Nuclear Physics and the Science of Emerging Programs

(Jefferson Lab, Past, Present & Future)

Anthony W Thomas

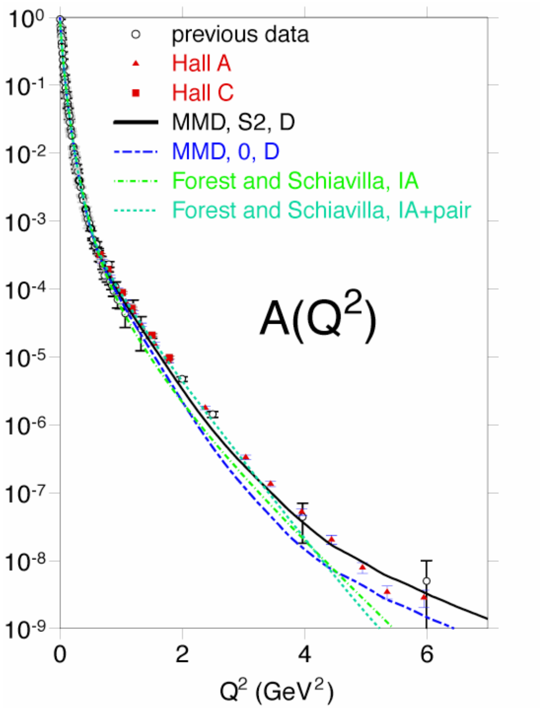
JLab is the Current International Flagship for Hadron Physics

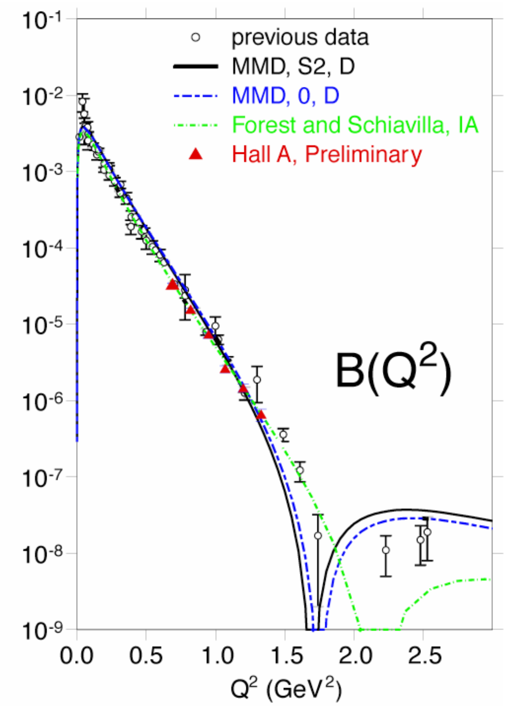
- Important competition in limited areas from Bates, Elsa, Hermes, MAMI, Spring 8….
- Complementary work at: Compass, IKP Jülich, Fermilab, RHIC…
- Through C12, IUPAP has initiated work on International Cooperation in Nuclear Physics (Committee chaired by AWT meets at INPC2004 in Göteberg, June 27 – follows earlier work by Feshbach and later Frois)

JLab Program Touches Key Problems in Nuclear & Particle Physics & Beyond

- Origin of nuclear forces: QCD and nuclear saturation
- Hadron properties in-medium: precursors of quark-gluon phase transition at RHIC and astrophysics of "n-stars"
- Matter with strangeness and role of heavy quarks in "normal matter"
- Exploration of new phenomena in QCD – exotic/new mesons and baryons and nature of confinement
- Search for physics beyond Standard Model

JLab Data Reveal Deuteron's Size and Shape





For elastic e-d scattering:

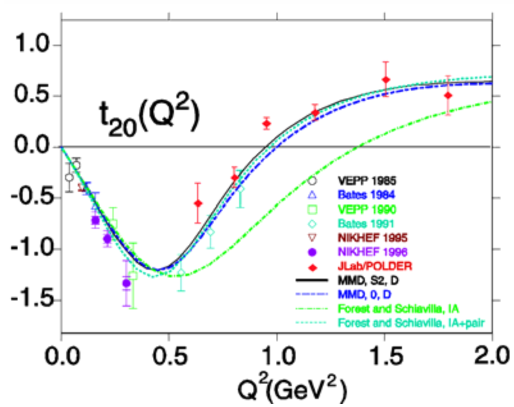
$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A + B \tan^2 \tfrac{\theta}{2}\right]$$

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

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

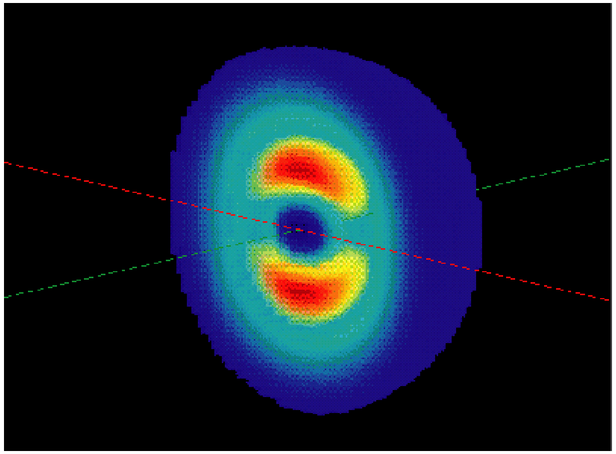
- 3rd observable needed to separate G_C and G_Q

→ *tensor polarization* t_{20}

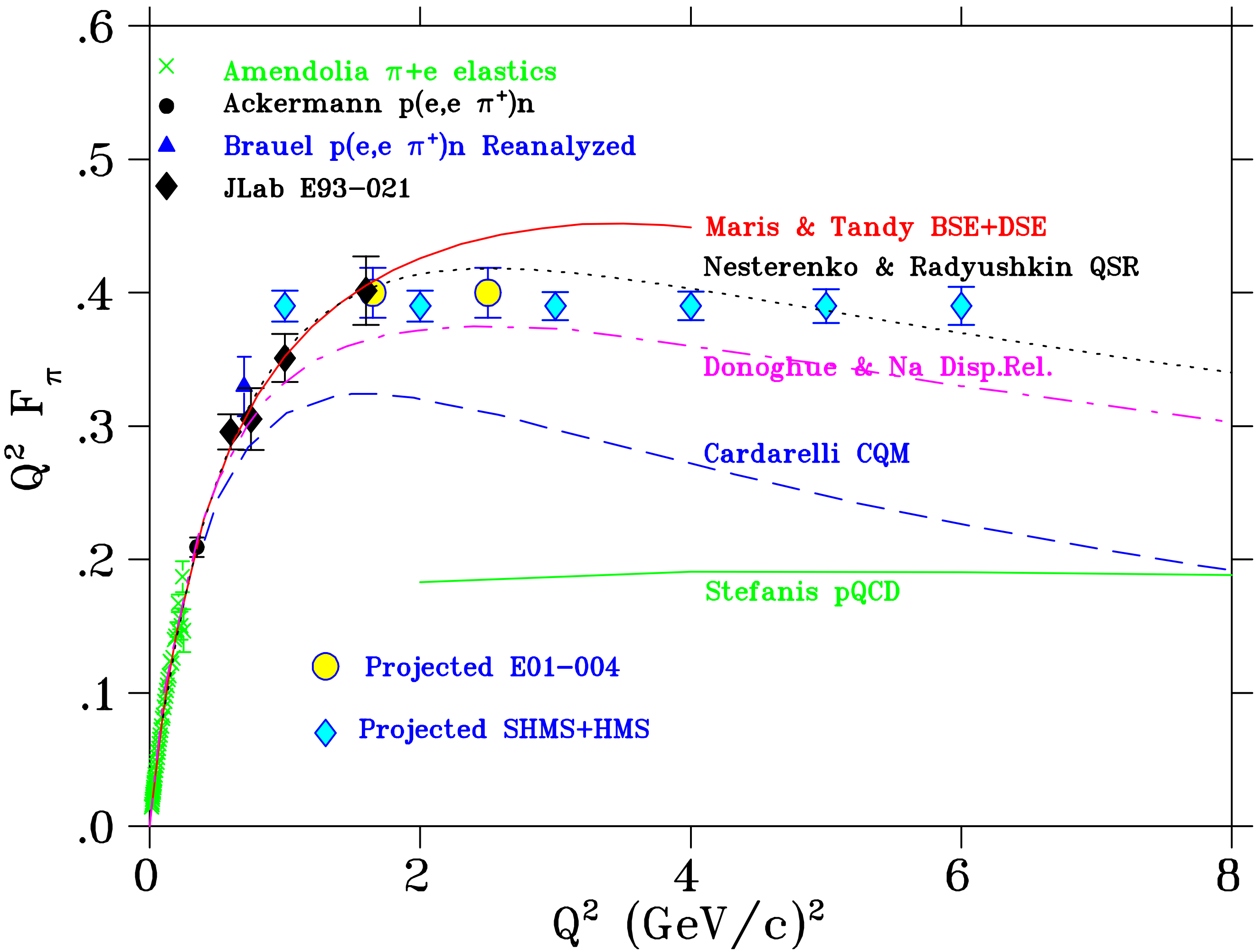


Combined Data ->
Deuteron's Intrinsic Shape

The nucleon-based description works down to < 0.5 fm



Charged Pion Electromagnetic Form Factor

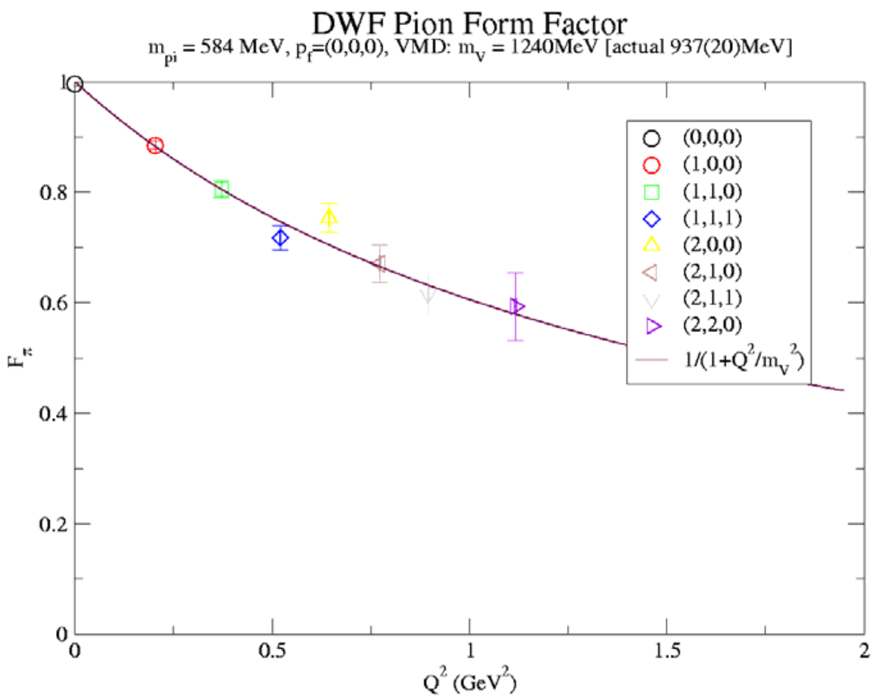


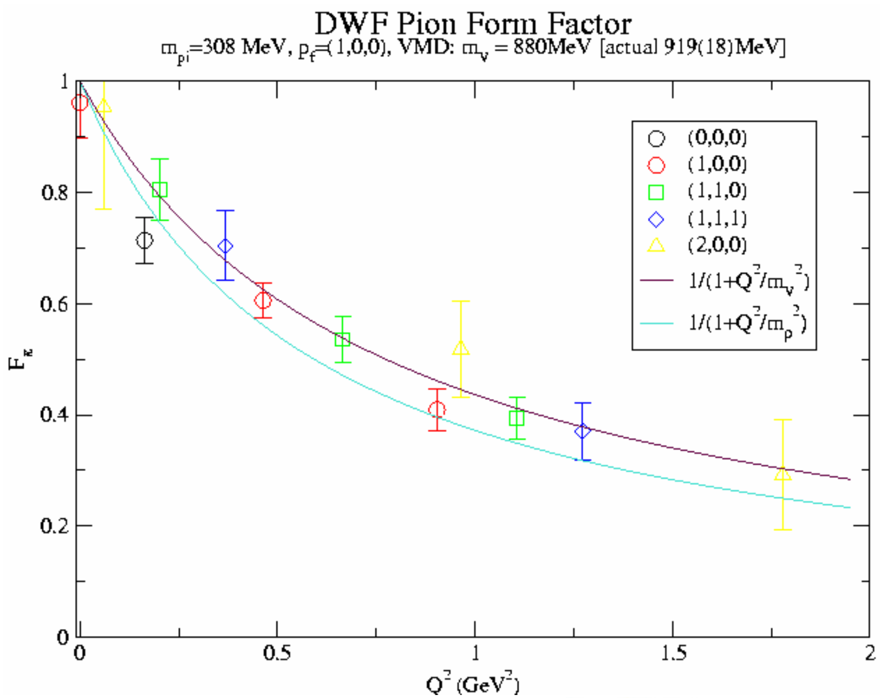
Partially Quenched DWF Form Factor

- DWF $F_{\pi}(Q^2,t)$: LHPC (Edwards, Richards ….)
  — Smaller mass close to experimental VMD.

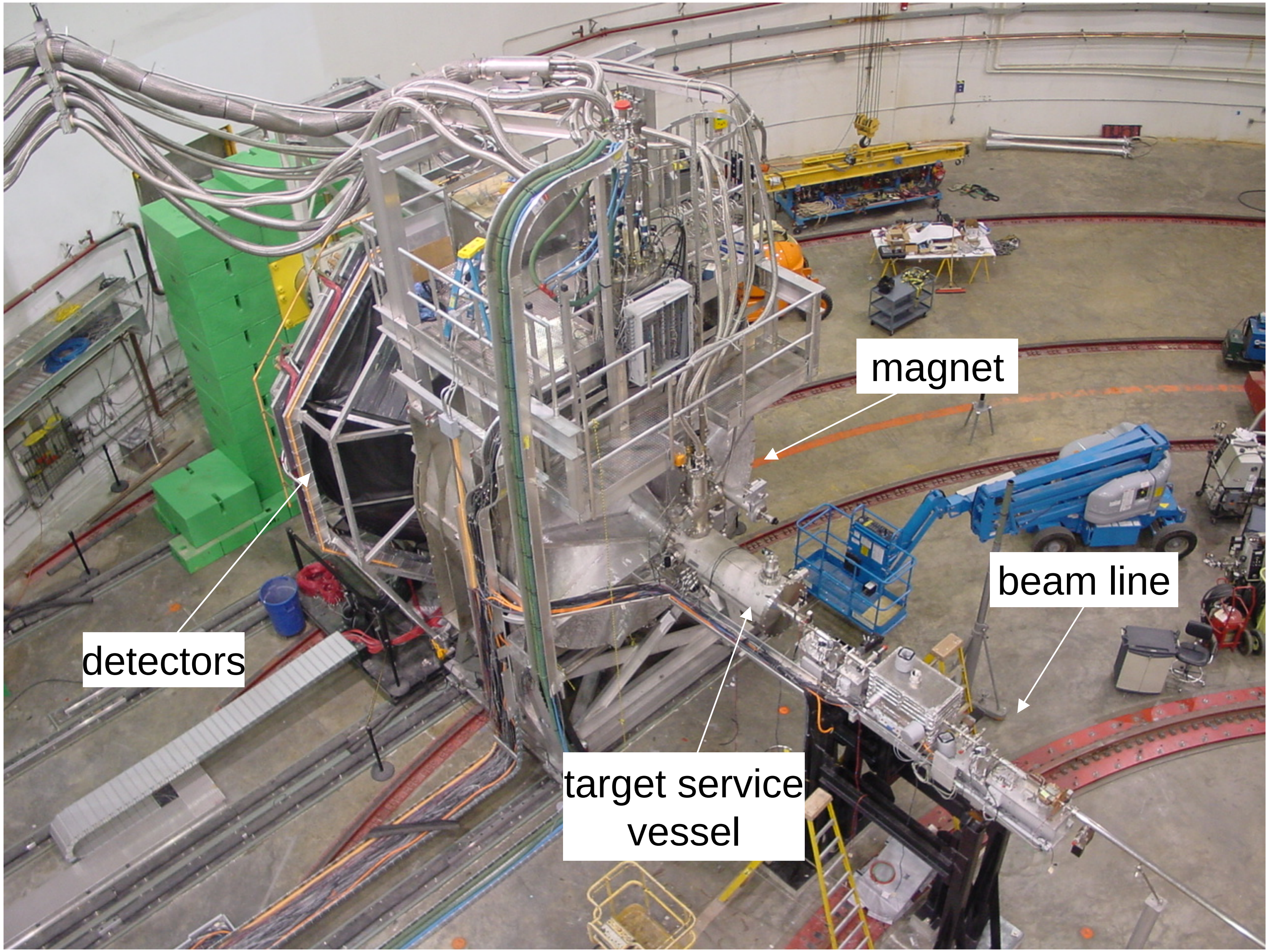
$$\left.\frac{\partial F(Q^2)}{\partial Q^2}\right|_{Q^2=0} = \frac{1}{6}\langle r^2\rangle \quad \rightarrow \langle r^2\rangle = \frac{6}{m_V^2}$$

