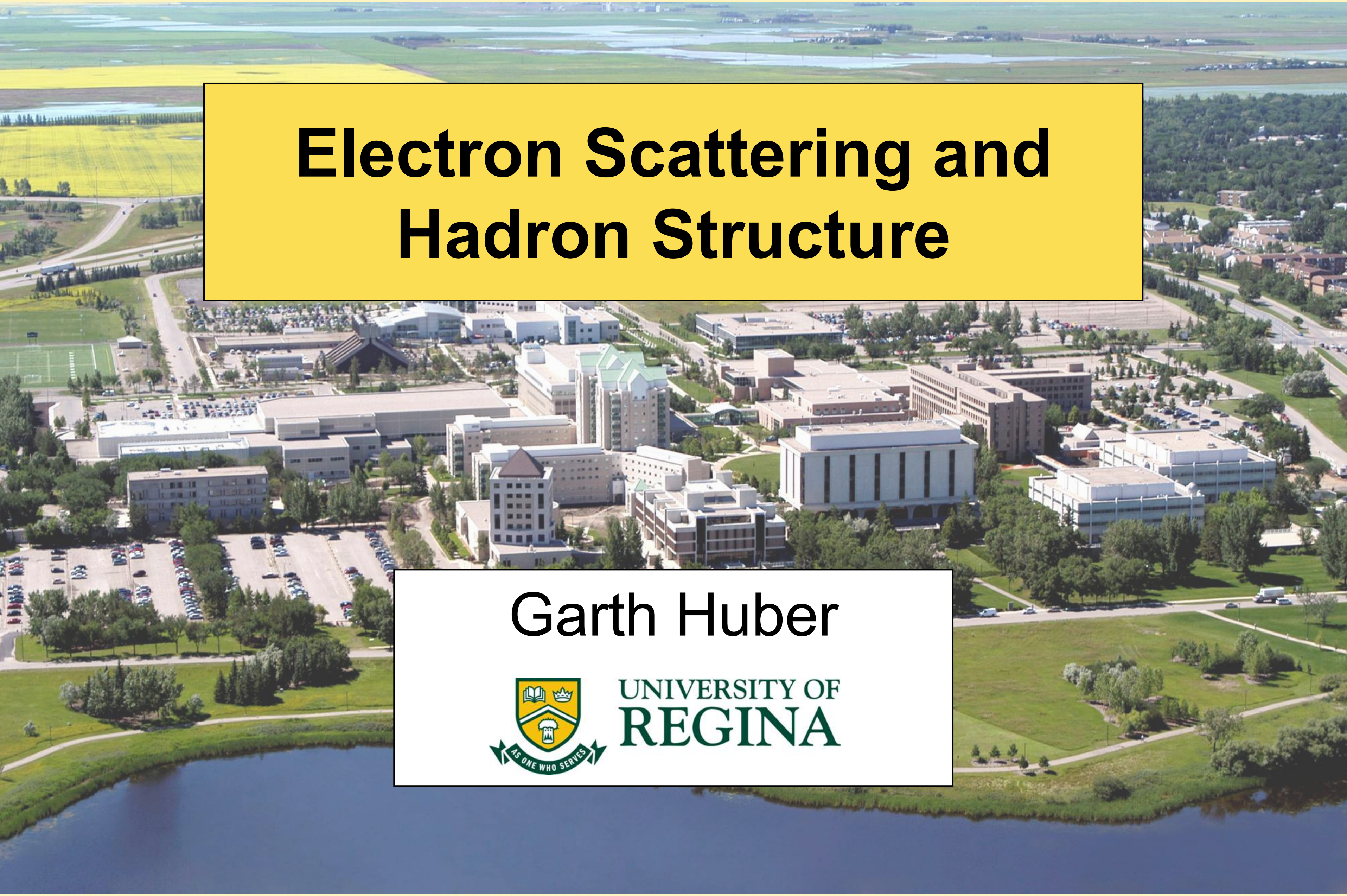
Electron Scattering and Hadron Structure



Garth Huber

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University of Manitoba, December 1, 2006.

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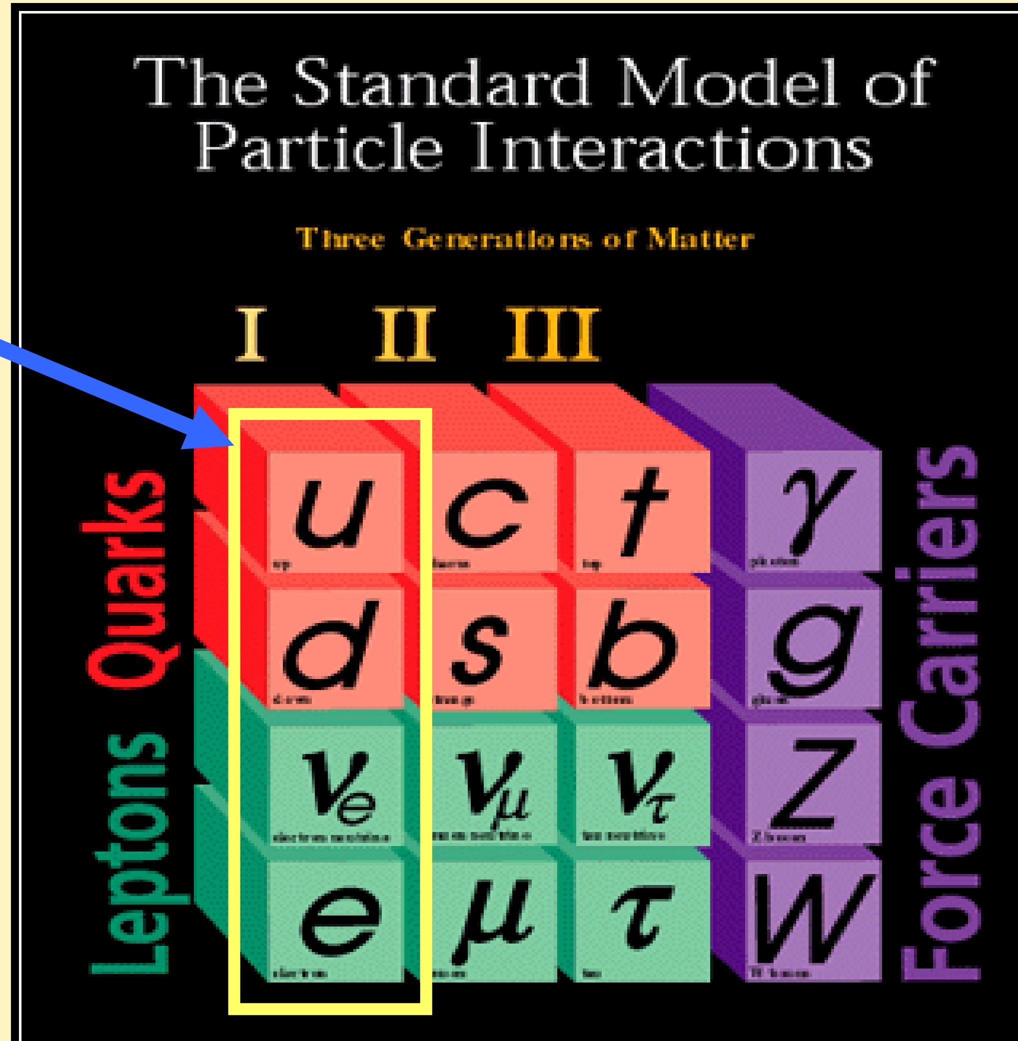
Quarks, Leptons and their Fundamental Interations

The ground state of matter.



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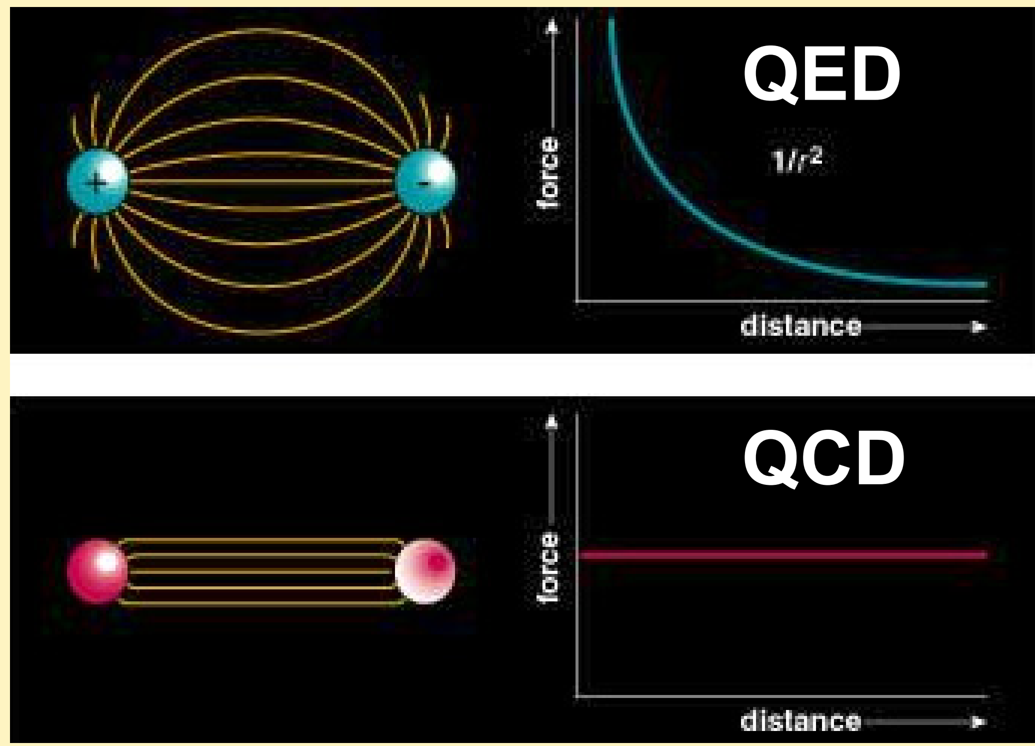
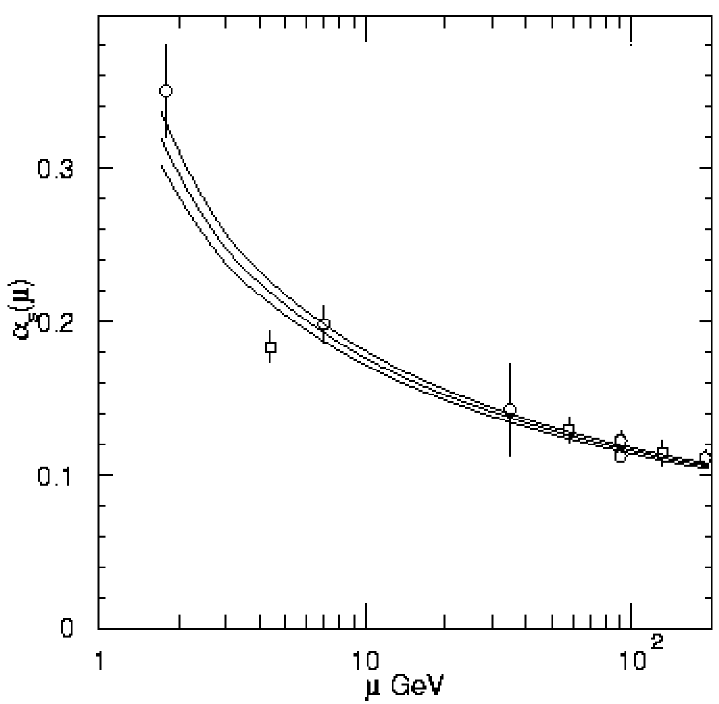
Quantum Electrodynamics
Quantum Chromodynamics

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



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.
- QCD calculations are complex.
  - QCD-based models are often used.
  - Lattice QCD holds much promise.

