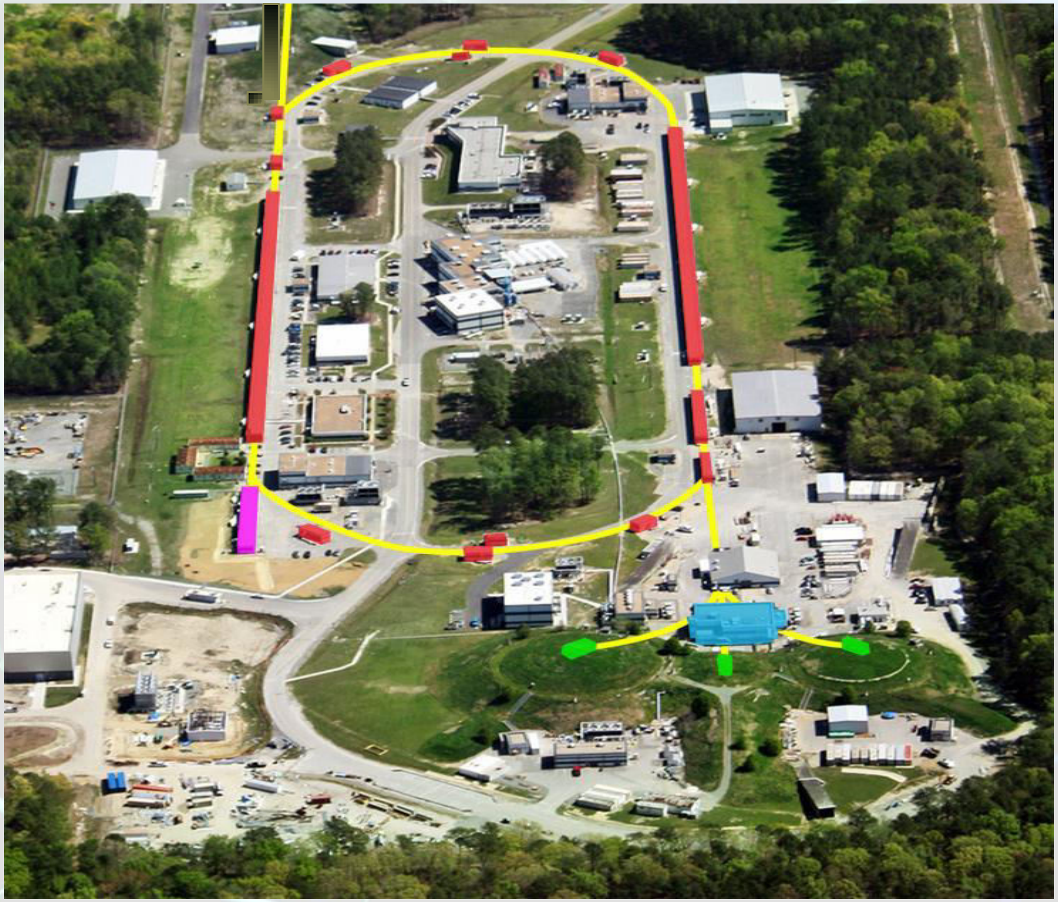
The Particle/Nuclear Interface - I

Thia Keppel

CTEQ Summer School



Lecture Scheme

in·ter·face
ˈin(t)ərˌfās/ *noun*
1. a point where two systems, subjects, etc., meet and interact.

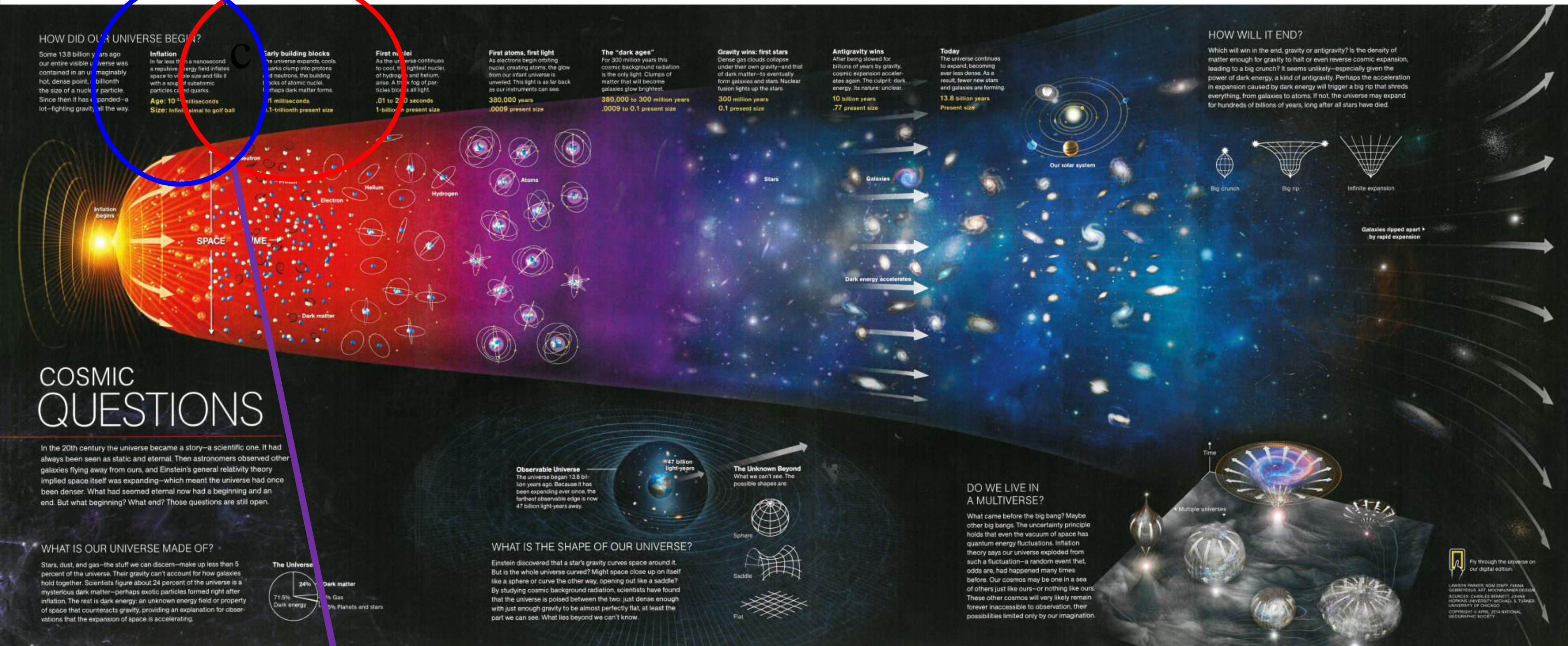
DAY 1

- Introduction
- History and Basics of Electron Scattering – *Some Reminders*
- Jefferson Lab
- 1D to 3D Nucleon Structure
  - Form Factors and PDFs
  - Large x
- Nucleons in the Nuclear Medium

DAY 2

- *Finish What I Didn't Yet From Day 1!*
- The Electron Ion Collider

Particle and Nuclear Physics - Related Questions

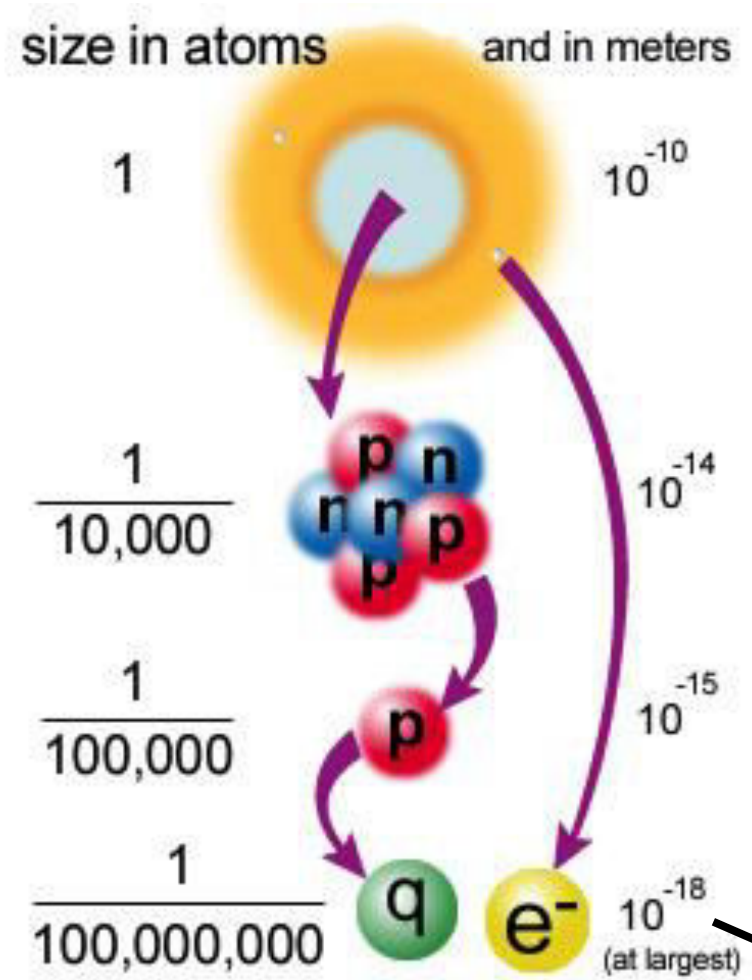


NATIONAL GEOGRAPHIC

Nuclear Physics Seeks 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/lepton 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!

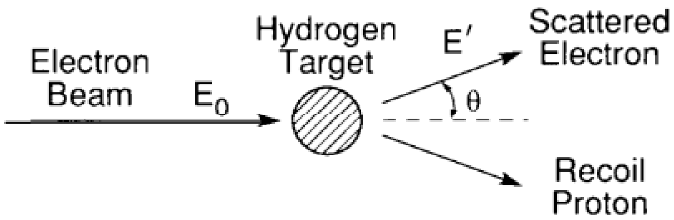
$$d_{probed} \propto \lambda\!\!\!^{-} = \frac{\hbar}{p} \approx 10^{-18}\ \mathrm{m}$$

short distance -> large momentum
(Uncertainty Principle!)

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



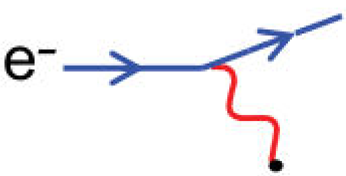
$$q = (E_0 - E', \vec{q}\,)$$

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

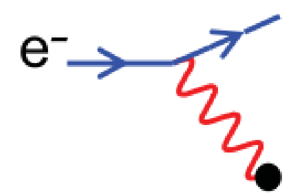
electron is left with less energy after meeting the proton

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

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



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



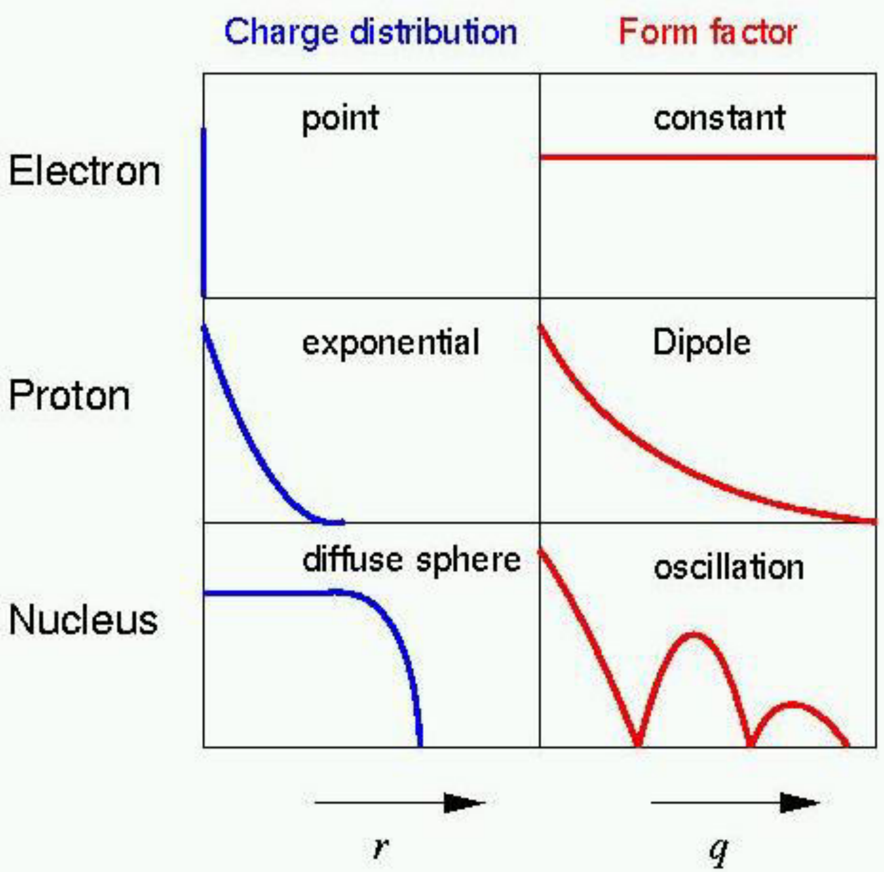
proton when $\frac{\hbar}{Q}$ >> than its size

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

Charge and Magnetic Moment Distributions

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

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



- Elastic cross section

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

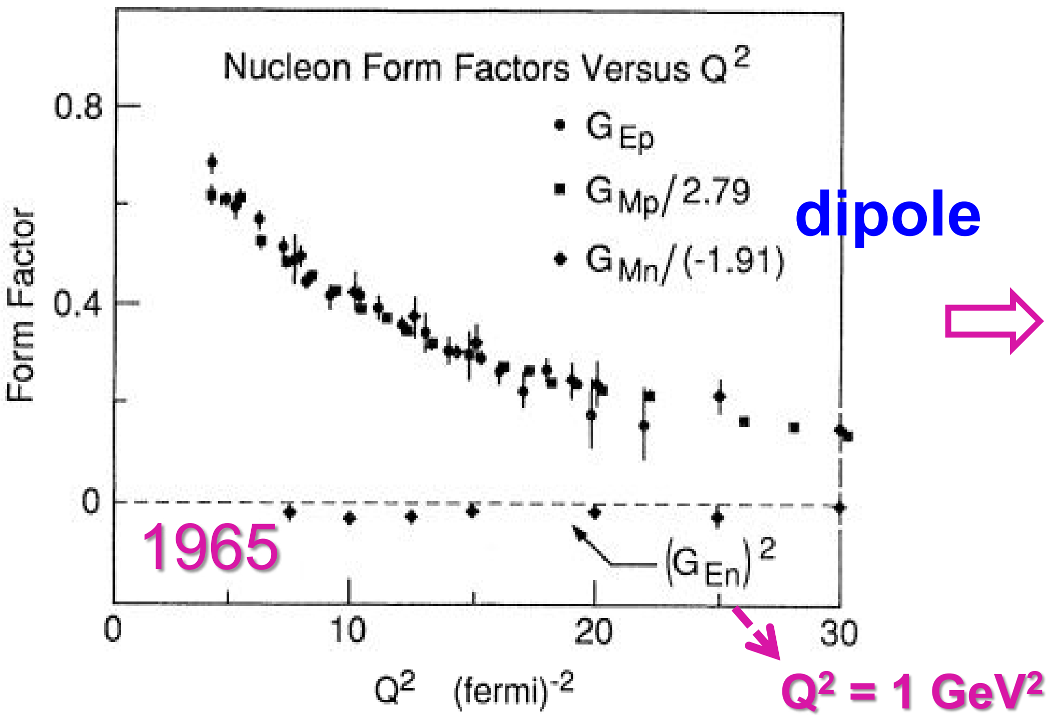
- Form factor

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

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…



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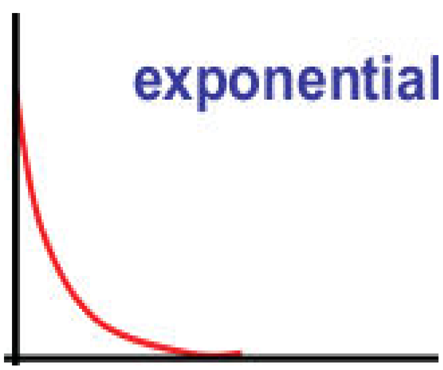
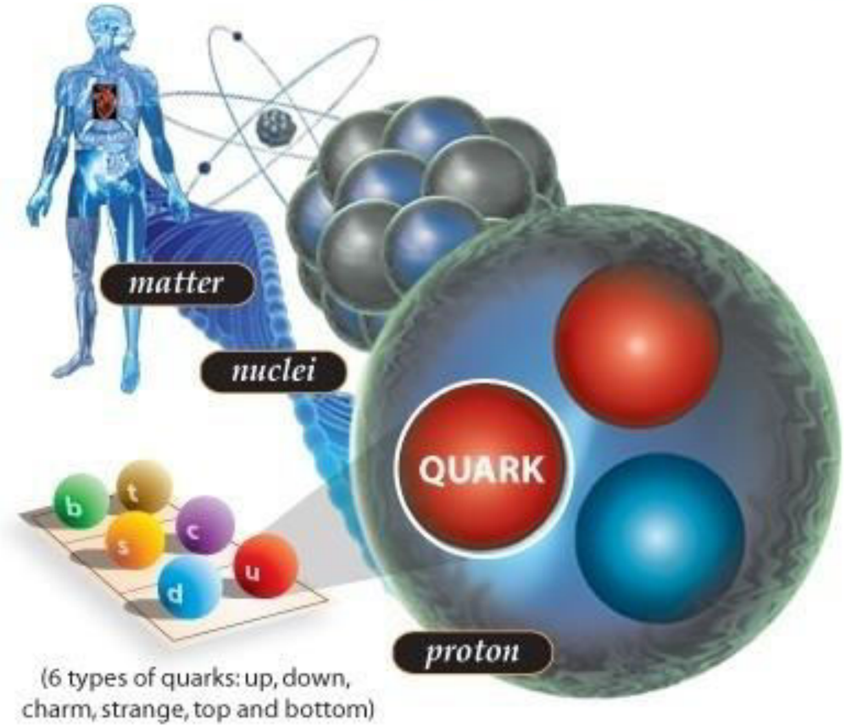
Distribution of Charge or Magnetic Moment



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

Actually, highly relativistic…

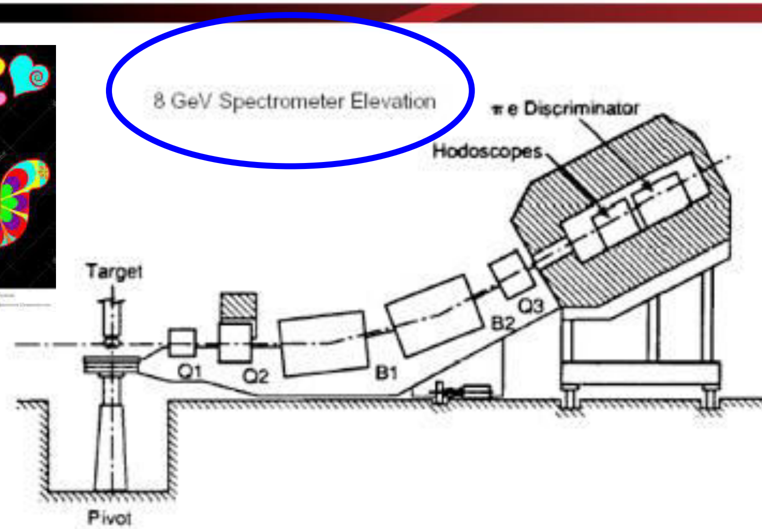
- Protons and neutrons swirl in a heavy atomic nucleus with speeds of up to some ¾ c. More commonly, their speed is some ¼ the speed of light. They are "strong-forced" to reside in a small space.

