Science Overview and the Experimental Program

L. Cardman

The Structure of the Science Presentations

- Overview of the Experimental Program – Scientific Motivation and Progress (LSC)
- Detailed Talks on Three Cross-Cutting Efforts in the JLab "Campaigns" to understand Hadronic and Nuclear Structure:
  - Hadrons in the Nuclear Medium (Rolf Ent)
  - The Pentaquark (Volker Burkert)
  - Hadron Form Factors (Kees de Jager)
- Experimental Hall Technical Developments, Ops Status, and Future Experimental Requirements (Dennis Skopik)
- Theory (Tony Thomas)
- Progress and Plans for Nuclear Physics Research at 12 GeV and Beyond (Tony Thomas [previous talk] and Allison Lung)

JLab's Scientific Mission

- How are the hadrons constructed from the quarks and gluons of QCD?
- What is the QCD basis for the nucleon-nucleon force?
- Where are the limits of our understanding of nuclear structure?
  - To what precision can we describe nuclei?
  - To what distance scale can we describe nuclei?
  - Where does the transition from the nucleon-meson to the QCD description occur?

To make progress toward these research goals 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?

Nuclear Physics: The Core of Matter, The Fuel of Stars

(NAS/NRC Report, 1999)

Science Chapter Headings:

The Structure of the Nuclear Building Blocks

The Structure of Nuclei

Matter at Extreme Densities

The Nuclear Physics of the Universe

Symmetry Tests in Nuclear Physics

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?

Volker's and Kees' talks

3. How does the NN Force arise from the underlying quark and gluon structure of hadronic matter?

Rolf's talk

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?

Rolf's talk

Symmetry Tests in Nuclear Physics

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

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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)

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} **Kees (2004)**

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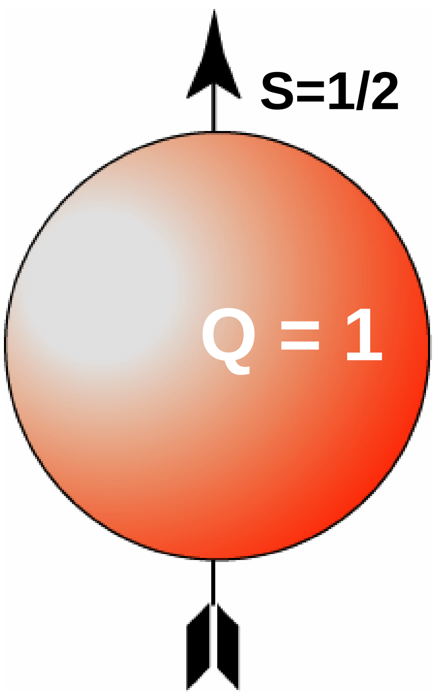
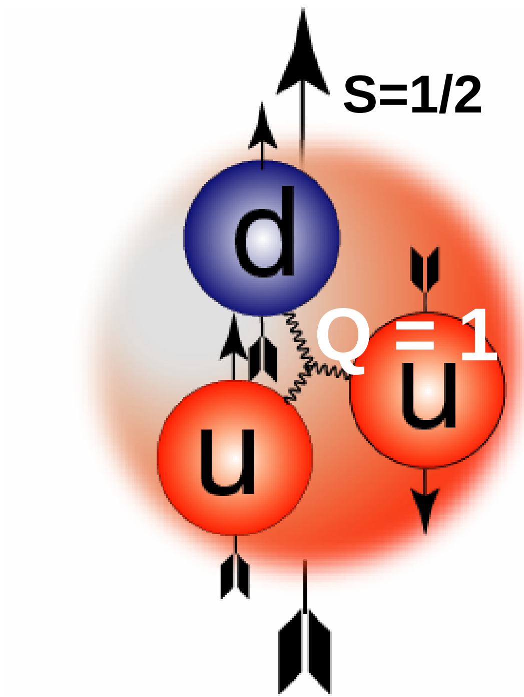
The Proton (and Neutron) are the “Hydrogen Atoms” of QCD

<u>What we “see” changes with spatial resolution</u>

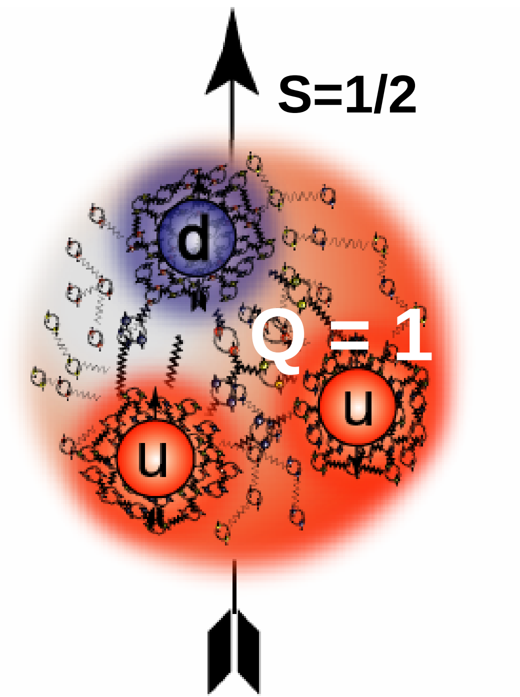
>1 fm
Nucleons



0.1 — 1 fm
Constituent quarks and glue



< 0.1 fm
“bare” quarks and glue

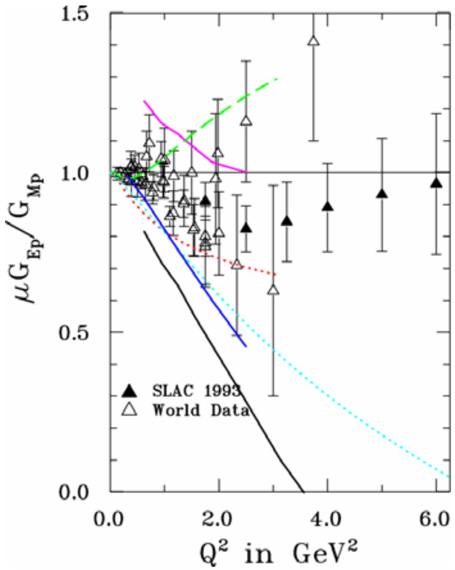


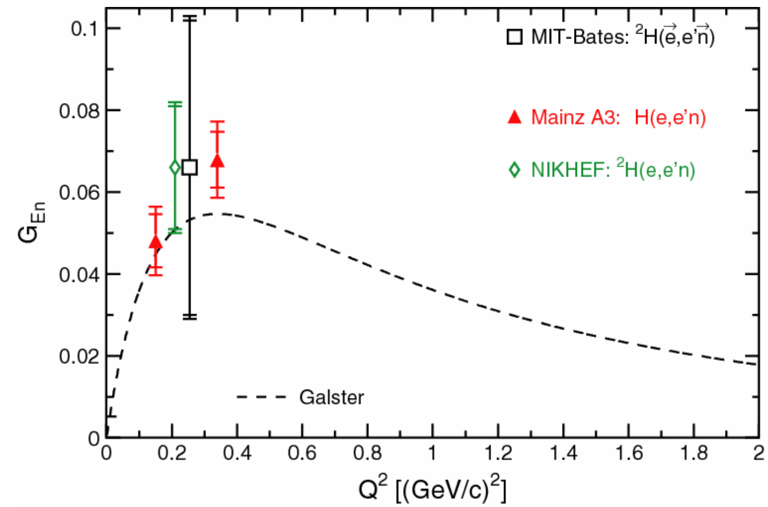
JLab Data on the EM Form Factors Provide a Testing Ground for Theories Constructing Nucleons from Quarks and Glue

Before JLab

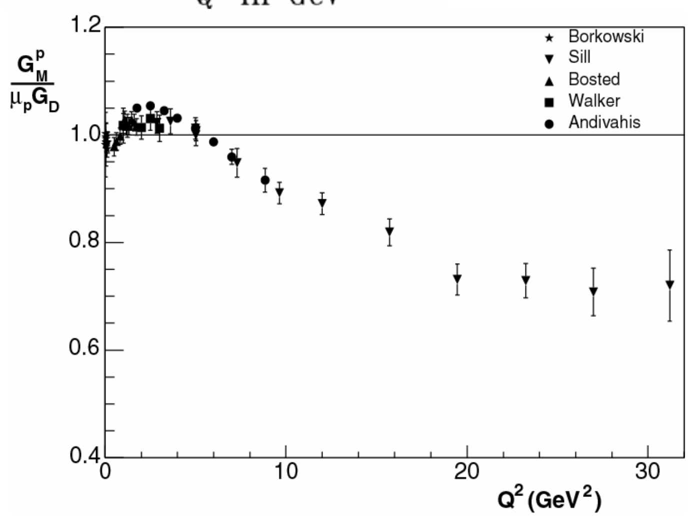
Proton | **Neutron**

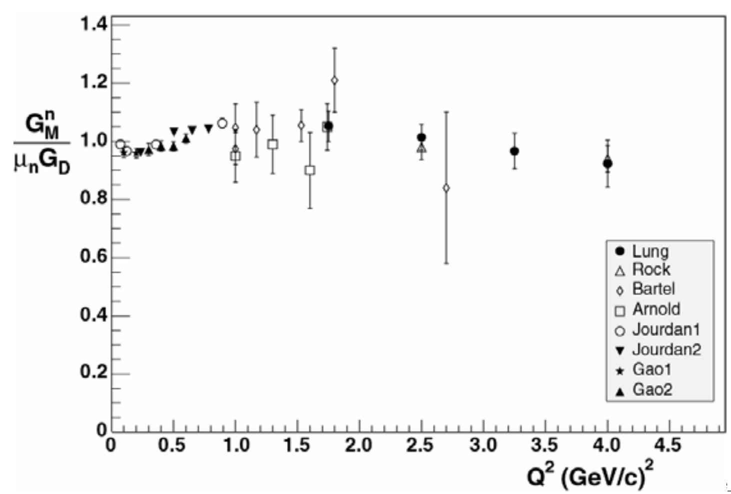
Electric





Magnetic



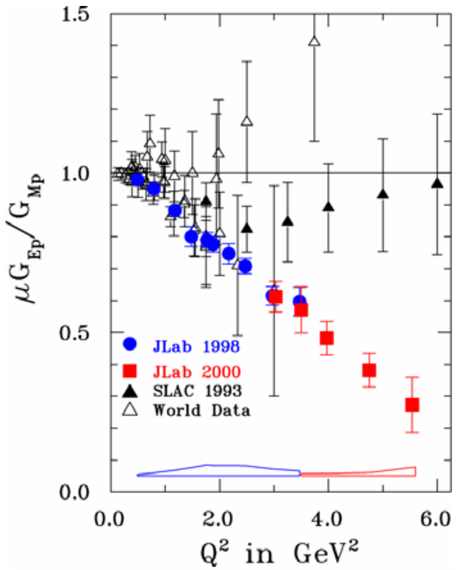


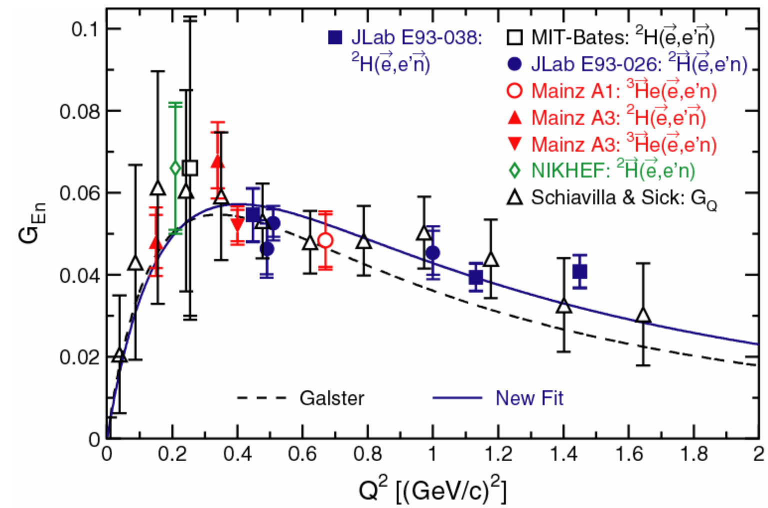
JLab Data on the EM Form Factors Provide a Testing Ground for Theories Constructing Nucleons from Quarks and Glue

Today

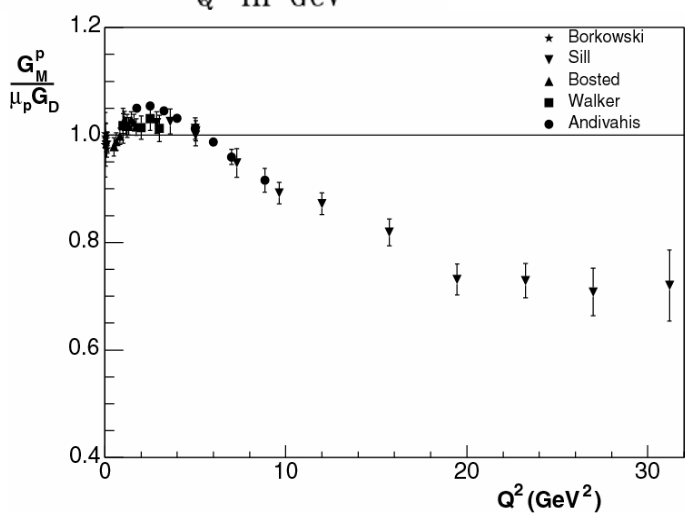
Proton | **Neutron** | **Kees' Talk**

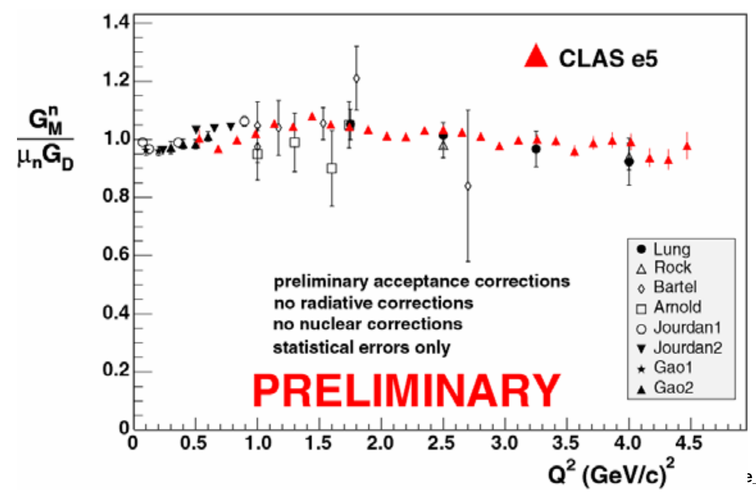
Electric





Magnetic





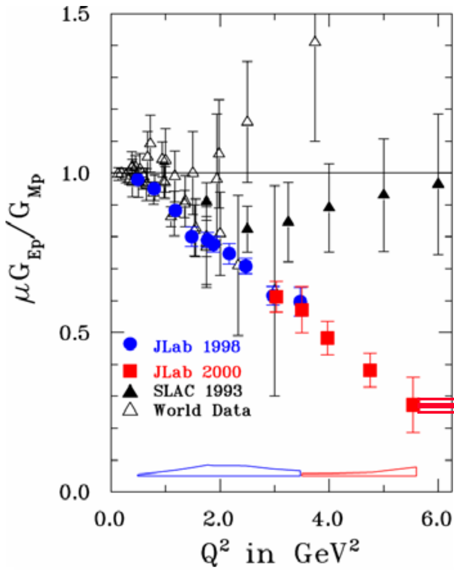
JLab Data on the EM Form Factors Provide a Testing Ground for Theories Constructing Nucleons from Quarks and Glue

