A Brief History of PVES*

P. A. Souder

Acknowledgement: HAPPEX and PREx collaborations

*PVES: Parity Violating Electron Scattering

Outline

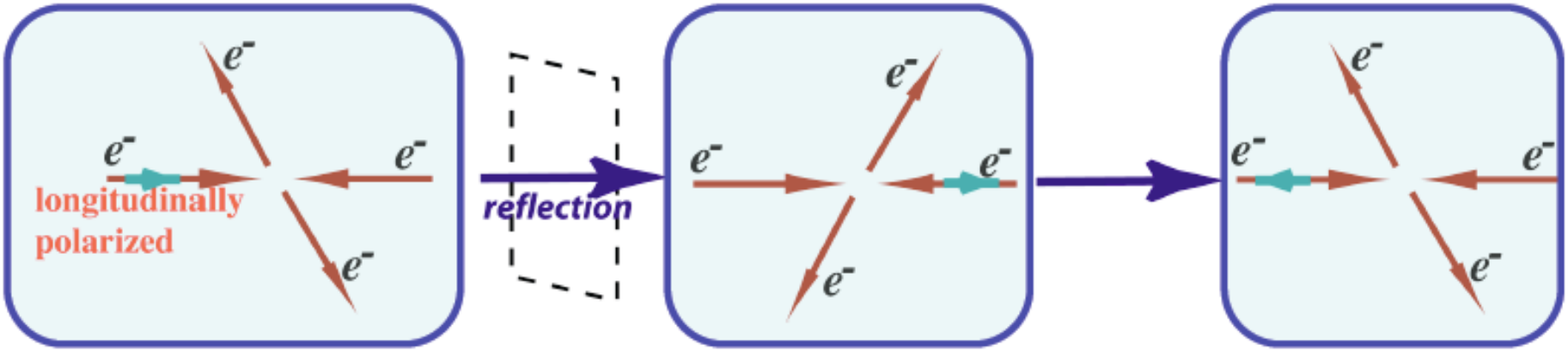
- History
- Strange Quarks
- Future Experiments at JLab

Parity: Mirror Symmetry

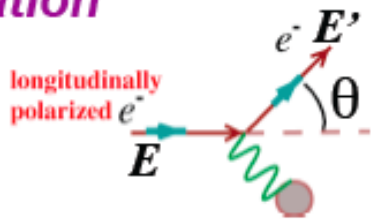
credit: P. Reimer

People and electrons have one thing in common:
mirror symmetry

Mirror Asymmetry: e^-e^-



- *One of the incident beams longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*



4-momentum transfer

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

Parity Violating Asymmetry:

$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}}$$

σ : *scattering probability*

$$\sigma \propto |A_\gamma + A_{weak}|^2$$

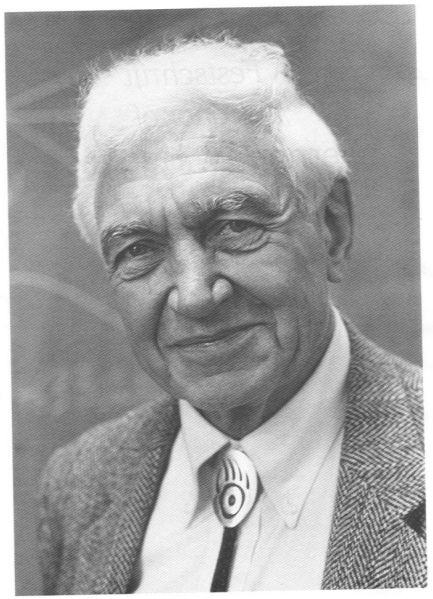
$$A_{PV} \sim \frac{A_{weak}}{A_\gamma} \approx \frac{G_F Q^2}{4\pi\alpha}$$

A_{PV} is of the order of 10^{-3} to 10^{-7}.