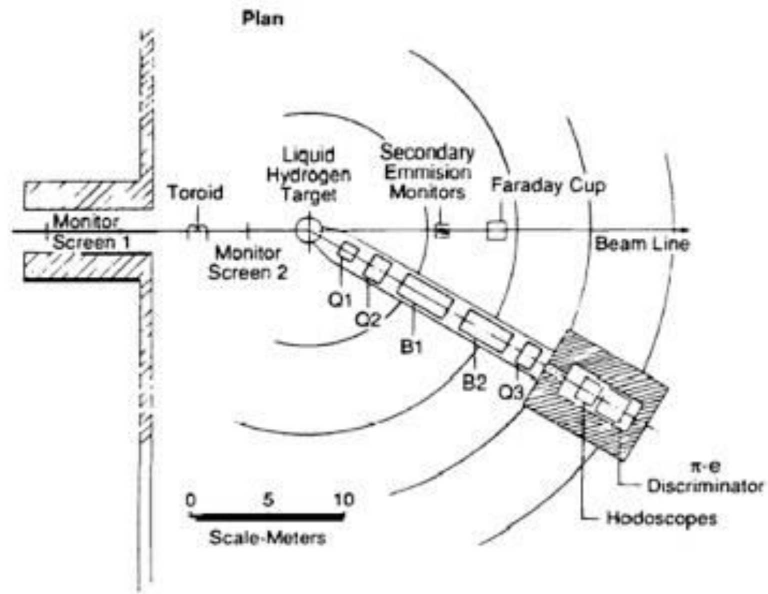


- Quarks (and gluons) are "confined" to the even smaller space inside protons and neutrons. Because of this, they swirl around with the speed of light.

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

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

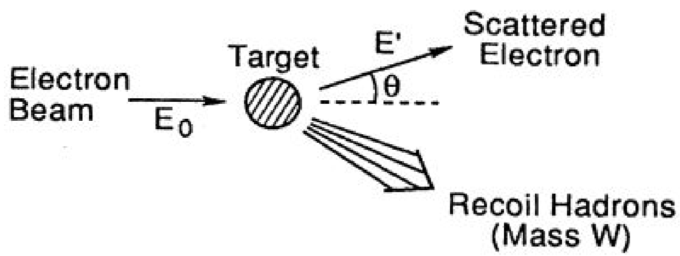




Matter Puzzle: What's Inside the Proton?

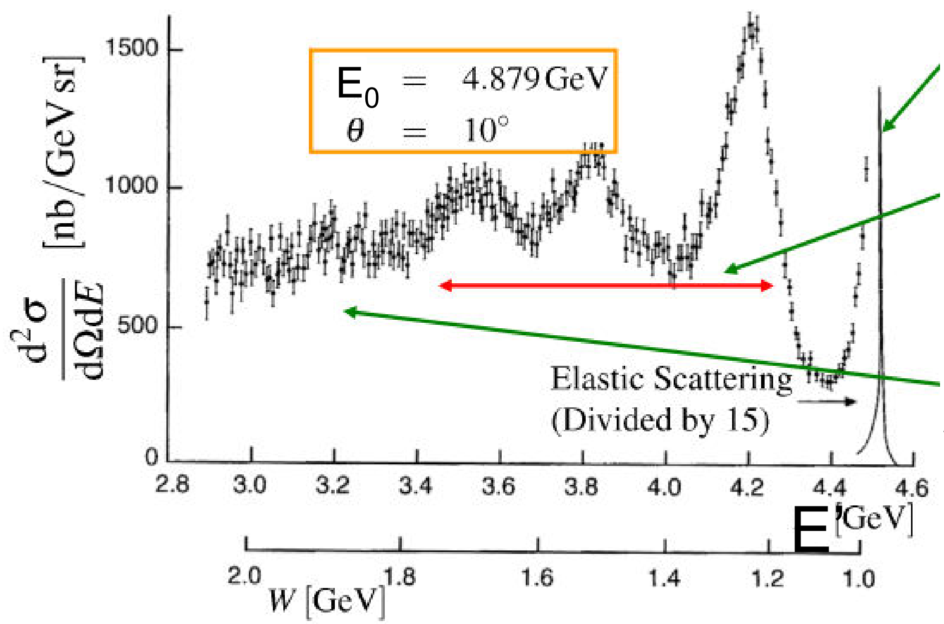
- Is the proton elementary?

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



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

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

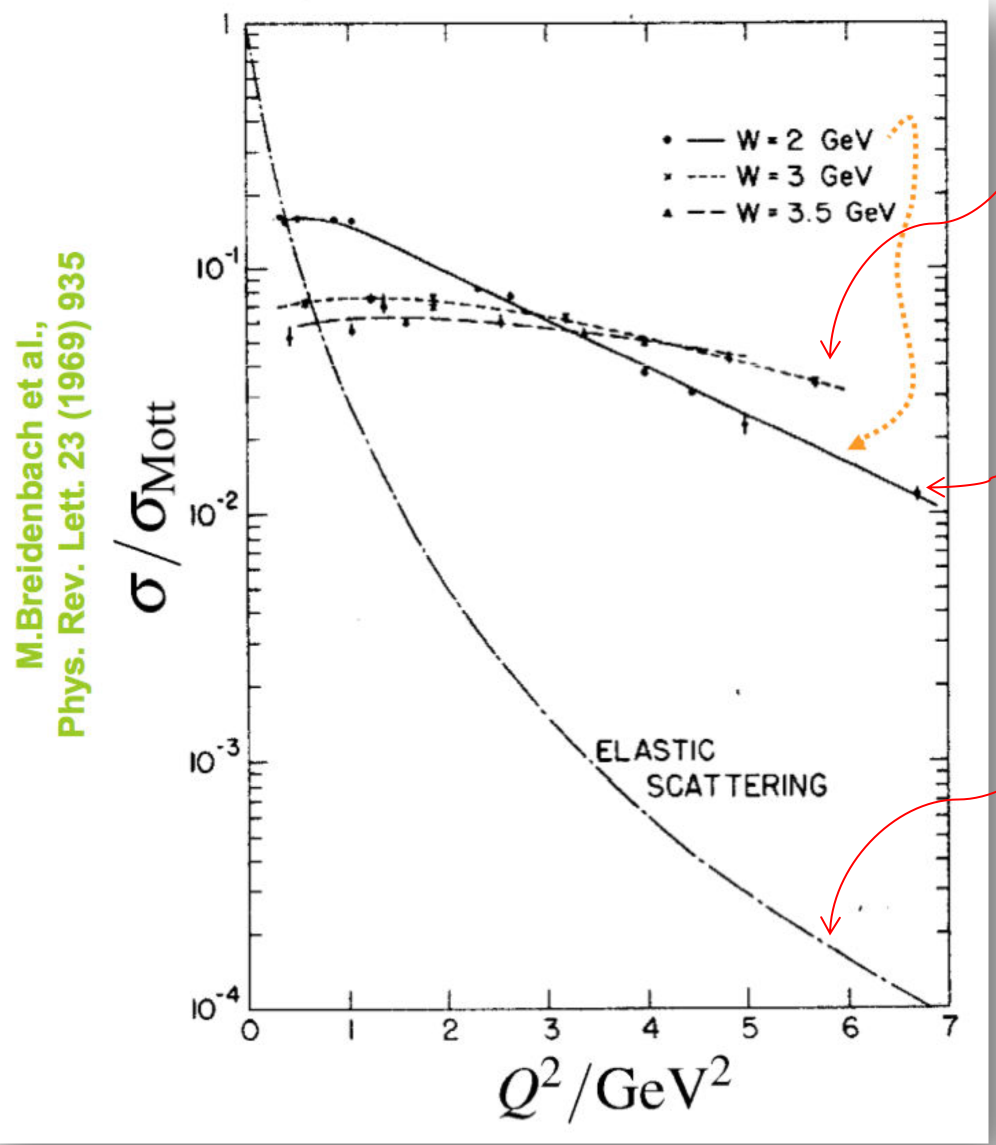


Elastic scattering: proton stays intact, $W = M$

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*

Looking deep inside the Proton



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

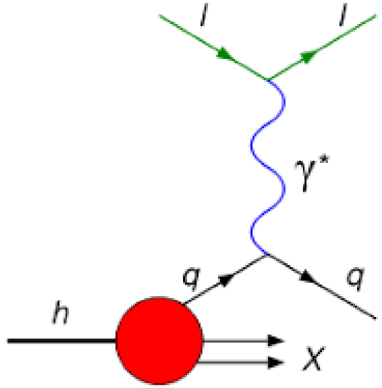
Scattering off point-like objects within the proton

- **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)

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

Structure Functions in Deep Inelastic Electron-Nucleon Scattering



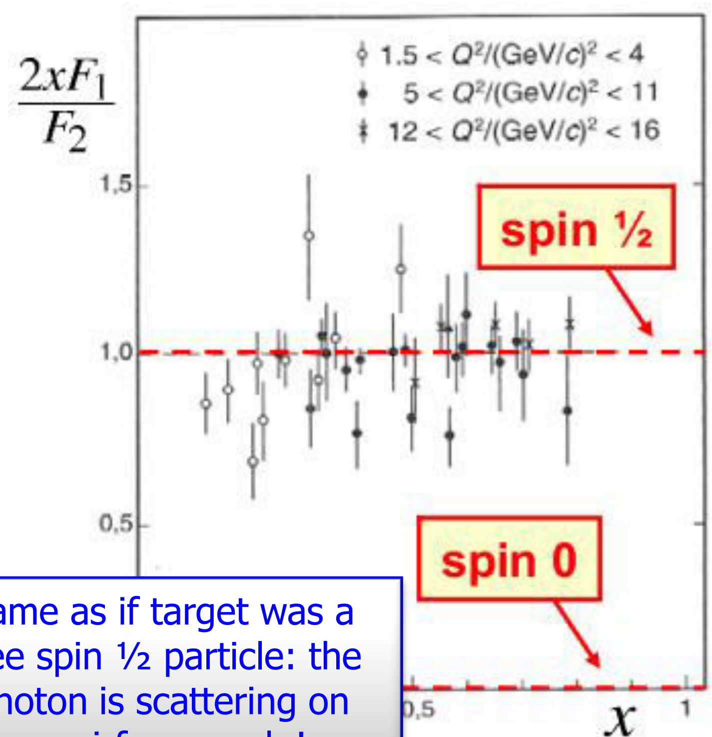
Probability of inelastic interaction:

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

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

- Account for the sub-structure of the protons and neutrons
- x = fraction of nucleon momentum carried by struck quark
- Give access to *partonic structure* of the nucleon, i.e.

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

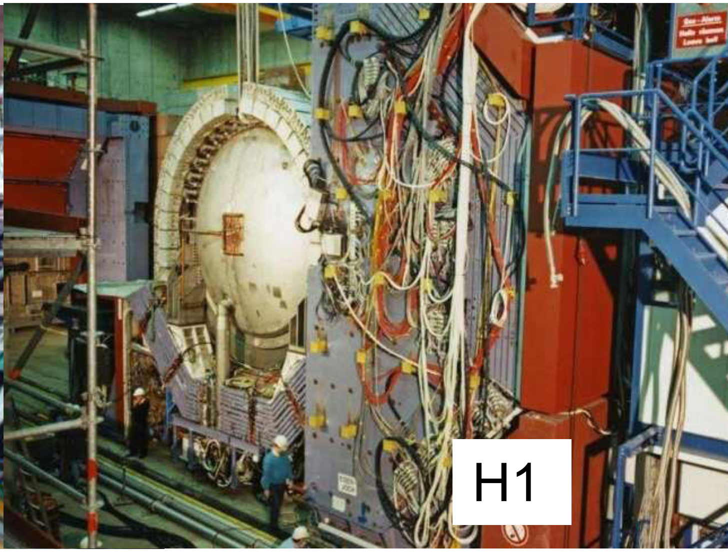


Same as if target was a free spin ½ particle: the photon is scattering on quasi-free quark !

- 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*

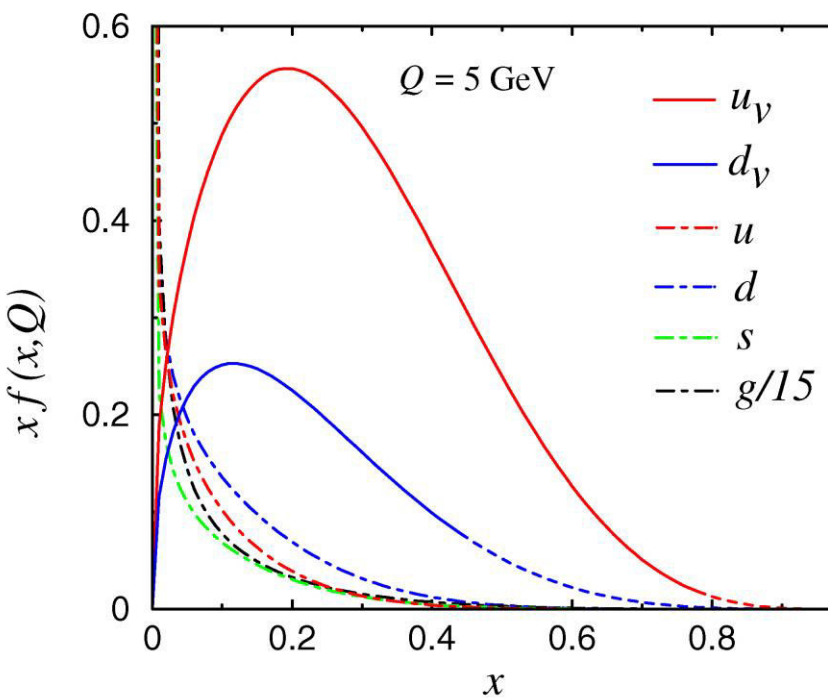
Fast forward….

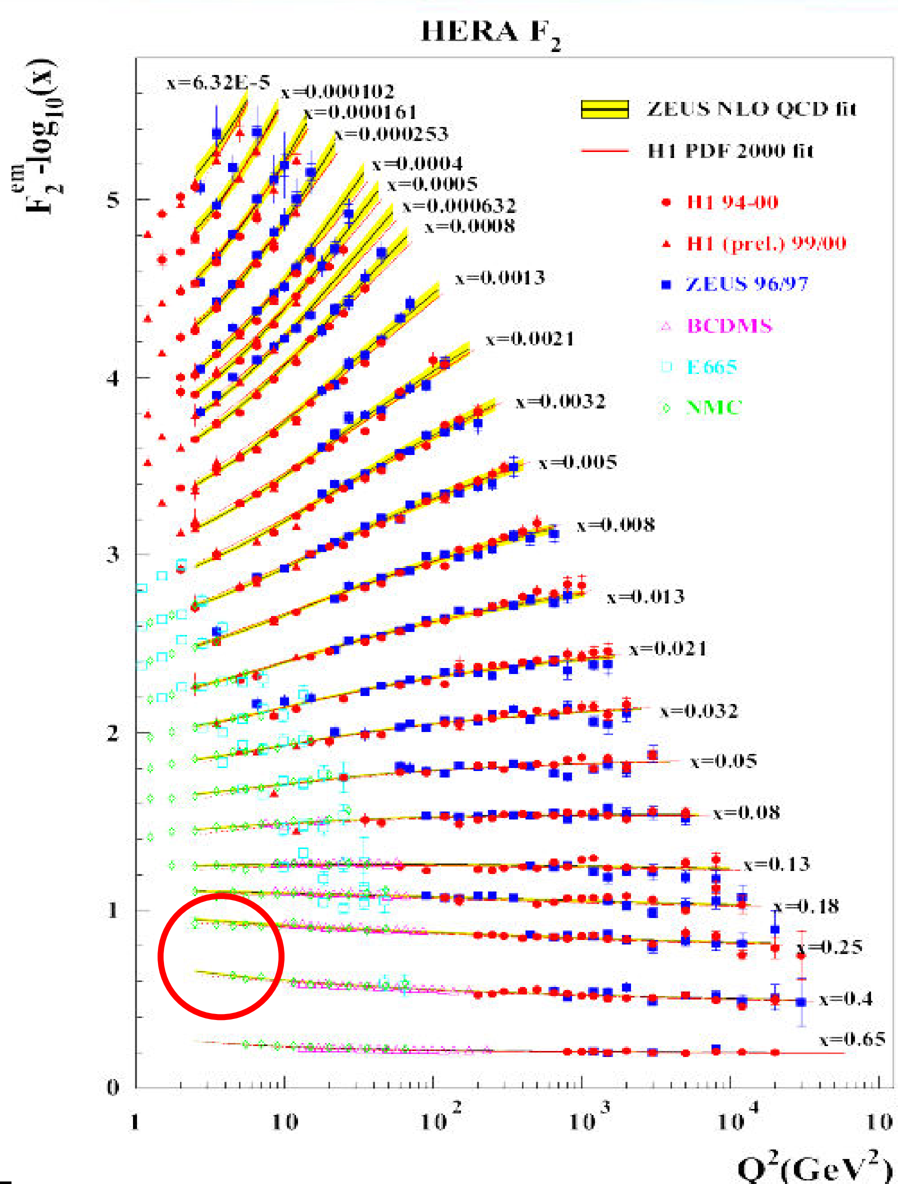
30+ years of charged lepton Deep Inelastic Scattering at *multiple* laboratories including SLAC (to ~2000), CERN 80-90s EMC, NMC, BCDMS..), DESY (90s – 21st century H1, ZEUS,...), and ***more!***



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

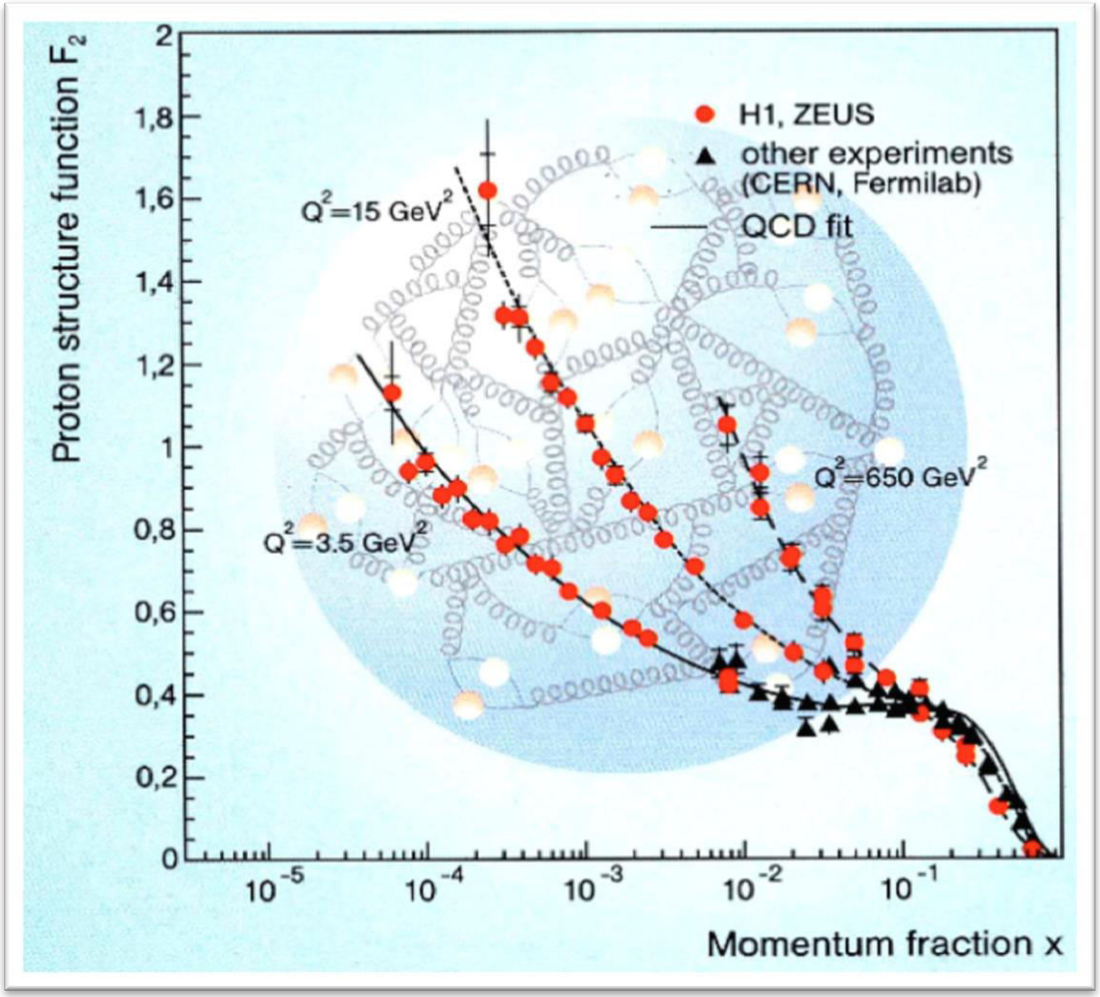
F_2^p Structure Function measured over impressive range of x and Q^2