- Charge radius (crude analysis):
  — Exp. h r^{2}i = 0.439(8)fm^2 , VMD ! 0.405fm^2
  — Statistical: 0.156(5)fm^2, 0.310(6)fm^2 strong mass dependence



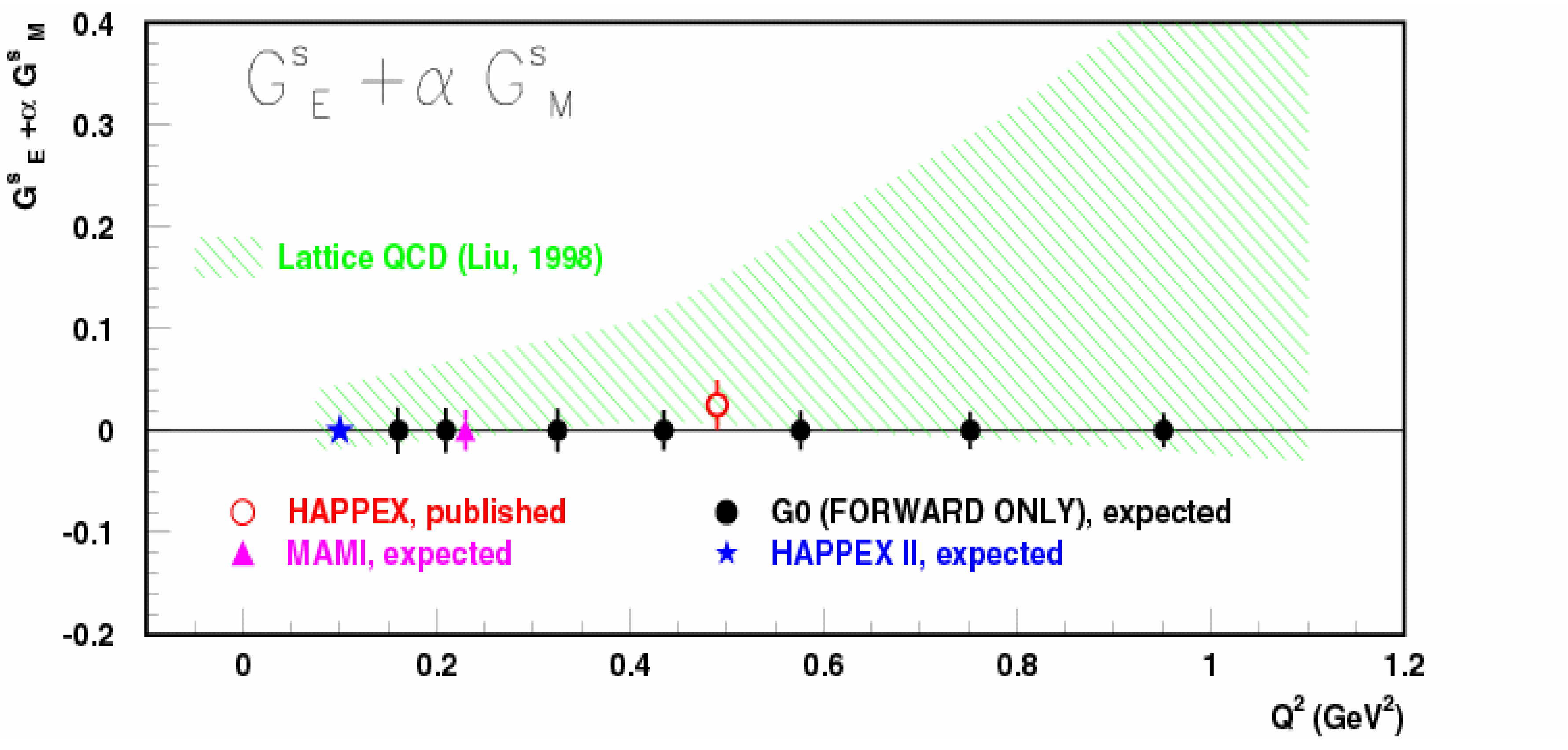


G0 Experiment in Hall C



Strange Form Factors G_E^s and G_M^s

Expected Forward Angle Results by late 2003



s_ℓ may be estimated from the Kaon loop integrals

- Regulated by a dipole form factor with $\Lambda = 0.8$ GeV

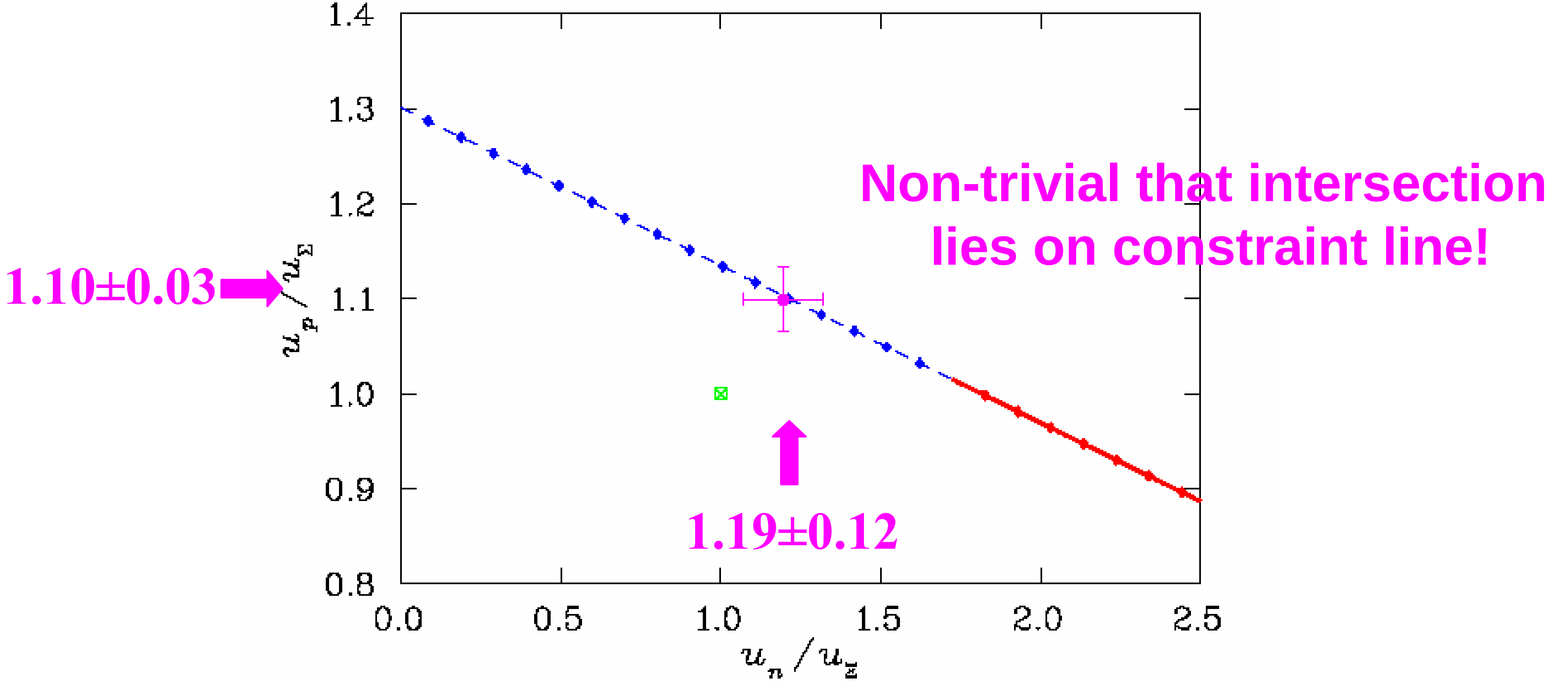
$$ {}^{\ell}R_d^s = \frac{s_\ell}{d_\ell} = \frac{-0.036}{-0.258} = 0.140 $$

- Repeating the calculation for $\Lambda = 0.8 \pm 0.2$ GeV provides

$$ {}^{\ell}R_d^s = \frac{s_\ell}{d_\ell} = 0.140 \pm 0.040 $$

(dots are steps of 0.01 μ_N)

Hence $G_M^{\;s} = -0.051 \pm 0.021\ \mu_N$



Use Happex to Extract Strangeness Charge Radius

$G_E^s + 0.39\ G_M^s = 0.025 \pm 0.020 \pm 0.014$ at $0.4\ \mathrm{GeV}^2$ (HAPPEX)

Plus lattice calculation of G_M^s and assumed dipole form

$\Rightarrow$ $\langle r^2 \rangle_s = -0.021 \pm 0.015\ \mathrm{fm}^2$

c.f. $\langle r^2 \rangle = -0.113\ \mathrm{fm}^2$ in case of the neutron

Cosmology & Physics Beyond the Standard Model

- "Unified theories applied to cosmology suffer generically from a problem of predicting time-dependent coupling constants"
  Fujii, Omote & Nishakoa, Prog. Th. Phys. 92 (1994) 3.

- "..in cosmology with extra dimensions people try to find solutions with external dimensions expanding while extra dimensions remain static. But at present no mechanism for keeping internal spatial scale static has been found.
  Li & Gott, Phys. Rev. D58 (1998) 103513

- "$d R_{KK} / dt \neq 0$ … could give rise to observable time variation in the fundamental 'constants' of our 4D world and thereby provide a window to the extra dimensions"
  Marciano, PRL 52 (1984) 489

Recent Evidence for dα /dt

Quasar (QSO) absorption spectra)

$\Delta \alpha / \alpha$ = -1.9 § 0.5 £ 10^{-5} for z>1

Webb, Flambaum, Churchill, Drinkwater, Barrow, PRL 82 (1999) 884

But if α varies so do other 'constants'…

e.g. Langacker et al., Phys Lett B528 (2002) 121; Calmet & Fritsch, Eur. P. J. C24 (2002) 639; Marciano, PRL 52 (1984) 489

$\delta \Lambda_{QCD} / \Lambda_{QCD}$ ¼ 34 $\delta \alpha / \alpha$; $\delta m / m$ ¼ 70 $\delta \alpha / \alpha$

) $\delta(m/\Lambda_{QCD}) / (m/\Lambda_{QCD})$ ¼ $\underline{35}\ \delta \alpha / \alpha$

N.B. values are highly model dependent BUT large coefficients are generic for GUTS!

Limits on Variation of m_q/Λ_{QCD}

- **Big Bang Nuclear-Synthesis**

- **Oklo Natural Reactor**

- **Quasar absorption spectra**

- **Laboratory clock experiments !**

N.B. Precision of 10^{-15} possible
c.f. 10^{-5} in 10^{9} years!

e.g. Karshenboim, Can. J. Phys. 78 (2000) 639)

Ratios of hyperfine structure levels in different atoms very Sensitive to changes in magnetic moments

Limits from Atomic Hyperfine Structure

1st limits: **Flambaum & Shuryak, PR D65 (2002) 103503**

Using H, Cs, Hg^+) $\delta \ln (m_q/\Lambda_{QCD}) < 5$ £ 10^{-13}

More recently: **Flambaum, Leinweber, Thomas & Young, hep-ph/0402098**

Updated F&S and derived new limits for hyperfine transitions in: H, Rb, Cs, Yb^+, Hg^+ and optical transition in Hg

Sample Results

Cs clock, frequency standard

$$V(^{133}Cs) = \alpha^{2.83}(\frac{m_q}{\Lambda_{QCD}})^{0.110}(\frac{m_s}{\Lambda_{QCD}})^{0.017}\frac{m_e}{m_p}$$

$$V(^2H) = \alpha^2(\frac{m_q}{\Lambda_{QCD}})^{-0.018}(\frac{m_s}{\Lambda_{QCD}})^{-0.045}\frac{m_e}{m_p}$$

$$V(^{199}Hg^+) = \alpha^{4.3}(\frac{m_q}{\Lambda_{QCD}})^{-0.118}(\frac{m_s}{\Lambda_{QCD}})^{0.0013}\frac{m_e}{m_p}$$

Use ratio of hyperfine frequencies:

$$X(Cs/Rb) = \frac{V(Cs)}{V(Rb)} = \alpha^{0.49}[m_q/\Lambda_{QCD}]^{0.174}[m_s/\Lambda_{QCD}]^{0.027}$$

$$V(^{171}Yb^+) = \alpha^{3.5}(\frac{m_q}{\Lambda_{QCD}})^{-0.118}(\frac{m_s}{\Lambda_{QCD}})^{0.0013}\frac{m_e}{m_p}$$

$\sim \alpha^8$ under quoted GUT scenario

$$V(^{111}Cd^+) = \alpha^{2.6}(\frac{m_q}{\Lambda_{QCD}})^{-0.118}(\frac{m_s}{\Lambda_{QCD}})^{0.0013}\frac{m_e}{m_p}$$