The Science Problem

Quantum Chromodynamics (QCD) in the confinement regime:

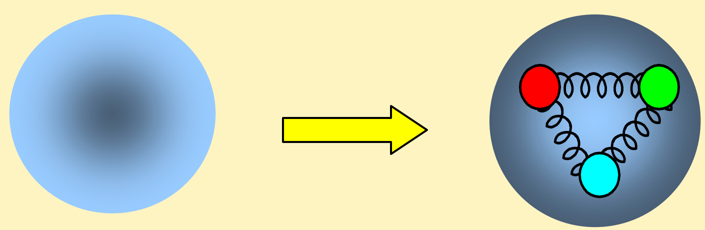
How does it work?

- **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!

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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.

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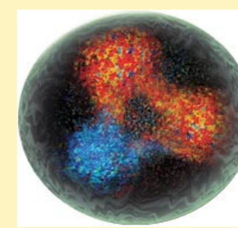
Why electron scattering experiments?

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]

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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.

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

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

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

$\rightarrow$ 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.

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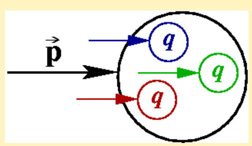
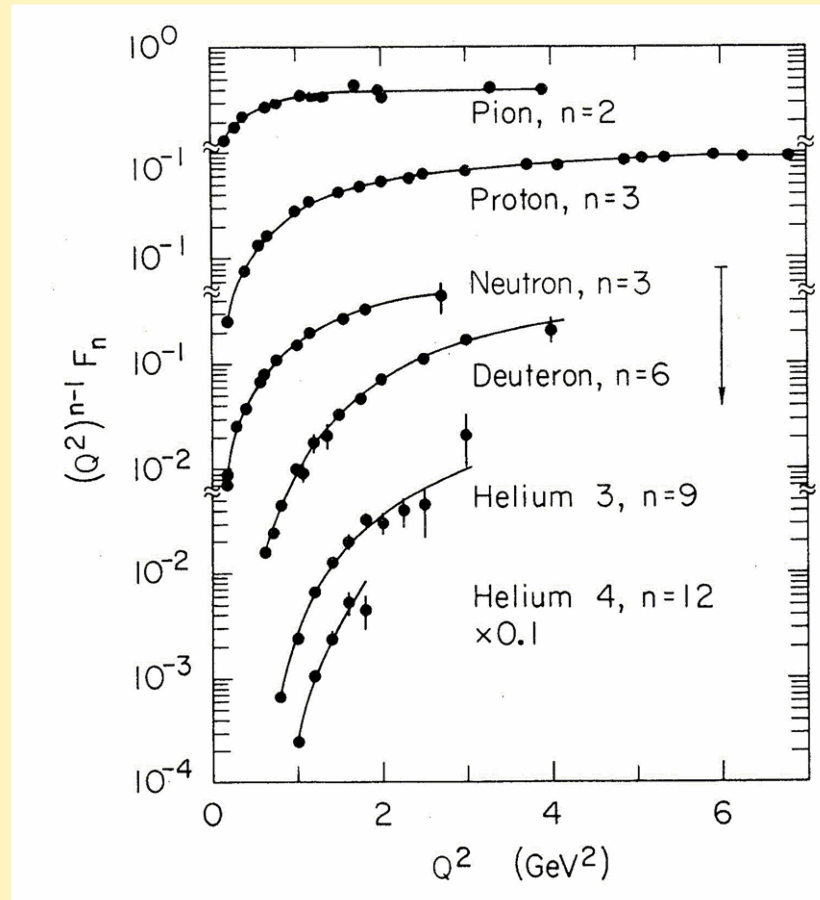
An early pQCD Prediction:
- Dimensional Scaling at Large Momentum

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.





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

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

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

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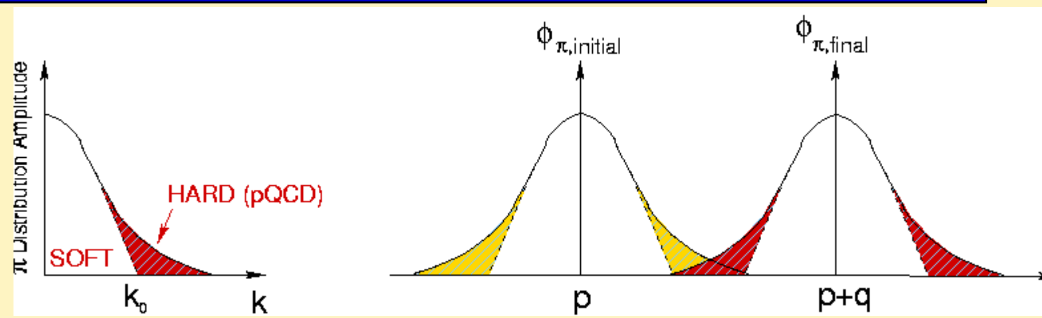
Transition to pQCD at only $Q^2 \approx 1$ GeV^2?

Consider a pQCD calculation at very high Q^2
for pseudoscalar meson ($J^P=0^-$) form factors (e.g. pion)

In quantum field theory,
F_π is the overlap integral

$$F_{\pi^+}(Q^2) = \int \phi_\pi^*(p)\phi_\pi(p+q)dp$$

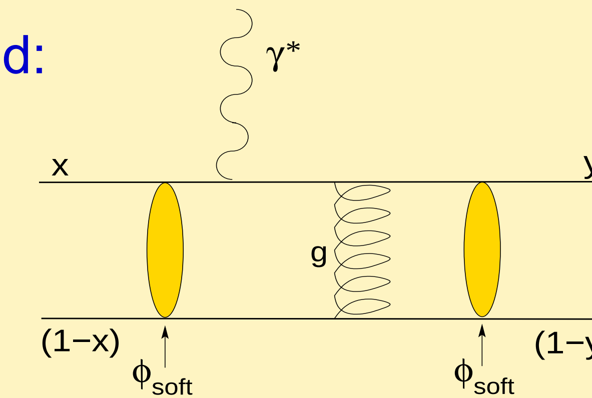


At large Q^2, perturbative QCD (pQCD) can be used:

$$F_{\pi^+}(Q^2) = \int_0^1 dx \int_0^1 dy \, \frac{2g^2}{3xyQ^2} \phi(x)\phi(y)$$

$g^2 = \frac{4}{3}\pi\alpha_s$ (q-γ coupling const)^2

xyQ^2 virtuality of exchanged gluon



As $Q^2 \to \infty$, only the hard portion remains

$$\phi_\pi(x) \to 6 f_\pi x(1-x)$$

f_π=132 MeV $\pi^+ \to \mu^+\nu$ coupling constant.

$$F_\pi(Q^2) \xrightarrow[Q^2\to\infty]{} \frac{8\pi\alpha_s f_\pi^2}{Q^2}$$

QCD Asymptotic Limit

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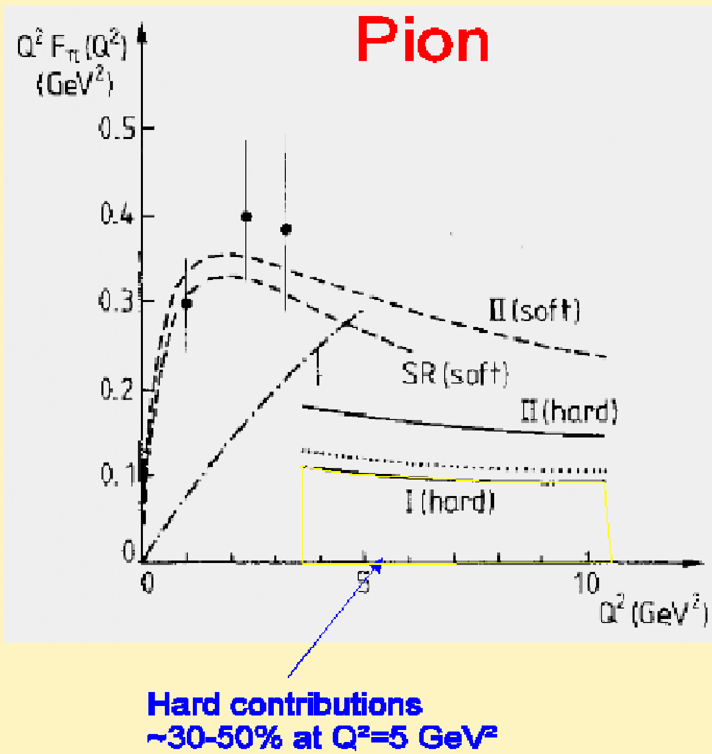
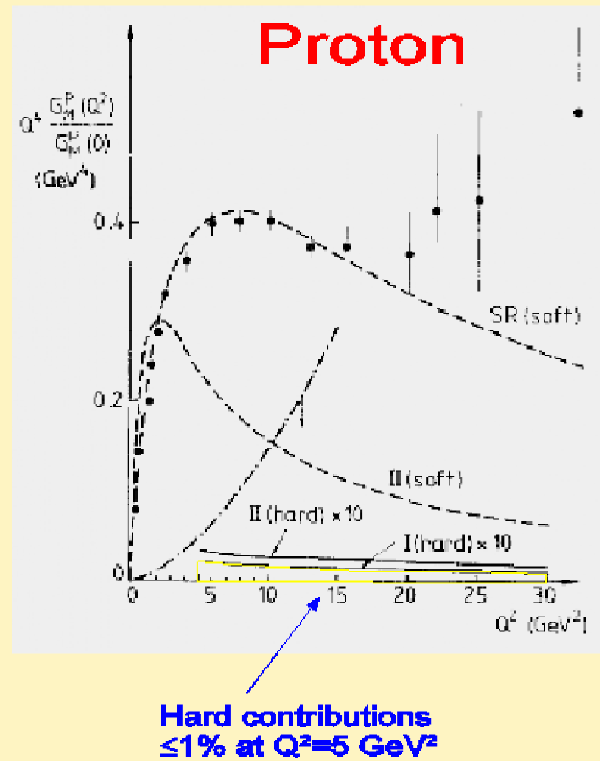
At experimentally accessible Q^2, both the hard and soft parts of the parton distribution function contribute.

→ no clear answer from theory (yet) on relative contributions.





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

The transition from the Soft to Hard QCD regime is best observed experimentally with simple systems such as the π^+ form factor.

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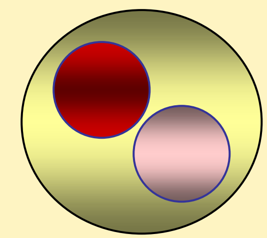
Pion and Kaon Charge Form Factor Data

Spin 0: π and K Electromagnetic 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:

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

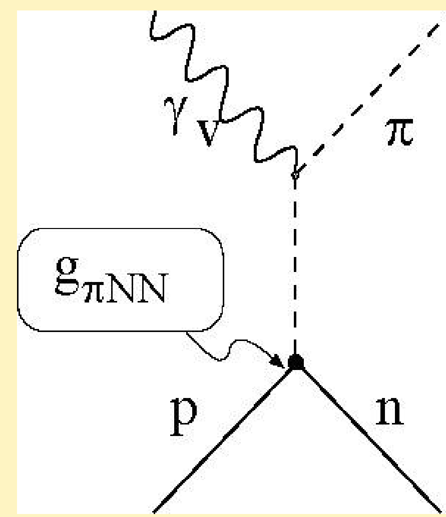


To access higher Q^2 one must use an experimentally "unclean": moving virtual target…

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

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

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



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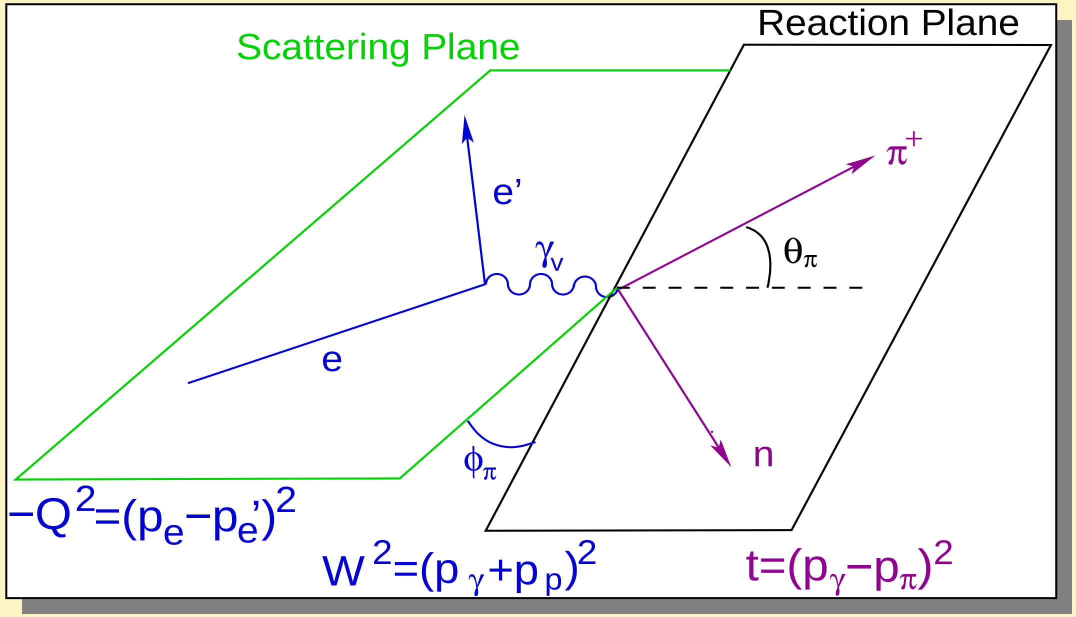

$$2\pi\frac{d\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

1. **Need to take data at smallest available $-t$, so σ_L has maximum contribution from the π^+ pole.**
   - For given Q^2, higher W allows smaller $|t_{min}|$.
2. **Extraction of F_π requires t dependence of σ_L to be known.**
   - Only three of Q^2, W, t, θ_π are independent.
   - Vary θ_π to measure t dependence.
   - Since non-parallel data needed, LT and TT must also be determined.

