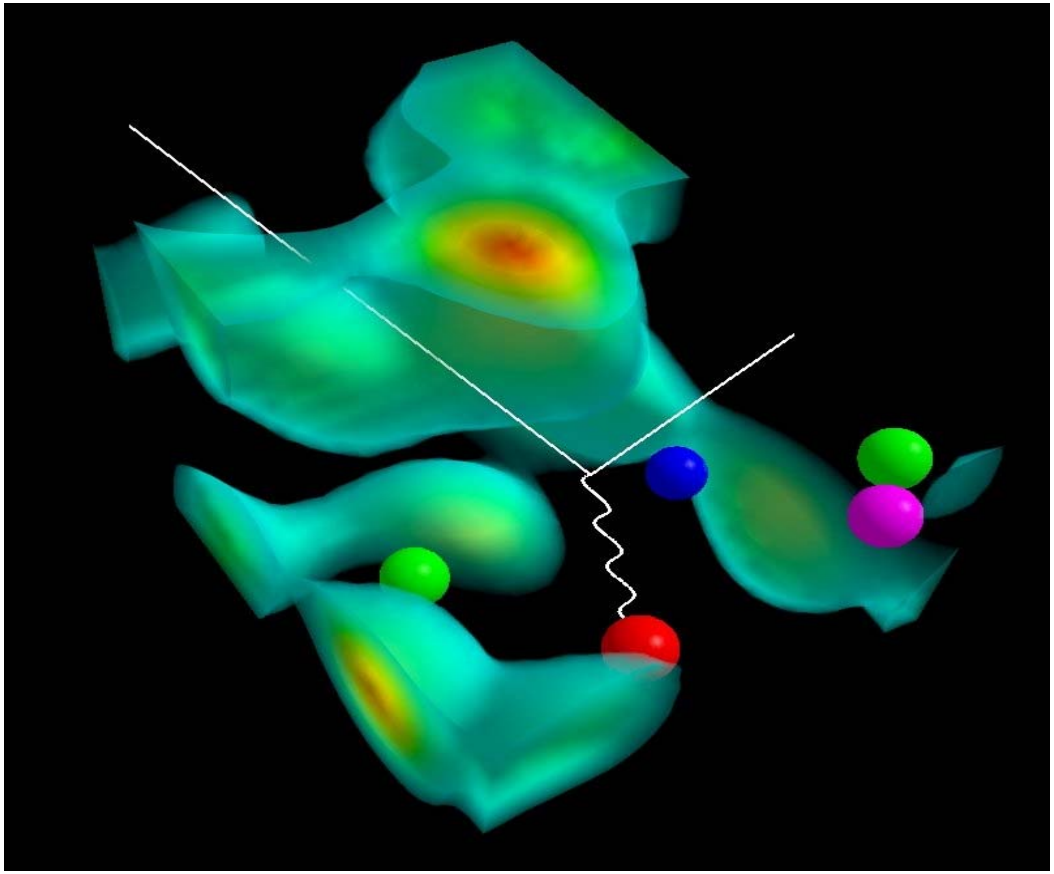
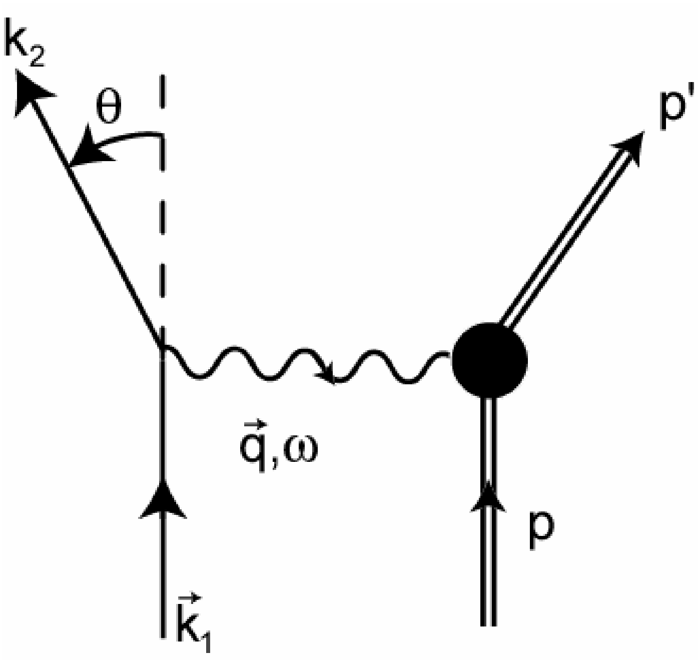
Precise Electro-Weak Studies: An Essential Element of the World-Wide Nuclear Physics Program



Anthony W. Thomas

Rutgers Town Meeting : January 13th 2007

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:

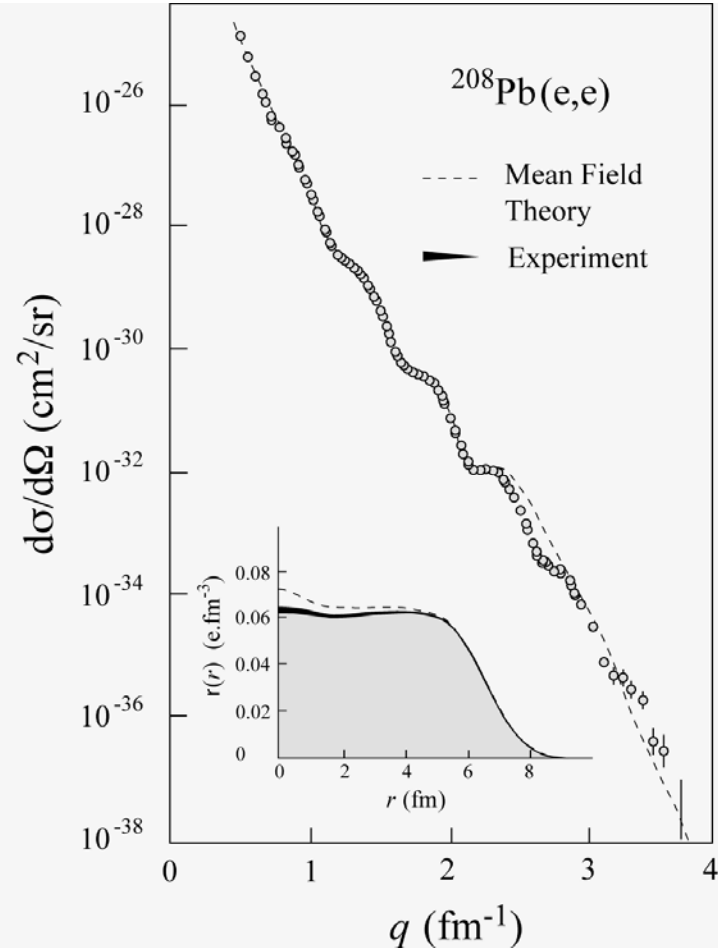
$\lambda \cong 2\pi/q$ **(1 fm ⇔ 1 GeV/c)**

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

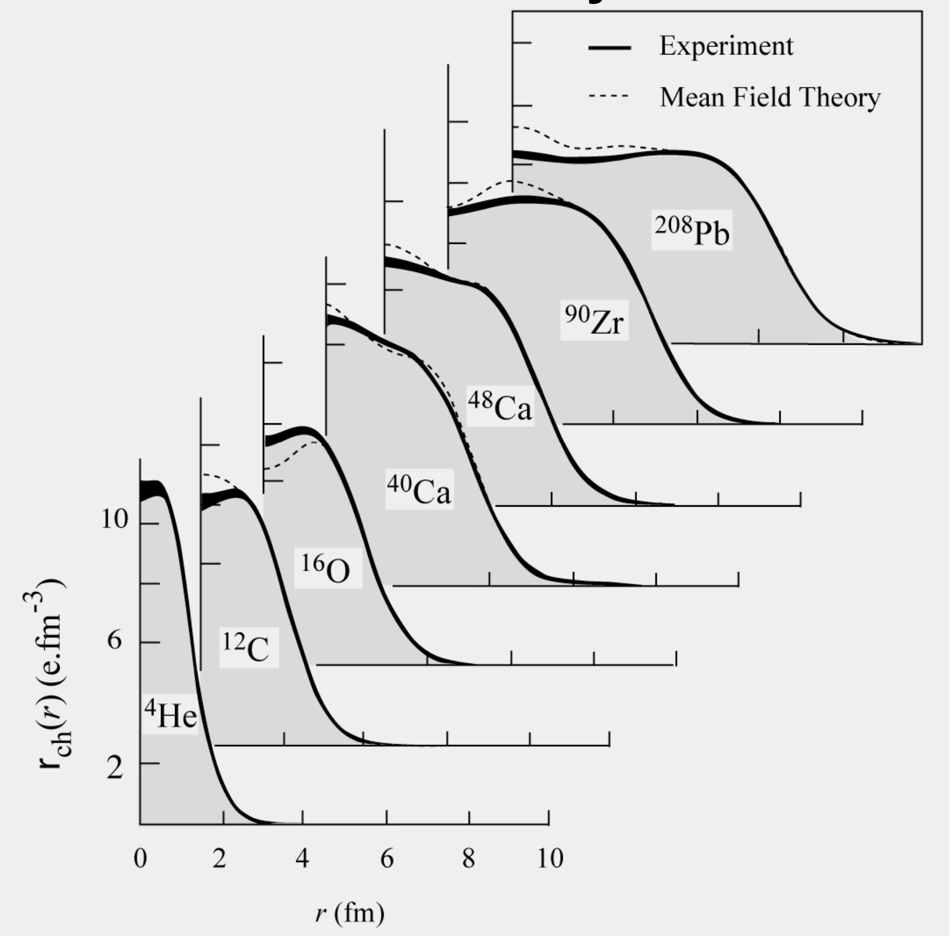
$Q^2 = -q^2 = $ 4-Momentum Transfer

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

(e,e) ⇒ Nuclear Charge Distributions



From Stanford to Saclay and Nikhef

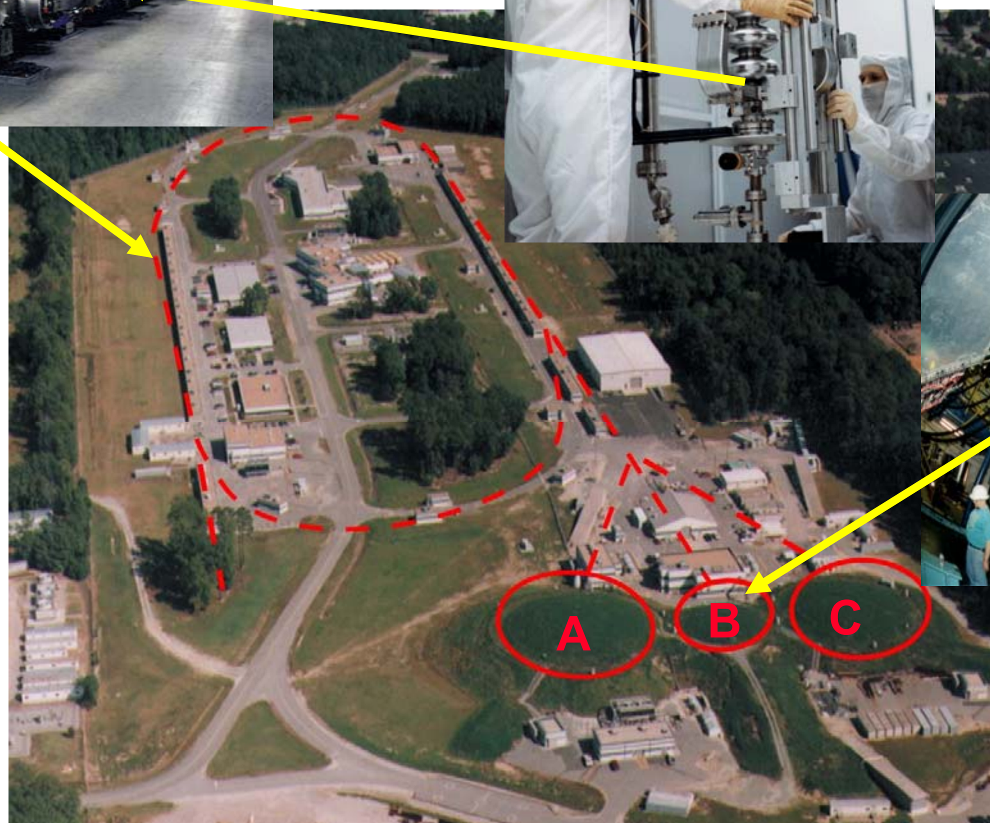


Model-independent analysis ⇒ accurate nuclear charge distributions

JLab: Unique Forefront Capabilities for Science

Cryomodules in the accelerator tunnel

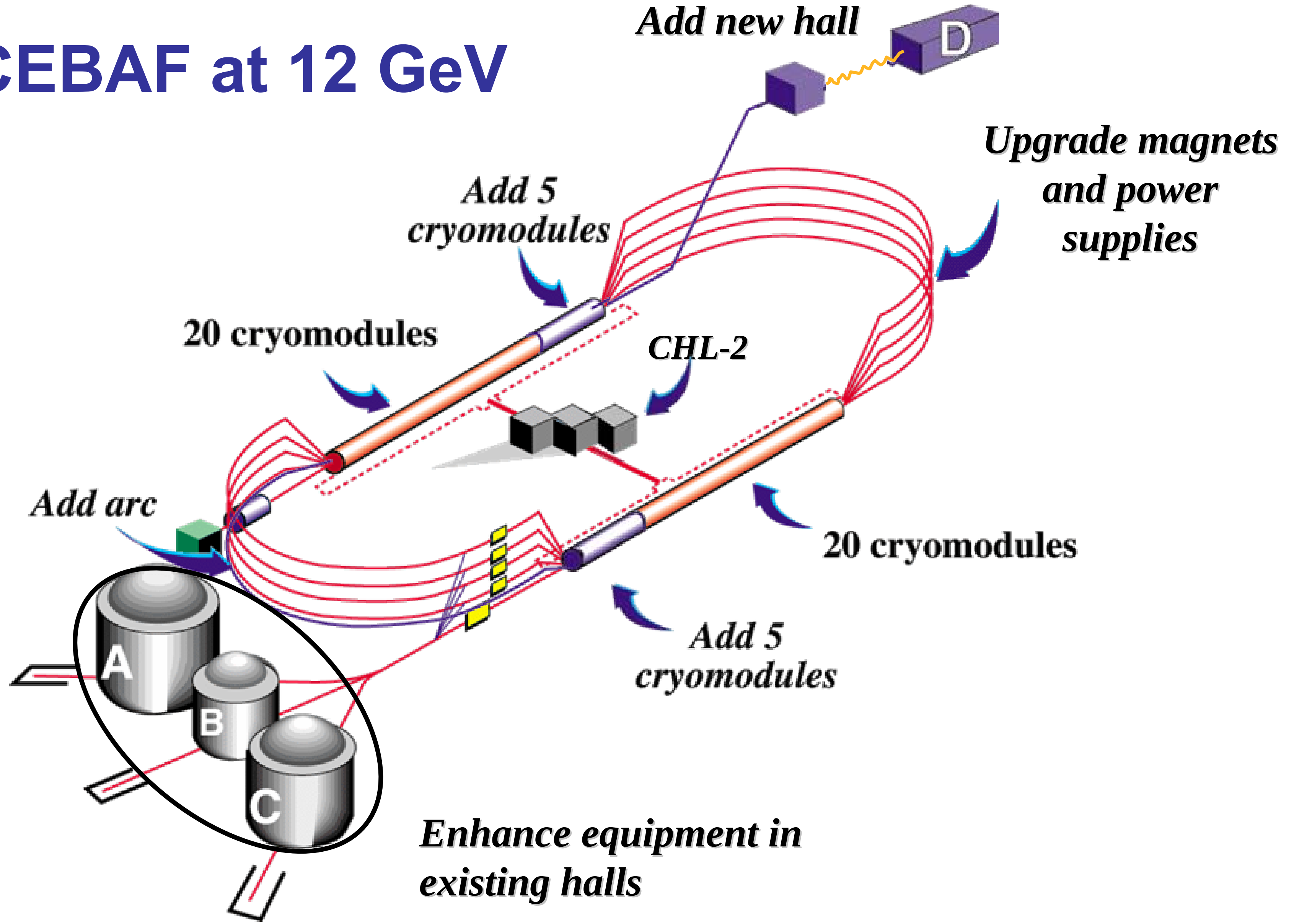
Superconducting radiofrequency (SRF) cavities undergo vertical testing.



An aerial view of the recirculating linear accelerator and 3 experimental halls.

CEBAF Large Acceptance Spectrometer (CLAS) in Hall B

CEBAF at 12 GeV



CD-1 Announced at JLab on Valentines Day 2006
By Secretary Bodman

DOE Review of Progress – January 2007

12 GeV Upgrade Project is on track in their preparations and readiness for CD-2 approval in September 2007

CD-3 (Approve Construction Start) is expected in late 2008

Highlights of the 12 GeV Program

- Revolutionize Our Knowledge of Spin and Flavor Dependence of Valence PDFs

- Revolutionize Our Knowledge of Distribution of Charge and Current in the Nucleon

- Totally New View of Hadron (and Nuclear) Structure: GPDs
  - Determination of the quark angular momentum

Highlights of the 12 GeV Program….2

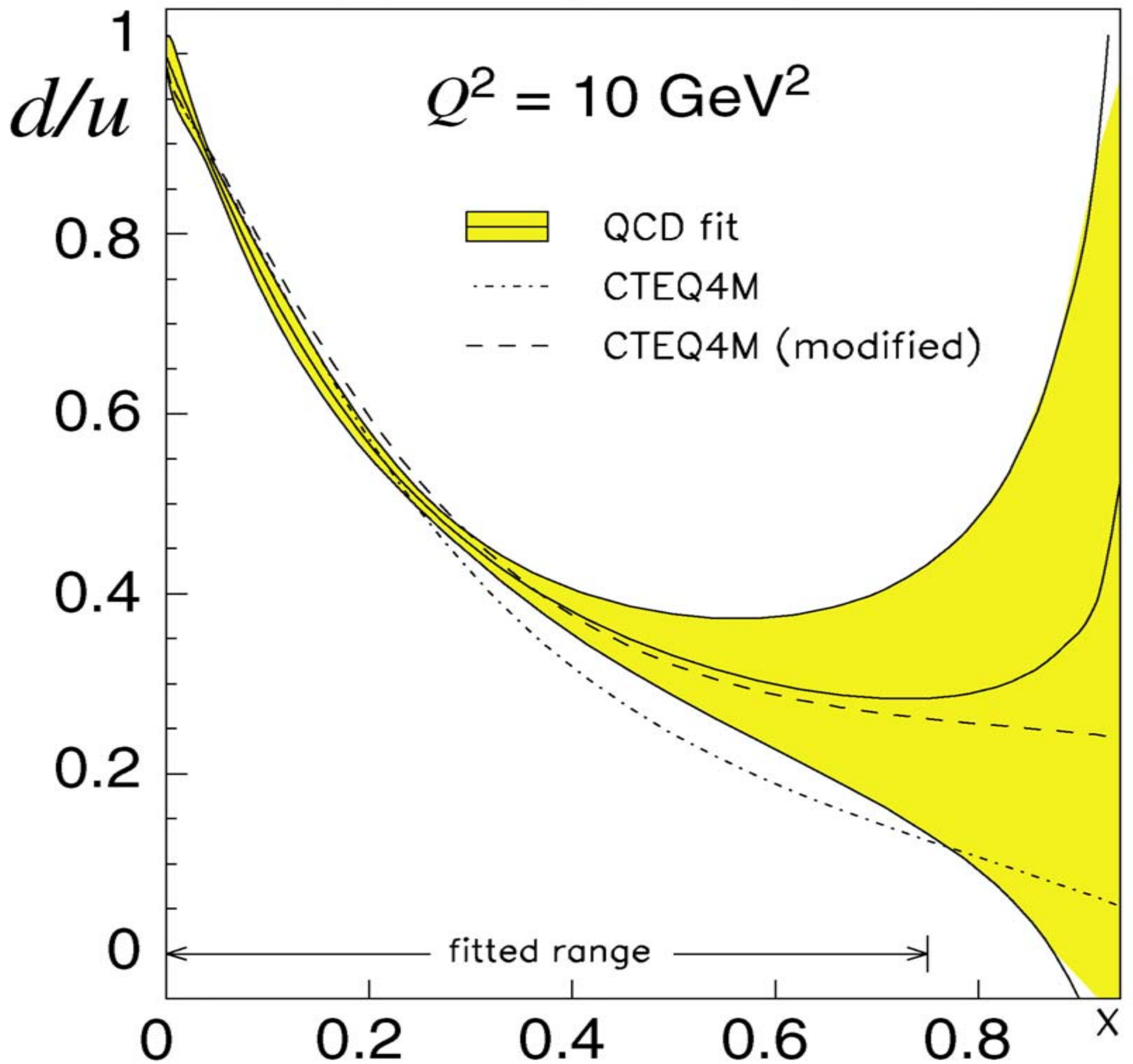
- Exploration of QCD in the Nonperturbative Regime:
  - Existence and properties of exotic mesons
- New Paradigm for Nuclear Physics:
  Nuclear Structure in Terms of QCD
  - Spin and flavor dependent EMC Effect
  - Study quark propagation through nuclear matter
- Precision Tests of the Standard Model
  - Parity Violating DIS & Möller

6 GeV Highlights Leading to the 12 GeV Upgrade

- **Parton Distribution Functions**
- Form Factors
- Generalized Parton Distributions
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model

