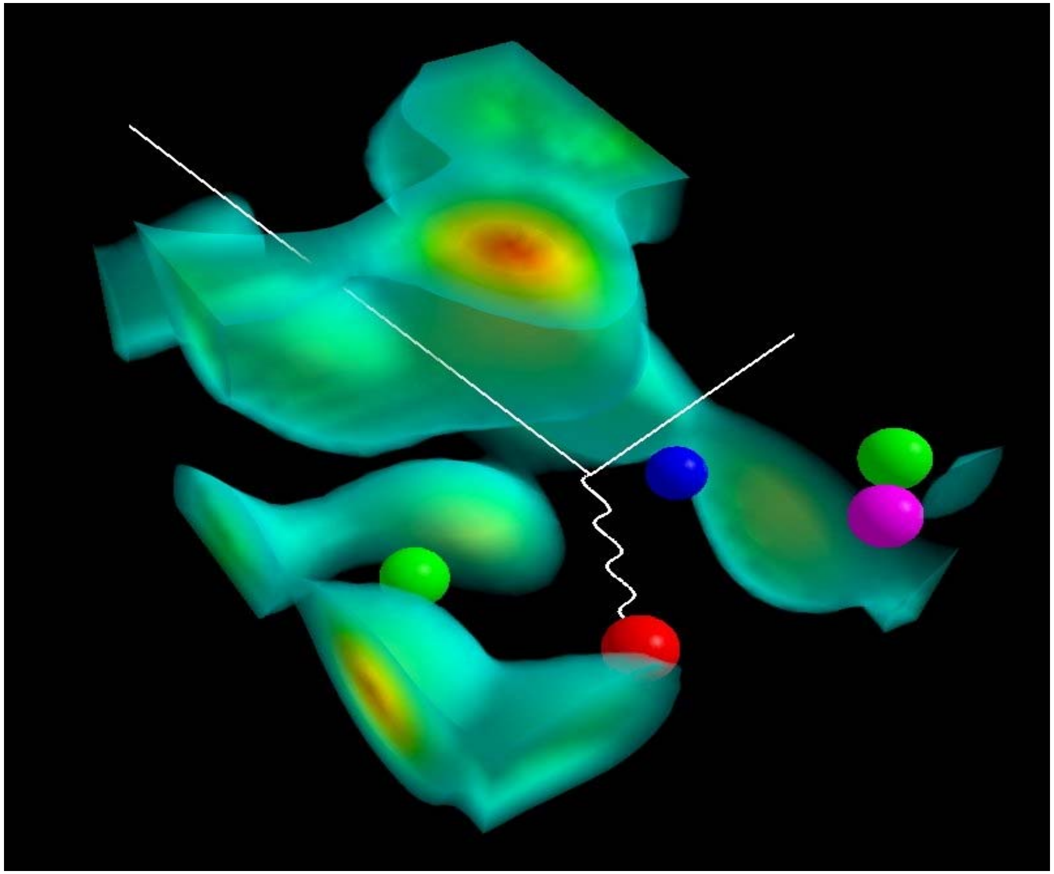
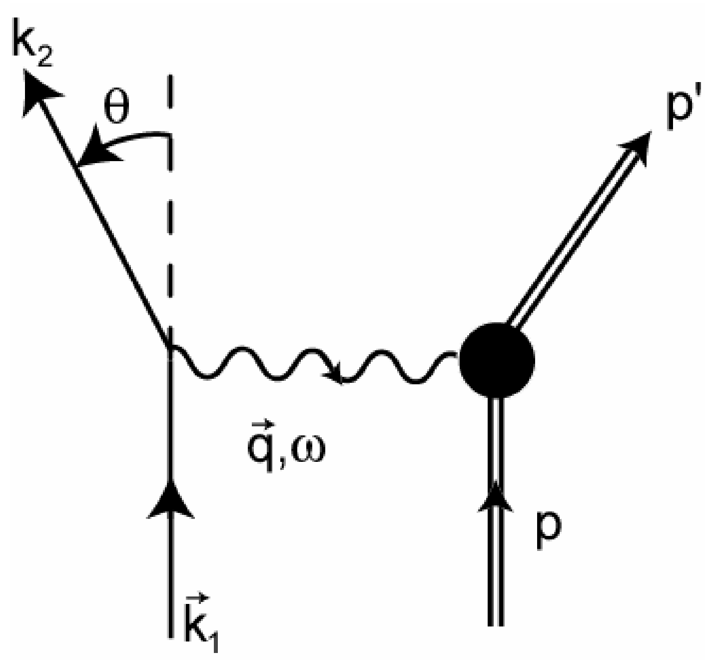
# Precise Electro-Weak Studies: An Essential Element of the World-Wide Nuclear Physics Program




**Anthony W. Thomas**


**Baryons 07 – Seoul Korea : June 12th 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:

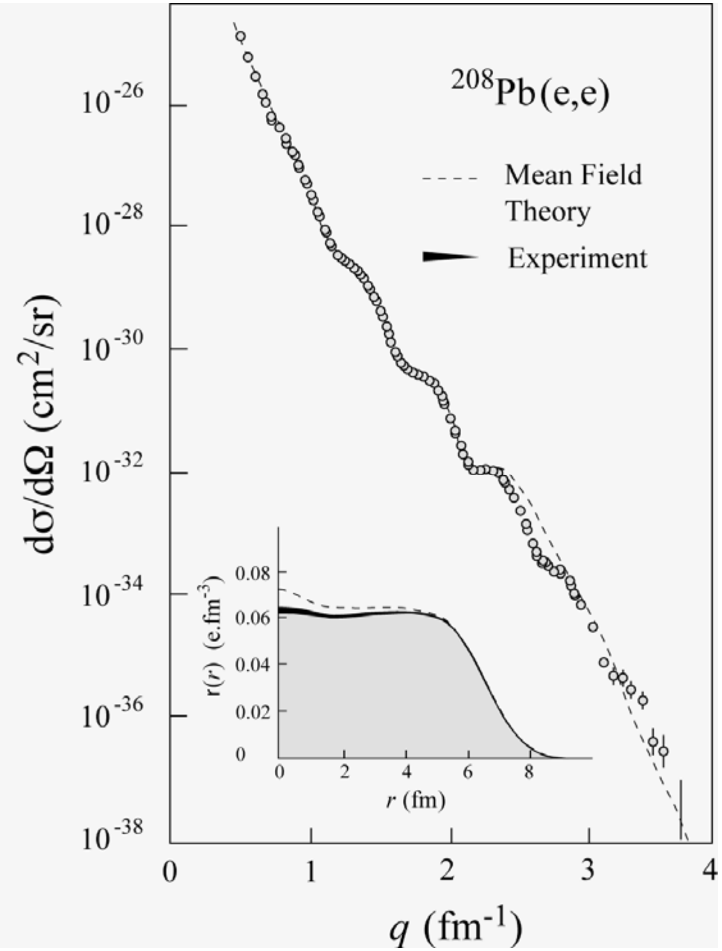
$\lambda \cong 2\pi/q$ **(1 fm ⇔ 1 GeV/c)**

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

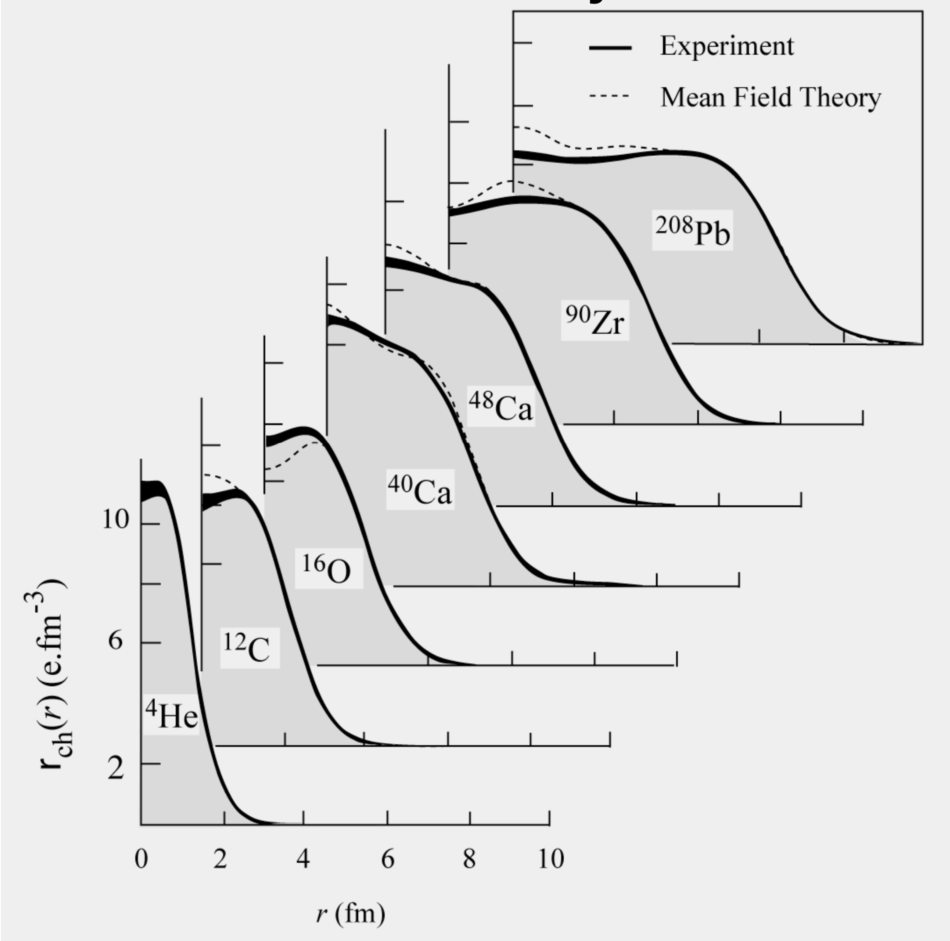
$Q^2 = -q^2 =$ 4-Momentum Transfer

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

# (e,e) ⇒ Nuclear Charge Distributions




## From Stanford to Saclay and Nikhef

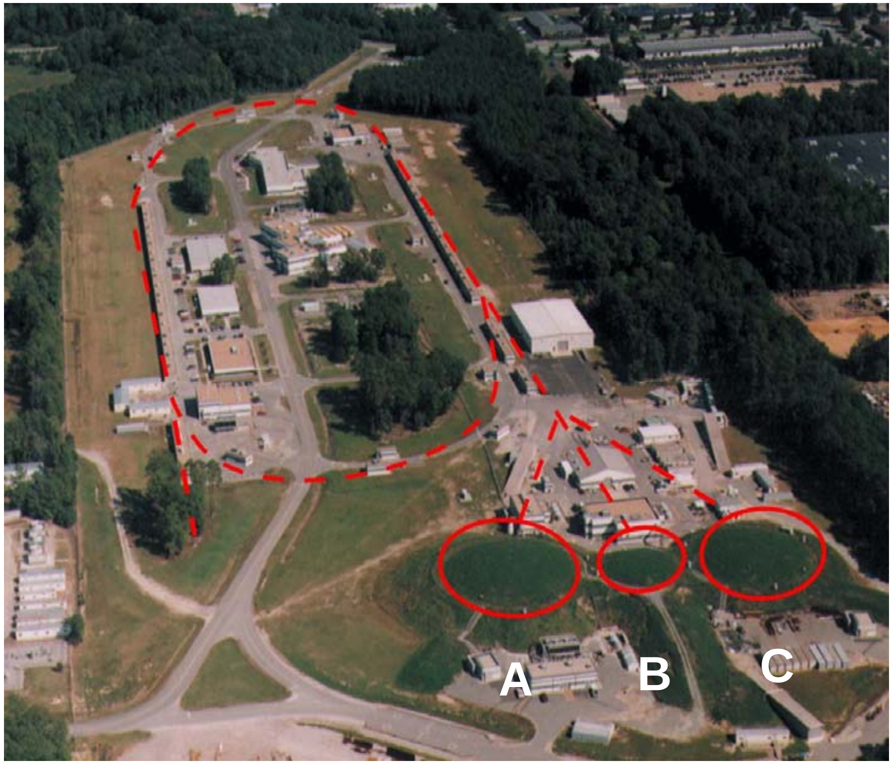



**Model-independent analysis ⇒ accurate nuclear charge distributions**

# Jefferson Lab Today

**2000 member international user community engaged in exploring quark-gluon structure of matter**

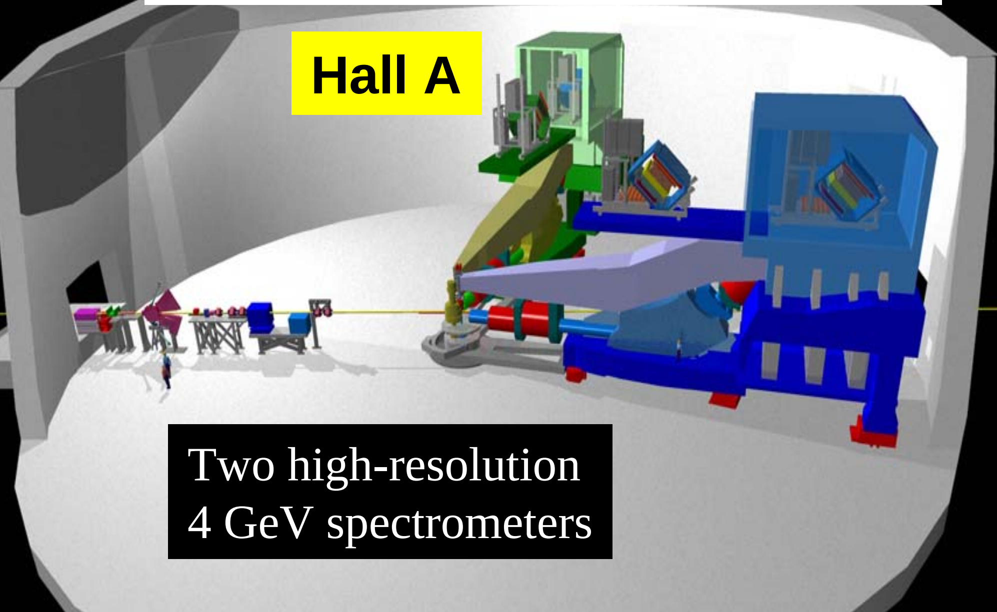
**Superconducting accelerator provides 100% duty factor beams of unprecedented quality, with energies to 6 GeV**