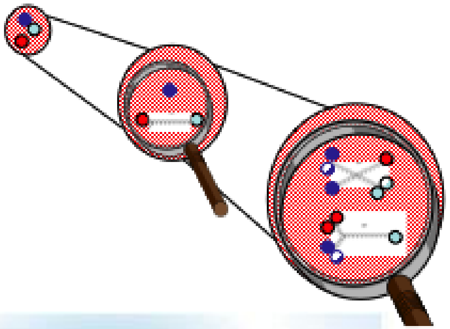


Allows extraction of *Parton Distribution Functions* f(x,Q^2) - think momentum distribution of quarks

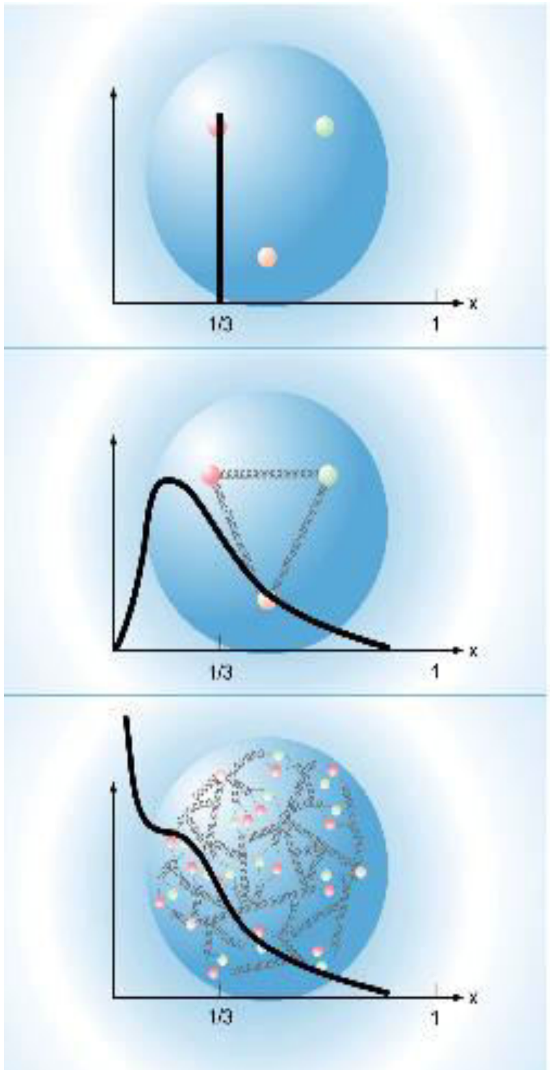
Scaling Violations

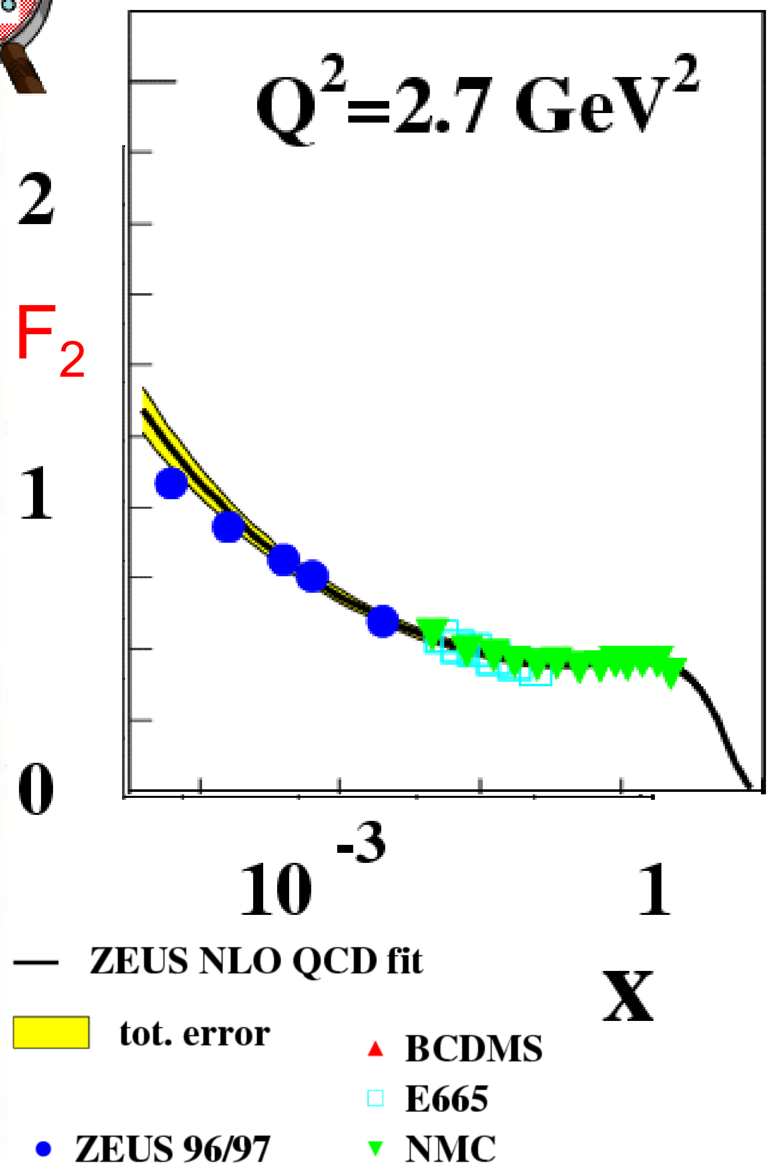


- Scaling violation is due to the fact that the quarks radiate gluons that can "materialize" as q-qbar pairs (sea quarks)
- Increasing Q^2 increases the resolution of the probe ($\sim\hbar/\sqrt{Q^2}$) and thus increases the probability of seeing these (abundant) low x partons
- The parton distribution 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



Proton Structure Function F_2





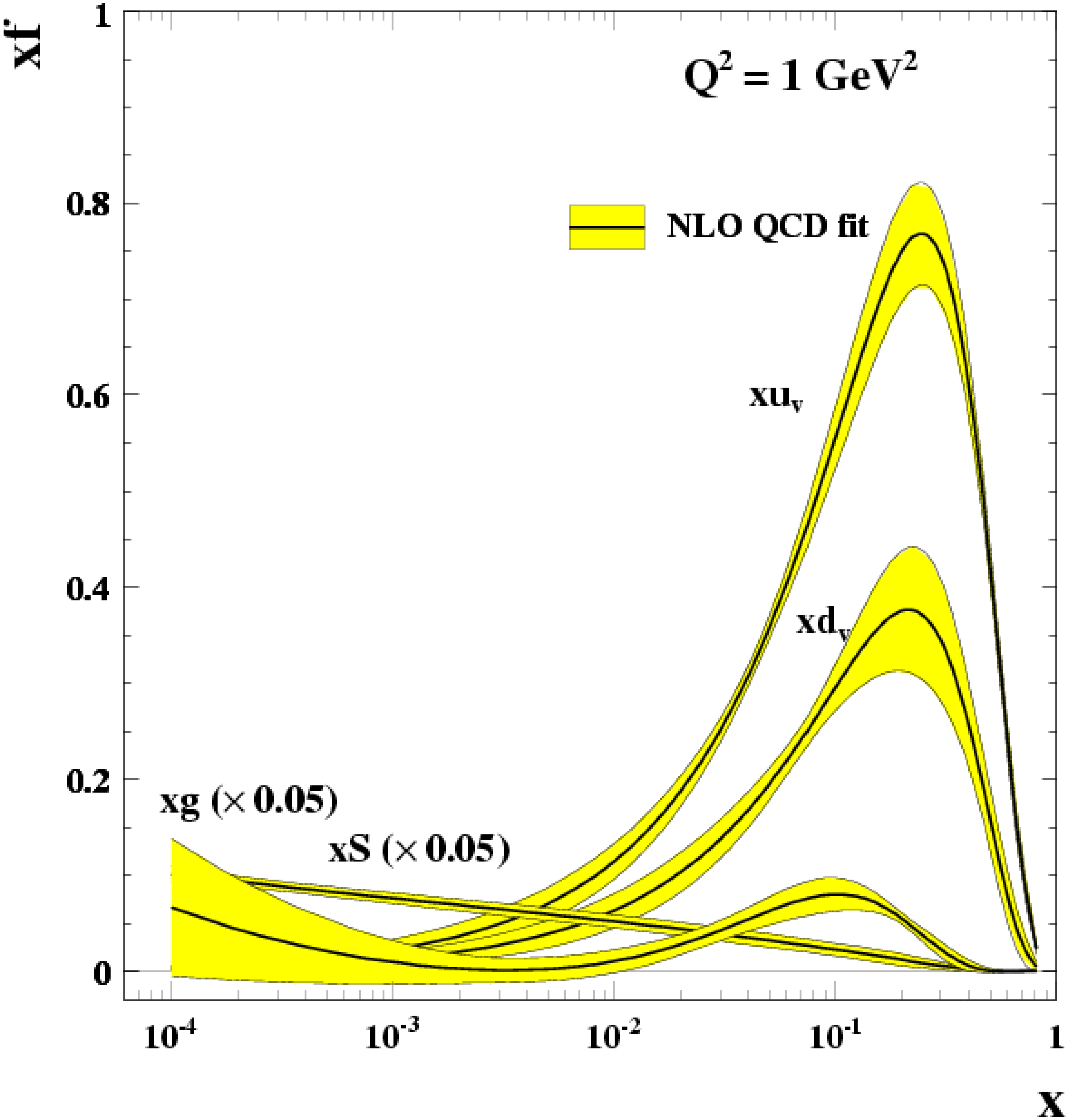
Q^2 dependence described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations

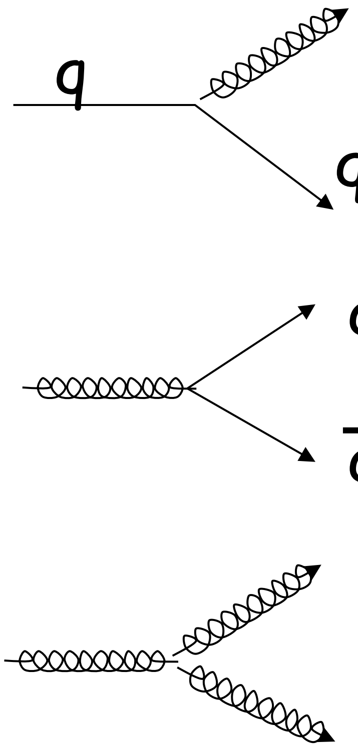
Increasing Q^2:

- 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

Parton Distribution Functions and QCD Evolution



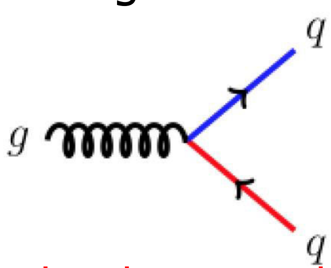


Valence quarks maximum around *x=0.2; f(x) →0* for x→1 and x→0

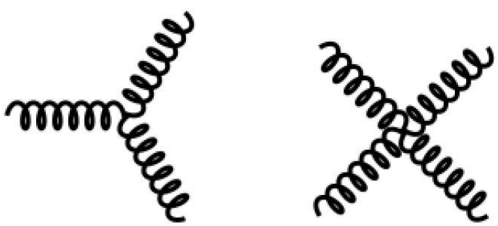
Sea quarks and gluons - contribute at low values of x

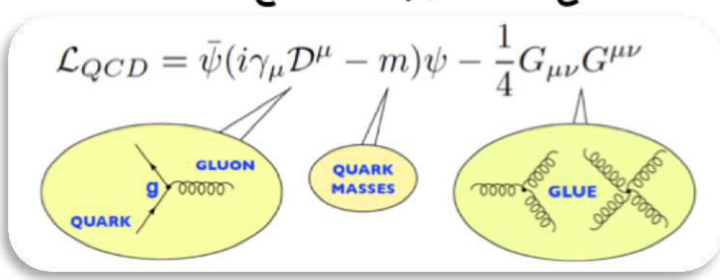
Quantum Chromo Dynamics

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

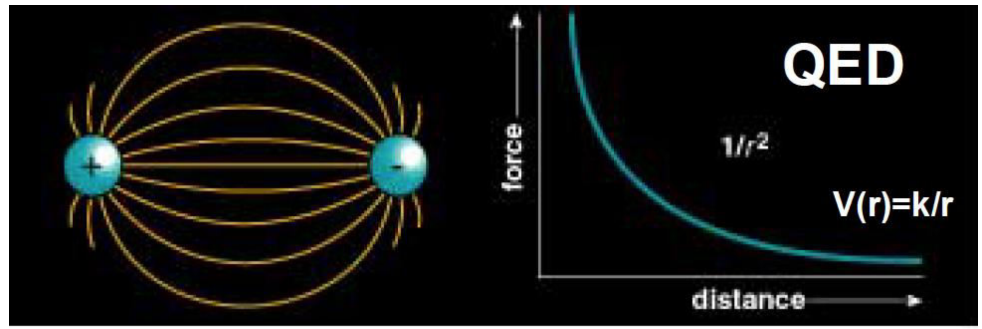


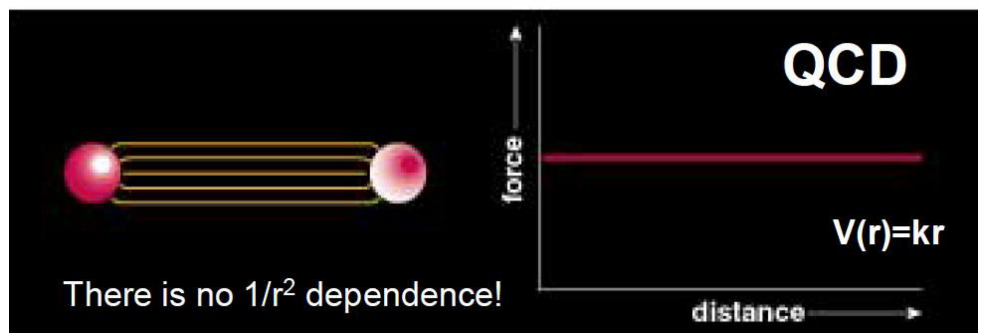
Gluons carry color charge, and we can draw 3- and 4- gluon diagrams *(self-interaction)*



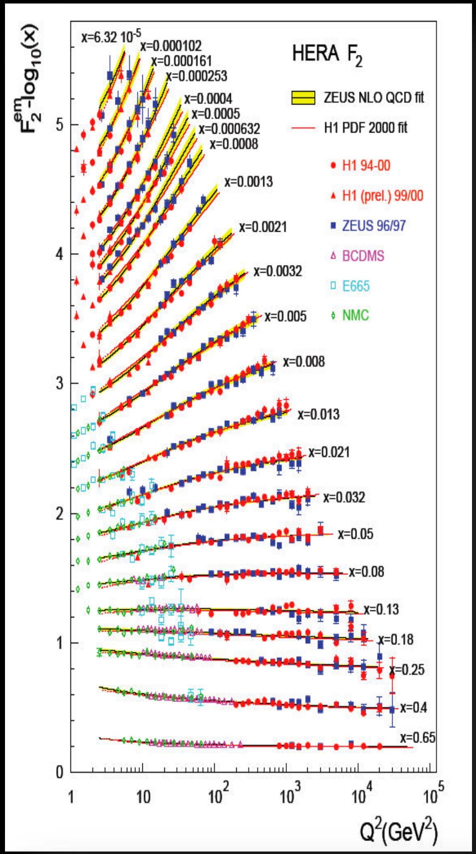


The strong force does not get weaker with large distances (opposite to the EM force) and blows up at distances around 10^{-15} m (the radius of the nucleon)



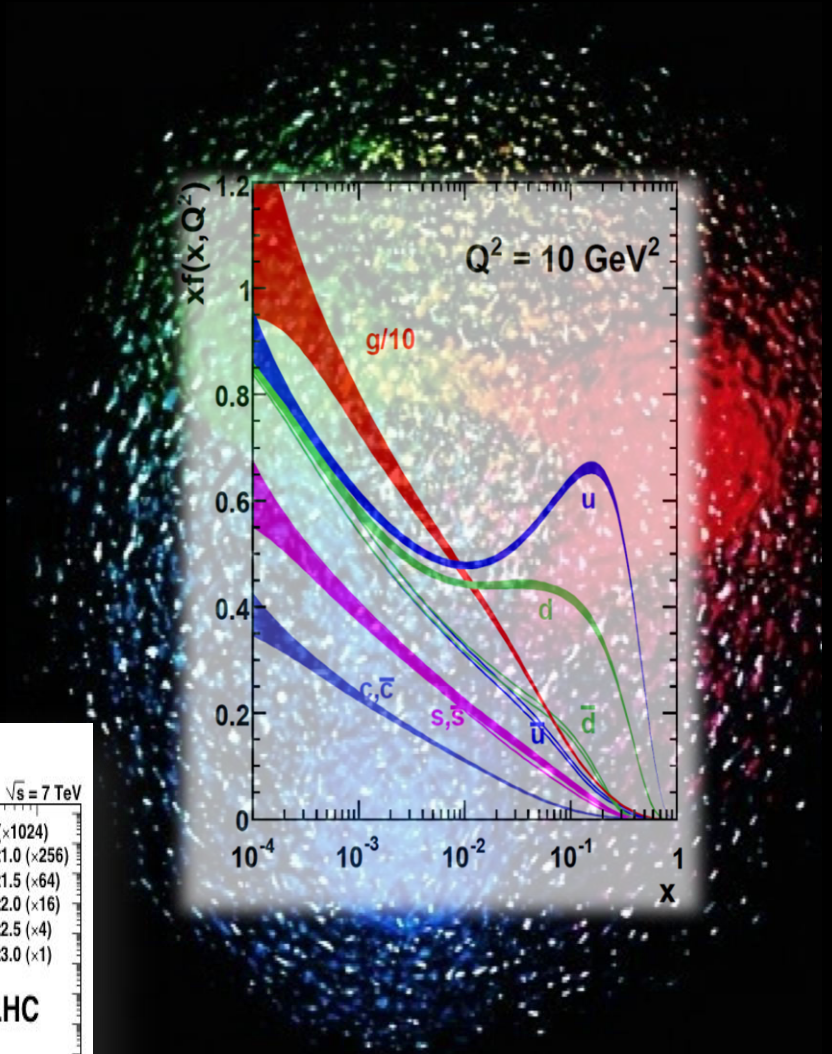


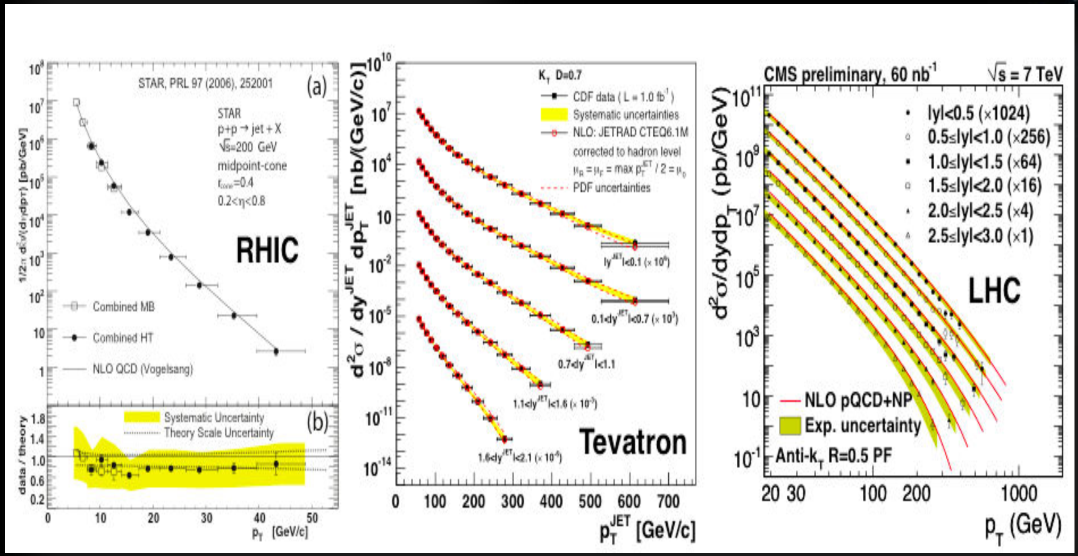
QCD Success !



