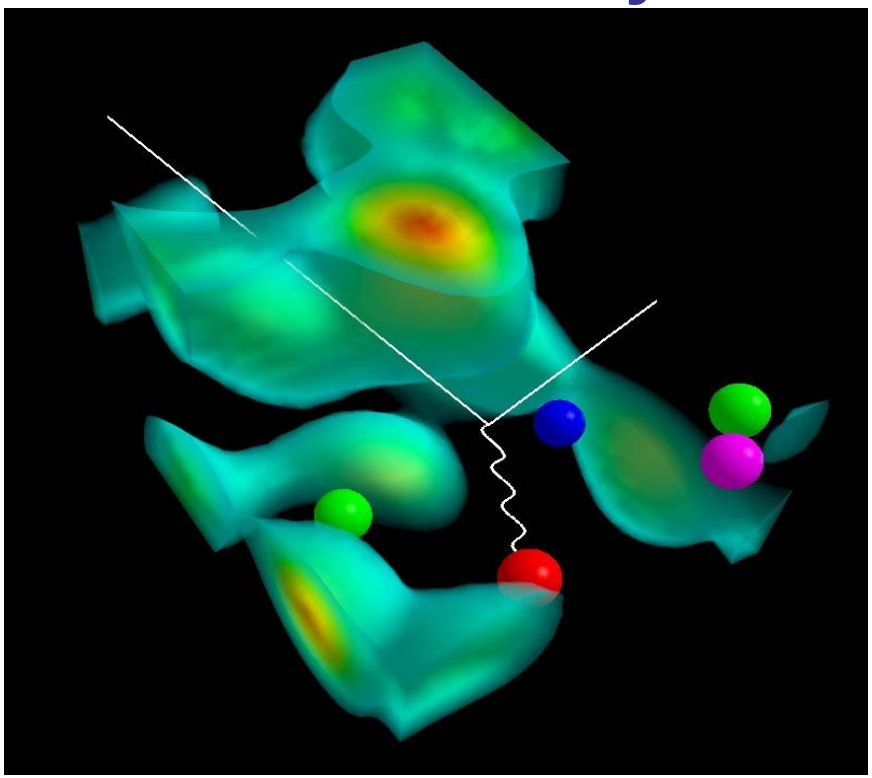
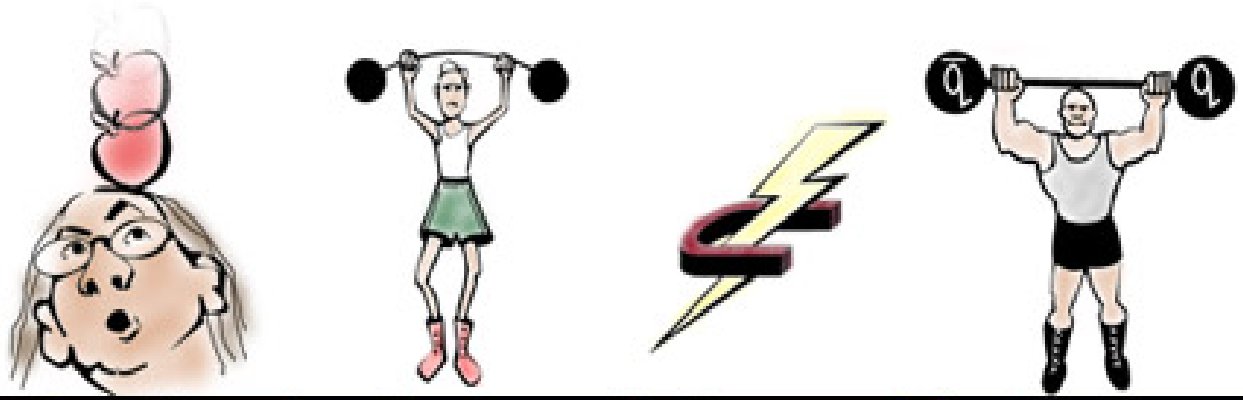
Precise Electro-Weak Studies: An Essential Component of the World-Wide Nuclear Physics Program



Anthony W. Thomas

HUGS at Jefferson Lab: May 29th 2007

Fundamental Forces



	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

There are four fundamental forces:

- **Gravity:** holds us to the earth, binds solar systems, galaxies..
- **Electromagnetic:** e.m. radiation, chemistry, biology..
- **Weak:** radioactivity, neutrino physics of supernovae, etc.
- **Strong:** all familiar matter, nuclear energy, powers sun & stars

Building Blocks of the Universe

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	–1	d down	0.006	–1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	–1	s strange	0.1	–1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	–1	b bottom	4.3	–1/3

- **Each quark comes in 3 "colours": red, green and blue.**
- **Leptons do not carry color charge.**

These are the building blocks of matter!

Force Carriers of the Universe

BOSONS

force carriers
spin = 0, 1, 2, ...

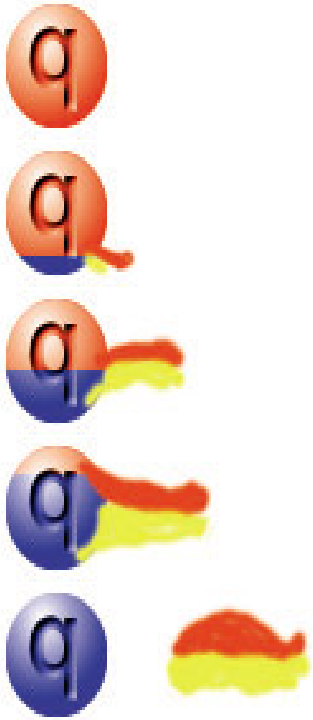
Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- **The massless photon mediates the long-range e.m. interactions.**
- **Gluons carry color and mediate the strong interaction.**
- **The very massive W^-, W^+, and Z^0 bosons mediate the weak interaction**

Quantum Chromodynamics (QCD)

- **Photons do not carry electric charge.**
- **Gluons *do* carry colour charge!**
- **Gluons can directly interact with other gluons!**
- **This is new!**



A red quark emitting a red anti-blue gluon to leave a blue quark.

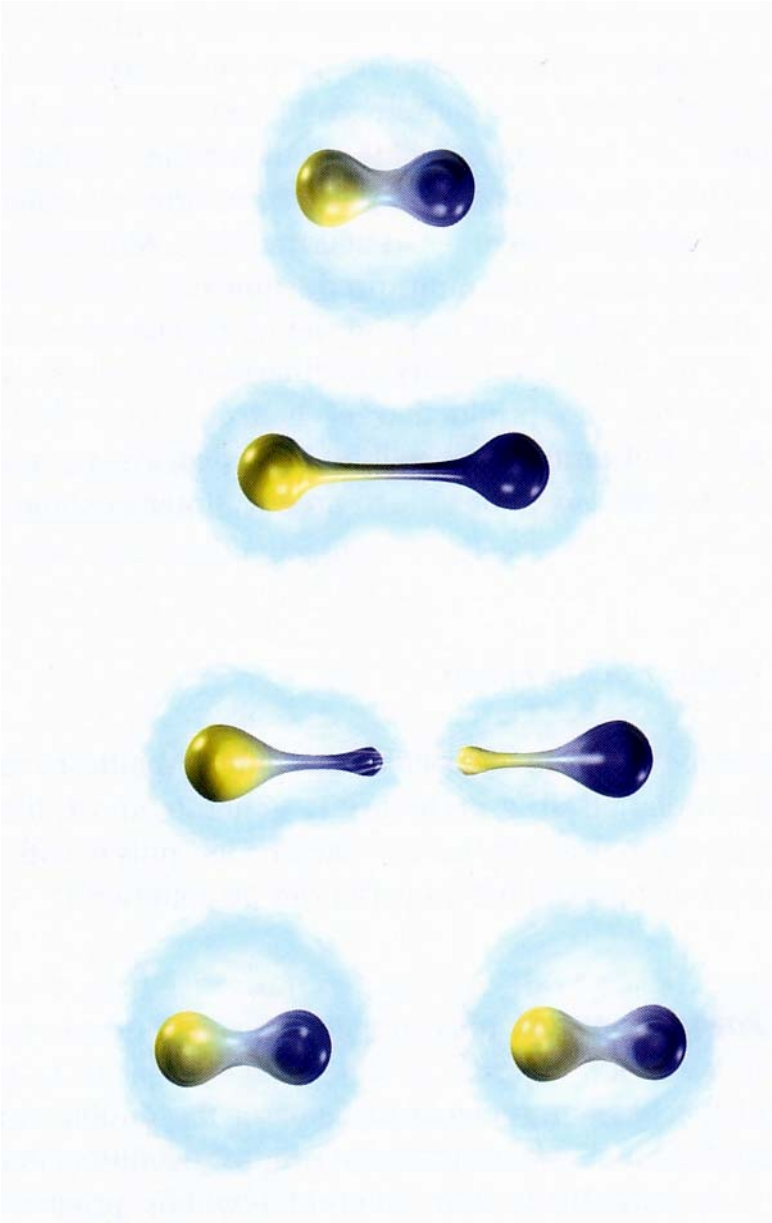
Quark-quark force grows WEAKER as quarks come close
≡ "Asymptotic Freedom"

QCD

Mesons $q\bar{q}$ Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

- **Mesons are made up of a quark - anti-quark pair with equal and opposite color charges.**
- **PION is special has zero mass as $m_{u,d} \rightarrow 0$**

$$m_\pi^2 \sim m_{u,d}$$

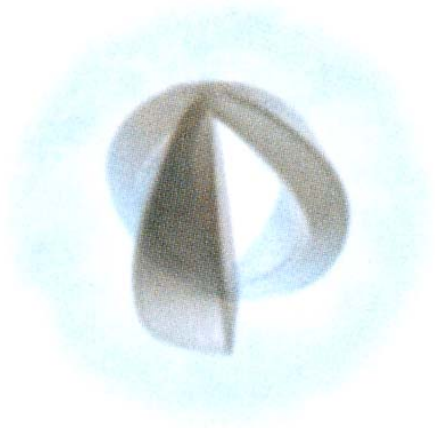


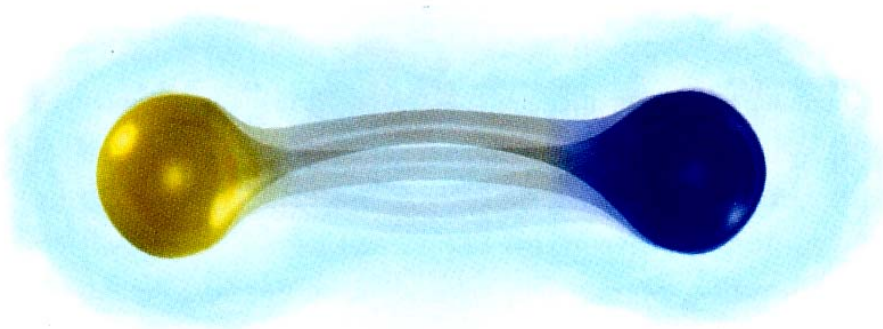
String Breaking

It is impossible to isolate a quark.

- Quarks are "*Confined* "
- Restoring force is 10 tons regardless of separation!
- String can break BUT makes two colorless objects!

QCD: Exotics





QCD predicts the existence of exotic mesons

Glueballs are mesons without valence quarks

Other exotics involve excitation or vibration of gluons

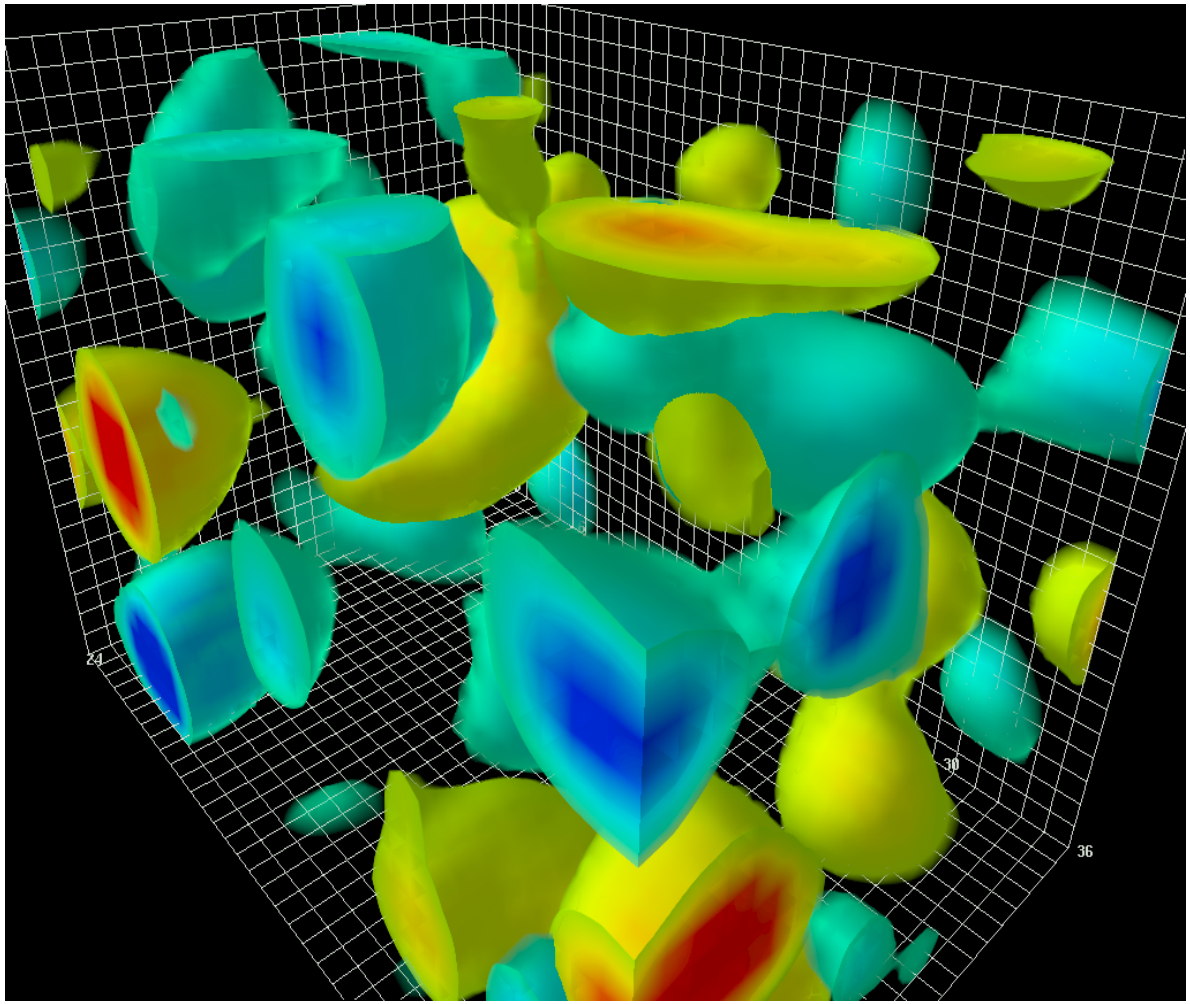
QCD and the Origin of Mass

u + u + d = proton

mass: $0.003 + 0.003 + 0.006 \neq 0.938$

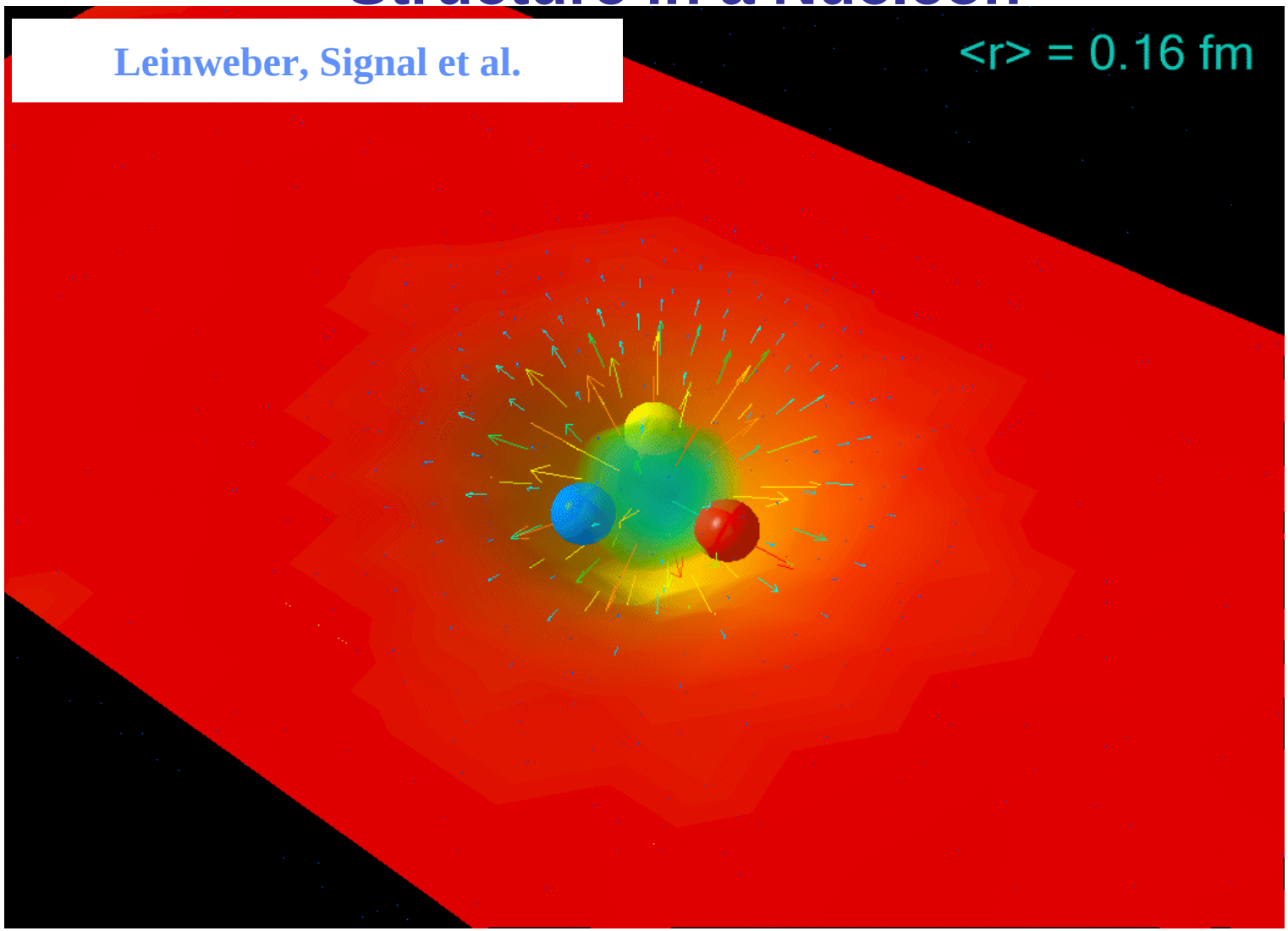
HOW does the rest of the proton mass arise?