After 35 years:
Miserable Lack of Knowledge of Valence d-Quarks

M. Botje, Eur. Phys. J. C14, 285-297, 2000

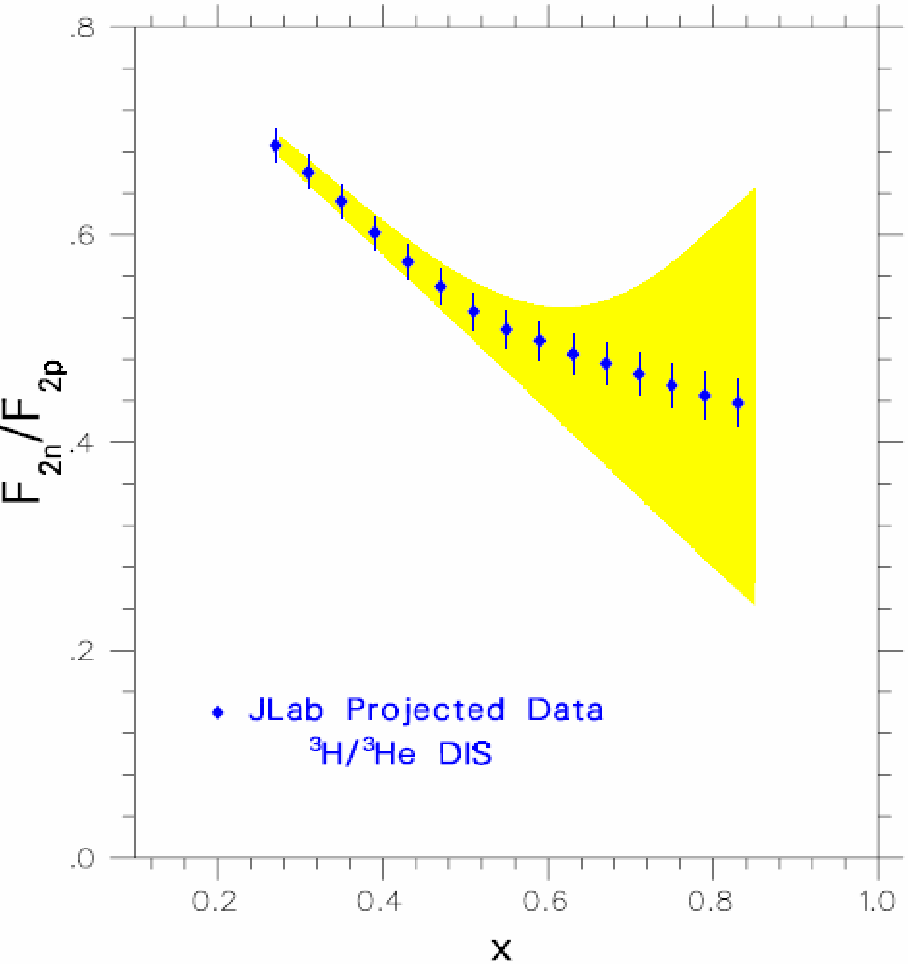


pQCD

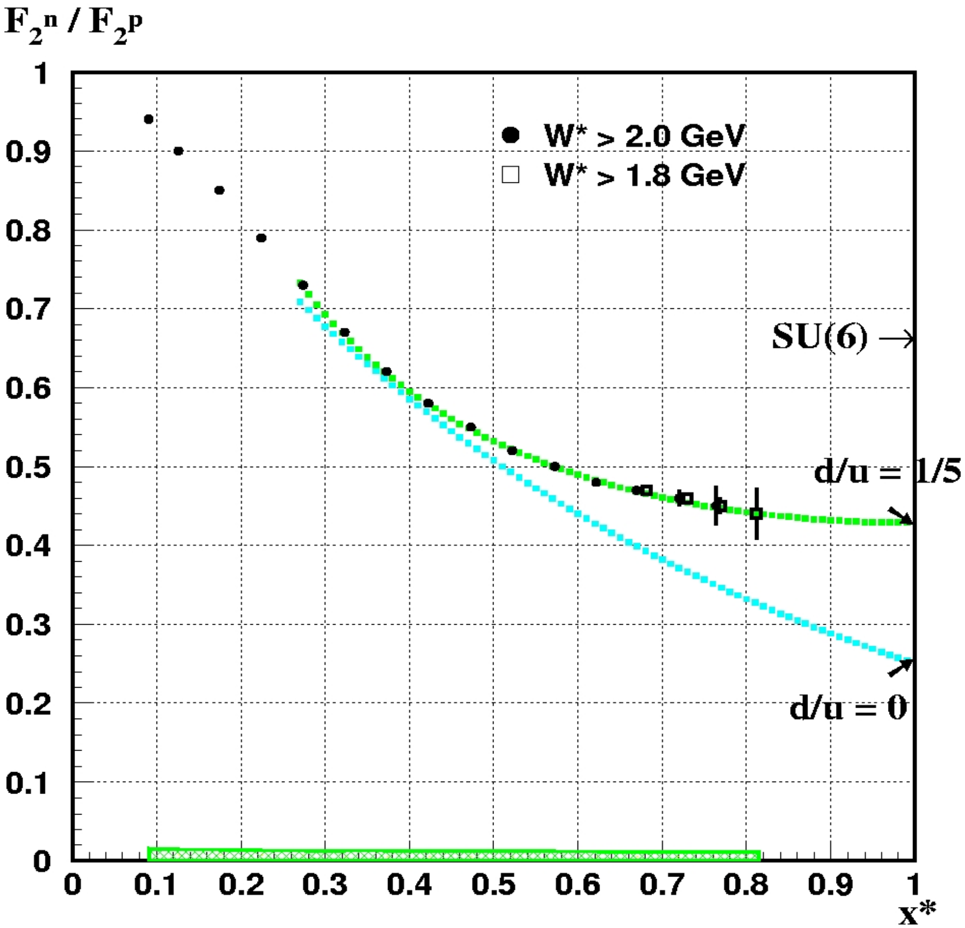
di-quark correlations

12 GeV : Unambiguous Flavor Structure x→ 1

Hall A 11 GeV with HMS

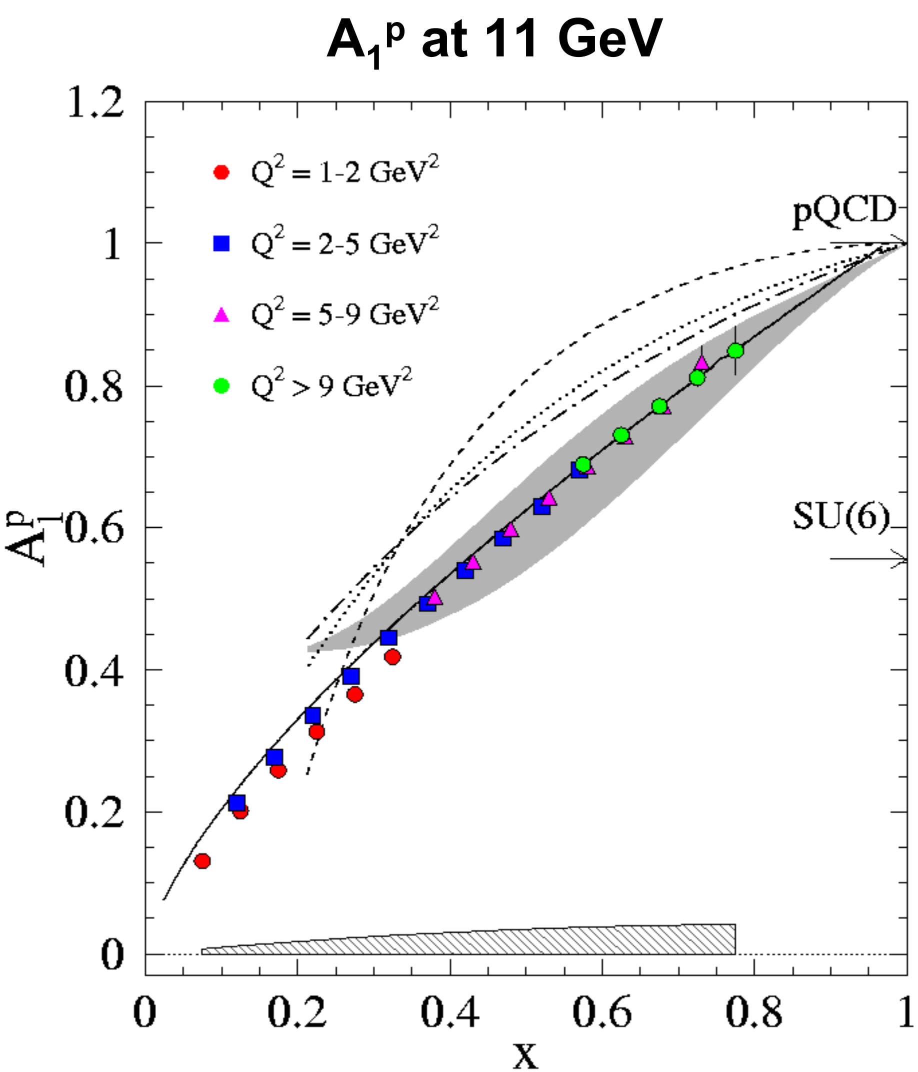


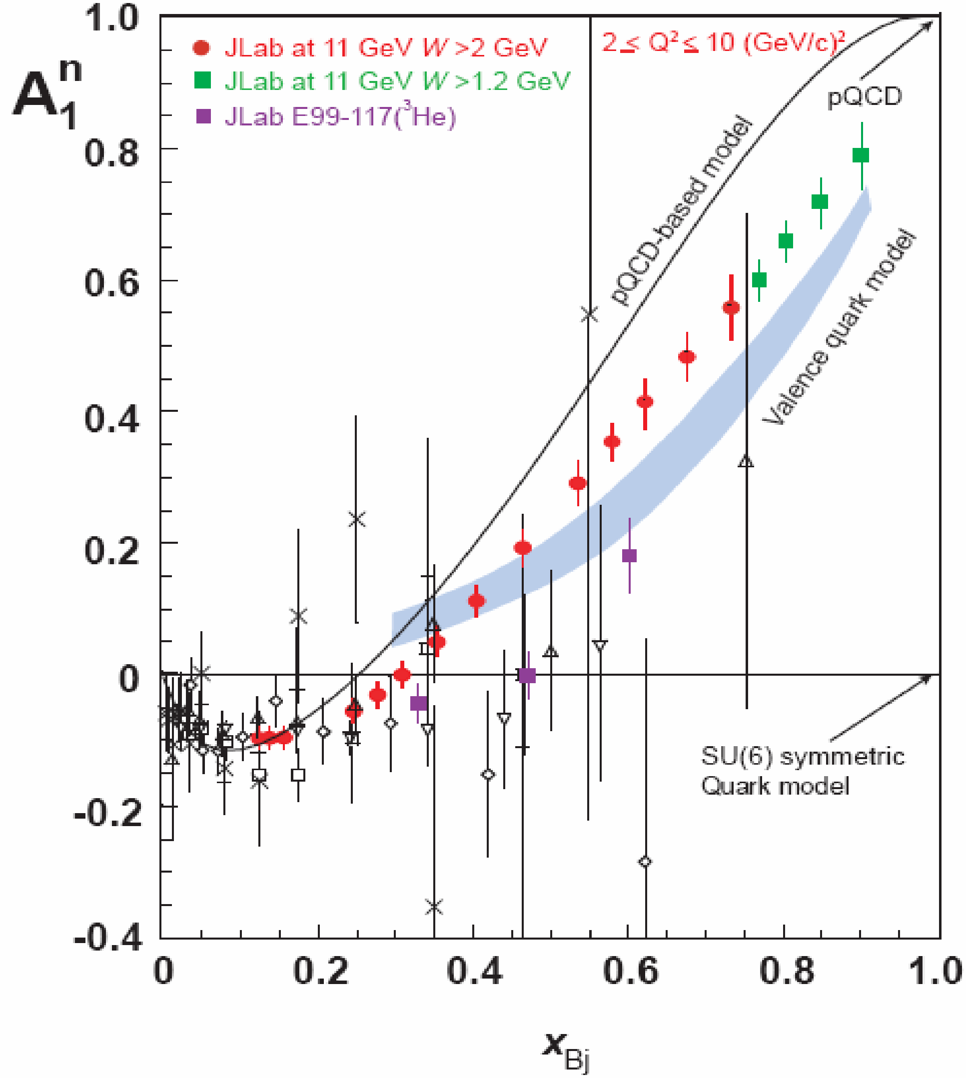
Hall B 11 GeV with CLAS12



Initial investigation with BONUS early 06 successful

12 GeV : Unambiguous Resolution of Valence Spin

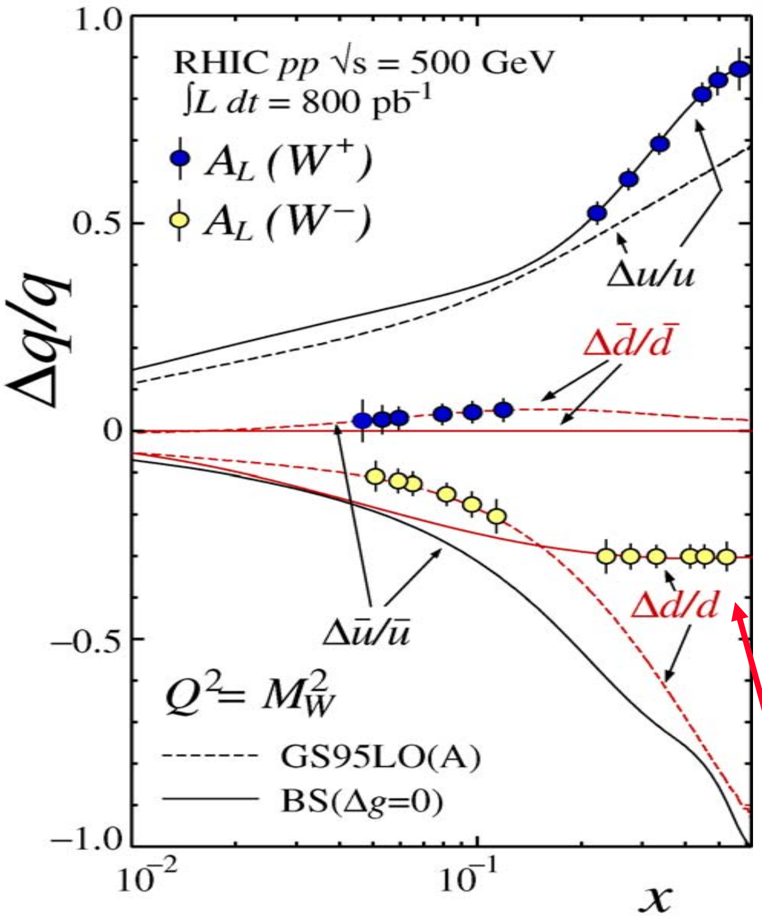




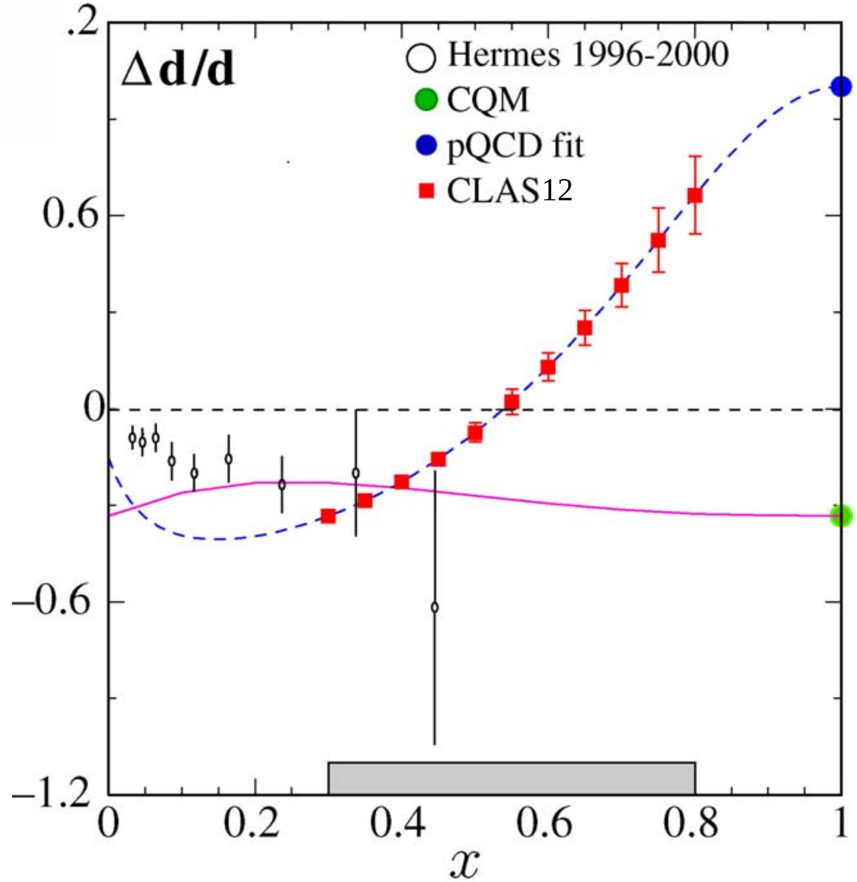
Complements Spin-Flavor Dependence at RHIC

At RHIC with W production

$$A_L^{W^+} \approx \frac{\Delta u(x_1)\,\bar{d}(x_2) - \Delta\bar{d}(x_1)\,u(x_2)}{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2)}$$



At JLab with 12 GeV upgrade

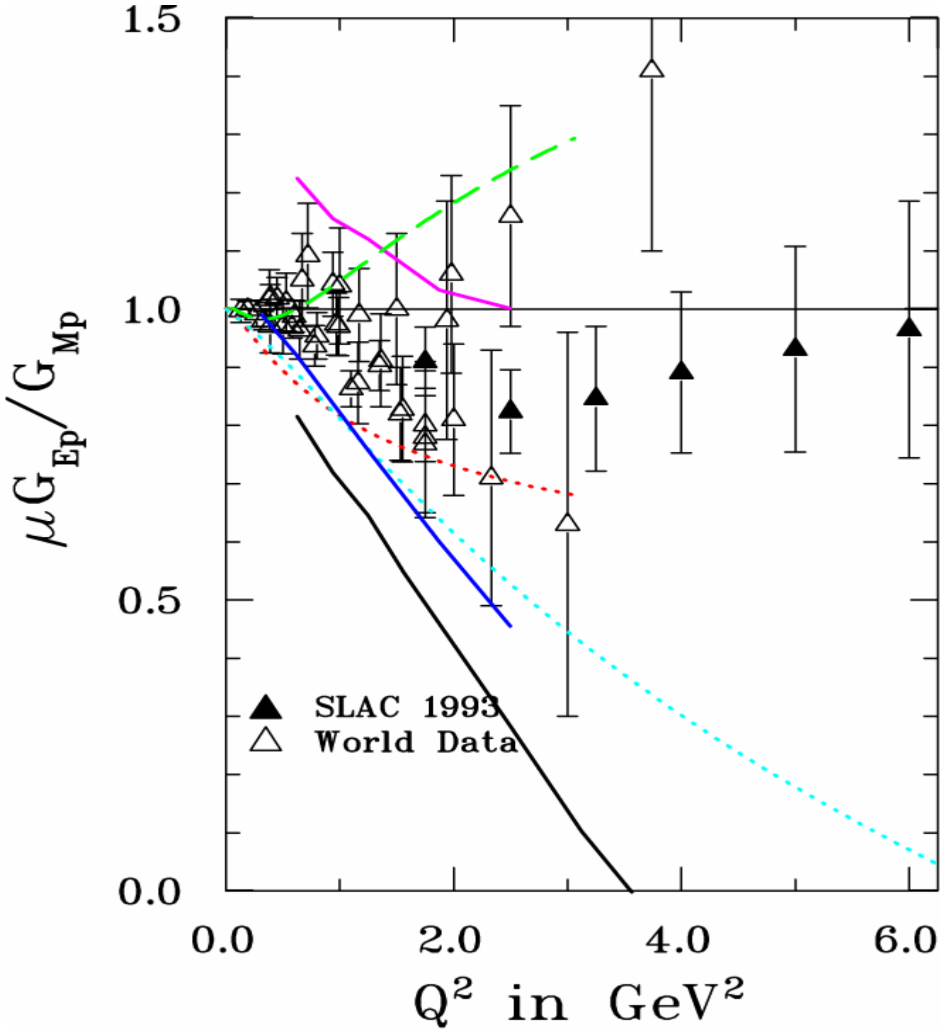


Stops below x=0.5 AND needs valence d(x)

6 GeV Highlights Leading to the 12 GeV Upgrade

- Parton Distribution Functions
- Form Factors
- Generalized Parton Distributions
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model

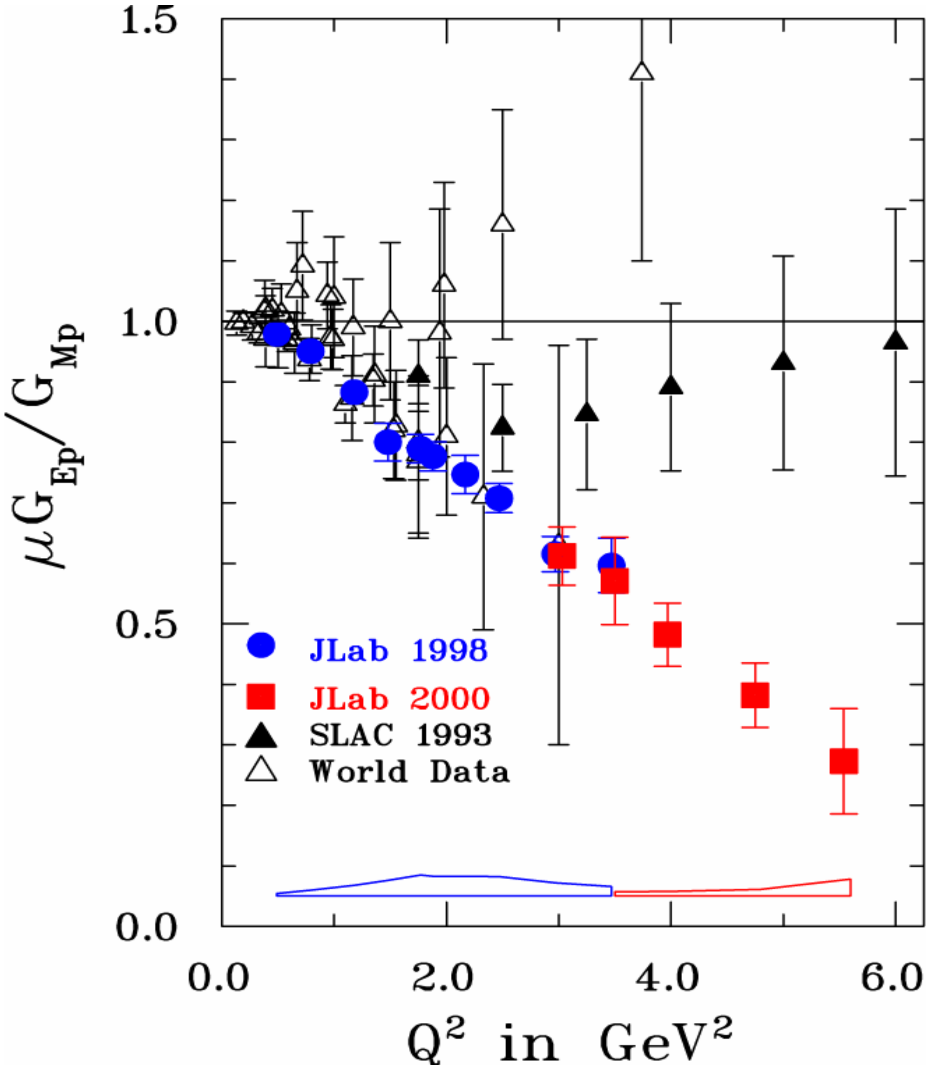
Initial Investigation of Charge vs Current in the Proton at SLAC