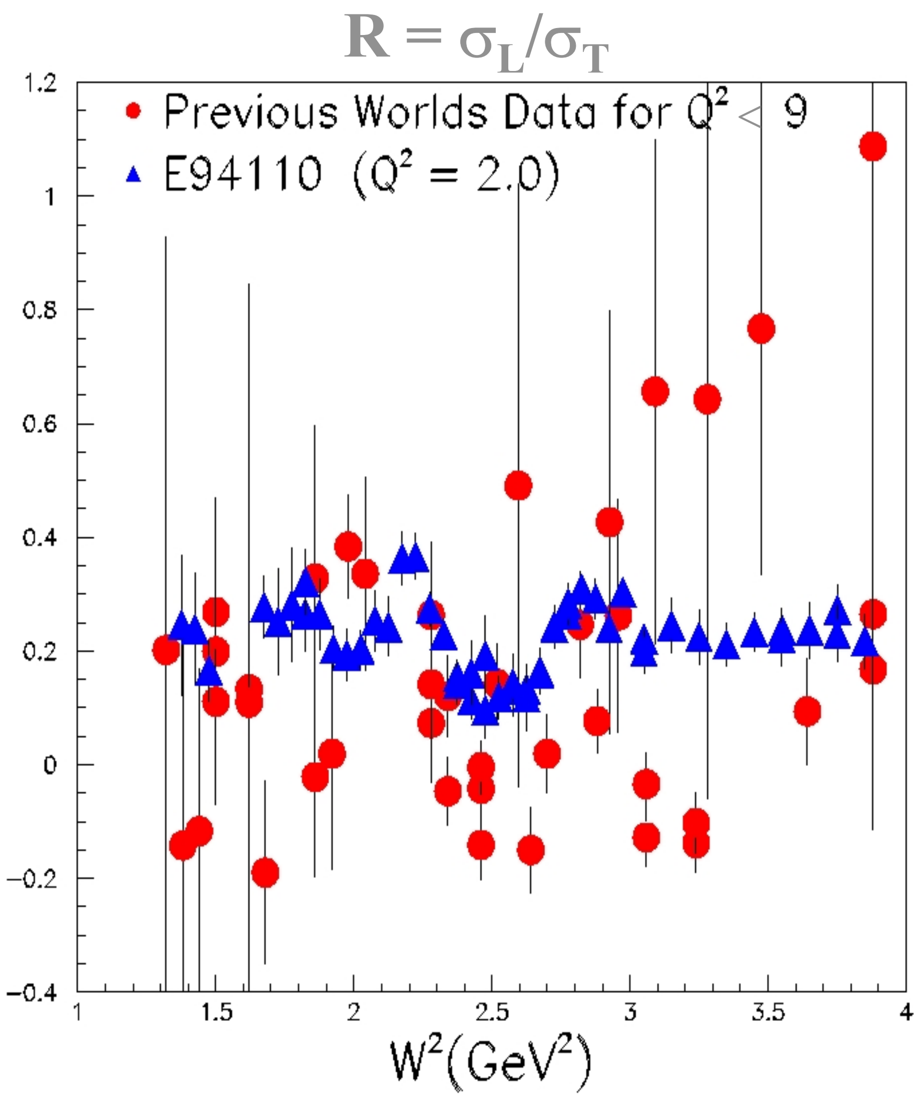
Current best experimental determination:

$$\frac{1}{X(Cs/Rb)}\frac{dX(Cs/Rb)}{dt} = (0.2 \pm 7) \times 10^{-16}/year$$

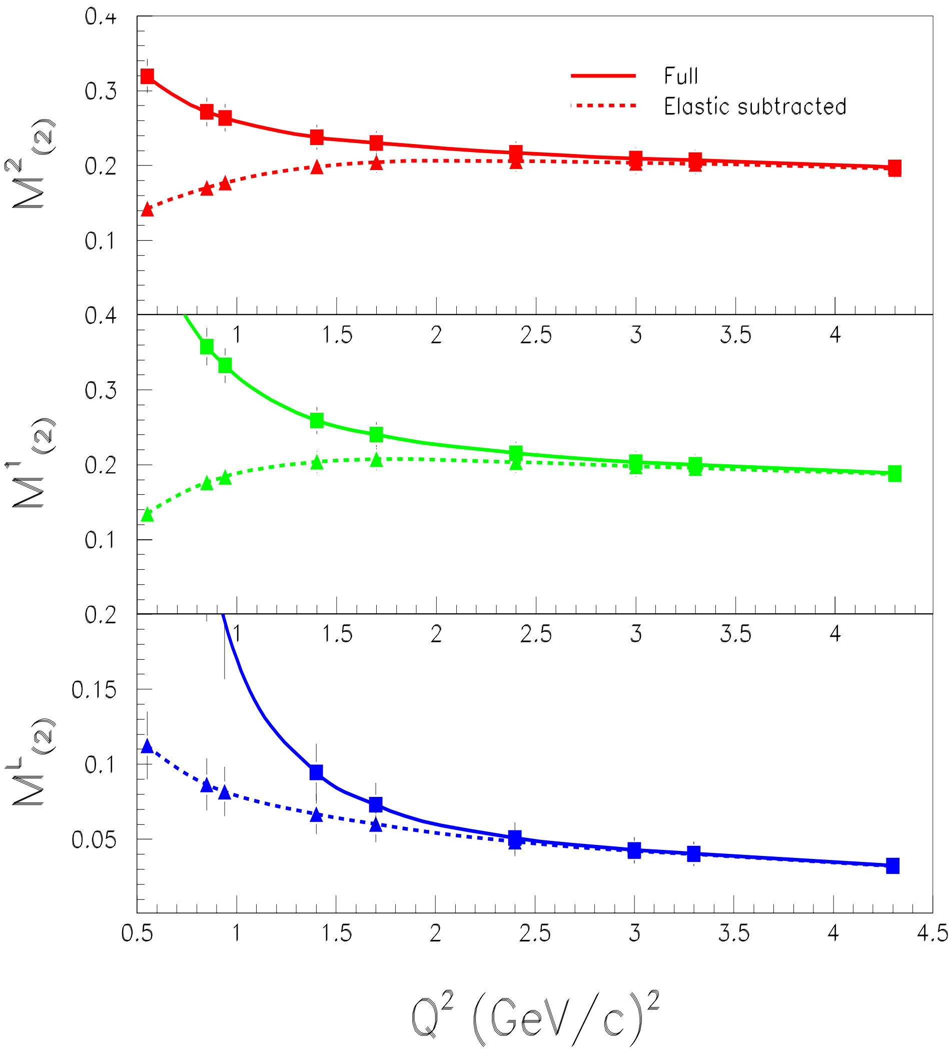
H. Marion, PRL 90 (2003) 150801

$\delta\alpha/\alpha < 10^{-16}$/year under GUT scenario

Measured $R = \sigma_L/\sigma_T$ in Resonance Region

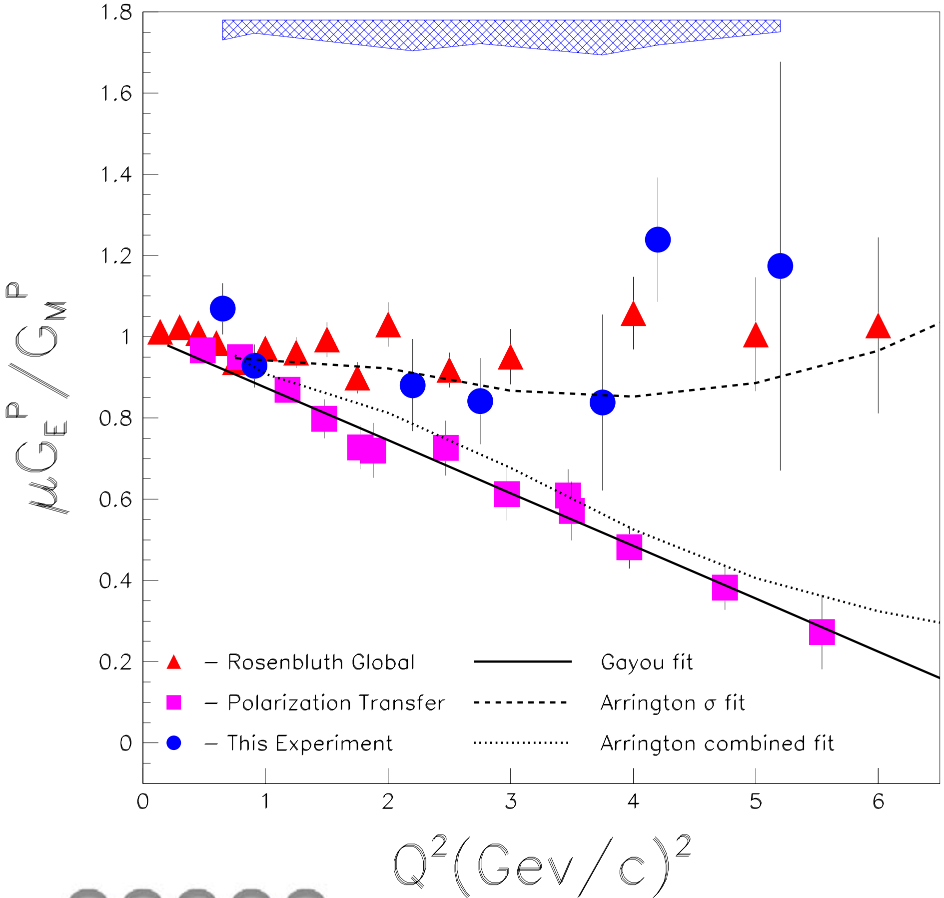


+ Low-Q^2 Moments

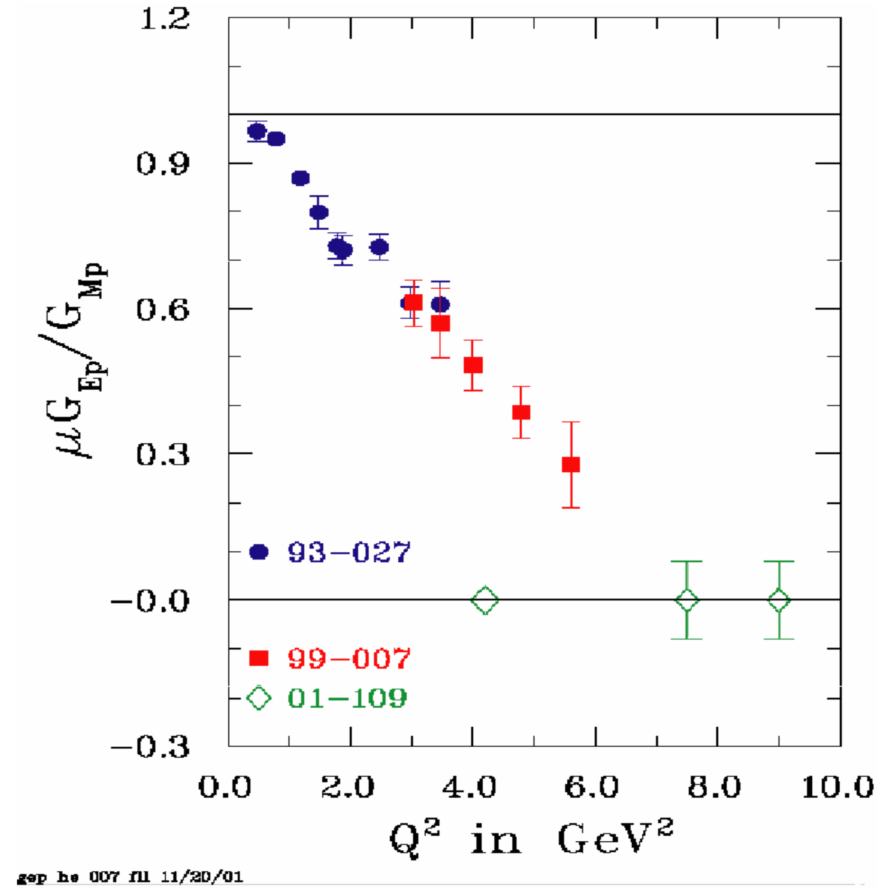


Important Spin-Off on Proton Form Factor Issue

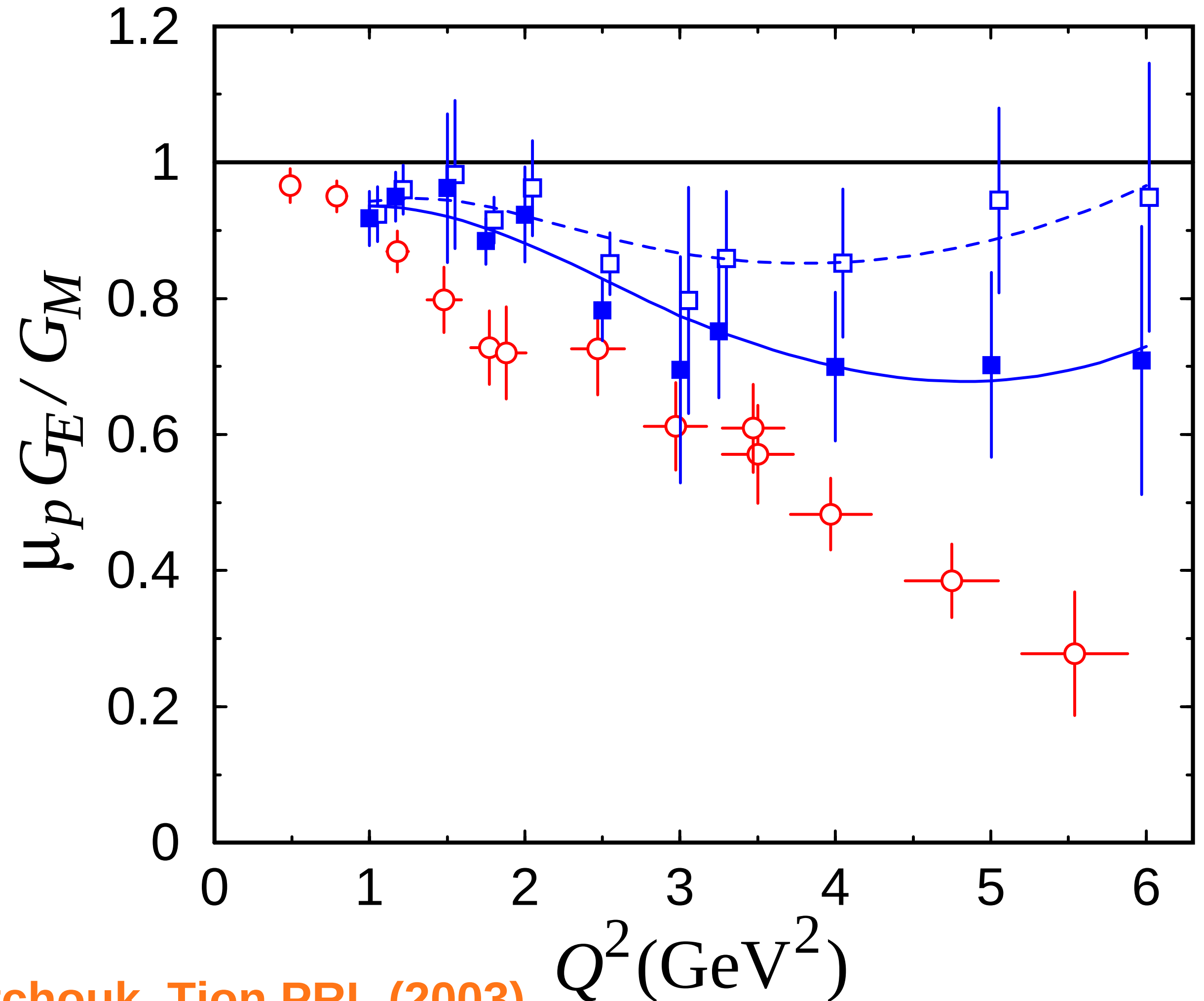
As spin-off, L/T separations in the elastic channel agree with those from previous SLAC experiments, confirming the discrepancy with the polarization transfer technique (submitted to PRC)



Upcoming Experiment:
Access ratio with Polarization Transfer Technique to $Q^2 = 9$
(Using 200 msr Calorimeter)



Estimate of 2- photon Exchange Effects



Blunden, Melnitchouk, Tjon PRL (2003)

N only… so far

Quark Level Description of Finite Nuclei
(e.g. Quark Meson Coupling Model)

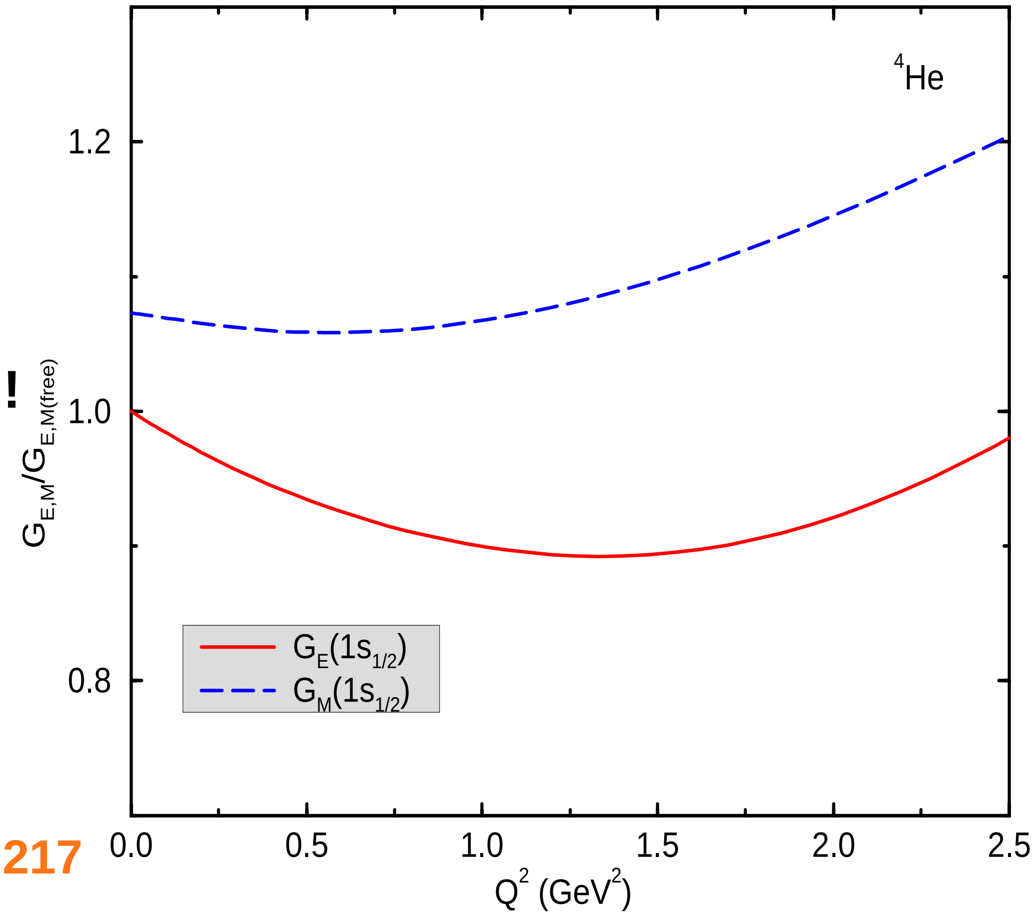
- **MAJOR CONCEPTUAL CHANGE:**
  What occupies shell model orbits are nucleon-like quasi-particles

