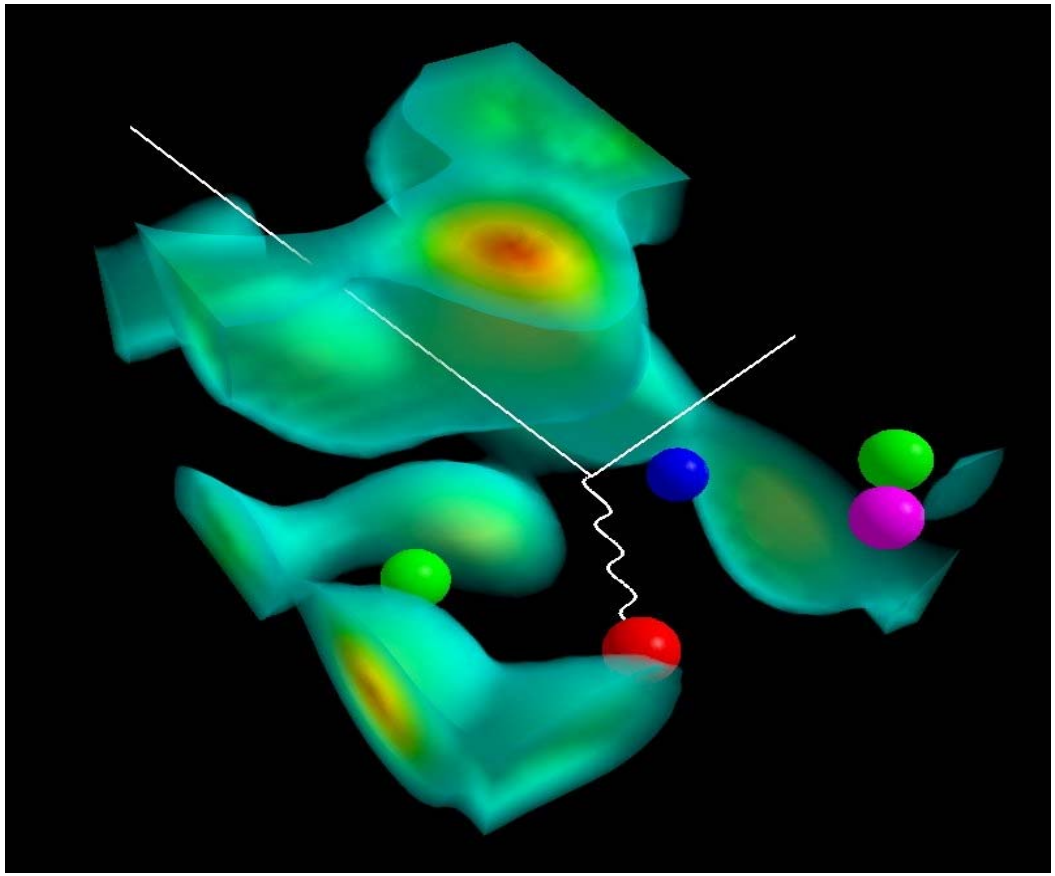
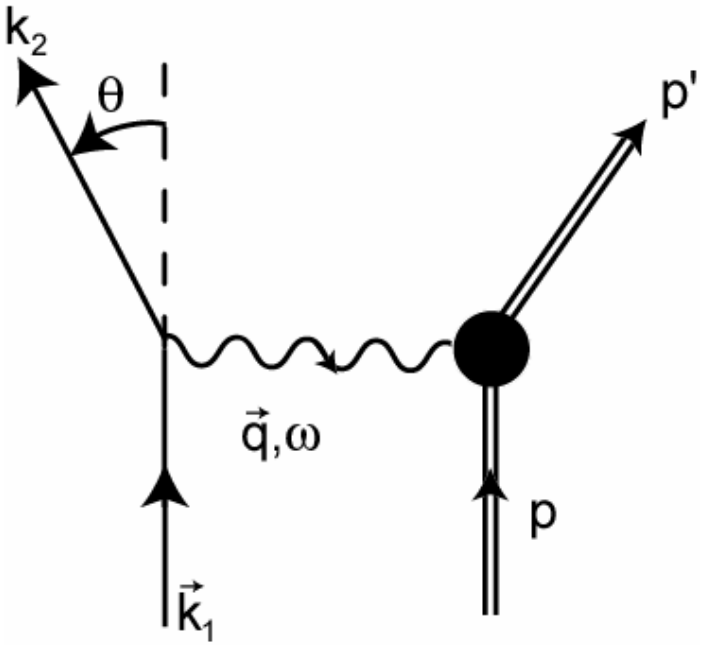
Precise Electro-Weak Studies: An Essential Element of the World-Wide Nuclear Physics Program



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:

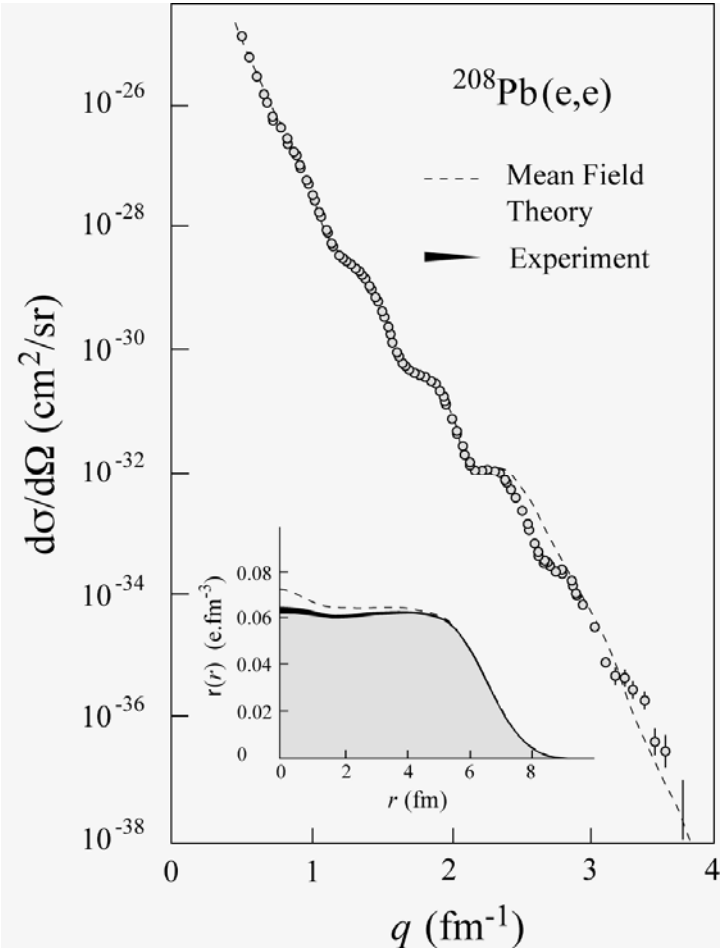
$\lambda \cong 2\pi/q$ **(1 fm ⇔ 1 GeV/c)**

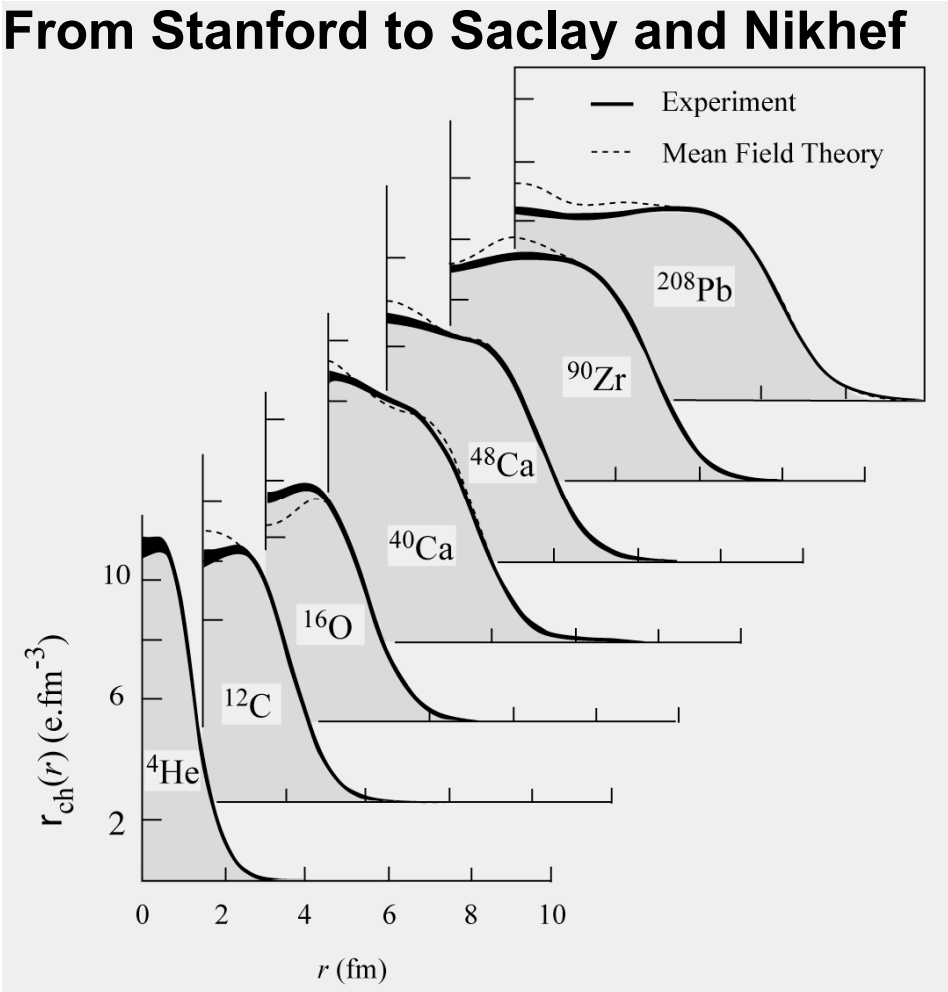
$$S_{fi} = \frac{-e^2}{\Omega}\,\bar{u}(k_2)\,\gamma^{\mu}\,u(k_1)\,\frac{1}{q^2}\int e^{iq\cdot x}\,\langle f|\hat{J}_{\mu}(x)|i\rangle\,d^4x$$

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

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

(e,e) ⇒ Nuclear Charge Distributions



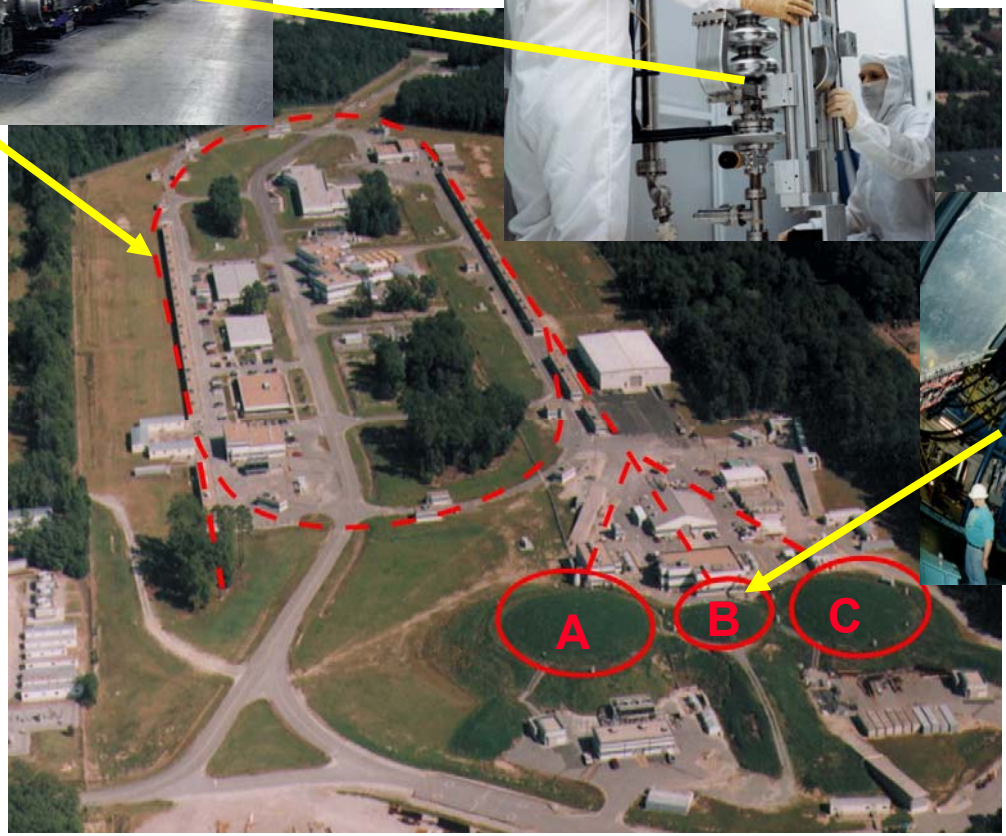


Model-independent analysis ⇒ accurate nuclear charge distributions

JLab: Unique Forefront Capabilities for Science

Cryomodules in the accelerator tunnel

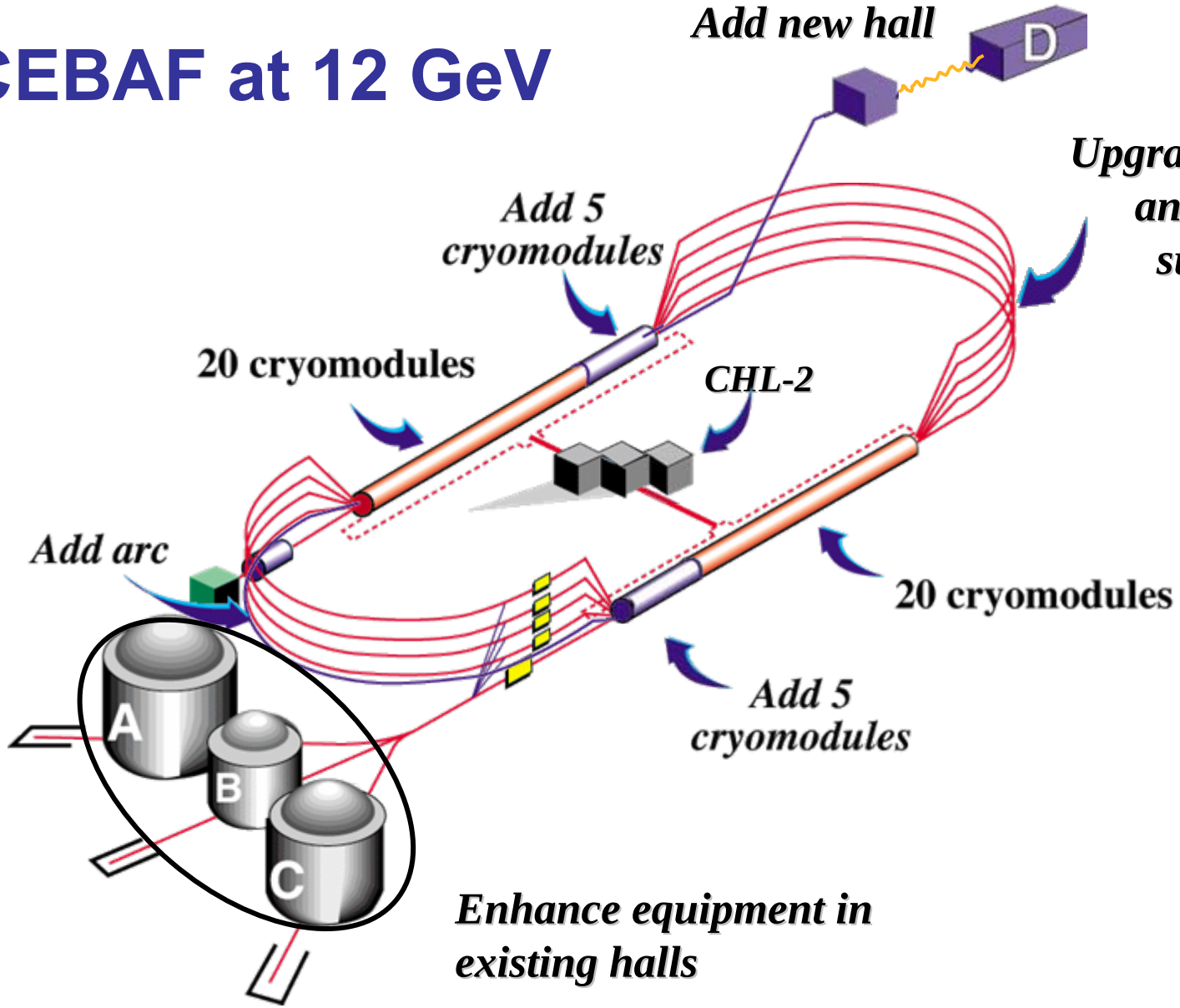
Superconducting radiofrequency (SRF) cavities undergo vertical testing.