- Distribution of charge and magnetization in the proton seemed identical

- The experiments were limited by the precision of absolute cross section measurements

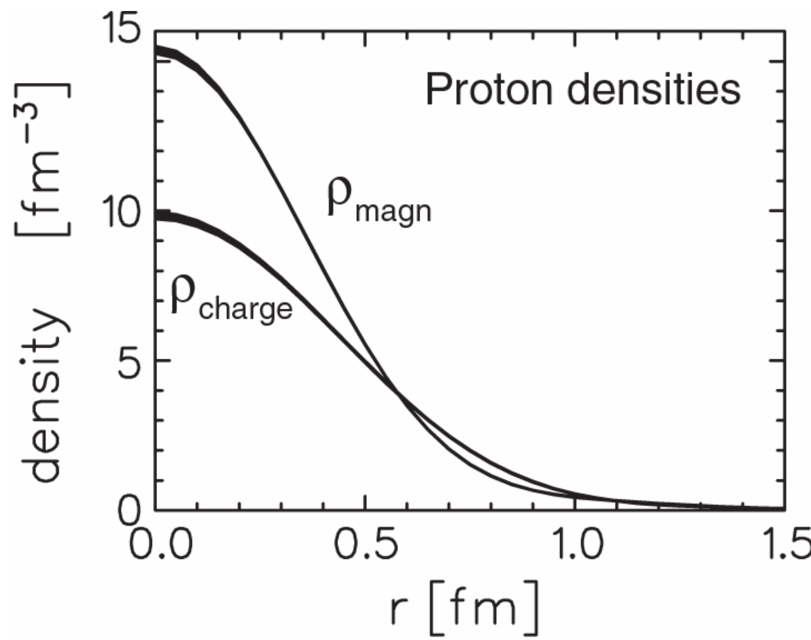
JLab Data Rewrote the Text Book



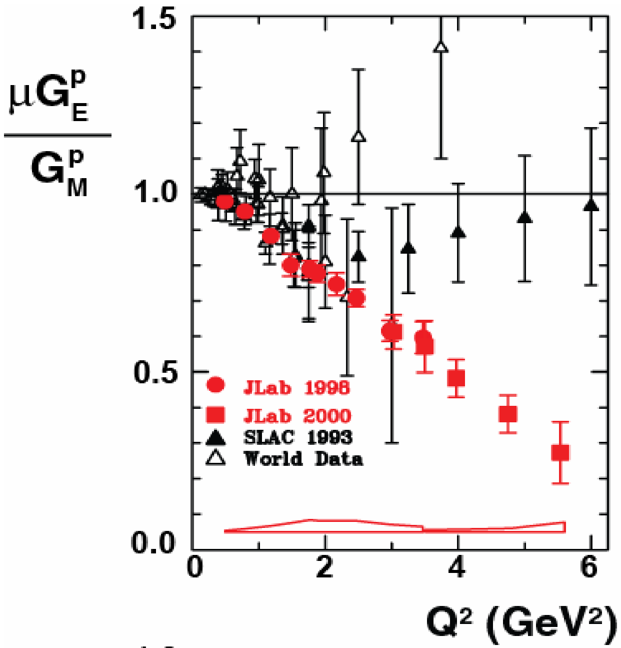
- High Intensity
- High Duty Factor
- High Polarization

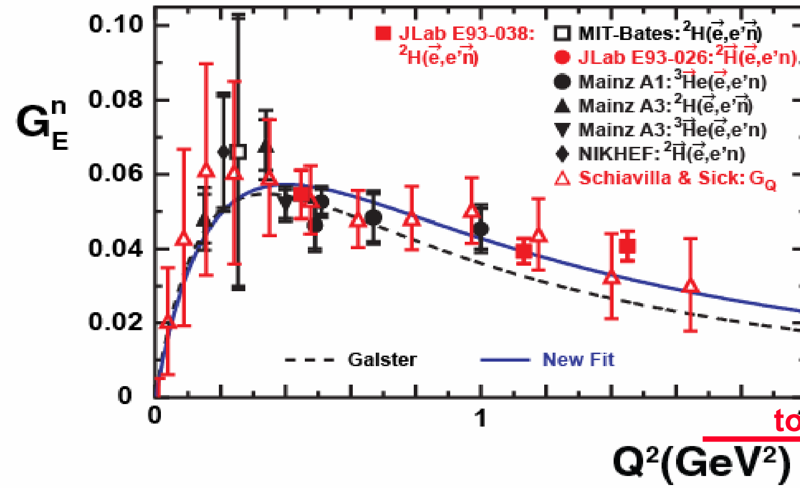
⇒ Revolutionized our knowledge

⇒

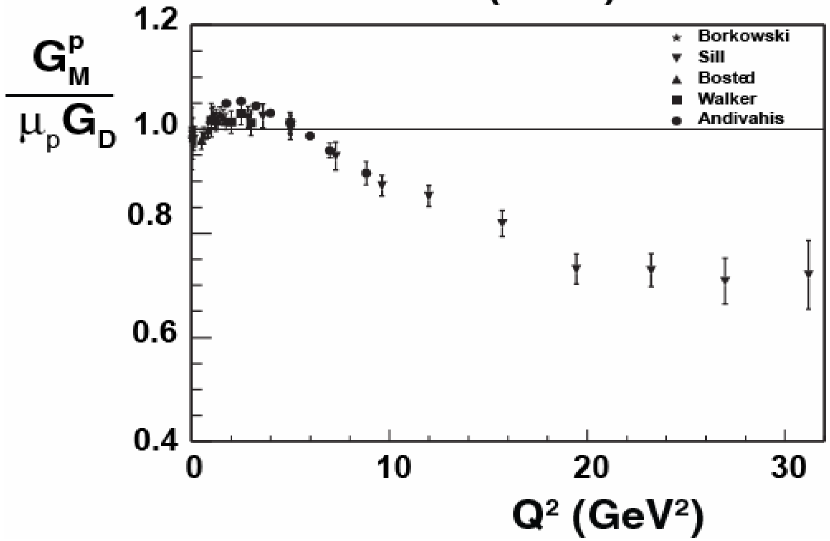


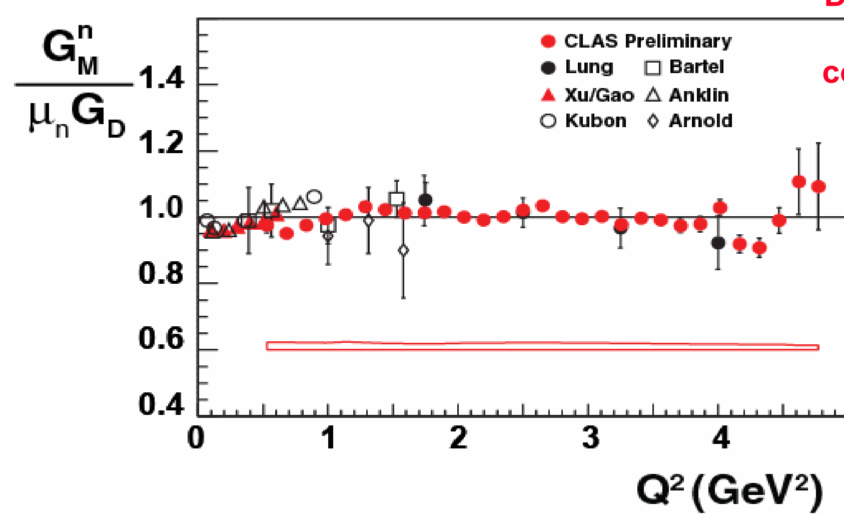
Overview of 6 GeV Form Factor Data



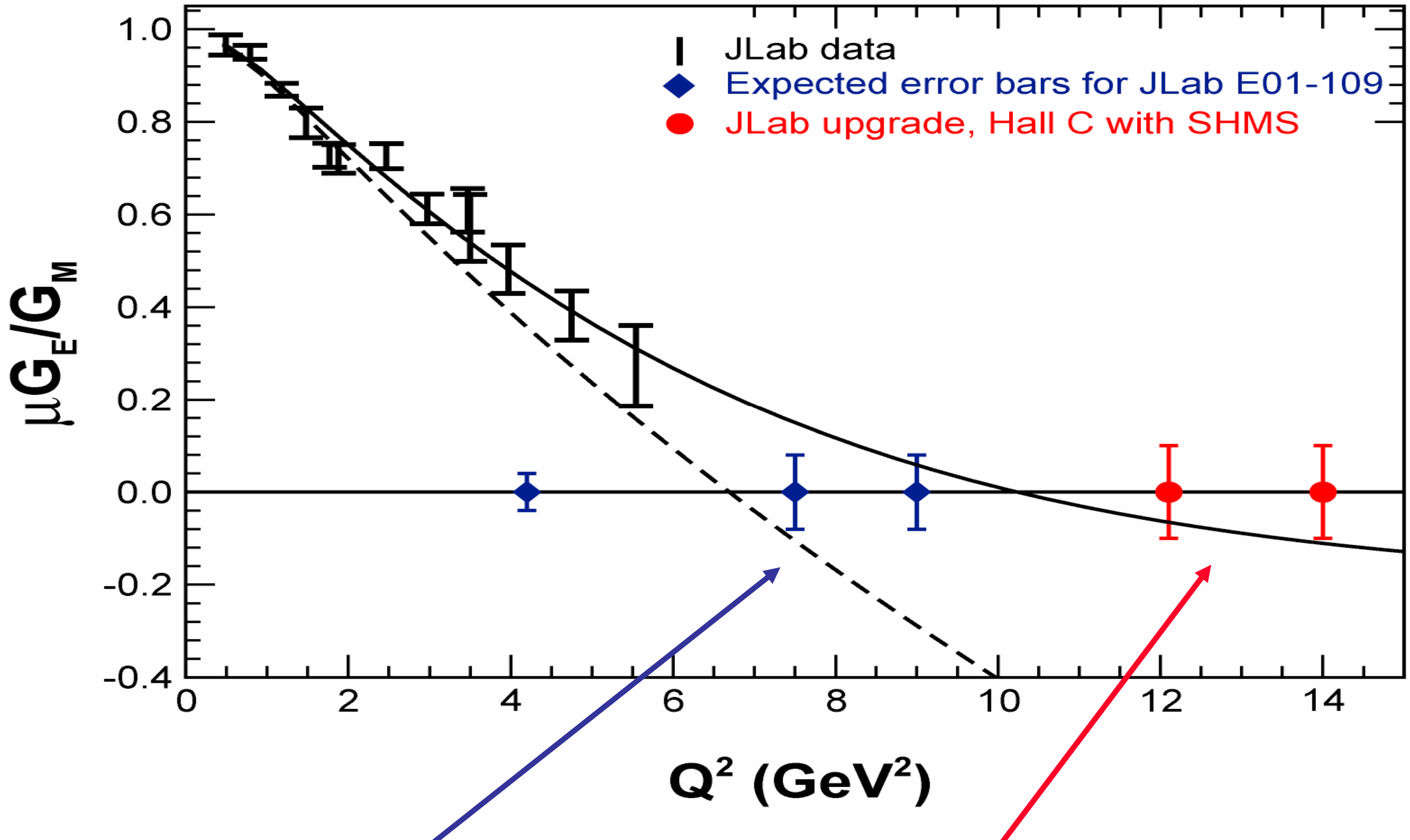


to 3.5 GeV^2
(Hall A)
Data-taking just completed





Future Measurements on G_E^p



- Perdrisat *et al*. E01-109 — will increase range of Q^2 by 50% in FY08 (range of Q^2 for neutron will double over next 3-4 years)
- **With 12 GeV and SHMS in Hall C : similarly for G_M^n (and G_E^n)**

Flavor Decomposition of Vector Form Factors

- **Proton target**

$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^{p\gamma} G_E^{pZ} + \tau G_M^{p\gamma} G_M^{pZ} - \frac{1}{2}(1-4\sin^2\theta_W)\varepsilon' G_M^{p\gamma} \tilde{G}_A^p}{\varepsilon (G_E^{p\gamma})^2 + \tau (G_M^{p\gamma})^2}$$

Neutral-weak form factors

Axial form factor

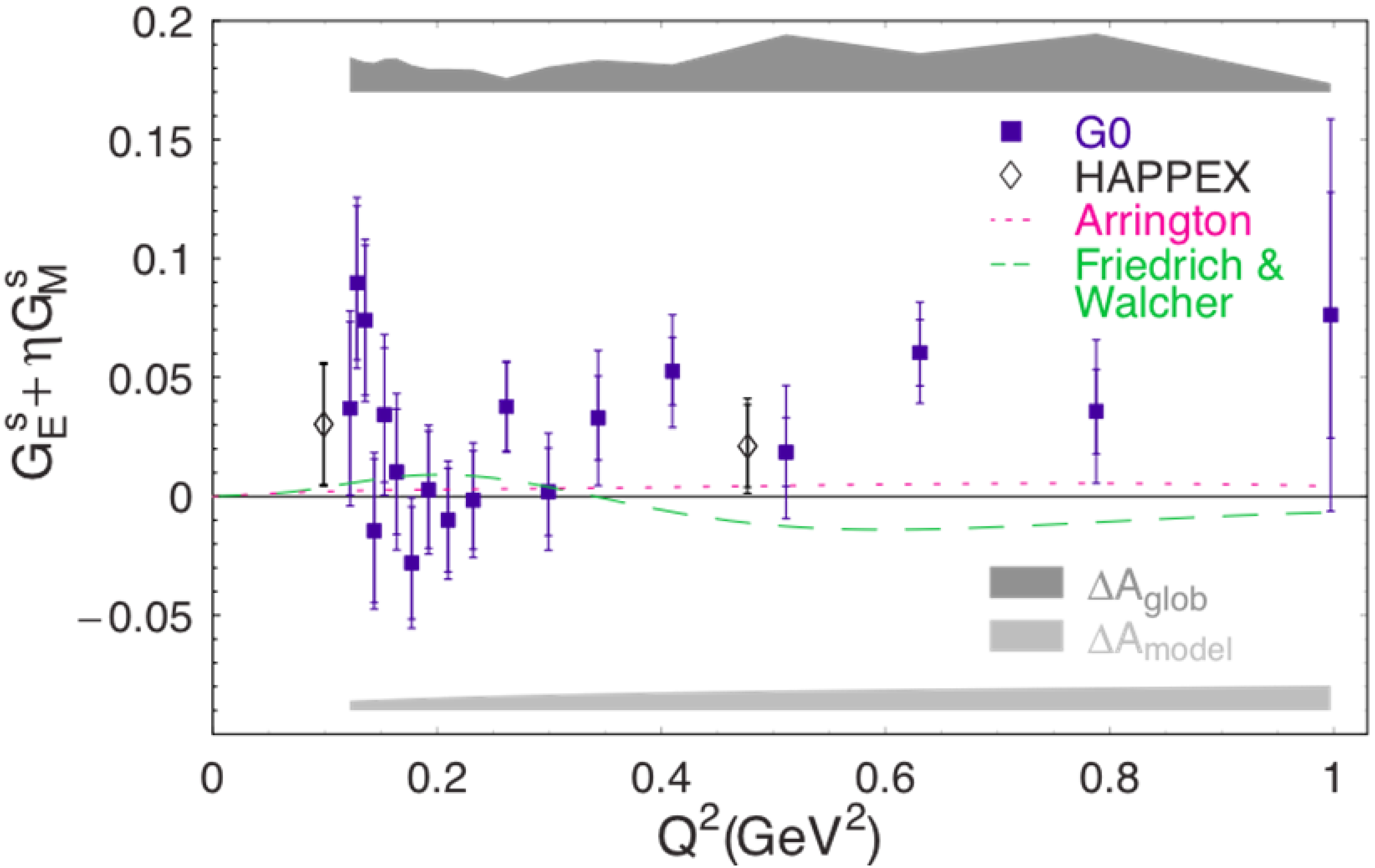
$$4G_{E,M}^{pZ} = (1-4\sin^2\theta_W) G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^{s}$$

Proton weak charge (tree level)

Strangeness

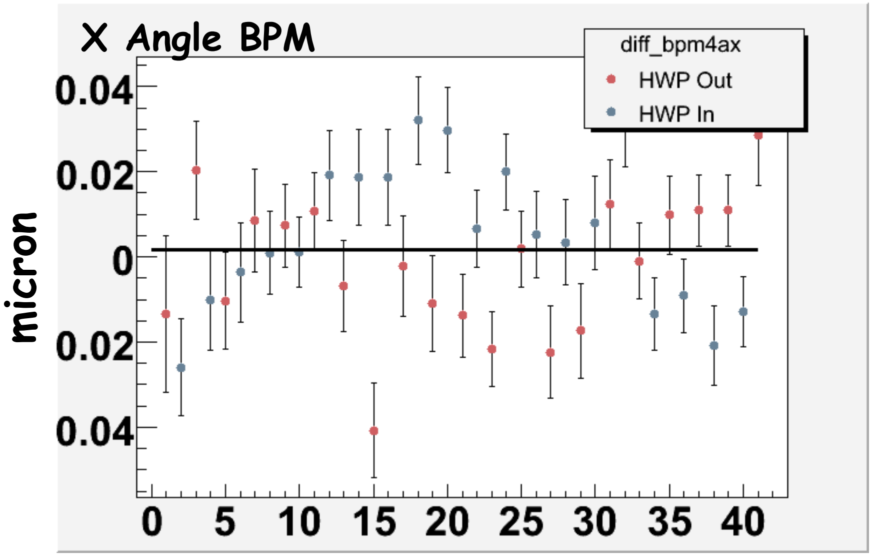
Using charge symmetry: given $G_{E,M}^{p\gamma,\ n\gamma,\ pZ} \Rightarrow G_{E,M}^{u,\ d,\ s}$

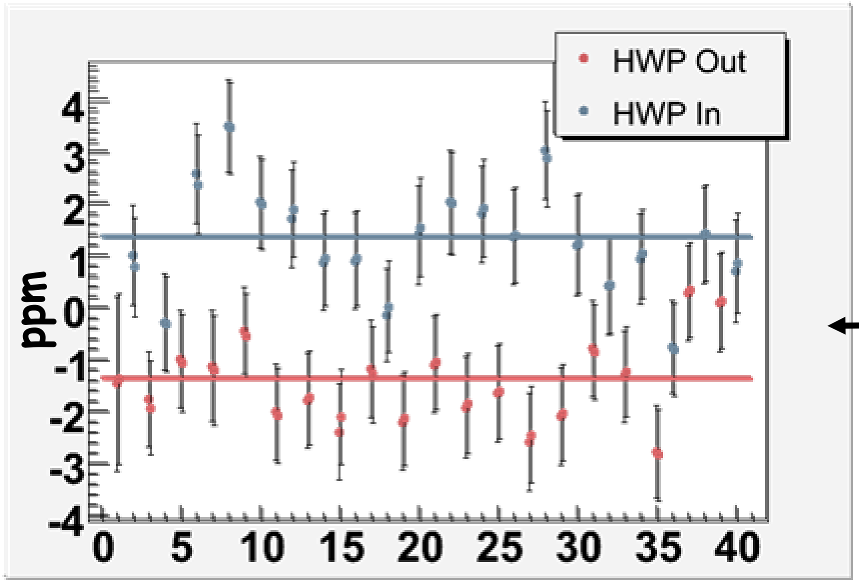
World Data Dominated by G0 from JLab



Q^2 – dependence : G0 Phys Rev Lett 95 (2005)

Latest HAPPEx Run : Outstanding Achievement !