- **Have: new mass, M_N^*; new form factors, etc.**

- **EXPERIMENTAL EVIDENCE?**

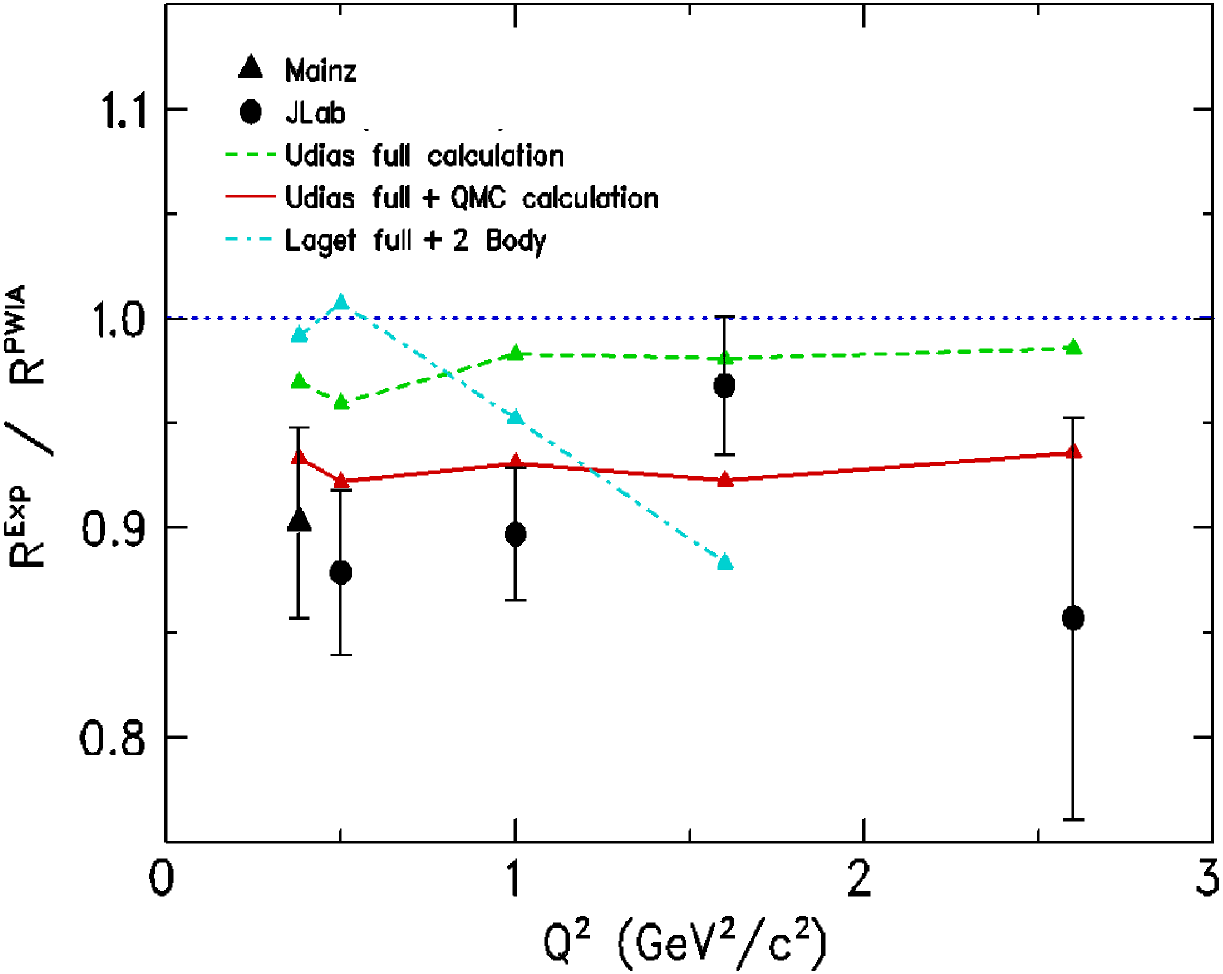
- **First have to ask the question!**

- **Changes are subtle:**



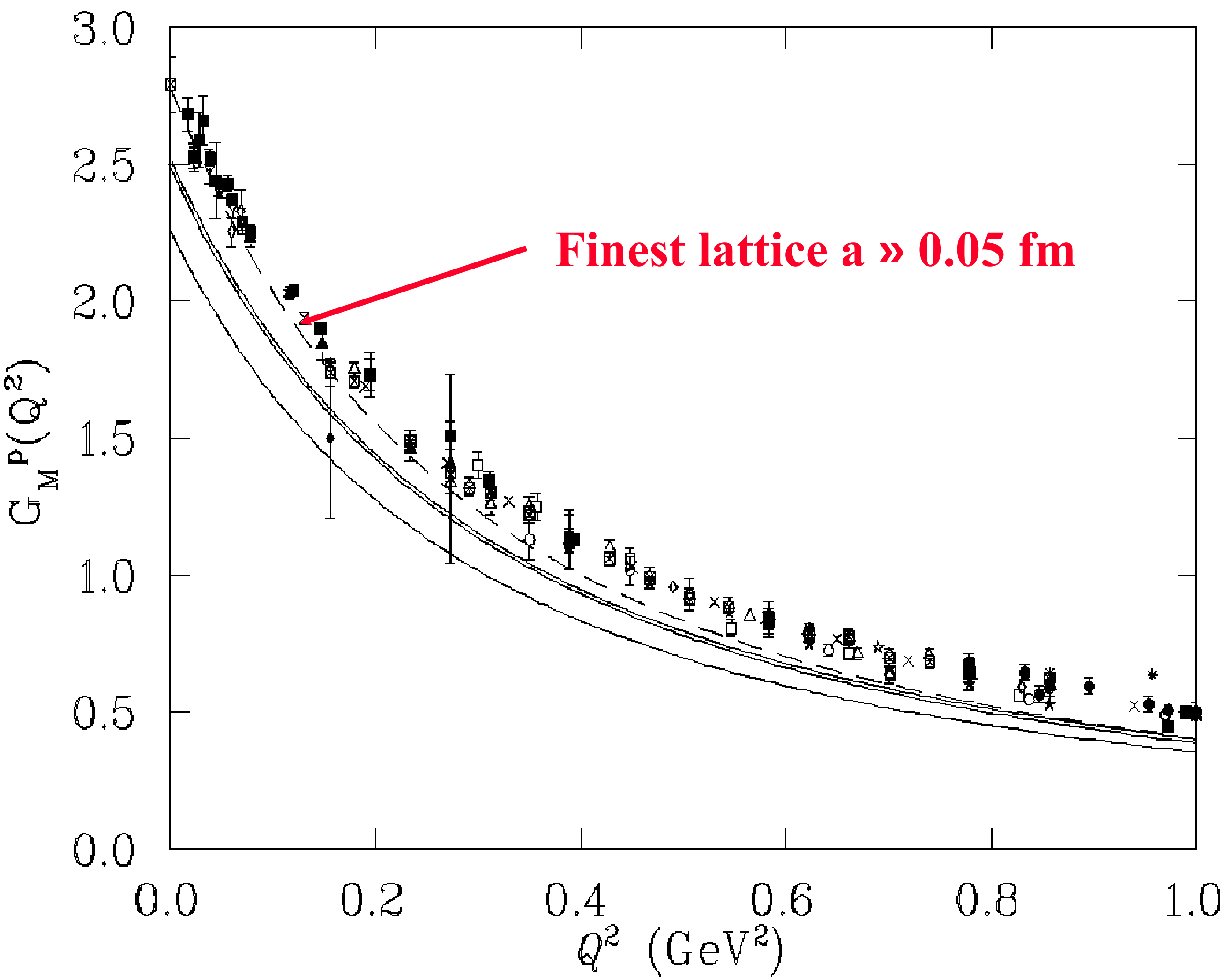
Lu *et al.*, Phys. Lett. B417 (1998) 217

Jefferson Lab & Mainz



Full theoretical analysis: Udias *et al.*

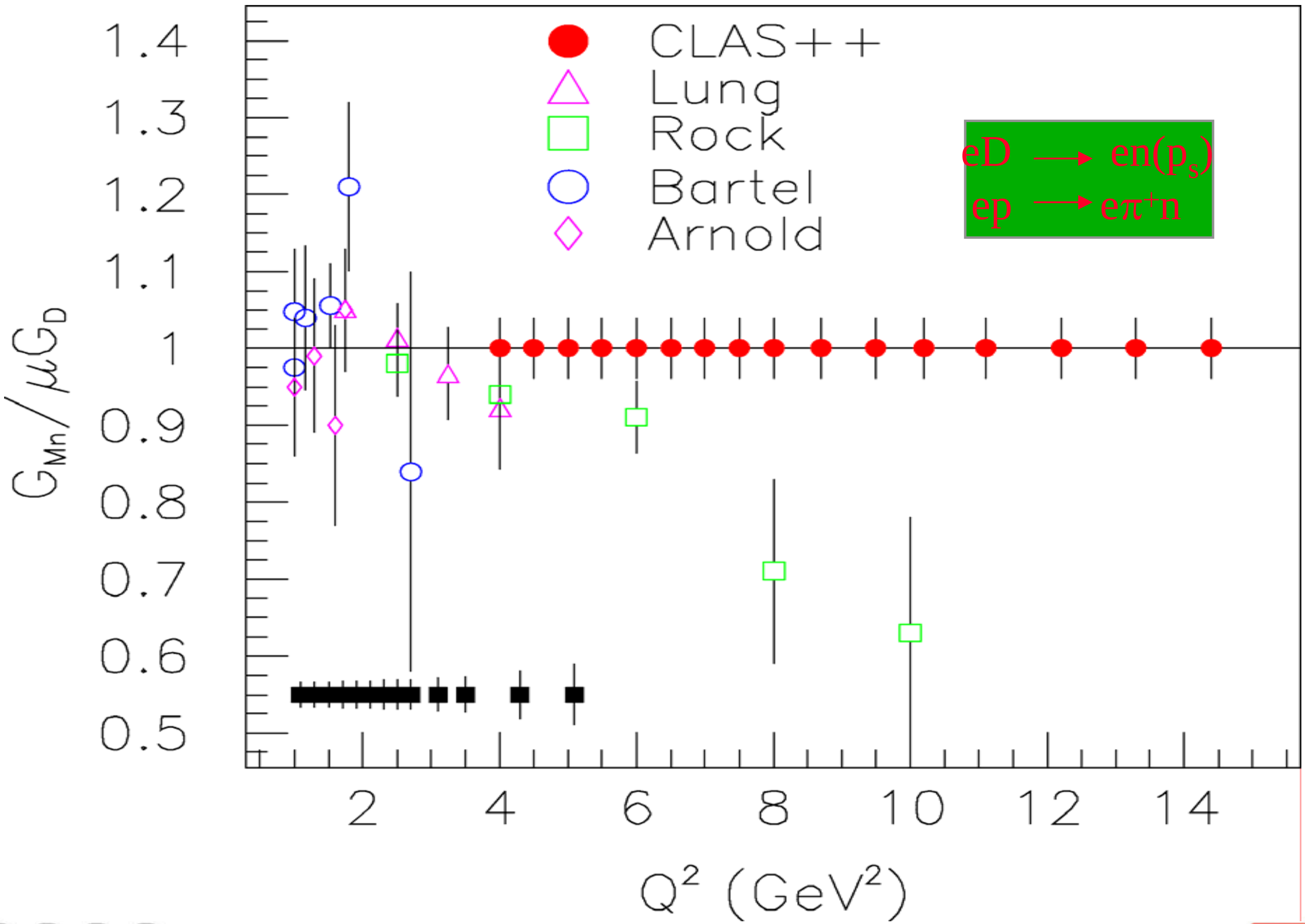
Chiral Extrapolation of G_M^p



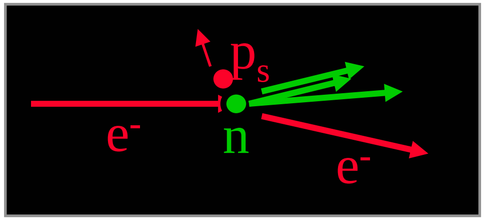
Ashley et al., 2003 (QCDSF data)

