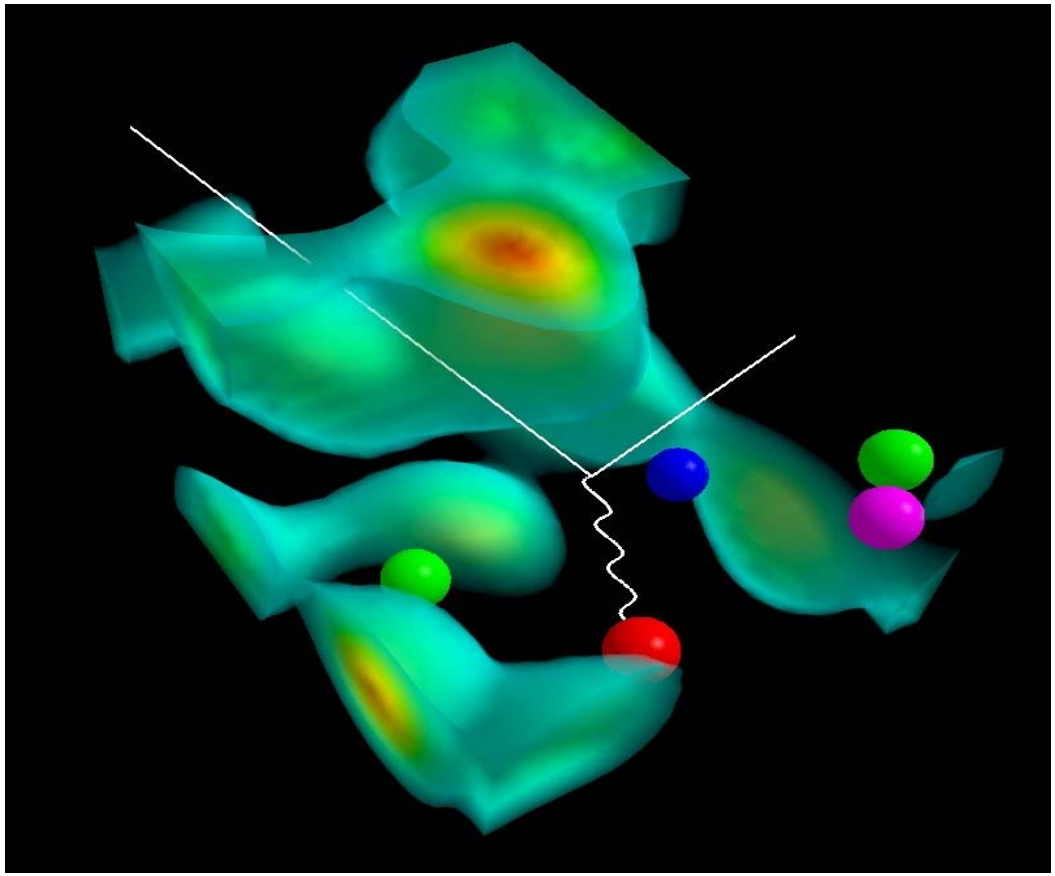
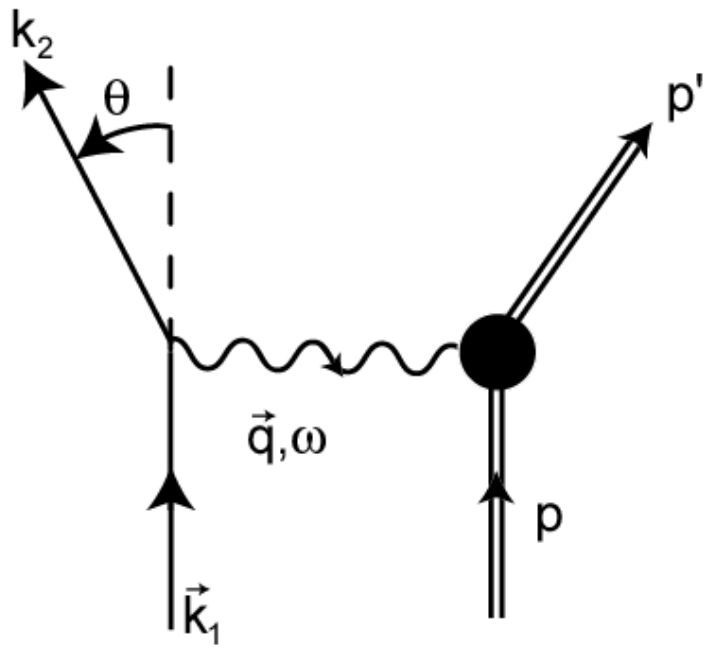
Precise Electro-Weak Studies: An Essential Element of the World-Wide Nuclear Physics Program



Anthony W. Thomas

BNL : February 5th 2008

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:

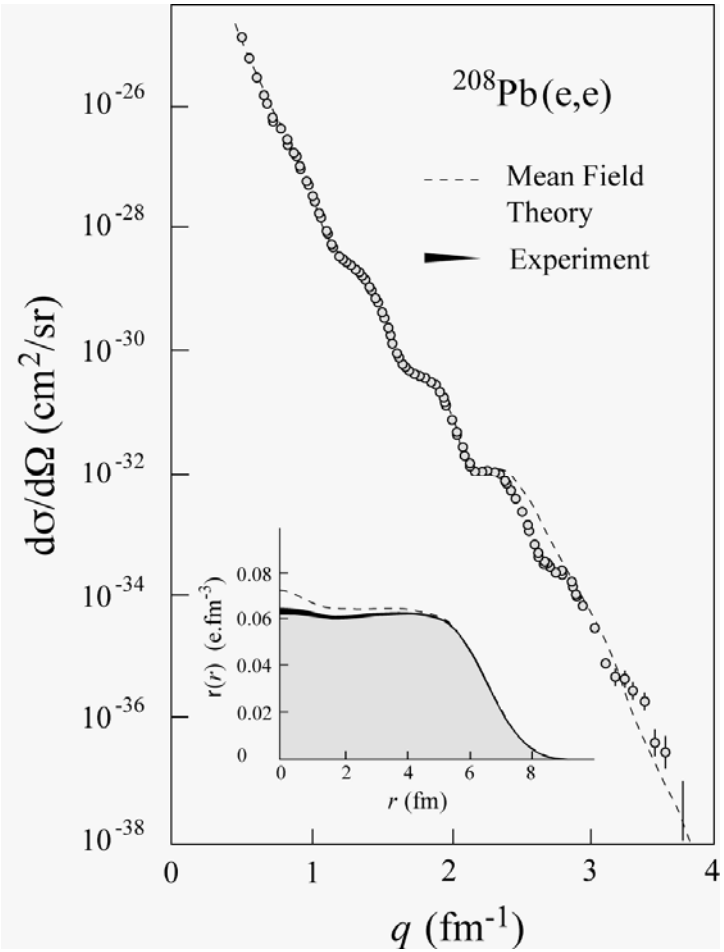
  $\lambda \cong 2\pi/q$ **(1 fm ⇔ 1 GeV/c)**

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

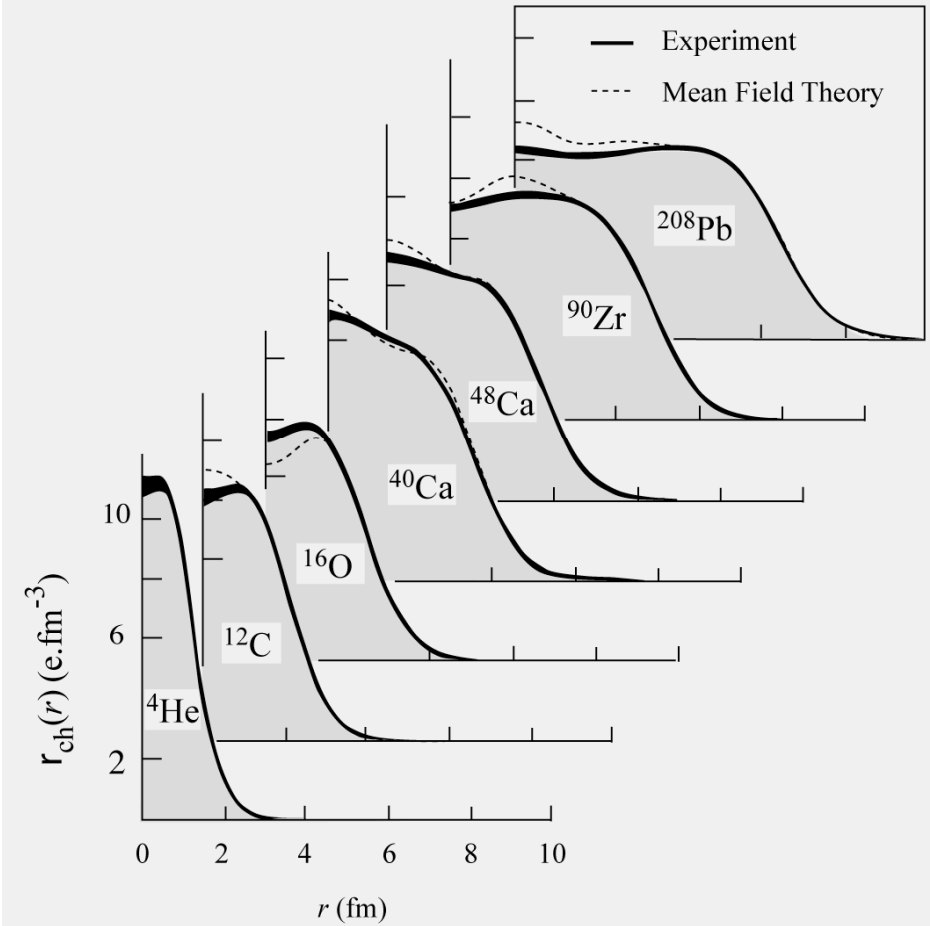
$Q^2 = -q^2 =$ 4-Momentum Transfer

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

(e,e) ⇒ Nuclear Charge Distributions

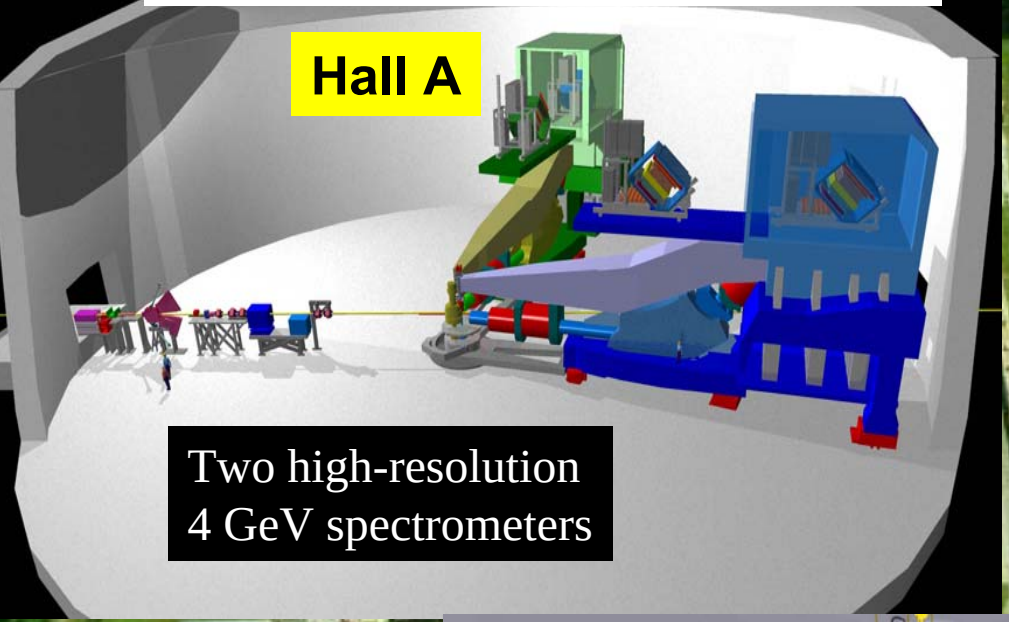


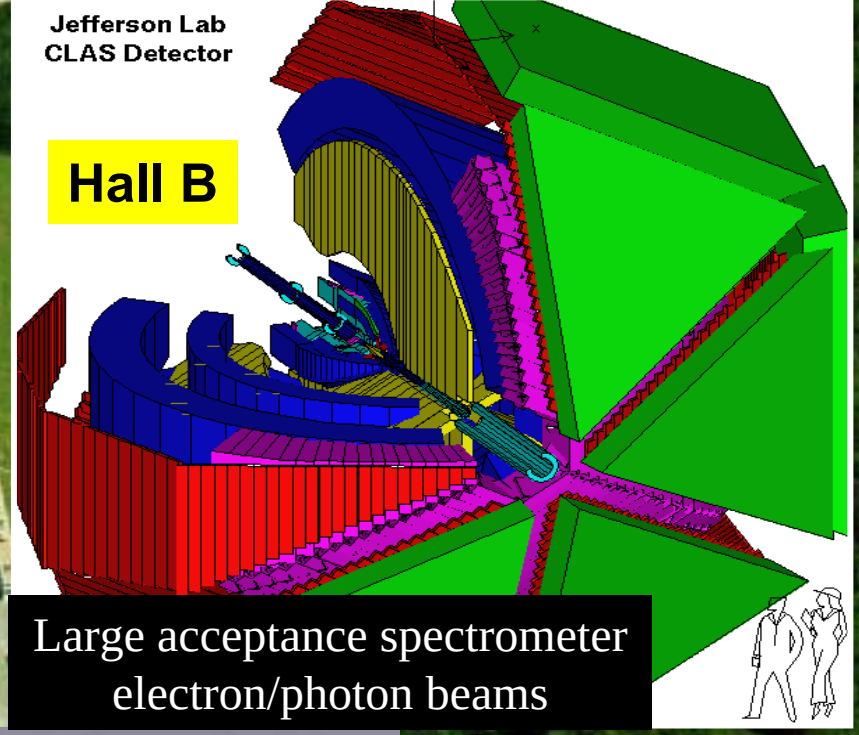
From Stanford to Saclay and Nikhef



Model-independent analysis ⇒ accurate nuclear charge distributions

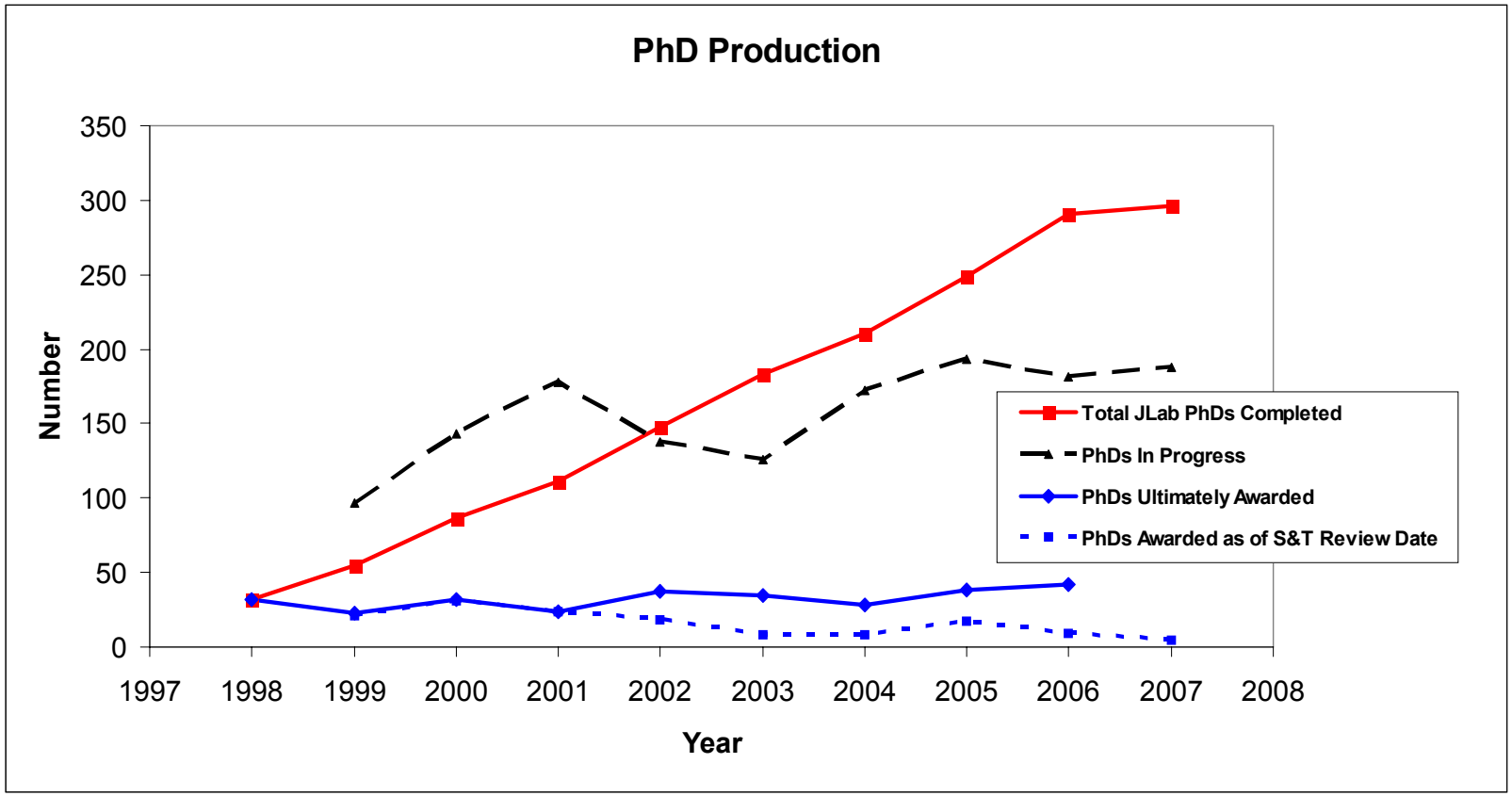
Jefferson Lab Today





Users / Students

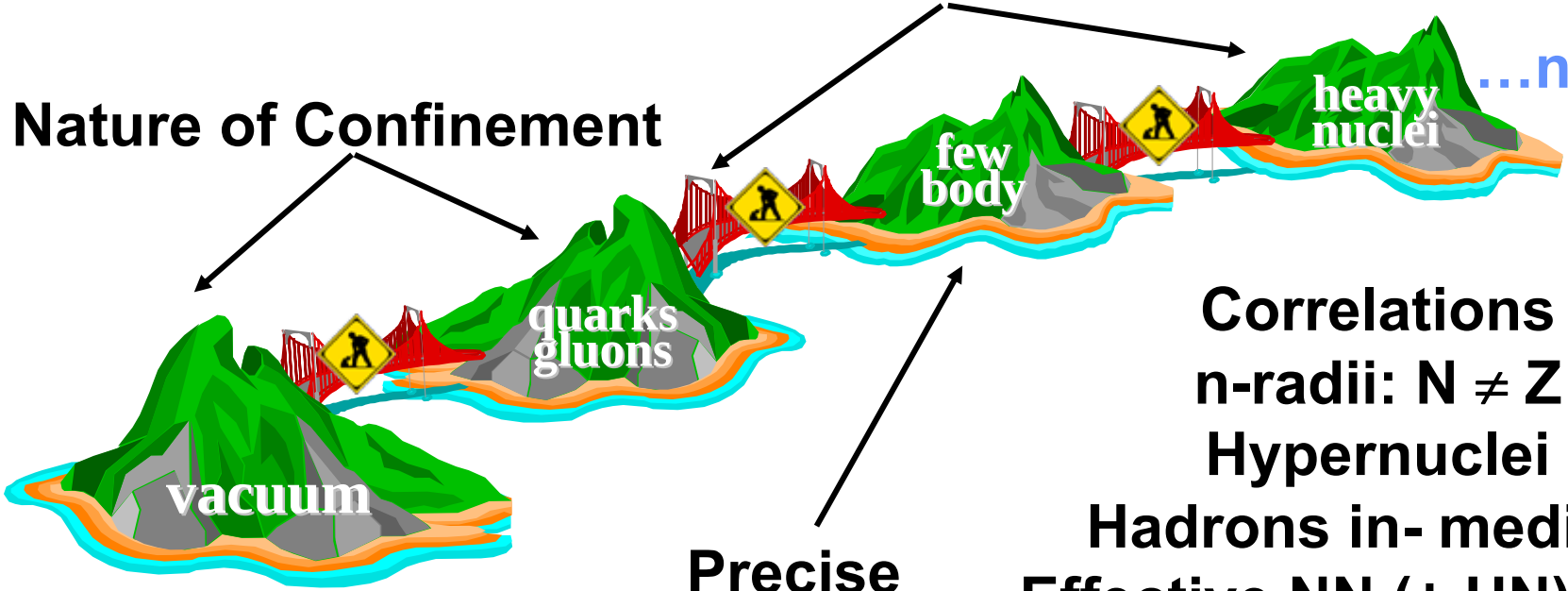
- Active Users: 1,200
  - Largest nuclear physics user base at any laboratory worldwide
- Produce ~ 30% of US PhDs in Nuclear Physics annually