Surpassed Beam Asymmetry Goals for Hydrogen Run

Energy: -0.25 ppb

X Target: 1 nm

X Angle: 2 nm

Y Target : 1 nm

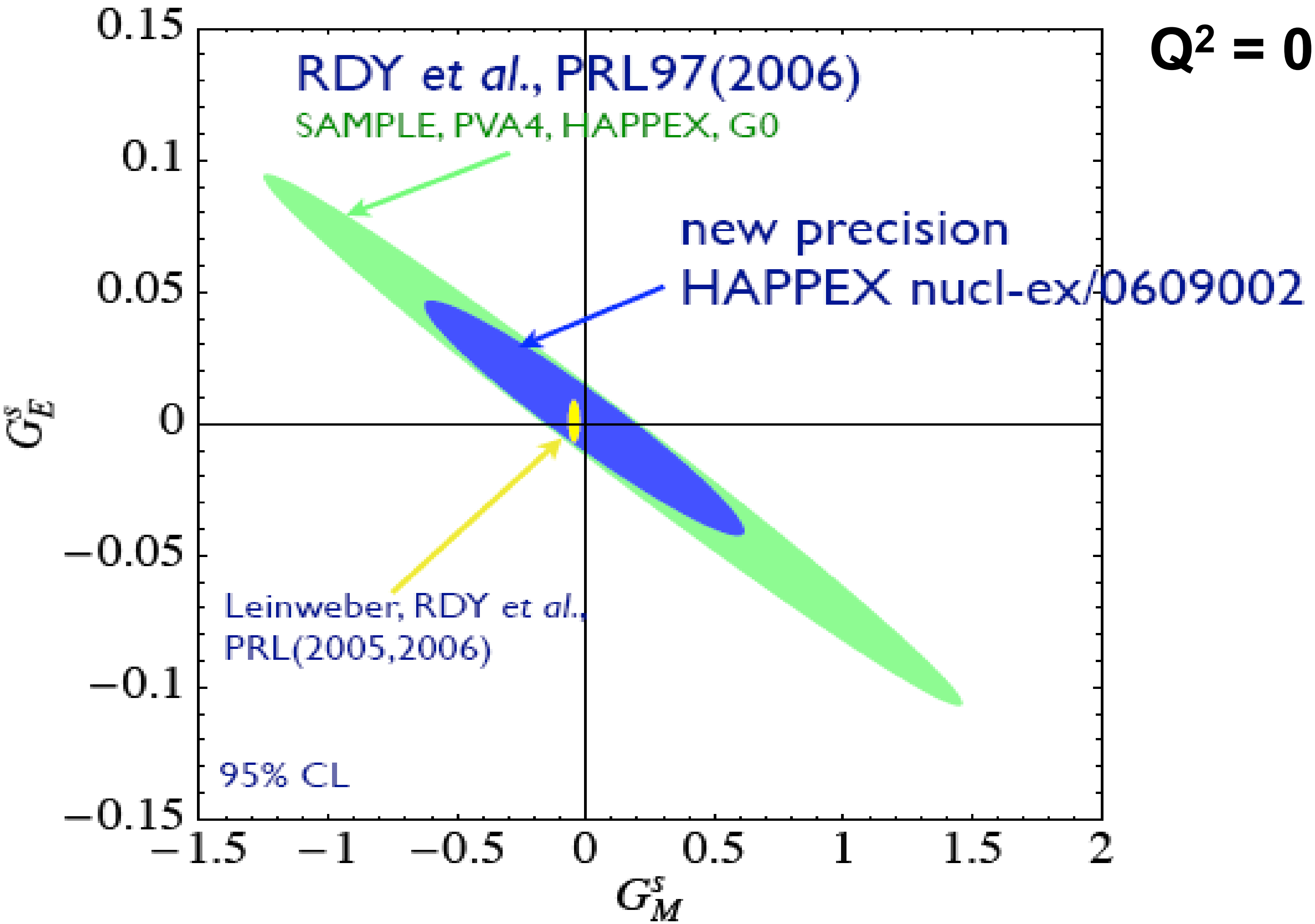
Y Angle: <1 nm

← **Corrected and Raw**

Total correction for beam position asymmetry on Left, Right, or ALL detector: 10 ppb

from Kent Paschke

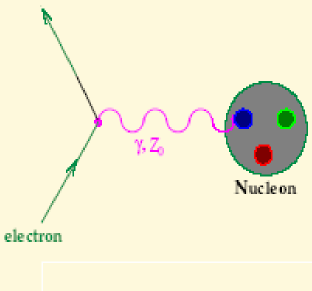
Factor of two from latest HAPPEx Measurement



$Q^2 = 0.1$ GeV^2

$G_E^s = 0.002 \pm 0.018$ $\quad G_M^s = -0.01 \pm 0.25$

PREX : ^{208}Pb Radius Experiment



Low Q^2 elastic e-nucleus scattering

(E = 850 MeV, $\Theta = 6^o$)

Z^0 **(Weak Interaction)** : **couples mainly to neutrons**

$$\frac{dA}{A} = 3\% \rightarrow \frac{dR_n}{R_n} = 1\%$$

Measure a Parity Violating Asymmetry

$$A = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_P(Q^2)} \right]$$

Applications:

- **Fundamental check of Nuclear Theory**
- **Input to Atomic PV Expts**
- **Neutron Star Structure**

Nuclear Structure

After more than 70 years, the neutron density of a heavy nucleus is a fundamental nuclear-structure observable that remains elusive!

- As fundamental as the charge density of a heavy nucleus
  - ⋆ *cf.* proton and neutron electromagnetic structure
- Reflects a poor understanding of the symmetry energy of NM
  - ⋆ Symmetry energy penalty imposed for breaking $N = Z$ balance
- Pure neutron matter well constrained at $\rho \approx (2/3)\rho_0$
- Slope is completely unconstrained by available nuclear data!

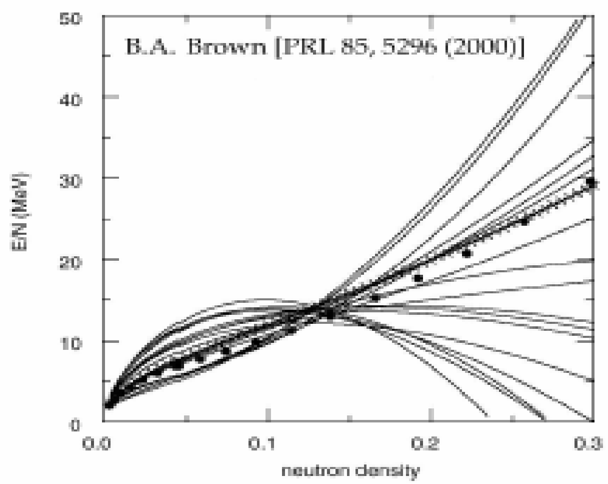


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

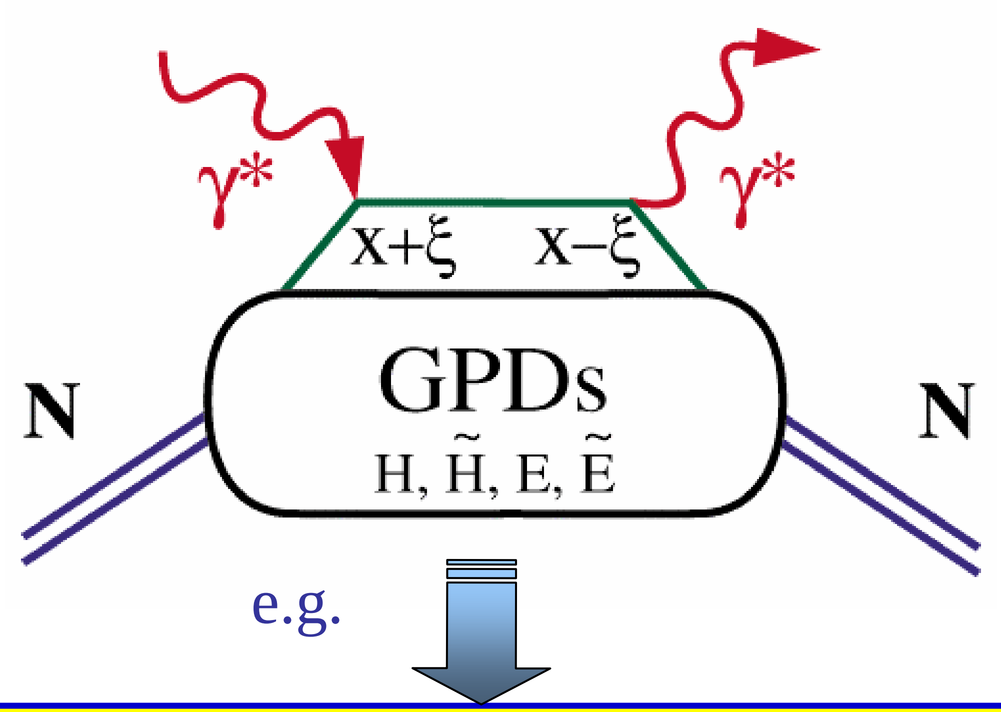
Adding the neutron radius of a single heavy nucleus to the database will eliminate the large dispersion in the plot!

6 GeV Highlights Leading to the 12 GeV Upgrade

- Parton Distribution Functions
- Form Factors
- **Generalized Parton Distributions**
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model

Studies of the Generalized Parton Distributions (GPDs): New Insight into Hadron Structure

HP 2008



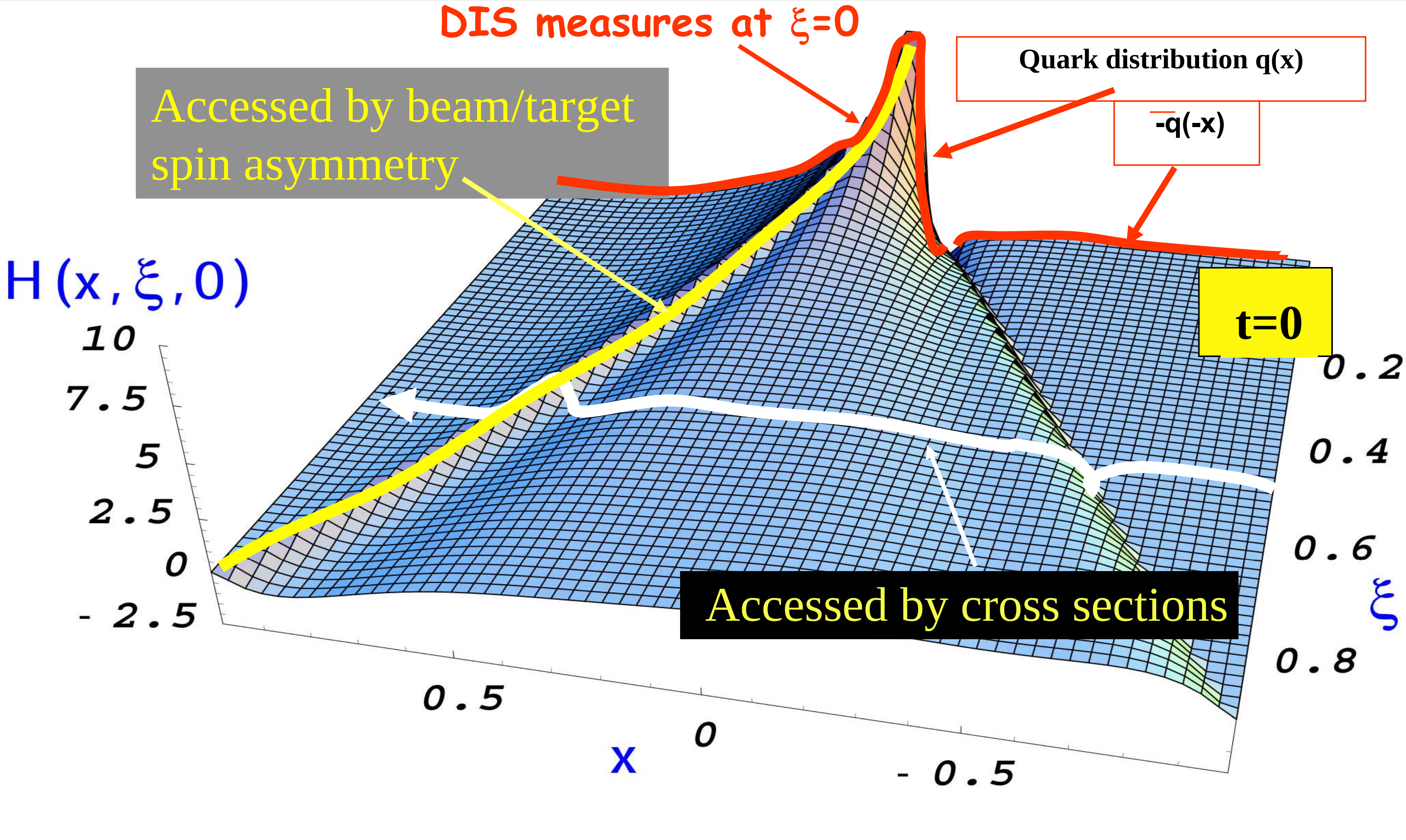
X. Ji & A. Radyushkin (1996)

Quark angular momentum (Ji's sum rule)

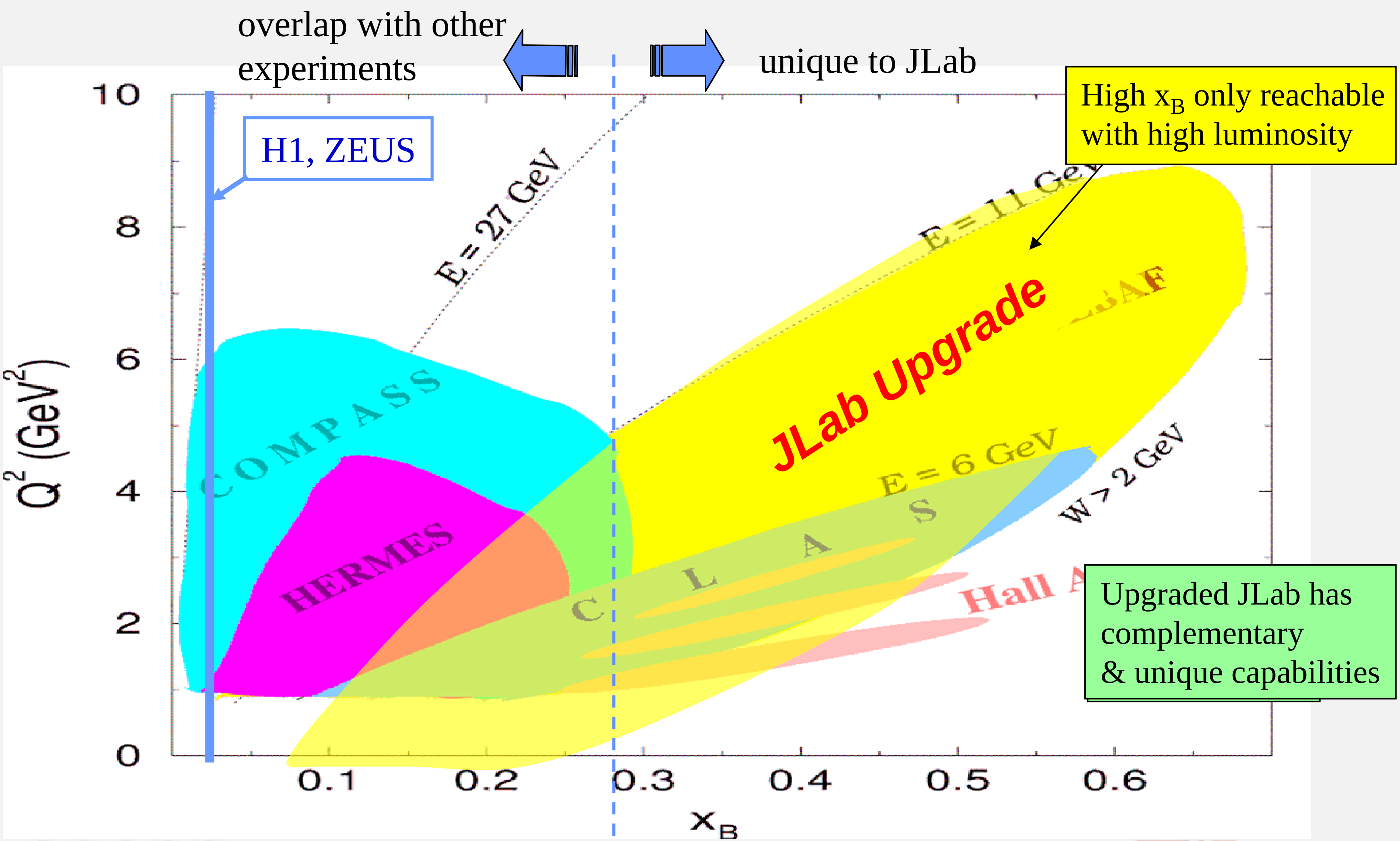
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0) \right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

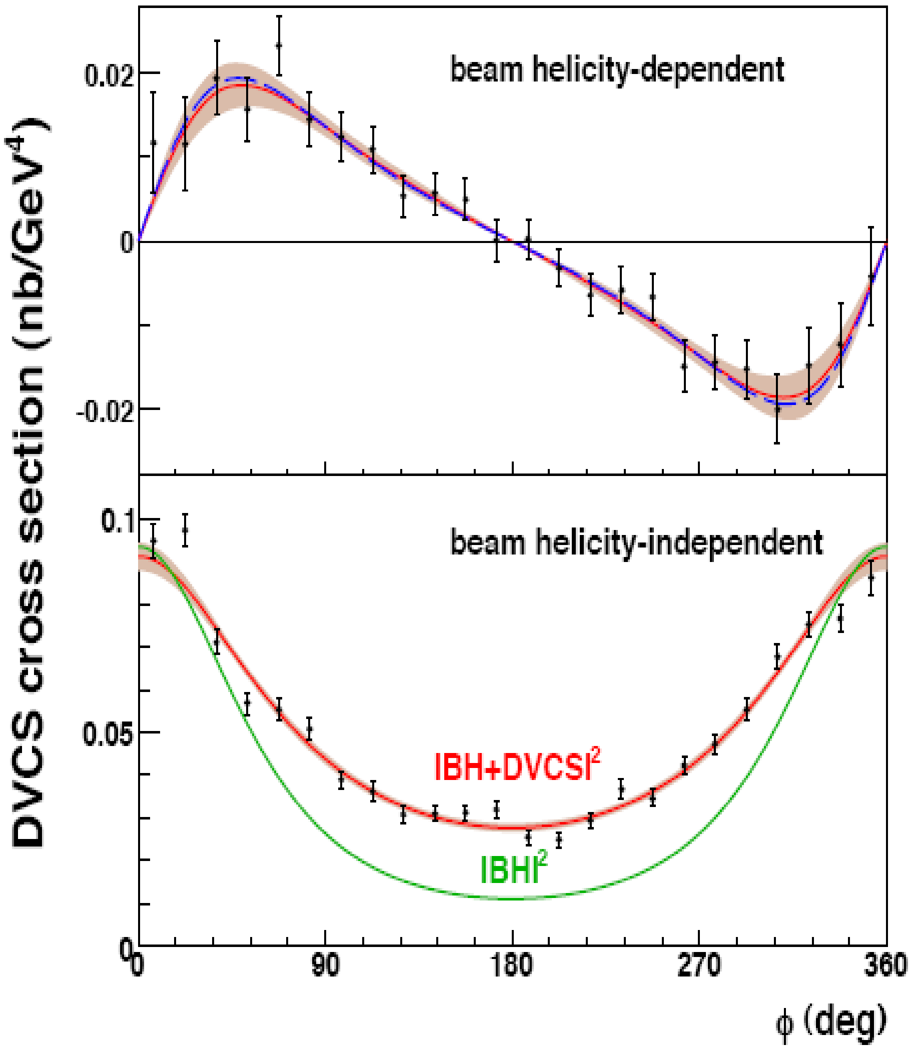
Access GPDs through x-section & asymmetries

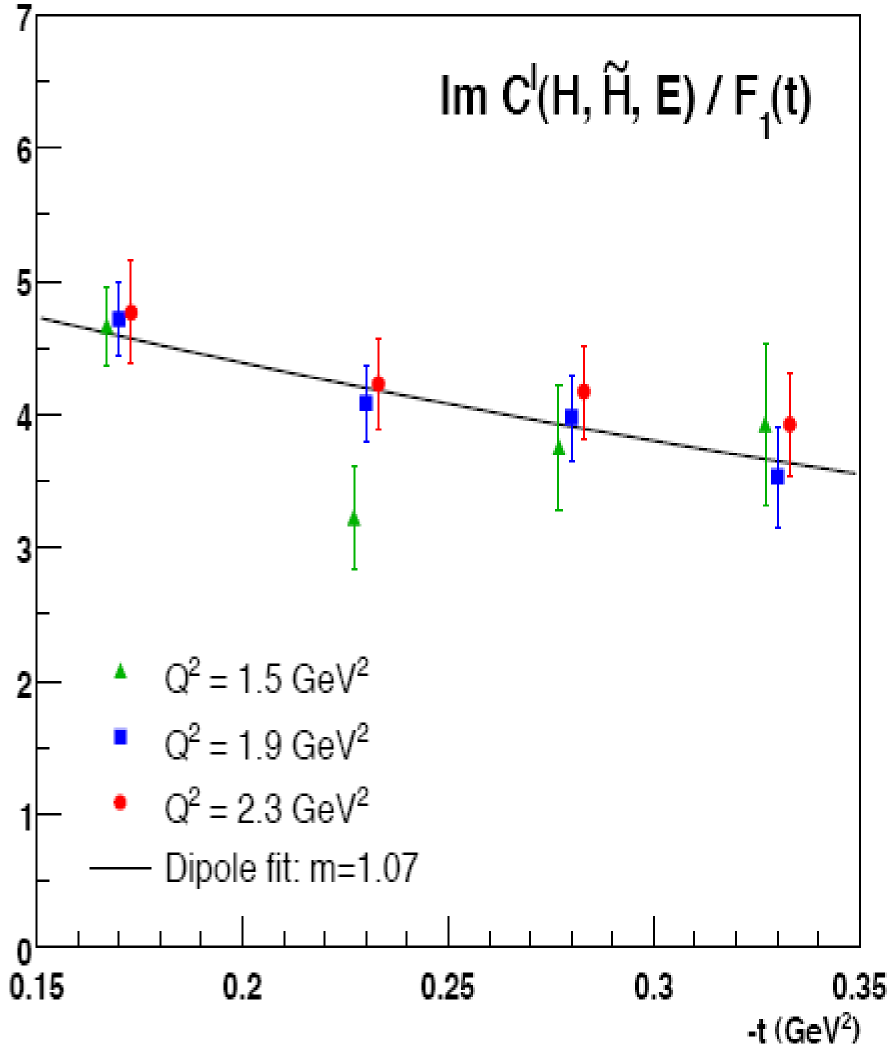


Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade

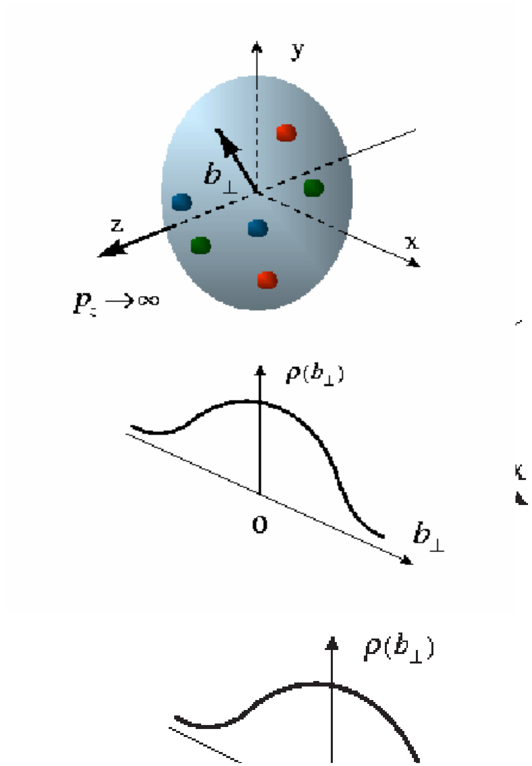


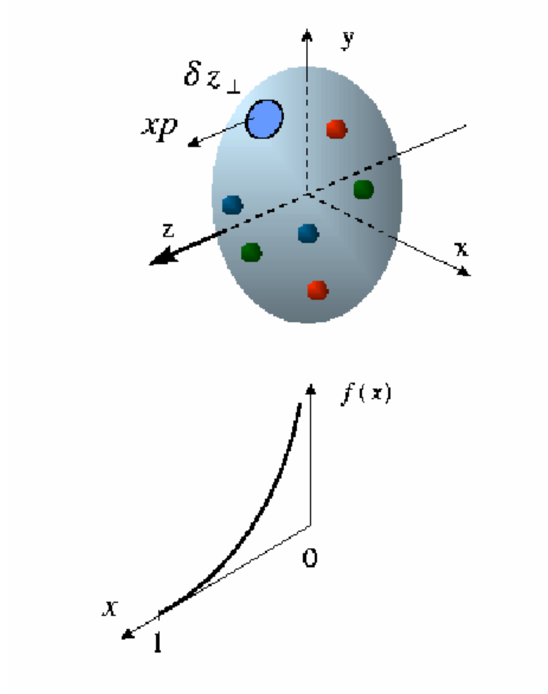
Recent Hall A Data: Suggests in Scaling Regime Even at Relatively Low Q^2