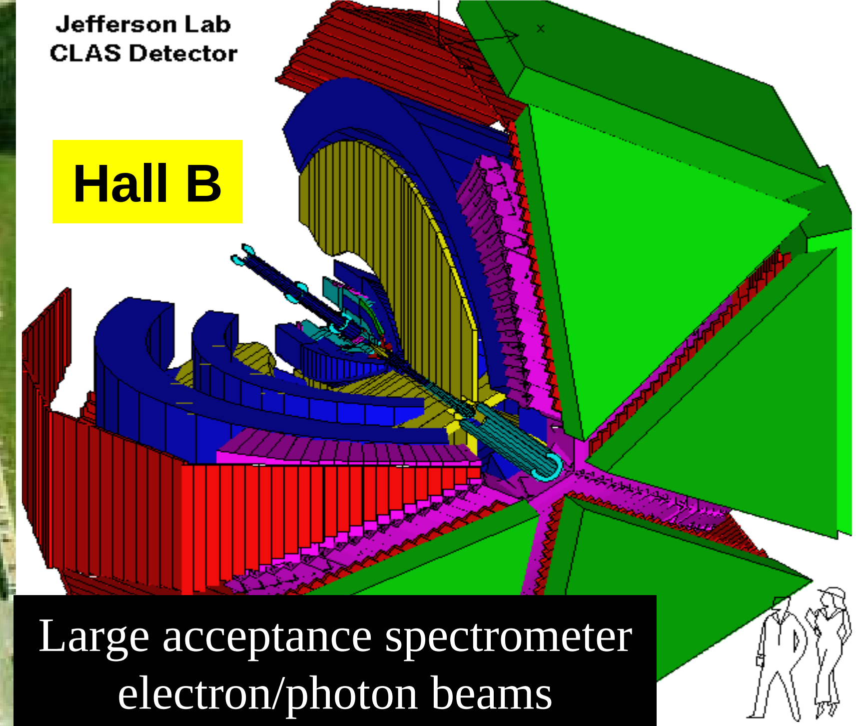


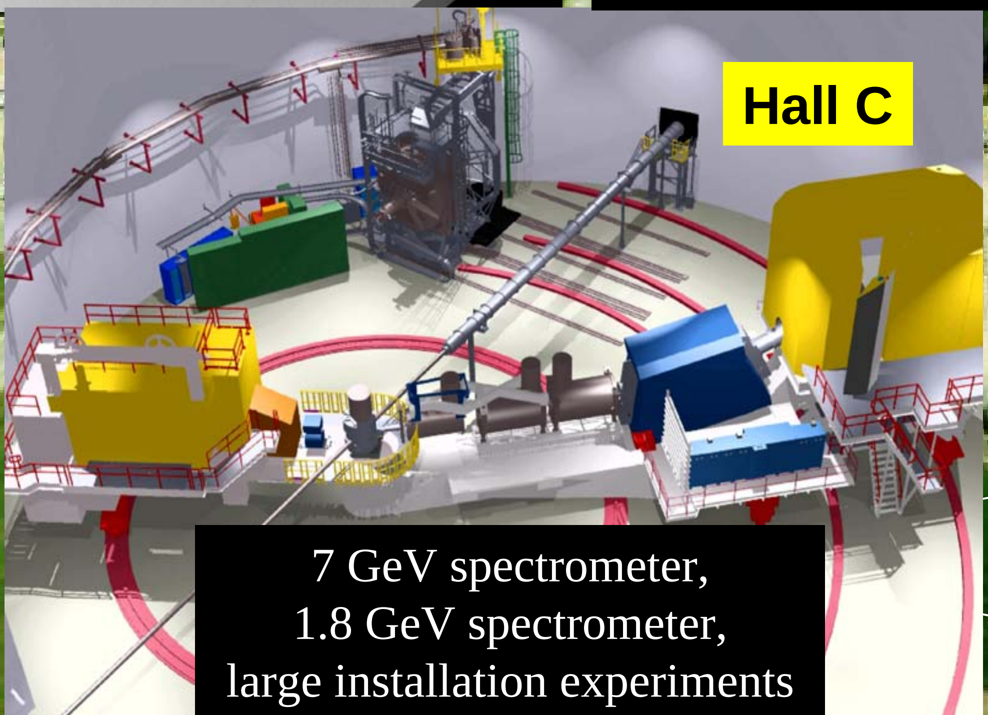

**CEBAF's innovative design allows delivery of beam with unique properties to three experimental halls simultaneously**

**Each of the three halls offers complementary experimental capabilities**

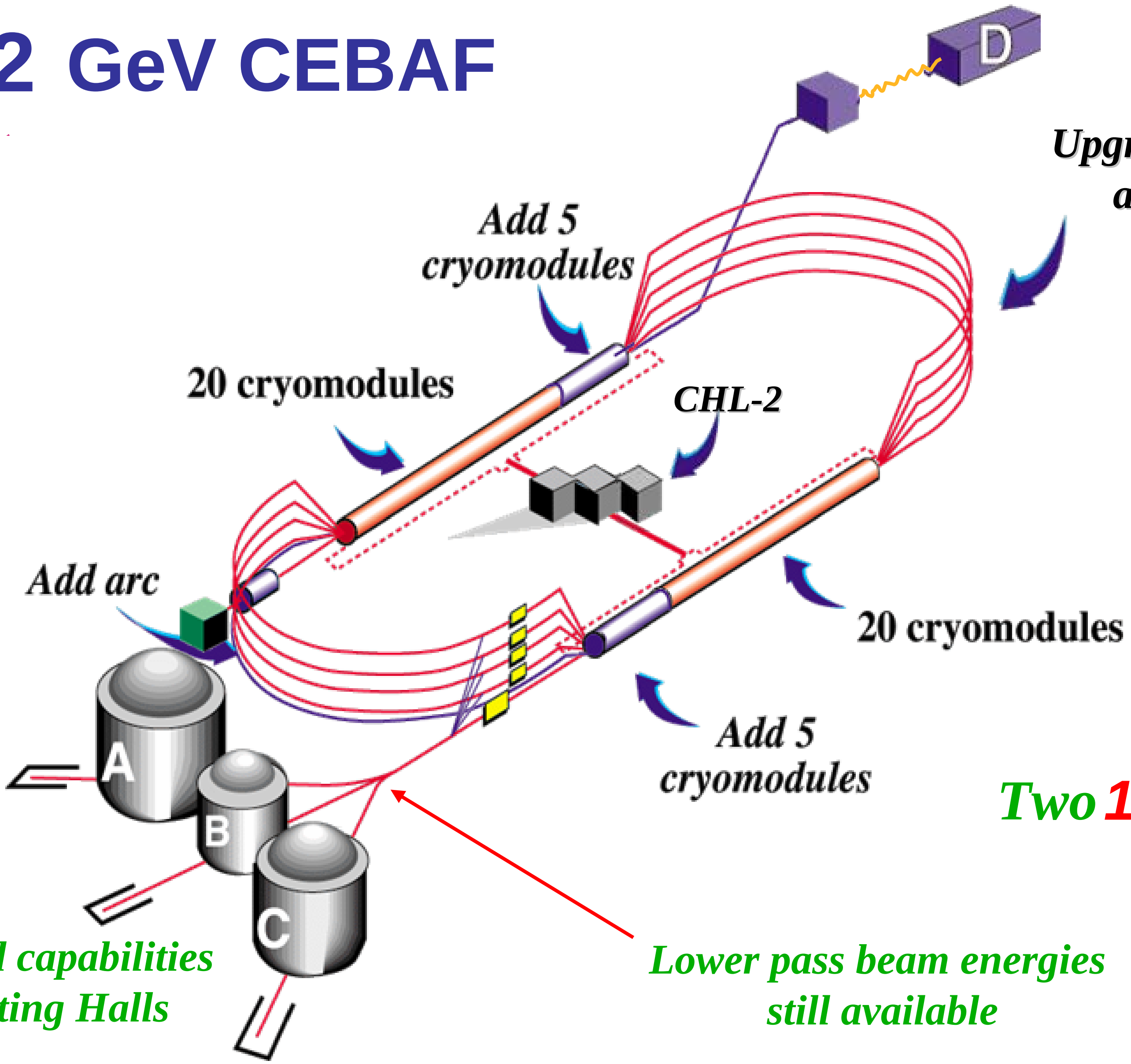
# Jefferson Lab Today




# 12 GeV CEBAF

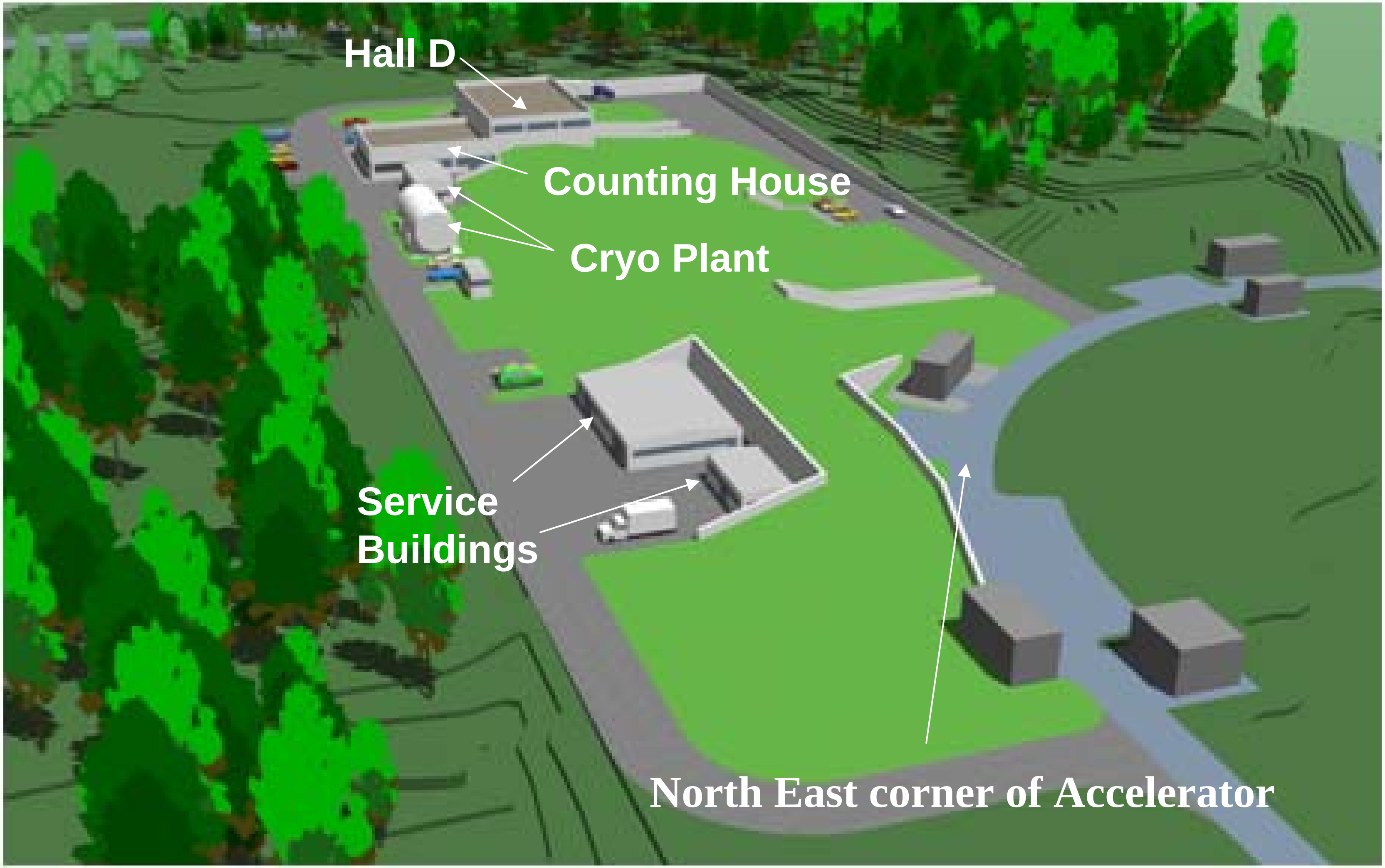



*Two **1.1** GV linacs*

*Enhanced capabilities in existing Halls*

*Lower pass beam energies still available*

# Architect's Rendering of Hall D Complex



# NSAC: LRP Recommendations – Galveston May 2007

- **We recommend the completion of the 12 GeV Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.**
- **We recommend the construction of the Facility for Rare Isotope Beams, FRIB, a world-leading facility for the study of nuclear structure, reactions and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.**
- **We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet unseen violations of time-reversal symmetry, and other key ingredients of the new standard model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to US leadership in core aspects of this initiative.**
- **The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.**

# 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

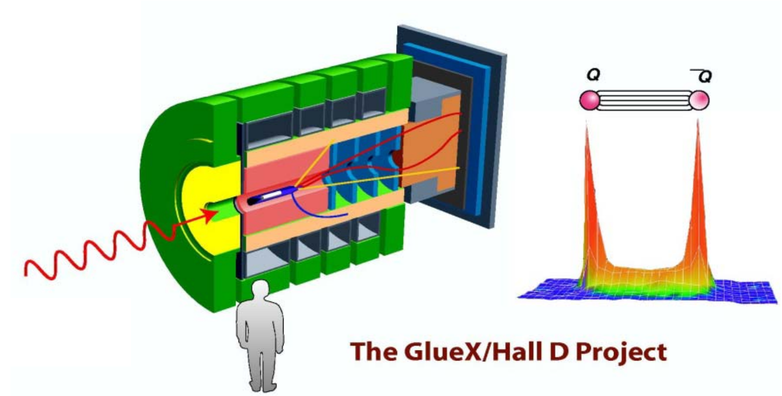
  - Determination of the quark angular momentum

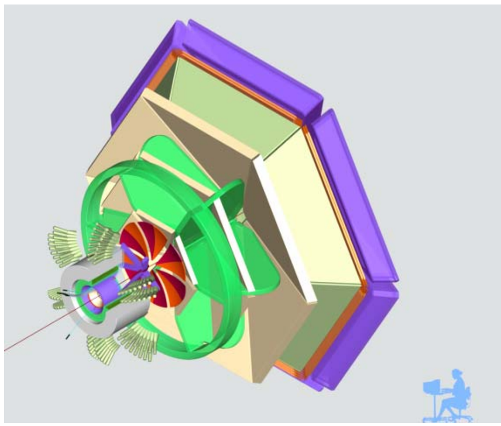
# Highlights of the 12 GeV Program….2

- **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**

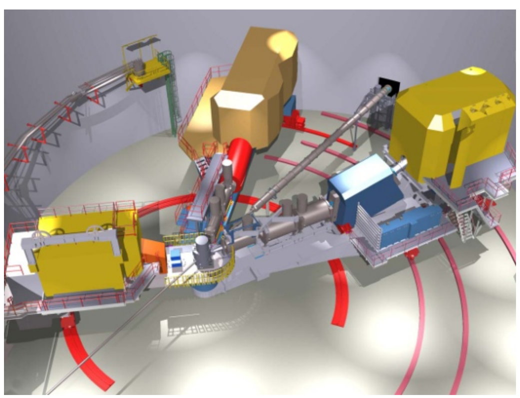
# 12 GeV Capabilities

**Hall D – exploring origin of confinement by studying exotic mesons**

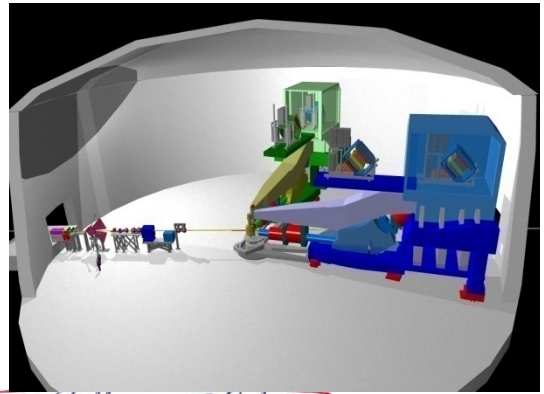


**Hall B – understanding nucleon structure via generalized parton distributions**

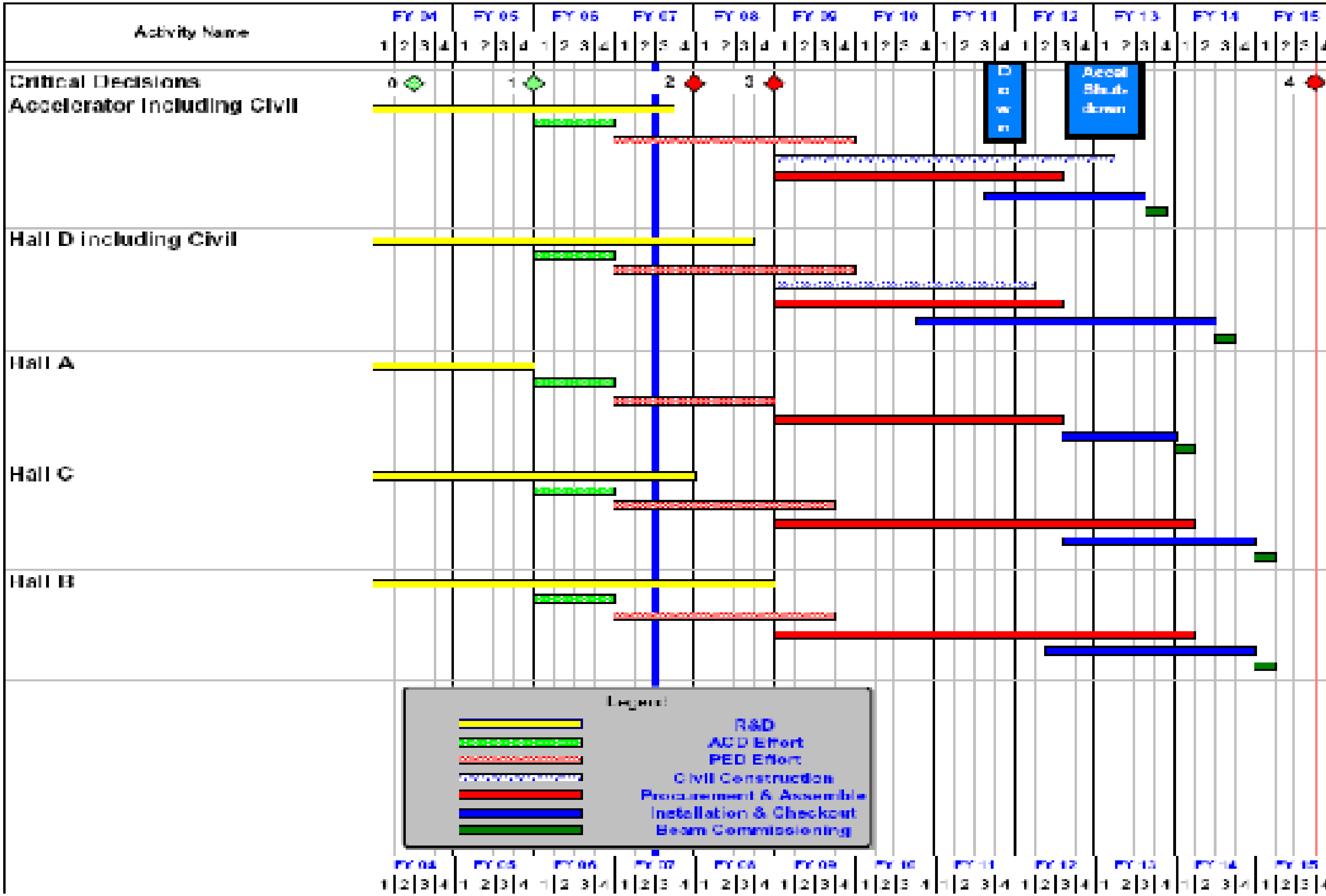


**Hall C – precision determination of valence quark properties in nucleons and nuclei**



**Hall A – major installation experiments: symmetry tests, short range correlations, form factors, hyper-nuclear physics….**

# 12 GeV Schedule

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Current Schedule

# CD-2 → September '07

- **December & January: DOE Project Status Review**
  - **"The 12 GeV Upgrade Project is on track in their preparations and readiness for the SC IPR, OECM EIR and September 2007 CD-2 approval."**
- **June 26-28: Critical Decision 2 Review, stage I**
  - **SC Independent Project Review (IPR): conducted by Dan Lehman (DOE SC Office of Project Assessment)**
- **Aug 6-10 (tentative): Critical Decision 2 Review, stage II**
  - **External Independent Review (EIR): conducted by DOE Office of Engineering Construction Management (OECM)**

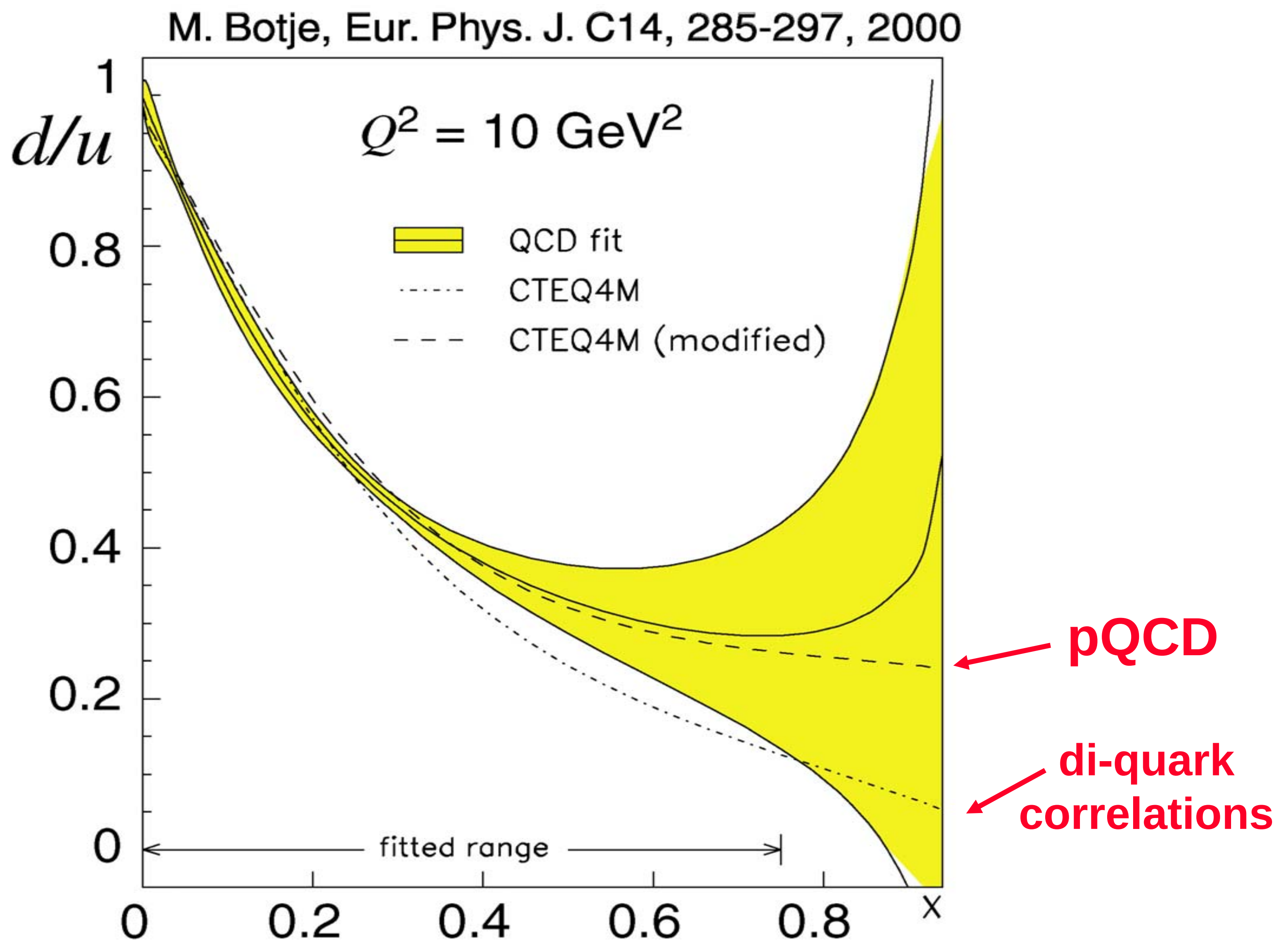
## Aug 6-10: JLab PAC32

- **Second review of 12 GeV proposals – "commissioning experiments"**
- **Key step in identifying the research interests and contributions of international collaborators**

# Anticipated Highlights of the 1st 5 Years

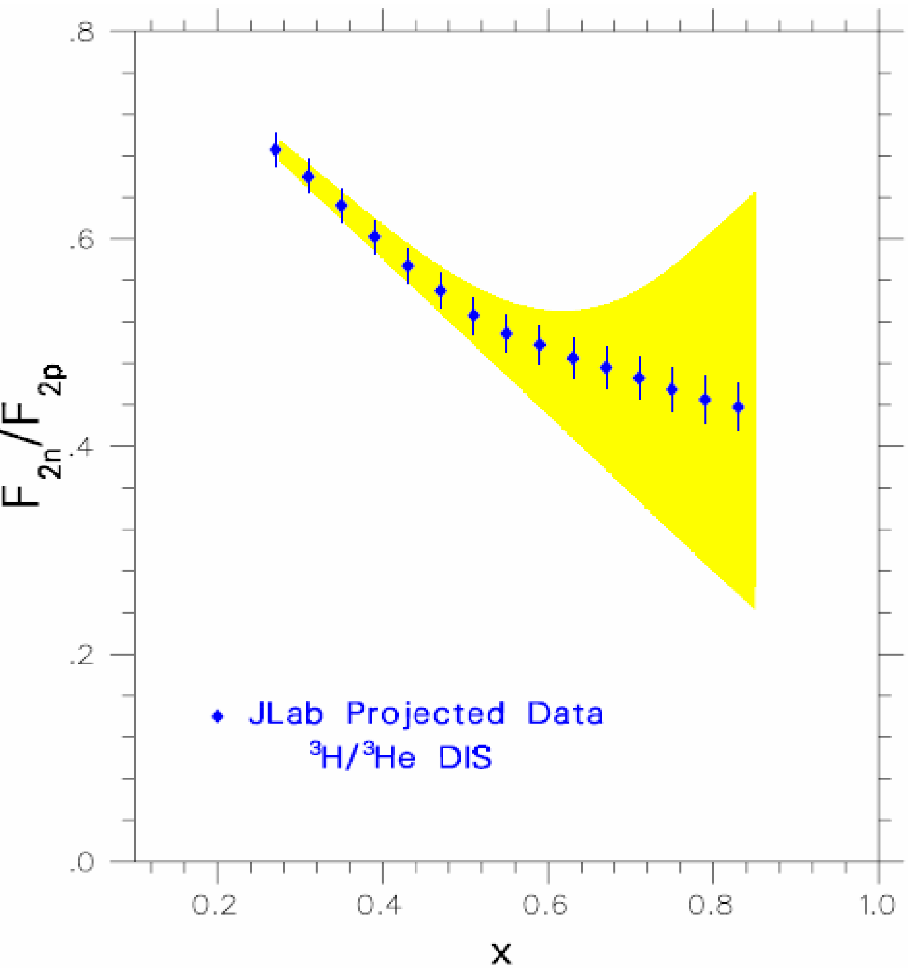
- **Parton Distribution Functions**
- **Form Factors**
- **Generalized Parton Distributions**
- **Exotic Meson Spectroscopy:**
  **Confinement and the QCD vacuum**
- **Nuclei at the level of quarks and gluons**
- **Tests of Physics Beyond the Standard Model**

