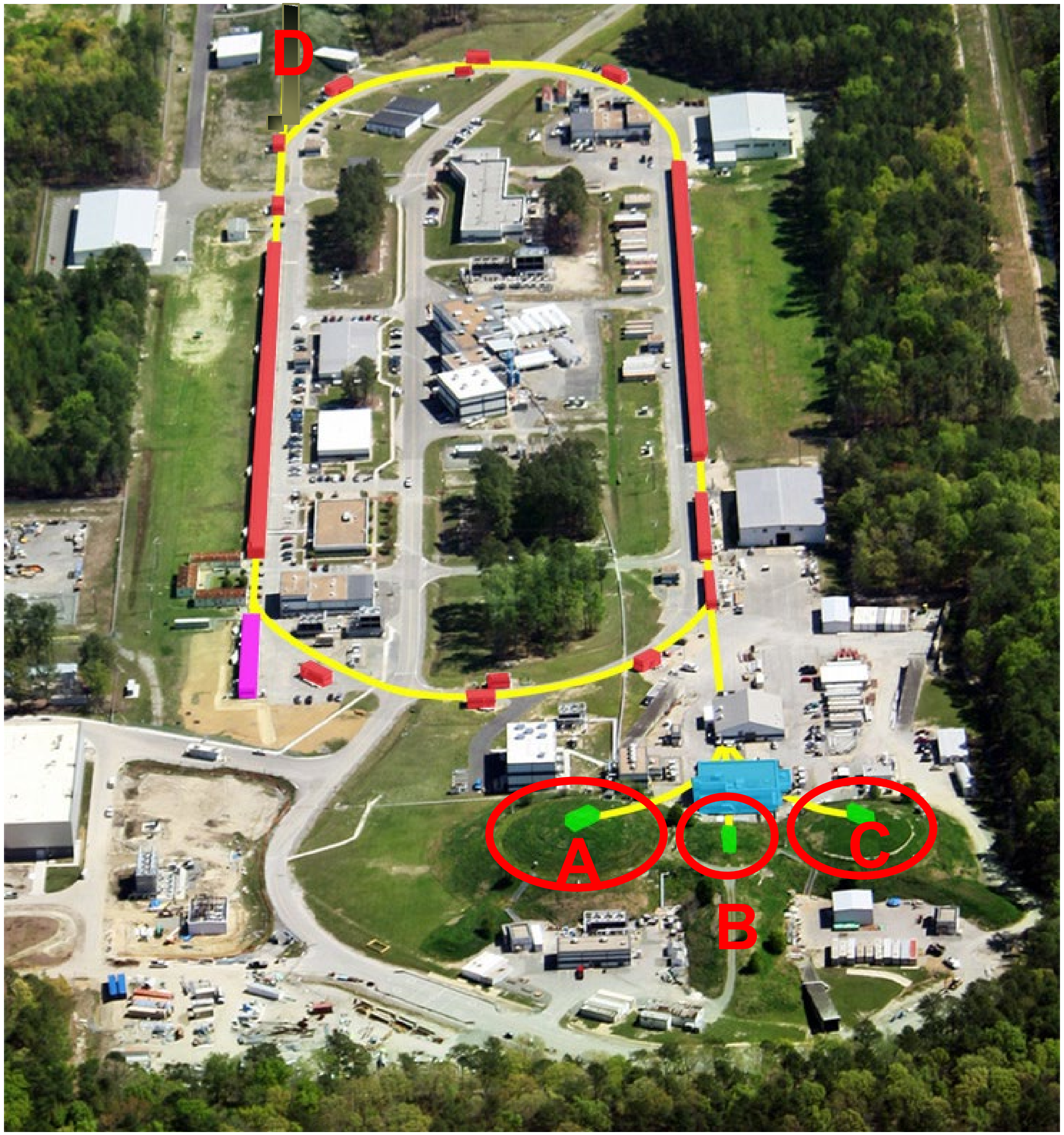
$$\lambda \sim \frac{\hbar c}{\sqrt{Q^2}}$$

CHALLENGES

- The interaction is weak → small cross sections
- Small cross sections also in large x "valence" regime
- Would also like coincidence measurements with struck/created hadrons



Jefferson Lab **Continuous Electron Beam** Accelerator Facility



1995 - 2012…

Energy 0.4 — 6.0 GeV

• 200 μA, polarization 85%

• Simultaneous delivery 3 halls

• 500+ PhDs completed

• On average 22 US PhDs per year, roughly 25-30% of US PhDs in nuclear physics

•1530 users in FY2016, ~1/3 international from 37 countries

~2016 - …..