Program Central to Nuclear Science

Quark-Gluon Structure
Of Nucleons and Nuclei

Nature of Confinement



…n-stars

Correlations
n-radii: N ≠ Z
Hypernuclei
Hadrons in- medium
Effective NN (+ HN) force

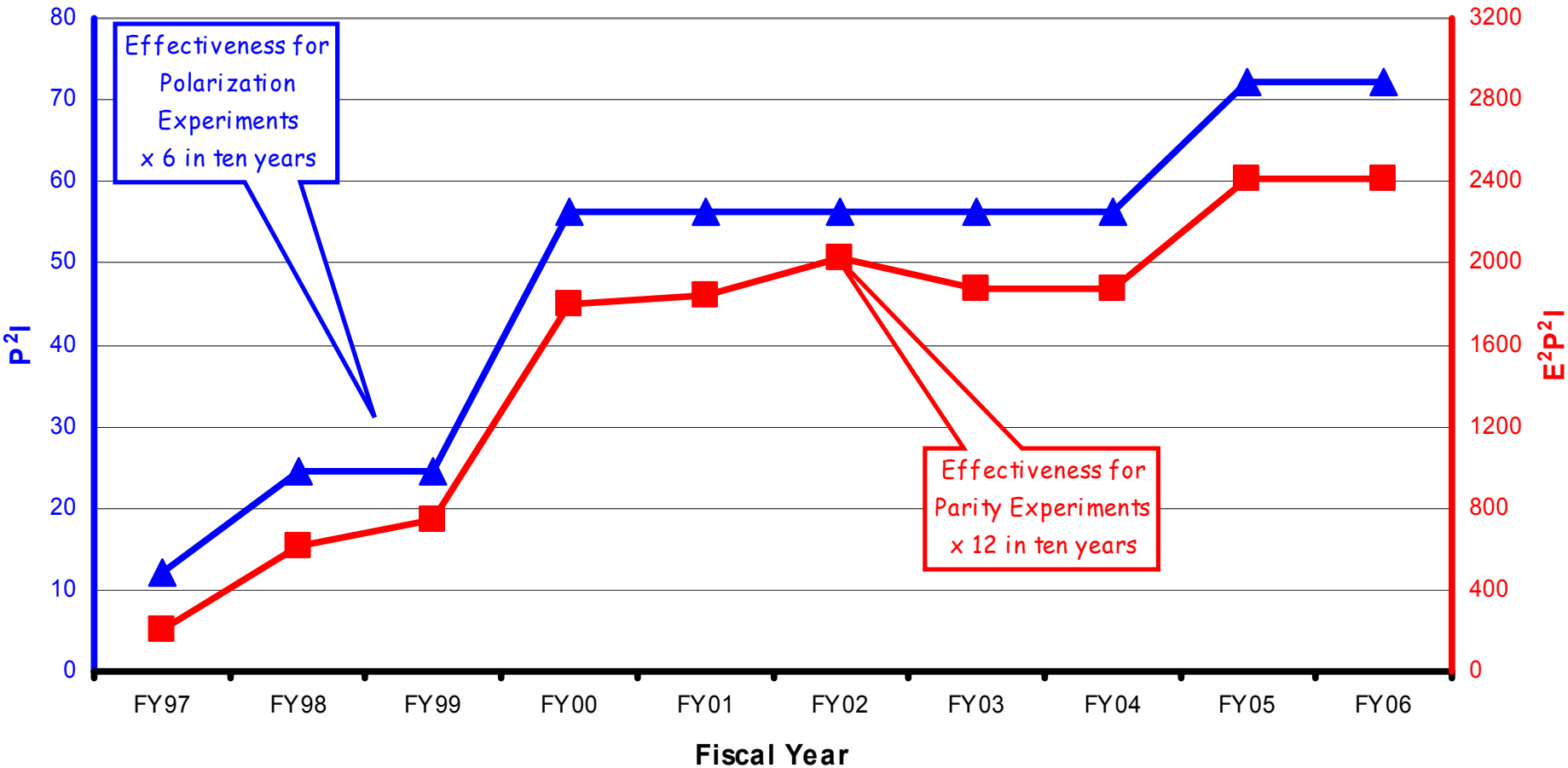
Precise
few-nucleon
calculations

Exotic mesons
and baryons

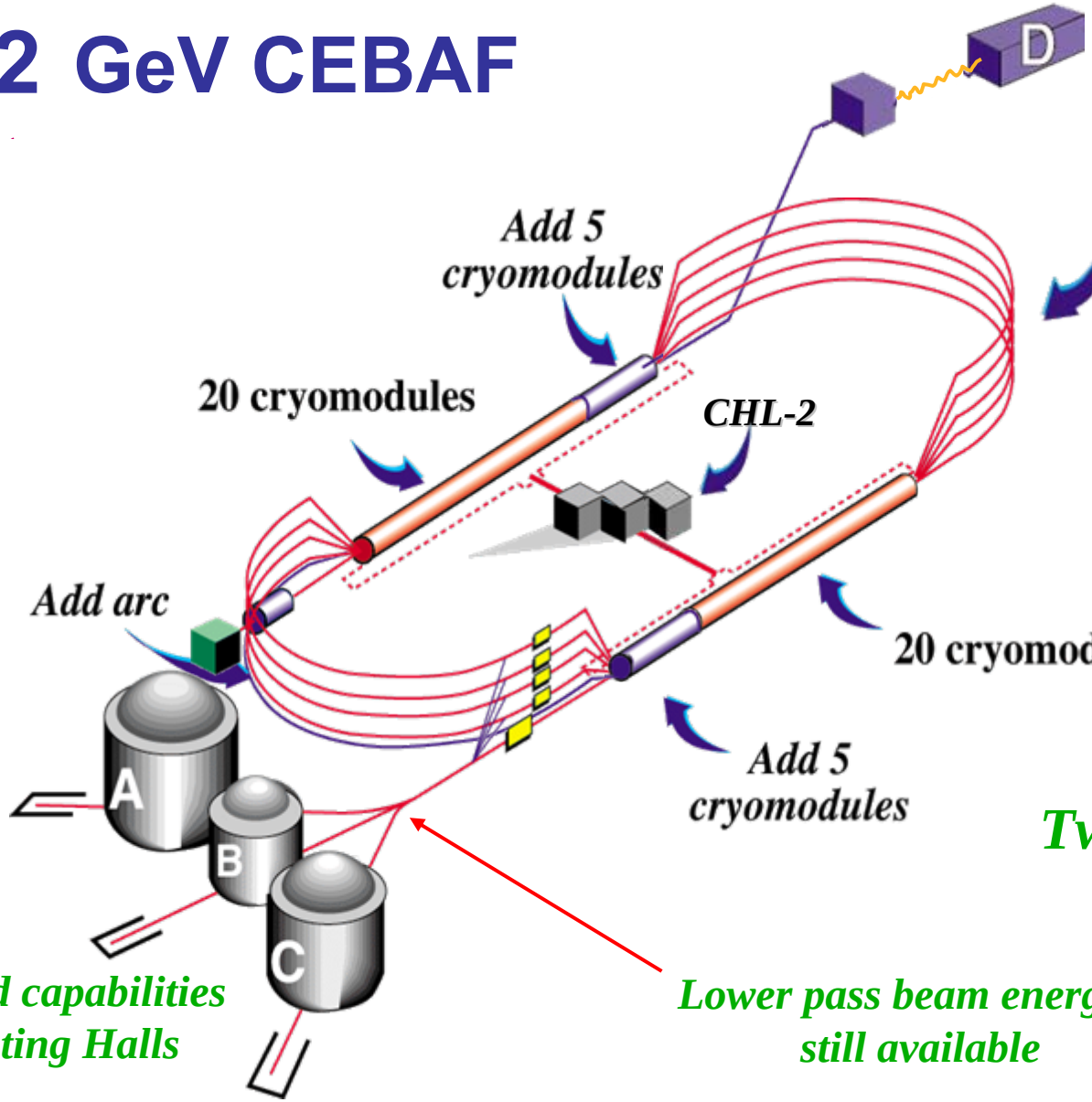
Highlights of First 10 Years

- Discovery of unexpected structure in G_E^p
- Determination of strangeness content of the nucleon
- Study of deformation of Δ and transition form factors of nucleon excited states
- Major new results for spin dependent structure functions
- New information on correlations in nuclei – tensor force
- Order of magnitude in precision test of Standard Model
- Duality, counting rules, pion form factor & lifetime, significant program in hypernuclear physics……

Effectiveness for Polarization and Parity Experiments



12 GeV CEBAF



Two 1.1 GV linacs

Enhanced capabilities in existing Halls

Lower pass beam energies still available

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.

12 GeV Upgrade: Status

- DOE SC Office of Project Assessment held Independent Project Review (IPR) on June 26-28, 2007 - evaluating project "baseline" cost, schedule, and technical performance

- Successfully concluded

- "Phase II" of the CD-2 review process (OECM External Independent Review)

- CD-2 Approval: obtained Nov 9th

- On track for CD-3 Approval (Construction Start) September 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**

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

Revolutionize Our Knowledge of Spin and Flavor Dependence of Valence PDFs

- **In over 35 years of study of DIS no-one has had the facilities to map out the <u>crucial valence region</u>**

- **Region is fundamental to our understanding of hadron structure: i.e. how nonperturbative QCD works!**

Role of di-quark correlations?

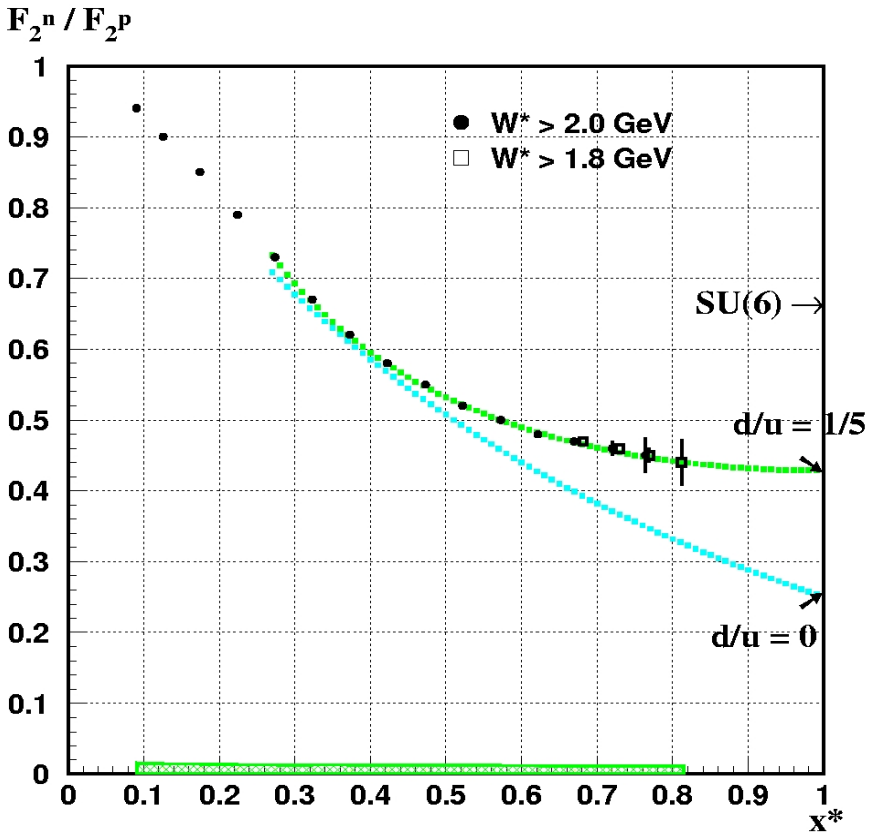
Role of hard scattering: pQCD / LCQCD guidance?

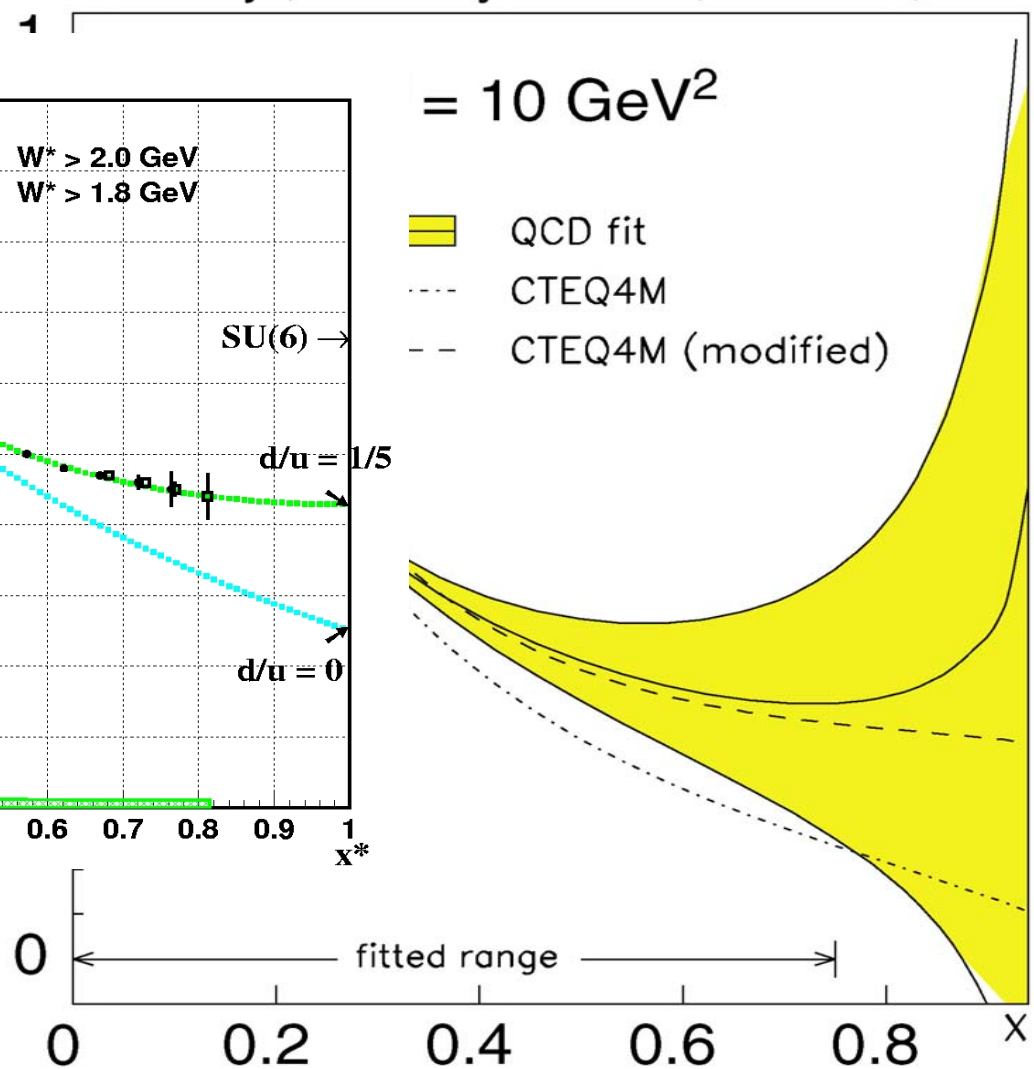
Breaking of SU(6) symmetry?

Moments of PDFs (and GPDs) from Lattice QCD….