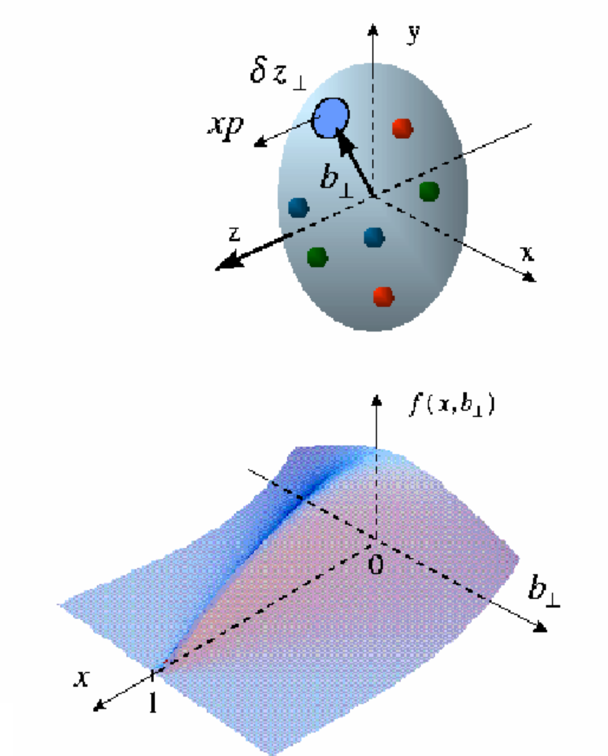




The Next Generation of Proton Structure Experiments







Elastic Scattering

transverse quark distribution in Coordinate space

DIS

longitudinal quark distribution in momentum space

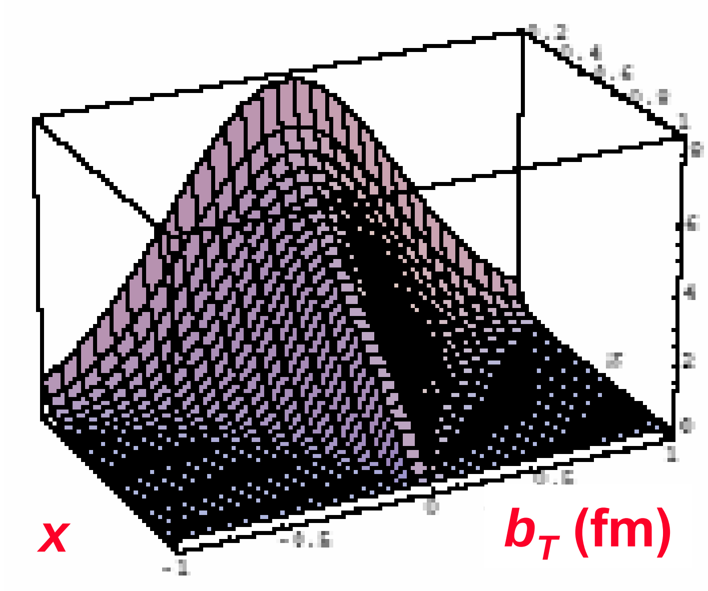
GPDs

The fully-correlated Quark distribution in both coordinate and momentum space

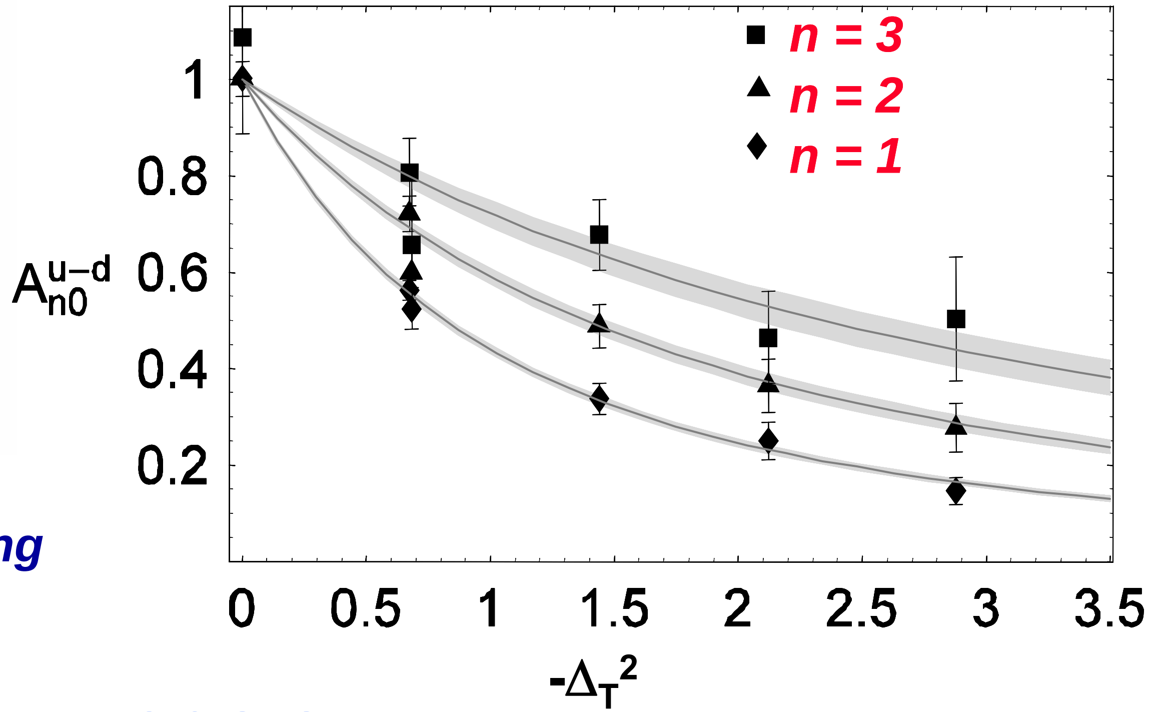
Moments of Flavor-NS PDFs and GPDs - I

- **Lattice QCD can compute both moments of GPD's with respect to *x*, and *t*-dependence**

$$A^q_{n0}(-\vec{\Delta}_\perp^2) = \int d^2b_\perp \, e^{i\vec{\Delta}_\perp \cdot \vec{b}_\perp} \int_{-1}^{1} dx \, x^{n-1} q(x, \vec{b}_\perp)$$



Lattice data: m_π = 740 MeV



Decrease slope : decreasing transverse size as $x \to 1$

Burkardt

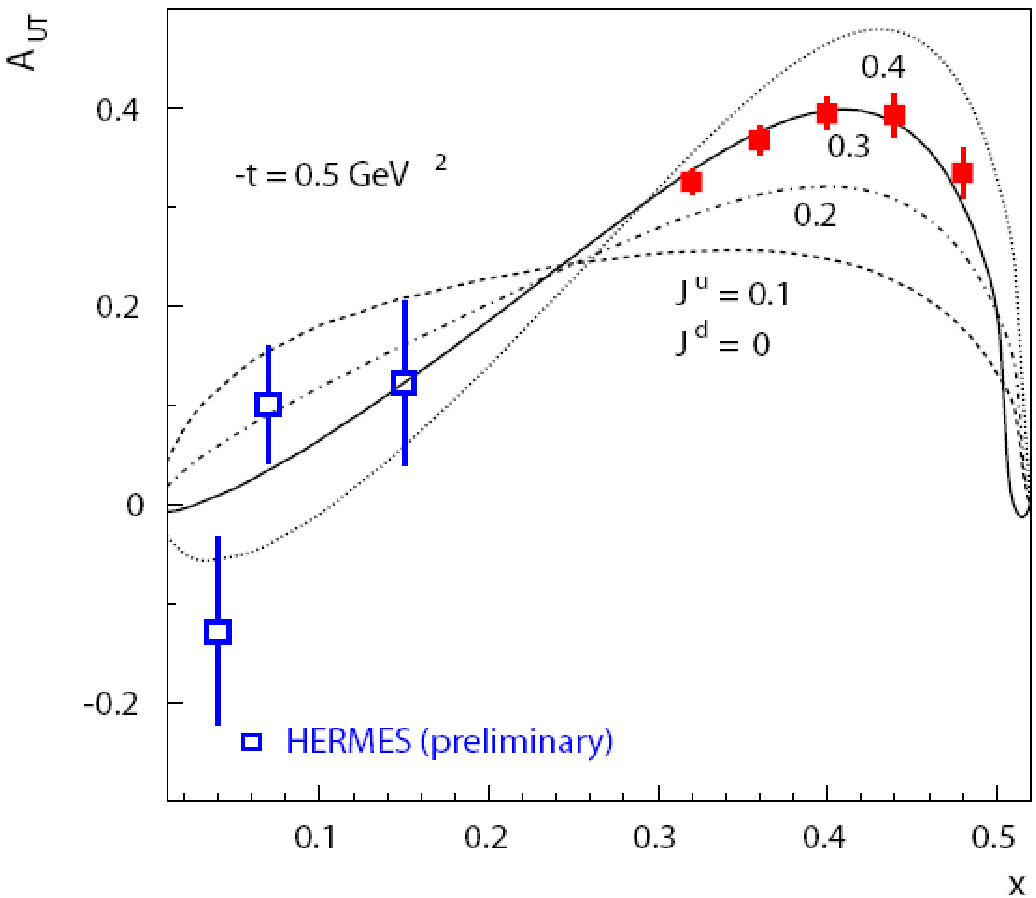
From: LHPC & SESAM

At 12 GeV: Exclusive ρ^0 with transverse target

$$A_{UT} = -\frac{2\Delta\,(\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

ρ^0

$A \sim (2H^u + H^d)$
$B \sim (2E^u + E^d)$



$Q^2 = 5 GeV^2$

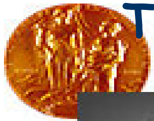
Asymmetry depends linearly on the GPD E, which enters Ji's sum rule.

K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001

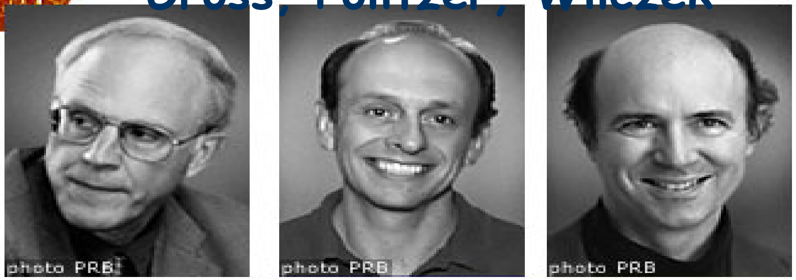
6 GeV Highlights Leading to the 12 GeV Upgrade

- Parton Distribution Functions
- Form Factors
- Generalized Parton Distributions
- **Exotic Meson Spectroscopy:**
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model

QCD: Unsolved in Nonperturbative Regime



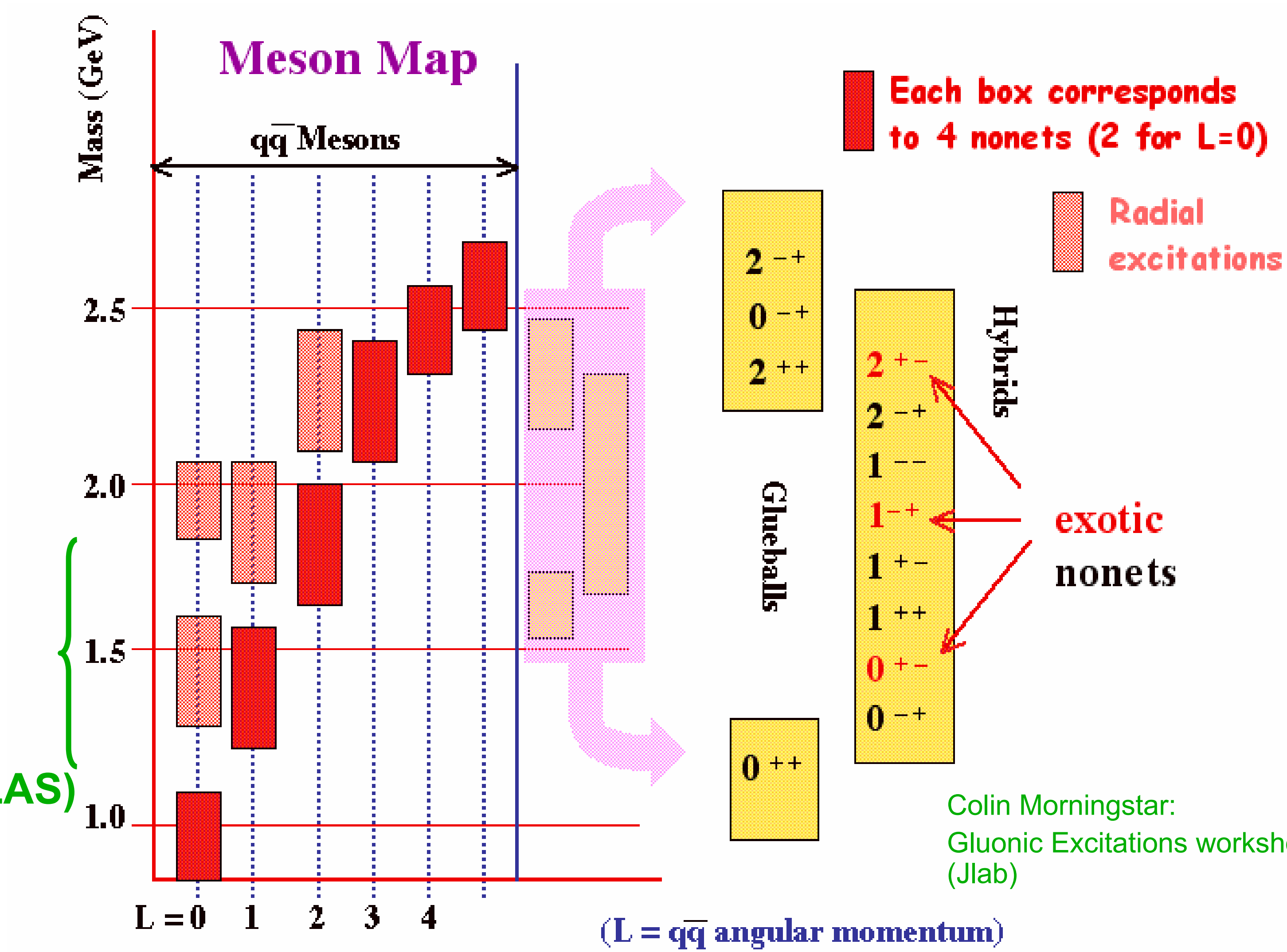
The Nobel Prize in Physics 2004
Gross, Politzer, Wilczek



- **2004 Nobel Prize awarded for “asymptotic freedom”**
- **BUT in nonperturbative regime QCD is still unsolved**
- **One of the top 10 challenges for physics!**
- **Is it right/complete?**
- **Do glueballs, exotics and other apparent predictions of QCD in this regime agree with experiment?**

JLab at 12 GeV is uniquely positioned to answer!

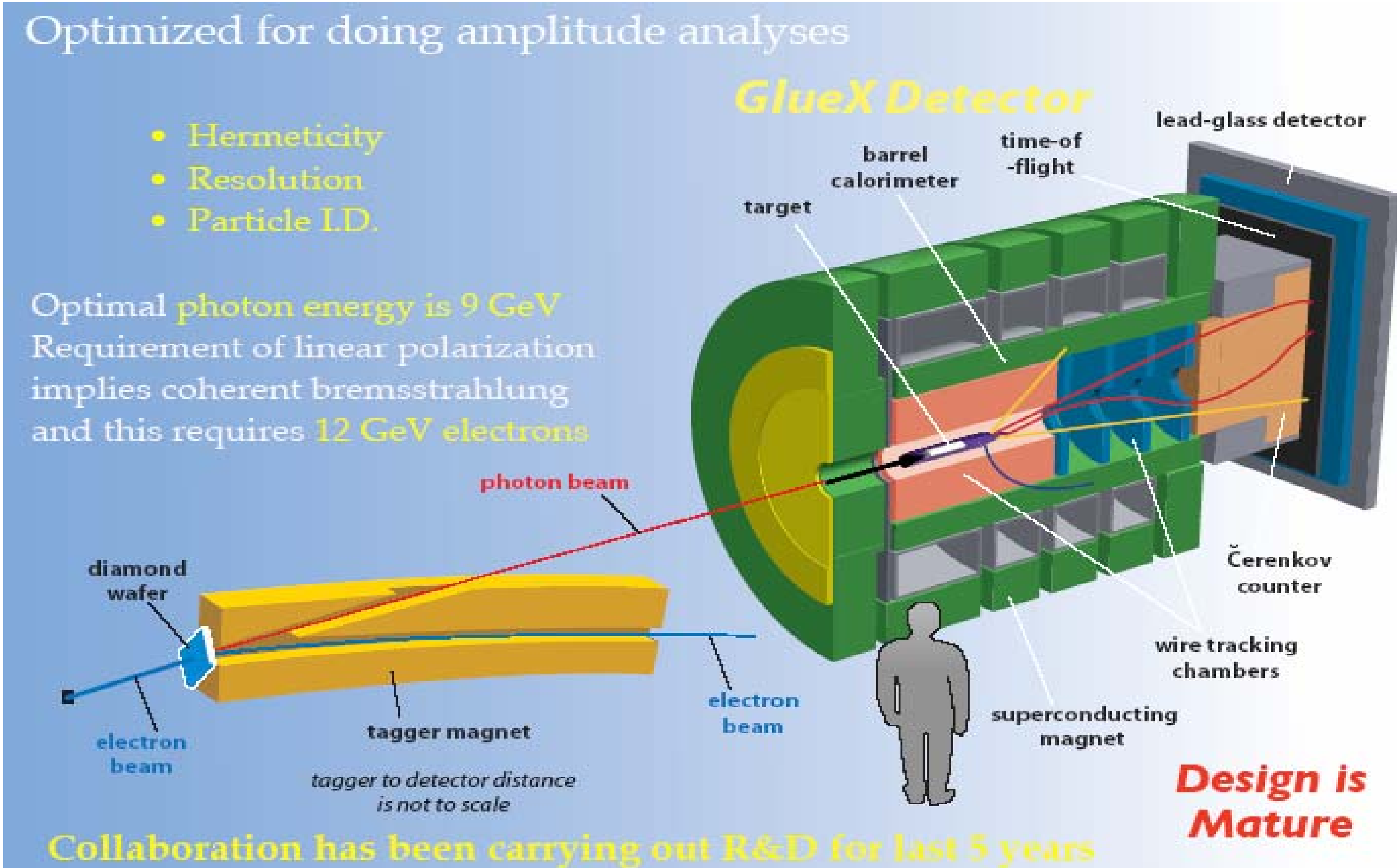
Glueballs and hybrid mesons



Initial search FY07 – G12 (CLAS)

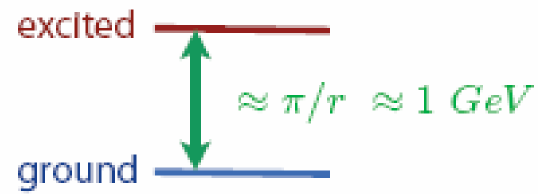
Colin Morningstar:
Gluonic Excitations workshop, 2003 (Jlab)

Gluex: Hall D


Optimized for doing amplitude analyses
GlueX Detector
• Hermeticity
• Resolution
• Particle I.D.
Optimal photon energy is 9 GeV
Requirement of linear polarization
implies coherent bremsstrahlung
and this requires 12 GeV electrons
lead-glass detector
time-of
-flight
barrel
calorimeter
target
photon beam
diamond
wafer
Čerenkov
counter
wire tracking
chambers
electron
beam
tagger magnet
electron
beam
superconducting
magnet
tagger to detector distance
is not to scale
Design is
Mature
Collaboration has been carrying out R&D for last 5 years

Masses and Widths of Hybrid Mesons

Masses and Widths



widths are expected to be of order 150-200 MeV

LQCD Mass Predictions for: $J^{PC} = 1^{-+}$

Author		1^{-+} Mass (GeV/c^2)	
Collab.	Year	$u\bar{u}/d\bar{d}$	$s\bar{s}$
UKQCD	(1997)	1.87 ± 0.20	2.0 ± 0.2
MILC	(1997)	$1.97 \pm 0.09 \pm 0.30$	$2.170 \pm 0.080 \pm 0.30$
MILC	(1999)	$2.11 \pm 0.10 \pm (sys)$	
SESAM	(1998)	1.9 ± 0.20	
Mei& Luo	(2003)	$2.013 \pm 0.026 \pm 0.071$	
Bernard *et al.*	(2004)	1.792 ± 0.139	2.100 ± 0.120