Topology of the QCD Vacuum

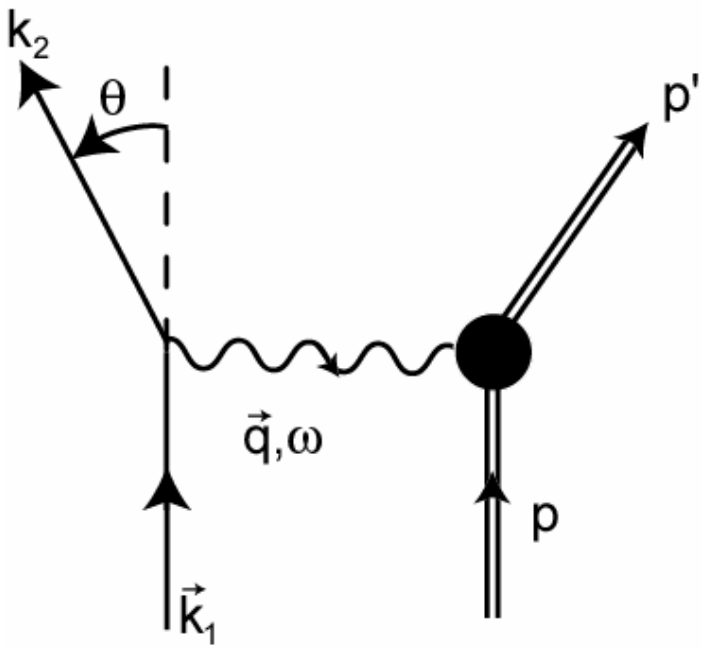


Leinweber: see CSSM web pages

Lattice QCD Simulation of Change of Vacuum Structure in a Nucleon



Electron Scattering Provides an Ideal Microscope for Nuclear Physics



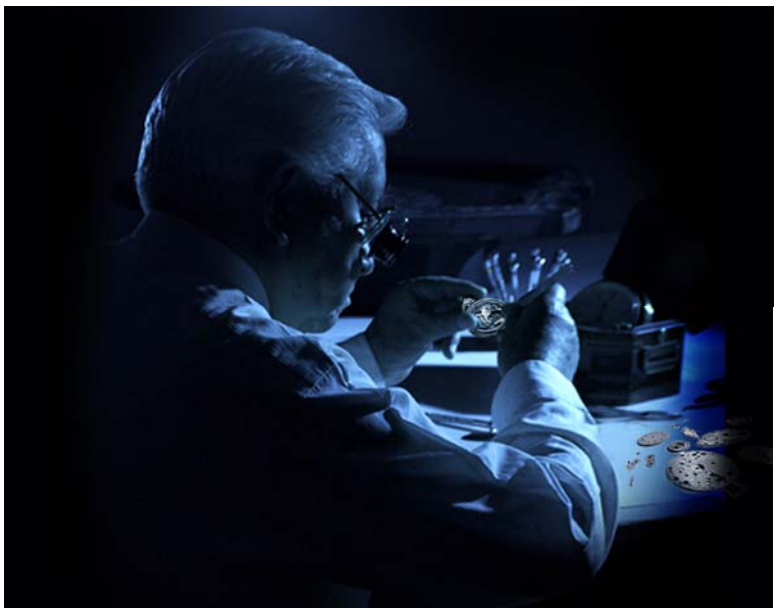
- Electrons are point-like
- The interaction (QED) is well-known
- The interaction is weak
- Vary *q* to map out Fourier Transforms of charge and current densities:

  $\lambda \cong 2\pi/q$ **(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

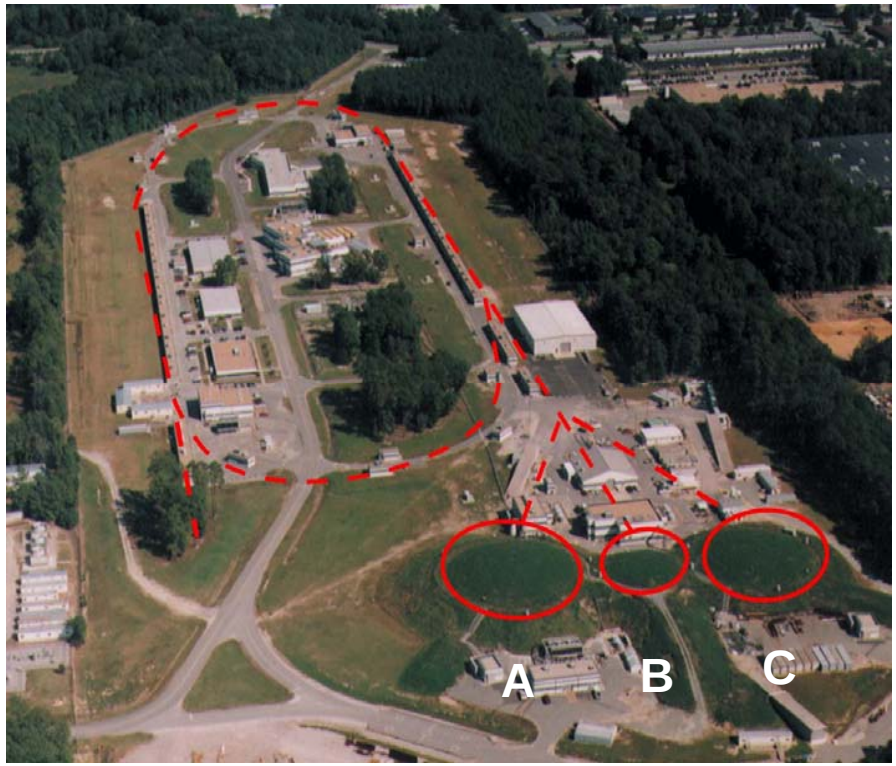
CEBAF's $\vec{e}$ and CW beams dramatically enhance the power of electron scattering



Jefferson Lab Today

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

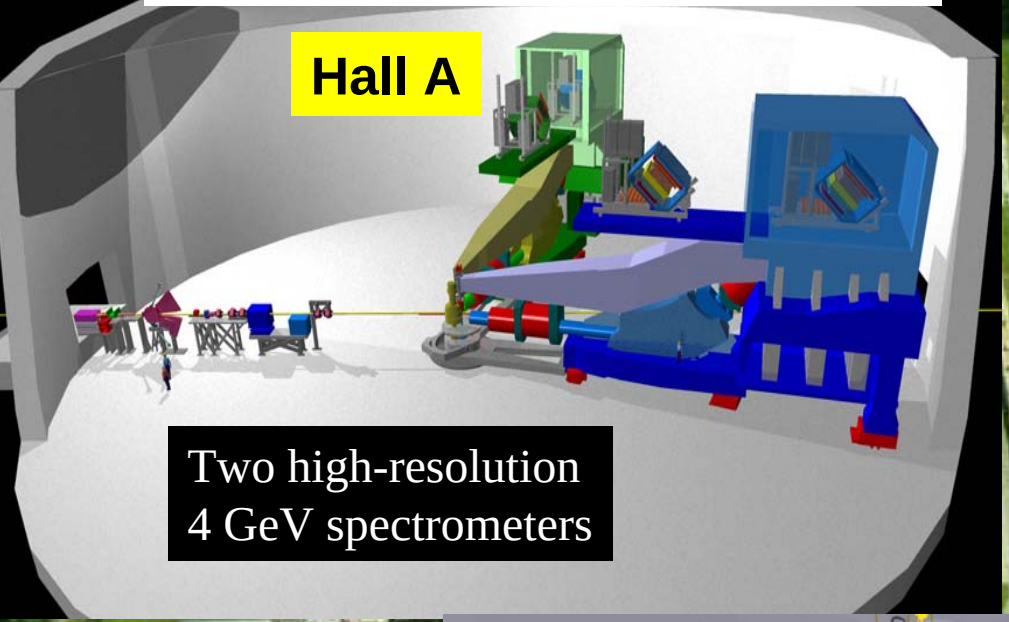
Superconducting accelerator provides 100% duty factor beams of unprecedented quality, with energies to 6 GeV

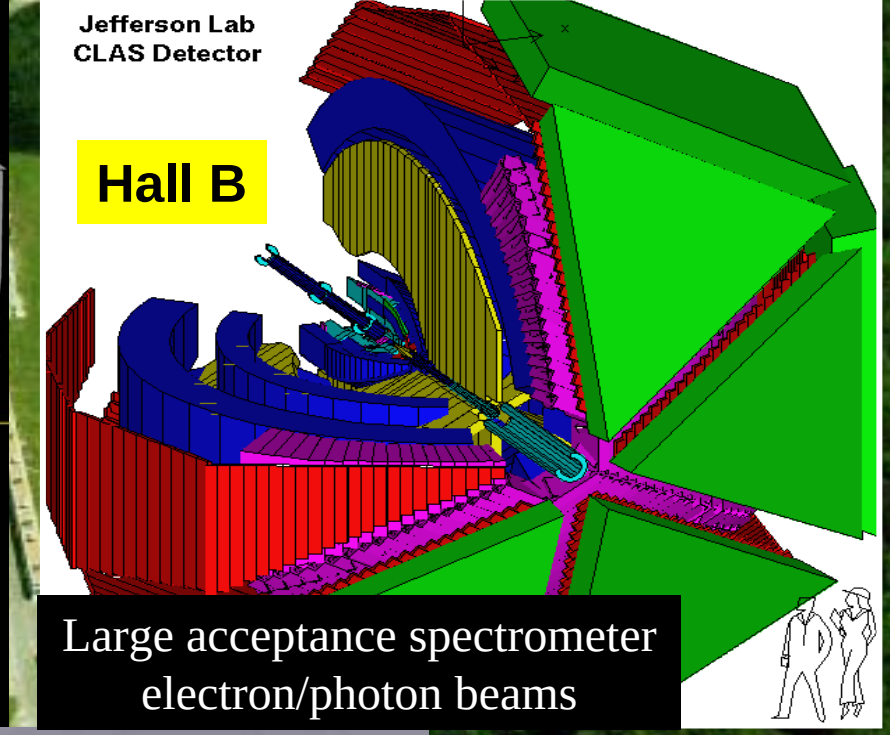


CEBAF's innovative design allows delivery of beam with unique properties to three experimental halls simultaneously

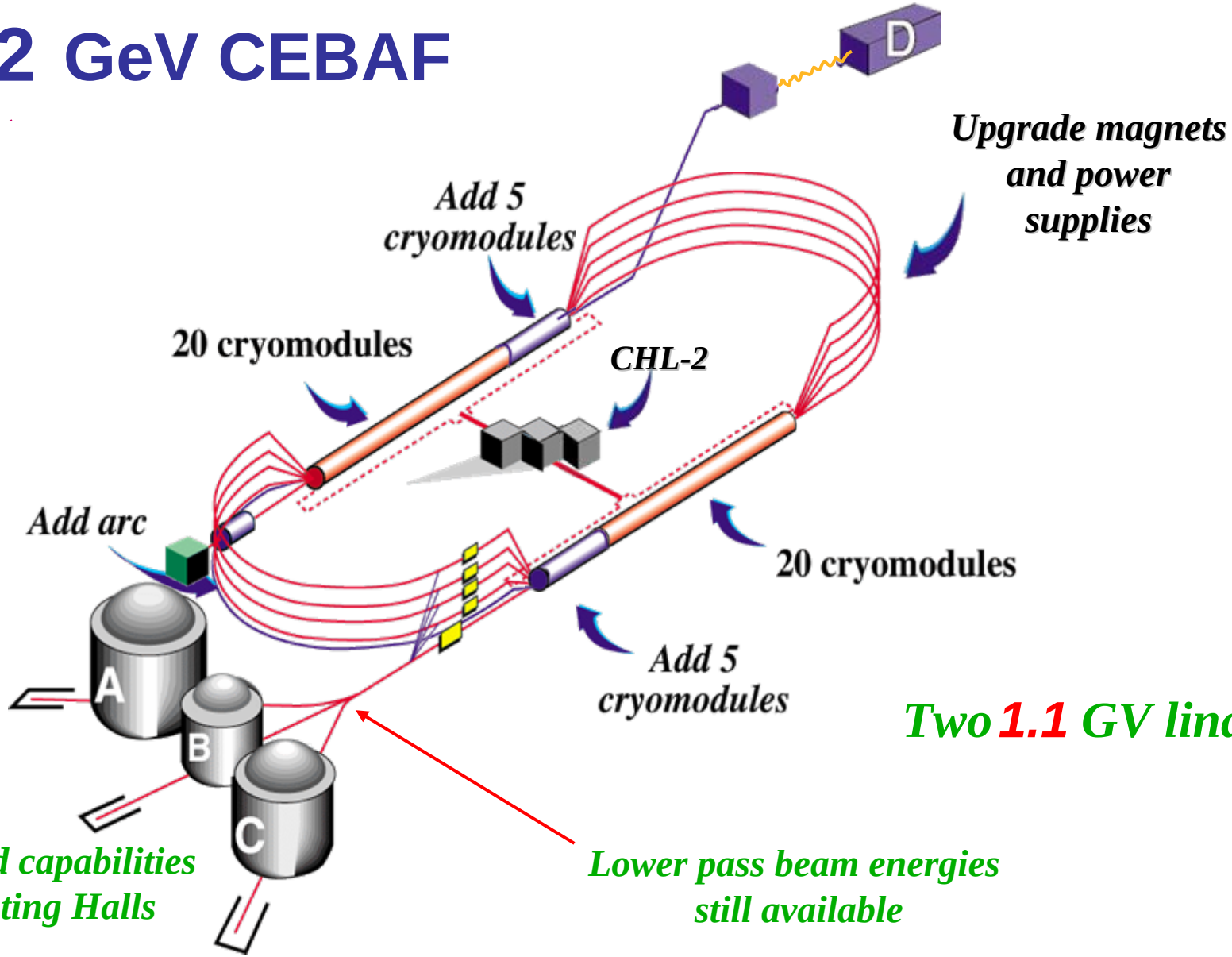
Each of the three halls offers complementary experimental capabilities

Jefferson Lab Today





12 GeV CEBAF

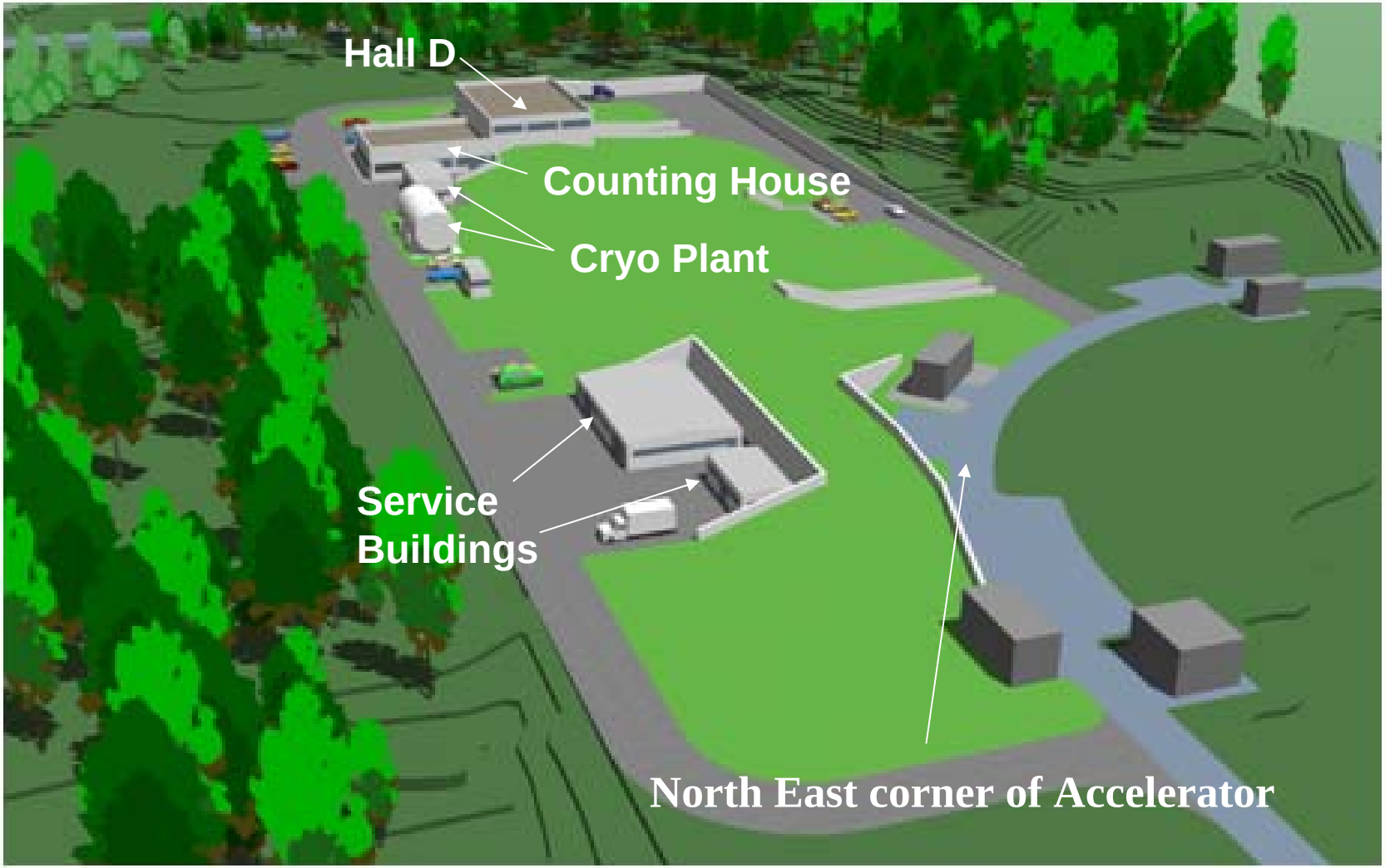


Two 1.1 GV linacs

Enhanced capabilities in existing Halls

Lower pass beam energies still available

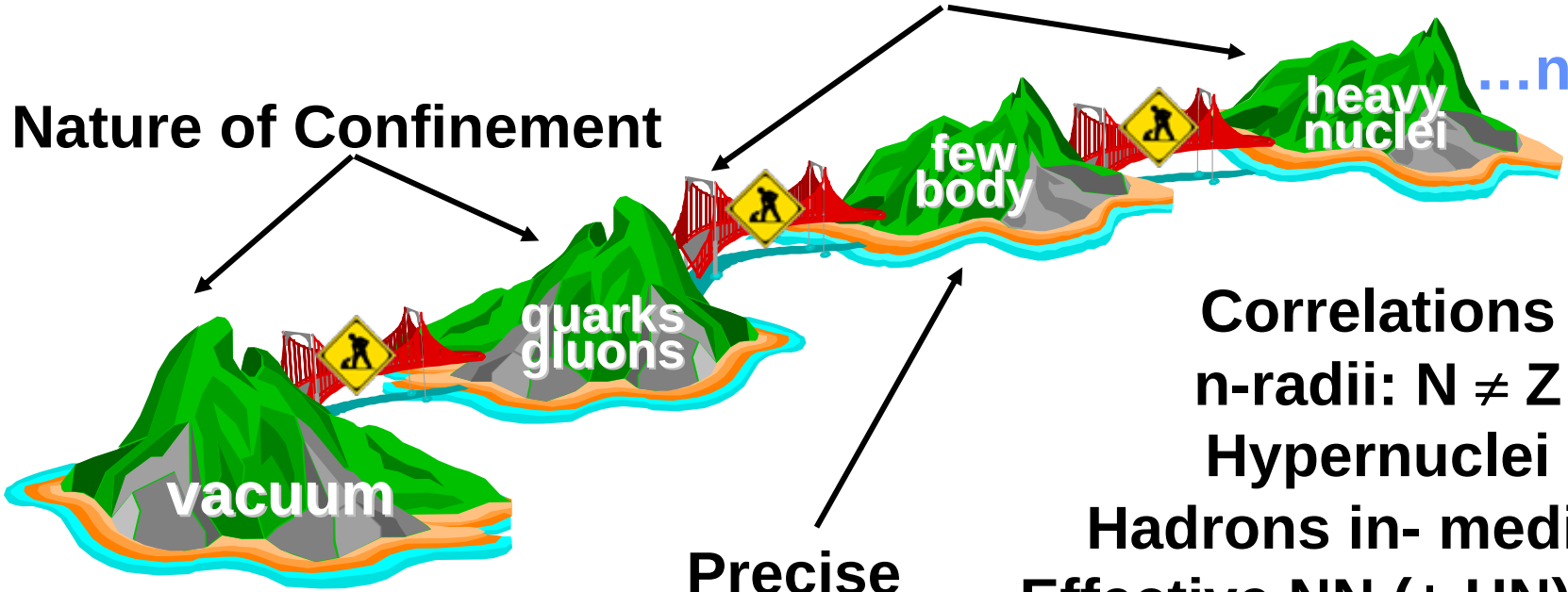
Architect's Rendering of Hall D Complex



Program Central to *all* of 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