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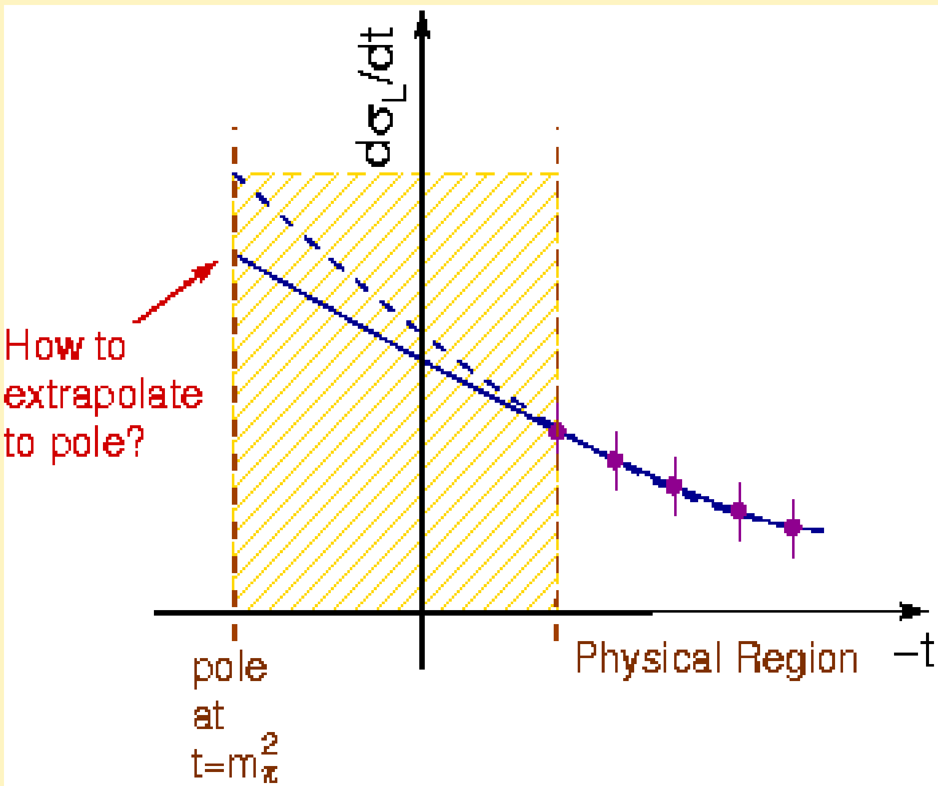
Extraction of form factor from σ_L data

PION Charge Form Factor:

$p(e,e'\pi^+)n$ data are obtained some distance from the $t=m_\pi^2$ pole.

➡ No reliable phenomenological extrapolation possible.



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.

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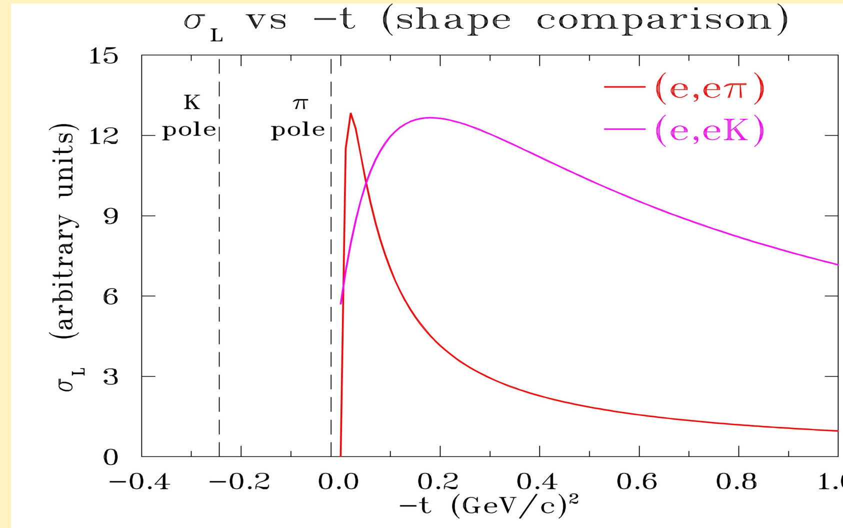
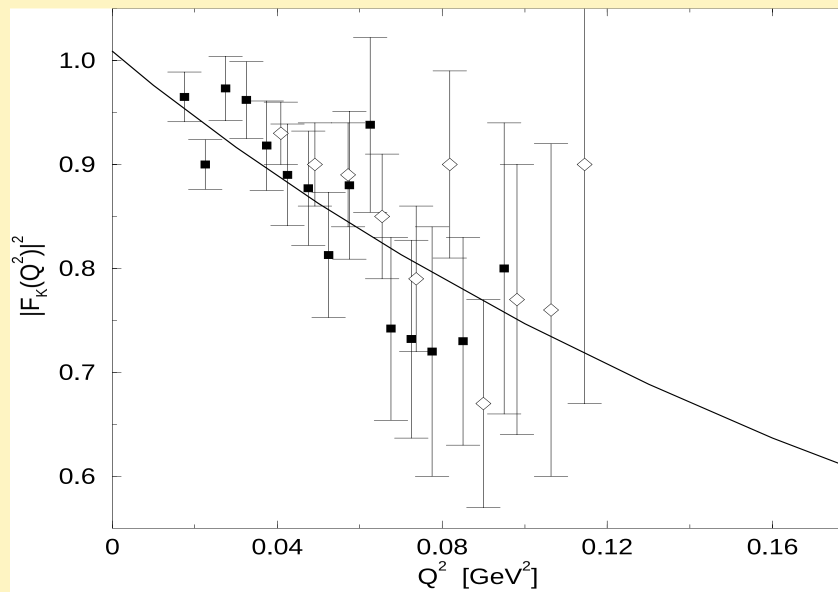
Extraction of form factor from σ_L data

KAON Charge Form Factor:

- K^+ pole is located even further away from the experimentally accessible region.
- Only low Q^2 elastic scattering data available.

- Trial extraction of K^+ form factor via $p(e,e'K^+)\Sigma^0,\Lambda^0$ near Q^2=2 GeV^2 at Jefferson Lab.
- Open question whether σ_L data are sufficiently sensitive to K^+ pole.





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F_π-1 and F_π-2 Experiments at Jefferson Lab

F_π-2 Goals:

- Extension of our earlier F_π-1 to the highest Q^2 possible with JLab 6 GeV electron beam.
- Higher W above resonance region.
- Repeat Q^2=1.60 GeV^2 closer to t=m_π pole.
  - ➡ reduced model uncertainties.

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

Experiment:

- Extract F_π via L/T/LT/TT Rosenbluth separation in $p(e,e'\pi^+)n$.
- Coincidence measurement between charged pions in HMS and electrons in SOS.
- Data acquired: F_π-1: 1997, F_π-2: 2003.

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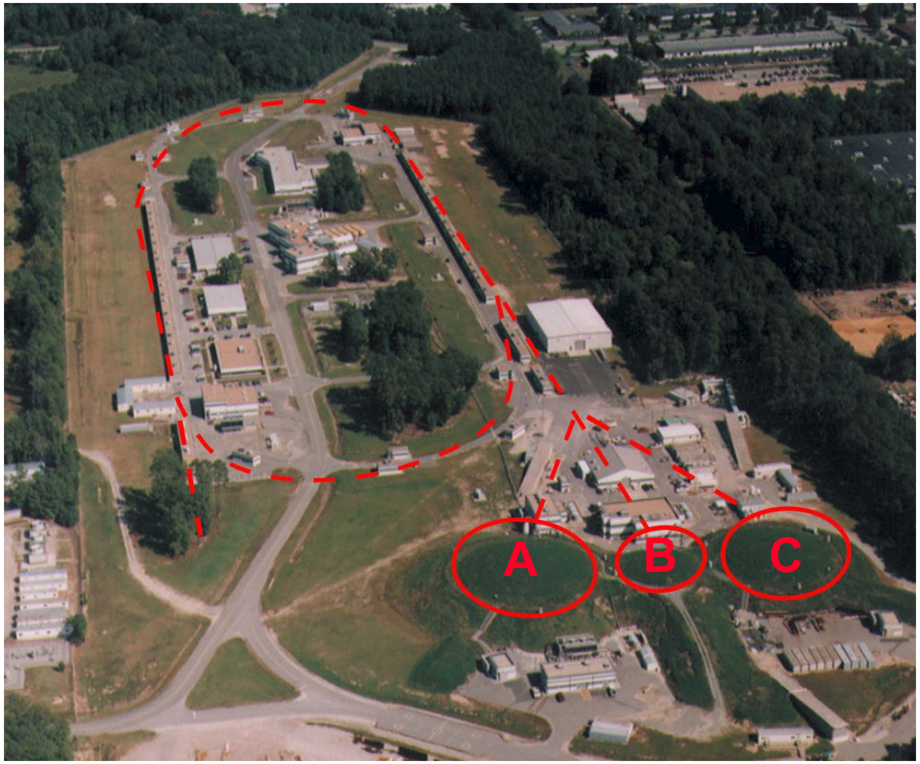
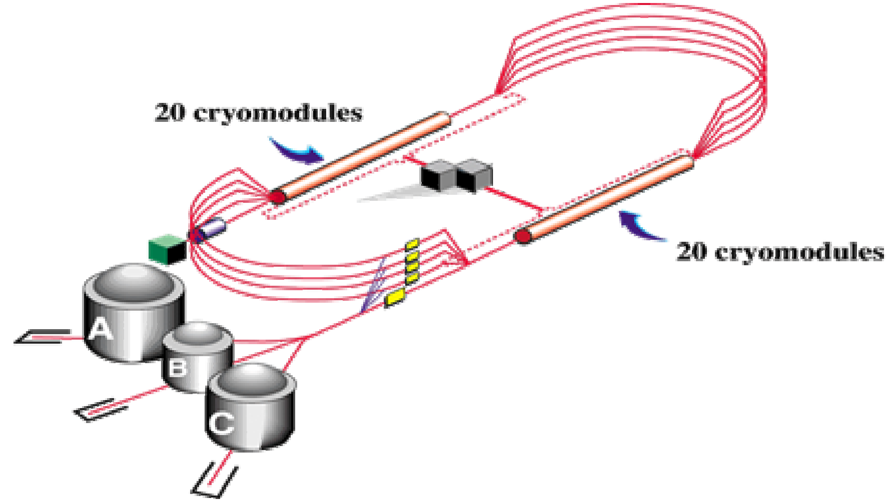




