The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1942-46

Sixth International Conference on Perspectives in Hadronic Physics

12 - 16 May 2008

Neutron Spin-Structure Studies and Standard Model Tests at JLab.

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USA

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Neutron Spin Structure

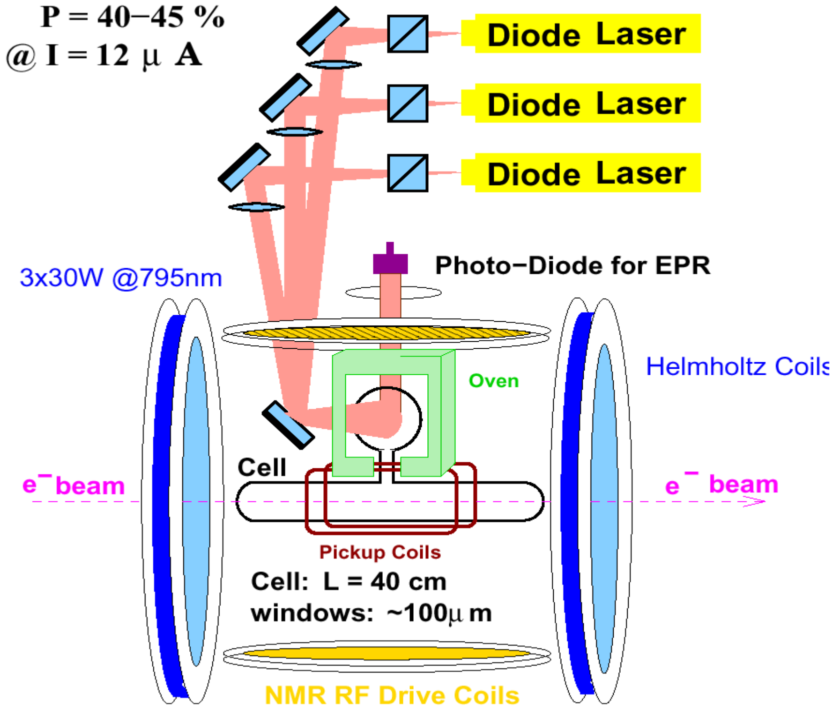
and

Standard Model Tests at Low Energy

Kees de Jager
Jefferson Lab
Perspectives in Hadronic Physics
Trieste
May 12 - 16, 2008

Thomas Jefferson National Accelerator Facility

Hall A Polarized ^{3}He Target



→Longitudinal, transverse or vertical polarization vector

→Luminosity = 10^{36} $cm^{-2}s^{-1}$ (best in the world)

→ High in-beam polarization
  > 50%

→Effective polarized neutron target

→ 7 completed experiments
  5 approved with 6 GeV
  3 approved with 12 GeV

Long-term outlook:

→Polarization > 60%
  with current up to 100 μA

Moments of spin structure functions

$$\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \frac{Q^2}{16\pi^2\alpha} I_{GDH}(Q^2)$$

GDH Sum Rule $I_{GDH}(0)$ — Generalized GDH Integral $I_{GDH}(Q^2)$ — Bjorken Sum Rule Γ_1^{p-n}

Burkhardt-Cottingham sum rule

$$\Gamma_2(Q^2) = \int_0^1 g_2(x,Q^2)\,dx = 0$$

First moments

Spin Polarizabilities $\gamma_0(Q^2), \delta_{LT}(Q^2)$

Higher twists & color Polarizabilities $d_2(Q^2), f_2(Q^2)$

Higher moments

0 — 1 — 10 — ∞ Q^2

Chiral perturbation

OPE
LQCD in future

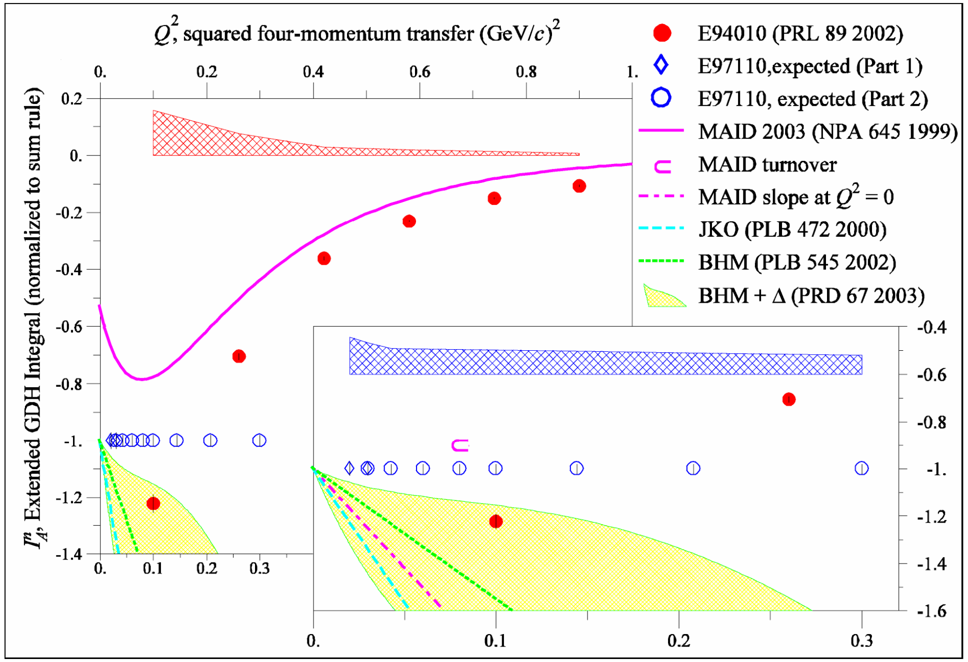
pQCD

GDH Sum Rule and Spin Structure of ^{3}He

and Neutron with Nearly Real Photons

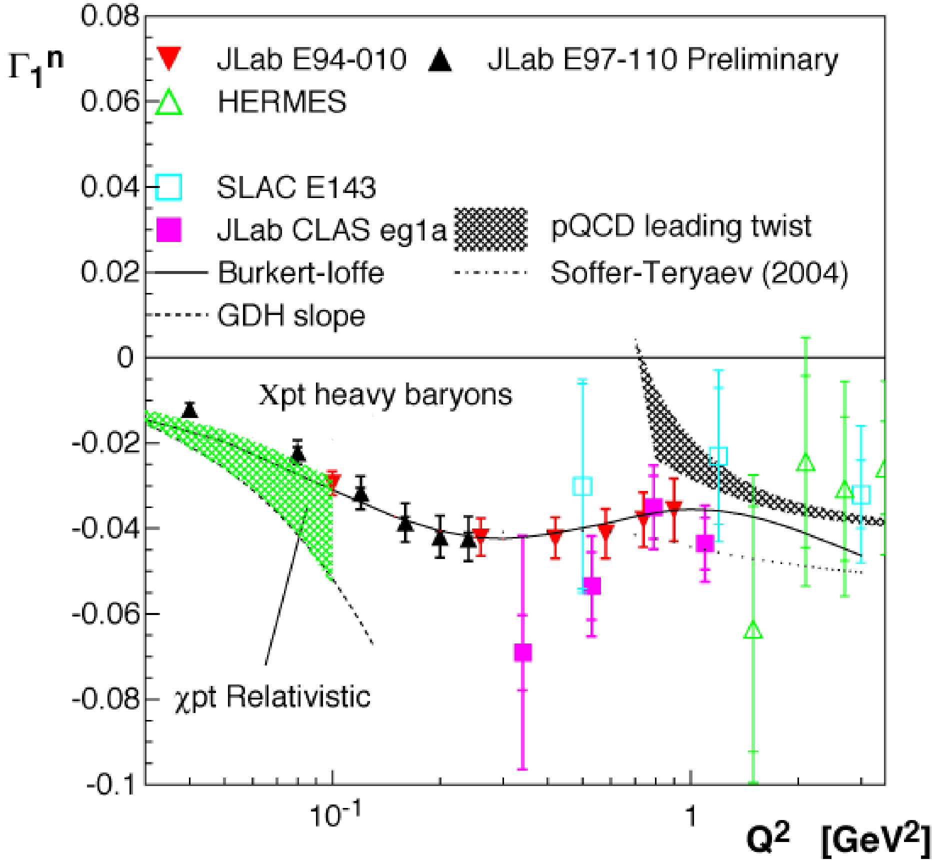
Spokespersons: J. P. Chen, A. Deur, F. Garibaldi
Thesis student: V. Sulkosky

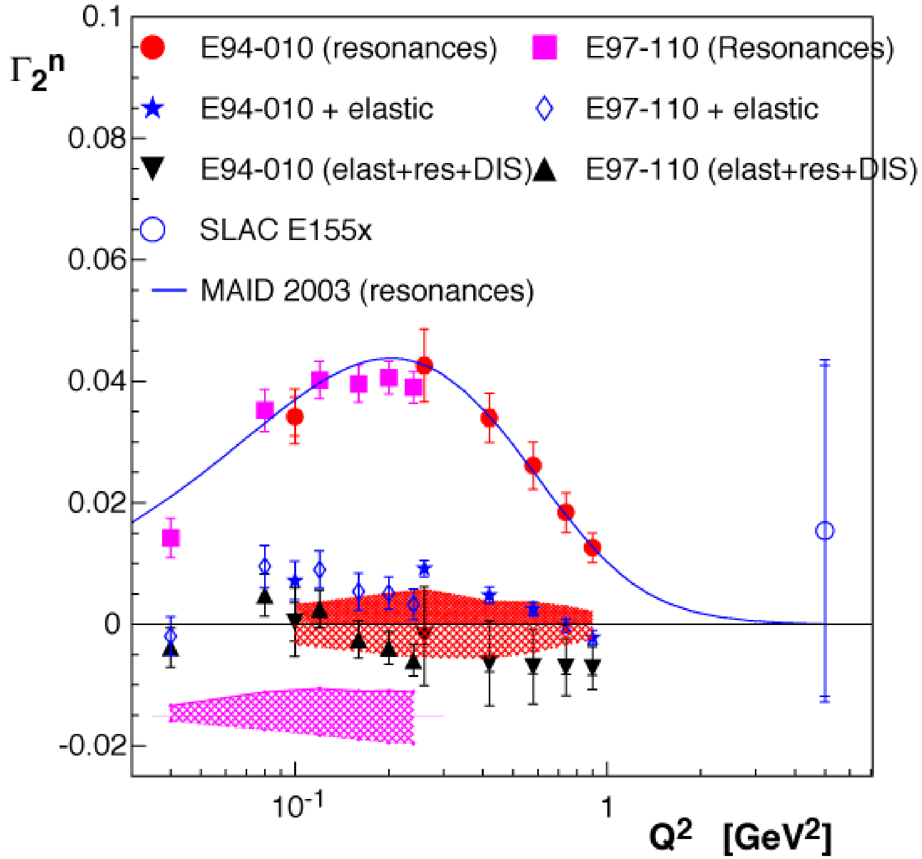
- Q^2 evolution of spin structure moments and sum rules (generalized GDH, Bjorken and B-C sum rules)
- Transition from quark-gluon to hadron DOF
- Results published in five PRL/PLB