Planned Extensions w/ 6 GeV beams

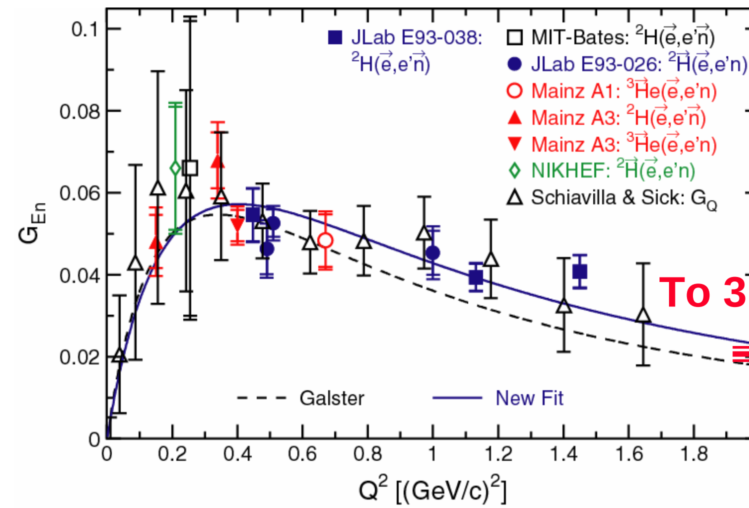
Kees' Talk

Proton **Neutron**

Electric

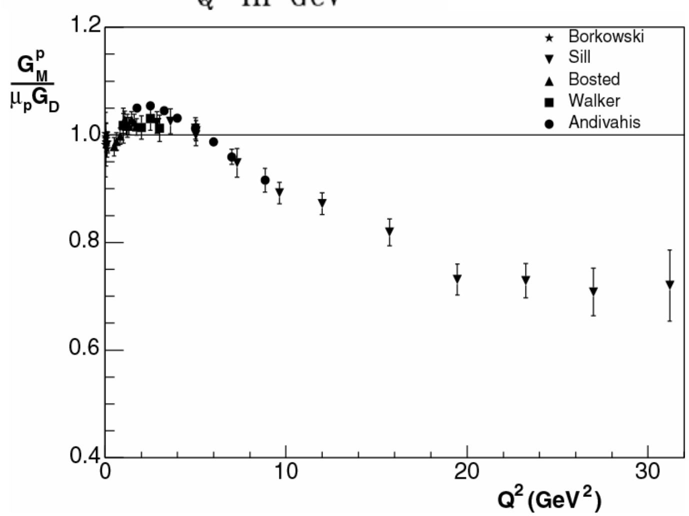


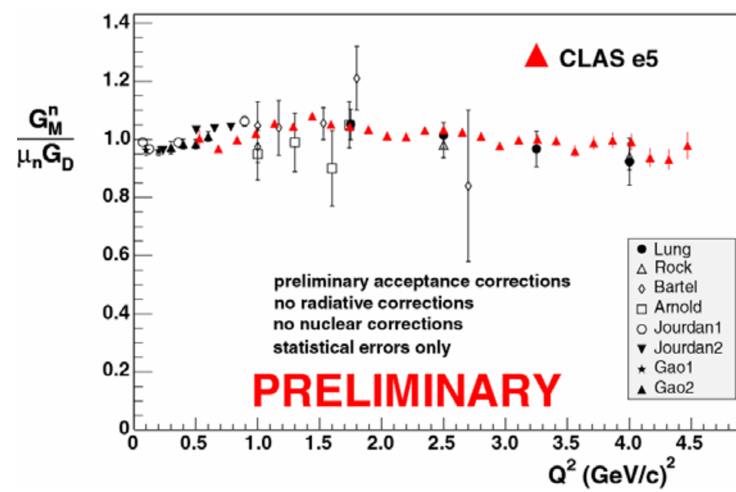
To 9 GeV²



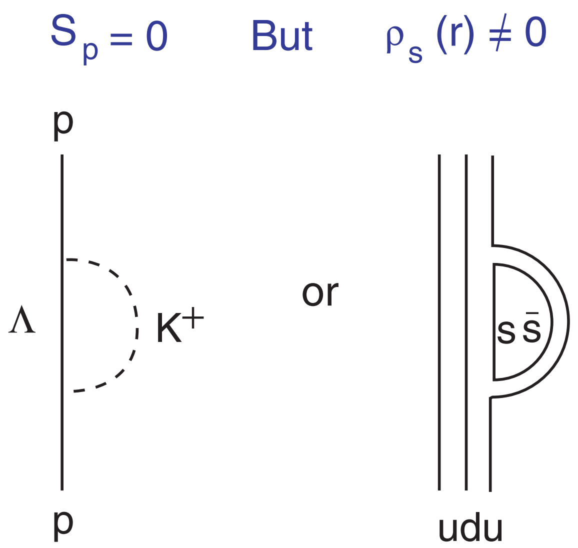
To 3.5 GeV²

Magnetic

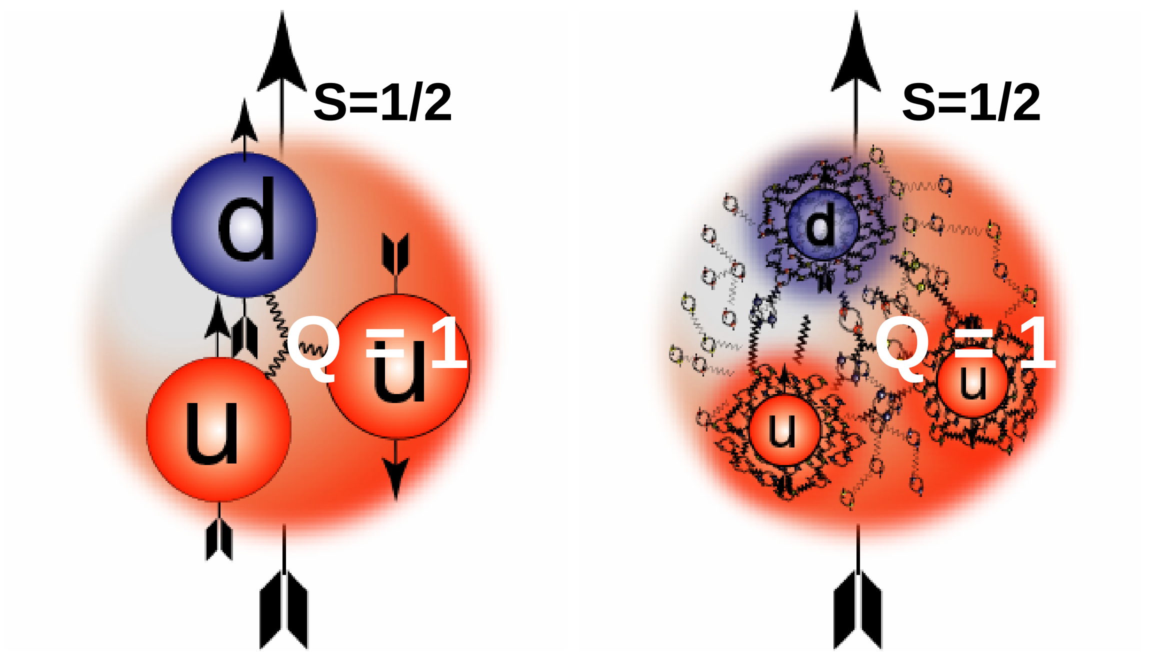




Measurements of the Strange Quark Distribution Will Provide a Unique New Window into Hadron Structure

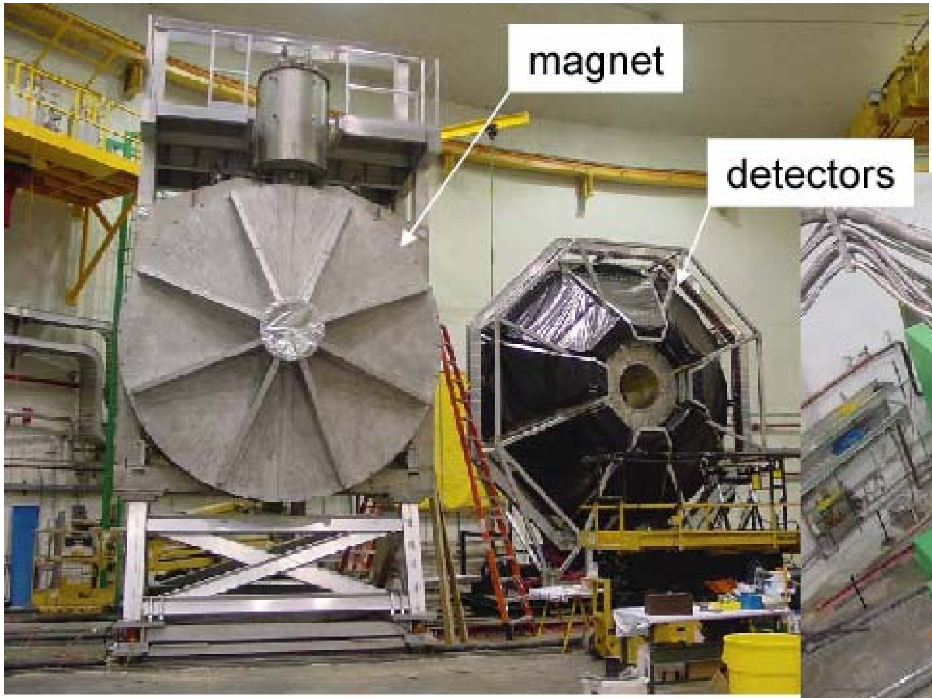


Unlike G_E^n, the $s\bar{s}$ pairs come uniquely from the sea; there is no "contamination" from pre-existing u or d quarks



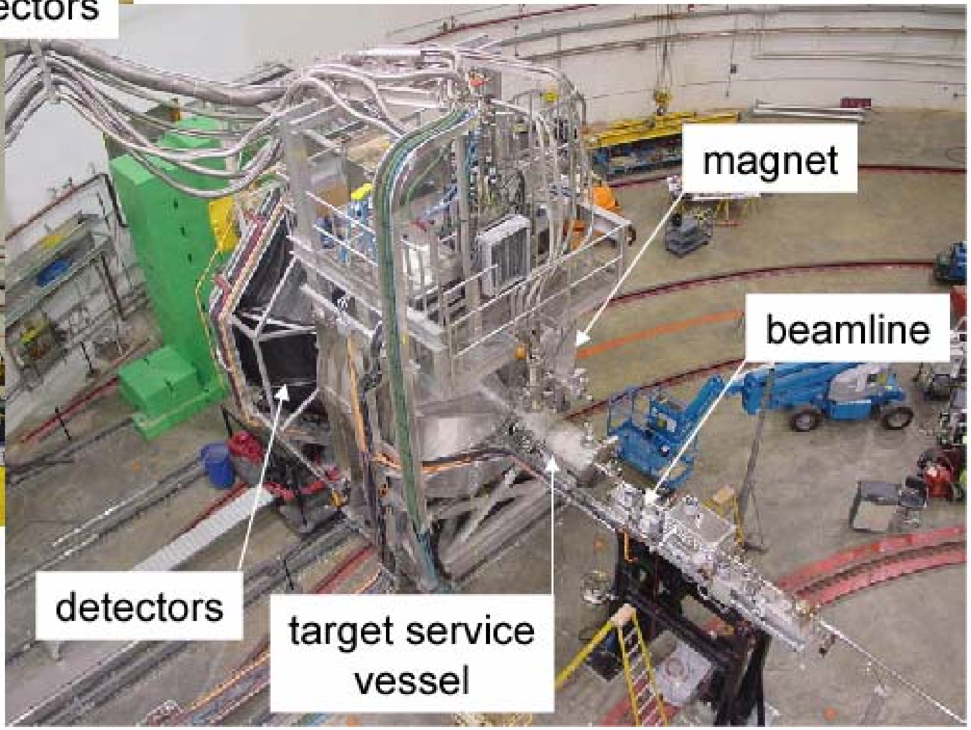
As is the case for G_E^n, the strangeness distribution is very sensitive to the nucleon's properties

G0 Installed, Completed 1st Forward Angle Run Successfully



Hall C, April 02

Hall C, August 02



G0 Update

D. Beck UIUC
June 04

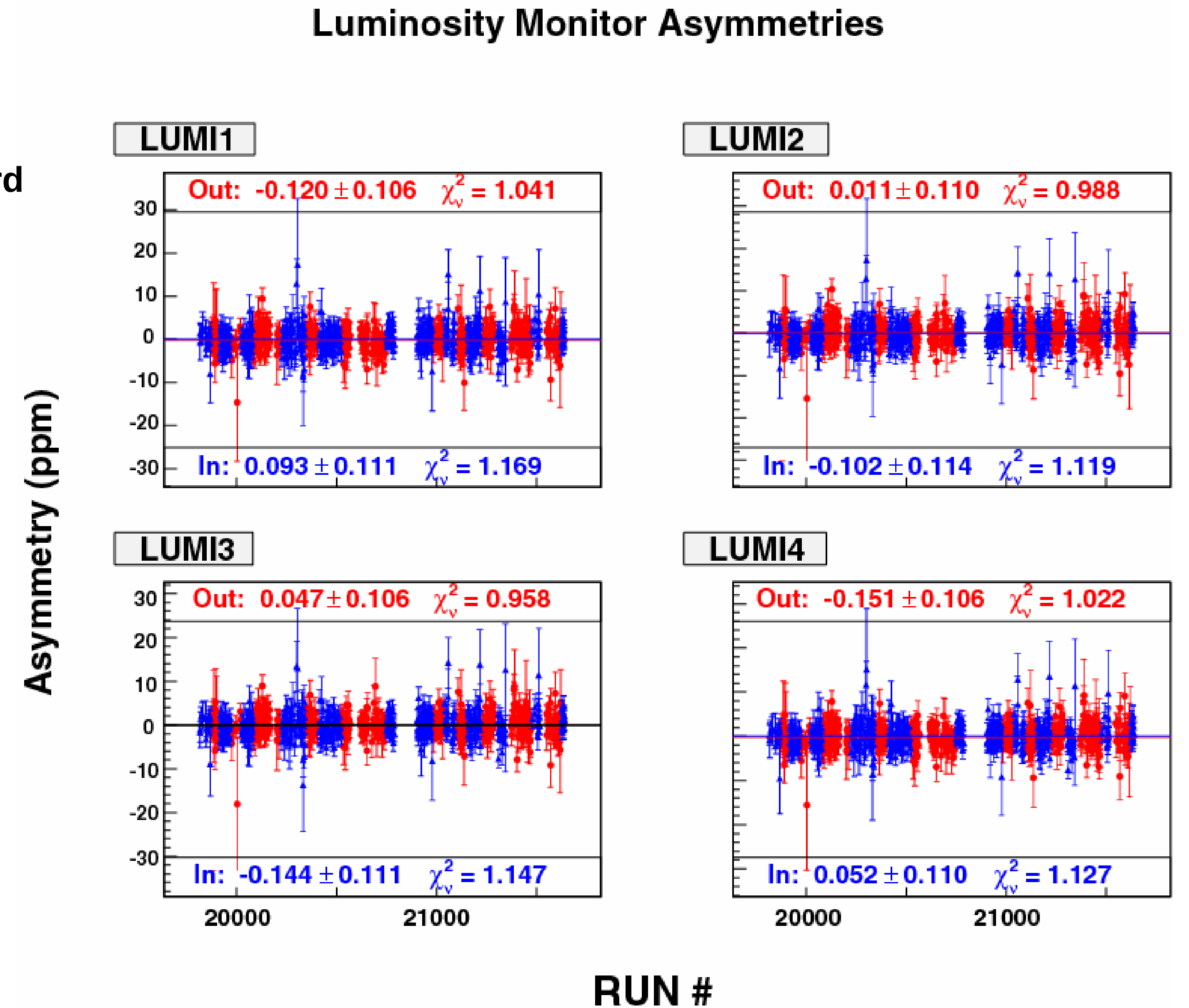
G0 forward angle run successfully completed!

- Magnet, target, detectors, electronics, DAQ commissioned and ready (Jan. 03)
- Beam properties specifications (“parity quality”) met (Jan. 04)
  - feedback for charge asymmetry, beam position differences used successfully
  - beam pickoff used successfully for t.o.f. measurements
  - *helicity-correlated charge asymmetry ~ 1 ppm*
  - *helicity-correlated position differences ~ 20 nm*
- Background measurements (Jan. 04)
  - primarily empty (H_2 gas) target for subtraction
- Production running (Feb. – May 04)
  - measure forward asymmetries for $0.1 < Q^2 < 1$ GeV^2
  - asymmetries from 2 – 40 ppm
  - ~ 700 h on LH_2 target as proposed
  - false asymmetries very small
    - helicity-correlated beam properties well-controlled
    - other sources of false asymmetries manageable
  - detailed analysis beginning

G0 Update: False Asymmetries

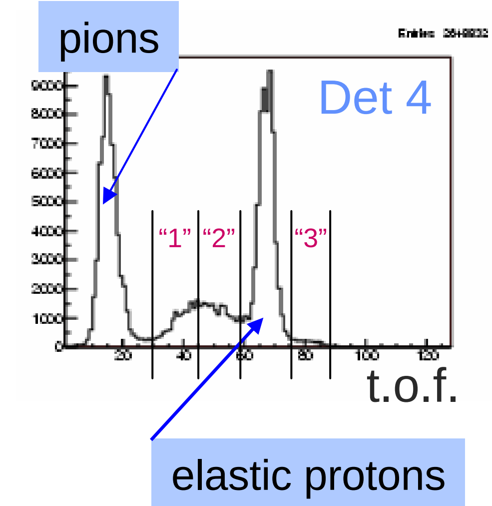
Checked for other sources of false asymmetries using four auxiliary forward angle detectors

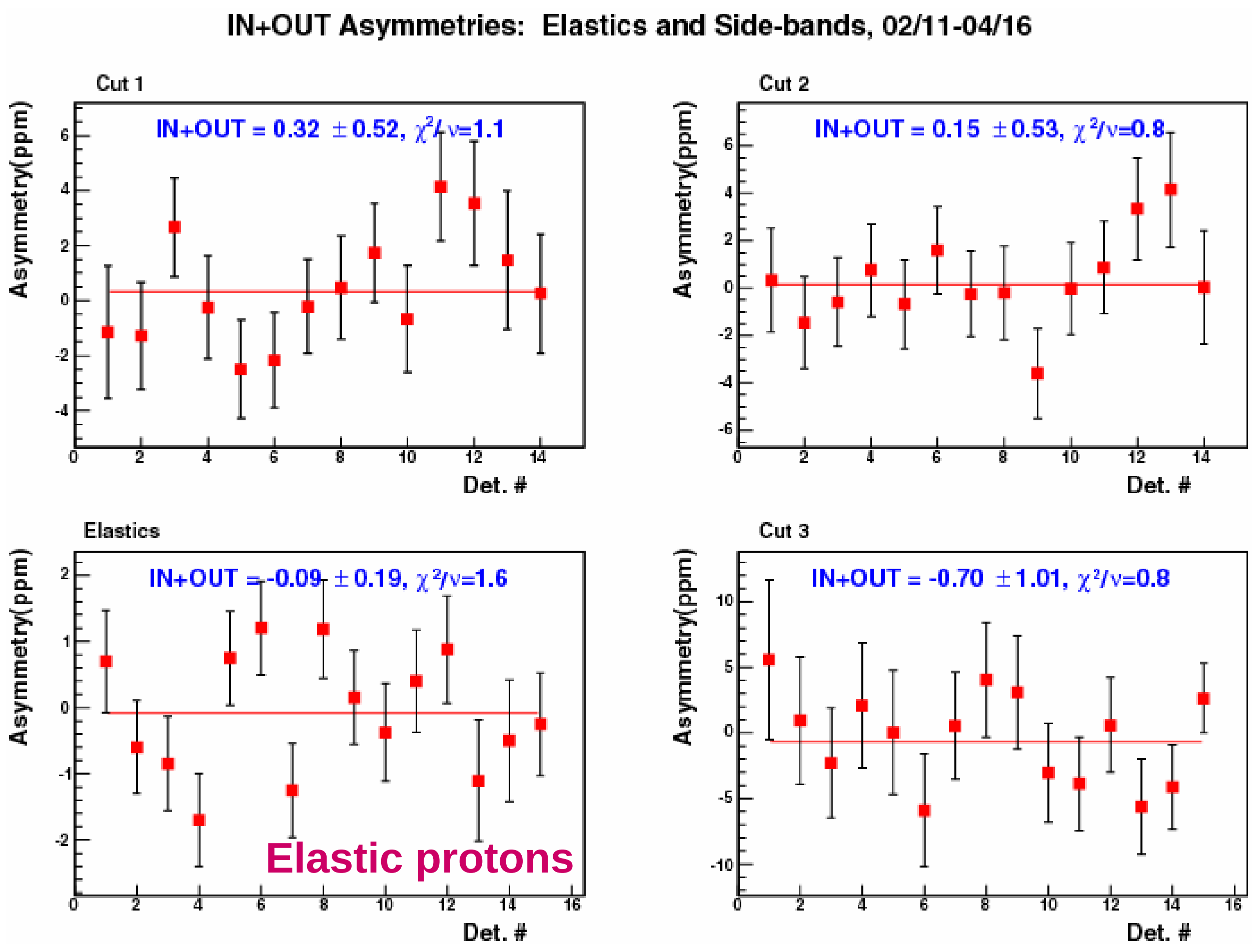
Physics asymmetry <0.1 ppm



G0 Update: False Asymmetries

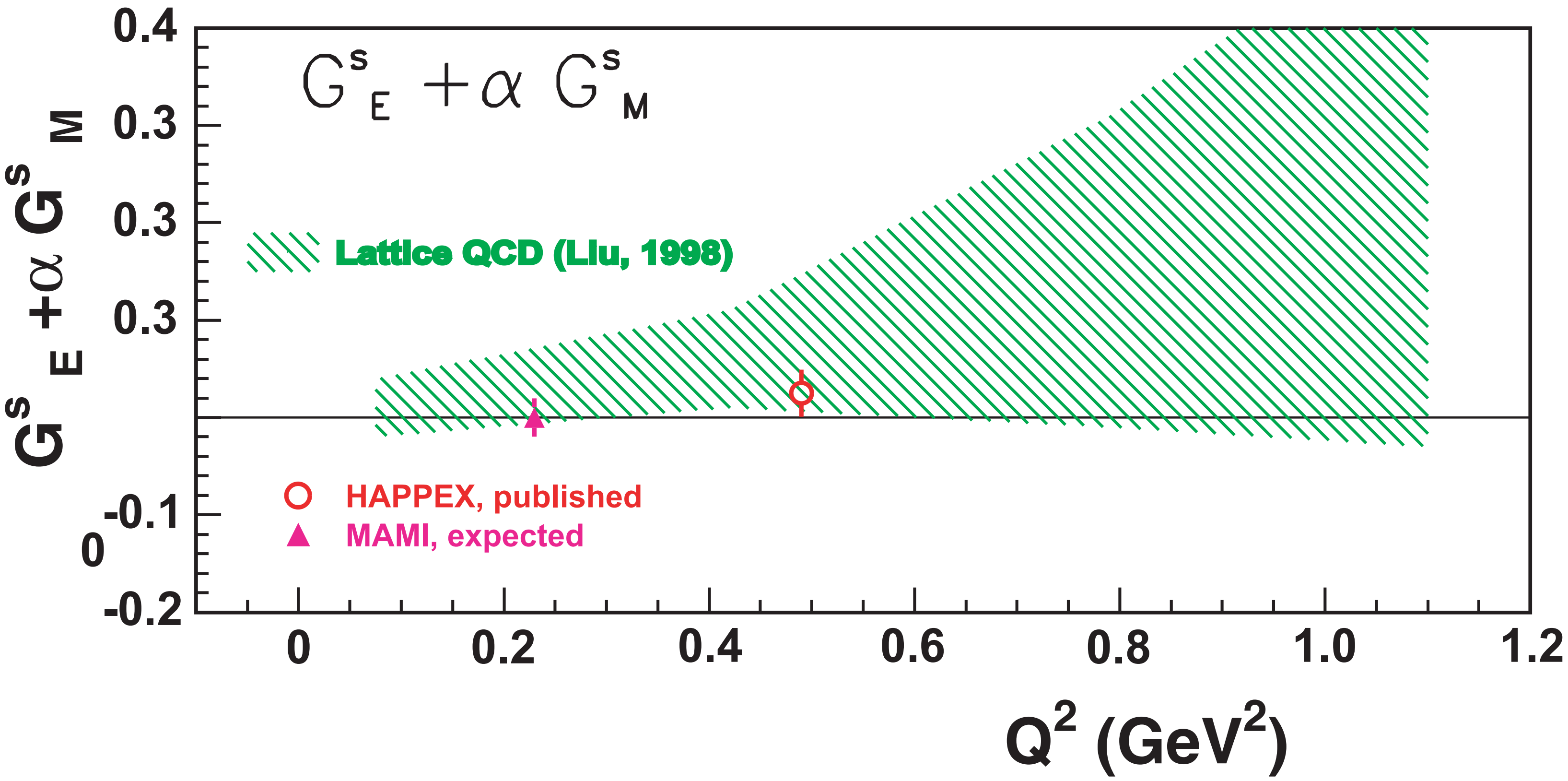
- Check for asymmetries in electronics
  - measure zero with uncertainty of ~ 0.2 ppm
  - time-of-flight spectrum split into four sections: 3 inelastic and one elastic (lower left)