Two Cold Superconducting Linacs

Continuous Polarized Electron Beam

$E \rightarrow 6$ GeV

$> 100\ \mu$A

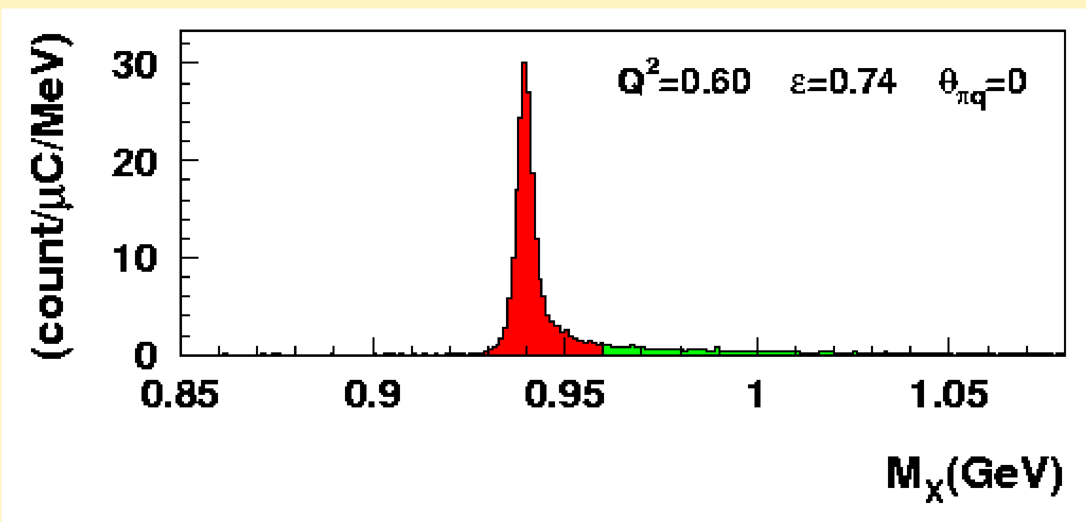
up to 80% polarization

concurrent to 3 Halls

First beam delivered in 1994

$p(e,e'\pi^+)n$ Event Selection

- **Coincidence measurement between charged pions in HMS and electrons in SOS.**
- π^+ detected in HMS – Aerogel Cerenkov and Coincidence time for PID.
- Electrons in SOS – identified by Cerenkov /Calorimeter.
- **After PID cuts, almost no random coincidences remain.**



Missing mass cut assures exclusivity.

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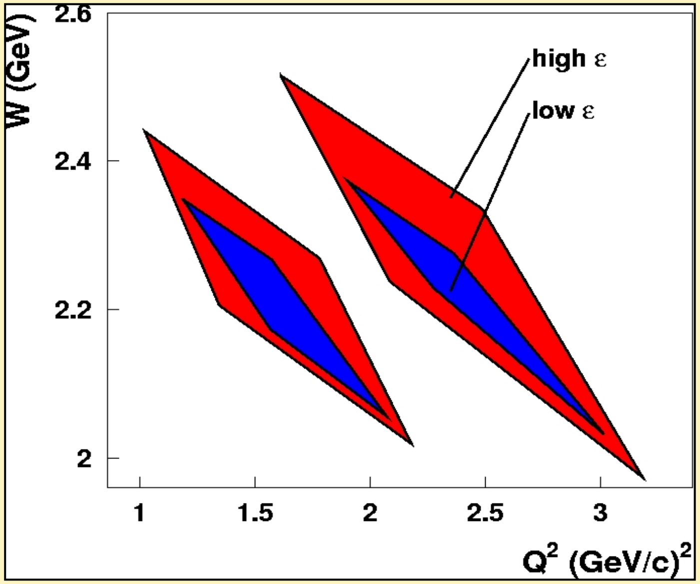
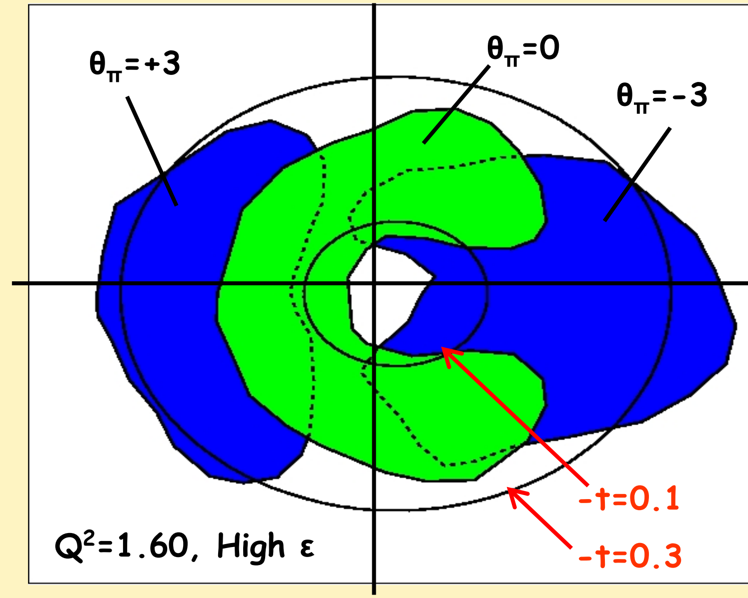
Kinematic Coverage





Radial coordinate ($-t$) Azimuthal coordinate (φ).

- Overlapping data at high and low ε are required for L/T separation.
- Diamond cuts define common (W,Q^2) coverage at both ε.

- Measurements over $0<\varphi<2\pi$ are required to determine LT, TT contributions versus $-t$.
- HMS settings ±3^o left and right of the q-vector are used to obtain good φ-coverage over a range of $-t$.
- Technique demands good knowledge of spectrometer acceptances.

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Magnetic Spectrometer Calibrations

- **Over-constrained *p(e,e'p)* reaction and *e*+^{12}C reactions used to calibrate spectrometer acceptances, momenta, offsets, etc.**
  - **Beam energy and spectrometer momenta determined to <0.1%.**
  - **Spectrometer angles to ~0.5 mr.**
  - **Agreement with published *p+e* elastics cross sections <2%.**

- **Per data *t*-bin (F_π-2):**
  - Typical statistical error: **1-2%**.
  - Uncorrelated syst. unc. in σ_{UNS} common to all *t* bins: **1.8(1.9)%**.
  - Additional uncorrelated unc. also uncorrelated in *t*: **1.1(0.9)%**.
  - Total correlated uncertainty: **3.5%**.

- **Uncorrelated uncertainties in σ_{UNS} are amplified by $1/\Delta\varepsilon$ in L-T separation.**
- **Scale uncertainty propagates directly into separated cross section.**

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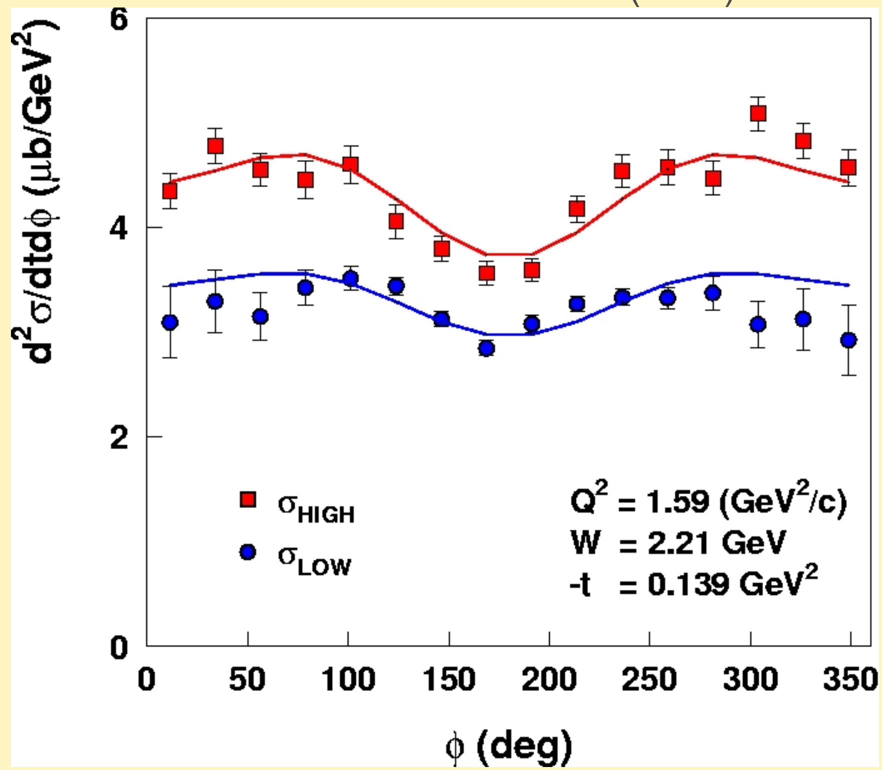
Experimental Cross Section Determination

- Compare experimental yields to Monte Carlo of the experiment:
  - Radiative effects, pion decay, energy loss, multiple scattering
  - COSY model for spectrometer optics.

$$\left(\frac{d\sigma(\overline{W},\overline{Q}^2,t,\phi)}{dt}\right)_{exp} = \frac{\langle Y_{exp}\rangle}{\langle Y_{MC}\rangle}\left(\frac{d\sigma(\overline{W},\overline{Q}^2,t,\varphi)}{dt}\right)_{MC}$$

- Extract σ_L by simultaneous fit using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε).

Fπ-2 data: PRL **97**(2006)192001.



Only Statistical Uncertainties Shown.

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

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After σ_L is determined, a model is required to extract $F_\pi(Q^2)$

Model incorporates π^+ production mechanism and spectator neutron effects:

VGL Regge Model:

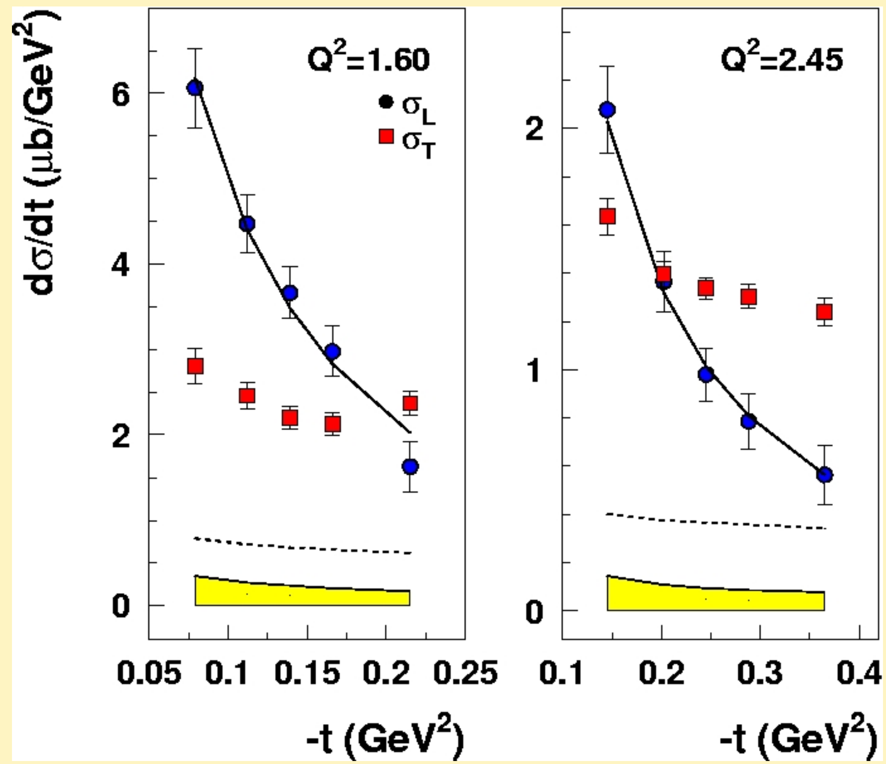
- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$

  replaced by π and ρ Regge propagators.
  - Represents the exchange of a series of particles, compared to a single particle.
- Model parameters fixed from pion photoproduction.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff).