- **Measured generalized GDH at Q^2 near zero for ^{3}He and neutron**
  - **Slope at Q^2 ~ 0 benchmark test of χPT**

Preliminary Results for E97-110

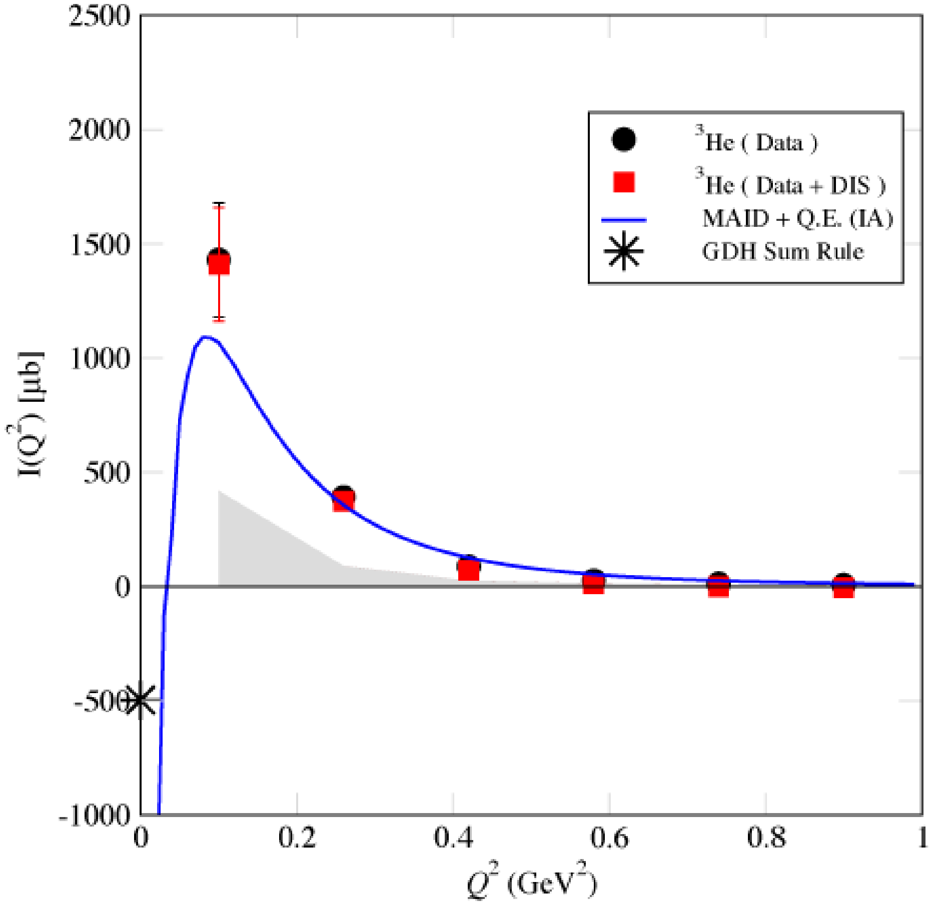


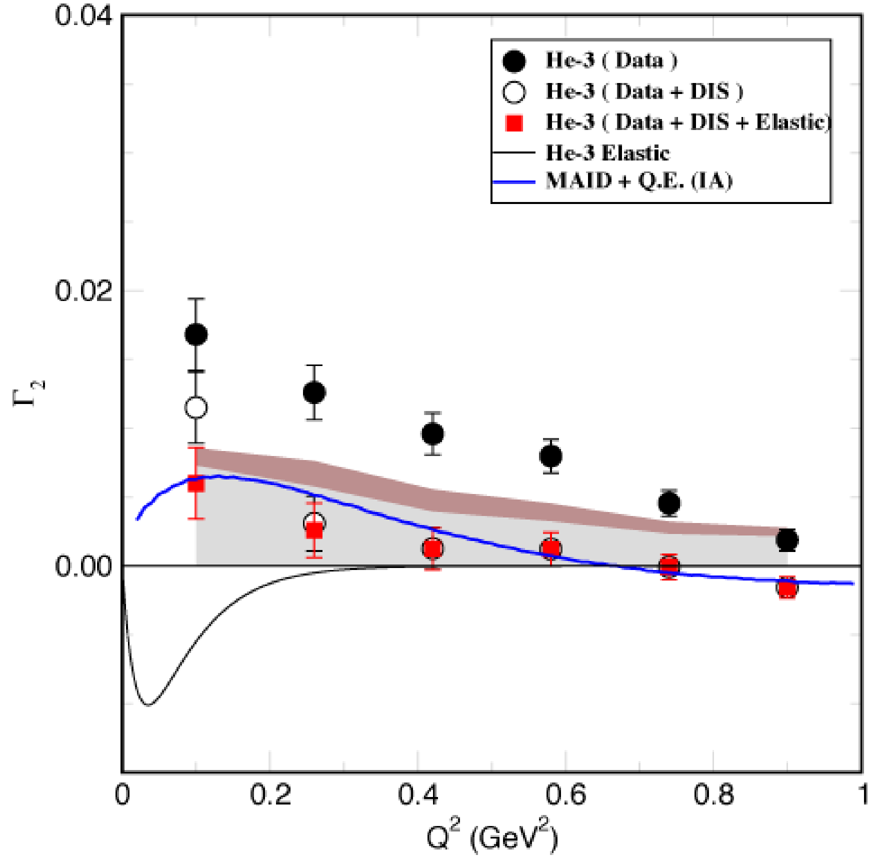


- → Needed (SC) septum magnets to reach low Q^2-values
- → Data taken in 2003
- → Preliminary analysis in good agreement with χPT
- → Need ^{3}He calculations for accurate neutron extraction

New Hall A ^{3}He Results

- Q^2 evolution of moments of ^{3}He spin structure functions
- Test Chiral perturbation theory predictions at low Q^2
- Need Chiral PT calculations for ^{3}He
- B-C sum rule satisfied within uncertainties





Submitted to PRL

Generalized Spin Polarizabilities

→ Consider Spin-flip VVCS cross sections: $\sigma_{TT}(Q^2,\nu)$, $\sigma_{LT}(Q^2,\nu)$
In the low-energy expansion, the $O(\nu^3)$ term gives
the generalized forward spin polarizability, γ_0, and
the generalized longitudinal-transverse spin polarizability, δ_{LT}

$$\gamma_0(Q^2) = (\frac{1}{2\pi^2})\int_{\nu_0}^{\infty} \frac{K(Q^2,\nu)}{\nu}\frac{\sigma_{TT}(Q^2,\nu)}{\nu^3}d\nu$$

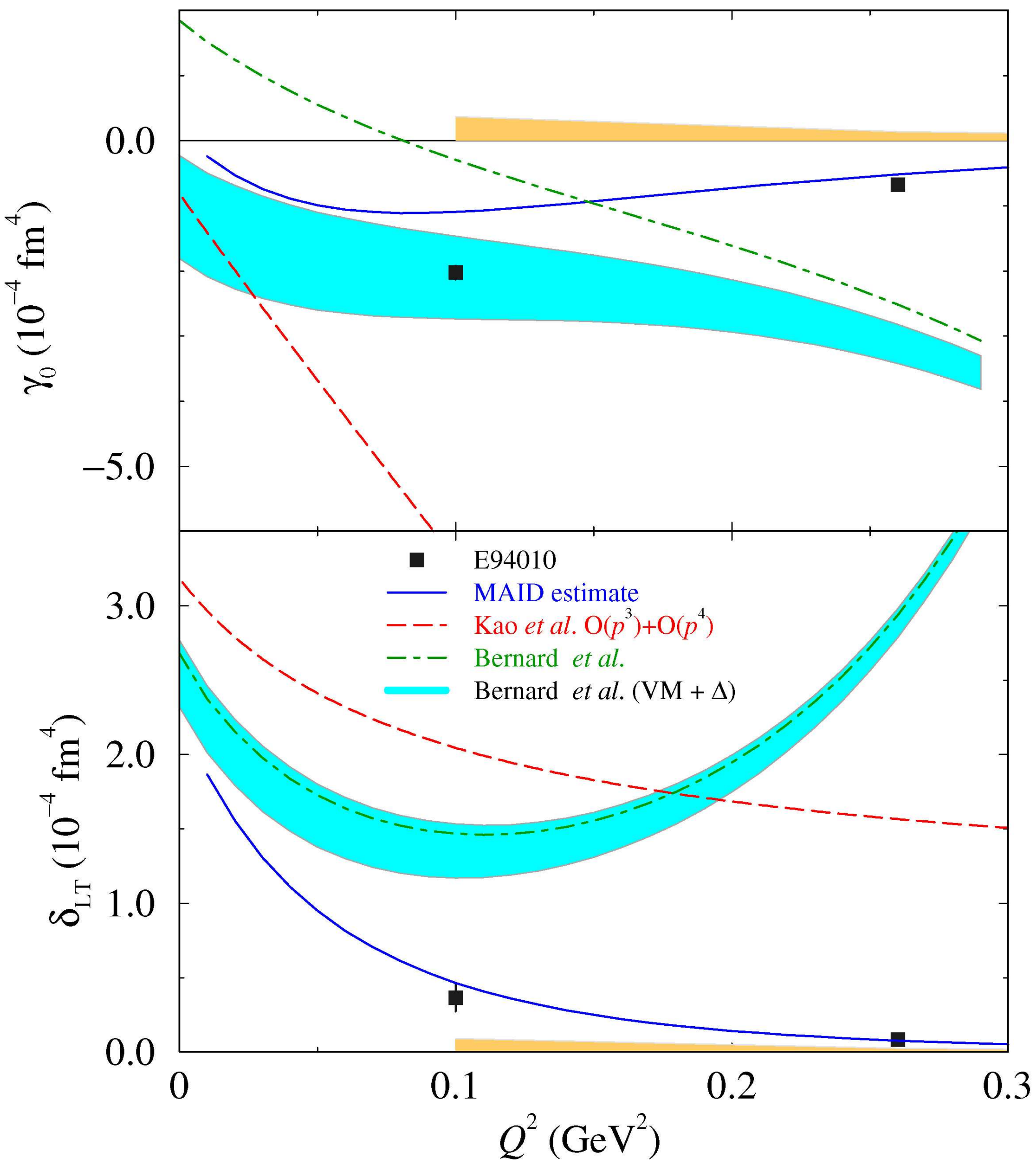
$$= \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2[g_1(Q^2,x) - \frac{4M^2}{Q^2}x^2 g_2(Q^2,x)]dx$$