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

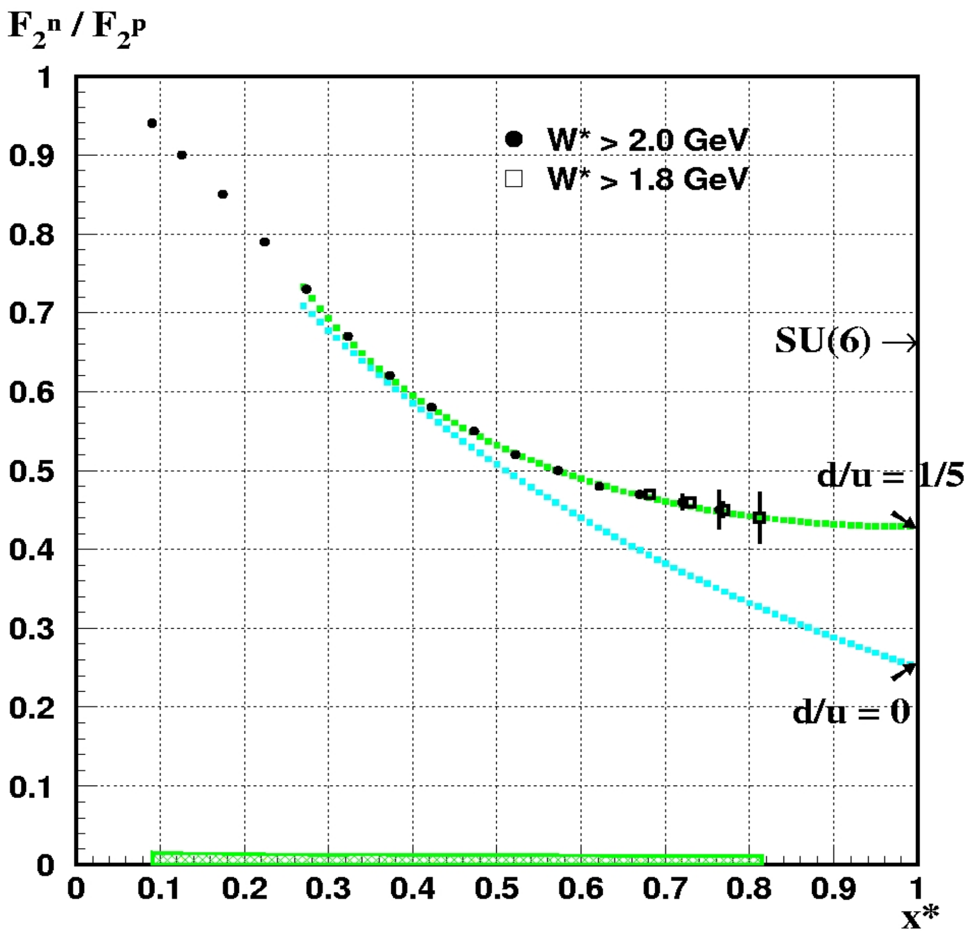


# 12 GeV : Unambiguous Flavor Structure $x \to 1$

**Hall A 11 GeV with HMS**

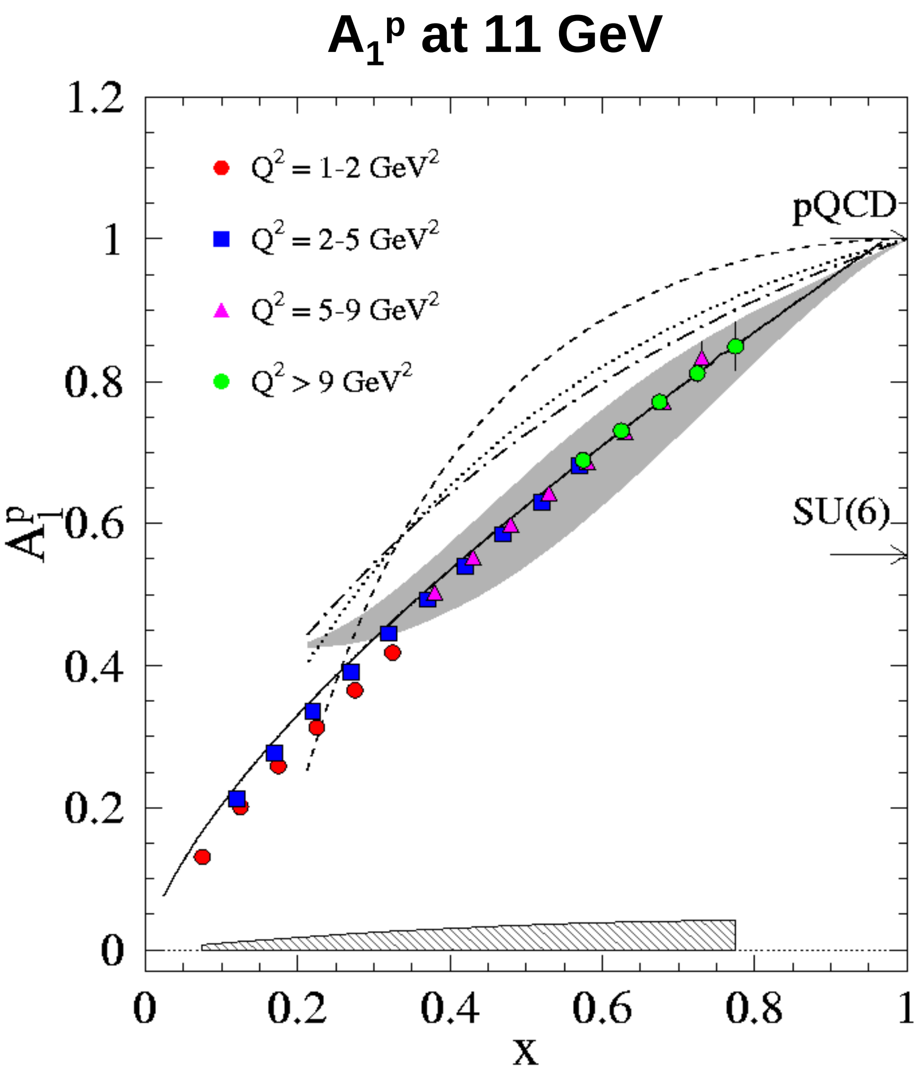


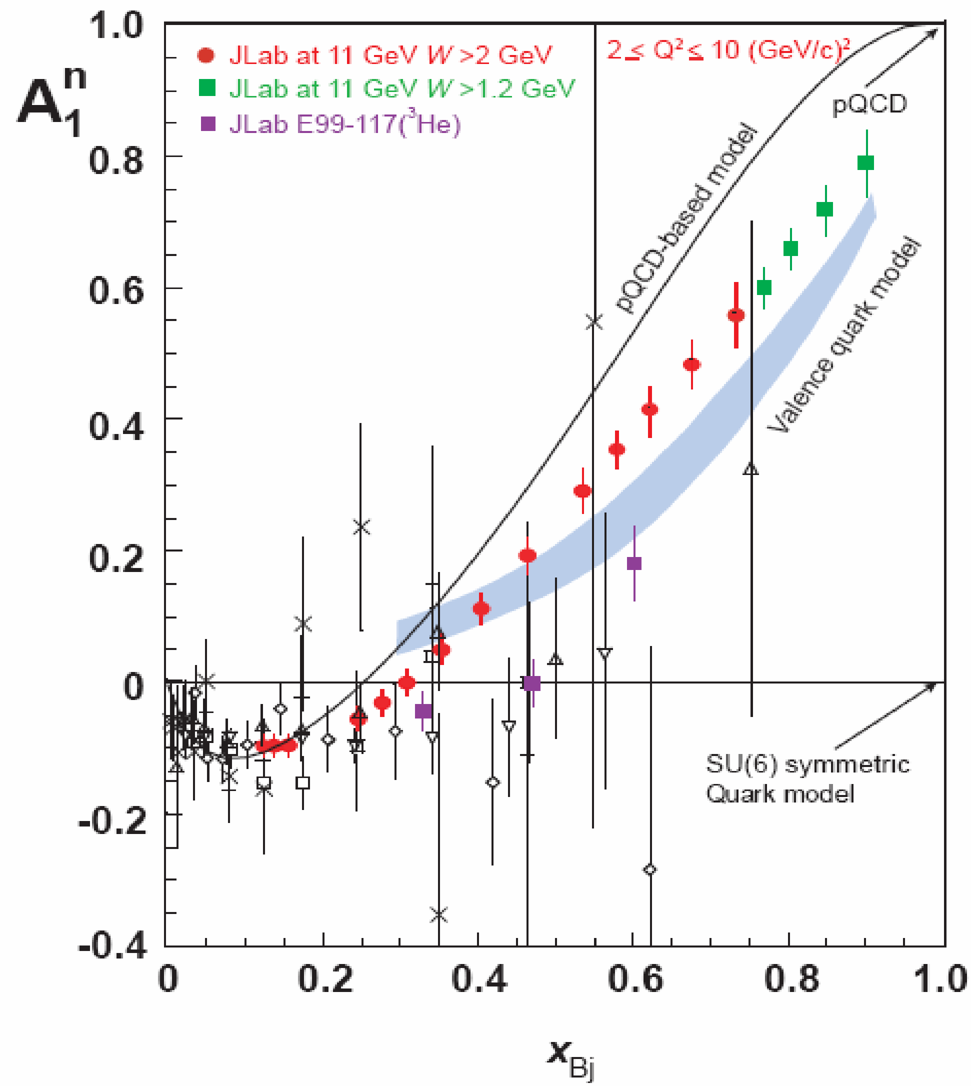

**Hall B 11 GeV with CLAS12**




**Initial investigation with BONUS early 06 successful**

# 12 GeV : Unambiguous Resolution of Valence Spin

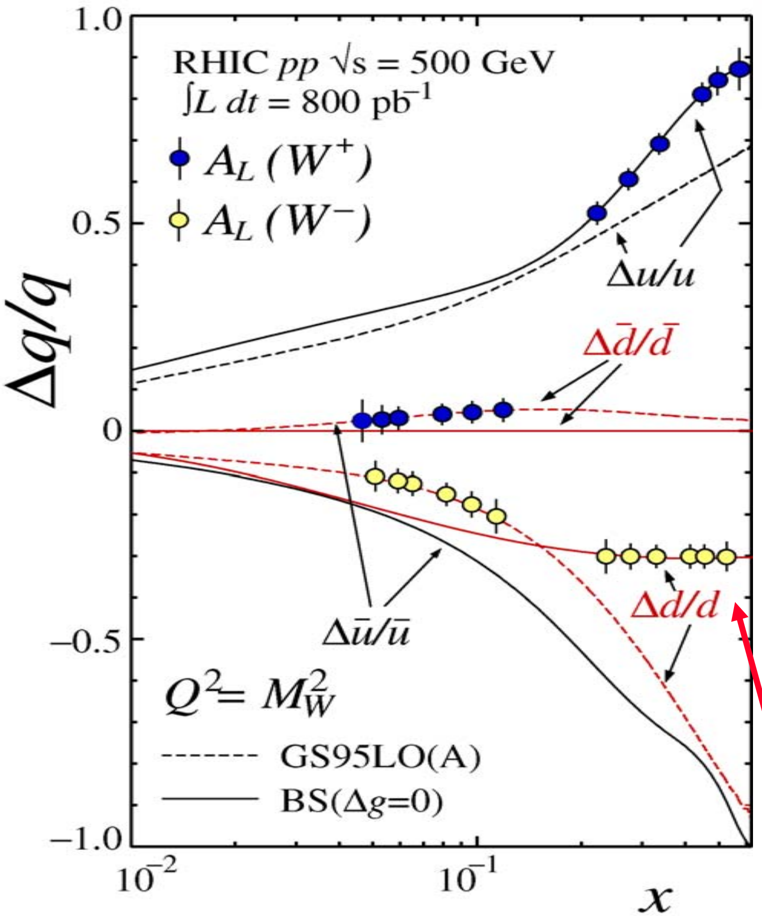


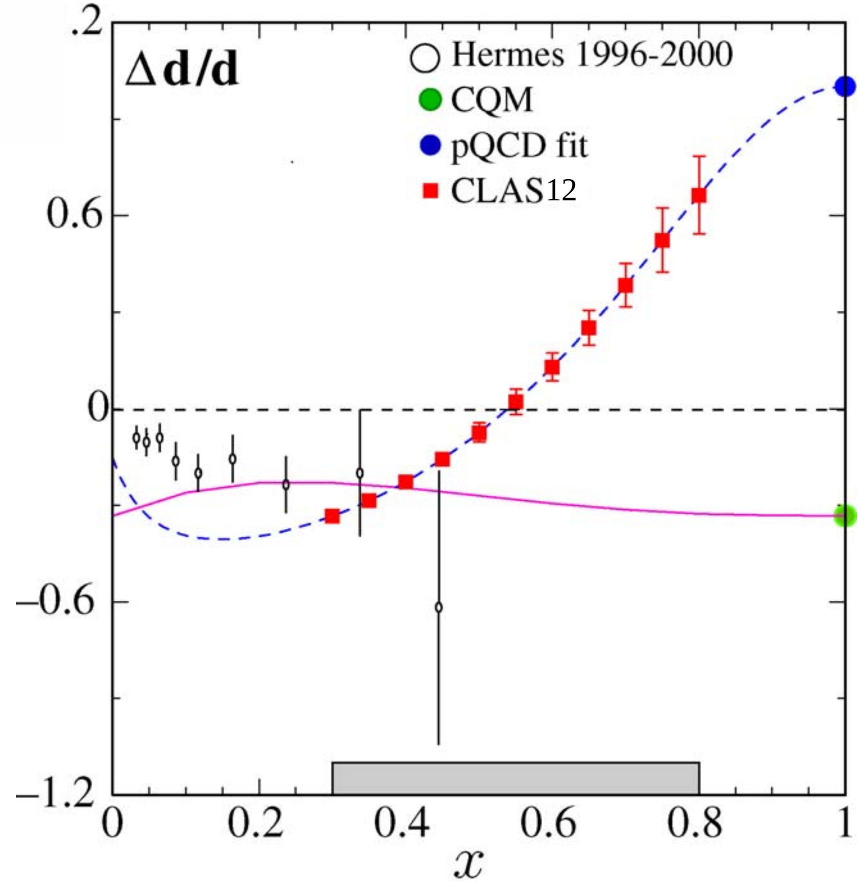
# Complements Spin-Flavor Dependence at RHIC

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)**

# Anticipated Highlights of the 1st 5 Years

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- **Form Factors**
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- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
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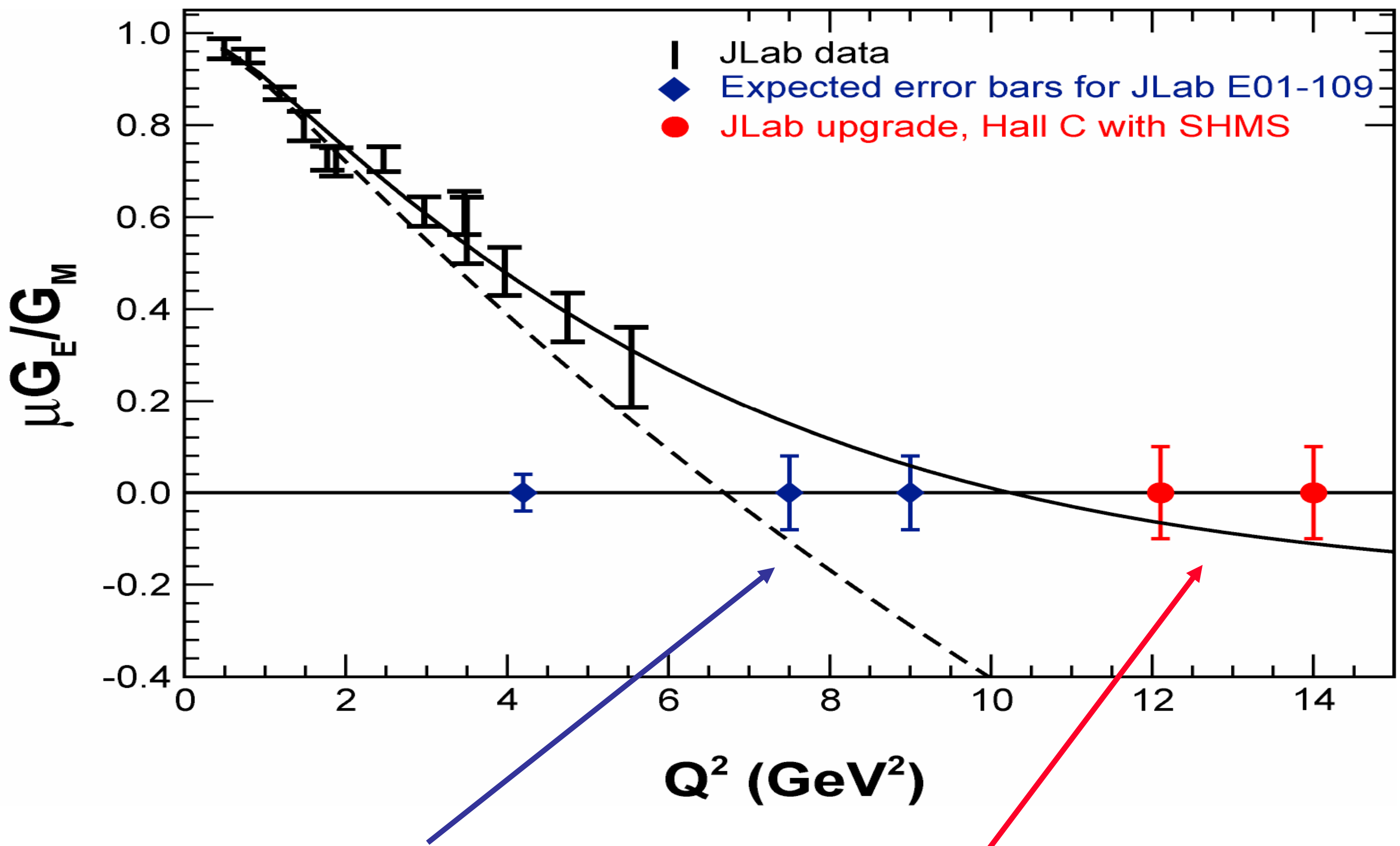
# Future Measurements on $G_E^p$




