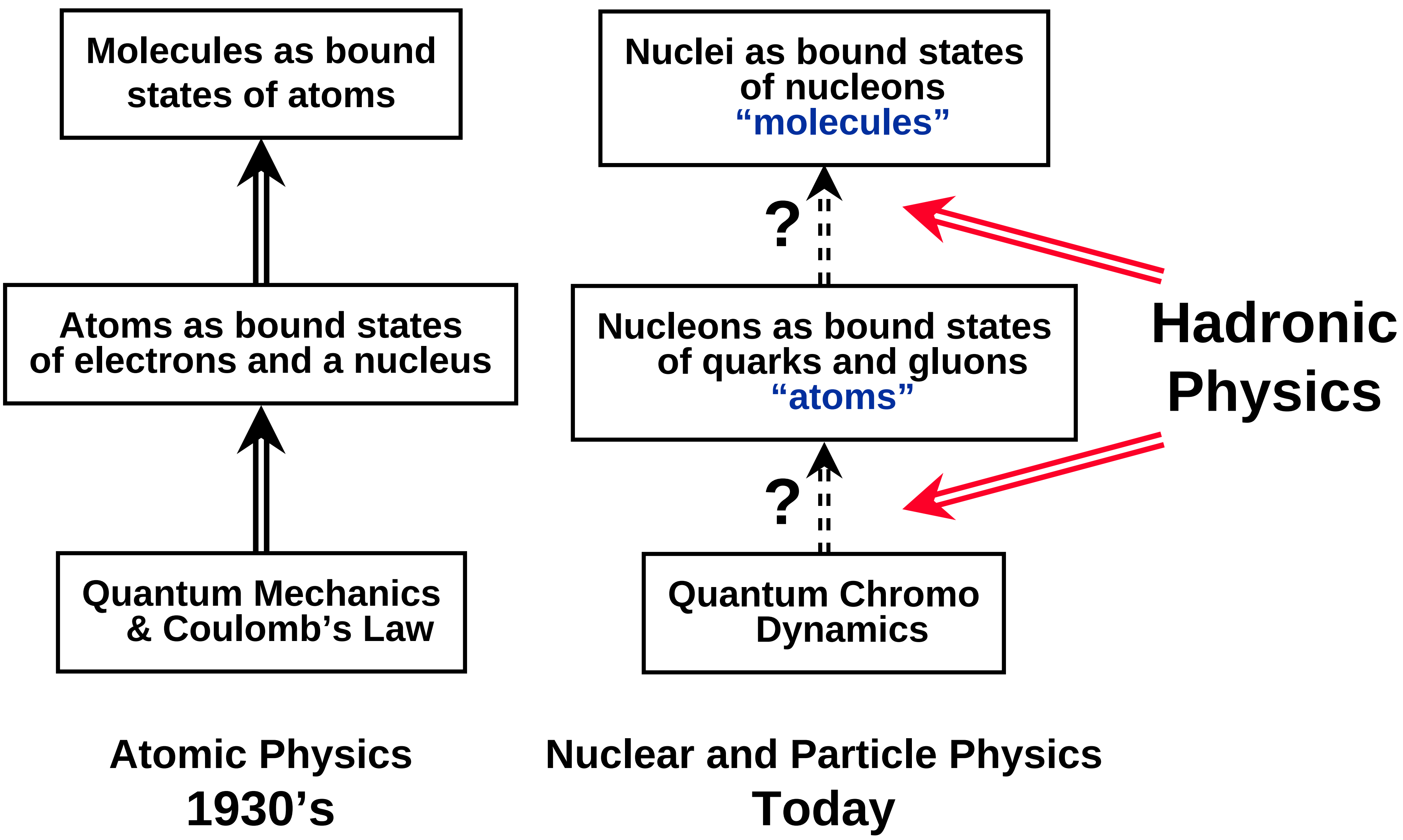
Building Nucleons and Nuclei from Quarks and Glue: Results from the Research Program Using CEBAF @ Jefferson Lab

L. Cardman

CEBAF @ Jefferson Lab

- A 4 GeV (now 5.7 GeV), high intensity, cw electron accelerator built to investigate the structure of mesons, nucleons, and nuclei
- The approved research program:
  - 159 experiments on a broad variety of topics
  - An International User Community:
    1028 PhD scientists from 182 Institutions in 30 Countries
- Research operations began 10/95
  - in full operation for 7½ years (since 11/97)
  - data for 118 full experiments and parts of 10 more are complete
  - results are emerging regularly in the published literature

Atomic Physics versus Quark Physics



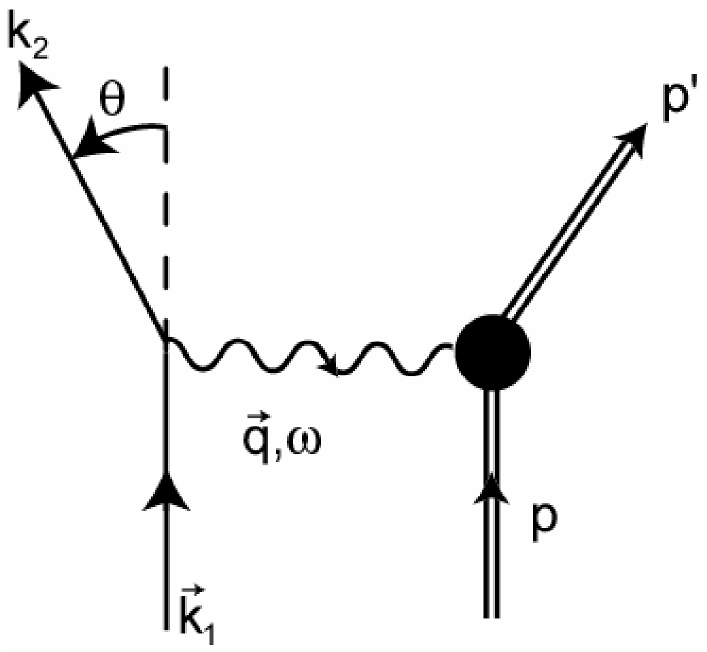
JLab's Scientific Mission

- Understand how hadrons are constructed from the quarks and gluons of QCD
- Understand the QCD basis for the nucleon-nucleon force
- Explore the limits of our understanding of nuclear structure
  - high precision
  - short distances
  - the transition from the nucleon-meson to the QCD description

To make progress in these areas we must address critical issues in "strong QCD":

- What is the mechanism of confinement?
- Where does the dynamics of the q-q interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime?
- How does Chiral symmetry breaking occur?

Electron Scattering Provides an Ideal Microscope for Nuclear Physics



- Electrons are point-like
- The interaction (QED) is well-known
- The interaction is weak
- Vary *q* to map out Fourier Transforms of charge and current densities:

$\lambda \cong 2\pi/q$ **(1 fm ⇔ 1 GeV/c)**

$$S_{fi} = \frac{-e^2}{\Omega} \bar{u}(k_2)\,\gamma^{\mu}\, u(k_1) \frac{1}{q^2} \int e^{iq\cdot x} \langle f | \hat{J}_{\mu}(x) | i \rangle d^4x$$

$\vec{q} = \vec{k}_1 - \vec{k}_2 =$ Momentum Transfer

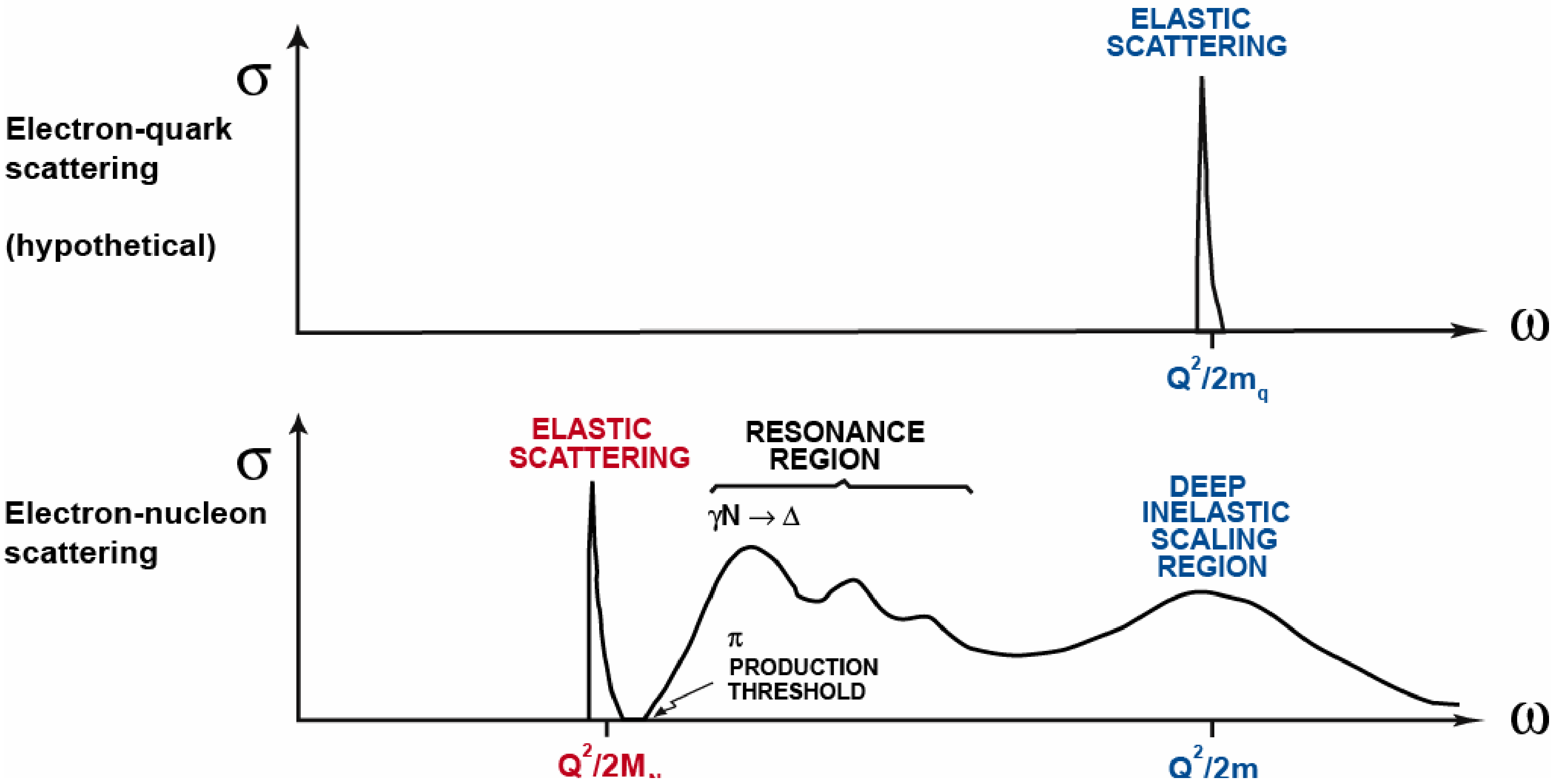
$\omega = E_p - E_{p'} =$ Energy Transfer

$Q^2 = -q^2 =$ 4-Momentum Transfer

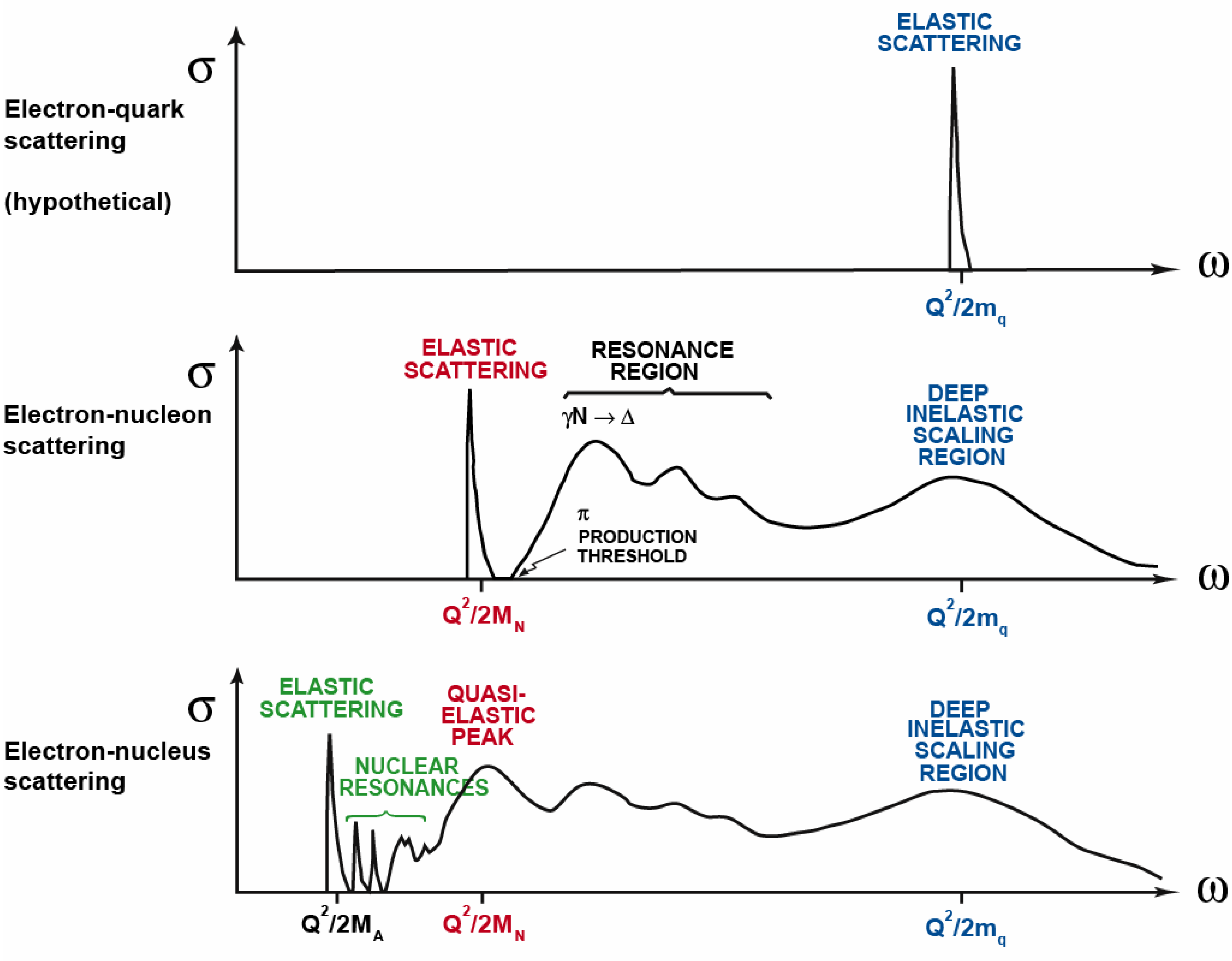
CEBAF's $\vec{e}$ and CW beams dramatically enhance the power of electron scattering

Electron Scattering

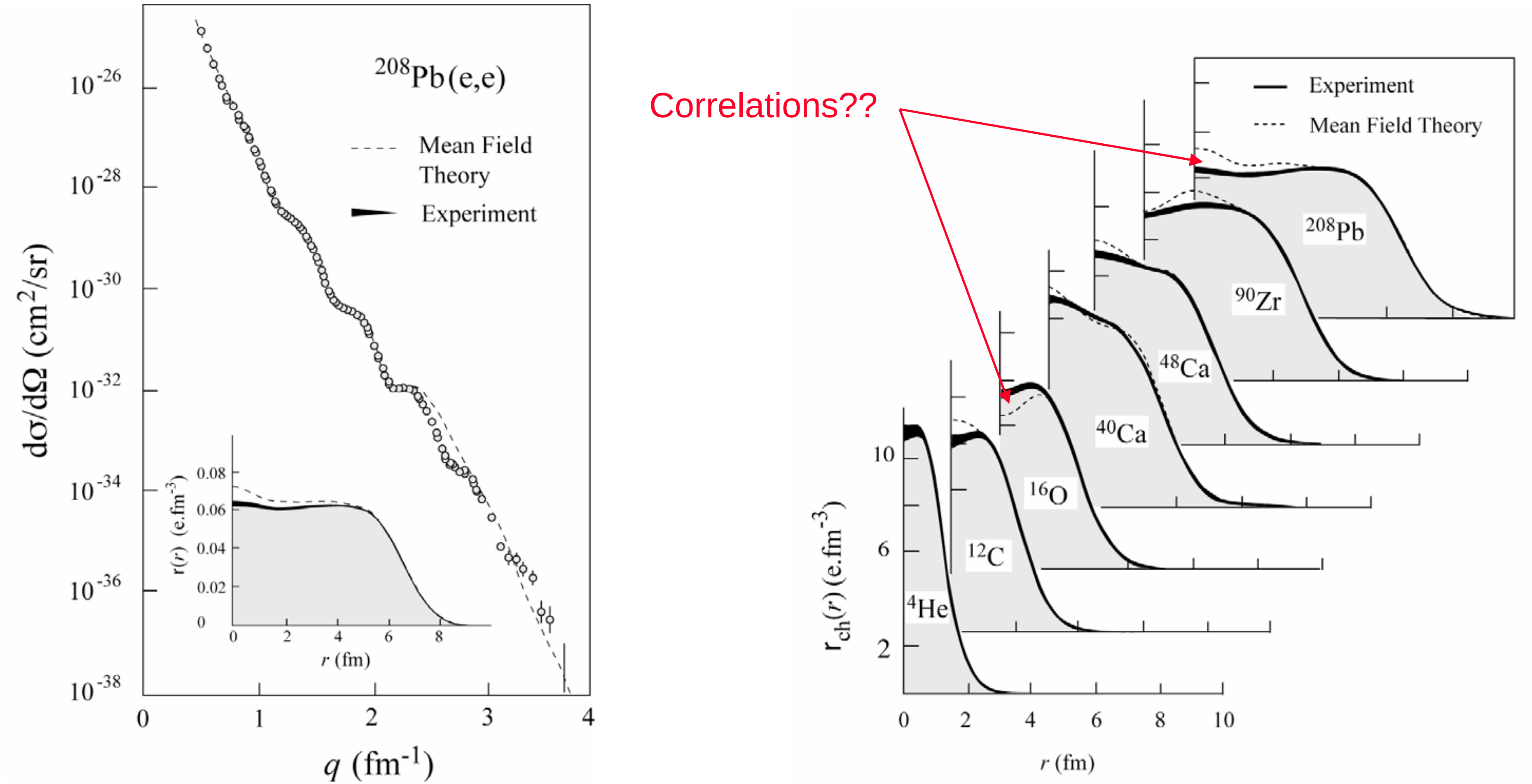
Electron Scattering



Electron Scattering



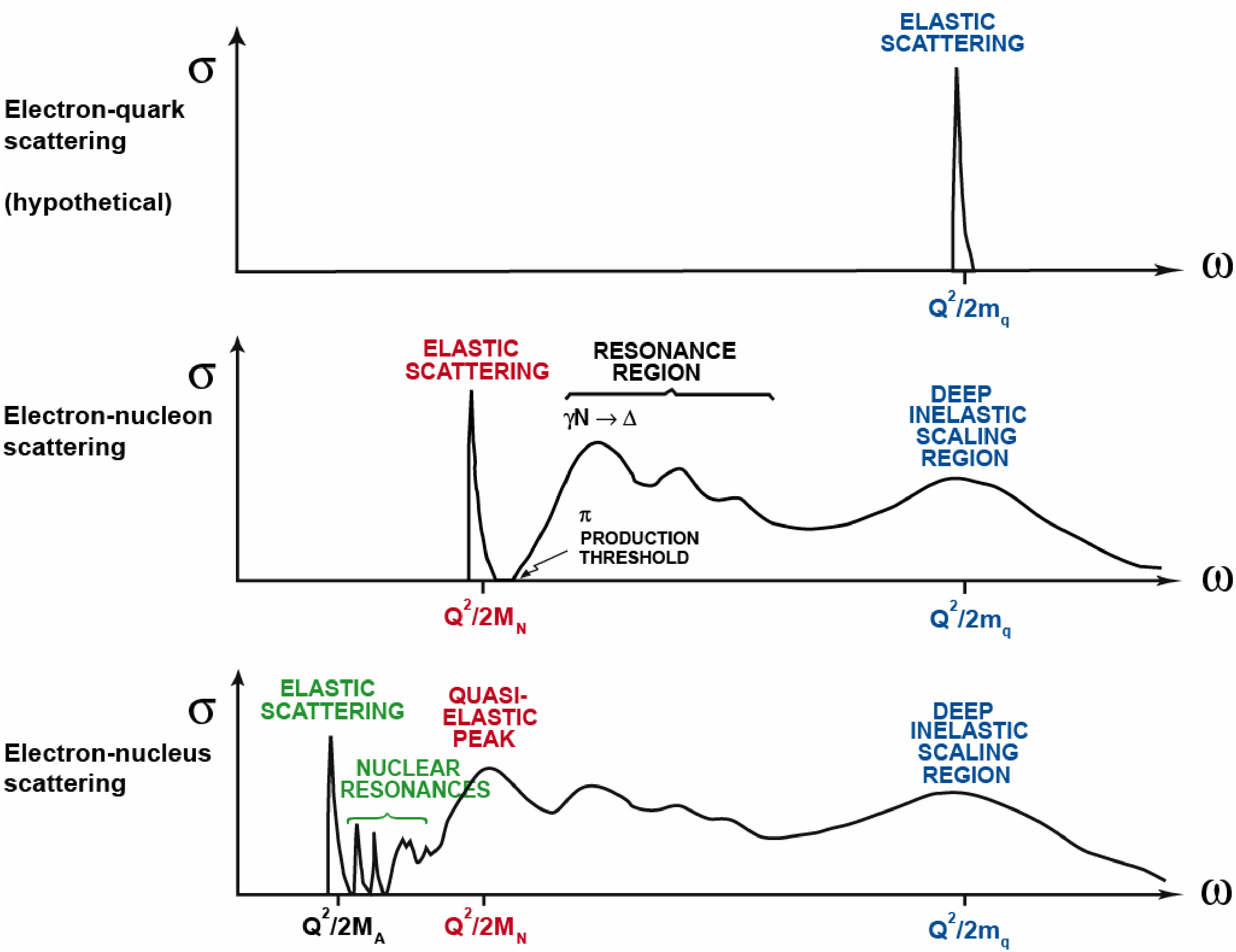
(e,e) ⇒ Nuclear Charge Distributions



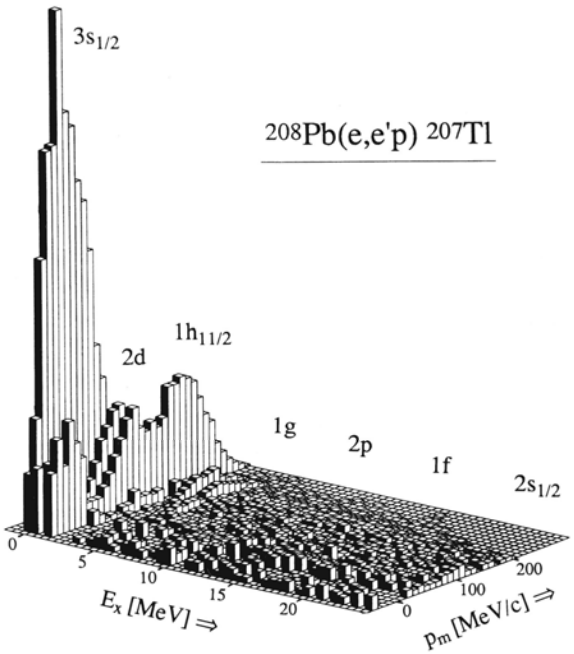
In '70s large data set was acquired on elastic electron scattering (mainly at Saclay) over large Q^2-range and for variety of nuclei

"Model-independent" analysis of these data provided accurate results on charge distribution for comparison with the best available theory: Mean-Field Density-Dependent Hartree-Fock