$$\delta_{LT}(Q^2) = (\frac{1}{2\pi^2})\int_{\nu_0}^{\infty} \frac{K(Q^2,\nu)}{\nu}\frac{\sigma_{LT}(Q^2,\nu)}{Q\nu^2}d\nu$$

$$= \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2[g_1(Q^2,x) + g_2(Q^2,x)dx$$

Neutron Spin Polarizabilities

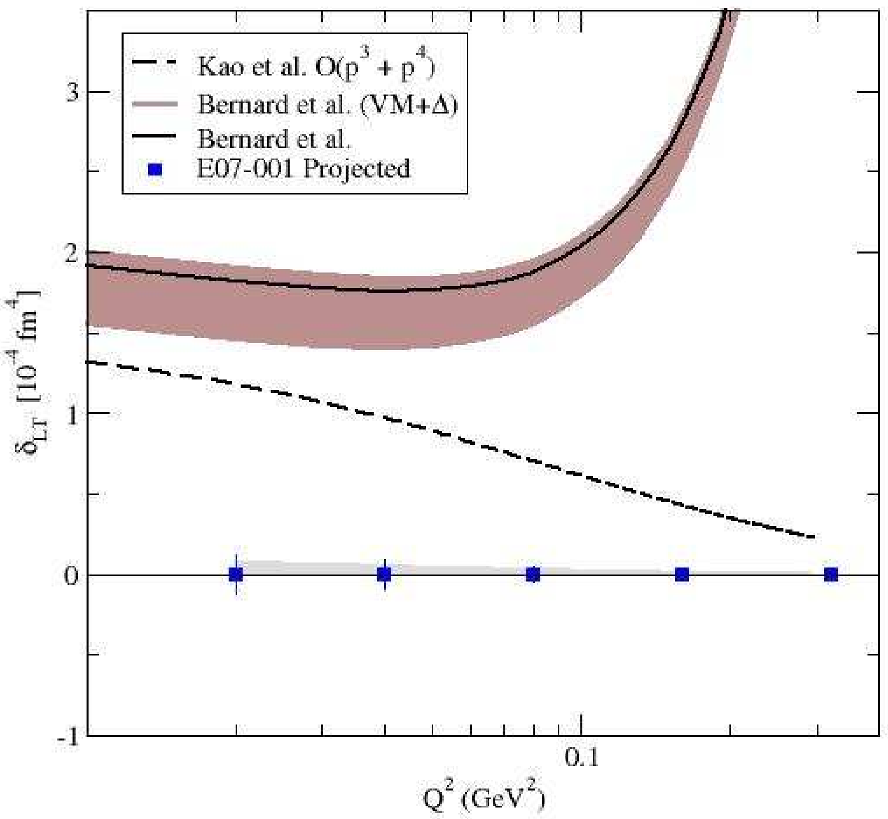
- χPT expected to work at low Q^2 (up to ~ 0.1 GeV^2?)
  - γ_0 sensitive to resonance,
  - δ_{LT} insensitive to resonance
- E94-010 results:
  - PRL 93 (2004) 152301
- Bernard's χPT calculation with resonance for γ_0 agrees with data at Q^2 = 0.1 GeV^2
- Significant disagreement between data and both χPT calculations for δ_{LT}
- Good agreement with MAID model predictions



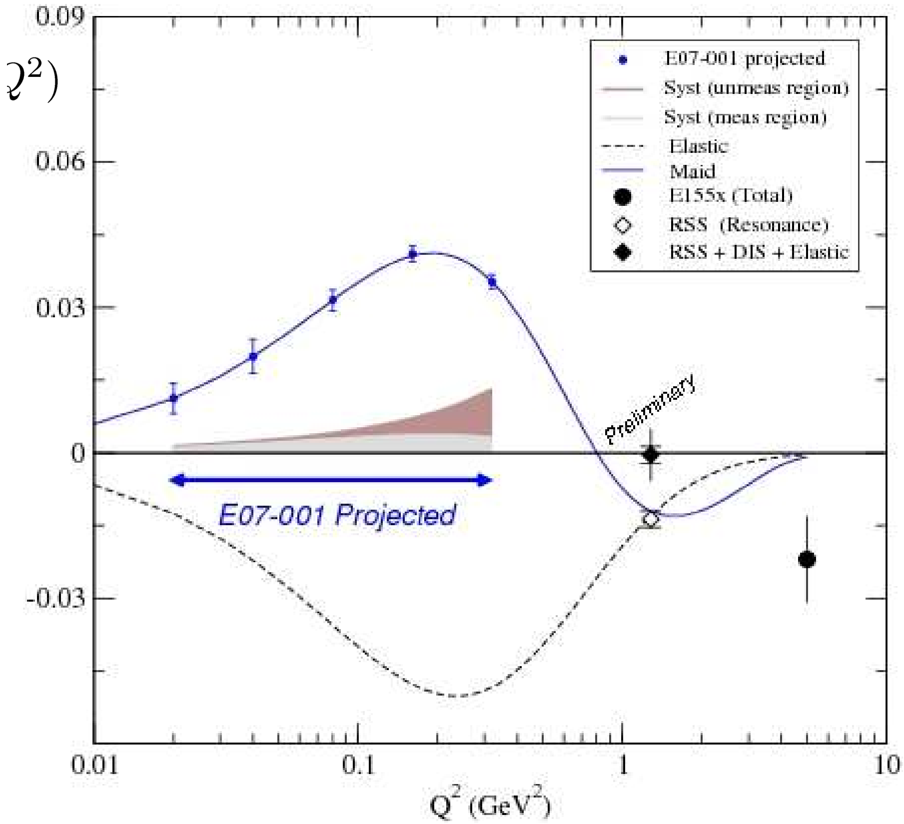
Experiment E08-027 g_2^p

Measure the transverse spin structure on the proton
Needs DNP polarized target in Hall A and septum magnets
Expected to run in 2012

LT Spin Polarizability



Burkhardt-Cottingham Sum Rule



d_2: twist-3 matrix element

➞ 2^{nd} moment of g_2-g_2^{WW}

d_2: twist-3 matrix element

$$d_2(Q^2) = 3\int_0^1 x^2[g_2(x,Q^2) - g_2^{WW}(x,Q^2)]dx$$

$$= \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx$$

Color polarizabilities

Provide a benchmark test of Lattice QCD at high Q^2

χPT and Model (MAID) at low Q^2

Avoid issue of low-x extrapolation

Color "Polarizabilities"

X.Ji 95, E. Stein et al. 95

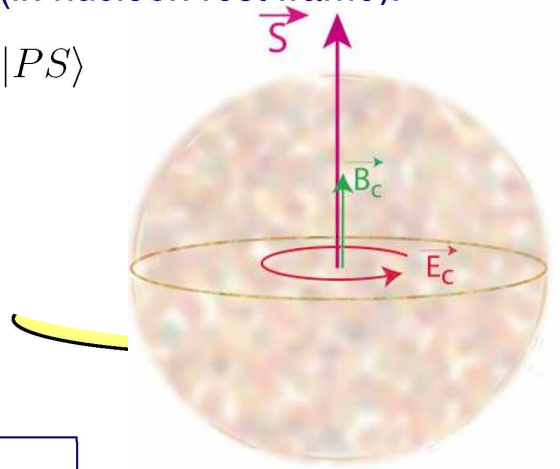
How does the gluon field respond when a nucleon is polarized ?