- 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 $G_E^n$)**

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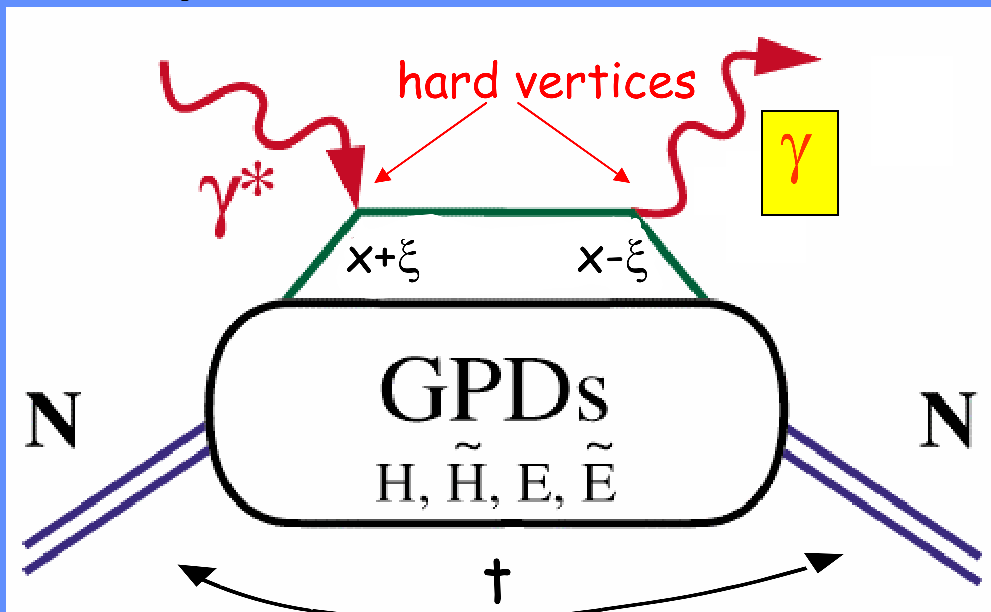
# GPDs & Deeply Virtual Exclusive Processes
## - New Insight into Nucleon Structure

### Deeply Virtual Compton Scattering (DVCS)




x – quark momentum fraction

ξ- longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

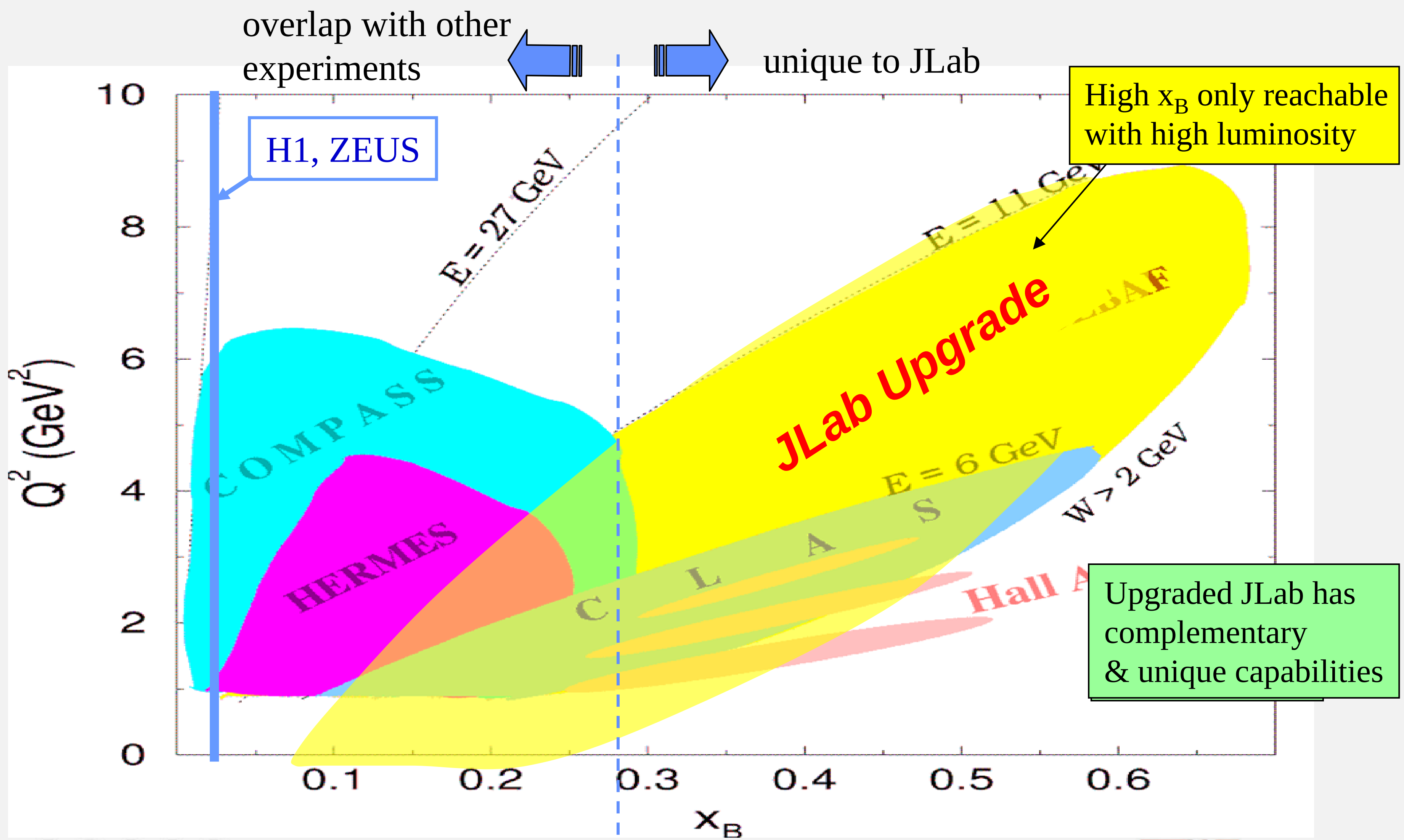
H(x,ξ,t), E(x,ξ,t), . . . "Generalized Parton Distributions"

**Quark angular momentum (Ji 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)

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

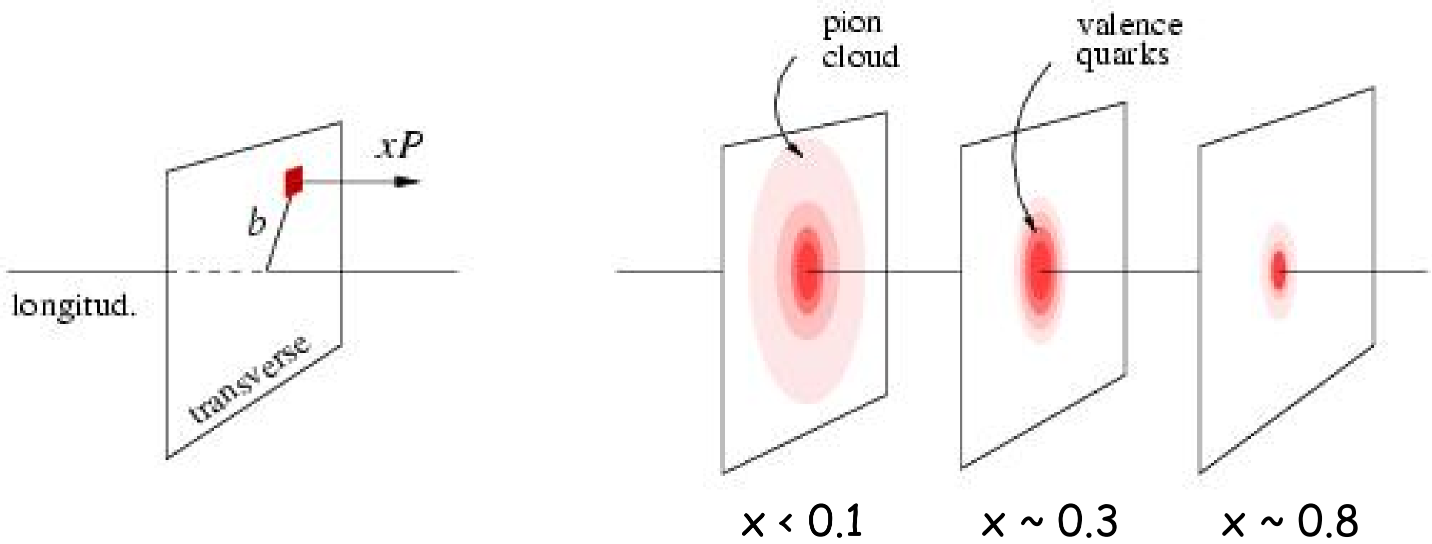


# What's the use of GPDs?

## 1. Allow for a unified description of form factors and parton distributions

## 2. Allows for Transverse Imaging

Fourier transform in momentum transfer




**gives transverse size of quark (parton) with longitudinal momentum fraction x**

## 3. Allows access to quark angular momentum (in model-dependent way)

# The path towards the extraction of GPDs

**Use polarization!**

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$$\vec{e}\, p \longrightarrow e p \gamma$$

$$\Delta\sigma_{LU} \sim \sin\phi\, \mathrm{Im}\{F_1 H + \ldots\} d\phi$$

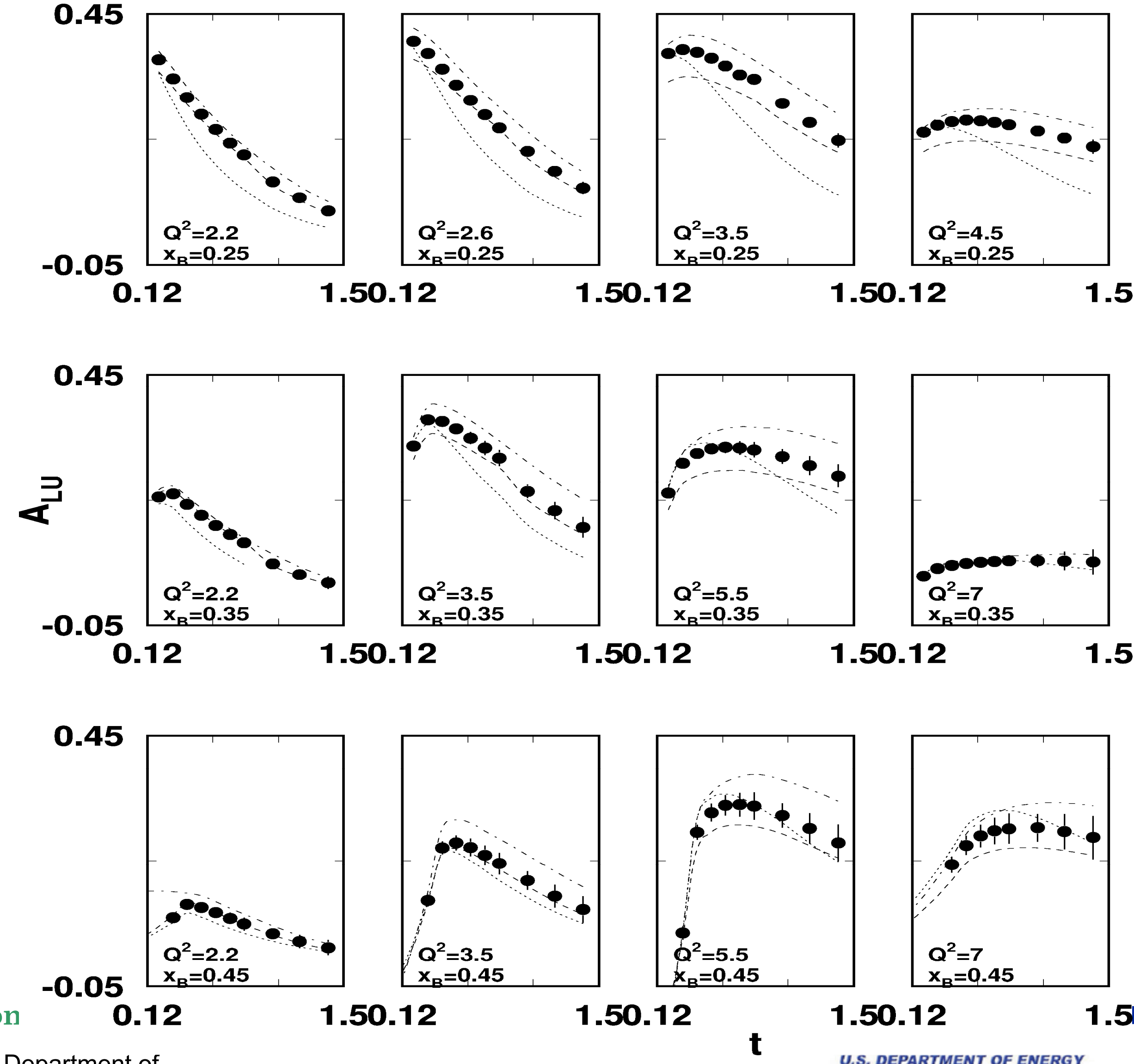
Kinematically suppressed

$H(\xi, t)$

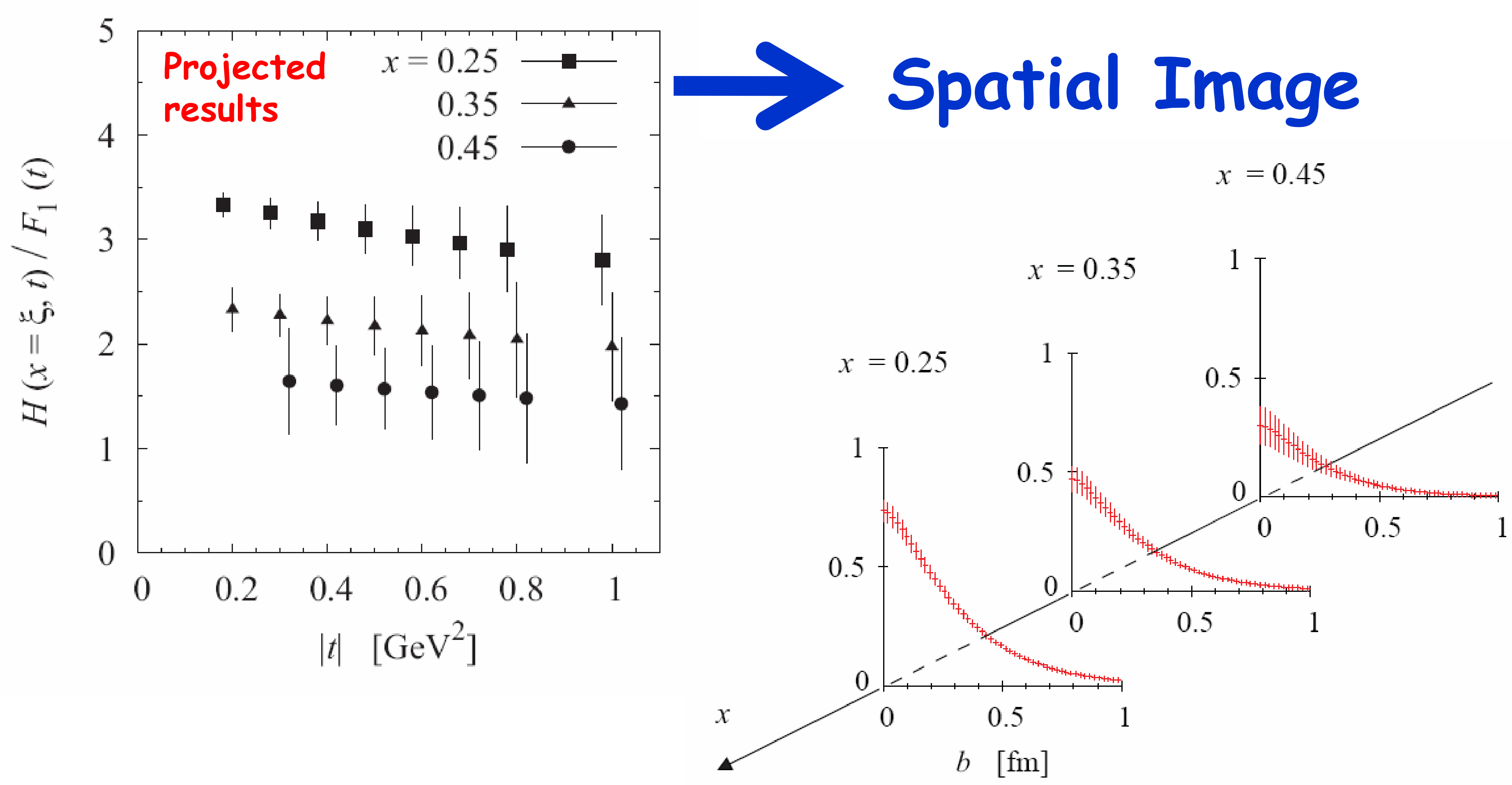
$\xi = x_B/(2-x_B)$

$k = t/4M^2$

**Subset of projected results**



# Projected precision in extraction of GPD H at x = ξ



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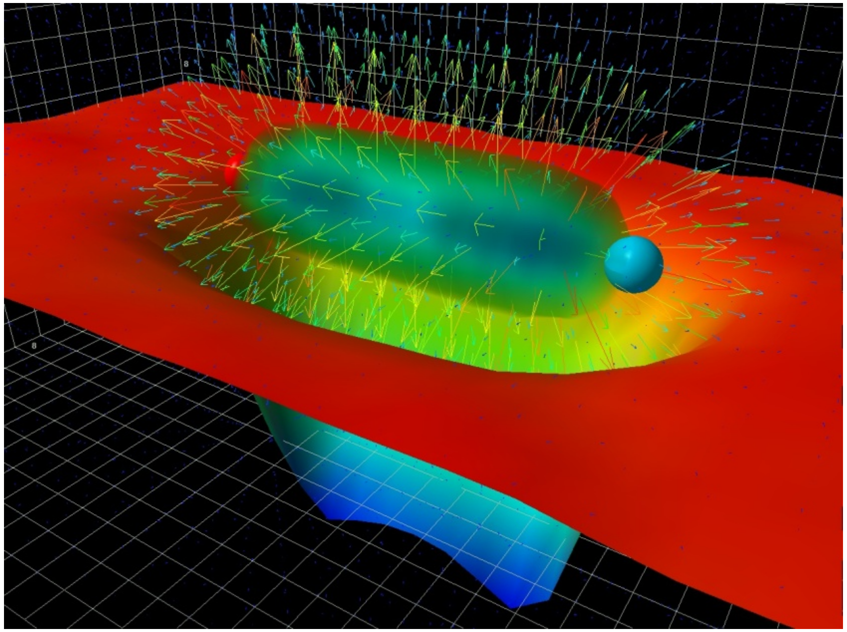
# Gluonic Excitations and the Origin of Confinement



QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

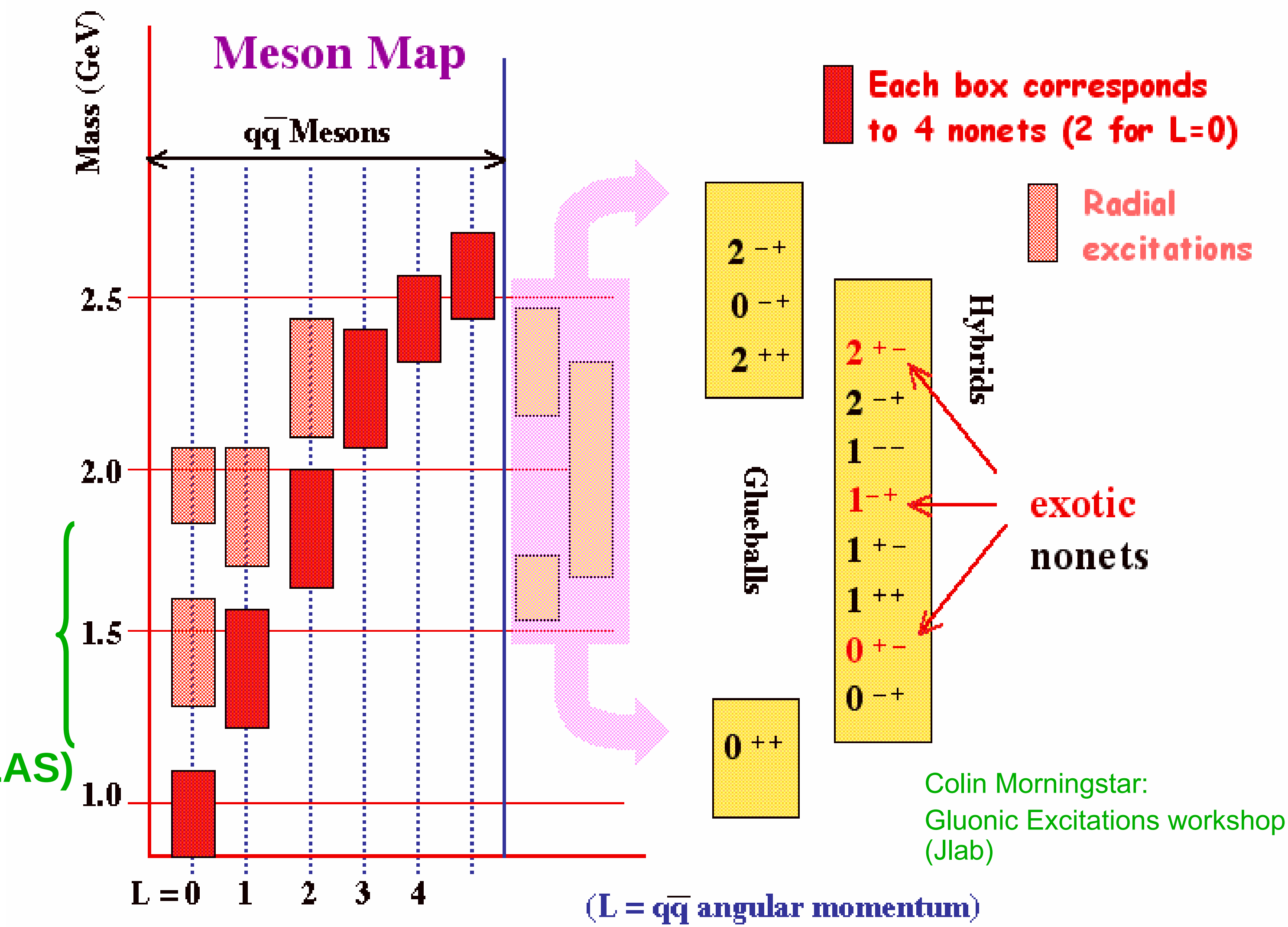
**With the upgraded CEBAF, a linearly polarized photon beam, and the GlueX detector, Jefferson Lab will be uniquely poised to:**

**- discover these states,**

**- map out their spectrum, and**

**- measure their properties**

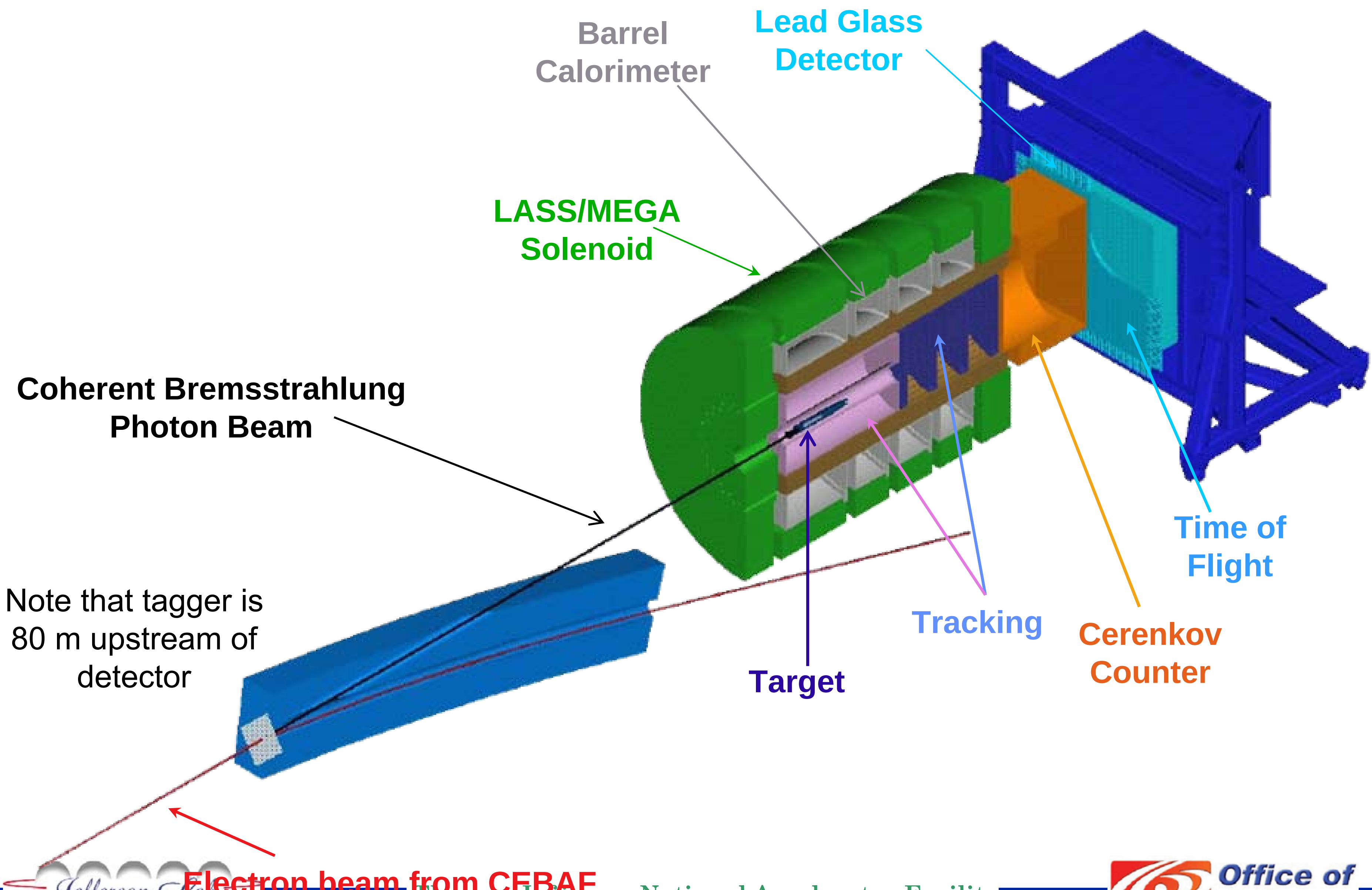
# Glueballs and hybrid mesons




**Initial search FY07 – G12 (CLAS)**

Colin Morningstar:
Gluonic Excitations workshop, 2003 (Jlab)

# Hall D GlueX Detector



# Finding the Exotic Wave

(Double-blind M. C. exercise)

$\gamma \rightarrow$ V(ector Meson) S = 1

An exotic wave ($J^{PC} = 1^{-+}$) was generated at level of 2.5 % with 7 other waves. Events were smeared, accepted, passed to PWA fitter.

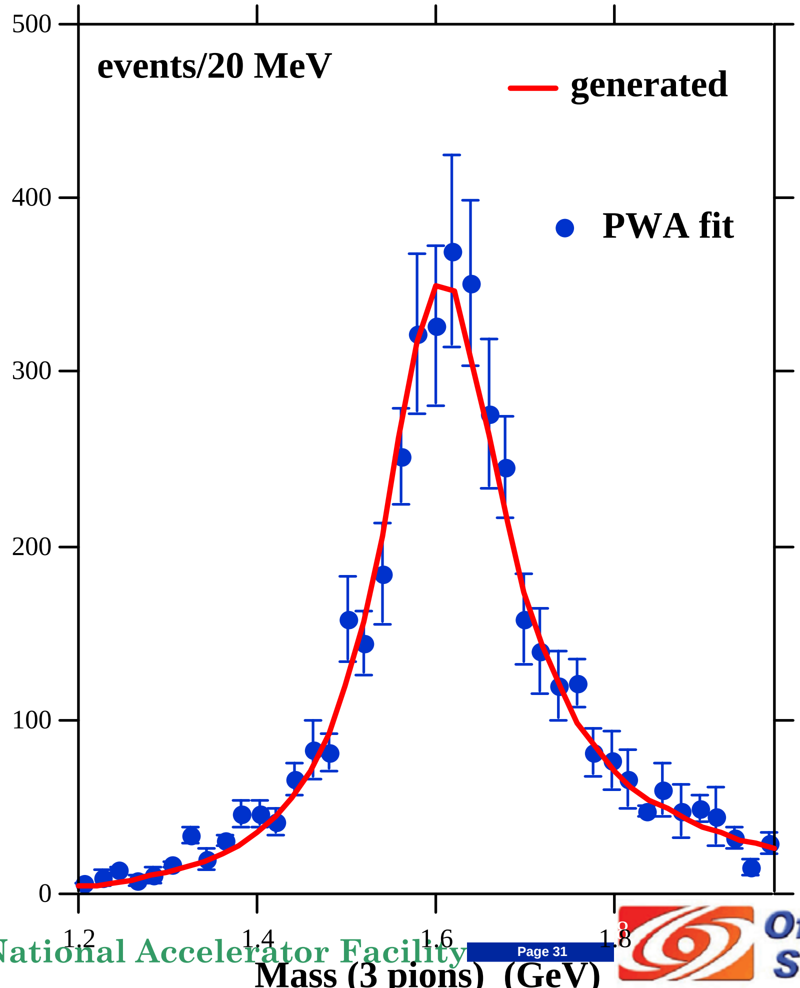
$$X(\text{exotic}) \rightarrow \rho\pi \rightarrow 3\pi$$

**Mass**

Input: 1600 MeV
Output: 1598 +/- 3 MeV

**Width**

Input: 170 MeV
Output: 173 +/- 11 MeV




Statistics shown here correspond to a few days of running.

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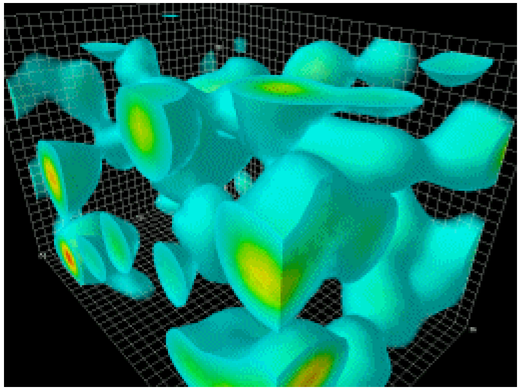
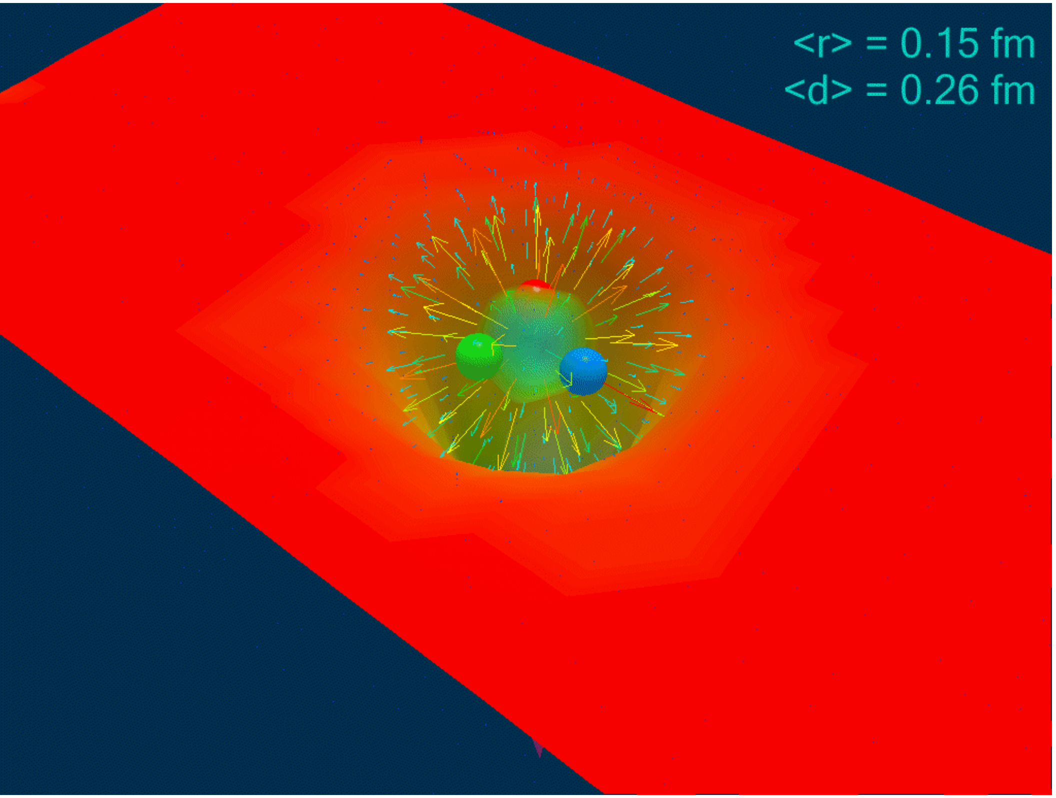
# The QCD Lagrangian and Nuclear "Medium Modifications"

The QCD vacuum



Long-distance gluonic fluctuations



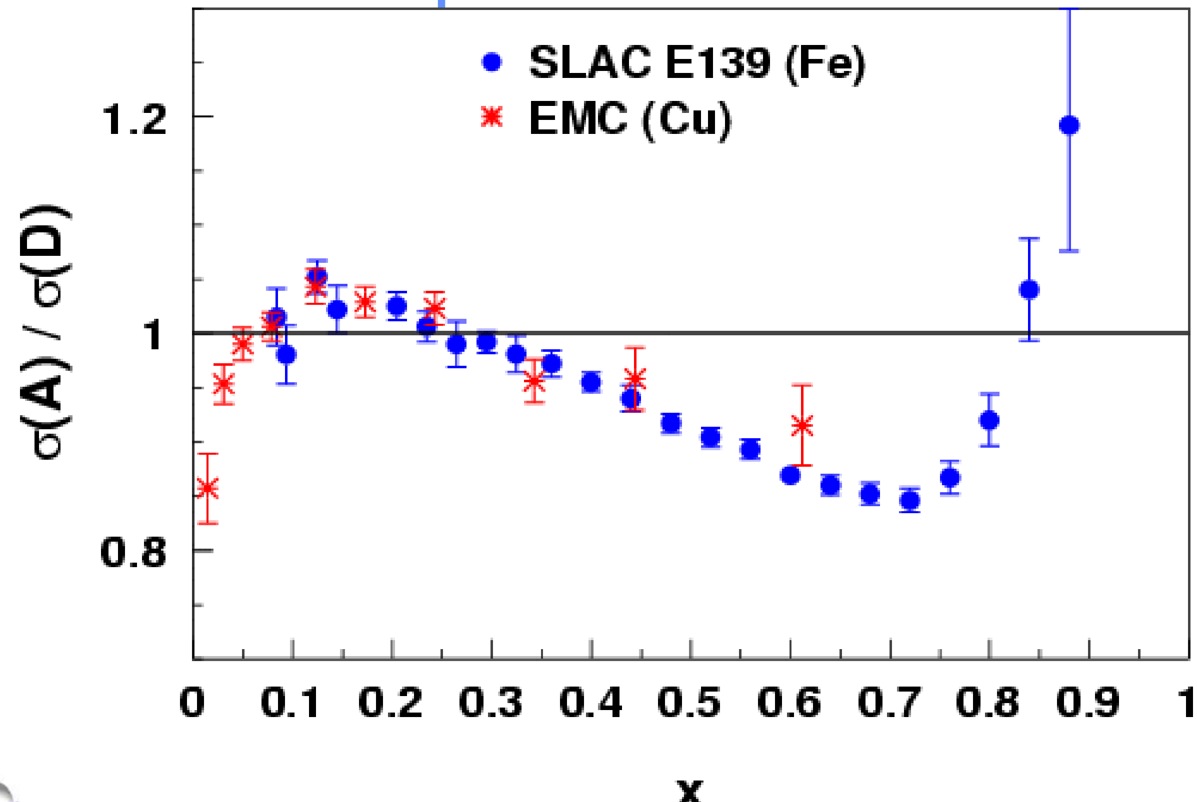

Lattice calculation demonstrates *reduction of chiral condensate* $\langle q\bar{q}\rangle$ of QCD vacuum in presence of hadronic matter

**Does the quark structure of a nucleon get modified by the suppressed QCD vacuum fluctuations in a nucleus?**

Leinweber, Signal et al

# 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?



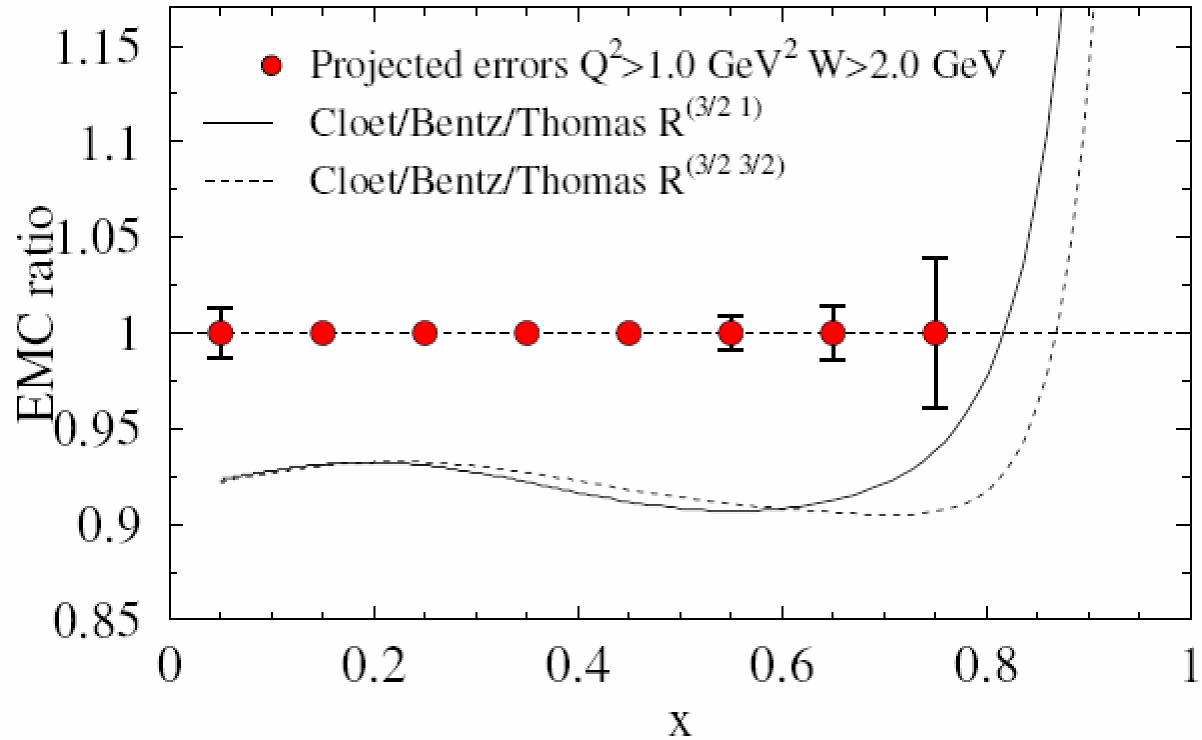

J. Ashman *et al*., Z. Phys. C57, 211 (1993)

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

# $g_1$(A) – "Polarized EMC Effect"

- New calculations indicate larger effect for polarized structure function than for unpolarized: <u>scalar field modifies lower components of Dirac wave function</u>
- Spin-dependent parton distribution functions for nuclei nearly unknown
- Can take advantage of modern technology for polarized solid targets to perform systematic studies – Dynamic Nuclear Polarization

$\frac{g_{1A}(^7Li)}{g_{1p}}$ (polarized EMC effect)




Curve follows calculation by W. Bentz, I. Cloet, A. W. Thomas.