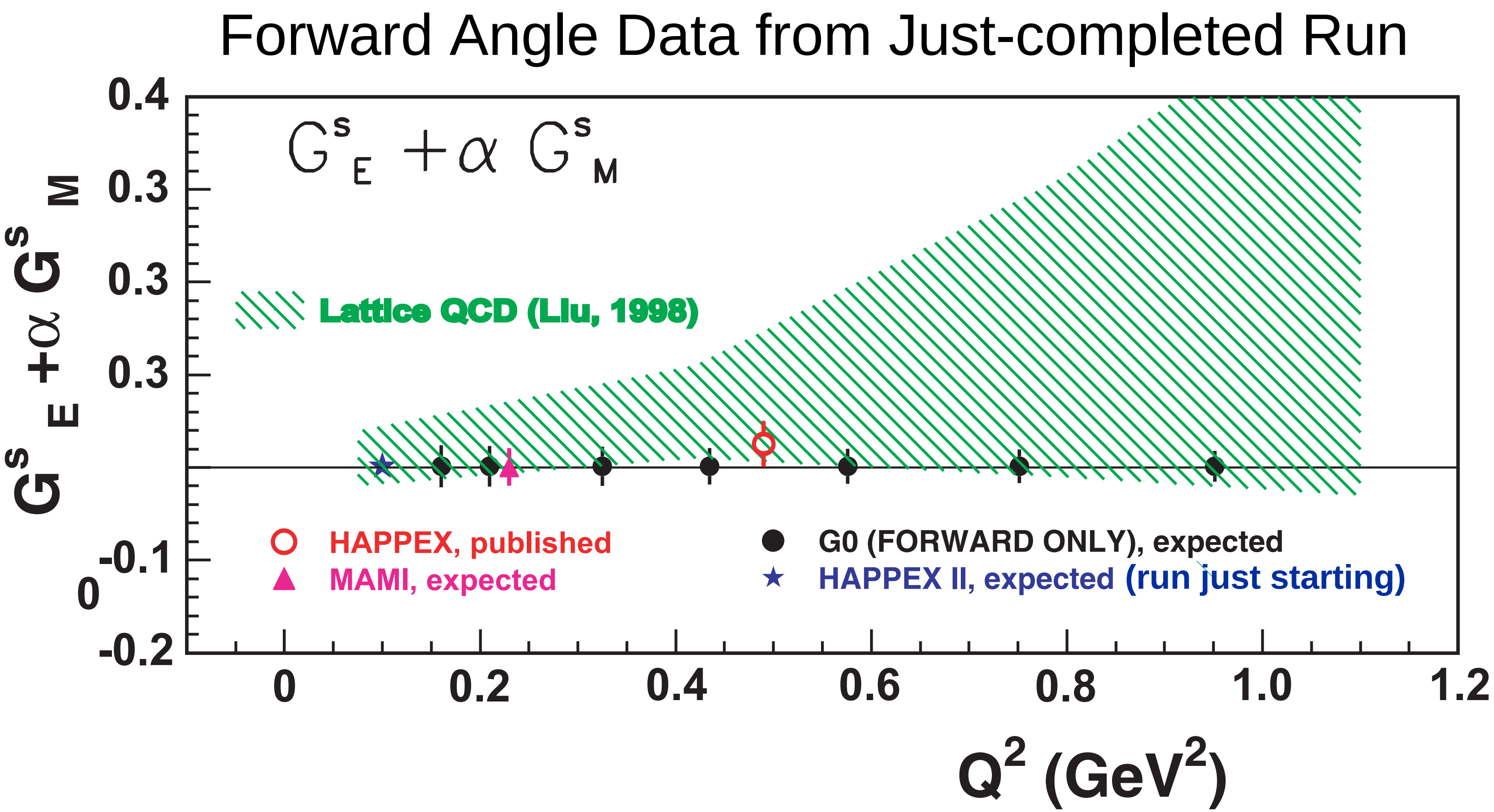


Strange Form Factors G_E^s and G_M^s

What we have on the books now



Strange Form Factors G_E^s and G_M^s



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VCS in the resonance region (Hall A)

Volker will discuss the pentaquark, and Tony the N* program

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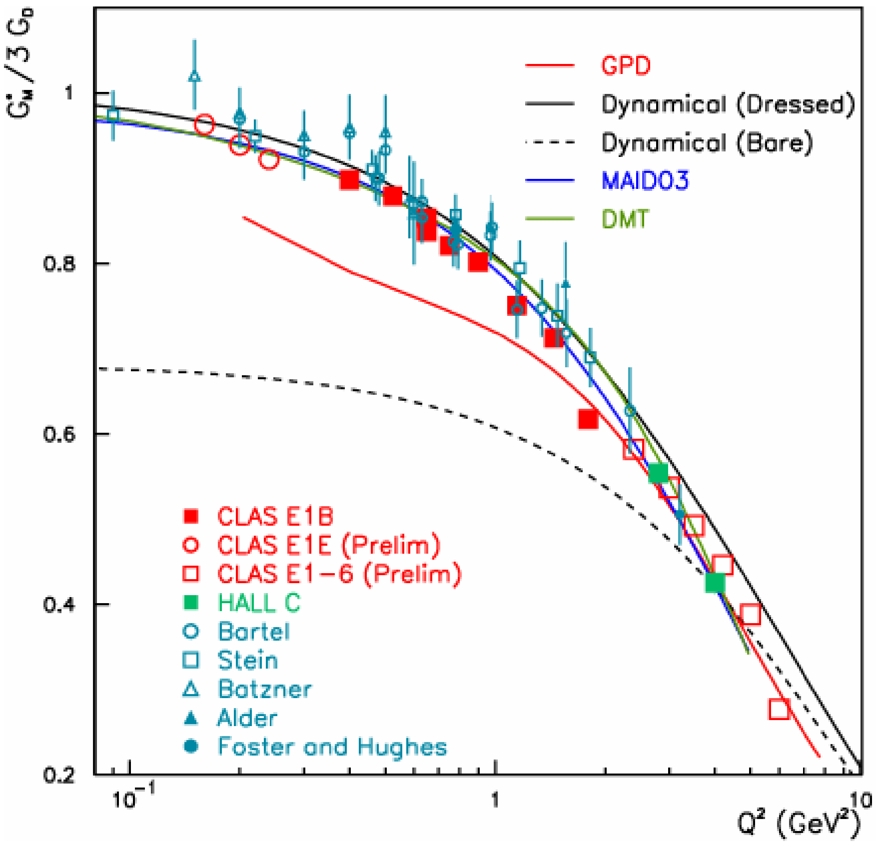
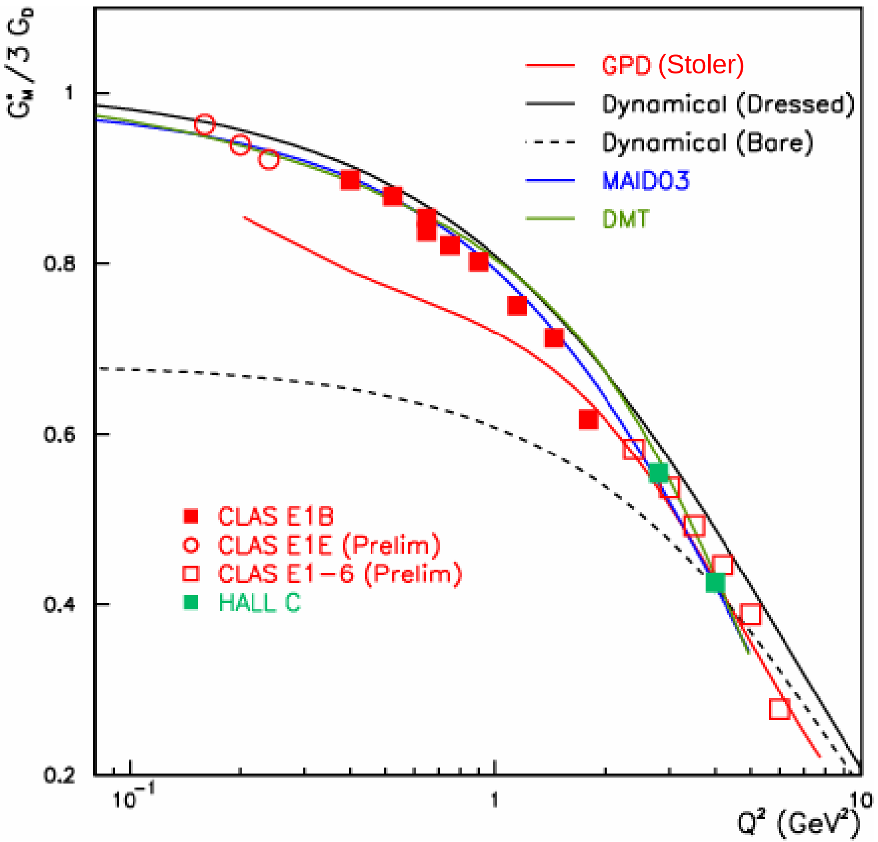
N-Δ(1232) Magnetic Transition Form Factor

Inclusive & exclusive

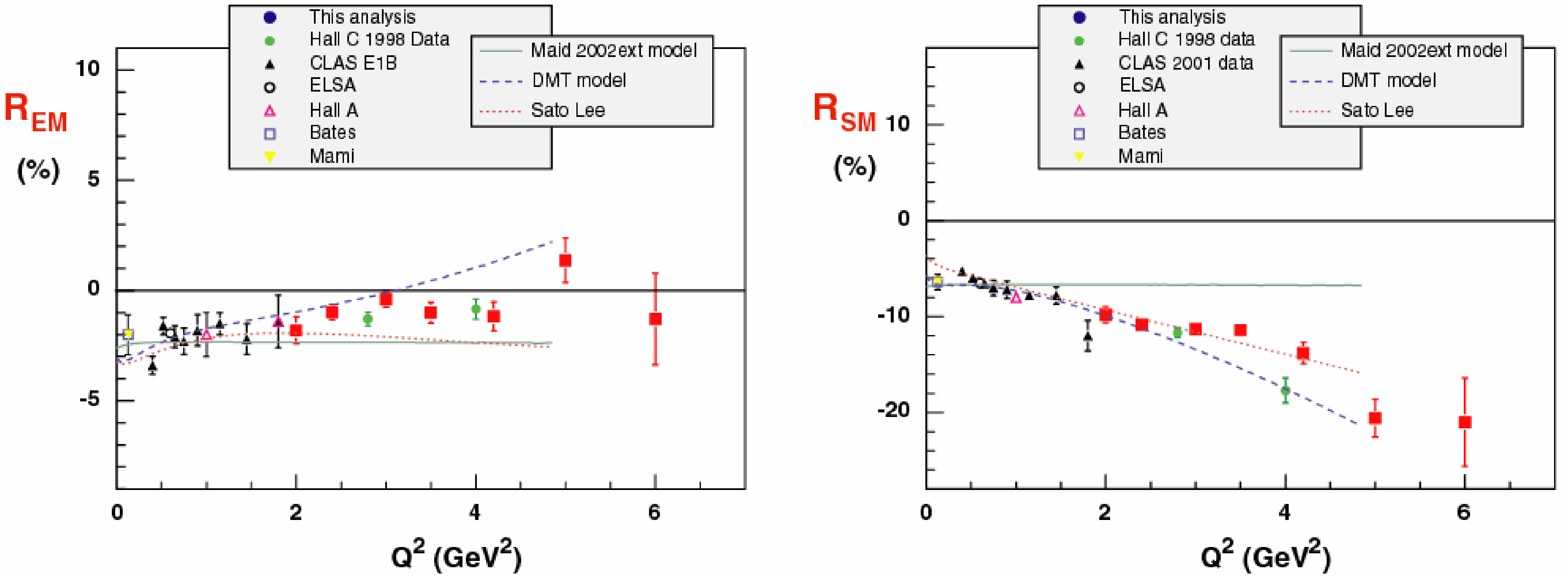


Exclusive $p\pi^0$ only



CLAS R_{EM}, R_{SM} Transition Form Factors

preliminary

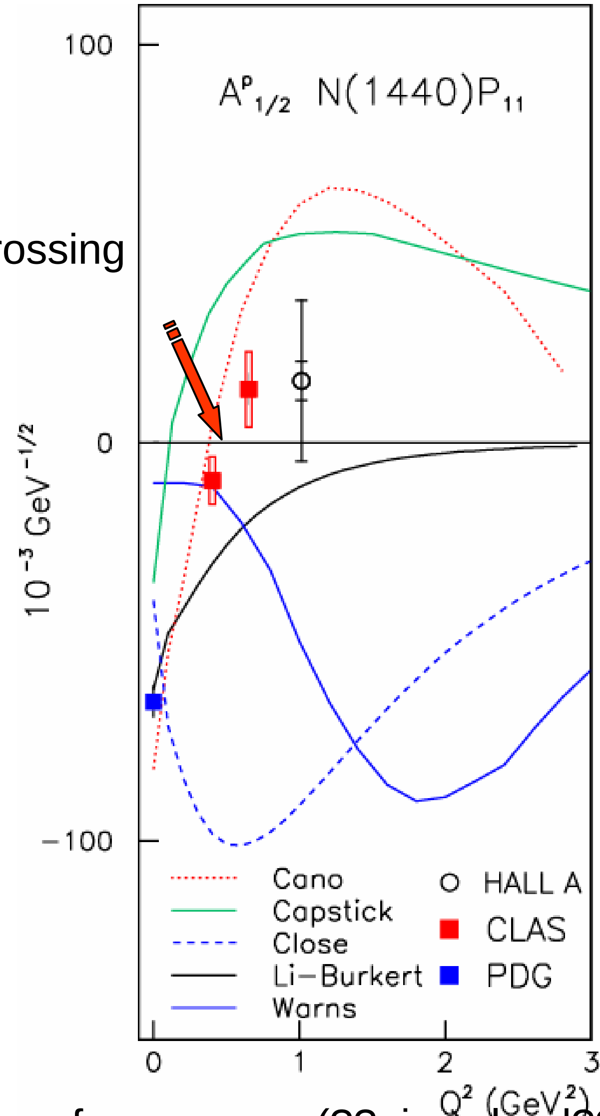


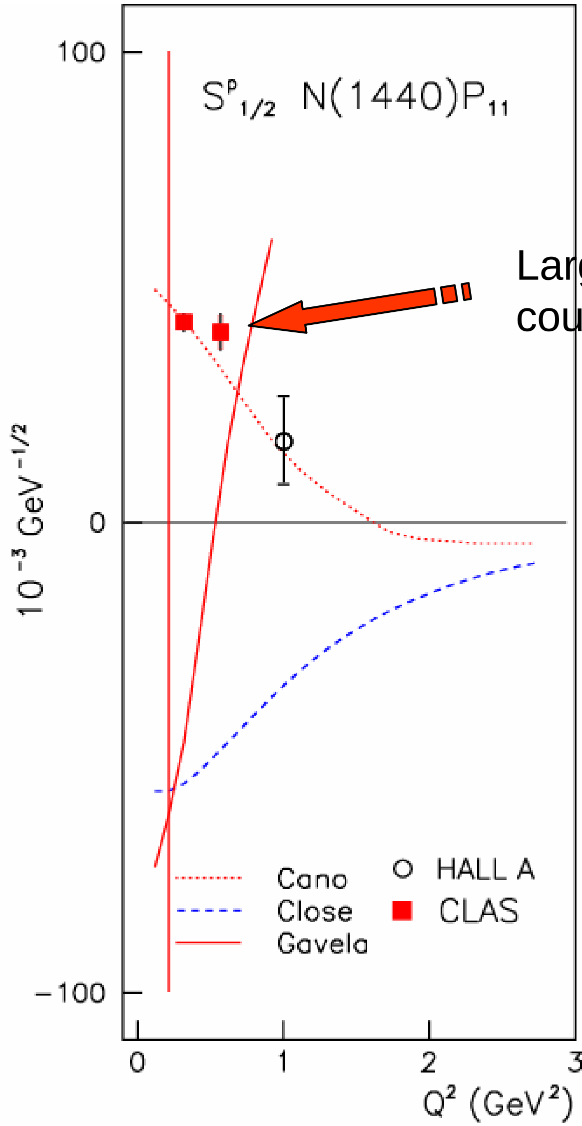
- Note: E01-002 (in Hall C) has extended these form factors to 7.5 GeV^2

  These data are under in the early stages of analysis and there are no results available yet

First Results from JLab Global Analysis

Zero crossing





Large longitudinal coupling!

ommenet re physics of cano curve (??pion cloud??)