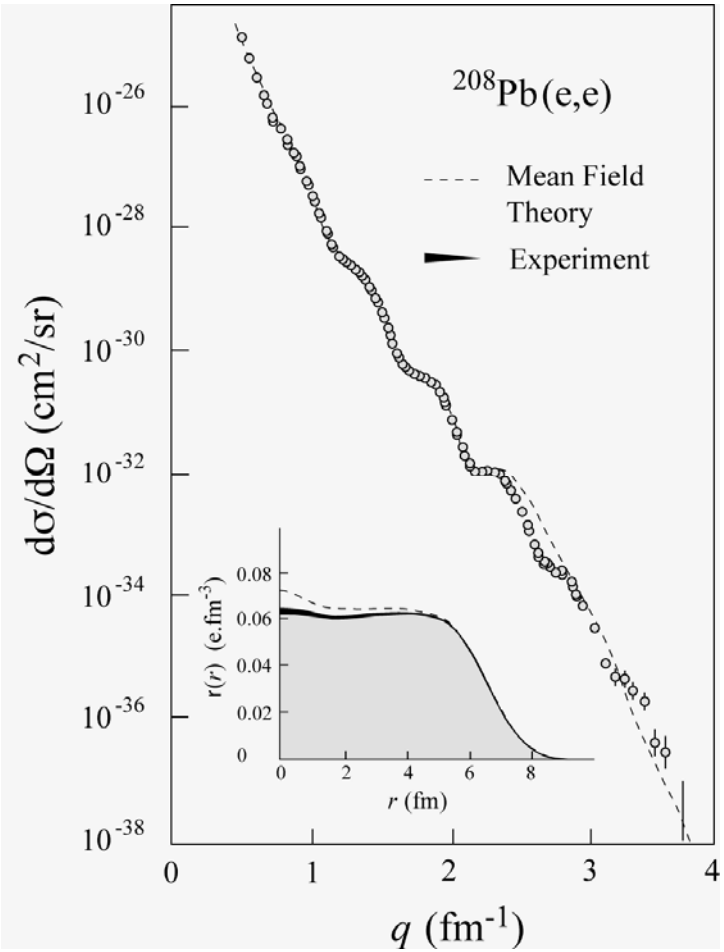
Precise few-nucleon calculations

Exotic mesons and baryons

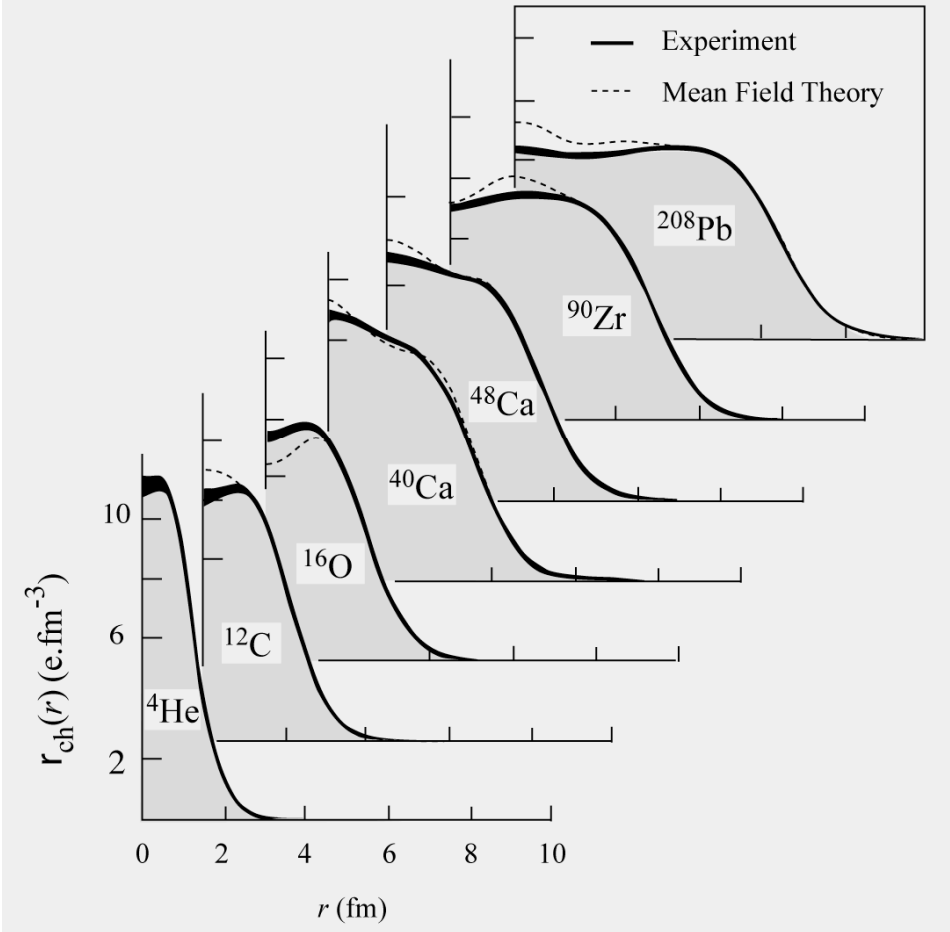
6 GeV Highlights Leading to the 12 GeV Upgrade

- 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

(e,e) ⇒ Nuclear Charge Distributions

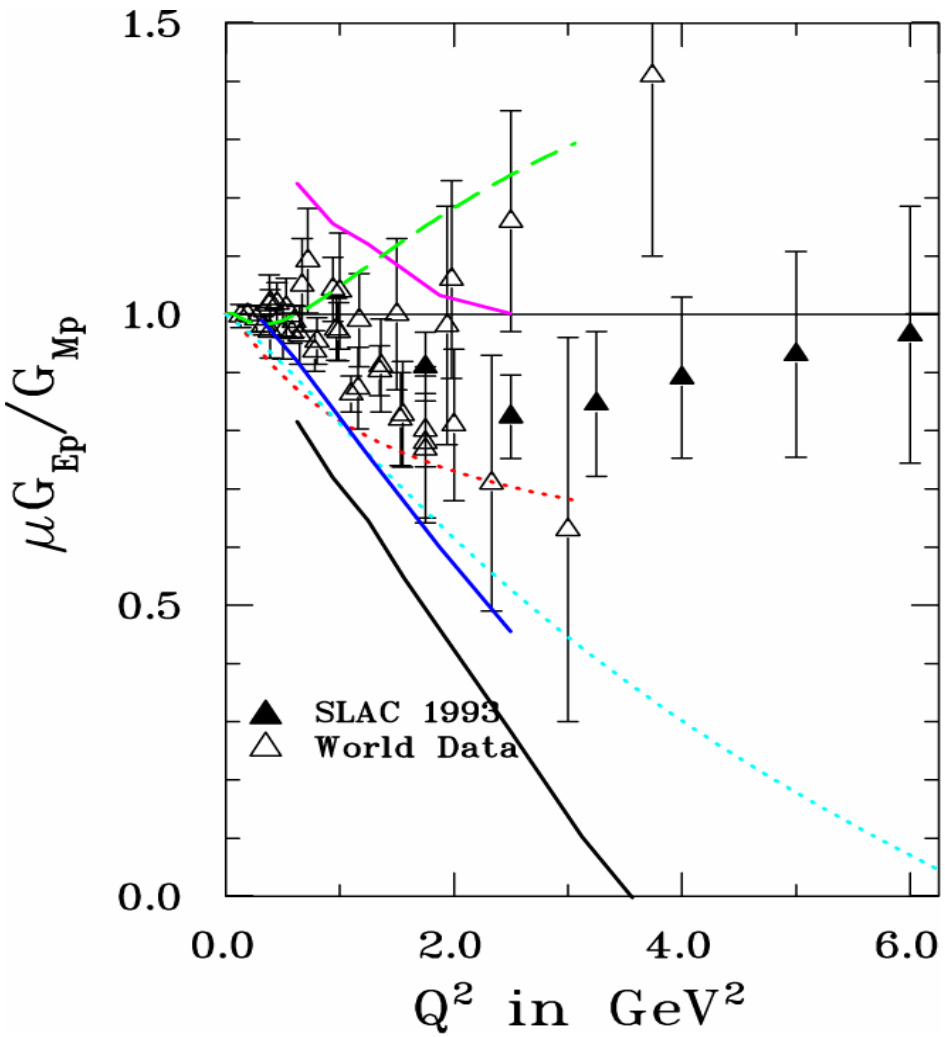


From Stanford to Saclay and Nikhef



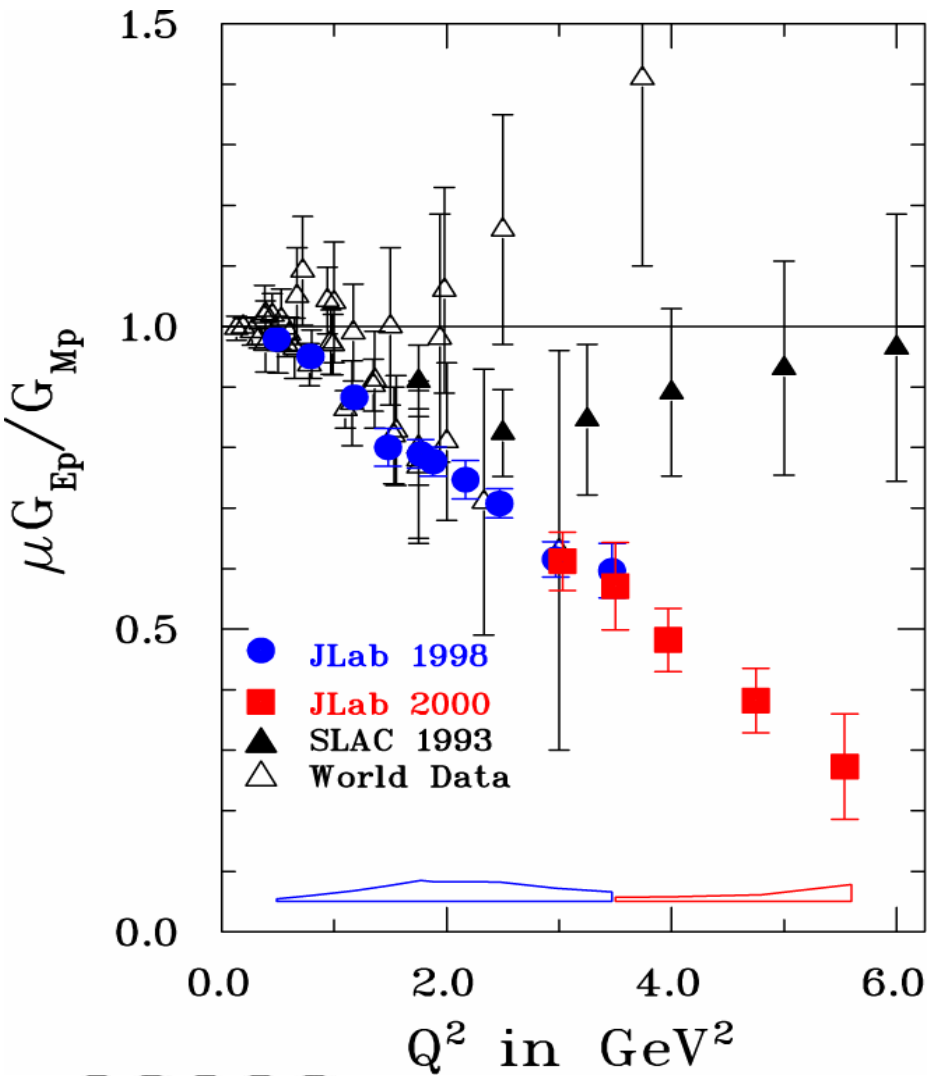
Model-independent analysis ⇒ accurate results on charge distributions

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

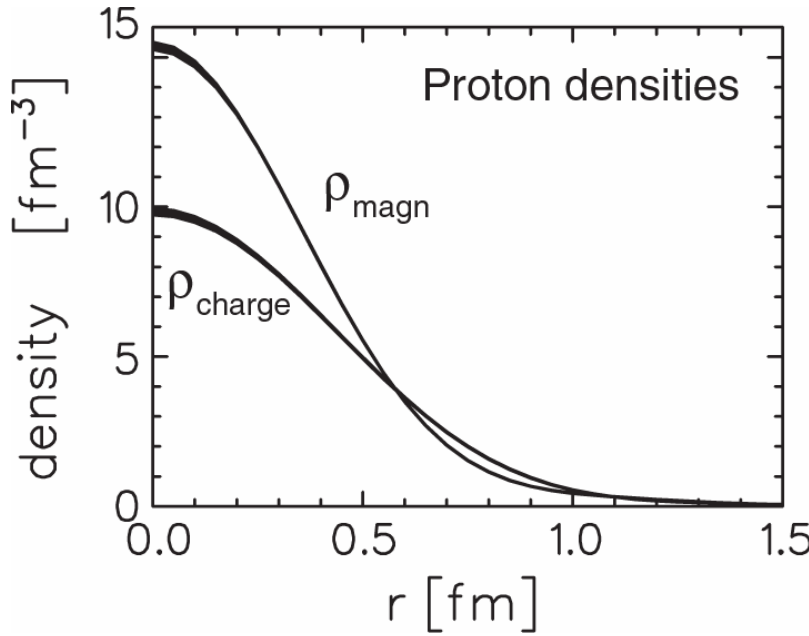
JLab Data Rewrote the Text Book



- High Intensity
- High Duty Factor
- High Polarization

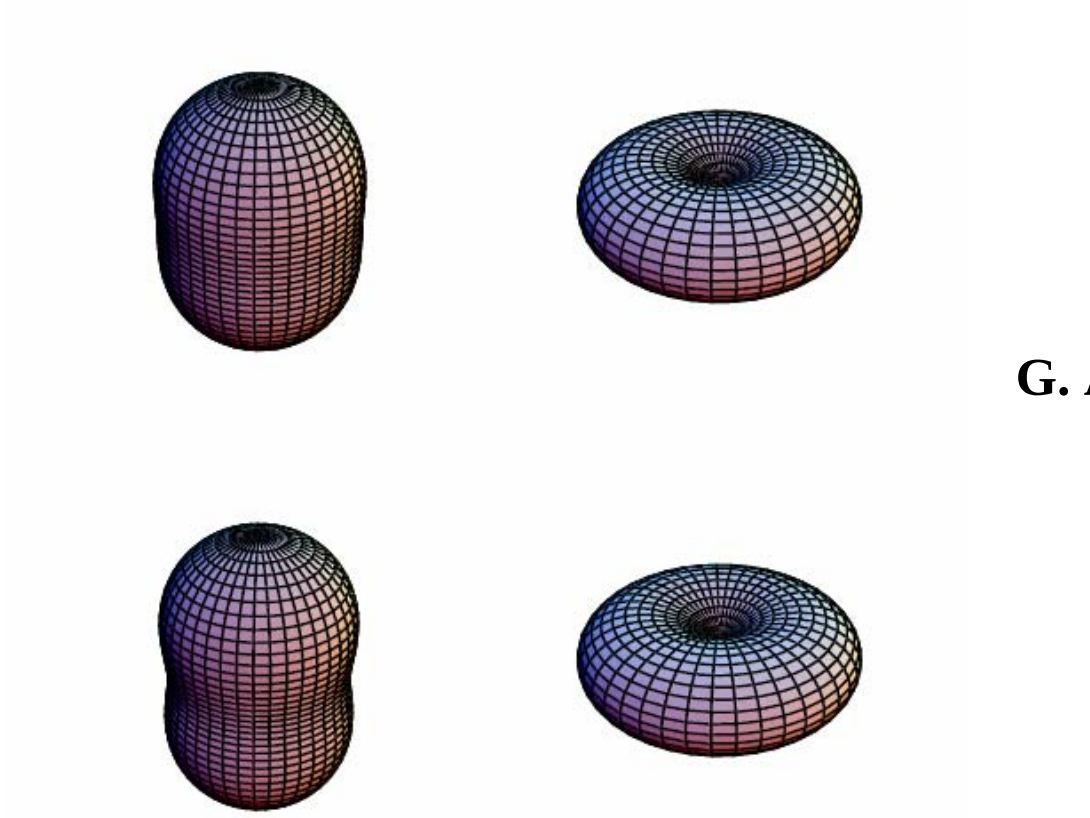
⇒ Revolutionized our knowledge

⇒



Yields New Information on Shape of Nucleon

K = 0 GeV

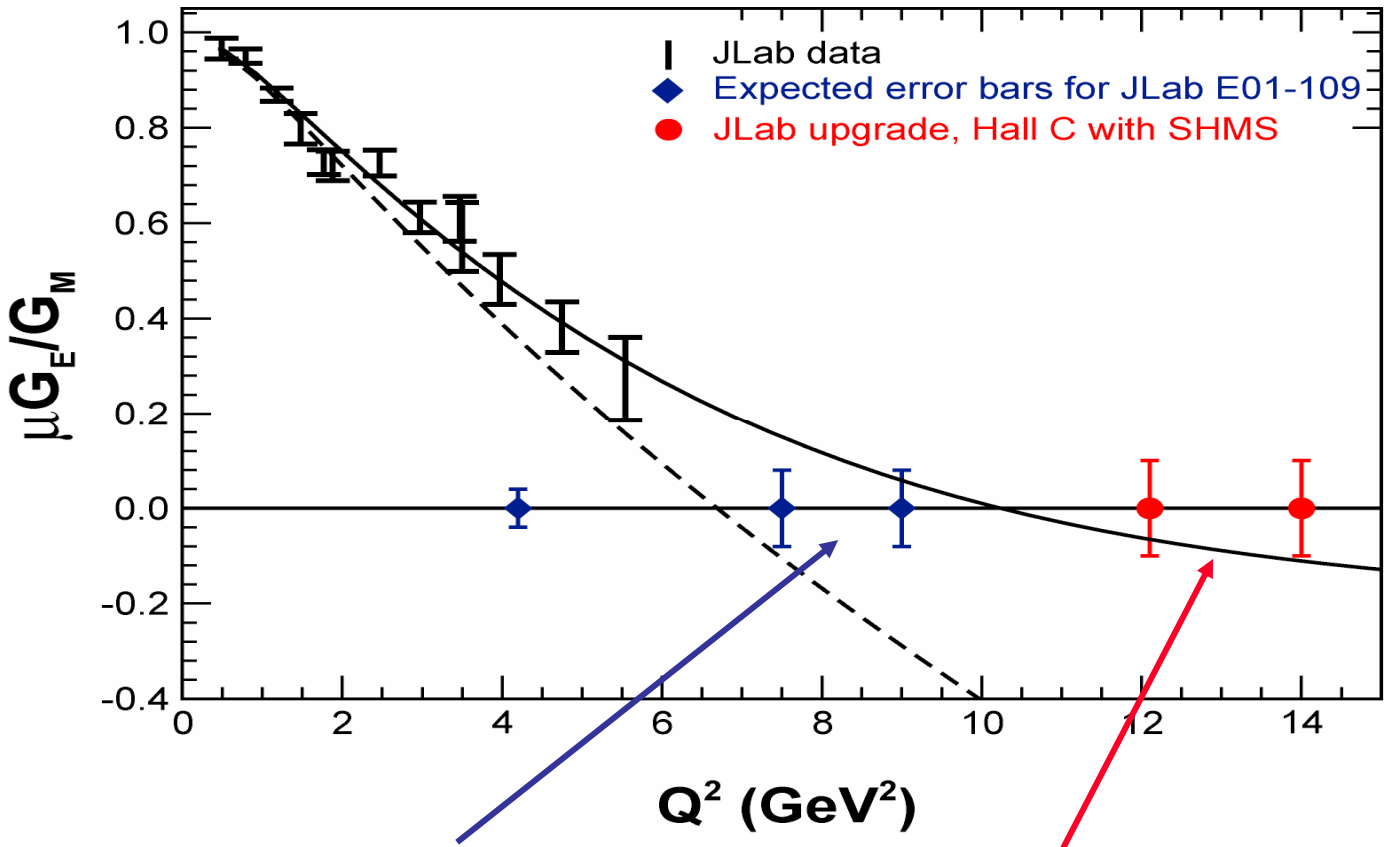


G. A. Miller 2003

K = 1 GeV

Quark spin parallel / anti-parallel to proton spin

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



HP 2010

- Perdrisat *et al*. E01-109 — will increase range of Q^2 by 50% in 2007 (range of Q^2 for n will double over next 3-4 years)
- With 12 GeV and SHMS in Hall C

Strangeness Widely Believed to Play a Major Role – Does It?