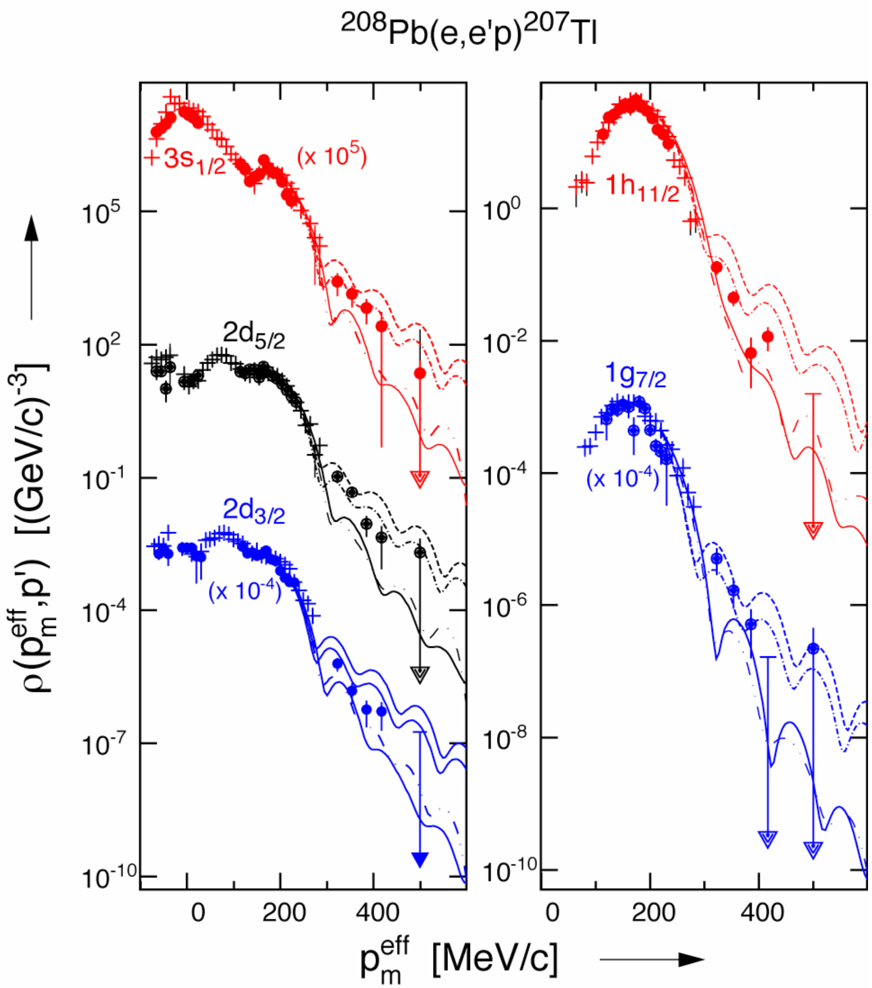
Electron Scattering

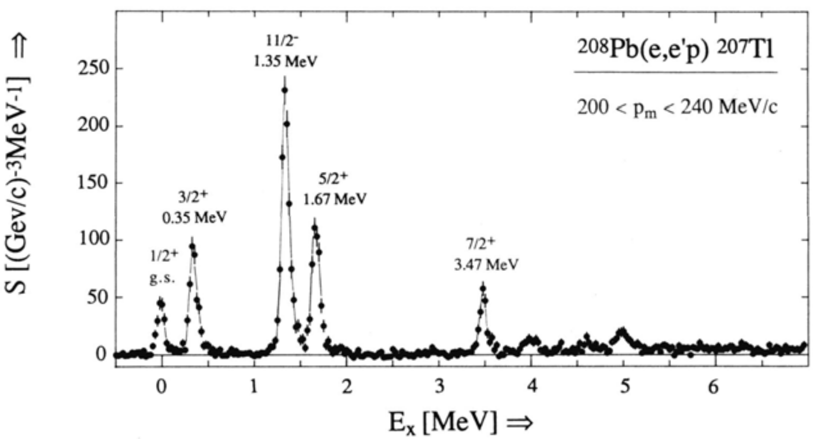


(e,e'p) ⇒ Nucleon Momentum Distributions, Shell-by-Shell



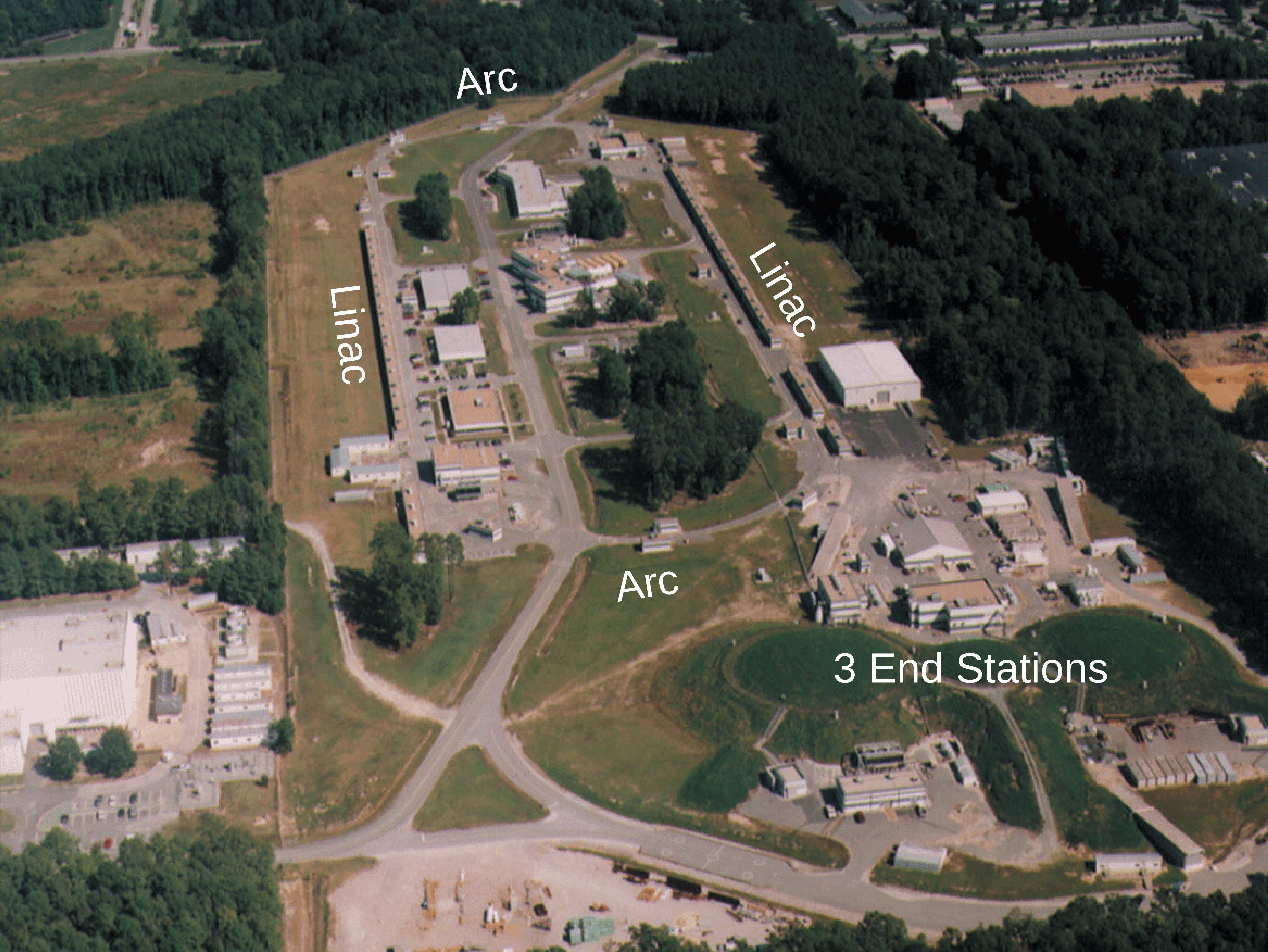
$$p_m = E_e - E_{e'} - p = q - p$$
$$E_m = \omega - T_p - T_{A-1} = E_{sep} + E_{exc}$$





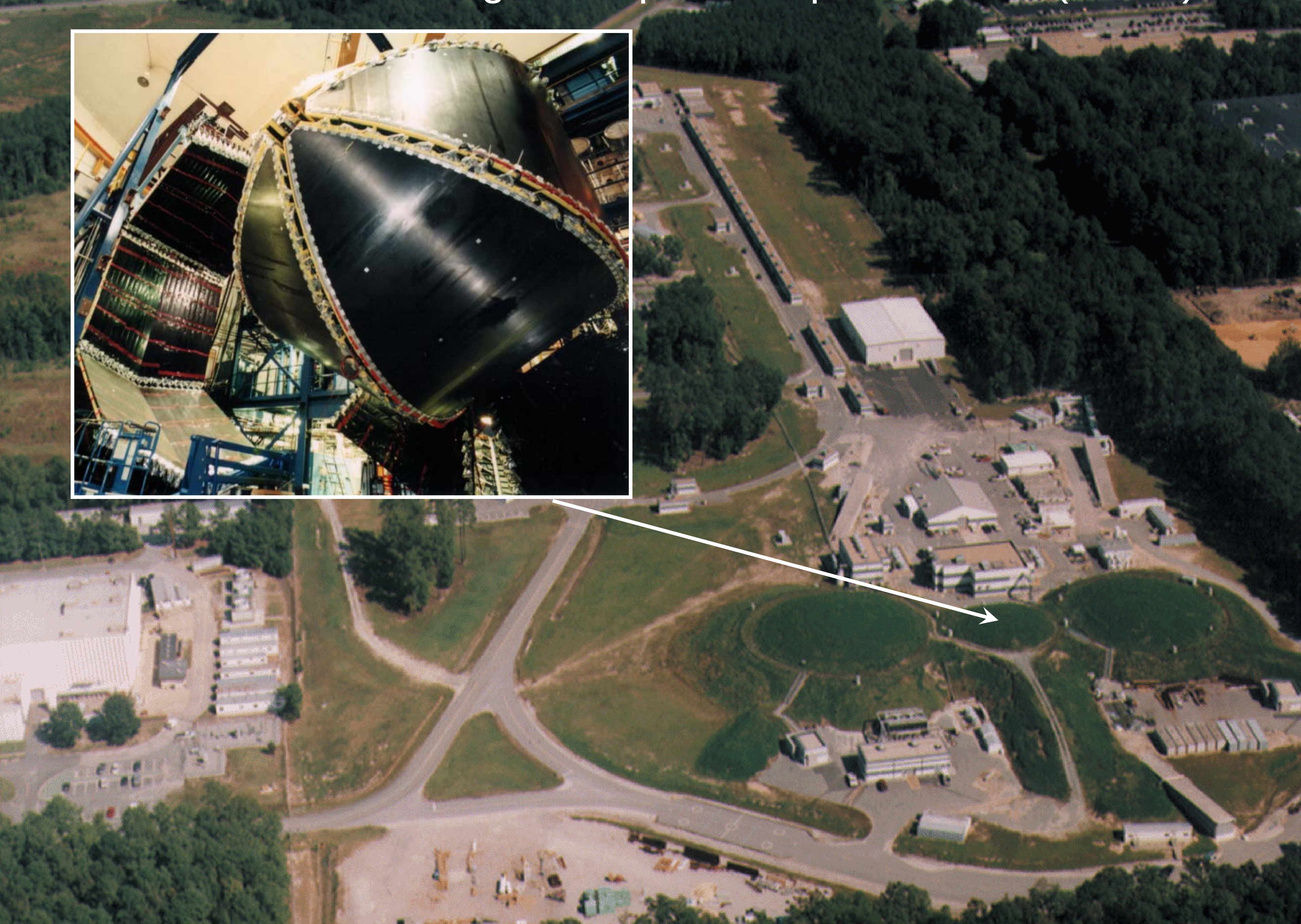
CEBAF Design Parameters

- **Primary Beam: Electrons**
- **Beam Energy: 4 GeV (with upgrade path)**
  - $10 > \lambda > 0.1$ fm
  - nucleon $\rightarrow$ quark transition
  - baryon and meson excited states
- **100% Duty Factor (cw) Beam**
  - coincidence experiments
- **Three Simultaneous Beams with Independently Variable Energy and Intensity**
  - complementary, long experiments
- **Polarization (beam and reaction products)**
  - spin degrees of freedom
  - weak neutral currents


Arc
Linac
Linac
Arc
3 End Stations

Hall A: Two High Resolution (10^{-4}) Spectrometers

Hall B: The CEBAF Large Acceptance Spectrometer (CLAS)



Hall C: A High Momentum and a Broad Range Spectrometer

Setup Space for Unique Experiments

JLab Scientific “Campaigns”

The Structure of the Nuclear Building Blocks

1. How are the nucleons made from quarks and gluons?
2. What are the mechanism of confinement and the dynamics of QCD?
3. How does the NN Force arise from the underlying quark and gluon structure of hadronic matter?

The Structure of Nuclei

4. What is the structure of nuclear matter?
5. At what distance and energy scale does the underlying quark and gluon structure of nuclear matter become evident?

Symmetry Tests in Nuclear Physics

6. Is the “Standard Model” complete? What are the values of its free parameters?

1. How are the Nucleons Made from Quarks and Gluons?

Why are nucleons interacting via V_{NN} such a good approximation to nature?

How do we understand QCD in the confinement regime?

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How do we understand QCD in the confinement regime?

A. What are the spatial distributions of u, d, and s quarks in the hadrons?

B. What is the excited state spectrum of the hadrons, and what does it reveal about the underlying degrees of freedom?

C. What is the QCD basis for the spin structure of the hadrons?

D. What can other hadron properties tell us about ‘strong’ QCD?

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How do we understand QCD in the confinement regime?

A. What are the spatial distributions of u, d, and s quarks in the hadrons?

G_E^p/G_M^p (3 techniques); higher Q^2 coming
G_E^n (2 expts in Hall C; higher Q^2 coming) G_M^n (Hall A; CLAS to high Q^2)
G_M^n to high Q^2 (CLAS)
HAPPEX, G0 forward angle, w/ G0 backward angle & HAPPEX II coming
F_π (new data to 5.75 GeV; w/ future extension at 12 GeV)

B. What is the excited state spectrum of the hadrons, and what does it reveal about the underlying degrees of freedom?

$N \rightarrow \Delta$ (All three halls)
Higher resonances (CLAS e1: η, π^0, $\pi^\pm$ production)
Missing resonance search (CLAS e1 and g1: ρ, ω production
VCS in the resonance region (Hall A)

C. What is the QCD basis for the spin structure of the hadrons?

Q^2 evolution of GDH integral and integrand for:
proton (CLAS) and neutron (Hall A) (w/ low Q^2 extensions coming for neutron)
A_1^n, g_2^n w/ 12 GeV follow-on (Hall A)
A_1^p (Hall C, CLAS)

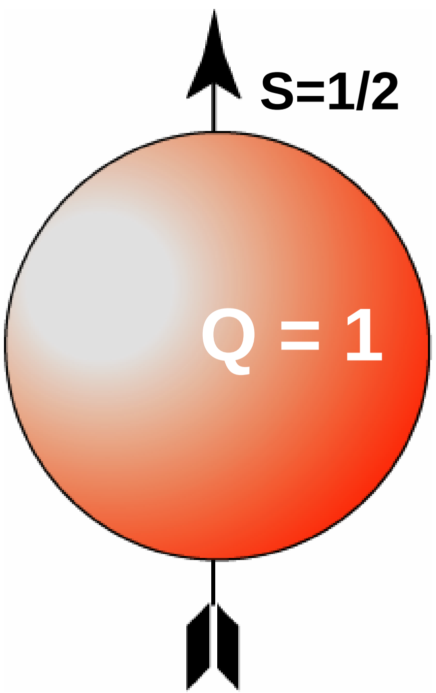
D. What can other hadron properties tell us about 'strong' QCD?

VCS (Hall A)
DVCS (CLAS, Hall A & CLAS coming)
Compton Scattering (Hall A)
Separated Structure Functions (Hall C)
Single Spin Asymmetries (CLAS, Hall A coming)

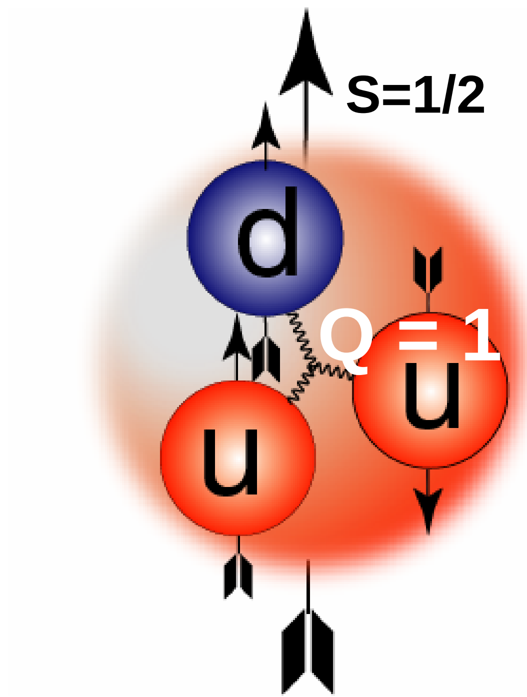
The Proton and Neutron are the "Hydrogen Atoms" of QCD

What we "see" changes with spatial resolution

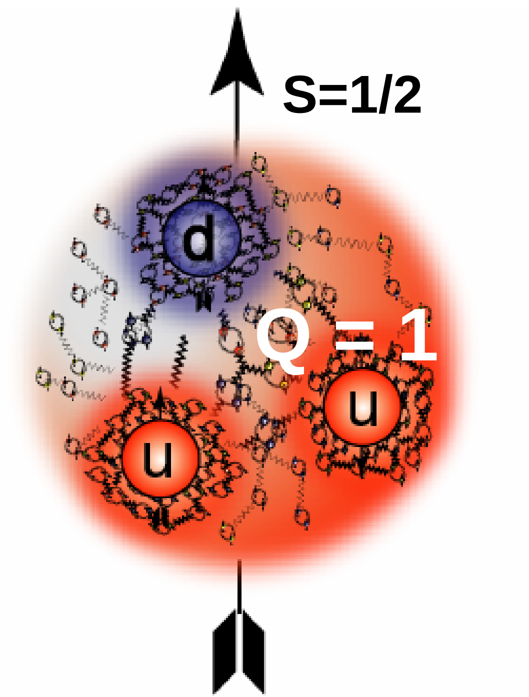
>1 fm
Nucleons



0.1 — 1 fm
Constituent quarks and glue



< 0.1 fm
"bare" quarks and glue



Nucleon (and Pion) Form Factors

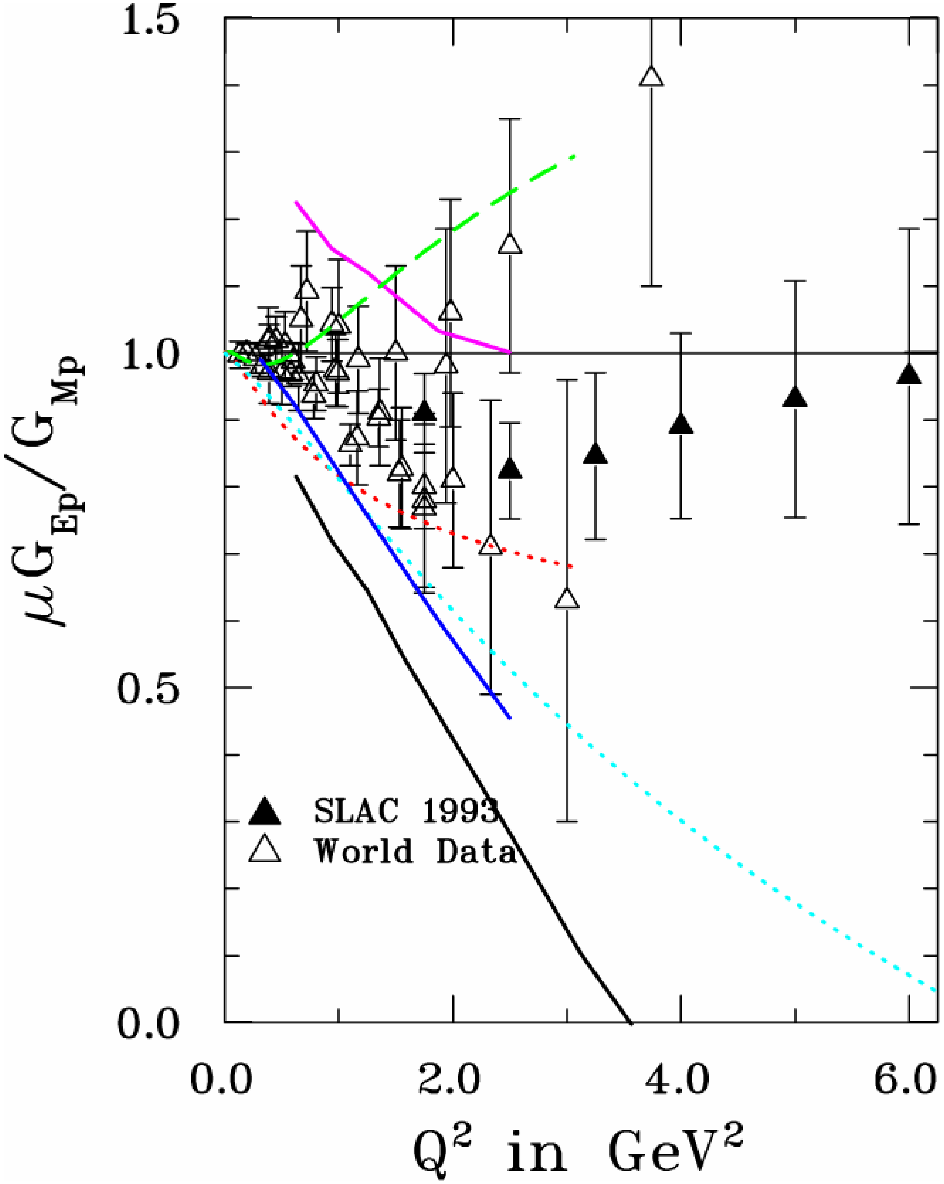
- Fundamental ingredients in “Classical” nuclear theory
- The spatial distribution of charge and magnetization provide a testing ground for theories constructing nucleons from quarks and gluons.
- Experimental insights into nucleon structure from the flavor decomposition of the nucleon form factors

PRECISION

$$\left.\begin{matrix} G_E^p & G_E^n & G_E^{p,Z} \\ G_M^p & G_M^n & G_M^{p,Z} \end{matrix}\right\} \Rightarrow \begin{matrix} G_E^u & G_E^d & G_E^s \\ G_M^u & G_M^d & G_M^s \end{matrix}$$

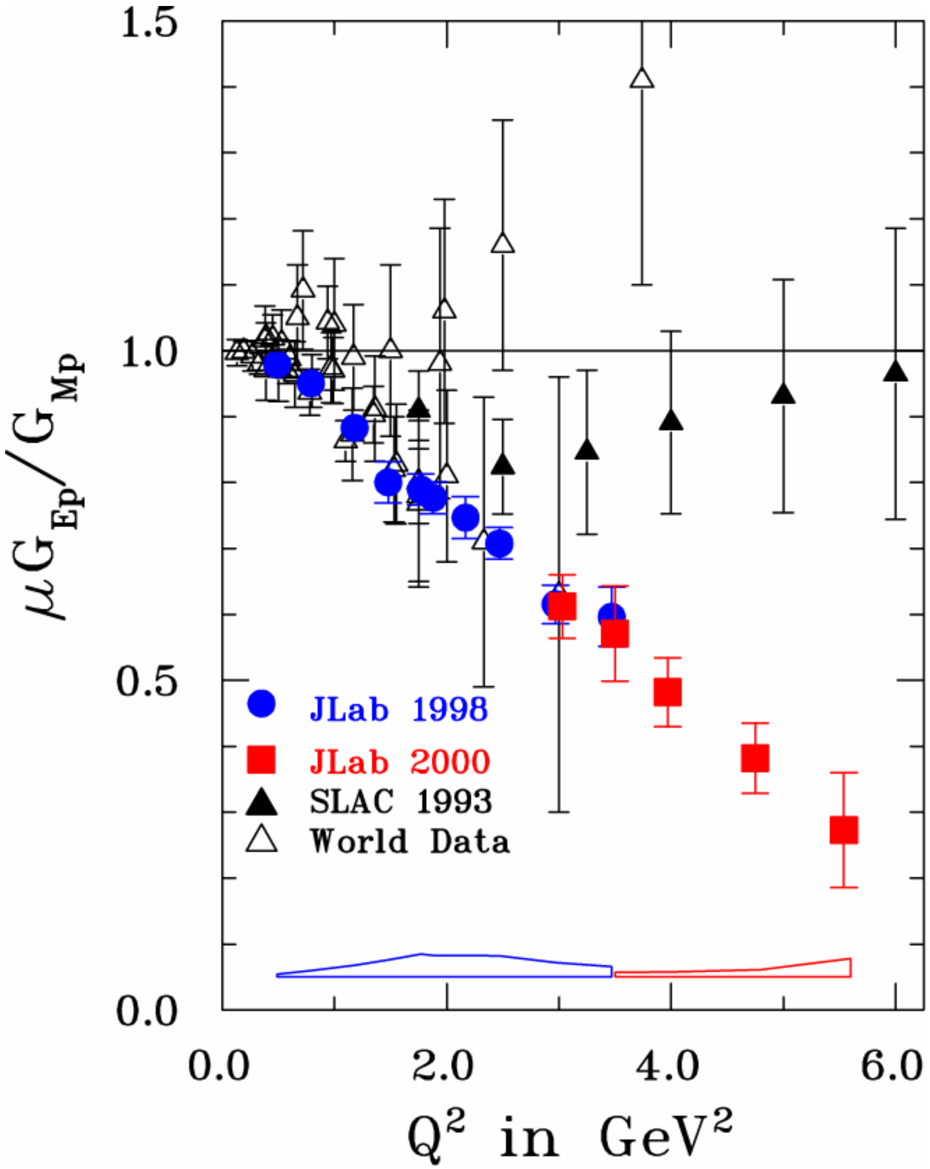
- Additional insights from the measurement of the form factors of nucleons embedded in the nuclear medium
  - implications for binding, equation of state, EMC…
  - precursor to QGP

JLab Data is Providing Fascinating Insights into the Proton's Structure



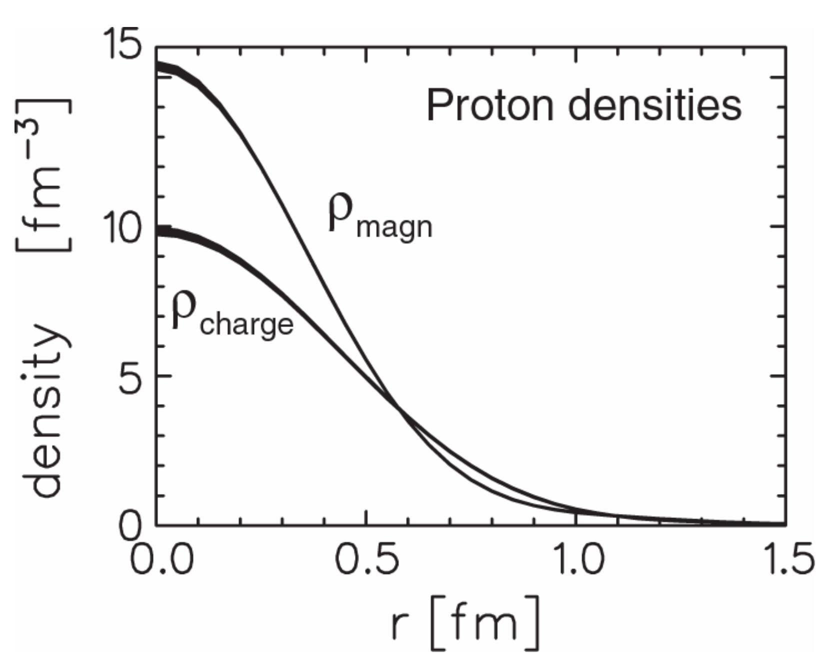
- G_E and G_M probe the charge and current distributions of the nucleon, respectively
- Previously available data implied that (within errors) the distribution of charge and magnetization in the proton were identical and were unable to distinguish among very different theories of nucleon structure
- The experiments were limited by the precision achievable in absolute cross section measurements at pairs of scattering angles

JLab Data is Providing Fascinating Insights into the Proton's Structure (cont)

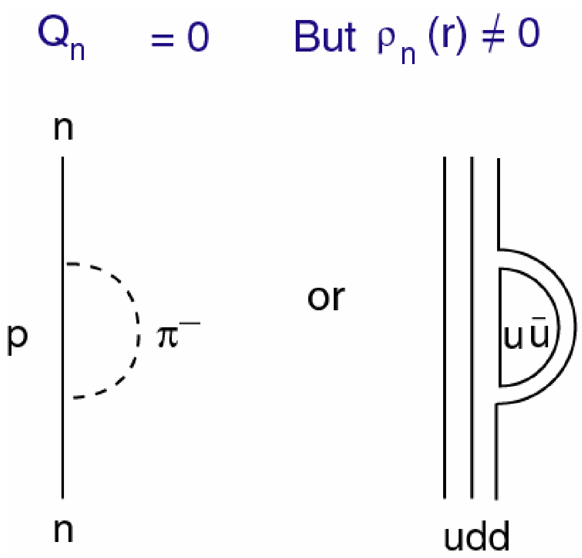


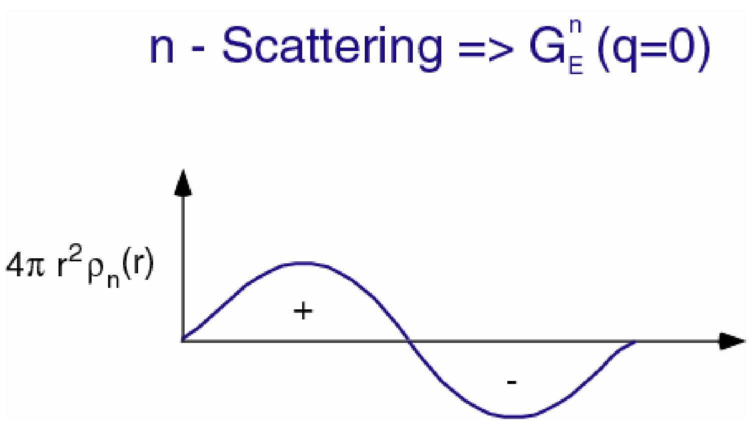
The combination of high intensity $\vec{e}$ beams and proton polarimetry has dramatically improved our knowledge of this fundamental system and revived theoretical interest in this important problem