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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 ($Q^2 \to 0$):

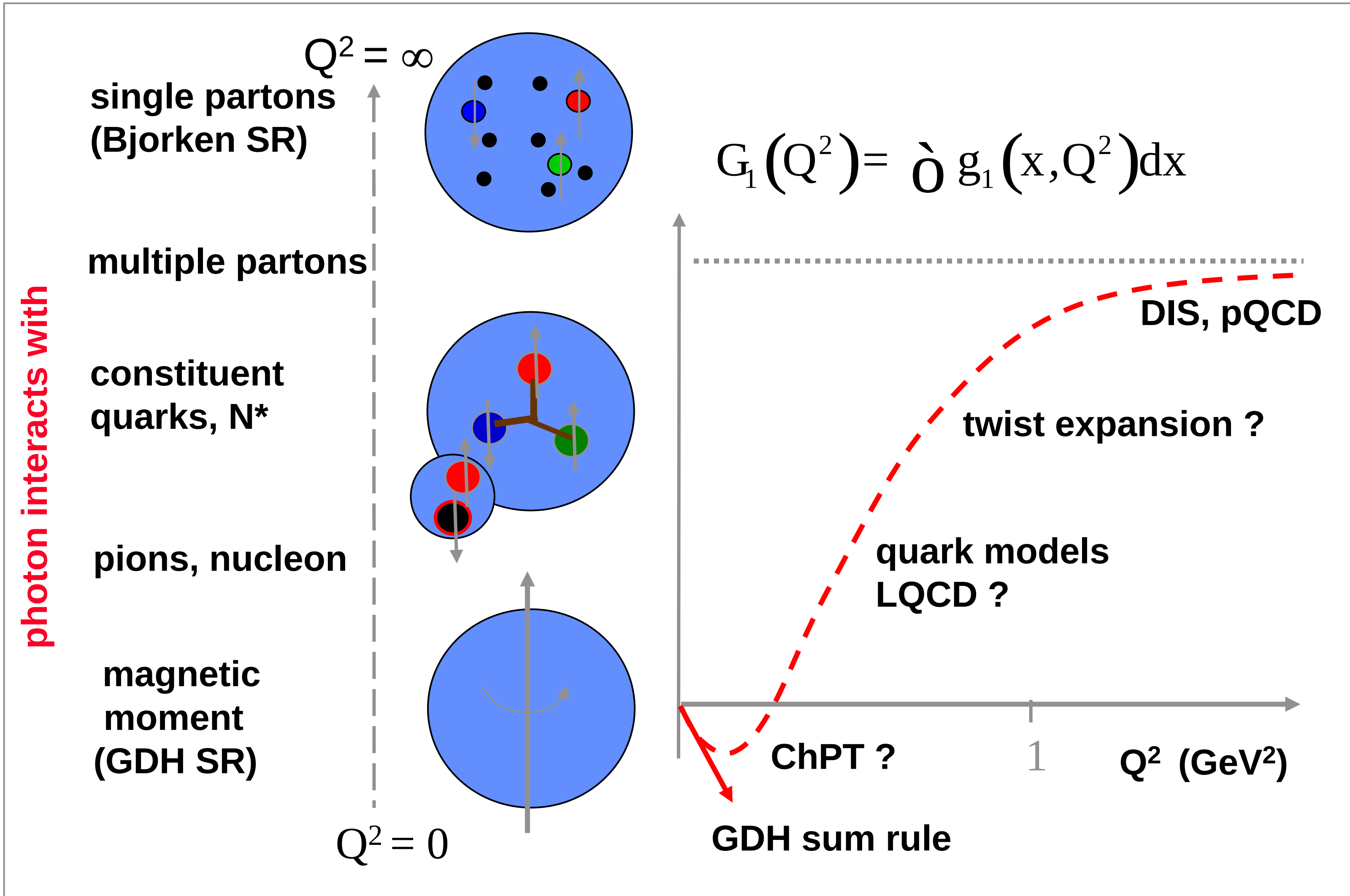
Basic assumptions: Lorentz invariance, gauge invariance, unitarity

Dispersion relation applied to forward Compton amplitude

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

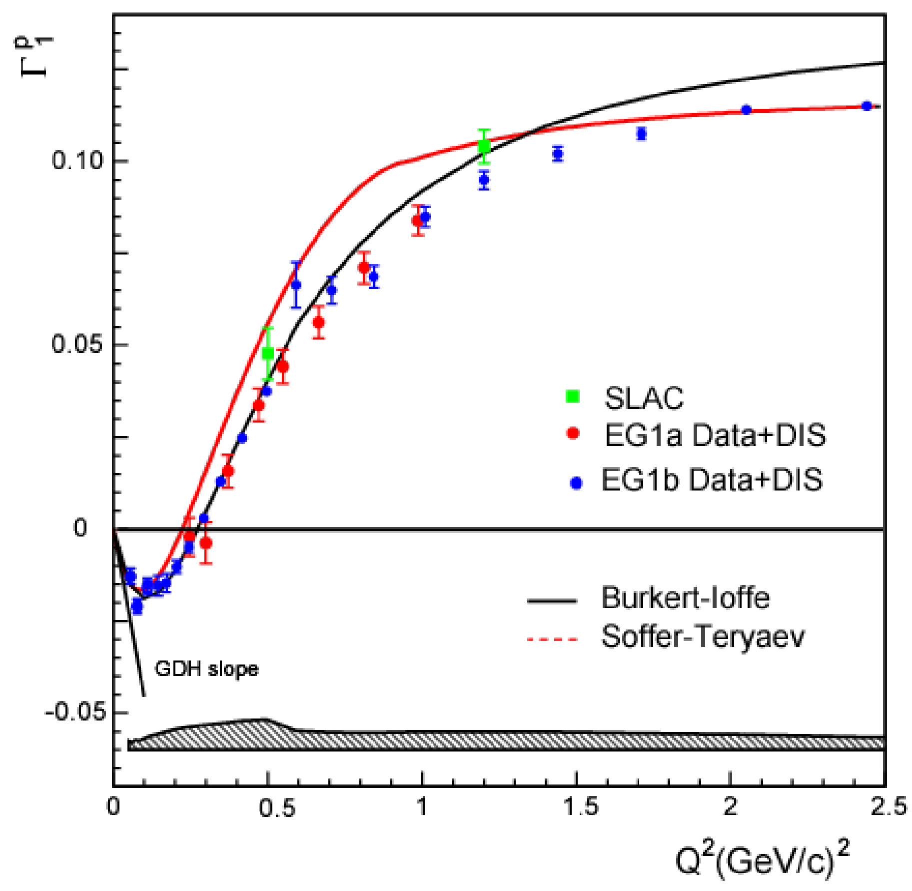
κ = nucleon anomalous magnetic moment

Moment of Proton Spin Structure Function vs Distance Scale

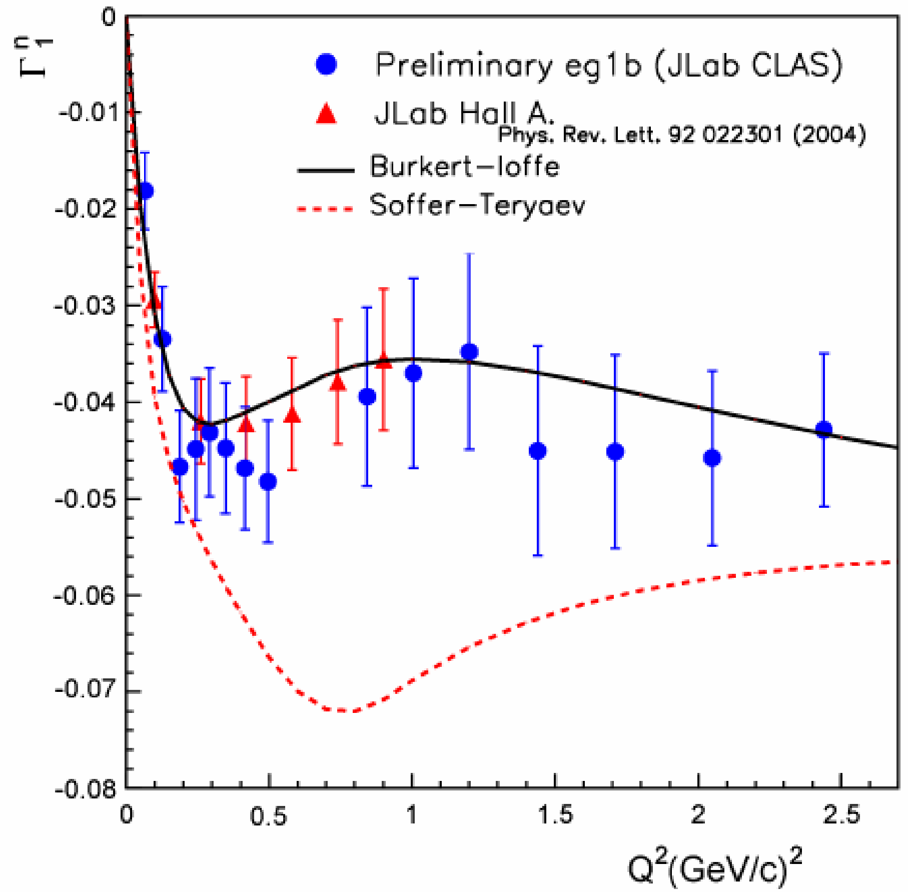


1^{st} Moment of $g_1(x,Q^2)$

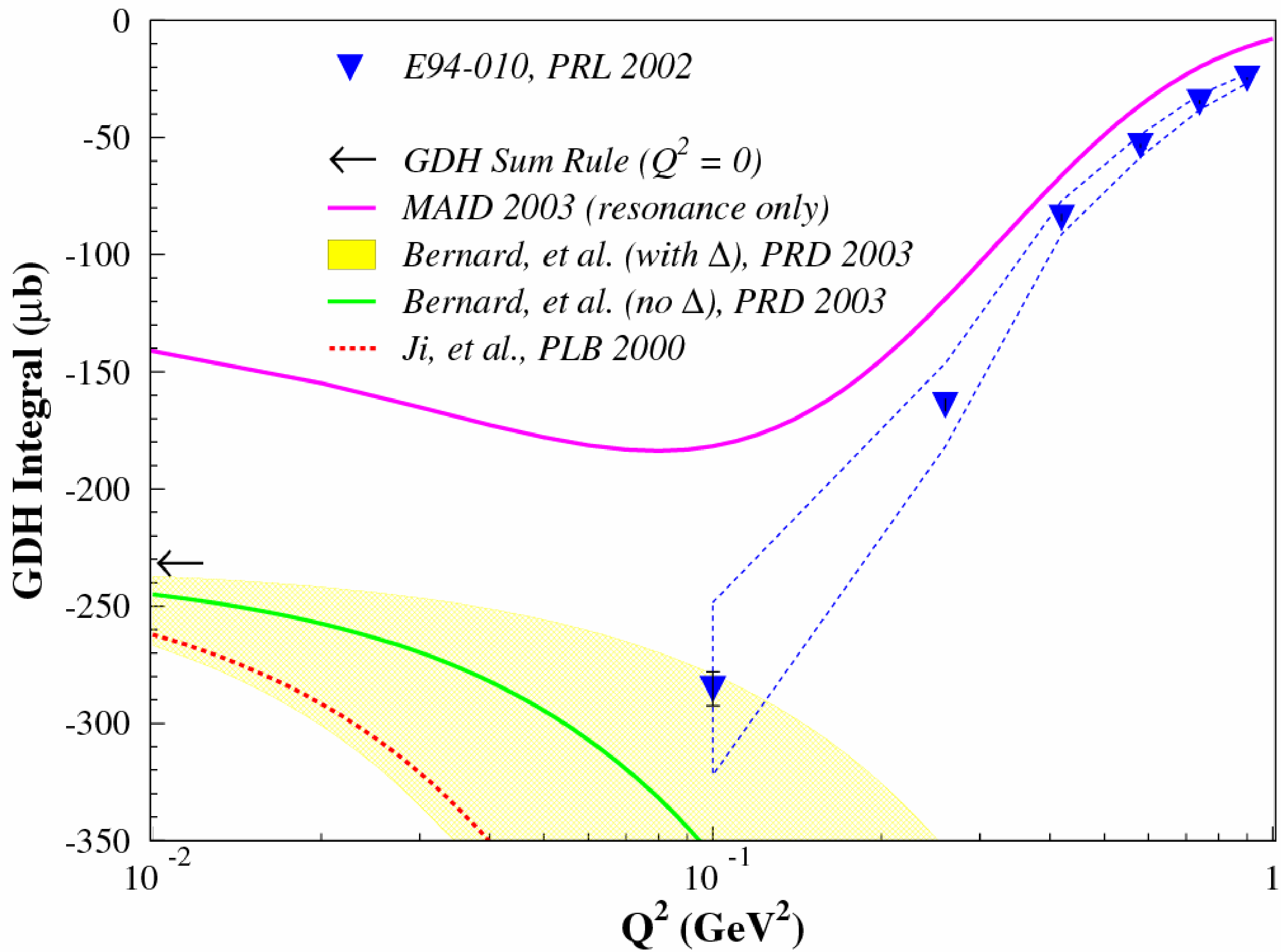
Proton



Neutron



New Hall A Data (Under Analysis) Will Push Our Knowledge of the 1st Moment for the Neutron Even Closer to the Photon Point, Where χPT Should Apply



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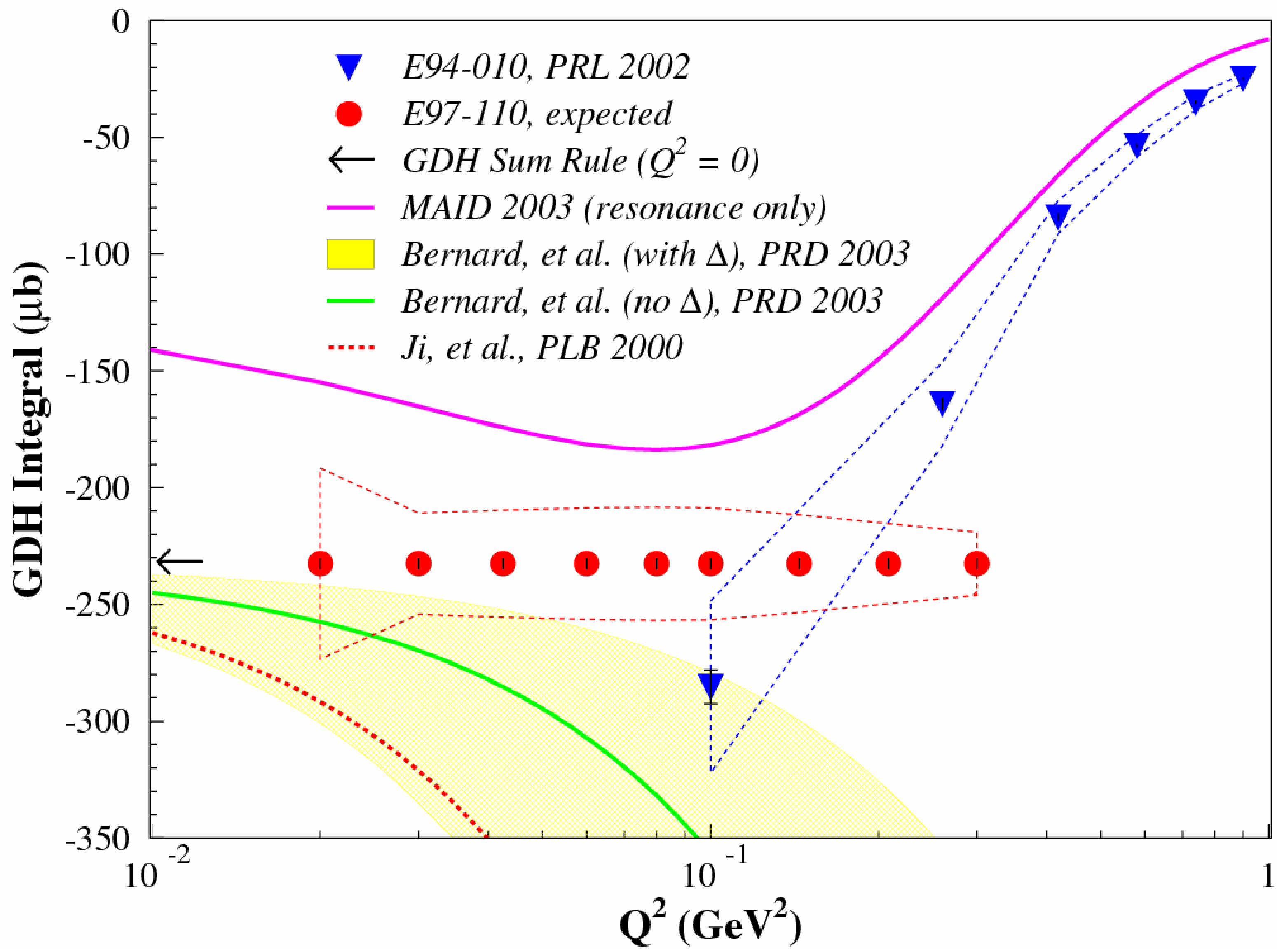
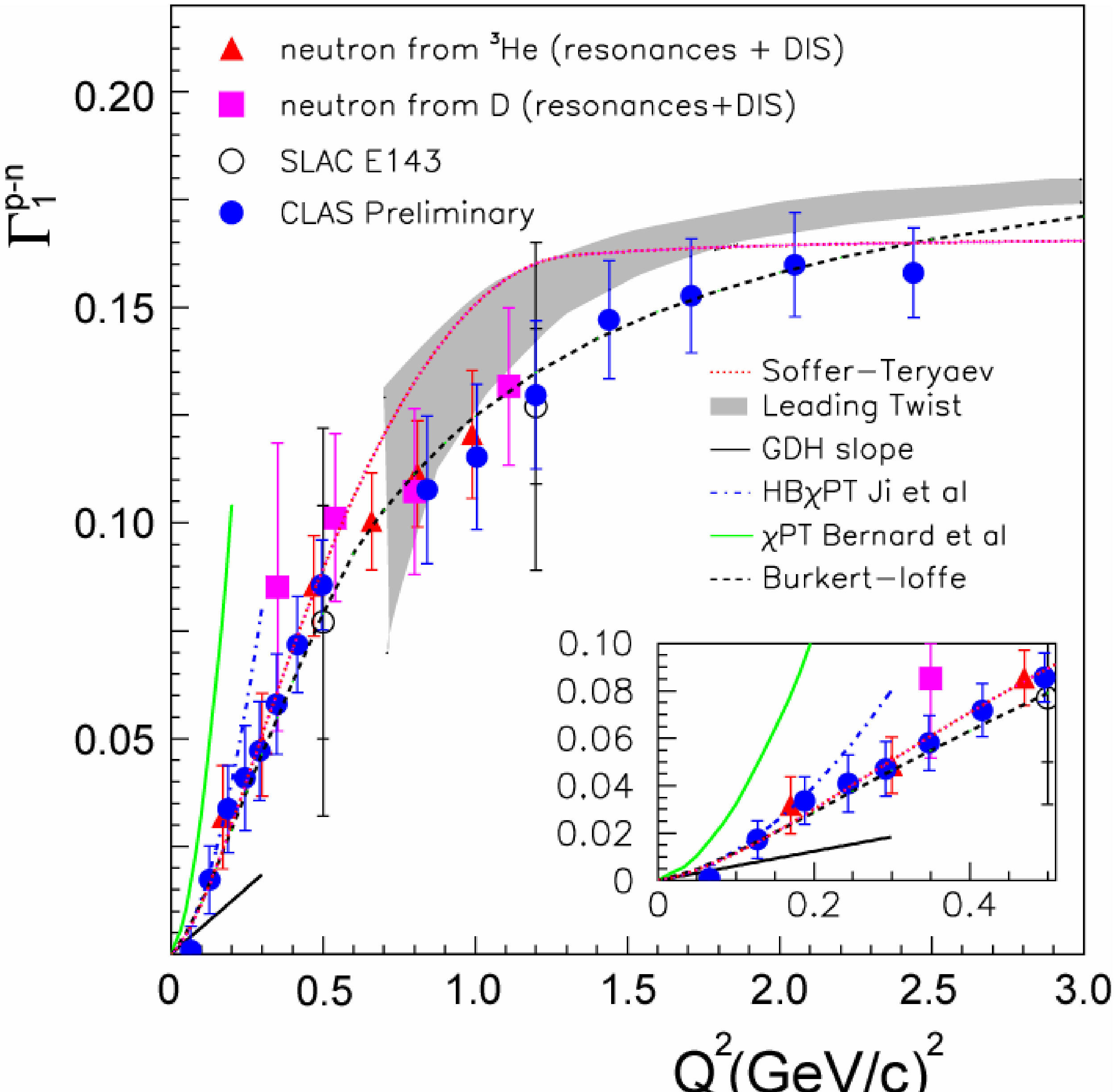


Bjorken Integral



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

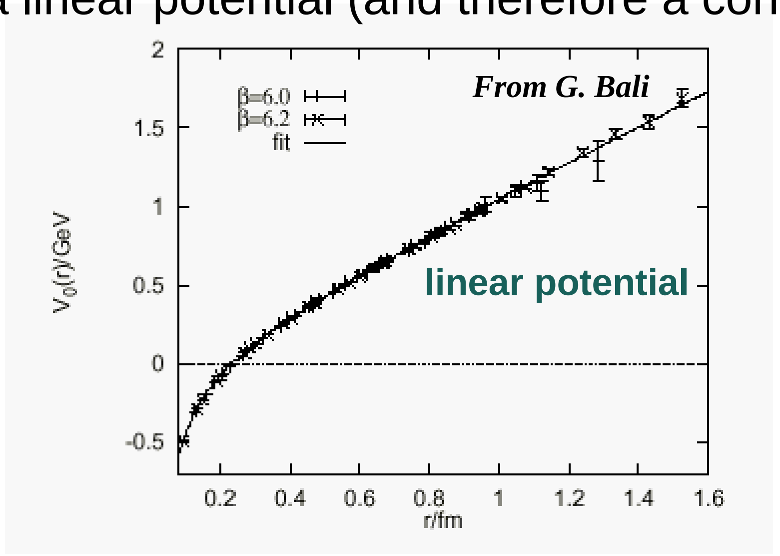
Data from CLAS now and planned,
12 GeV and Hall D are essential to this program

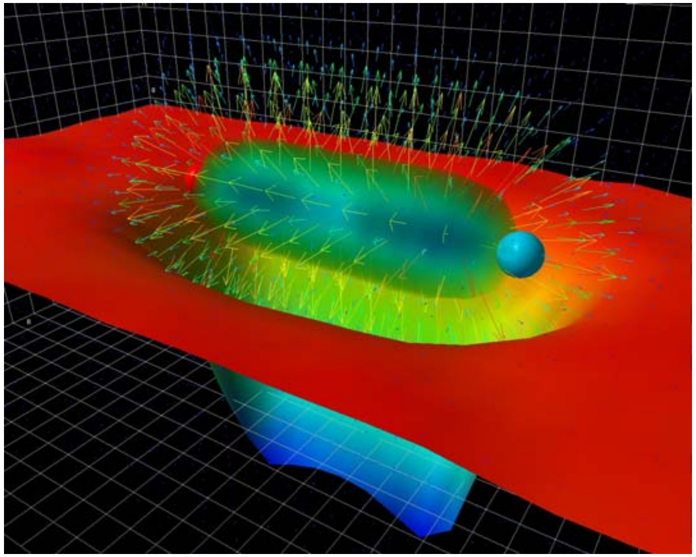
B. Where does the dynamics of the $q\text{-}\bar{q}$ interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime?