- **As much as 100 to 300 MeV of proton mass:**

$$M_N = \langle N(P)| -\frac{9\,\alpha_s}{4\,\pi}\,\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) + m_u\bar{\psi}_u\psi_u + m_d\bar{\psi}_d\psi_d + m_s\bar{\psi}_s\psi_s|N(P)\rangle$$

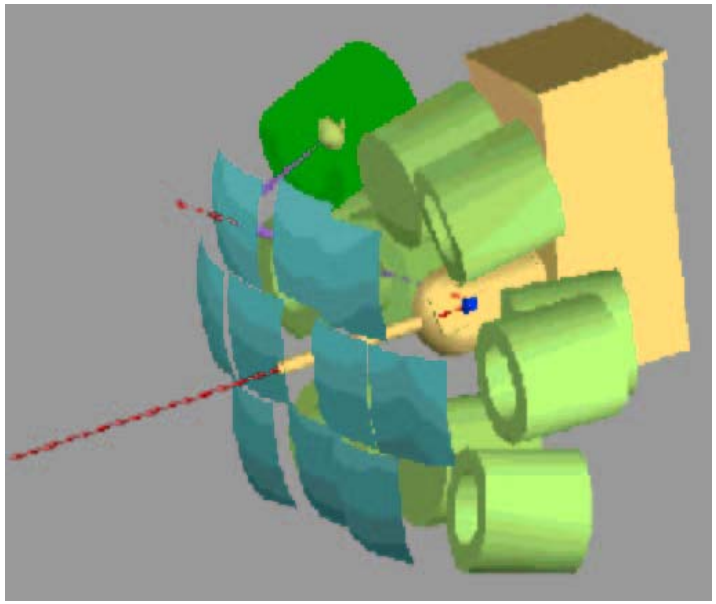
$$\Delta M_N^{s-\mathrm{quarks}} = \frac{y m_s}{m_u + m_d}\,\sigma_N$$

Through proton spin crisis:

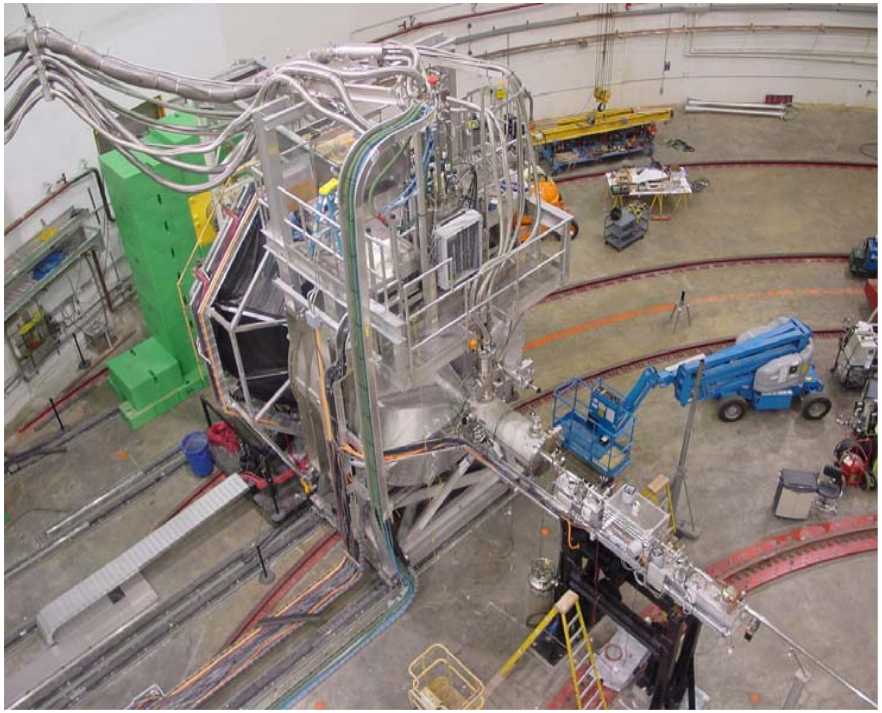
- **as much as 10% of the spin of the proton**

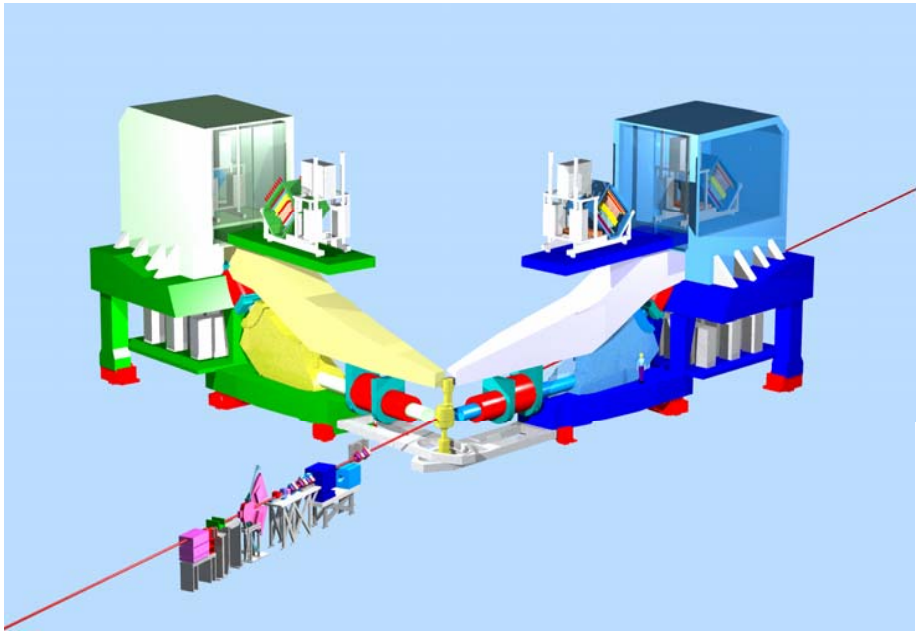
HOW MUCH OF THE ELECTRIC & MAGNETIC FORM FACTORS ?

MIT-Bates & A4 at Mainz



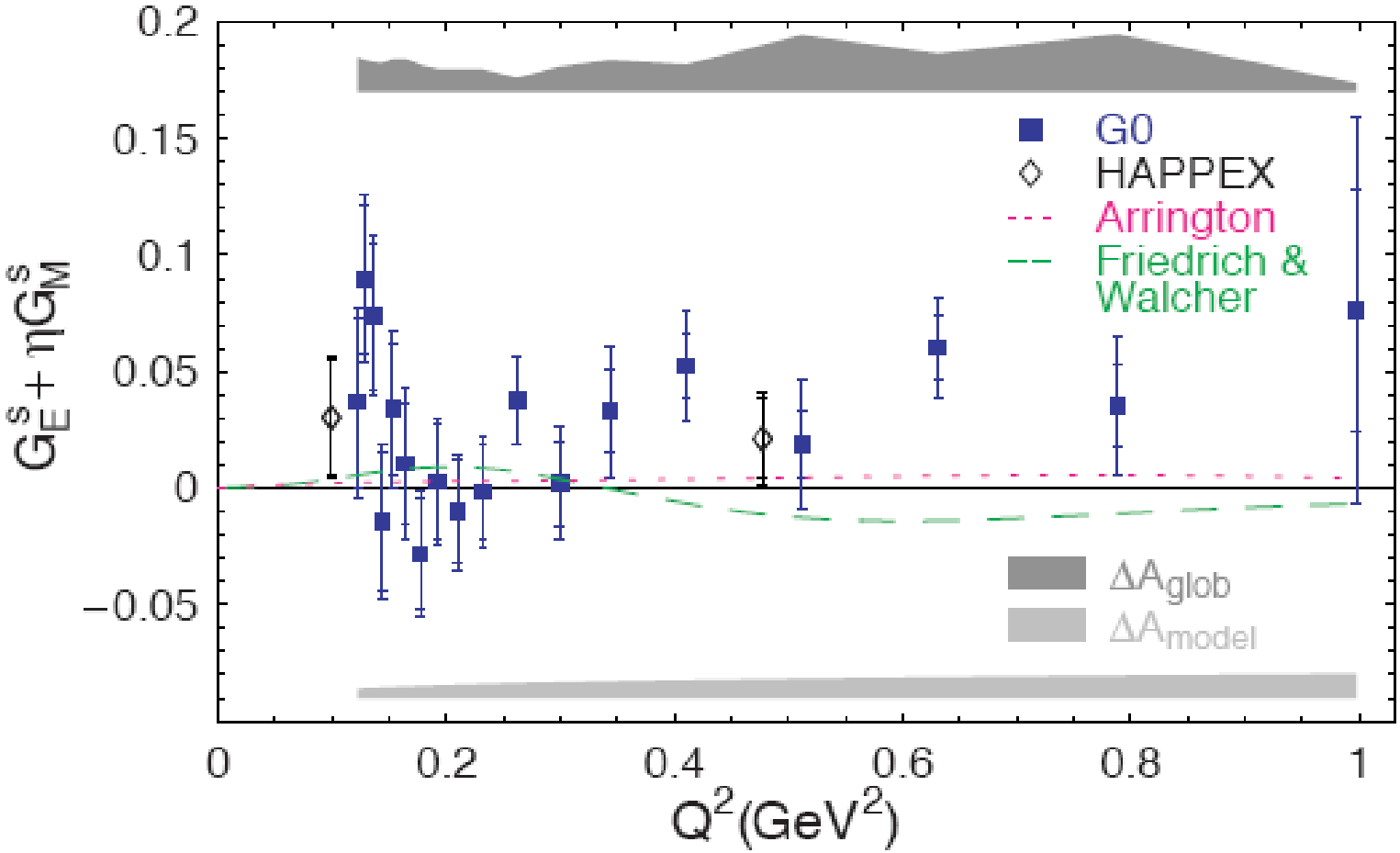
G0 and HAPPEx at Jlab





World Data – pre 2006 HAPPEx

PRL95(2005)



Systematic expansion in Q^2

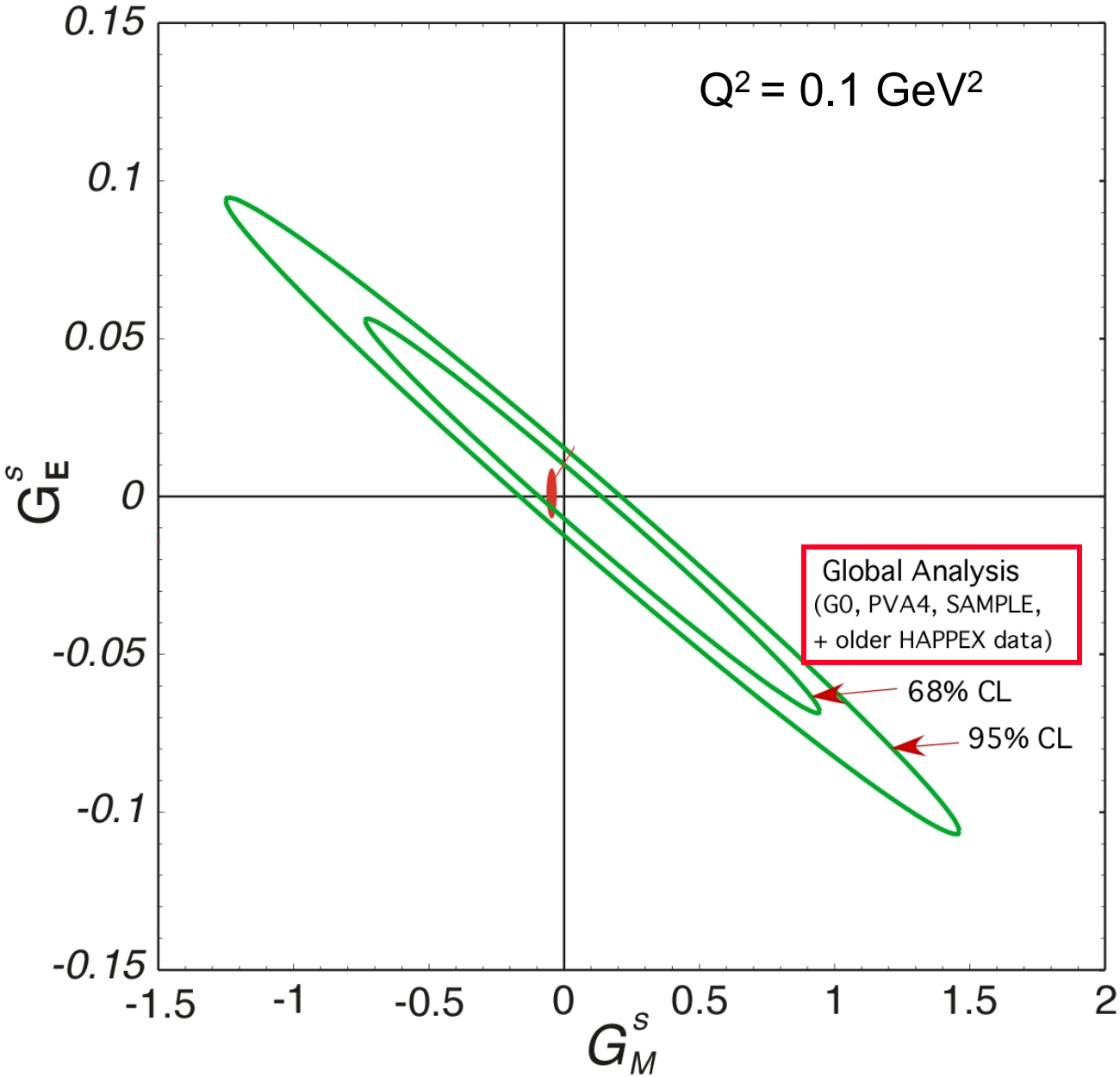
- Fit all PVES data $Q^2 < 0.3\,\mathrm{GeV}^2$ RDY *et al.*, PRL97(2006)
- Extract anapole FF

$$\tilde{G}_A^N = \tilde{g}_A^N (1 + Q^2/\Lambda^2)^{-2}$$

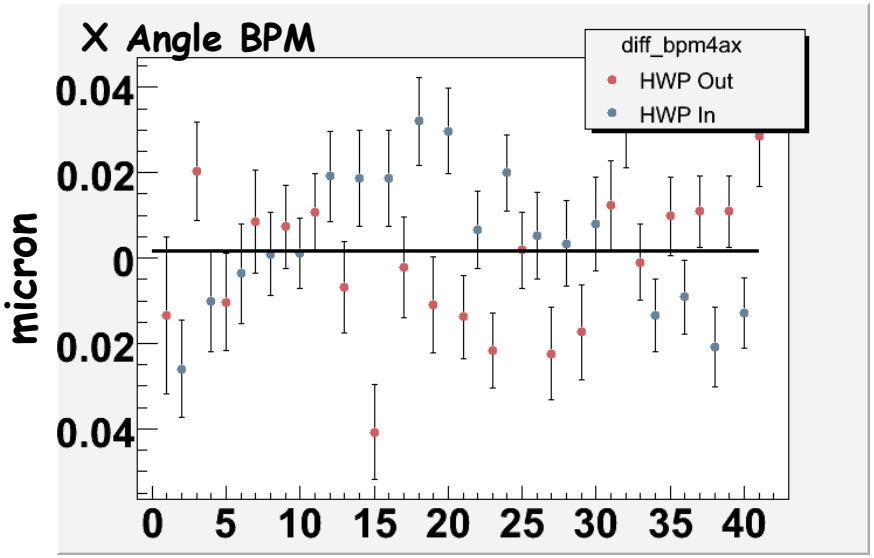
- Taylor expand strangeness

$$G_E^s = \rho_s Q^2 + \rho_s' Q^4 + \ldots$$
$$G_M^s = \mu_s + \mu_s' Q^2 + \ldots$$

Young, Roche, Carlini, Thomas – nucl-ex/0604010 (pre- latest HAPPEx)



Latest HAPPEx Run : Outstanding Achievement !