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**

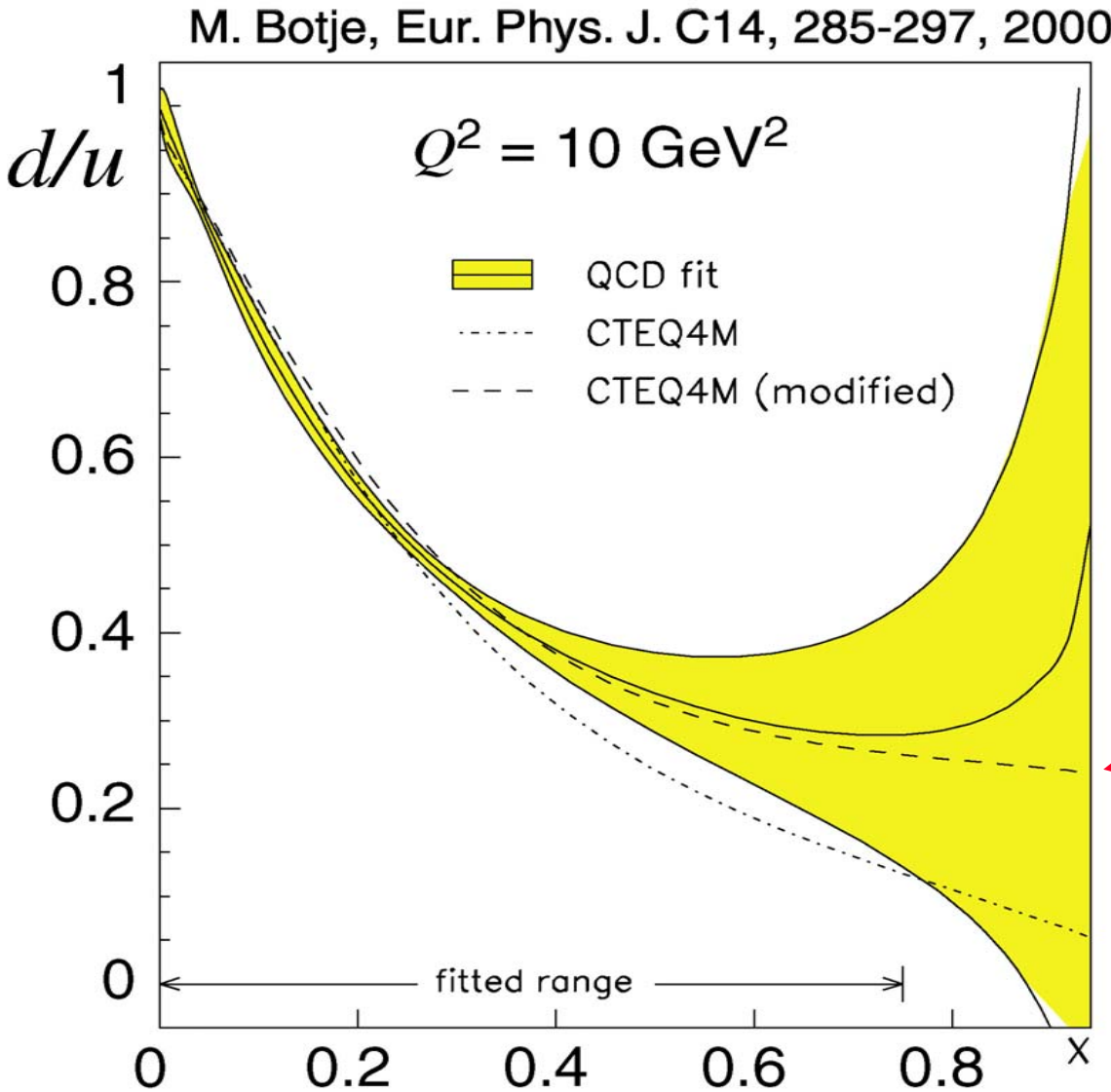
Highlights of the 12 GeV Program….2

- **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

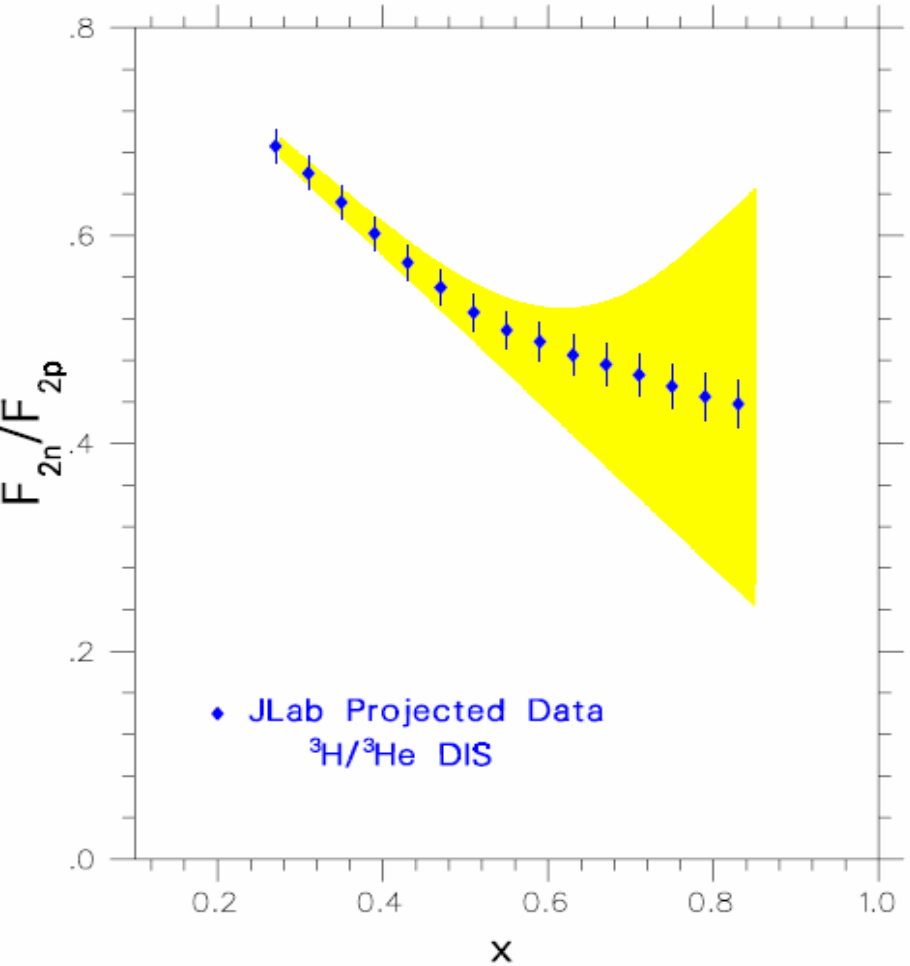


pQCD

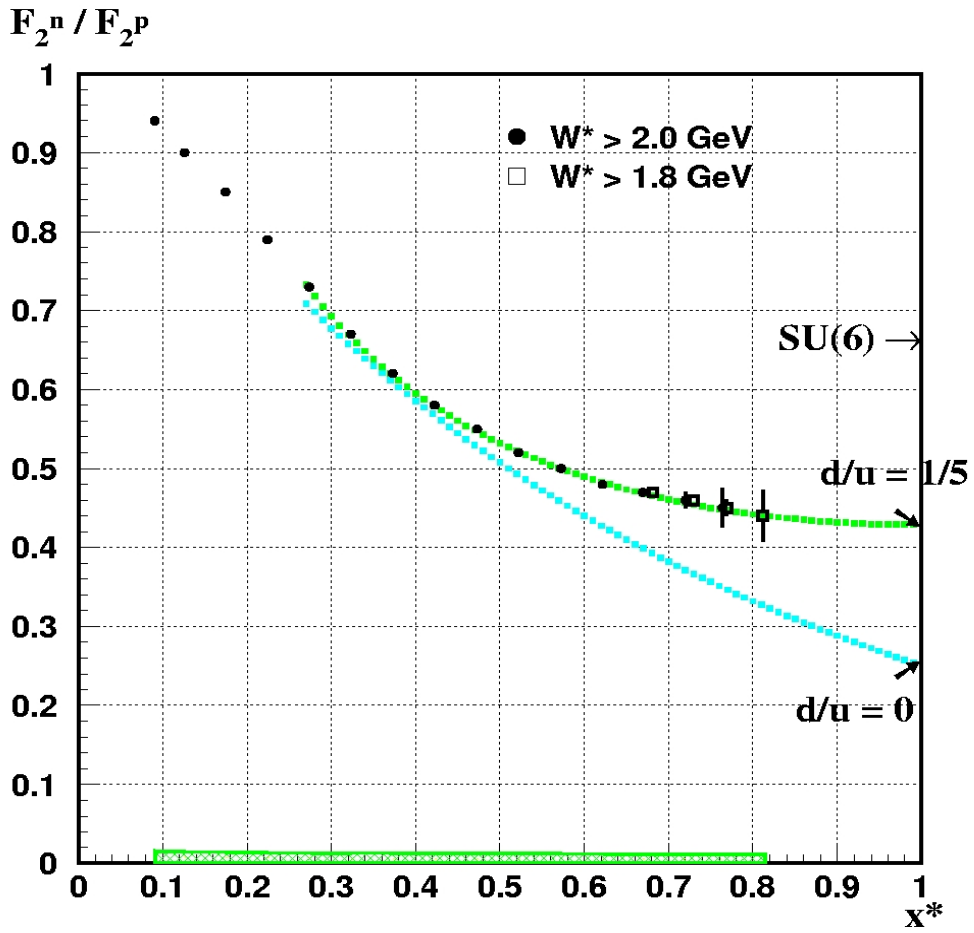
di-quark correlations

12 GeV : Unambiguous Flavor Structure x→ 1

Hall A 11 GeV with HMS

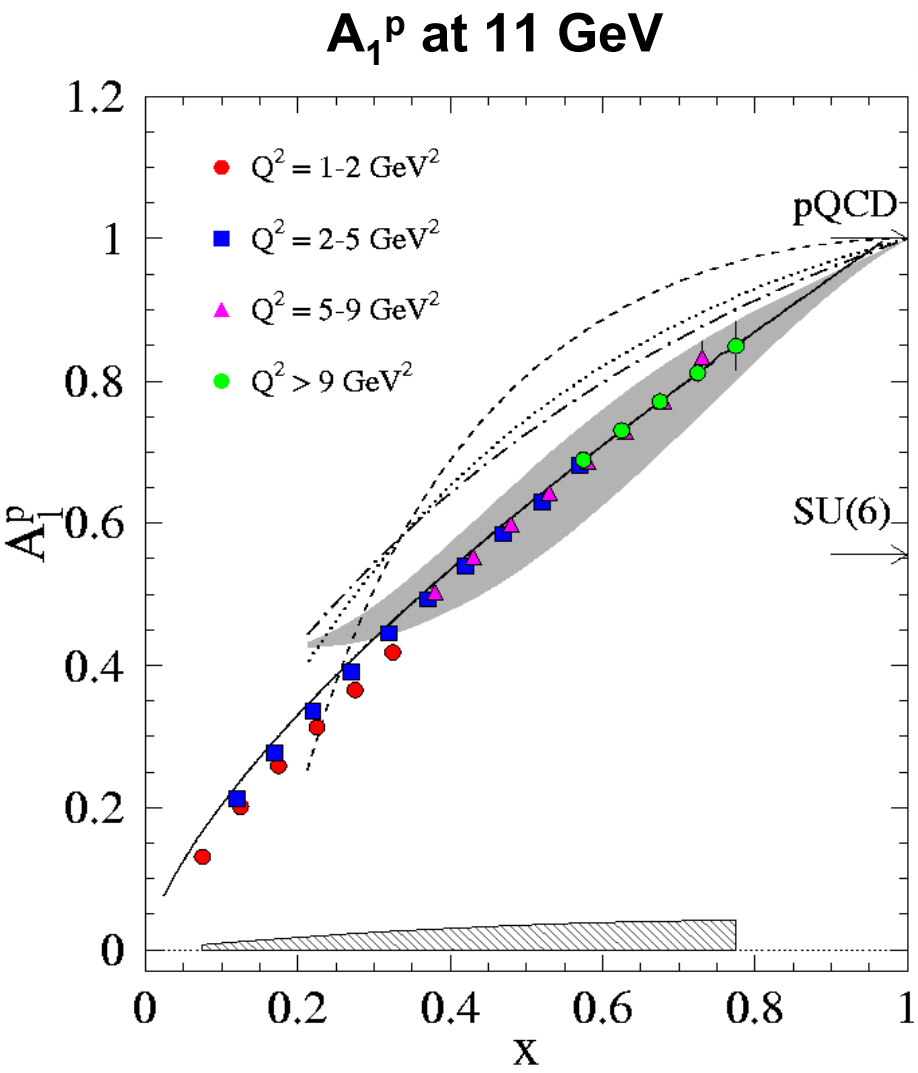


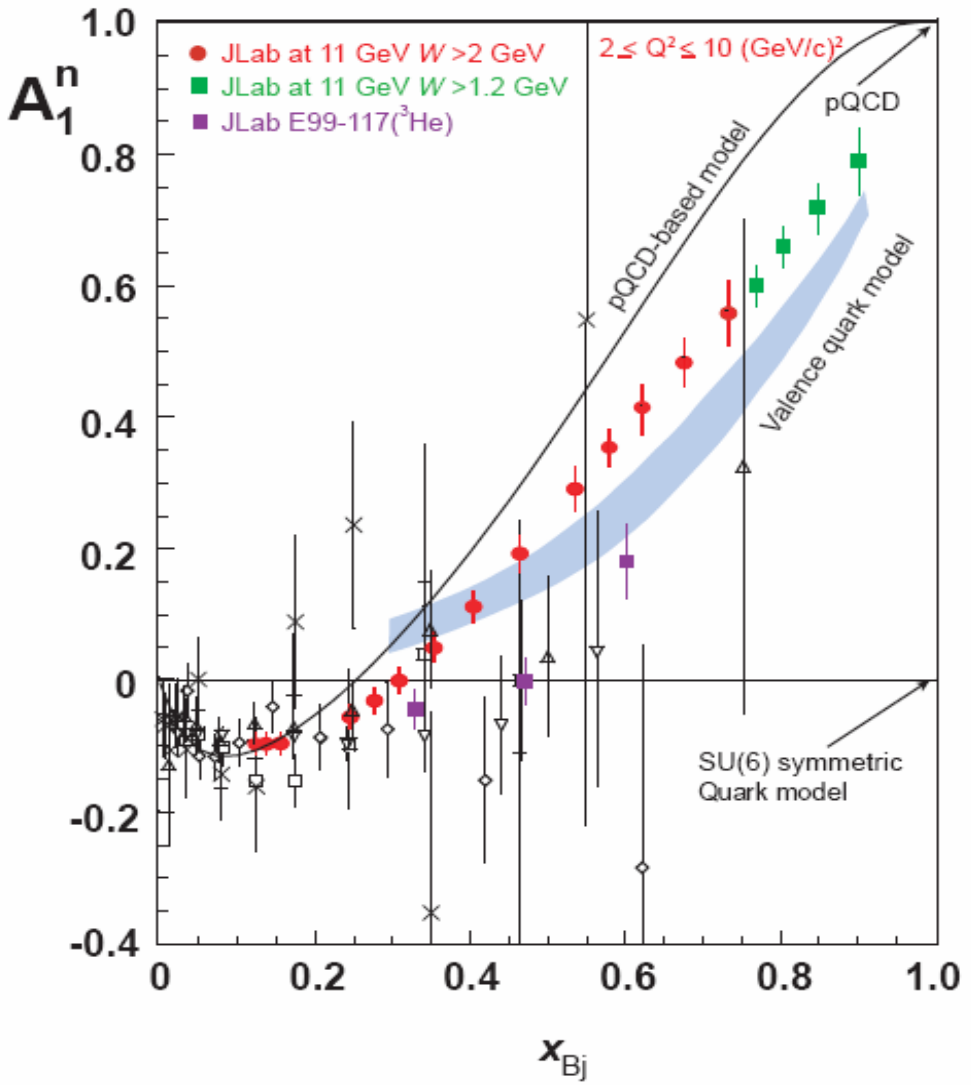
Hall B 11 GeV with CLAS12



Initial investigation with BONUS early 06 successful

12 GeV : Unambiguous Resolution of Valence Spin

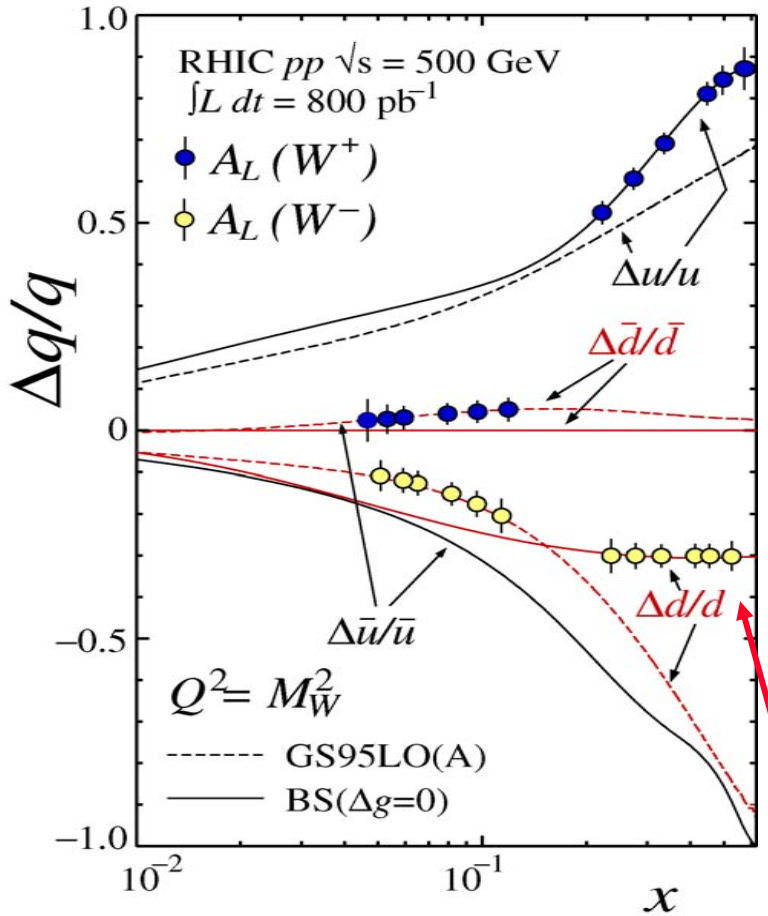




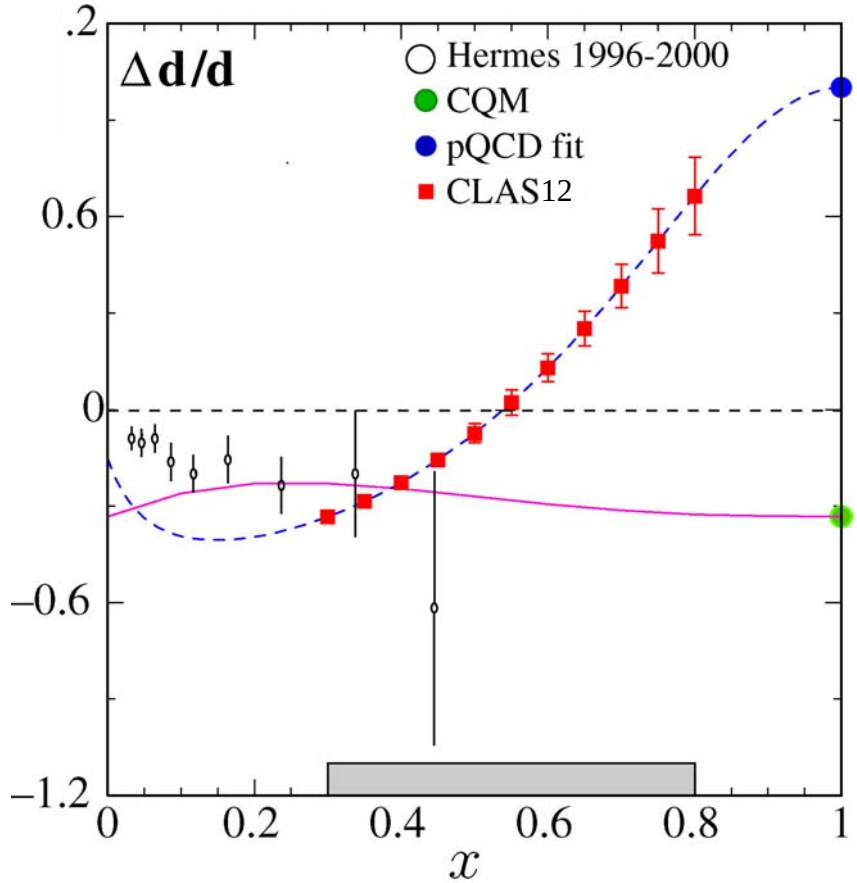
Complements Spin-Flavor Dependence at RHIC