Define color magnetic and electric polarizabilities (in nucleon rest frame):

$$\chi_{B,E} 2M^2 \vec{S} = \langle PS|\vec{O}_{B,E}|PS\rangle$$

where $\vec{O}_B = \psi^\dagger g\vec{\boldsymbol{B}}\psi$

$$\vec{O}_E = \psi^\dagger \vec{\alpha} \times g\vec{\boldsymbol{E}}\psi$$

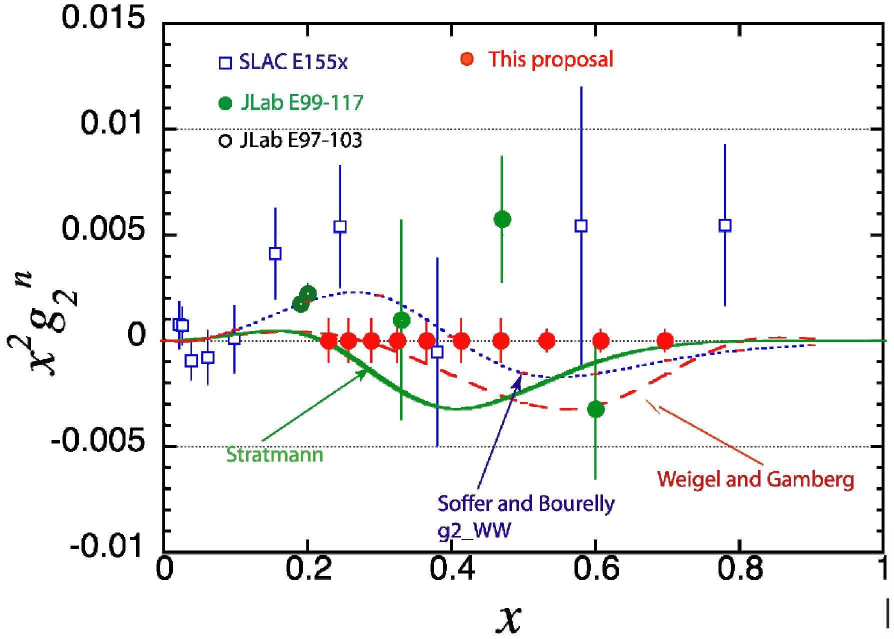


$$d_2 = (\chi_E + 2\chi_B)/8$$

$$f_2 = (\chi_E - \chi_B)/2$$

d_2 and f_2 represent the response of the color $\vec{B}$ & $\vec{E}$ fields to the nucleon polarization

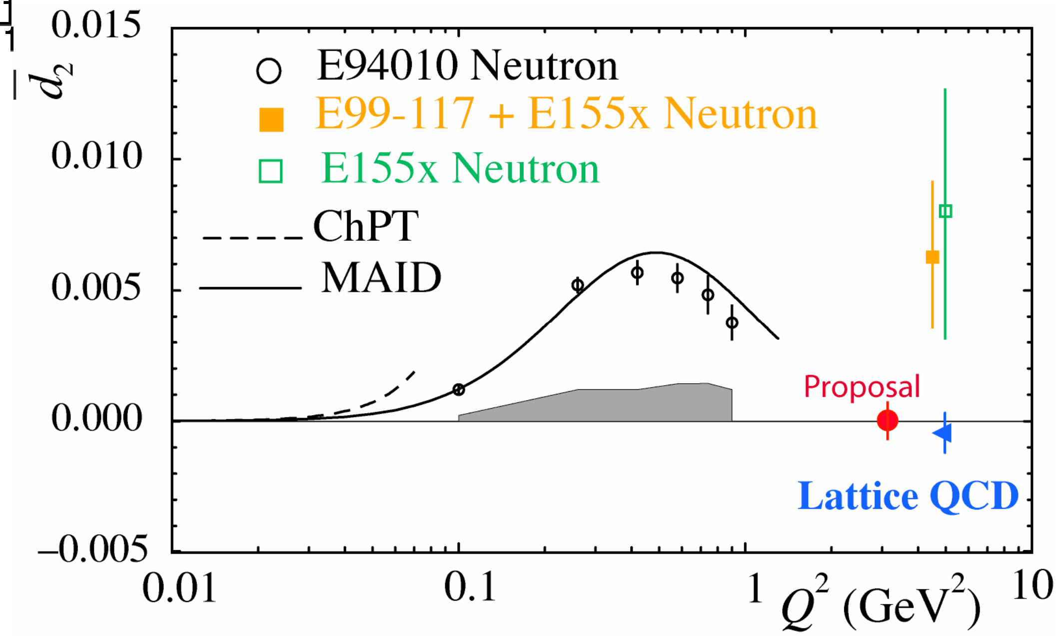
Color Polarizability: d_2^n (Hall A)



- At large Q^2, d_2 coincides with the reduced twist-3 matrix element of gluon and quark operators
- At low Q^2, d_2 is related to the spin polarizabilities

Approved experiment E06-114
Running in Spring 2009

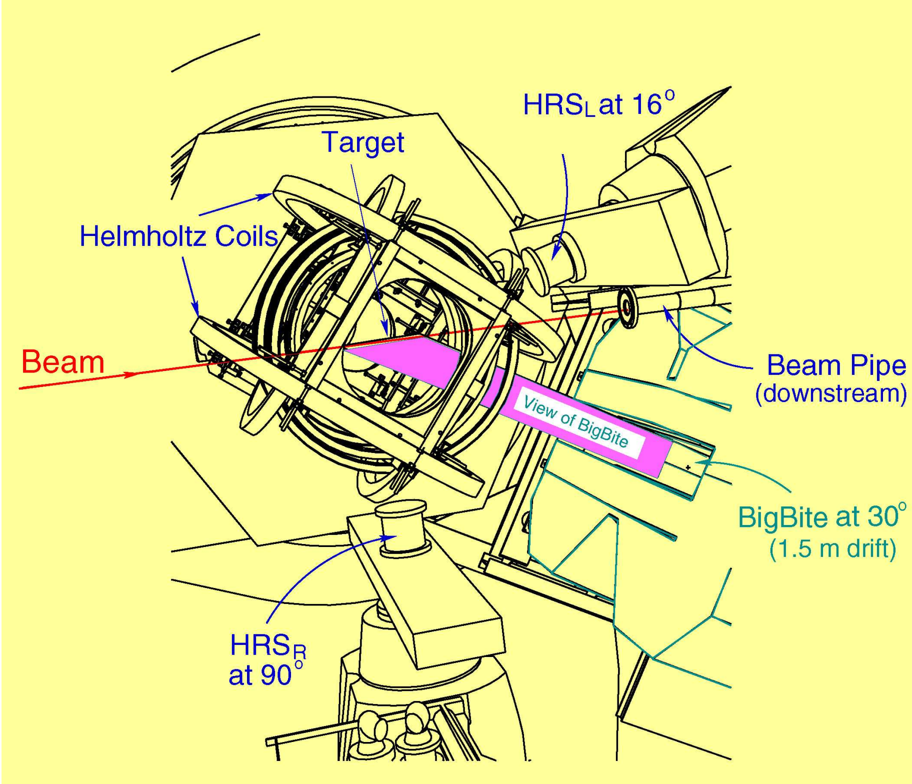
Spokespersons: S. Choi, X. Jiang, Z.-E. M, B. Sawatzky



Jlab Hall A E03-004 / ^{3}He $(e,e'\pi^{-/+})X$

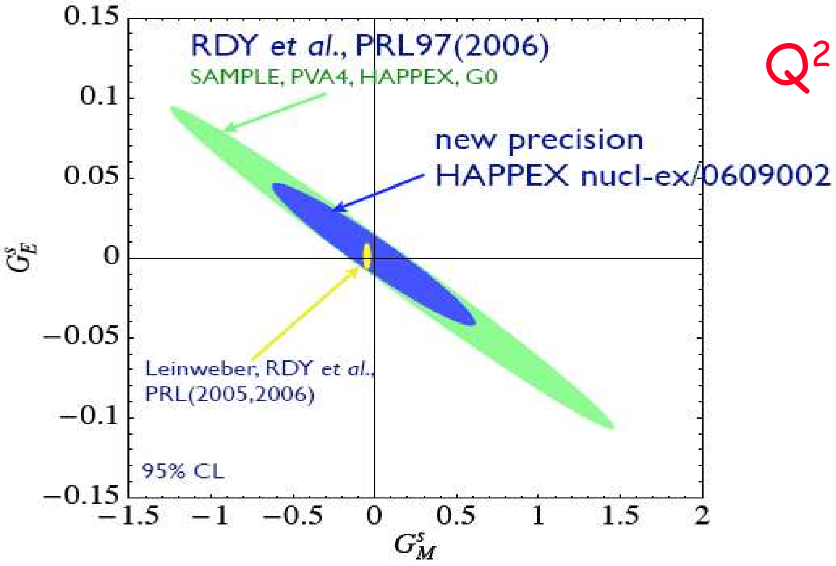
Spokespersons: J.-P. Chen, X. Jiang, J.-C. Peng
H. Gao, L. Zhu, G. Urciuoli

- Beam
  - Polarized (P~80%) e-, 15 μA, helicity flip at 60 Hz
- Target
  - Optically pumped Rb+K spin exchange ^{3}He, 50 mg/cm^2,~ 50% polarization
  - Transversely polarized with tunable direction
- Electron detection
  - Bigbite spectrometer, Solid angle 60 msr, θ = 30°
- Charged pion detection
  - HRS spectrometer, θ = 16°
- Transversity on neutron
  - Complementary to HERMES

