Electron Scattering and Hadron Structure

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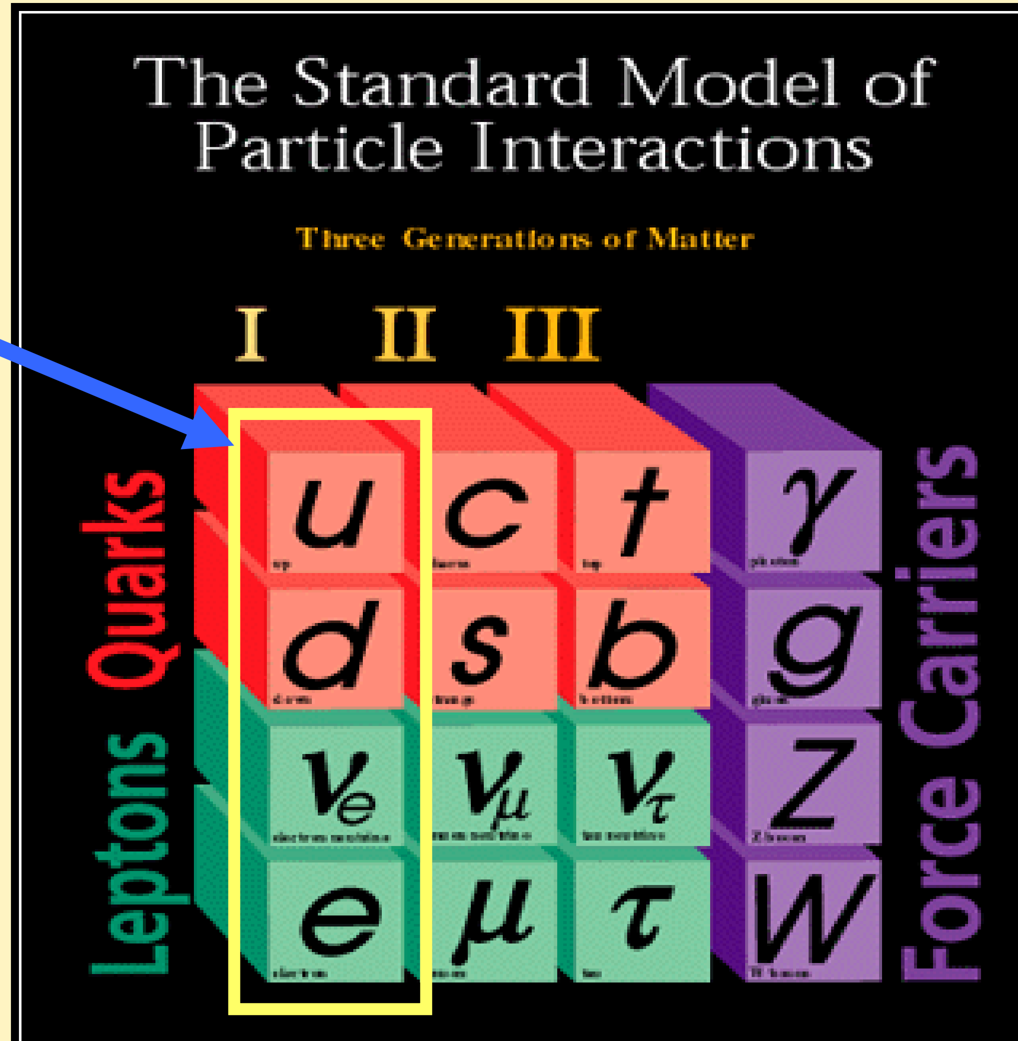
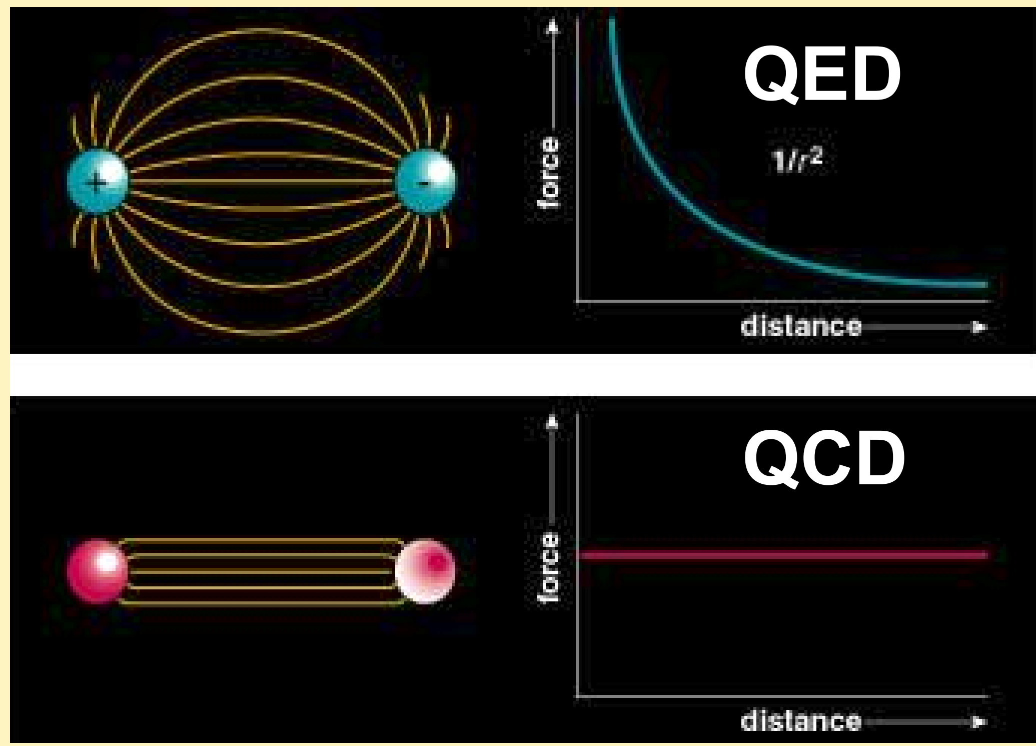
Quarks, Leptons and their Fundamental Interactions

The ground state of matter.



Quantum Electrodynamics
Quantum Chromodynamics

The gluons of QCD carry color charge and interact strongly (in contrast to the photons of QED).



Hadrons

Quarks (and their color charge) are confined inside strongly-interacting particles called hadrons.

Two families of hadrons:

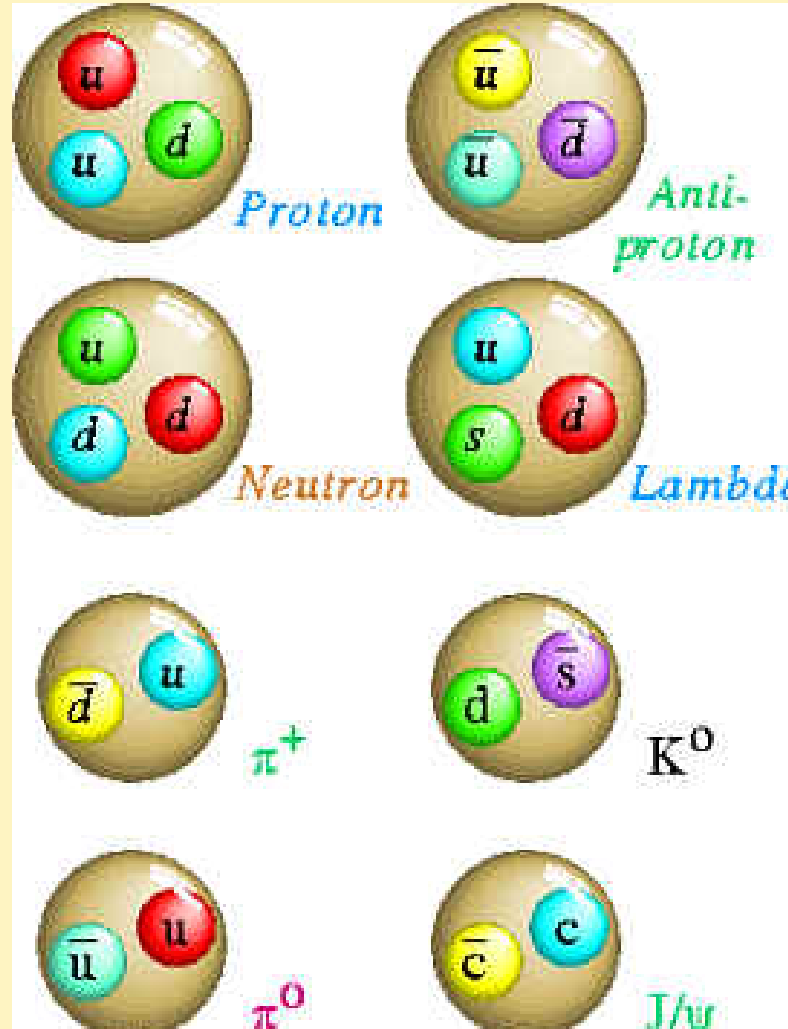
Baryons:

- Bosons (integer spin)
- Valence qqq structure

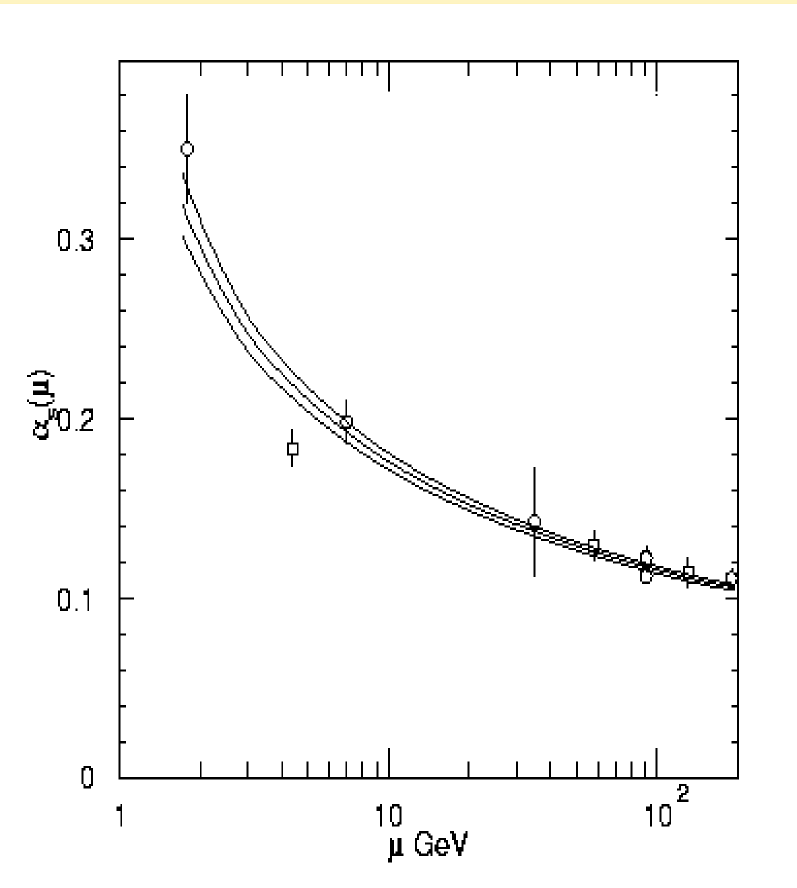
Mesons:

- Fermions (half-integer spin)
- Valence $q\bar{q}$ structure

Gluons and virtual quarks also contribute to hadron structure.



QCD's Dual Nature



Short Distance Interaction:

- Quarks inside protons behave as if they are nearly unbound.
  - Asymptotic Freedom.
- Short distance quark-quark interaction is feeble.
  - perturbative QCD (pQCD).

Long Distance Interaction:

- Quarks are strongly bound within hadrons.
  - Color confinement (strong QCD).
- QCD calculations are complex.
  - QCD-based models are often used.

The Physics Problem

Quantum Chromodynamics (QCD) in the confinement regime:

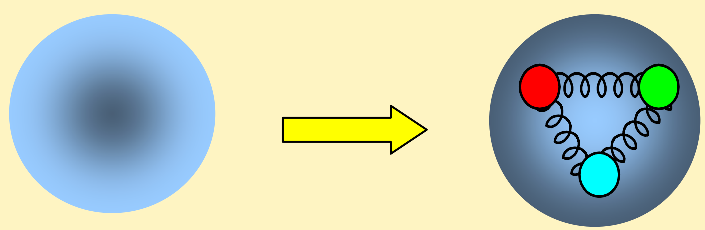
How does it work?

- What do we know?

QCD works in the perturbative (weak) regime

Many experimental tests led to this conclusion, example:

- Proton is not point-like; Elastic electron scattering (Nobel Prize: Hofstadter, 1961).
- Quarks and gluons/Partons are the constituents; Deep Inelastic electron Scattering (Nobel prize: Friedman, Kendall and Taylor, 1990).



Theory celebrated recently

Asymptotic freedom (Nobel prize: Gross, Politzer and Wilczek, 2004), **but**

Quantitative QCD description of the nucleon's properties

(i.e. understanding of the confinement regime) remains a puzzle!