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:
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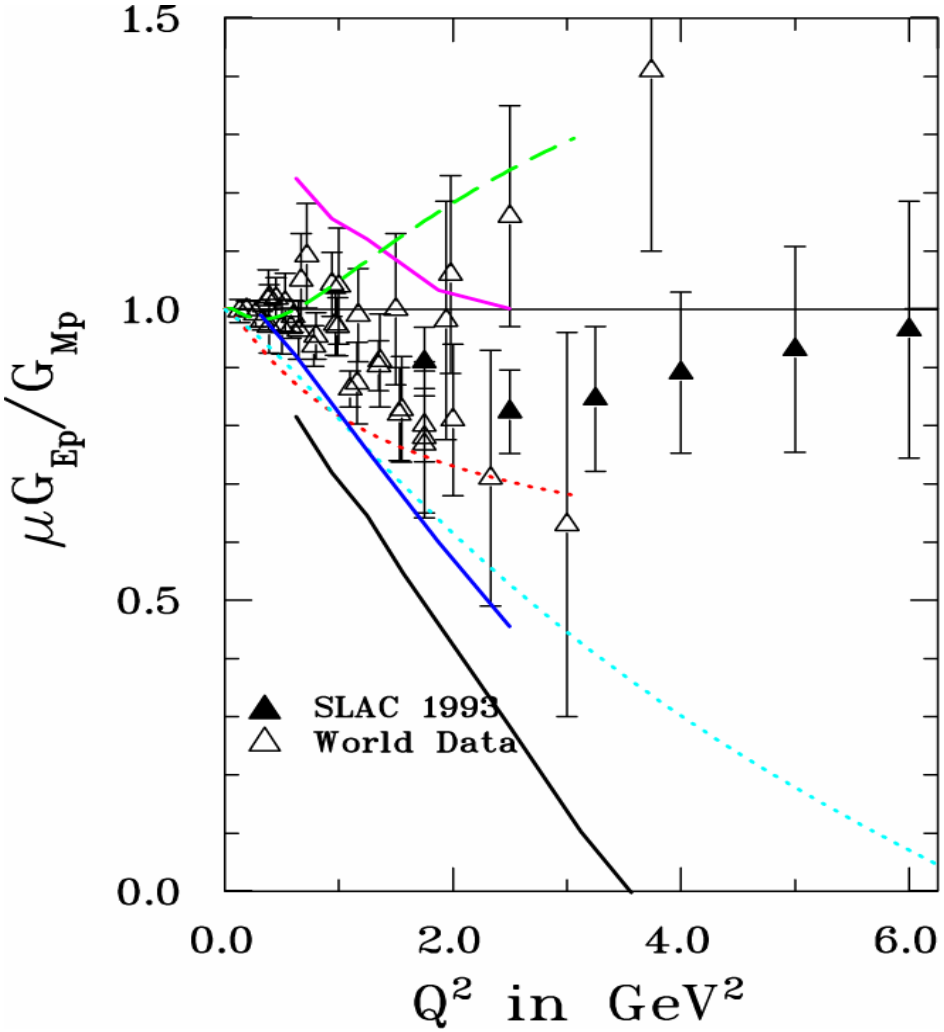
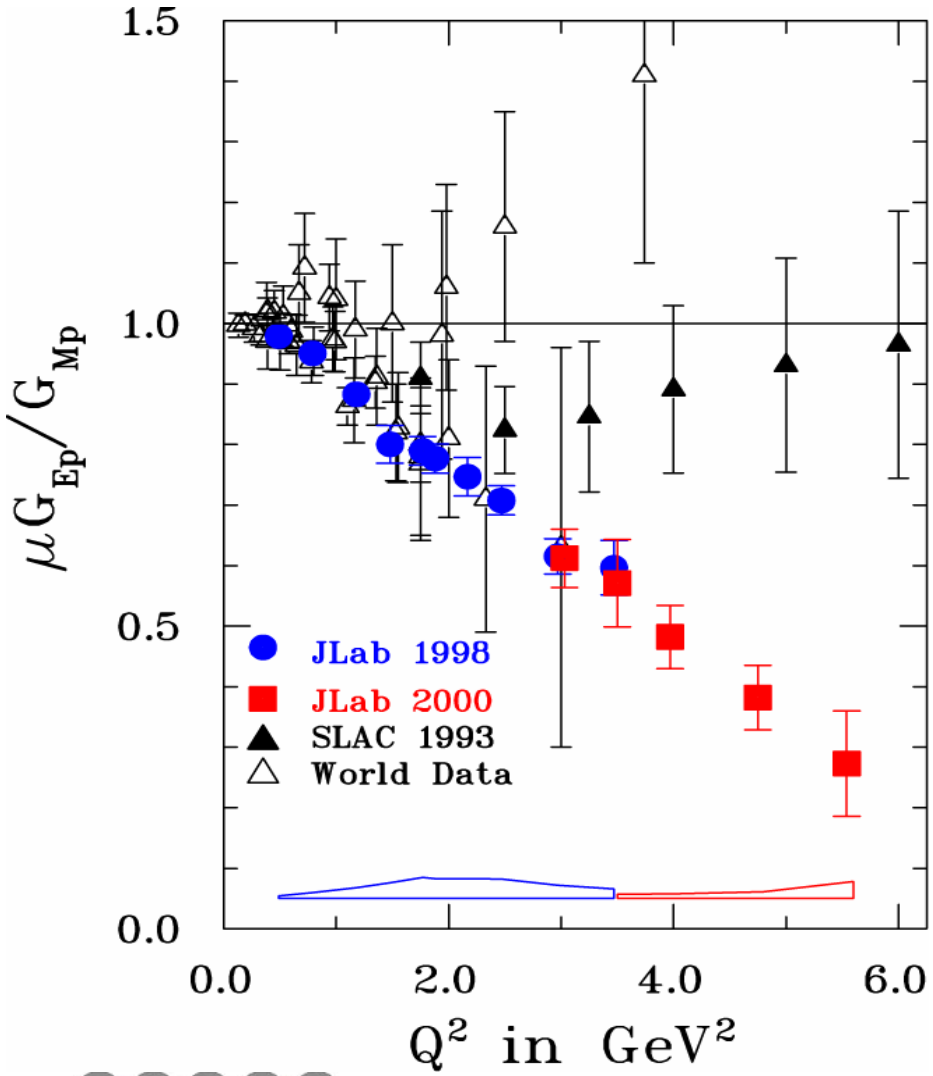
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model

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

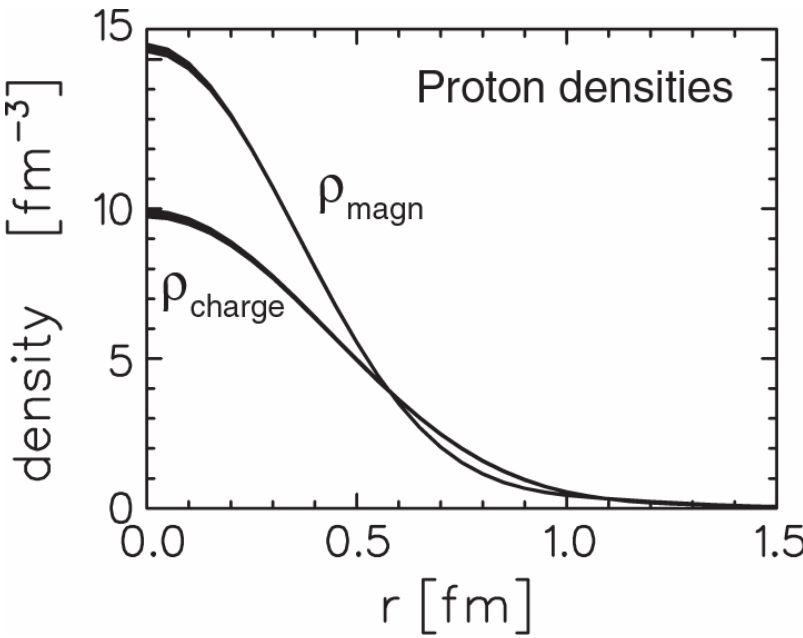
JLab Data Rewrote the Text Book



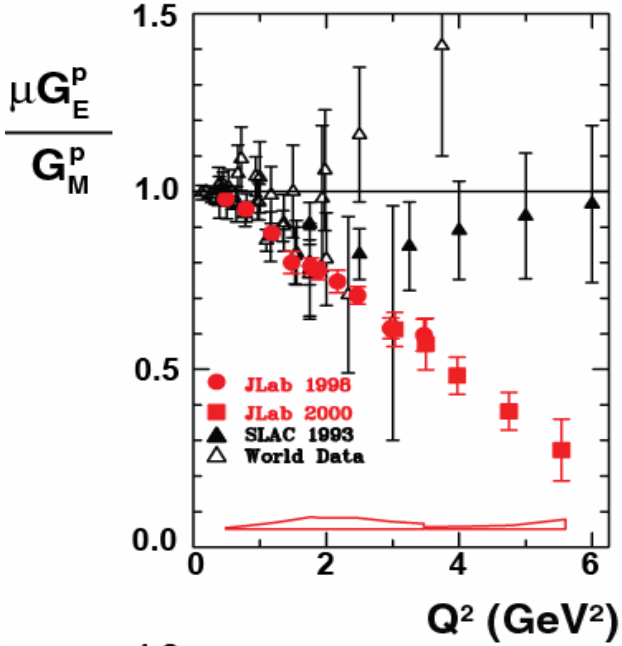
- High Intensity
- High Duty Factor
- High Polarization

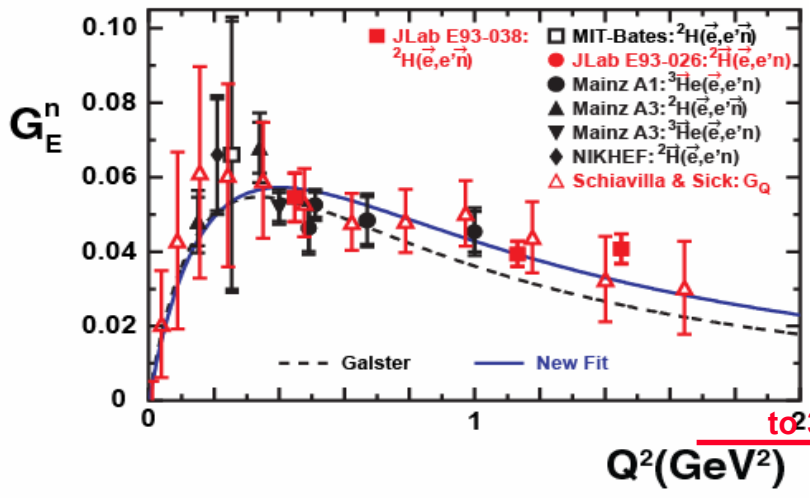
⇒ Revolutionized our knowledge

⇒

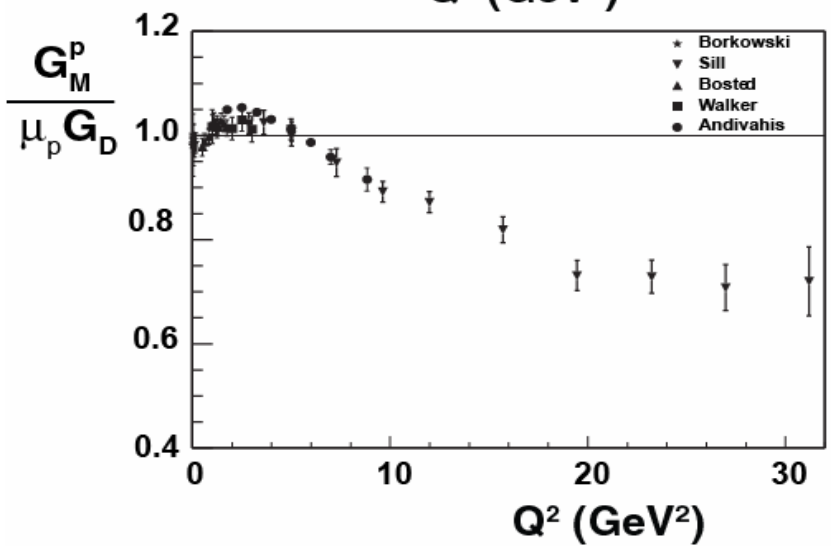


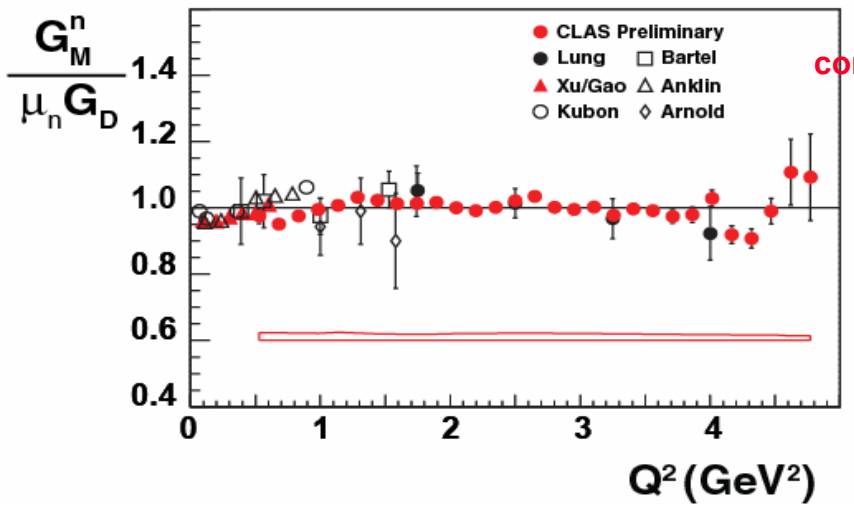
Overview of 6 GeV Form Factor Data



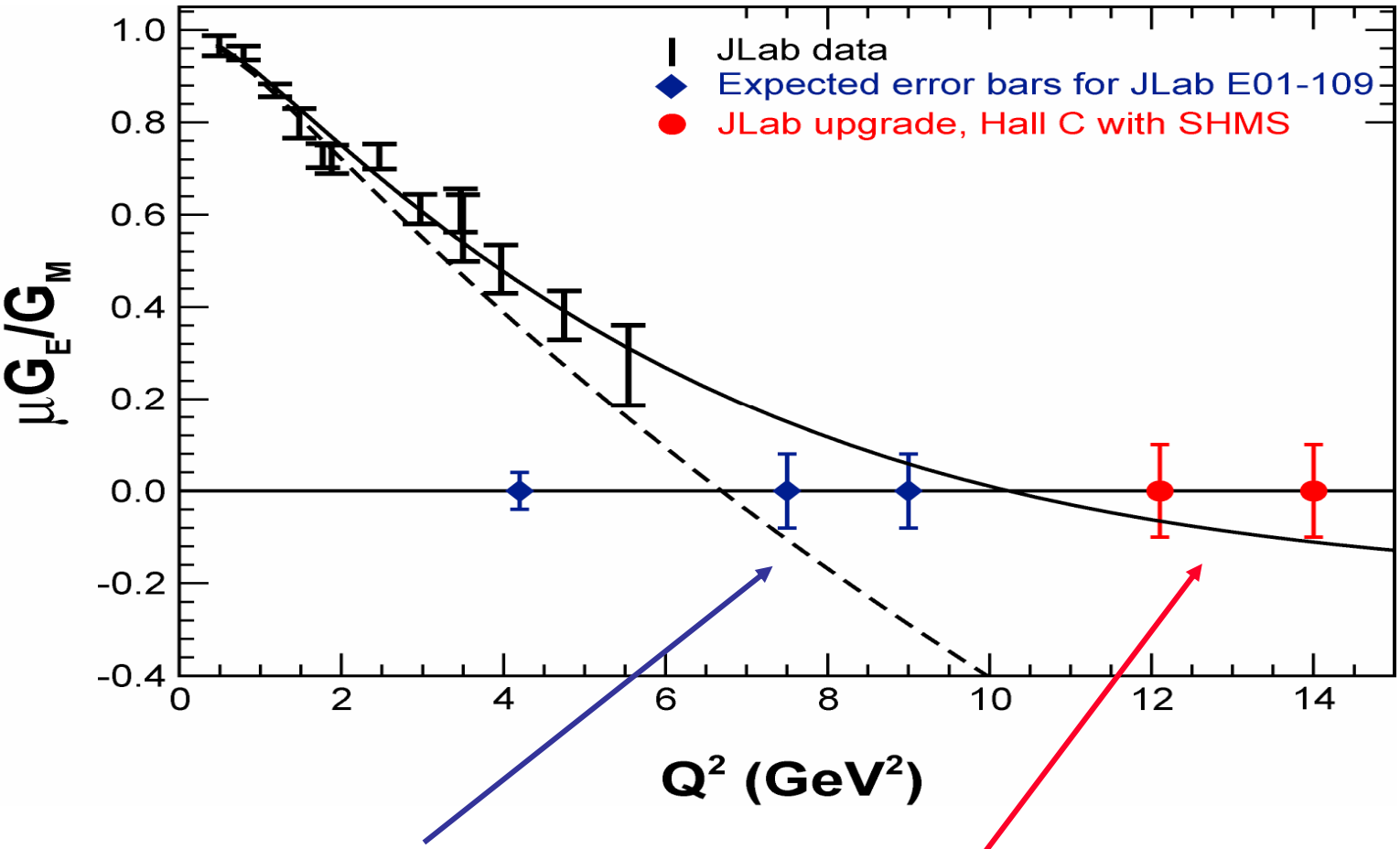


to 3.5 GeV^2 (Hall A) Data-taking just completed





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**

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

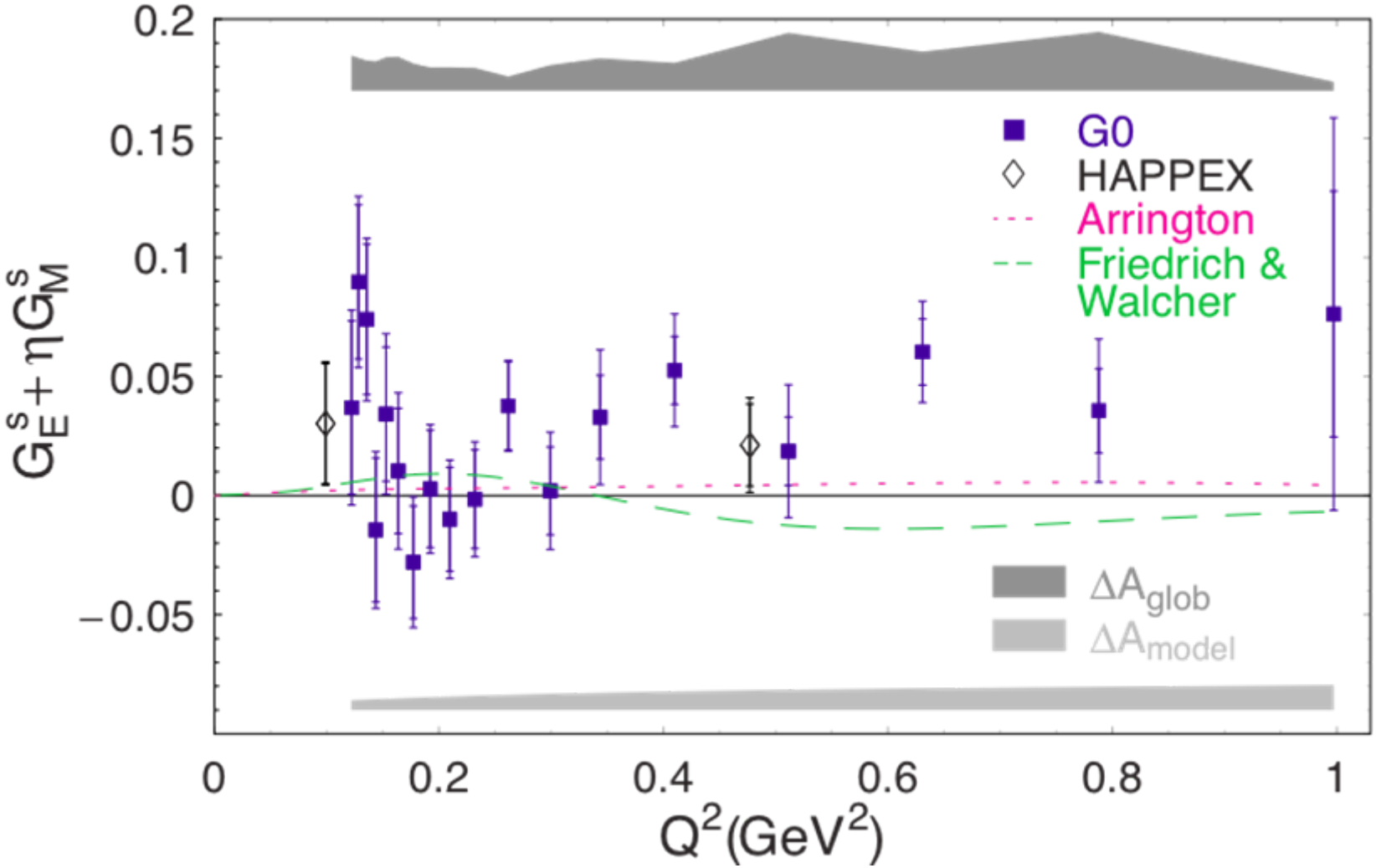
Neutral-weak form factors

Axial form factor

$$4G_{E,M}^{pZ} = \underbrace{(1 - 4\sin^2\theta_W) G_{E,M}^{p\gamma}}_{\text{Proton weak charge (tree level)}} - G_{E,M}^{n\gamma} - \underbrace{G_{E,M}^{s}}_{\text{Strangeness}}$$