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

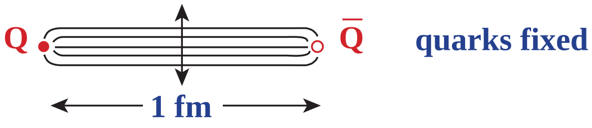
Gluonic Excitations and the Origin of Confinement

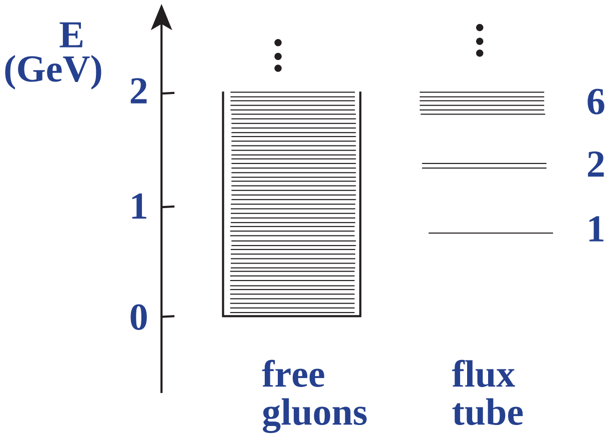
Theoretical studies of QCD suggest that confinement is due to the formation of "Flux tubes" arising from the self-interaction of the glue, leading to a linear potential (and therefore a constant force)





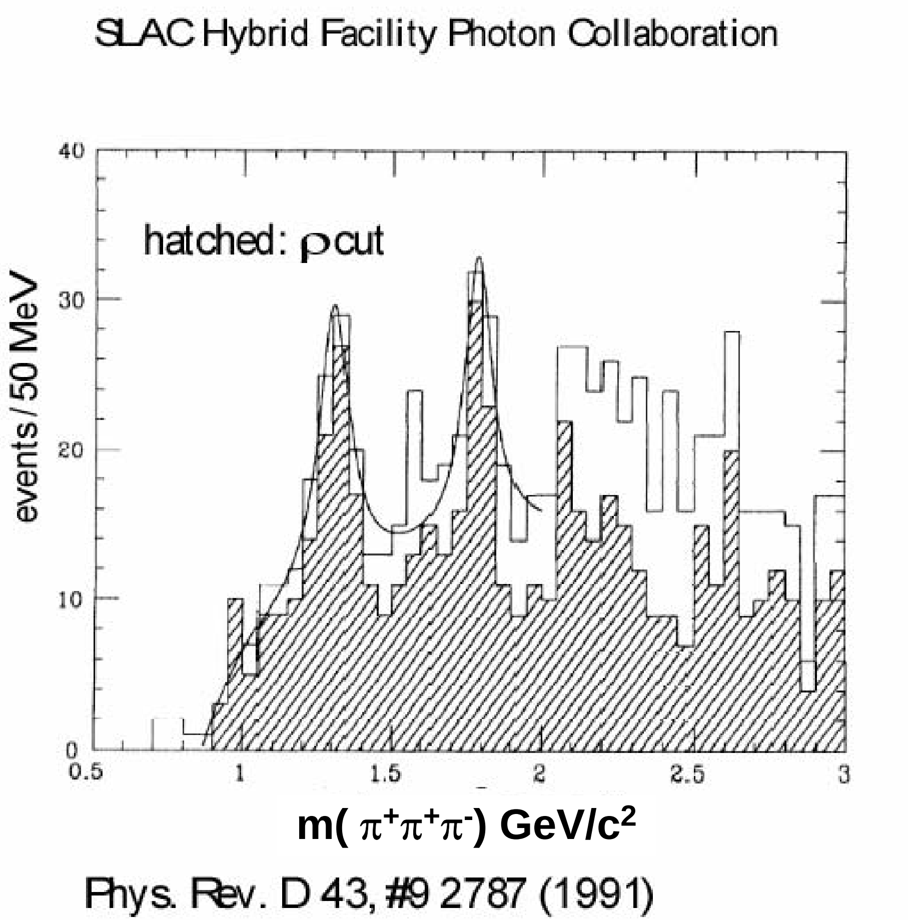
Experimentally, we want to "pluck" the flux tube (wiggle the hot dog?) and see how it responds

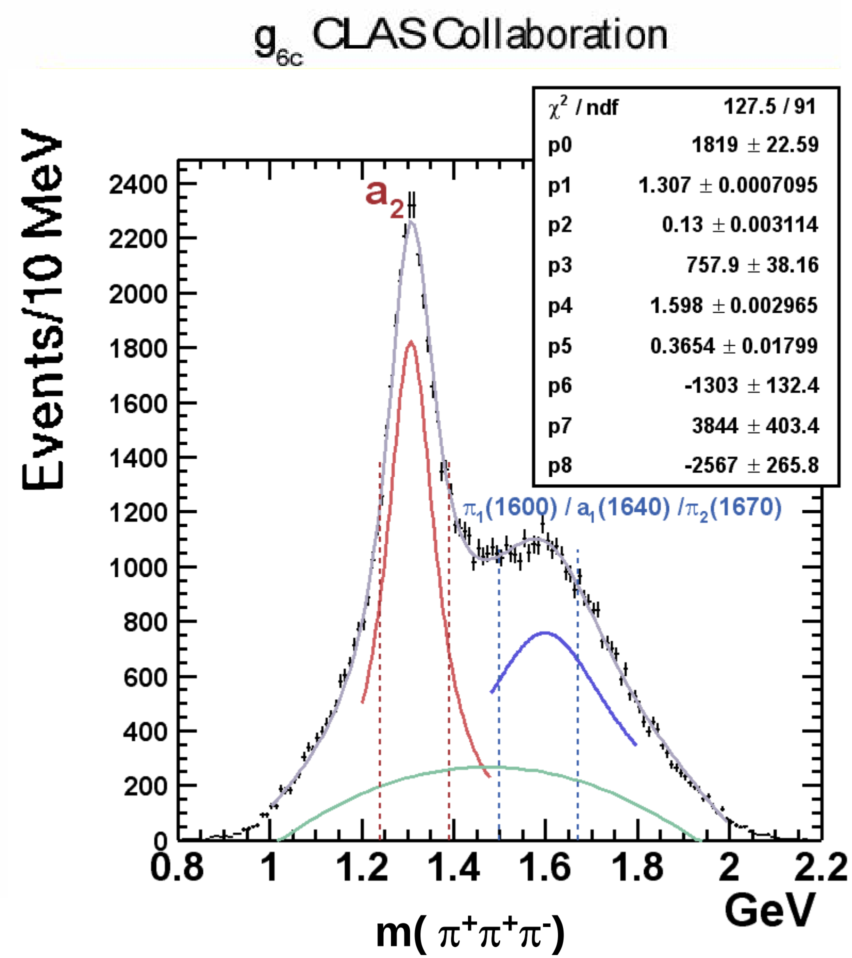




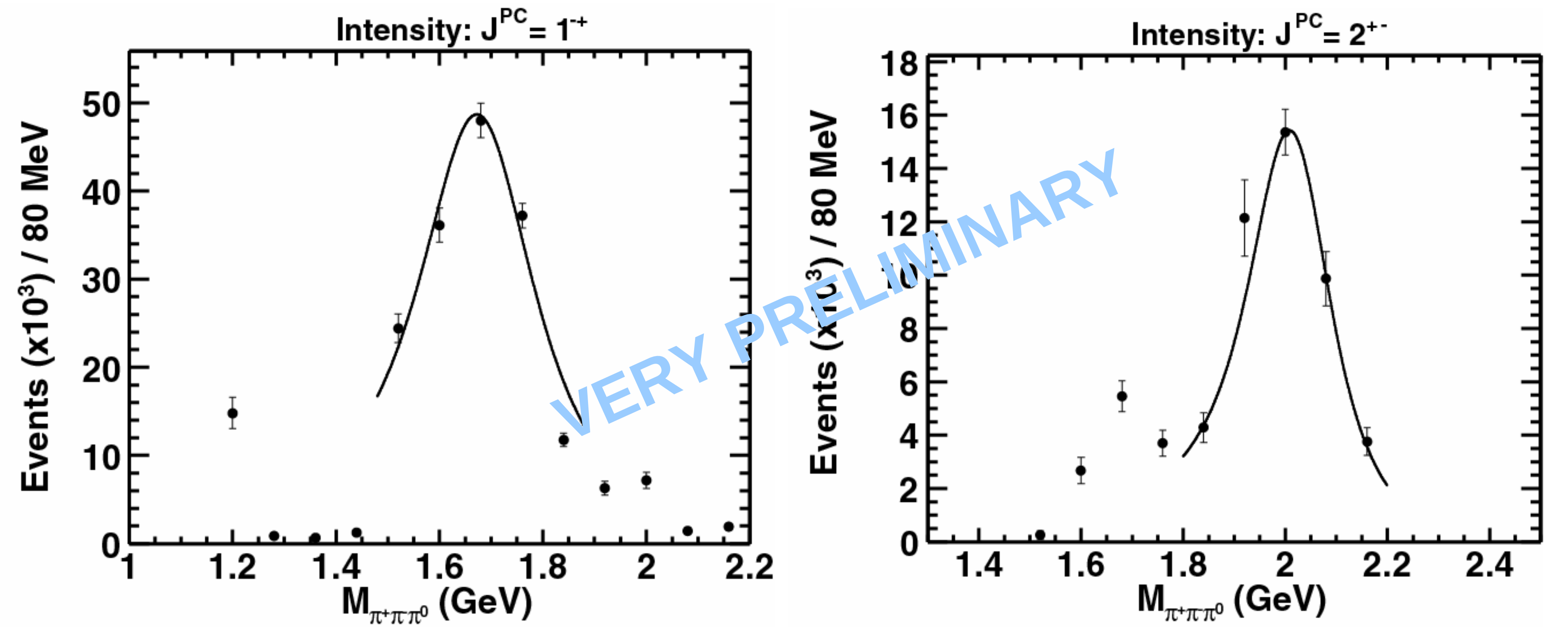
Ongoing Analysis of CLAS Data Demonstrates the Promise of Meson Photoproduction

~500x existing data on photo-production from a 1 month run with CLAS





Evidence for Additional Exotic States from Photoproduction data from CLAS g6c



$J^{PC}=1^{-+}$ Exotic Isovector State at 1600 MeV may be a 4-quark system (quatro-quark?) instead of a hybrid meson

$J^{PC}=2^{+-}$ Exotic Isoscalar State at 2020 MeV (and the $J^{PC}=1^{-+}$ 2000 MeV state seen in E852) may be the first identified hybrid mesons (match better with theory estimates of the expected energy and decays)

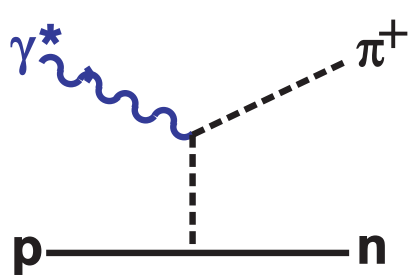
The Pion Form Factor

Where do the dynamics of the q-q interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime?

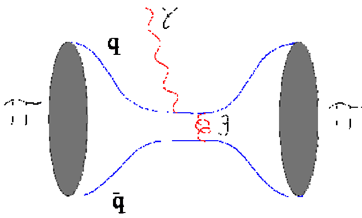
- It will occur earliest in the simplest systems; the pion form factor provides our best chance to determine the relevant distance scale experimentally

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)

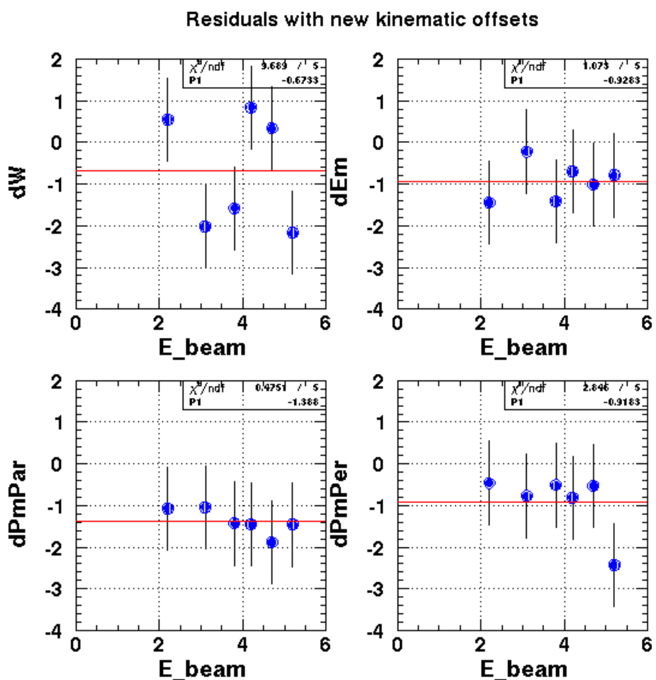


The Charged Pion Form Factor (F_π) Extension

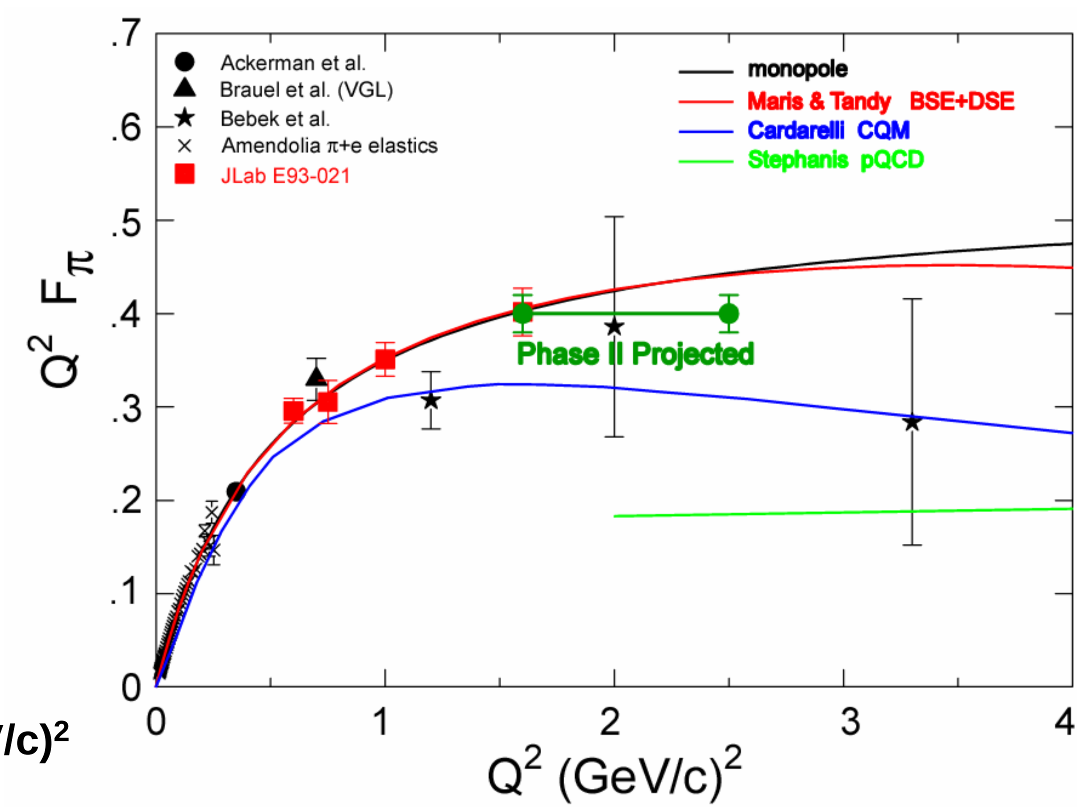


This last phase of the pre-12 GeV program extends measurements to higher Q^2 and tests the energy dependence of the Regge model used to extract F_π

The experiment ran successfully in July-August 2003. Systematic studies are in progress. The detectors have been calibrated and the kinematic offsets have been determined with MeV-level residuals



Projected Uncertainties:



These data will be extended to 6 (GeV/c)^2 with the 12 GeV Upgrade

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

Rolf (2004)

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 coming (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: $\gamma p \rightarrow K^+ \Lambda(\Sigma^0)$ (submitted to PRL)

   CLAS e1: $ep \rightarrow e' \pi^+ \eta$ (paper in review)

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)

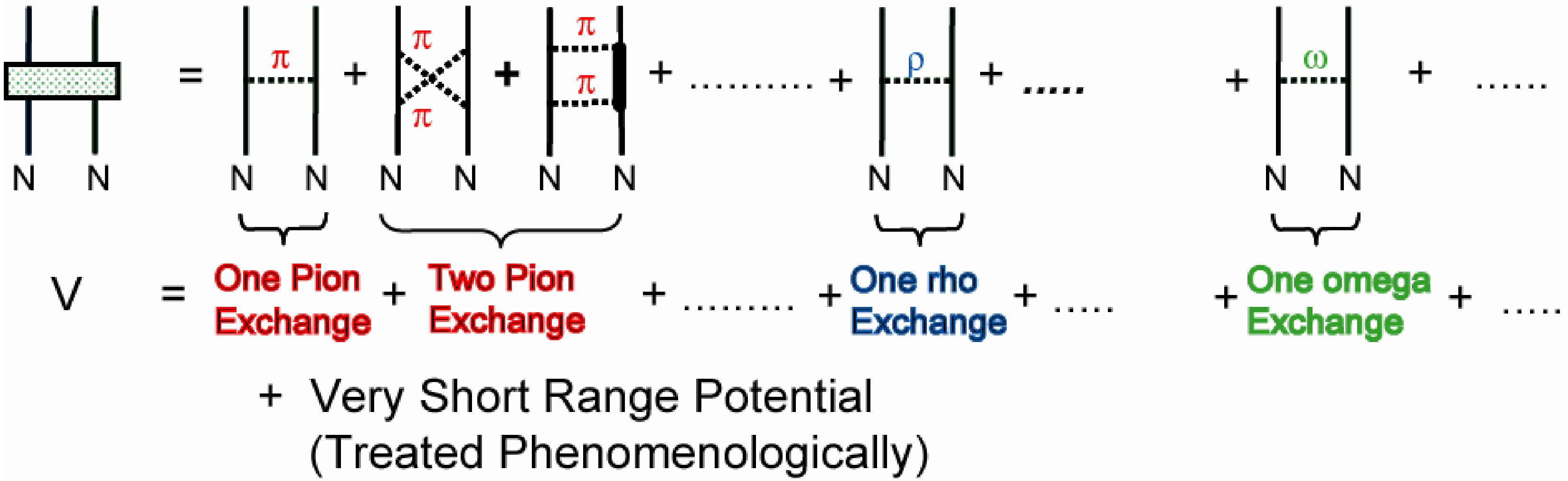
CLAS e2: $^{12}C(e,e'Np)$, $^{3}He(e,e'pp)$
$^{4}He(e,e'p)$ to high Q^2 and E_m
Sick (e,e'p) study