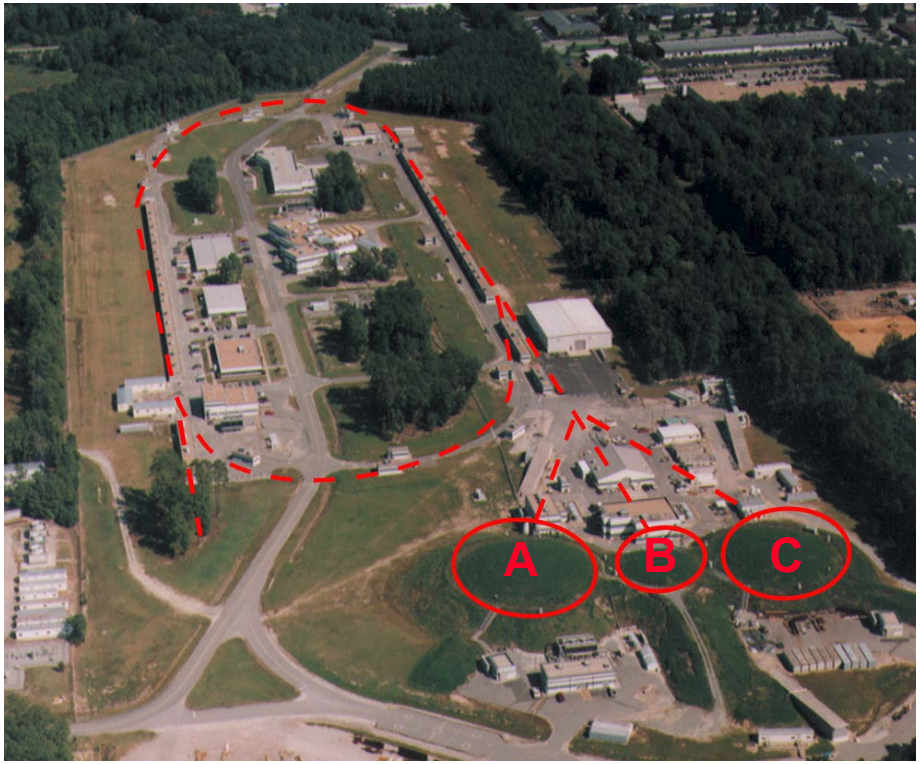
Physics Problems for the Next Millennium

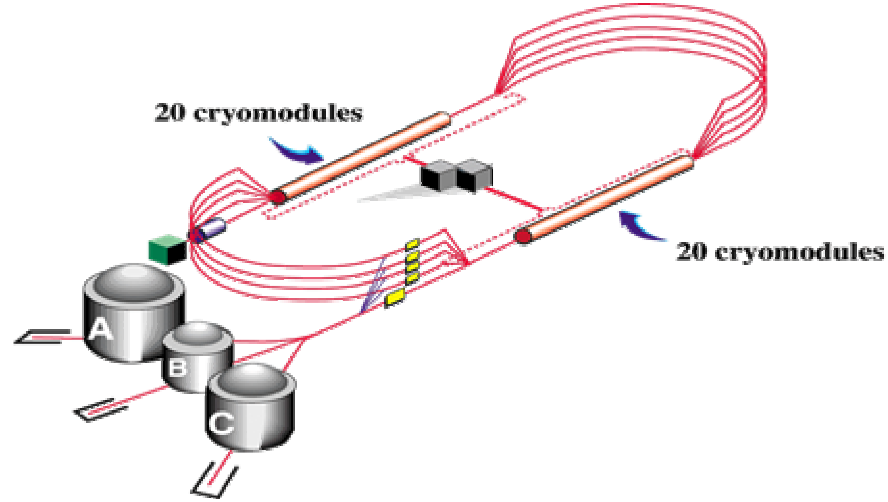
Selected by:

Michael Duff, David Gross, Edward Witten

Strings 2000

1. Size of dimensionless parameters.
2. Origin of the Universe.
3. Lifetime of the Proton.
4. Is Nature Supersymmetric?
5. Why is there 3+1 Space-time dimensions?
6. Cosmological Constant problem.
7. Is M-theory fundamental?
8. Black Hole Information Paradox.
9. The weakness of gravity.
10. Quark confinement and the strong force.





Two Cold Superconducting Linacs

Continuous Polarized Electron Beam

- $E \rightarrow 6$ GeV
- $> 100\ \mu A$
- up to 80% polarization
- concurrent to 3 Halls

First beam delivered in 1994

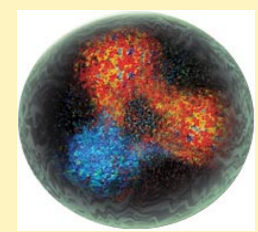
Why electron scattering experiments?

Transition from pQCD to Strong QCD needs data with high precision for a quantitative understanding of confinement.

1990's advancements:
Intense CW electron beams.
Polarized targets/polarimetry.
Improvement in polarized e sources.

Luminosity:
(SLAC, 1978) ~ 8×10^{31} cm^{-2}-s^{-1}
(JLab, 2000) ~ 4×10^{38} cm^{-2}-s^{-1}

$$d = 1 \rightarrow 0.1\,\mathrm{fm} \quad \Leftrightarrow \quad Q^2 = 0.1 - 10\,(\mathrm{GeV/c})^2$$



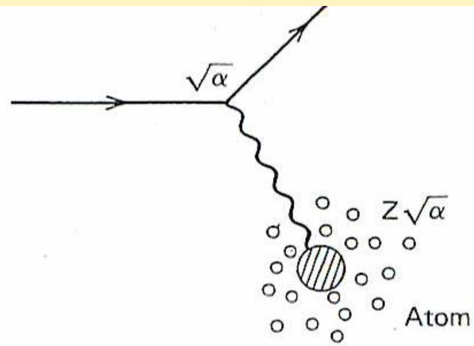
What quantities do we measure?

– Hadron form factors: pion, nucleon. [System responds coherently]

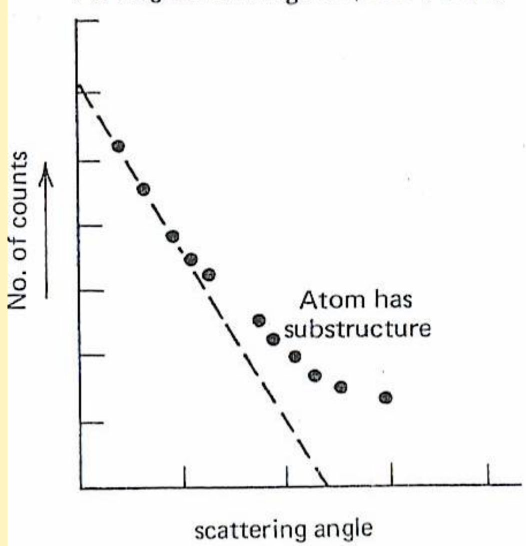
– Nucleon structure functions: [System responds incoherently]

Rutherford Scattering

Scattering
of α particle
by atom

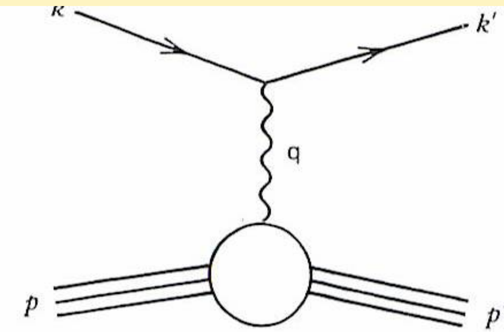


Au target *Phil. Mag.* xxi, 669 (1911)

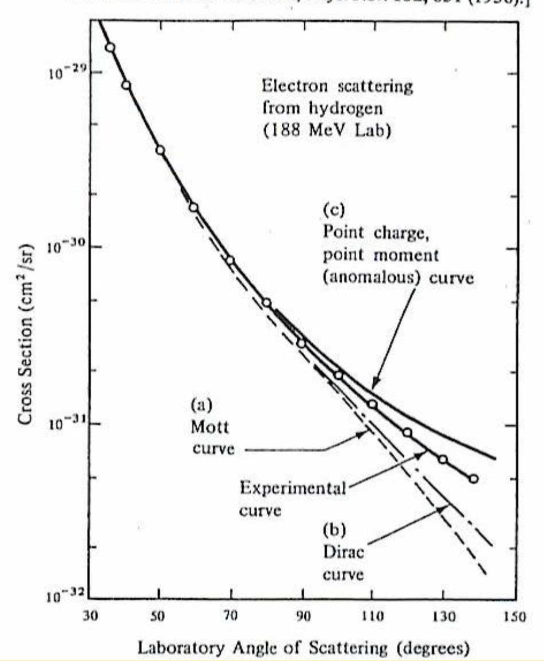


Proton Form Factor

Scattering
of electron
by proton



Electron–proton scattering with 188 MeV electrons. [R. W. McAllister and R. Hofstadter, *Phys. Rev.* **102**, 851 (1956).]



Elastic Form Factors

In general, the elastic scattering cross section from an extended target is

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\substack{\text{point}\\\text{object}}} \left|F(Q^2)\right|^2$$

In the case of an infinitely massive target, the form factor is simply the Fourier transform of the charge distribution.

$$F(Q^2) = \int \rho(\vec{x}) e^{i\vec{q}\cdot\vec{x}/\hbar} d^3x$$

Spin 0 mesons (π^+,K^+): electric charge form factor (F) only.

Spin ½ Nucleon: electric (G_E) and magnetic (G_M) form factors.

→ alternate representation in terms of spin non-flip (F_1) and spin flip (F_2) form factors.

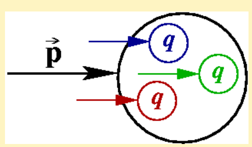
The measurements allow us to test our understanding of hadronic structure by comparison to QCD-based predictions.

An early pQCD Prediction:

- Dimensional Scaling at Large Momentum

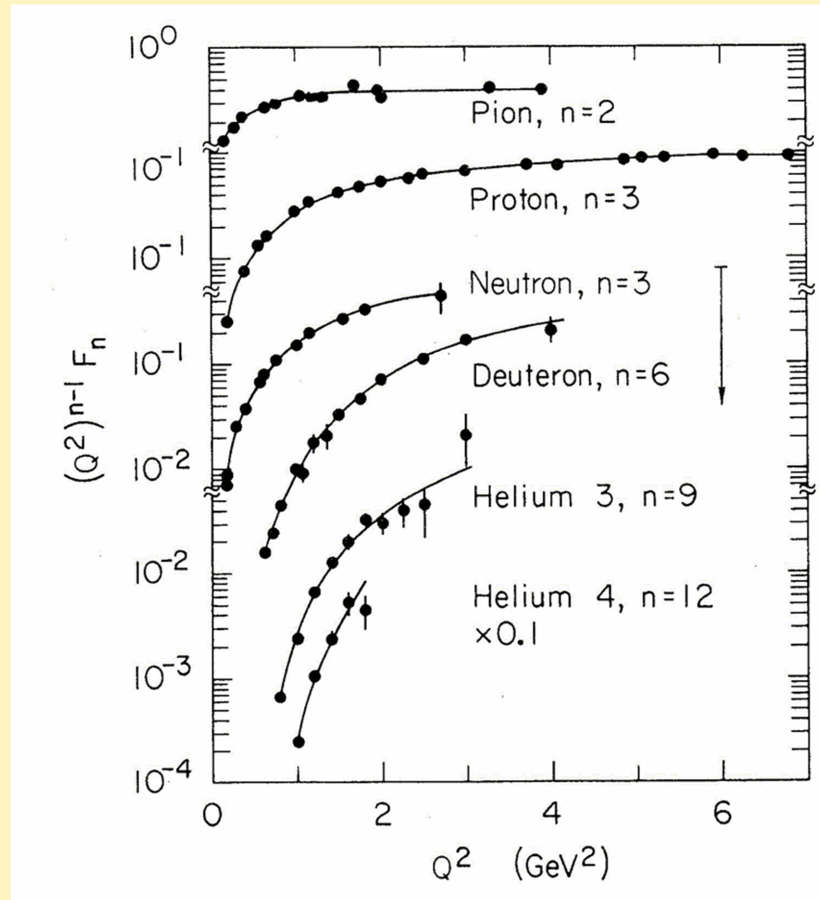
At infinite momentum, quarks are asymptotically free.

- Equivalent to turning off the strong interaction.
- The hadron becomes a collection of free quarks with equal longitudinal momenta.



Dimensional analysis of the hadron scattering amplitude in terms of the participating fields yields

$$F(Q^2) \propto \frac{1}{(Q^2)^{n-1}}$$



S.J. Brodsky, G.P. Lepage "Perturbative QCD", A.H. Mueller, ed., 1989.

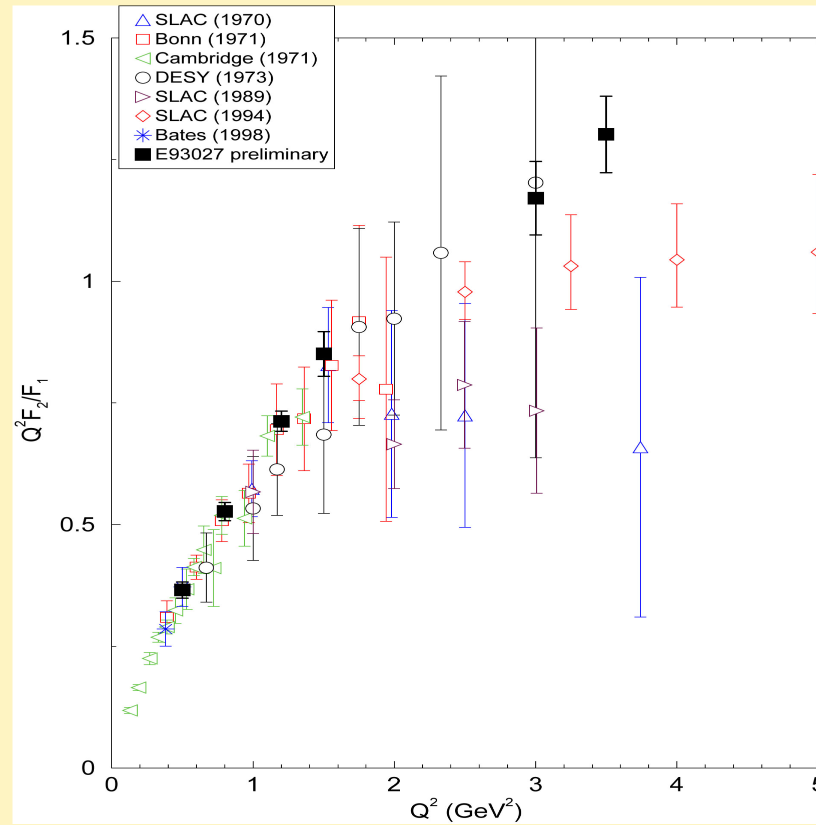
Proton Electromagnetic Form Factors

pQCD Dimensional Scaling Rule:

- $F_1(Q^2) \sim 1/Q^4$ (n=3).
- $F_2(Q^2) \sim 1/Q^6$ (n=3 with spin flip).
  - $Q^2F_2/F_1 \sim$constant.