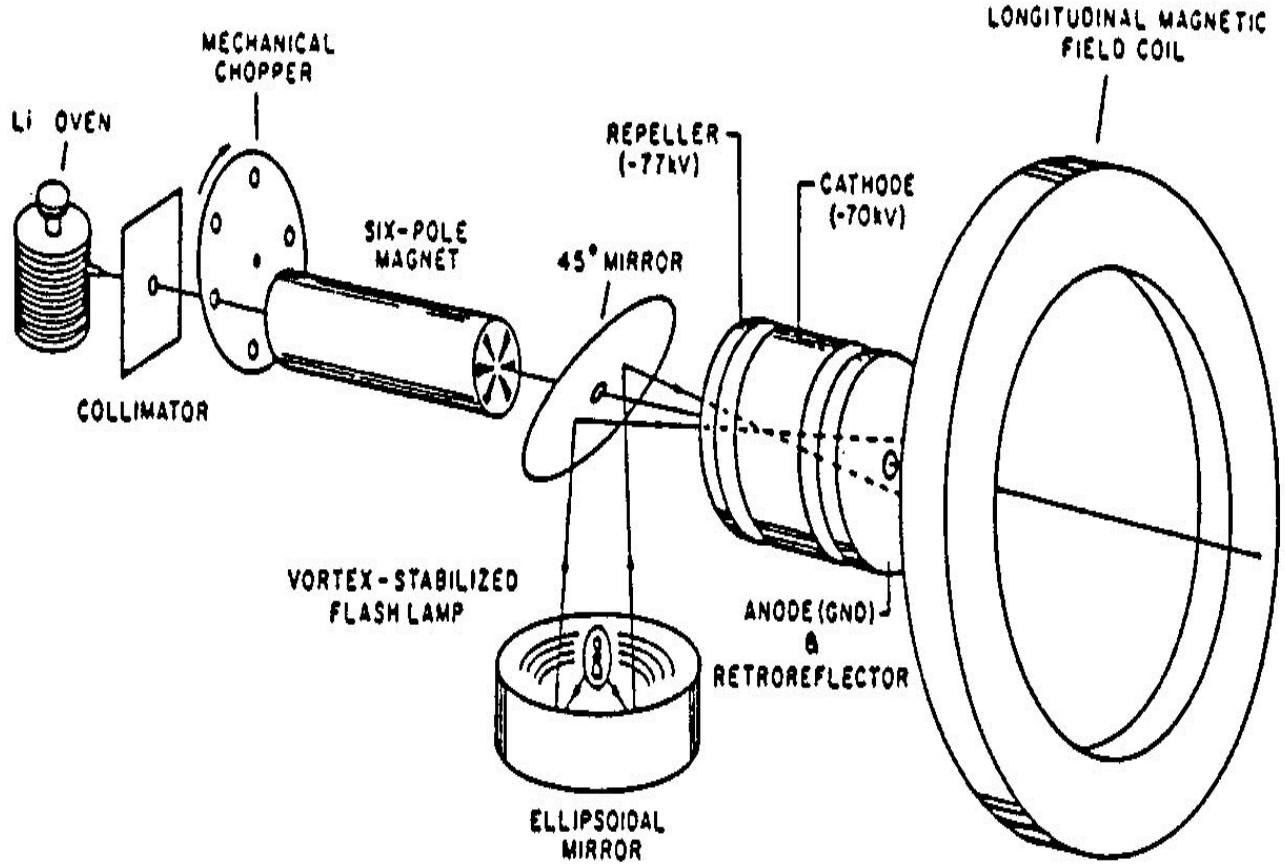
Motivation for Polarized Electrons: Pre 1970

- None!
- Nucleons were described by Bootstraps: No PDF's, TMD's, or GPD's.
- Weak neutral currents were "known" not to exist (from K decays (no charm)).

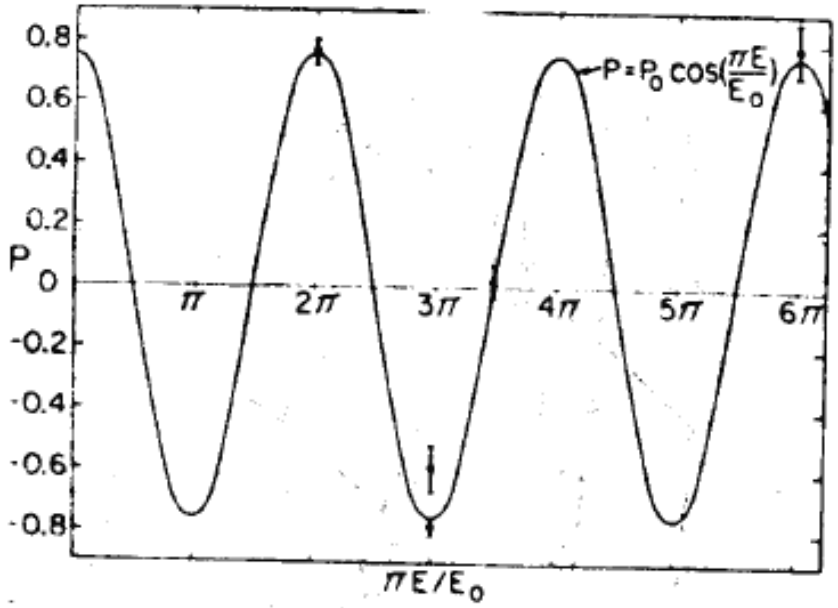
Peggy: The First Polarized Electron Source