CLAS^{++} : Neutron G_M^n

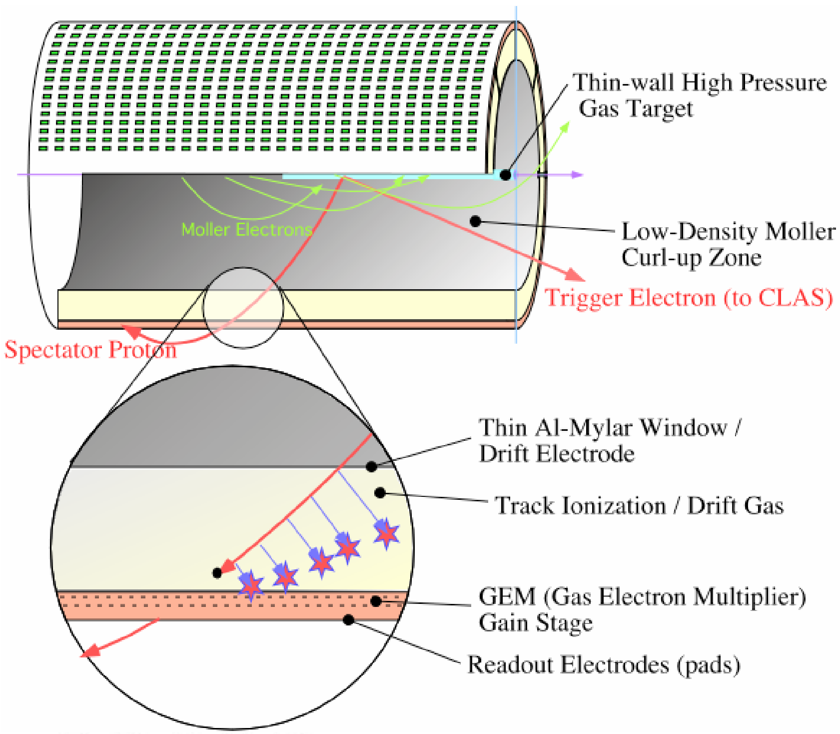
With 12 GeV Upgrade

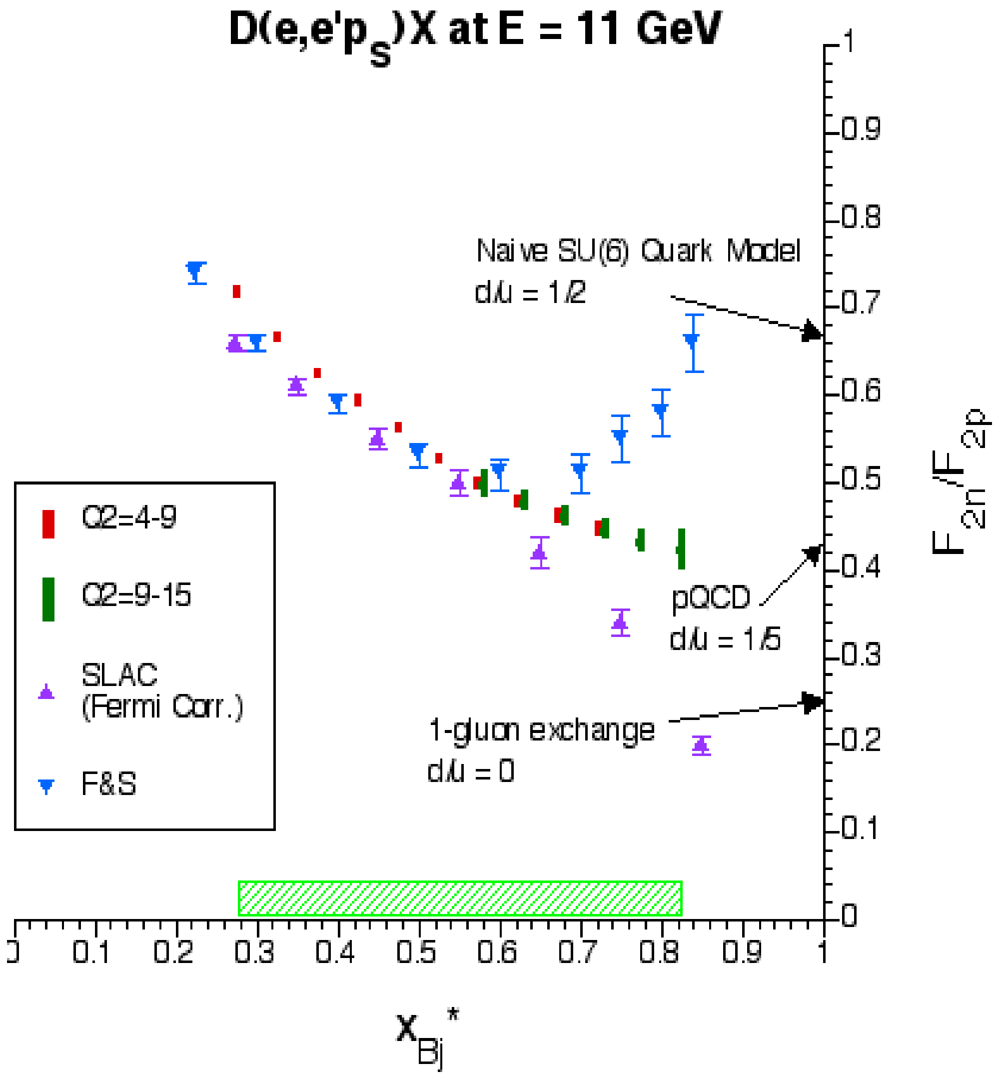


Structure of "Free" Neutrons - e.g. F_2^n



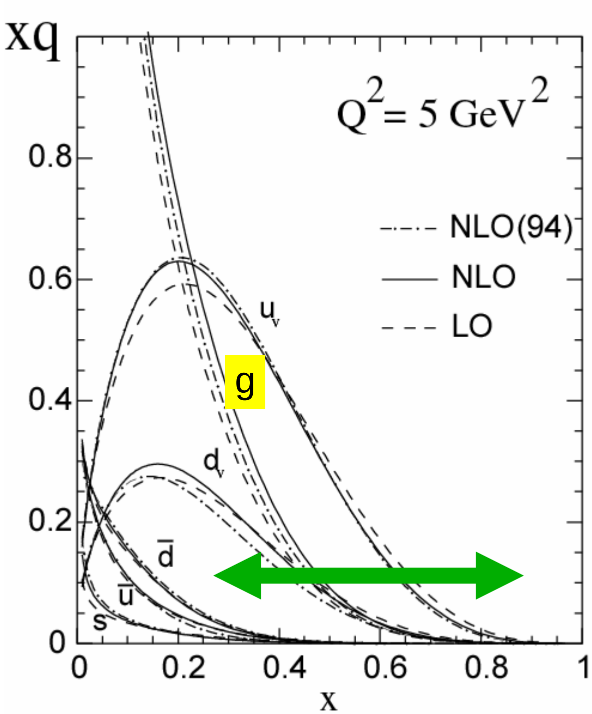
Requires detection of a slow recoil proton at backward angles and with momenta ~60-150MeV/c



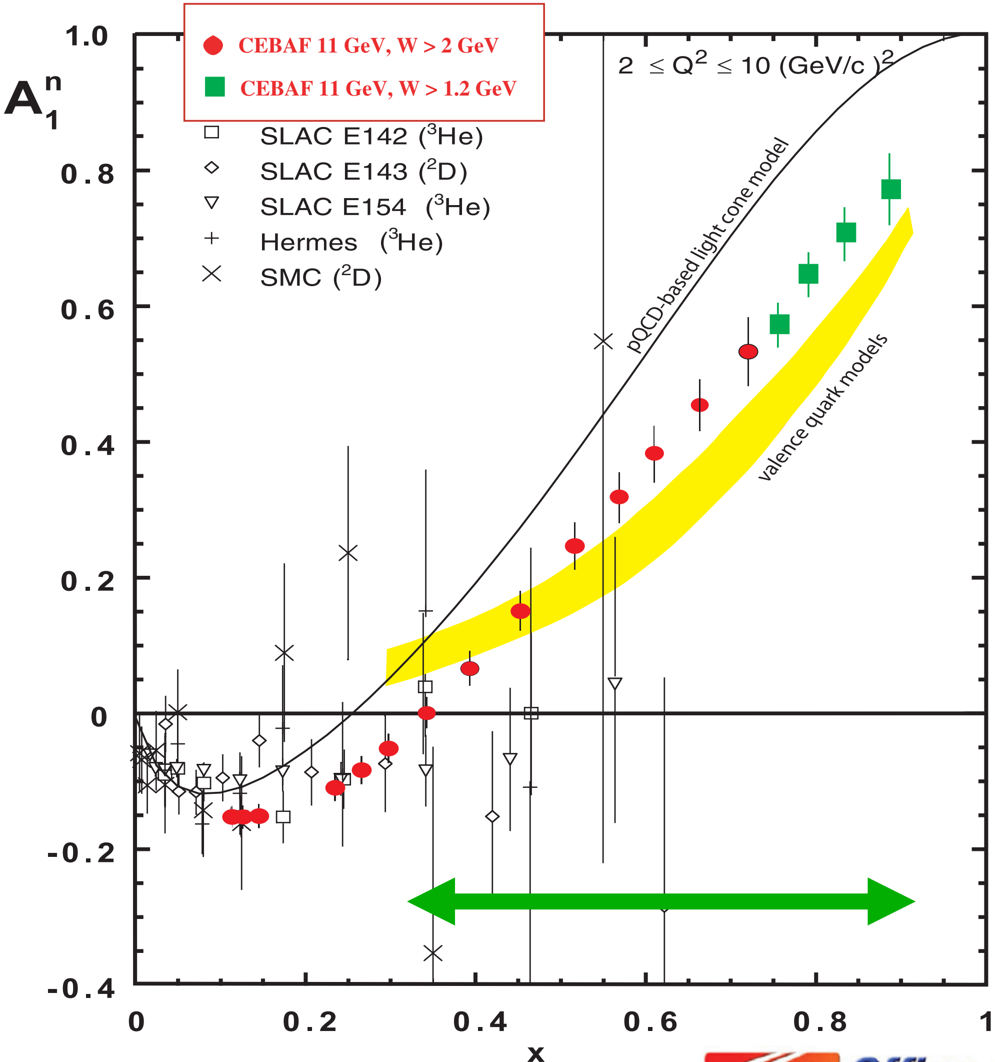


Measure Q^2 dependence simultaneously

Extending DIS to High x: The Neutron Asymmetry A_1^n



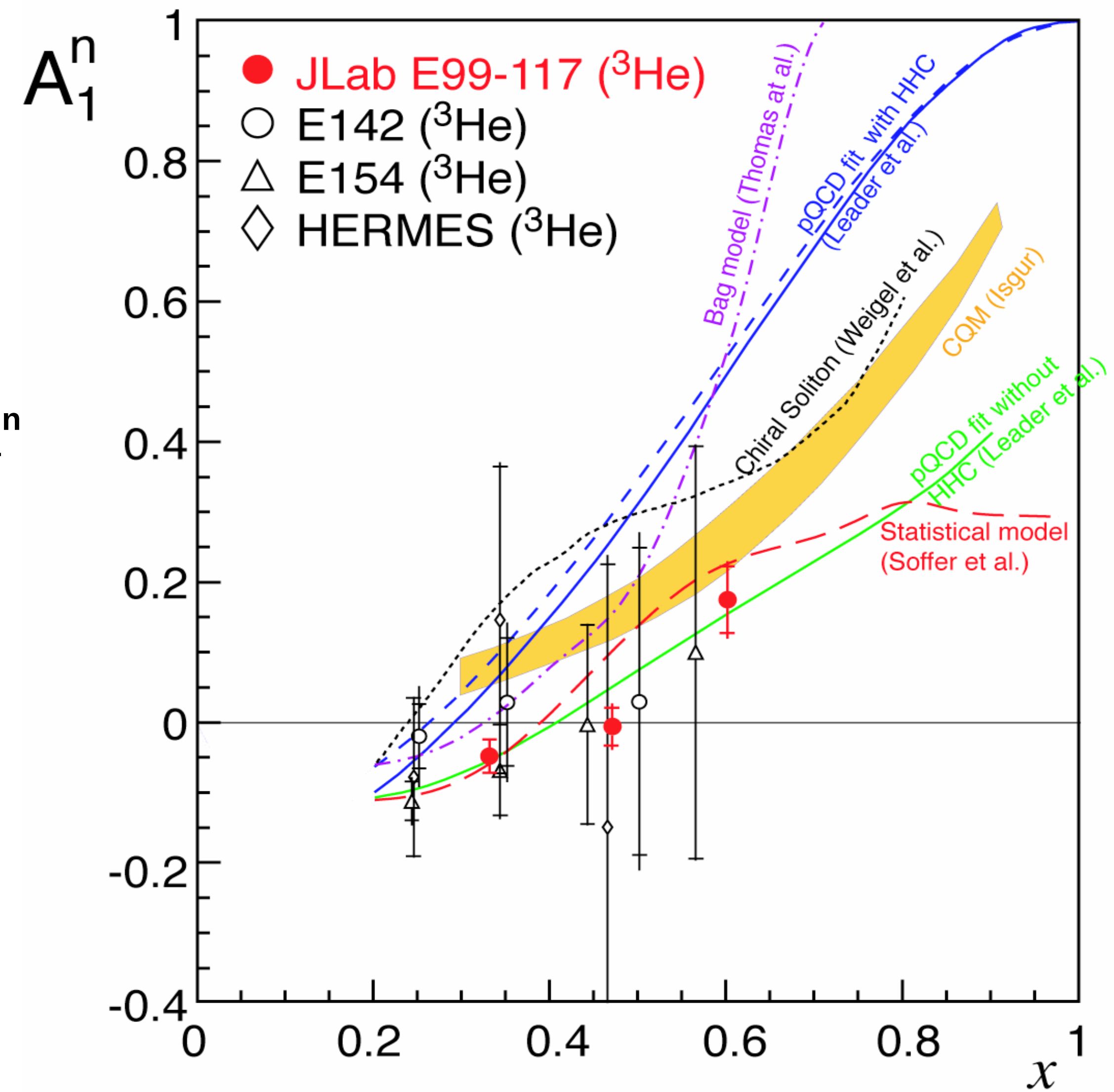
12 GeV will access the **valence quark regime** (x > 0.3), **where constituent quark properties are not masked by the sea quarks and glue**



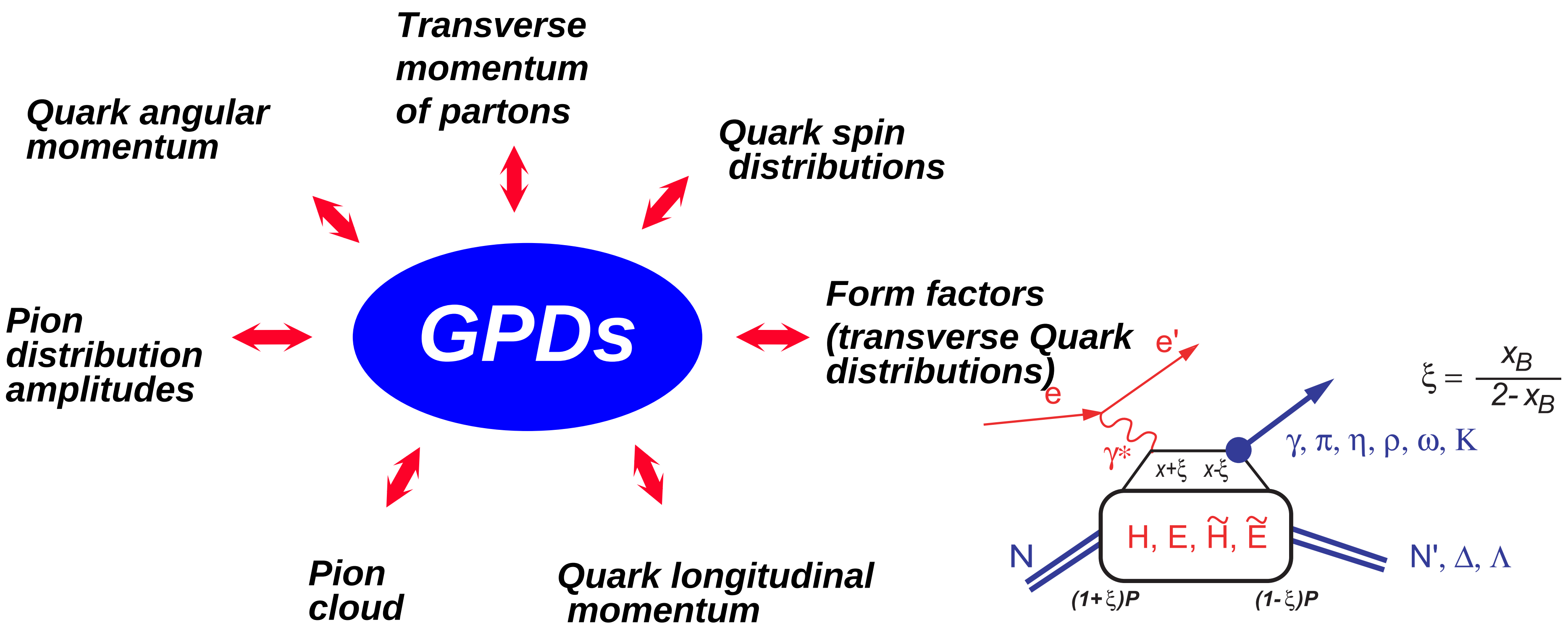
^{3}He Data Demonstrate Feasibility

New E99-117 data

provide first indication that A_1^n deviates from 0 at large x, but are clearly at variance with pQCD prediction assuming Hadron Helicity Conservation