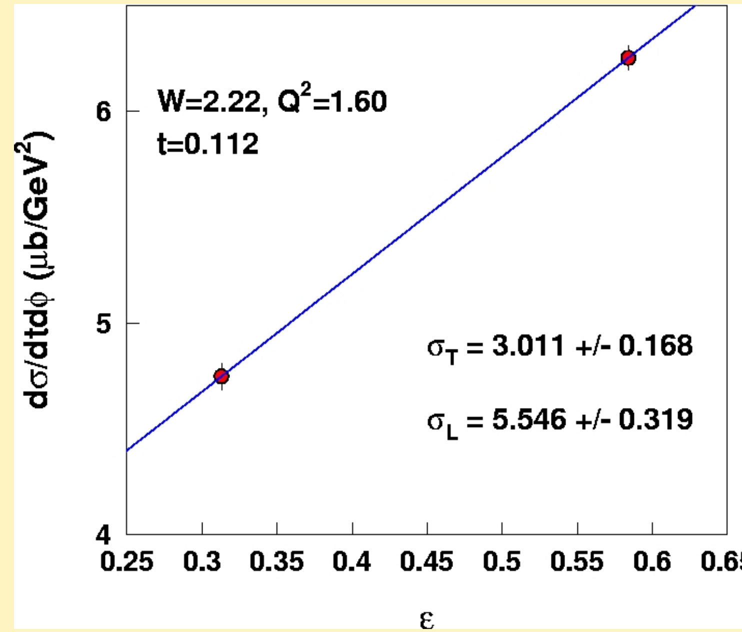
- Data indicate onset of pQCD scaling at only $Q^2 \approx 2$ GeV^2.
  - Seems low, given that the argument is made for infinite momentum.

World proton data set, 1997.



“Rosenbluth” L/T Separation Technique

A challenging technique that requires the delicate comparison of data at two different electron beam energies.



Virtual-photon polarization:

$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2} \tan^2 \frac{\theta_{e'}}{2} \right)^{-1}$$

$$\frac{d\sigma^{el}}{dQ^2} \rightarrow \varepsilon G_E(Q^2) + \tau G_M(Q^2)$$

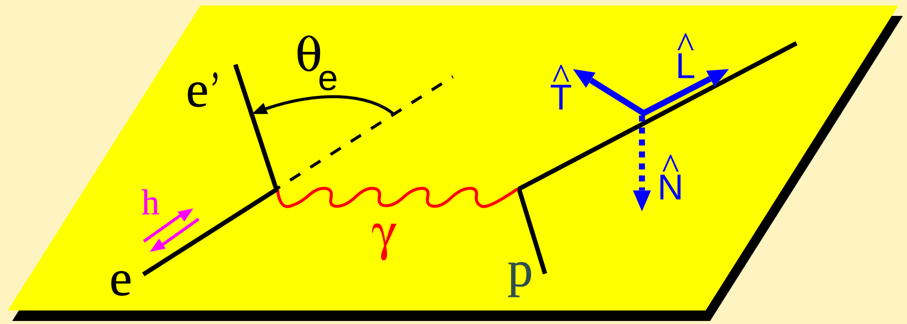
Magnetic contribution dominates cross section at high Q^2:

- F_1 data of fairly good quality.

Electric contribution at few % level:

- F_2 difficult to measure.
- Systematic error issues.

Polarization transfer technique



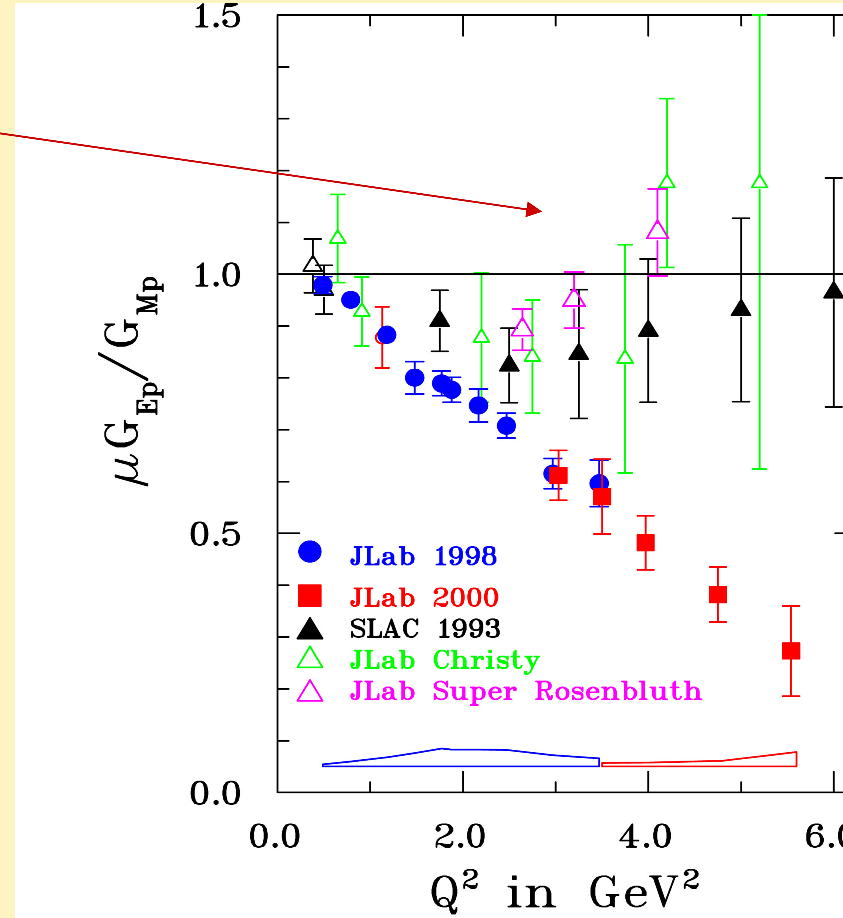
- Technique developed at Novosibirsk.
- Requires an intense polarized electron beam and a measurement of the polarization of the recoil nucleon.

$$\frac{G_E}{G_M} = -\frac{p_t}{p_l}\frac{E+E'}{2m}\tan\left(\frac{\theta_e}{2}\right)$$

Simultaneous measurement of transverse and longitudinal polarization components provides an accurate measurement of the form factor ratio.

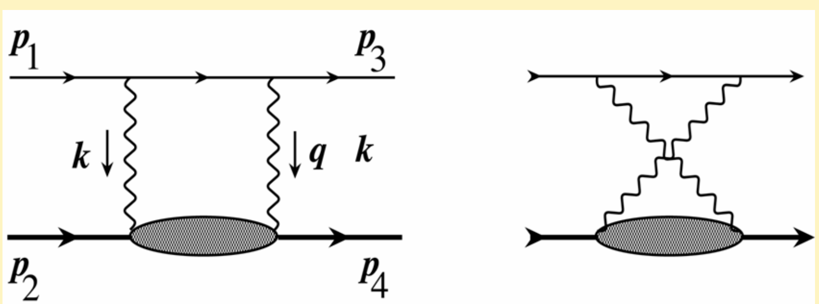
Comparison of Polarization and Rosenbluth techniques

2004 JLab "SuperRosenbluth" *(e,p)* cross sections data agree well with global cross secton fit.
(I.A. Qattan et al, PRL **94**(05)142301)



O. Gayou et al, PRL **88**(02)092301.

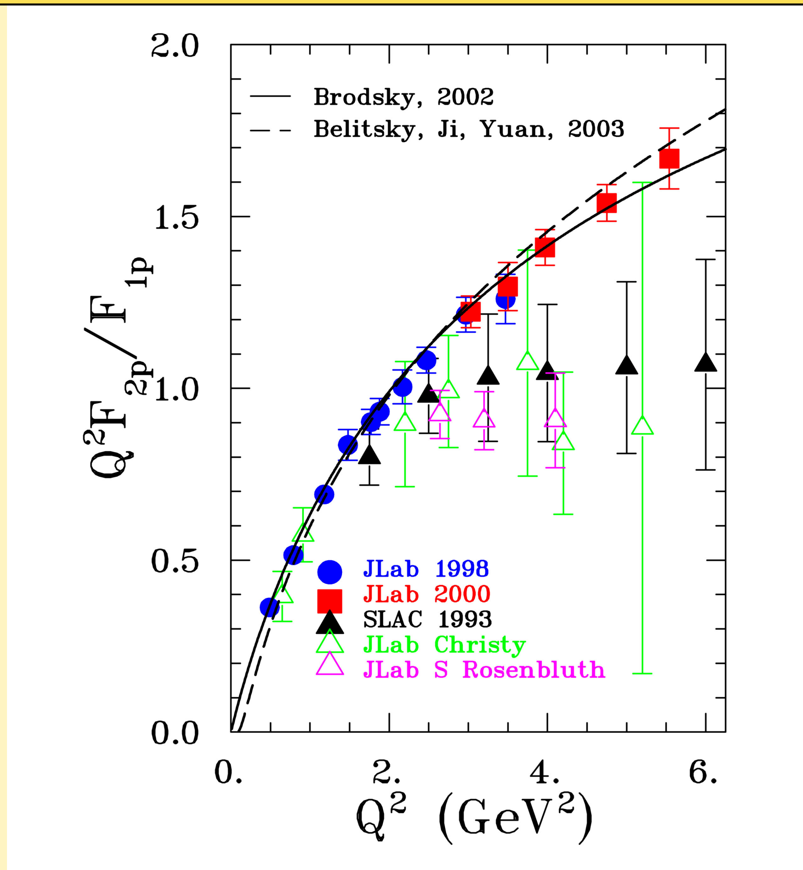
Likely culprit: 2-γ exchange impacts cross section data.
(P. Blunden et al, PRL **91**(03)142304)

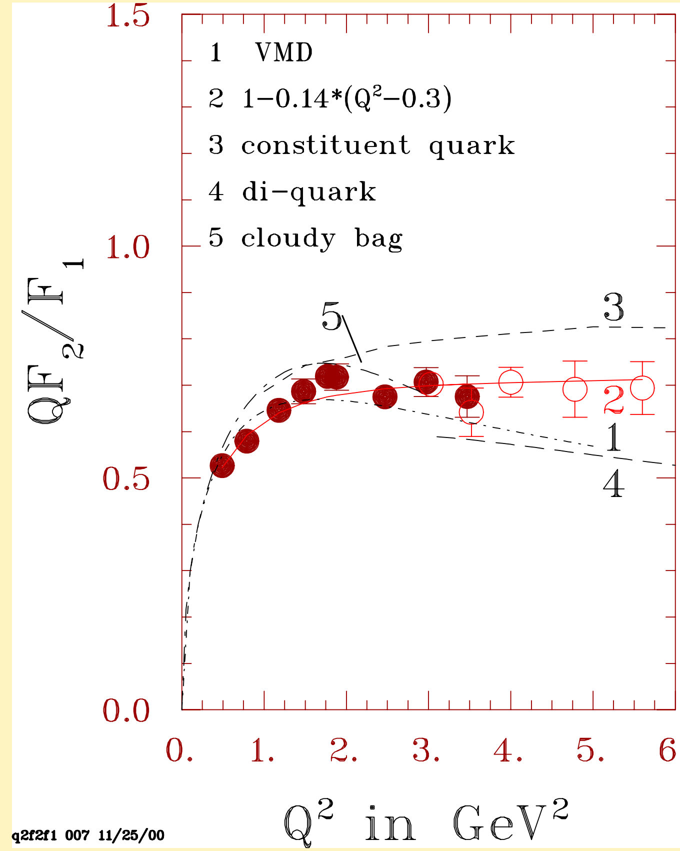


can be directly tested with
$\sigma(e^+)/\sigma(e^-)$ (Novosibirsk, JLab).

WHAT THIS MEANS: Elastic cross sections are accurate, but the polarization transfer measurements better represent G_E^p.