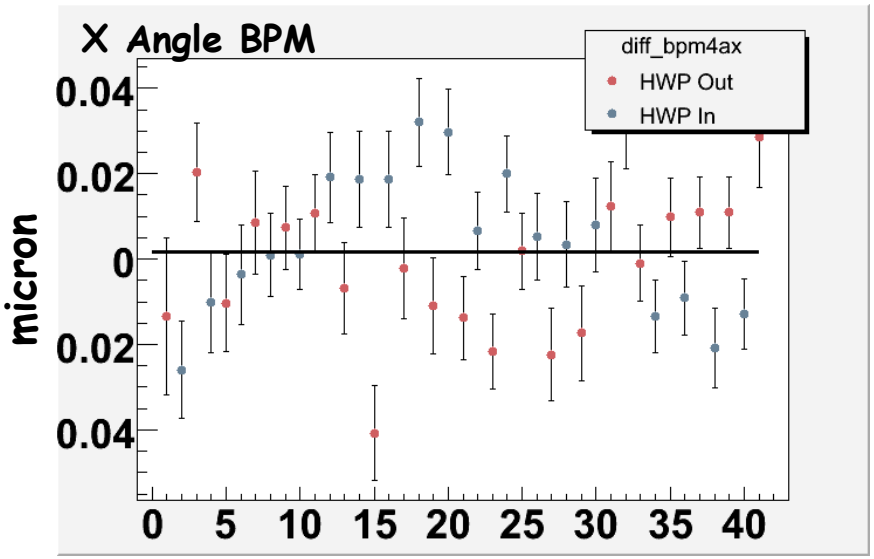
Using charge symmetry: given $G_{E,M}^{p\,\gamma,\, n\,\gamma,\, pZ} \Rightarrow G_{E,M}^{u,\, d,\, s}$

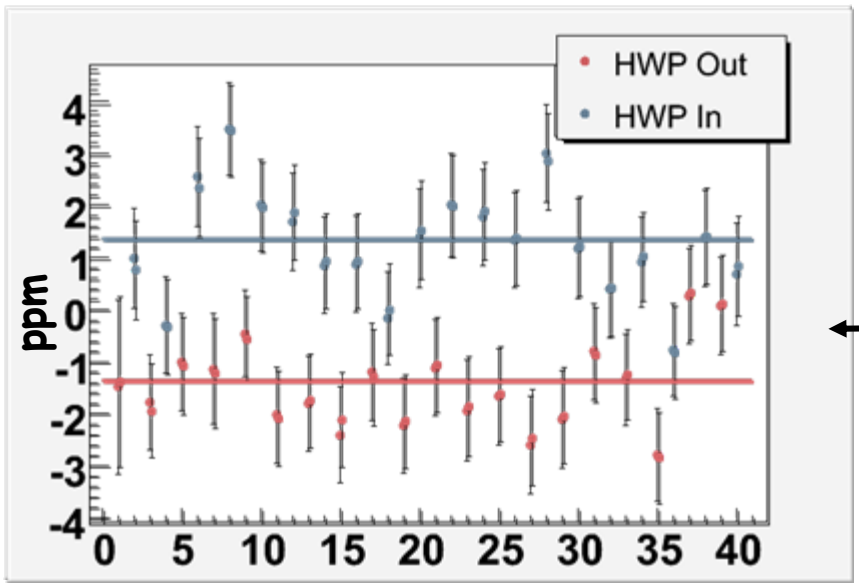
World Data Dominated by G0 from JLab



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

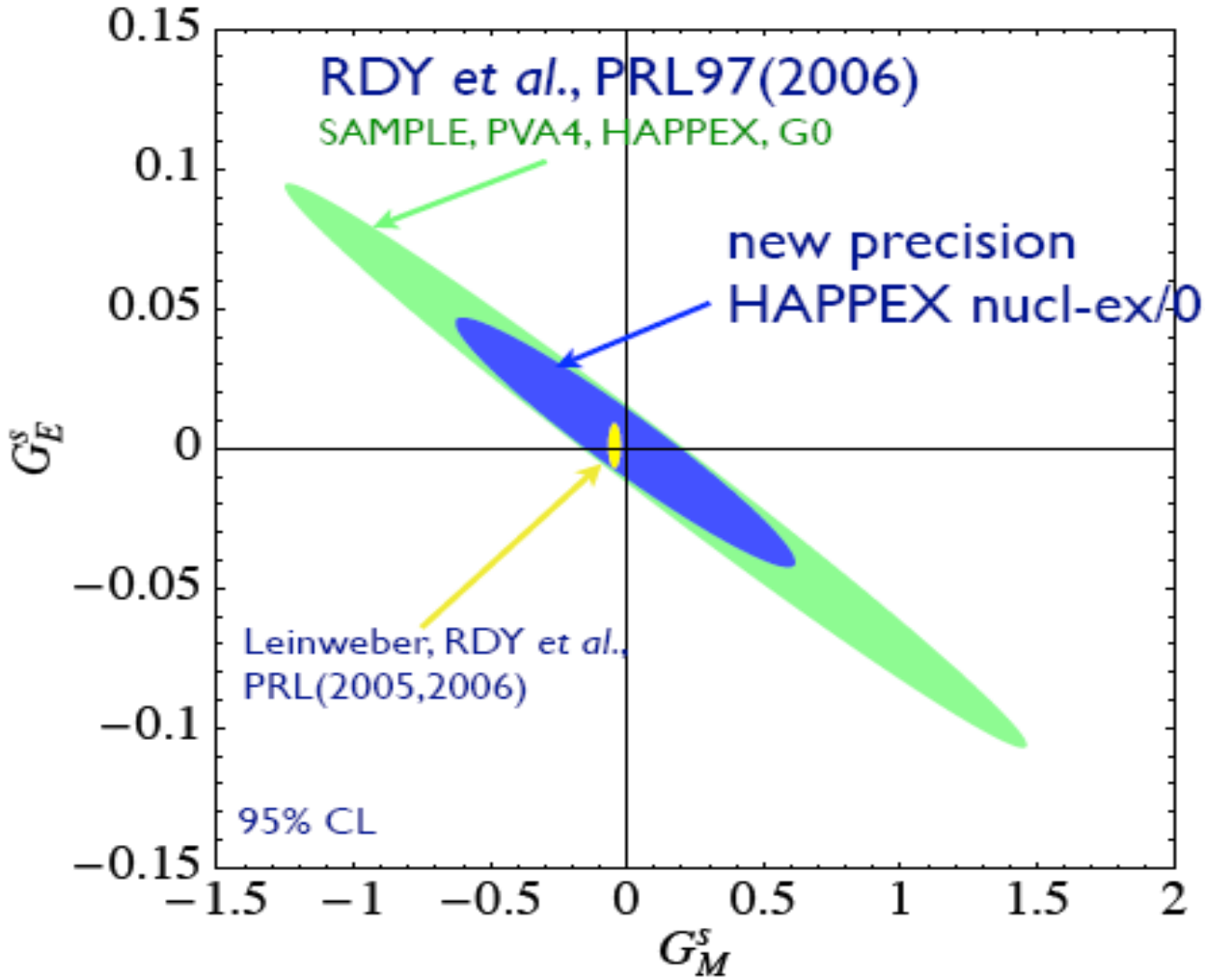
Y Angle: <1 nm

Corrected and Raw

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

from Kent Paschke

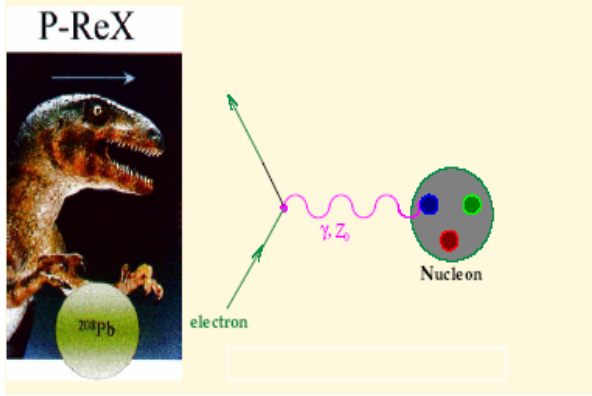
Factor of two from latest HAPPEx Measurement



$Q^2 = 0.1\ GeV^2$

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

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**

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

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!

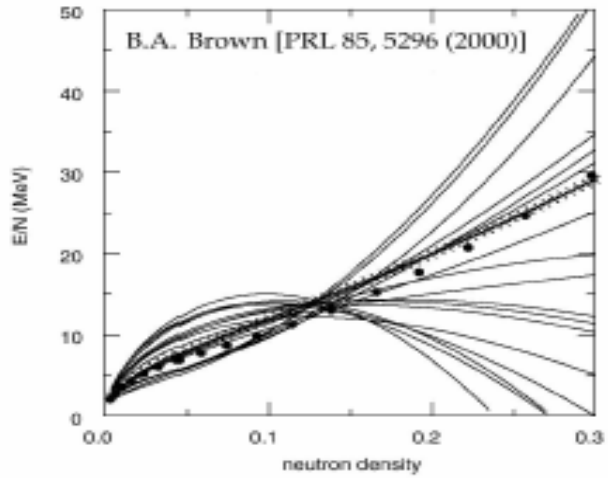


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

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

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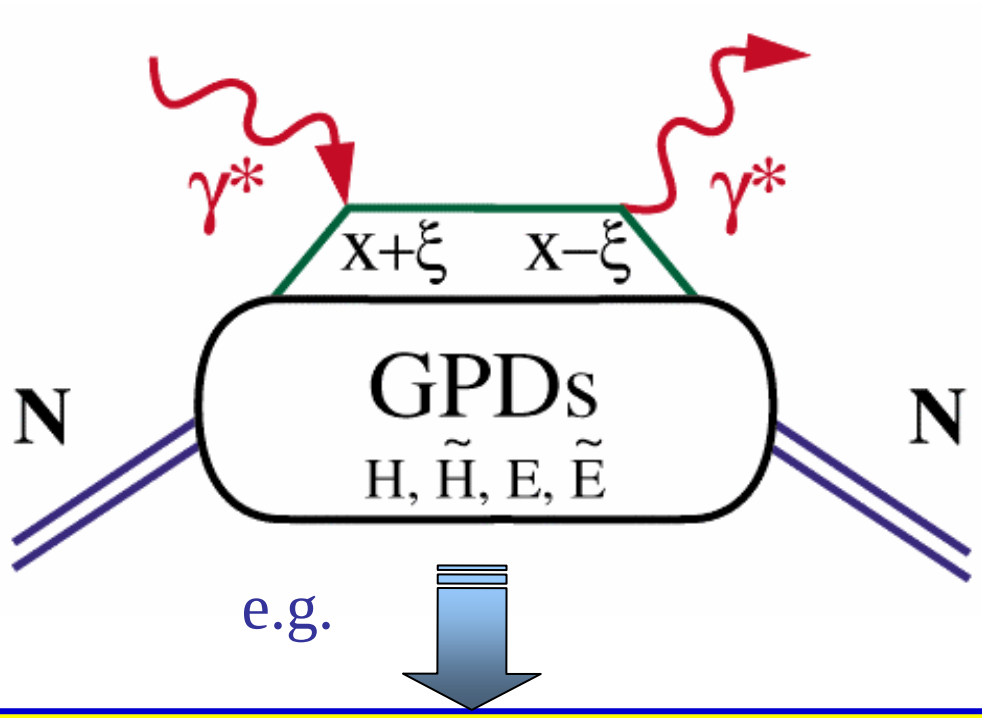
Studies of the Generalized Parton Distributions (GPDs): New Insight into Hadron Structure

HP 2008



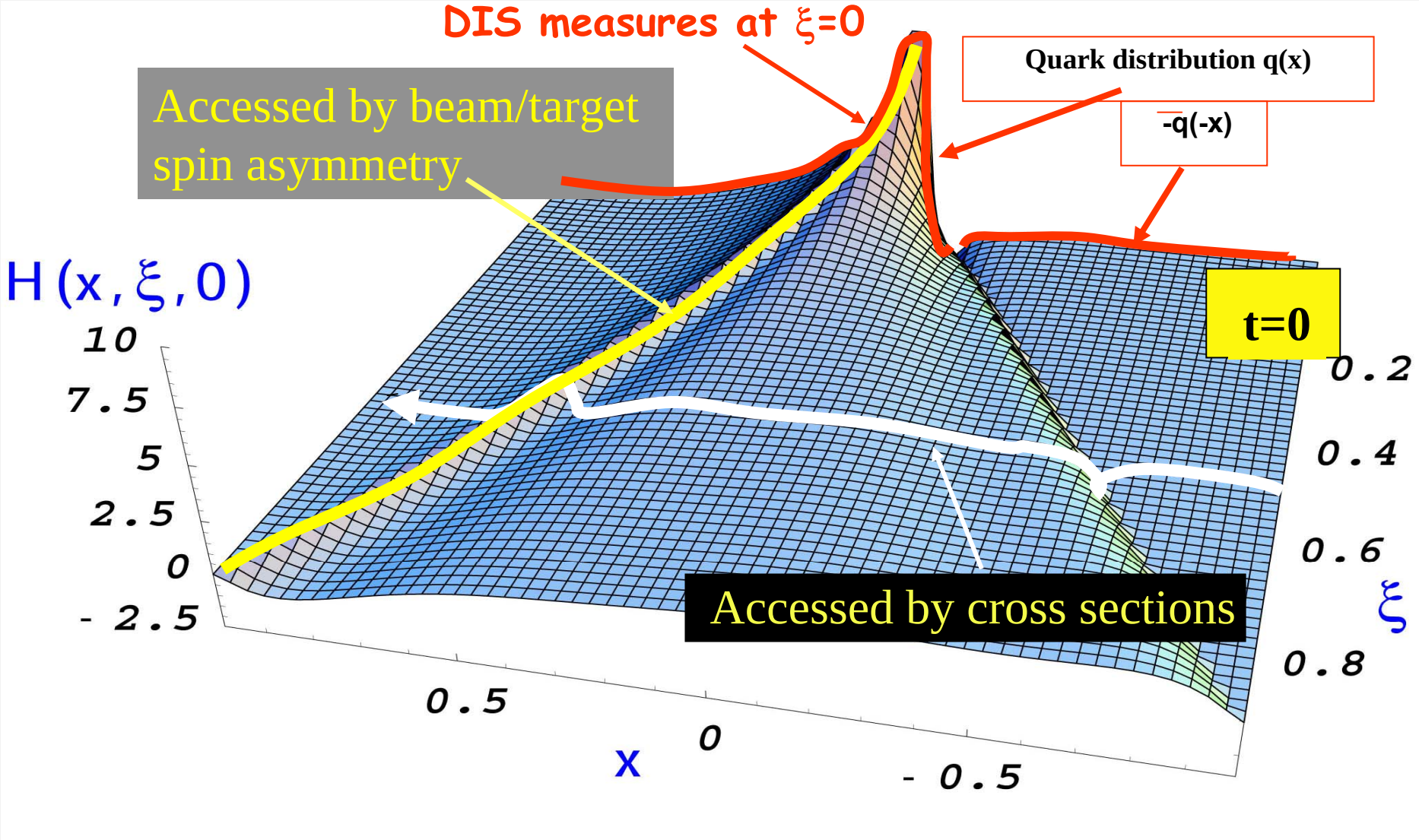
X. Ji &
A. Radyushkin
(1996)

Quark angular momentum (Ji's sum rule)

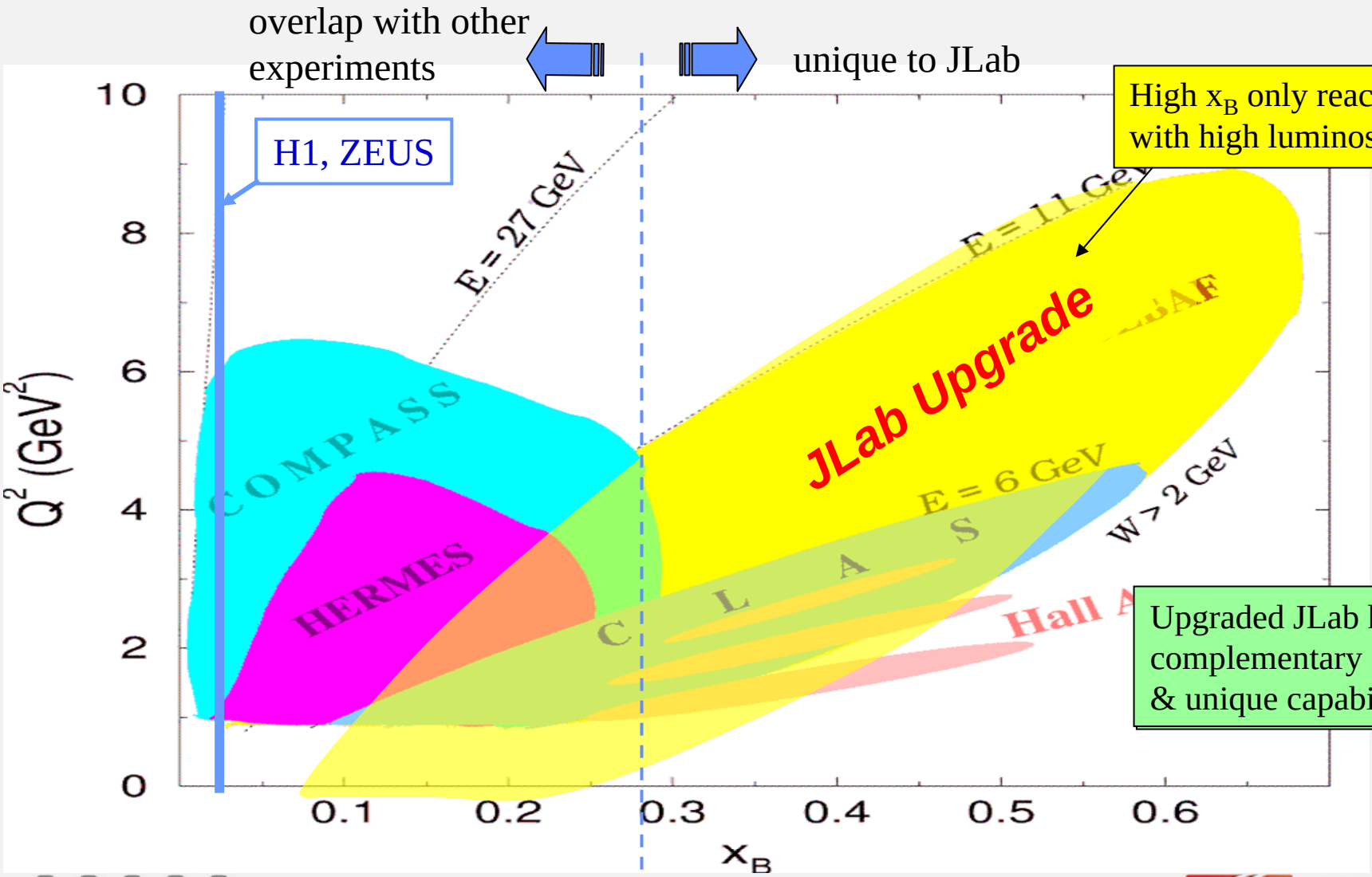
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

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

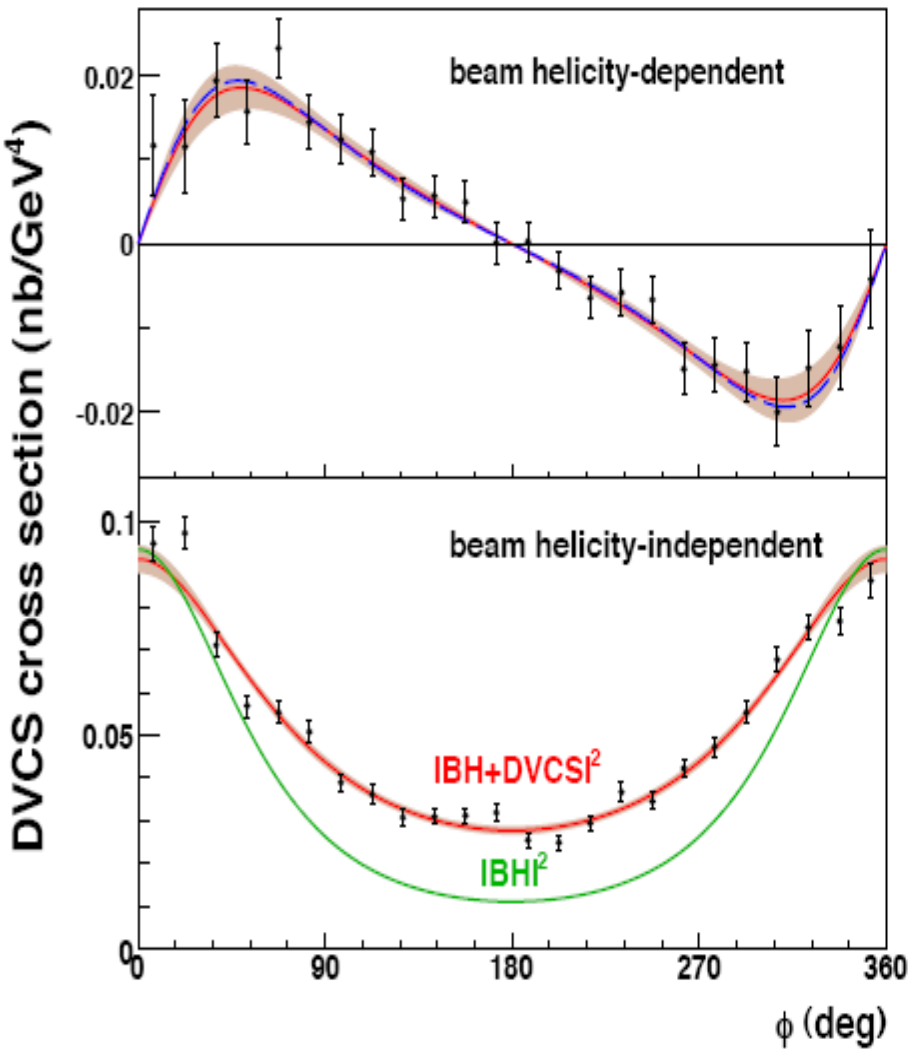
Access GPDs through x-section & asymmetries