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)

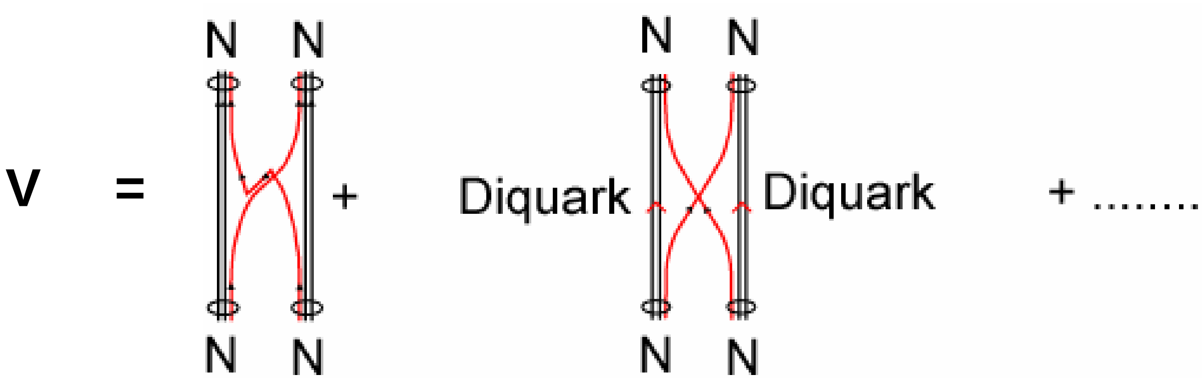
HNSS Experiment
First Hall A Results; Upcoming HKS data

Understanding the *N-N* Force

In terms of mesons and nucleons:

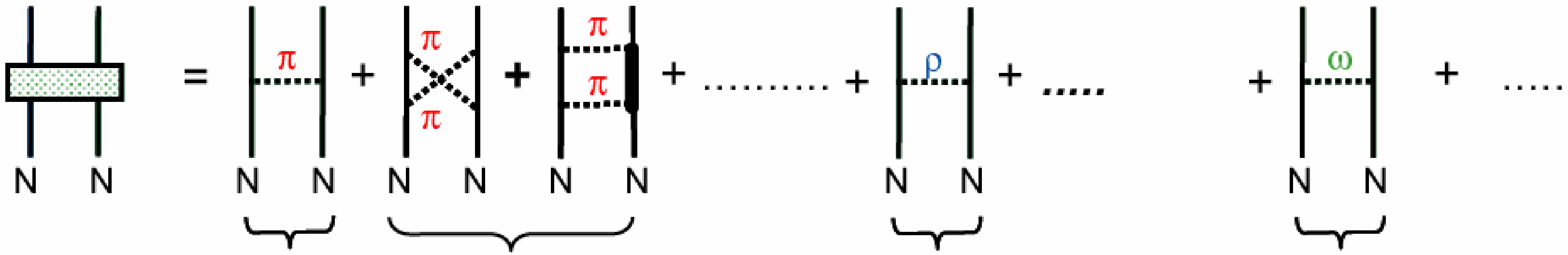


Or in terms of quarks and gluons:



Hypernuclei Provide Essential Clues

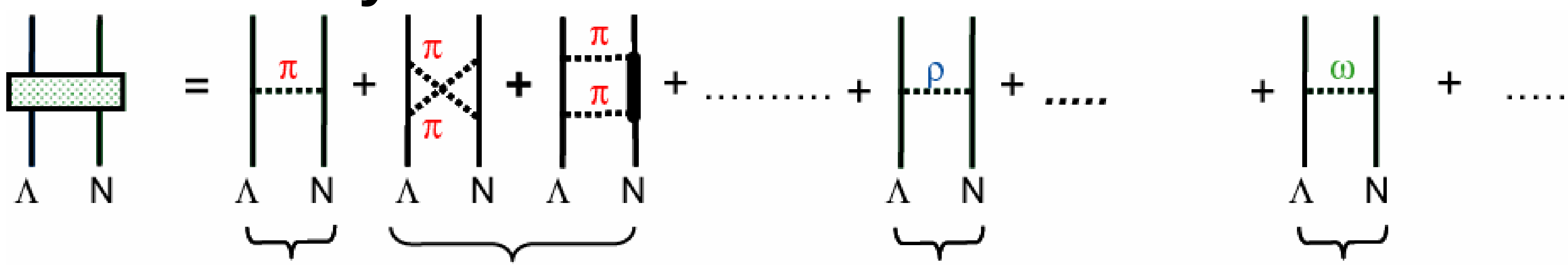
For the N-N System:



V = One Pion Exchange + Two Pion Exchange + ... + One rho Exchange + ... + One omega Exchange + ...

+ Very Short Range Potential (Treated Phenomenologically)

For the Λ-N System:

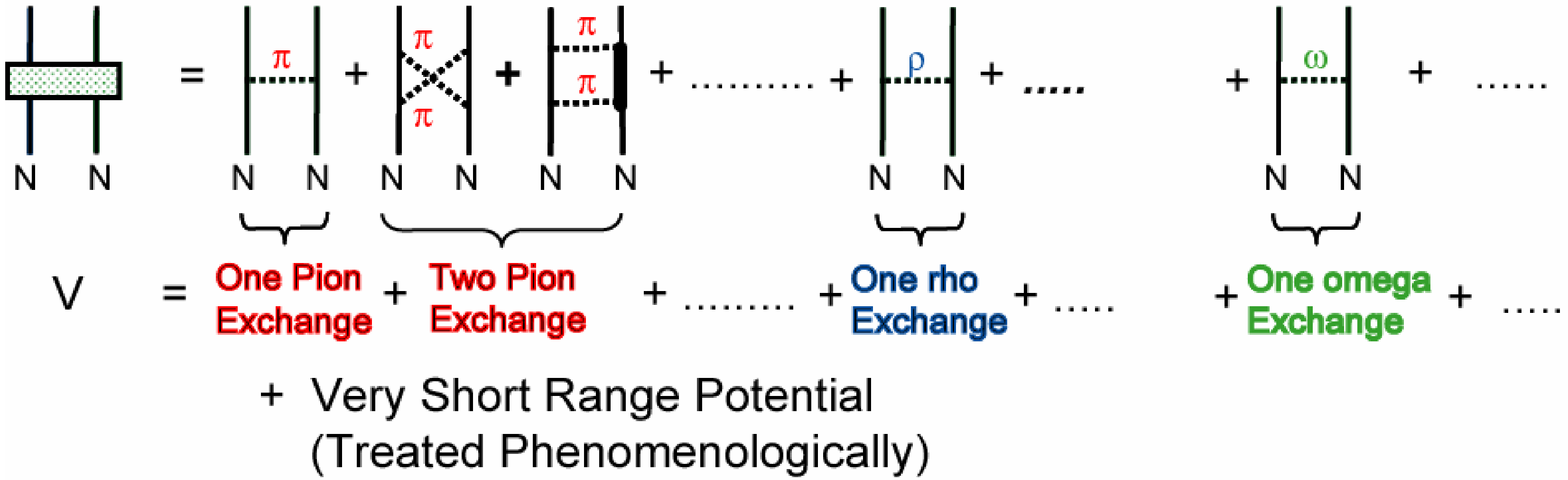


V = One Pion Exchange + Two Pion Exchange + ... + One rho Exchange + ... + One omega Exchange + ...

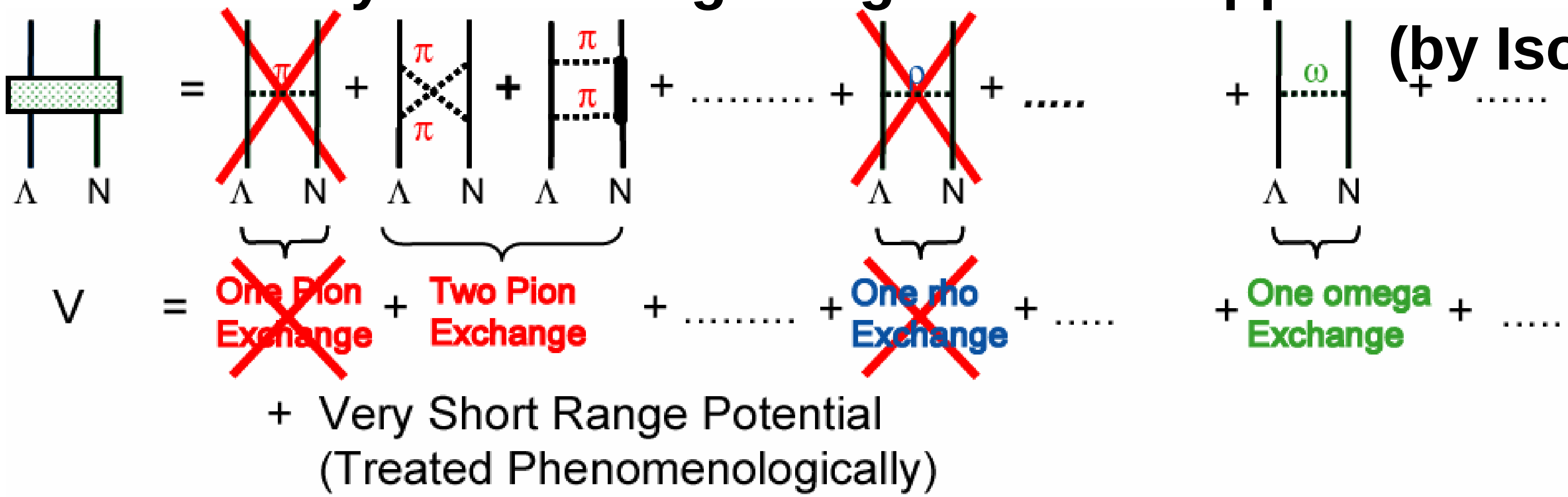
+ Very Short Range Potential (Treated Phenomenologically)

Hypernuclei Provide Essential Clues

For the N-N System:



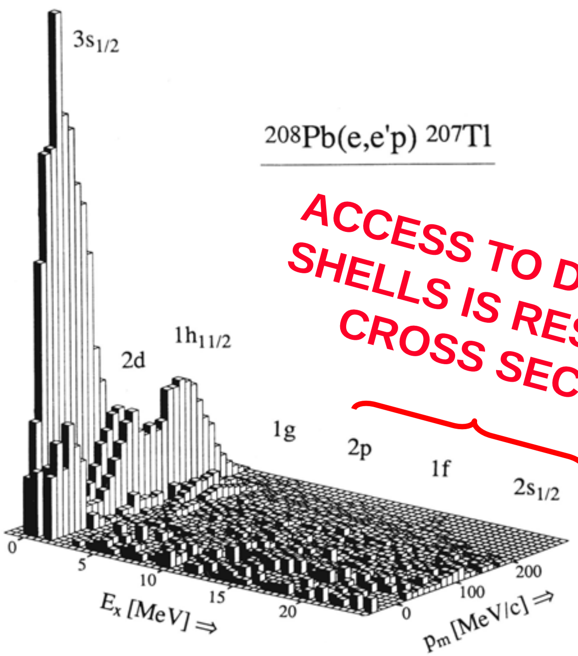
For the Λ-N System: Long Range Terms Suppressed (by Isospin)



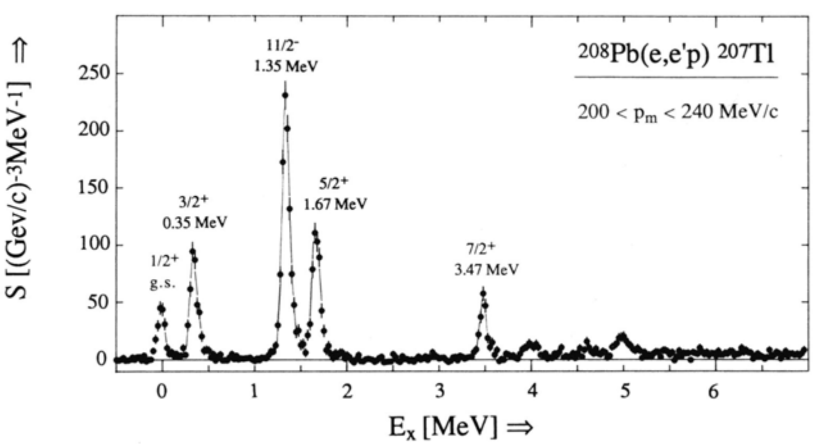
(e,e'p) ⇒ Nucleon Momentum Distributions, Shell-by-Shell

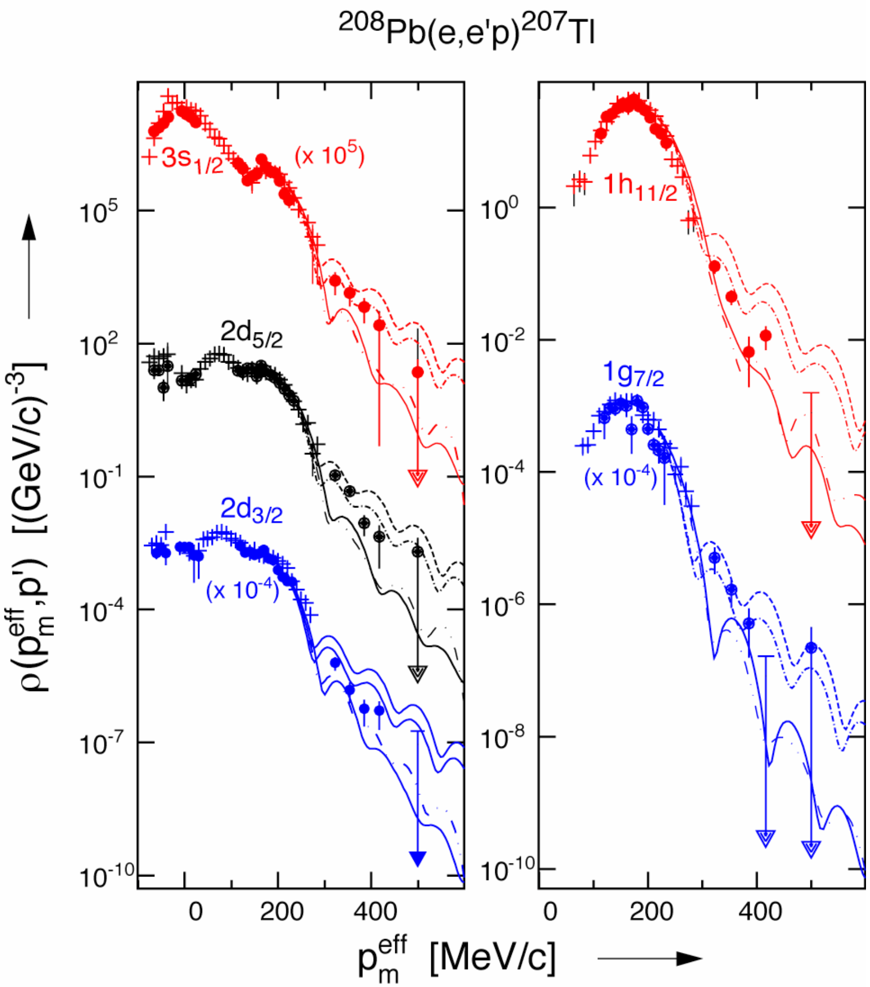
$$p_m = E_e - E_{e'} - p = q - p$$

$$E_m = \omega - T_p - T_{A-1} = E_{sep} + E_{exc}$$



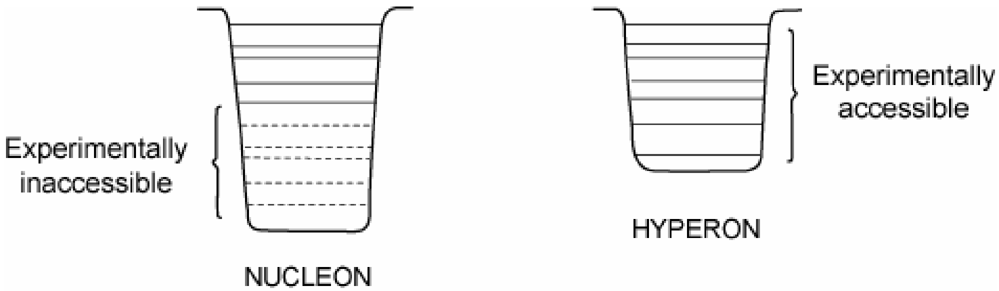
ACCESS TO DEEPLY LYING SHELLS IS RESTRICTED BY CROSS SECTION, FSI





"Impurities" Solve the Problem:

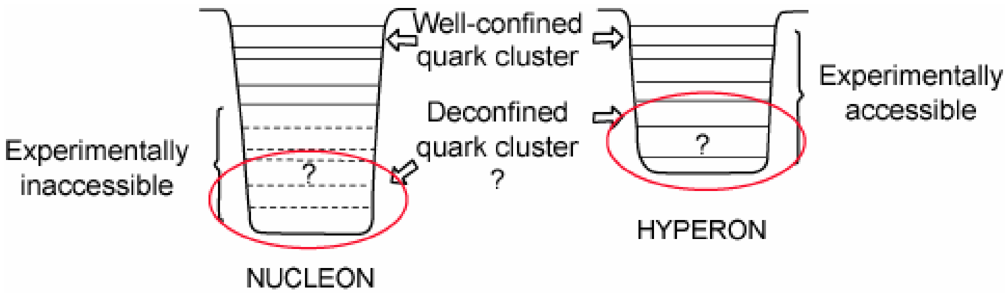
The distinguishability of the hyperon permits us to probe deeply-bound shells in nuclei



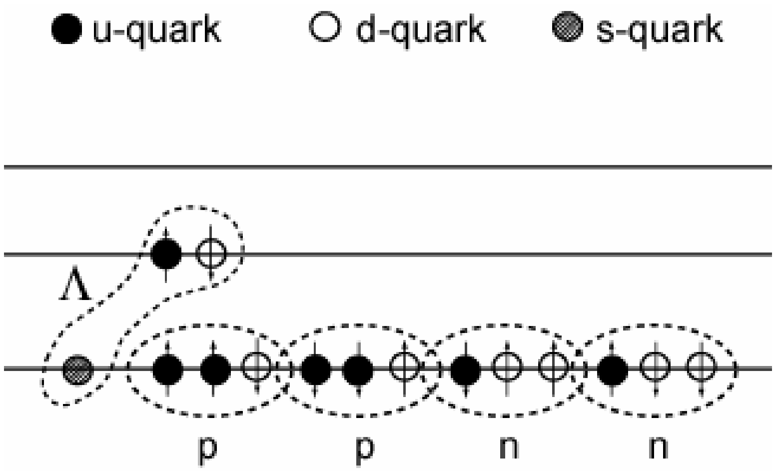
Possible single-particle orbitals for nucleons and for a hyperon. The nucleon orbitals are occupied up to the Fermi surface, while the hyperon orbitals are unoccupied.