⇒

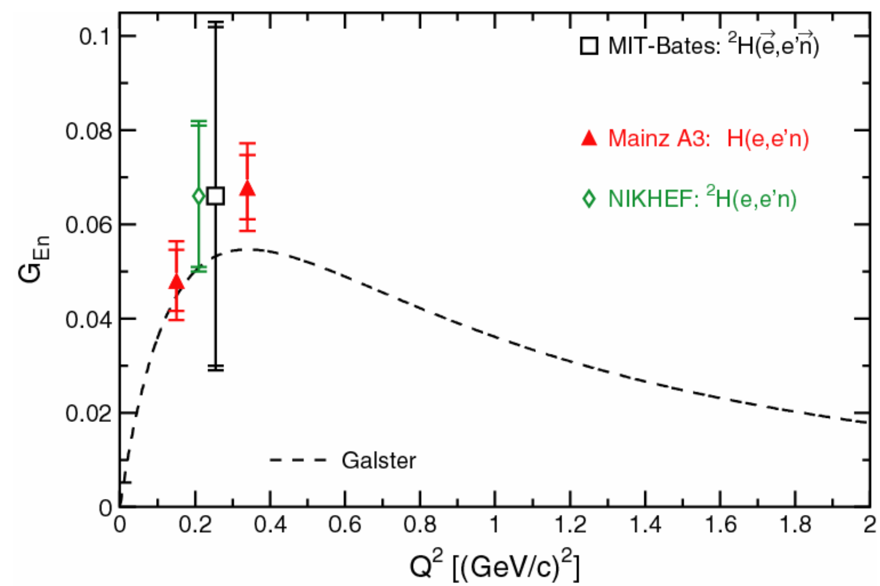


The Neutron's Charge Distribution Provides Further Insights into Hadron Structure

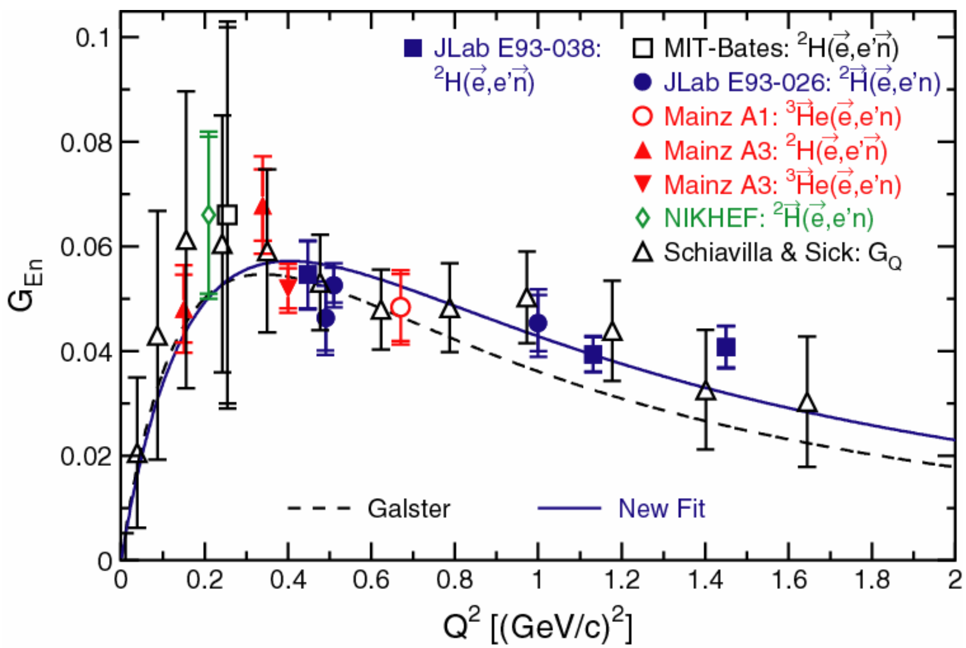




Previously available data limited to modest Q^2, just barely sensitive to details beyond the RMS radius



The Neutron's Charge Distribution Provides Further Insights into Hadron Structure (cont)



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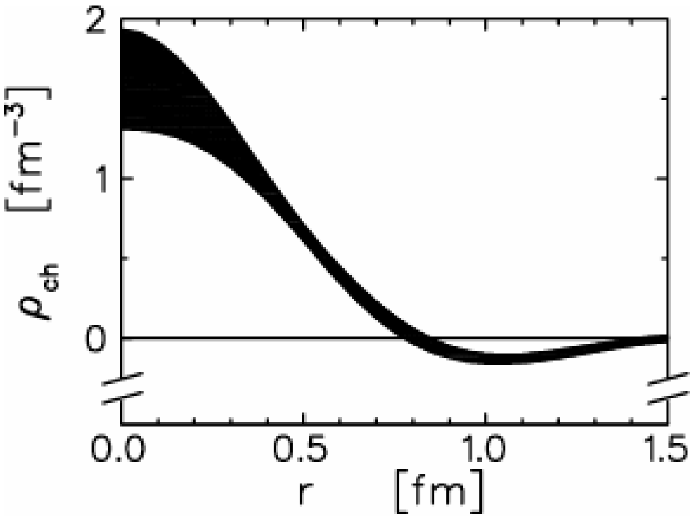


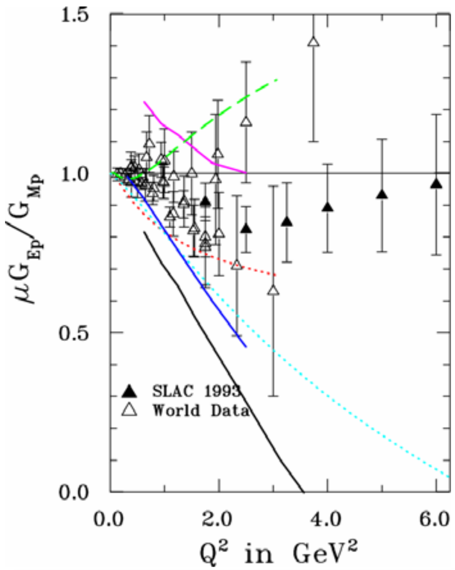
- New neutron electric form factor data reveal the shape of the charge distribution
- And the importance of relativistic effects in nucleon structure

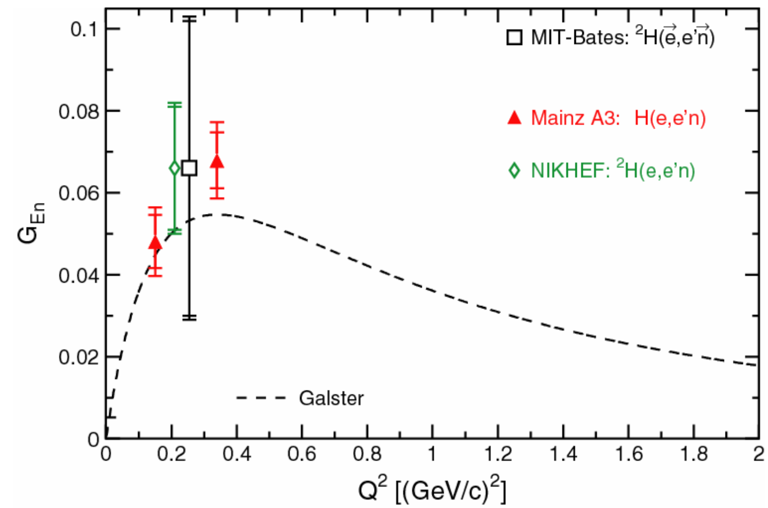
JLab data on the EM form factors provide a testing ground for theories constructing nucleons from quarks and glue

Before JLab

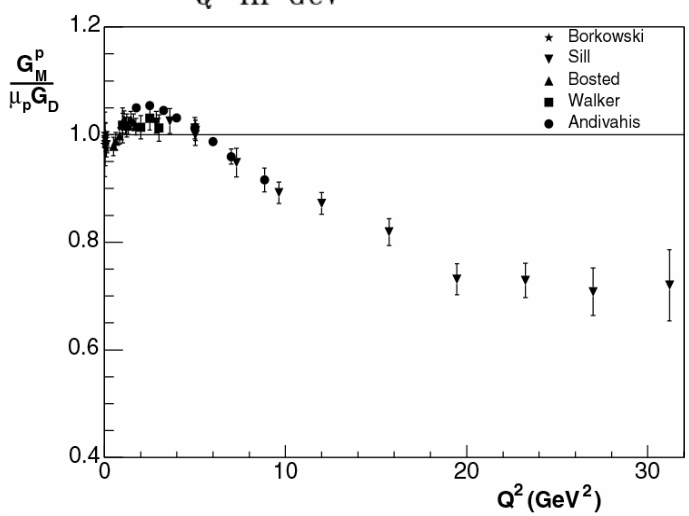
Proton | **Neutron**

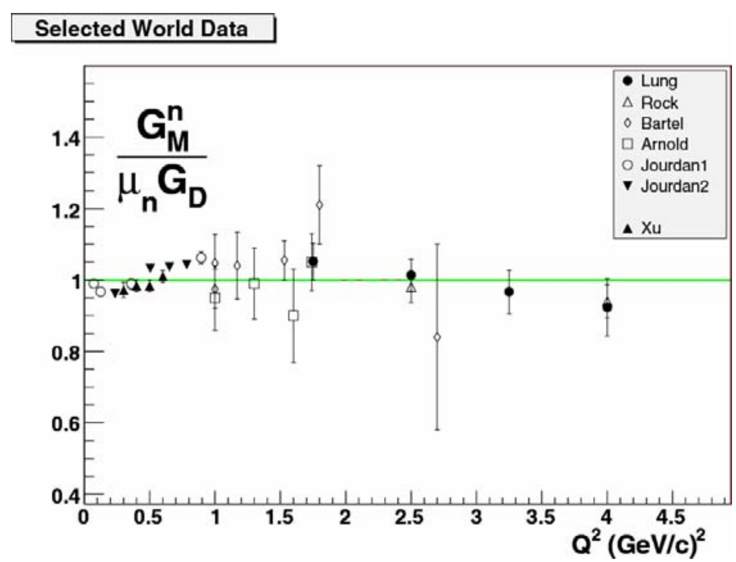
Electric





Magnetic





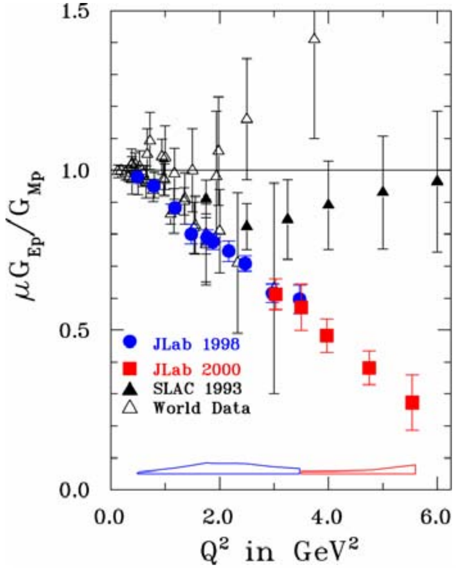
JLab data on the EM form factors provide a testing ground for theories constructing nucleons from quarks and glue

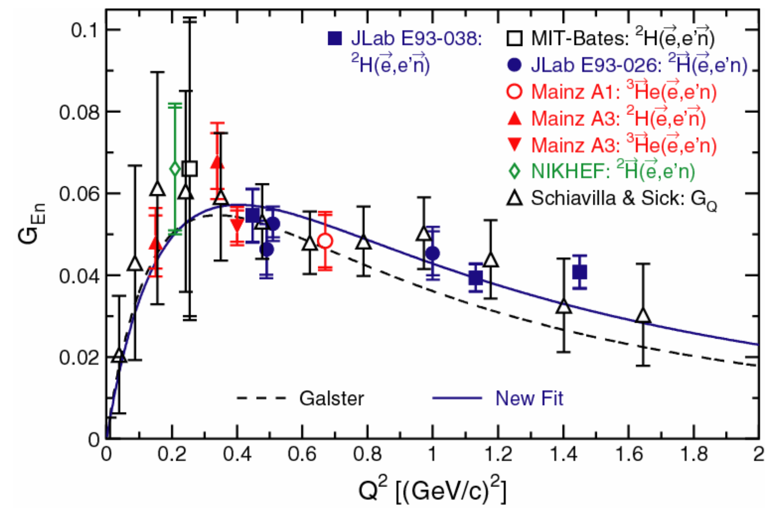
Today

Proton

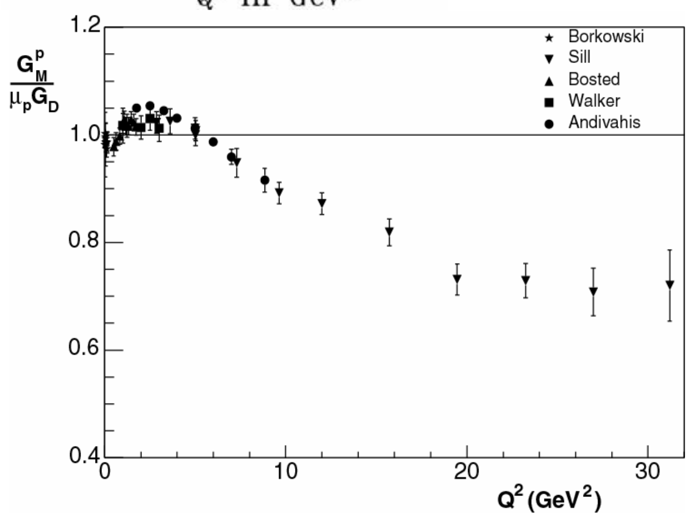
Neutron

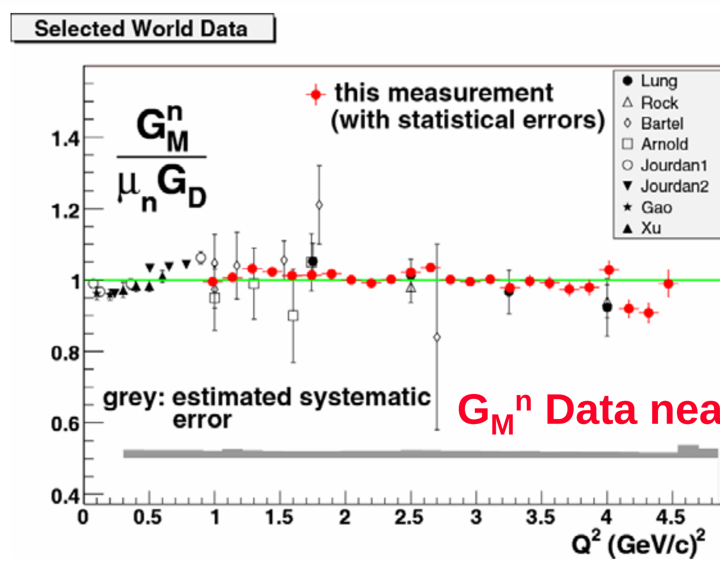
Electric





Magnetic





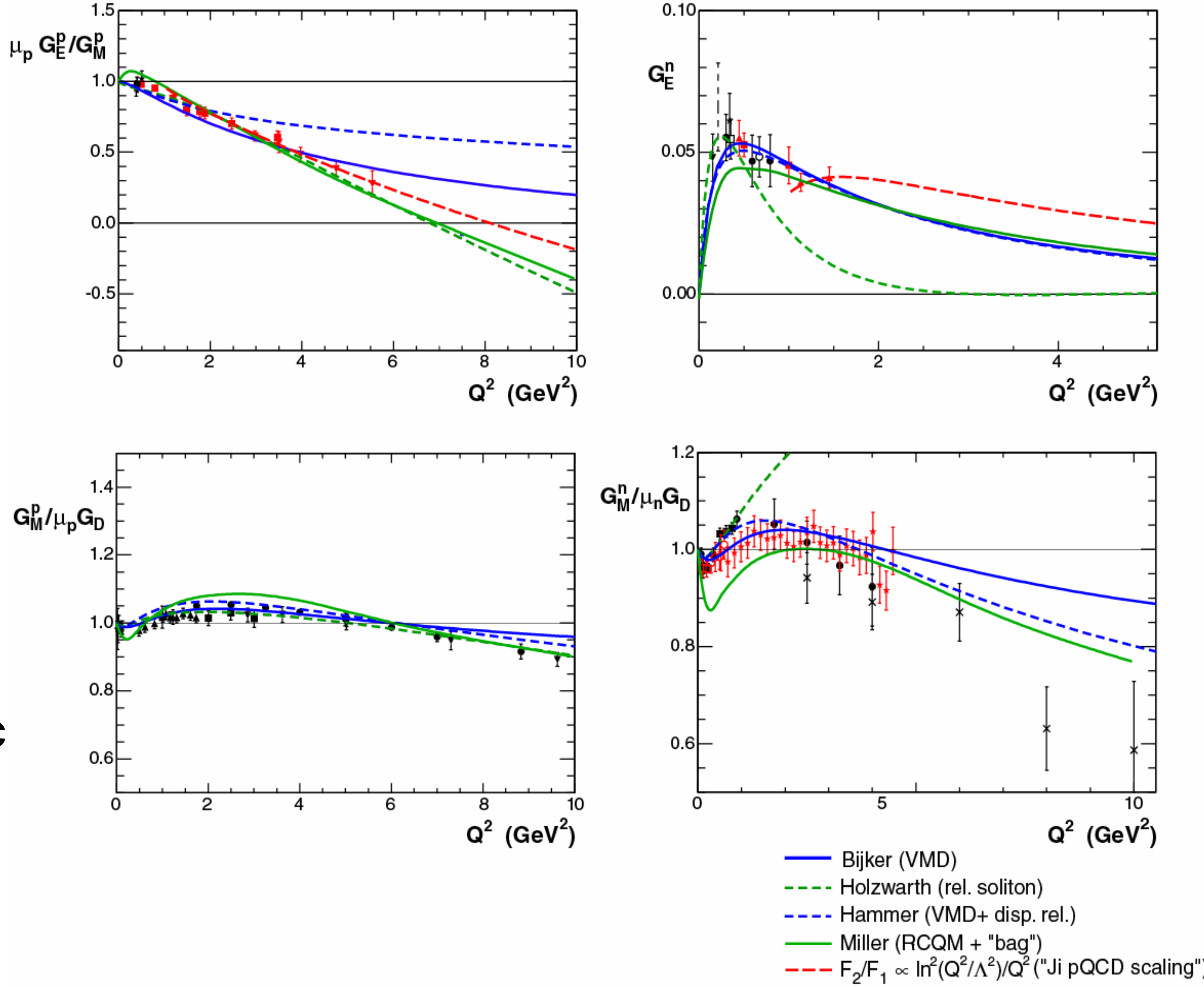
G_M^n Data nearly final

Data have had a substantial impact on our theoretical understanding of hadron structure

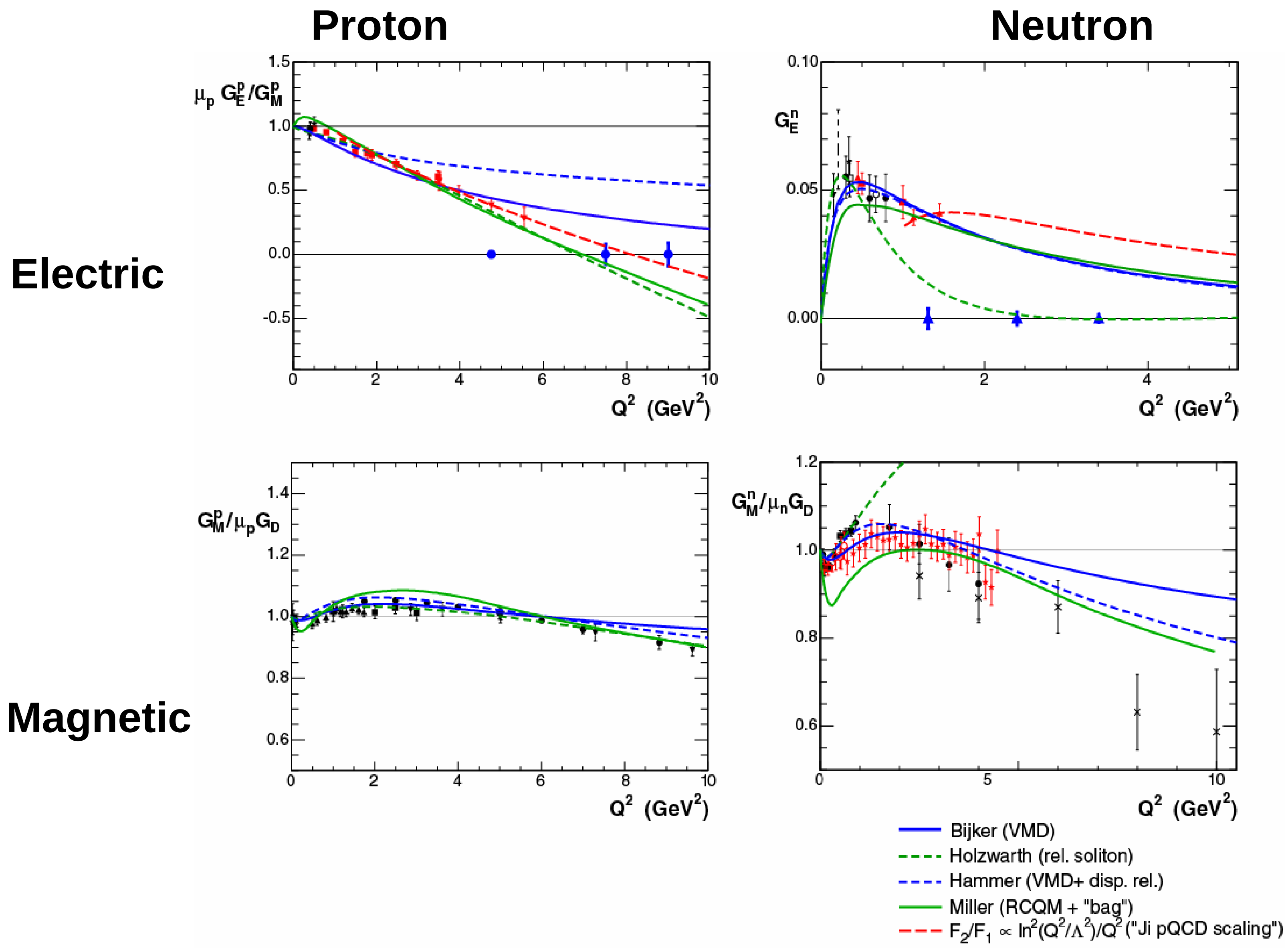
Proton | **Neutron**

Electric

Magnetic



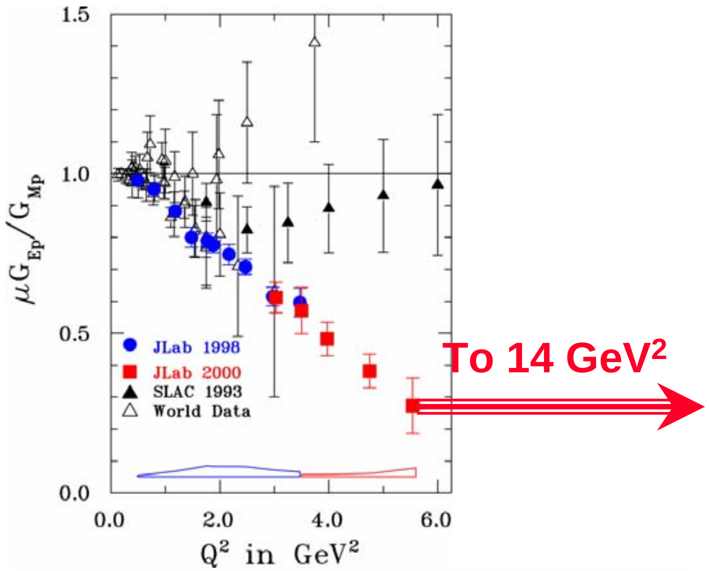
Planned extensions w/ 6 GeV beam will further refine our understanding

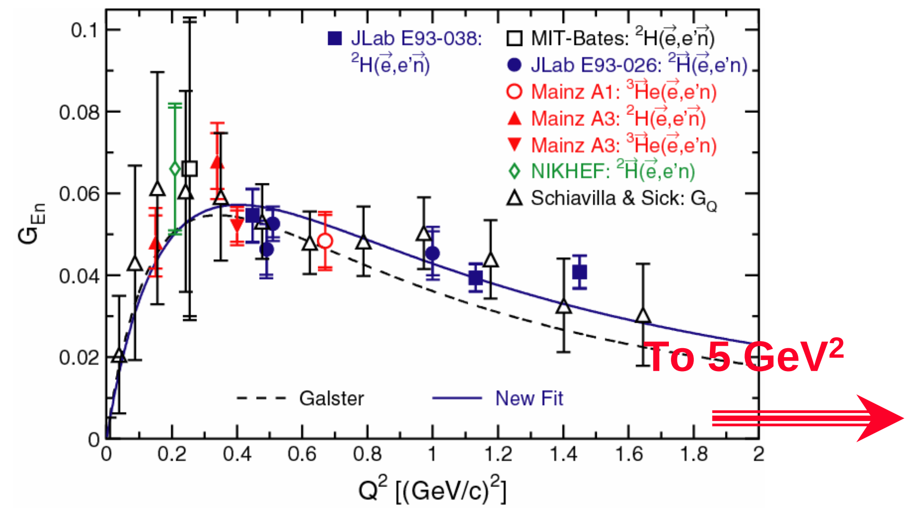


… and the 12 GeV Upgrade will extend these data to even smaller distance scales

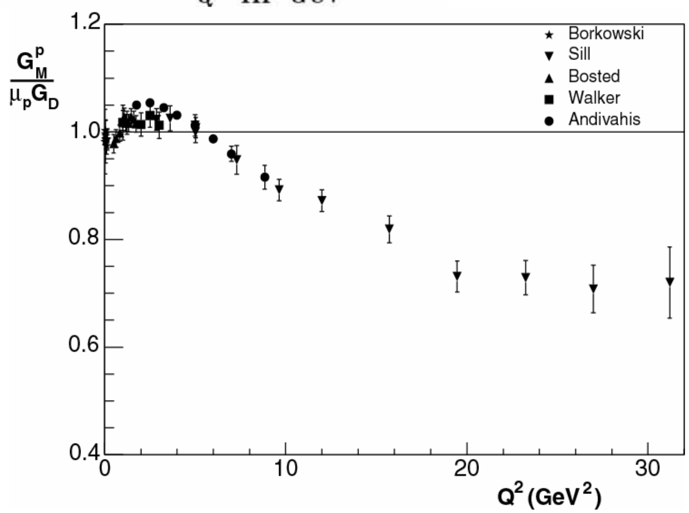
Proton | **Neutron**

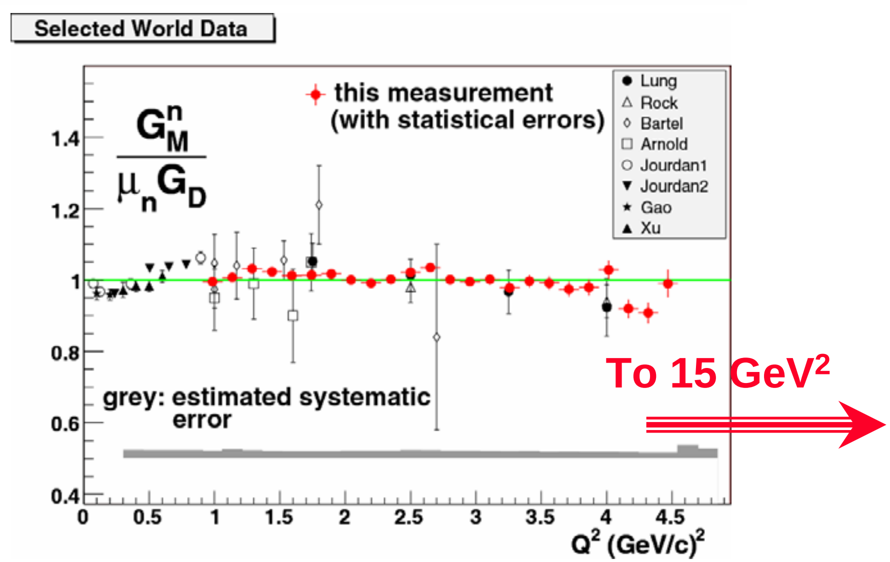
Electric





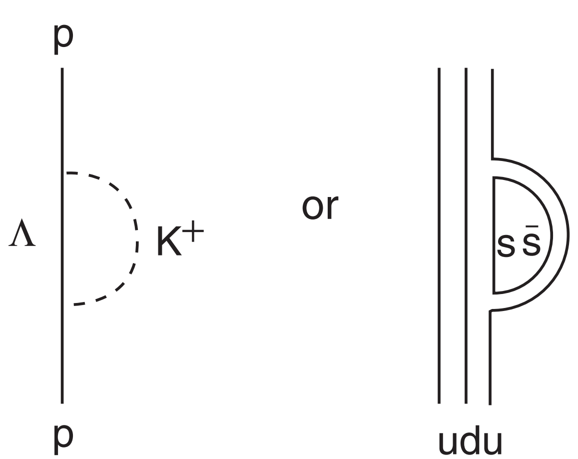
Magnetic



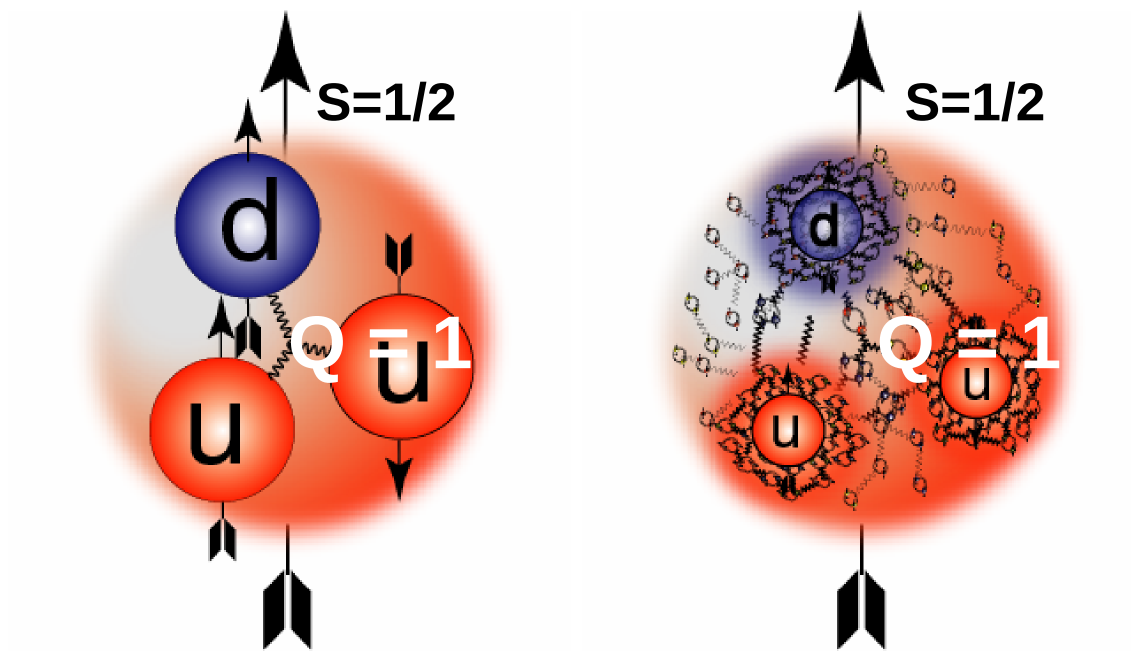


Measurements of the Strange Quark Distribution Are Providing a Unique New Window into Hadron Structure