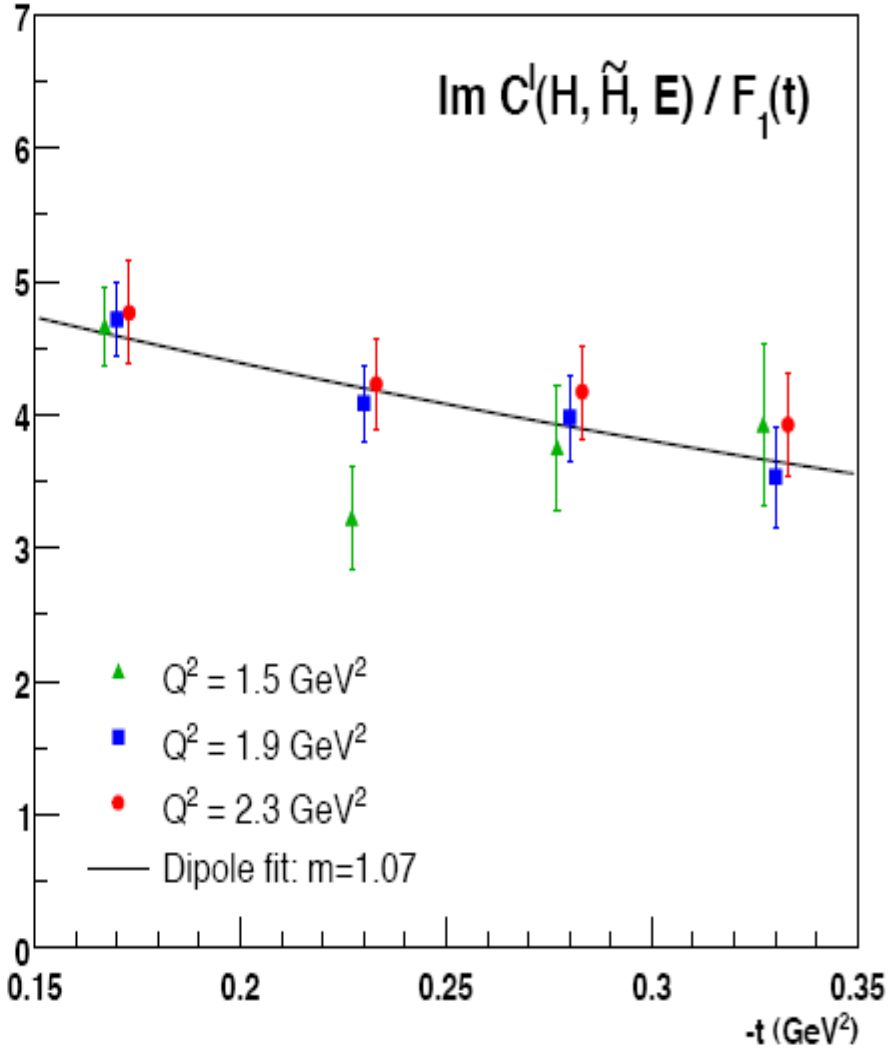


Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade

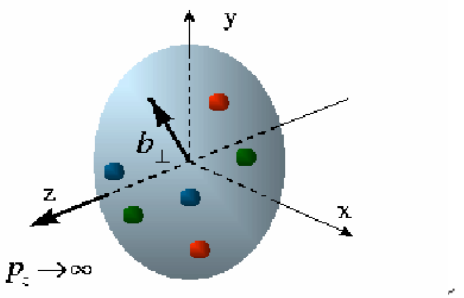


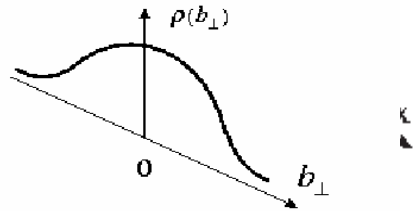
Recent Hall A Data: Suggests in Scaling Regime Even at Relatively Low Q^2

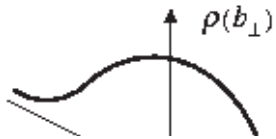




The Next Generation of Proton Structure Experiments

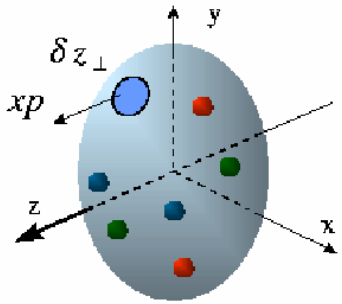


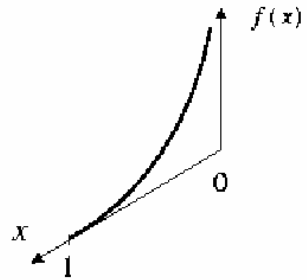




Elastic Scattering

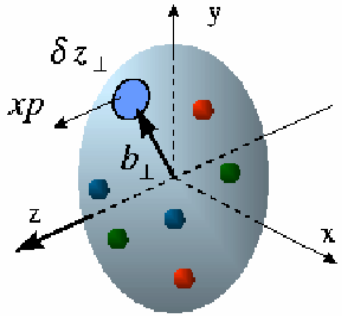
transverse quark distribution in Coordinate space

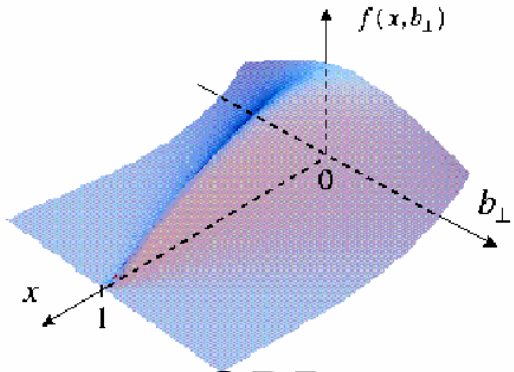




DIS

longitudinal quark distribution in momentum space





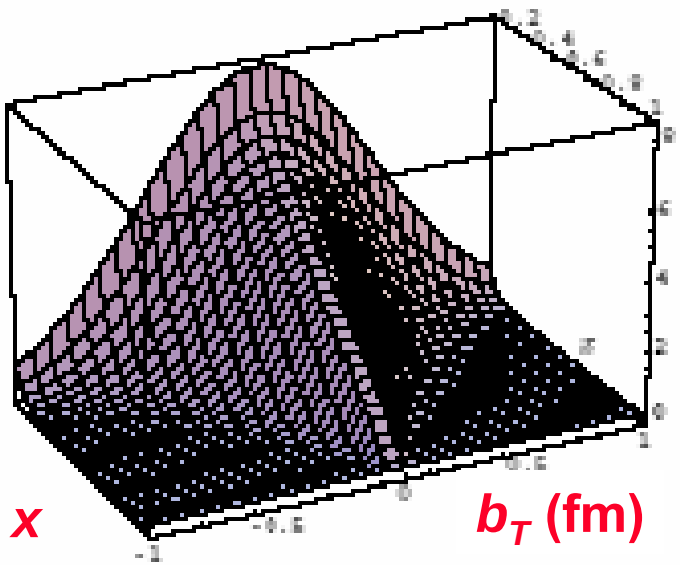
GPDs

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

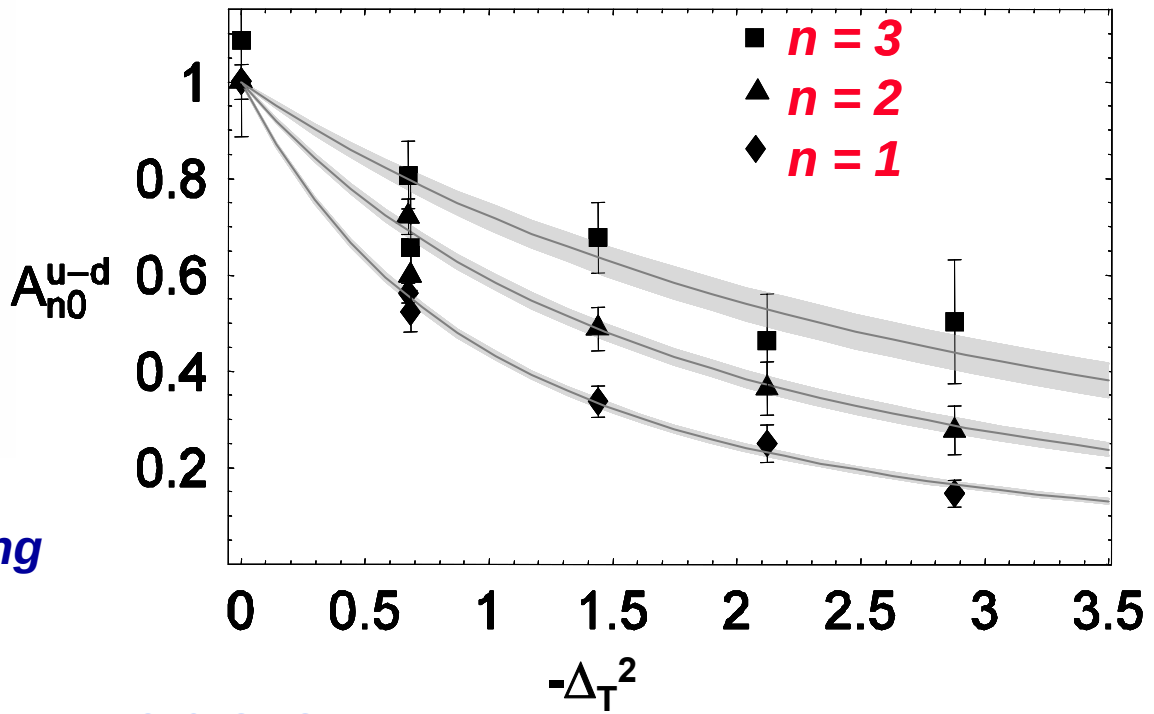
Moments of Flavor-NS PDFs and GPDs - I

- **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 → 1

Burkardt

From: LHPC & SESAM

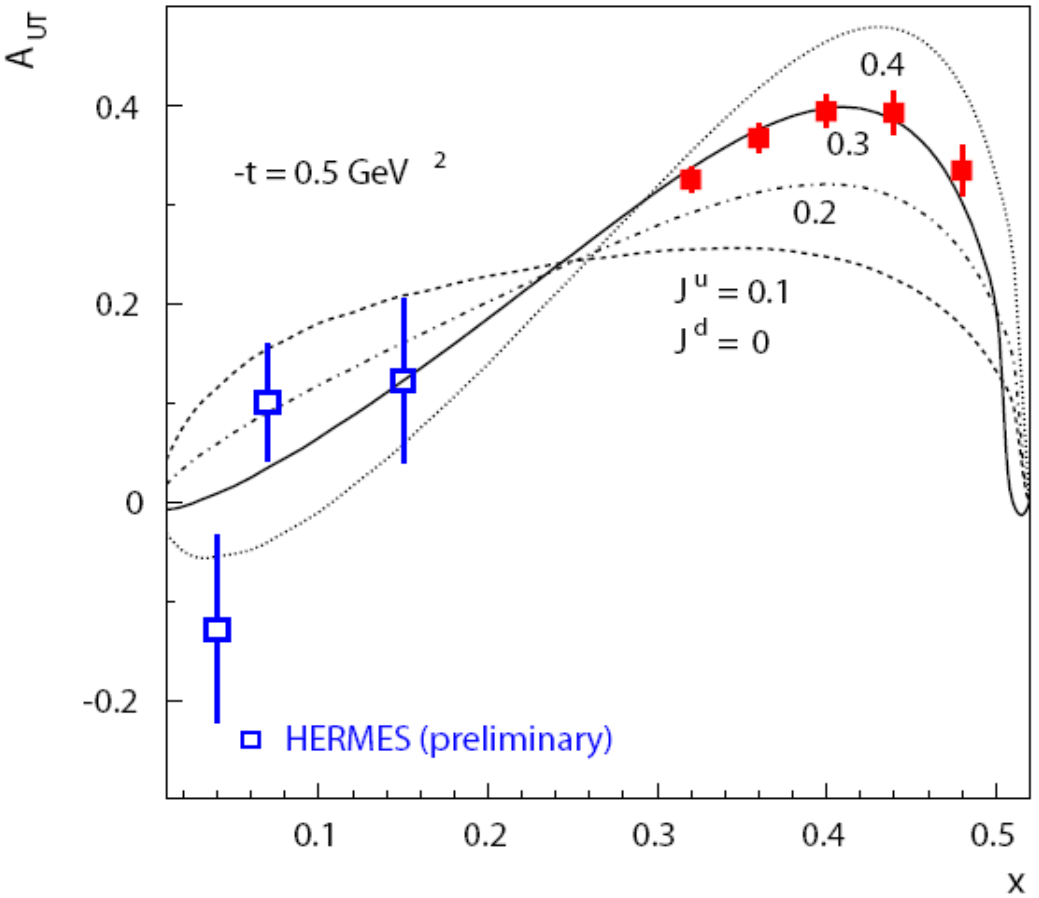
At 12 GeV: Exclusive ρ^0 with transverse target

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

ρ^0

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

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



$Q^2 = 5\mathrm{GeV}^2$

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

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

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- **Exotic Meson Spectroscopy:**
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- Tests of Physics Beyond the Standard Model

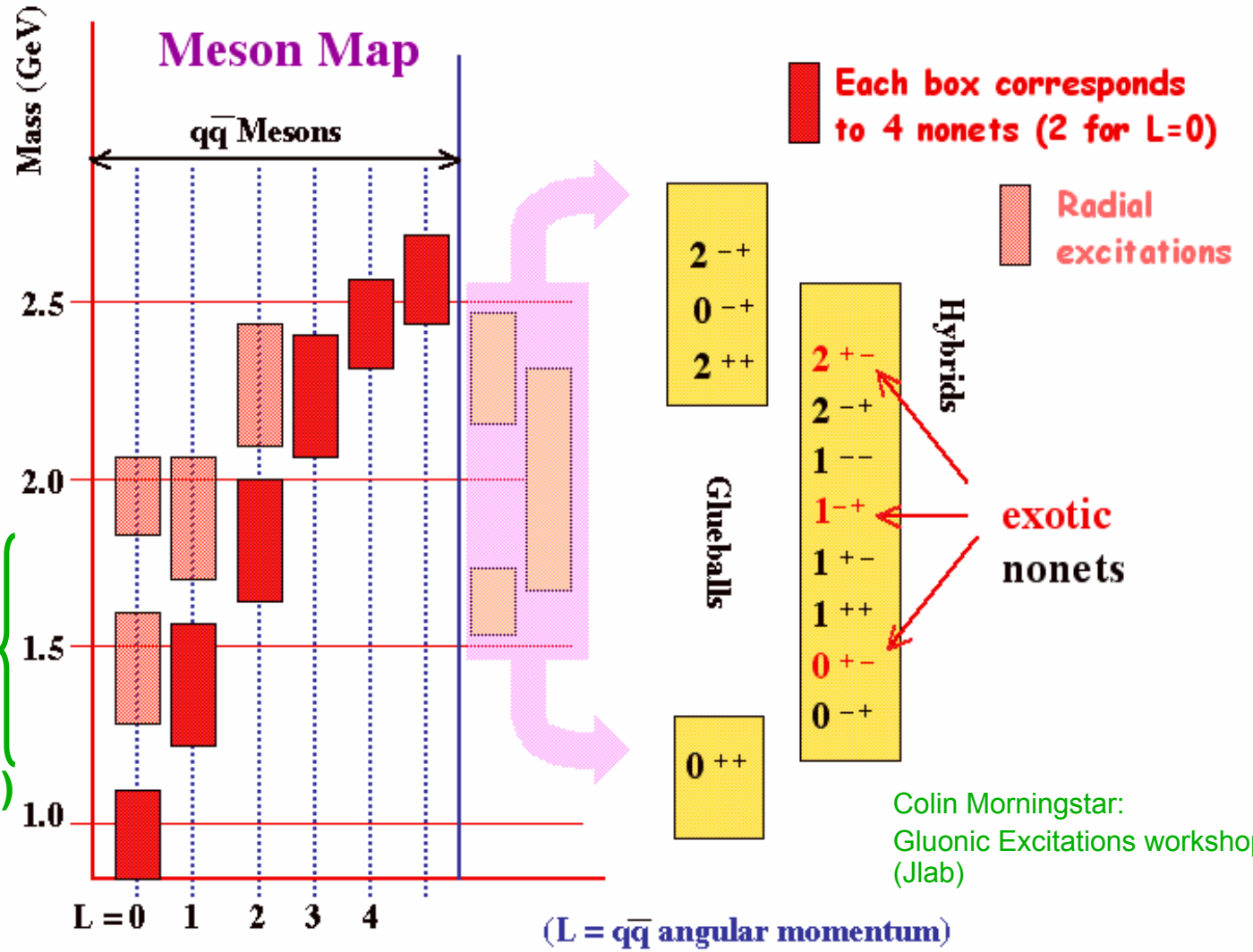
QCD: Unsolved in Nonperturbative Regime

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)

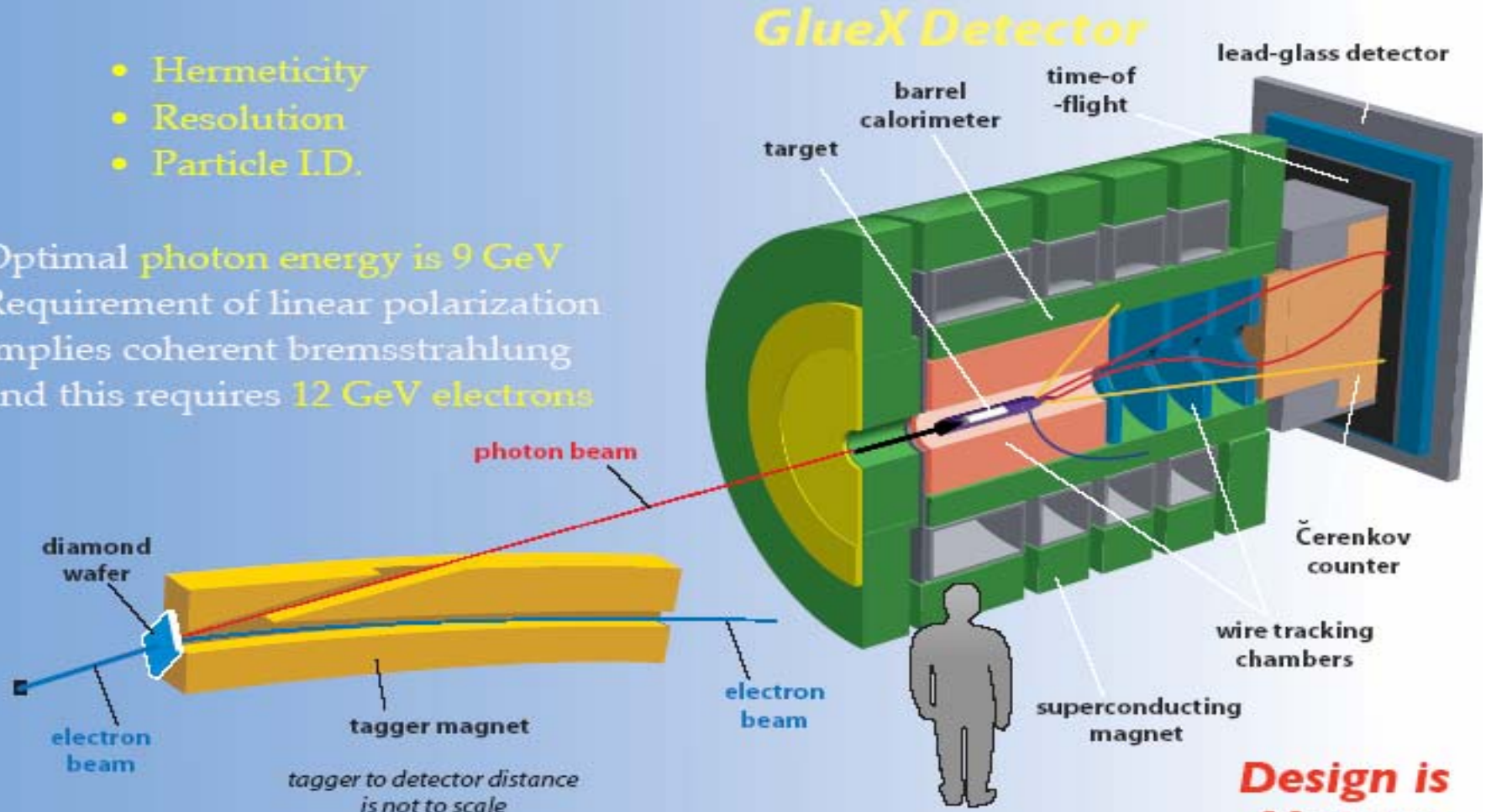
Colin Morningstar:
Gluonic Excitations workshop, 2003 (Jlab)

Gluex: Hall D

Optimized for doing amplitude analyses

- Hermeticity
- Resolution
- Particle I.D.