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

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

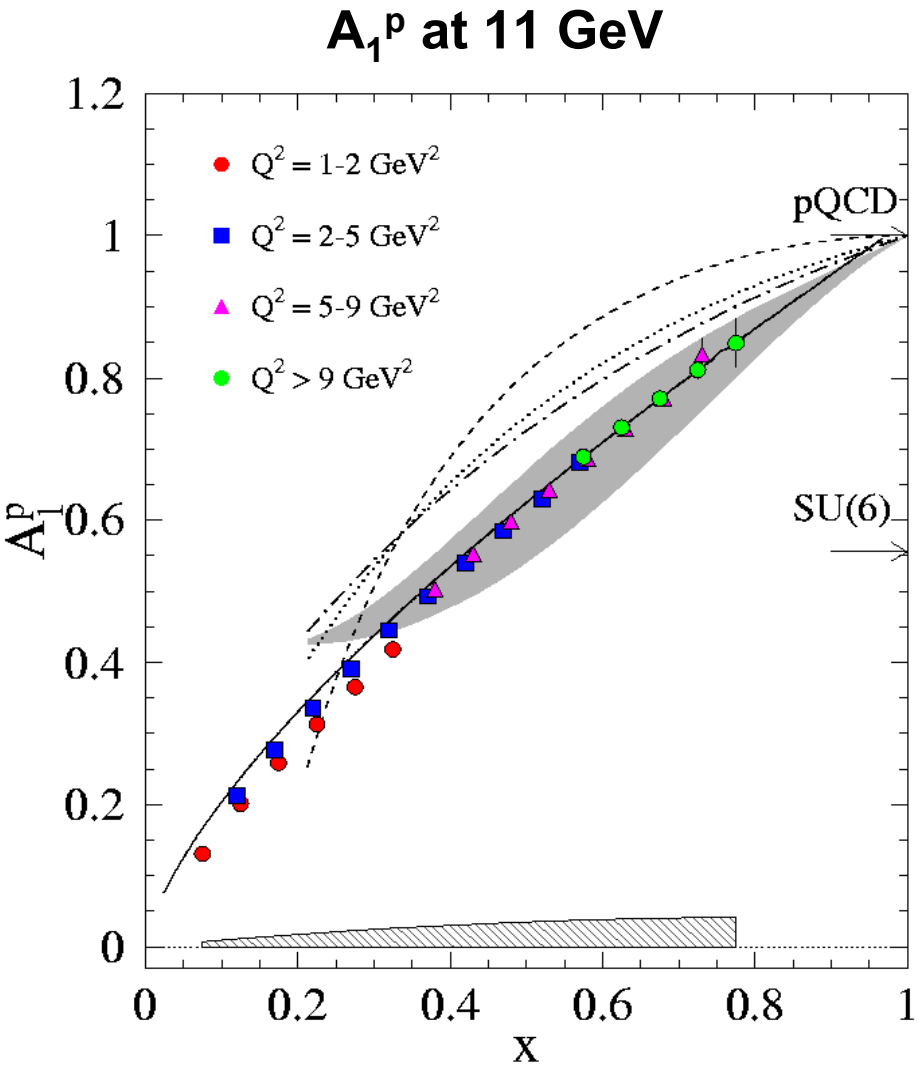


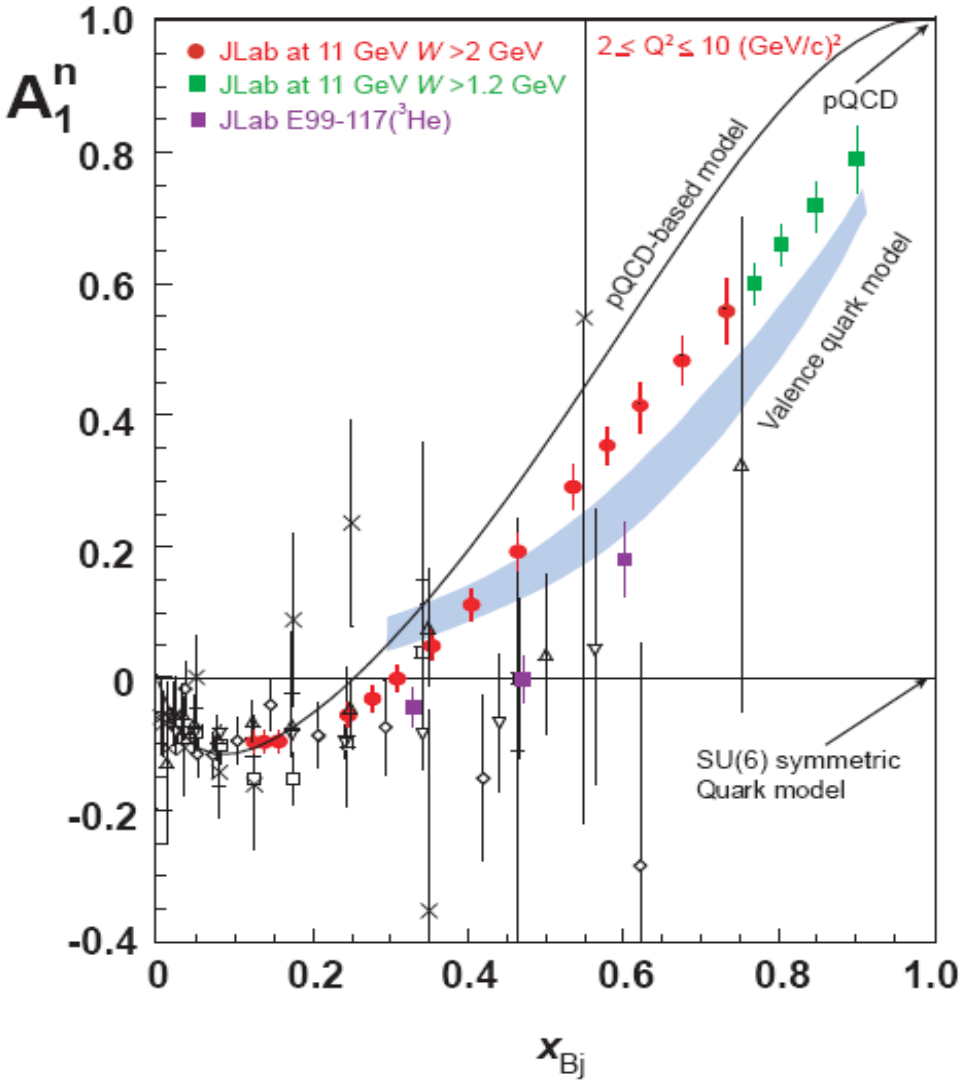


pQCD

di-quark correlations

12 GeV : Unambiguous Resolution of Valence Spin

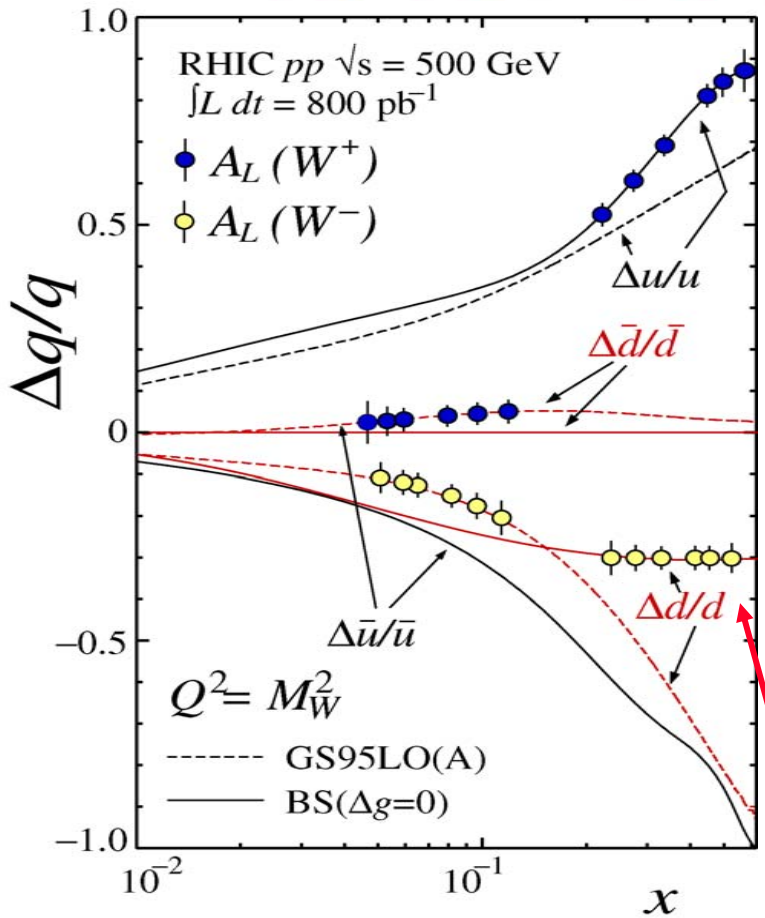




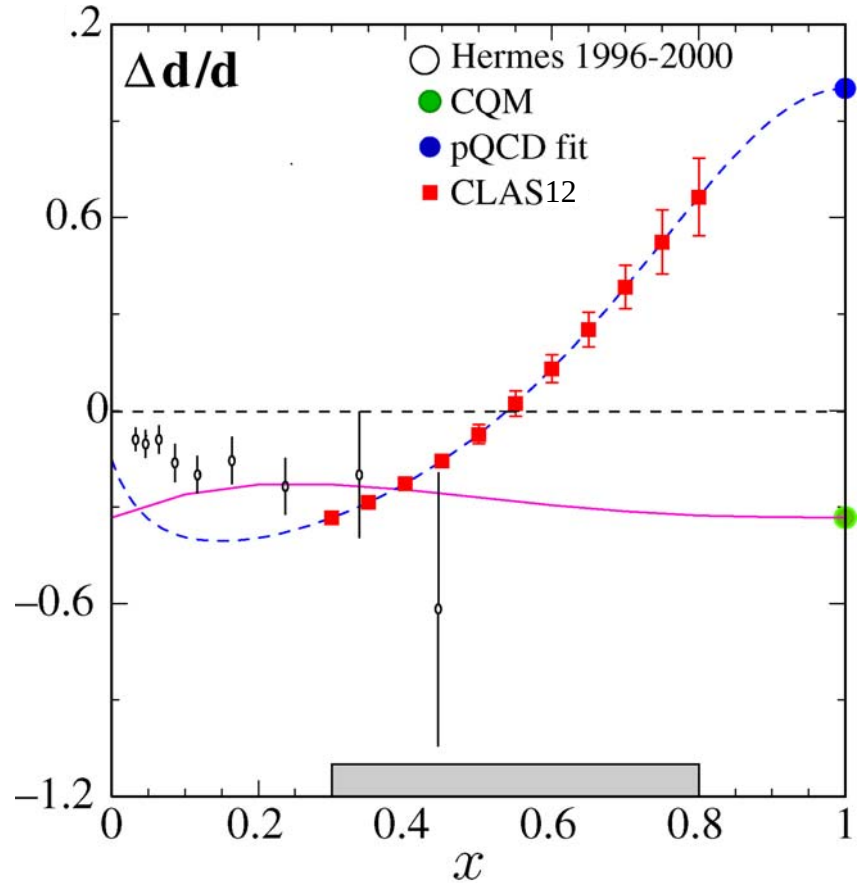
Complements Spin-Flavor Dependence at RHIC

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

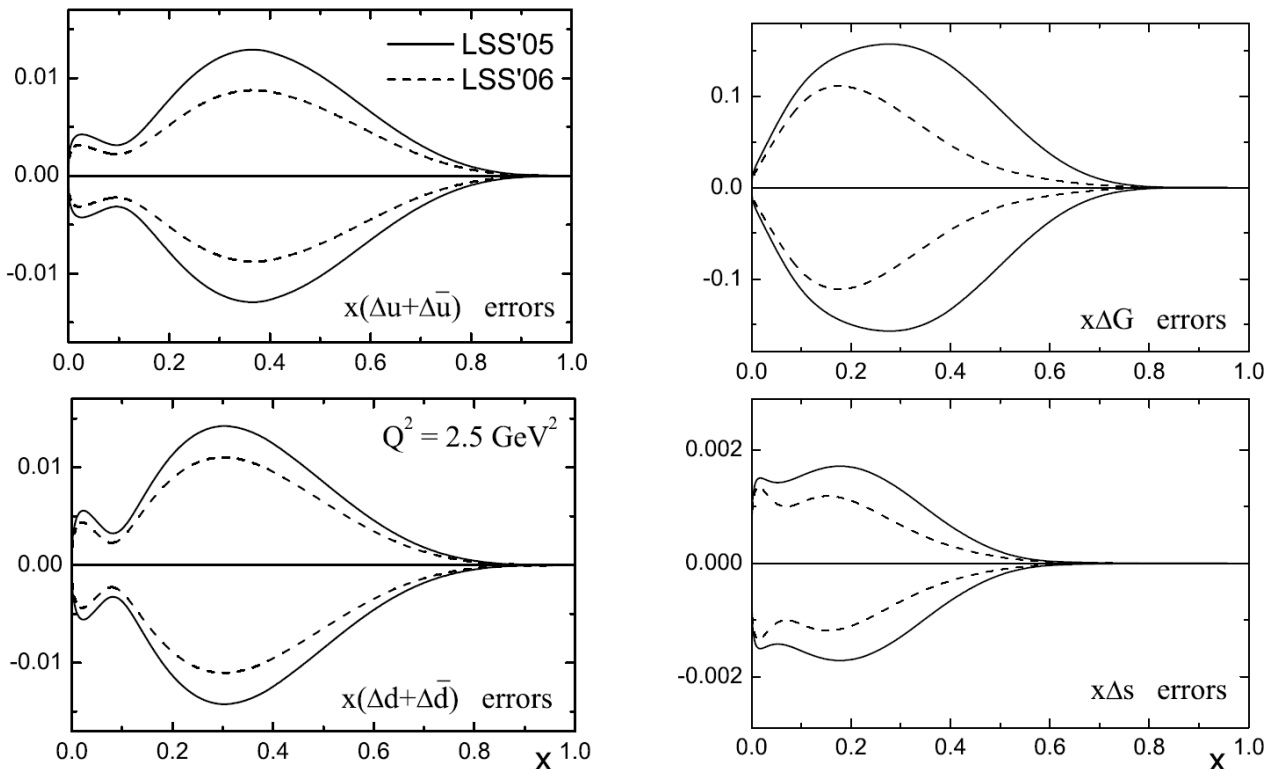


Stops below x=0.5 AND needs valence d(x)

Impact of CLAS Precision Data on Parton Distribution Functions

CLAS precision data more than doubled the data points in the DIS region from 30 years of high energy polarized structure function measurements.

The much improved control of higher twist (HT) effects achieved with these data allows to use them in global fits of the world data to extract PDFs.



At moderate x_B=0.4, the relative uncertainty of xΔG is reduced by a factor 3 and of $\Delta s-\Delta\bar{s}$ by a factor 2.

Conclude
$|\Delta G| < 0.3$
at $Q^2 = 1\ GeV^2$

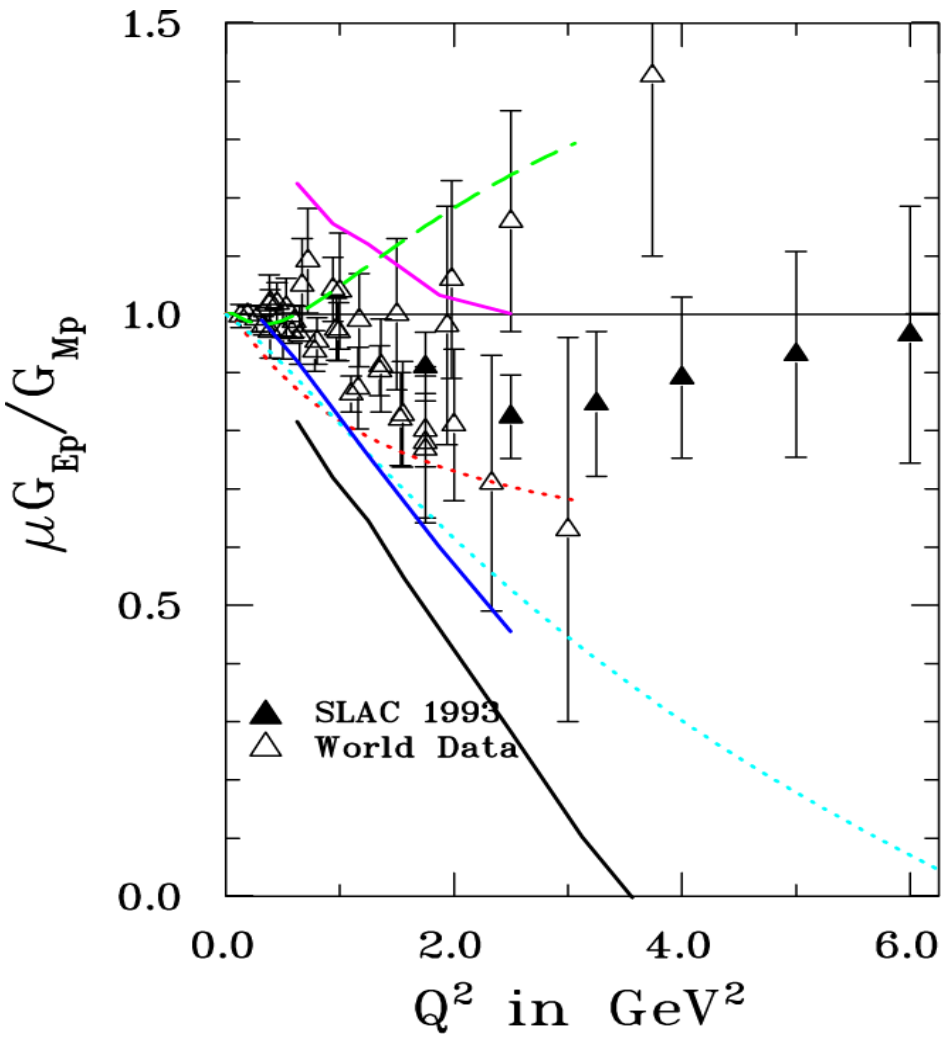
The dashed lines include the CLAS data in the analysis (LSS'06).

E. Leader, A. Sidorov, D. Stamenov, Phys.Rev.D75:074027,2007.

Anticipated Highlights of the 1st 5 Years

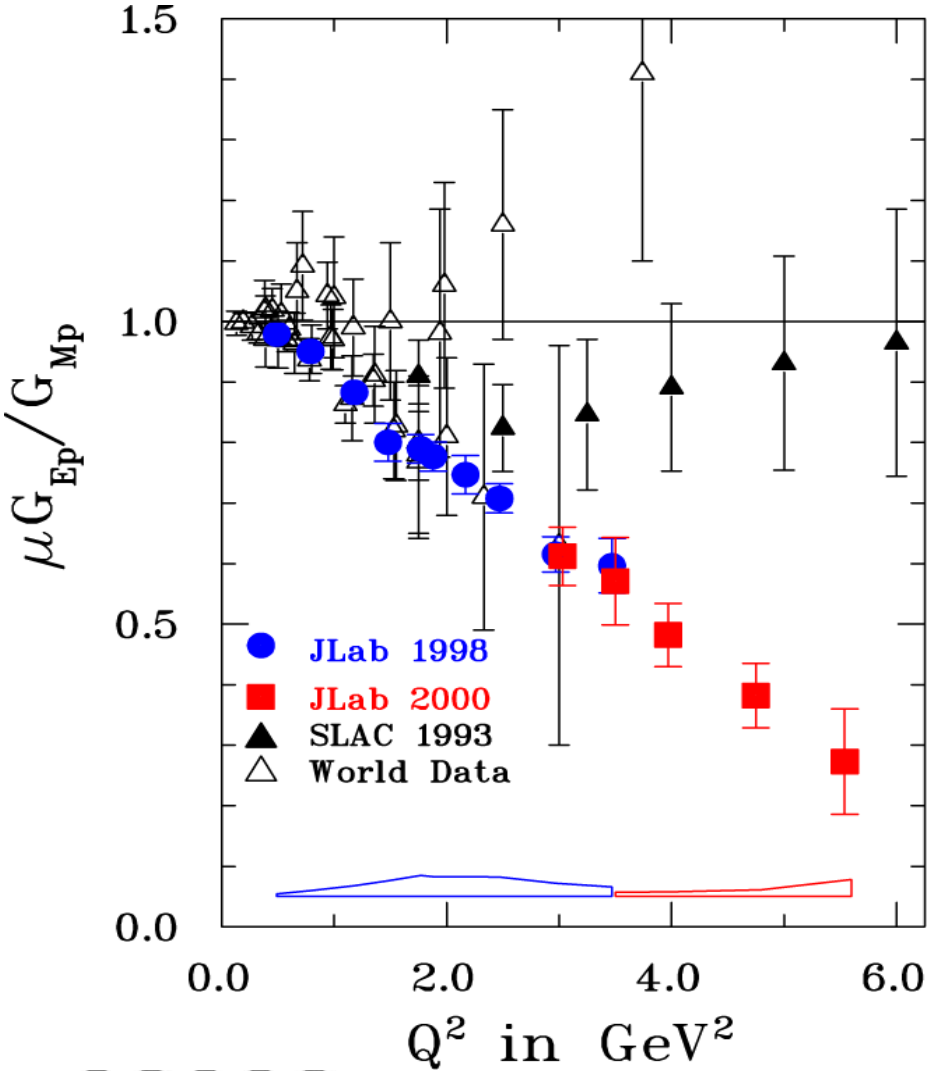
- Parton Distribution Functions
- **Form Factors**
- Generalized Parton Distributions
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model