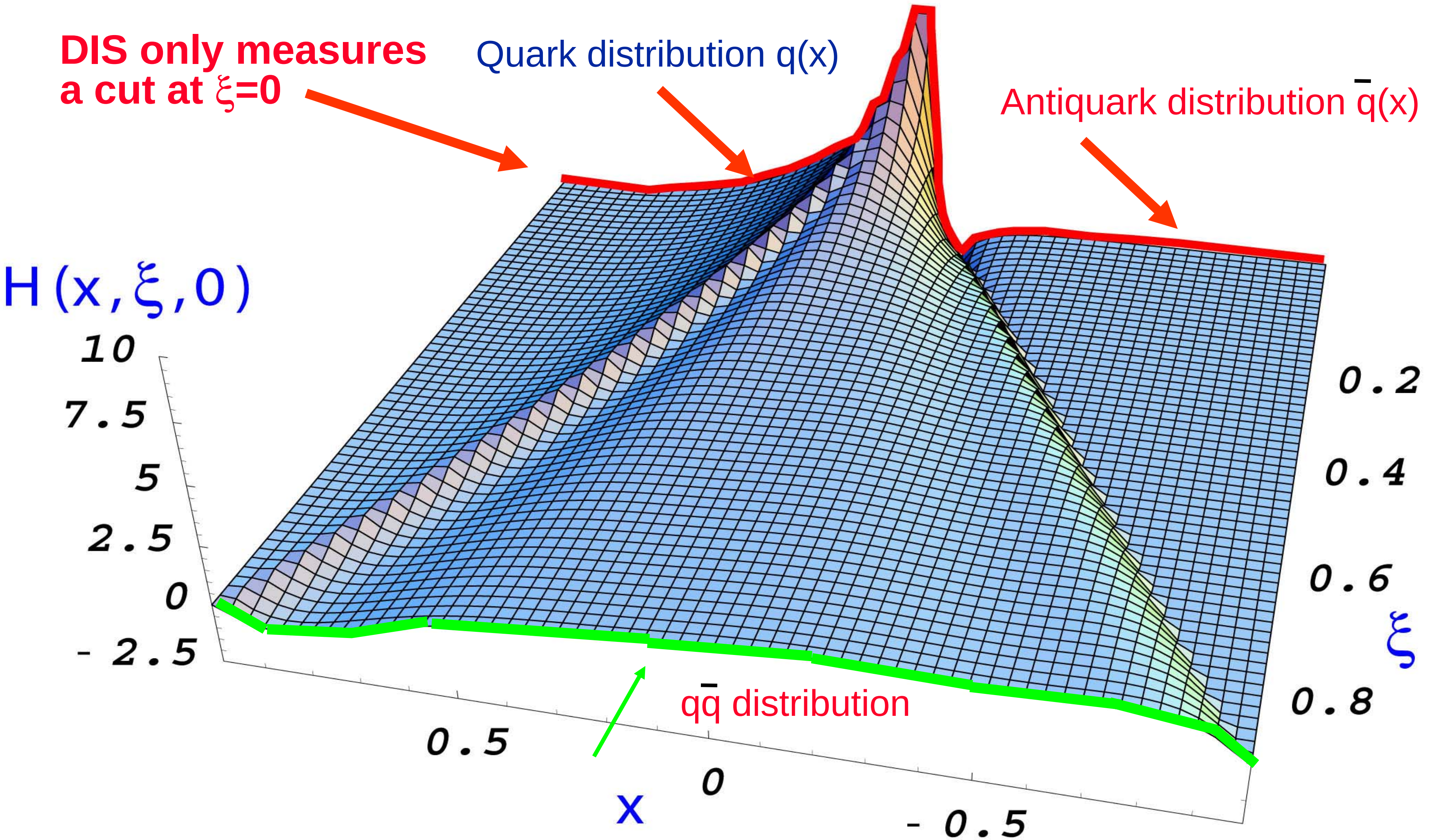
Unified Description of Hadron Structure via Generalized Parton Distributions



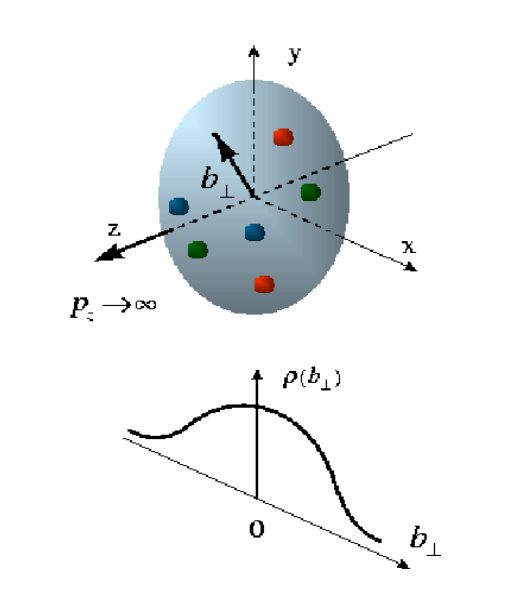
H, E - unpolarized, $\tilde{H}, \tilde{E}$ - polarized GPD

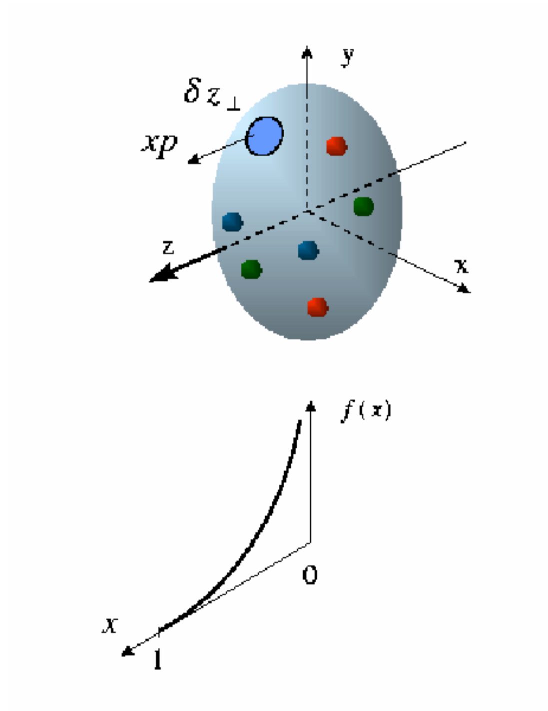
The GPDs Define Nucleon Structure

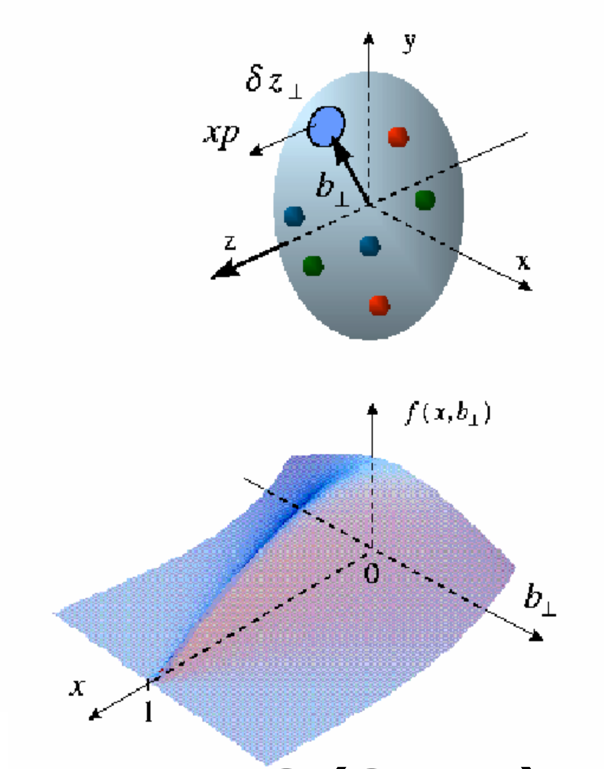
GPDs: Much More Information than DIS



Proton Properties Measured in Different Experiments







Elastic Scattering

transverse quark distribution in Coordinate space

DIS

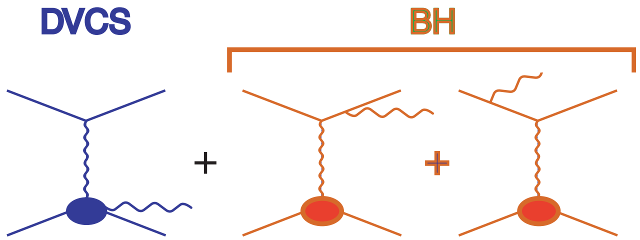
longitudinal quark distribution in momentum space

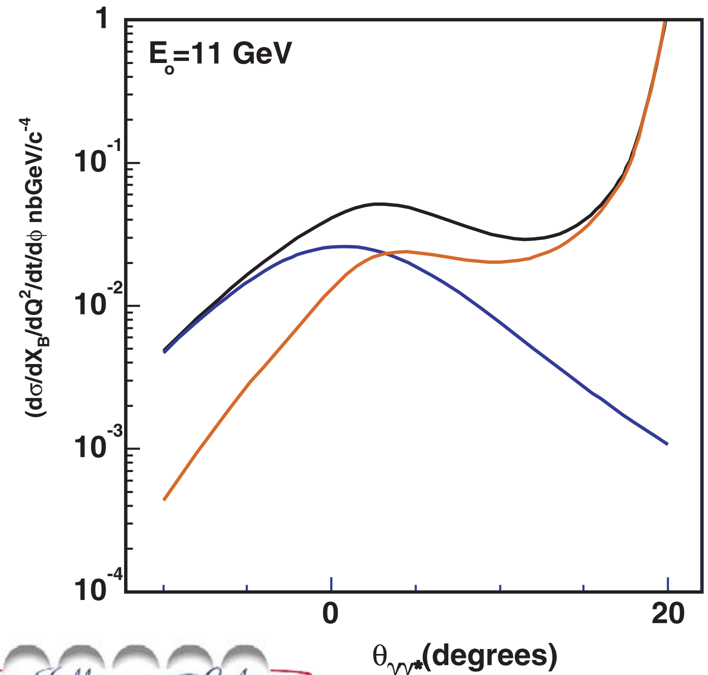
DES (GPDs)

Fully-correlated quark distribution in both coordinate and momentum space

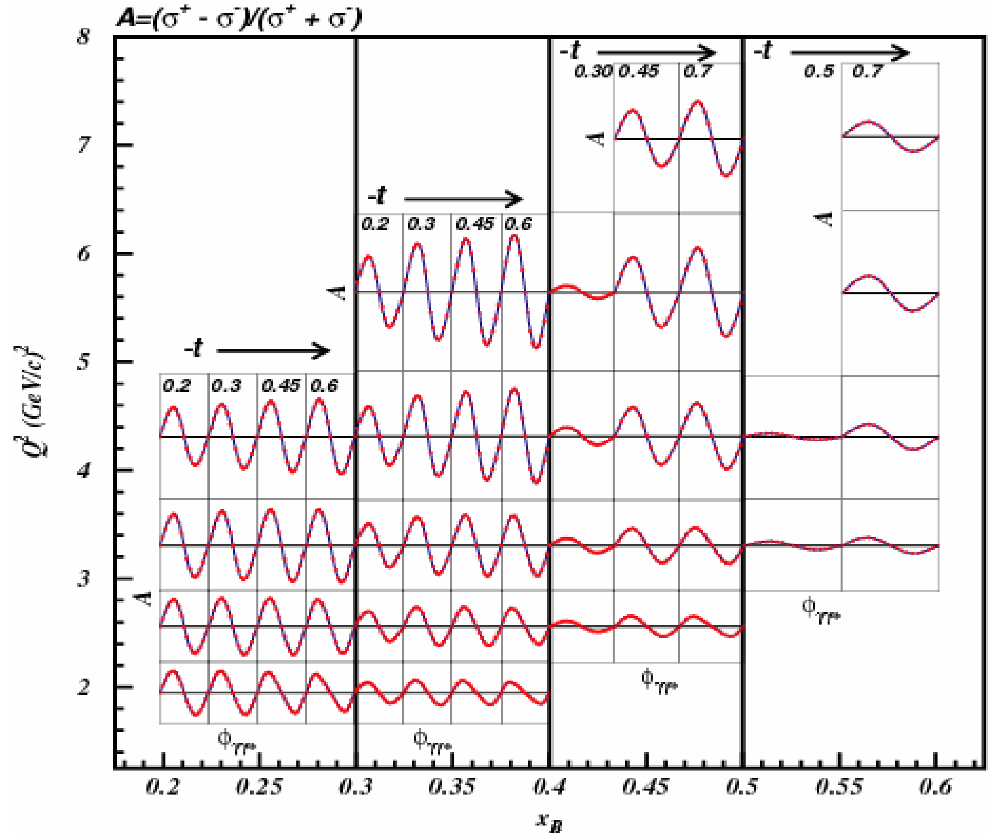
DVCS: Single-Spin Asymmetry in $\vec{e}p \to epg$ Measures phase and amplitude directly

DVCS and Bethe-Heitler are coherent
⇒ can measure amplitude AND phase

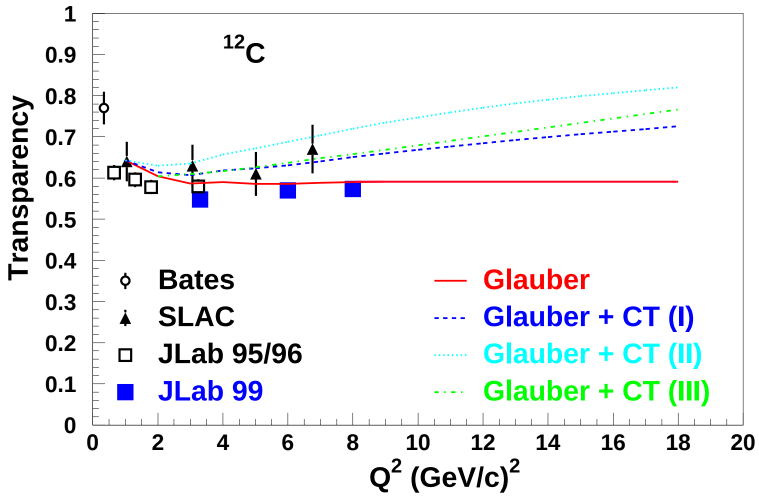




DVCS at 11 GeV can cleanly test correlations in nucleon structure
(data shown – 2000 hours)

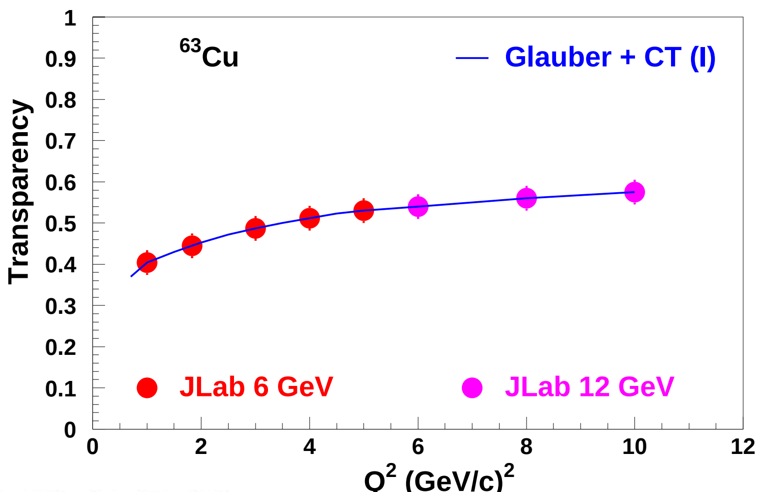


Color Transparency – Now and at 12 GeV



Hall C (e,e’p) experiments at 4 and 5.5 GeV show no evidence for color transparency

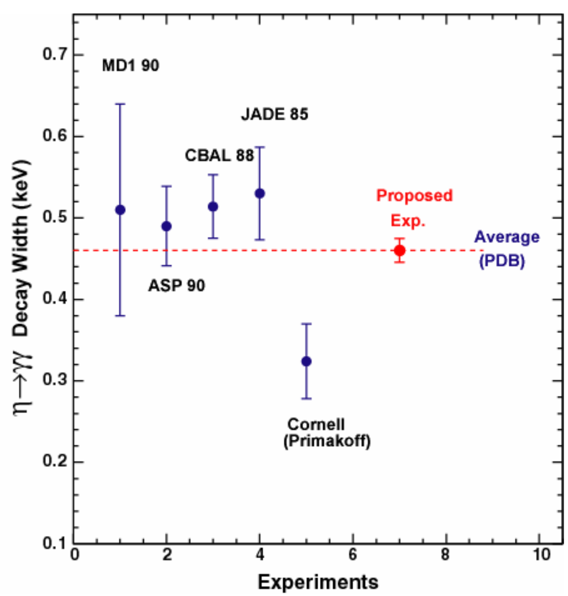
Extending these data to 12 GeV will either reveal color transparency or force us to rethink our understanding of quark-based models of the nucleus