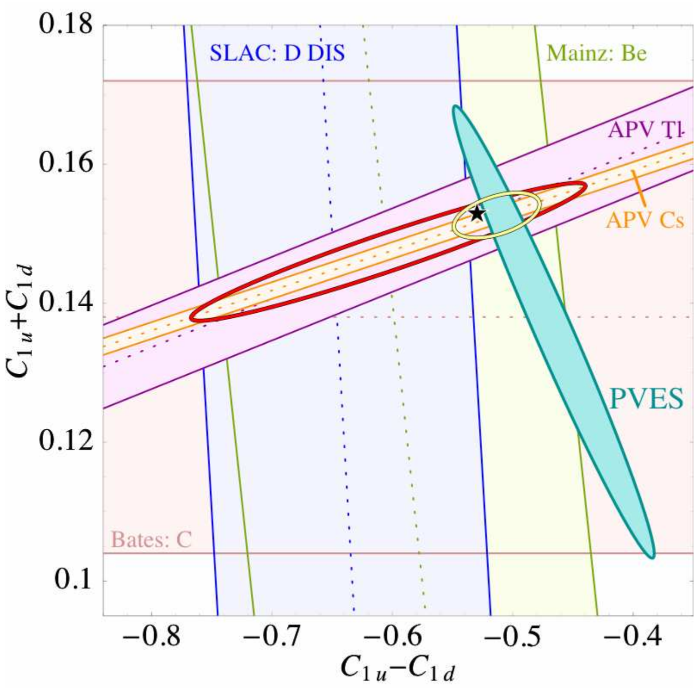


Standard Model Tests at Low Energy

Outstanding Precision for Strange Form Factors

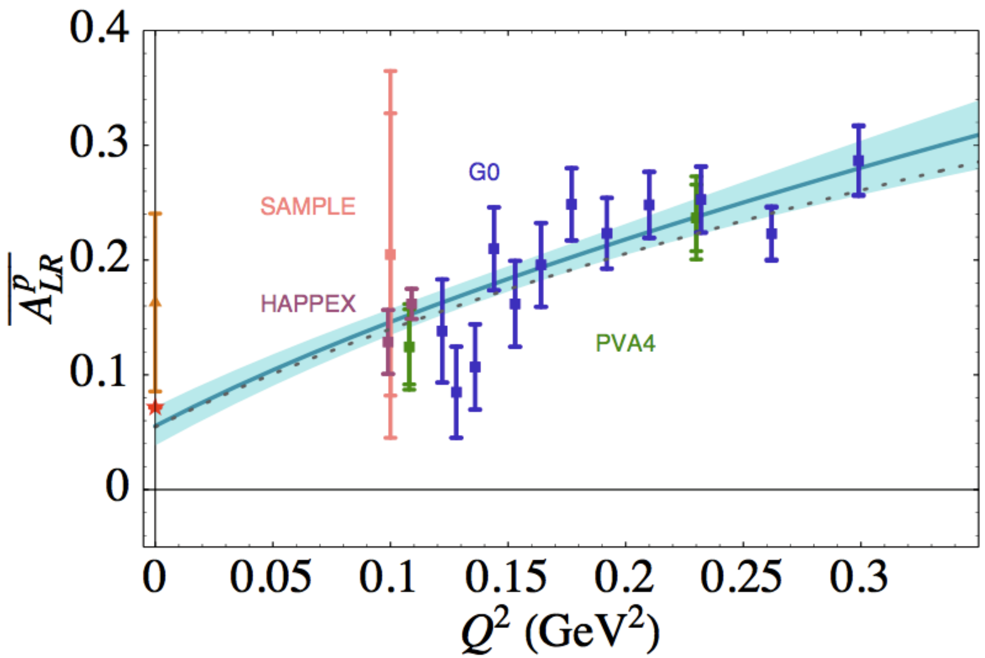


$Q^2 = 0.1\ GeV^2$



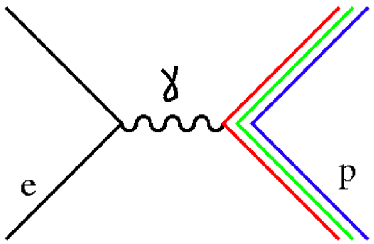
This has recently been shown to enable a dramatic improvement in precision in testing the Standard Model

Outstanding Precision for Strange Form Factors

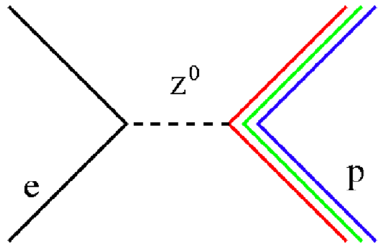


C_{iq} denote the V/A electron-quark coupling constants

Extraction of Q^p_{weak}



As $Q^2 \to 0$



measures Q^p – proton's electric charge

measures Q^p_{weak} – proton's weak charge

The Q_{weak} experiment measures the parity-violating analyzing power A_z

$$A_z = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \simeq -3 \times 10^{-7}$$ **(-300 ppb)**

$$A_z \xrightarrow[\substack{Q^2 \to 0 \\ \theta \to 0}]{} \frac{-G_F}{4\pi\alpha\sqrt{2}} \left[Q^2 Q^p_{weak} + Q^4 B(Q^2) \right]$$

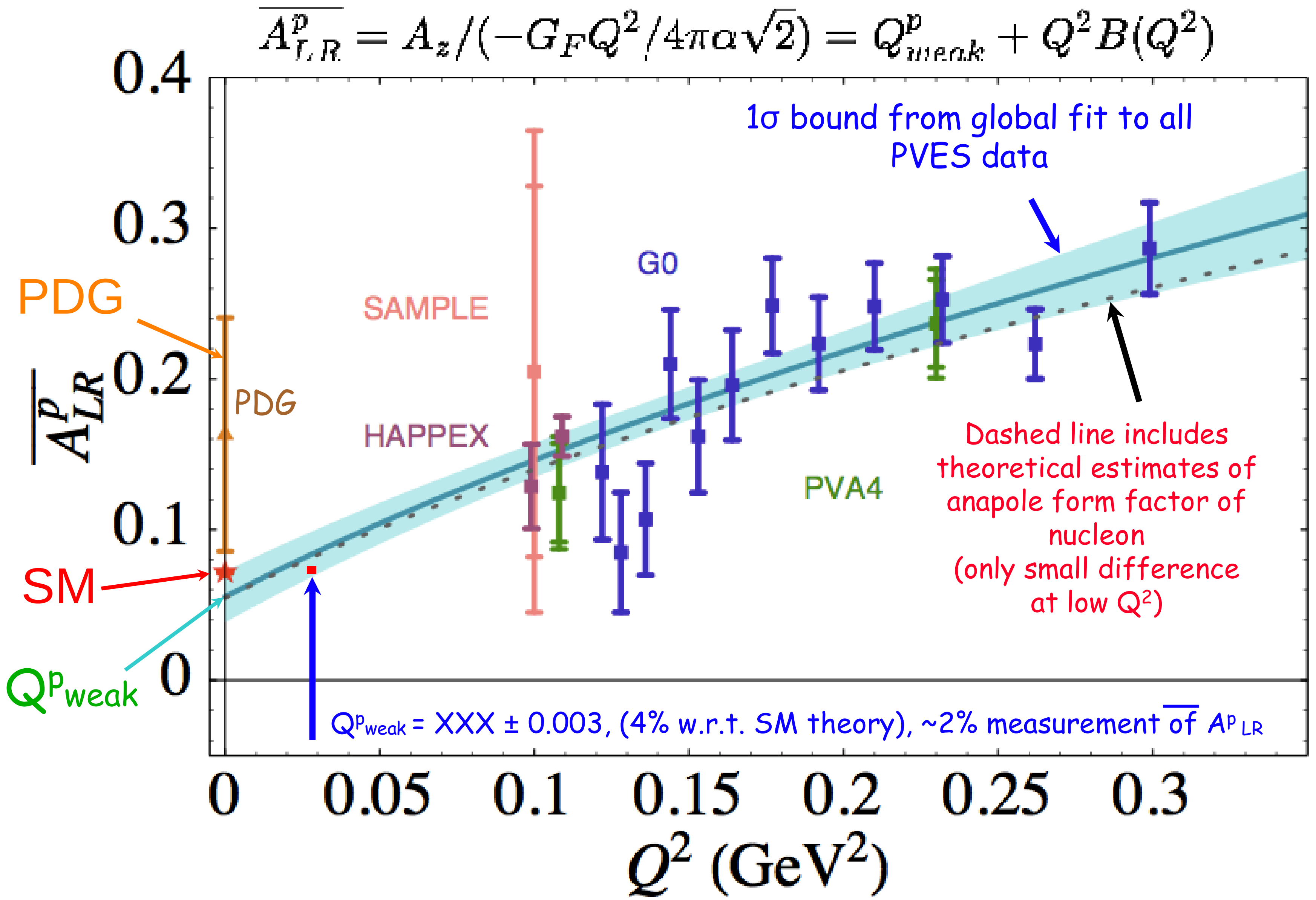
Contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$,
Extracted using global fit
of existing PVES experiments!

$$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072 \text{ (at tree level)}$$

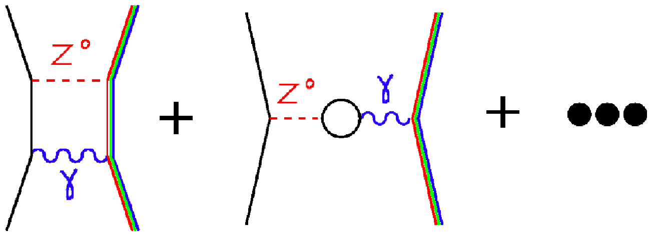
- Q^p_{weak} is a well-defined experimental observable
- Q^p_{weak} has a definite prediction in the electroweak Standard Model