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

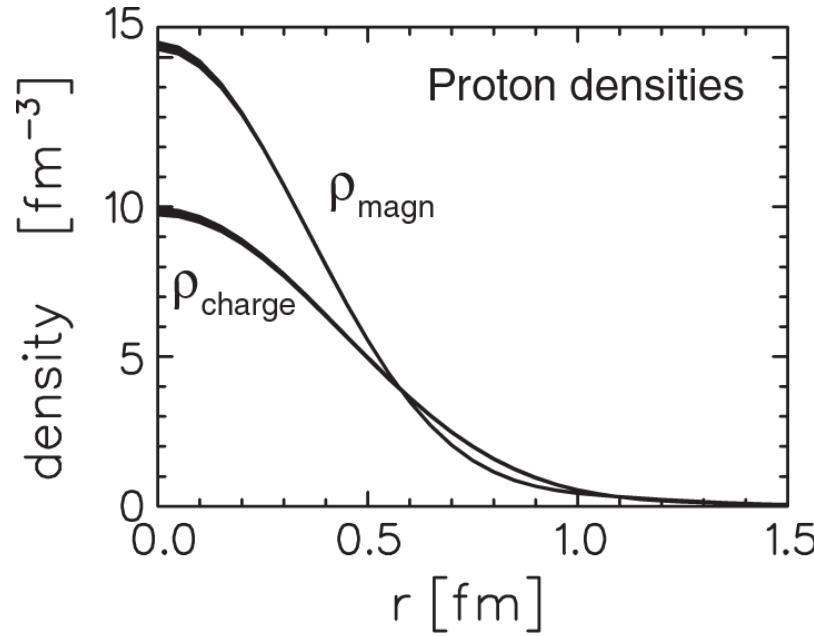
JLab Data Rewrote the Text Book



- High Intensity
- High Duty Factor
- High Polarization

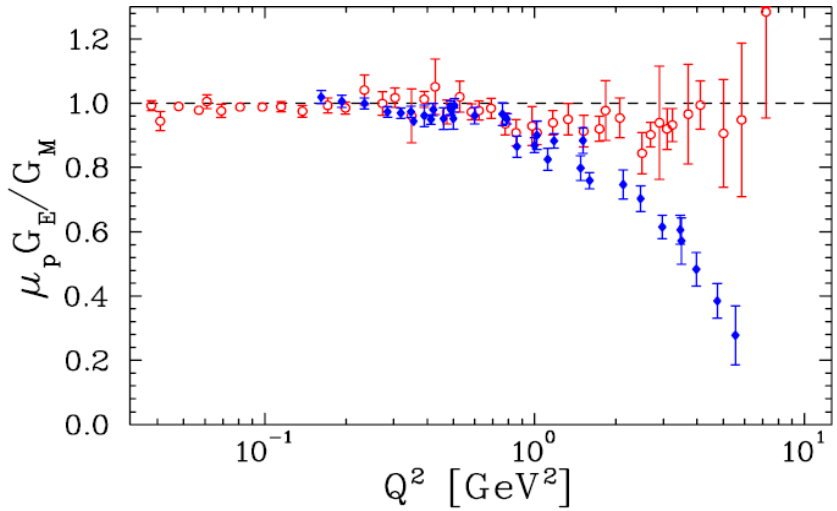
⇒ Revolutionized our knowledge

⇒

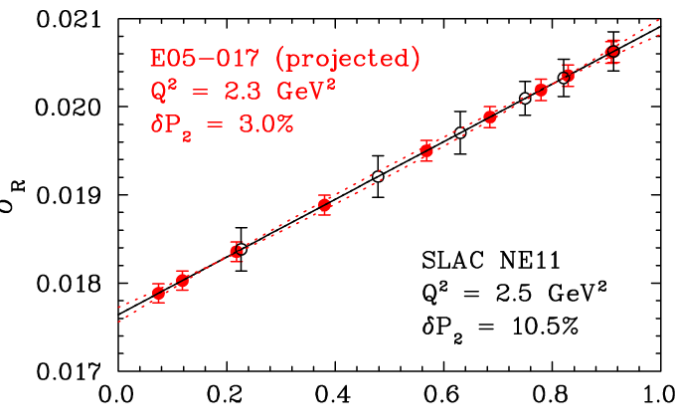


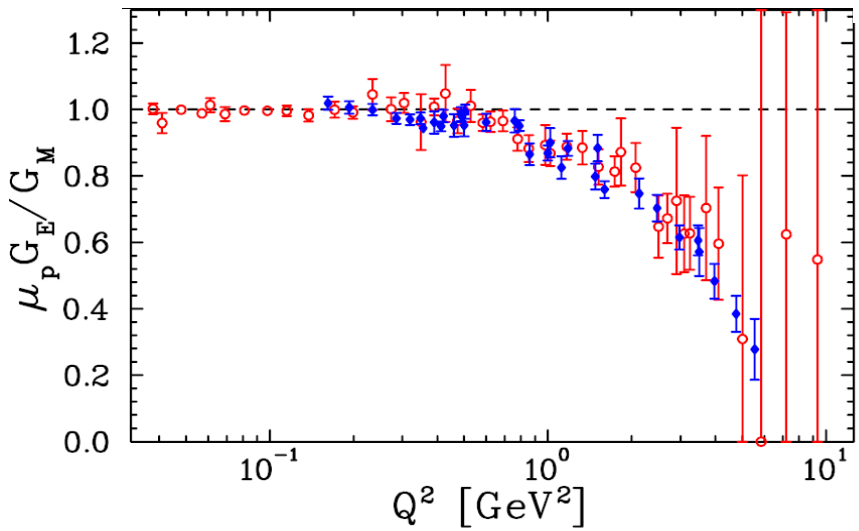
Latest Theoretical Insights

- **Two photon exchange explains most of the difference**



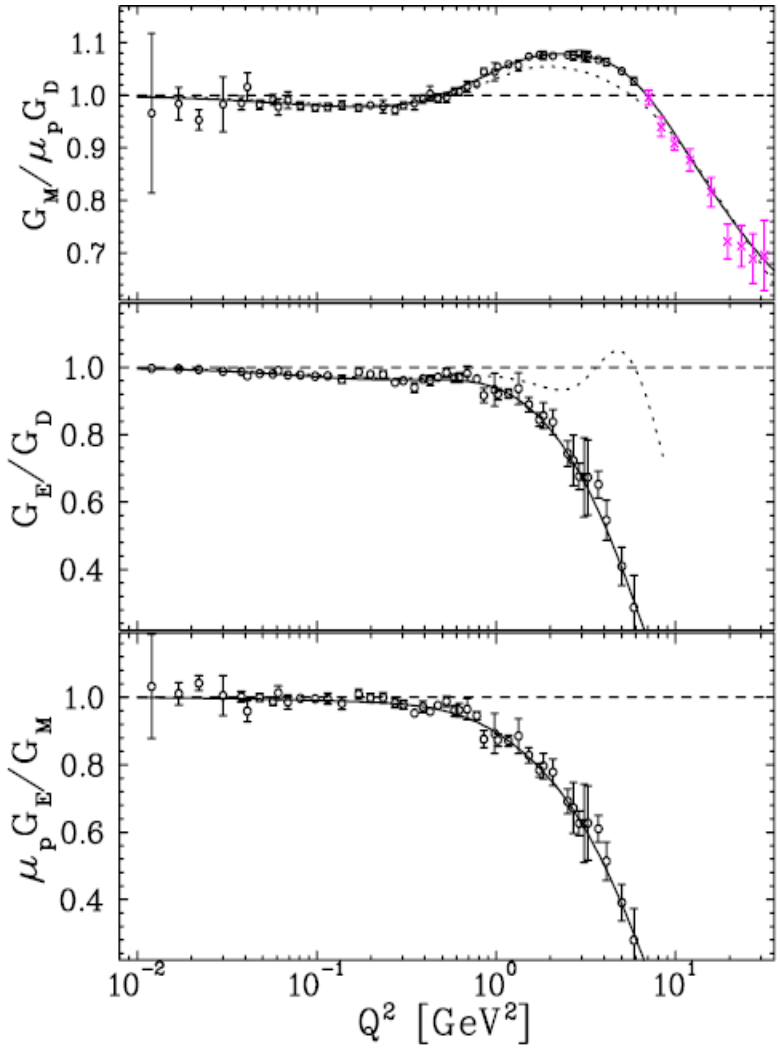
Arrington, Melnitchouk, Tjon, arXiv:0707.1861 (2007)

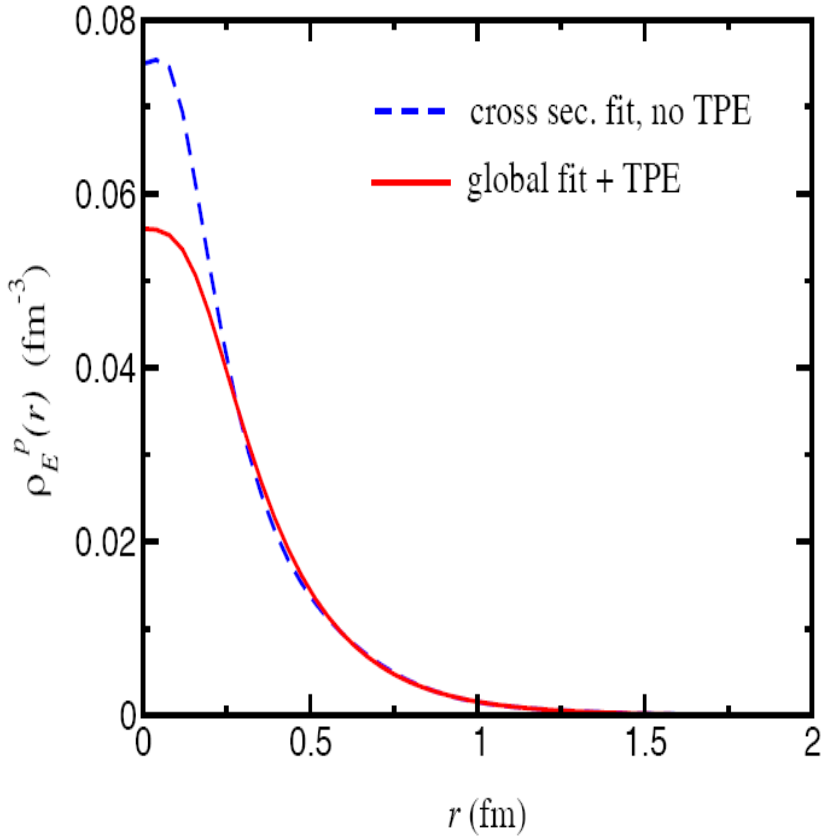




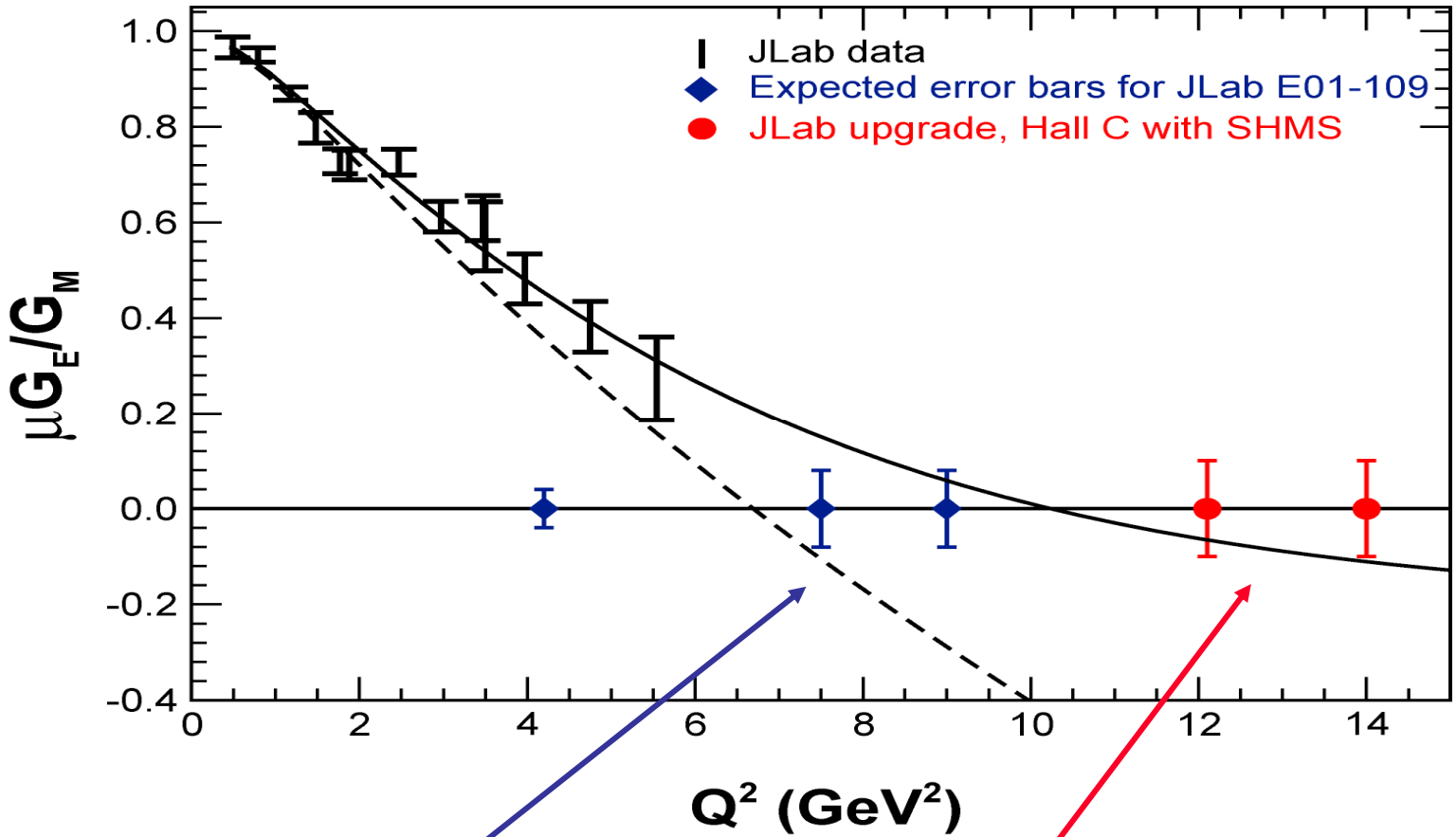
E05-017 data taking just completed

⇒ 30% Correction to Central Charge Density of p





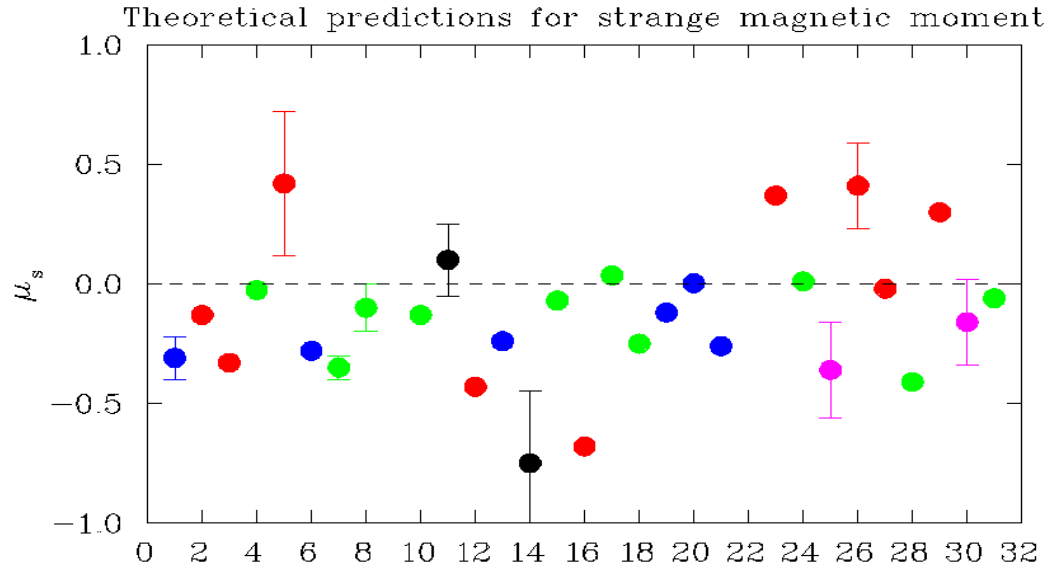
Future Measurements on G_E^p



- 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)**

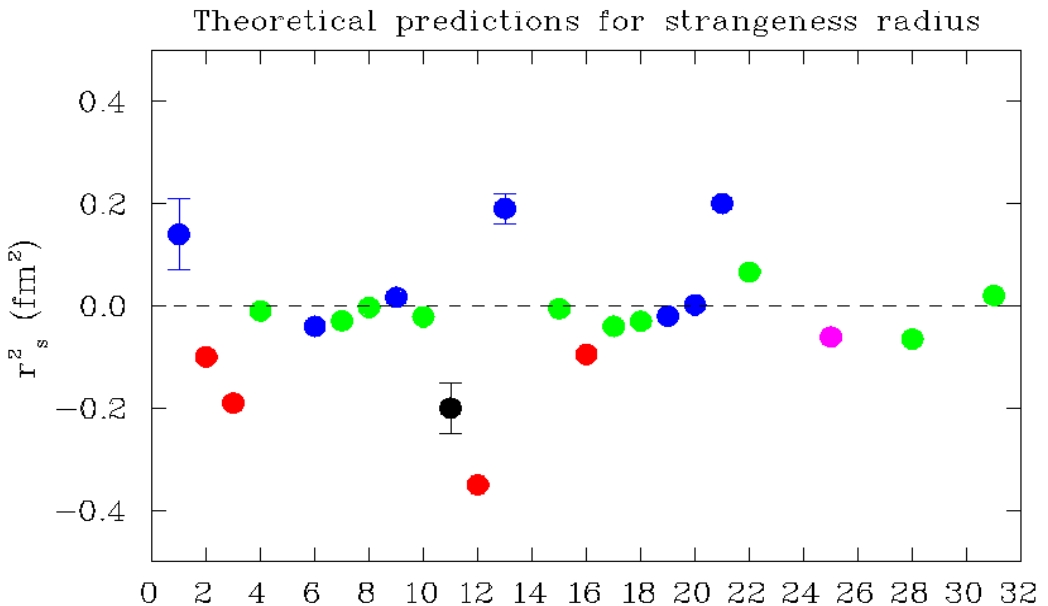
Role of Strange Quarks in the Nucleon

Early Theoretical predictions at $Q^2 = 0$



$$\mu_s \equiv G_M^s(Q^2 = 0)$$

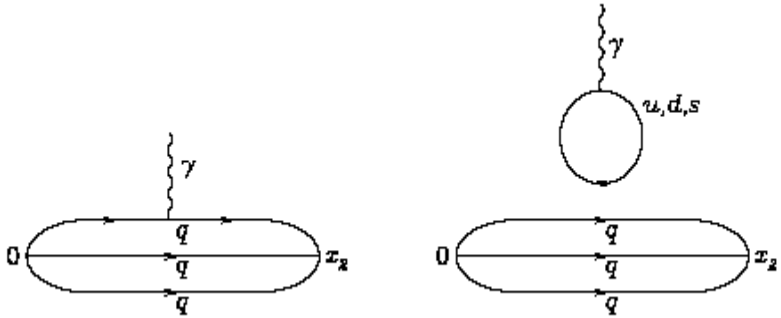
Non-zero value of G^s_E or G^s_M requires spatial separation of s and $\bar{s}$



$$r_s^2 \equiv -6\left[\frac{dG_E^s}{dQ^2}\right]_{Q^2=0}$$

from Mark Pitt

Magnetic Moments within QCD



CS

$$p = 2/3\, u^p - 1/3\, d^p + O_N$$

$$n = -1/3\, u^p + 2/3\, d^p + O_N$$

$$2p + n = u^p + 3\, O_N$$

$$(\text{and } p + 2n = d^p + 3\, O_N)$$

$$\Sigma^+ = 2/3\, u^\Sigma - 1/3\, s^\Sigma + O_\Sigma$$

$$\Sigma^- = -1/3\, u^\Sigma - 1/3\, s^\Sigma + O_\Sigma$$

$$\Sigma^+ - \Sigma^- = u^\Sigma$$

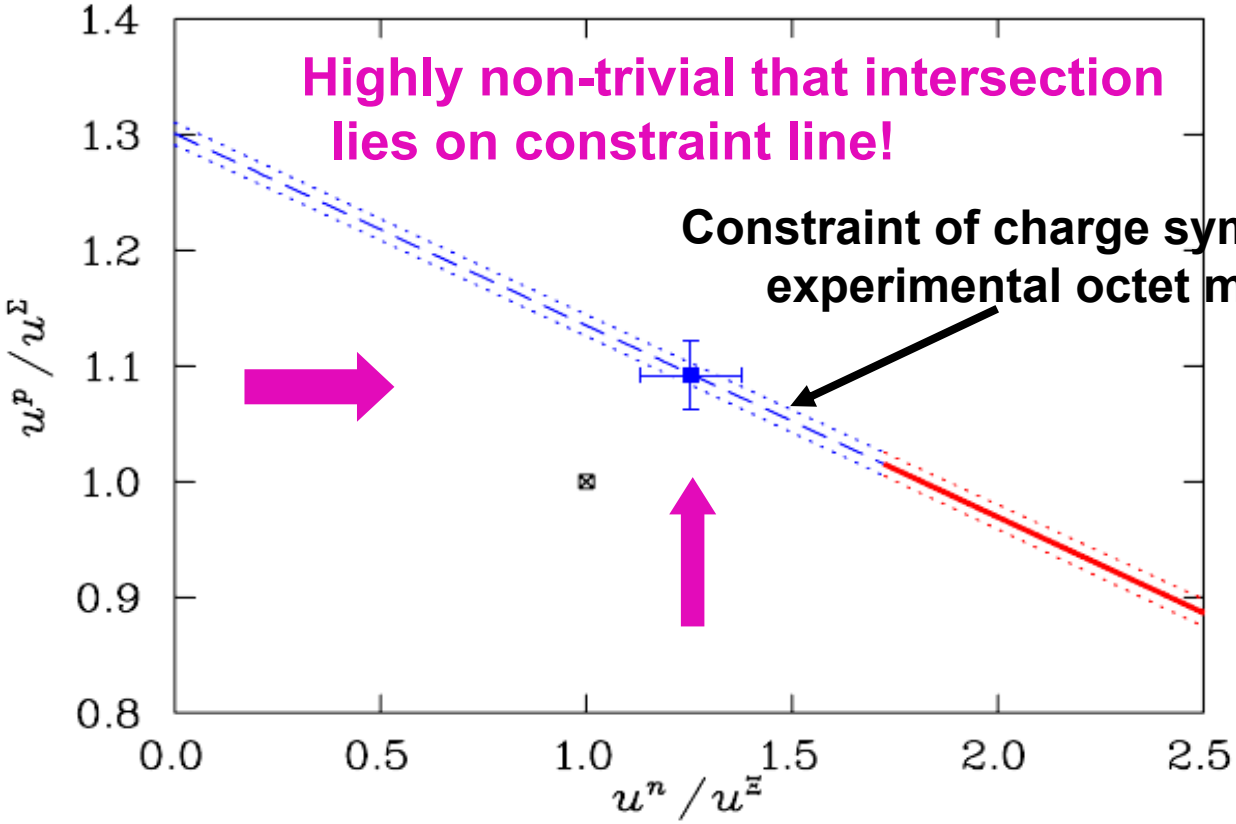
HENCE: $O_N = 1/3\, [\, 2p + n - (u^p / u^\Sigma)\, (\Sigma^+ - \Sigma^-)\,]$