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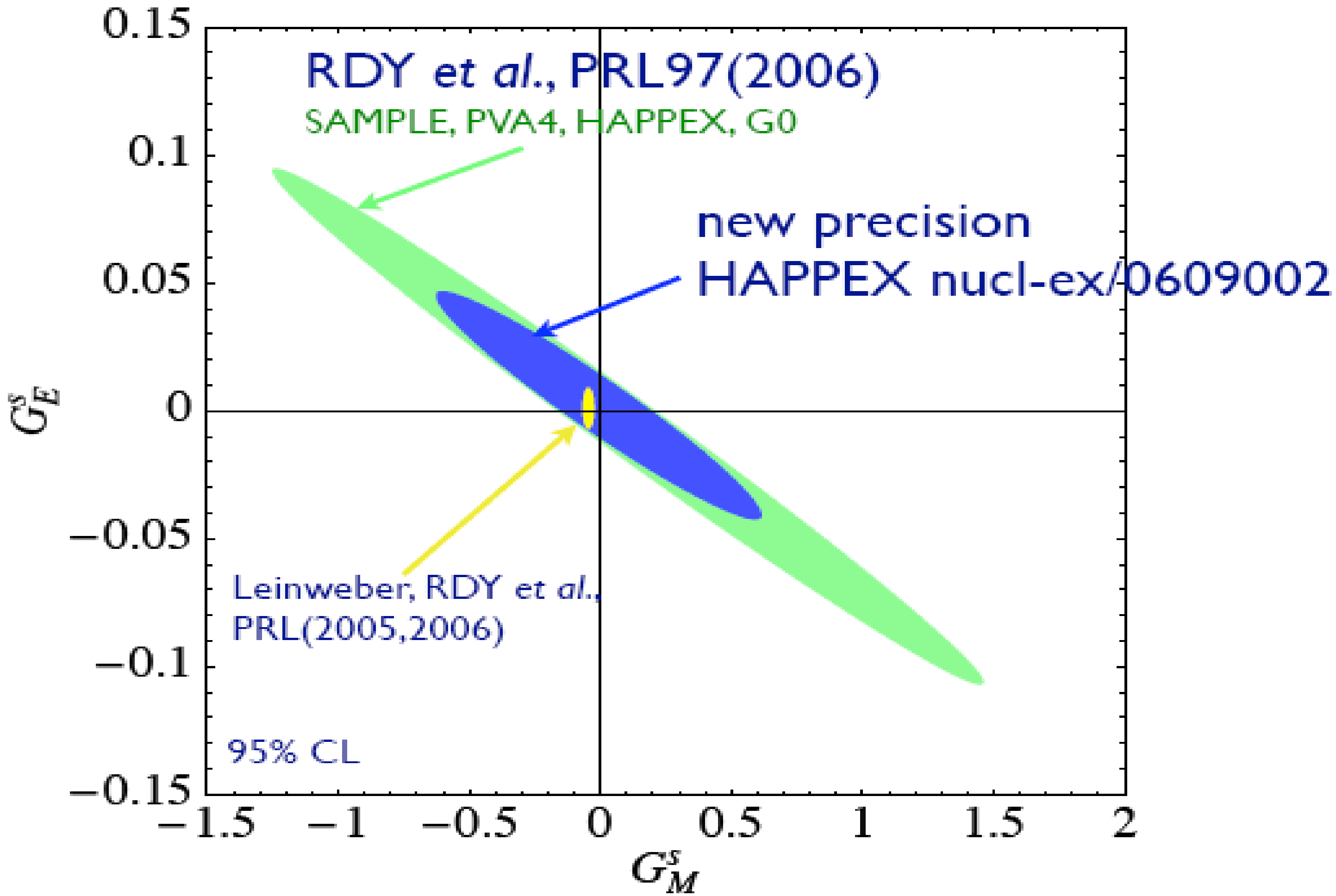
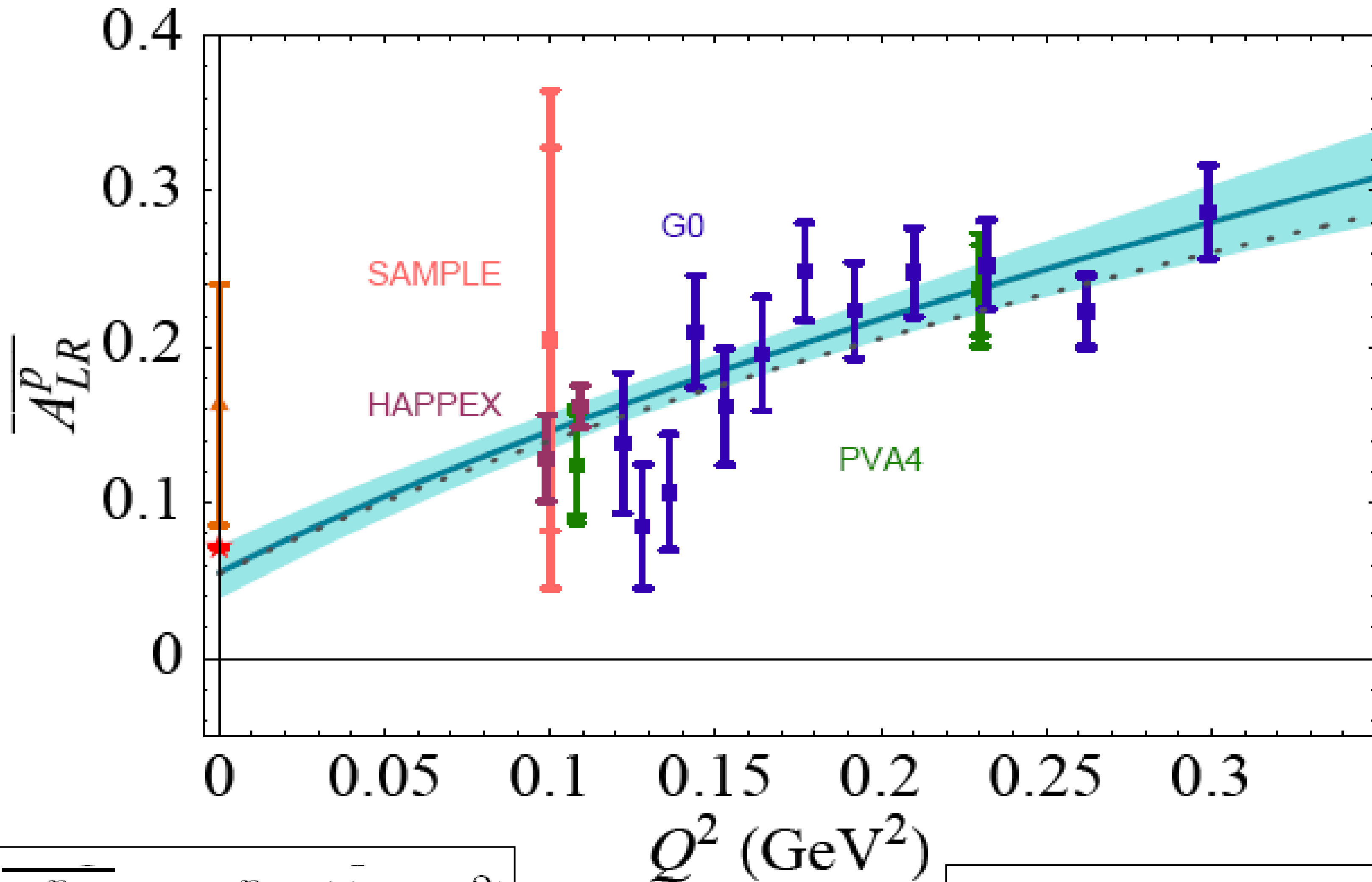
# Kent Paschke: Will show Precision of PVES for Strange Form Factors




**Can we achieve meaningful accuracy in testing the Standard Model now?**

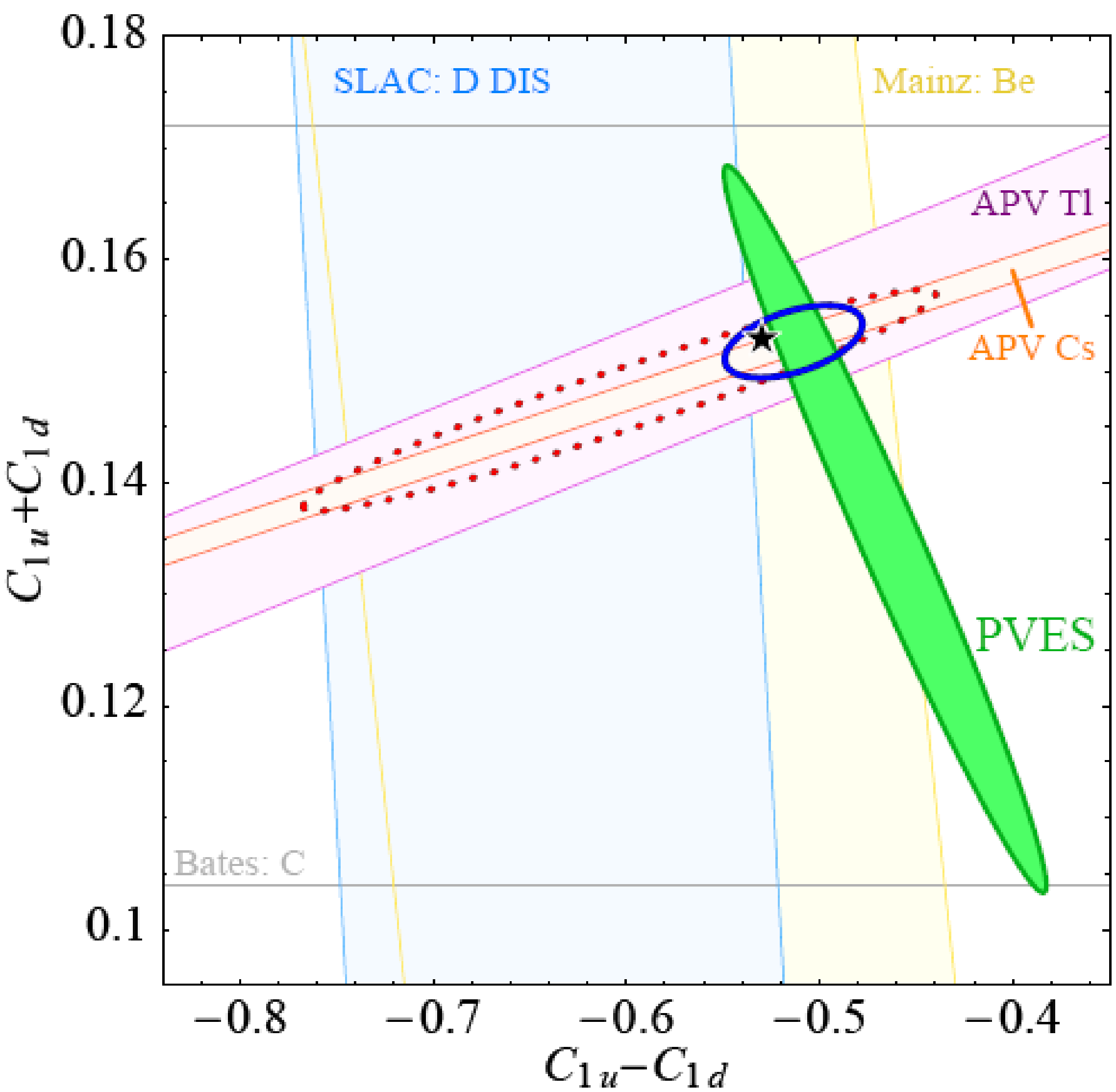
# $Q^2$-Slope of PV Asymmetry at $\theta = 0^o \Rightarrow Q_{weak}$




$$\overline{A^p_{LR}} \equiv A^p_{LR}/(A_0 Q^2)$$

$$A_0 = -G_\mu/(4\pi\alpha\sqrt{2})$$

# New update on $C_{1q}$ couplings




(Young et al. hep-ph/0704.2618)

Dramatic improvement in knowledge of weak couplings!

**Factor of 5 increase in precision of Standard Model test**

# Sensitivity to New Physics Beyond Standard Model

- One may be sensitive to a new heavy Z' boson contributing to a new contact interaction
- Imagine a new Z' which has exactly the same couplings to the SM fermions and mass $M_{Z'} \gg M_Z$
  - Simplest Kaluza-Klein excitation from a compact 5th dimension (circle radius *R*)

$$M_{Z_1}^2 = M_Z^2 + \frac{1}{R^2}$$

95% CL $\quad M_{Z_1} > 1.04\,\mathrm{TeV} \quad R < 2 \times 10^{-4}\,\mathrm{fm}$

# 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)

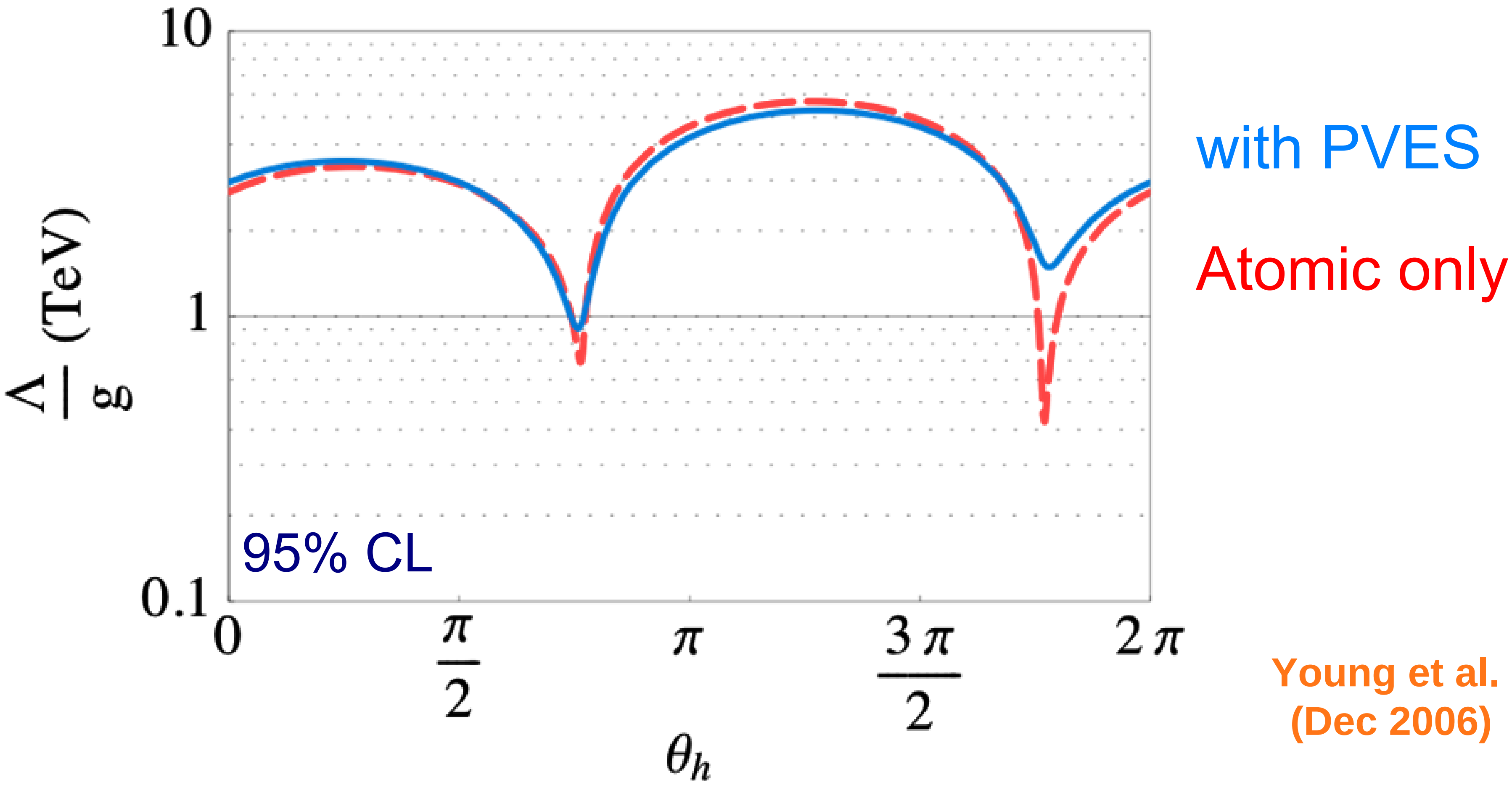
$$\mathcal{L}_{NP}^{PV} = \frac{g^2}{4\Lambda^2} \bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

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 $\dfrac{g^2}{\Lambda^2}$

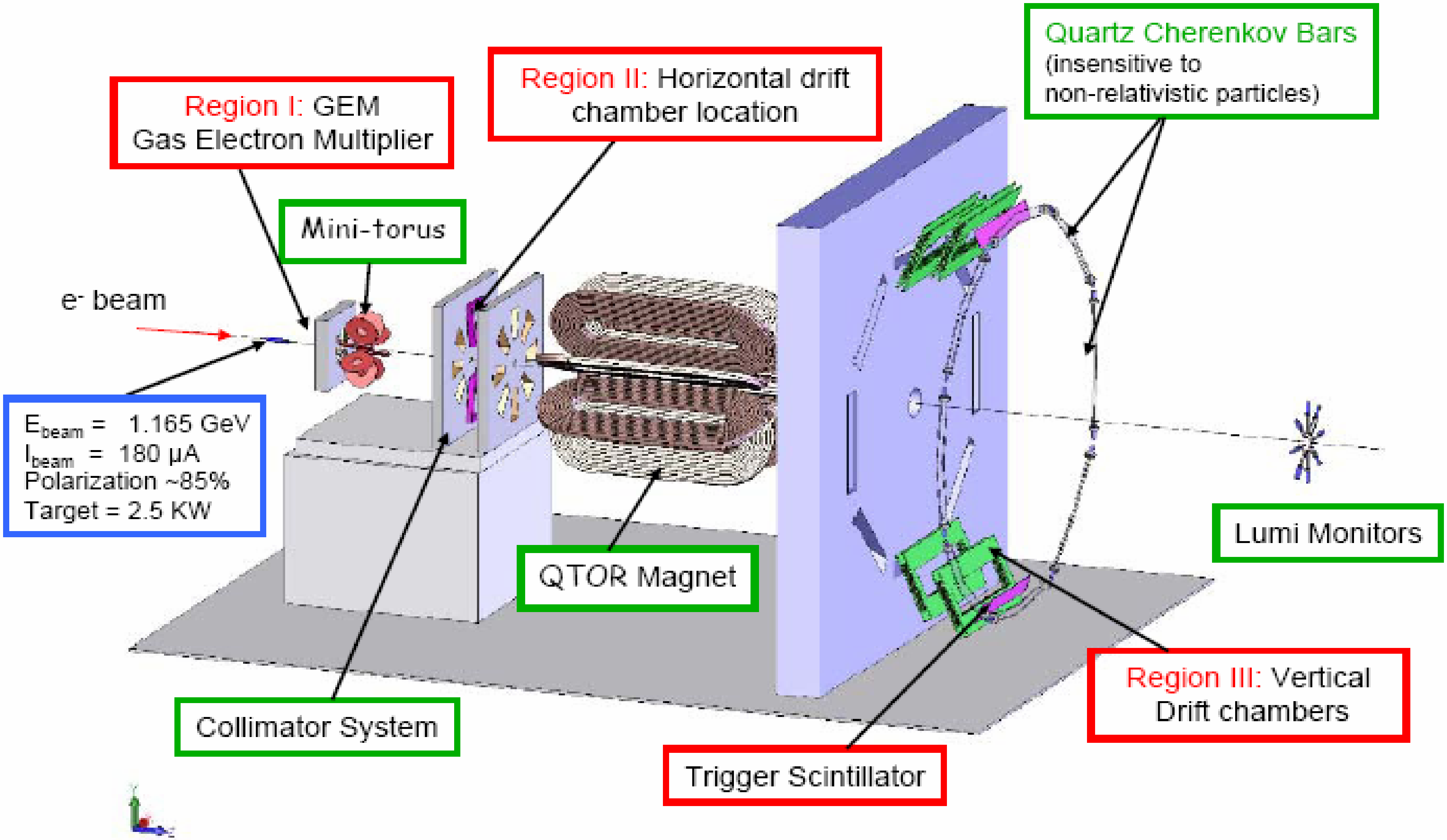
# Lower bound on New Physics scale: Current