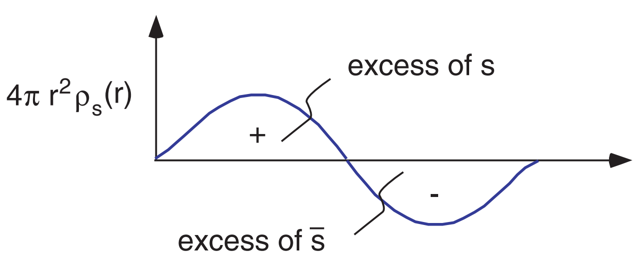
$S_p = 0$ But $\rho_s(r) \neq 0$



Unlike G_E^n, the $s\bar{s}$ pairs come uniquely from the sea; there is no "contamination" from pre-existing u or d quarks



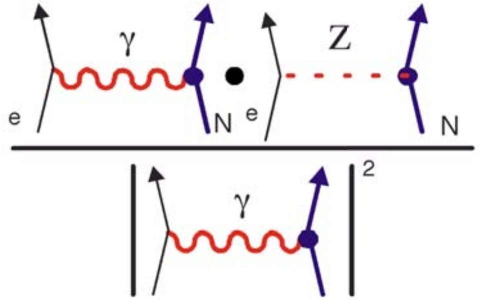
As is the case for G_E^n, the strangeness distribution is very sensitive to the nucleon's properties



Strange Quark Currents in the Nucleon G_E^s, G_M^s

Polarized Electron
Unpolarized Target

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



For a Nucleon:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^e}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}$$

forward angles
HAPPEX, Mainz, G^0: sensitive to

G_E^s and G_M^s

backward angles
SAMPLE, G^0: sensitive to

G_M^s and G_A^e

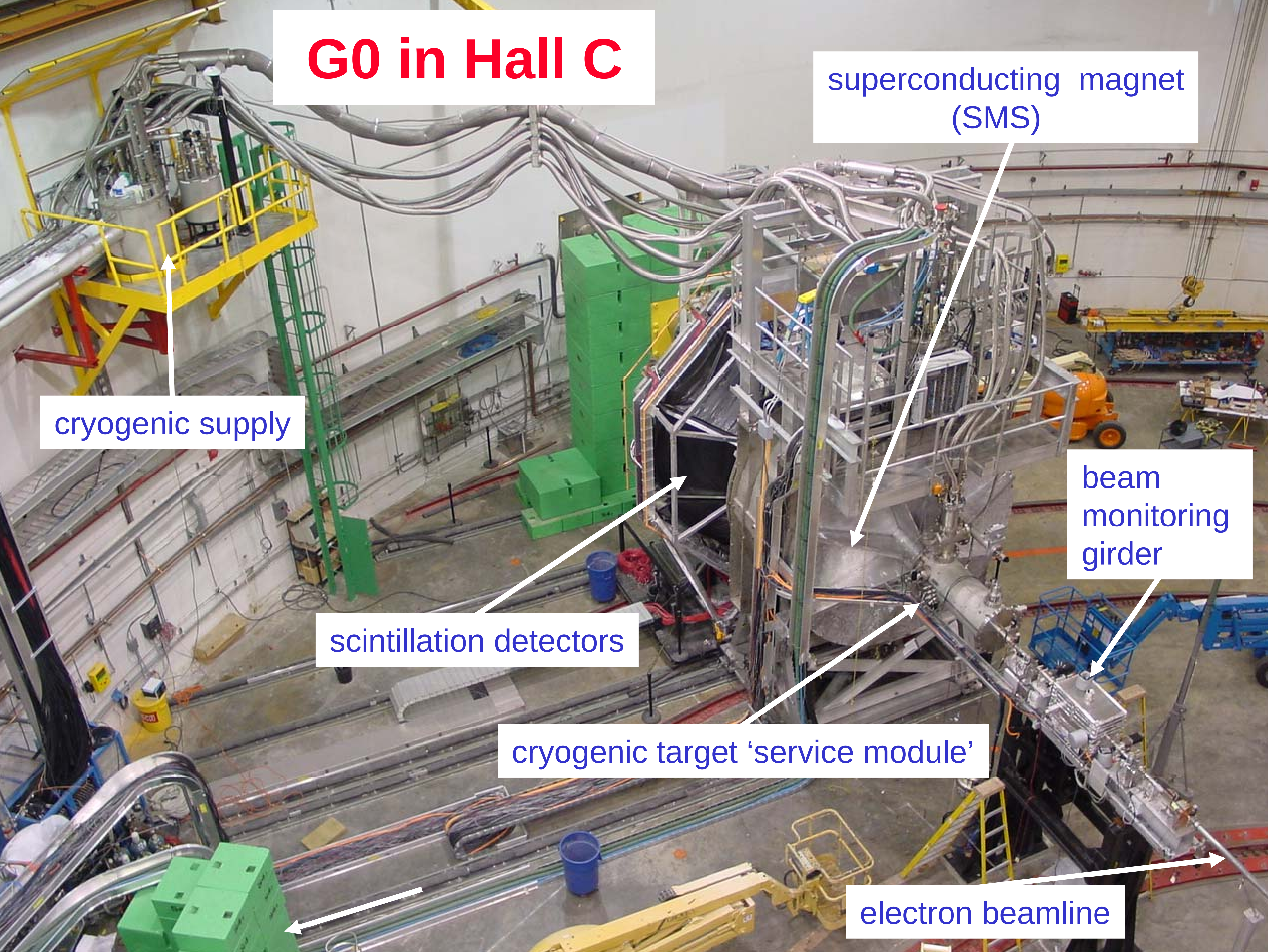
weak charge
of the proton

Q^p_{weak}

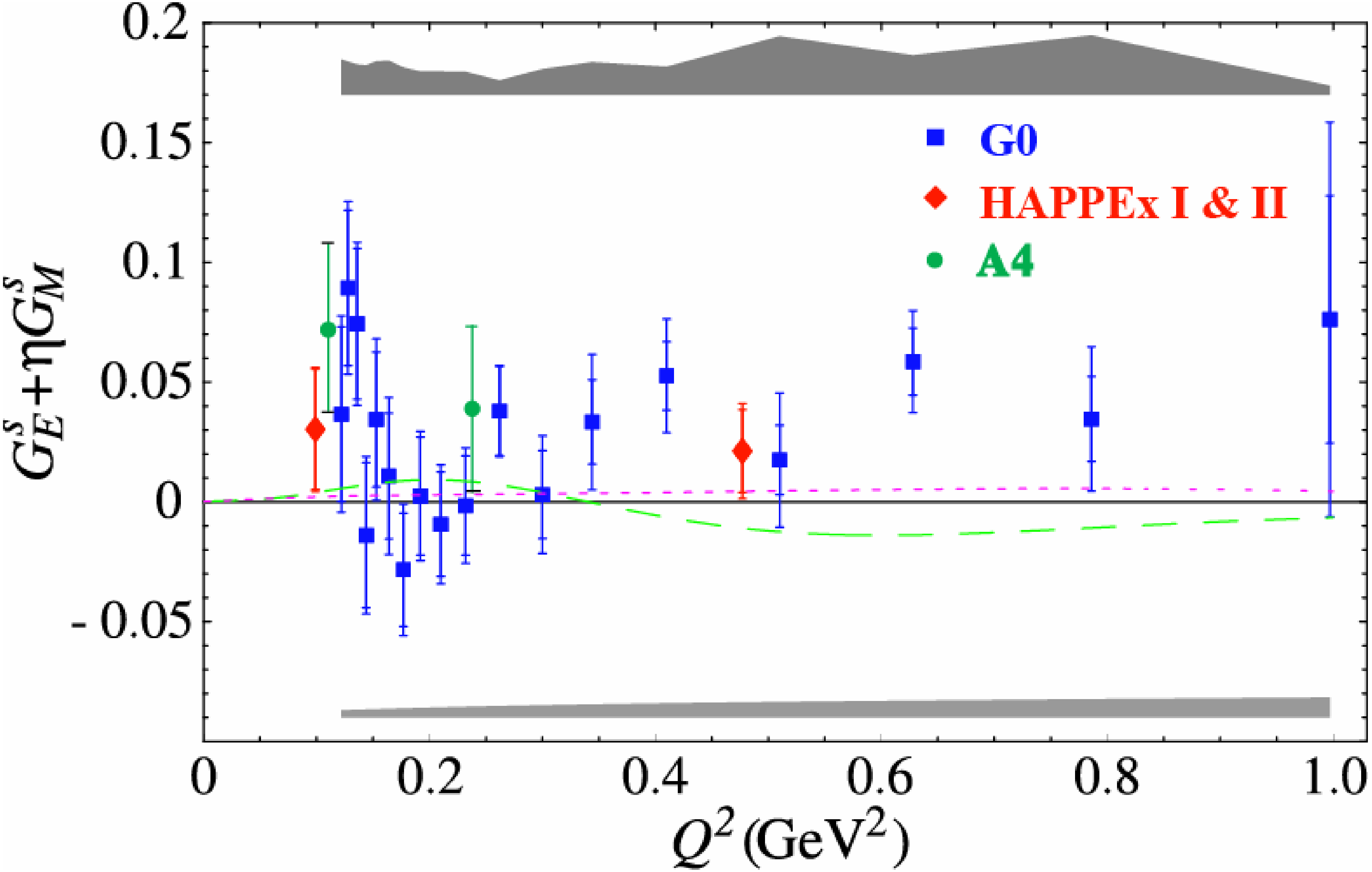
$\varepsilon = 1 / [1 + 2(1+\tau)\tan^2 \theta/2]$ $\varepsilon' = [\tau (1+\tau)(1-\varepsilon^2)]^{-1/2}$

$\tau = Q^2/4m^2$ Q^2 is the four momentum transfer

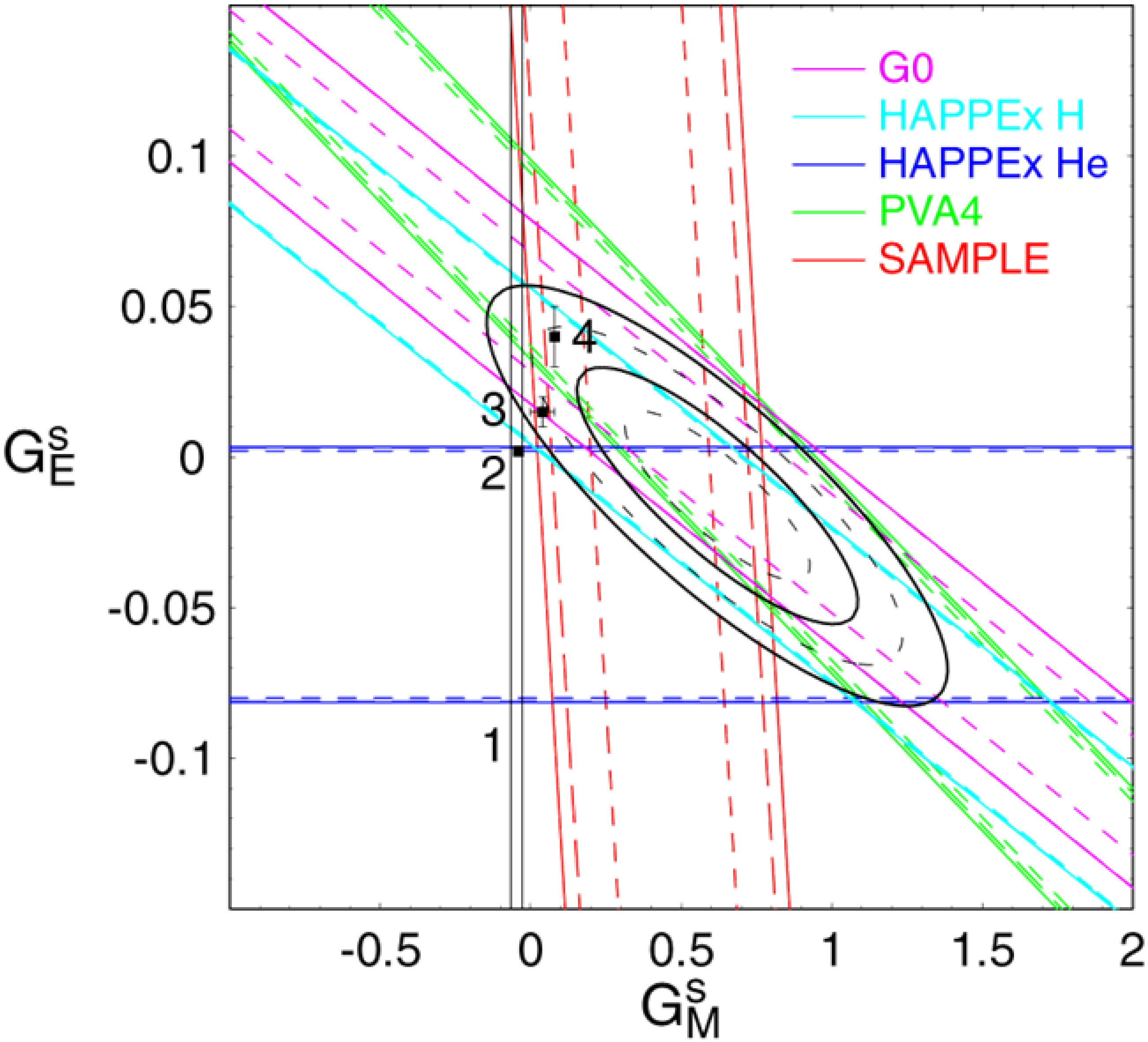
θ is the laboratory electron scattering angle


G0 in Hall C
superconducting magnet (SMS)
cryogenic supply
beam monitoring girder
scintillation detectors
cryogenic target 'service module'
electron beamline

Strange Quark Contribution to Proton



World Data @ $Q^2 = 0.1\ GeV^2$



$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31$

$\pm 0.62\ 2\sigma$

Contours

- - - - 1σ, 2σ

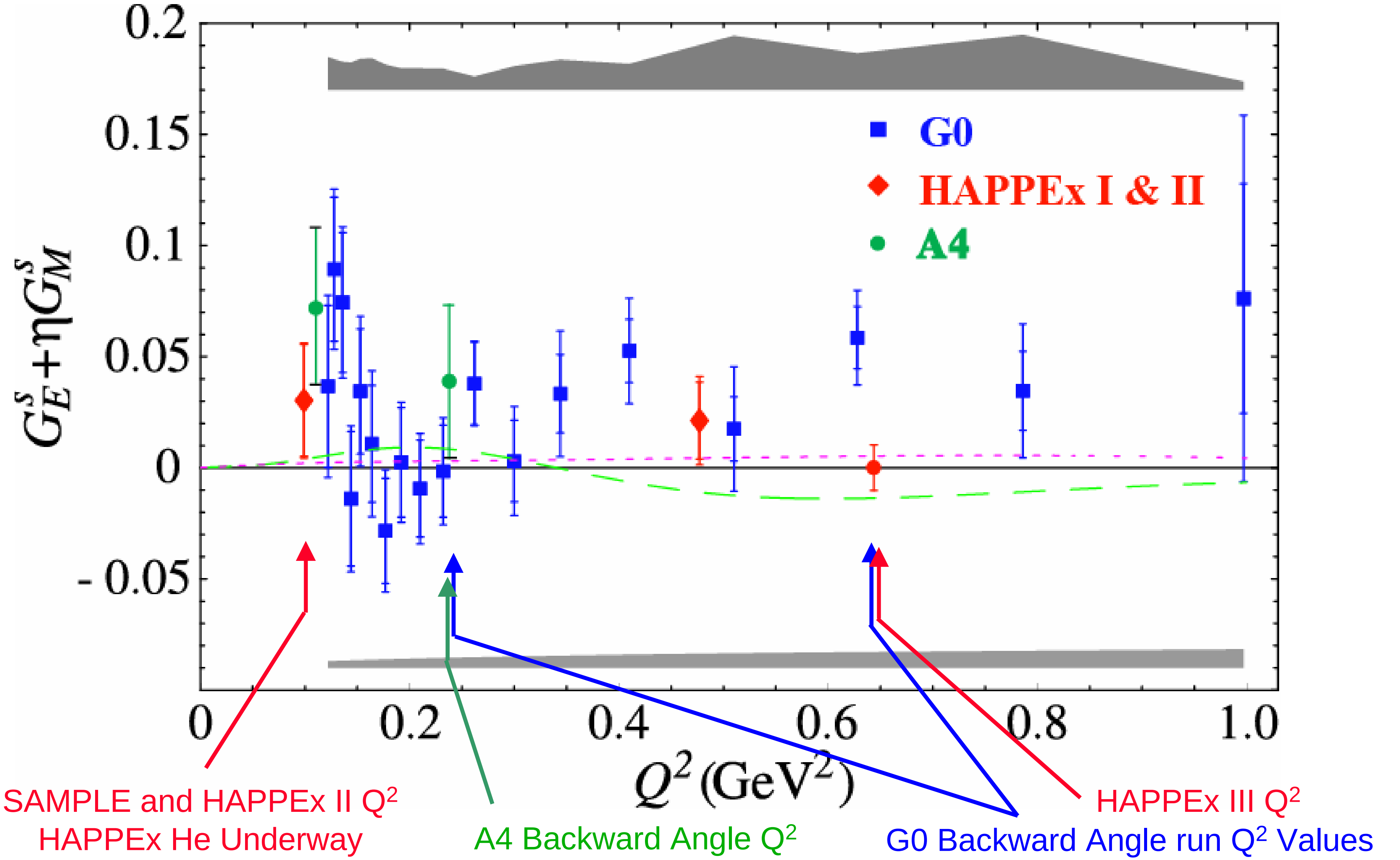
—— 68.3, 95.5% CL

Theories

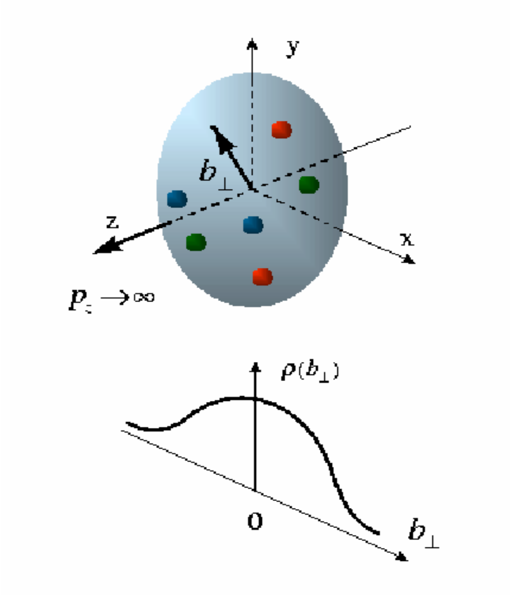
1. Leinweber, et al. PRL **94** (05) 212001
2. Lyubovitskij, et al. PRC **66** (02) 055204
3. Lewis, et al. PRD **67** (03) 013003
4. Silva, et al. PRD **65** (01) 014016

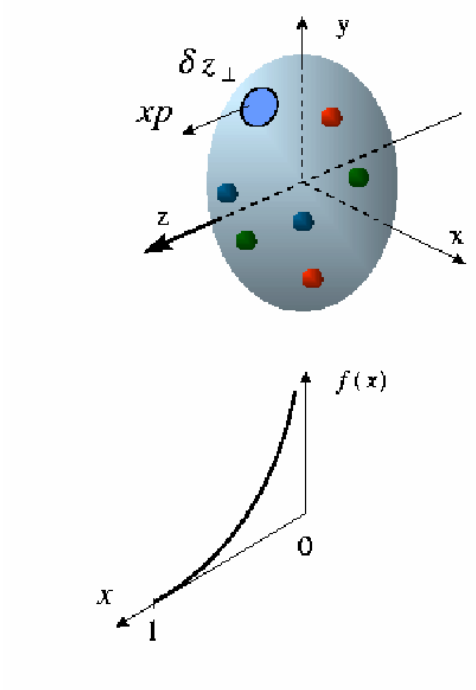
http://www.npl.uiuc.edu/exp/G0/Forward

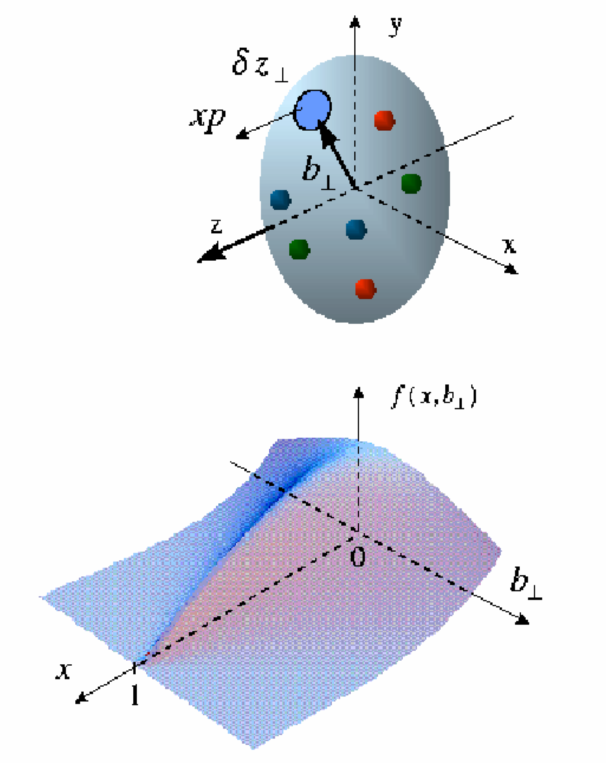
Plans to Extend the Data Set



The Next Generation of Proton Structure Experiments





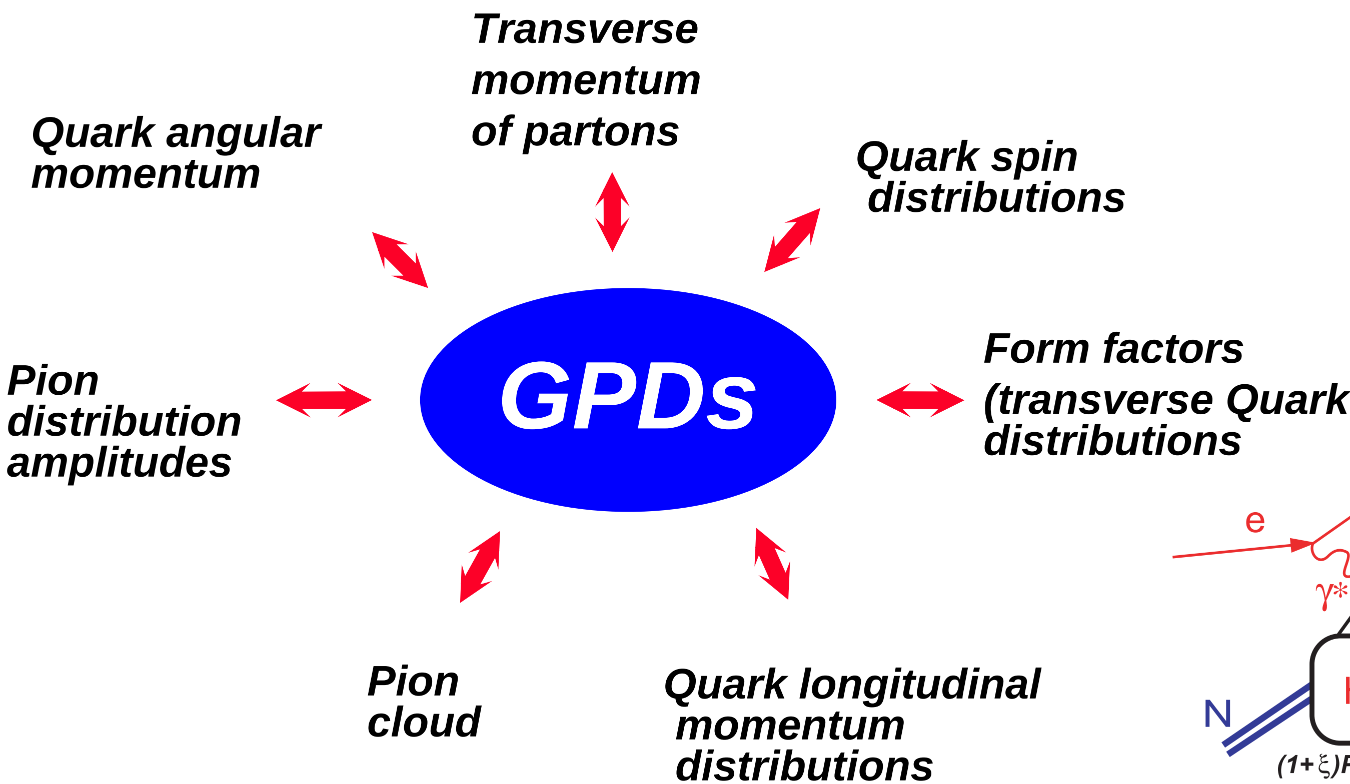


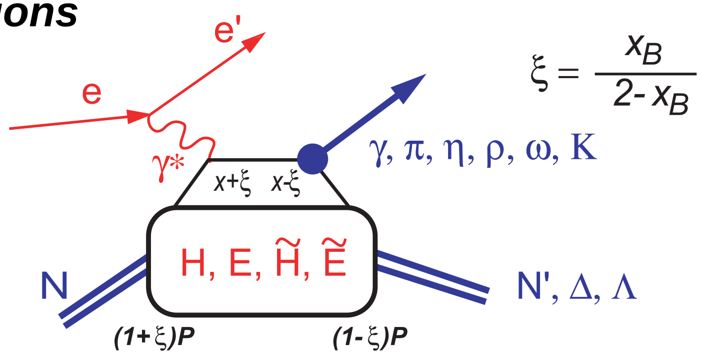
Elastic Scattering
transverse quark distribution in Coordinate space