Just these ratios from Lattice QCD

OR $O_N = 1/3\, [\, n + 2p - (u^n / u^\Xi)\, (\Xi^0 - \Xi^-)\,]$

Modern Lattice QCD Result for G_M^s

1.10±0.03

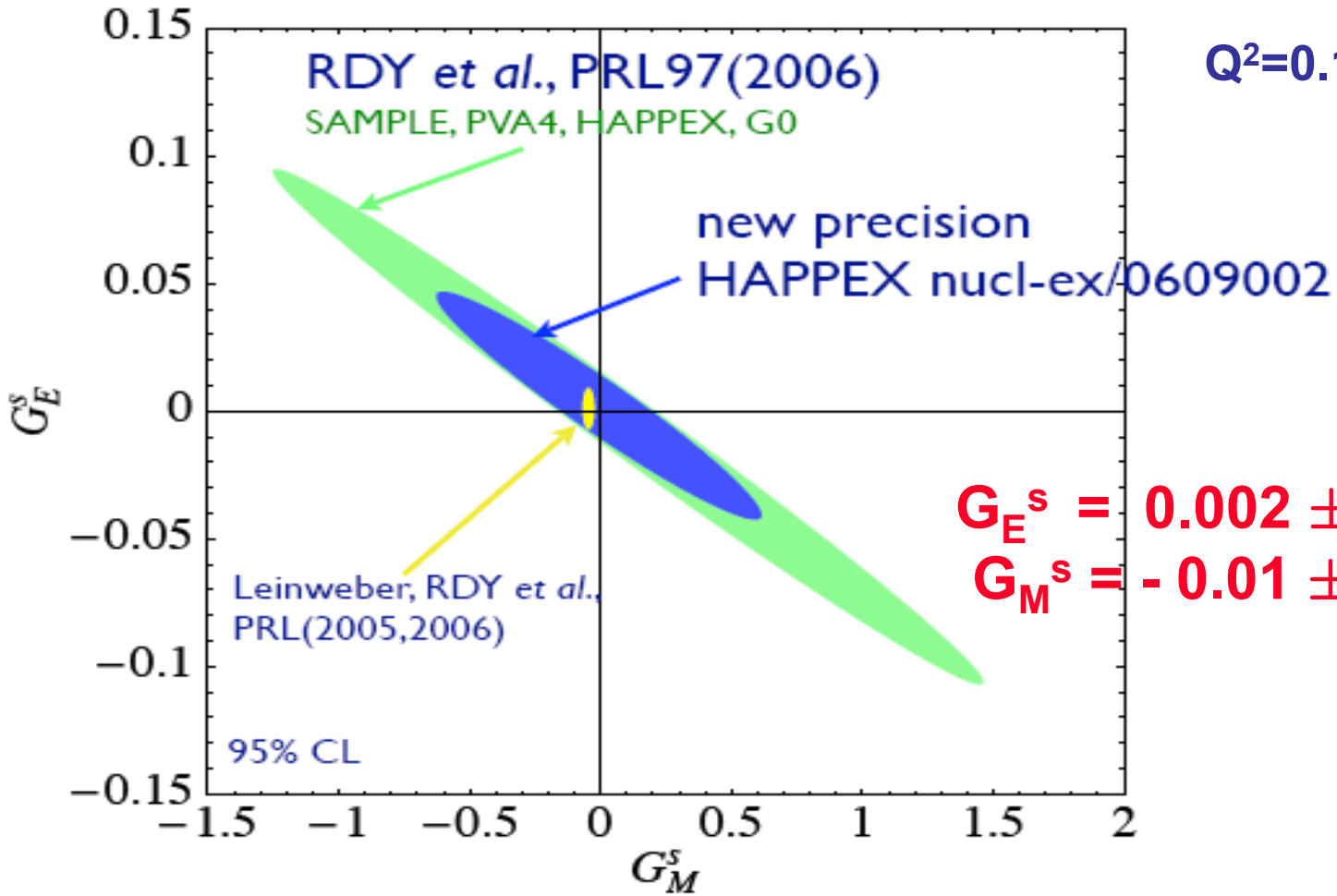


1.25±0.12

Yields :G_M^s = -0.046 ± 0.019 μ_N

Leinweber et al., (PRL June '05) hep-lat/0406002

PVES at 6 GeV Has Achieved Outstanding Precision for Strange Form Factors



Q^2=0.1 GeV^2

G_E^s = 0.002 ± 0.018
G_M^s = - 0.01 ± 0.25

This has recently been shown to enable a dramatic improvement in precision in testing the Standard Model

Anticipated Highlights of the 1st 5 Years

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- Generalized Parton Distributions
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
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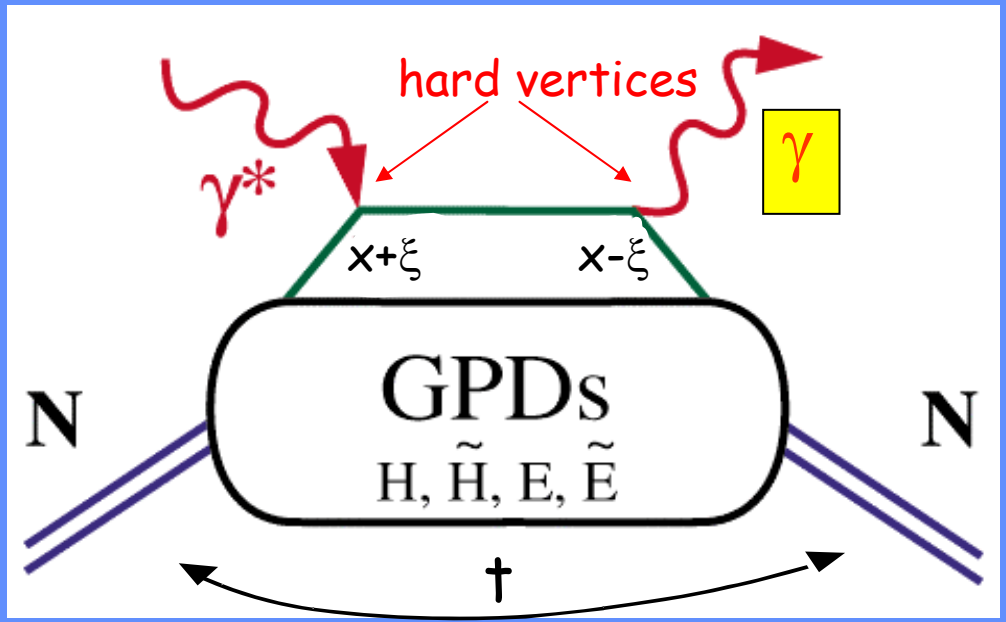
GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x - quark momentum fraction

ξ- longitudinal momentum transfer

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

At large Q^2 : QCD factorization theorem → hard exclusive process can be described by 4 transitions (Generalized Parton Distributions) :

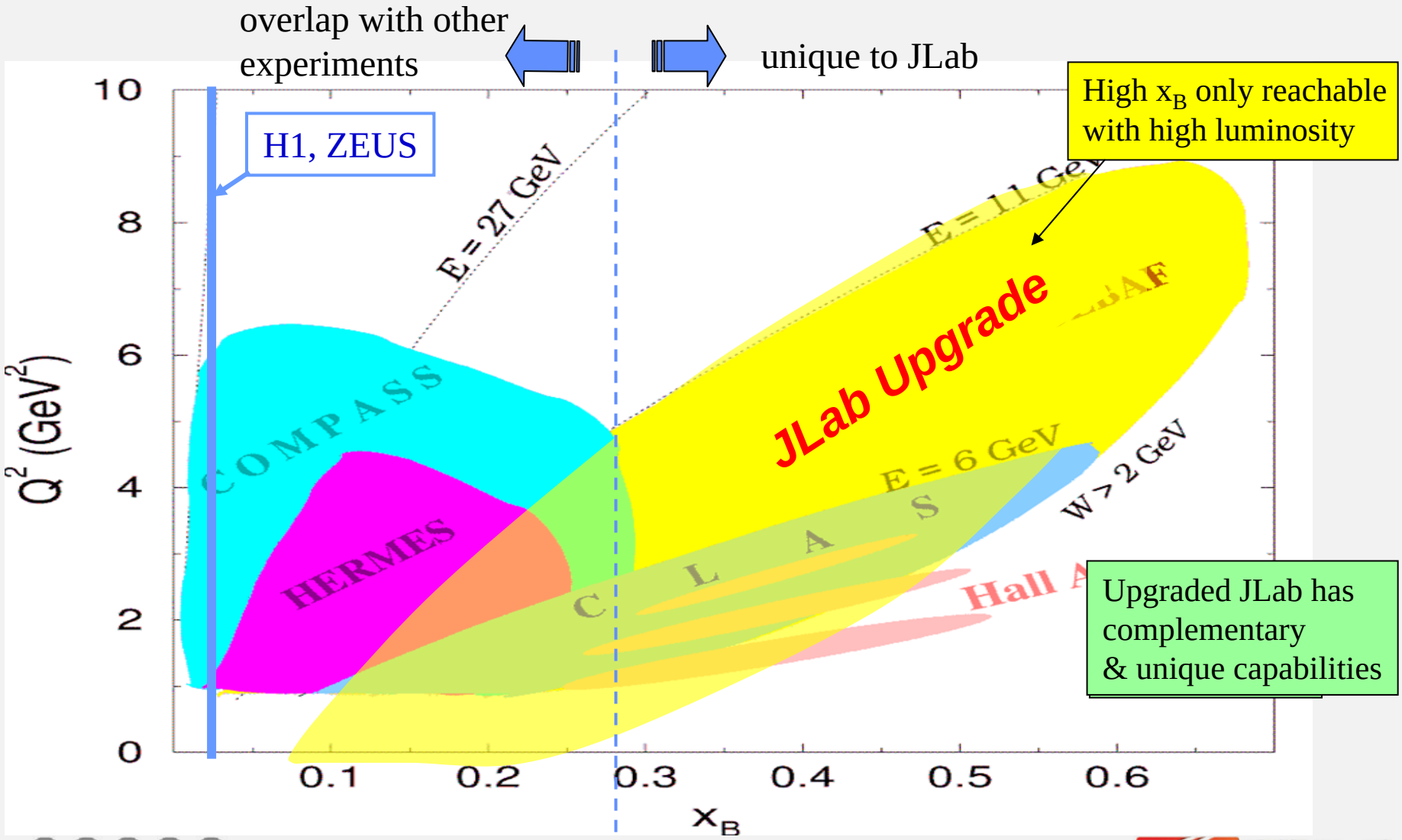
Vector : $H(x, \xi, t)$

Tensor : $E(x, \xi, t)$

Axial-Vector : $\tilde{H}(x, \xi, t)$

Pseudoscalar : $\tilde{E}(x, \xi, t)$

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



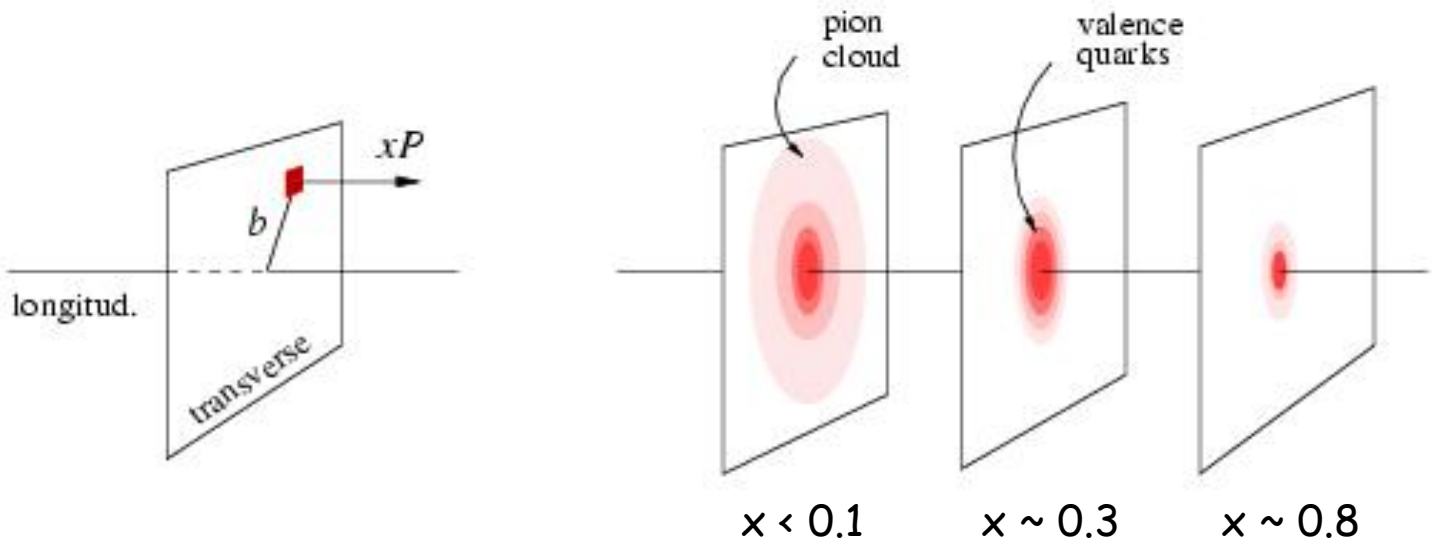
Upgraded JLab has complementary & unique capabilities

Why the interest in 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 a model-dependent way)

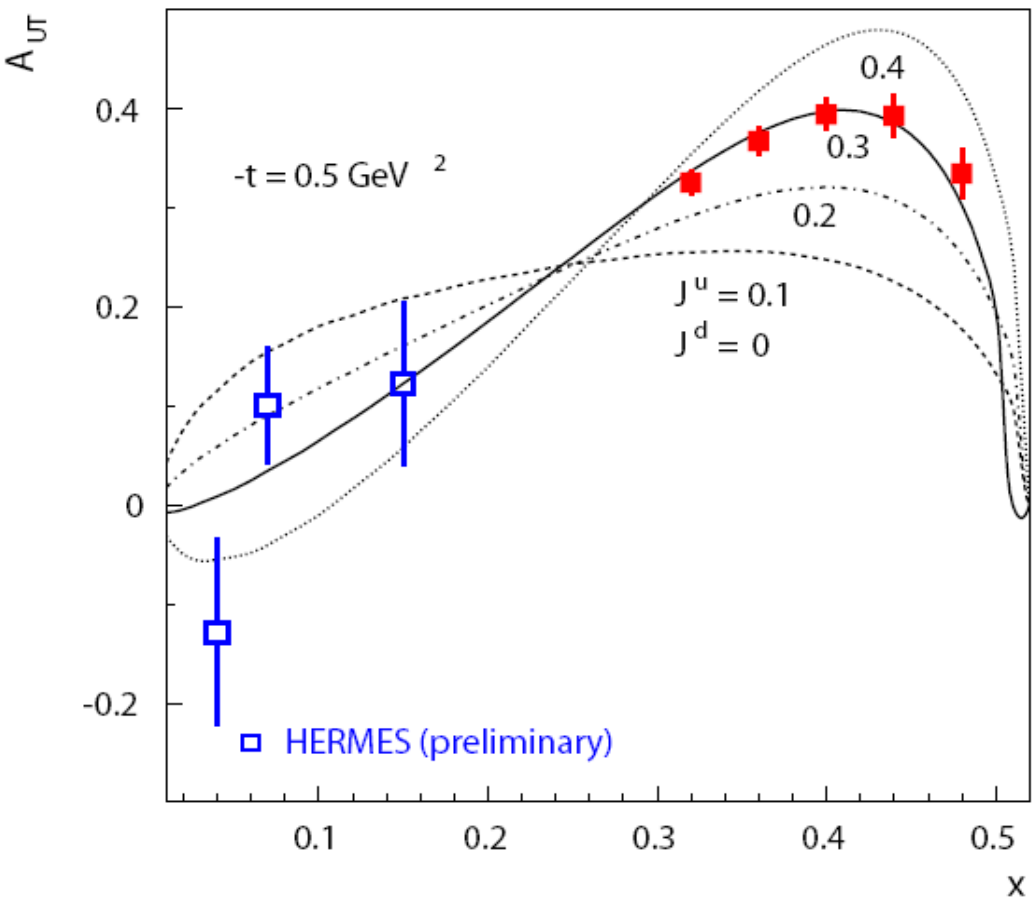
At 12 GeV: e.g. Exclusive ρ^0 with transverse target expect to determine quark orbital angular momentum