Optimal photon energy is 9 GeV
Requirement of linear polarization implies coherent bremsstrahlung and this requires 12 GeV electrons

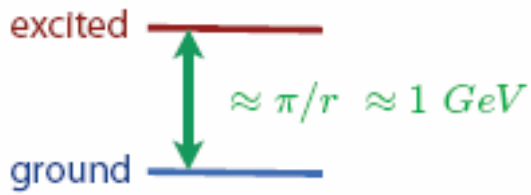


Design is Mature

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}

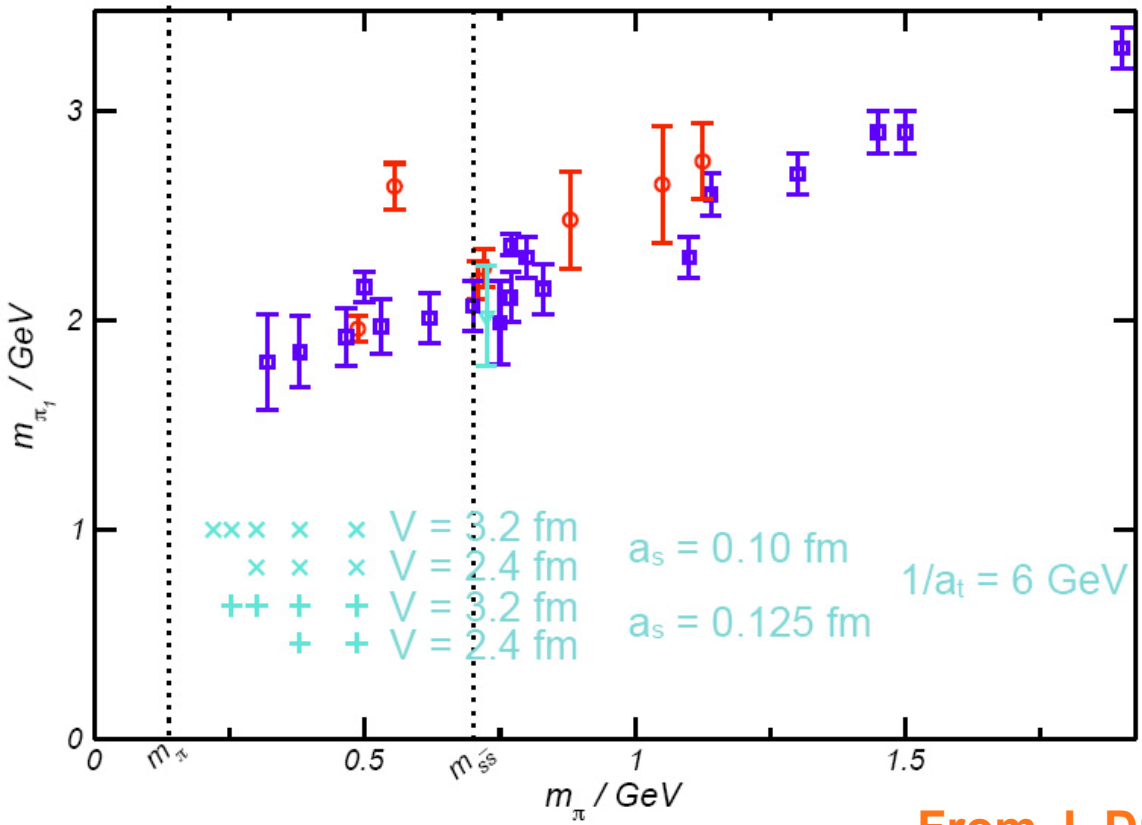
Multiplet	J^{PC}	Mass (GeV/c^2)
π_1	1^{-+}	1.9 ± 0.2
b_2	2^{+-}	2.0 ± 0.11
b_0	0^{+-}	2.3 ± 0.6

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

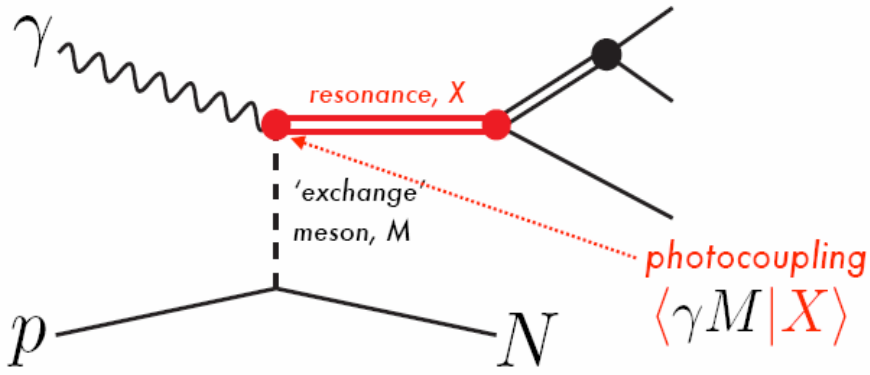
—- ideal for spectroscopy

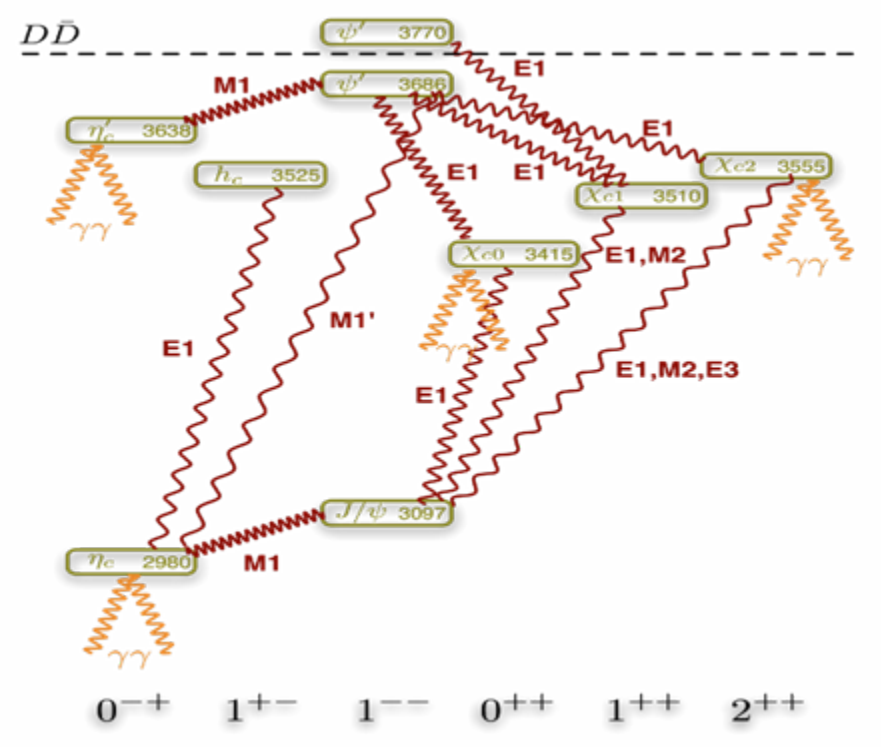


From J. Dudek

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

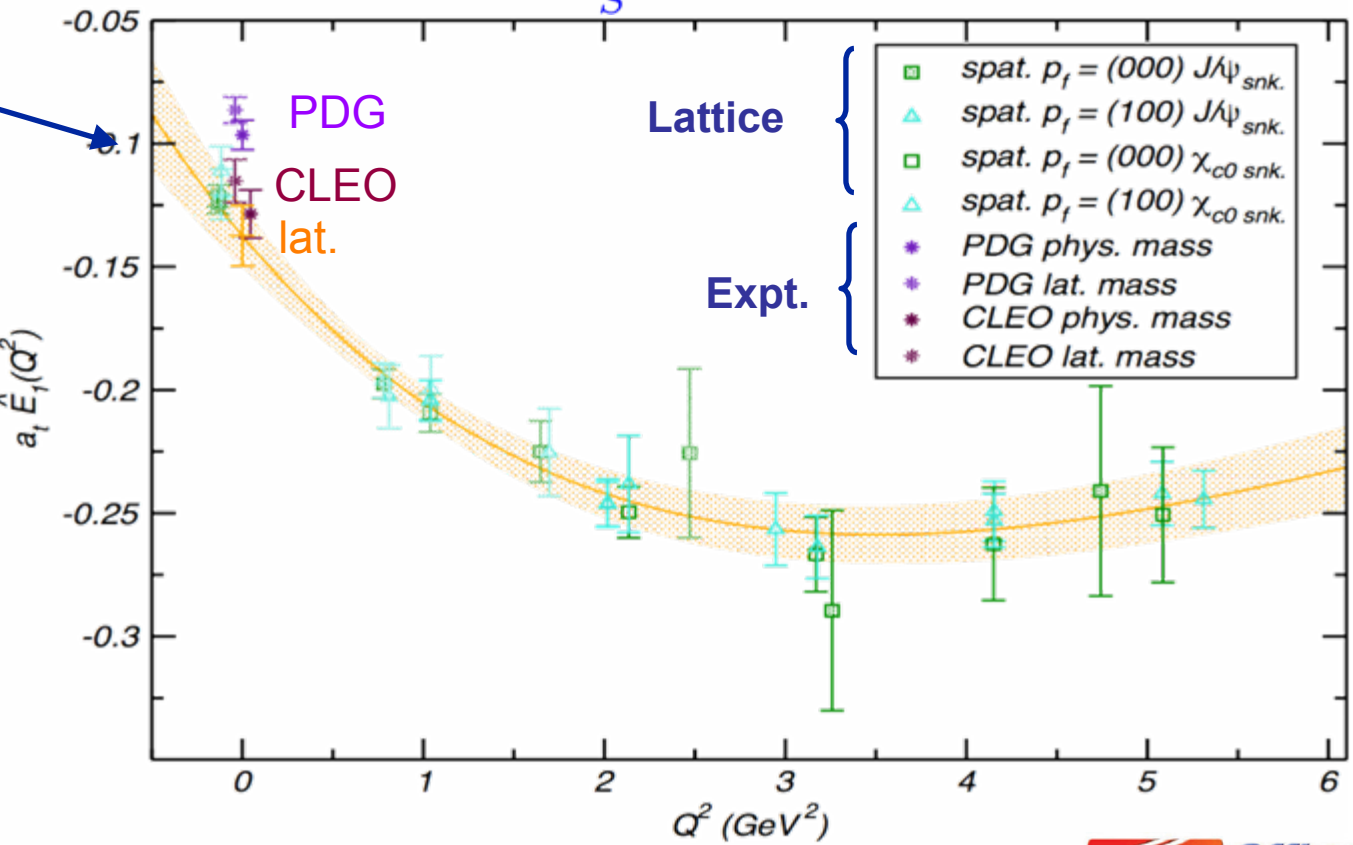
Photocouplings

Dudek, Edwards, Richards, PRD73, 074507

- Recent study of transitions between conventional mesons, e.g. **S → γ V**

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

Not used in the fit



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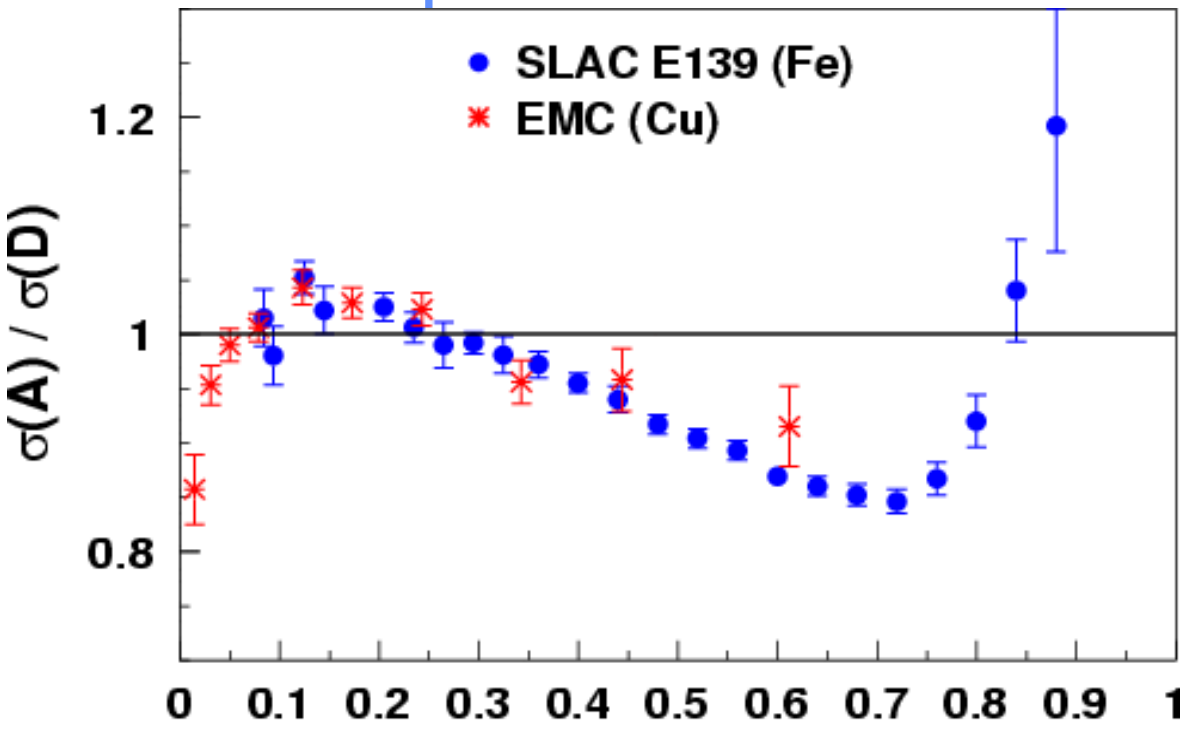
The EMC Effect: Nuclear PDFs

- 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)

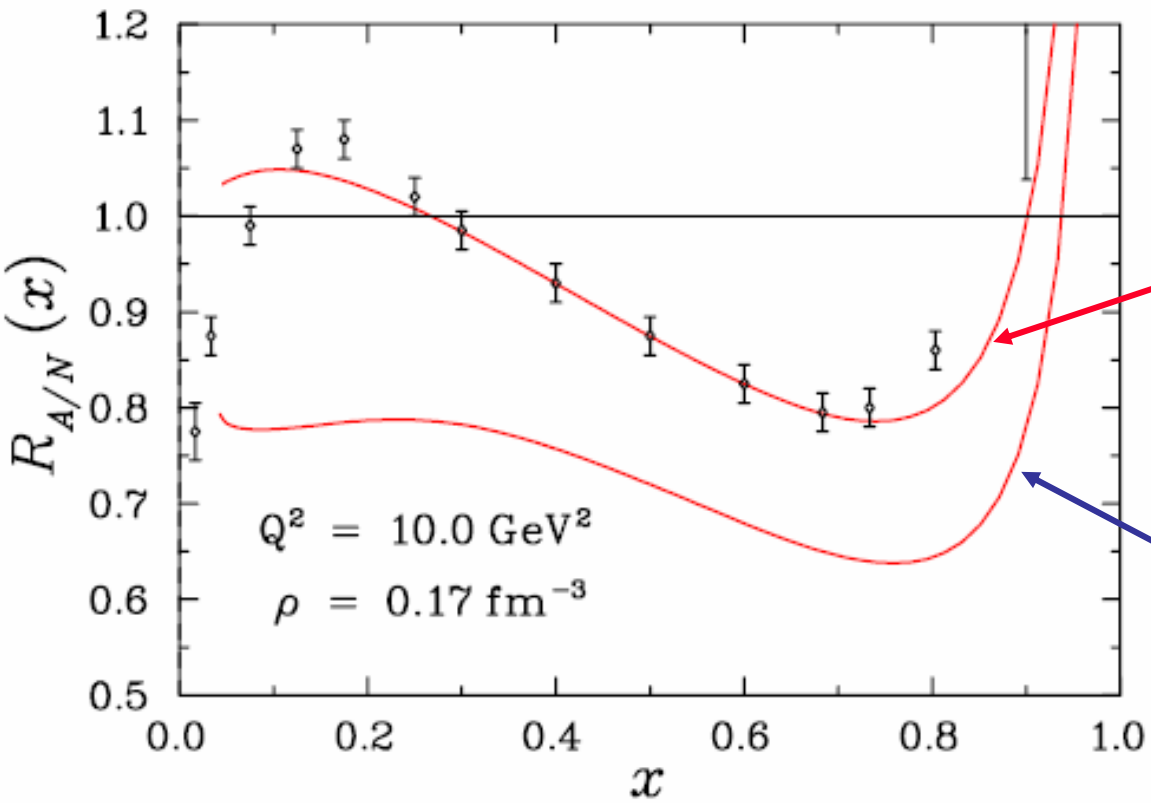
J. Gomez *et al.*, Phys. Rev. D49, 4348 (1994)