Parity-Violating Asymmetry Extrapolation

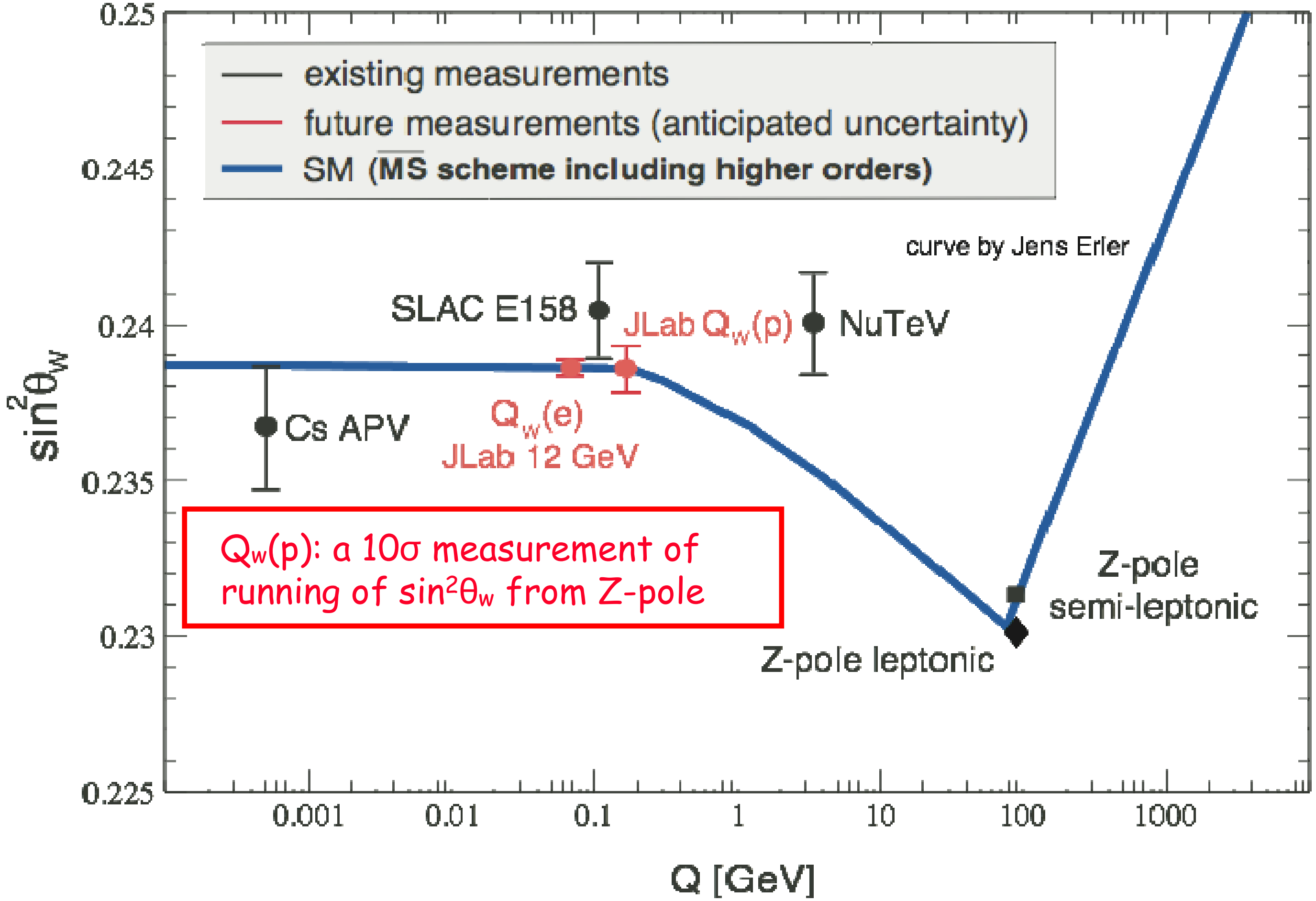
(Ross Young et al.)



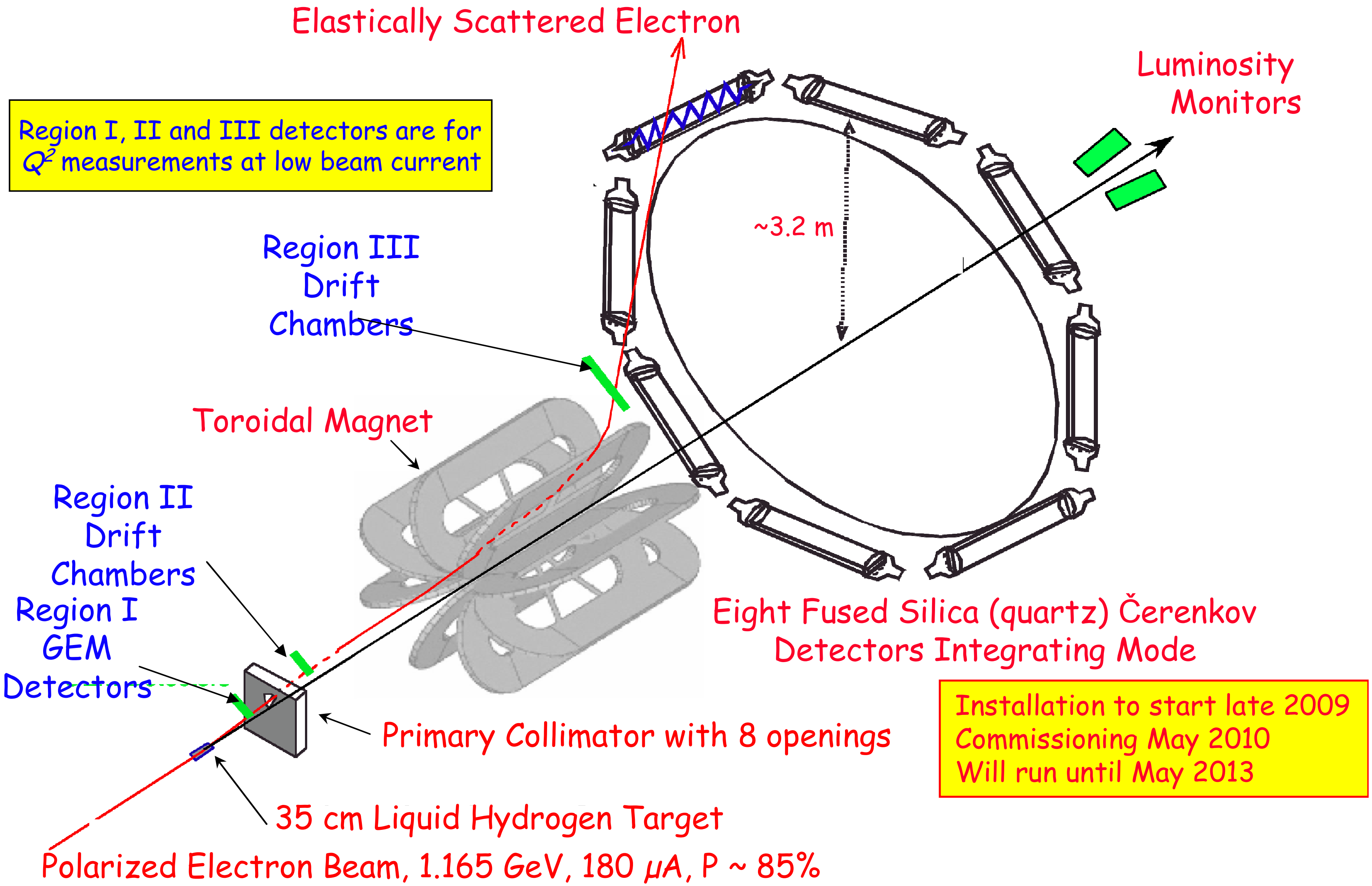
"Running of $\sin^2\theta_W$" in the Electroweak Standard Model



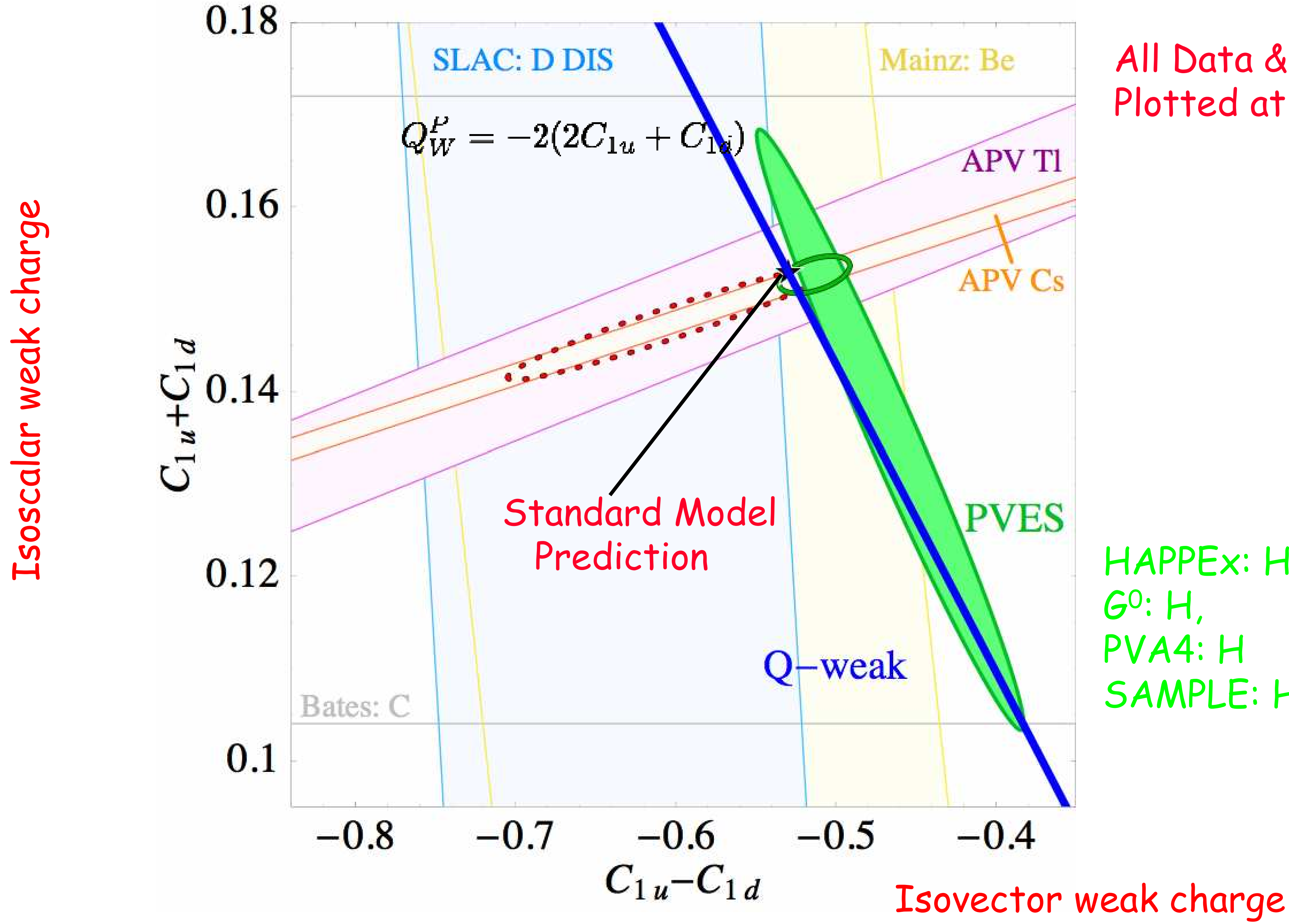
Radiative corrections cause $\sin^2\theta_W$ to change with Q. Any discrepancy of $\sin^2\theta_W$ with the standard model prediction indicates new physics.