Jefferson Lab Proton F_2/F_1 Data



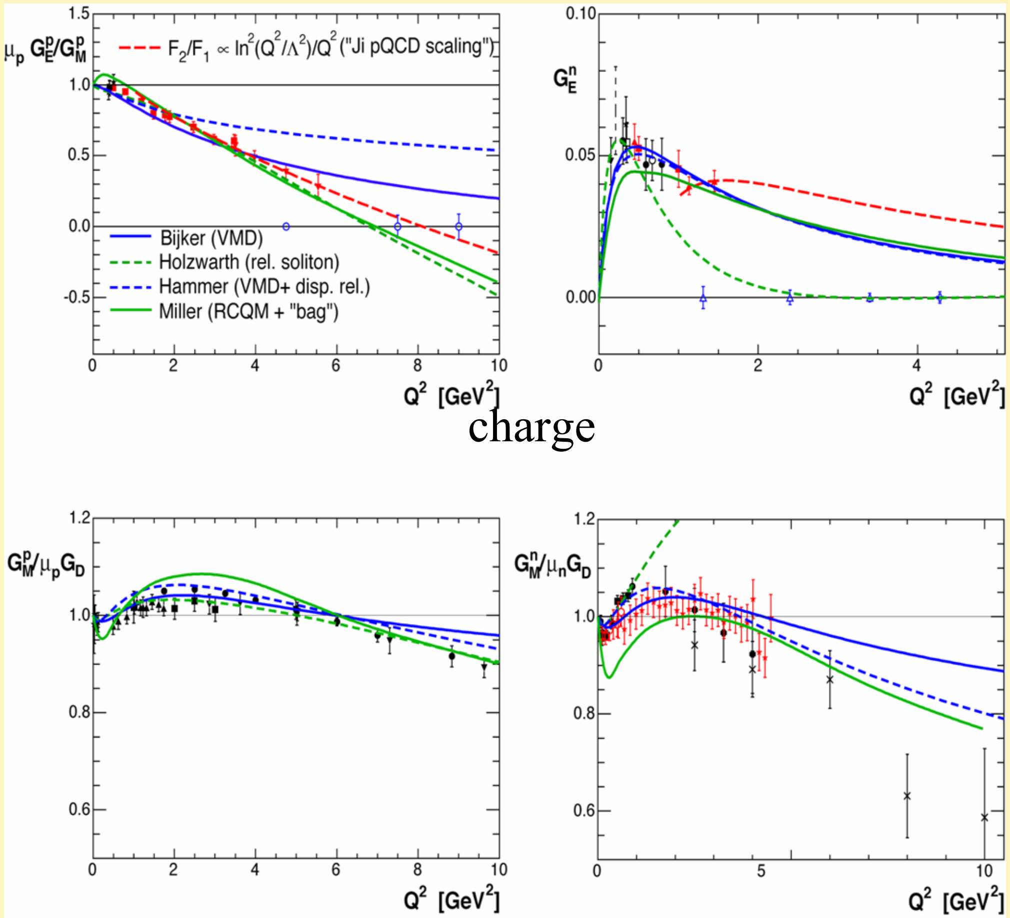


- JLab data show that Q^2 scaling was "premature".
- The data instead show a remarkable scaling with Q, which was not anticipated.
- Higher twist and other soft contributions produce $ln(Q^2)$ corrections which give rise to Q-like scaling (Belitsky, Ji, Yuan, PRL **91**(03) 092003).

Global analysis of *p* and *n* Form Factors

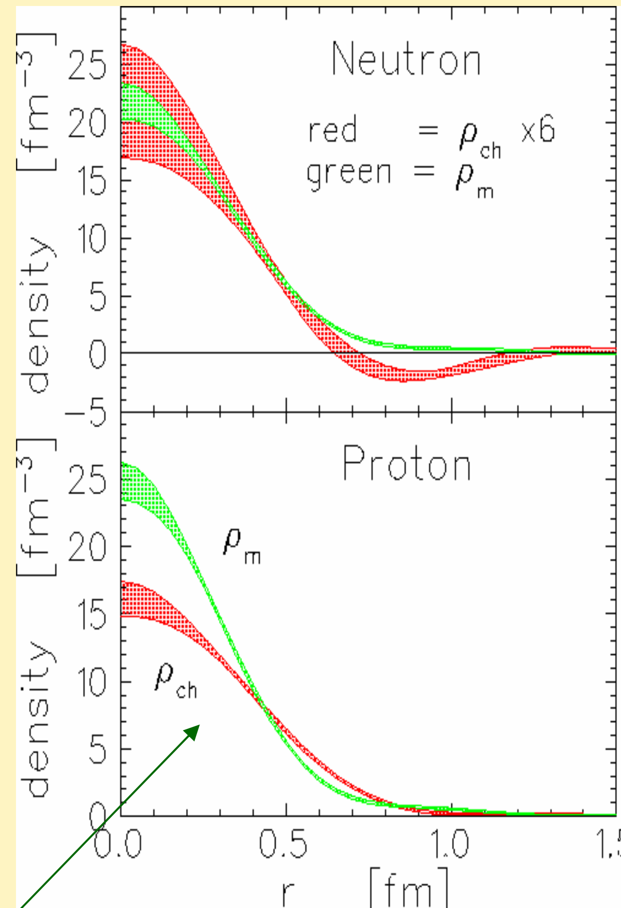
J.J. Kelly, PRC **66** (2002) 065203

proton neutron



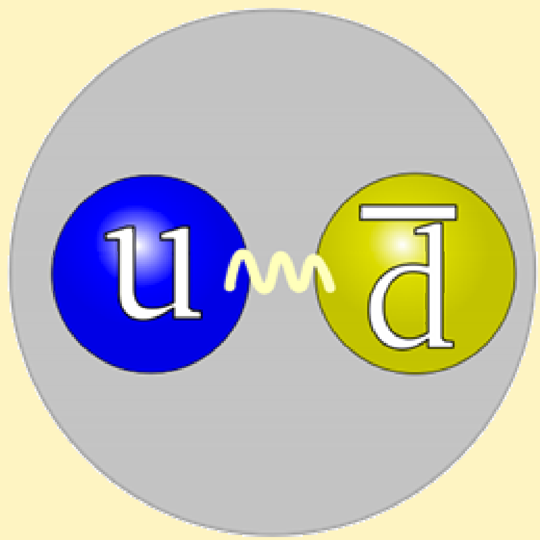
charge

magnetization

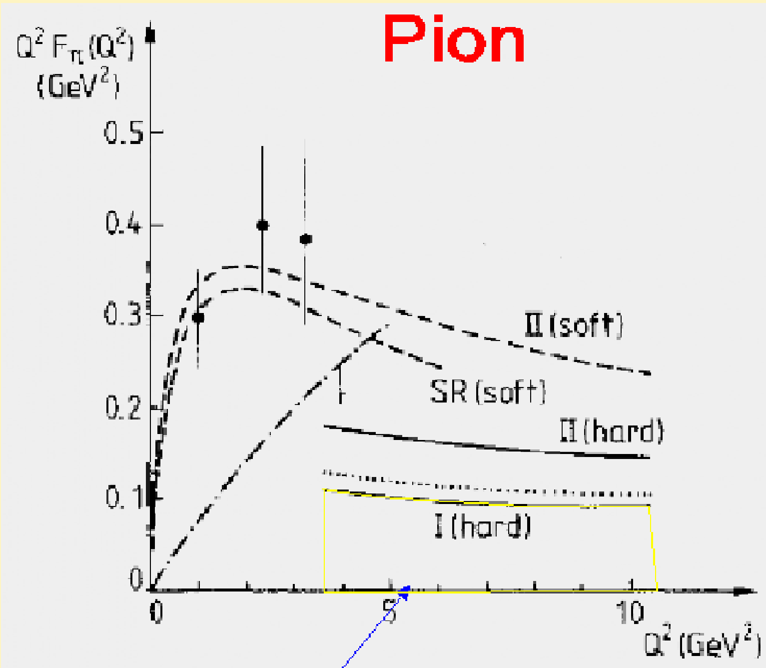


JLab polarization data show depletion of charge in proton interior.

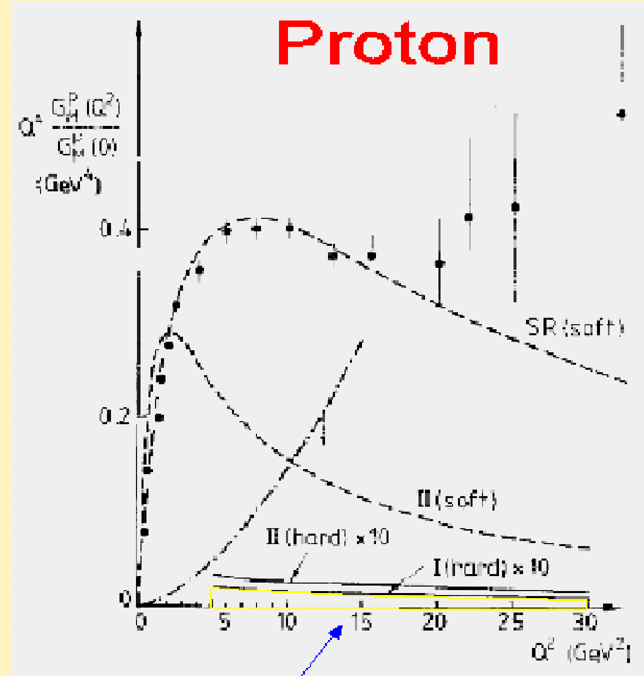
Meson Form Factors



The pion as a QCD Laboratory



Hard contributions
~30-50% at Q^2=5 GeV²



Hard contributions
≤1% at Q^2=5 GeV²

Isgur & Llewellyn-Smith, PRL 52(84)1080

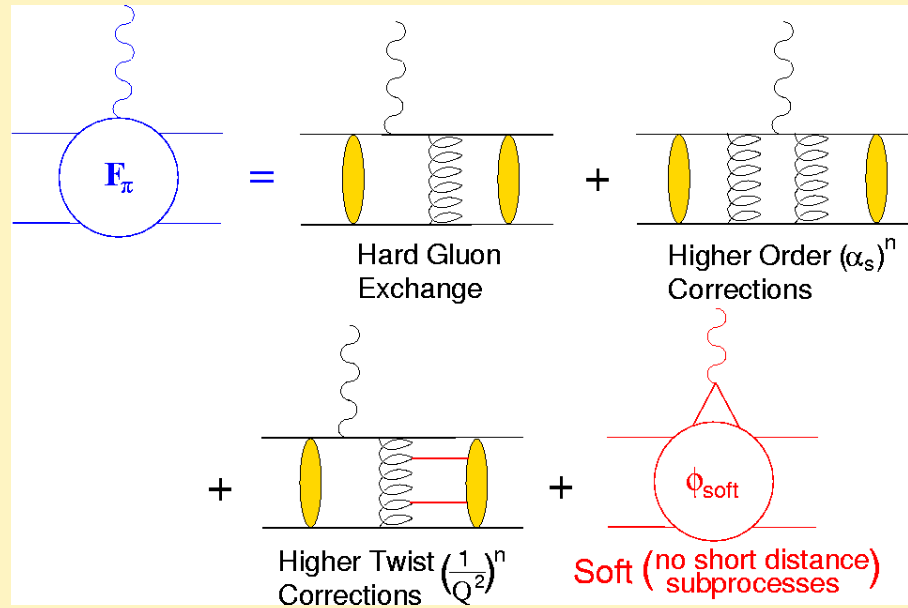
Transition from perturbative QCD to Strong QCD is most easily studied with simple $q\bar{q}$ systems such as the pion

Meson Form Factors and QCD

- The simple $q\bar{q}$ valence quark structure of mesons presents the ideal laboratory for testing our understanding of bound quark systems

→ all hadronic structure models use the π^+ as a test case.

"The positronium atom of QCD"



Excellent opportunity for studying the **QCD transition** from effective degrees of freedom to quarks and gluons.

i.e. from the strong QCD regime to the hard QCD regime.

Jefferson Lab is the only experimental facility capable of the necessary measurements.

π^+ and K^+ Form Factors

At low Q^2<0.3 GeV^2 the $\pi^+(K^+)$ form factor can be measured exactly using high energy $\pi^+(K^+)$ scattering from atomic electrons.

300 GeV experiment at CERN SPS measures $\pi^+(K^+)$ charge radii:

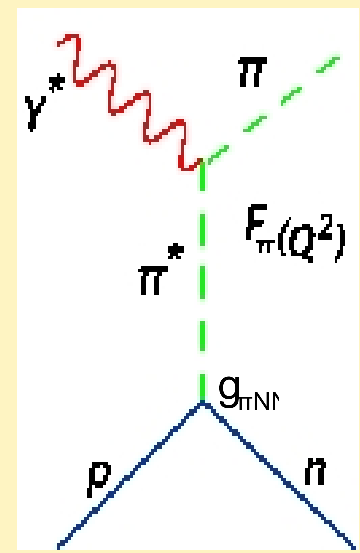
$$r_\pi = 0.672 \pm 0.008 \text{ fm}$$
$$r_K = 0.560 \pm 0.031 \text{ fm}$$

To access higher Q^2 one must use an experimentally "unclean": moving virtual target…

$$2\pi \frac{d\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

$\varepsilon = [1+2(1+\tau)\tan^2(\theta/2)]^{-1}$

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)} g^2_{\pi NN}(t)\, F^2_\pi(Q^2,t)$$



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Virtual-photon polarization:

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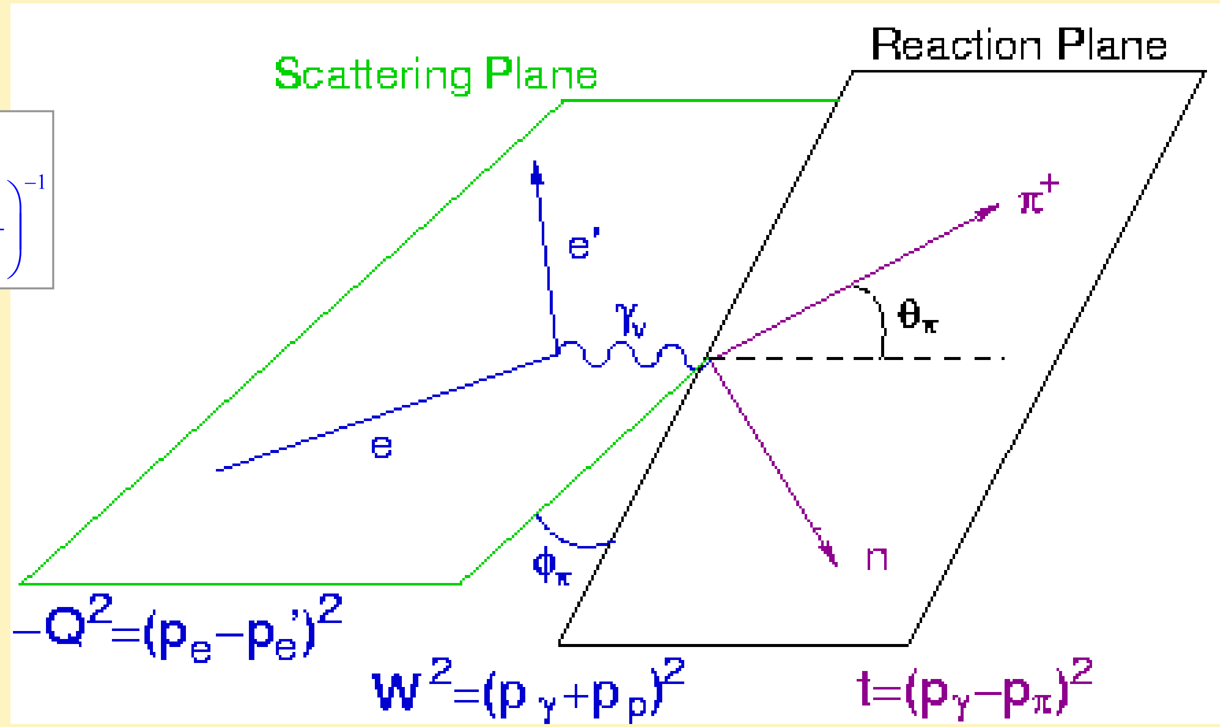
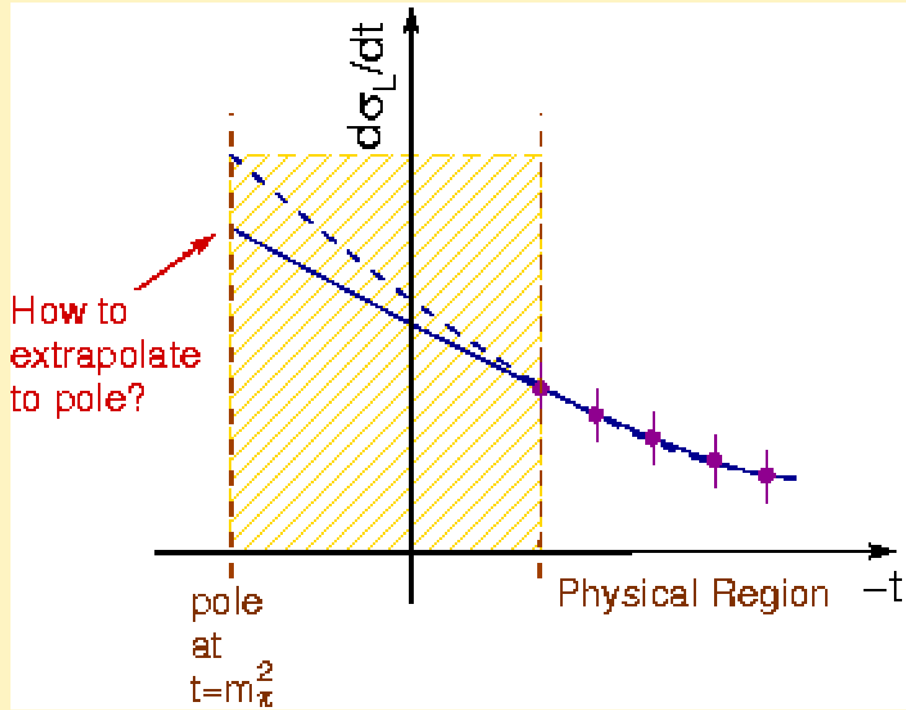


Need to take data at smallest available –*t*, so σ_L has maximum contribution from the π^+ pole.

- Reduced model uncertainty in F_π extraction.
- For given Q^2, higher W allows smaller $|t_{min}|$.

Extraction of π^+ Form Factor in $p(e,e'\pi^+)n$

- π^+ electroproduction can only access $t<0$ (away from pole)
- Early experiments used "Chew-Low" technique
  - measured $-t$ dependence
  - Extrapolate to physical pole
- This method is unreliable – different fit forms consistent with data yet yield very different FF

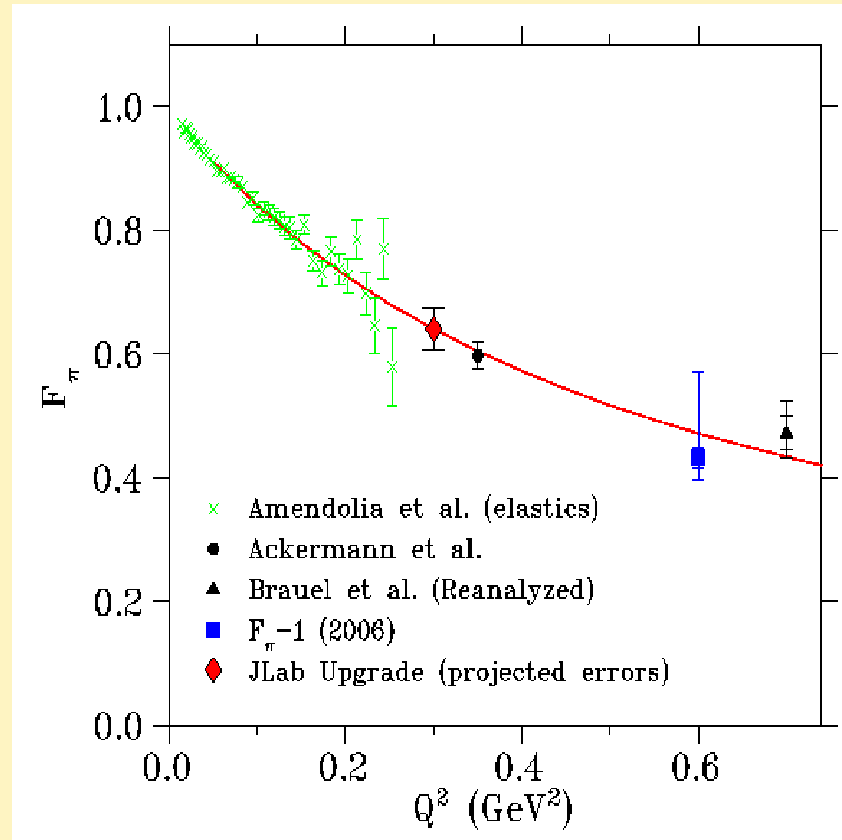


A more reliable approach is to use a model incorporating the π^+ production mechanism and the `spectator' nucleon to extract $F_\pi(Q^2)$ from σ_L.

→ *t-pole* "extrapolation" is implicit, but one is only fitting data in physical region

Check of Pion Electroproduction Technique

- **Does electroproduction really measure the physical form-factor since we are starting with an off-shell pion?**
- This can be tested making $p(e,e'\pi^+)n$ measurements at same kinematics as π+e elastics
- Looks good so far:
  - Ackermann electroproduction data at $Q^2 = 0.35$ GeV^2 consistent with extrapolation of SPS elastic data.

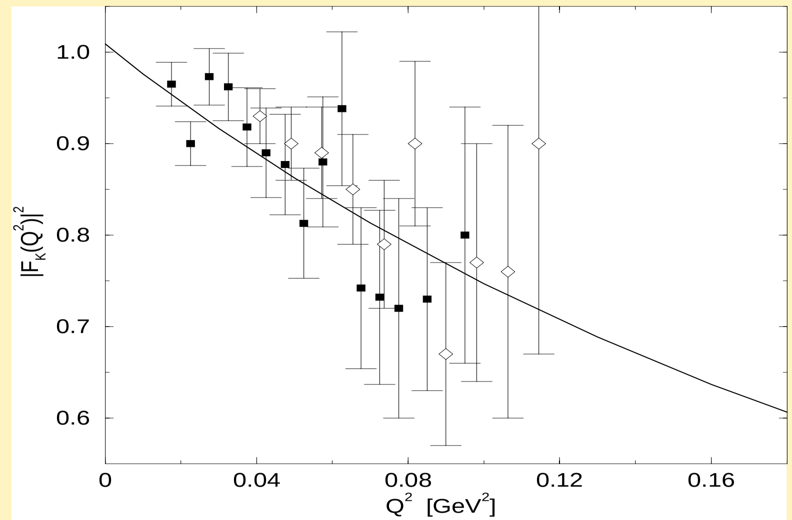


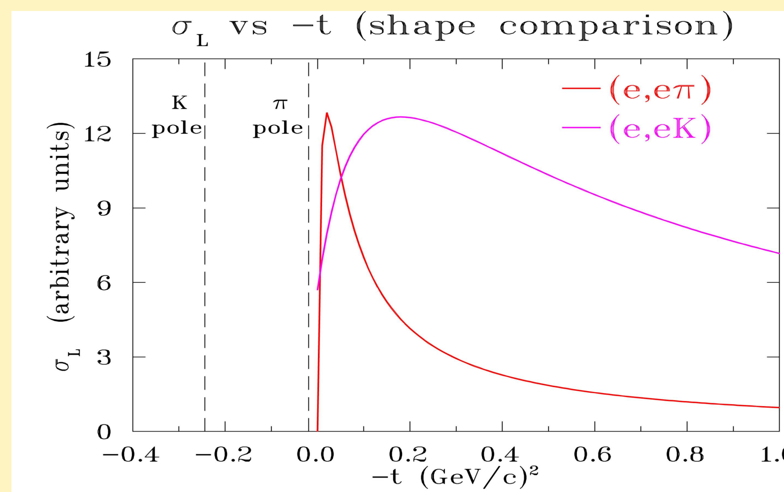
An improved test will be carried out after the JLab 12 GeV upgrade
→smaller Q^2 (=0.30 GeV^2)
→$-t$ closer to pole (=0.005 GeV^2)

Measurement of K^+ Form Factor

- Similar to π^+ form factor, elastic K^+ scattering from electrons used to measure charged kaon for factor at low Q^2
  [Amendolia et al, PLB 178, 435 (1986)]

- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K⁺)Λ*** ?
- Kaon pole further from kinematically allowed region
- Can we demonstrate that the "pole" term dominates the reaction mechanism?





Test Extraction of K^+ Form Factor at JLab

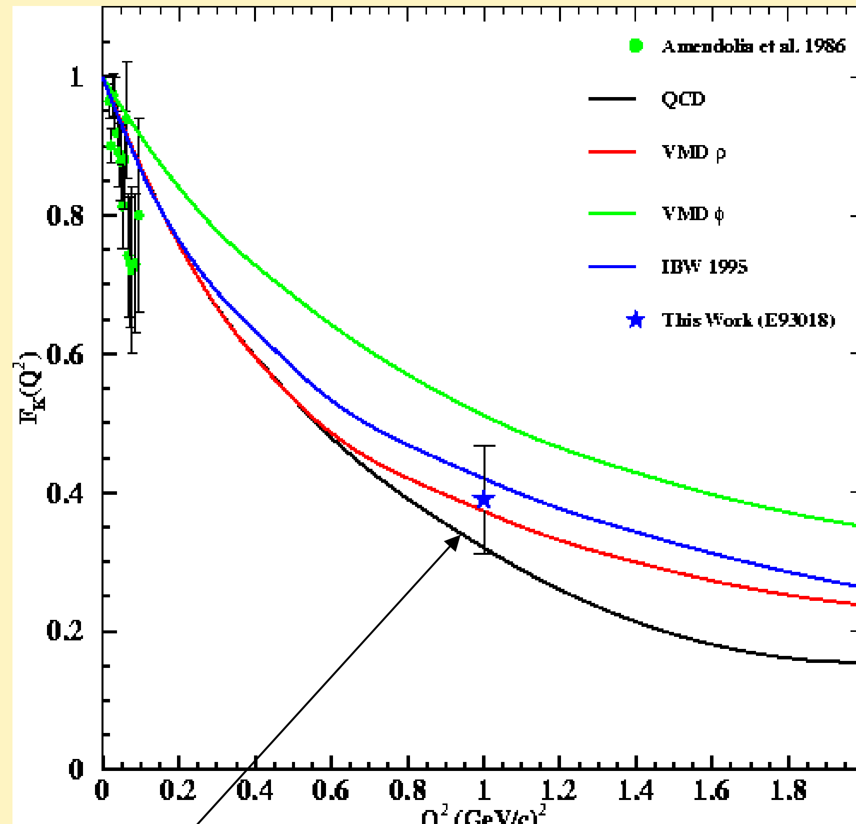
- JLab experiment E93-018 extracted $-t$ dependence of K^+ longitudinal cross section near $Q^2=1$ GeV^2.
- A trial Kaon FF extraction was attempted using a simple Chew-Low extrapolation technique