DIS
longitudinal quark distribution in momentum space

DES (GPDs)
The fully-correlated Quark distribution in both coordinate and momentum space

Developing a Unified Description of Hadron Structure via the Recently Devised Generalized Parton Distributions

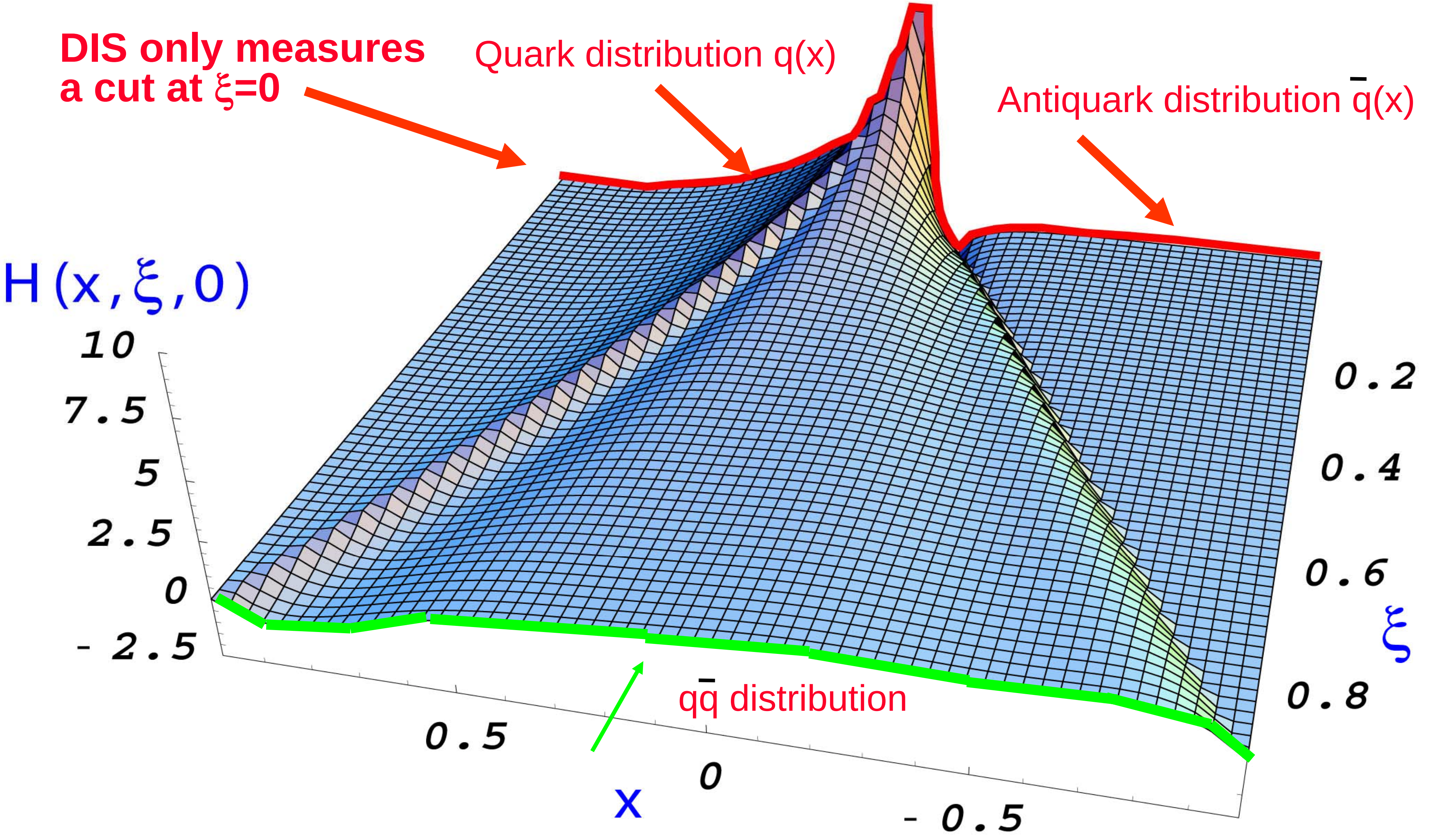




H, E - unpolarized, H̃, Ẽ - polarized GPD

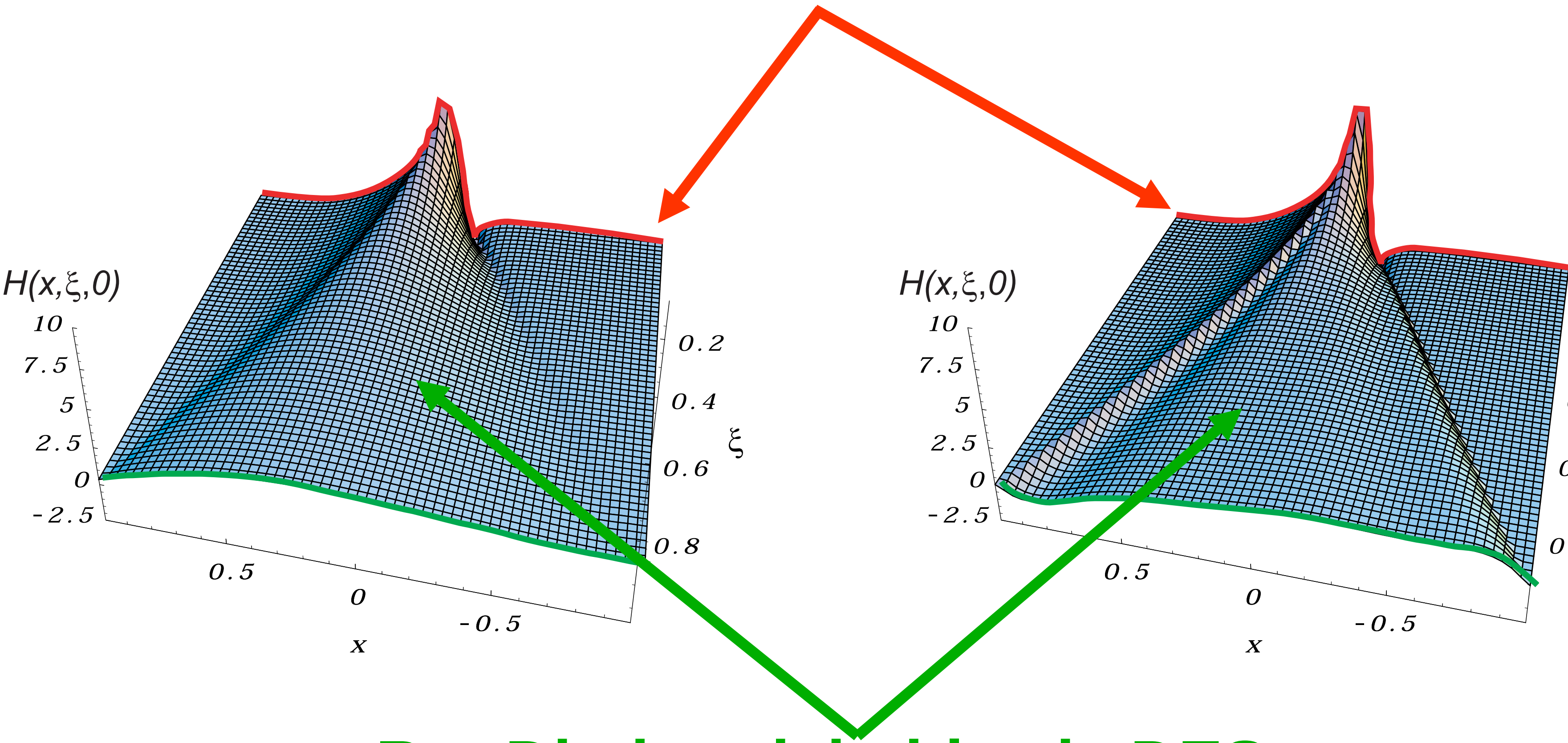
The GPDs Define Nucleon Structure

Generalized Parton Distributions Contain Much More Information than DIS



……that Provides Direct Access to the Quark Correlations in the Nucleon

Nucleon Structure Models with Very Different Correlations Can Be Identical in DIS



But Distinguishable via DES

1. How are the Nucleons Made from Quarks and Gluons?

Why are nucleons interacting via V_{NN} such a good approximation to nature?

How do we understand QCD in the confinement regime?

A. What are the spatial distributions of u, d, and s quarks in the hadrons?

- G_E^p/G_M^p (3 techniques); higher Q^2 coming
- G_E^n (2 expts in Hall C; higher Q^2 coming) G_M^n (Hall A; CLAS to high Q^2)
- G_M^n to high Q^2 (CLAS)
- HAPPEX, G0 forward angle, w/ G0 backward angle & HAPPEX II coming
- F_π (new data to 5.75 GeV; w/ future extension at 12 GeV)

B. What is the excited state spectrum of the hadrons, and what does it reveal about the underlying degrees of freedom?

- $N \rightarrow \Delta$ (All three halls)
- Higher resonances (CLAS e1: η, π^0, $\pi^\pm$ production)
- Missing resonance search (CLAS e1 and g1: ρ, ω production
- VCS in the resonance region (Hall A)

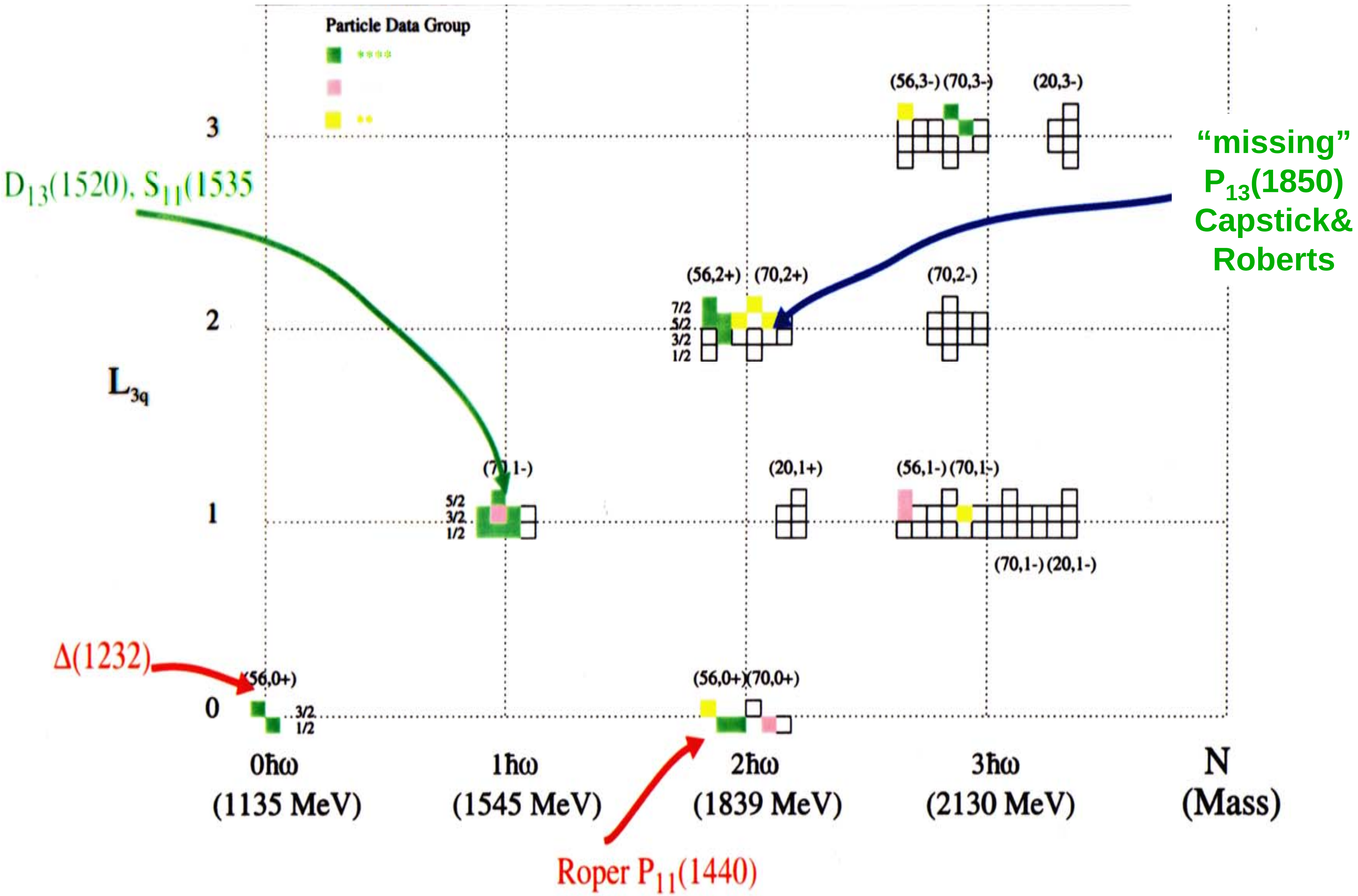
C. What is the QCD basis for the spin structure of the hadrons?

- Q^2 evolution of GDH integral and integrand for:
  - proton (CLAS) and neutron (Hall A) (w/ low Q^2 extensions coming for neutron)
- A_1^n, g_2^n w/ 12 GeV follow-on (Hall A)
- A_1^p (Hall C, CLAS)

D. What can other hadron properties tell us about 'strong' QCD?

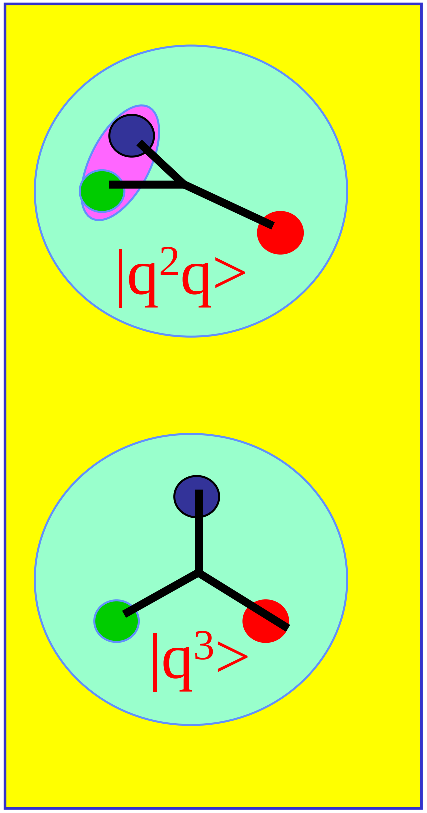
- VCS (Hall A)
- DVCS (CLAS, Hall A & CLAS coming)
- Compton Scattering (Hall A)
- Separated Structure Functions (Hall C)
- Single Spin Asymmetries (CLAS, Hall A coming)

The Search for "Missing States" in the Quark Model Classification of N*



“Missing” Resonances?

Problem: symmetric CQM predicts many more states than have been observed (in πN scattering)



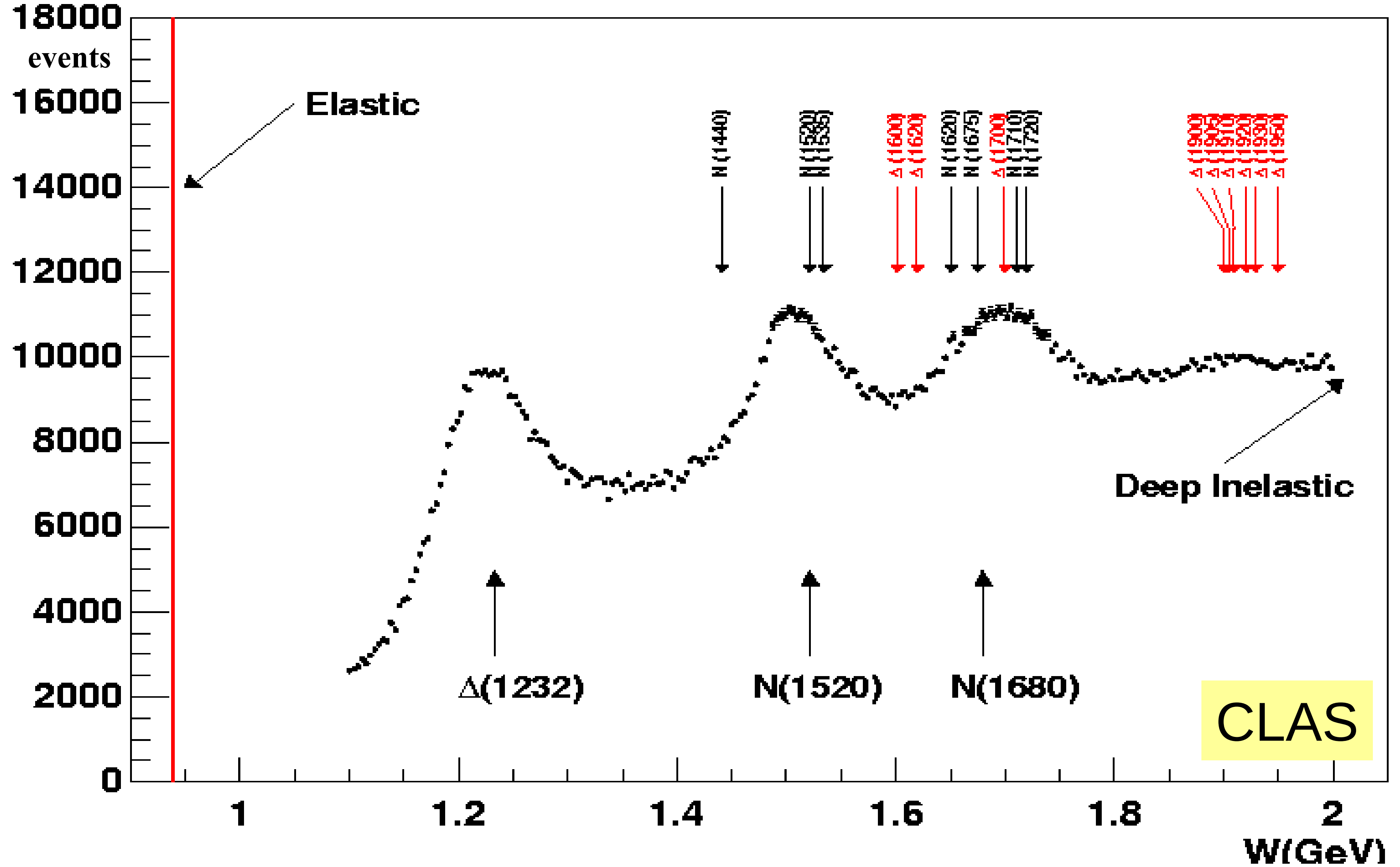
Two possible solutions:

1. di-quark model
   fewer degrees-of-freedom
   open question: mechanism for q^2 formation?

2. not all states have been found
   possible reason: decouple from πN-channel
   model calculations: missing states couple to
   $N\pi\pi$ ($\Delta\pi$, $N\rho$), $N\omega$, KY

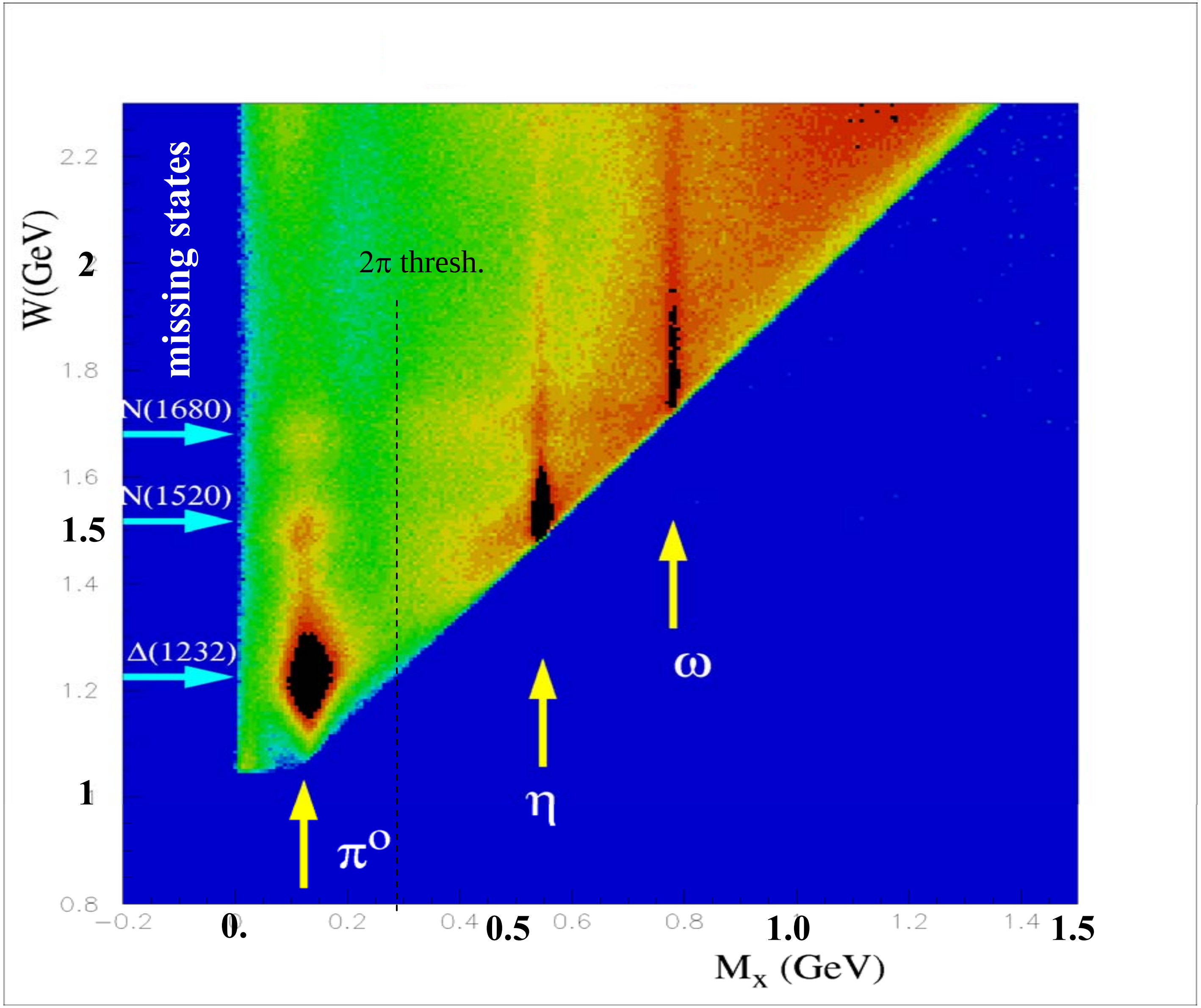
γ coupling not suppressed $\rightarrow$ electromagnetic excitation is ideal

e p → e X at 4 GeV

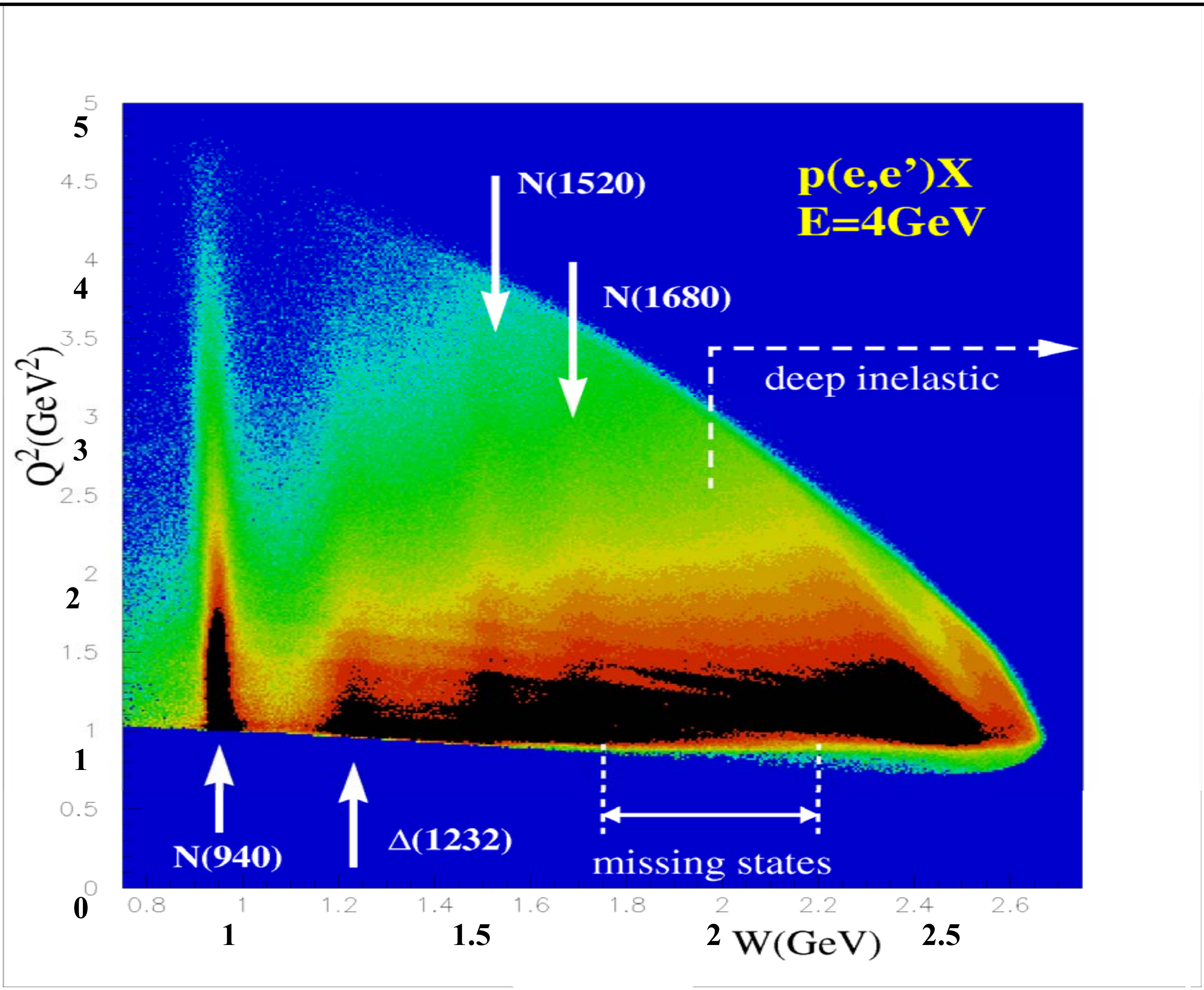


18000
events
16000
14000
12000
10000
8000
6000
4000
2000
0
Elastic
N(1440)
N(1520)
N(1535)
Δ(1600)
Δ(1620)
N(1620)
N(1675)
Δ(1700)
N(1710)
N(1720)
Deep Inelastic
Δ(1232)
N(1520)
N(1680)
CLAS
1
1.2
1.4
1.6
1.8
2
W(GeV)