Measure e-p @ 0.3 TeV (HERA)

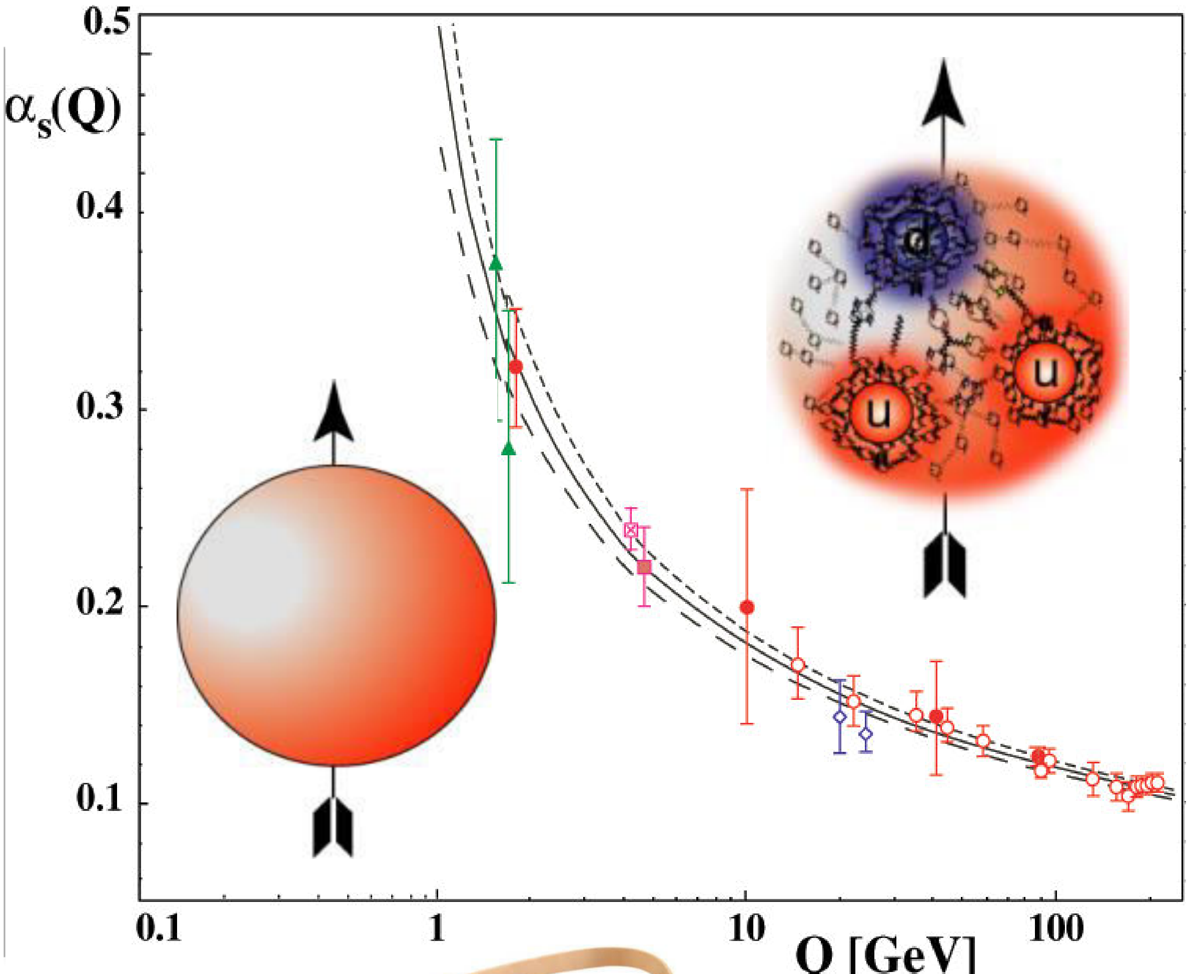
p-p and p-$\bar{p}$ at 0.2, 1.96, and 7 TeV





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

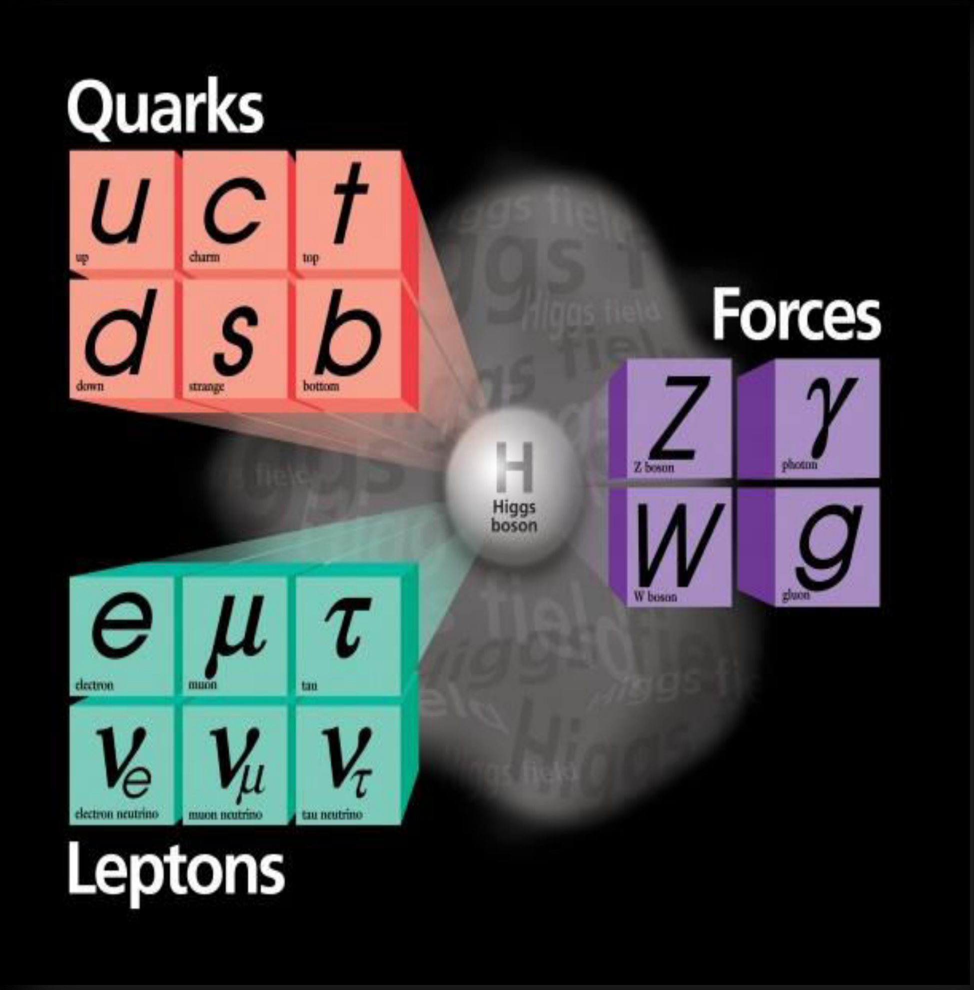
Quarks can be removed from the proton, but cannot be isolated!!!

We never see a free quark

QCD still unsolved in non-perturbative region

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

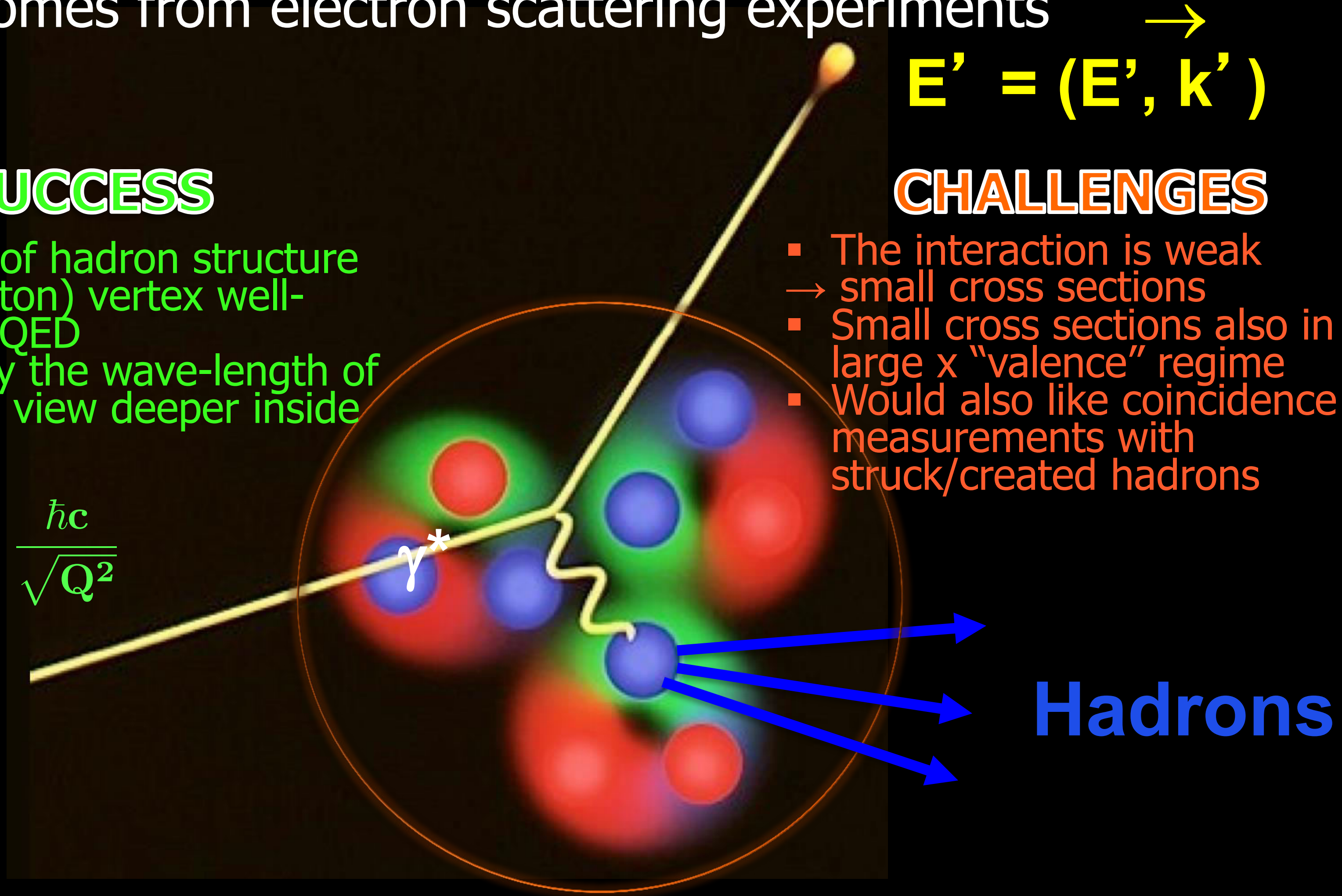
From the D. Gross Nobel Lecture (2004):



"It is sometimes claimed that the origin of mass is the Higgs mechanism that is responsible for the breaking of the electroweak symmetry that unbroken would forbid quark masses. This is incorrect. Most, 99%, of the proton mass is due to the kinetic and potential energy of the massless gluons and the essentially massless quarks, confined within the proton."

Lepton Scattering: a Powerful Tool

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



SUCCESS

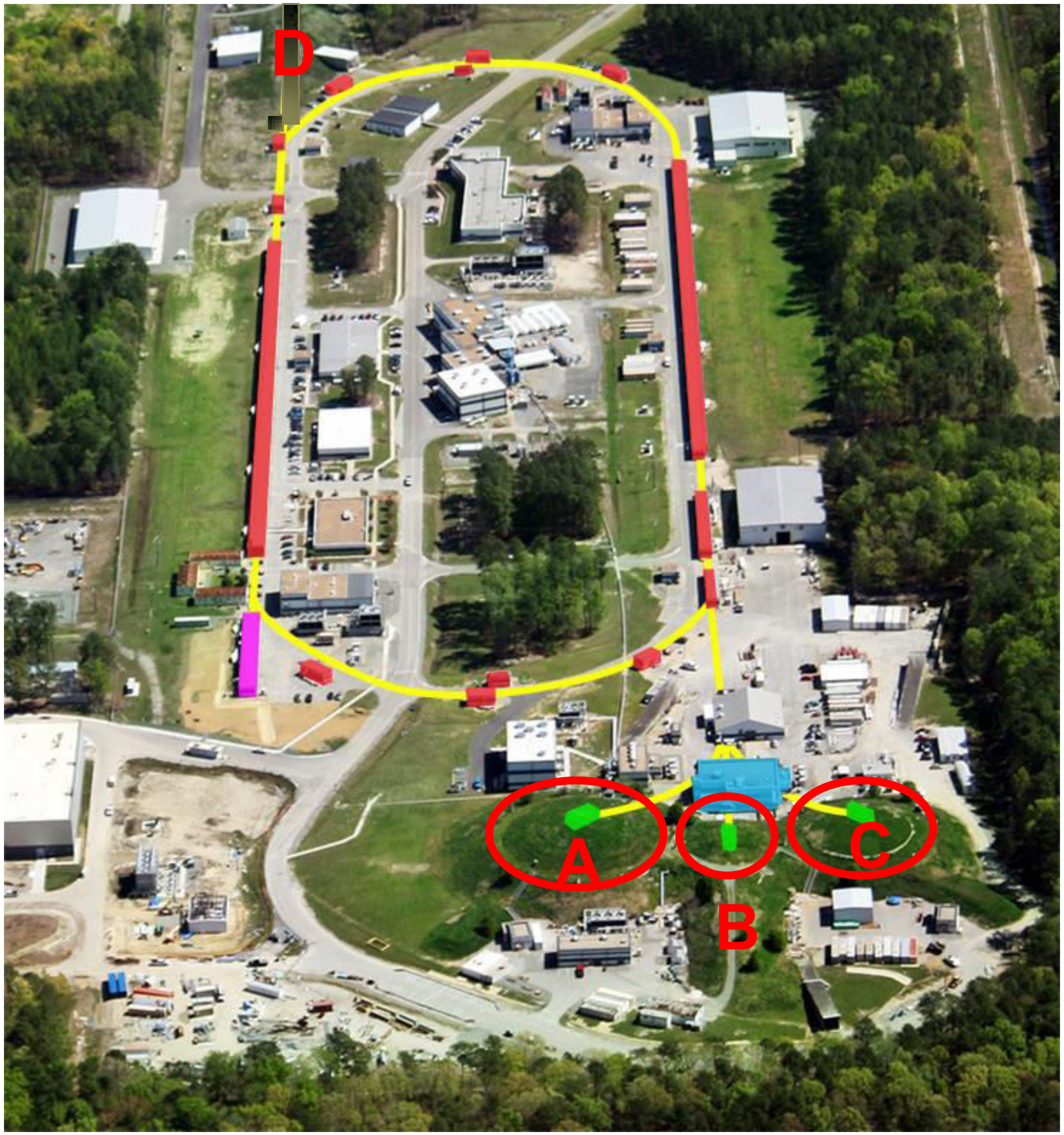
- Clean probe of hadron structure
- Electron (lepton) vertex well-known from QED
- One can vary the wave-length of the probe to view deeper inside the hadron

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

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

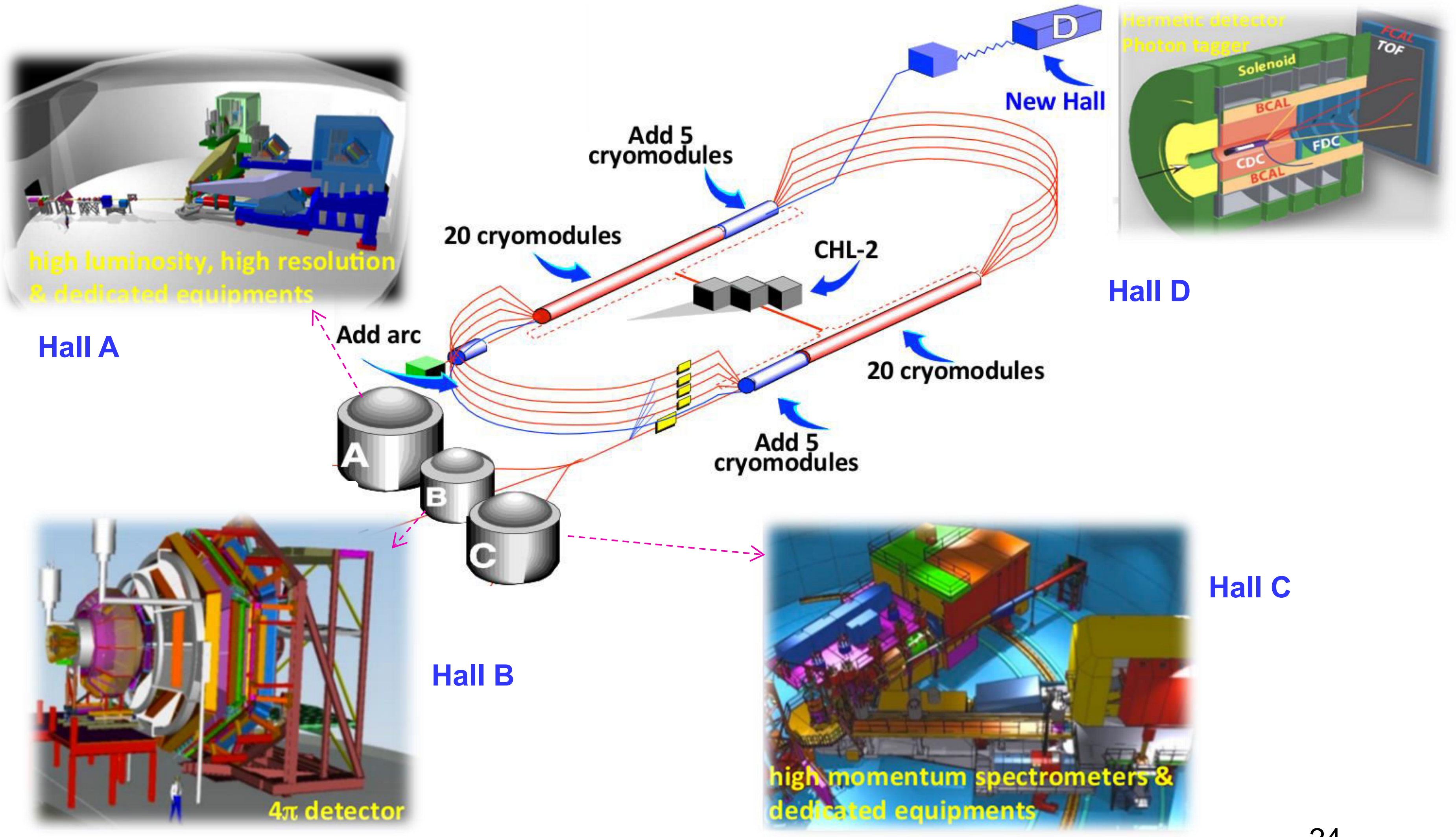
~2016 - …..

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: 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…



“Part of what we will tell you this semester is wrong.