Surpassed Beam Asymmetry Goals for Hydrogen Run

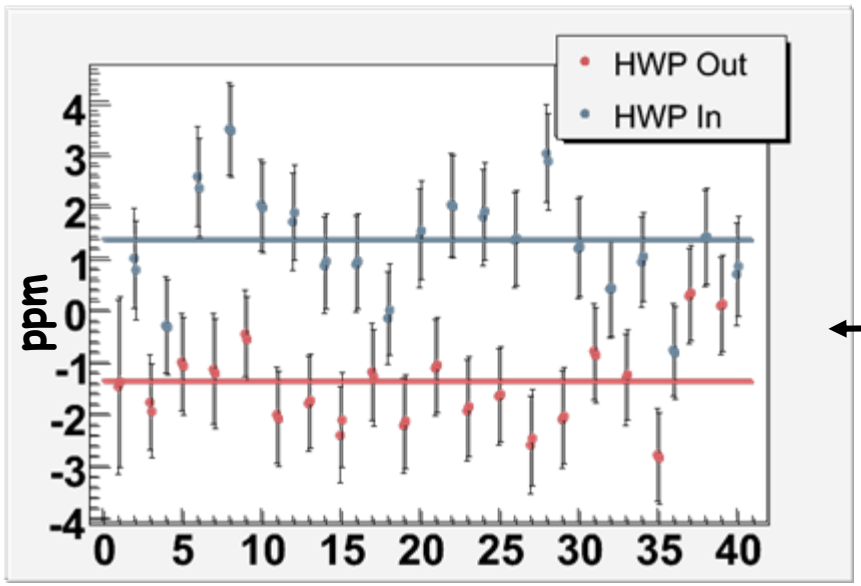
Energy: -0.25 ppb

X Target: 1 nm

X Angle: 2 nm

Y Target : 1 nm

Y Angle: <1 nm

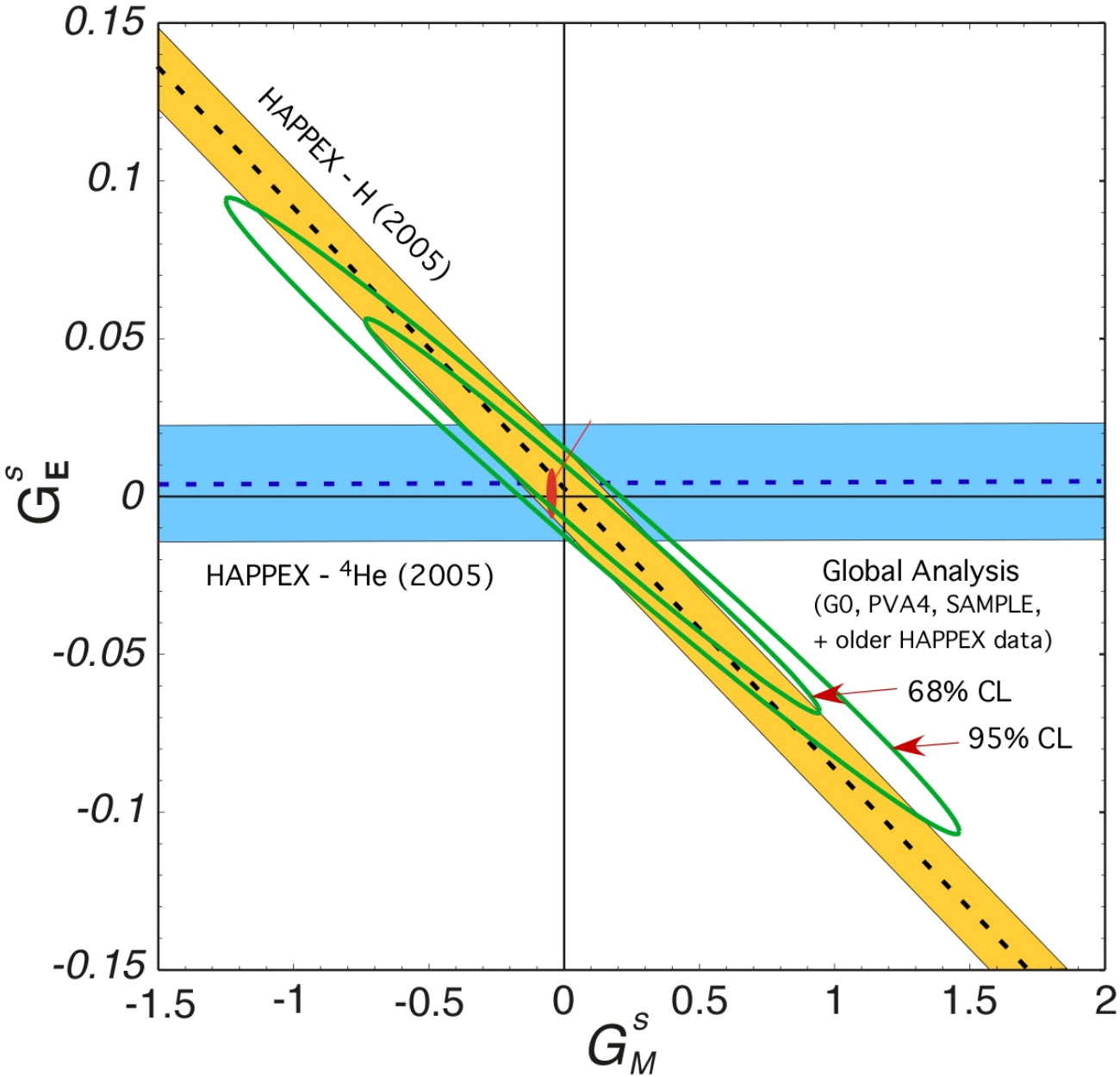


Corrected and Raw

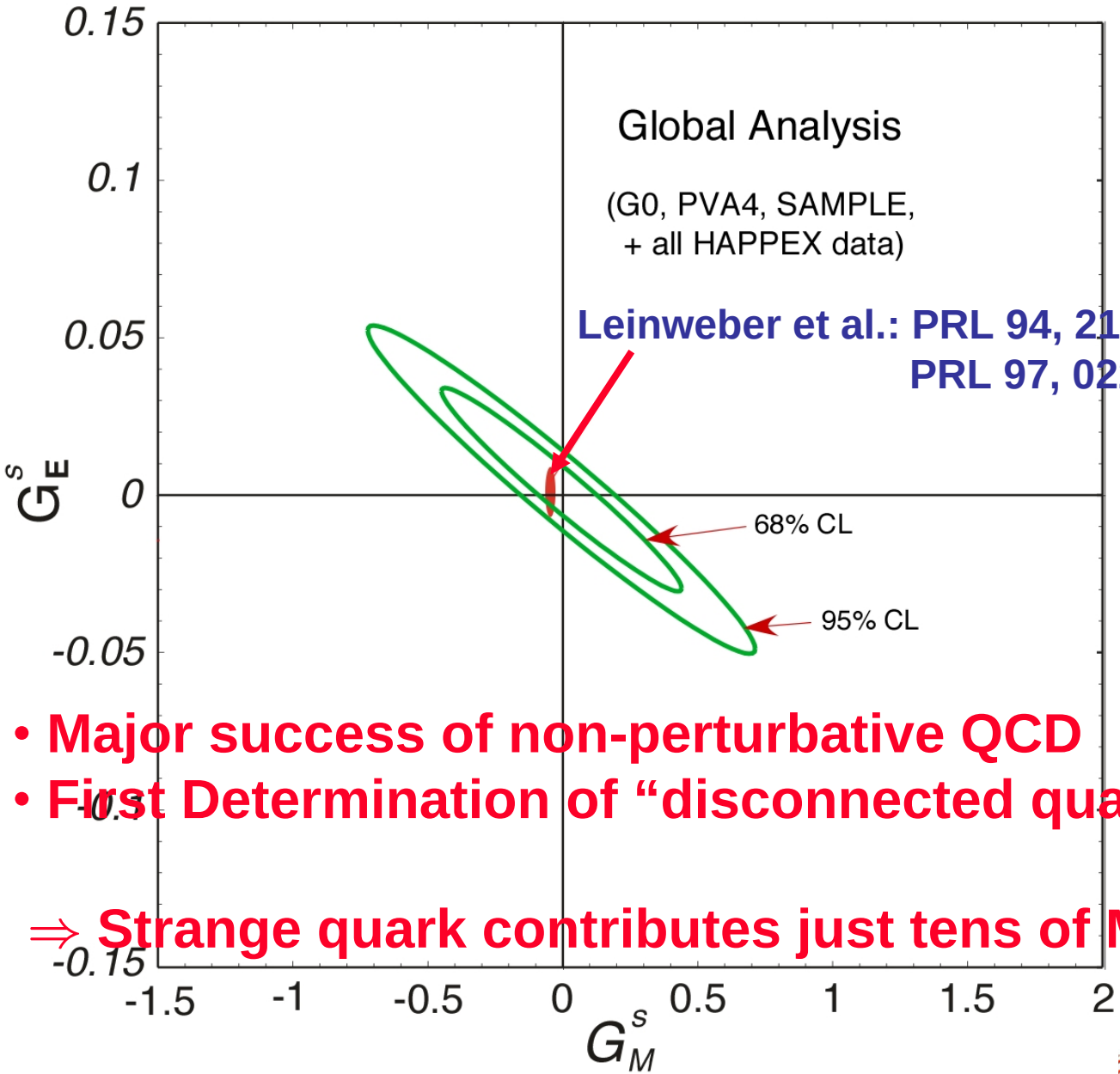
Total correction for beam position asymmetry on Left, Right, or ALL detector: 10 ppb

from Kent Paschke

Superimpose NEW HAPPEx Measurement (April APS Meeting)



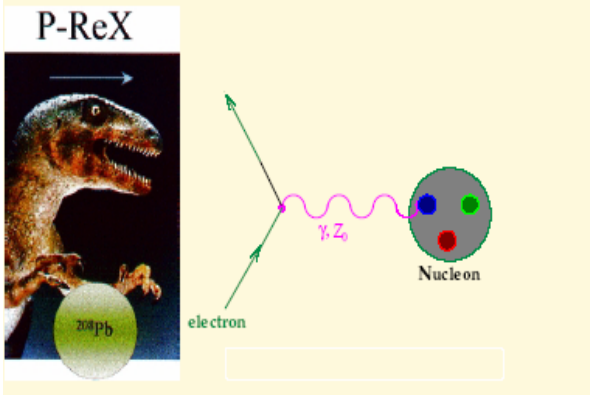
Include new HAPPEx data : halves errors of previous world data !



- **Major success of non-perturbative QCD**
- **First Determination of "disconnected quark loop"**

⇒ Strange quark contributes just tens of MeV to M_N

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:

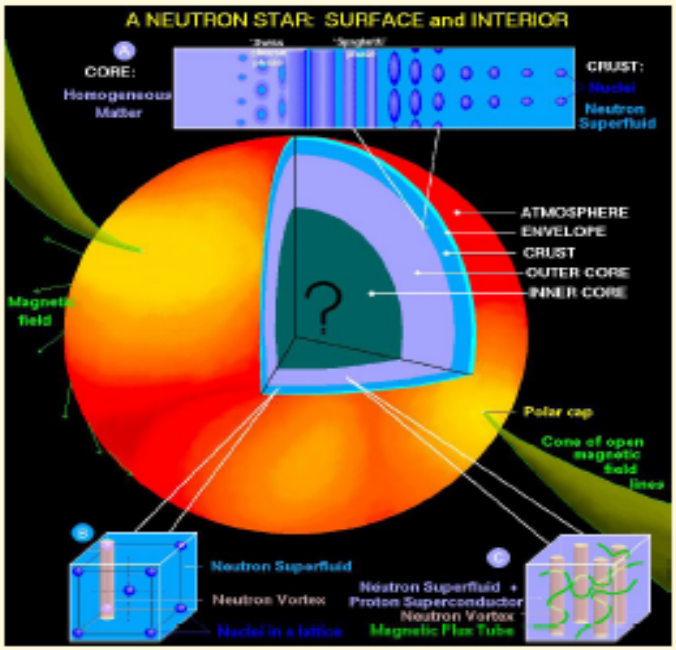
- **Fundamental check of Nuclear Theory**
- **Input to Atomic PV Expts**
- **Neutron Star Structure**

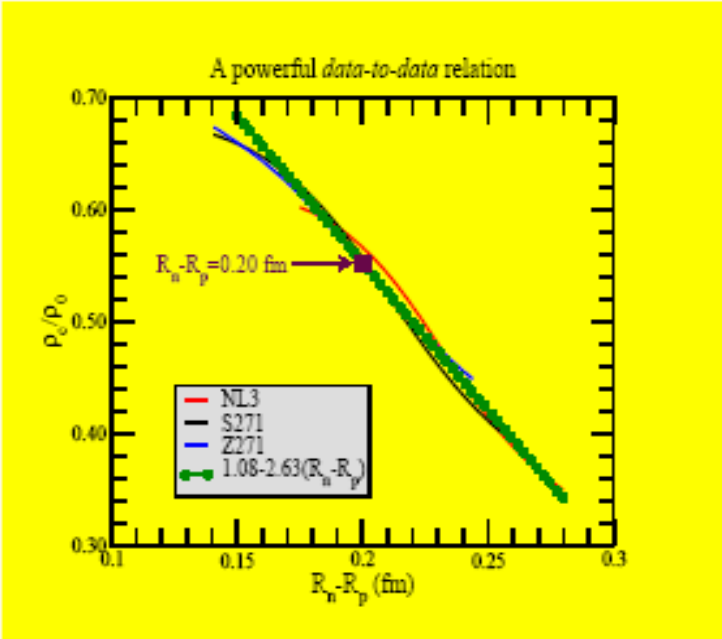
Neutron Skin and Neutron Stars

(Nuclear Astrophysics at Jefferson Lab)

The neutron skin of ^{208}Pb and the crust of a neutron star are made up of similar material: neutron-rich matter at (slightly) subnuclear densities

- Neutron stars contain a solid crust above a uniform liquid mantle
- The stiffer the EOS the lower the transition to non-uniform matter
  - ⋆ Energetically unfavorable to separate into low- and high-density regions
- The stiffer the EOS the larger the neutron skin of a heavy nucleus



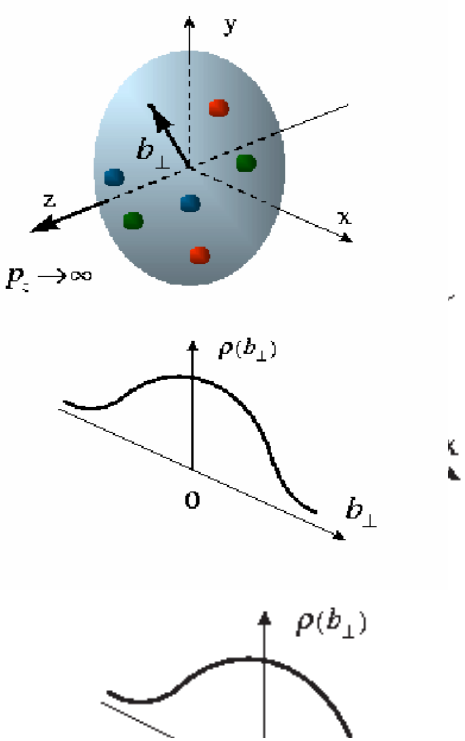


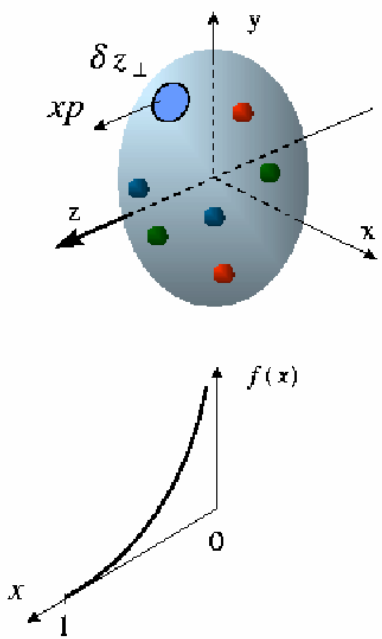
A powerful data-to-data relation: The thicker the neutron skin of a heavy nucleus, the lower the transition density from uniform to non-uniform neutron-rich matter ...

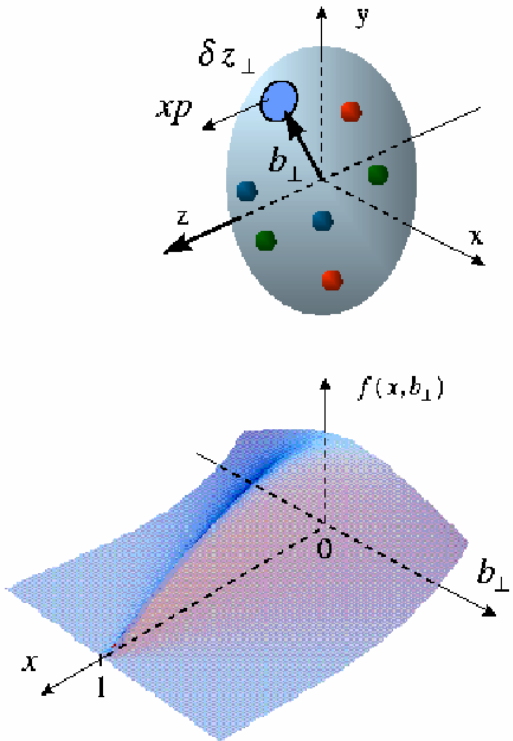
6 GeV Highlights Leading to the 12 GeV Upgrade

- 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 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

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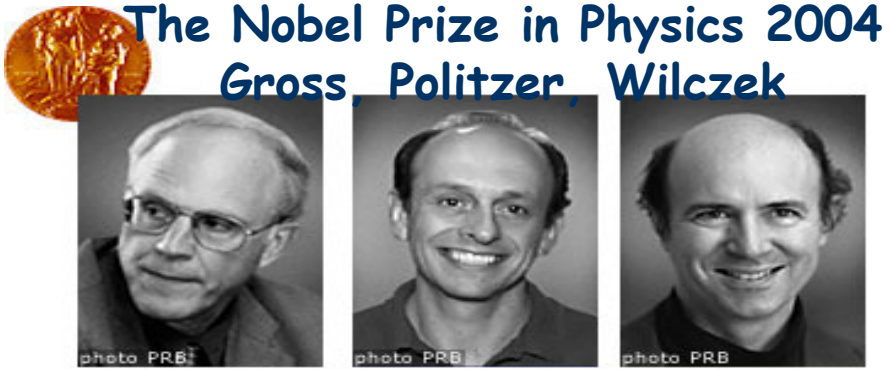
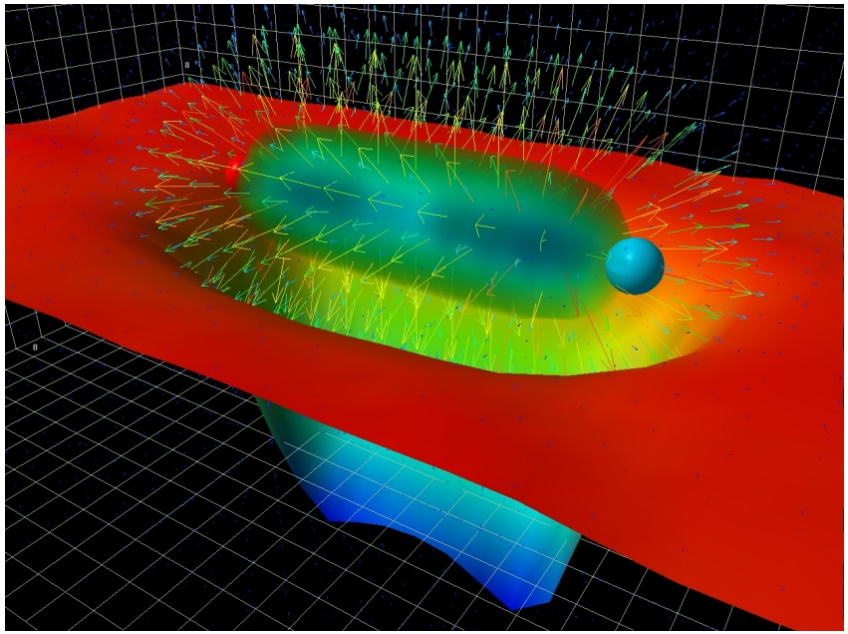
QCD: Unsolved in Nonperturbative Regime



- **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!