$$\sigma_L \approx \frac{-2tQ^2}{(t-m_K^2)^2} k(eg_{K\Lambda N})^2 F_K^2(Q^2)$$

$g_{K\Lambda N}$ poorly known

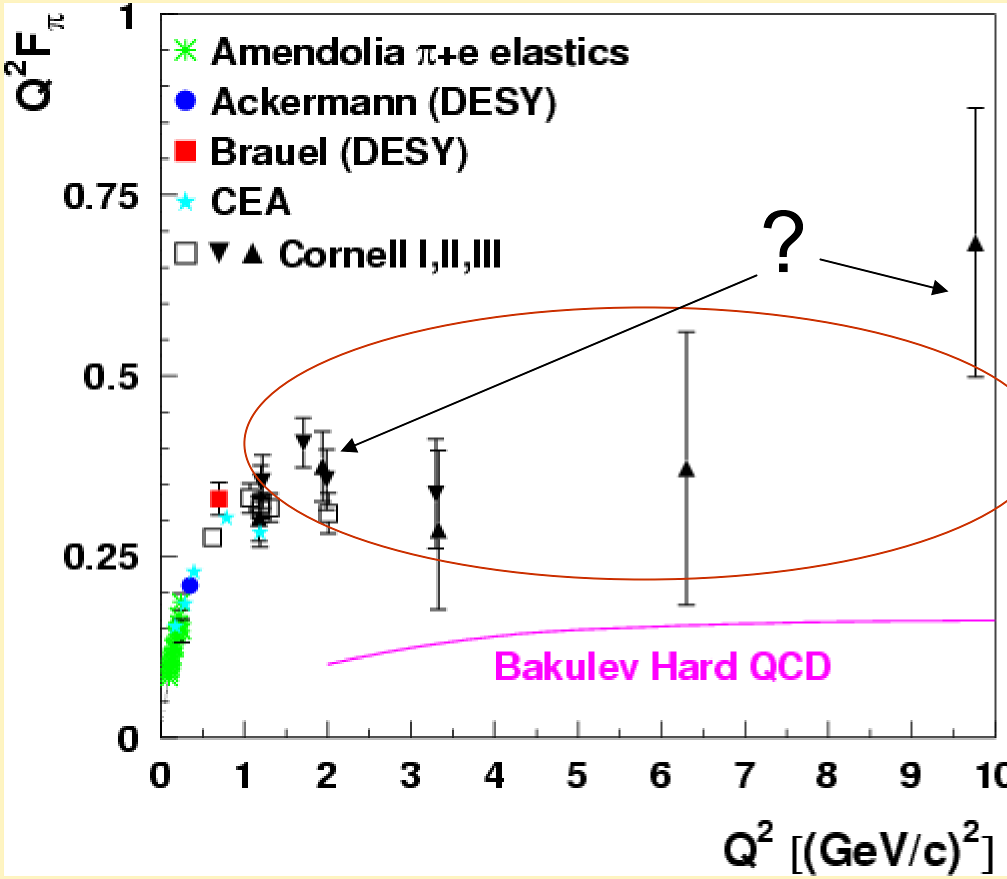
Better measurements of the *K^+* form factor are planned.

G. Niculescu, PhD. Thesis, Hampton U.



"Chew-Low" type extraction

World π^+ Data Set, 1997



- Problematic L/T separation.
  - Older data at larger Q^2 (> *1* GeV^2) extracted F_π from unseparated cross sections.
  - Used extrapolation of σ_T fit at low Q^2 to isolate σ_L.
- Analysis based on assumptions with systematic errors that are difficult to quantify.
  - Data taken far from pole, with $-t_{min}$ *as high as 40* m_π^2.

“[we] question whether F_π has been truly determined for large Q^2.” - C.E. Carlson, J. Milana, PRL **65**(1990)1717.

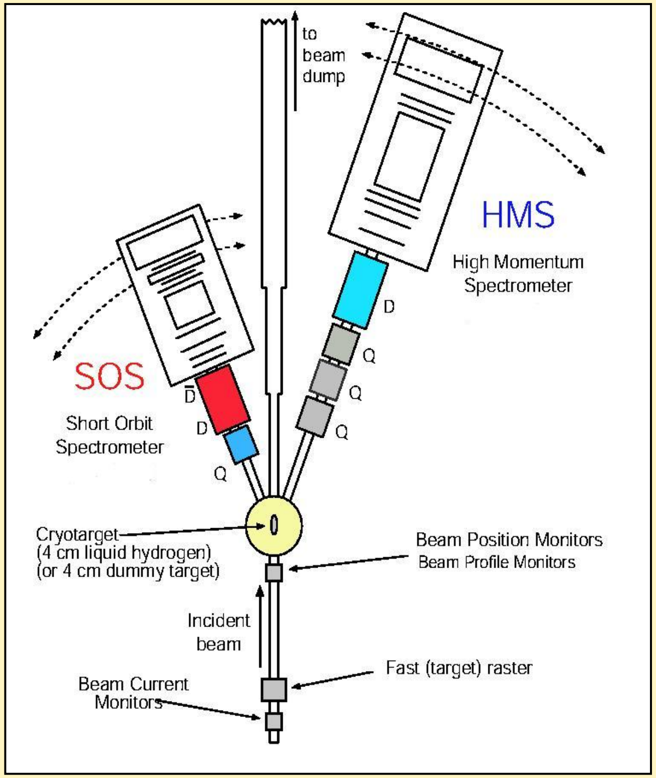
F_π Program at JLab

- 2 F_π experiments have been carried out at JLab *(spokespersons H. Blok, G. Huber, D.Mack)*
  - F_π-1: $Q^2=0.6\text{-}1.6$ GeV^2
  - F_π-2: $Q^2=1.6,\ 2.45$ GeV^2
- Second experiment took advantage of higher beam energy to access larger *W*, smaller *-t*

Expt	Q^2 (GeV^2)	W (GeV)	$\lvert t_{min}\rvert$ (Gev^2)	E_e (GeV)
F_π-1	0.6-1.6	1.95	0.03-0.150	2.445-4.045
F_π-2	1.6,2.45	2.22	0.093,0.189	3.779-5.246

- Full deconvolution of *L/T/TT/LT* terms in cross section
- Ancillary measurement of π^-/π^+ (separated) ratios to test reaction mechanism
- Both experiments ran in experimental Hall C: F_π-1 in 1997 and F_π-2 in 2003

JLab F_π Experiment Details



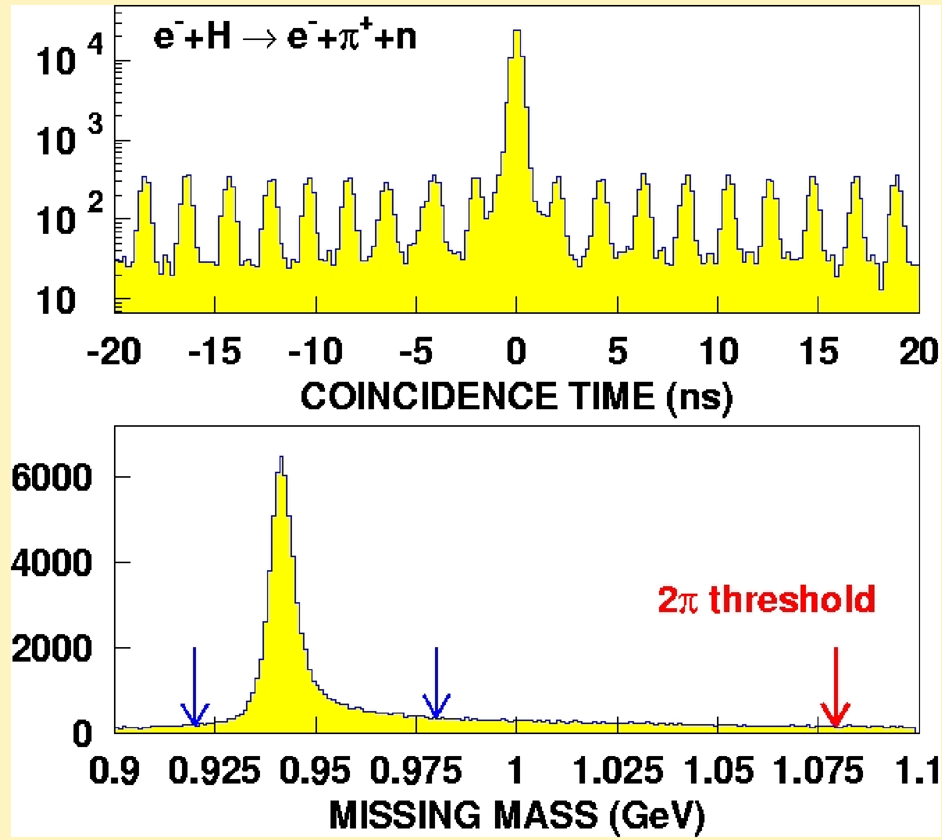
- Short Orbit Spectrometer = e^-
- High Momentum Spectrometer = π^+
  - →Relatively small acceptance – easily understood
  - →"Pointing", kinematics well constrained
- Cryogenic targets, high currents yield relatively fast measurement

p(e,e'π^+)n Event Selection

Coincidence measurement between charged pions in HMS and electrons in SOS.

Easy to isolate exclusive channel

- Excellent particle identification
- CW beam minimizes "accidental" coincidences
- Missing mass resolution easily excludes 2-pion contributions



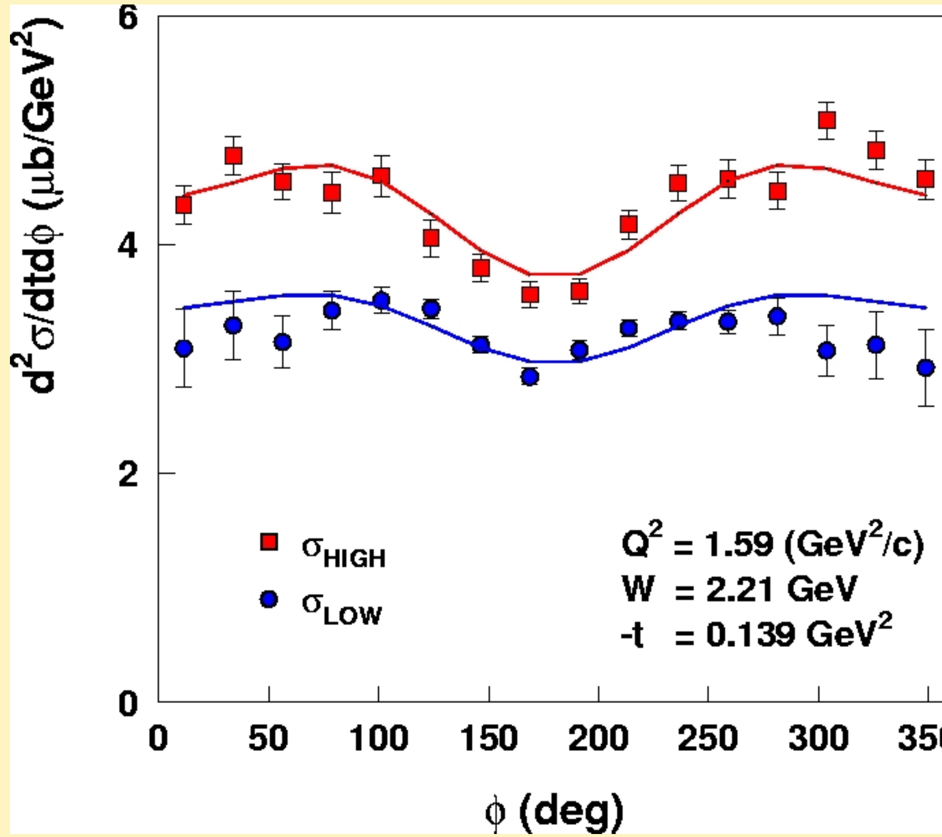
Missing mass cut assures exclusivity.

Measuring σ_L

$$2\pi\frac{d^2\sigma}{dt\,d\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

- Rosenbluth separation required to isolate σ_L
  - Measure cross section at fixed ($W, Q^2, -t$) at 2 beam energies
  - Simultaneous fit at 2 ε values to determine σ_L, σ_T, and interference terms

- **Control of point-to-point systematic uncertainties crucial due to $1/\Delta\varepsilon$ error amplification in σ_L**
- Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …