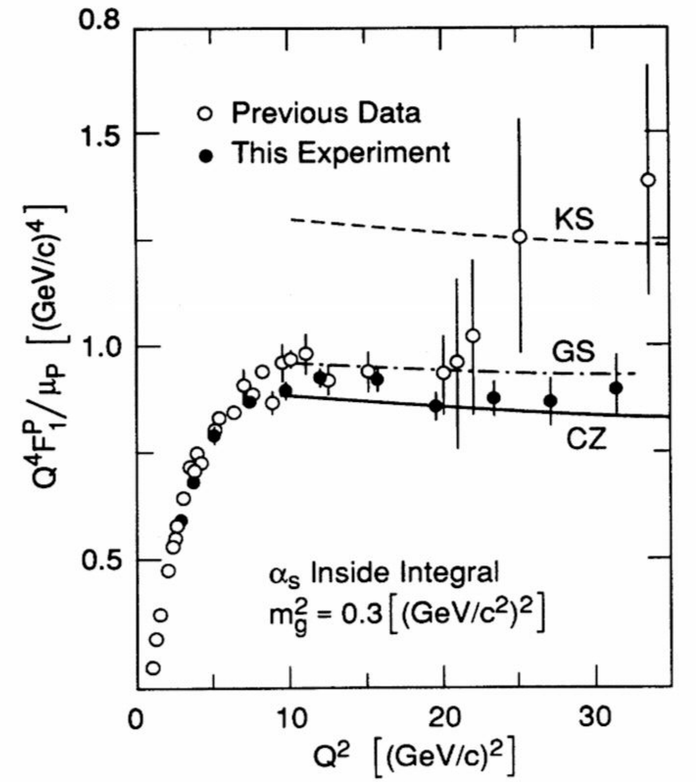
The problem is that we do not know what part.”

\- Multiple sources

“True wisdom is knowing what you don't know”

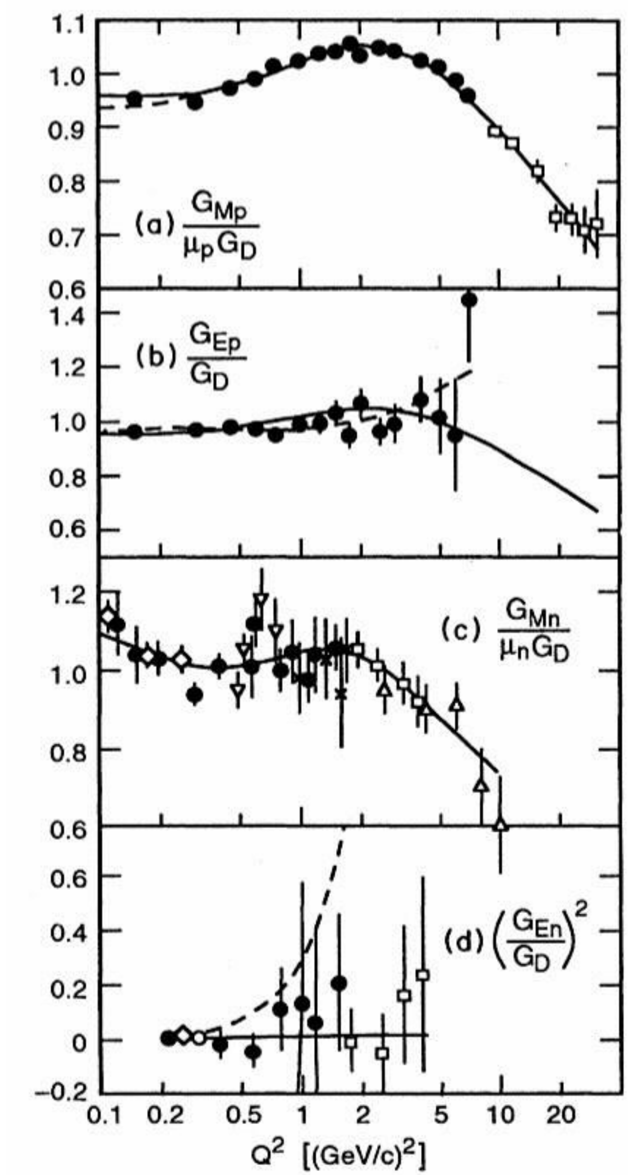
\- Confucius

Pre-JLab Results for the Form Factors



Sill et al,1993

Bosted et al,1995



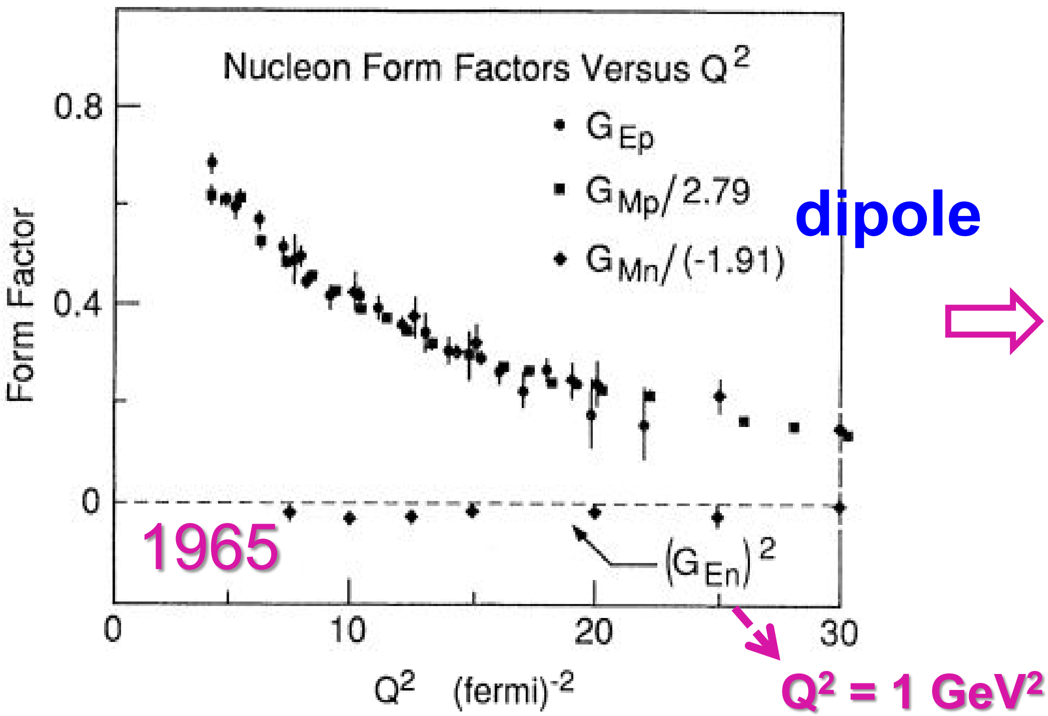
Note log scale!

How Do the Charge and Magnetic Moment Distribute?

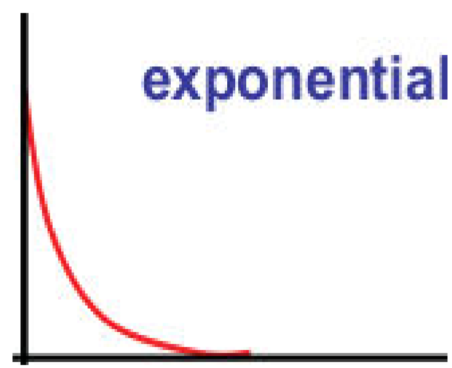
Probability of elastic interaction:

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

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

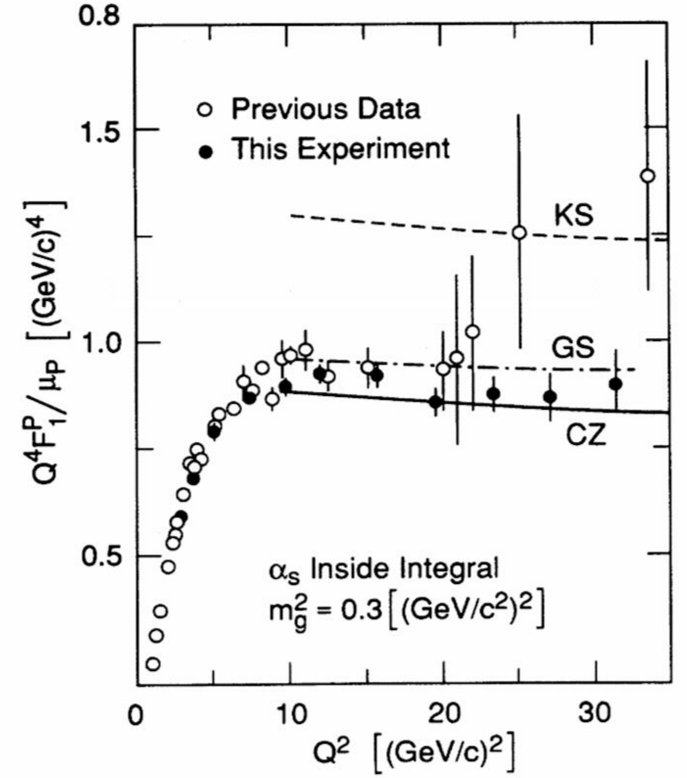


Distribution of Charge or Magnetic Moment



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

Pre-JLab Results for the Form Factors



Sill et al,1993

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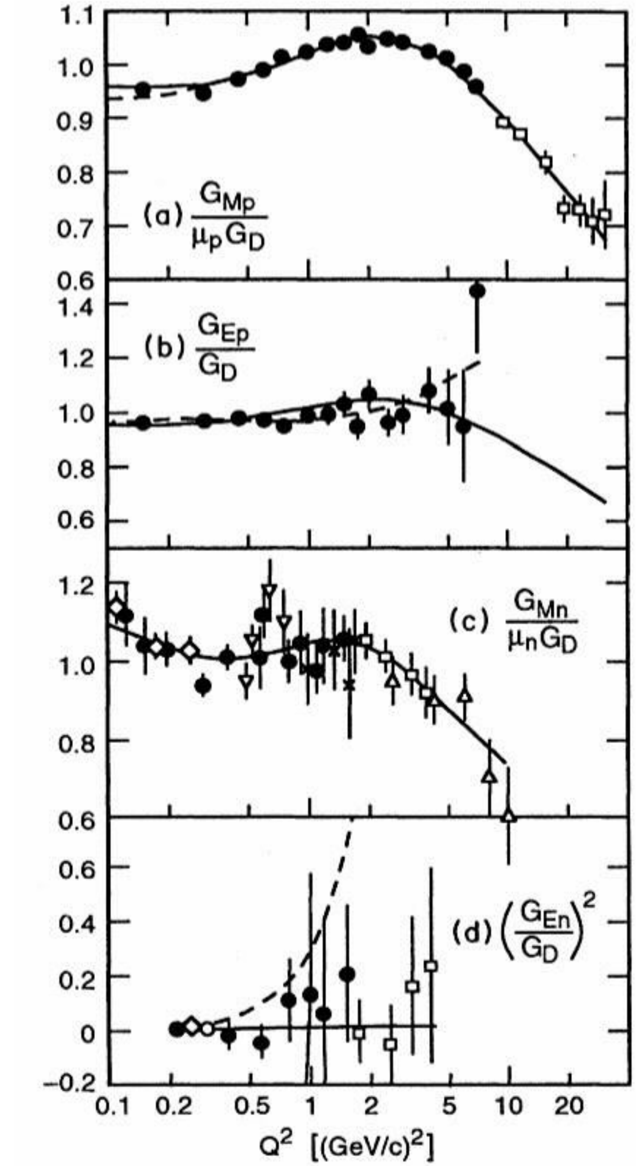
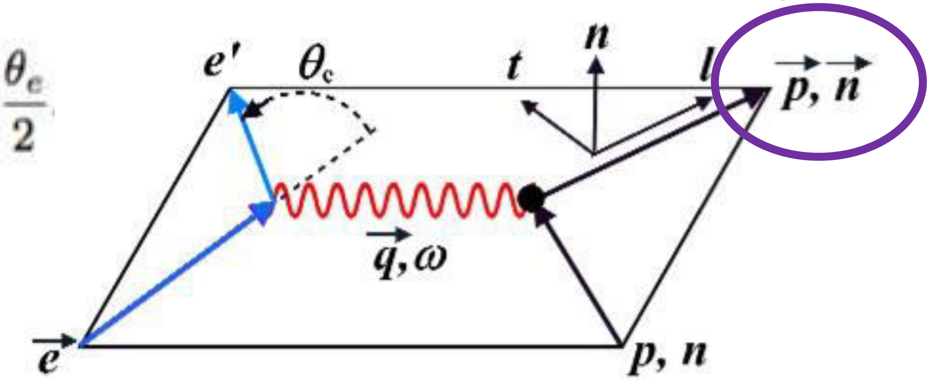


Note log scale!

Polarization Transfer in Elastic Electron-Proton Scattering

$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\frac{(E_{beam}+E_e)}{2M}\tan\frac{\theta_e}{2}$$

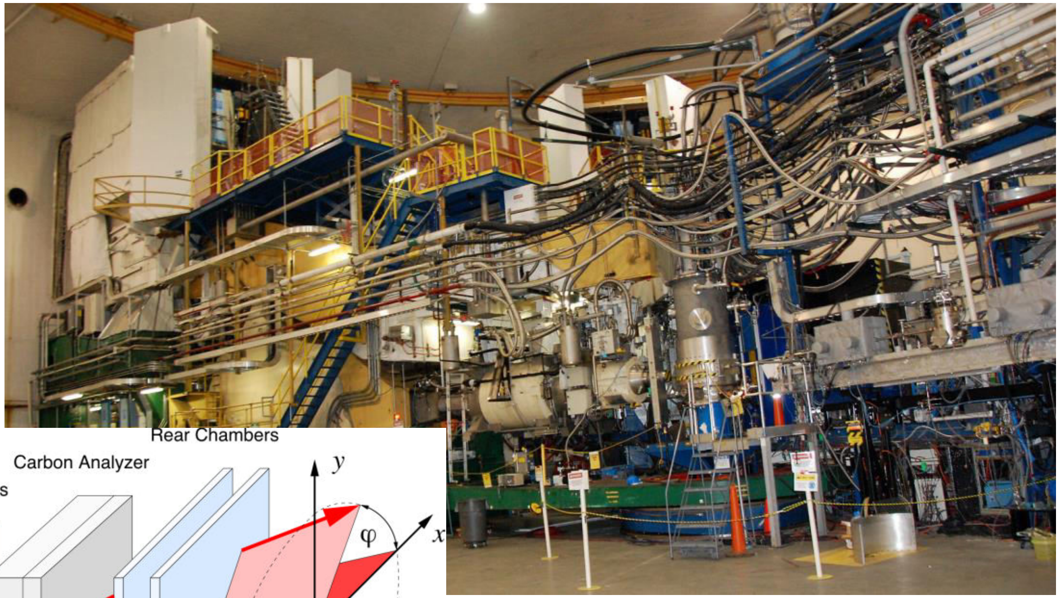


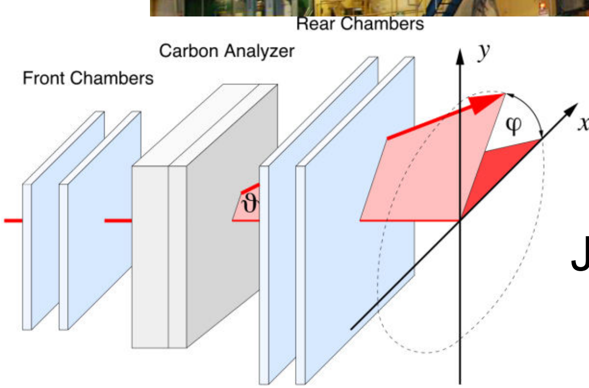
Longitudinally polarized electron beam

- The double-polarization approach obtains the FF *ratio* by measuring two polarization components simultaneously.

- Employ a combination of spin precession in a magnetic spectrometer and a proton polarimeter.

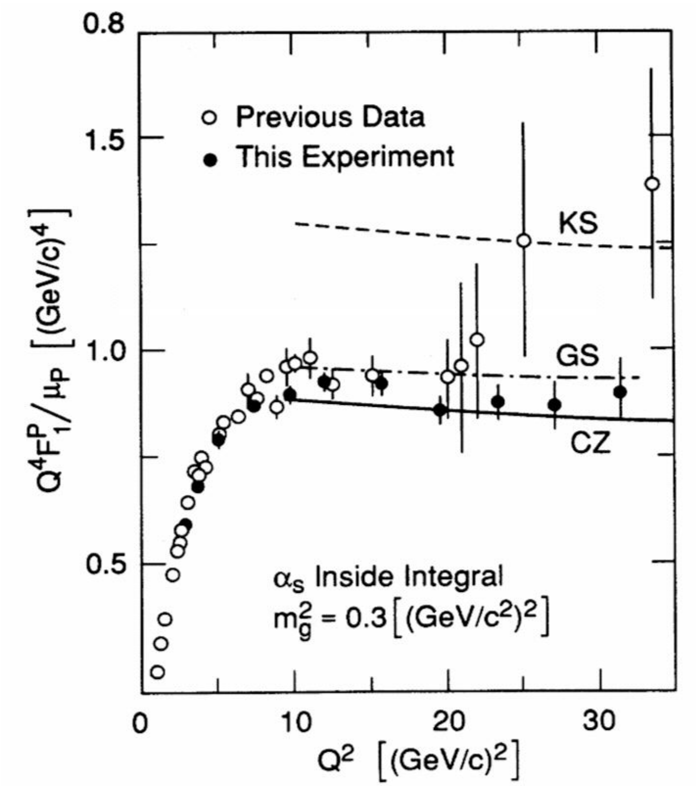
- A single measurement of the azimuthal angular distribution of the proton scattered in a secondary target gives both the longitudinal, Pl, and transverse, Pt, polarization.



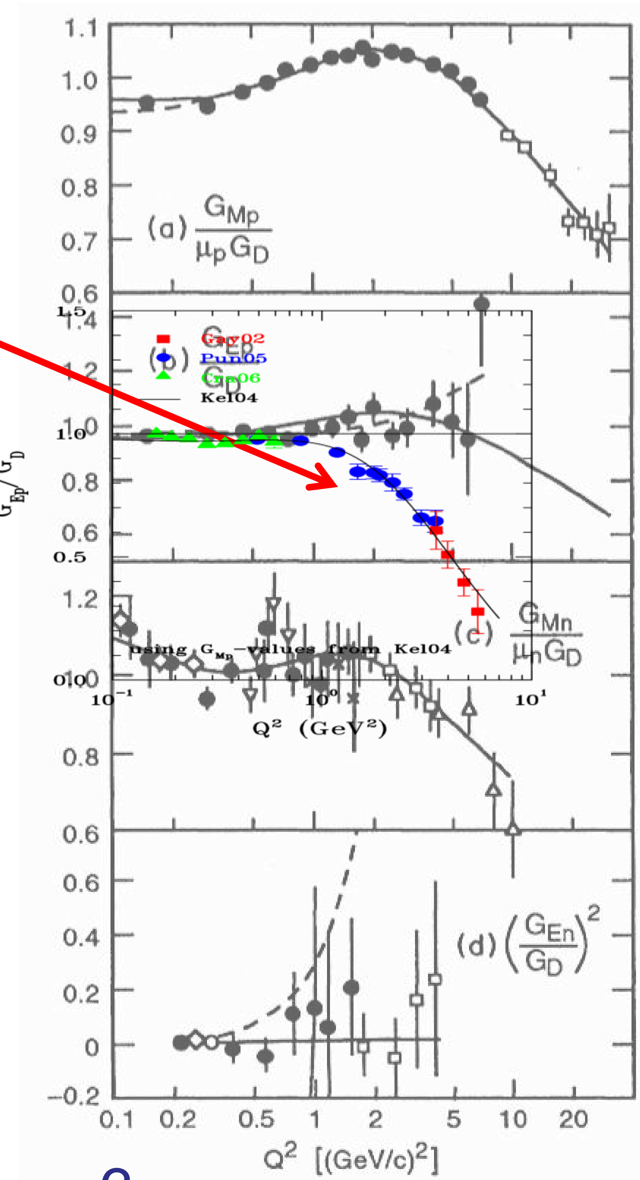


JLab Hall A HRS spectrometer

Surprising Result for the Form Factors…



Jefferson Lab polarization transfer results!!