Gluonic Excitations and the Origin of Confinement

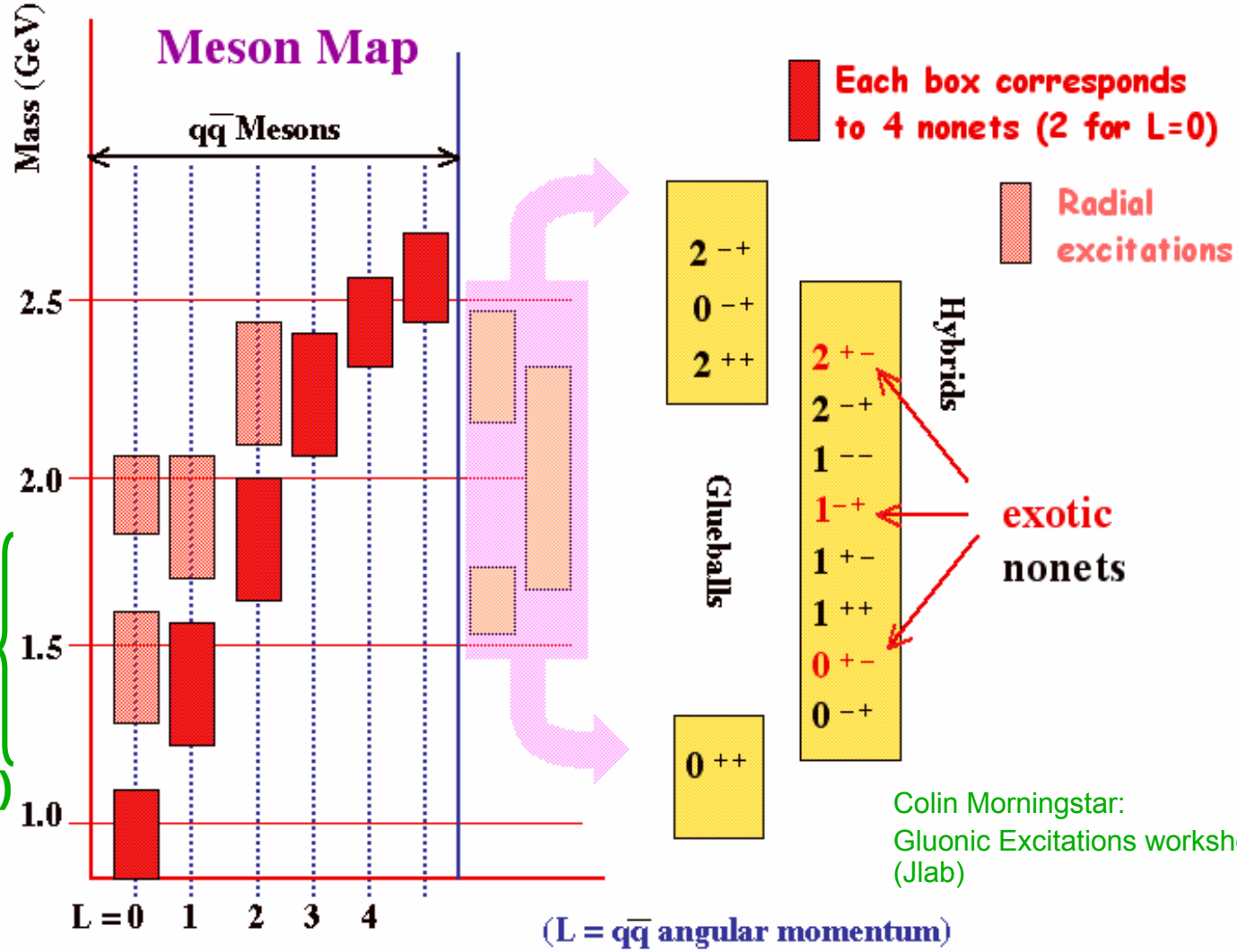


QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

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**

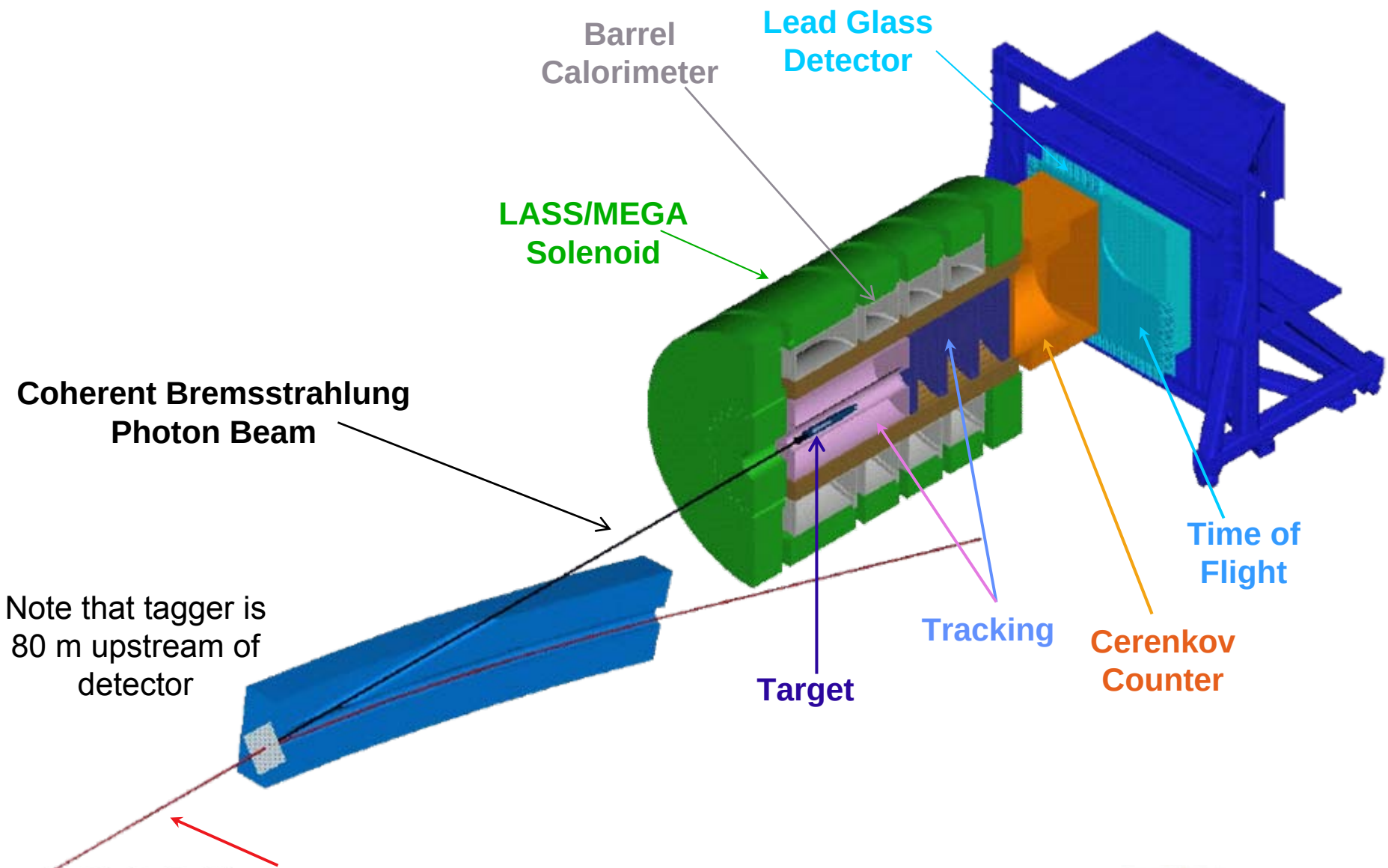
Glueballs and hybrid mesons



Initial search FY07 – G12 (CLAS)

Colin Morningstar:
Gluonic Excitations workshop, 2003 (Jlab)

Hall D GlueX Detector

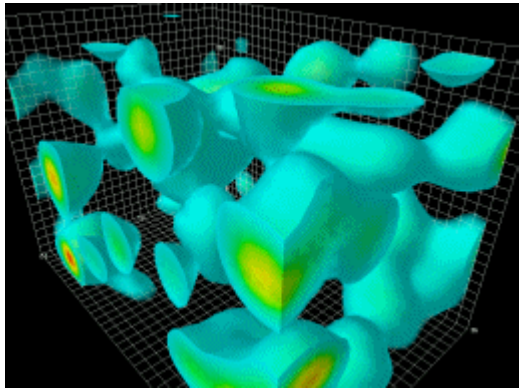


6 GeV Highlights Leading to the 12 GeV Upgrade

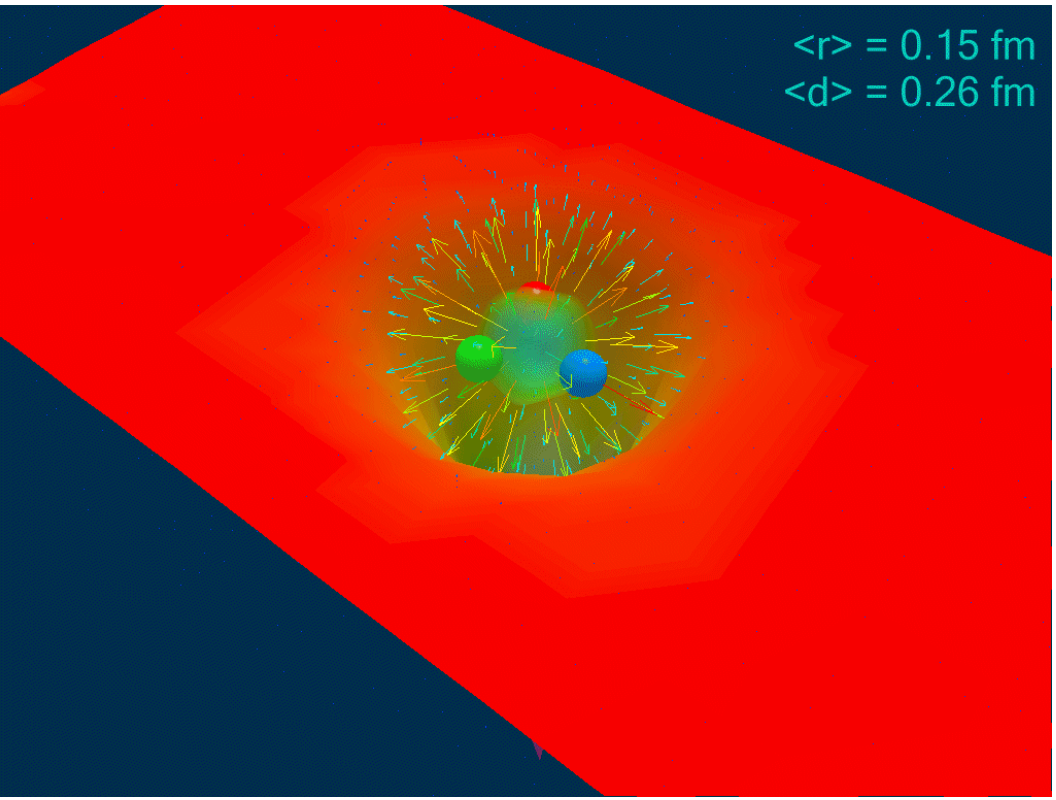
- Parton Distribution Functions
- Form Factors
- Generalized Parton Distributions
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- **Nuclei at the level of quarks and gluons**
- Tests of Physics Beyond the Standard Model

The QCD Lagrangian and Nuclear "Medium Modifications"

The QCD vacuum



Long-distance gluonic fluctuations



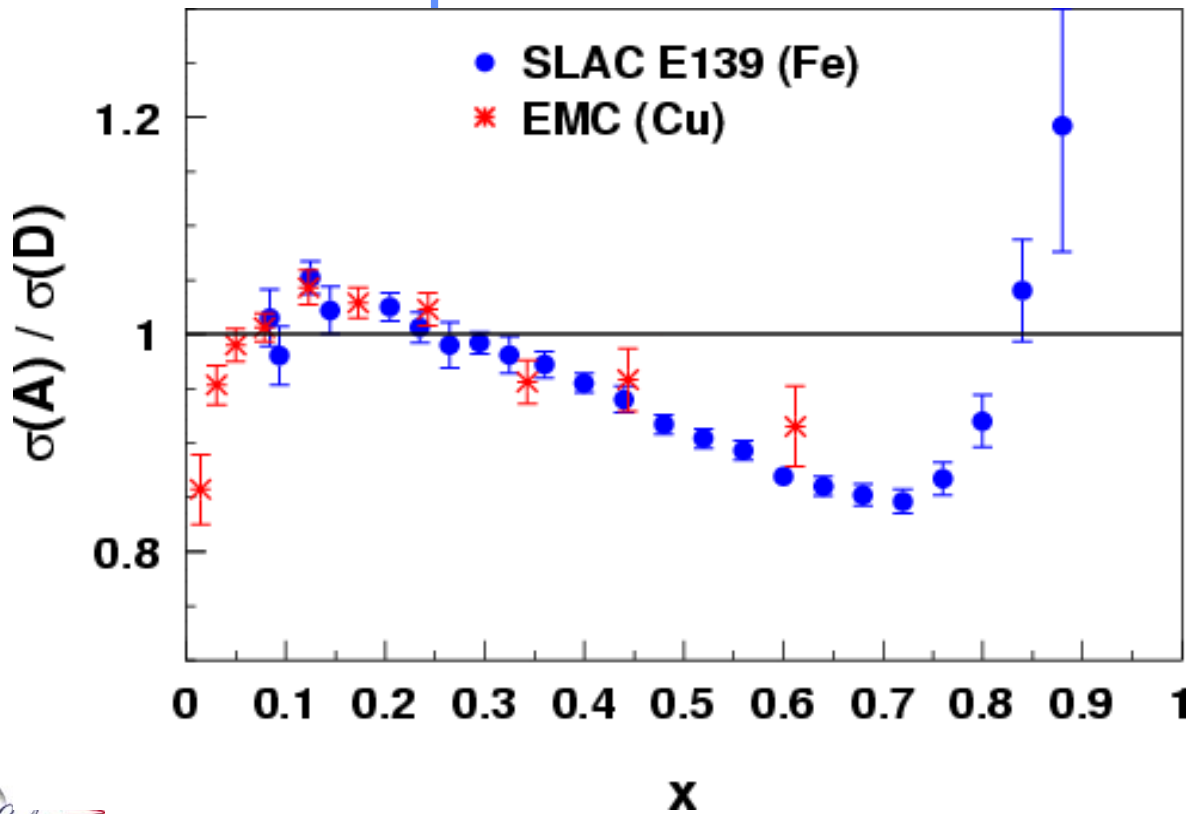
Lattice calculation demonstrates *reduction of chiral condensate* $\langle q\bar{q} \rangle$ of QCD vacuum in presence of hadronic matter

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?



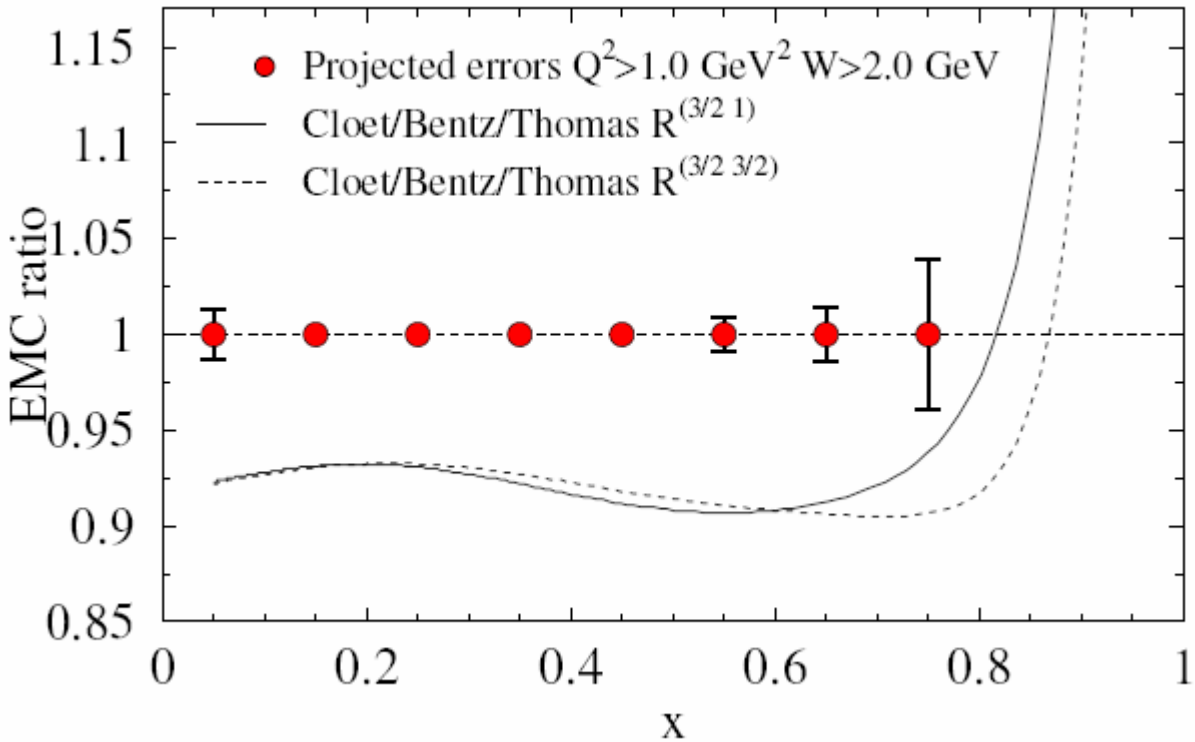
J. Ashman *et al.*, Z. Phys. C57, 211 (1993)

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

$g_1(A)$ – "Polarized EMC Effect"

- **New calculations indicate factor of 2 bigger effect for polarized structure function than for unpolarized**
- **Scalar field modifies lower components of Dirac wave function**
- **Spin-dependent parton distribution functions for nuclei nearly unknown**