V. W. Hughes

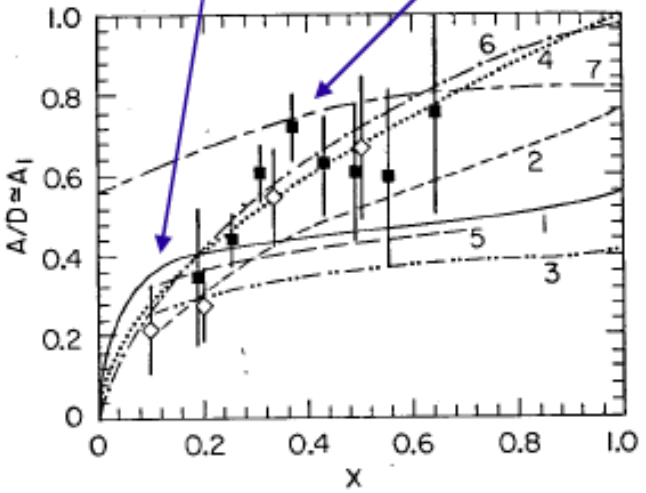


Results: Nov, 1974



First high energy polarized electron beam. Polarization is 75% as shown by Moller scattering

First spin-structure functior
Data: E-80 and E-130



1. Symmetrical Valence Quark Model (Kuti, Weisskopf, 1971).
2. Current Quarks (Close, 1974).
3. Orbital Angular Momemtum, (Look, Fischbach, Sehgal, 1977).
4. Unsymmetrical Model (Carlitz, Kaur, 1977).
5. MIT Bag Model (Jaffe, Hughes, 1977).
6. Source Theory (Schwinger, 1977).
7. Quark – Geometrodynamics (Preparata, 1981).

First PVES

PHYSICAL REVIEW D VOLUME 18, NUMBER 7 1 OCTOBER 1978

Search for parity violation in deep-inelastic scattering of polarized electrons by unpolarized deuterons

W. B. Atwood, R. L. A. Cottrell, H. DeStaebler, R. Miller, H. Pessard,* C. Y. Prescott, L. S. Rochester, and R. E. Taylor
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

M. J. Alguard, J. Clendenin, P. S. Cooper, R. D. Ehrlich,† V. W. Hughes, and M. S. Lubell
Yale University, New Haven, Connecticut 06520

G. Baum and K. P. Schüler
University of Bielefeld, Bielefeld, West Germany

K. Lübelsmeyer
Technische Hochschule Aachen, Aachen, West Germany

(Received 17 April 1978)

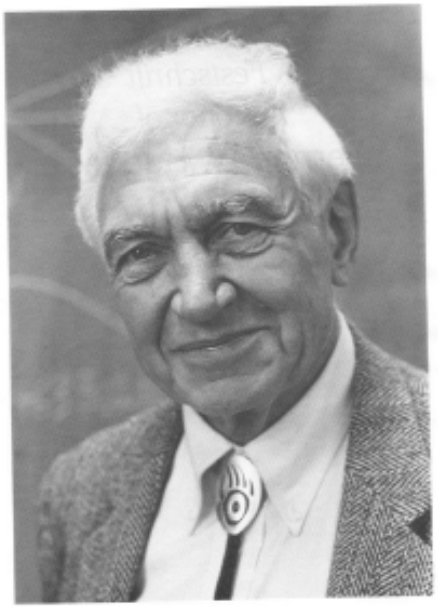
We report on recent asymmetry measurements for inelastic scattering of longitudinally polarized electrons from an unpolarized deuterium target at 19.4 GeV. Using the SLAC 20-GeV/c and 8-GeV/c spectrometers, the helicity-dependent cross-section asymmetries were measured at Q^2 values of 1.2 and 4.2 $(\mathrm{GeV}/c)^2$, and were found to be less than 2×10^{-3} and 7×10^{-3}, respectively.