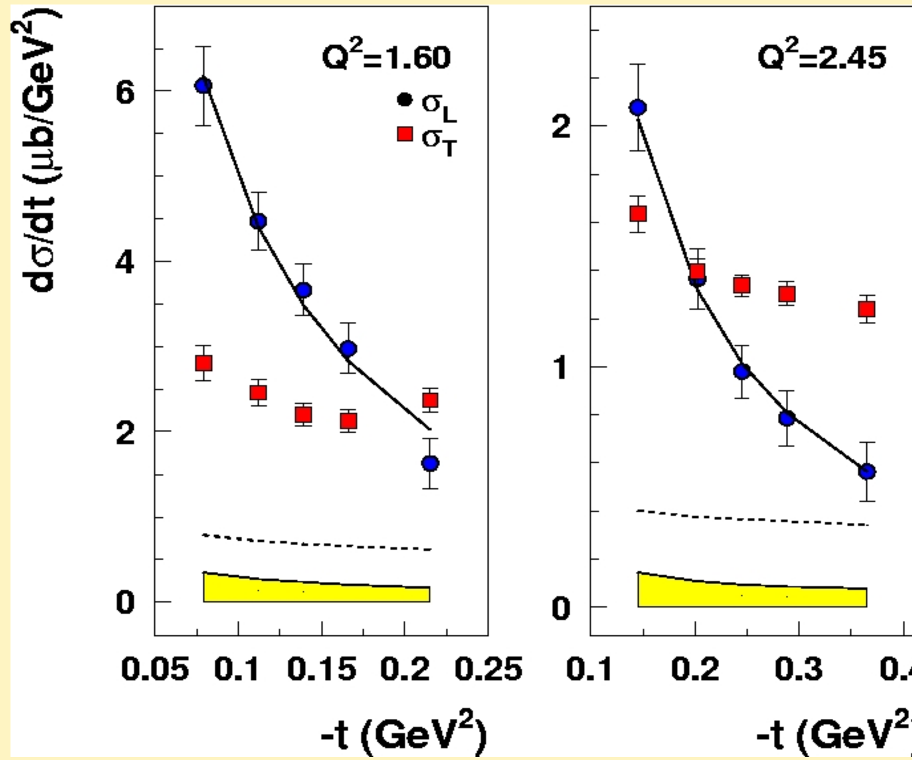
Horn et al, PRL97, 192001,2006

F_π Extraction from JLab data

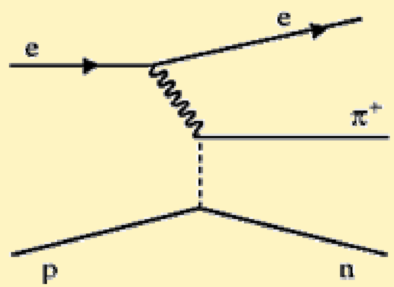
- Model is required to extract F_π from σ_L
- JLab F_π experiments used the VGL Regge model *[Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)]*
  - Propagator replaced by π and ρ Regge trajectories
  - Most parameters fixed by photoproduction data
  - 2 free parameters: Λ_π, Λ_ρ
  - At small $-t$, σ_L only sensitive to Λ_π

$$F_\pi(Q^2) = \frac{1}{1 + Q^2 / \Lambda_\pi^2}$$

*Horn et al, PRL**97**, 192001,2006*



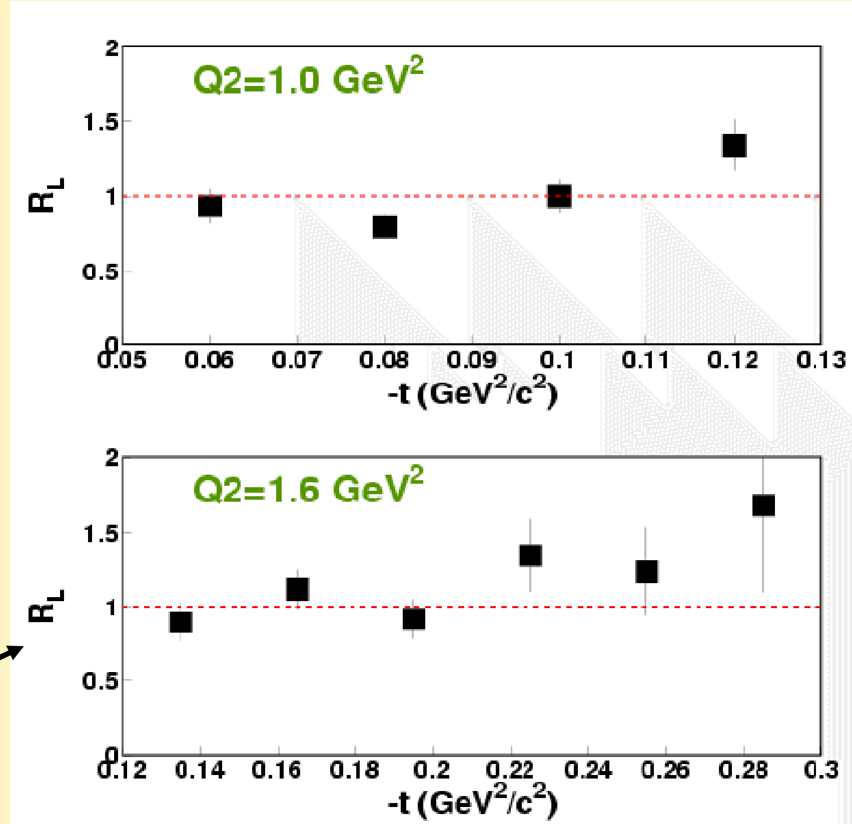
Experimental check that other processes do not "contaminate" σ_L



Pion pole diagram (*t*-channel) is purely isovector.

- Compare π^+ production from the proton with π^- production from the neutron.

$$R_L = \frac{\sigma_L[n(e,e'\pi^-)p]}{\sigma_L[p(e,e'\pi^+)n]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

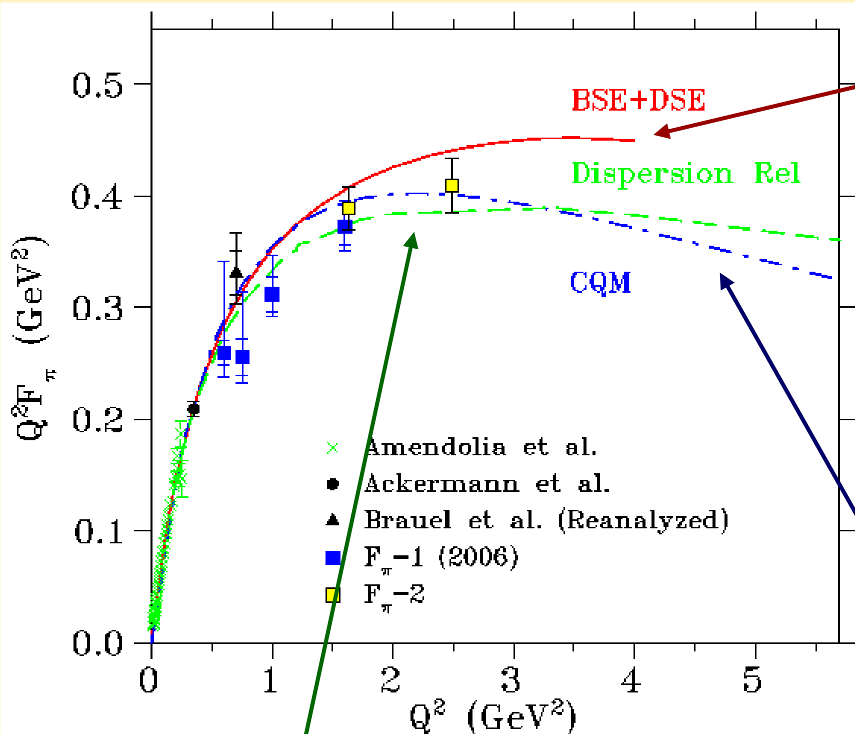


- Isoscalar backgrounds (such as $b_1(1235)$ contributions to the *t*-channel) will dilute the ratio.

"NEARLY FINAL" RESULTS:
Analysis performed by Dr. Cornel Butuceanu, a UofR postdoc stationed at JLab.

Comparison with QCD-based Calculations

JLab results in a region of Q^2 where model calculations begin to diverge.



Bethe-Salpeter/Dyson-Schwinger:
*[P. Maris and P. Tandy, Phys.Rev.C **62**(2000)055204]*
- B-S equation is conventional formalism for relativistic bound states.
- D-S expansion in terms of <u>dressed</u> quark propagators, consistent w/ confinement.
- Model parameters fixed from f_π and m_π, then r_π and F_π predicted.

Disperson Relation with QCD Constraint:
*[B.V. Geshkenbein, Phys.Rev.D **61**(2000)033009]*
- Uses constraints posed by **causality** and **analyticity** to relate the timelike and spacelike domains of the pion form factor on the complex plane.
- Additional constraints, such as behavior of F_π in asymptotic region, imposed.

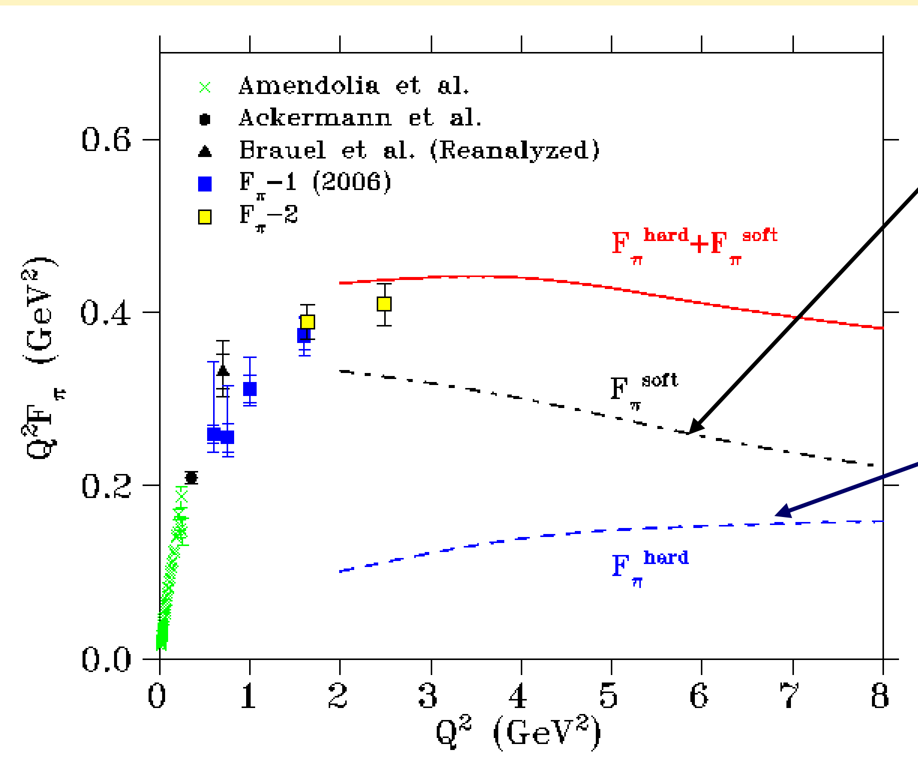
Constituent Quark Model:
*[C-W. Hwang, Phys.Rev.D **64**(2001)034001]*
- Relativistic constituent quarks and effective interaction on the light front
- Consistent treatment of quark spins.
- Wave function parameters determined from f_π and $\pi^0\rightarrow\gamma\gamma$ decay width, then charge and transition FF's and π^0 branching ratios predicted.

The role of Soft and Hard QCD in F_π

pQCD LO+NLO Calculation:

Analytic perturbation theory at the parton amplitude level.

*A.P. Bakulev, K. Passek-Kumericki, W. Schroers, & N.G. Stefanis, PRD **70** (2004) 033014.*



SOFT QCD:

- Extra piece needed to describe data.
- Model-dependent.
- Estimated from local quark-hadron duality model.

HARD QCD:

- Pion distribution amplitude consistent to 1σ level with CLEO πγ transition data.
- Hard component is only slightly larger than that calculated with asymptotic DA in all considered schemes.

What do our results mean?