Schematic of the Q^p_{weak} Experiment



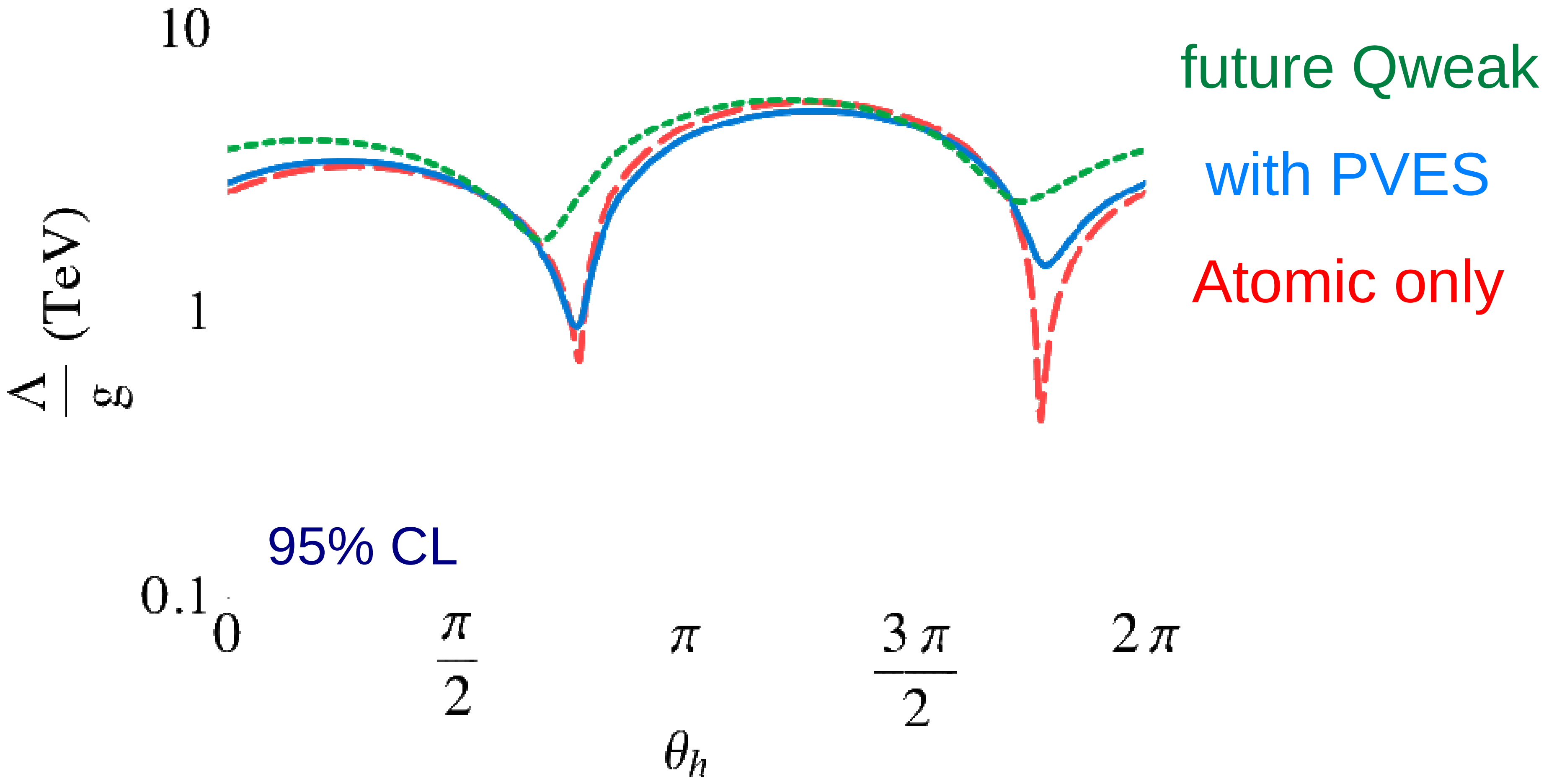
Impact of Q_{weak} on C_{1q}



All Data & Fits
Plotted at 1 σ

HAPPEx: H, He
G^0: H,
PVA4: H
SAMPLE: H, D

Lower Bound for “Parity Violating” New Physics



Qweak constrains new physics to beyond 2 TeV

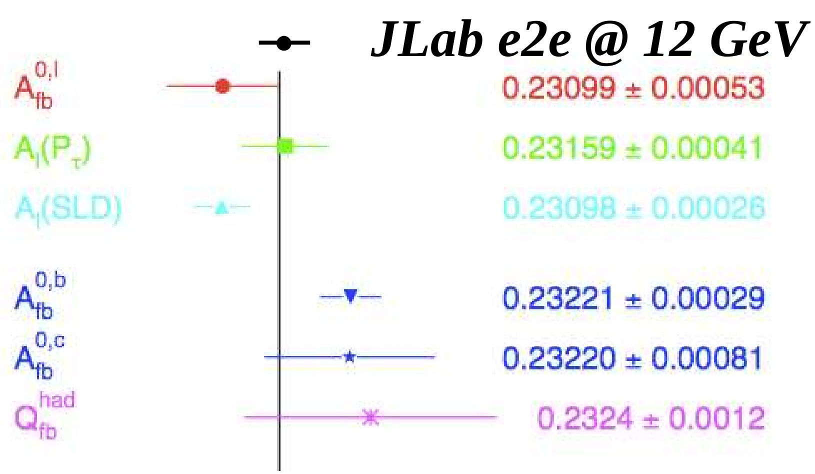
Analysis by Ross Young, ANL

Future Possibilities (Purely Leptonic)

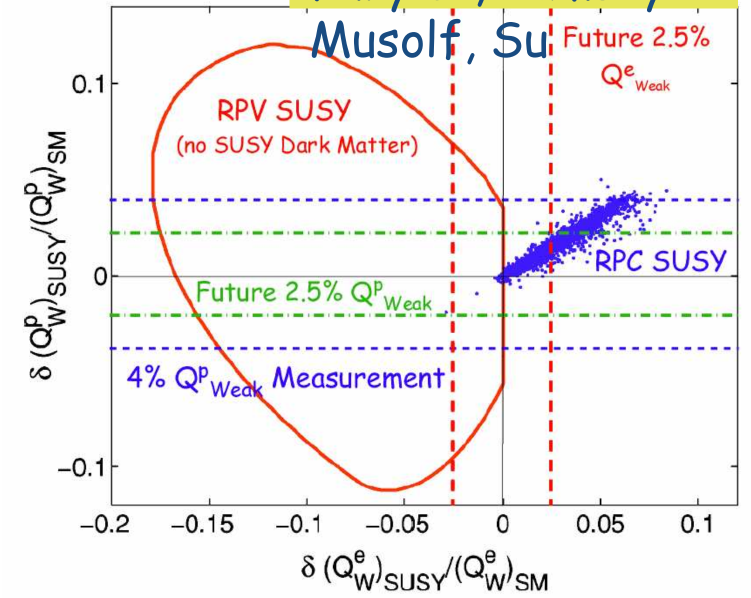
Møller at 11 GeV at JLab

Higher luminosity and acceptance ➡ $\sin^2\theta_W$ to ± 0.00025 ***e.g. Z' reach***
Λ_{ee} ~ 25 TeV reach ***~ 2.5 TeV***

- Comparable to single Z-pole measurement: shed light on 4σ disagreement
- Best low-energy measurement until ILC or ν-Factory
- Could be launched ~ 2015



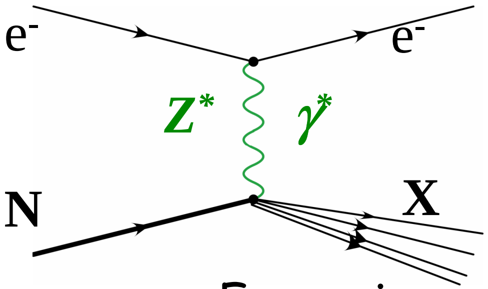
Kurylov, Ramsey-Musolf, Su



Does Supersymmetry (SUSY) provide a candidate for dark matter?