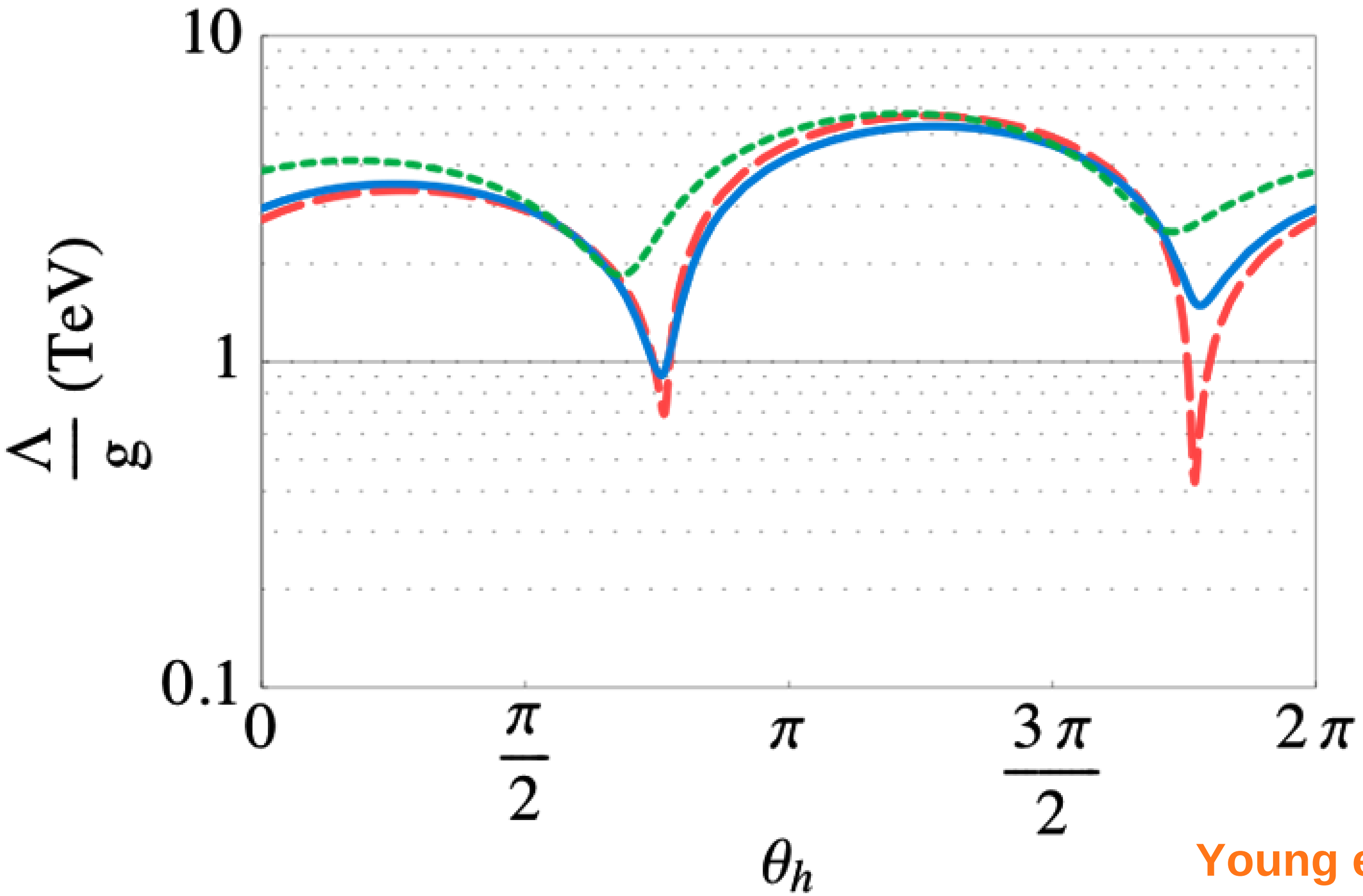

Young et al. (Dec 2006)

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

# $Q_{weak}$ Apparatus



# New Physics Limits
# (if result consistent with Standard Model)




future Qweak

with PVES

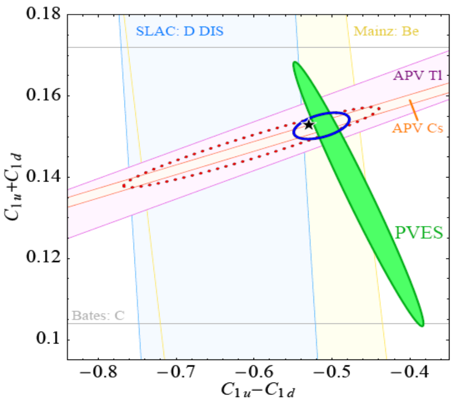
Atomic only

95% CL

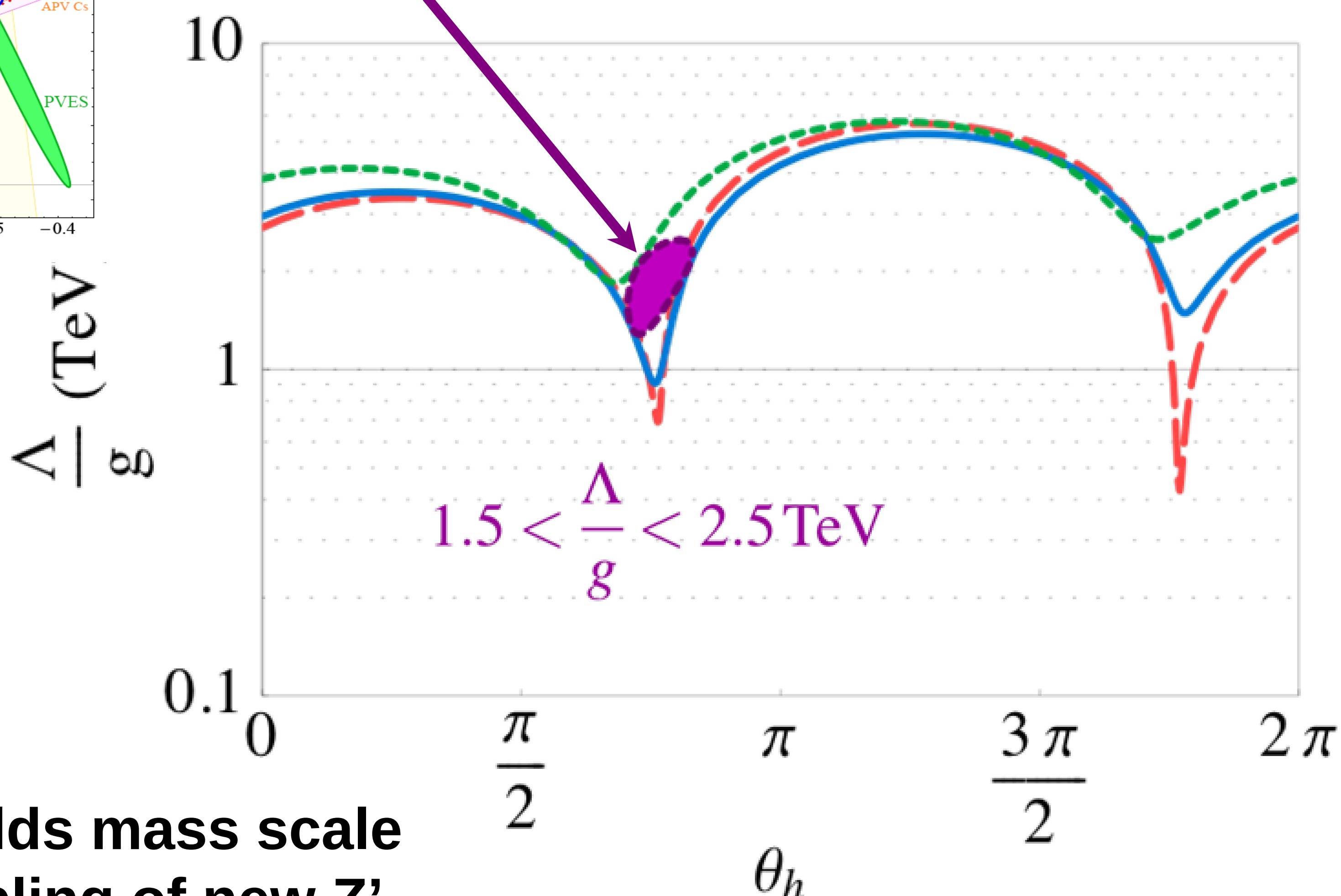
Young et al. (Dec 2006)

Qweak constrains new physics to beyond 2 TeV

# But: $Q_{weak}$ has real discovery potential!




central value of current PVES measurement




**$Q_{weak}$ yields mass scale and coupling of new Z'**

Young et al. (Dec 2006)

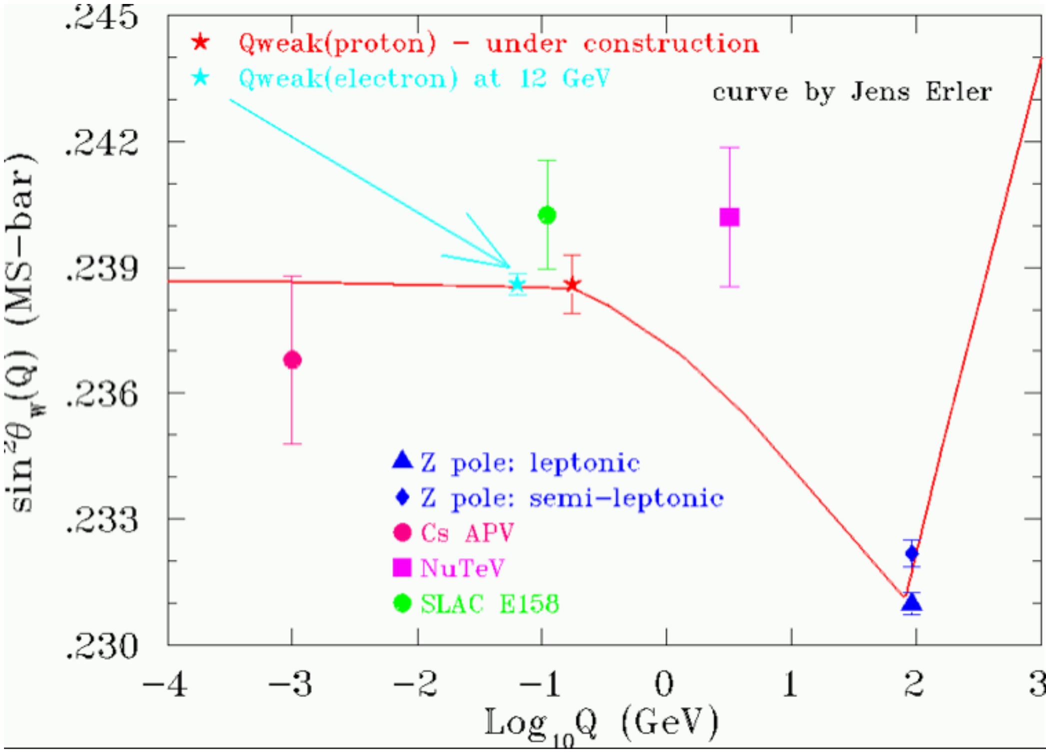
# Future Möller Experiment at 12 GeV

**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"**

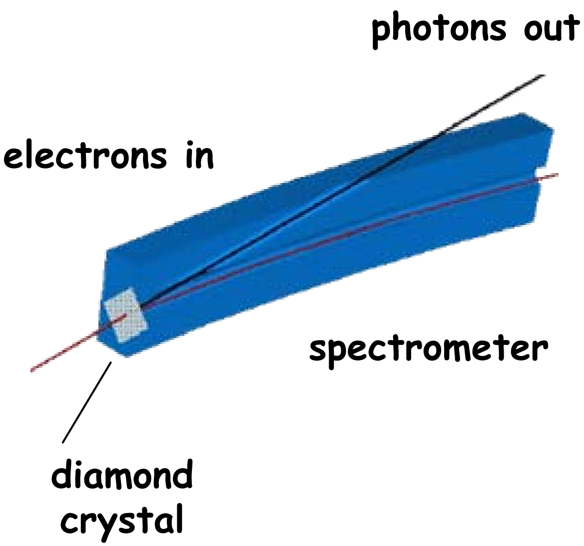


# Summary

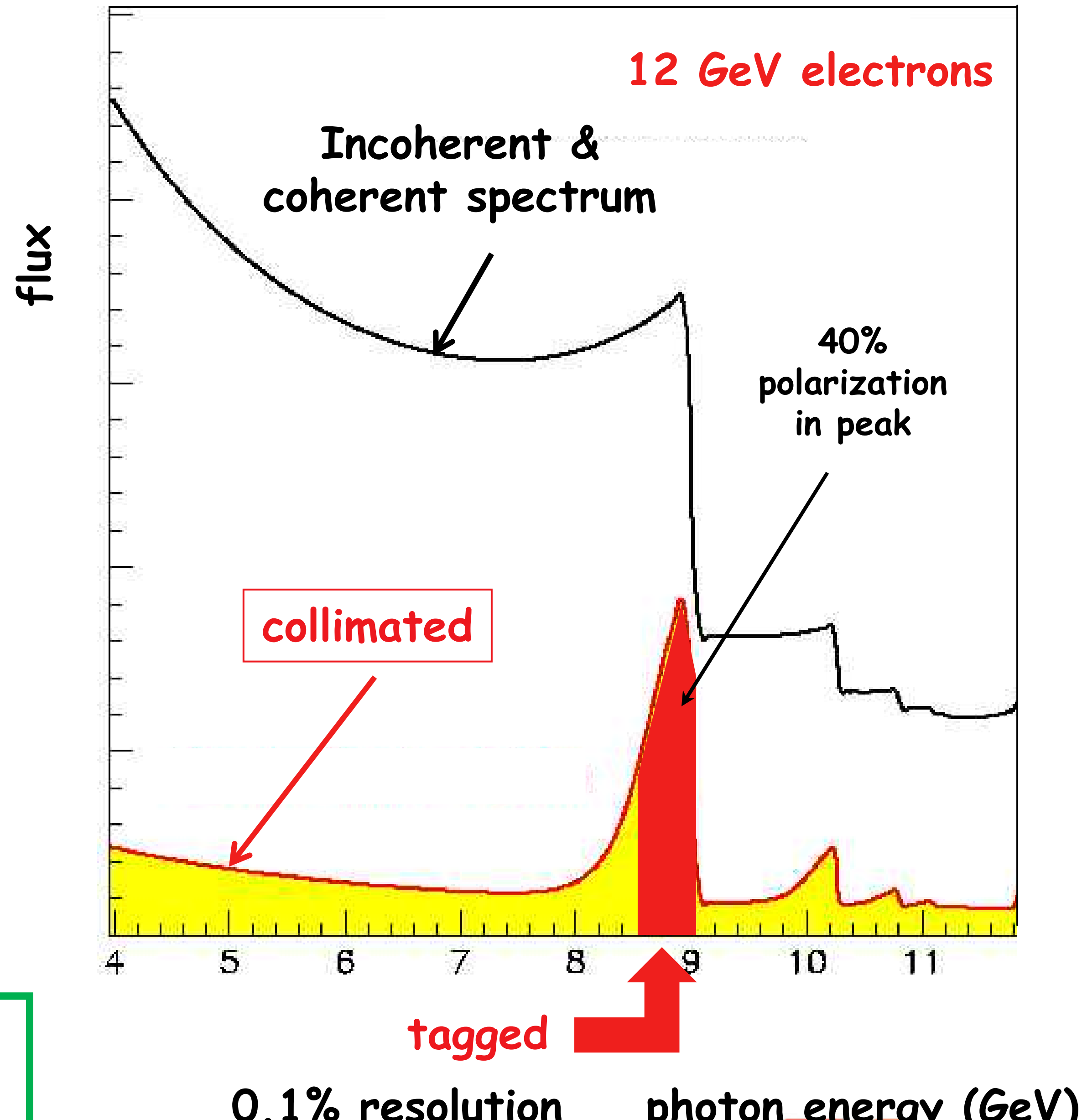
- I have provided just a snapshot of a very exciting and novel scientific program.
- Now I extend a warm invitation on behalf of everyone at JLab to come and join the fun!

# Coherent Bremsstrahlung

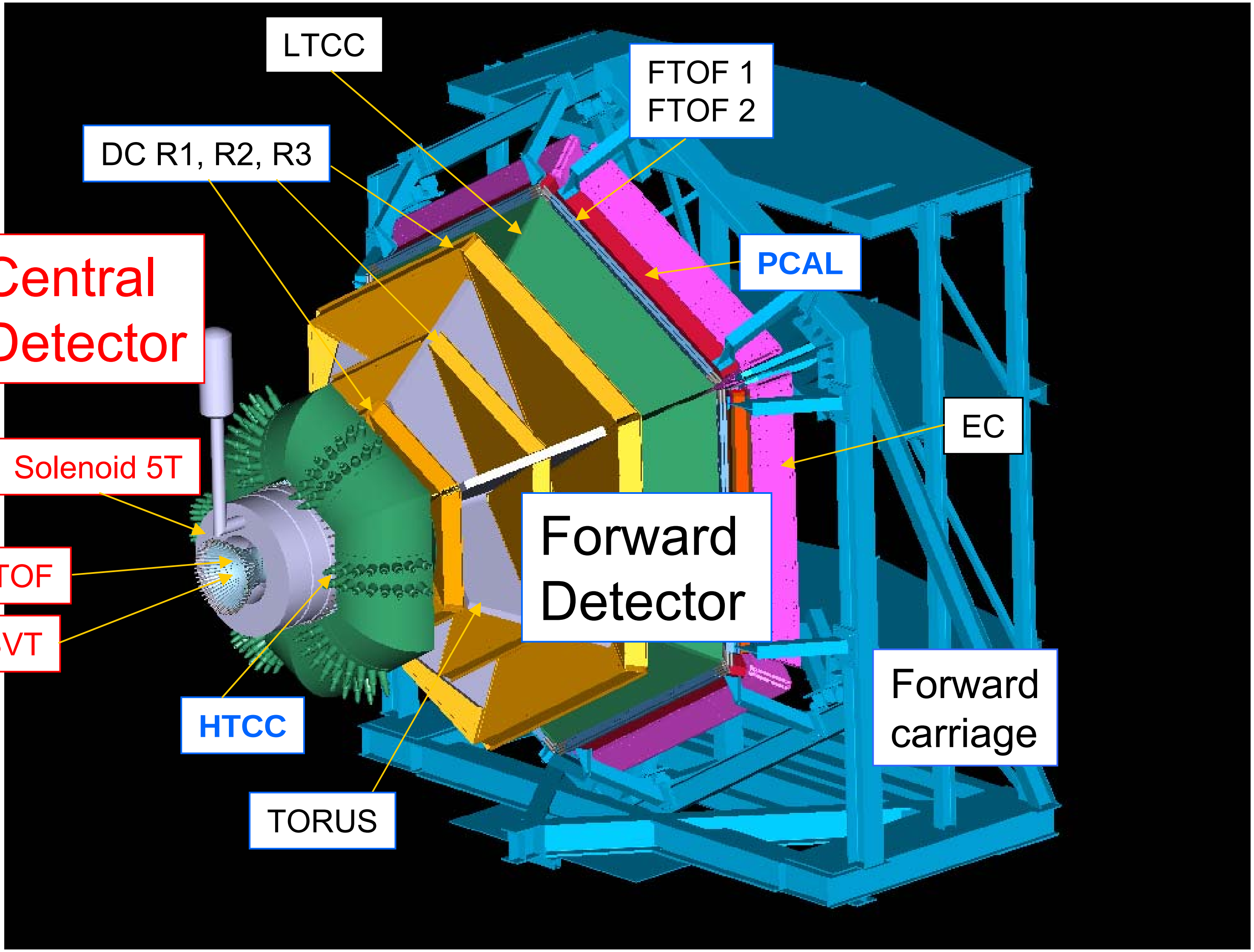
**This technique provides requisite energy, flux and polarization**