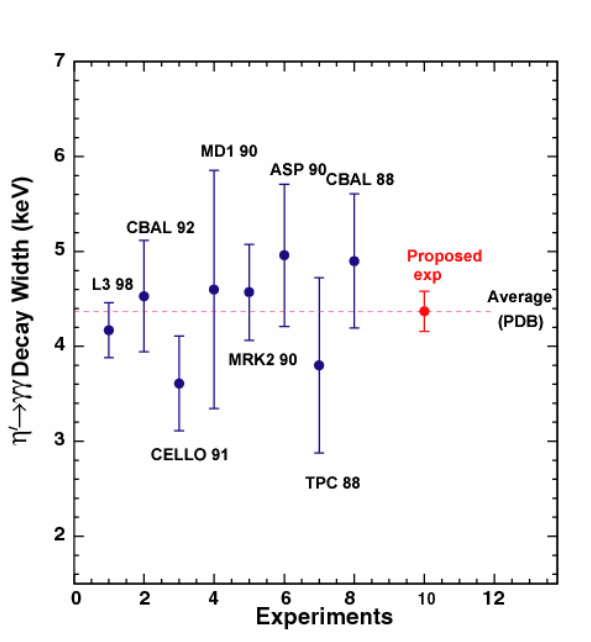


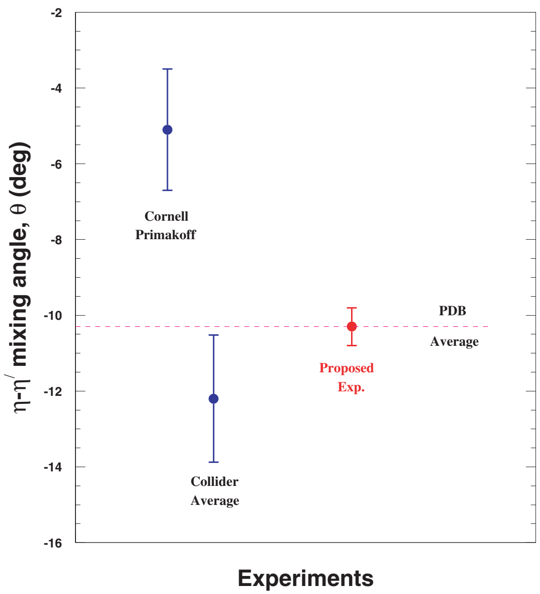
12 GeV will also permit similar measurements using the (e,e’□) reaction, which is expected to show color transparency at lower Q^2

Determine Fundamental Parameters of the Standard Model

Primakoff Effect Measurements:



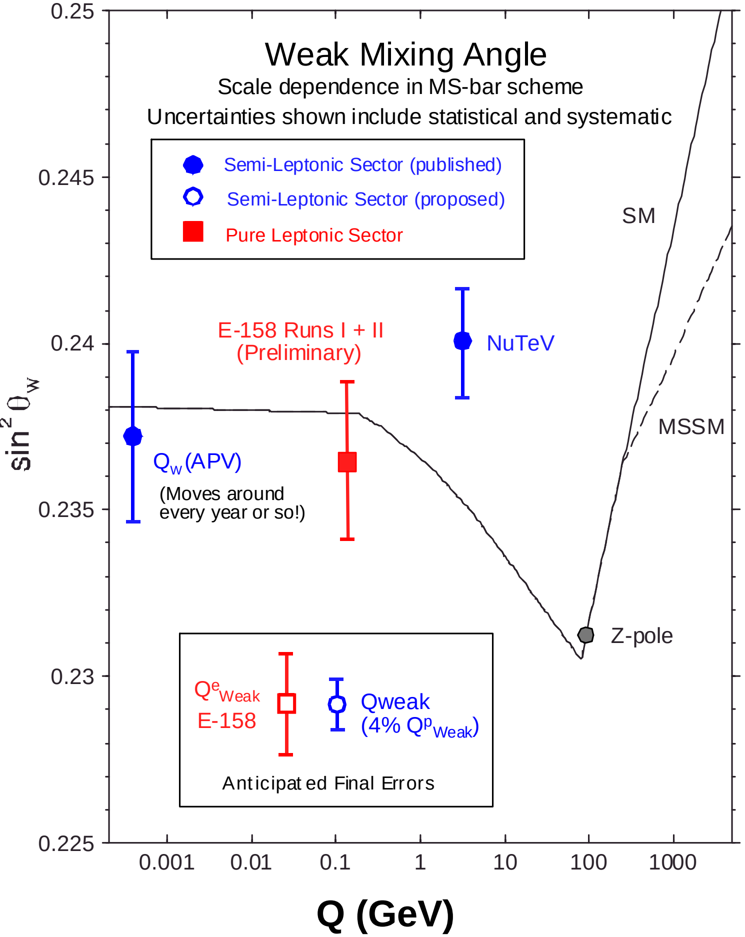




$\Gamma(\eta\rightarrow\gamma\gamma)$ **and** $\Gamma(\eta'\rightarrow\gamma\gamma)$ $\Rightarrow$ **$\eta\eta'$ mixing and quark mass ratio SM Tests**

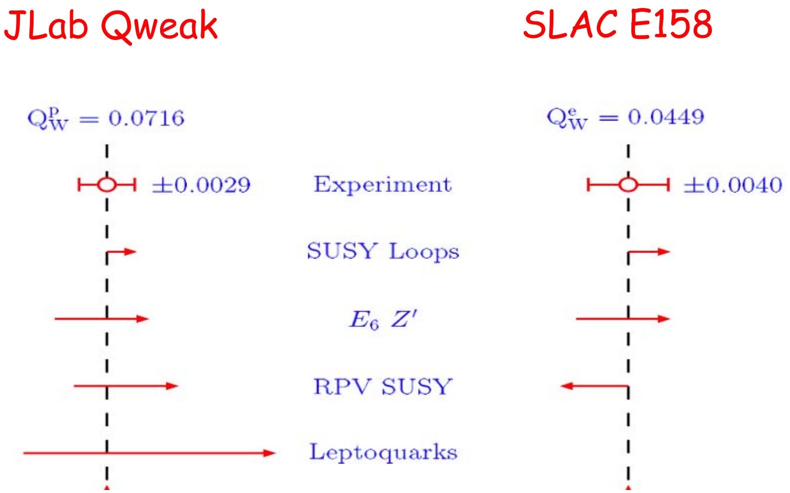
And Test Its Predictions: The Q^p_{Weak} Experiment

"Physics beyond the Standard Model at the TeV Scale"



- 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:**

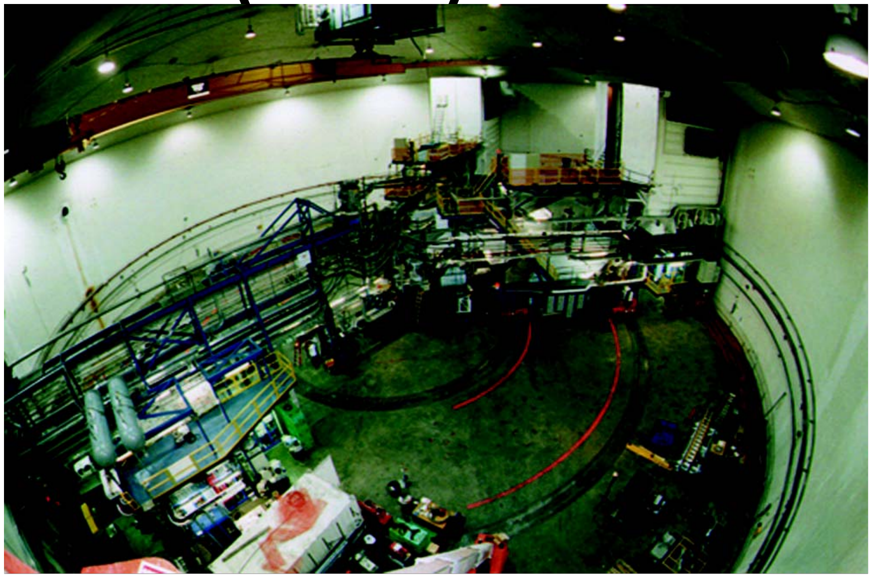
$$\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_F\left|\Delta Q^p_W\right|}} \approx 4.6\ \text{TeV}$$

Q_{Weak} will provide a stringent stand alone constraint on Lepto-quark based SM extensions.

With APV and SLAC E158 results Q_{Weak} will constrain SM extensions based on extra Z's.

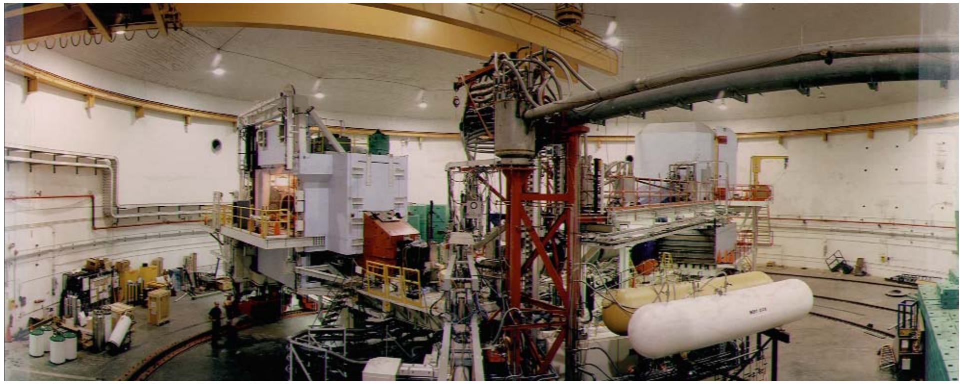
Plans for 12 GeV Began With The Equipment in the Existing Experimental Halls

Hall A (2 HRS)



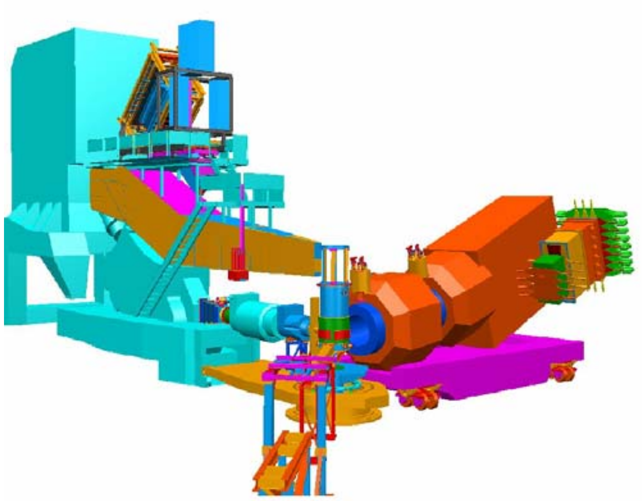
Hall B (CLAS)

Hall C (SOS/HMS)

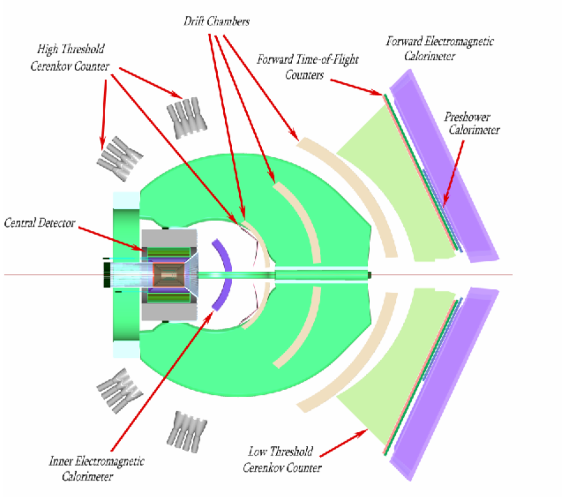


And Ended With Enhanced and/or Complementary Equipment in Halls A, B, & C and a New Hall D

A



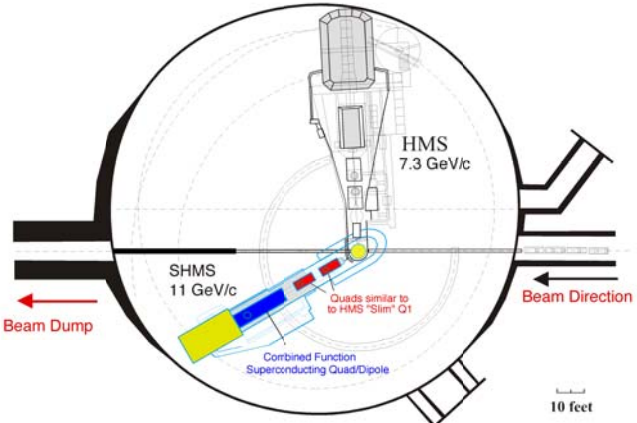
B



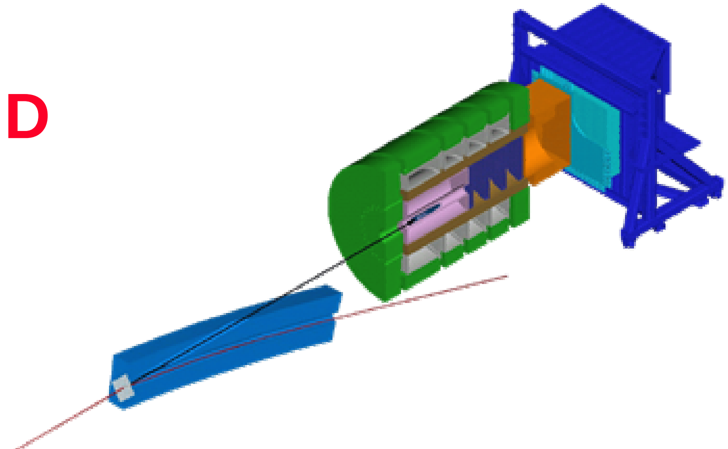
Medium Acceptance Detector (MAD) high luminosity and intermediate angles