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

ρ^0

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

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

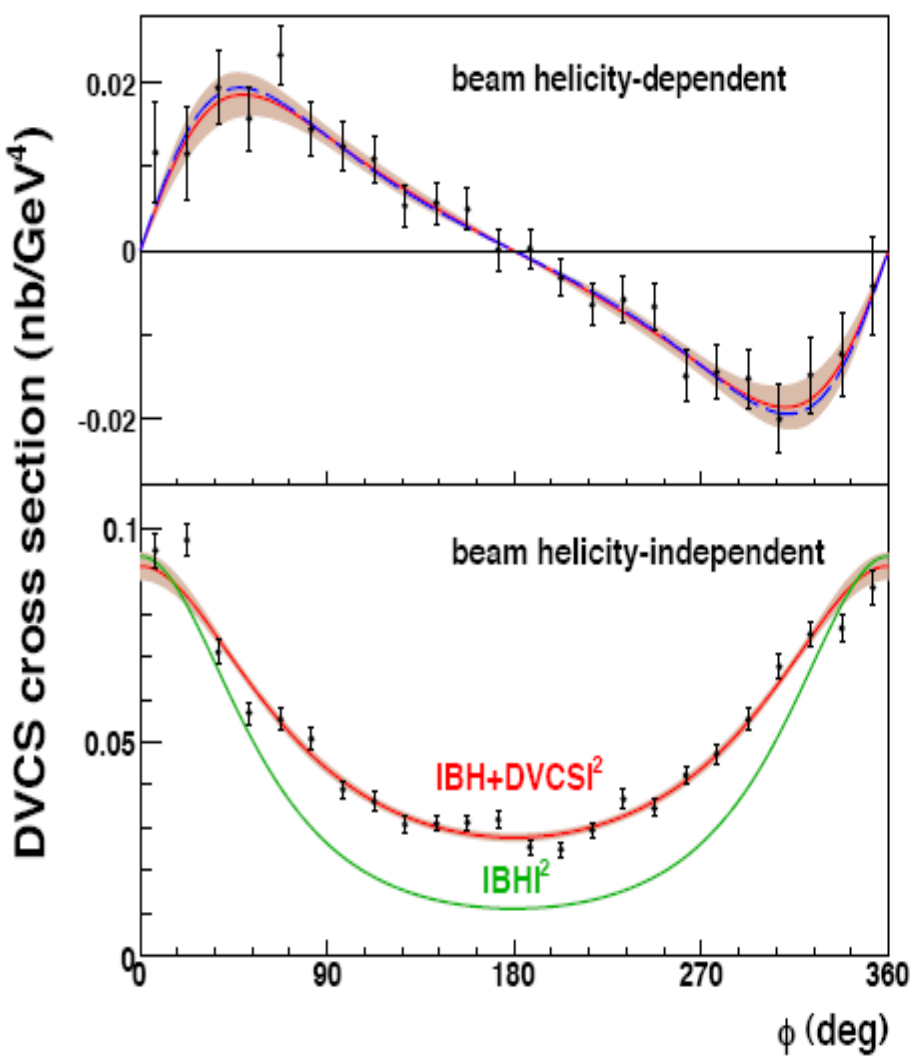


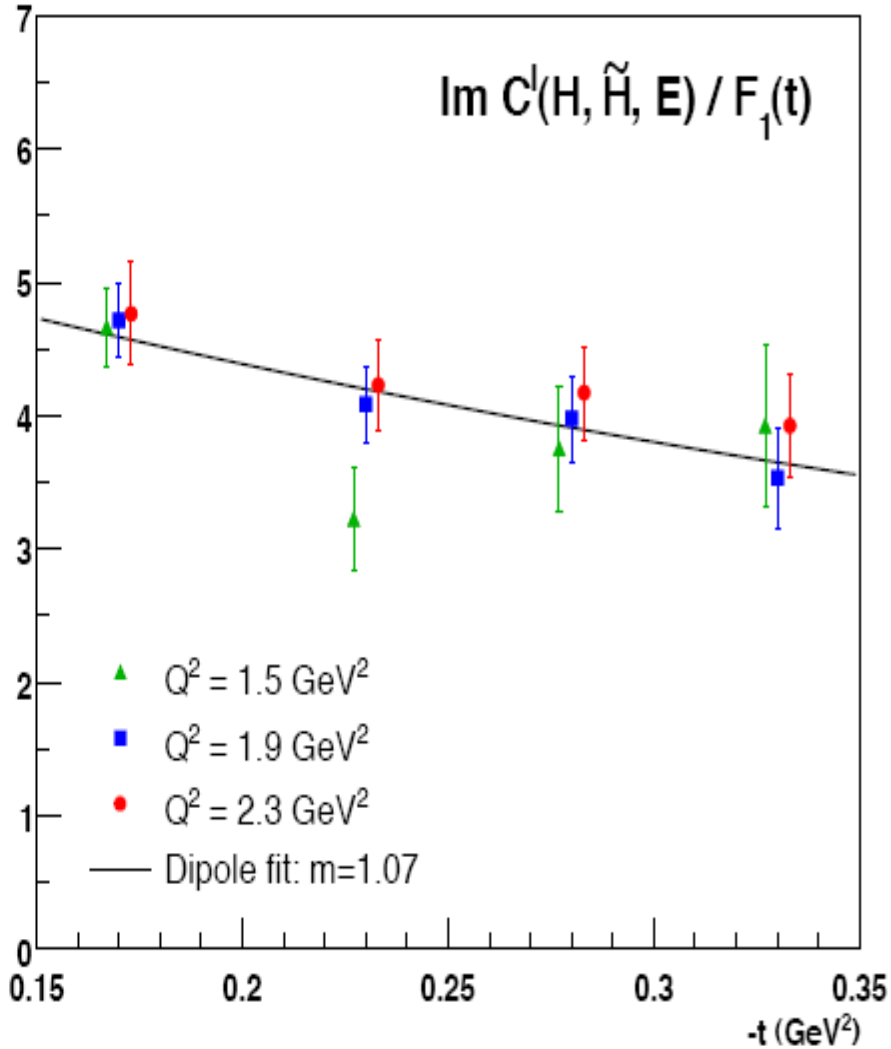
$Q^2 = 5\mathrm{GeV}^2$

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

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

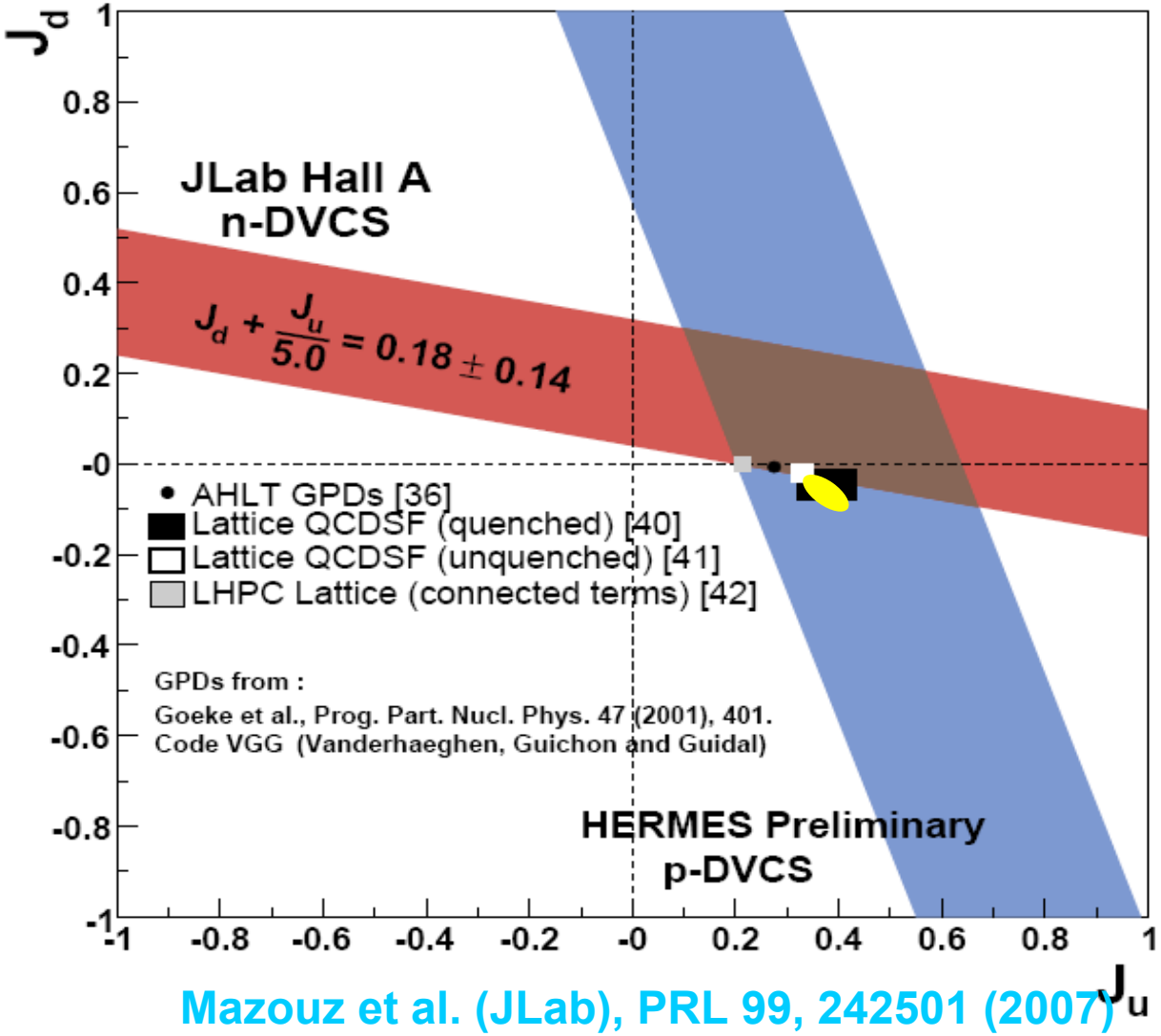
Recent Hall A Data: Suggests in Scaling Regime Even at Relatively Low Q^2





Experimental Constraints

Comparison with model of Myhrer & Thomas (hep-ph/0709.4067)



Model Dependence?

Mazouz et al. (JLab), PRL 99, 242501 (2007)

Anticipated Highlights of the 1st 5 Years

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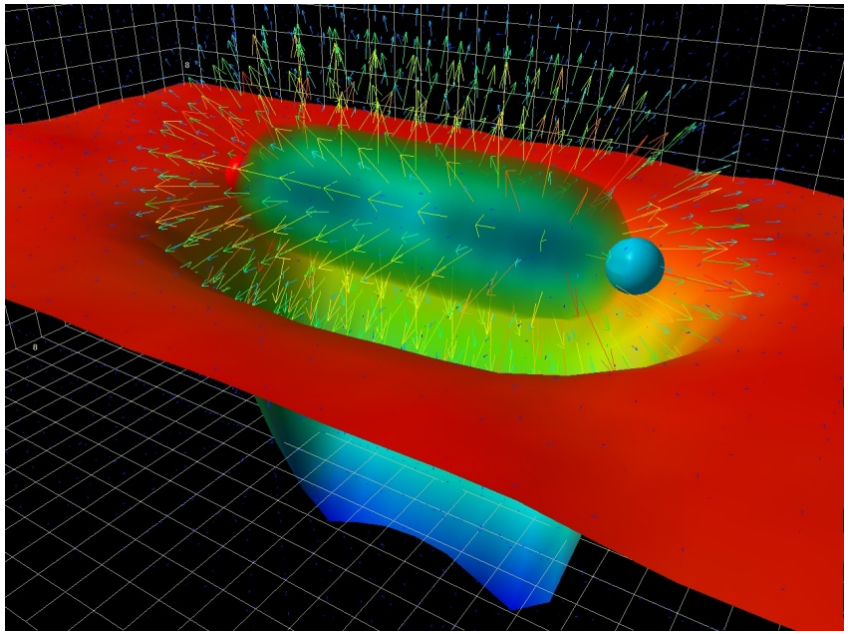
- Form Factors
- Generalized Parton Distributions
- **Exotic Meson Spectroscopy:**
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model

Gluonic Excitations and the Origin of Confinement

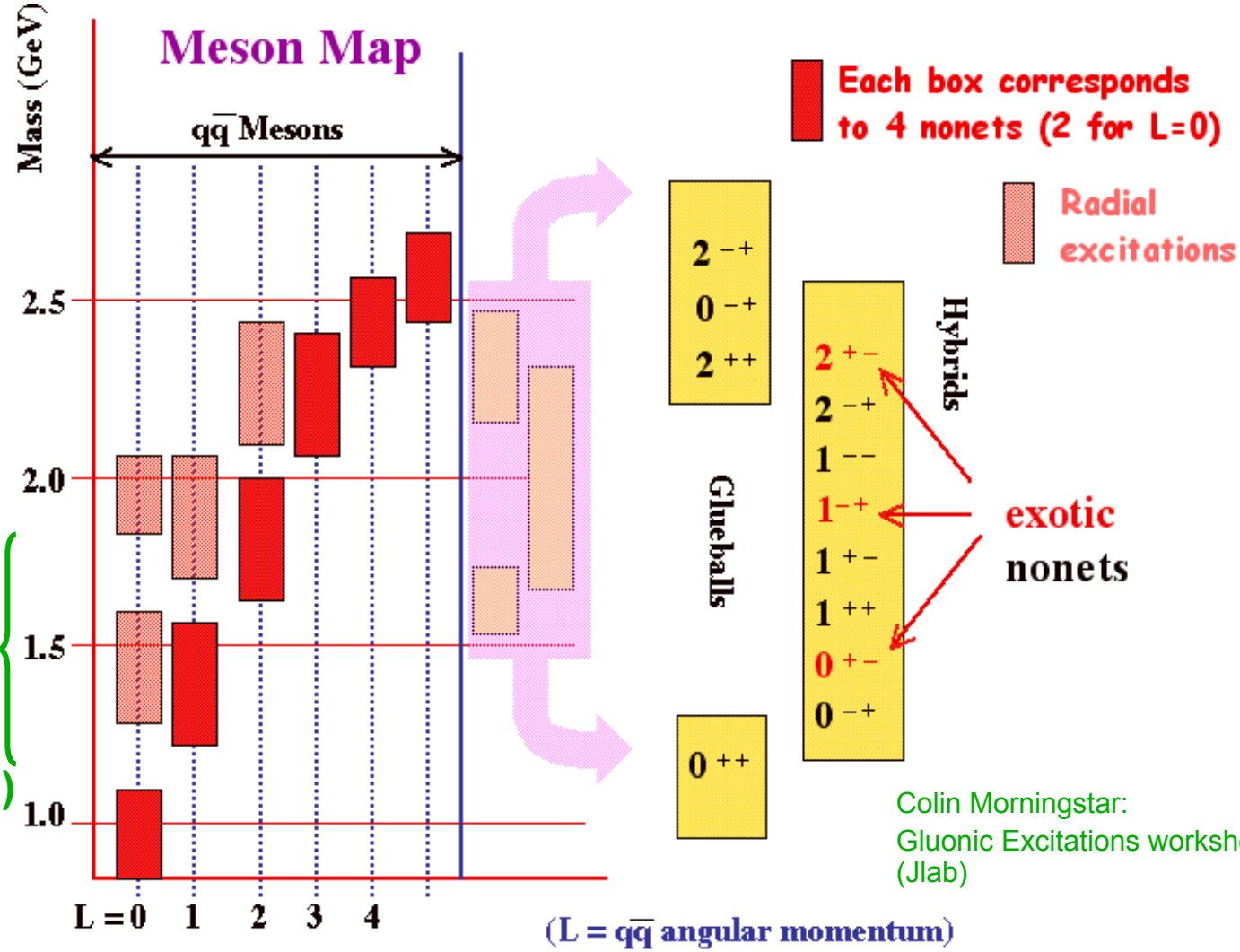


QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

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

- **discover these states,**
- **map out their spectrum, and**
- **measure their properties**

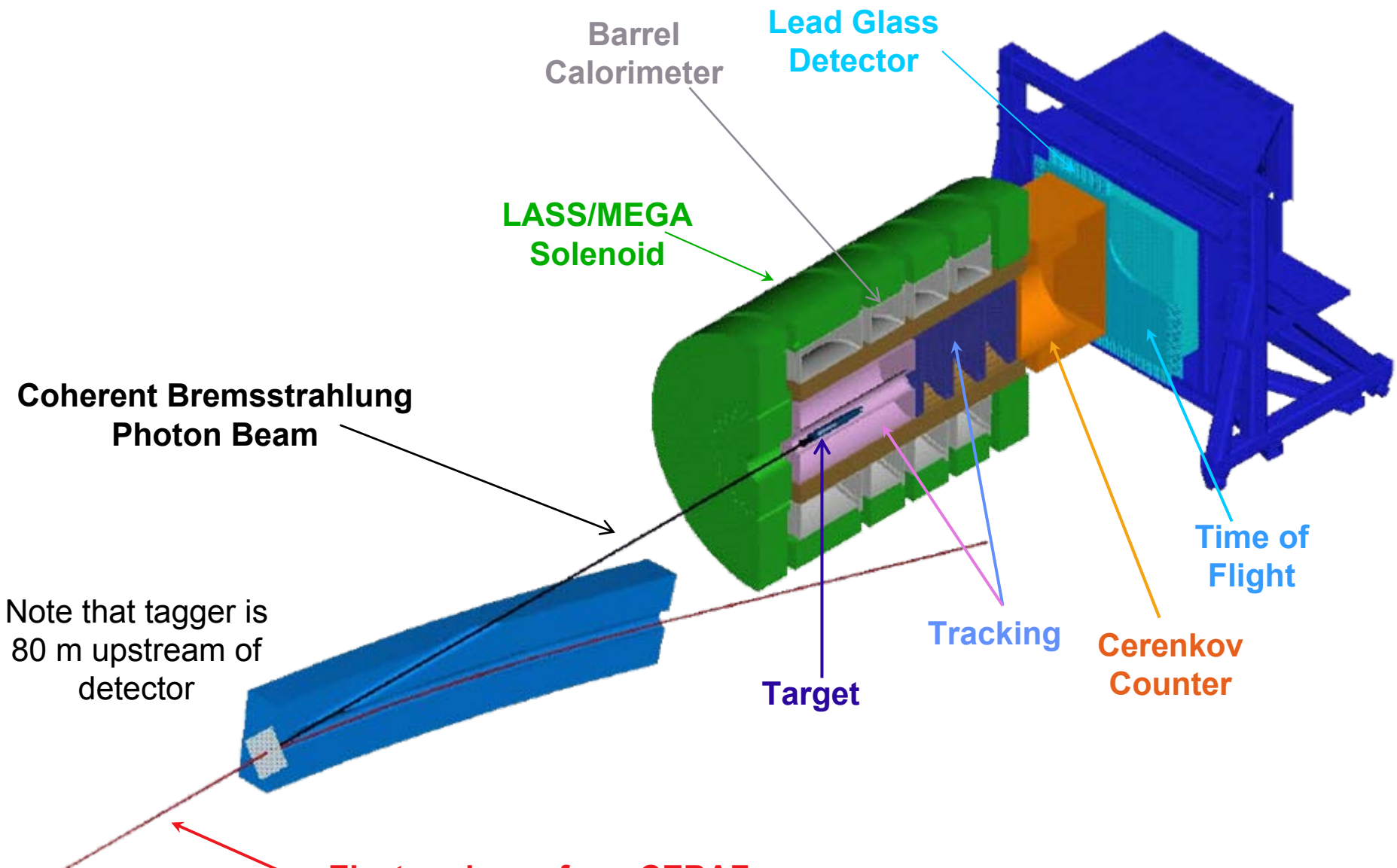
Glueballs and hybrid mesons



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.

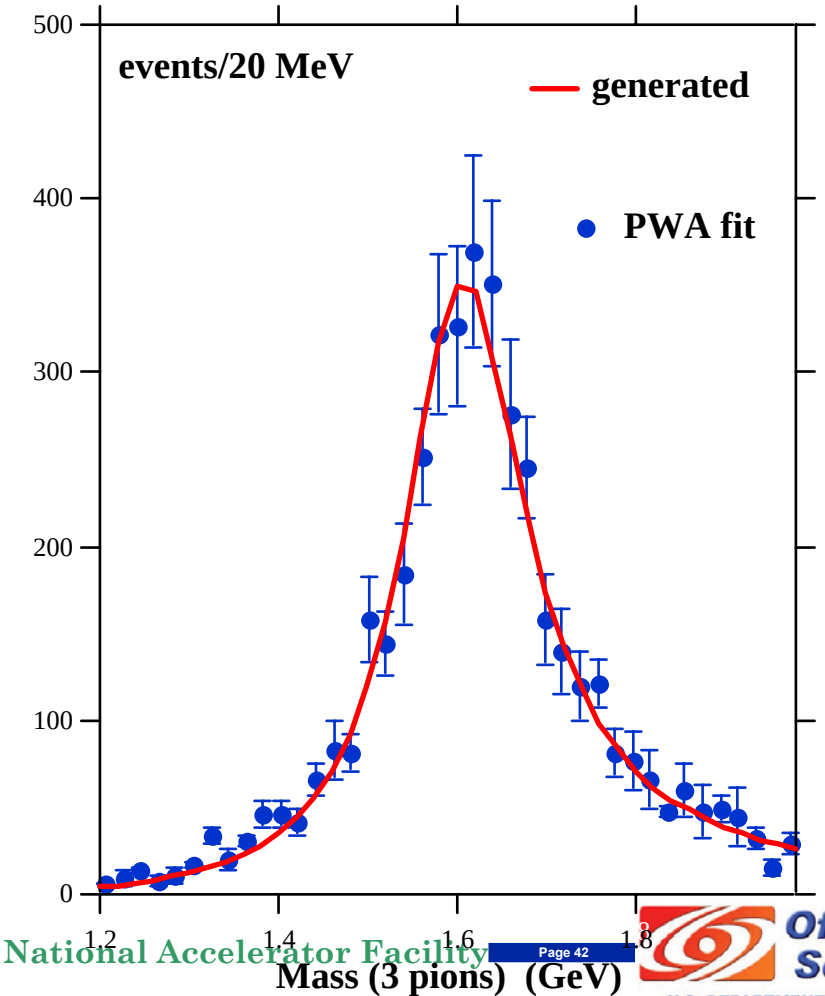
$$X(\text{exotic}) \rightarrow \rho\pi \rightarrow 3\pi$$

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.

Anticipated Highlights of the 1st 5 Years

- Parton Distribution Functions
- Form Factors
- Generalized Parton Distributions
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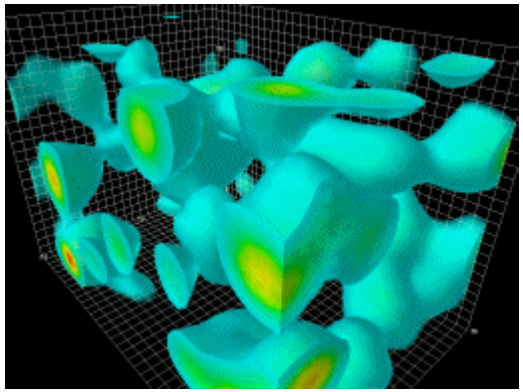
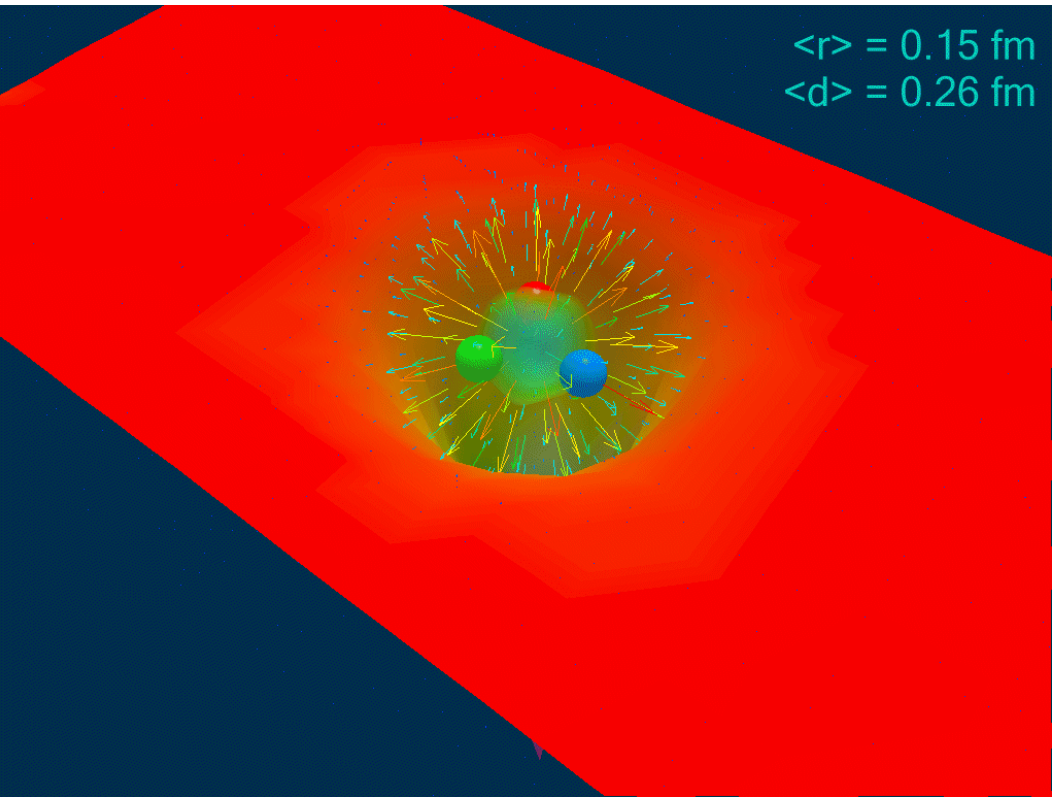
The QCD Lagrangian and Nuclear "Medium Modifications"

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

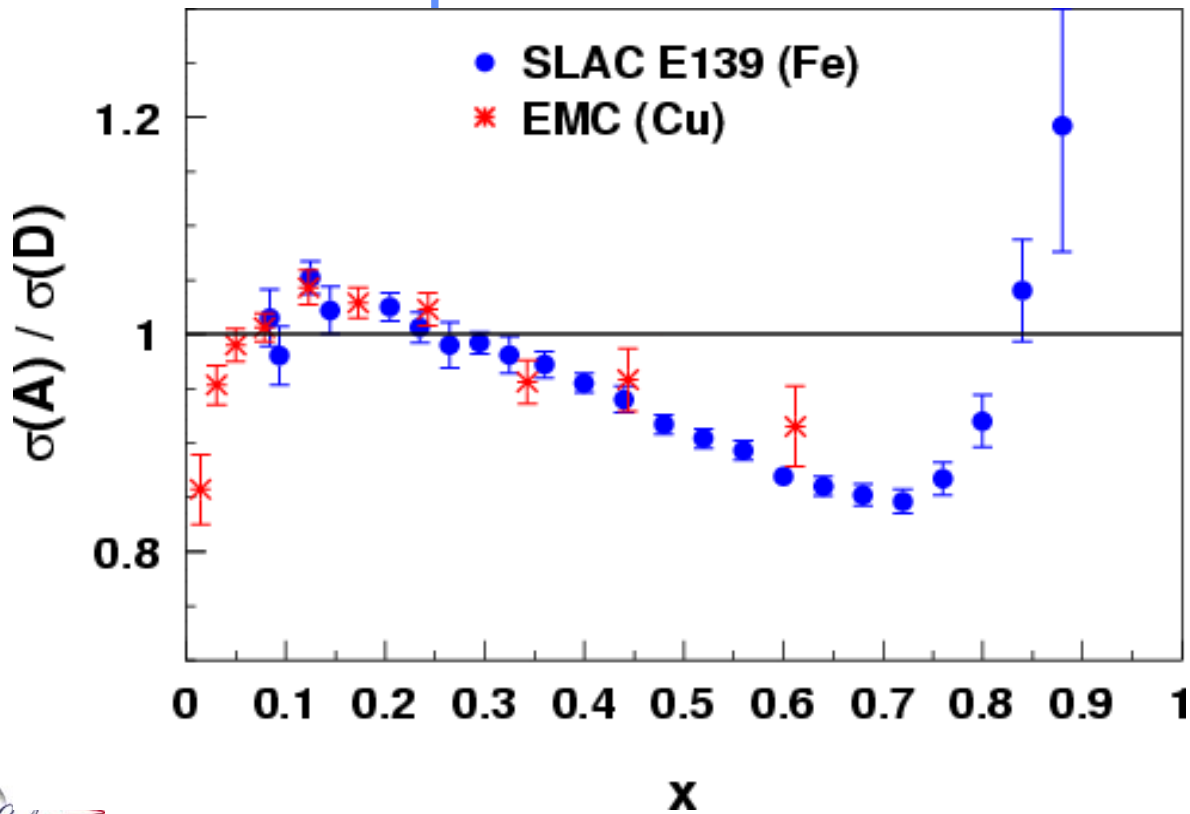
Does the quark structure of a nucleon get modified by the suppressed QCD vacuum fluctuations in a nucleus?