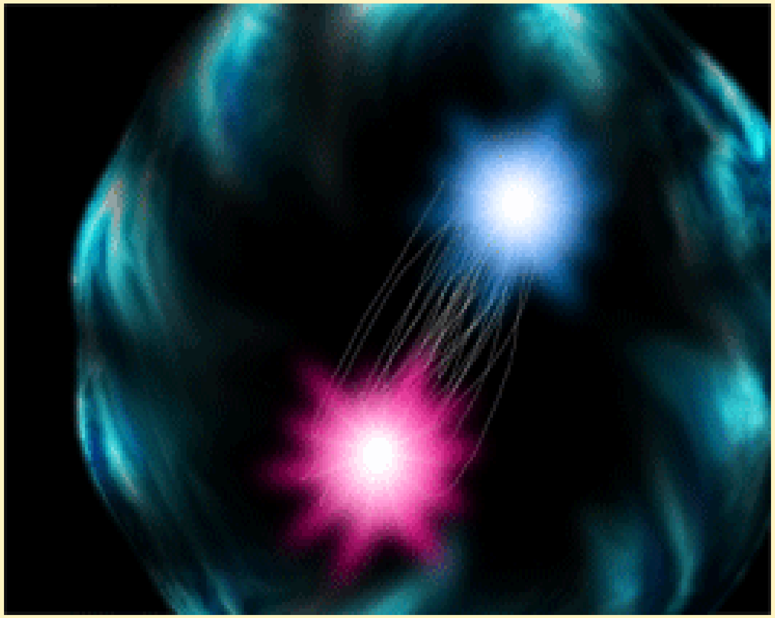


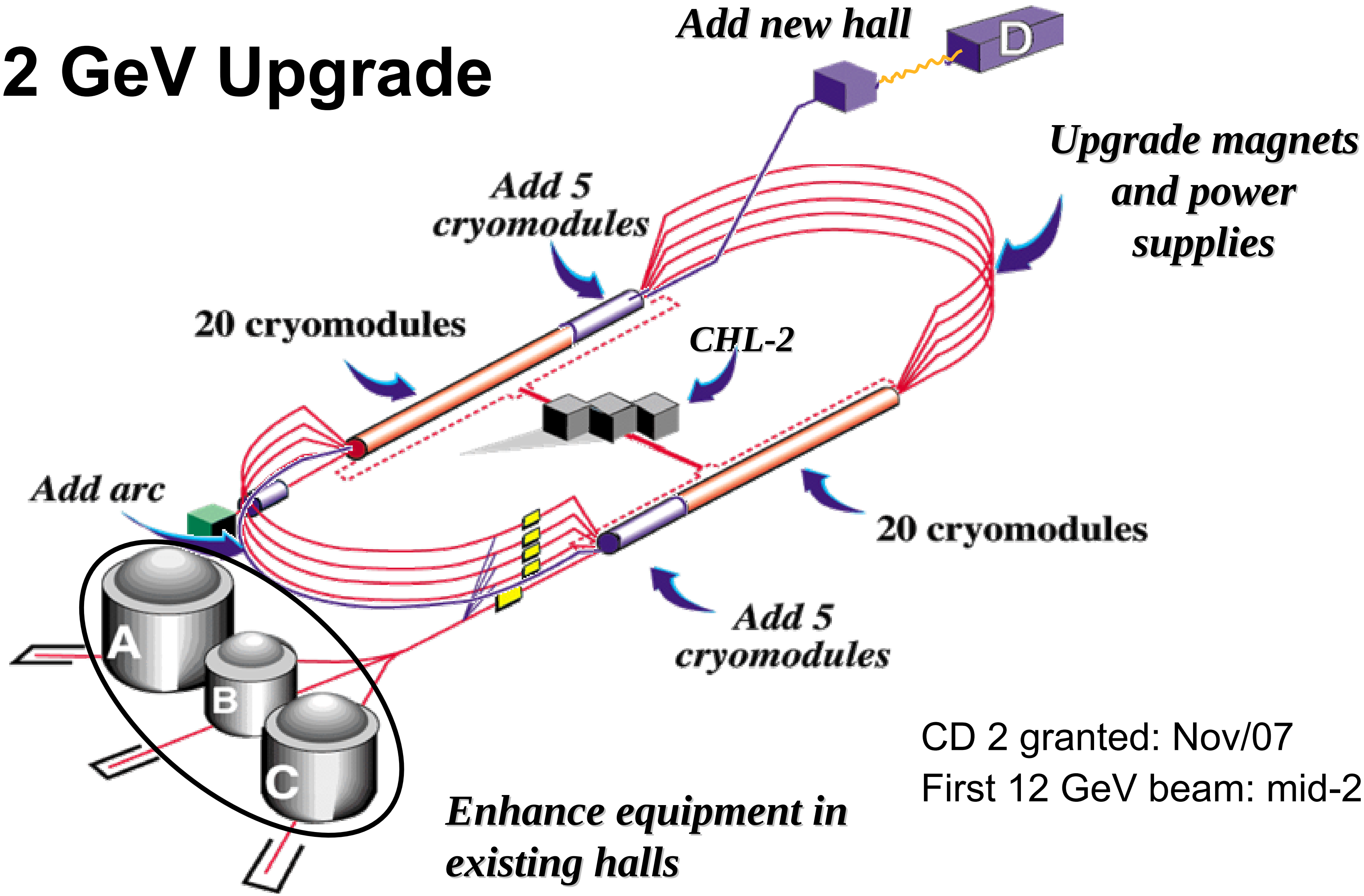
Figure courtesy of Jefferson Lab

- Our F_π results are still far from the values predicted by pQCD.
- At the distance scales that our experiment has probed (0.15<r<0.30 fm), the π^+ structure is not governed by the two valence quarks.
- Virtual quarks and gluons dominate.
- **The pion is "softer" than the old Cornell results indicated.**

We plan to extend these measurements to shorter distance scales to discover the scale where valence quarks dominate pion's structure.

→ **Different theoretical viewpoints on whether higher-twist mechanisms dominate until very large momentum transfer or not.**

12 GeV Upgrade

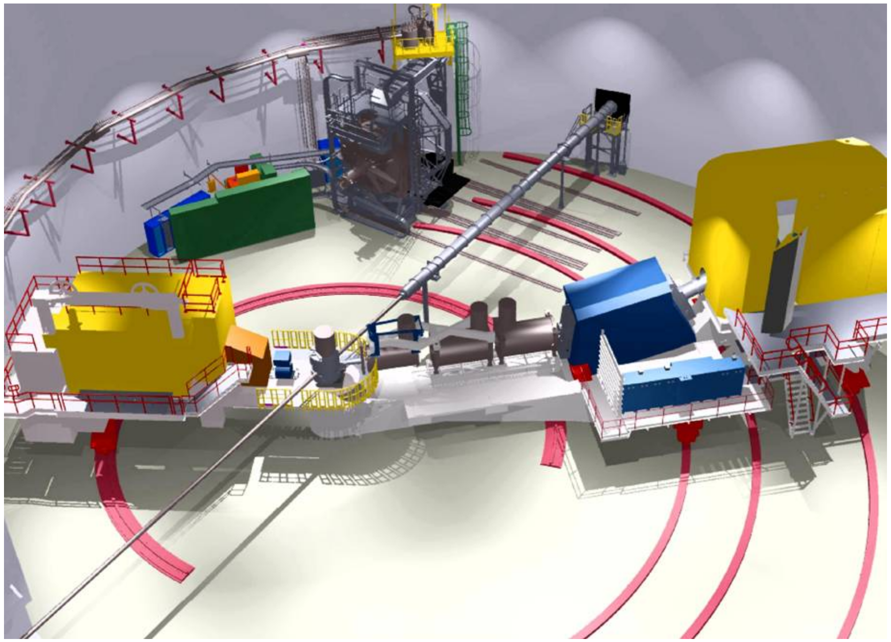


CD 2 granted: Nov/07

First 12 GeV beam: mid-2013

Experimental Hall C

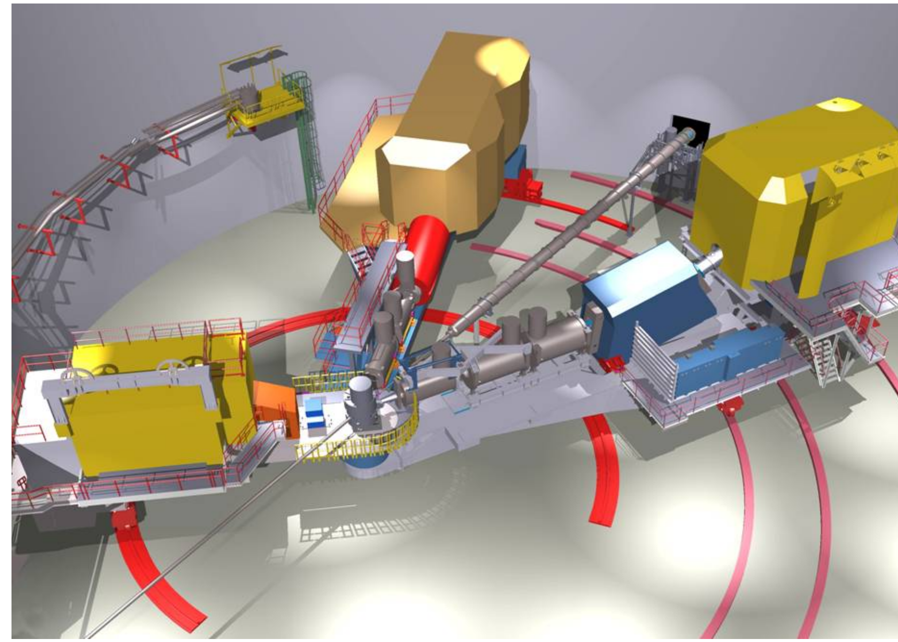
At the present 6 GeV Beam Energy



Hall C's High Momentum Spectrometer, Short Orbit Spectrometer and specialized equipment for studying:

- The strange quark content of the proton.
- Form factors of simple quark systems.
- The transition from hadrons to quarks.
- Nuclei with a strange quark embedded.

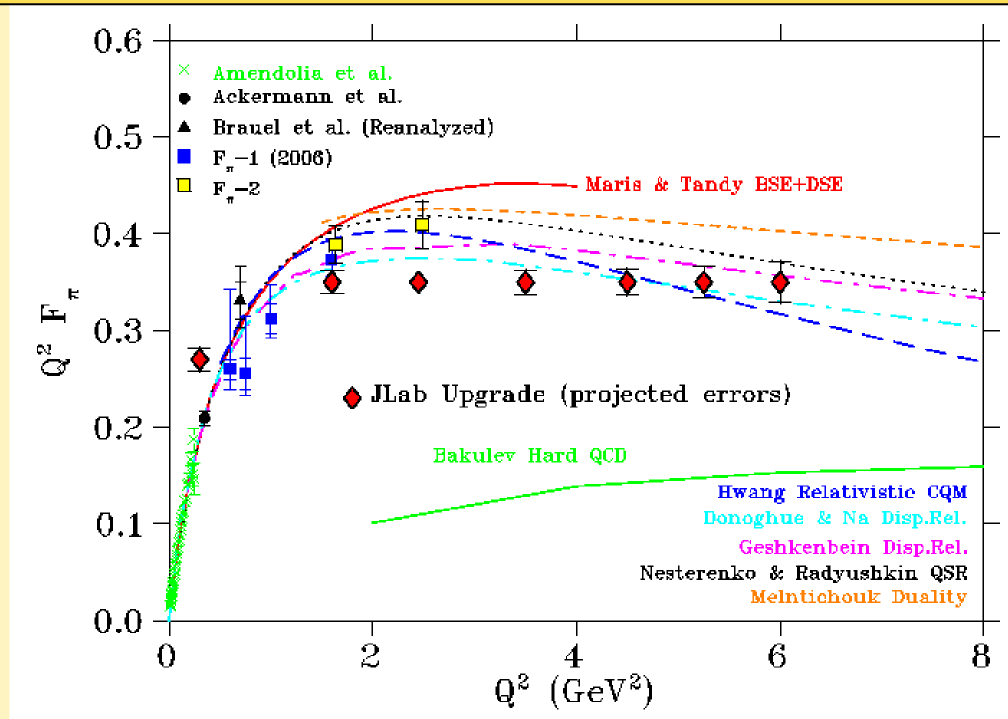
After the 12 GeV Upgrade



Add a Super- High Momentum (12 GeV) Spectrometer for studying:

- Super-fast (high x_B) quarks.
- Form factors of simple quark systems.
- The transformation of quarks into hadrons.
- Quark-quark correlations.

$F_{\pi^+}(Q^2)$ after JLab 12 GeV Upgrade

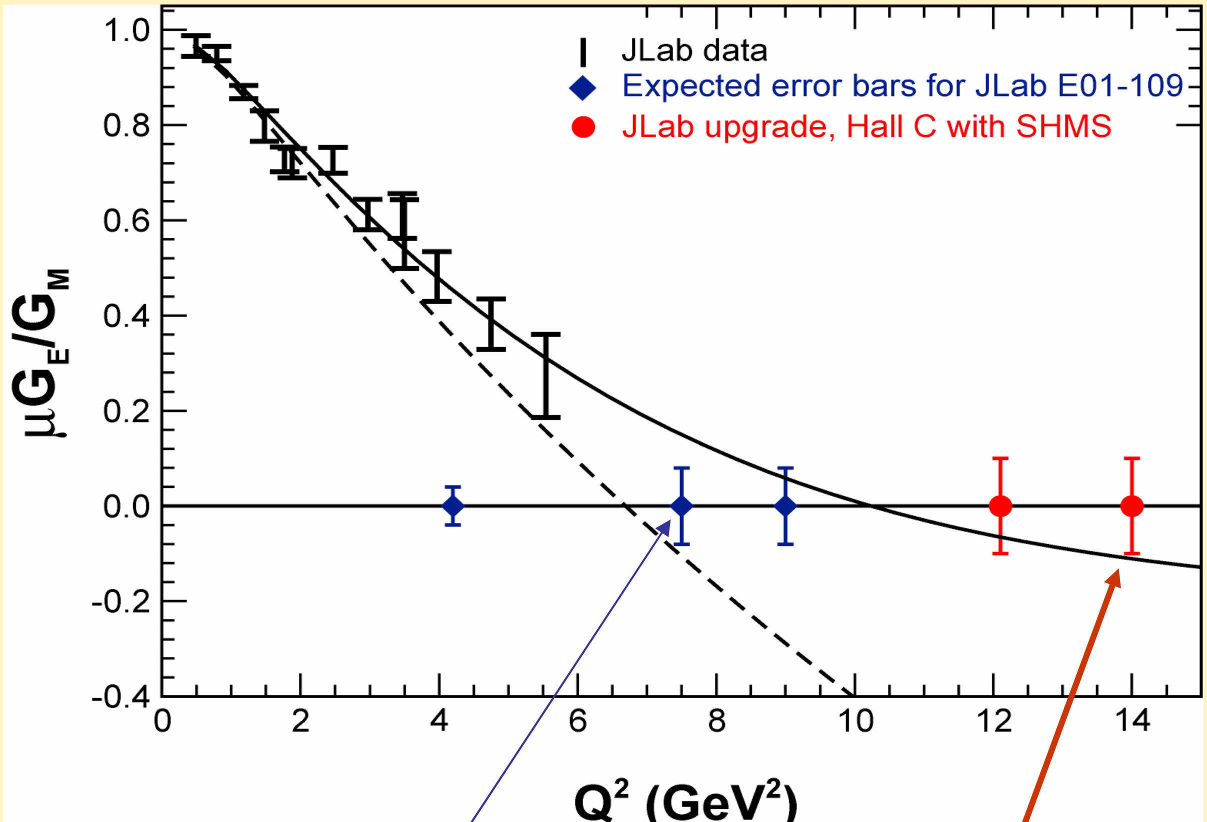


E12-06-101:
G. Huber and
D. Gaskell
spokespersons

11 GeV electron beam and SHMS spectrometer with θ=5.5^o capability will allow:

- Best test to date of electroproduction method at Q^2=0.30 GeV^2.
- Stringent test of model-dependence in F_π extraction.
- **Precision data up to Q^2=6.0 GeV^2 to study the transition to hard QCD.**

Planned probe of the Charge and Current Distributions in the Proton at <0.1 fm at JLab



full: Lomon
dashed: Miller

- E01-109 in progress
- SHMS in Hall C at 11 GeV

Summary

The past 10 years have seen good progress in developing a quantitative understanding of the electromagnetic structure of the lightest mesons and the nucleon.

- Much credit goes to the continuous electron beam provided by the Jefferson Lab superconducting linac, and advances in electron scattering techniques.

QCD has shown itself to be a richer field than originally expected as a result of the improved level of precision of the data.

In the next few years, we look forward to:

- More results for the pion form factor and possibly the Kaon.
- Deeper understanding of the proton's charge and magnetic structure.

Will we begin to see the transition to the perturbative QCD regime?