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

C



D

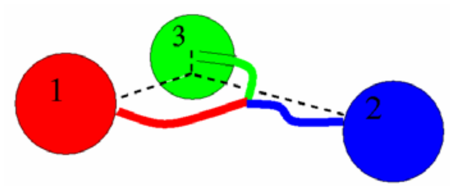


Super High Momentum Spectrometer (SHMS) high luminosity and forward angles

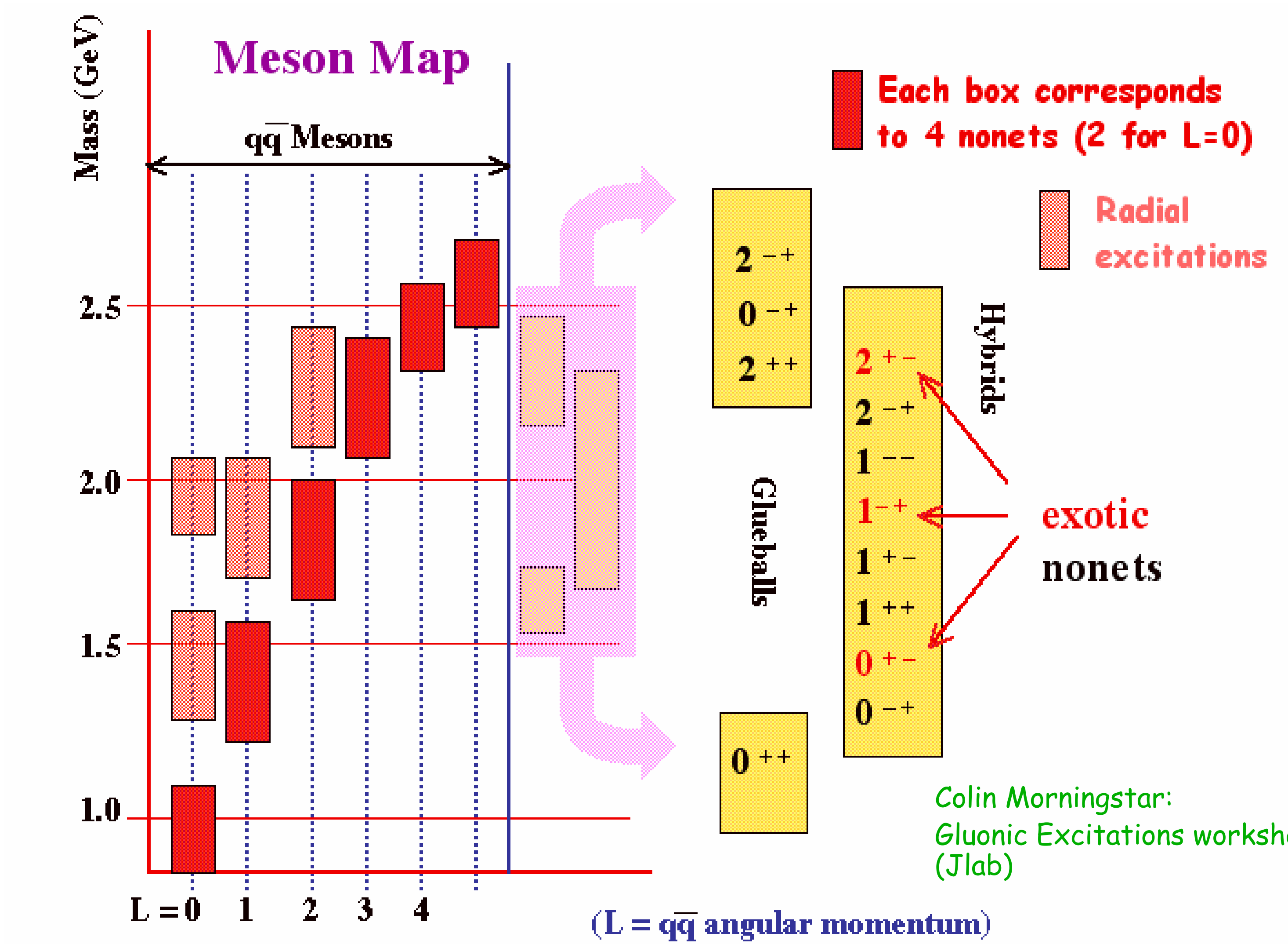
9 GeV tagged polarized photons and a 4π hermetic detector

Entirely new forms of matter

- **Gauge-field configurations provide confining potential**
  - **—States of pure glue exist**
    - **Exotic states not light**
    - **Others mix with** $q\bar{q}$
  - **—Glue may not be in ground state**
    - **Hybrid mesons: exotic quantum numbers**
    - **Hybrid baryons: no exotics, mix with** qqq



Glueballs and hybrid mesons



Colin Morningstar:
Gluonic Excitations workshop, 2003 (Jlab)

Applied Science Program at JLab

- All physical properties (except density) of materials determined by the electrons & phonons & their dynamics.

- New generations of tools allow deeper understanding of properties of materials.

- JLab's FEL allows us to probe:

  timescales upon which electrons/phonons react to their environment
  energy scales upon which correlated electron-electron and phonon-vibrational excitations occur.

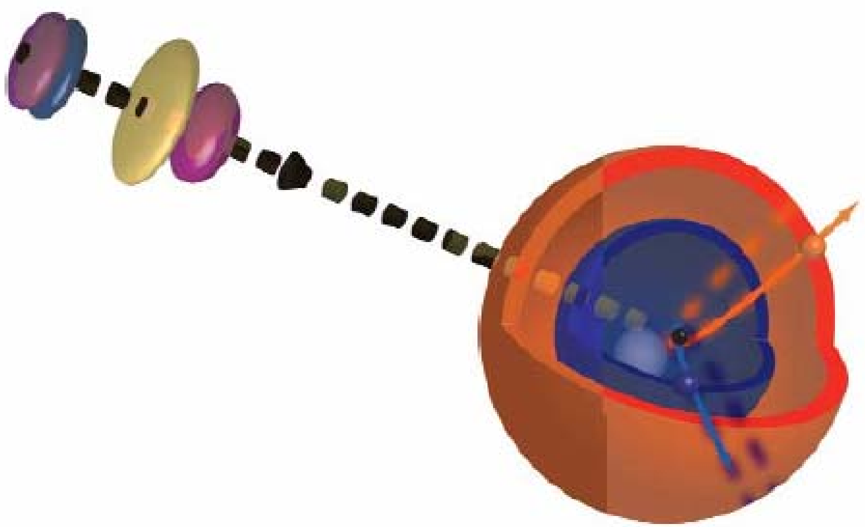
- Multiple photons allow controlled out-of-equilibrium dynamics to be investigated.

Examples of Discovery Class Proposals

- **Chemical reactions and molecular dynamics**
- **Protein function**
- **Superconducting bandgaps**
- **Giant magnetoresistance, correlated electron effects and coupling to phonon bands**

Benefits of multiple photons, tunability, short pulses

Bob Jones UVa



Dance of the electrons. In the experiment by Pisharody and Jones (1), a sequence of four laser pulses excites the two valence electrons into radial wave packets whose corresponding classical orbits are indicated. The outer electron (orange) is shown both in terms of one of its classical orbits and in terms of its radial wave packet. The electron excited into the lower energy orbit (blue) is shown in one of its classical orbits. Varying the timing of the pulses allows control of the collision dynamics of the two electrons.

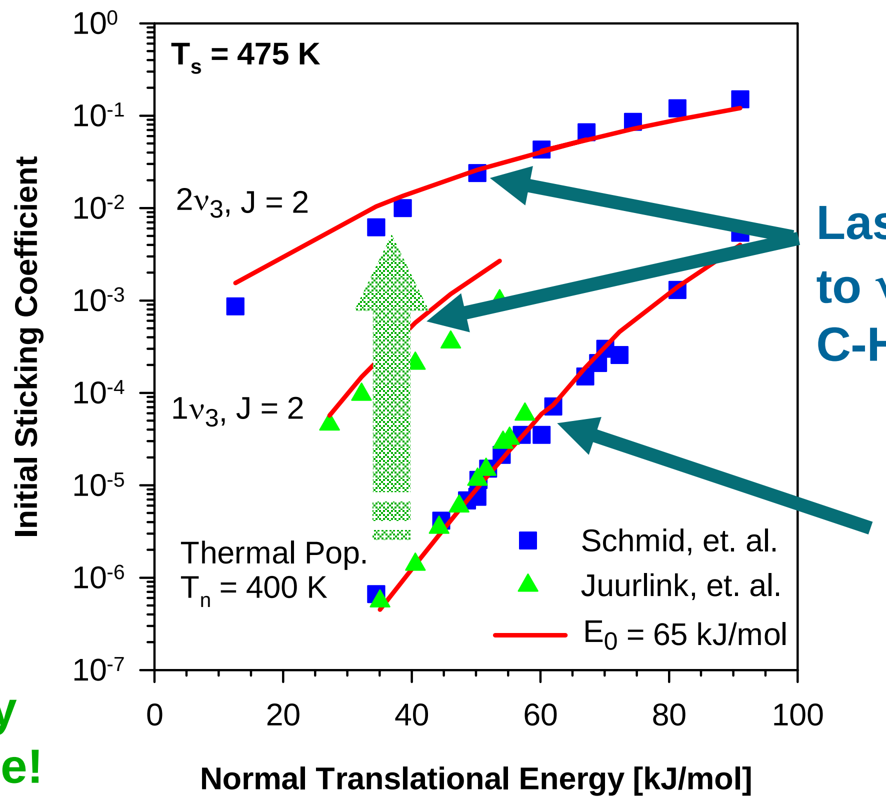
SCIENCE **303** 813 (2004) - FEBRUARY 6, '04

Probing Two-Electron Dynamics of an Atom

S. N. Pisharody and R. R. Jones*

Coherent short-pulse laser excitation has been used to control the approximate energy and relative proximity of two valence electrons within the same alkaline-earth atom, thereby providing insight into the dynamical evolution of a three-body Coulomb system. Our time-domain experiments enable direct experimental study of the electron dynamics at the classical limit of a two-electron atom. As an example, we look at the mechanism of autoionization for one two-electron configuration class and find that the doubly excited atom decays through a single violent electron-electron collision rather than a gradual exchange of energy between the electrons.

Benefits of High Repetition Rate & Tunability



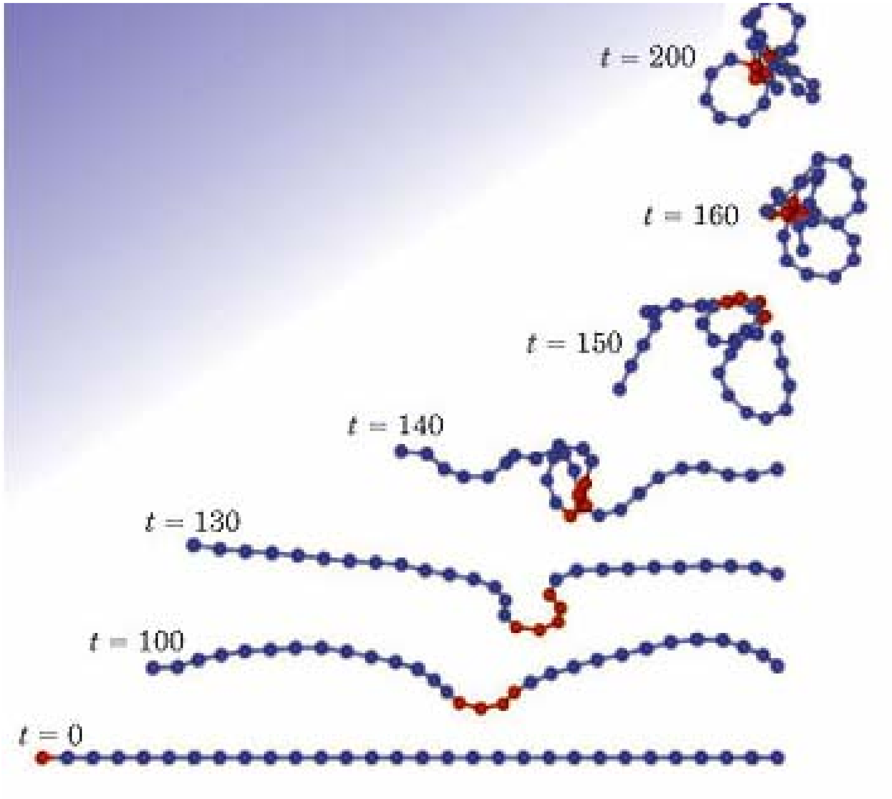
IR-laser pumping increases reaction probability by many orders of magnitude!

Dissociative chemisorption of a CH_4 molecular beam incident on a Ni(100) surface with and without laser excitation.

Ian Harrison, UVa
Microcanonical Unimolecular Rate Theory at Surfaces – IR Photochemistry in Catalysis

Non-linear Dynamical Effects Using High Field THz Light

High electric fields are predicted to generate localized modes!



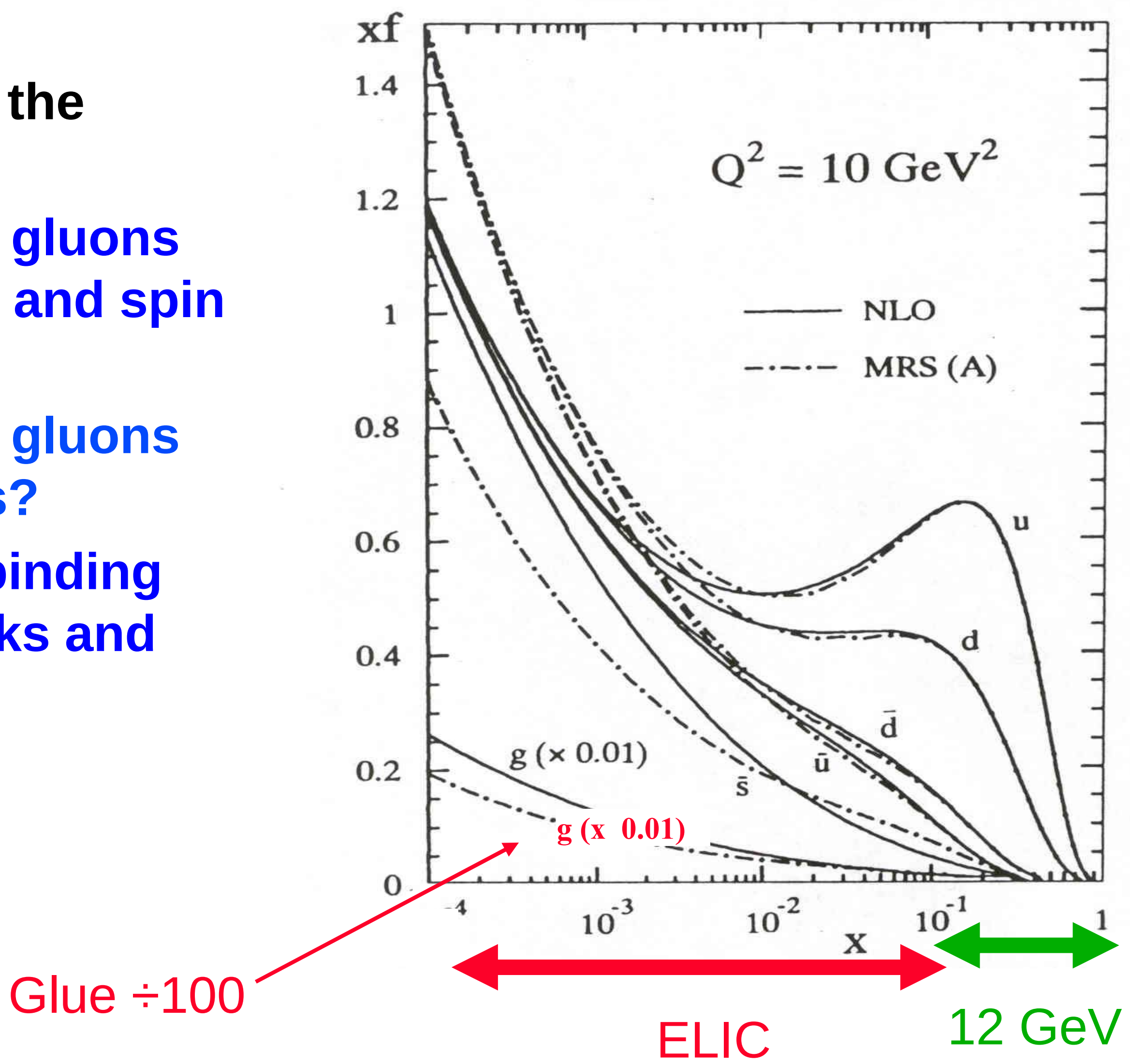
A biopolymer chain buckles and folds on itself due to an instability produced by a nonlinear localized mode – Physics Today Jan. 2004 p43. Mingaleev et al Europhys. Lett. **59** 403 (2002)

JLab collaboration with Al Sievers, Cornell U.

CEBAF II/ELIC Upgrade - Science

Science addressed by the second Upgrade:

- **How do quarks and gluons provide the binding and spin of the nucleons?**
- **How do quarks and gluons evolve into hadrons?**
- **How does nuclear binding originate from quarks and gluons?**



NSAC Facilities Subcommittee Conclusions

- SCIENCE (Category 1 – Absolutely Central) **The research program of this type of facility at JLab, similar in many ways to the electron-ion collider EIC that received a preliminary endorsement in LRP 2002, will be absolutely central to nuclear physics**
- READINESS (Category 3 - mission and/or technical requirements not yet fully defined) **This project is still in an early stage of development.**
- Indeed case for 25 GeV fixed target vs e-ion collider needs to be worked through carefully over next 5 years.

World Community in 2011 and Beyond

- Three major new facilities investigating nuclear physics at hadronic level (QCD) :
  GSI (Germany), JHF (Japan) and JLab*

- Complementary programs
  (e.g. charmed vs light-quark exotics, hadrons in-medium..)

- GSI and ISAC (TRIUMF) also overlap RIA

- Wonderful opportunities to build international community and take our field to a new level

* Unique: only electromagnetic machine