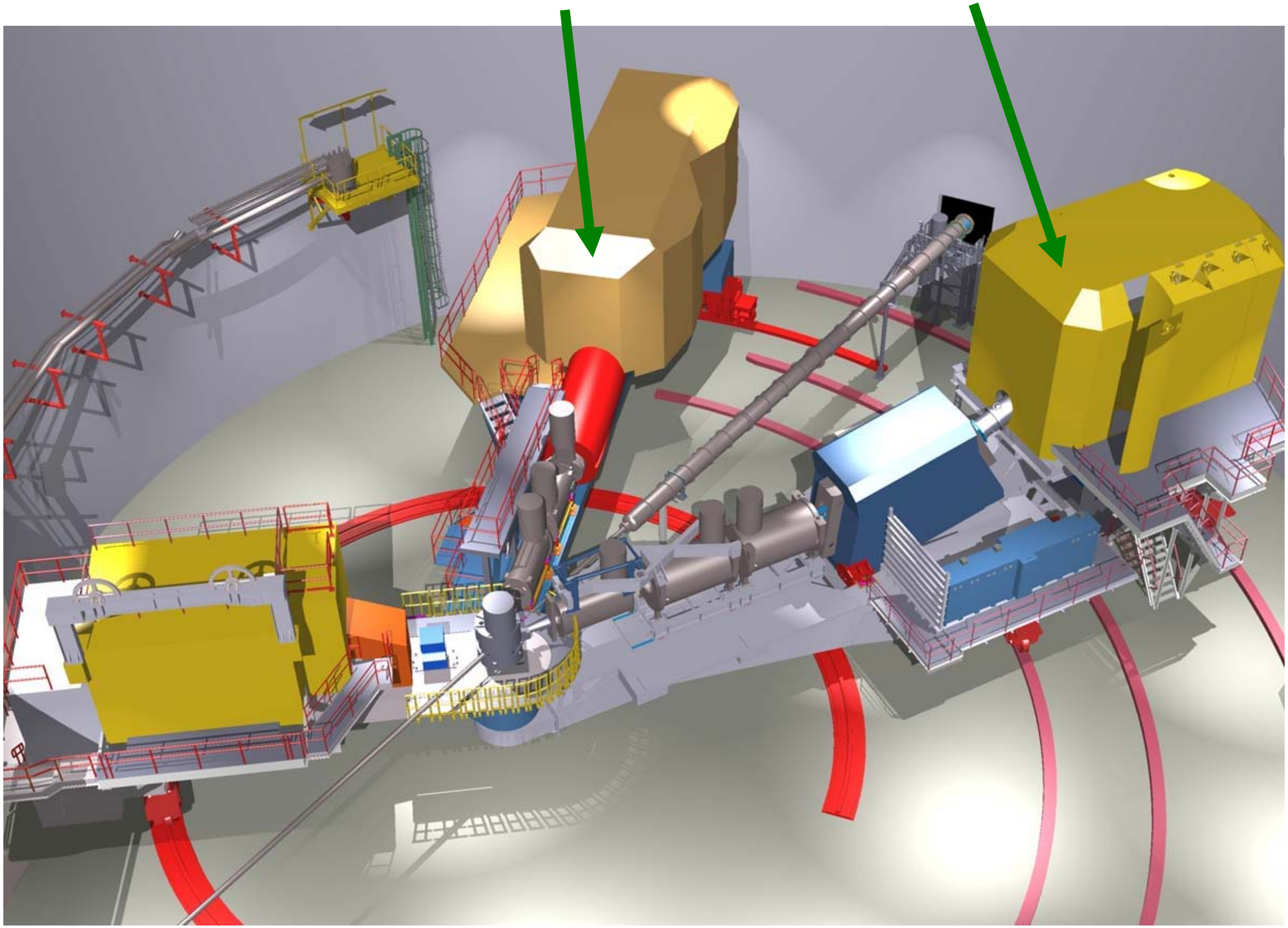

Good "acceptance" up to M ~ 2.5 GeV



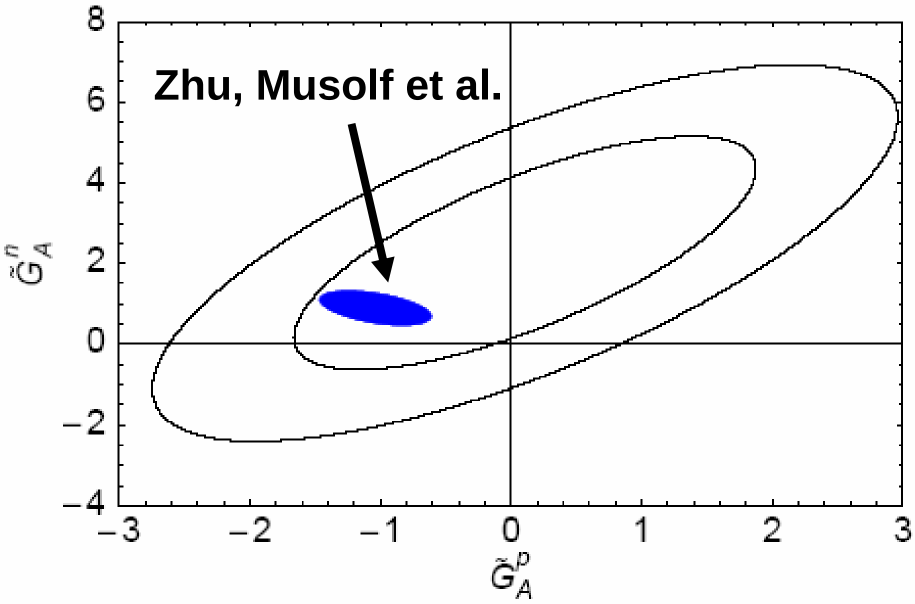
# Hall B - CLAS12



# Hall C:  SHMS and HMS



# Axial Form Factors

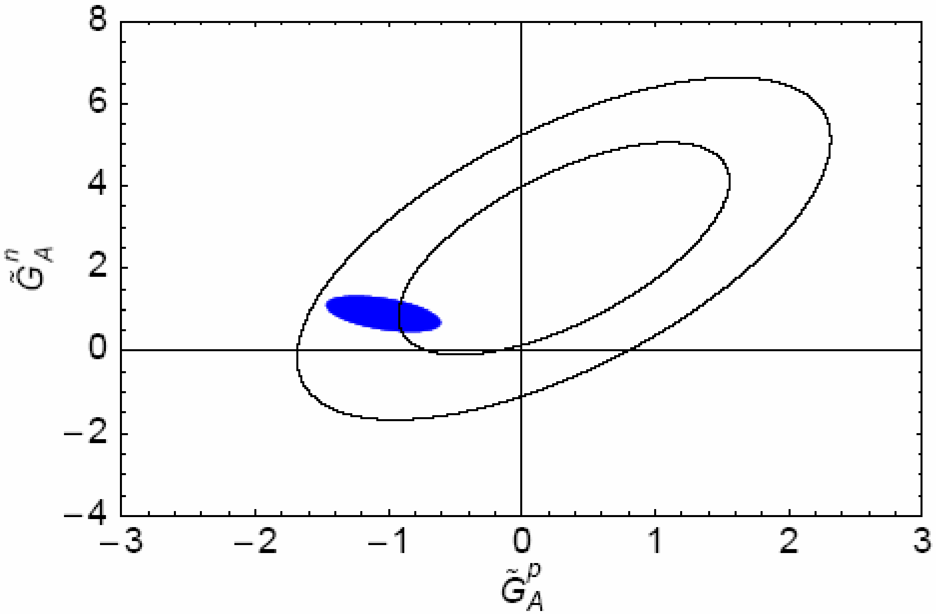



**World Data pre-latest HAPPEx**

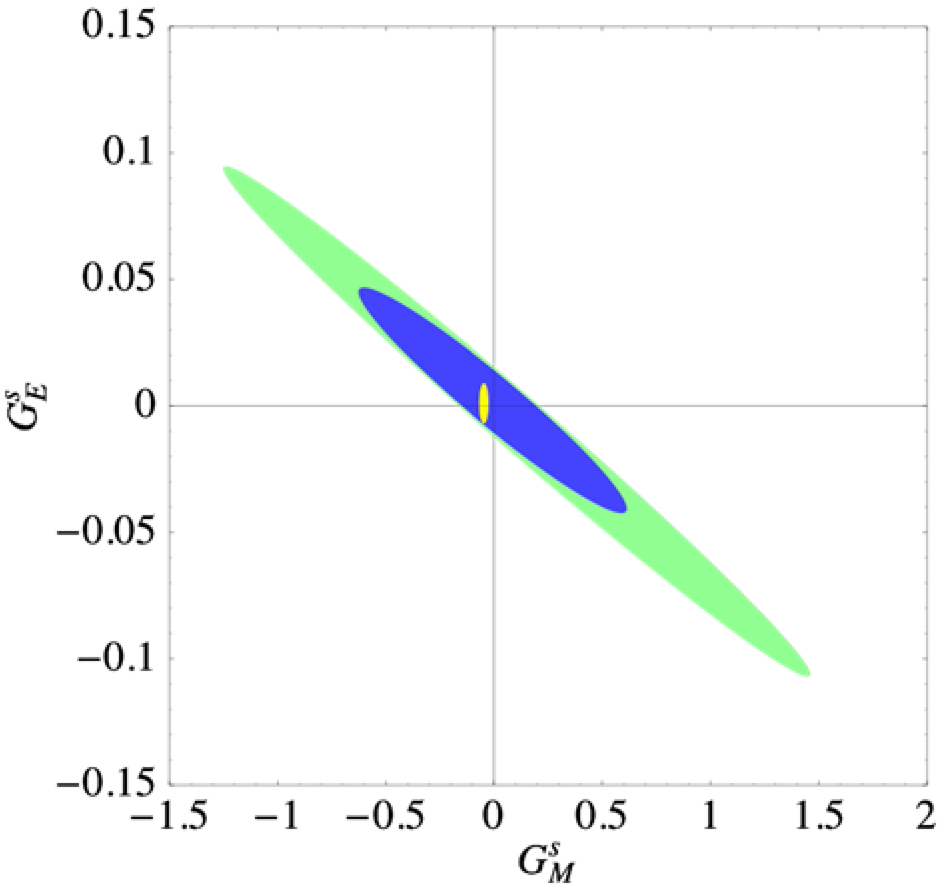
**(Young et al., nucl-ex/0604010)**

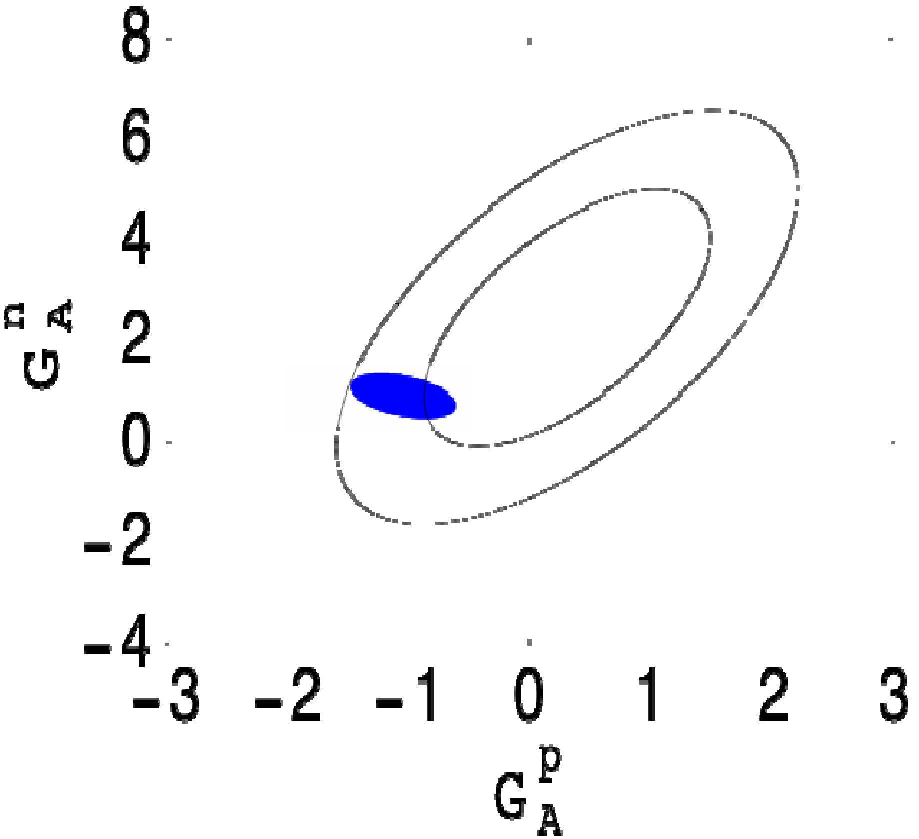
**World Data with new HAPPEx**

**(Young, Roche, Carlini and Thomas, extended analysis)**



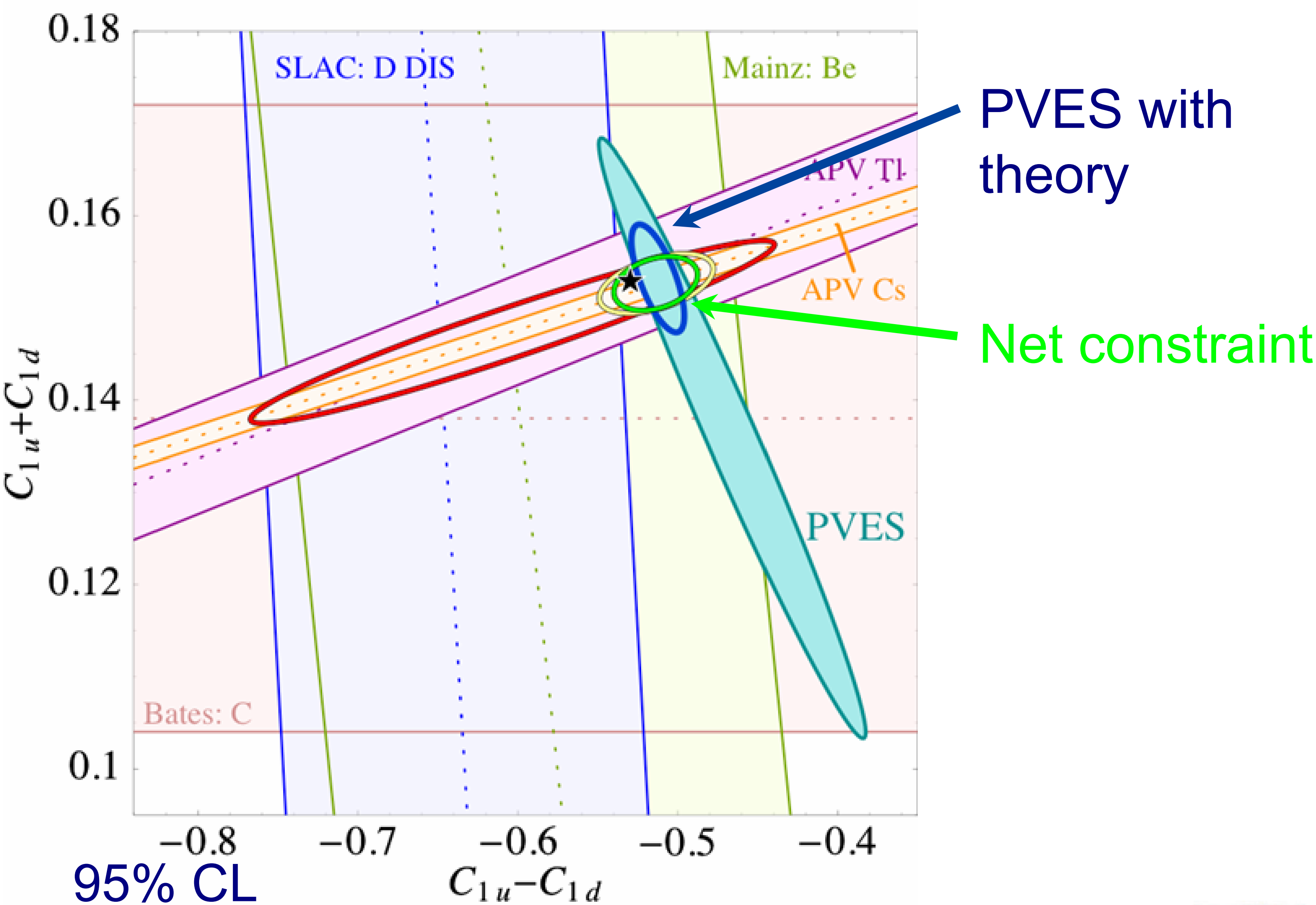
# Theory Constraint?



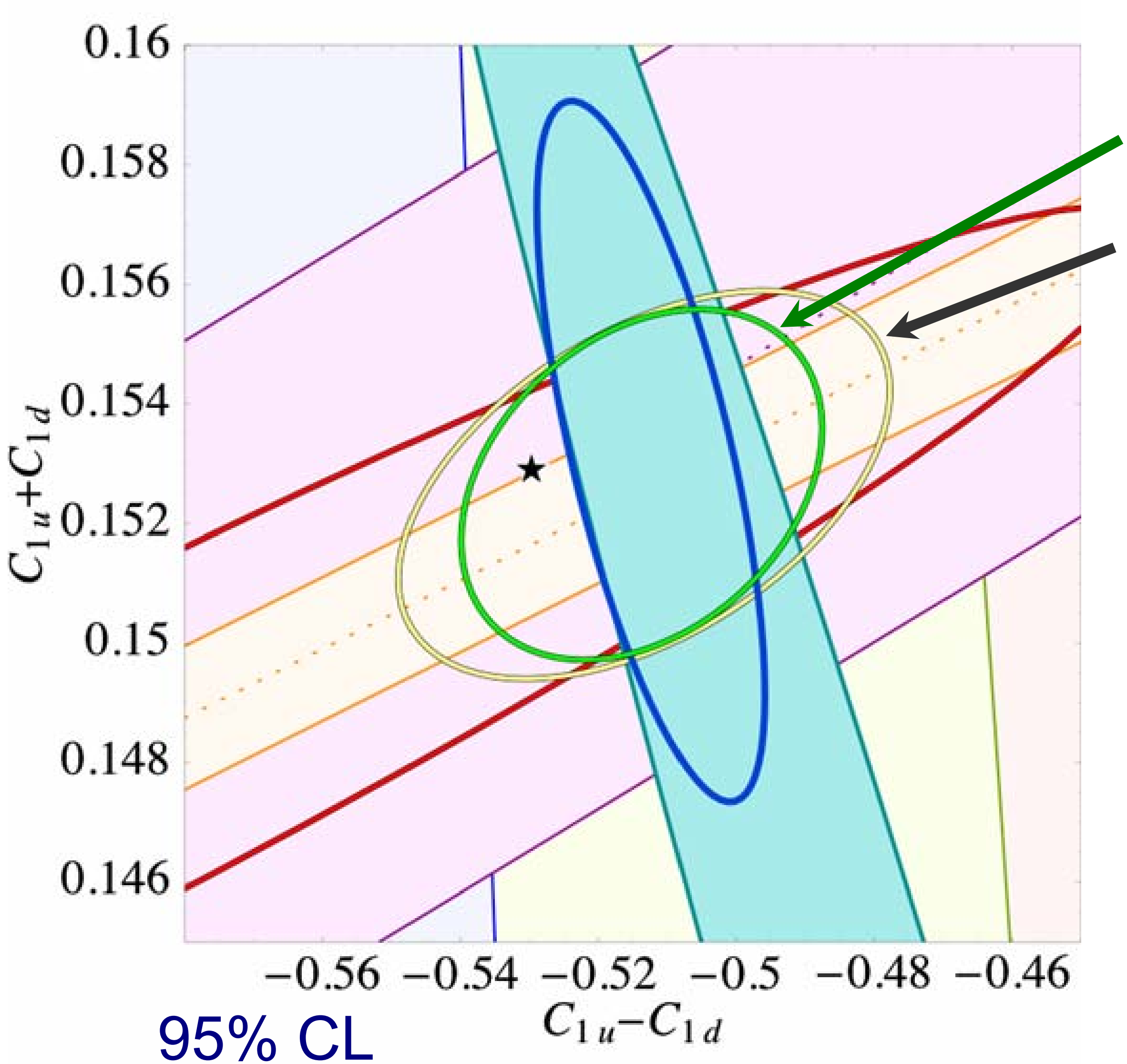

Repeat analysis with theory as an input

# Impact of theory?




95% CL

# Conclusions unchanged




95% CL

Results largely insensitive to best theory constraints.
Can simply use experimental constraints!

# AIM: Establish a New Paradigm for Nuclear Physics

**In the 21st Century we have the challenge to unify our understanding of nuclear systems over otherwise impossible ranges of density and strangeness in terms of THE best candidate for a fundamental theory of the strong force: QCD**

- **Precision electron scattering is essential to guide this unification**

- **On world scene JLab will beautifully complement the work in this area by J-PARC and GSI as well as RIA**

- **12 GeV will play a crucial role in solving one of the 10 outstanding problems in modern physics: origin of confinement**