CLAS: ep → epX, E = 4GeV



CLAS Coverage for ep → e'X E = 4 GeV



Tentative Discoveries of New N* States with CLAS Data

Mass (MeV) $L_{2I,2J}$	Reactions used	Data from CLAS (%)	Analysis techniques & group	* Ratings (V. Burkert subjective)	State expected in model ?	Comments
1720±15MeV Γ ~ 90 MeV P_{13} or P_{33}	$ep \rightarrow ep\pi^+\pi^-$ $\gamma p \rightarrow p\pi^+\pi^-$	100%	JLab-MSU Dynamical Isobar Model	***	Large N_c spectroscopy $[70,2^+]$	Could be first state from Large N_c Needs confirmation
$1840 \pm ^{15}_{40}$ Γ=140 MeV P_{11}	$\gamma p \rightarrow K^+\Lambda$ $\gamma p \rightarrow K^{+/0}\Sigma$	> 60%	CC PWA	***	$[Q^3]$ - yes $[Q^2Q]$ - no	*If confirmed, would kill $[Q^2Q]$ model*
1875 ± 25 D_{13}	$\gamma p \rightarrow K^+\Lambda$ $\gamma p \rightarrow K^{+/0}\Sigma$	> 60%	CC PWA	**	$[Q^3]$ – no	$[Q^3]$ predicts higher mass D_{13} states
$2170 \pm ^{25}_{50}$ D_{13}	$\gamma p \rightarrow K^+\Lambda$ $\gamma p \rightarrow K^{+/0}\Sigma$	> 60%	CC PWA	**	$[Q^3]$ - yes	[Q3] predicts several D_{13} with close masses
~1800 S_{11}	$\gamma p \rightarrow p\eta$ $\gamma p \rightarrow K^+\Lambda$	> 75%	Chiral CQM analysis	*	ChQM - yes $[Q^3]$ - no	Could P_{11} seen in $K\Lambda$, $K\Sigma$?
Various states S_{11}, P_{11}, D_{13}, P_{13} seen in some analysis	$\gamma p \rightarrow K^+\Lambda$ $\gamma p \rightarrow K^{+/0}\Sigma$	> 75%	Kaon MAID	*	Some expected in $[Q^3]$	Masses of higher mass states not stable

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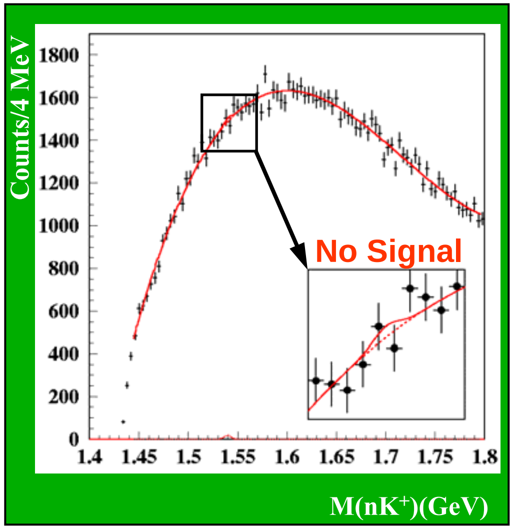
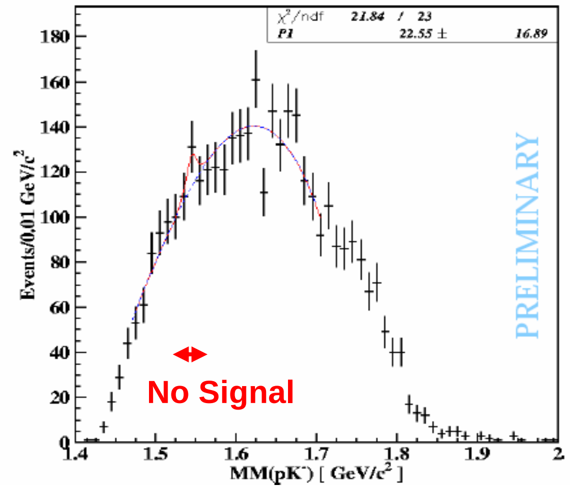
Searches for Pentaquark Baryons

- Broad program to search for the $\Theta^+(1540)$ and possible partners
  - E03-113 $\gamma D \rightarrow> K^+K^-pn$ (K. Hicks)
  - E04-021 $\gamma p \rightarrow K_sK^+n$, … (M. Battaglieri)
  - E04-010 $\gamma D \rightarrow \Xi^{--} X$, .. (E. Smith)
  - E04-005 $\gamma p \rightarrow X$ (D. Weygand)
  - E04-012 $\gamma^* p \rightarrow K+x$ (P. Reimer, B. Wojtsekhowski)
  - E05-009 $\gamma^* n \rightarrow K^-K^+n$ (G. Cates et al)
- 3 CLAS and one Hall A experiments have data; results from Hall A; preliminary results from 2 CLAS experiments

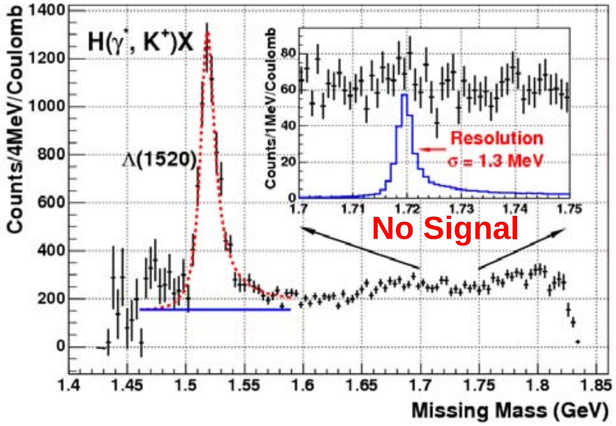
$\gamma\, p \rightarrow K_sK^+n$



$\gamma\, D \rightarrow K^+K^-\, pn$



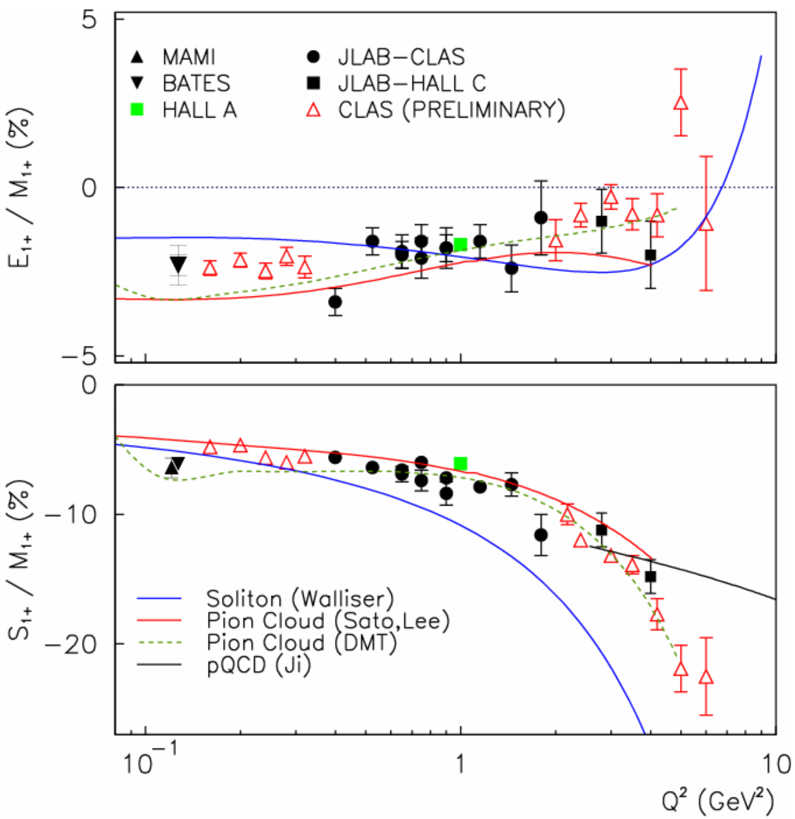
$\gamma^*\, p \rightarrow K^+\, x$



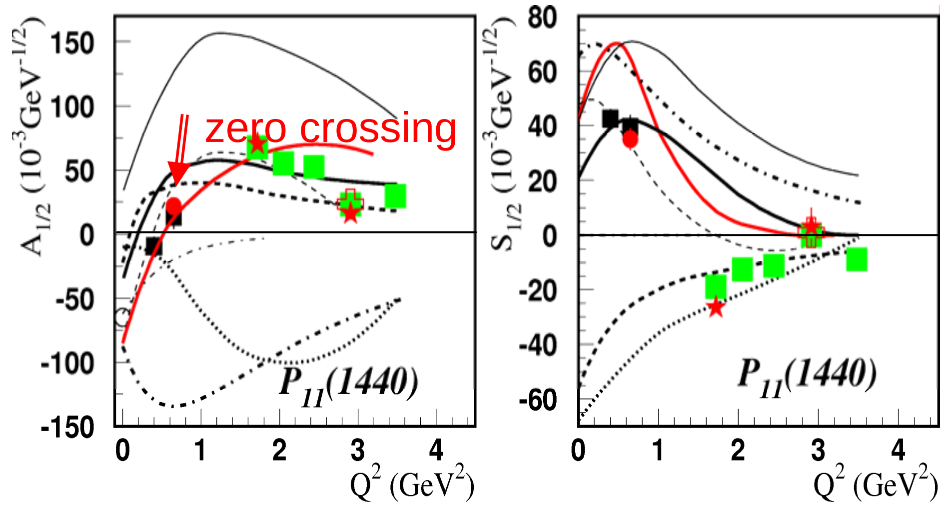
E04-005 will provide additional information parasitically as part of a CLAS high energy photo- production study, and E05-009 (in Hall A) with significantly higher resolution and luminosity over a narrow range, providing greater sensitivity

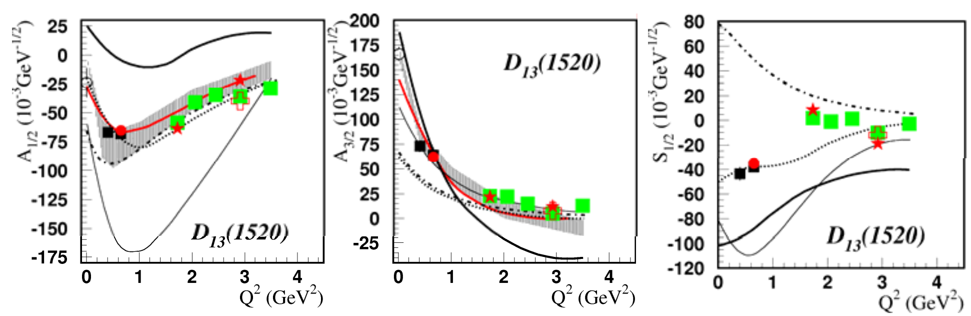
Transition Form Factors are Elucidating Nucleon Structure

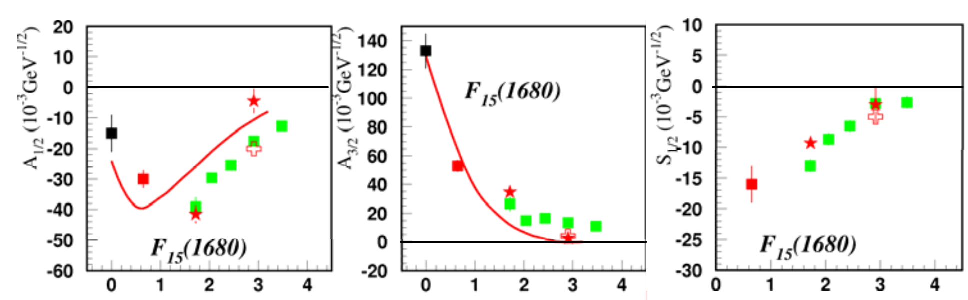
N-Δ
(revealed the importance of the pion cloud)



Roper
(saw "through" the pion cloud to the CQM core)







The same analysis is now being applied to accesses the transition form factors of other nucleon resonances with large Nπ coupling ($S_{11}(1535)$, $D_{13}(1520)$, $F_{15}(1680)$), with more to come

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Transition Form Factors
Pentaquark Searches

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- Single Spin Asymmetries (CLAS, Hall A coming)

Spin Integrals Are Constrained at Extremes of Distance Scales by Sum Rules

Bjorken Sum Rule ($Q^2 \to \infty$):

Basic assumptions: Isospin symmetry

Current Algebra or Operator Product Expansion within QCD

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \int \{ g_1^p(x,Q^2) - g_1^n(x,Q^2) \} dx = \frac{1}{6} g_A C_{NS}, \text{ as } Q^2 \to \infty$$

$g_A = 1.2601 \pm 0.0025$ neutron β-decay coupling constant

C_{NS} Q^2-dependent QCD correction ($\to 1$ as $Q^2 \to \infty$)

GDH Sum Rule ($Q^2 \to 0$):

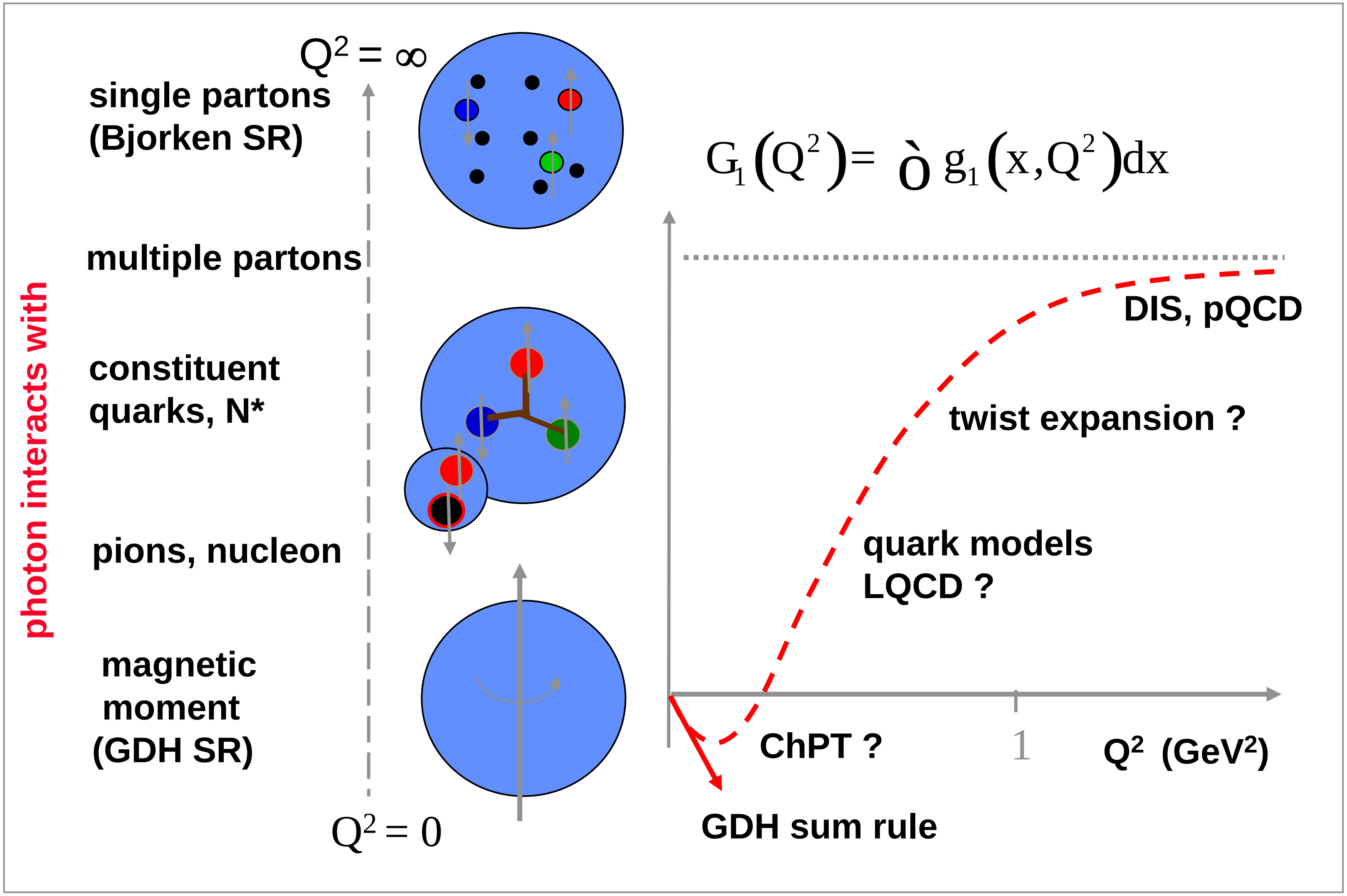
Basic assumptions: Lorentz invariance, gauge invariance, unitarity

Dispersion relation applied to forward Compton amplitude

$$\int_{\nu_{in}}^{\infty} \left(\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu) \right) \frac{d\nu}{\nu} = -\frac{2\pi^2 \alpha_{EM}}{M^2} \kappa^2$$

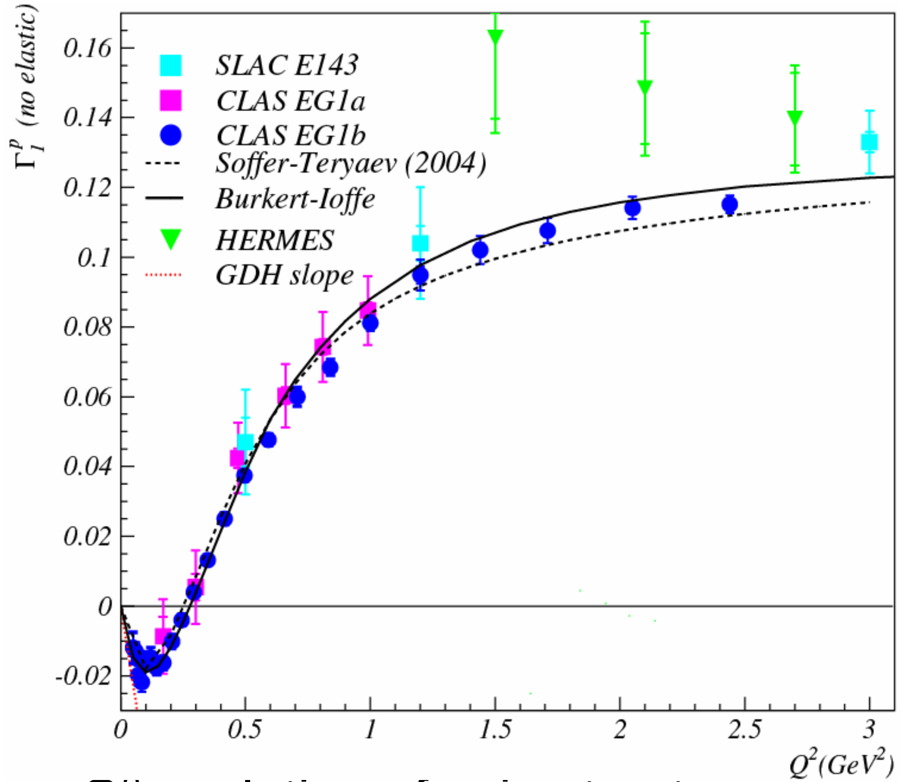
κ = nucleon anomalous magnetic moment

Anticipated Evolution of the Moment of the Proton Spin Structure Function with Distance Scale

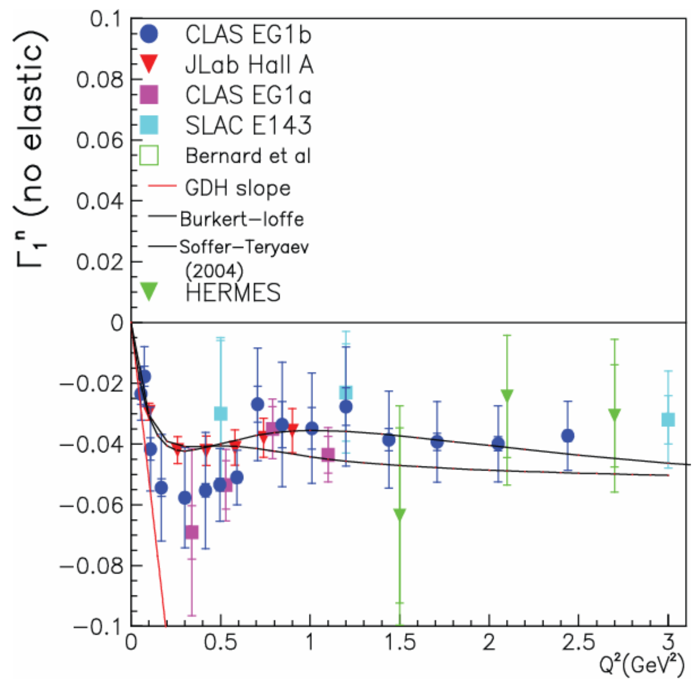


Spin Structure Function Integrals $\Gamma_1 = \int g_1(x,Q^2)dx$

Proton



Neutron



Q^2 evolution of spin structure moments and sum rules:

- Smooth transition from quark-gluon to coherent hadron
- pQCD (OPE, higher twists) at high to intermediate Q^2
- Test Lattice QCD in the transition region

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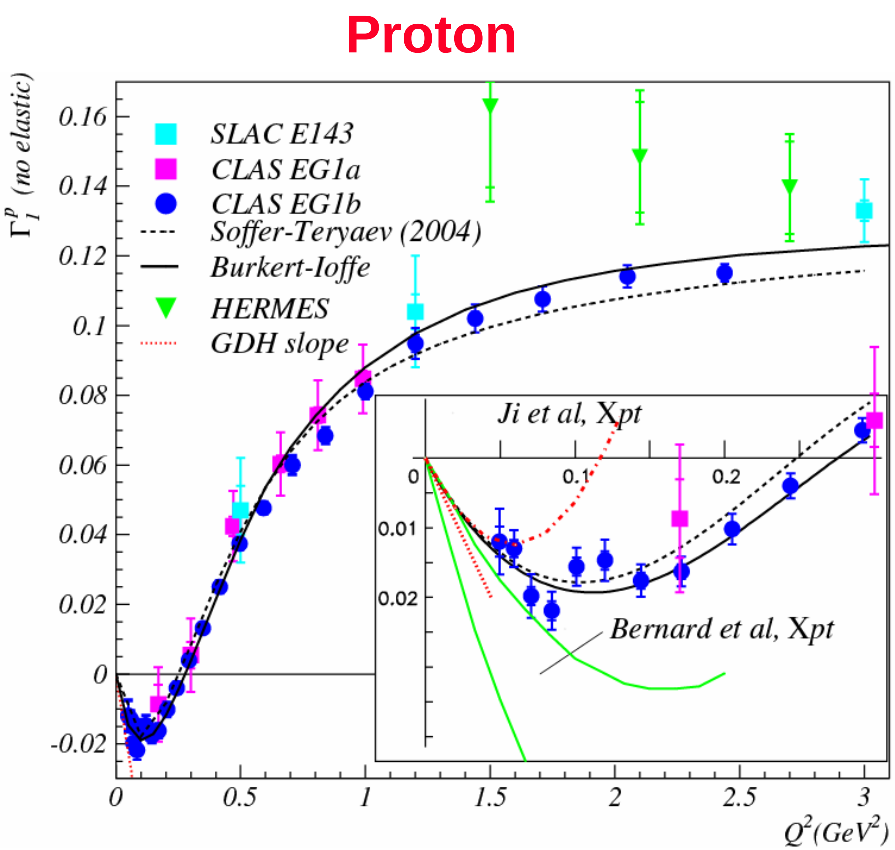
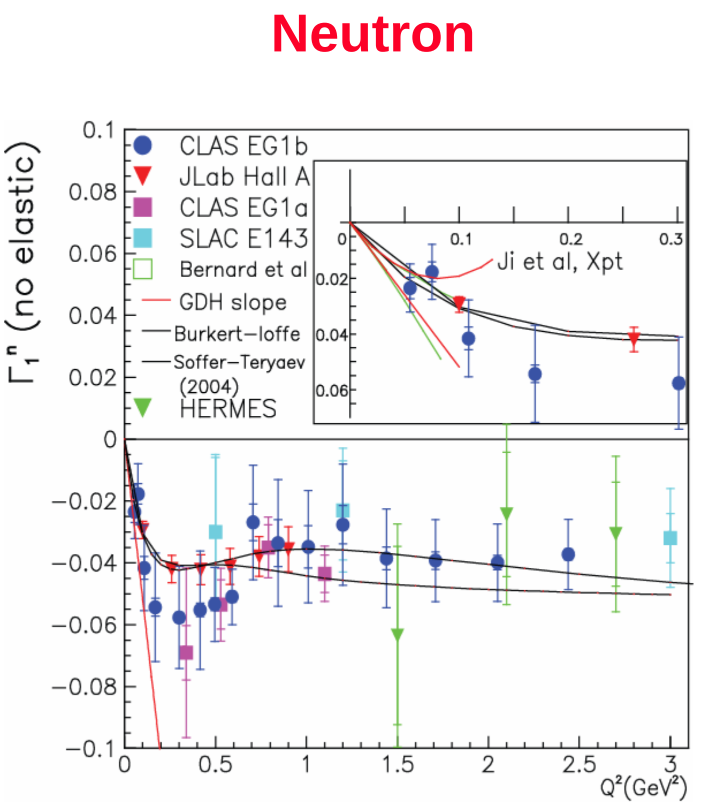




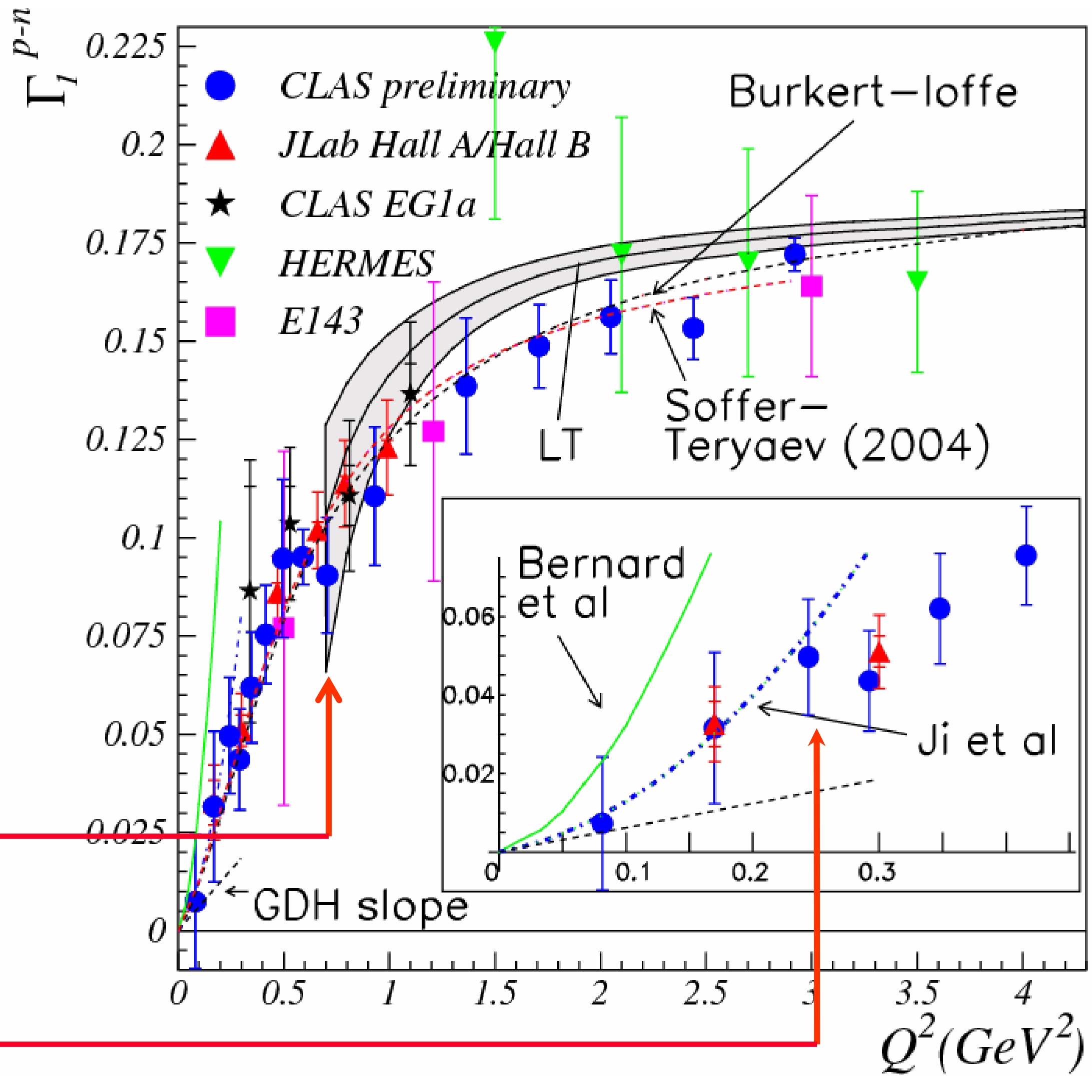
Q^2 evolution of spin structure moments and sum rules:

- Smooth transition from quark-gluon to coherent hadron
- pQCD (OPE, higher twists) at high to intermediate Q^2
- Test Lattice QCD in the transition region
- Test Chiral perturbation theory predictions at low Q^2

Bjorken Integral $\Gamma_1^p - \Gamma_1^n$

- First significant measurement in range Q^2 = 0.05–2.5 GeV^2

Is a fundamental description of the Bjorken integral possible at all distances?



pQCD and OPE seem to work for $Q^2 > 0.75$ GeV^2.