[Vanderhaeghen, Guidal, Laget, PRC **57**(1998)1454]

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

Fit to σ_L to model gives F_π at each Q^2.



Fπ-2 data: PRL **97**(2006)192001.

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature.

Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.

Λ_π^2=0.513, 0.491 GeV^2, Λ_ρ^2=1.7 GeV^2.

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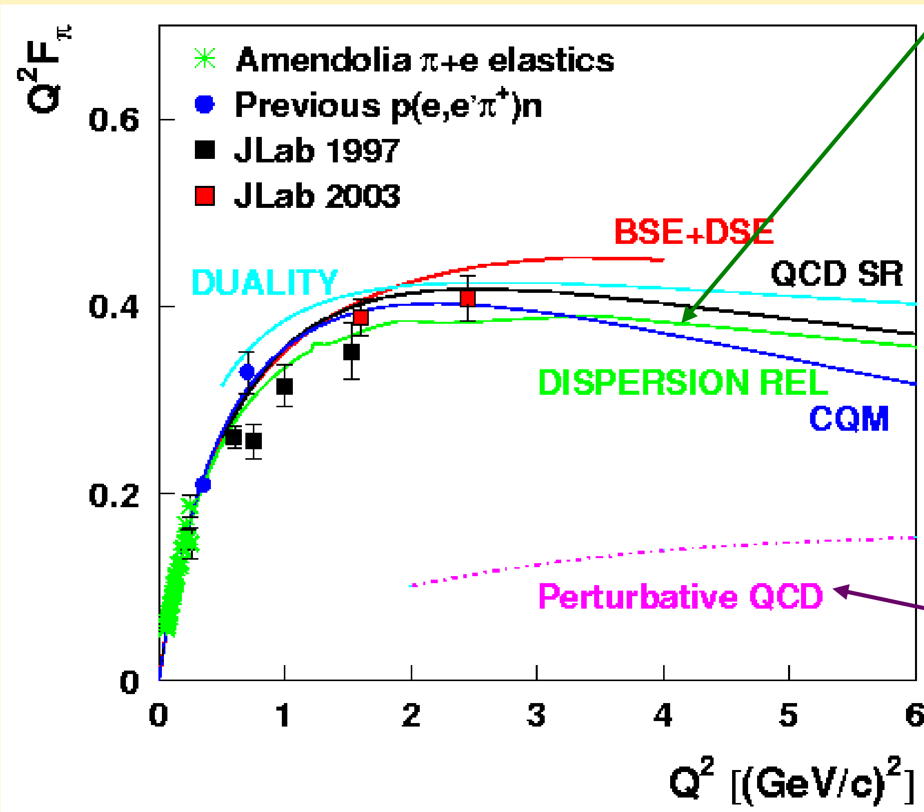
Comparison with QCD-based Calculations

$F\pi$-2 results in a region of Q^2 where model calculations begin to diverge.



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.
- **Relatively model-independent** but
  $\Rightarrow$ incomplete understanding of all the poles in the timelike region creates uncertainties.
- Additional constraints, such as behavior of F_π in asymptotic region imposed.

Still far from hard QCD prediction.

*[A.P. Bakulev et al, Phys.Rev.D **70**(2004)033014.]*

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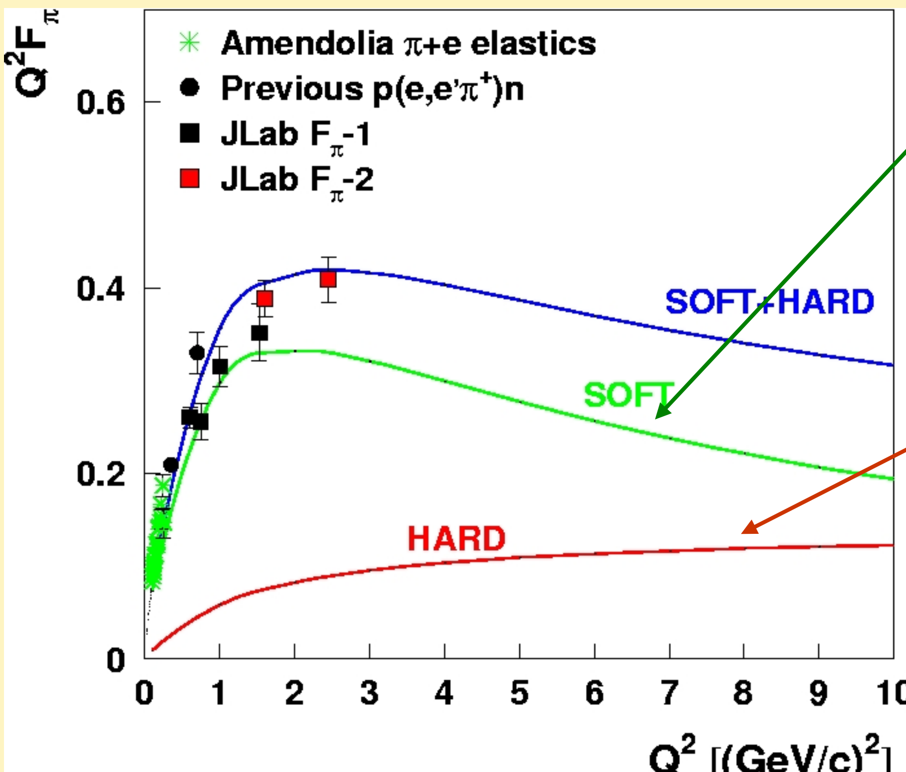
The role of Soft and Hard terms in F_π

QCD Sum Rules:

[V.A. Nesterenko and A.V. Radyushkin, Phys.Lett. ***B115****(1982)410]*

- Interpolation between perturbative and non-pertubative sectors using dispersion relation methods in combination with the Operator Product Expansion.
- Not rigorously derived from QCD, but an intuitive bridge between low and high energy properties of QCD.



SOFT: QCD Sum Rules used to give a local quark-hadron duality estimate with no free parameters.

$$F_\pi^{soft} = 1 - \frac{1+6s_0/Q^2}{(1+4s_0/Q^2)^{3/2}}$$

HARD: simple model based on the interpolation between the Q^2=0 value (related by Ward identity to $O(\alpha_s)$ term of 2-point correlator) and the asymptotic behavior.

$$F_\pi^{hard} = \frac{\alpha_s}{\pi}\frac{1}{(1+Q^2/2s_0)}$$

Duality Interval: $s_0 = 4\pi^2 f_\pi^2 \approx 0.7\ \mathrm{GeV}^2$

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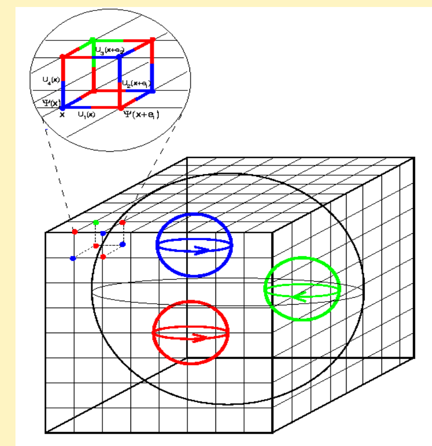
Lattice QCD (LQCD)

Lattice QCD promises to overcome theoretical uncertainties at low Q^2.

- All QCD-based models require confinement to be put in by hand.
- Lattice QCD allows the calculation to proceed from first principles.

Nonetheless, LQCD involves a number of approximations:

- *Lattice discretization errors.*
  - Use improved LQCD actions.
- *Chiral extrapolation of LQCD results in the pion mass.*
- *Quenching errors.*
  - Need to include disconnected quark loops.



Past: LQCD calculations confined only to the heavy quark sector.

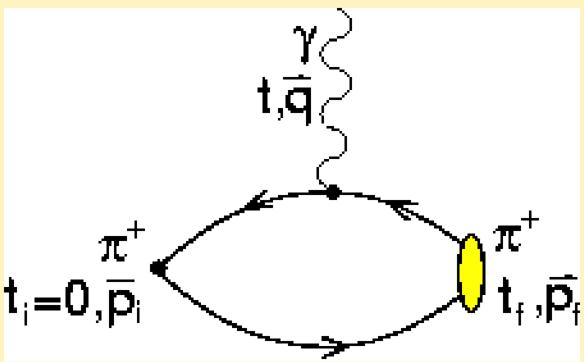
Now: Advances in computational techniques may permit their application to the light quark sector with greater authority.

Future: LQCD has great potential to revolutionize our understanding of QCD and allow precision predictions of hadronic properties to be made.

Lattice QCD example: $F_\pi(Q^2)$

The first LQCD calculations of F_π (1980's) used m_π~1 GeV.

- Calculation up to Q^2=1 GeV^2 consistent with pion charge radius, within (large) error.



Recently, four different lattice groups have pursued F_π calculations.

Goal: to perform calculation with significantly smaller quark masses than before, and eventually attain larger values of Q^2.

Lower pion mass → Larger N_sxN_sxN_sxN_t lattice.

→ More rapidly converging action and faster CPU.

Higher Q^2 → Finer lattice spacing.

→ Improved pion operators.

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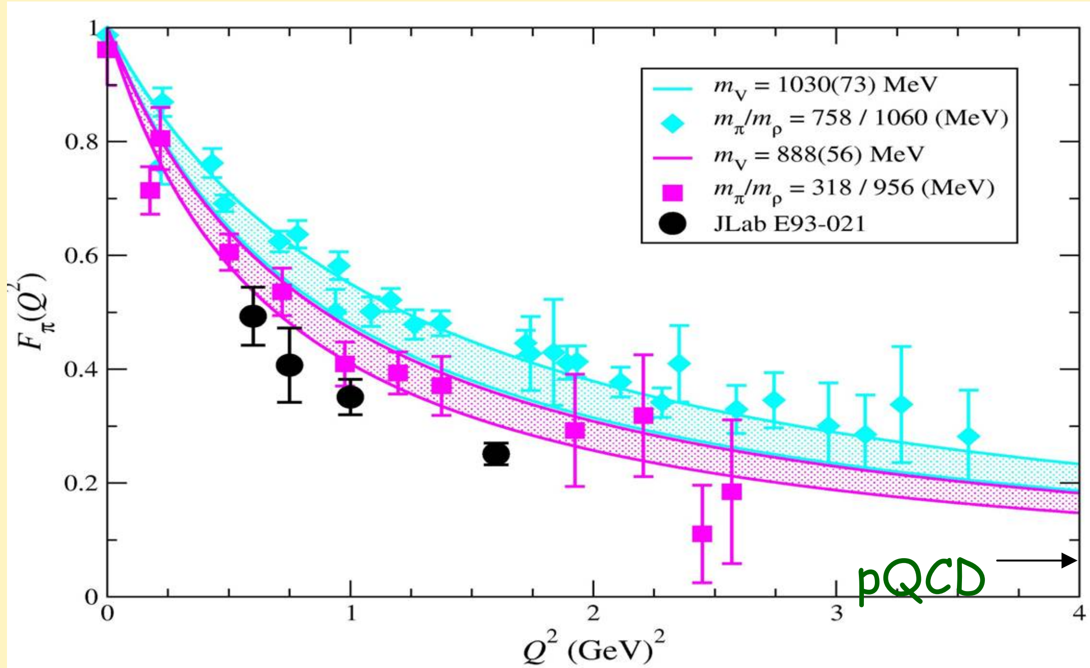
Best Calculation: Unquenched Lattice QCD

Unquenched domain-wall action calculation by Lattice Hadron Physics Collaboration (JLab/Regina/Yale).



F. Bonnet et al,
PRD **72**(2005)054506.

Now: LQCD calculations are consistent with experimental data, within large statistical and systematic (chiral extrapolation) errors.

- Primary aim is to test proof-of-principle of various calculation techniques.

Next decade: hope to see dynamical (unquenched) calculations of F_π with pion mass sufficiently low to yield small chiral extrapolation uncertainties.