LQCD Mass Predictions for other exotic J^{PC}

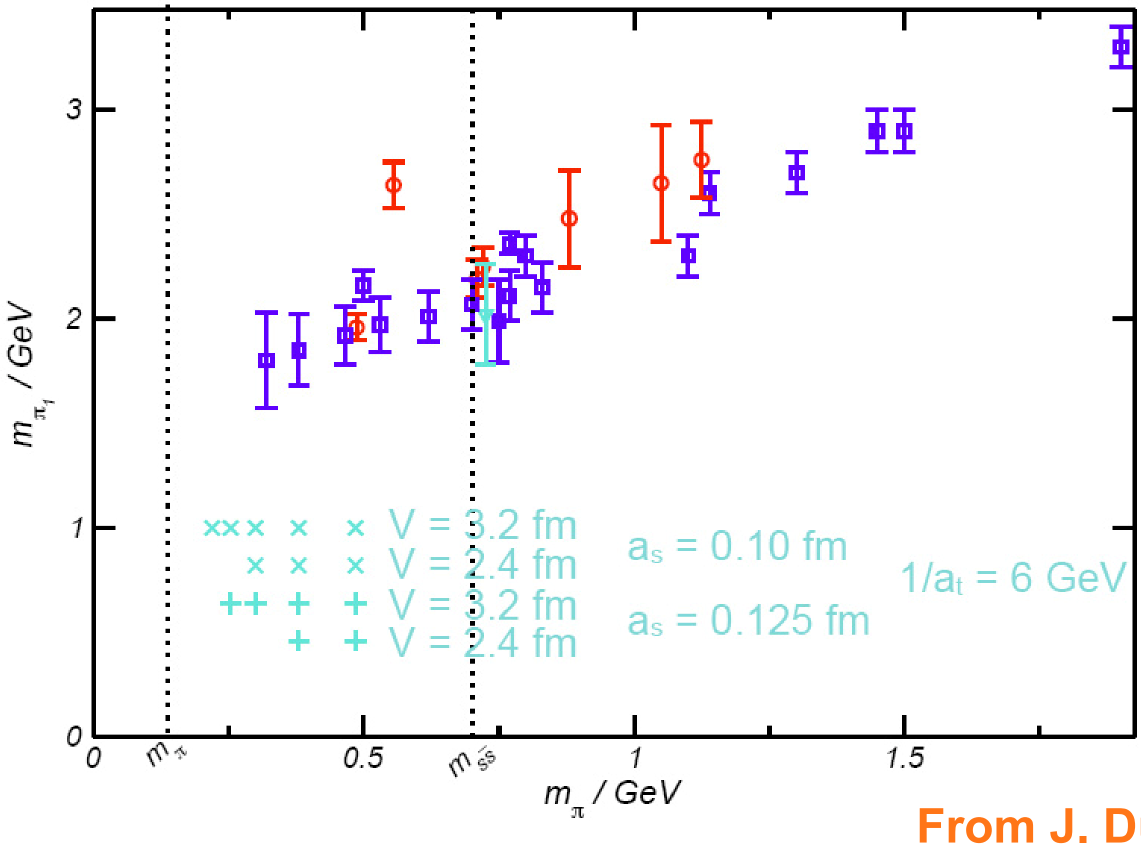
Multiplet	J^{PC}	Mass (GeV/c^2)
π_1	1^{-+}	1.9 ± 0.2
b_2	2^{+-}	2.0 ± 0.11
b_0	0^{+-}	2.3 ± 0.6

above for $u\bar{u}/d\bar{d}$ for $s\bar{s}$ add ≈ 0.3 GeV

JLab plans in '06-'07

- Dynamical anisotropic Clover
- NF = 2+1 gauge fields in '06, '07

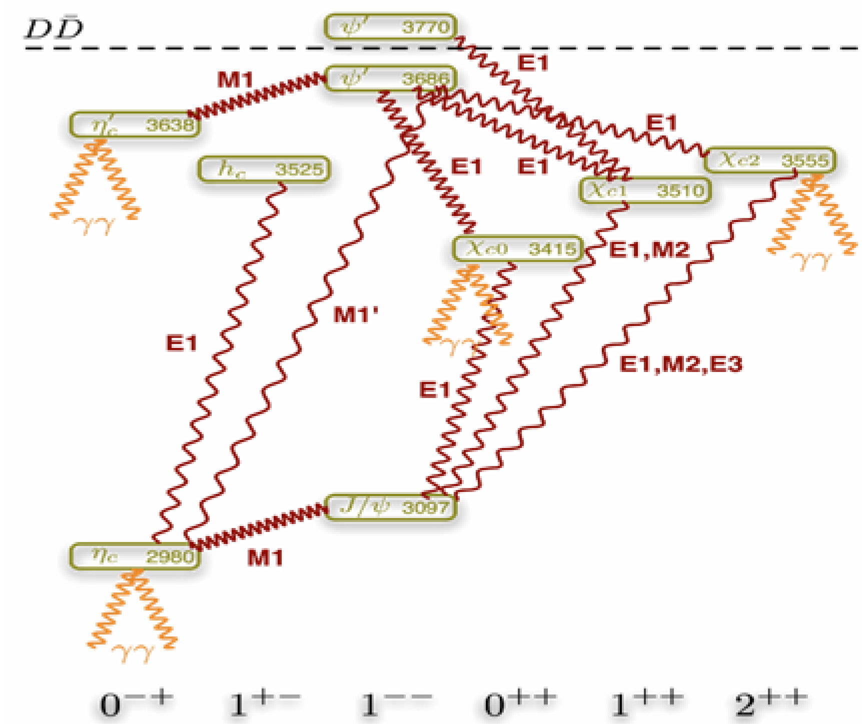
—- ideal for spectroscopy

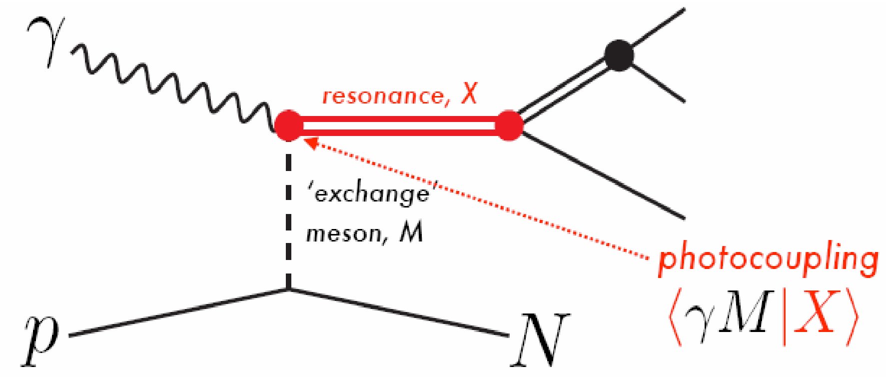


From J. Dudek

Lattice Estimates of Photo-production Rates for GlueX

- An important realization of JLab Theorists was that lattice QCD enabled calculation of photocouplings
- Guide experimental program as to expected photoproduction rates.





Initial exploration in Charmonium
- Good experimental data
- Allow comparison with QCD-inspired models
- Lattice computations pioneered at JLab

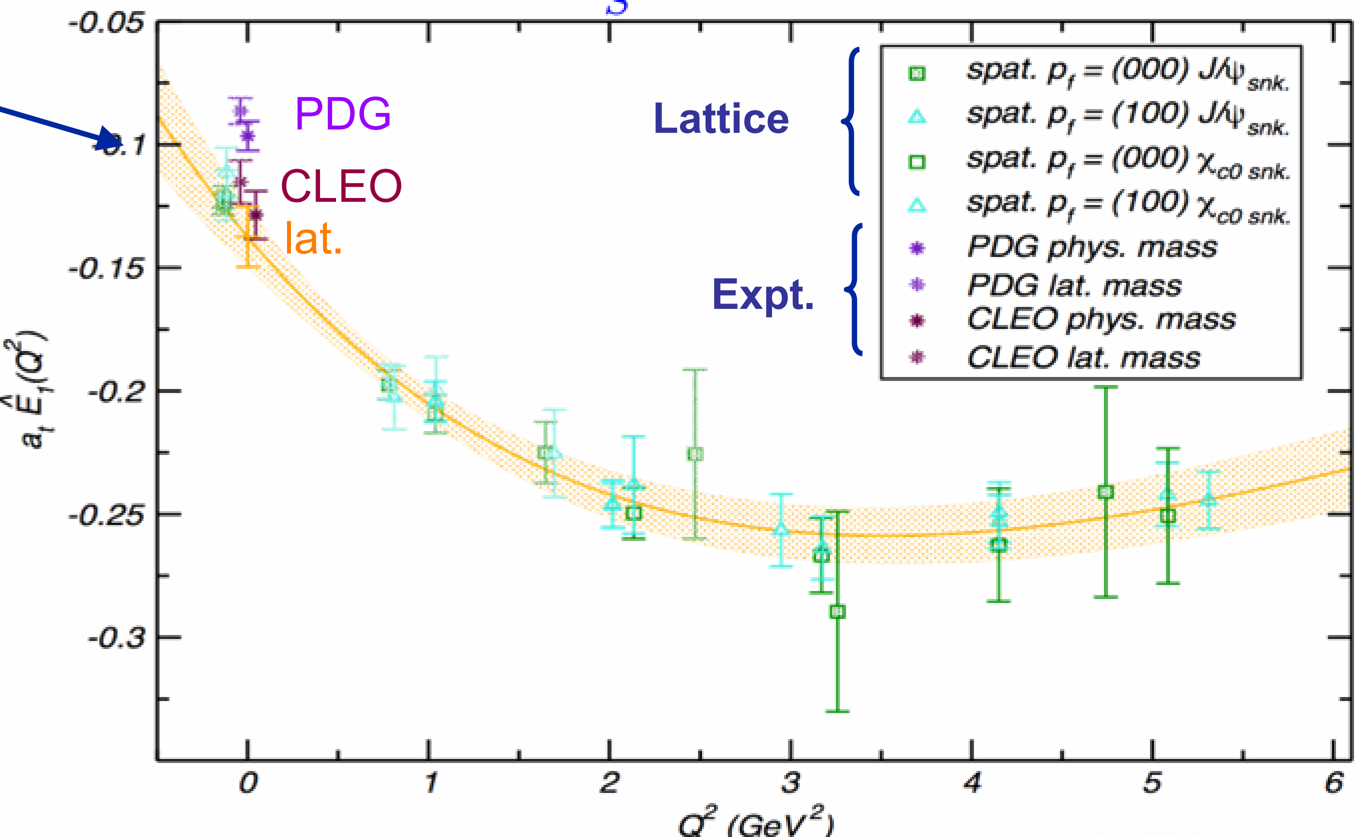
Photocouplings

Dudek, Edwards, Richards, PRD73, 074507

- Recent study of transitions between conventional mesons, e.g. **S** $\rightarrow \gamma$ **V**

$$\Gamma(\chi_{c0} \rightarrow J/\psi\,\gamma) = \frac{1}{8\pi}\frac{|\vec{q}\,|}{m_S^2}\,2\,(2e_c)^2\,|\,E_1(0)\,|^2$$

Not used in the fit

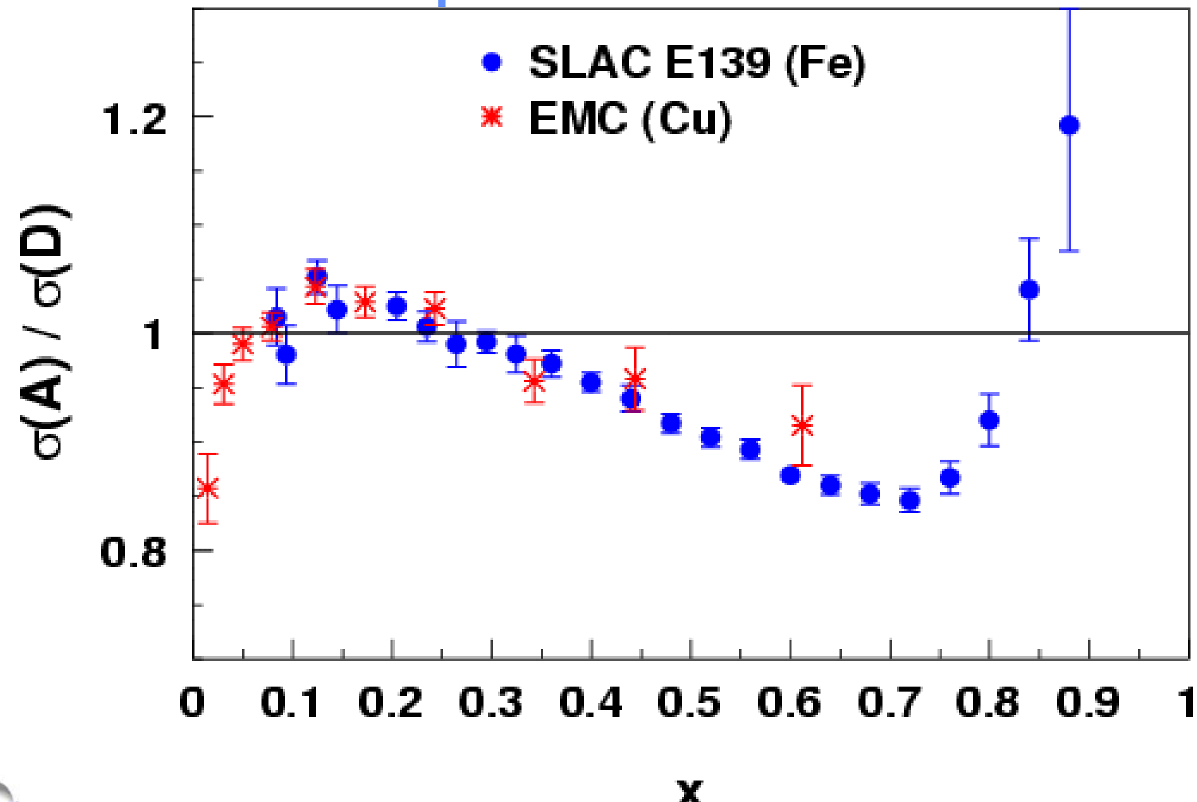


6 GeV Highlights Leading to the 12 GeV Upgrade

- Parton Distribution Functions
- Form Factors
- Generalized Parton Distributions
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- **Nuclei at the level of quarks and gluons**
- Tests of Physics Beyond the Standard Model

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 20 years ago
- Nearly 1,000 papers have been generated…..
- What is it that alters the quark momentum in the nucleus?



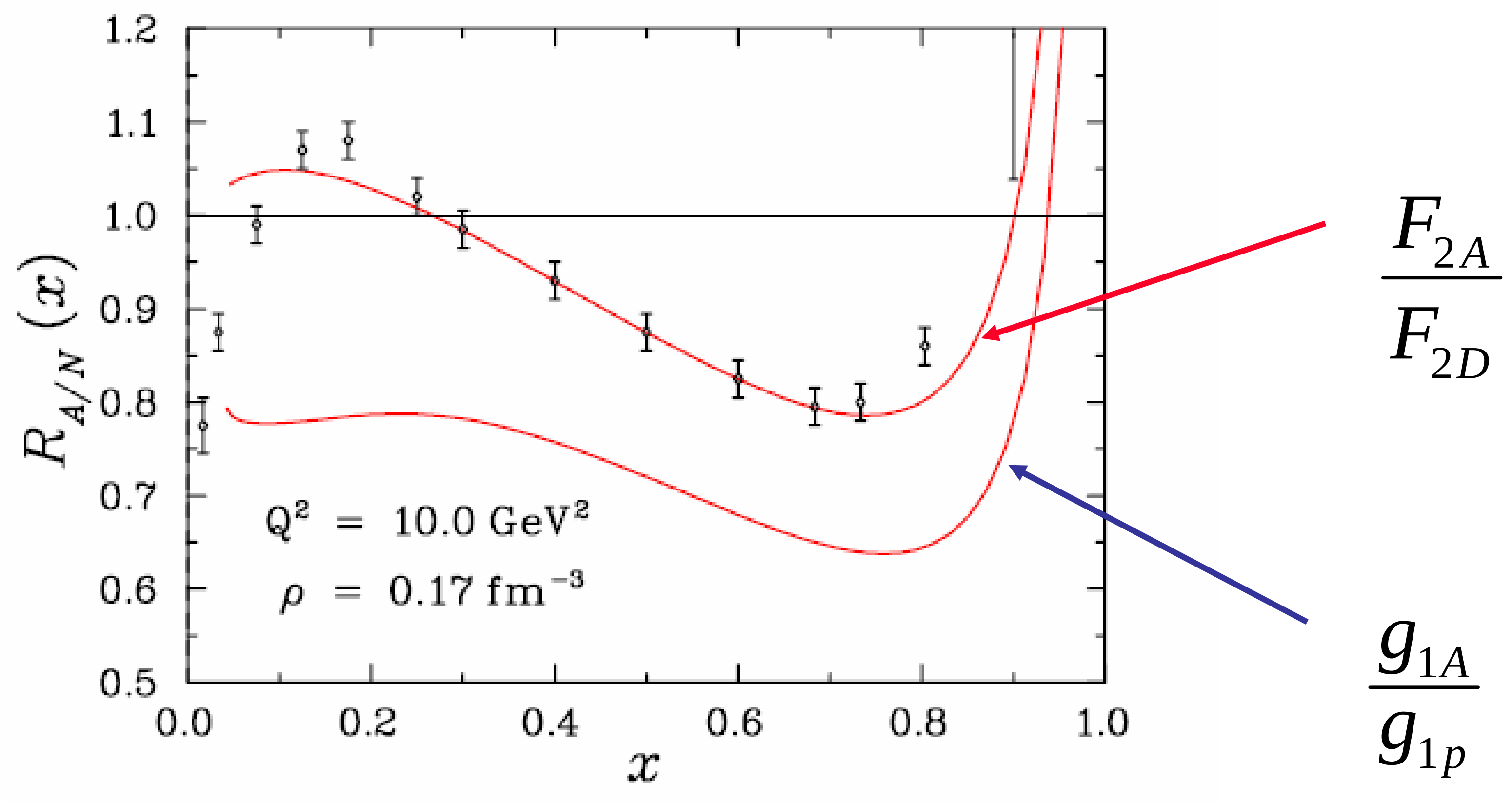
J. Ashman *et al.*, Z. Phys. C57, 211 (1993)

J. Gomez *et al.*, Phys. Rev. D49, 4348 (1994)

$g_1(A)$ – "Polarized EMC Effect"

- New calculations indicate larger effect for polarized structure than unpolarized: scalar field modifies lower cpts of Dirac wave function

  (Cloet, Bentz, AWT, Phys Rev Lett 95 (2005) 0502302)
- Spin-dependent parton distribution functions for nuclei unknown



Recent Calculations for Finite Nuclei

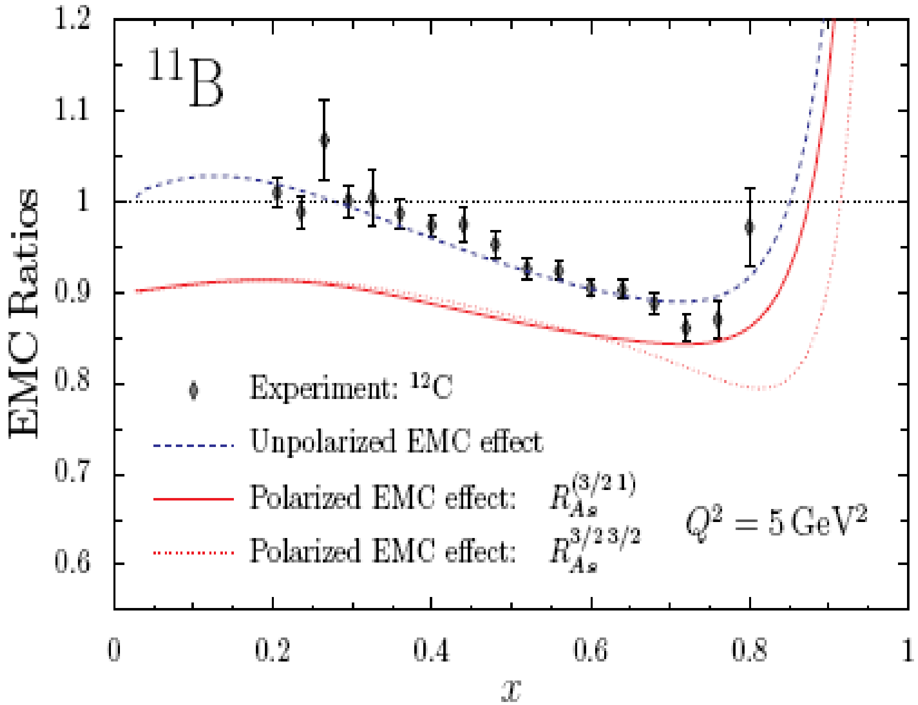


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

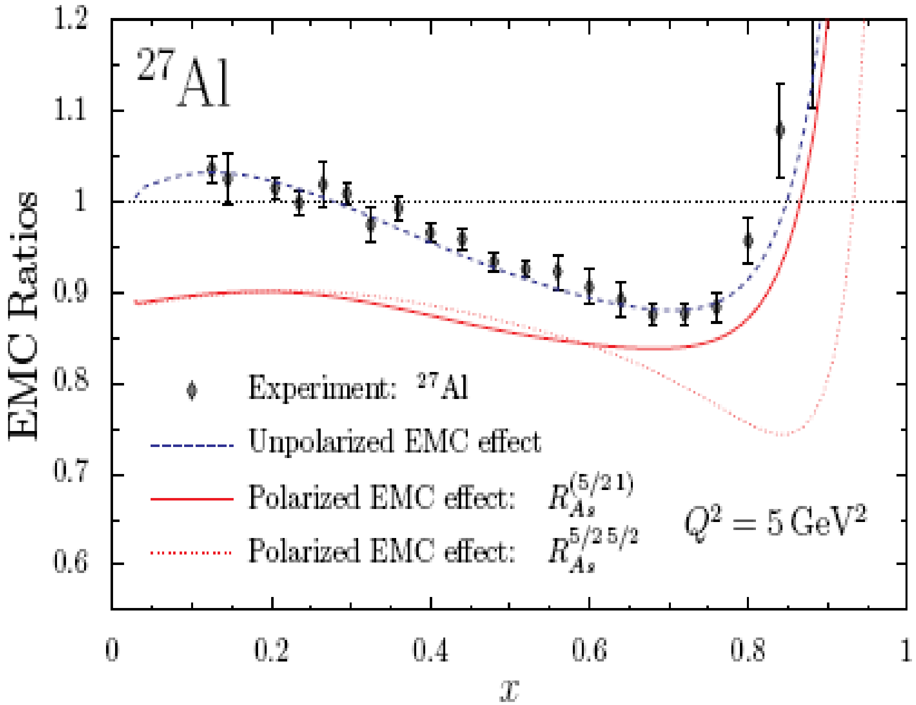


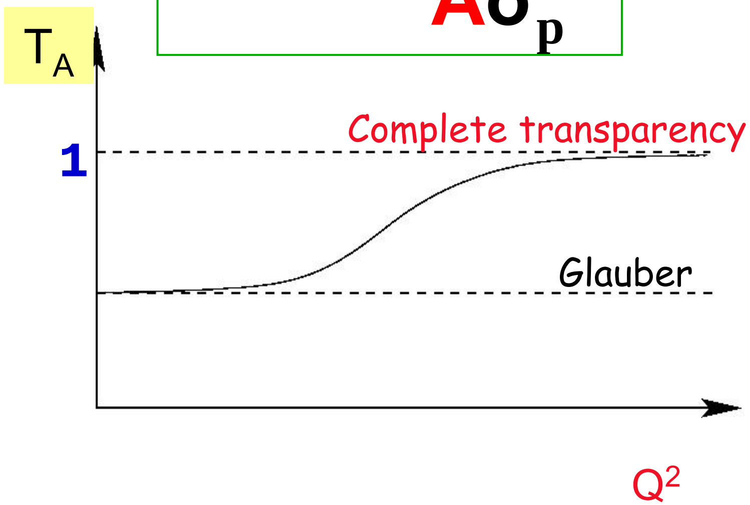
FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