HBχPT compatible with data for $Q^2 < 0.25$ GeV^2

2. What are the mechanism of confinement and the dynamics of QCD?

This program is a "bridge" between campaigns 1 and 2, and contributes coherently to both by directly studying key aspects of strong QCD directly

A. What is the origin of quark confinement?
(Understanding this unique property of QCD is the key to understanding the QCD basis of nuclear physics.)

- Lattice QCD Calculations favor the flux tube model
- Meson spectra will provide the essential experimental data:
  use the "two-body" system to measure V(r), spin dependence
  experimental identification of exotics tests the basic mechanism

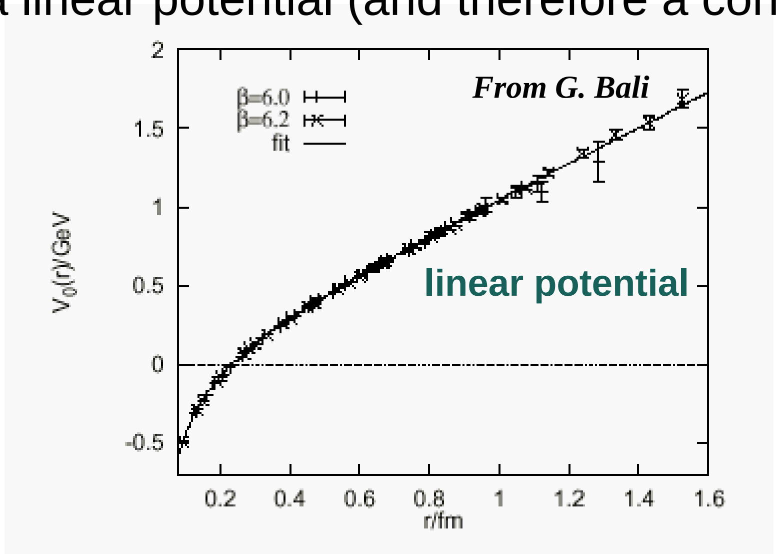
Data from CLAS now and planned,
12 GeV and Hall D are essential to this program

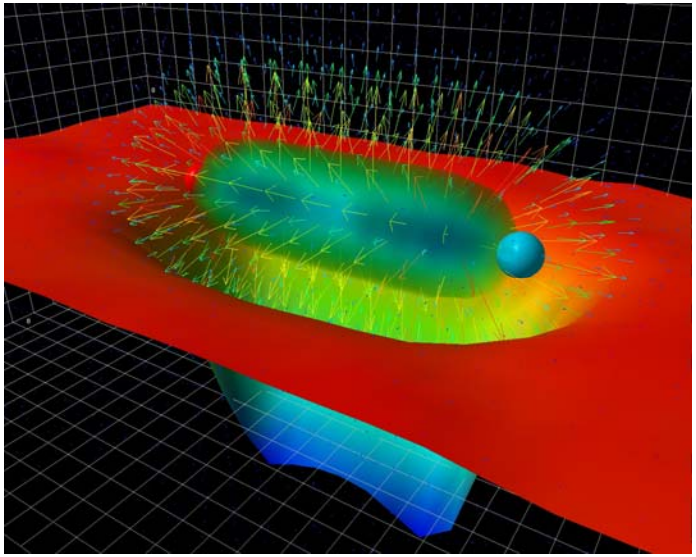
B. Where does the dynamics of the $q\text{-}\bar{q}$ interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime?

F_π (4 GeV so far; 6 GeV data under analysis, then 11 GeV w/ upgrade)
π^+/π^- ratio

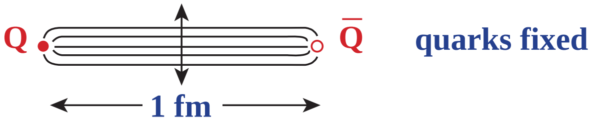
Gluonic Excitations and the Origin of Confinement

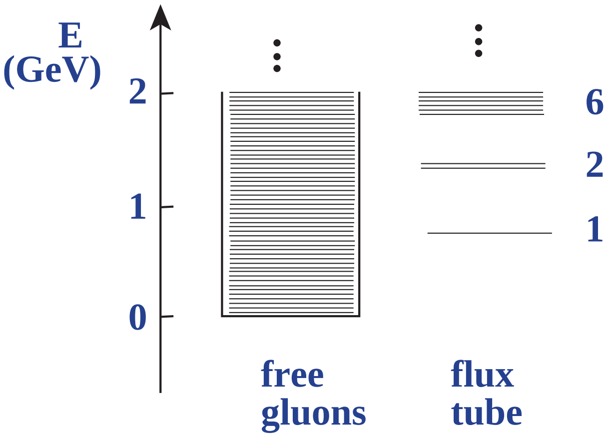
Theoretical studies of QCD suggest that confinement is due to the formation of "Flux tubes" arising from the self-interaction of the glue, leading to a linear potential (and therefore a constant force)





Experimentally, we want to "pluck" the flux tube (wiggle the hot dog?) and see how it responds





The Pion Form Factor

The pion is the simplest QCD bound system – the "positronium" of QCD

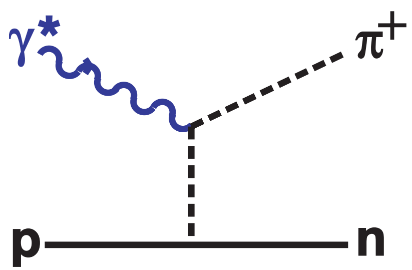
Experimental Studies of F_π provide a quantitative description of the internal structure of the pion in a region where first principle calculations are not feasible

Experimental Goals:

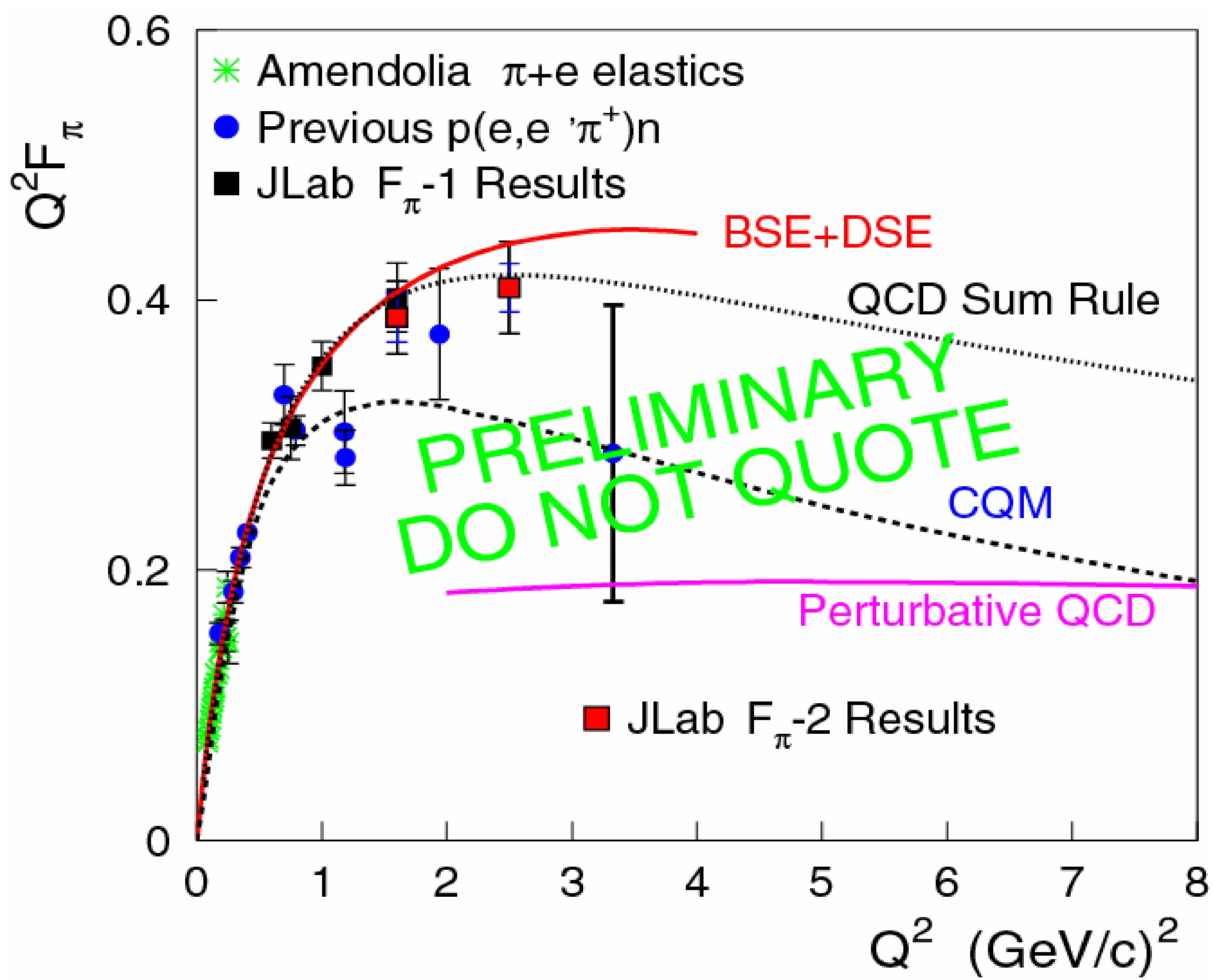
- Understand where do the dynamics of the q-q interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime
  (It will occur earliest in the simplest system)
- Constrain phenomenological models at low energies

To Measure $F_\pi(Q^2)$:

- At low Q^2 [$< 0.3\ (GeV/c)^2$]: use $\pi\ e^-$ scattering
  $\Rightarrow$ R_{rms}=0.66 fm
- At higher Q^2: use $^1H(e,e'\pi^+)n$
  (scatter from a virtual pion in the proton and extrapolate to the pion pole)



The Pion Form Factor



F_π will be extended to ~7 (GeV/c)^2 by the 12 GeV Upgrade

3. How Does the NN Force Arise from the Underlying Quark and Gluon Structure of Hadronic Matter?

We know:

- The long-range part of the force is well described by pion exchange
- The remainder involves the quark-gluon structure of the nucleon:
  quark exchange, color polarization, and glue-glue interaction

Unraveling this structure requires data from a broad range of experiments:

A. How well does a meson exchange-based NN force describe the few body form factors?
   - deuteron A, B, t_{20}
   - d(e,e'p)n

B. Is there evidence for the QCD structure of nuclear matter from "color transparency" in nucleon propagation?
   - Geesaman (e,e'p)
   - Milner (e,e'p) to higher Q^2
   - ρ photoproduction (CLAS)

C. Are the nucleon's properties modified in the nuclear medium?
   - G_E^p in ^{16}O and ^4He
   - $\gamma n \rightarrow \pi^- p$ in ^2H, ^4He

D. Nucleon-meson form factors
   - CLAS g1: $\gamma p \rightarrow K^+ \Lambda(\Sigma^0)$
   - CLAS e1: $ep \rightarrow e' \pi^+ \eta$

4. What is the Structure of Nuclear Matter?

A broad program of experiments taking advantage of the precision, spatial resolution, and interpretability of experiments performed using electromagnetic probes to address long-standing issues in nuclear physics and identify the limits of our understanding

A. How well does nuclear theory describe the energy and spatial structure of the single particle wavefunctions?
(use the (e,e'p) reaction to measure these wavefunctions)

^{16}O(e,e'p)
^{3,4}He(e,e'p) and ^{4}He($\vec{e}$,e'$\vec{p}$)
d(e,e'p), and d($\vec{e}$,e'$\vec{p}$)

B. Can the parameterized N-N force adequately describe the short-range correlations among the nucleons?
(use (e,e'p), (e,e'pp), (e,e'pn), …reactions and measure the Coulomb Sum Rule)

CLAS e2: ^{12}C(e,e'Np), ^{3}He(e,e'pp); also ^{3}He, ^{4}He, ^{12}C and ^{56}Fe(e,e') DIS
^{4}He(e,e'p) to high Q^2 and E_m
Sick (e,e'p) study

C. What can the introduction of an "impurity" (in the form of a Λ) tell us about the nuclear environment and the N-N force?
(electro-produce hypernuclei and measure their properties)

HNSS Experiment
First Hall A Results; Successful first HKS run in progress

5. At What Distance and Energy Scale Does the Underlying Quark and Gluon Structure of Nuclear Matter Become Evident?

We begin with ‘ab initio’ (“exact”) Calculations of the structure of few body nuclei, in which we assume:

- Nucleus has A nucleons interacting via force described by V_{NN}
- V_{NN} fit to N-N phase shifts
- Exchange currents and leading relativistic corrections in V_{NN} and nucleus

We test these calculations via electromagnetic interaction studies of few-body systems where precise, directly interpretable experiments can be compared with exact calculations

The goal is to determine the limits of the meson-nucleon description and to infer where a QCD-based description becomes substantially more straightforward

Push precision, λ to identify limits and answer the question

Deuteron:

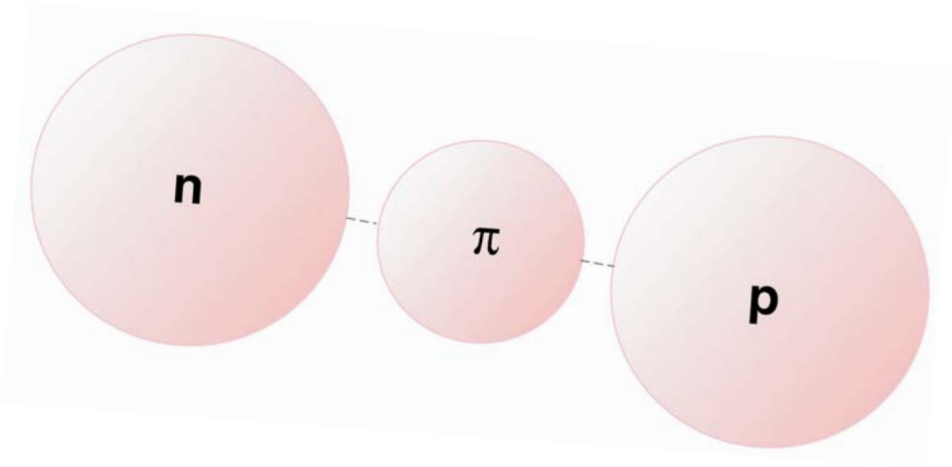
A, B, t_{20} form factors

photodisintegration (Halls C and A, and now CLAS)

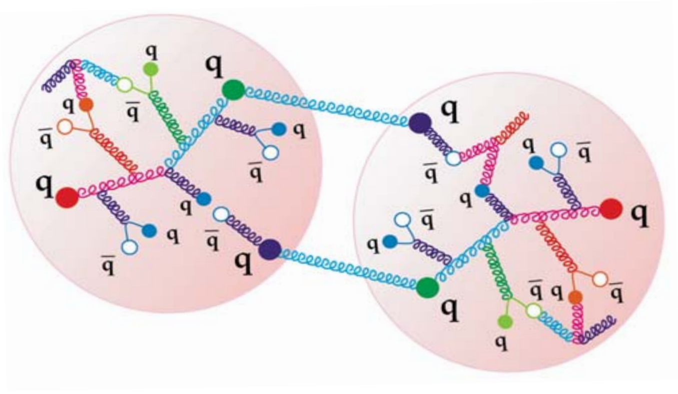
Induced polarization in photodisintegration

^{3}He form factors to high Q^2

Two Views of Deuteron Structure

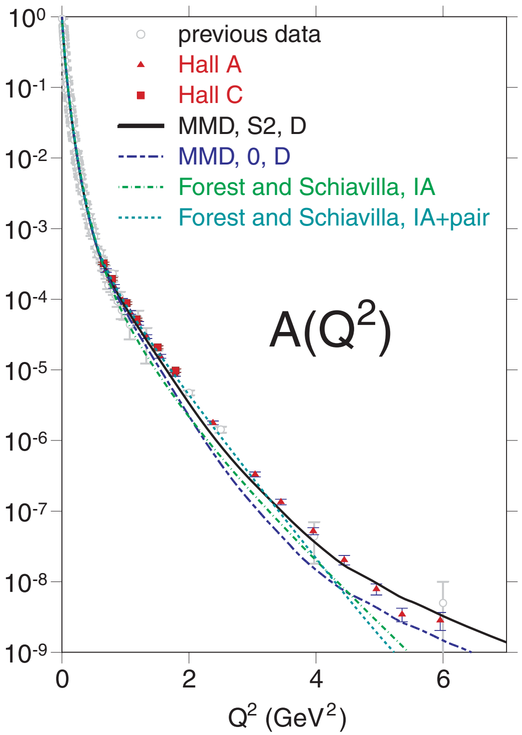


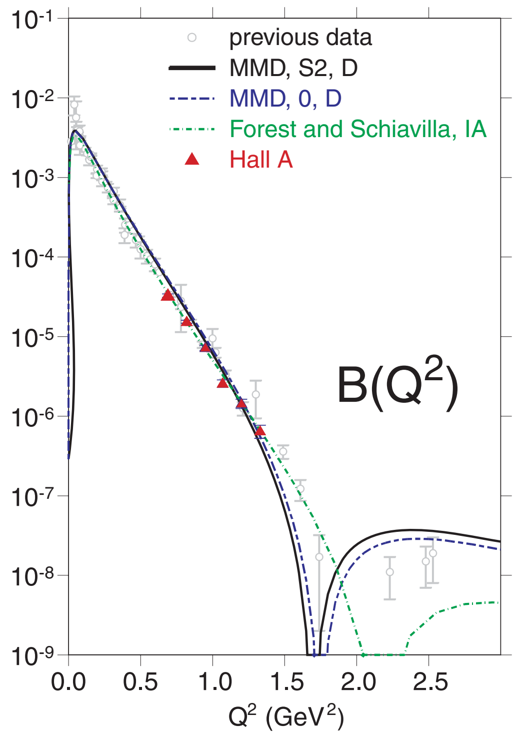
Two Nucleons interacting via the (pion-mediated) NN force



Two multi-quark systems interacting via the residue of the (gluon-mediated) QCD color force

JLab Data Reveals the Size and Shape of the Deuteron





For elastic e-d scattering:

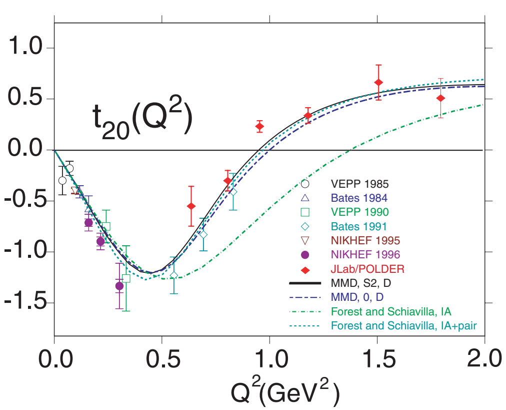
$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A + B \tan^2 \tfrac{\theta}{2} \right]$$

$$A(Q^2) = G_C^2 + \tfrac{8}{9}\tau^2 G_Q^2 + \tfrac{2}{3}\tau G$$

$$B(Q^2) = \tfrac{4}{3}\tau(1+\tau)G_M^2$$

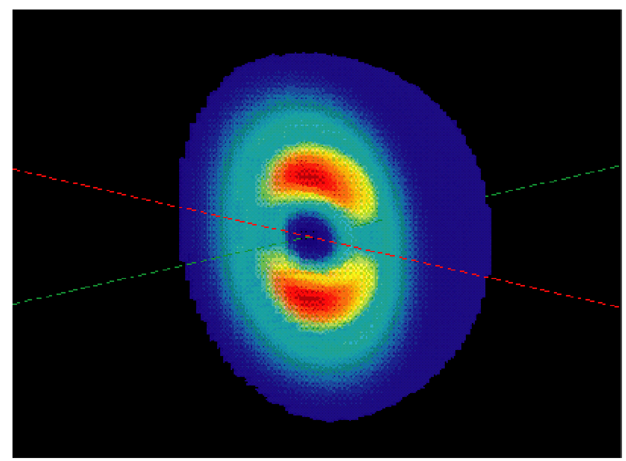
- 3rd observable needed to separate G_C and G_Q

→ *tensor polarization* t_{20}



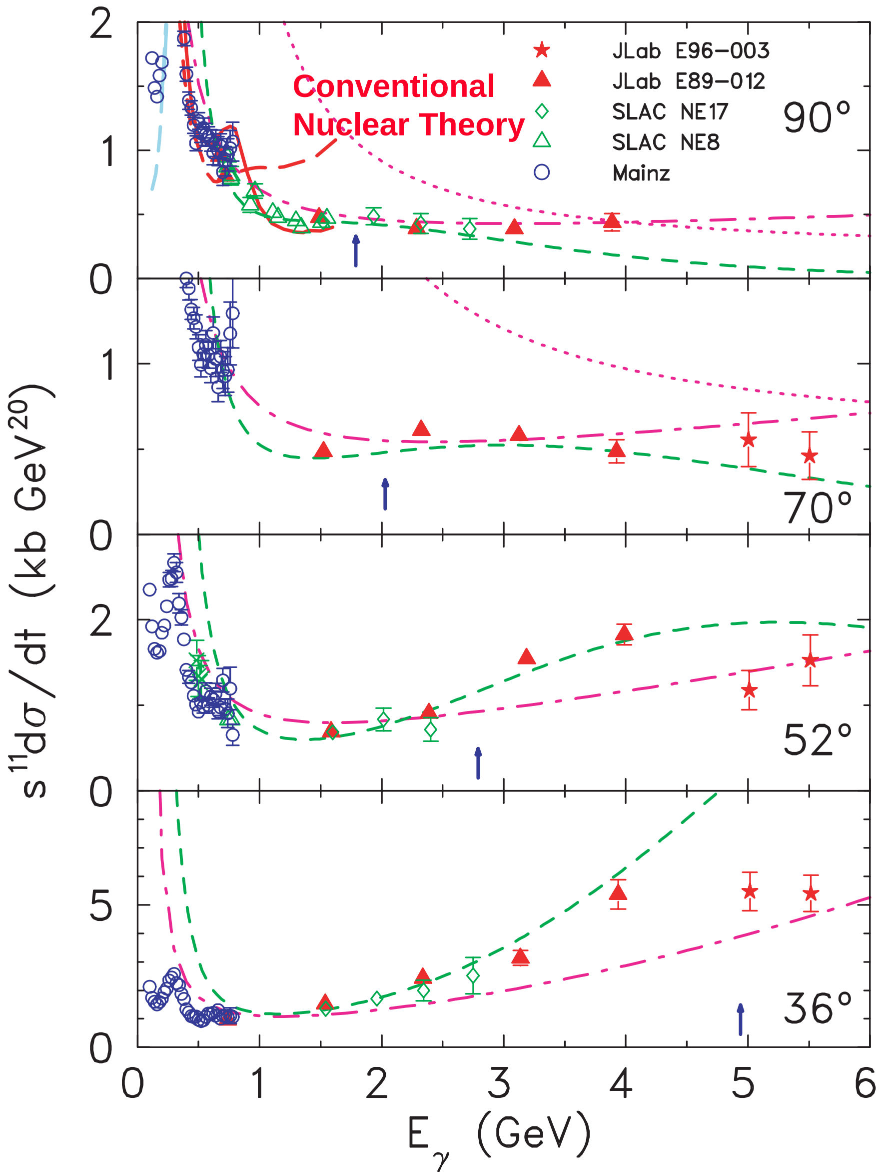
Combined Data ⟹

Deuteron's Intrinsic Shape



The nucleon-based description works to <0.5 fm

JLab d(γ,p) Data Identified the Transition to the Quark-Gluon Description

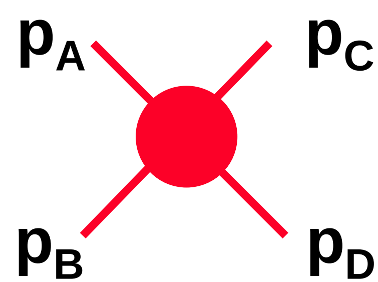


Deuteron Photodisintegration probes momenta well beyond those accessible in (e,e')
(at 90º, E_γ=1 GeV ⇔ Q^2= 4 GeV^2/c^2)

Conventional nuclear theory unable to reproduce the data above ~1 GeV

Scaling behavior ($d\sigma/dt \propto s^{-11}$) sets in at a consistent t = – 1.37 (GeV/c)^2 (see ↑)