Access deeply bound nuclear states

“Impurities” Solve the Problem:
The distinguishability of the hyperon permits us to probe deeply-bound shells in nuclei



Possible single-particle orbitals for nucleons and for a hyperon. The nucleon orbitals are occupied up to the Fermi surface, while the hyperon orbitals are unoccupied.

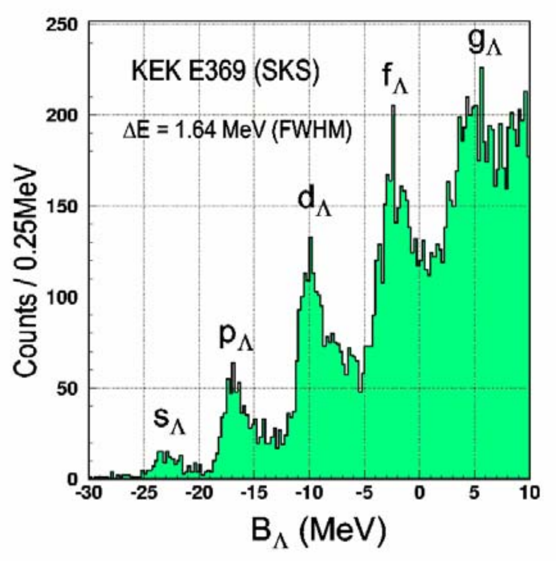


Access deeply bound nuclear states

and provide the opportunity to probe the quark structure of nuclear systems in new and different ways.

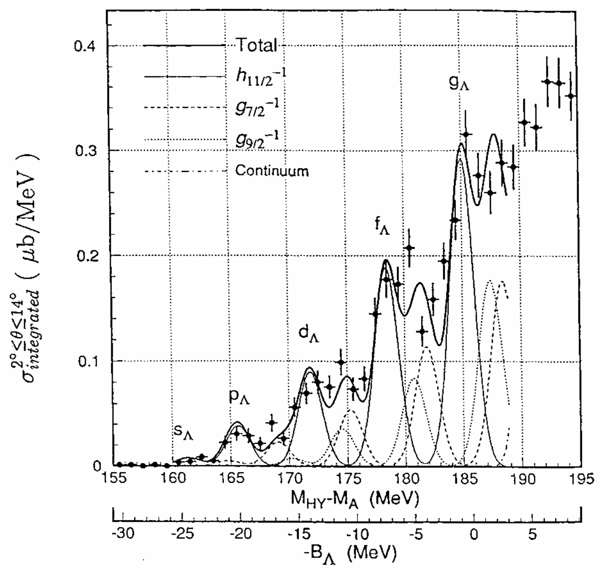
Λ Single Particle Potential

$^{89}Y(\pi^+,K^+)^{89}{}_{\Lambda}Y$



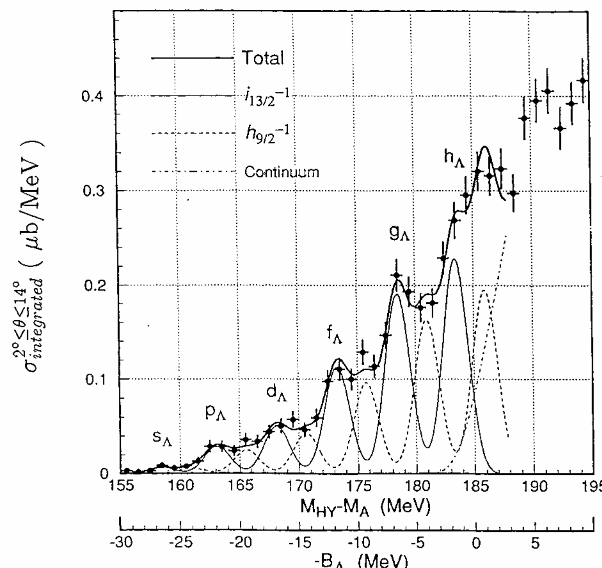
Hotchi et al., PRC 64 (2001) 044302

$^{139}La(\pi^+,K^+)^{139}{}_{\Lambda}La$



KEK E140a

$^{208}Pb(\pi^+,K^+)^{208}{}_{\Lambda}Pb$



Hasegawa et. al., PRC 53 (1996)1210

Textbook example of Single-particle orbits in a nucleus

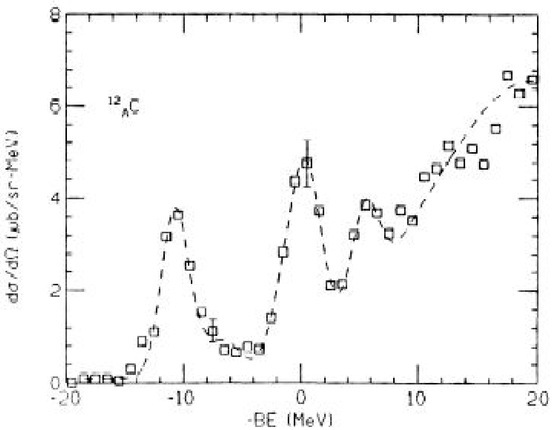
Λ Single particle states

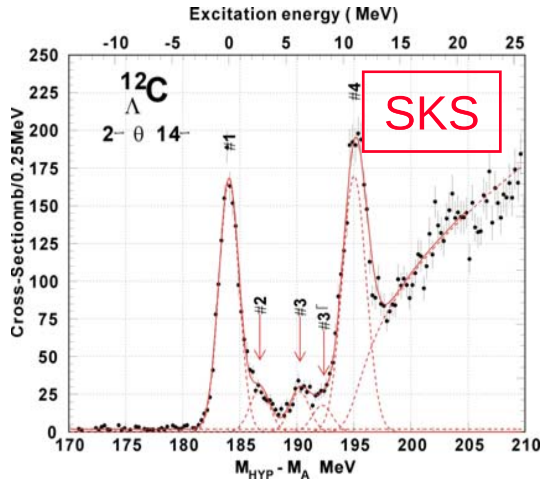
$\Rightarrow$ Λ-nuclear potential depth = - 30 MeV

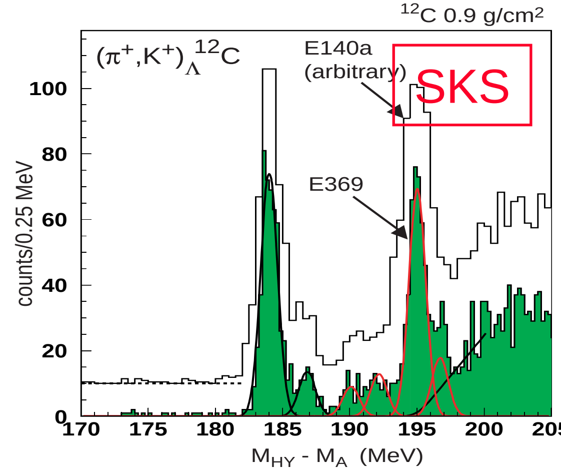
$\Rightarrow$ $V_{\Lambda N} < V_{NN}$

$^{12}{}_{\Lambda}C$ spectra

$^{12}C(\pi^+,K^+)$







BNL: 3 MeV(FWHM)

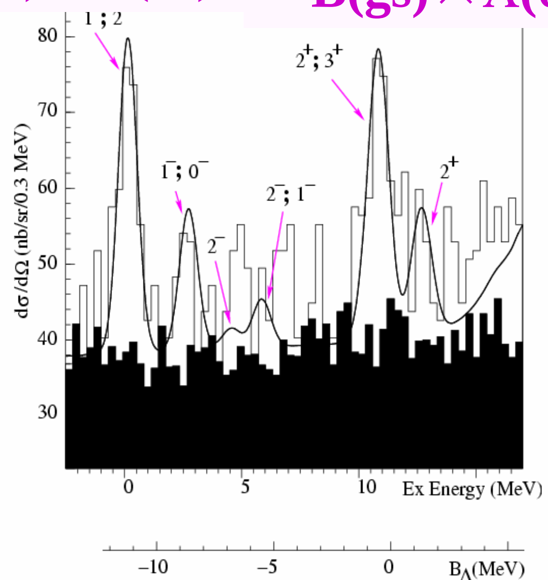
KEK336: 2 MeV (FWHM)

KEK E369: 1.45 MeV(FWHM)

E89-009 $^{12}C(e,e'K)$ HNSS

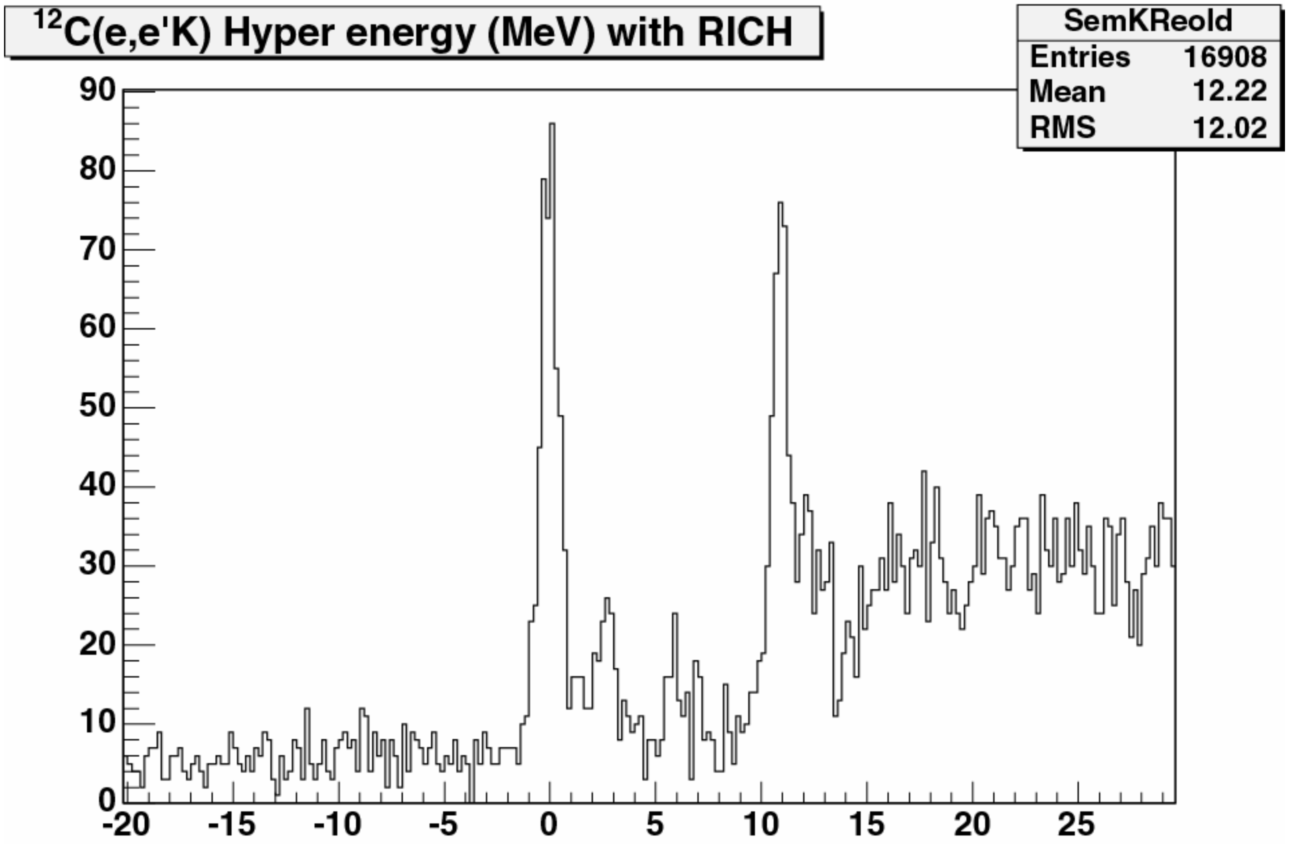
- **Demonstrated the feasibiltiy of the electroproduction of hypernuclei**
- **Achieved 0.9 MeV (FWHM) Resolution and provided information for future improvements**
- **Observed both S_{Λ} and P_{Λ} States in ^{12}C – in reasonable agreement w/ theory**
- **Large discrepancy w/ theory for the $^7He_{\Lambda}$ system (neutron rich)**

$^{11}B(gs)\times\Lambda(0s)$ $^{11}B(gs)\times\Lambda(0p)$



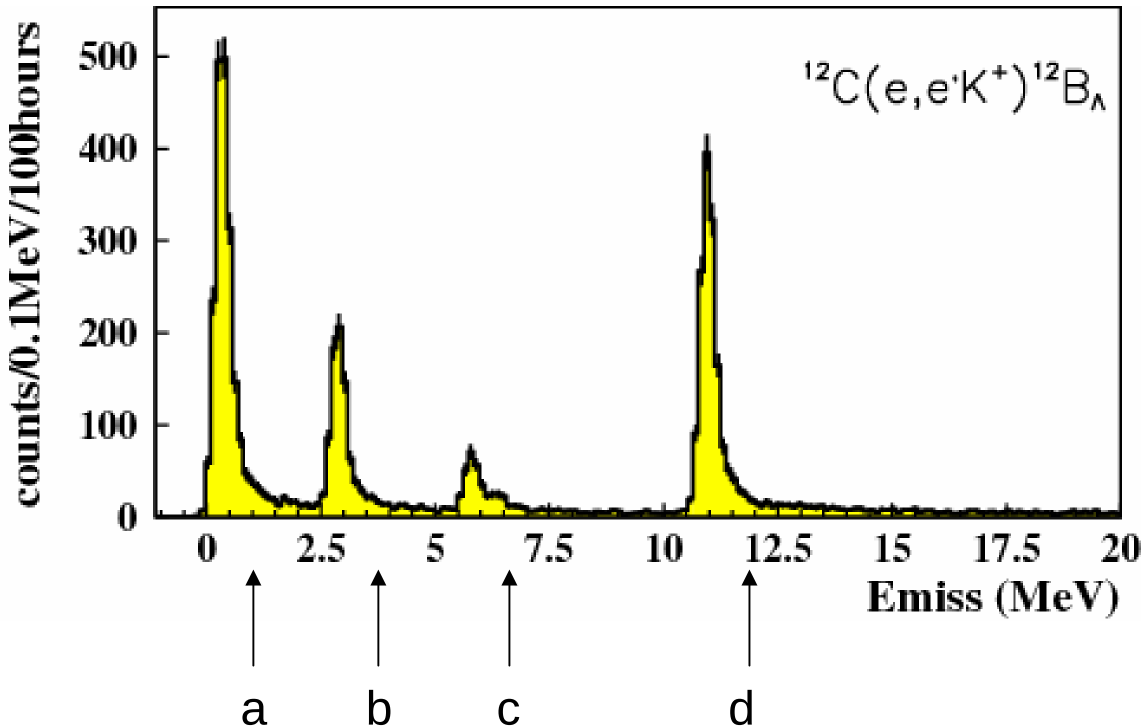
calc. by Motoba

HALL A E94-107: The 1st "Septum" Hypernuclear Experiment Near-Line (uncorrected) Results for $^{12}C\ (e,e'K)^{12}B_{\Lambda}$



- Enhanced count rate, better resolution, and reduced backgrounds obvious on-line (~3/4 of accumulated data shown)
- Analysis (in progress) with corrections for beam energy and including the first pass at septum-spectrometer optics corrections show that the experiment will achieve its goal of 400 keV energy resolution in the hypernucleus

HALL A E94-107: The 1st “Septum” Hypernuclear Experiment
Anticipated Results for $^{12}C\,(e,e'K)^{12}B_{\Lambda}$

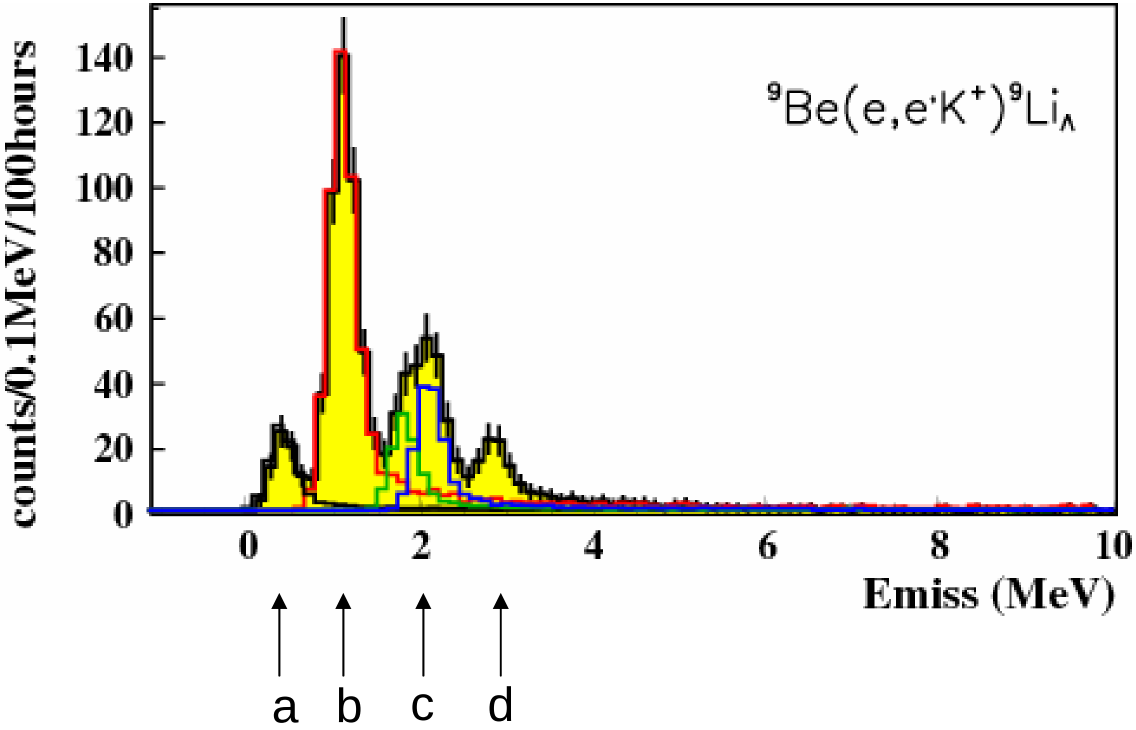


$$
\begin{aligned}
V_{N\Lambda} &= V_0(r) && \text{V (central)}\\
&+V_\sigma(r)\sigma_N\cdot\sigma_\Lambda && \Delta\ (\text{spin}-\text{spin})\\
&+V_{SO}(r)l_{\Lambda N}\cdot\sigma_\Lambda && S_\Lambda\ (\text{spin}-\text{orbit})\\
&+V_{SO}(r)l_{\Lambda N}\cdot\sigma_N && S_N\ (\text{spin}-\text{orbit})\\
&+V_T(r)S_{12} && T\ \ (\text{Tensor})
\end{aligned}
$$

$$S_{12} = 3(\sigma_N\cdot\vec{r})(\sigma_\Lambda\cdot\vec{r}) - (\sigma_N\cdot\sigma_\Lambda)$$

By measuring the absolute position and relative spacing of the “resolvable” peaks a,b,c and d we can learn about the N-Λ Interaction Potential parameters and the relative strengths of the terms: (spin-spin, spin-orbit, tensor, …)

HALL A E94-107: The 1st "Septum" Hypernuclear Experiment
Anticipated Results for ^{9}Be (e,e'K)^{9}Be$_{\Lambda}$