Leinweber, Signal et al

Operated by Jefferson Science Associates for the U.S. Department of Energy
Office of Science U.S. DEPARTMENT OF ENERGY

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?



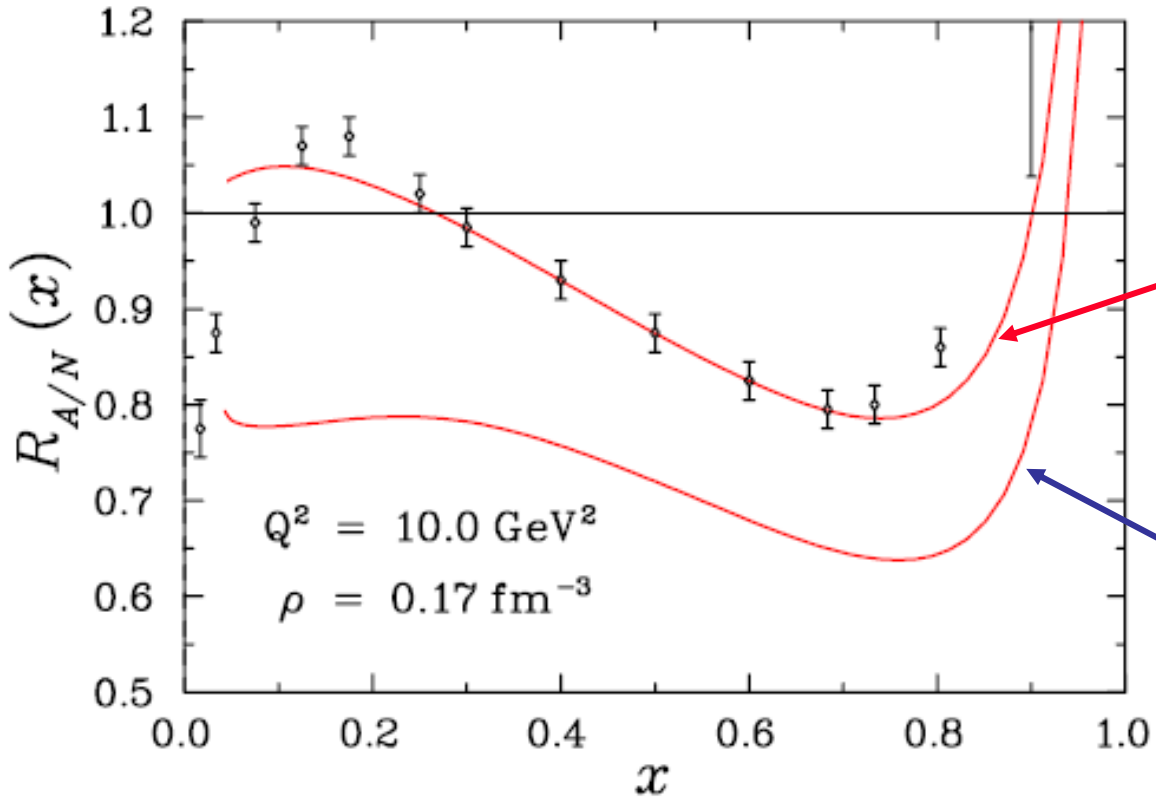
J. Ashman *et al.*, Z. Phys. C57, 211 (1993)

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

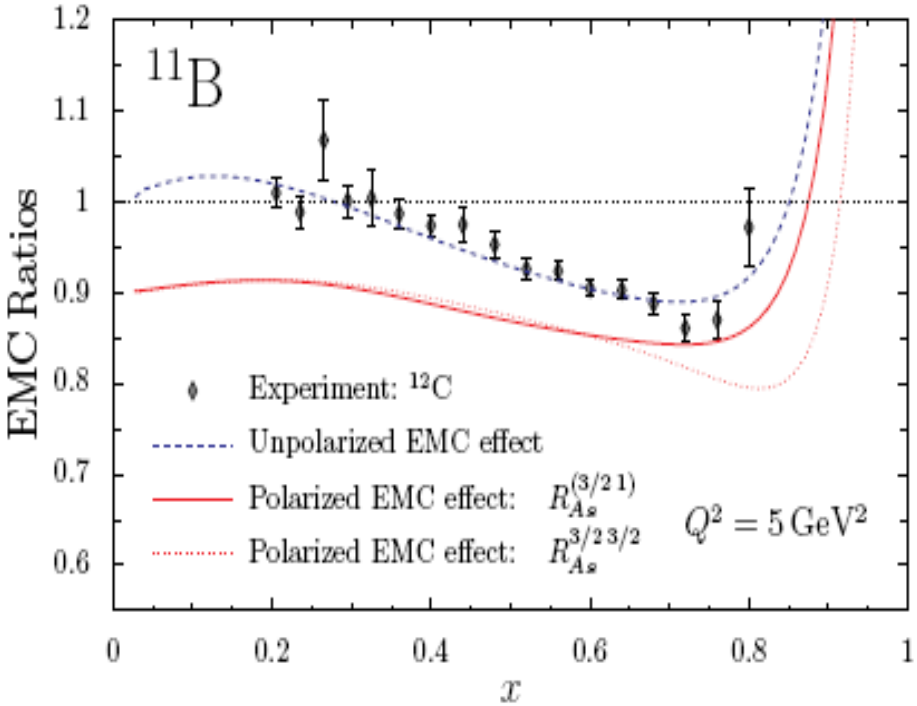


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

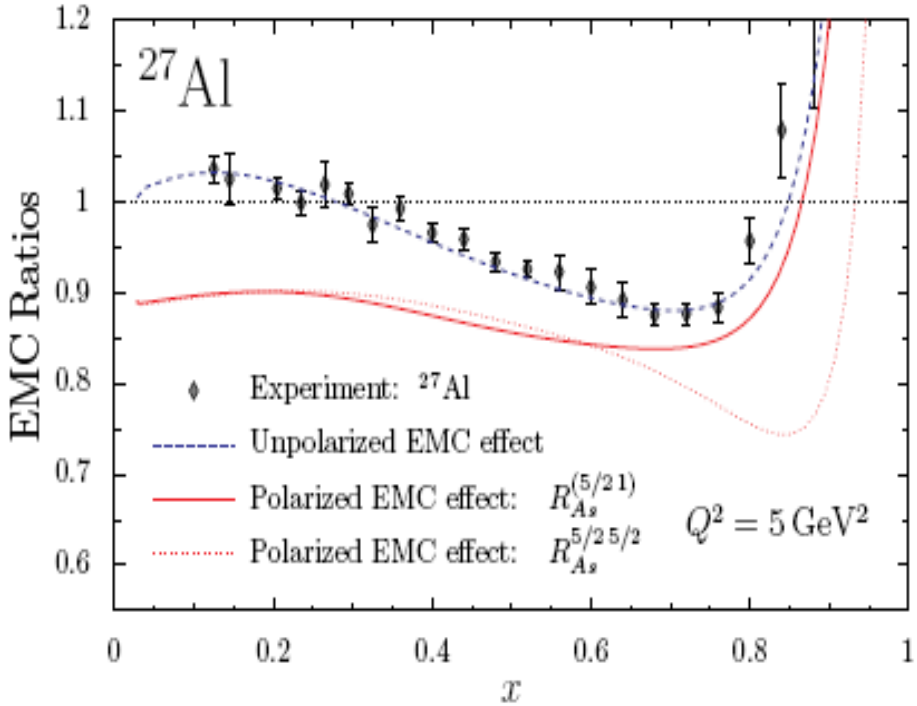


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

Cloet, Bentz, Thomas, nucl-th/0605061

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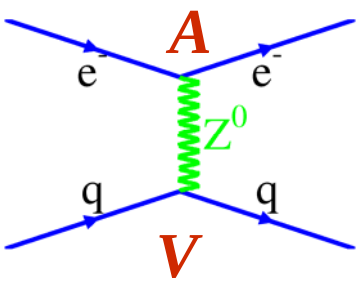
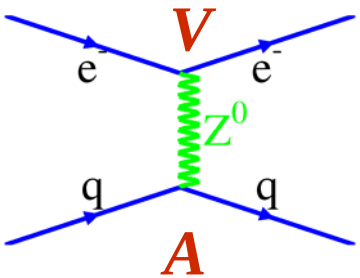
Electron-Quark Phenomenology



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



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

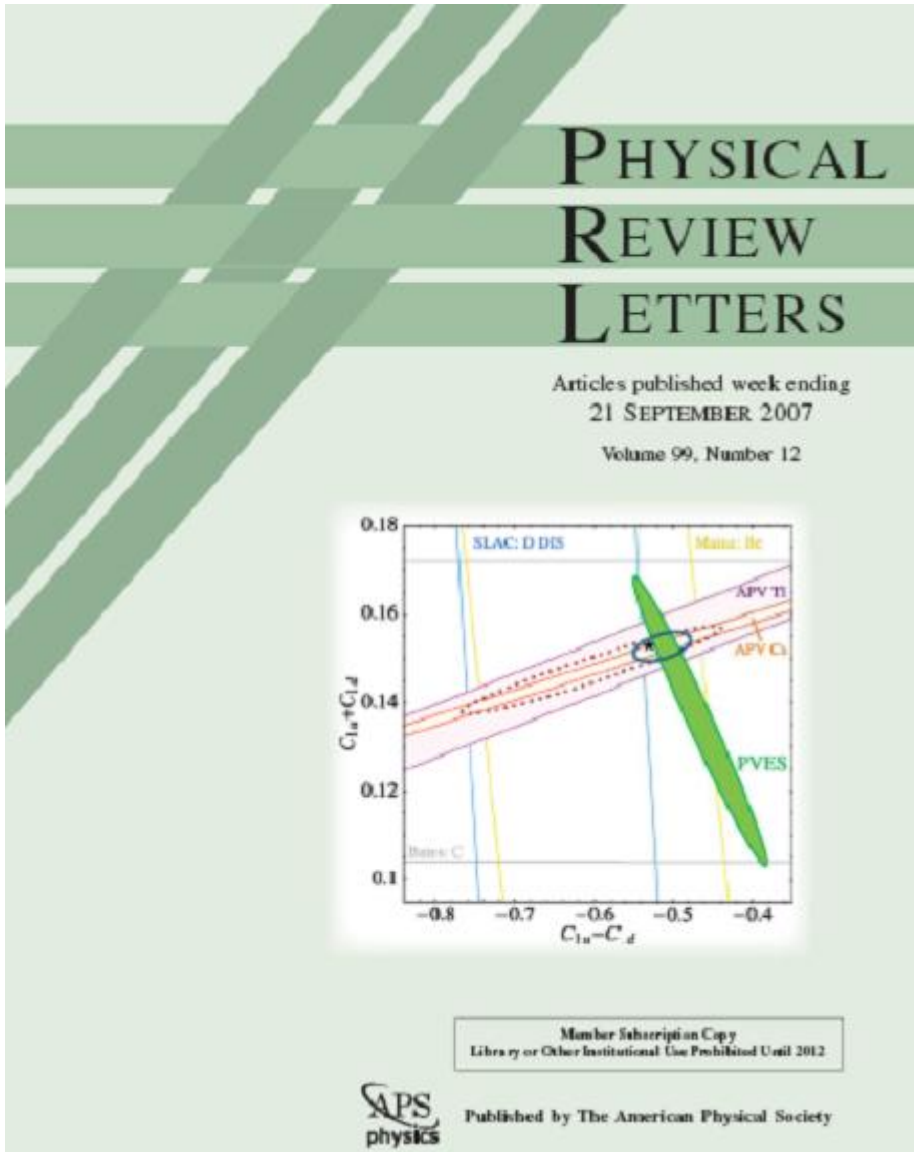
$$C_{1u} = -\tfrac{1}{2} + \tfrac{4}{3}\sin^2(\theta_W) \approx -0.19$$
$$C_{1d} = \tfrac{1}{2} - \tfrac{2}{3}\sin^2(\theta_W) \approx 0.35$$
$$C_{2u} = -\tfrac{1}{2} + 2\sin^2(\theta_W) \approx -0.04$$
$$C_{2d} = \tfrac{1}{2} - 2\sin^2(\theta_W) \approx 0.04.$$

C_{1u} and C_{1d} can 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

Deviations from the precise predictions of the Standard Model indicate new physics such as new Z′, compositeness…

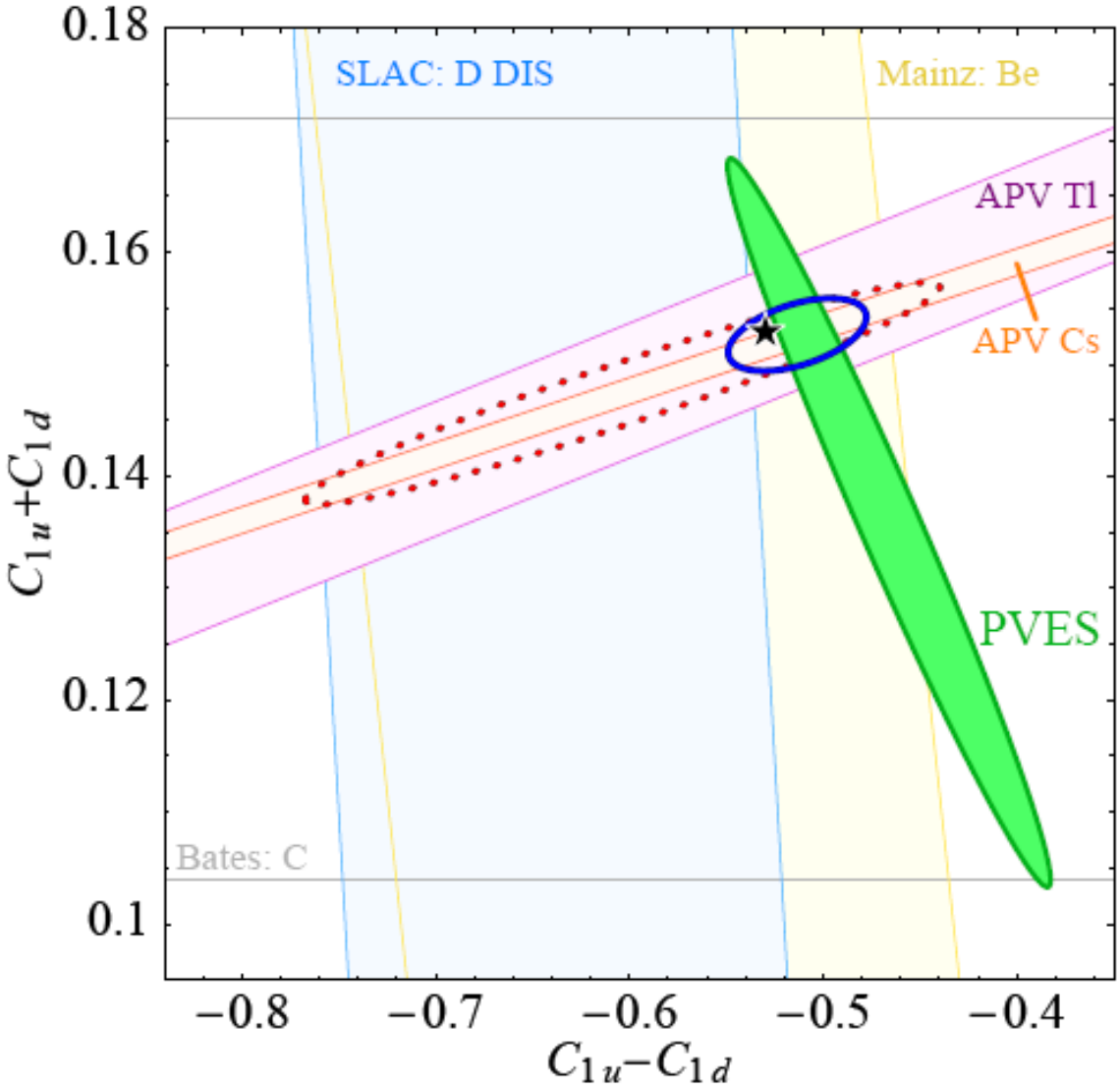
Impressive Gains in Testing the Standard Model



- A Jlab analysis of the world data on Parity Violating electron scattering, much of it taken at Jefferson Lab by the G0 and HAPPEx Collaborations, has led to a major improvement in the limits on the masses of possible new particles, e.g. Z', which are not part of the Standard Model of Nuclear and Particle physics.

- This work featured on the cover of Physical Review Letters in September.