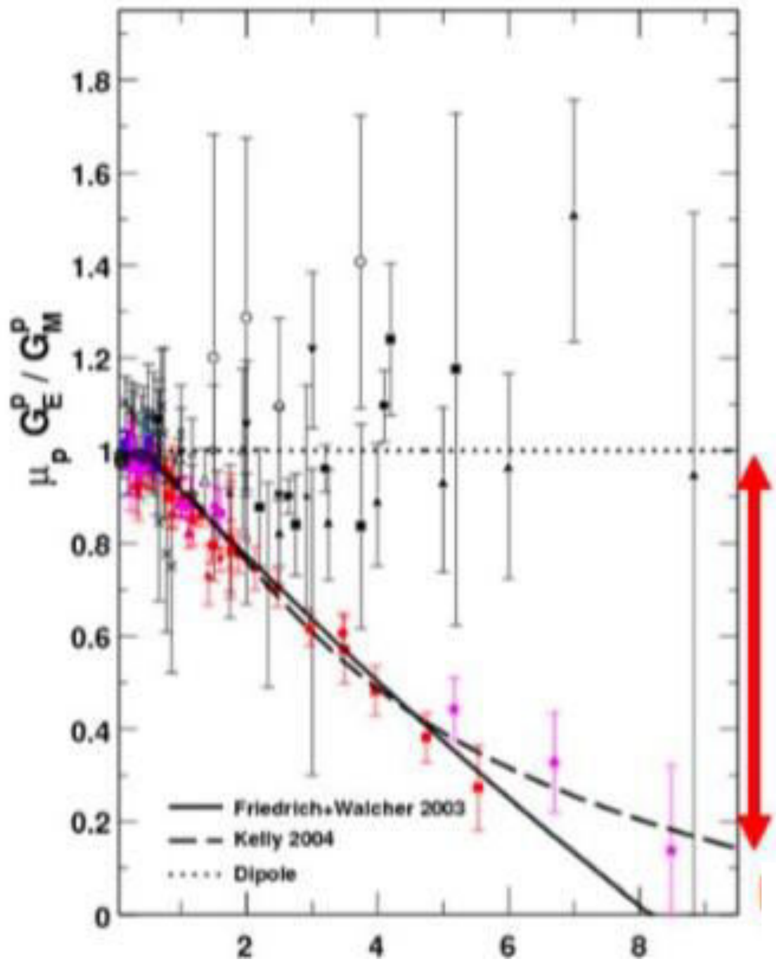
First paper
800+ citations!

1) e + p → e' + p
G_E^p/G_M^p constant

2) $\vec{e}$ + p → e' + $\vec{p}$
G_E^p/G_M^p drops with Q^2

What is going on?...

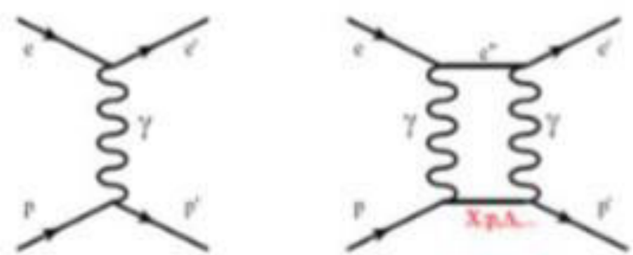
Proton Form Factor Ratio



Q^2

Jefferson Lab 2000–today

- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Contribution of multiple <u>hard</u> photon exchange accepted explanation



<u>Dramatic discrepancy!</u>

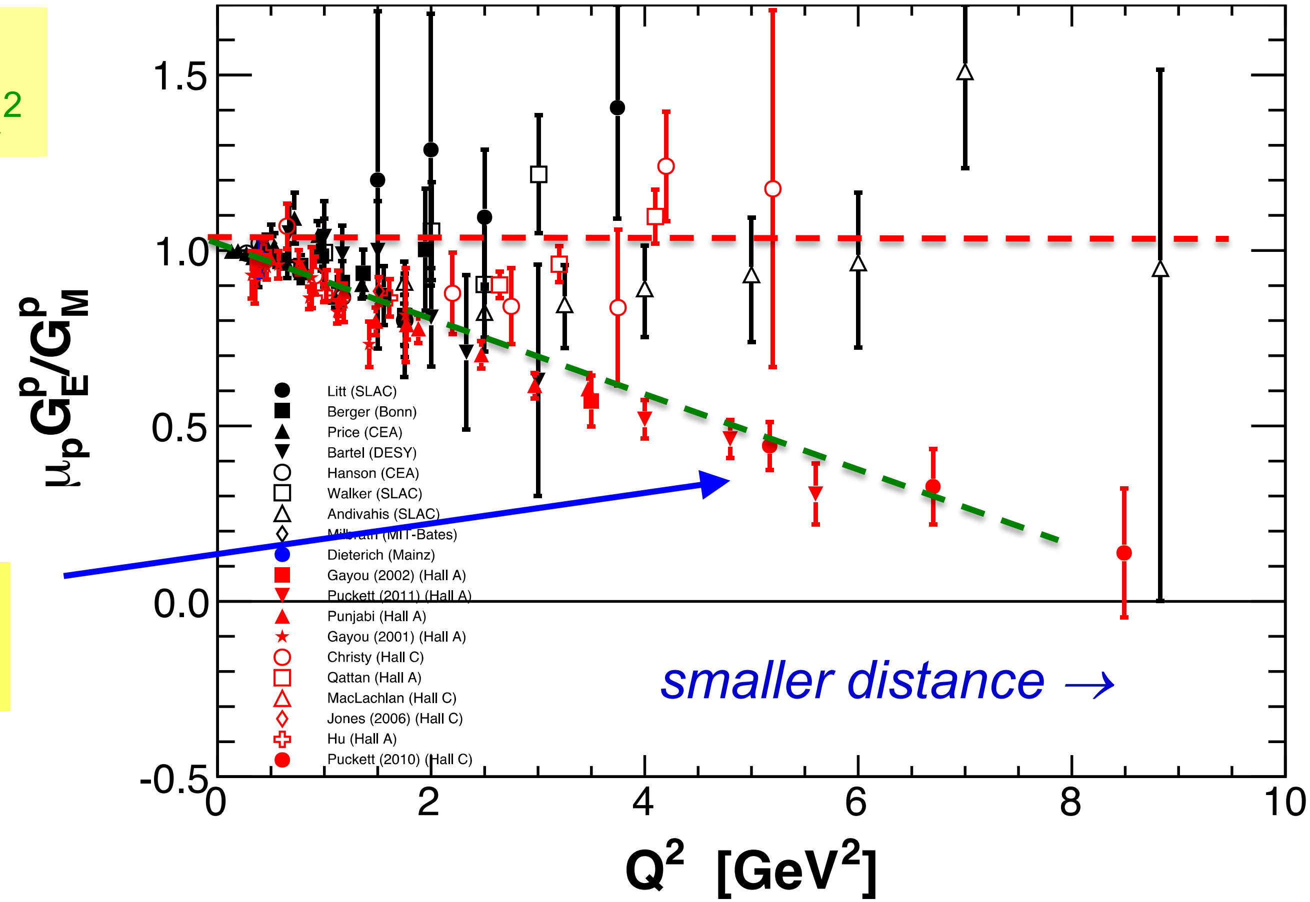
In general, polarization observables are rather insensitive to radiative corrections, as they are by definition a ratio of a polarized cross section to an unpolarized one.

Proton Charge and Magnetization

$\vec{e} + p \rightarrow e' + \vec{p}$
G_E^p/G_M^p drops with Q^2

Charge & magnetization distributions in the proton **<u>are different</u>**

charge depletion in interior of proton

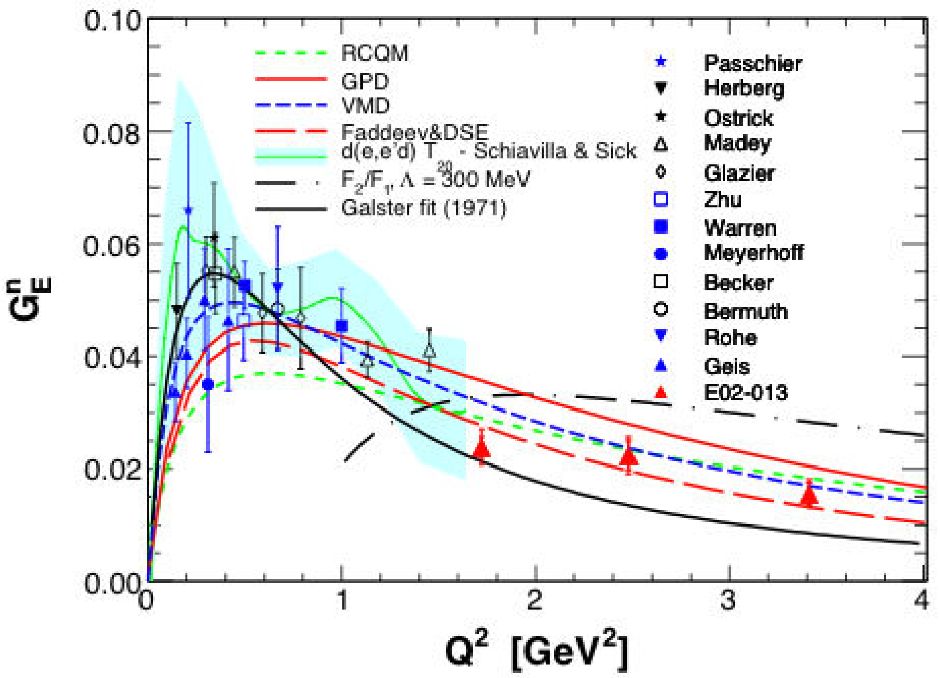


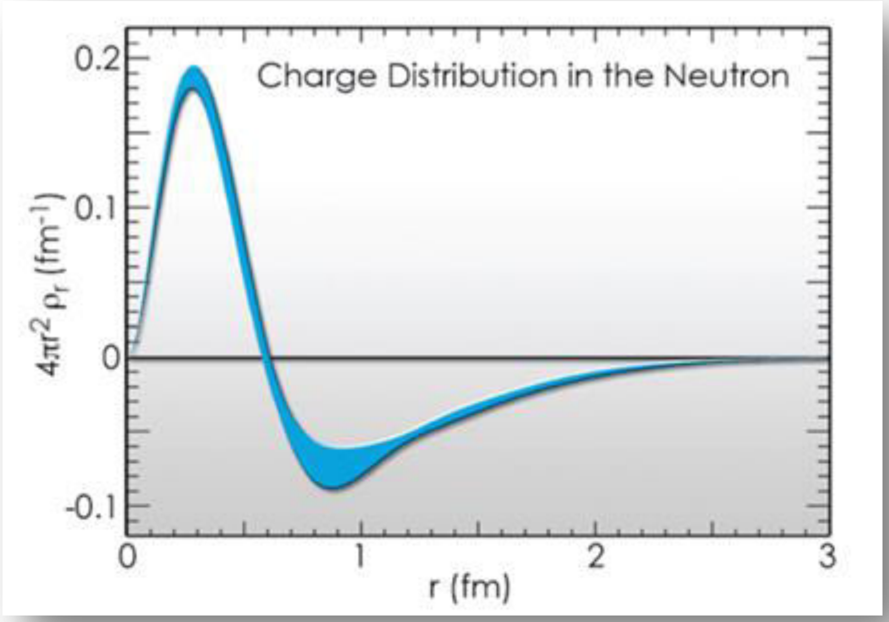
Orbital motion of quarks play a key role
(Belitsky, Ji + Yuan PRL 91 (2003) 092003)

Hall A — Also.. G_E^n is not zero…

Neutron has no charge, but does have a charge distributions: n = p + π^-, n = ddu. Use polarization to access. *"Guarantee" that electron hits a neutron AND electron transfers its polarization to this neutron.*

(Polarization Experiments only)

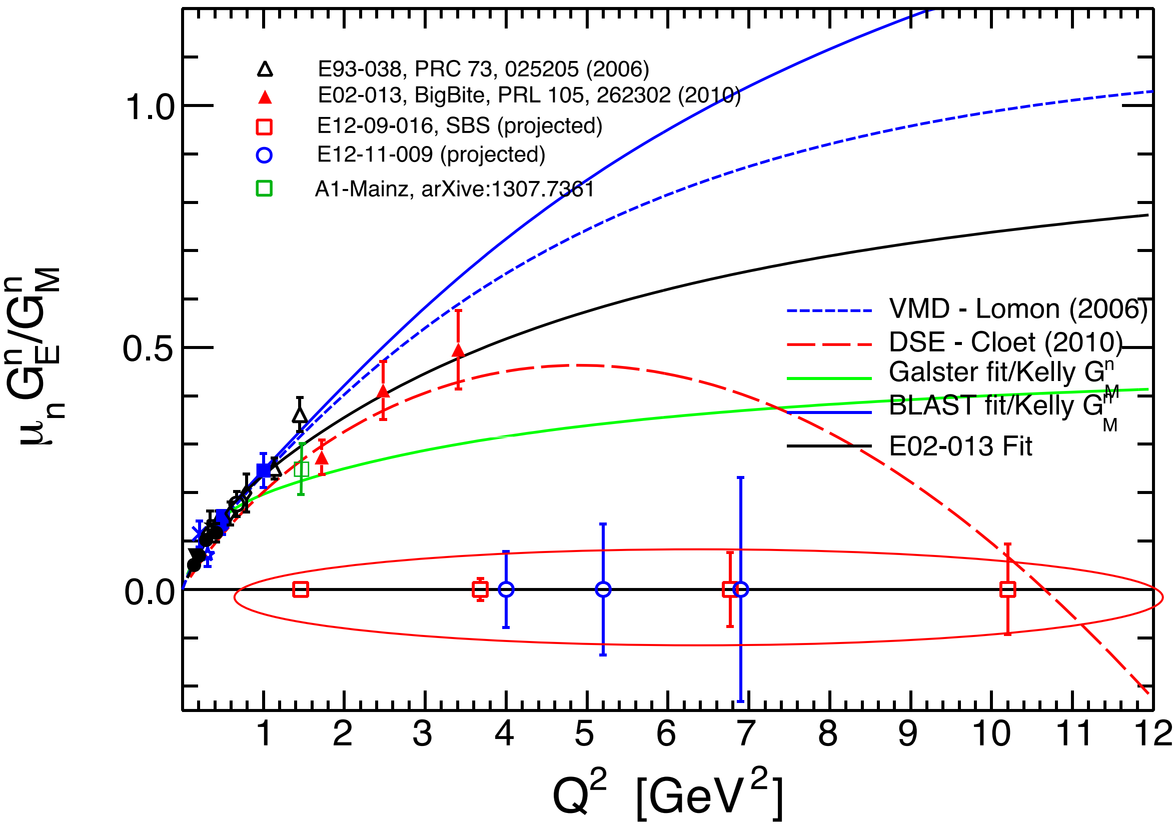




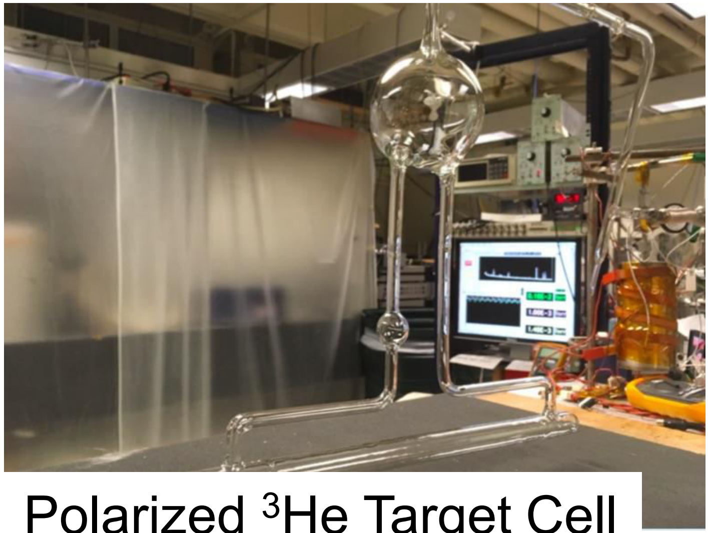
Combining proton and neutron: down quark has *more extended spatial charge distribution*. Could be due to significant influence of di-quarks?