Energy 0.4 — 12.0 GeV

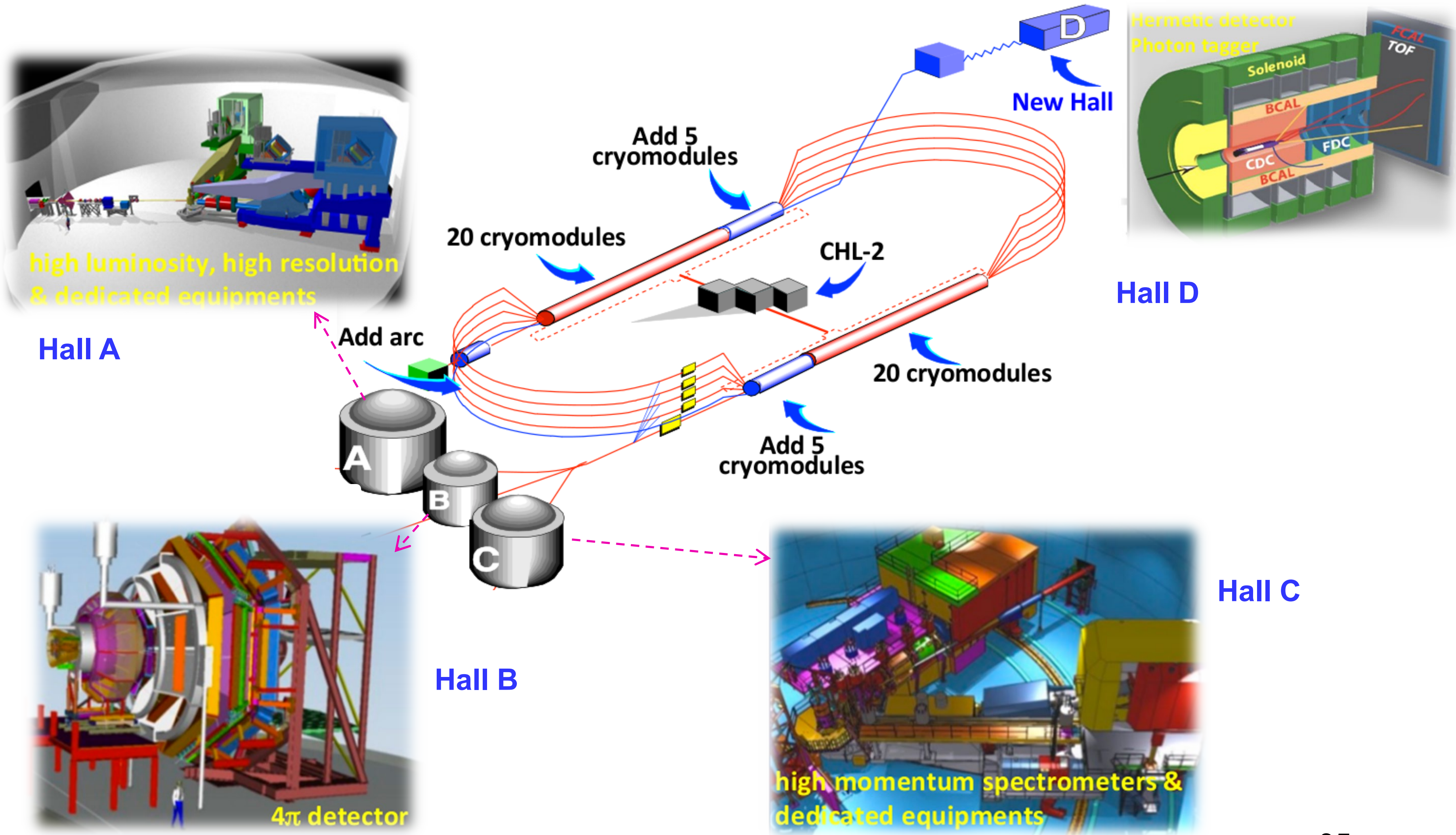
• 150 μA, polarization ~85%

• Simultaneous delivery 4 halls

• FY18: First try simultaneous delivery to 4 halls – A, B, C, D

Jefferson Lab at 12 GeV: What Are We After?

- **Jefferson Lab Mission**: mechanism of confinement, partonic structure of nucleon, quark and gluon dynamics in the nuclear medium, nucleon spin decomposition, role of gluonic excitations in mesons…



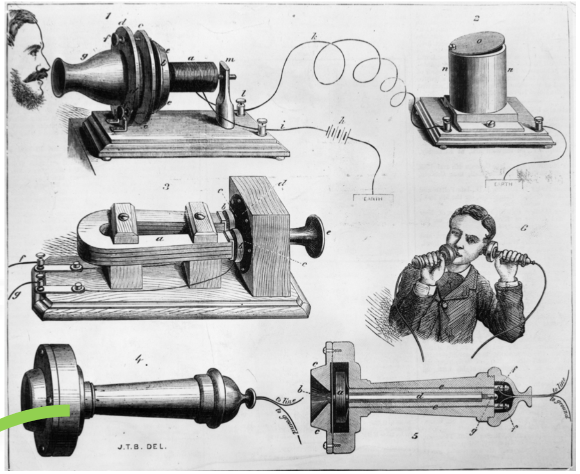
Lecture Scheme

DAYS 1 - 2

- ✓ Introduction
- ✓ History and Basics of Electron Scattering
- ✓ Jefferson Lab
- 1D Nucleon Structure

DAYS 2 - 3

- 3D Nucleon Structure
- Nucleons in the Nuclear Medium
- *Other topics*




Break

Get some rest
Have some
coffee

KEEP
CALM
AND
GET SOME
REST