- Higher Q^2 data are required to validate new LQCD methods.

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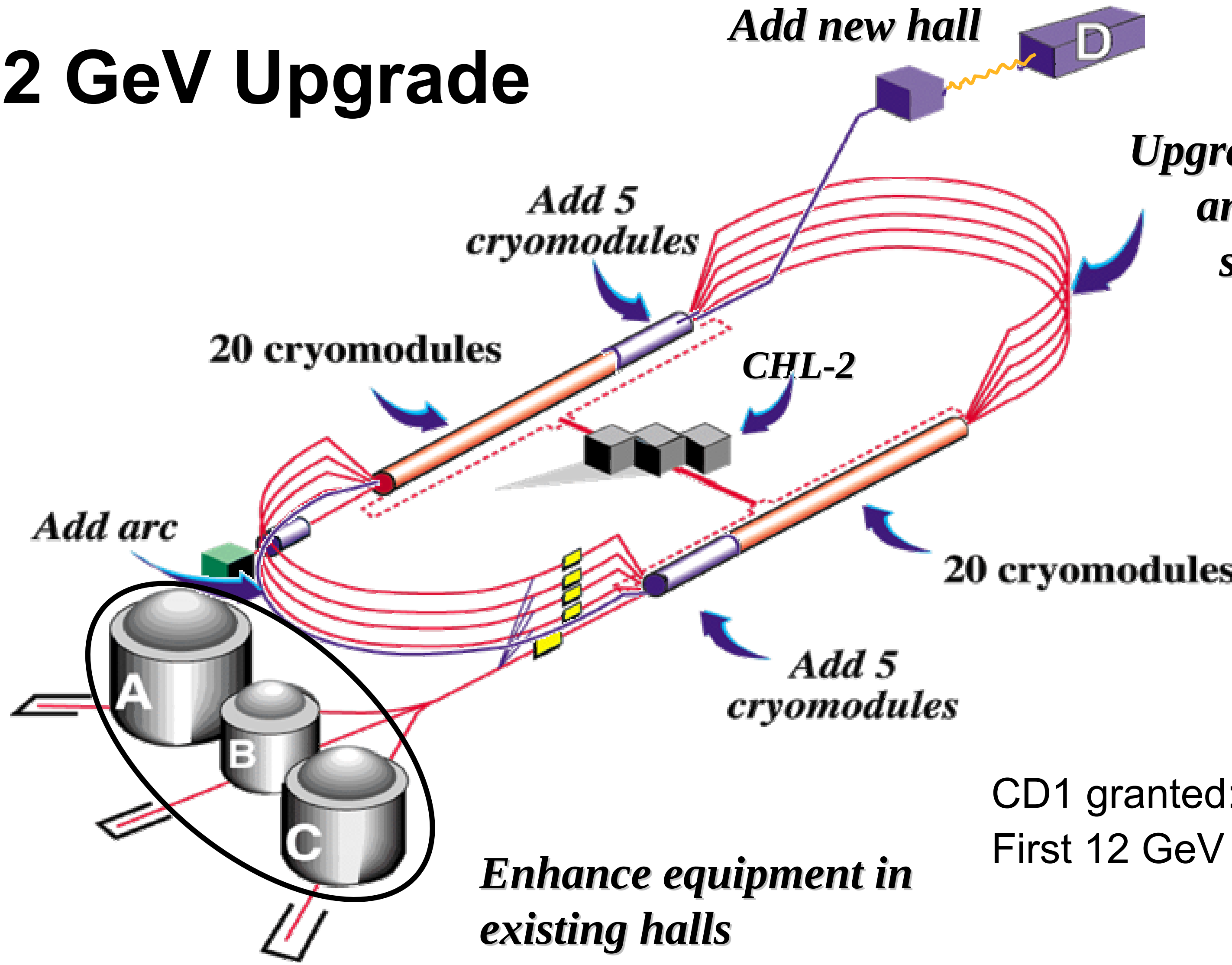
12 GeV Upgrade

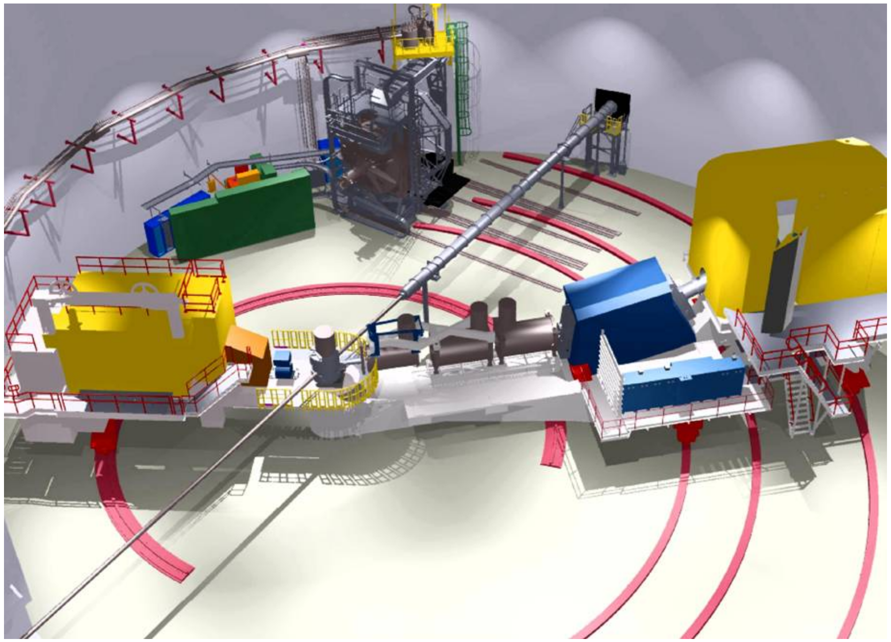


CD1 granted: Feb/06

First 12 GeV beam: mid-2013

Experimental Hall C

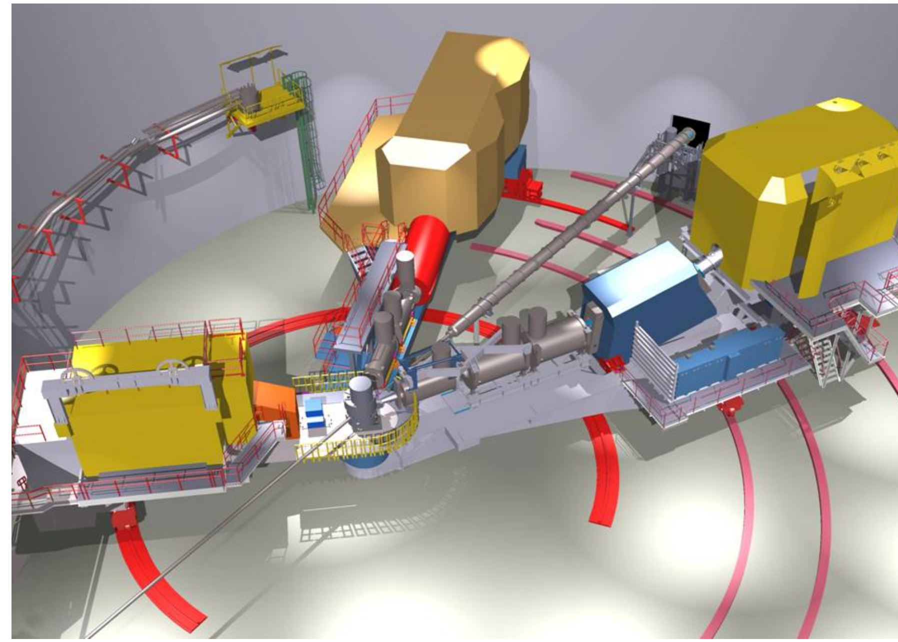
At the present 6 GeV Beam Energy



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.

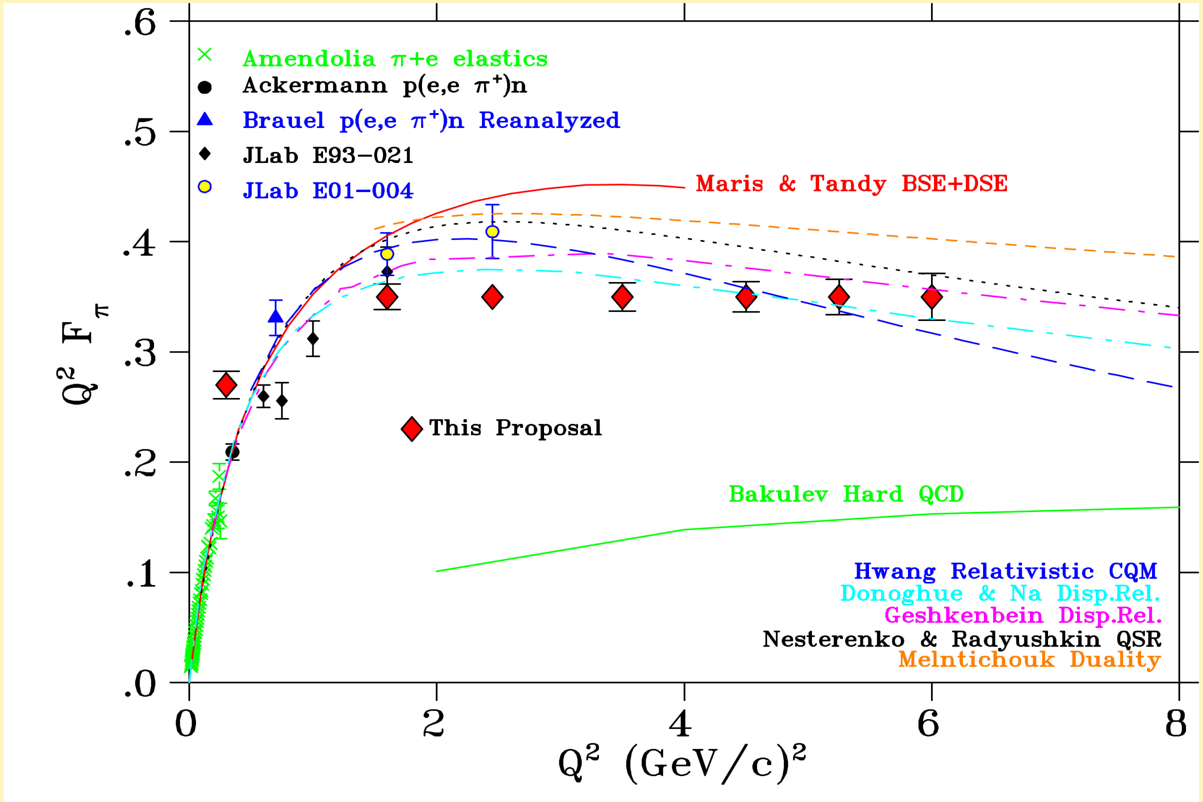
After the 12 GeV Upgrade



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.

12 GeV: Studying the transition to Hard QCD



JLab Proposal: 12-06-101

"Another important issue in the physics of confinement is understanding the transition of the behavior of QCD from low Q^2 to high Q^2. The pion is one of the simplest QCD systems available for study, and the measurement of its elastic form factor is the best hope for seeing this transition experimentally."

- U.S. Nuclear Science Advisory Committee (2002).