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



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

6 GeV Highlights Leading to the 12 GeV Upgrade

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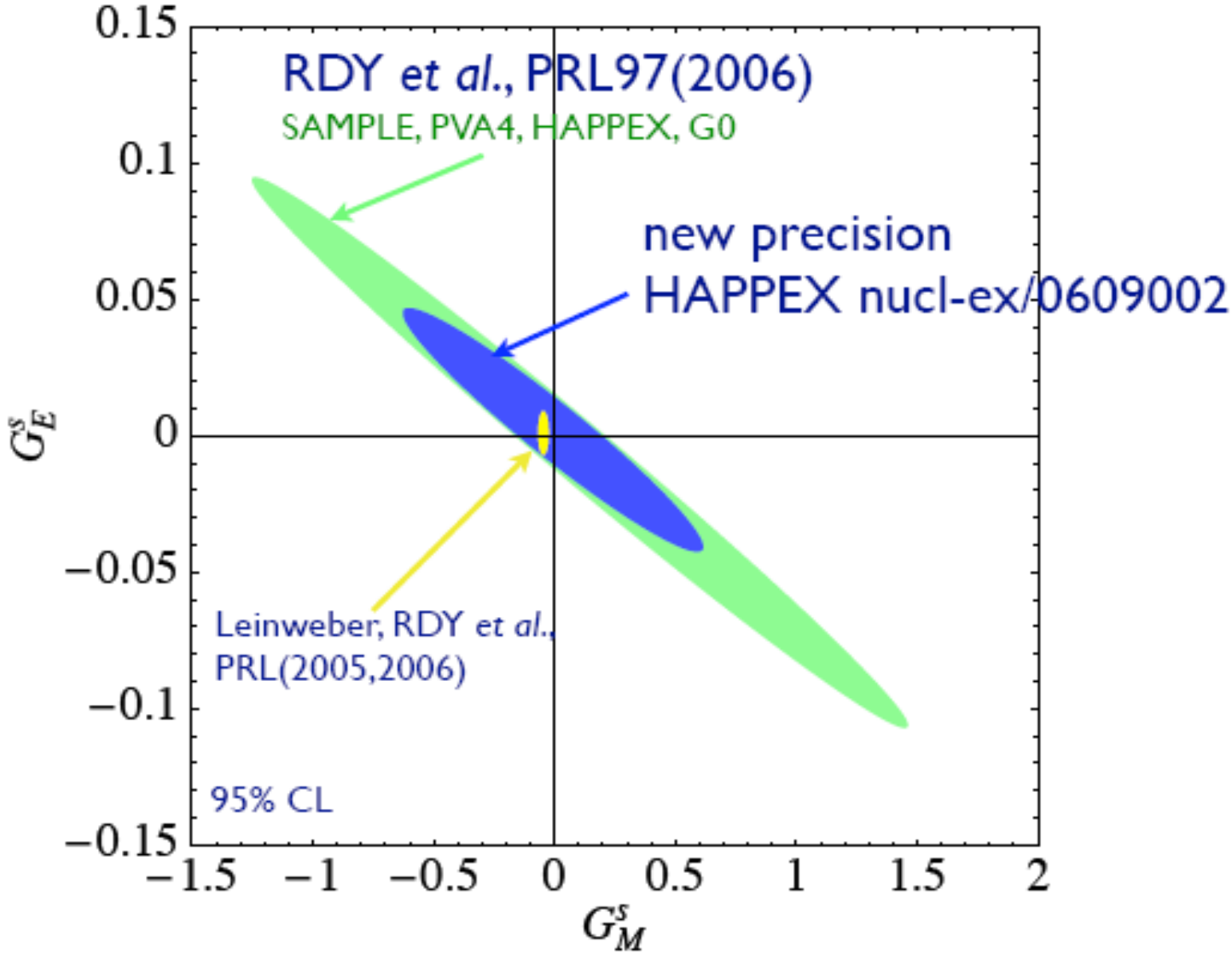
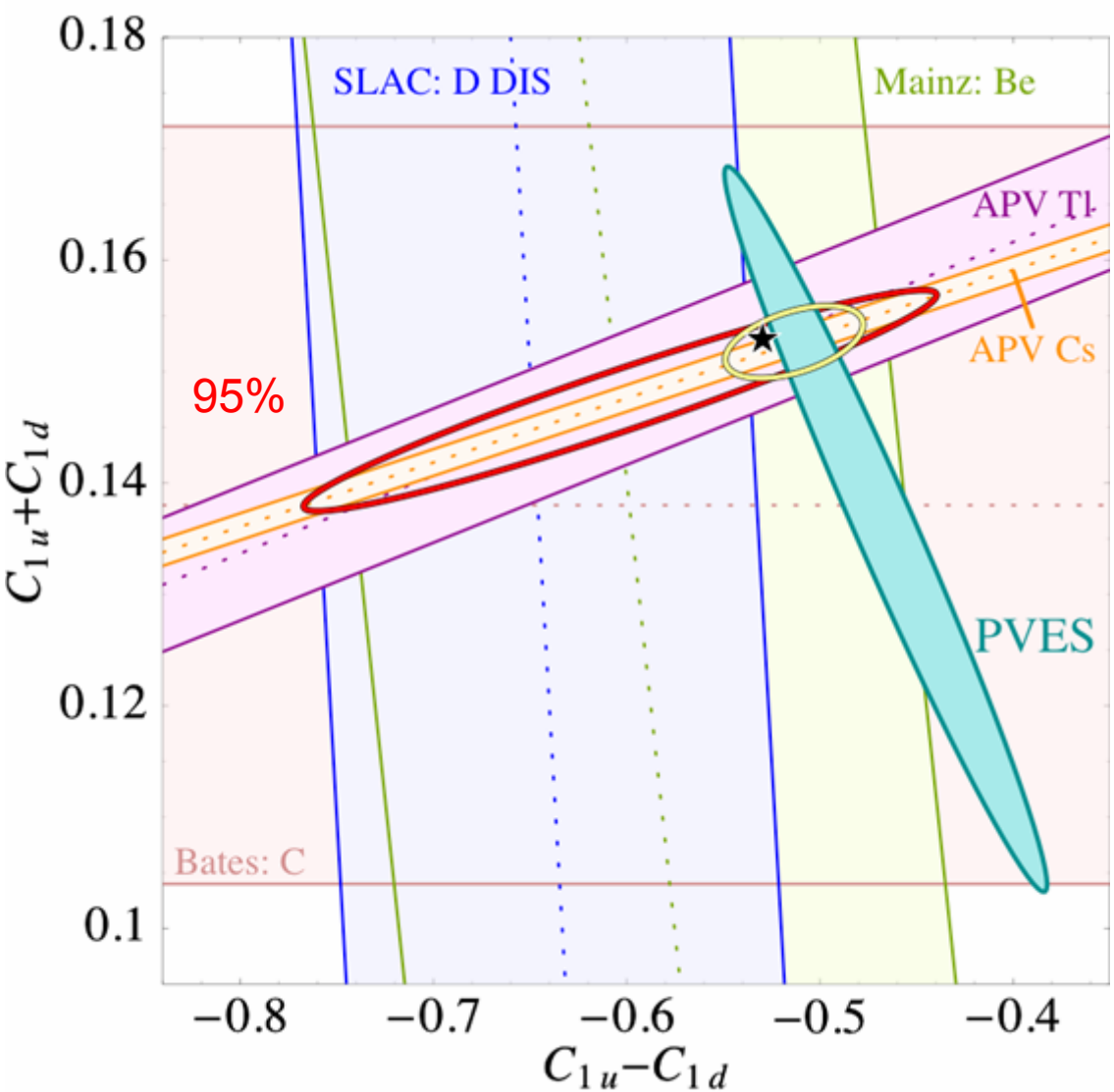
Recall: PVES Remarkably Precise …

Can We Test the Standard Model?



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

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

General Limits on Physics Beyond SM

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

Erler et al., PRD68(2003)

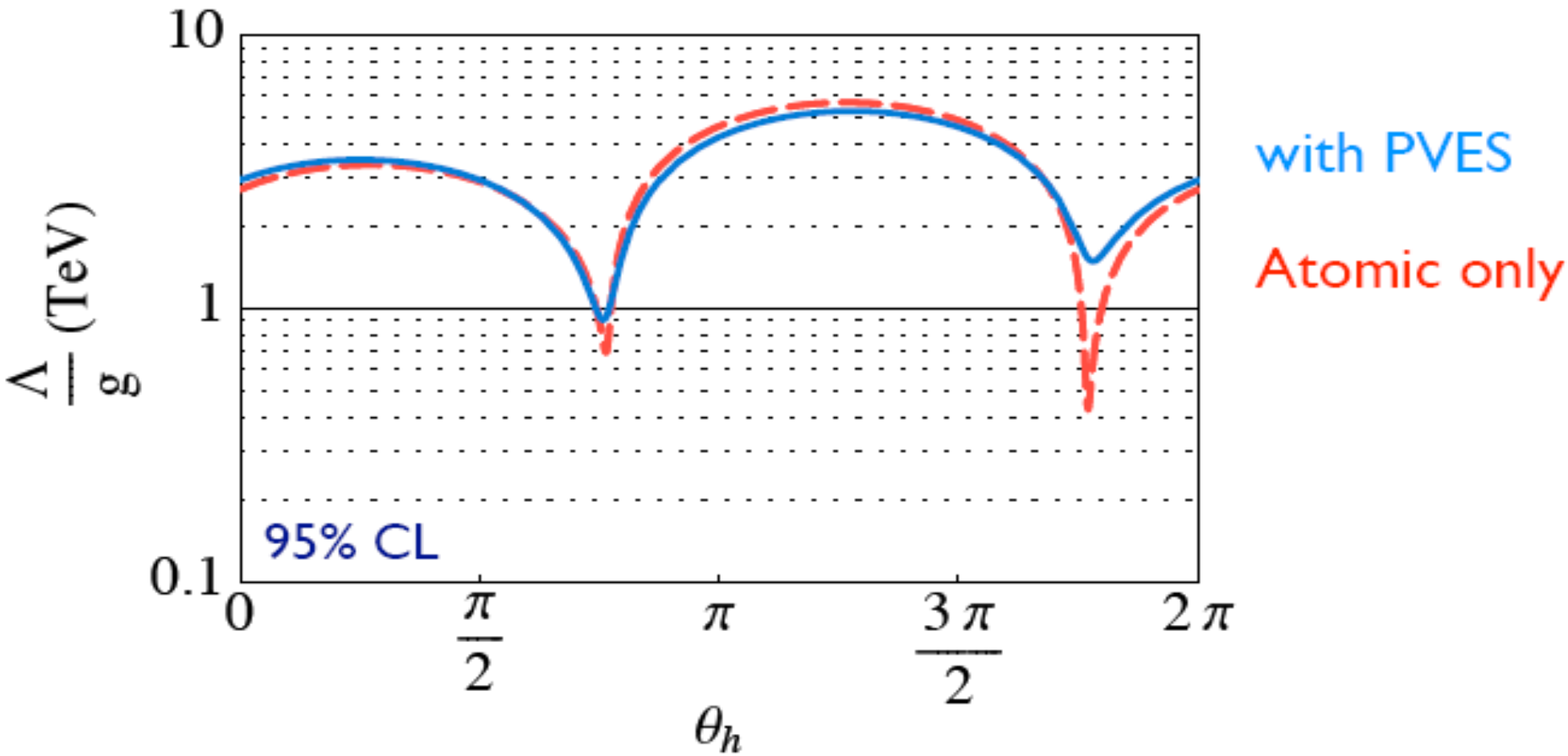
$$\mathcal{L}_{\mathrm{NP}}^{\mathrm{PV}} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

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

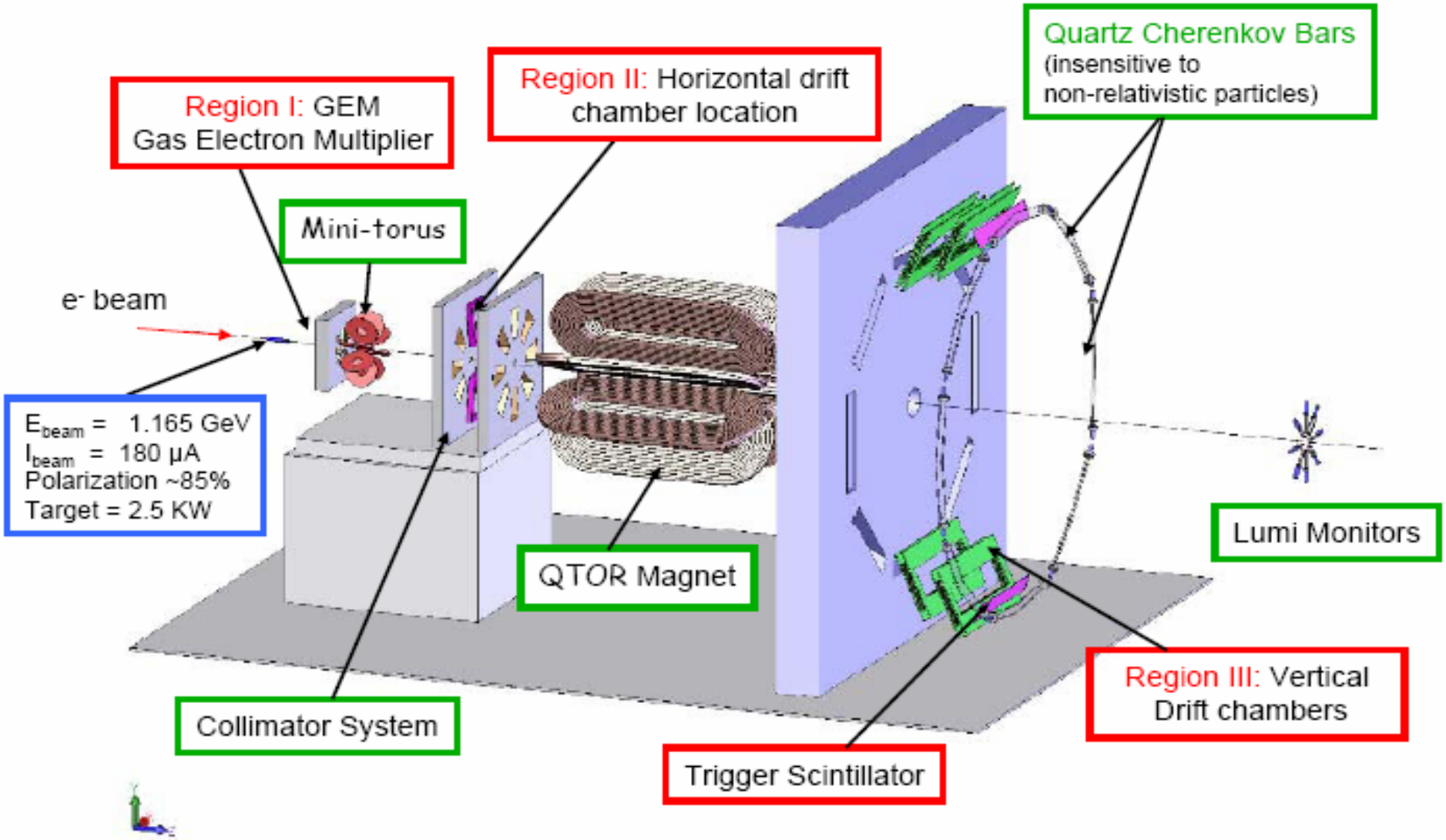
Raises Mass of New Z' to 0.9 TeV – from 0.4 TeV



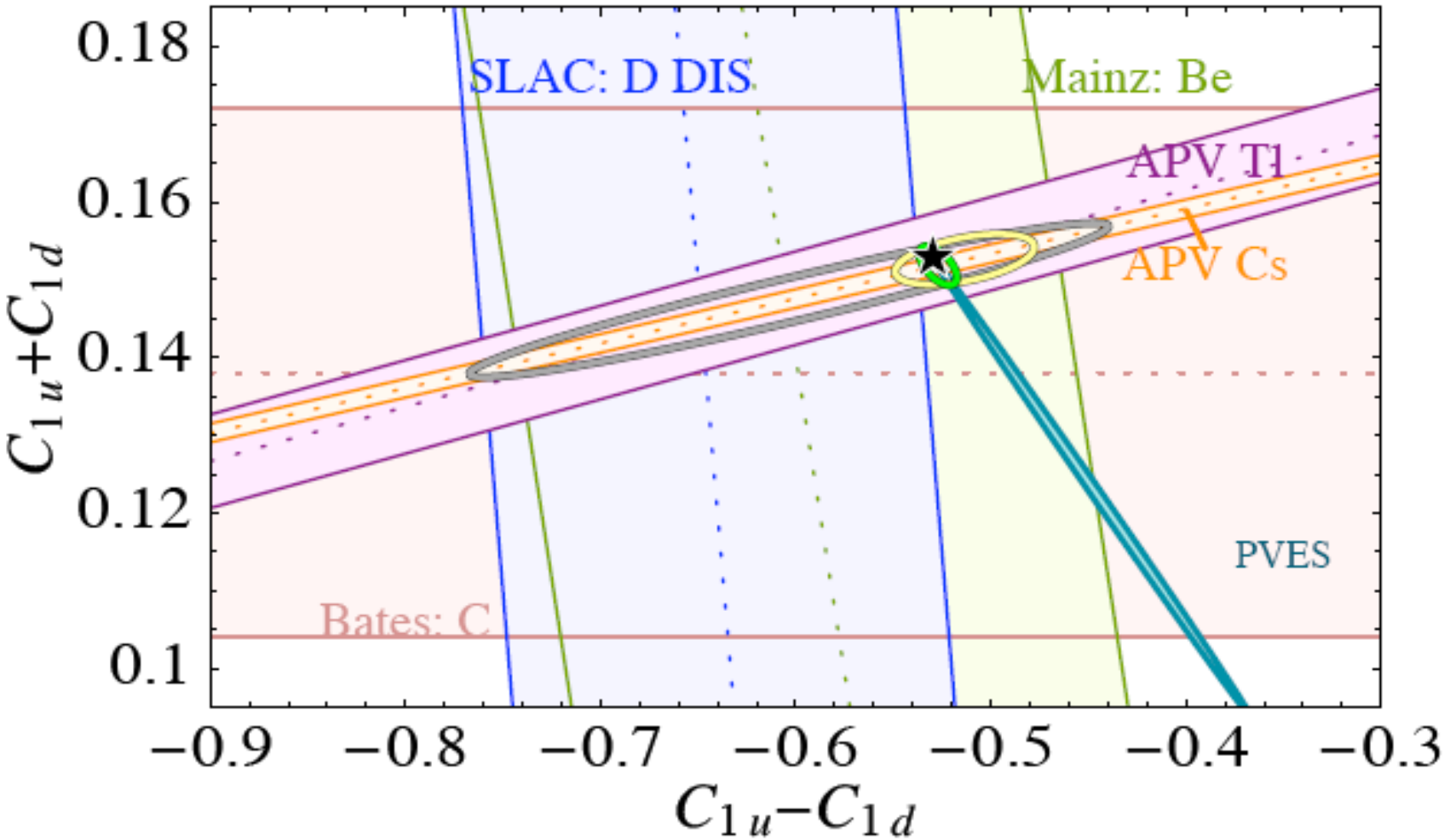
New physics scale >0.9 TeV! (from 0.4 TeV)