Cloet, Bentz, Thomas, nucl-th/0605061

CLAS

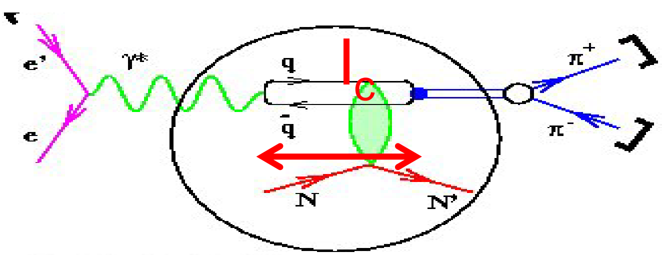
Color Transparency

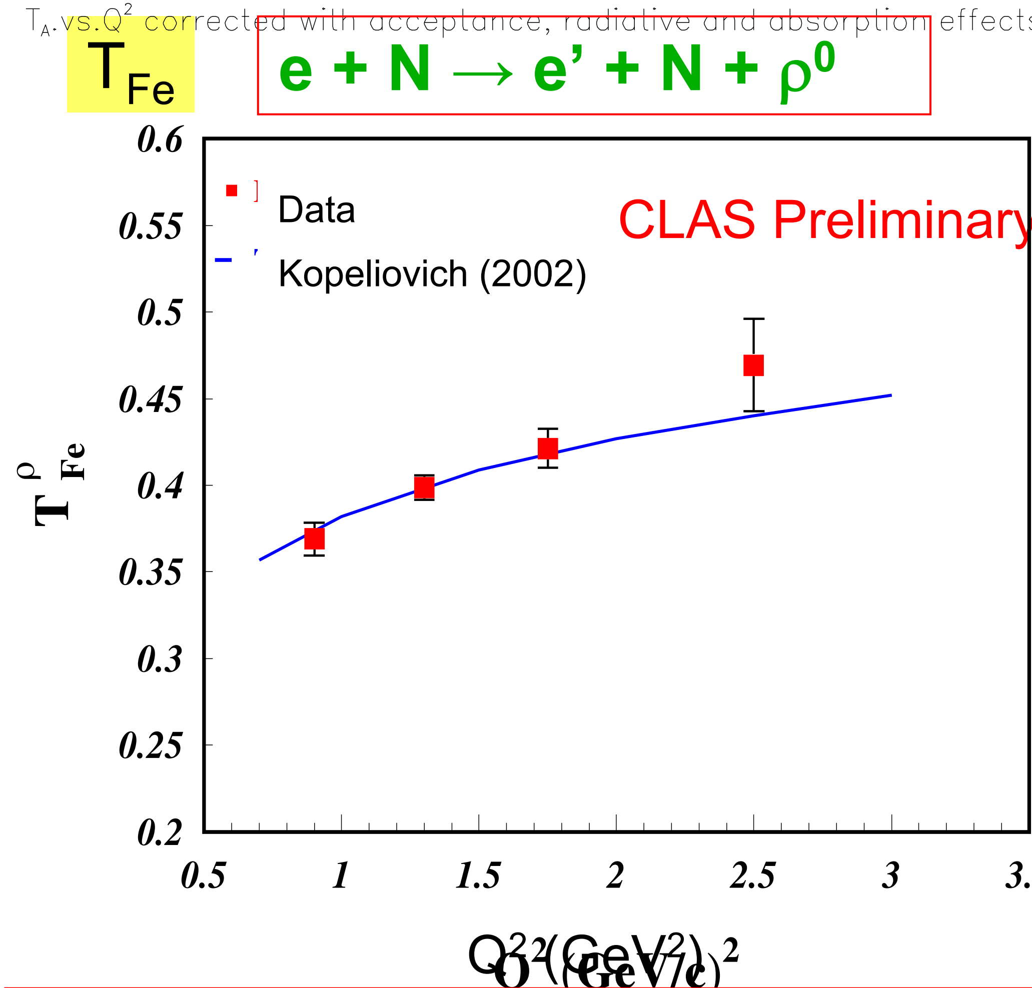
$$T_A = \frac{\sigma(A)}{A\sigma_p}$$



Measure at small coherence length

$\ell_c = 2\nu/(M^2 + Q^2)$, i.e. high Q^2, small ν



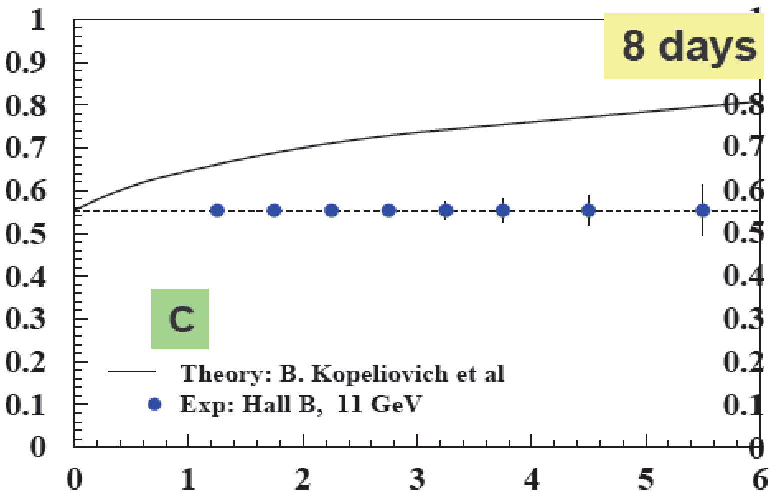


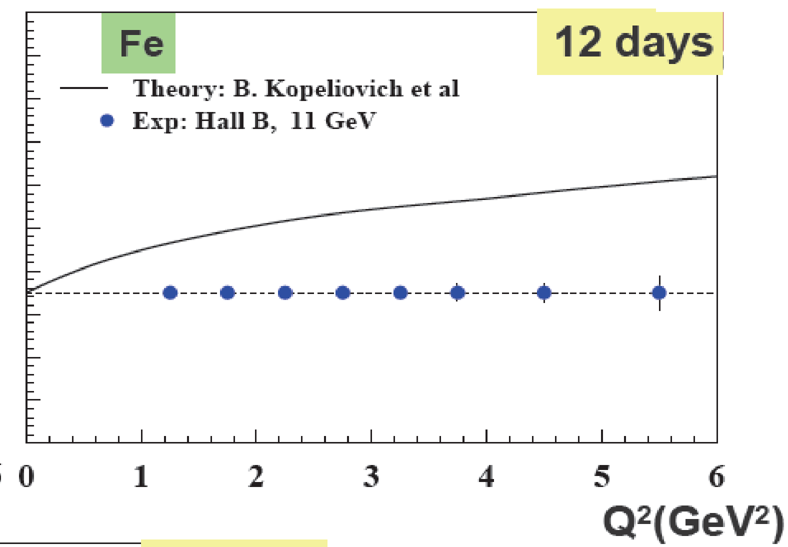
First hint of color transparency for ρ meson

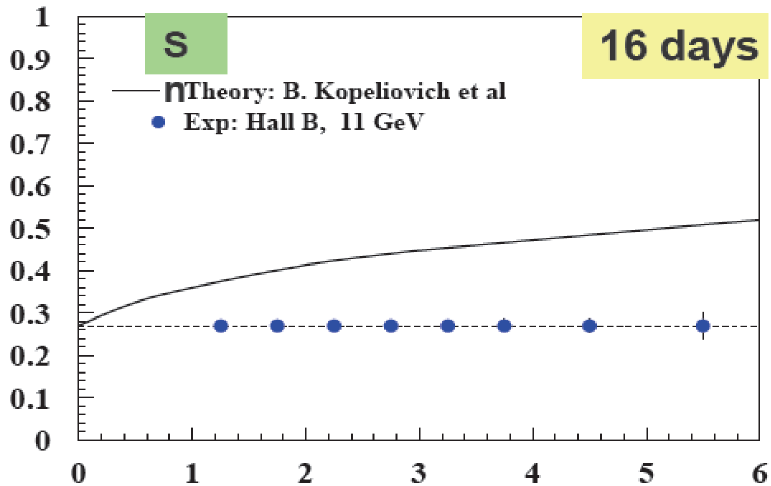
K. Hafidi

CLAS12 - Projected data for 12 GeV Upgrade

Color Transparency for: $e + N \rightarrow e' + N + \rho^0$



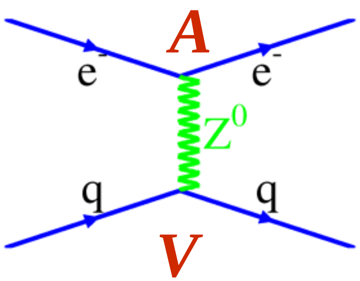




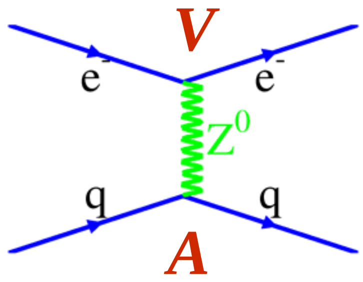
6 GeV Highlights Leading to the 12 GeV Upgrade

- Parton Distribution Functions
- Form Factors
- Generalized Parton Distributions
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- **Tests of Physics Beyond the Standard Model**

Electron-Quark Phenomenology



$$C_{1i} \equiv 2g_A^e g_V^i$$



$$C_{2i} \equiv 2g_V^e g_A^i$$

$$\begin{aligned} C_{1u} &= -\tfrac{1}{2} + \tfrac{4}{3}\sin^2(\theta_W) \approx -0.19 \\ C_{1d} &= \tfrac{1}{2} - \tfrac{2}{3}\sin^2(\theta_W) \approx 0.35 \\ C_{2u} &= -\tfrac{1}{2} + 2\sin^2(\theta_W) \approx -0.04 \\ C_{2d} &= \tfrac{1}{2} - 2\sin^2(\theta_W) \approx 0.04. \end{aligned}$$

C_{1u} and C_{1d} will be determined to high precision by APV and Qweak

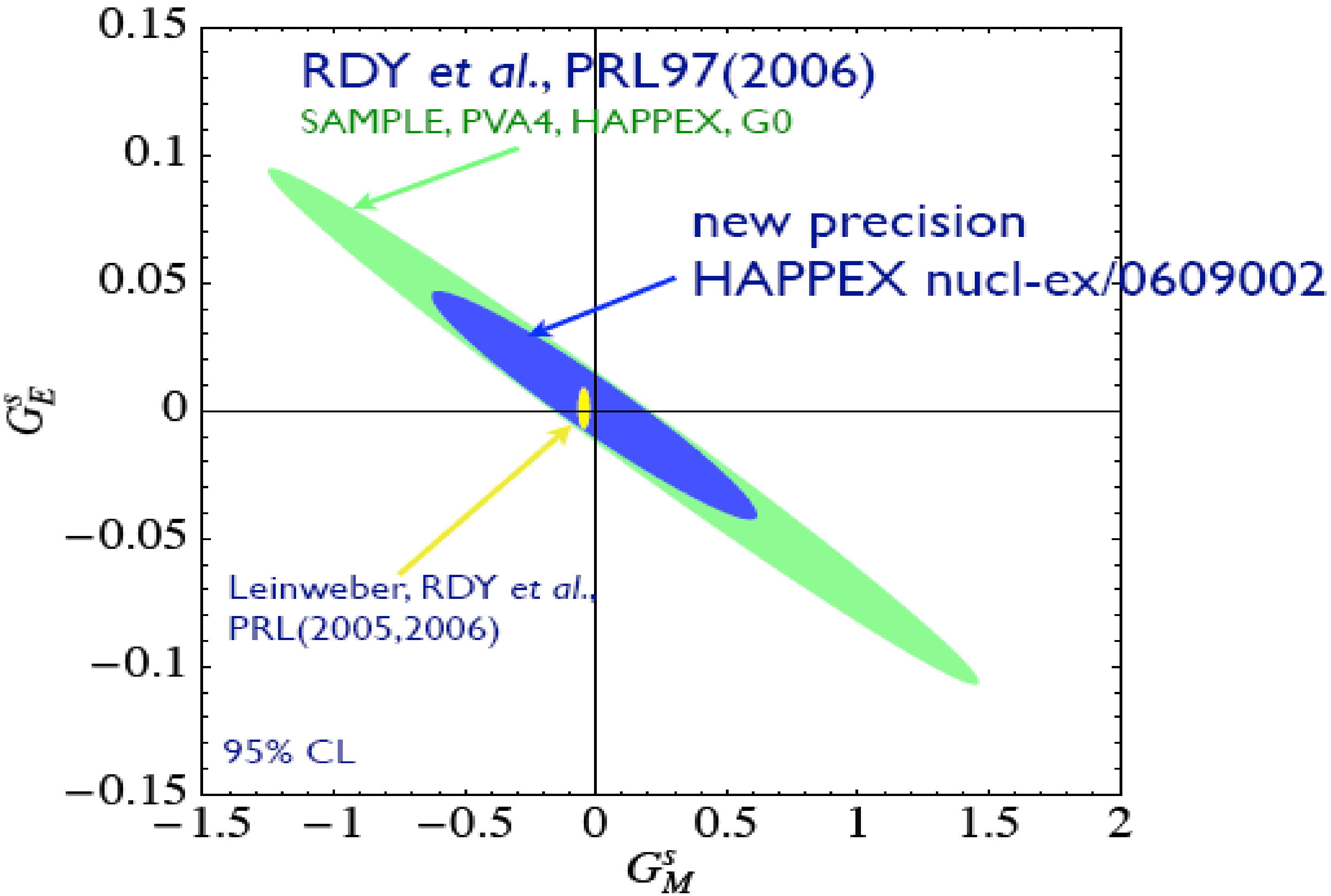
C_{2u} and C_{2d} are small and poorly known: can be accessed in PV DIS

New physics such as compositeness, new gauge bosons:

Deviations in C_{2u} and C_{2d} might be fractionally large

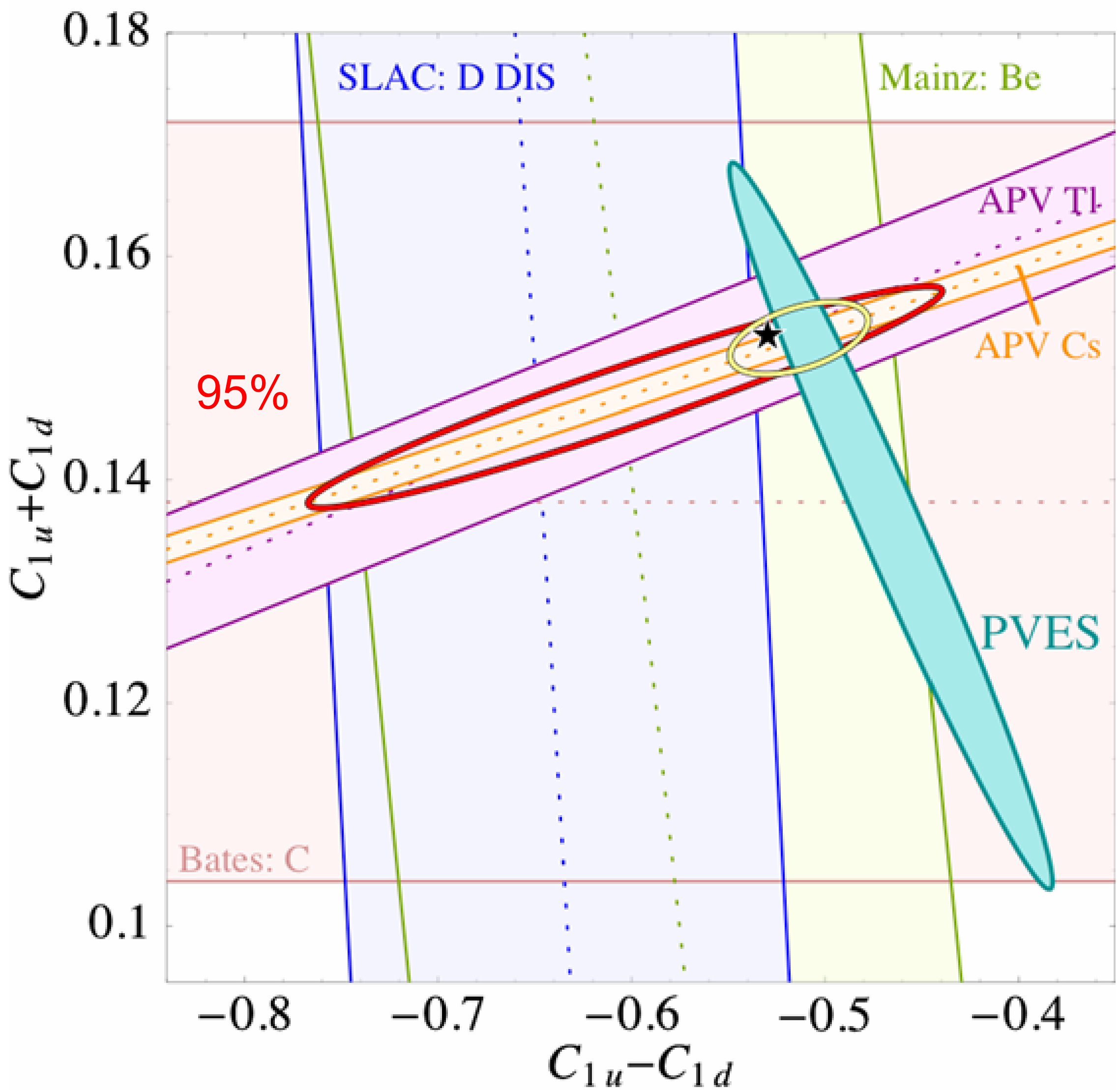
Proposed JLab upgrade experiment will permit increase in precision of measurement of $2C_{2u}$-C_{2d} by more than a factor of 20

Previously: Saw Precision of PVES for Strange Form Factors



Can we achieve meaningful accuracy in testing Standard Model now?

New update on C_{1q} couplings – Dec 2006



(Young et al.)

Dramatic improvement in knowledge of weak couplings!

Factor of 5 increase in precision of Standard Model test

Model-independent limits on New Physics

$$\mathcal{L}_{SM}^{PV} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}^{SM}\bar{q}\gamma^\mu q$$

Erler et al., PR D68 (2003)

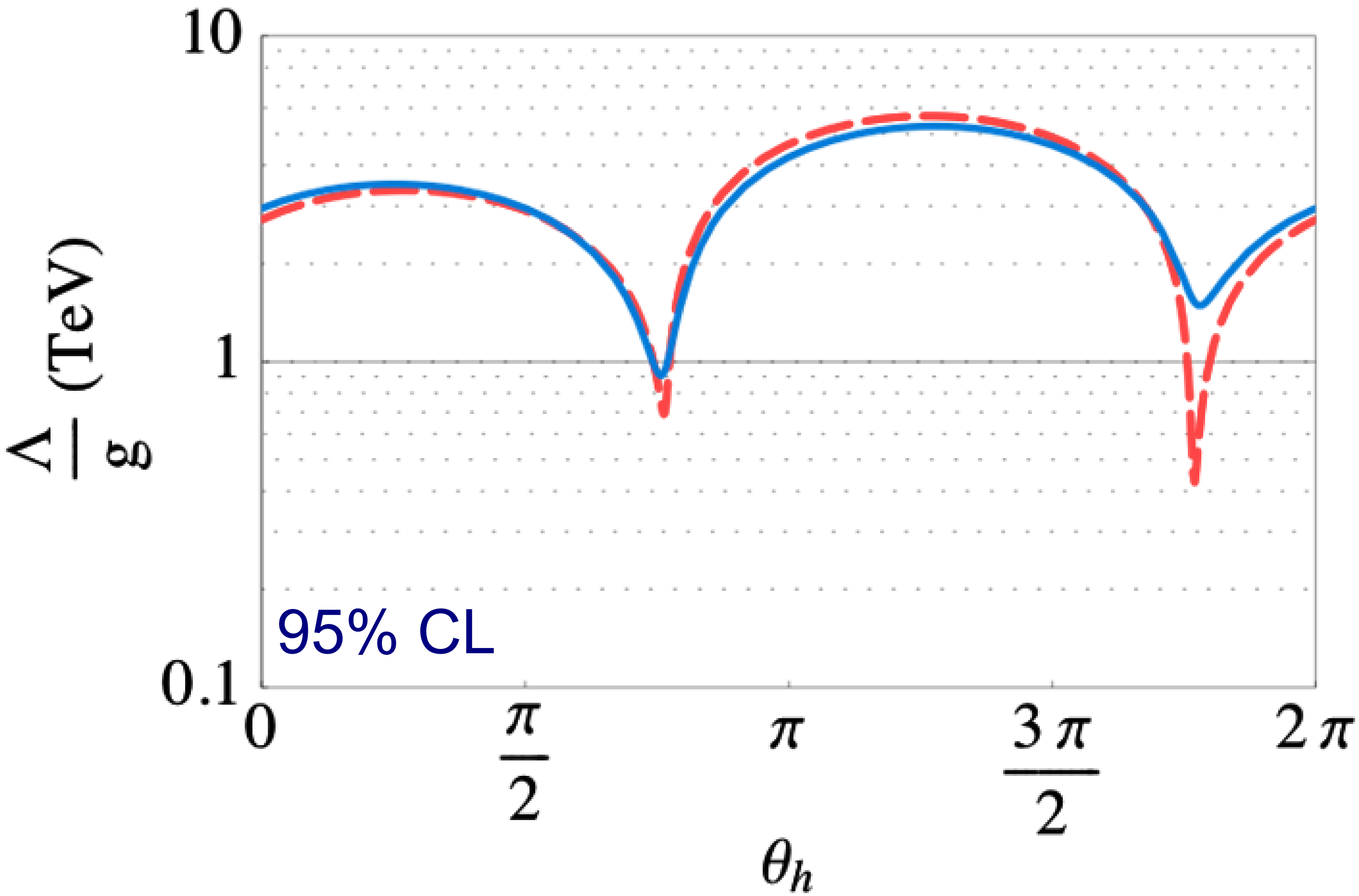
$$\mathcal{L}_{NP}^{PV} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

Full isospin coverage for limits on new physics!