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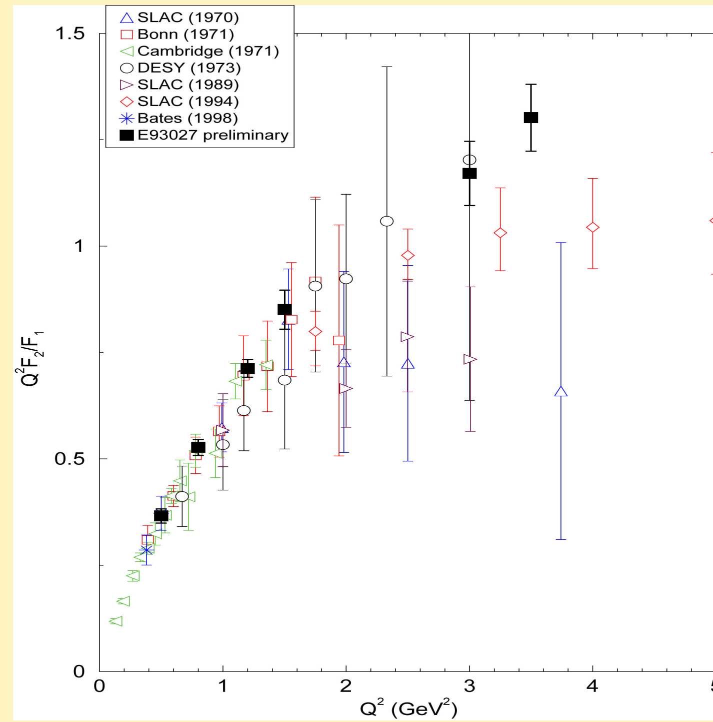
Nucleon
Electric and Magnetic
Form Factor Data

Spin ½: Elastic electron scattering from nucleons

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).
  - ➡ $Q^2 F_2/F_1 \sim$constant.
- Data indicate onset of pQCD scaling at only $Q^2 \approx 2$ GeV^2.

World proton data set, 1997.



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.

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

$\tau = Q^2/4M^2$

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

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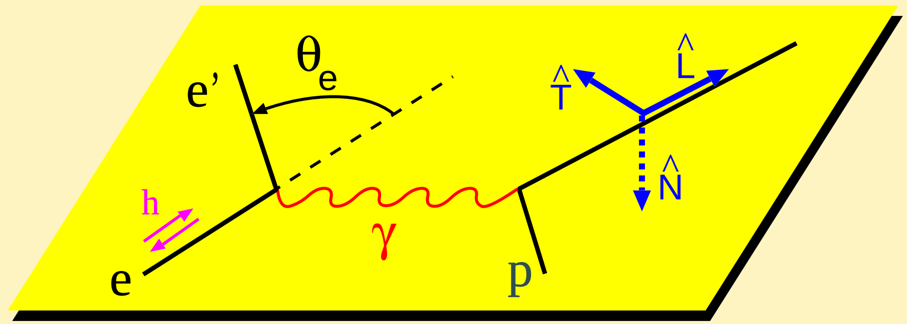
Polarization transfer technique



- Technique developed at Novosibirsk.
- Requires an intense polarized electron beam and Focal Plane Polarimeter to measure 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.**

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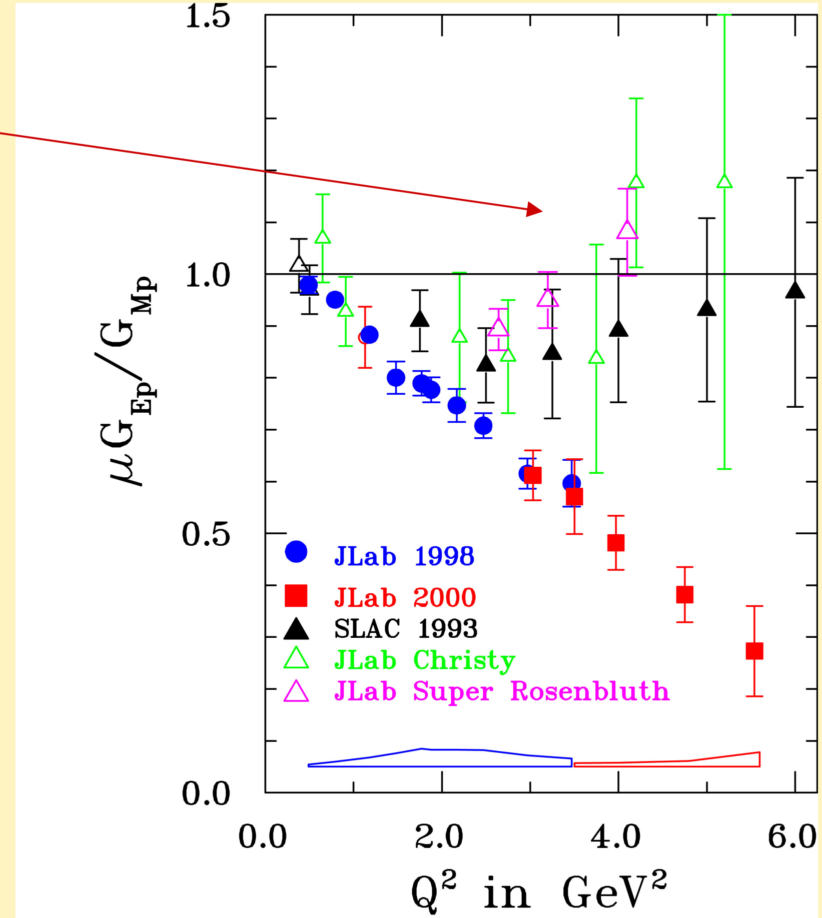
The proton: recoil polarization vs. cross sections

2004 JLab "SuperRosenbluth" *(e,p)* cross sections data agree well with global cross secton fit.

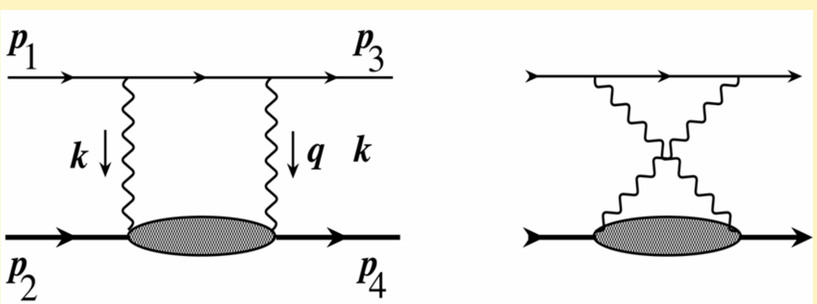
(I.A. Qattan et al, PRL **94**(05)142301)



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.

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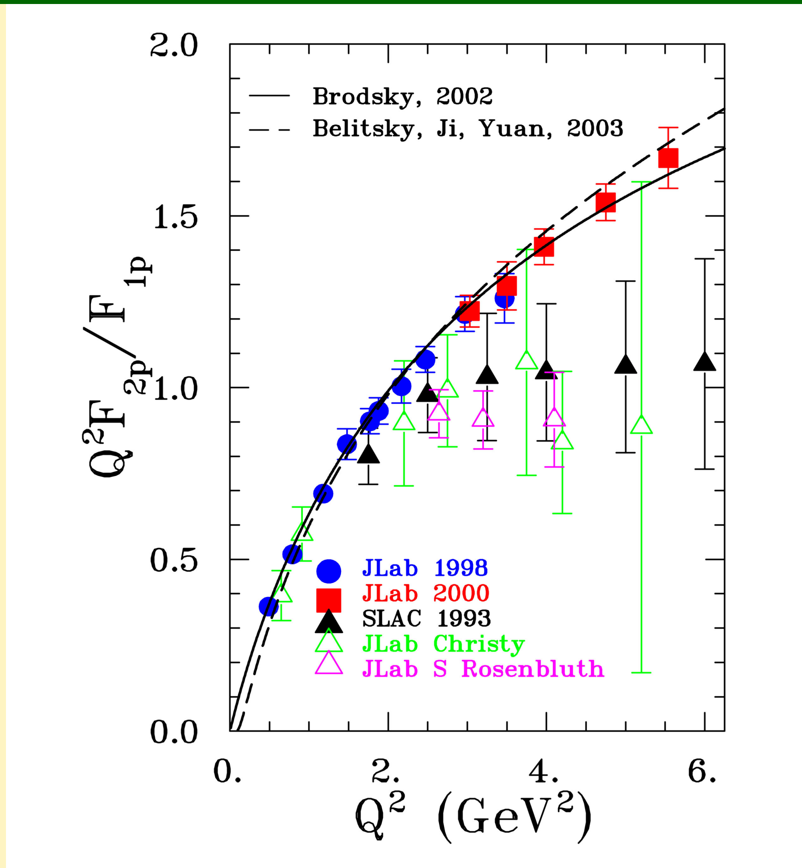
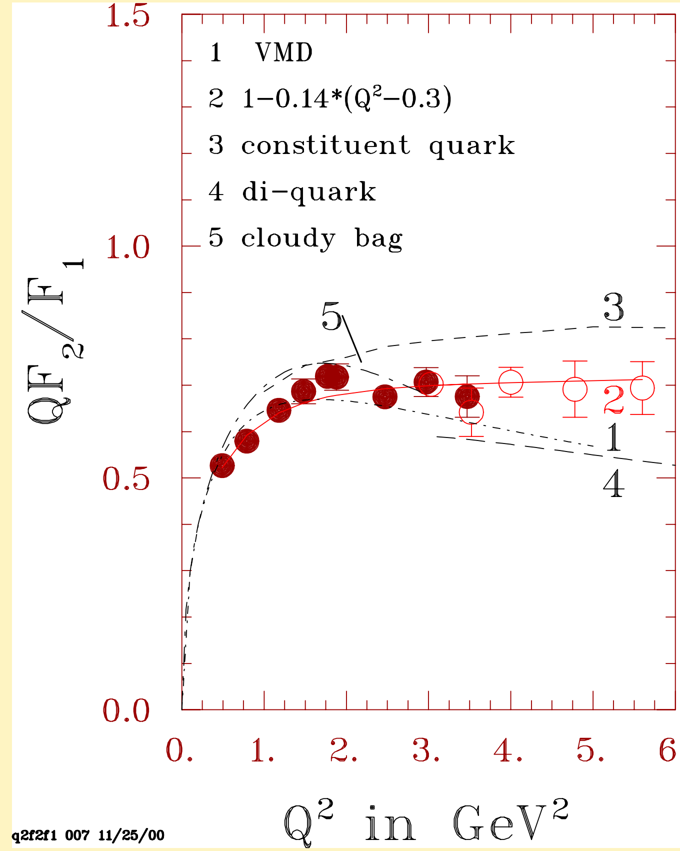
Jefferson Lab Proton F_2/F_1 Data





- 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).

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Neutron elastic form factors

$G_E\ (Q^2=0)$:	1	(p)
	0	(n)
$G_M\ (Q^2=0)$:	2.79 μ_N	(p)
	-1.91 μ_N	(n)

- **Obtaining good information on the neutron's electromagnetic structure is problematic, but significant progress has been made in recent years.**
  - Nuclear targets [^{2}H (d), ^{3}He] are required.
  - Introduces nuclear wave function uncertainties. Recent 2- and 3-N calculations have reduced the theoretical uncertainties due to target.
- G_M^n can be determined from *d(e,e'n)/d(e,e'p)* cross section ratio measurements or from $^3\overrightarrow{He}(\vec{e},e')$ electron spin asymmetry in kinematics where the neutron contribution dominates.
  - New results approach the precision of proton data (5%) up to Q^2=5 GeV^2.
- G_e^n is small, so the role of pion cloud or $q\bar{q}$ components are enhanced.
  - Two recent JLab double polarization experiments $\vec{d}(\vec{e},e'n)p,\ \ d(\vec{e},e'\vec{n})p$ now provide the first measurements above Q^2=1 GeV^2.