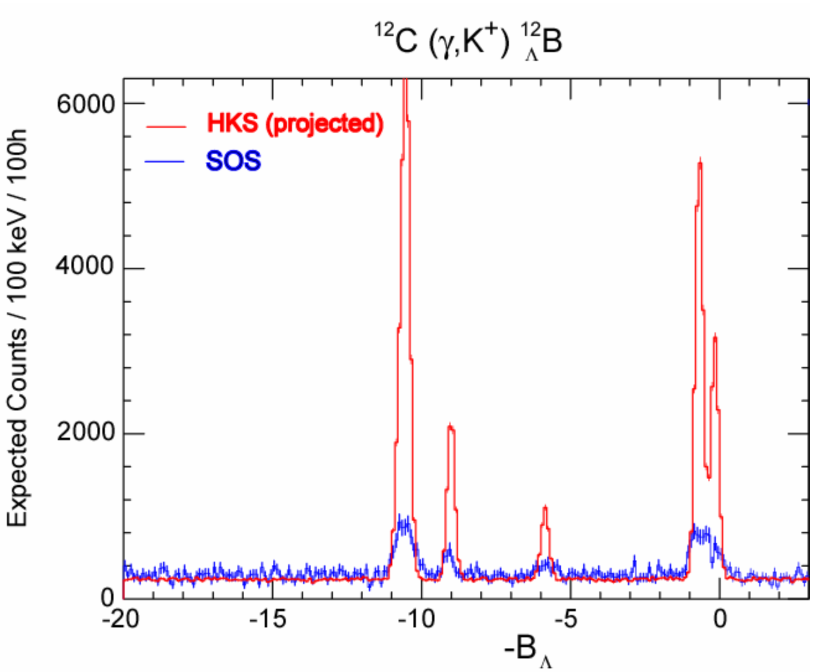
$$
\begin{aligned}
V_{N\Lambda} &= V_0(r) && \text{V (central)}\\
&+V_\sigma(r)\sigma_N\cdot\sigma_\Lambda && \Delta\ \text{(spin} - \text{spin)}\\
&+V_{SO}(r)l_{\Lambda N}\cdot\sigma_\Lambda && S_\Lambda\ (\text{spin} - \text{orbit})\\
&+V_{SO}(r)l_{\Lambda N}\cdot\sigma_N && S_N\ (\text{spin} - \text{orbit})\\
&+V_T(r)S_{12} && T\ \ \text{(Tensor)}
\end{aligned}
$$

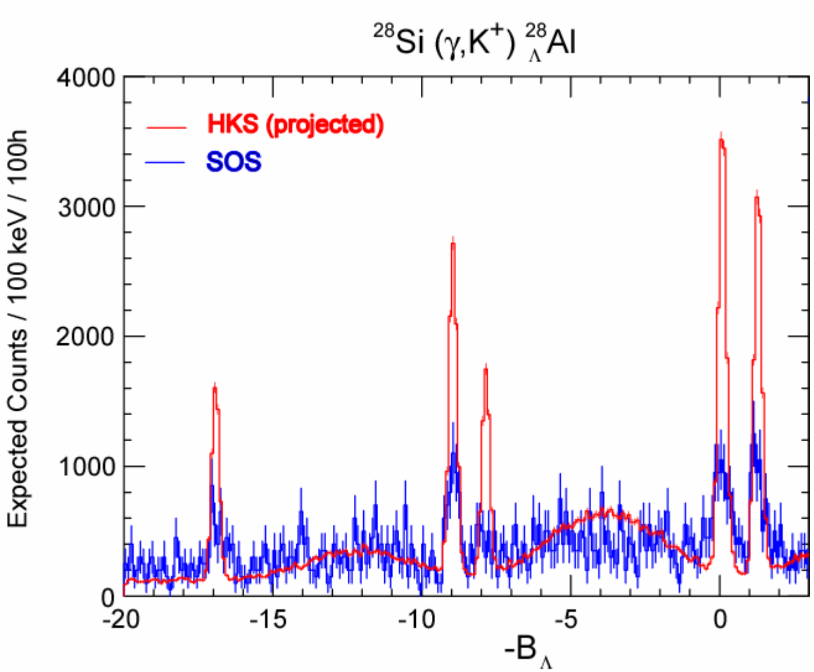
$$S_{12} = 3(\sigma_N\cdot\vec{r})(\sigma_\Lambda\cdot\vec{r}) - (\sigma_N\cdot\sigma_\Lambda)$$

In particular, from the Beryllium target hypernuclear spectrum, the spacing between the components of the first doublets (peaks a,b) provide information about the terms Δ, **S_Λ and T** of the Λ**N interaction potential** , while the spacing between the (unresolved) doublets c and d are mainly affected by the spin-orbit term **S_N**

Anticipated HKS Hypernuclear Spectra

(New JLab Facility developed by O. Hashimoto et al)

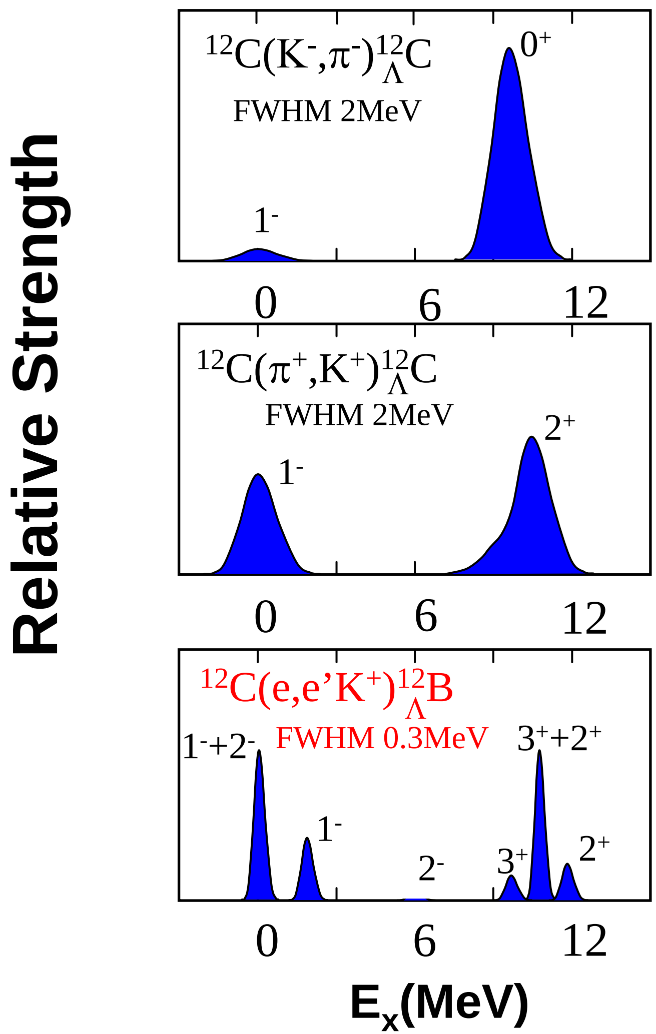




- Anticipate 300 keV (FWHM)
- Complements Hyperball for states that don't γ decay
- Complements π production with respect to spin, parity, and momentum transfer

With these new tools, the next generation of hypernuclear studies is now underway, with great promise for the future

Complementarity of (K$^-$,π^-), (π^+,K$^+$), and (e,e'K$^+$) Reactions



q **~ 100MeV/*c*** $\rightarrow$ **ΔI = 0**
$\rightarrow$ **substitutional states**
ΔS = 0
$\rightarrow$ **J = 0$^+$**

q **~ 300MeV/*c*** $\rightarrow$ **ΔI = 1, 2**
$\rightarrow$ **stretched states**
ΔS = 0
$\rightarrow$ **J = 1$^-$, 2$^+$**

q **~ 300MeV/*c*** $\rightarrow$ **ΔI = 1, 2**
$\rightarrow$ **stretched states**
ΔS = 0,1
$\rightarrow$ **J = 2$^-$, 3$^+$ (as well as 1$^-$, 2$^+$)**

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

Rolf (2004)

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

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)

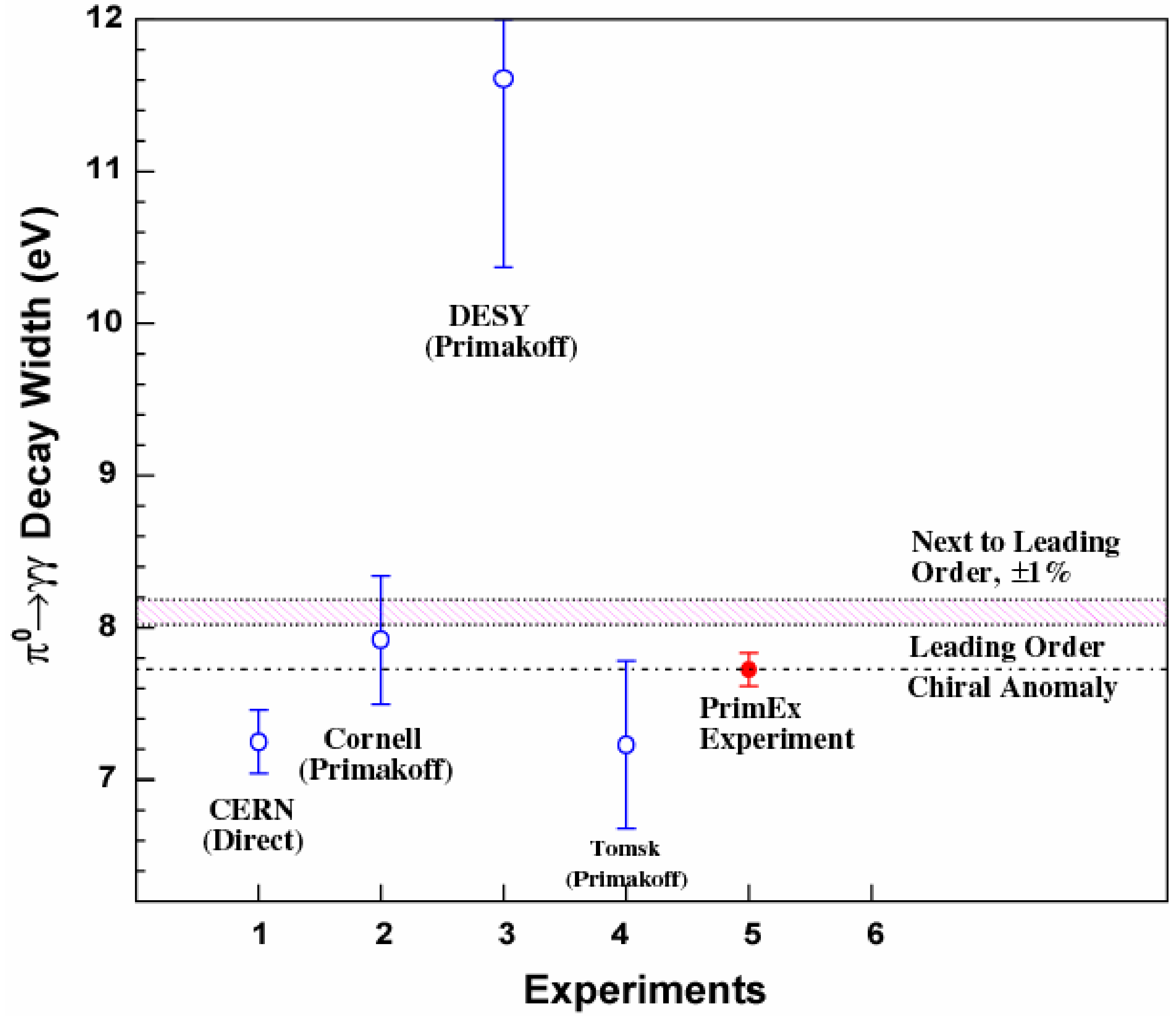
PrimEx: A Precision Measurement of the 2-photon Decay Width of the Neutral Pion

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

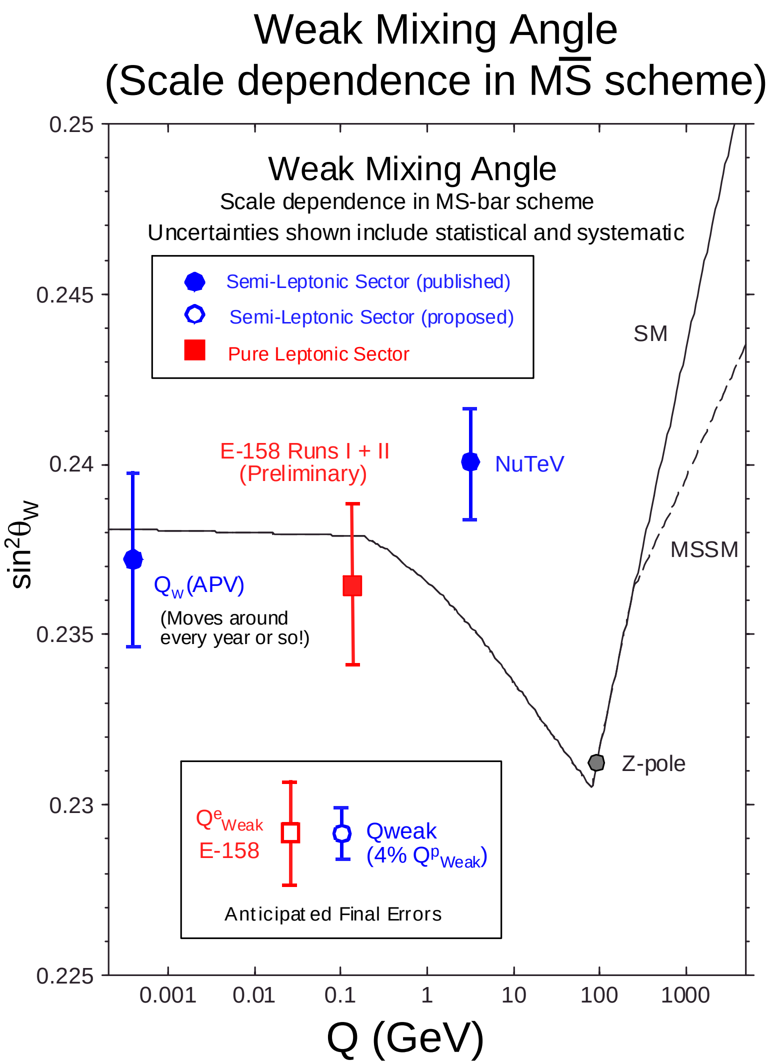
Experiment to begin late this FY

Test runs demonstrated photon flux measurements now accurate to <1%, a key requirement for the experiment's success

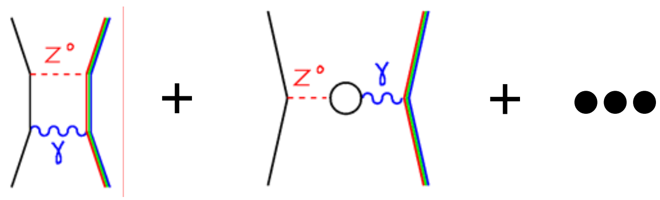


The Q^p_{Weak} Experiment

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) together make a powerful program to search for and identify new physics.

Issues from Last S&T Review

1. **Improve the long-range planning of accelerator capabilities needed to mount the approved experimental program.**

   Running 3-year draft schedule now developed and revised semi-annually

2. **Add experts in unusual areas (e.g. Standard Model tests) when such experiments are under consideration.**

   Our PAC is broad, independent, and generally qualified to review all proposals received. We have sought additional advice, via both direct contact with experts and special advisory committees, as appropriate

3. **Create a focused effort on N* analysis, including theorists, phenomenologists**

   Proposal developed, submitted and reviewed. Minor revisions in progress in response to suggestions received from highly favorable and supportive reviews. We hope funding will start ASAP

SC Goals for Hadronic Physics

- **Make precision measurements of fundamental properties of the proton, neutron and simple nuclei for comparison with theoretical calculations to provide a quantitative understanding of their quark substructure.**
  - Time frame – By 2015
  - Expert Review every five years rates progress as "Excellent"
  - <u>Minimally Effective</u> – Quark and gluon contributions to the nucleon's spatial structure and spin measured; theoretical tools for hadron structure developed and tested; data show how simple nuclei can be described at a nucleon or quark-substructure level for different spatial resolution of the data
  - **<u>Successful</u> – Quark flavor dependence of nucleon form factors and structure functions measured; hadron states described with QCD over wide ranges of distance and energy; the nucleon-nucleon interaction mechanisms determined from QCD; precise measurements of quark and gluon contributions to nucleon spin performed.**

10 SC Milestones in Hadronic Physics

Year	Milestones:
2008	Make measurements of spin carried by the glue in the proton with polarized proton-proton collisions at center of mass energy, $\sqrt{s_{NN}}$ = 200 GeV.
2008	Extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 - 0.4 , and squared momentum change, –t, less than 0.5 GeV^2 in measurements of deeply virtual Compton scattering.
2009	Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.
2010	Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, Q^2, of 3.5 GeV^2 and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 < 1$ GeV^2 .
2010	Characterize high-momentum components induced by correlations in the few-body nuclear wave functions via (e,e'N) and (e,e'NN) knock-out processes in nuclei and compare free proton and bound proton properties via measurement of polarization transfer in the $^4He(\vec{e},e'\vec{p})^3H$ reaction.
2011	Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 GeV^2 for the proton, and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x, Q^2)$ and $g_2(x,Q^2)$ for x=0.2-0.6, and $1 < Q^2 < 5$ GeV^2 for both protons and neutrons.
2012	Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range Q^2 = 0.1 – 7 GeV^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.
2013	Measure flavor-identified q and $\bar{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.
2014	Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.
2014	Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction.

JLab: 8 of 10 SC Milestones in Hadronic Physics

Year	Milestones:
2008	Make measurements of spin carried by the glue in the proton with polarized proton-proton collisions at center of mass energy, $\sqrt{s_{NN}}$ = 200 GeV.
2008	Extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 - 0.4 , and squared momentum change, –t, less than 0.5 GeV^2 in measurements of deeply virtual Compton scattering.
2009	Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.
2010	Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, Q^2, of 3.5 GeV^2 and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 < 1$ GeV^2 .
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JLab/SC Milestones in Hadronic Physics

Year	Milestones:
2008	Extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 - 0.4 , and squared momentum change, –t, less than 0.5 GeV^2 in measurements of deeply virtual Compton scattering. (APARATUS NEARING COMPLETION; DVCS EXPERIMENTS ON THE SCHEDULE ABOUT TO BE RELEASED)
2009	Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances. (MOST DATA IN HAND; WILL ADD FROZEN SPIN TARGET AND MORE PHOTOPRODUCTION OF OMEGAS. THE ANALYSIS IS THE ESSENTIAL WORK OF EBAC, AND WE WON'T MEET THIS MILESTONE WITHOUT FUNDING SHORTLY)
2010	Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, Q^2, of 3.5 GeV^2 and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 < 1$ GeV^2. (EXCELLENT PROGRESS ON THE EM FORM FACTORS; G0 FORWARD ANGLE IN HAND; G0 BACKWARD ANGLE DATA ESSENTIAL)
2010	Characterize high-momentum components induced by correlations in the few-body nuclear wave functions via (e,e'N) and (e,e'NN) knock-out processes in nuclei and compare free proton and bound proton properties via measurement of polarization transfer in the $^4He(\vec{e},e'\vec{p})^3H$ reaction. (GOOD PROGRESS: BigBite NEXT)
2011	Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 GeV^2 for the proton, and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x, Q^2)$ and $g_2(x,Q^2)$ for x=0.2-0.6, and $1 < Q^2 < 5$ GeV^2 for both protons and neutrons. (SUBSTANTIAL PROGRESS ON PROTON; BONUS UNDER CONSTRUCTION FOR NEUTRON)
2012	Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range $Q^2 = 0.1 – 7$ GeV^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons. (GOOD PROGRESS TO DATE; EBAC ESSENTIAL)
2014	Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence. (LQCD-funding!)
2014	Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction. (LQCD FUNDING!) S&T_7-04_Cardman_Science_Overview

Summary and Perspectives

- CEBAF's beam and experimental equipment provide a unique tool for nuclear physics
- Exciting physics results continue to emerge:
  - Testing the limits of classical nuclear theory
  - Exploring the QCD basis of the strong interaction and of the structure of nucleons and nuclei
- We are making excellent progress on the Milestones, but EBAC and LQCD funding will be essential