12 GeV G_E^n experiment

Asymmetry in the polarized electron scattering
from the polarized ^{3}He



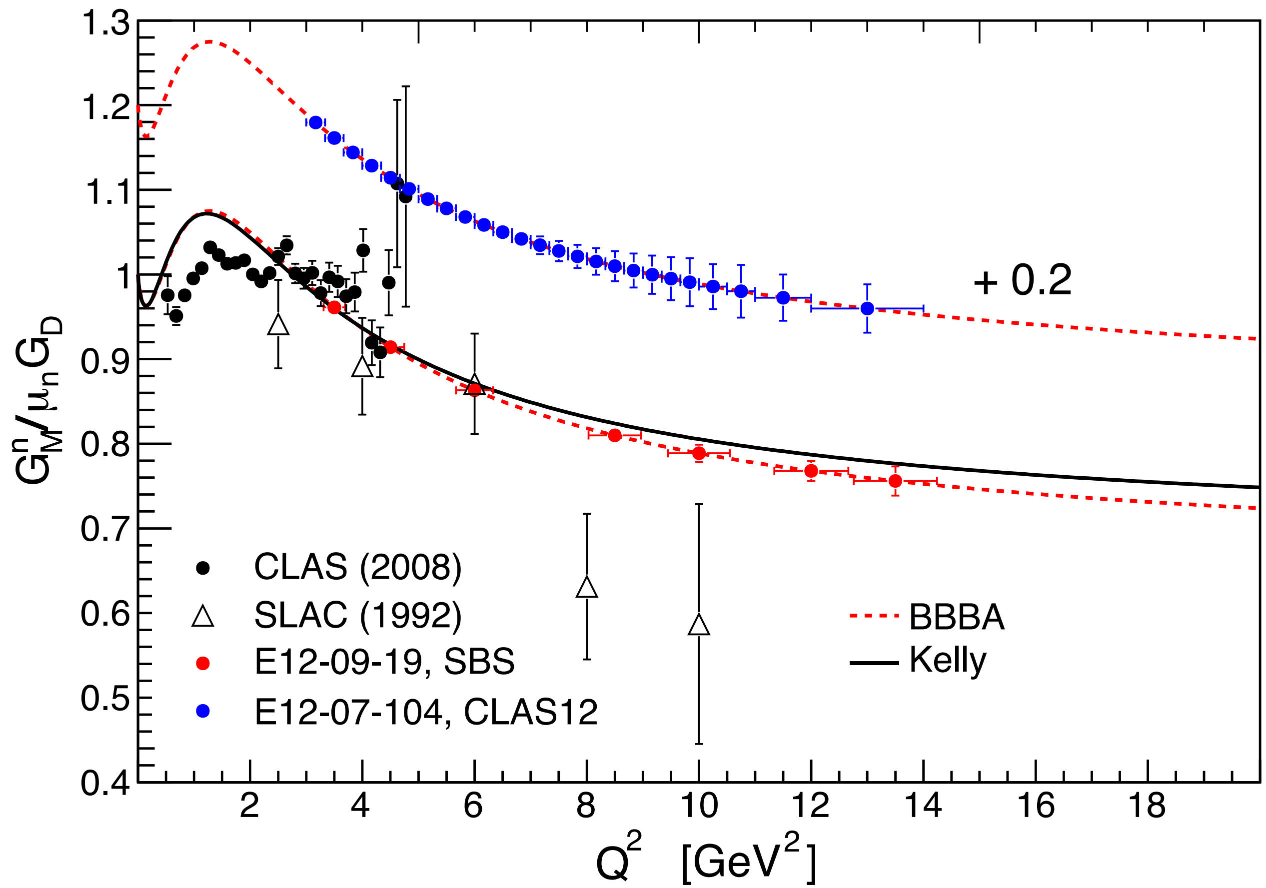
JLab Hall C SHMS

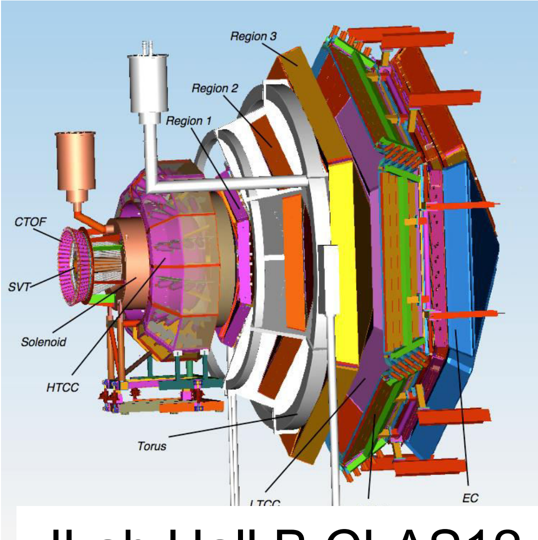


Polarized ^{3}He Target Cell
for Hall A

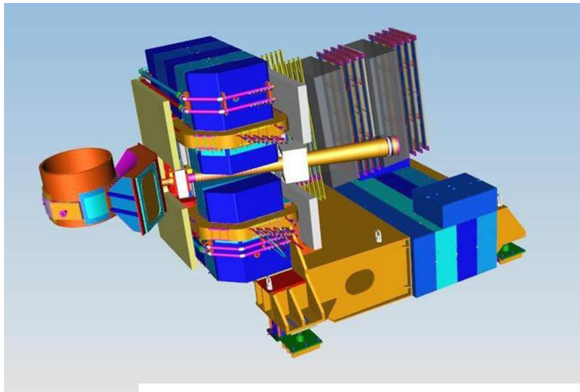
12 GeV G_M^n experiment

Ratio of the cross sections $D(e,e'n)$ and $D(e,e'p)$





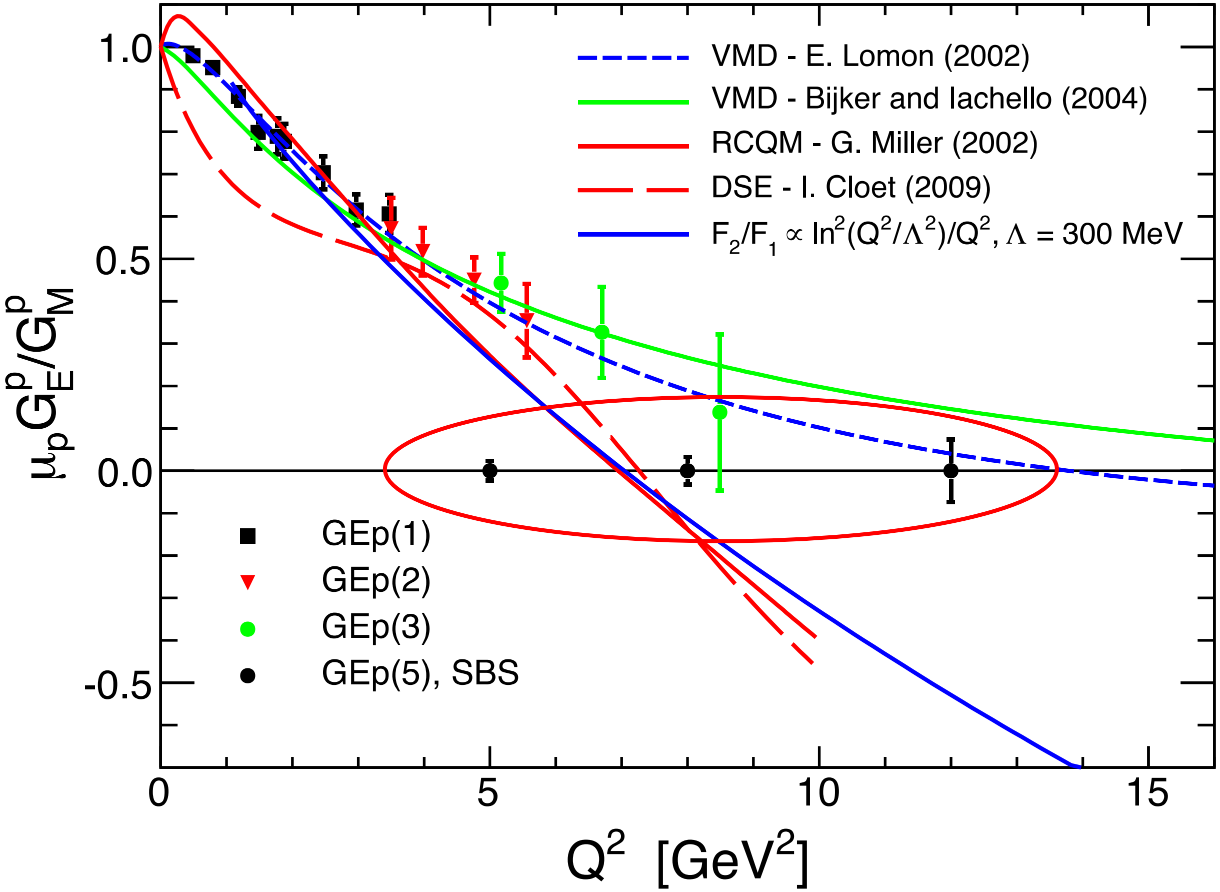
JLab Hall B CLAS12

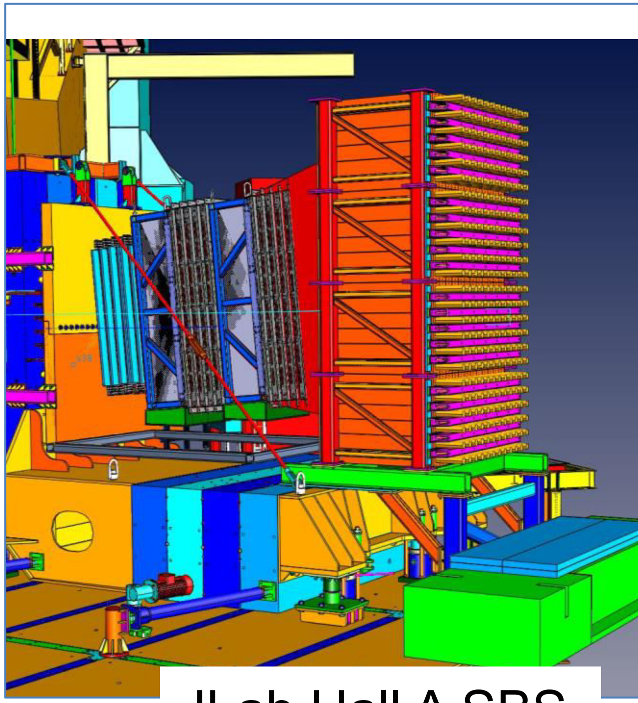


JLab Hall A SBS

12 GeV G_E^p experiment

Transverse polarization of the proton
in the polarized electron-proton scattering



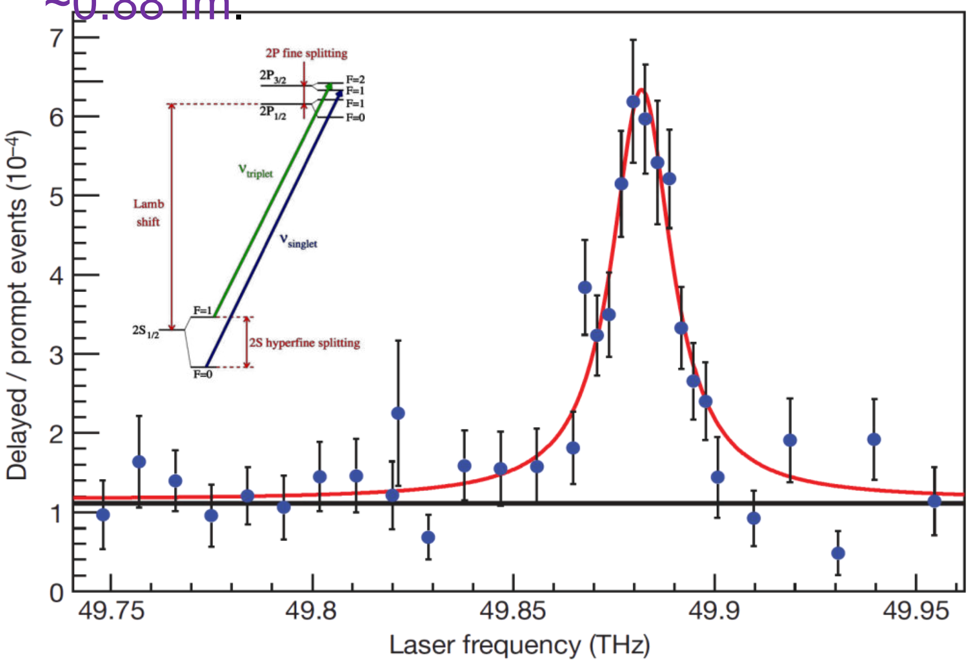


JLab Hall A SBS

Also measuring at low Q^2…

Muonic Hydrogen Data

- High precision results from Muonic Lamb shift data give a proton radius of 0.84 fm.
- This result contradicts many other extractions *- dominantly from electron scattering -* which have determined the proton radius to be ~0.88 fm.



$$E_{2p} - E_{2s} = 209.98 - 5.2262\, r_p^2 + 0.0347\, r_p^3 \text{ MeV}$$

Some Of The Possible Explanations

μH experiment wrong ?

eH theory wrong ?

Lamb shift difference of 310 ± 2 μeV

Beyond Standard Model

μH theory wrong ?
- 2γ corrections
- missing QED or EW corrections
- soft hadronic corrections

eH experiment + ep scattering wrong ?
- R_∞
- 2γ corrections
- low-Q^2 extrapolation

List of possible explanations from Franziska Hagelstein, University of Mainz

Jefferson Lab

Need the Slope of $G_E(Q^2)$ Using Low Q^2 Data

$$r_p \equiv \sqrt{\langle r^2 \rangle} = \left(-6 \, \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2} \bigg|_{Q^2=0} \right)^{1/2}$$

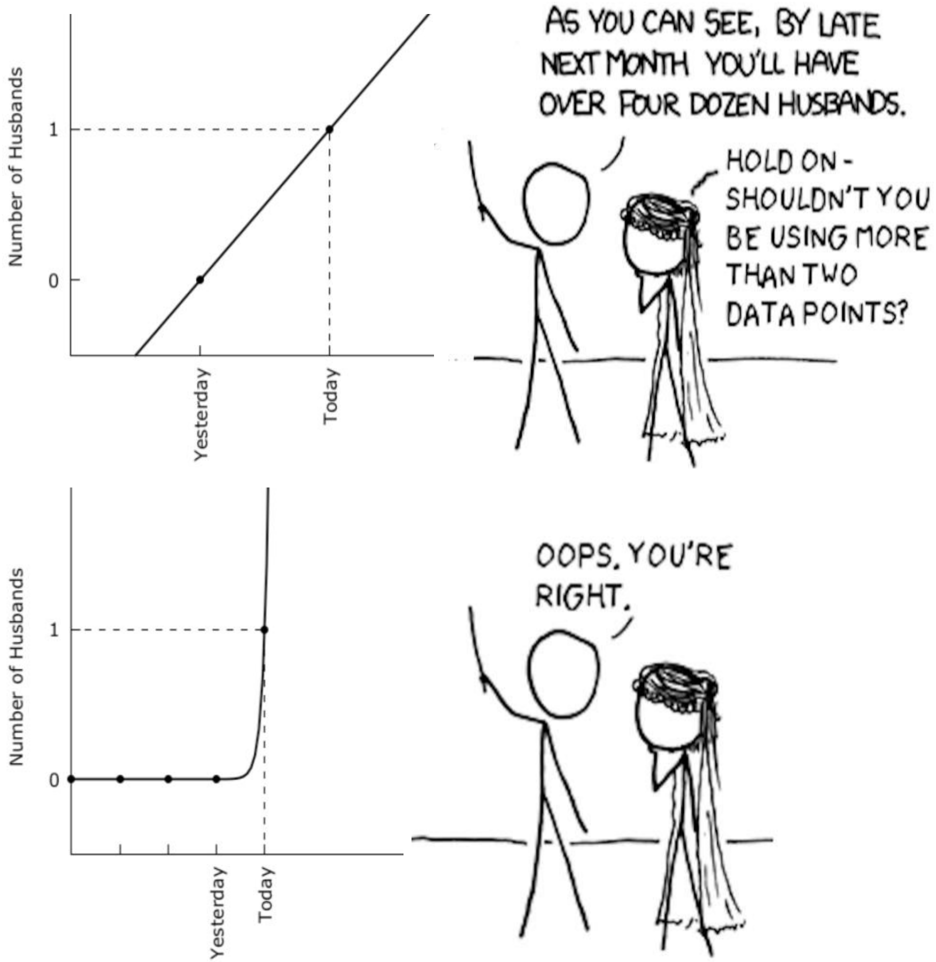
What is going to be what function to use for the fitting & extrapolating?

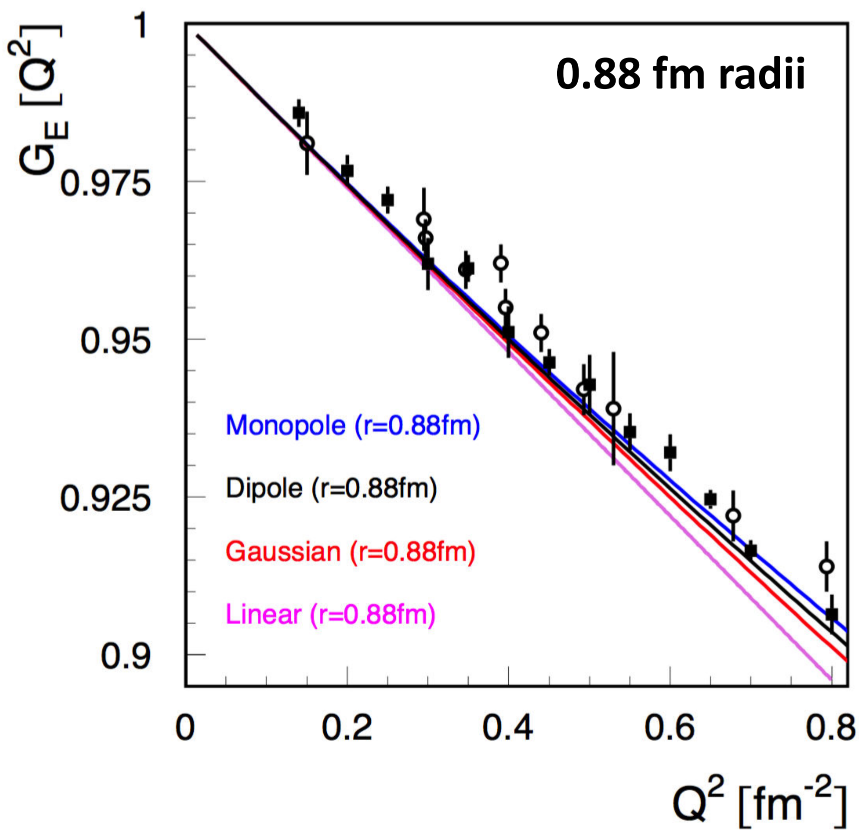
The answer to this question STRONGLY effects the answer!

$Q^2 < (1/0.88\ \text{fm})^2 < 1.2\ \text{fm}^{-2}$ to get the radius of the proton (equivalent to $\sim 0.05\ \text{GeV}^2$)

Plotting Published Results & Standard Functions

- These are NOT regressions, just the data as published and standard curves. -

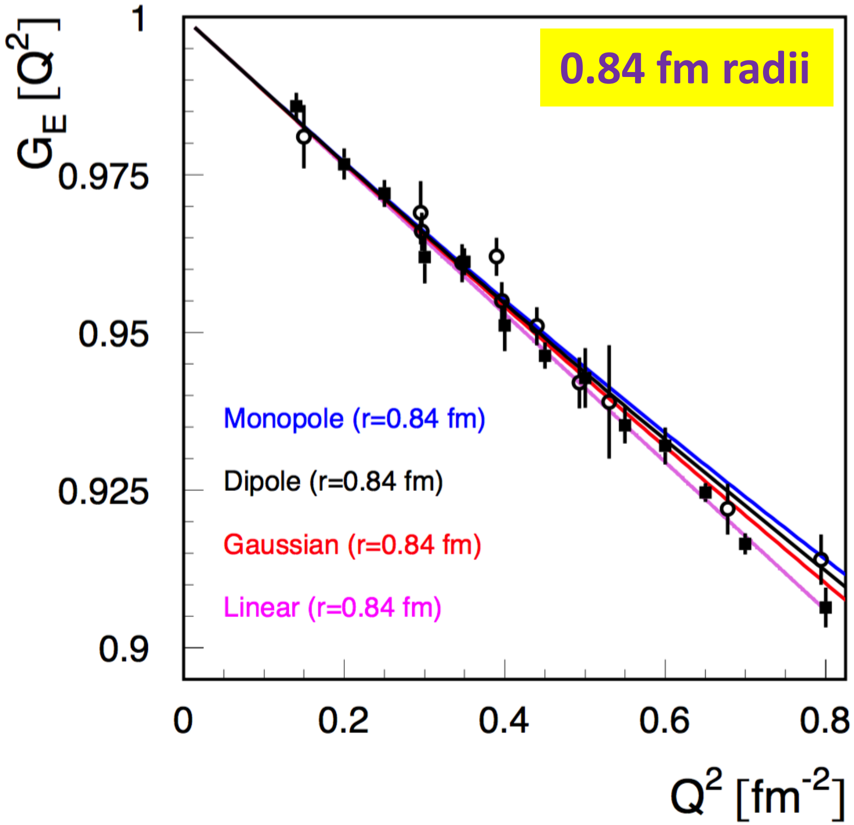


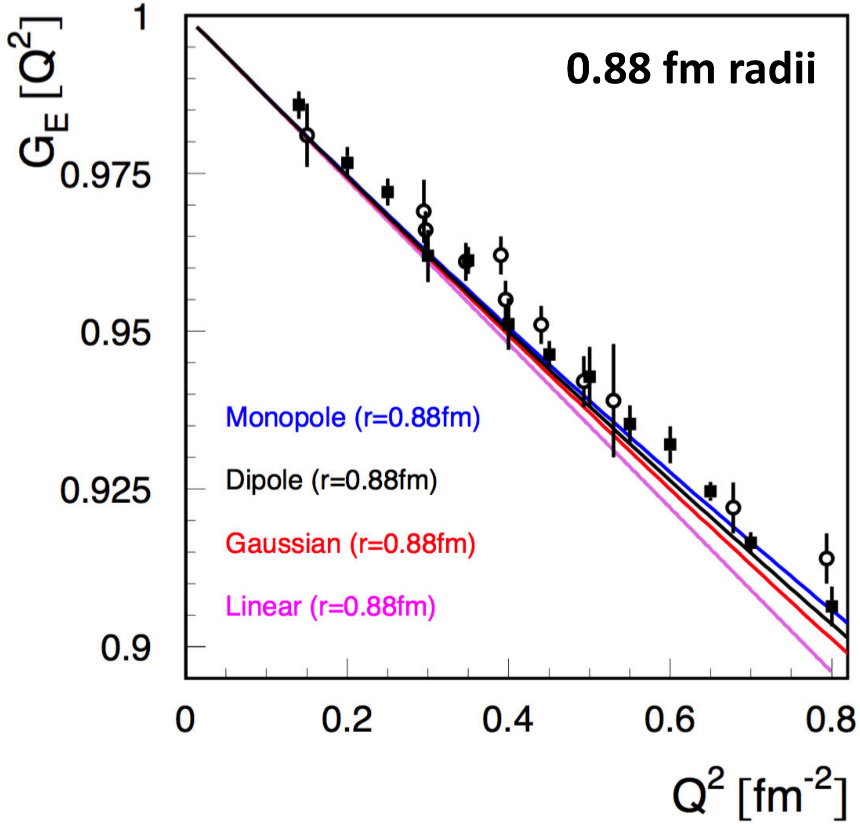


Closed Circles Mainz 1980 results and open circles Saskatoon 1974 results.

Plotting Published Results & Standard Functions

- These are NOT regressions, just the data as published and standard curves. -





Note how for a fixed radius, all functions come together as Q^2 gets < 0.4 fm^{-2}.

Need precision data at very low Q^2!