$g_1(A)$ – "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



$$\frac{F_{2A}}{F_{2D}}$$

$$\frac{g_{1A}}{g_{1p}}$$

Recent Calculations for Finite Nuclei

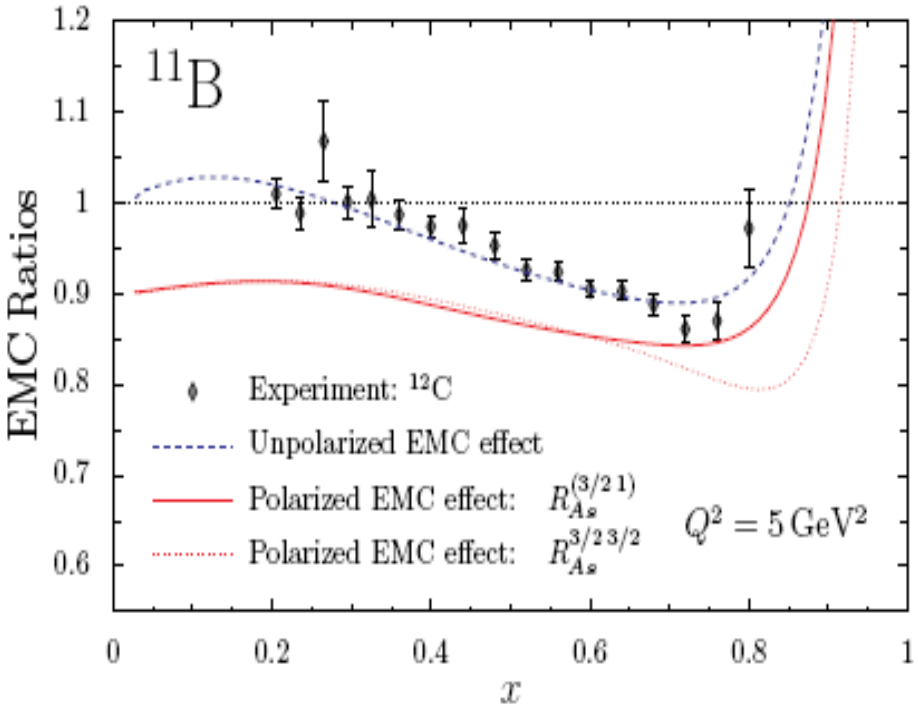


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

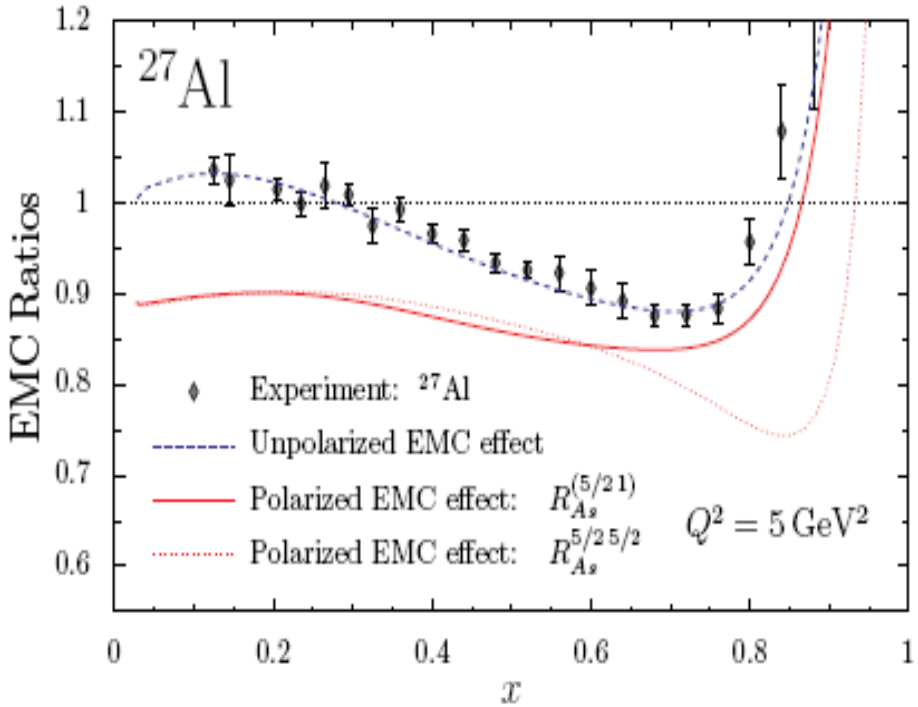


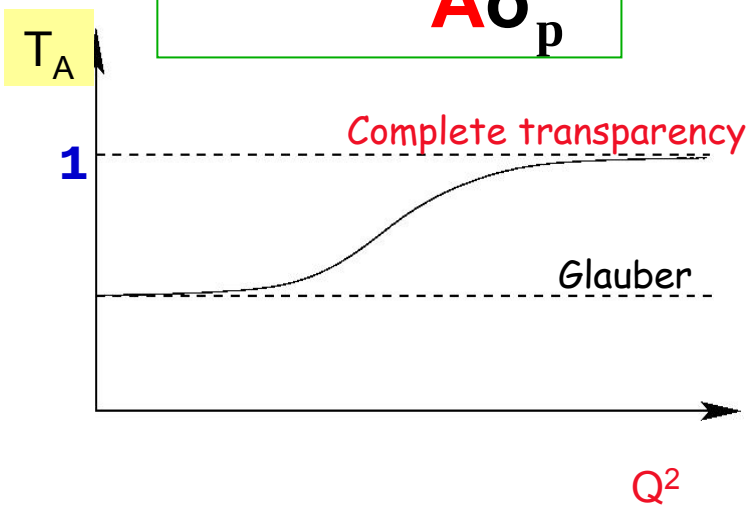
FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

Cloet, Bentz, Thomas, nucl-th/0605061

CLAS

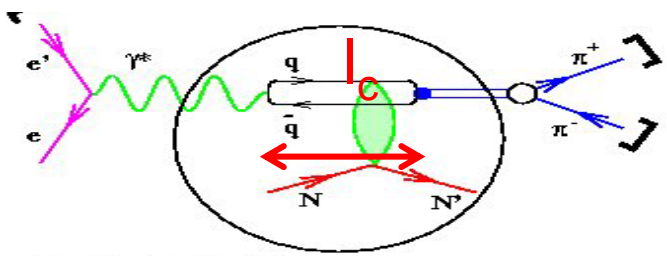
Color Transparency

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



Measure at small coherence length

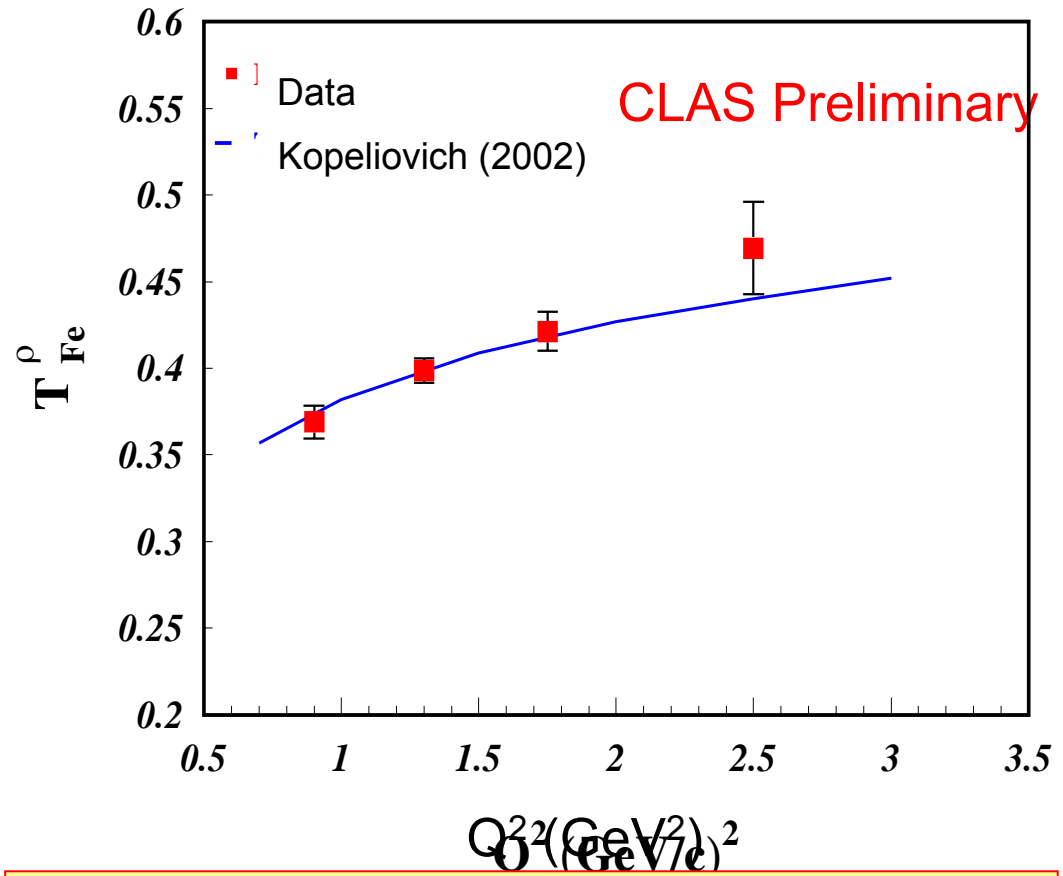
$\ell_c = 2\nu/(M^2 + Q^2)$, i.e. high Q^2, small ν



T_A.vs.Q^2 corrected with acceptance, radiative and absorption effects

T_{Fe}

$e + N \rightarrow e' + N + \rho^0$

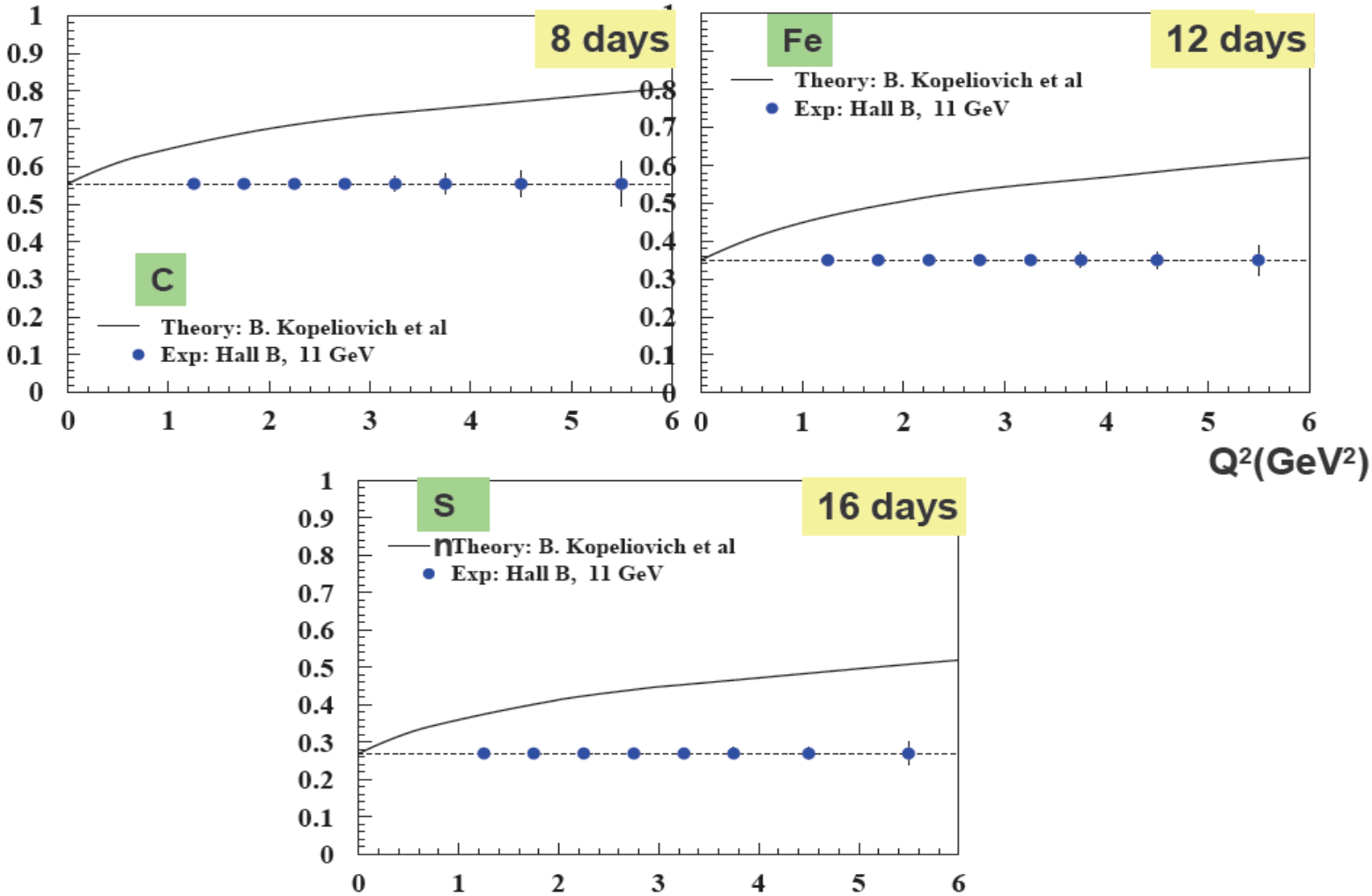


First hint of color transparency for ρ meson

K. Hafidi

CLAS12 - Projected data for 12 GeV Upgrade

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



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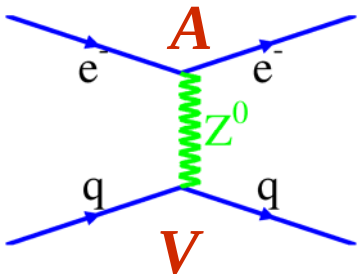
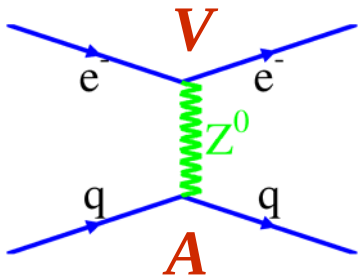
Electron-Quark Phenomenology



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



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

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

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

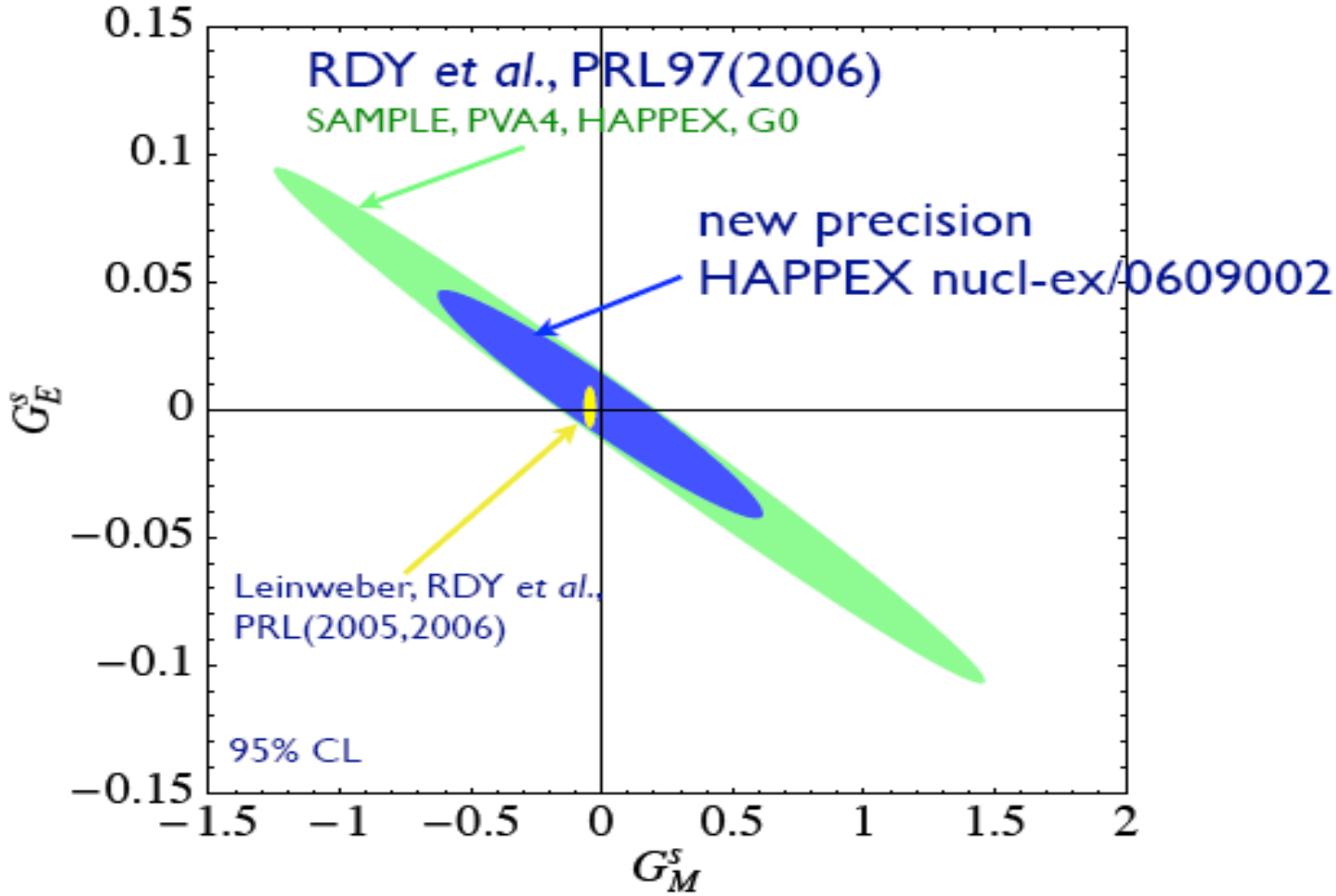
C_{2u} and C_{2d} are small and poorly known: can be accessed in PV DIS

New physics such as compositeness, new gauge bosons:

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

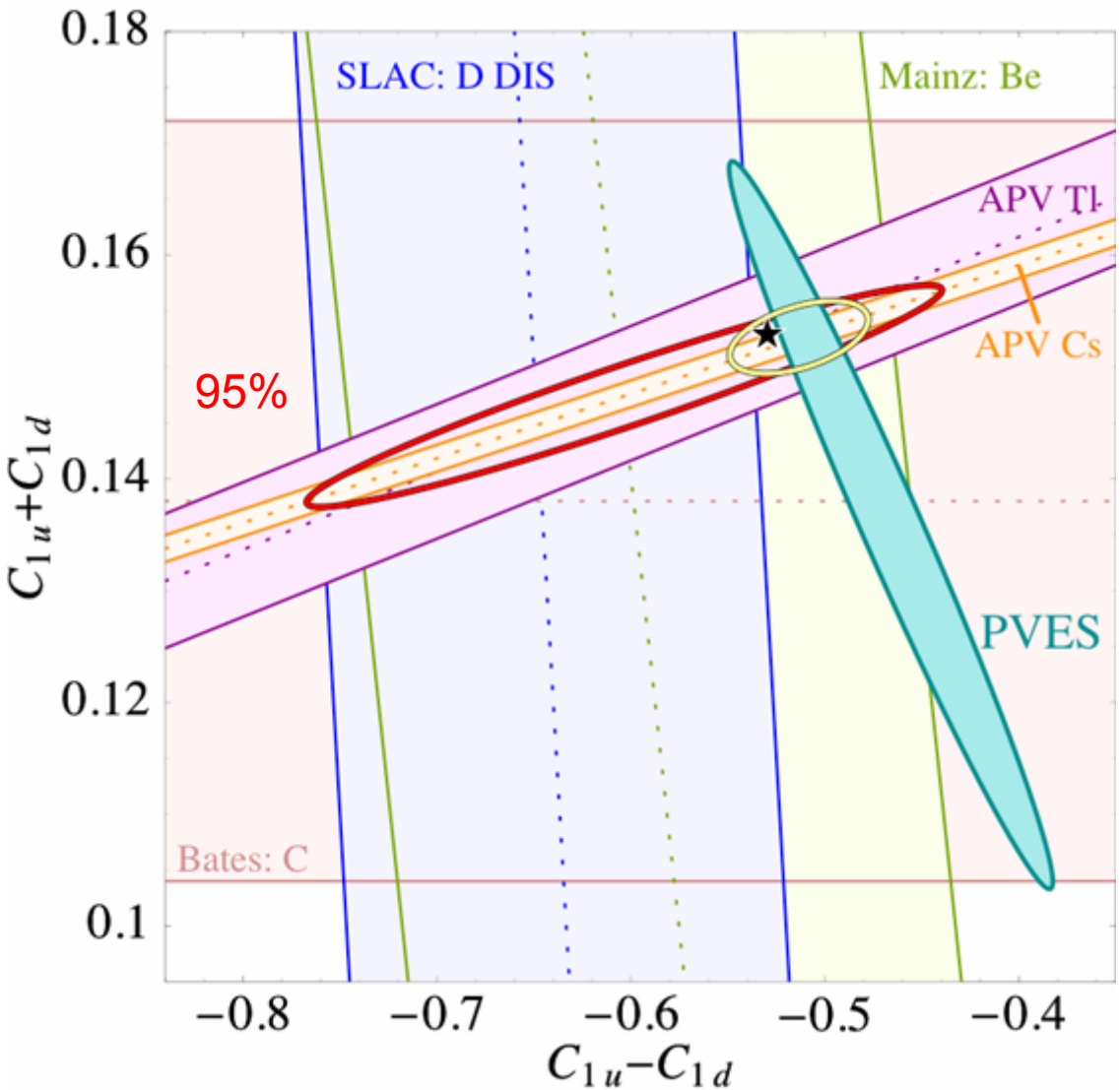
Proposed JLab upgrade experiment will permit increase in precision of measurement of $2C_{2u}$-C_{2d} by more than a factor of 20