- Neutralino is stable if baryon (B) and lepton (L) numbers are conserved
- In RPV B and L need not be conserved: neutralino decay

PV DIS at 11 GeV with an LD_2 target



$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$y \equiv 1 - E'/E$$

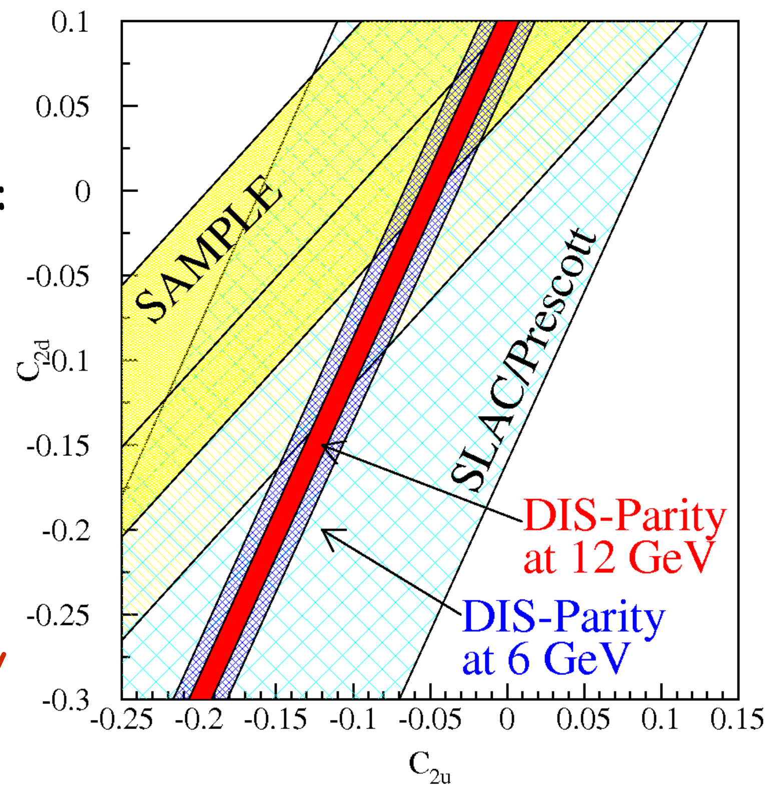
For an isoscalar target like ^2H,
the structure functions largely cancel in the ratio:

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots$$

$$b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

($Q^2 >> 1$ GeV^2 , $W^2 >> 4$ GeV^2, $x \sim 0.3$-0.5)

- Must measure A_{PV} to 0.5% fractional accuracy
- Luminosity and beam quality available at JLab



- 6 GeV experiment will launch PV DIS measurements at JLab (2009)
- Only 11 GeV experiment will allow tight control of systematic errors
- Important constraint should LHC observe an anomaly

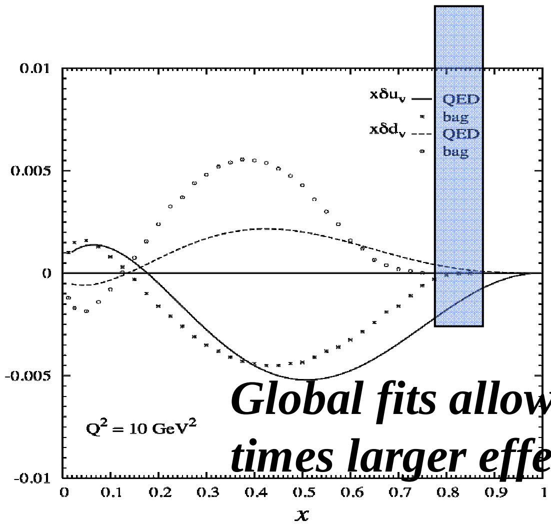
Precision High-x Physics with PV DIS

Charge Symmetry Violation (CSV) at High x: clean observation possible

$$\delta u(x) = u^p(x) - d^n(x)$$
$$\delta d(x) = d^p(x) - u^n(x)$$

$$\frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.3\frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

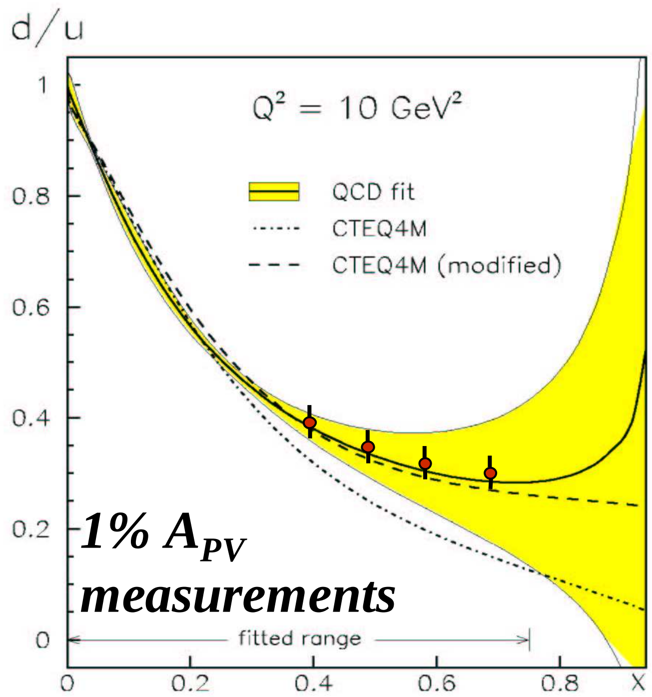
Londergan & Thomas



Global fits allow 3 times larger effects

- Direct observation of CSV at parton level
- Implications for high-energy collider pdfs
- Could explain large portion of the NuTeV anomaly

Requires 1% measurement of A_{PV} at x ~ 0.75



1% A_{PV} measurements

For hydrogen ¹H: $a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$

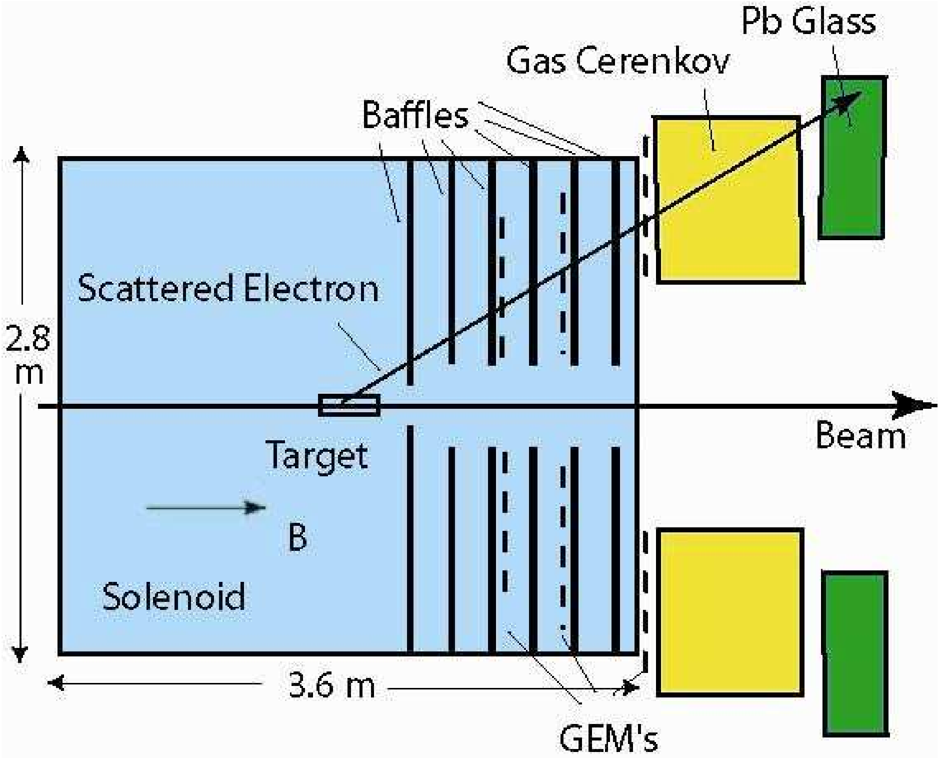
Longstanding issue: d/u as x→1

- Allows d/u measurement on a single proton

A Vision for Precision PV DIS Physics

- Hydrogen and Deuterium targets
- Better than 2% errors
  (unlikely that any effect is larger than 10%)
- x-range 0.25-0.75
- W^2 well over 4 GeV^2
- Q^2 range a factor of 2 for each x
  (except x~0.75)
- Moderate running times

- CW 90 μA at 11 GeV
- 40 cm liquid H_2 and D_2 targets
- Luminosity > $10^{38}/cm^2/s$



- solid angle > 200 msr
- count at 100 kHz
- on-line pion rejection of 10^2 to 10^3

Goal: Form a collaboration, start real design and simulations, after the successful pitch to US community at the 2007 Nuclear Physics Long Range Plan
Submit Letter of Intent to next JLab PAC (January 2009)

Summary and Conclusions

- Broad active program on neutron spin structure in Hall A with many new results to be expected in the next few years

- The parity-violating electron scattering program in Hall A has already provided first significant constraints on the Standard Model

- The future JLab program using parity violation has the potential to provide much more stringent tests, first through Qweak, then through an update of the SLAC E158 Møller experiment and through a broad study of Parity-Violating Deep-Inelastic Scattering

Acknowledgements

→ Many thanks to a long list of colleagues who willingly (or not) provided me with figures/slides/discussions:

- Roger Carlini
- Jian-ping Chen
- Krishna Kumar
- Zein-Eddine Meziani
- Paul Souder
- Ross Young

Energy Scale of an Indirect Search

- The sensitivity to new physics Mass/Coupling ratios can be estimated by adding a new contact term to the electron-quark Lagrangian:
  (Erler et al. PRD 68, 016006 (2003))

$$\mathcal{L}^{PV}_{e-q} = \mathcal{L}^{PV}_{SM} + \mathcal{L}^{PV}_{New}$$
$$= -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

where Λ is the mass and g is the coupling. A new physics "pull" ΔQ can then be related to the mass to coupling ratio:

$$\frac{\Lambda}{g} = \frac{1}{\sqrt{\sqrt{2}G_F}} \cdot \frac{1}{\sqrt{\Delta Q_W(p)}}$$

The TeV scale can be reached with a 4% Q_{weak} experiment.
If Q_{weak} didn't happen to be suppressed, we would have to do a 0.4% measurement to reach the TeV-scale.