Implies LHC cannot see in first 3 years of operation

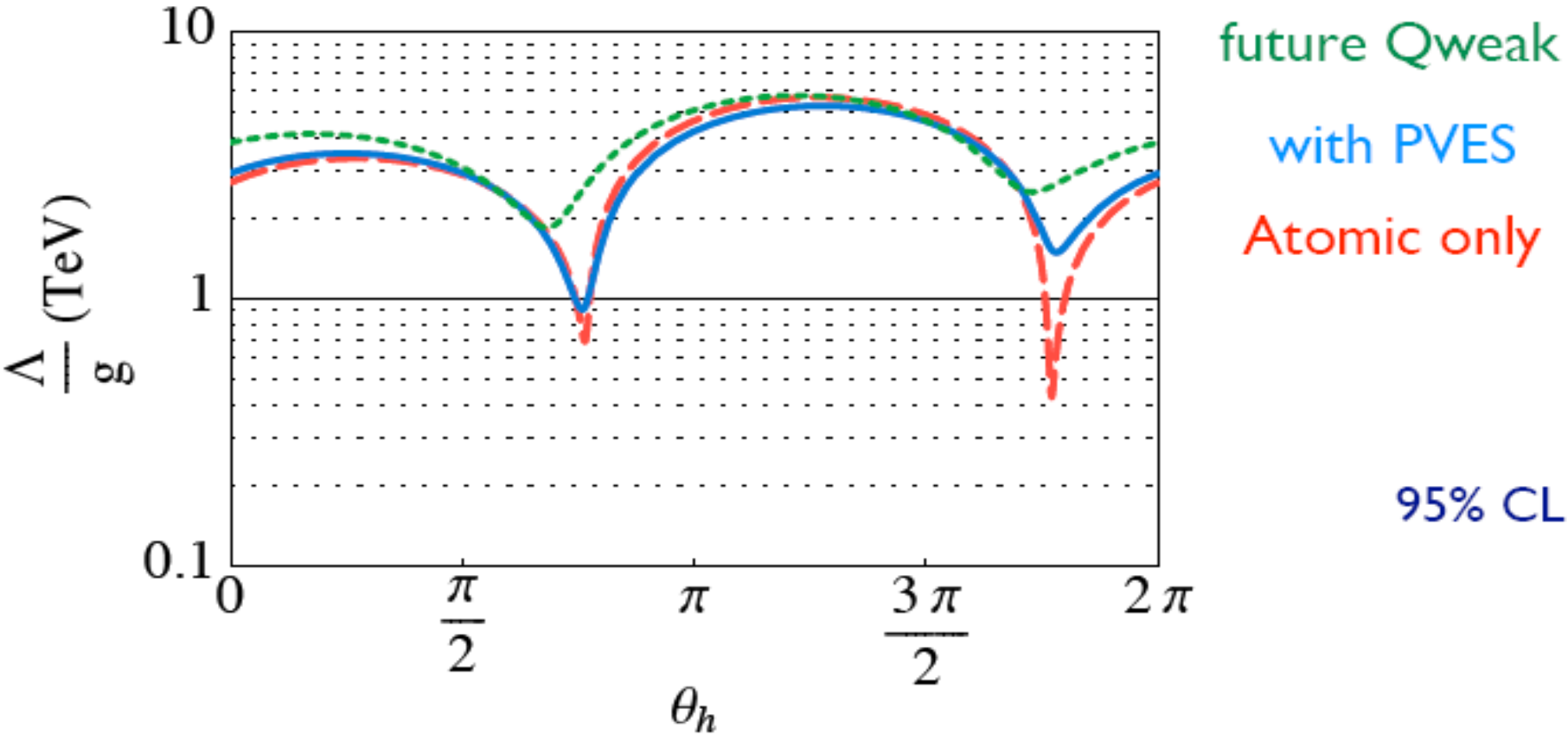
Q_{weak} Apparatus



Future Q_{weak} – IF in Agreement with SM



IF in accord with Standard Model…

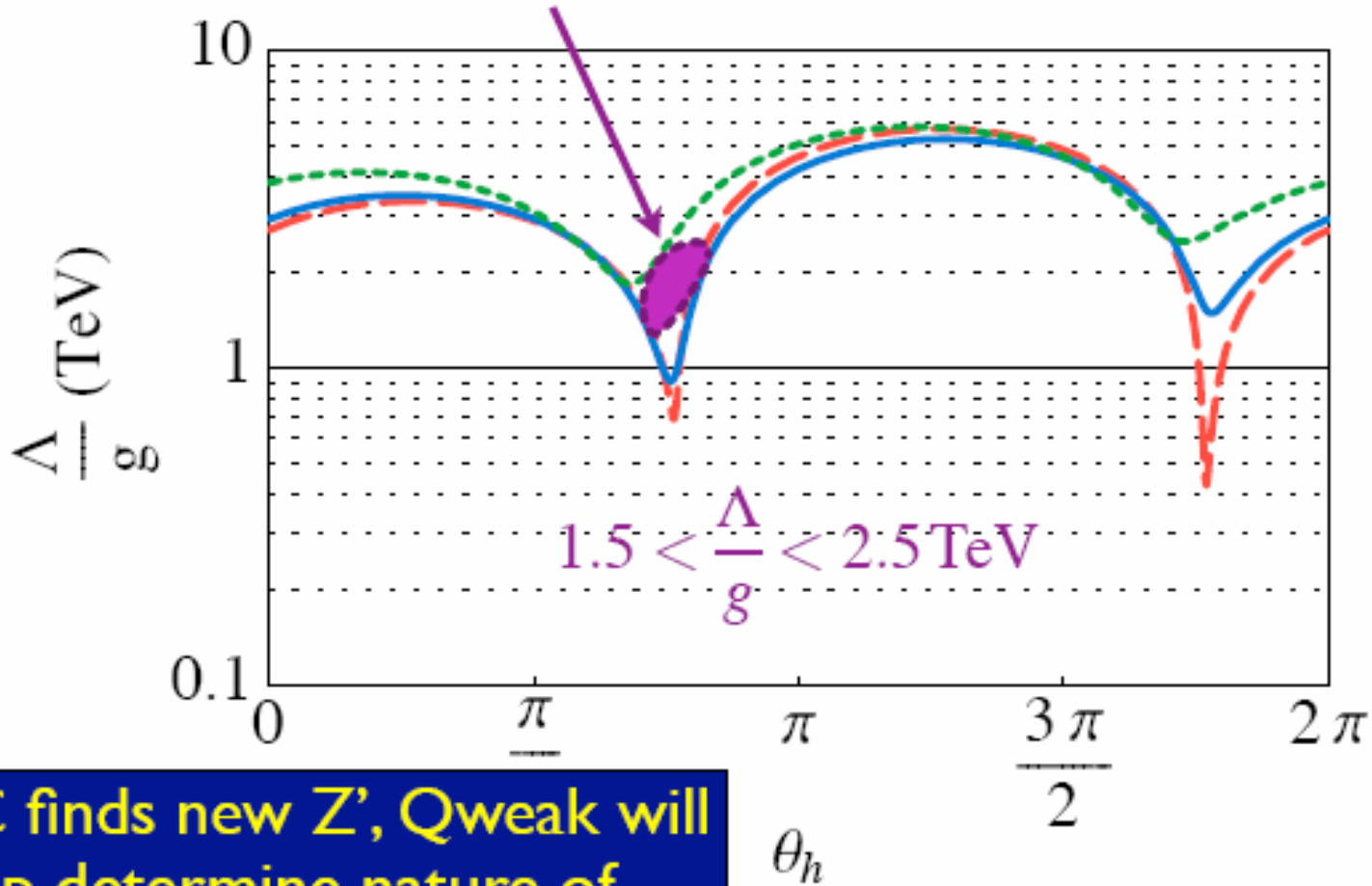


Qweak constrains new physics to beyond 2 TeV

⇒ **Another factor 10 in integrated luminosity at LHC**

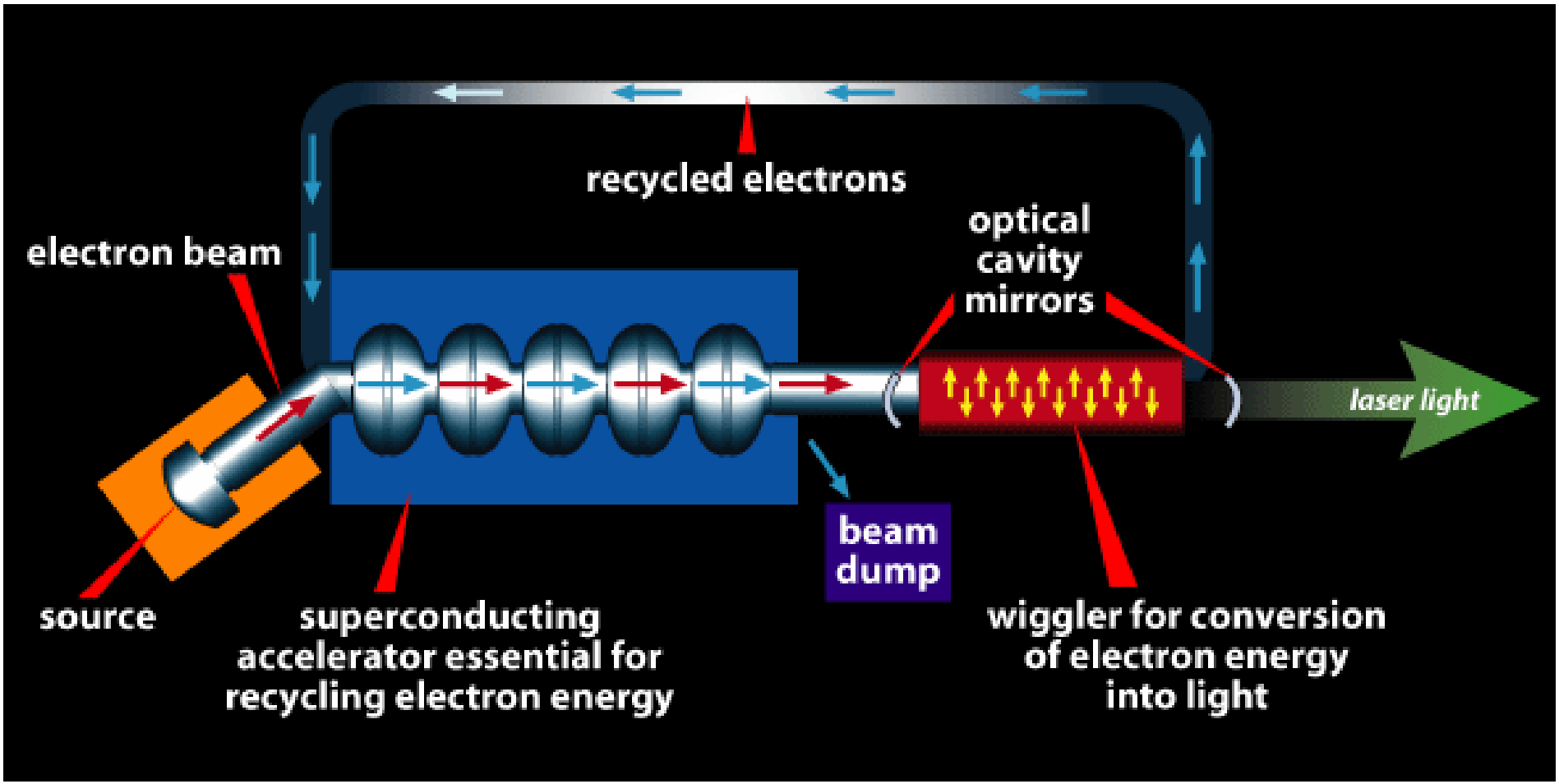
Or… Discovery

Assume Qweak takes central value of current measurements



If LHC finds new Z', Qweak will help determine nature of interaction

Jefferson Lab's Energy Recovered Linac / FEL
(Gwyn Williams)



Reminder: 100 mA at 3 GeV is 300 Megawatts(!!), so energy recovery essential

Worldwide FEL Capability

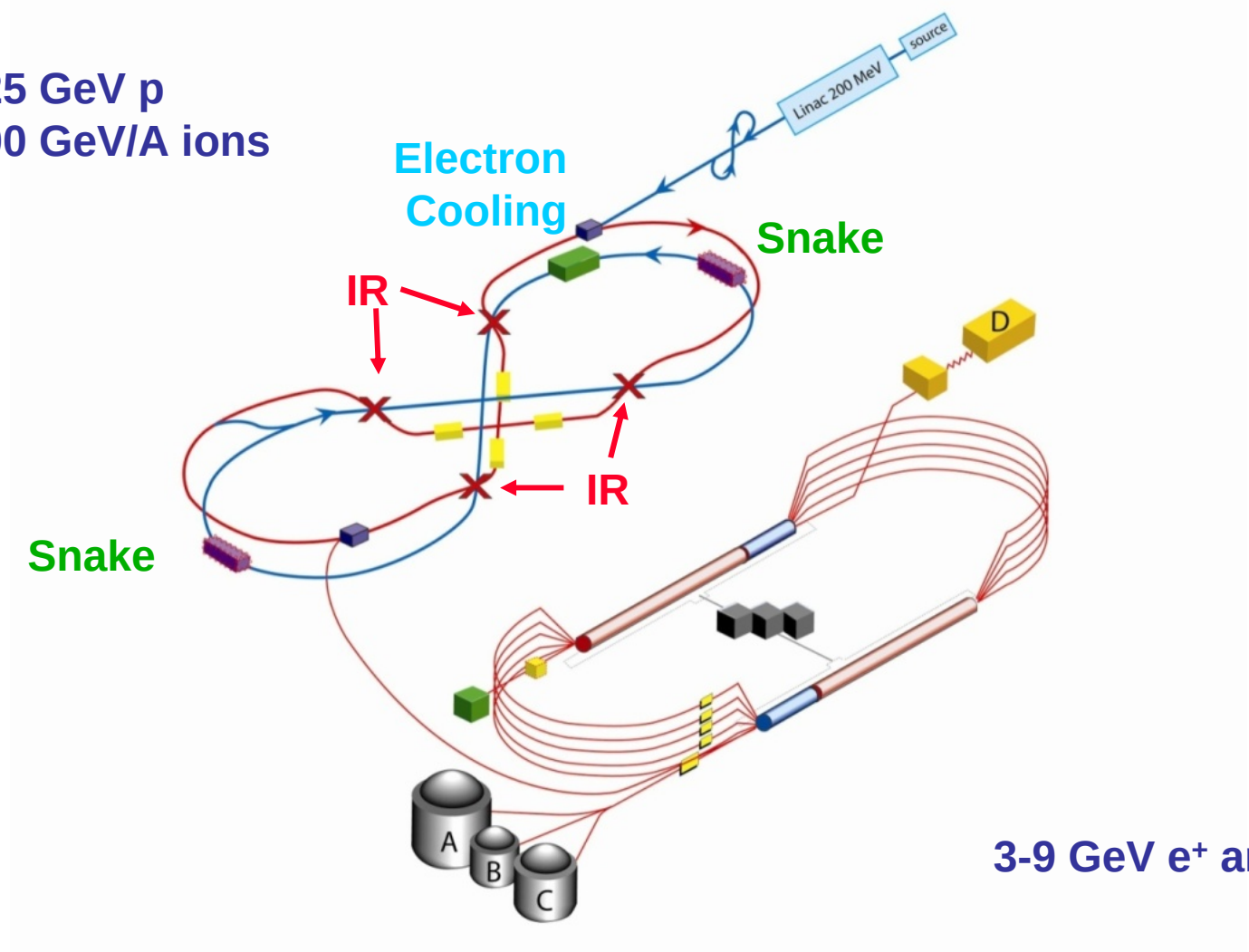
- JLab - 14,300 W at 1.6 microns
- Budker Institute (Russia) – 400 W at 60
- Vanderbilt University – 10 W at 6 m
- Los Alamos 11 W at 16.3 mic
- JAERI (Japan) < 2W
- Brookhaven << 1 W
- Argonne << 1 W
- Everyone el y

- JLab developing key techno and DOE funding: injector, mirrors, , superconducting rf cavities, energy re y; symbiosis with NP program was important to success

•Tremendous scientific potential based on this world leading technology

Long-term Landscape : ELIC

30-225 GeV p
30-100 GeV/A ions



3-9 GeV e^+ and e^-

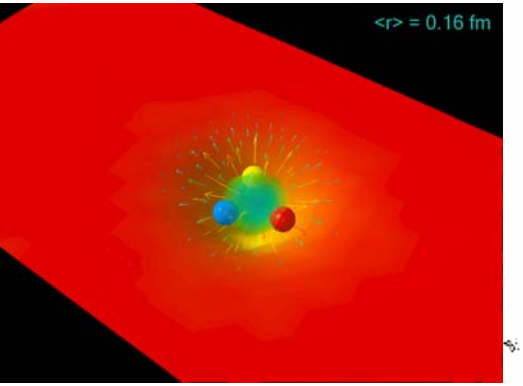
World Community in 2012 and Beyond

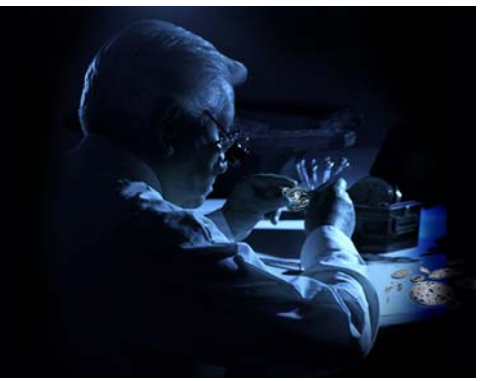
- With Upgrade will have three major new facilities investigating nuclear physics <u>at hadronic level</u> (QCD) : GSI (Germany), J-PARC (Japan) and JLab*

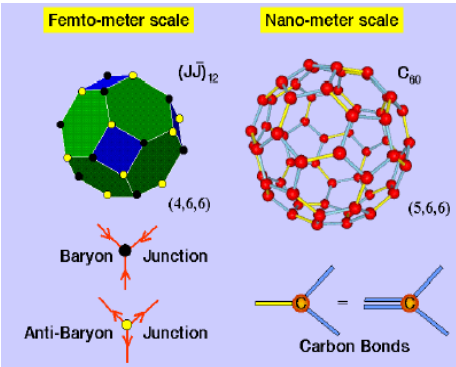
- Complementary programs

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

* Unique: only electromagnetic machine





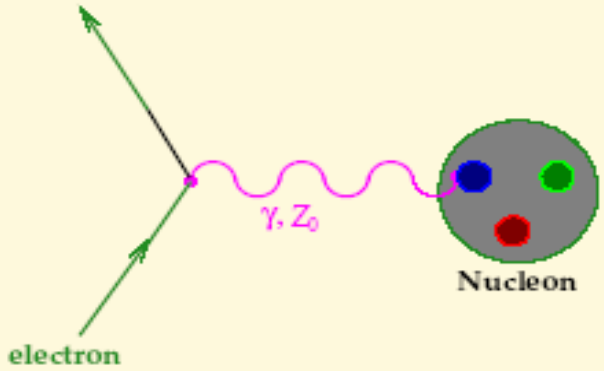


"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM."

End of Presentation

Clean Extraction of the Neutron Radius

[Horowitz, Pollock, Souder, and Michaels; PRC63, 025501 (2001)]



- PV asymmetry involves the interference of EM and NC amplitudes:

$$\mathcal{M}_{\mathrm{EM}} = \frac{4\pi\alpha}{Q^2} F_{\mathrm{EM}}(Q^2) = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$$\mathcal{M}_{\mathrm{NC}} = \frac{G_{\mathrm{F}}}{\sqrt{2}} F_{\mathrm{NC}}(Q^2) = \frac{G_{\mathrm{F}}}{\sqrt{2}} \left[(1 - 4\sin^2\theta_W) F_p(Q^2) - F_n(Q^2) \right]$$

- PV asymmetry provides a clean measurement of the neutron form factor

$$A_{\mathrm{PV}} \approx \frac{G_{\mathrm{F}} Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)} \; ; \quad \frac{1}{N} F_n(Q^2) = \left(1 - \frac{Q^2 R_n^2}{6} + \ldots \right)$$

PV electron scattering may do for neutron structure what electron scattering has done for proton structure!