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

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

Erler et al., PR D68 (2003)

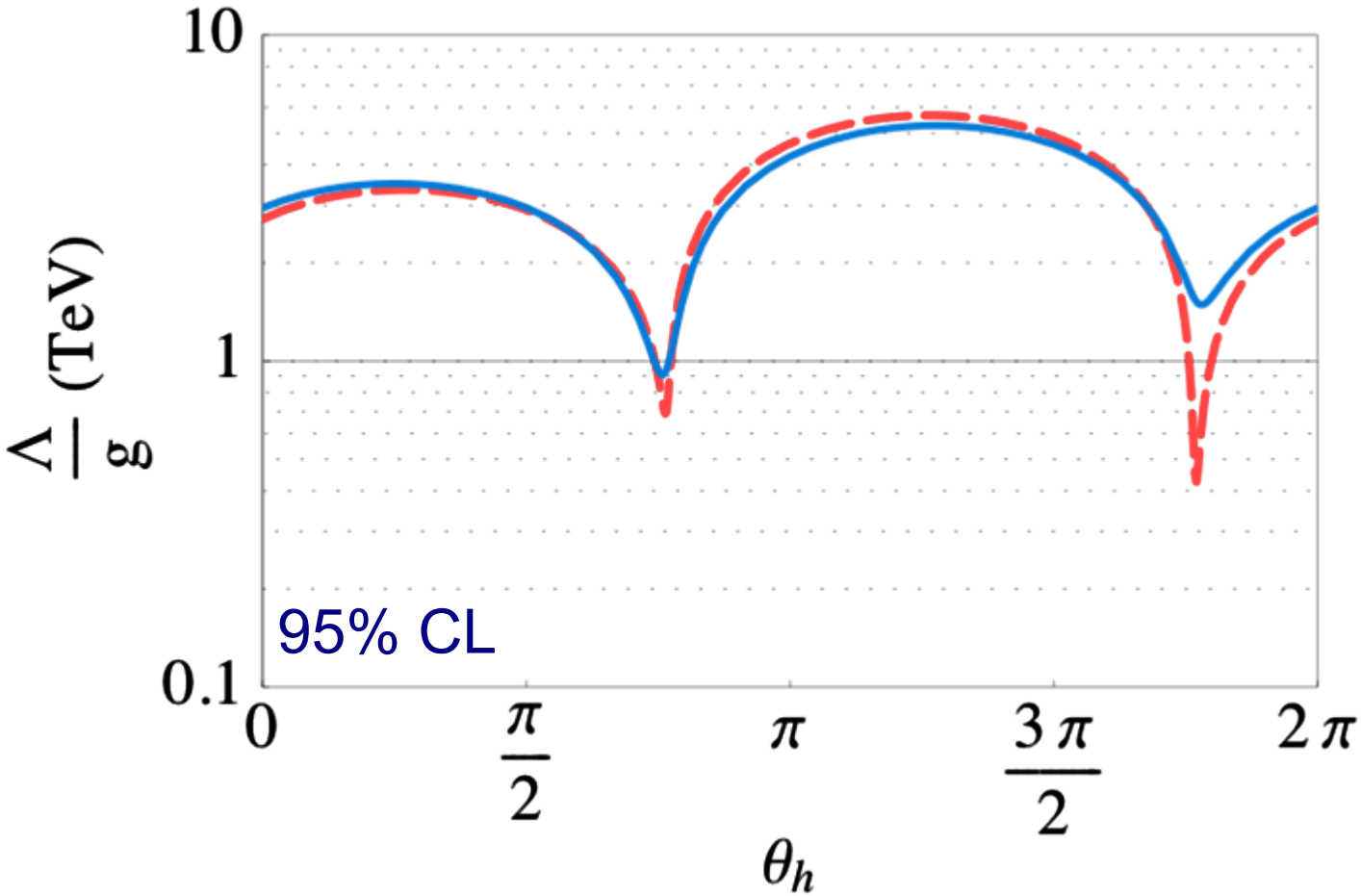
$$\mathcal{L}^{PV}_{NP} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h^q_V \bar{q}\gamma^\mu q$$

Full isospin coverage for limits on new physics!

$$h^u_V = \cos\theta_h \qquad h^d_V = \sin\theta_h$$

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

Lower bound on NP scale



with PVES

Atomic only

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:**

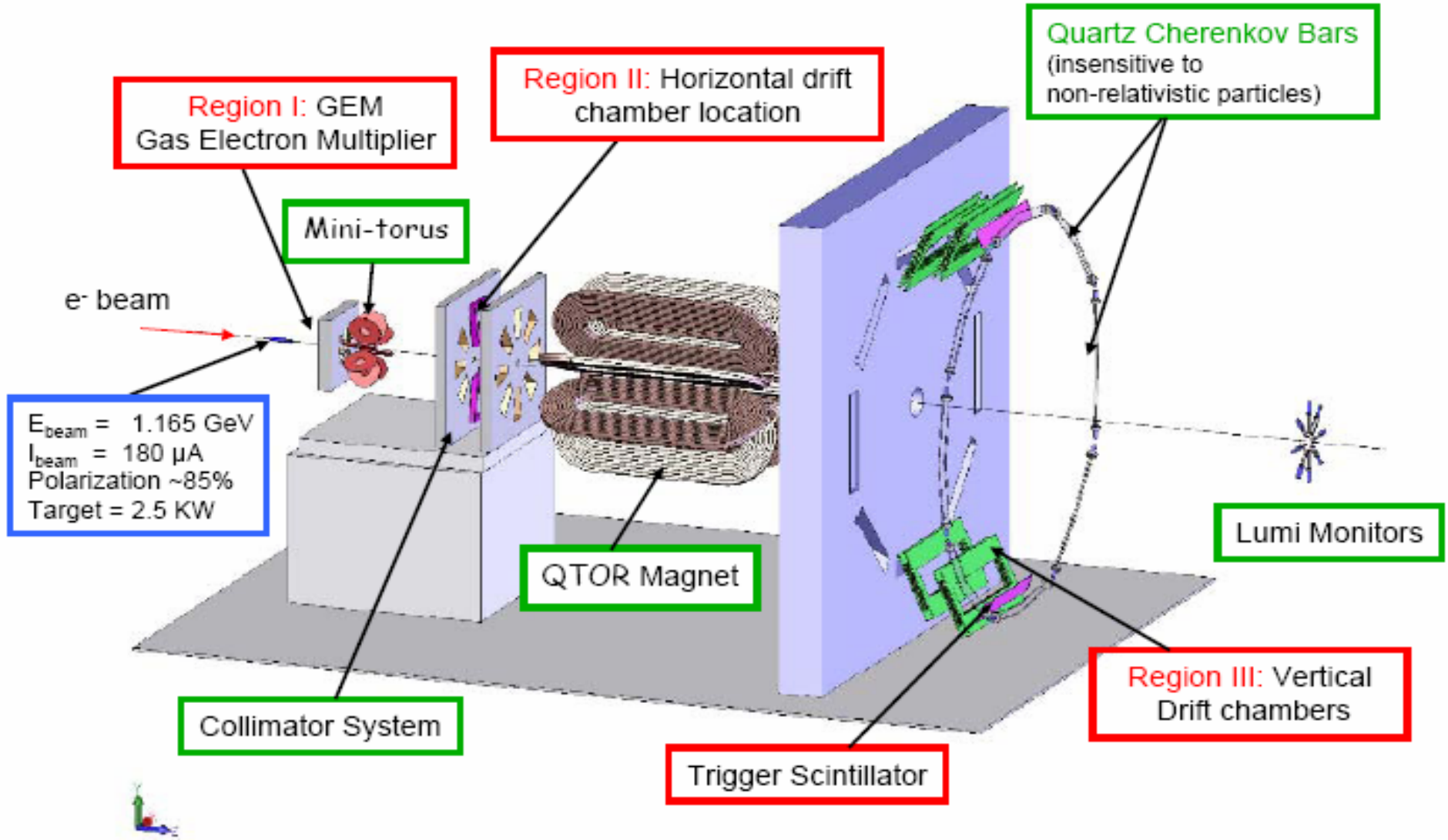
$$A_{LR} = -\frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}}\left[Q_{\text{weak}} + \beta_A \tilde{G}_A^p \sqrt{Q^2} + \beta_V Q^2 + \ldots\right]$$

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

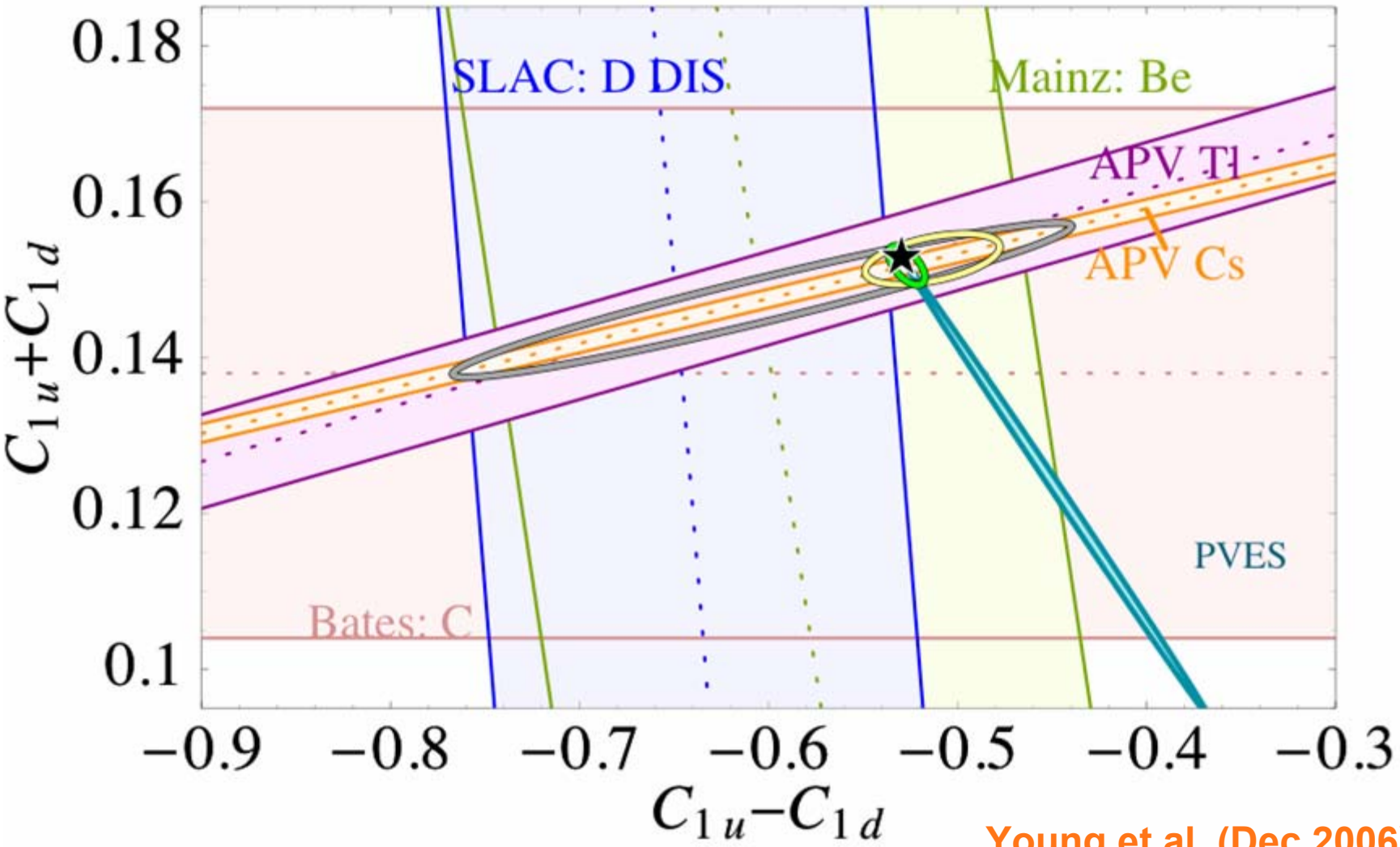
Anapole uncertainty

Strangeness uncertainty

Q_{weak} Apparatus

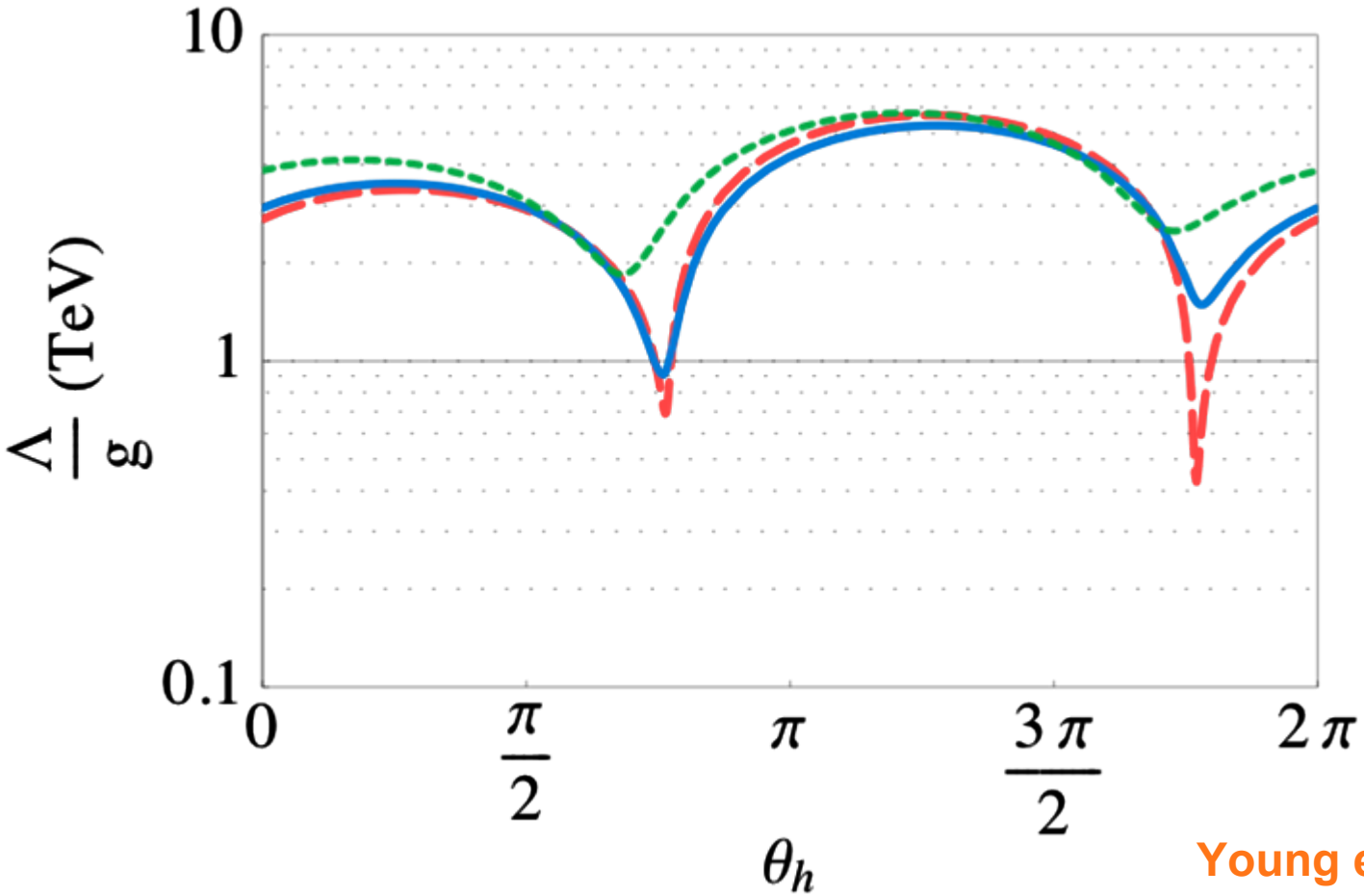


Possible Impact of Qweak



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

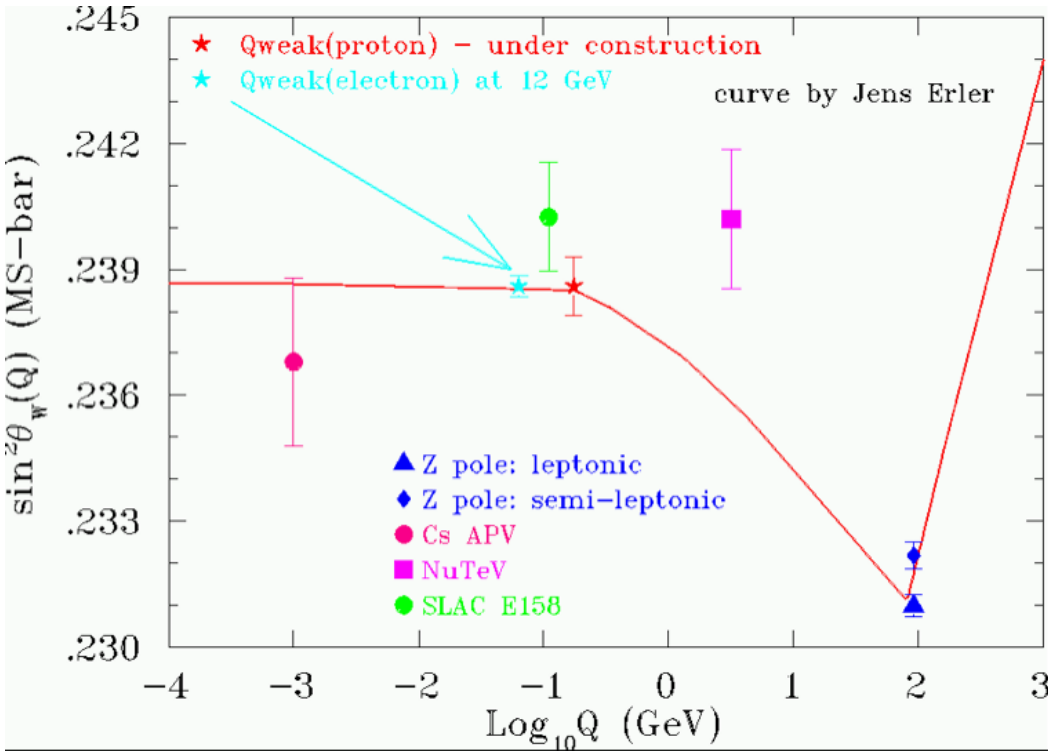
Future Möller Experiment at 12 GeV

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"

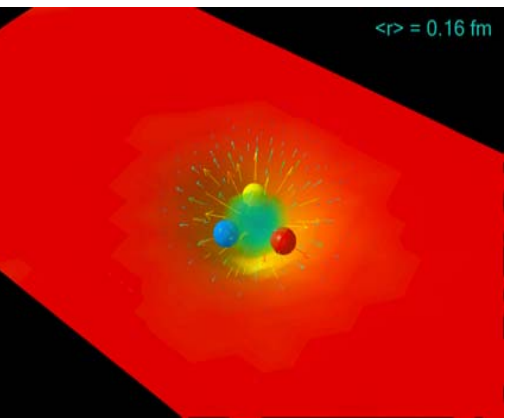


World Community in 2013 and Beyond

- 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