New update on C_{1q} couplings



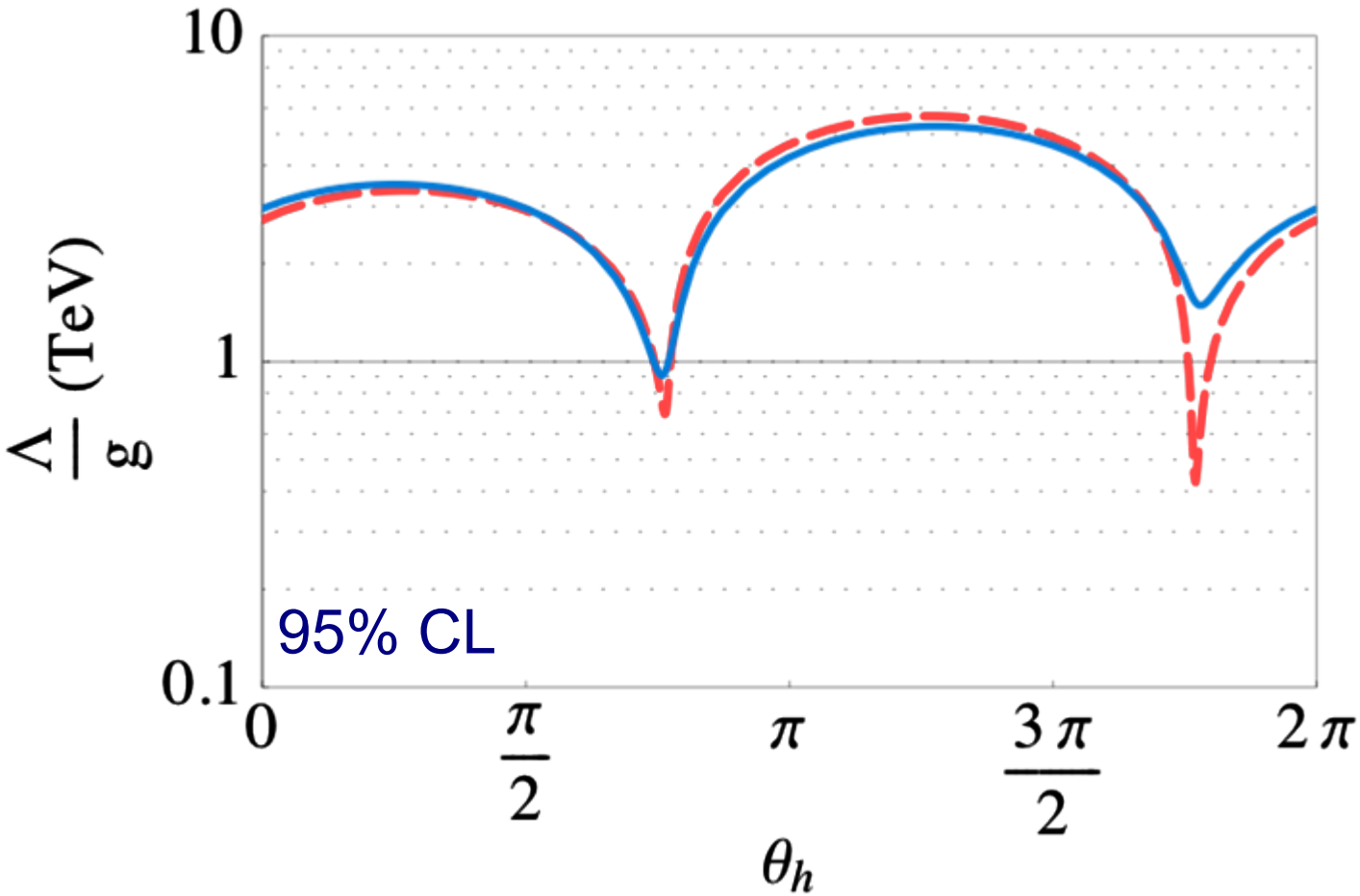
(Young et al., PRL Sept 07)

Factor of 5 increase in precision of Standard Model test

-Typically once a decade

Operated by Jefferson Science Associates for the U.S. Department of Energy

Lower bound on New Physics scale: Current



with PVES

Atomic only

Young et al.
(Dec 2006)

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

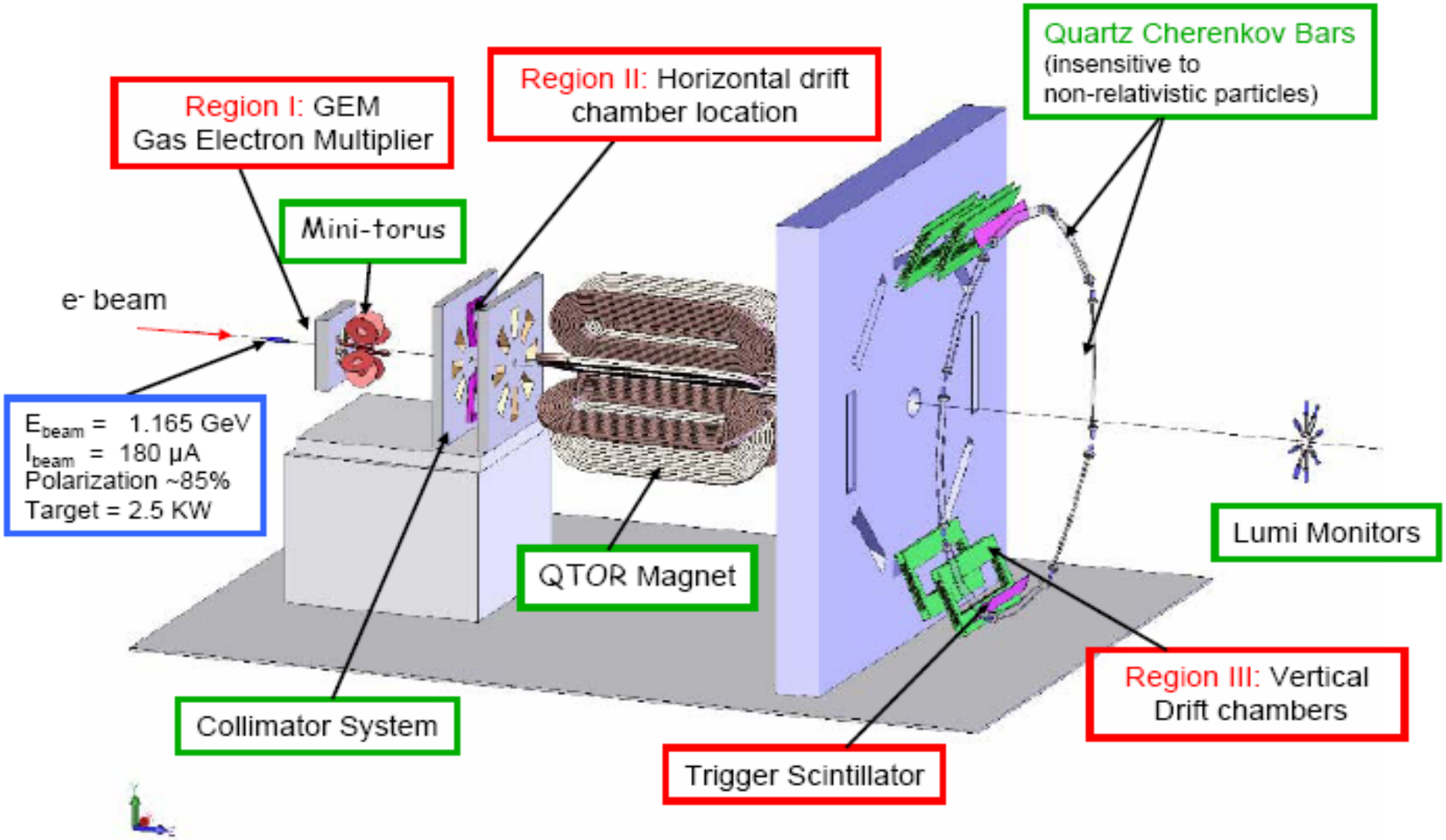
Sensitivity to New Physics Beyond Standard Model

- 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*)

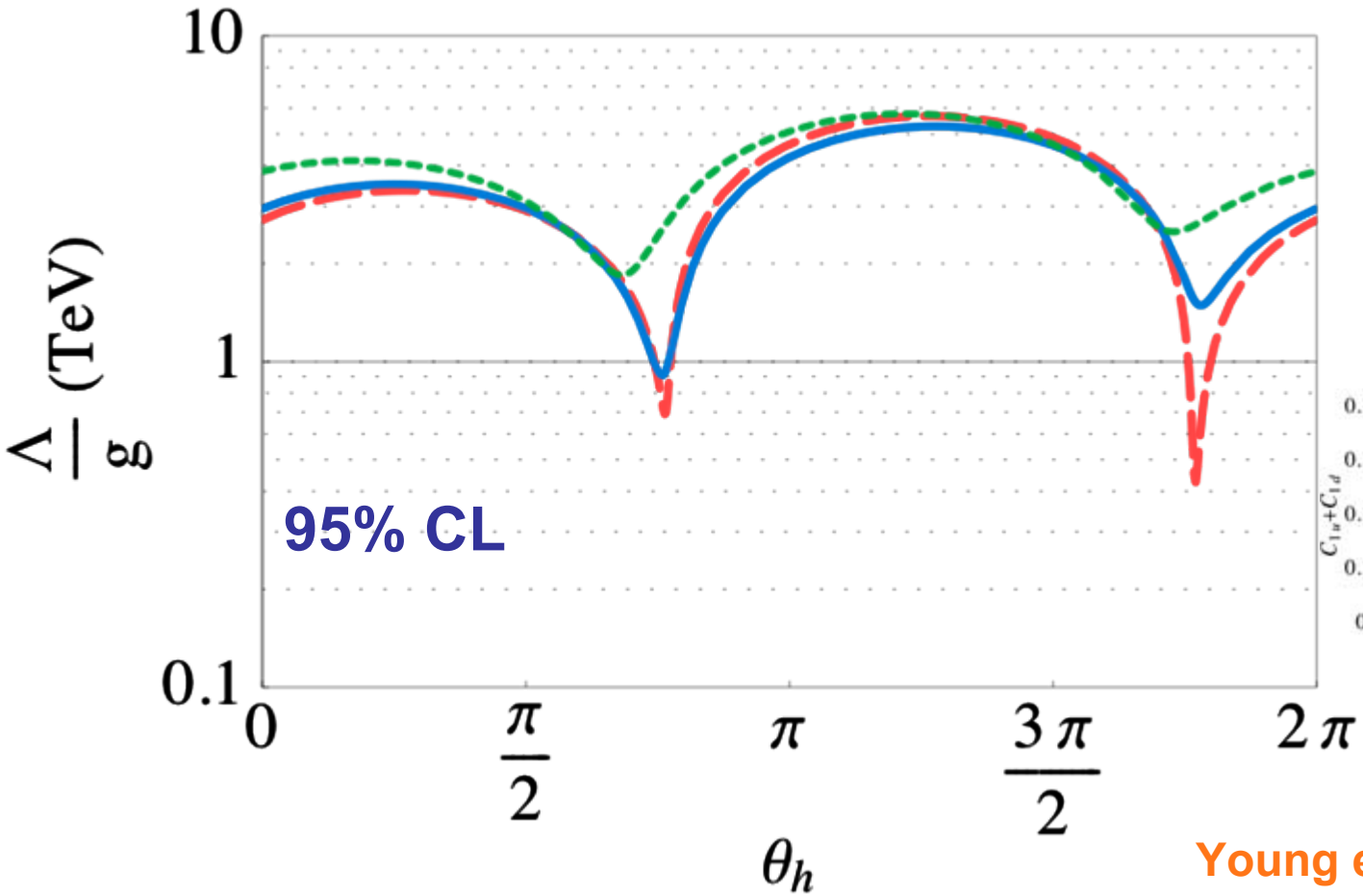
$$M_{Z_1}^2 = M_Z^2 + \frac{1}{R^2}$$

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

Q_{weak} Apparatus



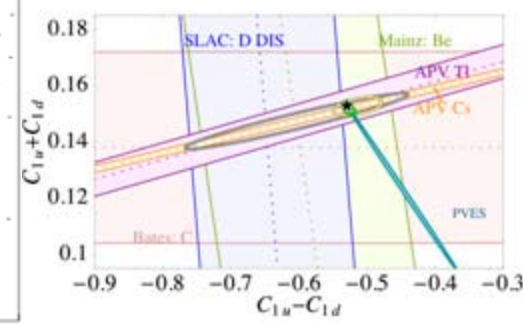
New Physics Limits
(if result consistent with Standard Model)



future Qweak

with PVES

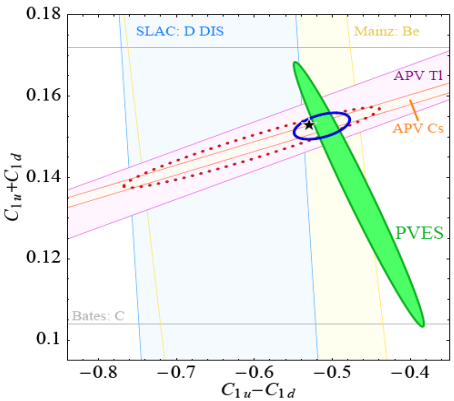
Atomic only



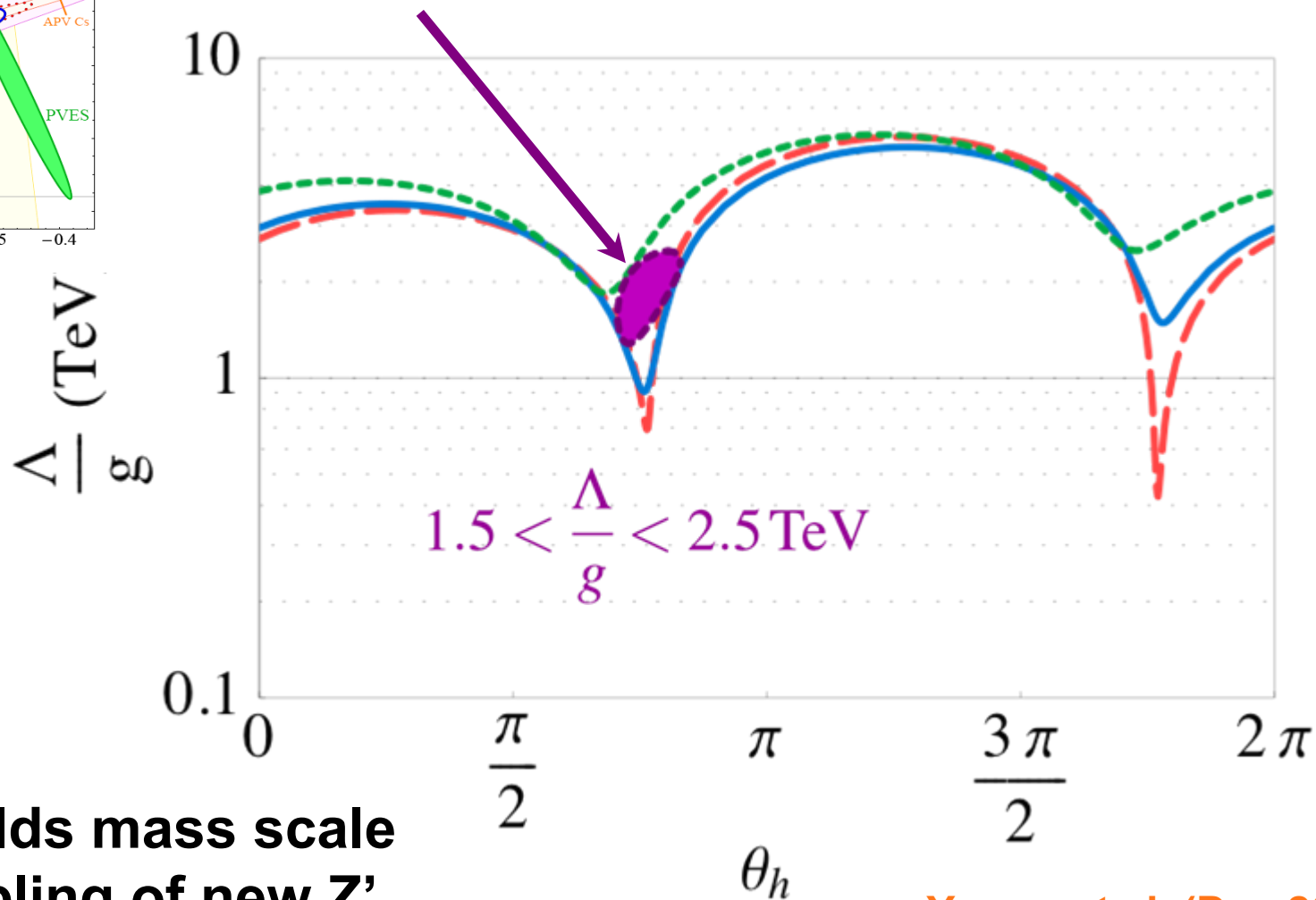
Young et al. (Dec 2006)

Qweak constrains new physics to beyond 2 TeV

Next Generation: 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)

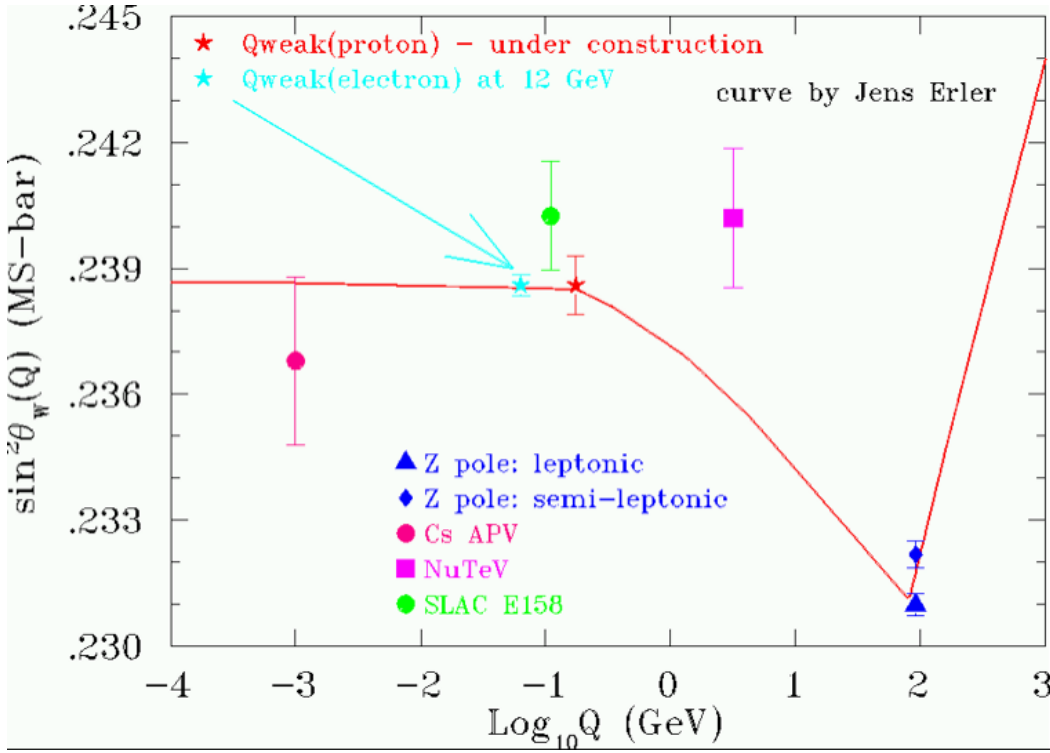
Future Möller Experiment at 12 GeV

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"

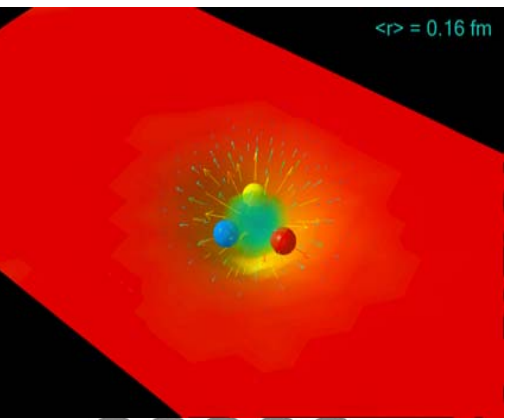


World Community in 2013 and Beyond

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

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

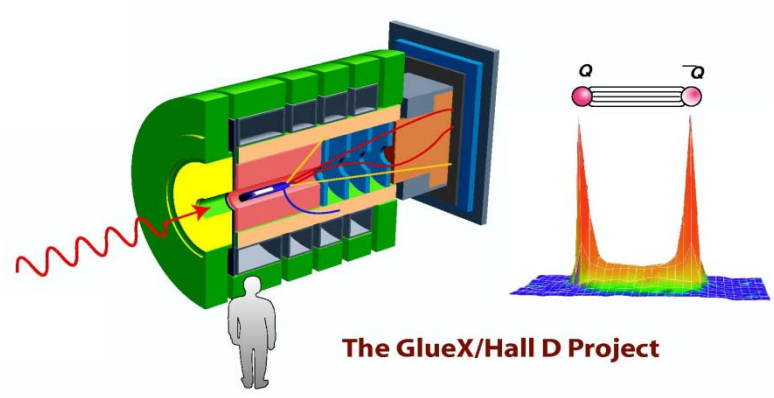
- Wonderful opportunities to build international community and take our field to a new level

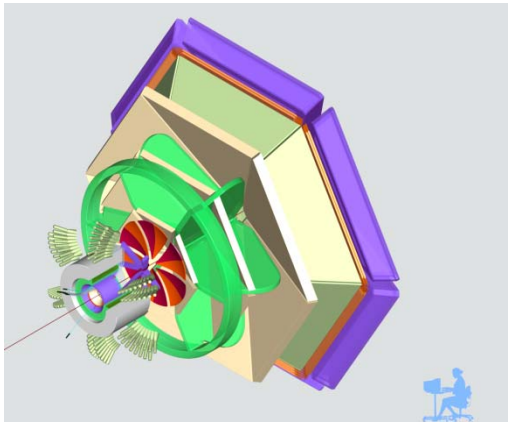


* Unique: only electromagnetic machine

12 GeV Capabilities

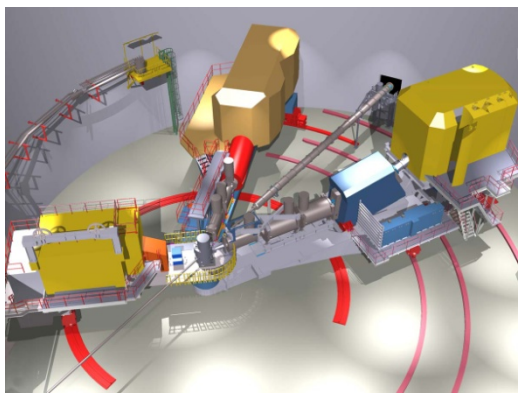
Hall D – exploring origin of confinement by studying exotic mesons

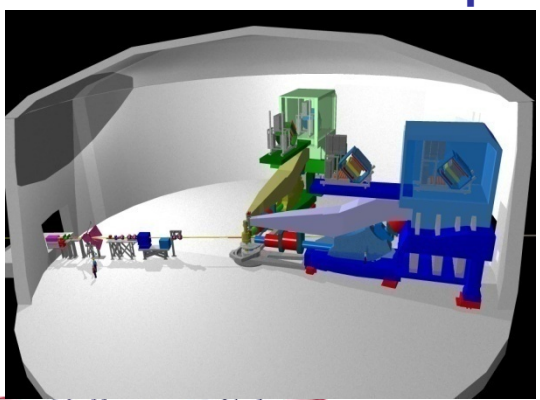




Hall B – understanding nucleon structure via generalized parton distributions

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….