$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$

Data sets limits on $\frac{g^2}{\Lambda^2}$

Lower bound on NP scale



Young et al. (Dec 2006)

New physics scale >0.9 TeV! (up from 0.4 TeV)

Future: Q_{weak} Experiment (2010: 6 GeV)

- **Precise measurement of the proton's weak charge in PVES**

$$Q^p_{\text{weak}} = -2(2C_{1u} + C_{1d}) \qquad Q^2 = 0.03\,\text{GeV}^2,\ \theta = 8^\circ$$

- **At low energy and small scattering angle:**

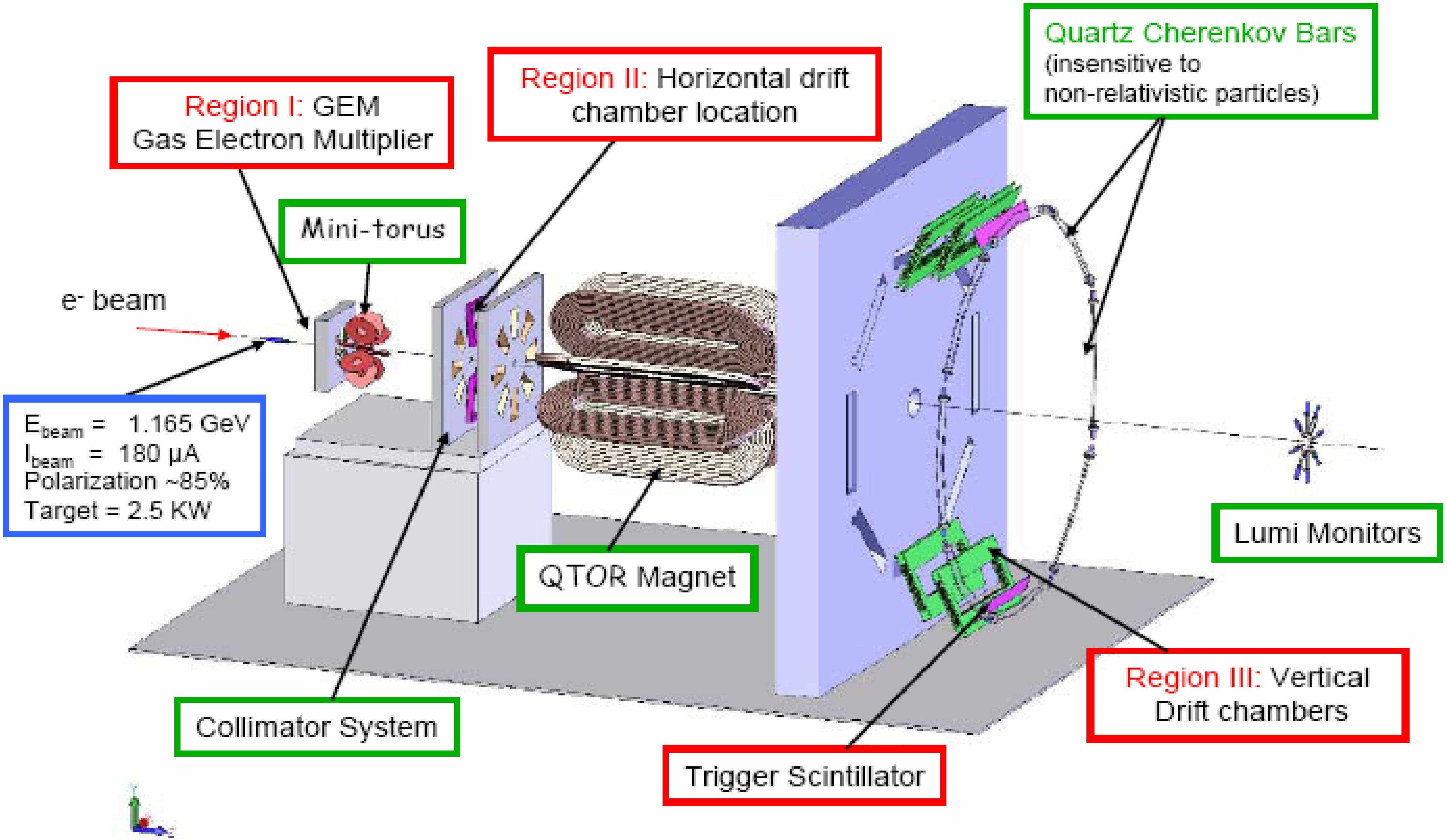
$$A_{LR} = -\frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}}\left[Q_{\text{weak}} + \beta_A \tilde{G}^p_A \sqrt{Q^2} + \beta_V Q^2 + \ldots\right]$$

$$\beta_A \propto \theta + O(\theta^3)$$

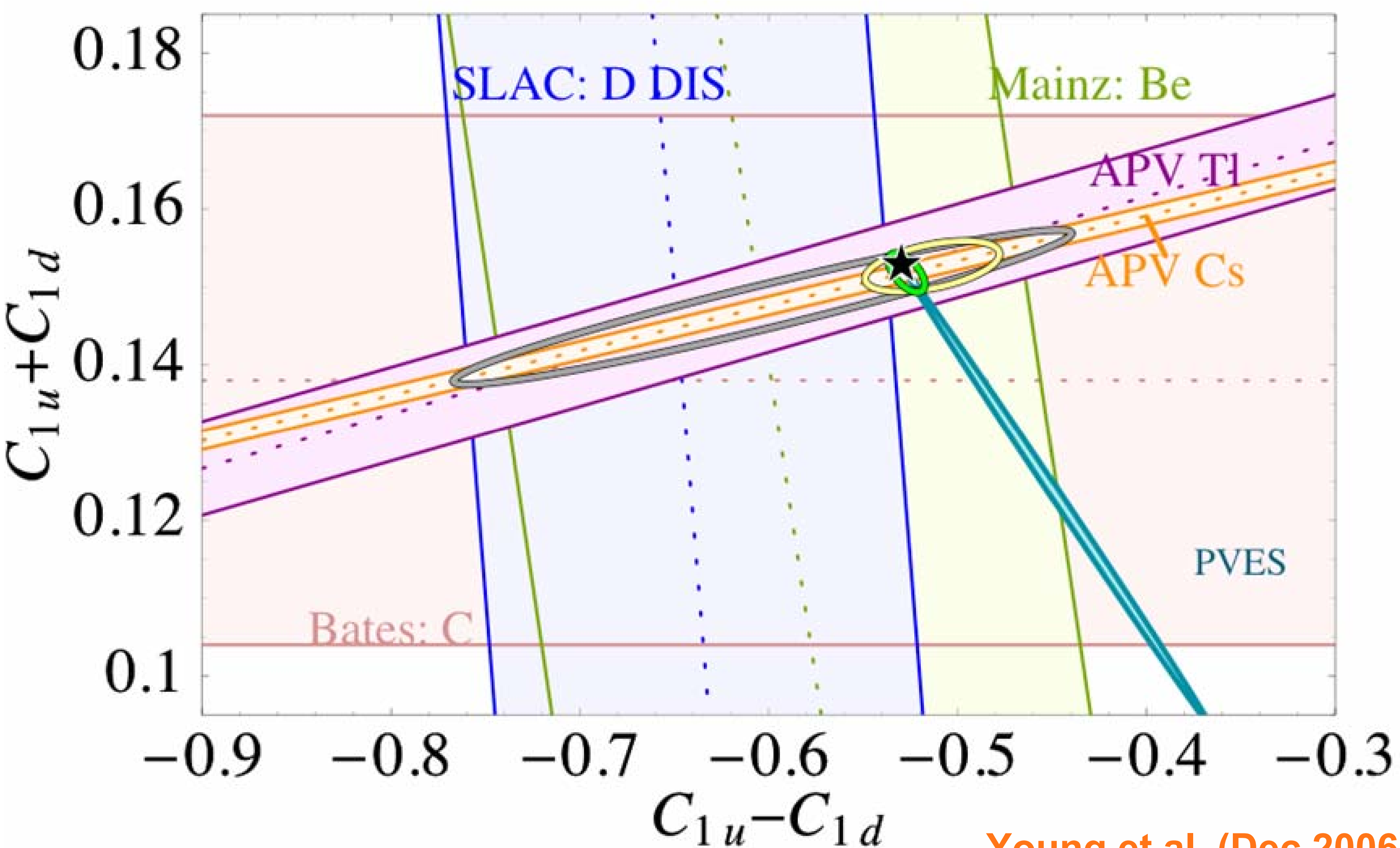
Anapole uncertainty

Strangeness uncertainty

Q_{weak} Apparatus

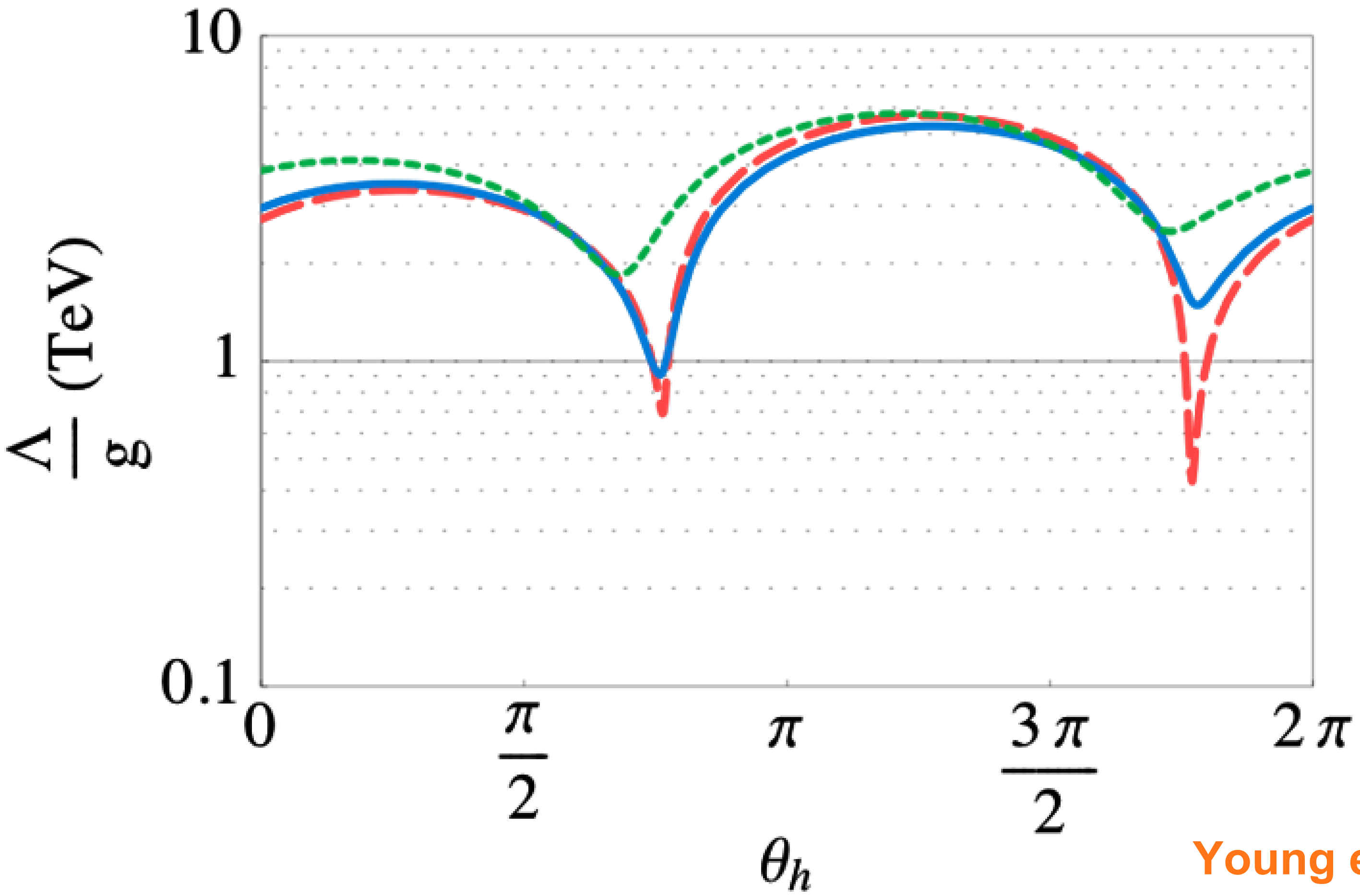


Possible Impact of Qweak



Young et al. (Dec 2006)

New Physics Limits
(if result consistent with Standard Model)



future Qweak

with PVES

Atomic only

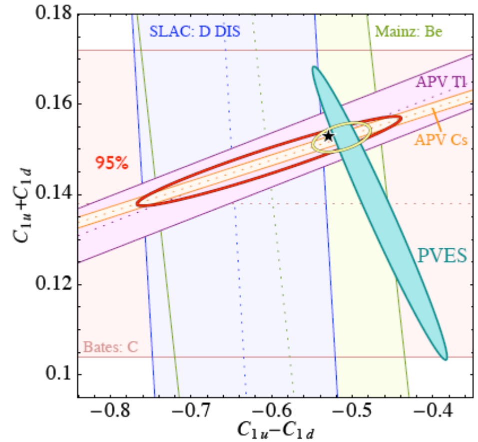
95% CL

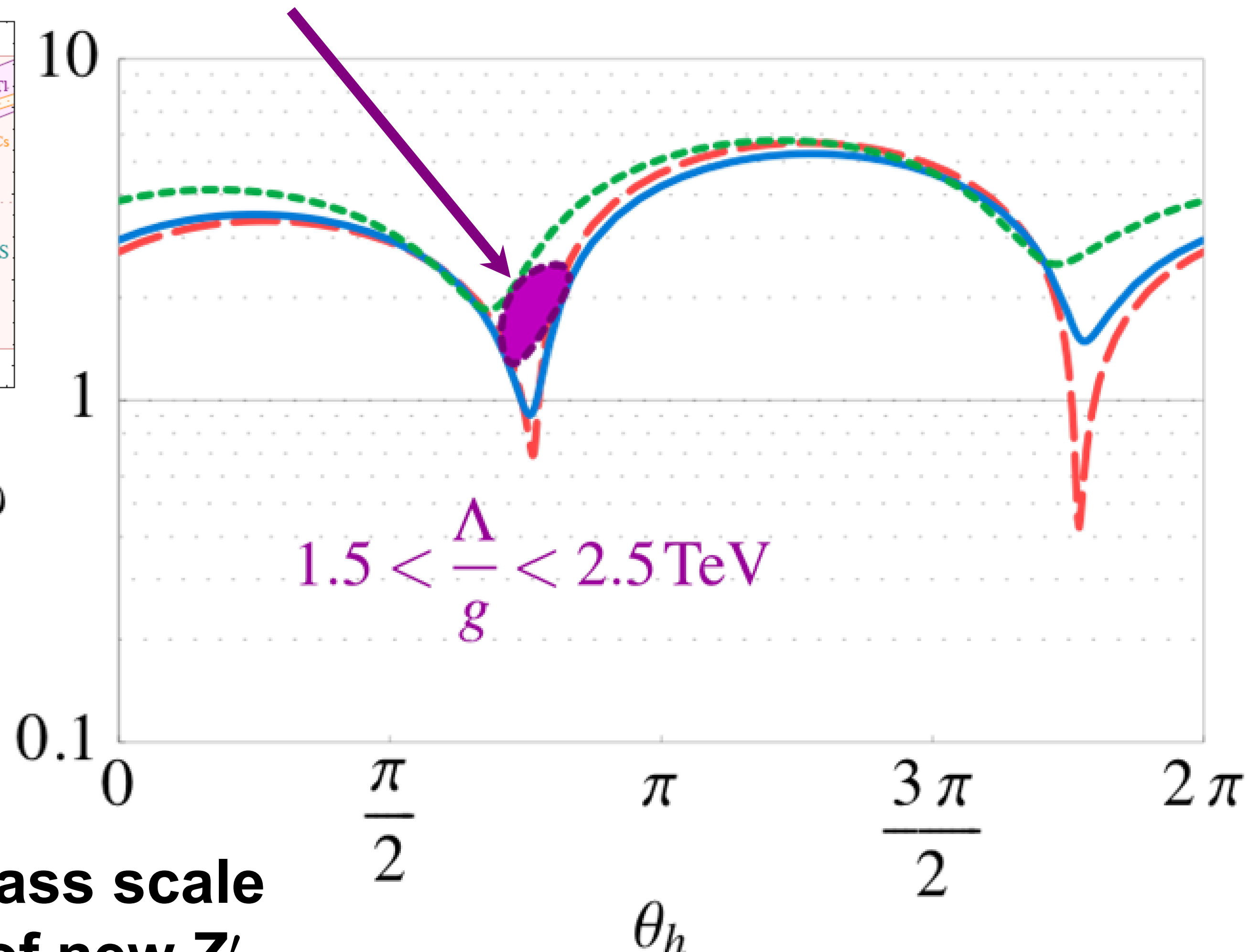
Young et al. (Dec 2006)

Qweak constrains new physics to beyond 2 TeV

But: Q_{weak} has real discovery potential!

IF: Q_{weak} takes central value of current PVES measurement





Q_{weak} yields mass scale and coupling of new Z′

Young et al. (Dec 2006)

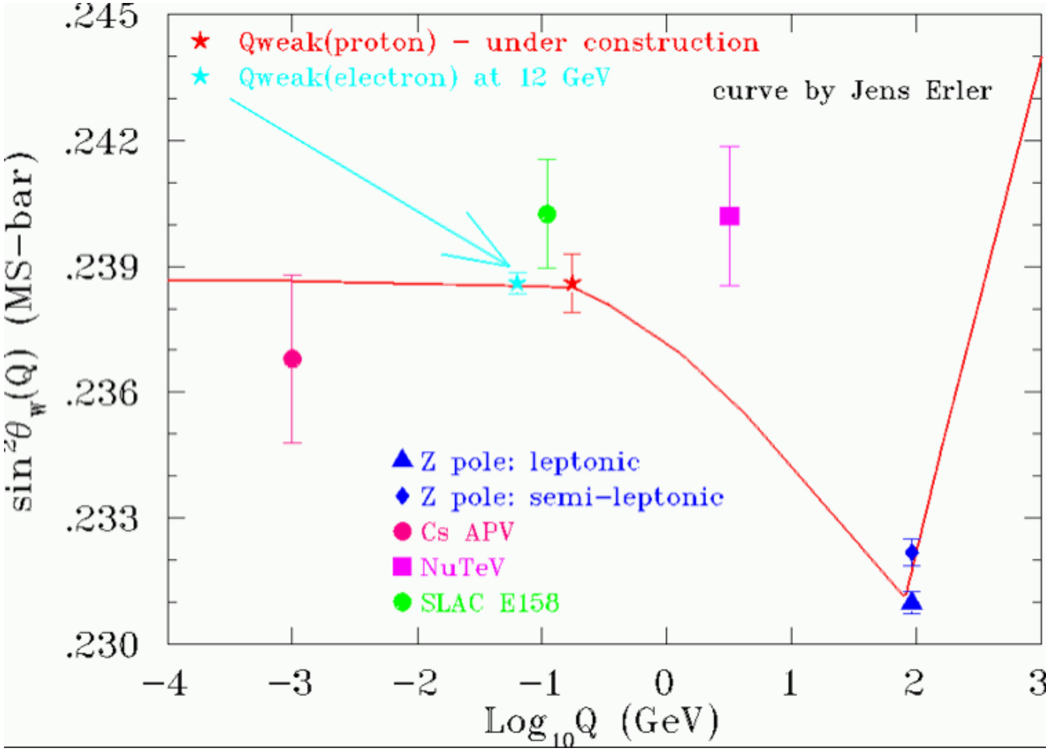
Future Möller Experiment at 12 GeV

Appears feasible to measure $\sin^2 \theta_W$ to $\pm$ 0.0002

Consensus Statement from December 2006 Workshop:

"There was overwhelming enthusiasm to aggressively proceed with the design of such an experiment"

"unique sensitivity to properties of new physics phenomena such as R-parity violating SUSY"

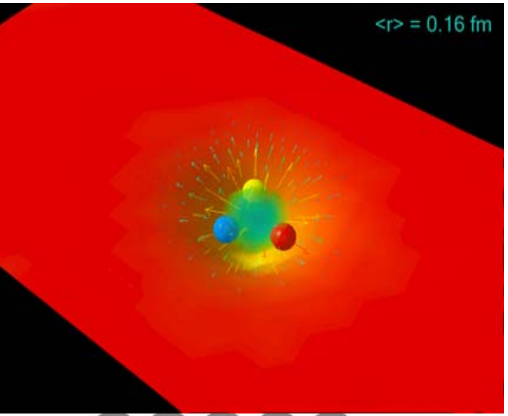


World Community in 2013 and Beyond

- With 12 GeV Upgrade will have three major new facilities investigating nuclear physics at quark level (QCD) : FAIR (GSI, Germany), J-PARC (Japan) and JLab*

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

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



* Unique: only electromagnetic machine