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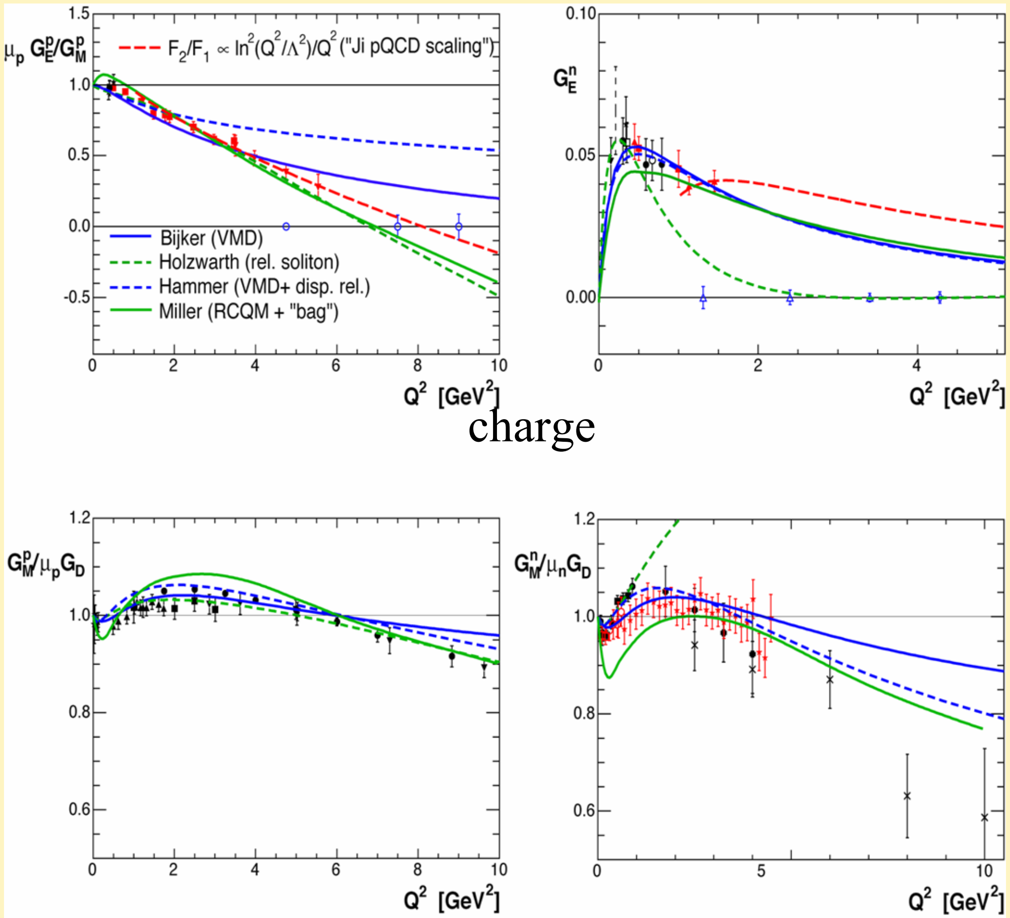
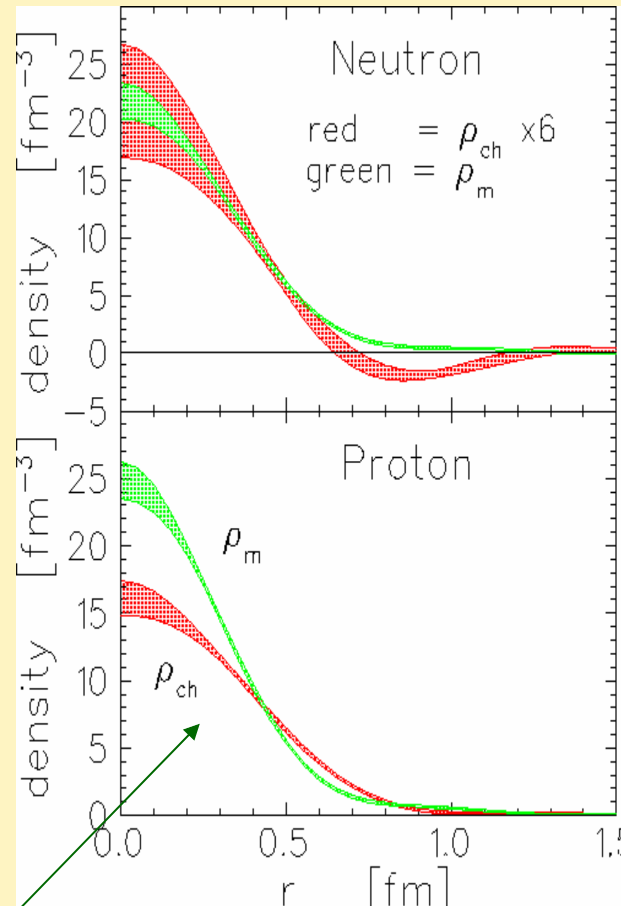
Global analysis of *p* and *n* Form Factors

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

proton neutron



magnetization



JLab polarization data
show depletion of
charge in proton interior.

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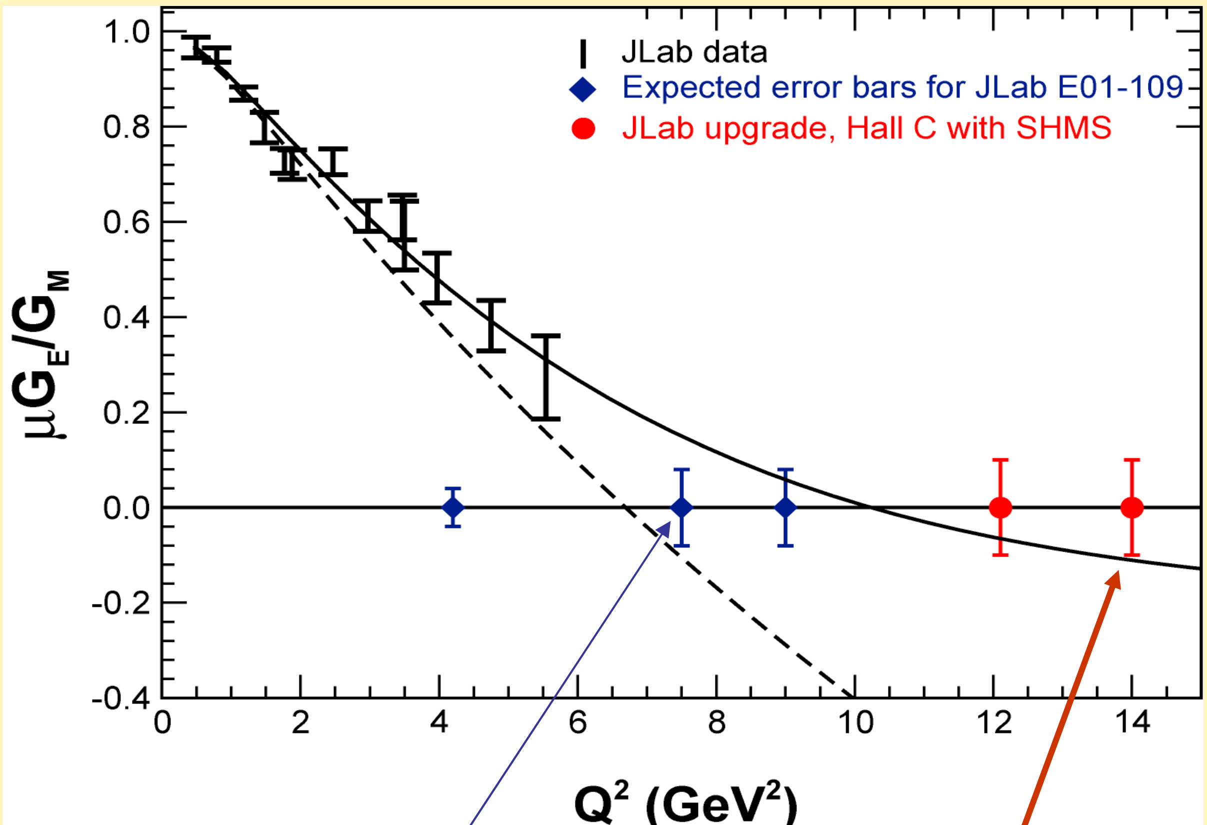
12 GeV: **Probe the Charge and Current Distributions in the Proton at <0.1 fm**



full: Lomon
dashed: Miller

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

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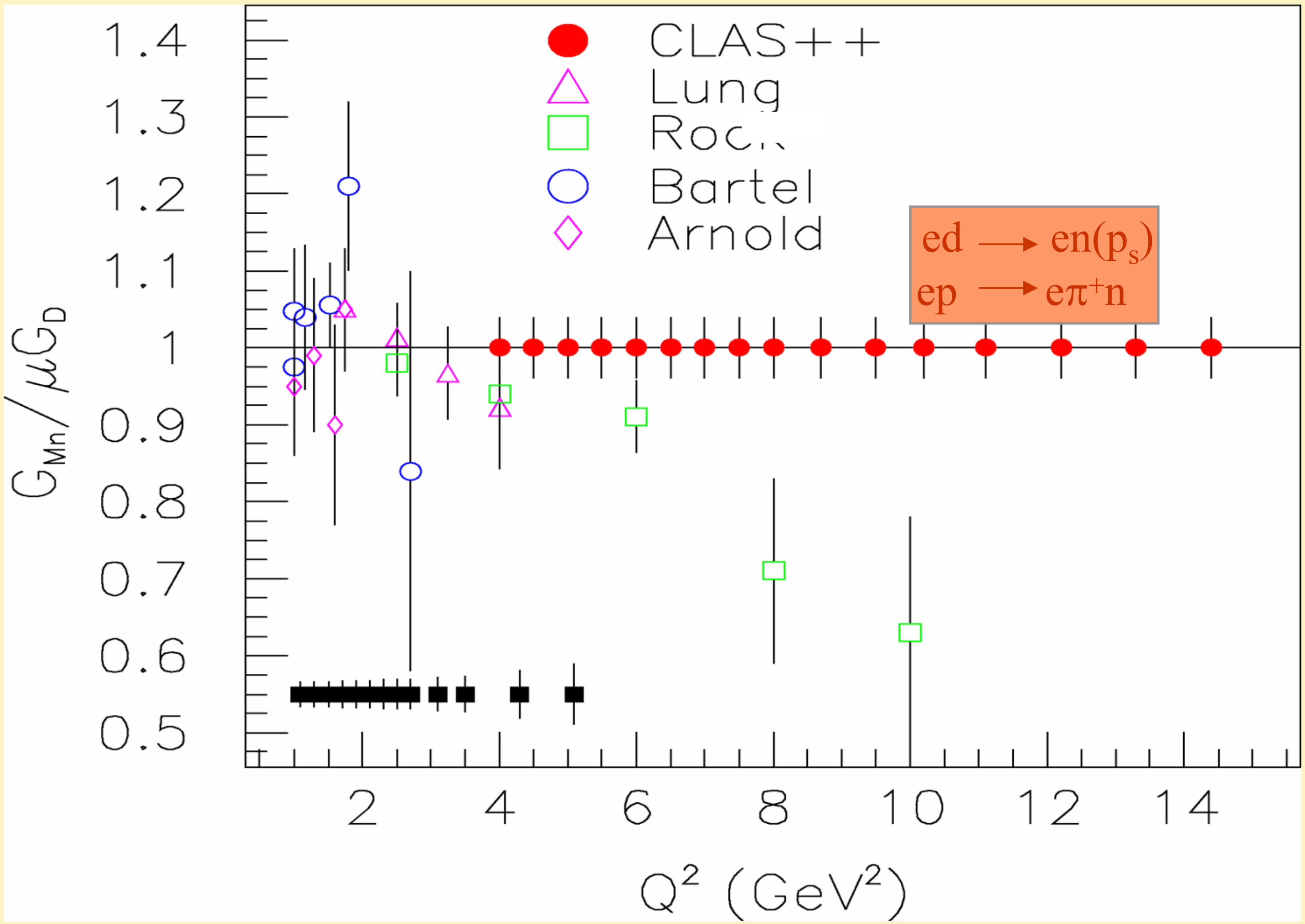
Planned Neutron G_M^n Measurements



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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 polarization techniques in electron scattering.

New puzzles have emerged as a result of the improved level of precision of the data.

In the next few years, we look forward to:

- Results for the pion form factor and possibly the Kaon.
- Deeper understanding of the proton's charge and magnetism and the role of quark orbital angular momentum.

Longer term View

Over the longer term, we look forward to continued development of Lattice QCD techniques for the light quark sector:

- Unquenched calculations.
- Usage of realistic pion mass and better Chiral extrapolations.
- Very promising, but not yet proven….

2012+: JLab 12 GeV upgrade will provide new insights:

- Structure of the nucleon.
- Transition between the hadronic and quark/gluon descriptions of matter.
- Many parts of program not discussed here….