⇒ seeing underlying quark-gluon description for scales below ~0.1 fm



$$d\sigma/dt \sim f(\theta_{cm})/s^{n-2}$$

Where $n=n_A + n_B + n_C + n_D$

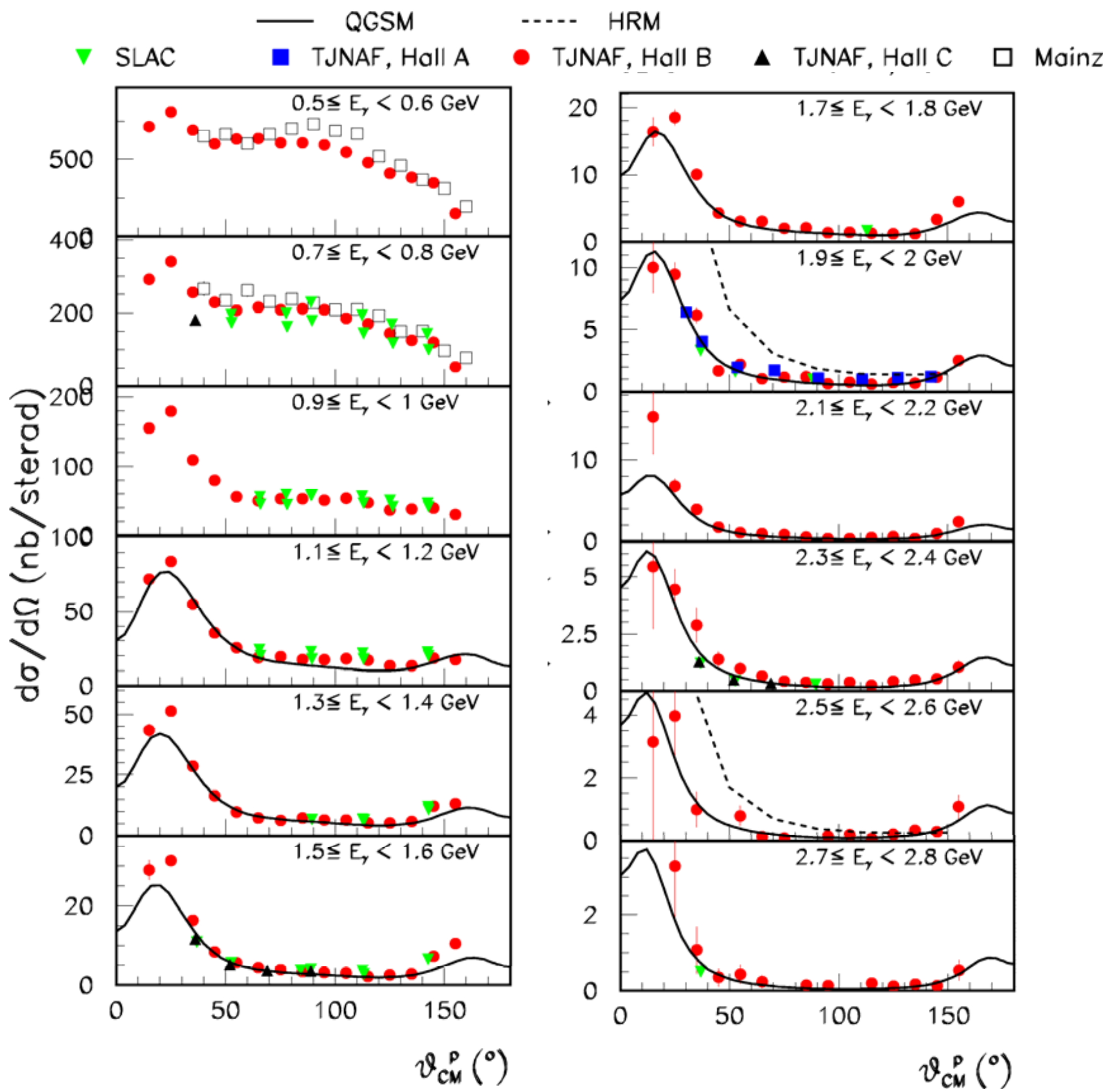
$s=(p_A+p_B)^2$, $t=(p_A-p_C)^2$

$\gamma d \rightarrow pn$ ⇔ $n=13$

Exploring the Transition Region

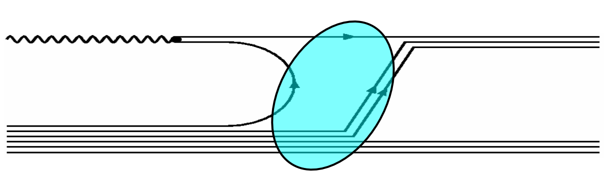
Now nearly complete angular distributions of D(γ,p)n up to E_γ = 3 GeV with CLAS

Excellent fit of data with ds/dt ∝ s^{-11} if starting fit at p_T ~ 1.0-1.3 GeV/c.



Quark Gluon String Model (Grishna, et al)

- Production in the intermediate states of a color string leading to factorization of amplitudes



- *t* channel : quark-gluon string (3 valence q + g's)

6. Is the "Standard Model" Complete? What Are the Values of Its Free Parameters?

The Standard Model (SM) has been broadly successful in describing phenomena in nuclear and particle physics. Traditional tests have been at the Z pole and through high-energy searches for new particles. JLab has launched a program aimed at both testing the theory and determining its constants in both the electro-weak and strong sectors using an alternate approach – precision measurements at low energies.

A. Is the Standard Model of Electro-weak Interactions Correct?
(Precision measurements at low energy provide tests comparable to moderate precision measurements at very high energies)

- Q_{Weak} - Test of Standard Model predictions in the Electro-weak Sector
- 12 GeV extensions

B. Does QCD Lagrangian accurately describe strongly-interacting matter, or is there physics beyond it?
(Test predictions of QCD at energies just above the pion threshold where Chiral Perturbation Theory [χPT] is expected to be valid)

- π^0 lifetime measurement (PRIMEX)
- Q^2 evolution of GDH integral at low Q^2

C. Complete our experimental information on the Standard Model through experiments that determine precisely its free parameters

- Radiative decay of π, η, and η' mesons. (12 GeV proposals)

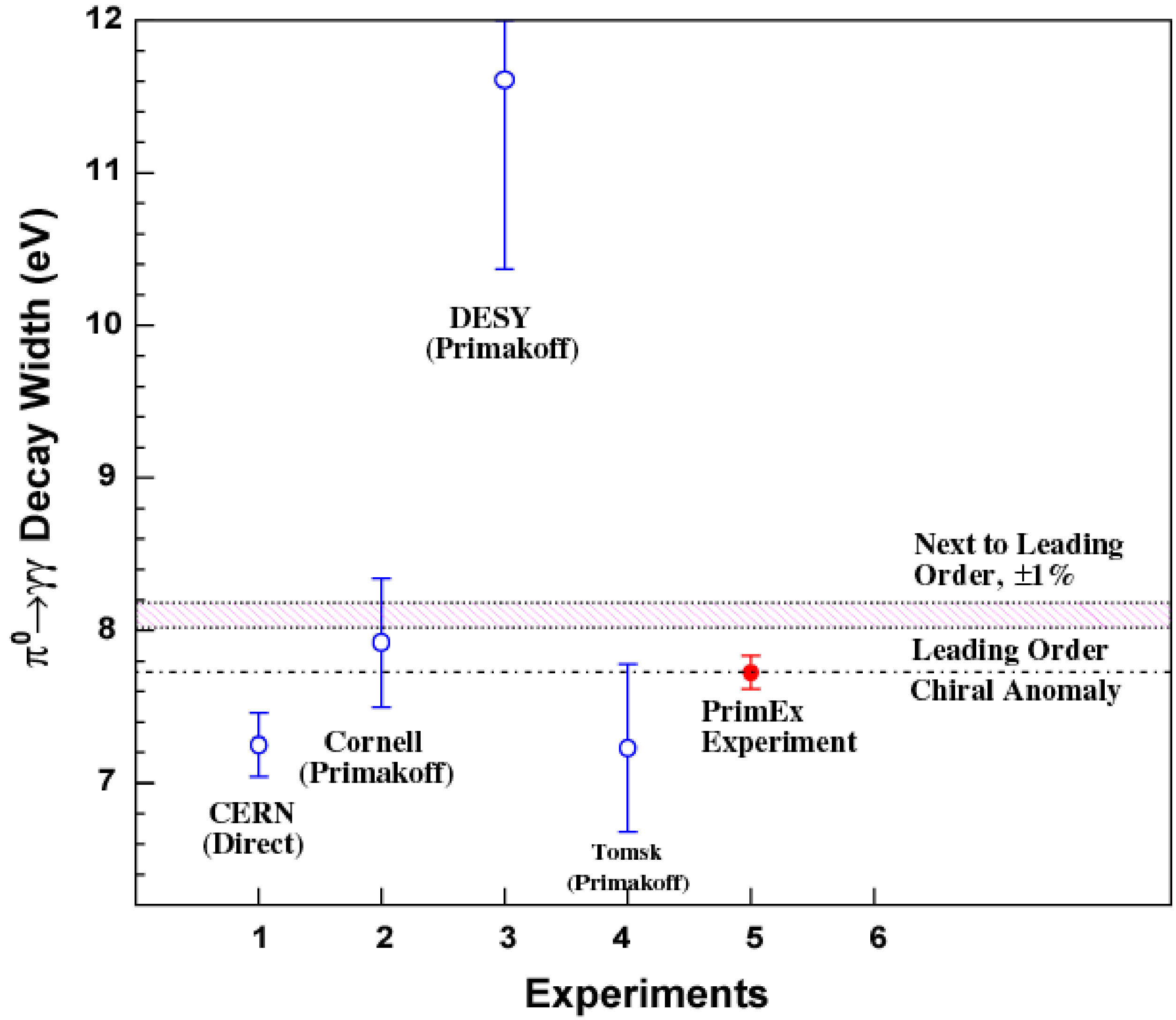
PrimEx: A Precision Measurement of the 2-photon Decay Width of the Neutral Pion

A High-precision (1.4%) measurement of the two photon decay width of the neutral pion

Will provide a stringent test of the predictions of the U(1) axial anomaly in QCD

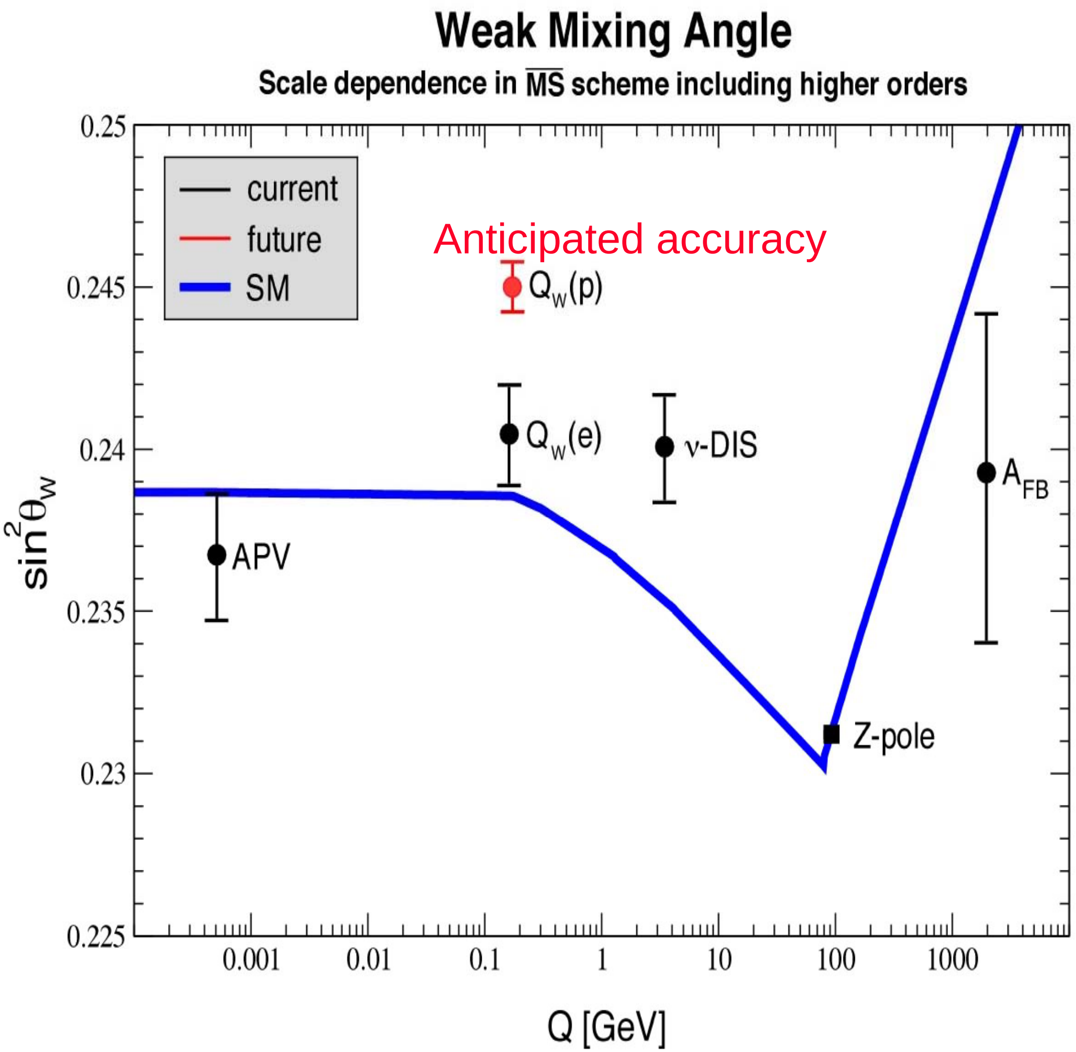
Experiment complete, data under analysis

Early results indicate the experiment will meet its goals

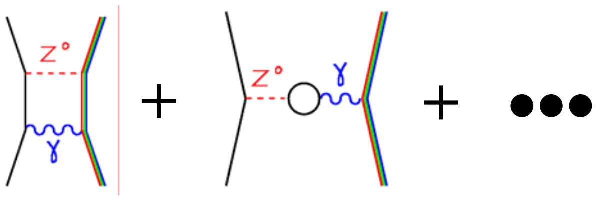


The Q^p_{weak} Experiment

The first measurement of the weak charge of the proton; a precision test of the Standard Model via a 10σ measurement of the predicted running of the weak coupling constant, and a search for evidence of new physics beyond the Standard Model at the TeV scale



- Electroweak radiative corrections
  → $\sin^2\theta_W$ varies with Q



- Extracted values of $\sin^2\theta_W$ must agree with Standard Model or new physics is indicated.

$$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072$$

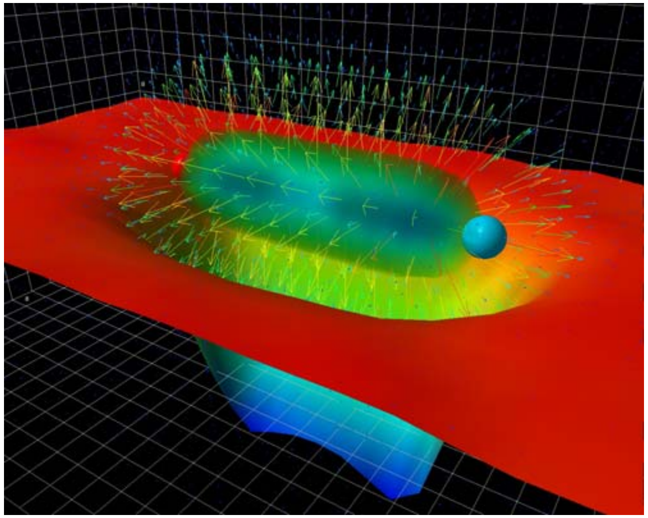
- A 4% Q^p_{Weak} measurement probes for new physics at energy scales to:

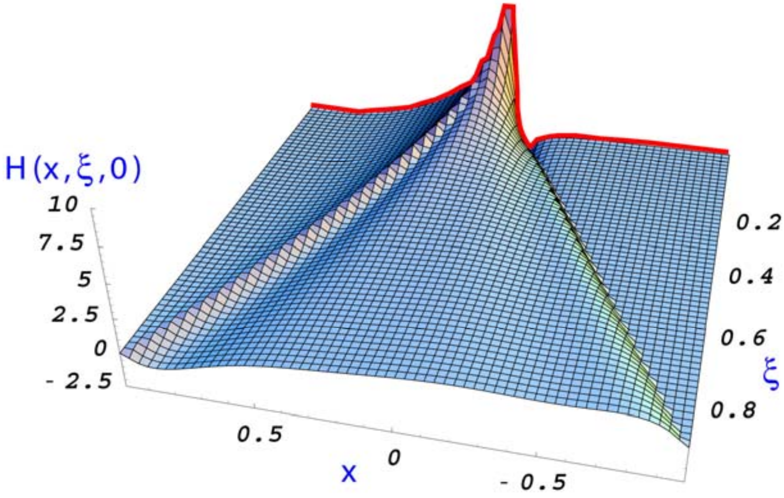
$$\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_F\left|\Delta Q^p_W\right|}} \approx 4.6 \text{ TeV}$$

- Q^p_{weak} (semi-leptonic) and E158 (pure leptonic) make a powerful program to search for and identify new physics.

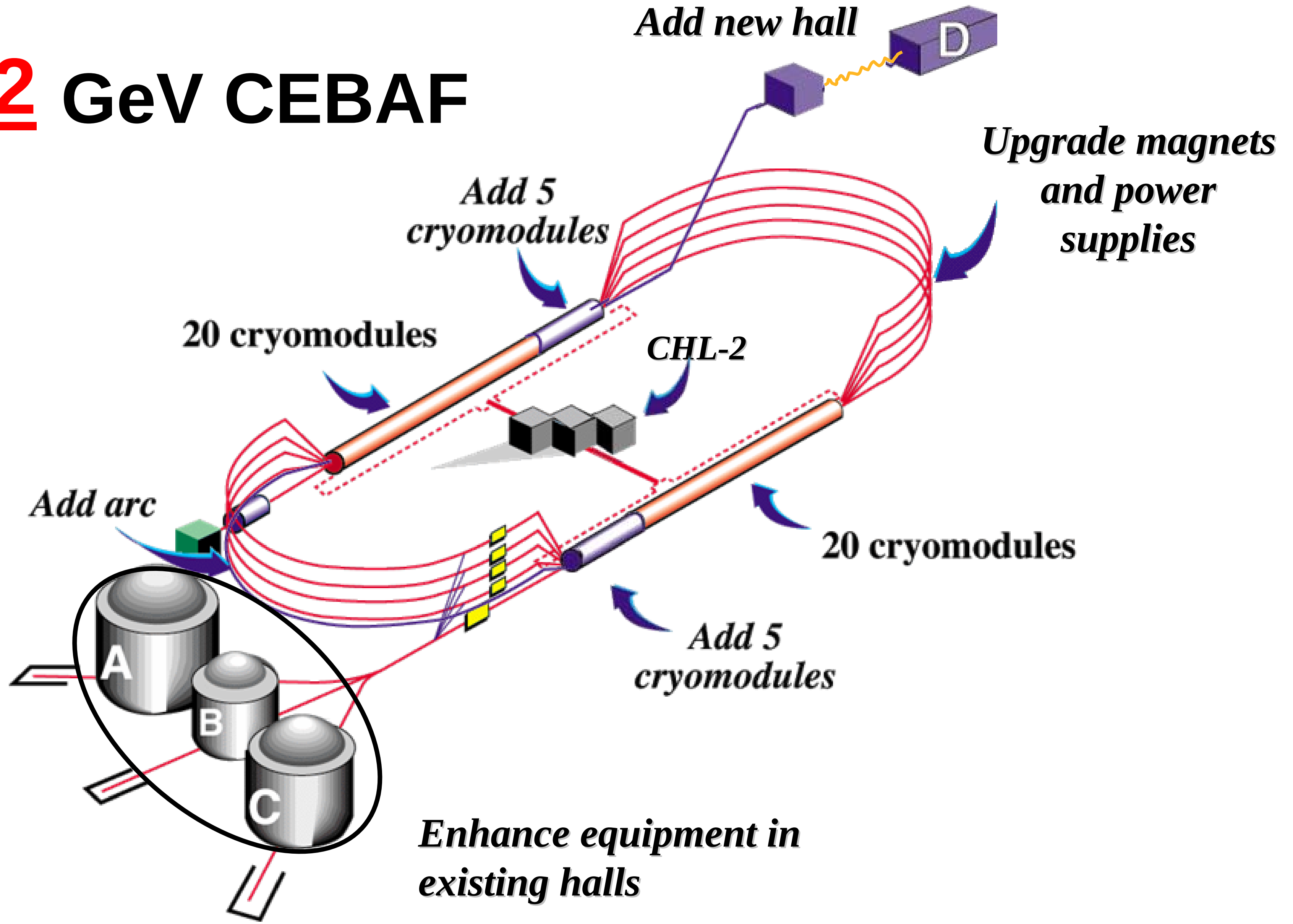
The JLab 12 GeV Upgrade
Major Programs in Four Areas:

- **The experimental study of the confinement of quarks – one of the outstanding questions of the 21st century physics**
- **Dramatic improvements in our knowledge of the fundamental quark-gluon structure of the nuclear building blocks**
- **Further exploration of the limits of our understanding of nuclei in terms of nucleons and the *N-N* force**
- **Precision experiments with sensitivity to TeV scale physics beyond the Standard Model**
- **And other science we can't foresee**



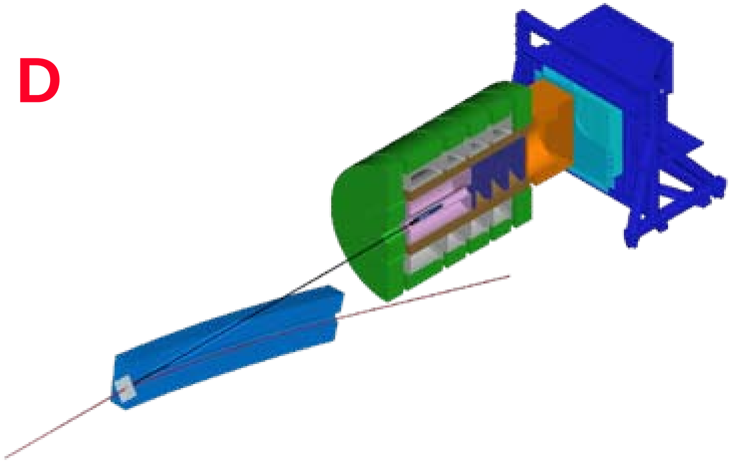


12 GeV CEBAF


Add new hall
D
Upgrade magnets and power supplies
Add 5 cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5 cryomodules
A
B
C
Enhance equipment in existing halls

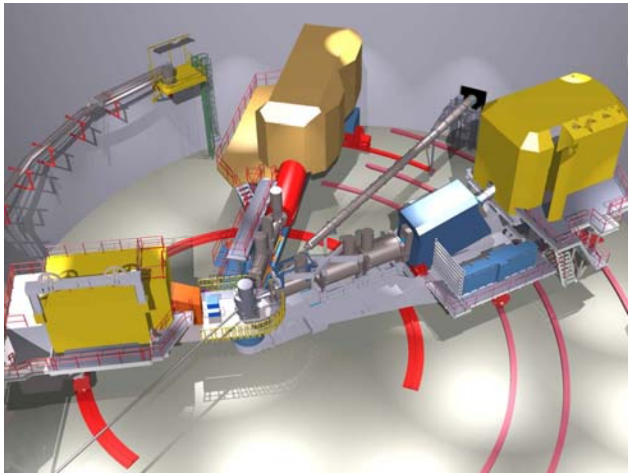
Enhanced Equipment in Halls A, B, & C and a New Hall D

D



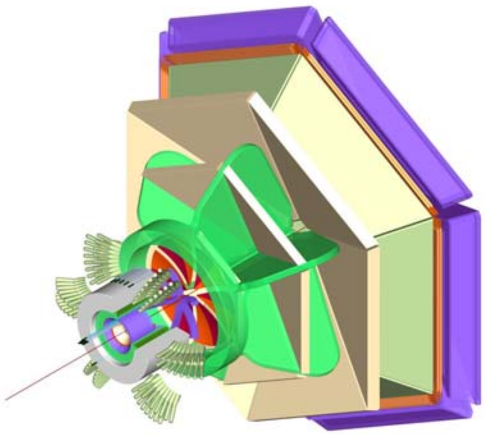
9 GeV tagged polarized photons and a 4π hermetic detector

C



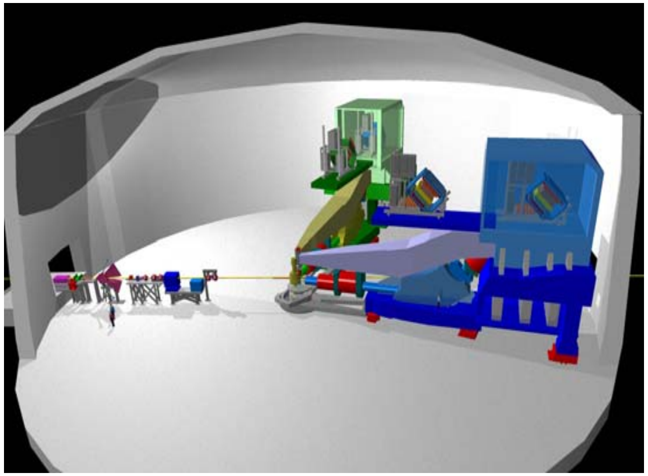
Super High Momentum Spectrometer (SHMS) at high luminosity and forward angles

B



CLAS upgraded to higher (10^{35}) luminosity and coverage

A



High Resolution Spectrometer (HRS) Pair, and specialized large installation experiments

12 GeV Upgrade: Project Schedule

Critical Decision (CD)		Presented at IPR	
CD-0 Mission Need		2QFY04 (Actual)	✓
CD-1 Preliminary Baseline Range		4QFY05	
CD-2A/3A Construction and Performance Baseline of Long Lead Items		2QFY07	
CD-2B Performance Baseline		4QFY07	
CD-3B Start of Construction		3QFY08	
CD-4 Start of Operations		1QFY13	

- 2004-2005 Conceptual Design (CDR)
- 2004-2008 Research and Development (R&D)
- 2006 Advanced Conceptual Design (ACD)
- 2007-2009 Project Engineering & Design (PED)
- 2007-2008 Long Lead Procurement
- 2008-2012 Construction
- 2011-2013 Pre-Ops (beam commissioning)

Progress Toward 12 GeV

- CD-0 in March 2004
- DOE Science Review (April 2005)
  - Formal DOE review, “Certified” the Science case for the Upgrade

    “The overall proposed program represents an impressive coherent framework of research directed towards one of the top frontiers of contemporary science: the exploration of confinement, a unique phenomenon of the strong Interaction, one of the four fundamental forces of nature.”

    “…these experimental studies are challenging, but feasible with the proposed upgrade,… they are essential to advance our theoretical understainding of confinement and the structure of hadrons and nuclei,… and they have a high probability for discoveries leading to significant paradigm shifts.”

    the upgrade “also provides a unique opportunity to use the electroweak interaction to search for physics beyond the Standard Model”
- DOE “CD-1” Review (July 2005)
  - Formally in preparation for DOE Critical Decision CD-1, which defines the Preliminary Baseline Range
  - Passed with flying colors: No action items; all CD-1 prerequisites certified as “met”
- Awaiting Formal CD-1
  - Expect this Fall

Summary and Perspectives

CEBAF@JLab is fulfilling its scientific mission:

- To understand how hadrons are constructed from the quarks and gluons of QCD
- To understand the QCD basis for the nucleon-nucleon force
- To explore the limits of our understanding of nuclear structure
    - high precision
    - short distances
    - the transition from the nucleon-meson to the QCD description

The 12 GeV Upgrade will greatly enhance the scientific “reach” of the facility.