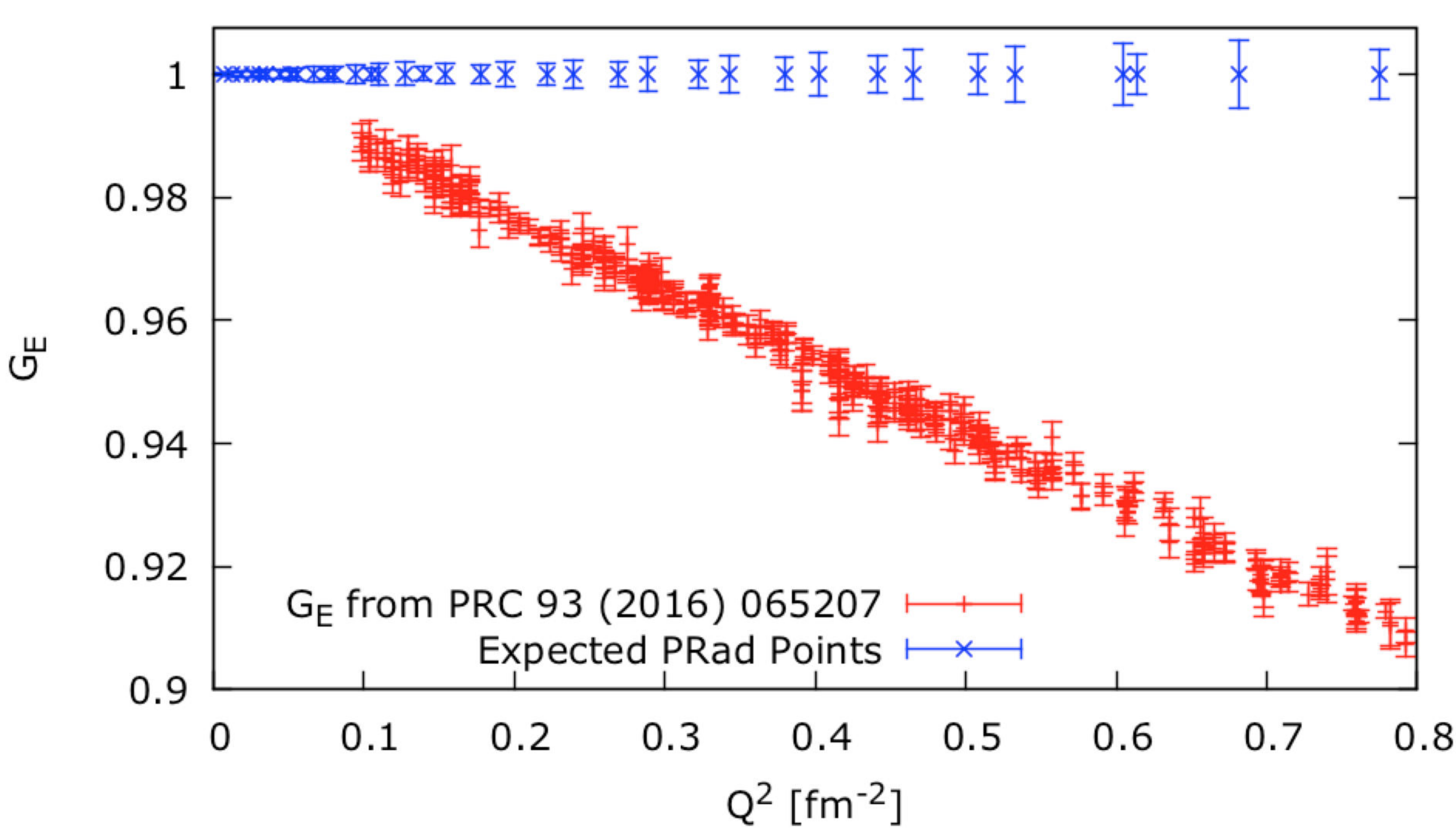
PRad: JLab Hall B Proton Radius Experiment

Small angle and small Q^2 to minimize the effects of G_M and provide best measurement of G_E

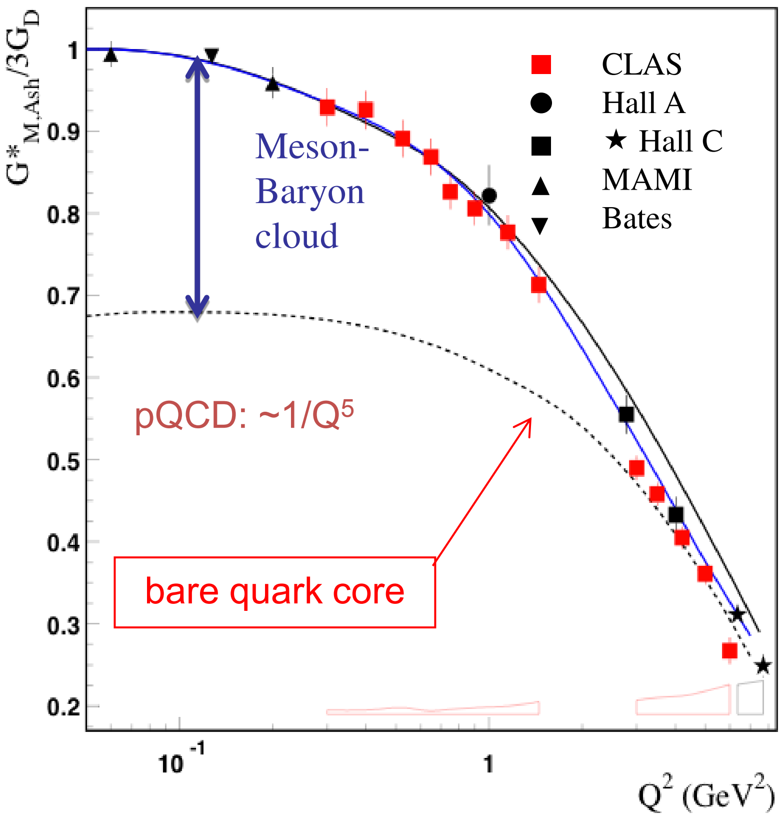
Gas Target (the proton) and GEM Detectors (scattering angles)

- The Collaboration & Hall B staff managed to get this experiment ready while installing CLAS12
- *The first completed experiment for the upgraded CEBAF accelerator.*

Expected Precision of PRad Data



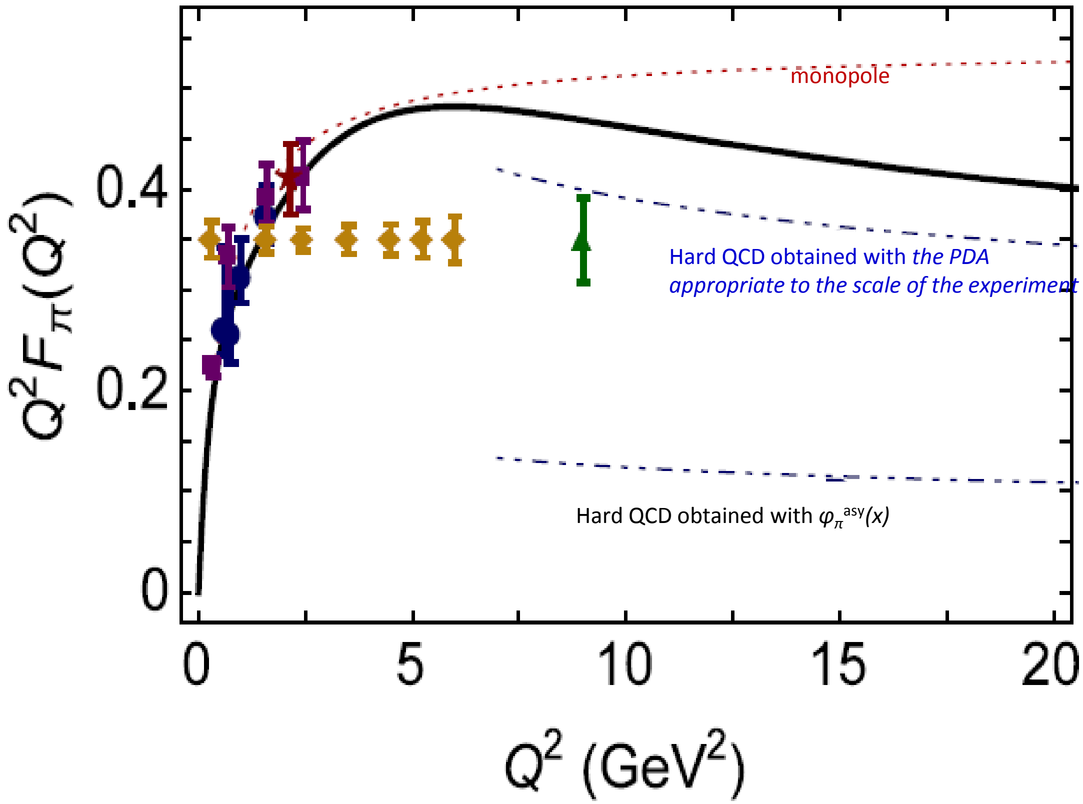
Other Form Factors – Testing QCD in the Confinement Regime



P_{11}(1232) Magnetic Dipole Transition Form Factor

CLAS12 will map numerous Resonances!

Pion FF – first quantitative access to hard scattering scaling regime?



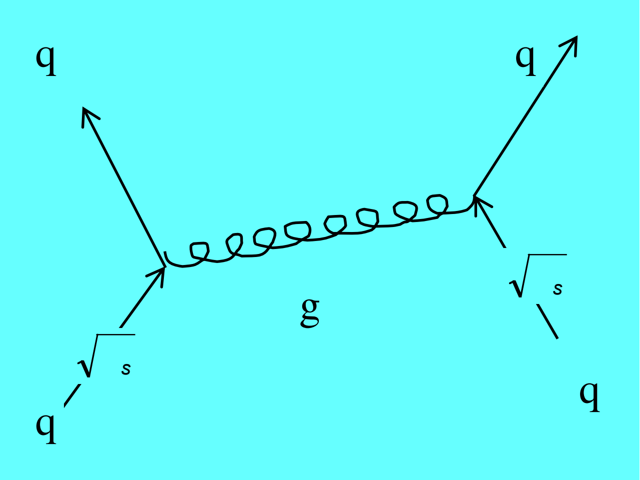
Low t = four-momentum transfer squared at the nucleon vertex

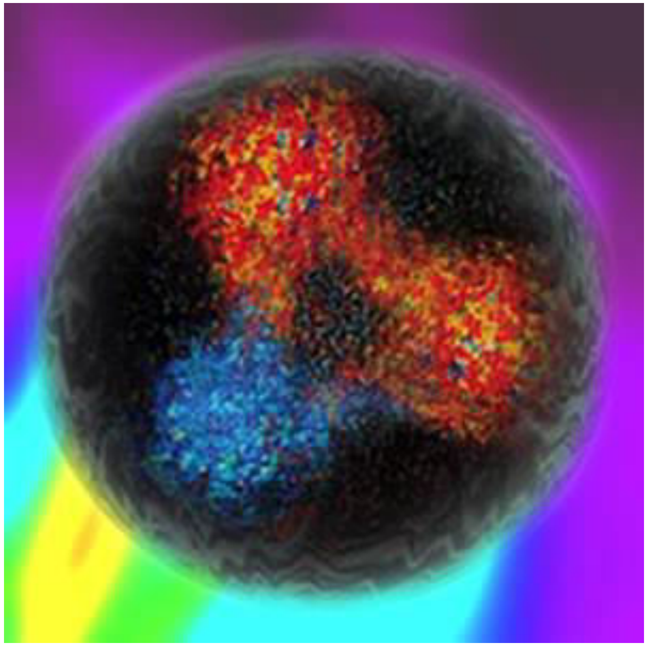
QCD and the Mechanism for Confinement

- Field theory for strong interaction:
  - quarks interact by gluon exchange
  - quarks carry a 'colour' charge
  - exchange bosons (gluons) carry colour $\Rightarrow$ self-interactions (cf. QED!)
- Hadrons are colour neutral:
  - $R\bar{R}$, $B\bar{B}$, $G\bar{G}$ or RGB
  - leads to confinement:

$$|q\rangle,\ |qq\rangle \text{ or } |qq\bar{q}\rangle \quad \text{forbidden}$$

- Can also have gluonic excitations….





Hall D: Gluonic Excitations and the Mechanism for Confinement

QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

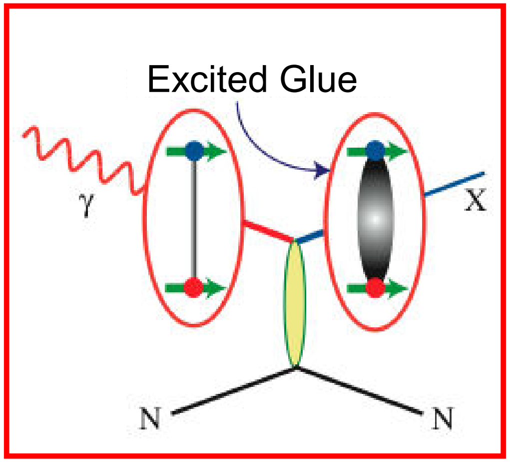
With the upgraded CEBAF, a linearly polarized photon beam, and the **GlueX detector**, Jefferson Lab will be uniquely poised to: - discover these states

- map out their spectrum
- measure their properties

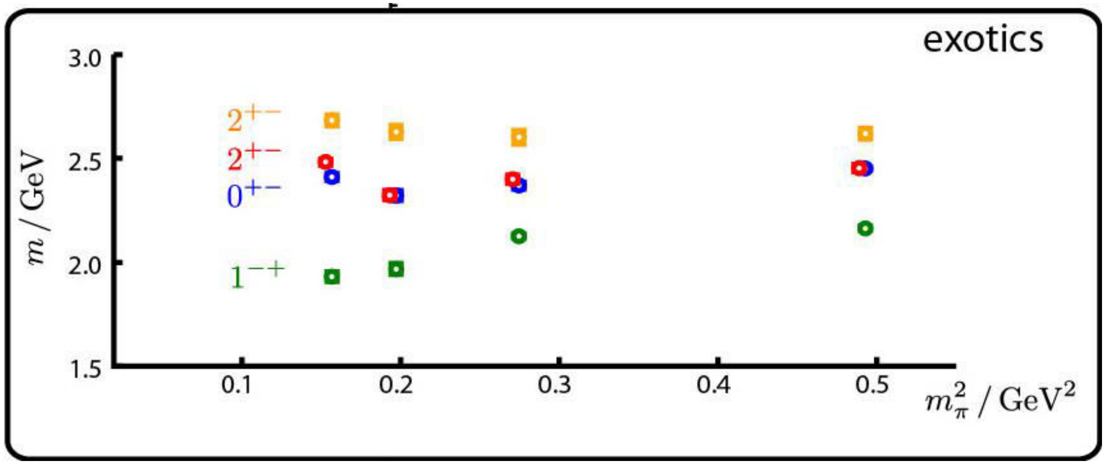
12 GeV electrons

States with Exotic Quantum Numbers

γ beam



Dudek et al.

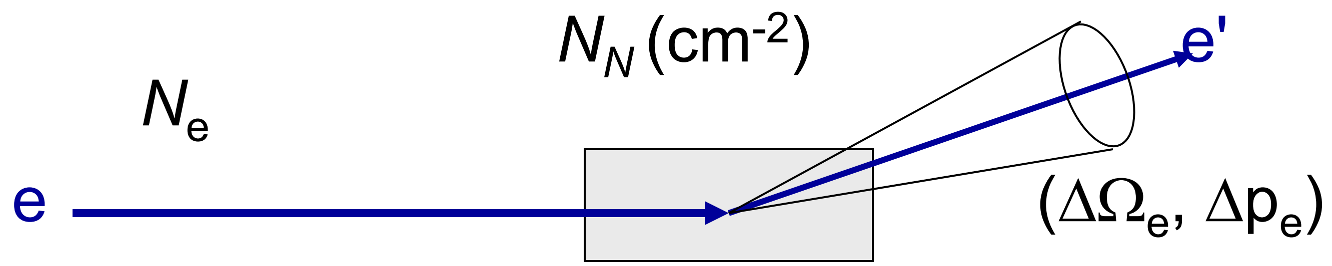



Break


Get some rest
Have some
coffee


KEEP
CALM
AND
GET SOME
REST

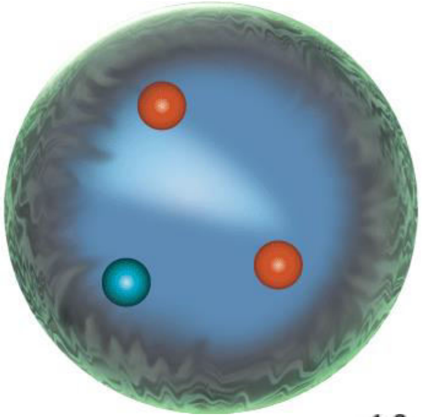
Extracting the (e,e') cross section



Scattering *probability* or cross section

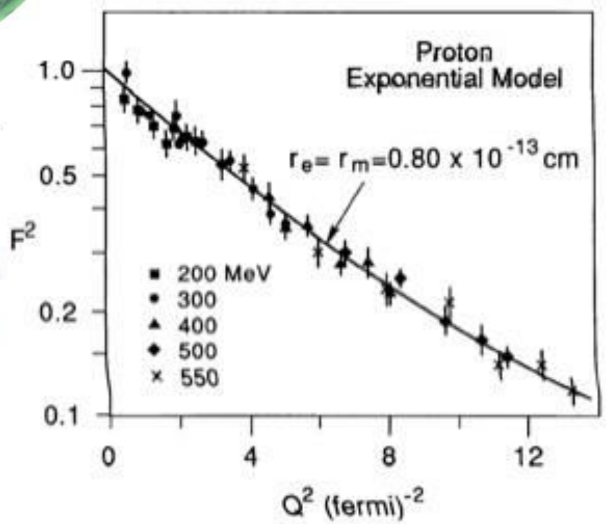
$$\left\langle \frac{d^3\sigma}{d\Omega_e dp_e} \right\rangle = \frac{\text{Counts}}{N_e N_N \Delta\Omega_e \Delta p_e}$$

e-p and e-d elastic scattering

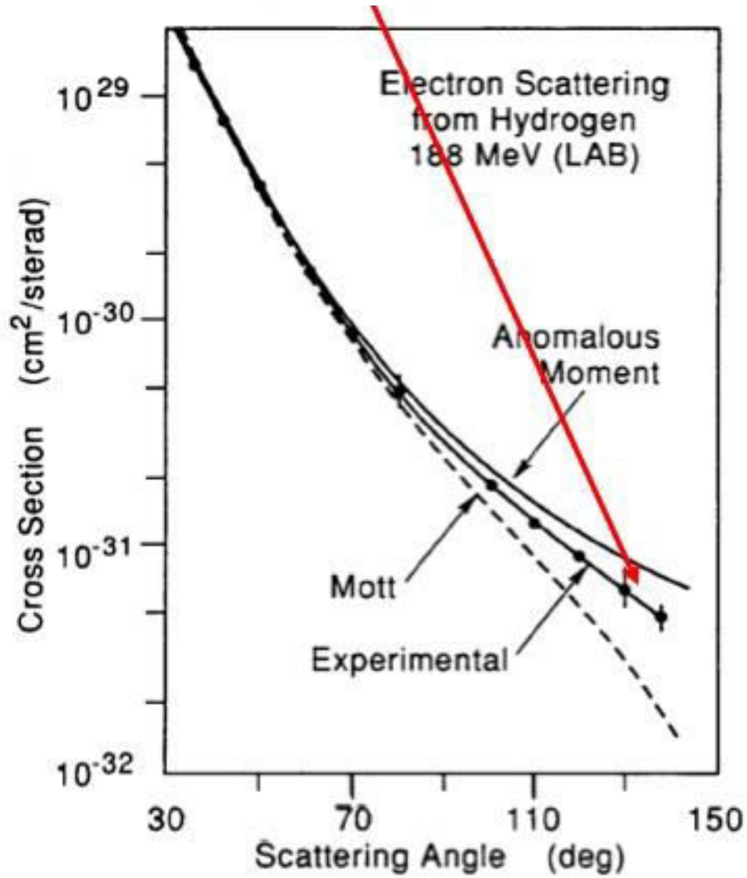


$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_0^2 \sin^4 \theta/2} \cdot \cos^2 \theta/2 \cdot \frac{E'}{E_0} \left[\frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \theta/2 \right]$$

First determination of the proton form factor



Protons have charge distribution



Deuterium smeared out by Fermi energy