$$Q^2 = 1.2\ (\mathrm{GeV}/c)^2:\quad A = (-8.2 \pm 4.4 \pm 9.3)\times 10^{-4},$$

$$Q^2 = 4.2\ (\mathrm{GeV}/c)^2:\quad A = (0.44 \pm 6.9 \pm 0.42)\times 10^{-3}.$$

Dominant error: imperfect helicity reversal

Major Discovery With Pol. e^-: The Z-Boson Violates Parity

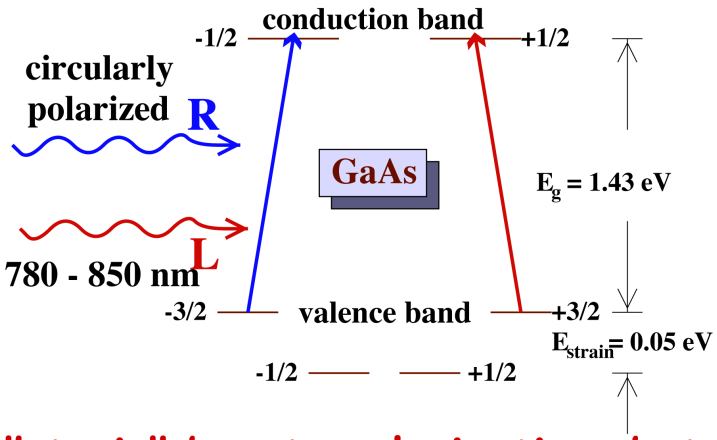


Vernon: Showed the way. Physics can be done with pol. electrons

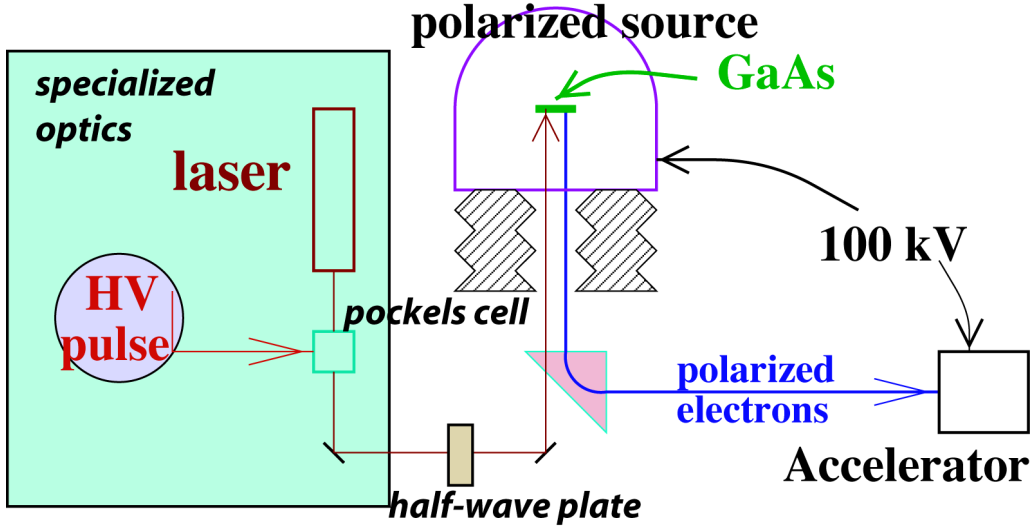
Sinclair: Built a better pol. Source (GaAs)

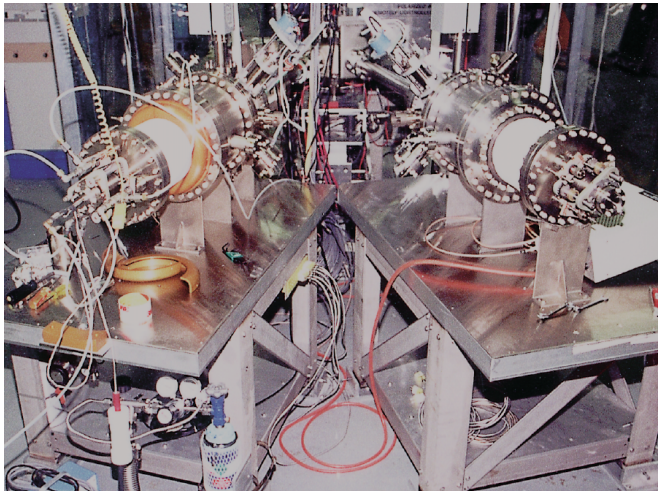
Prescott: spokesperson for the experiment that discovered parity violation in electron scattering

GaAs Polarized Source (Jlab Version)



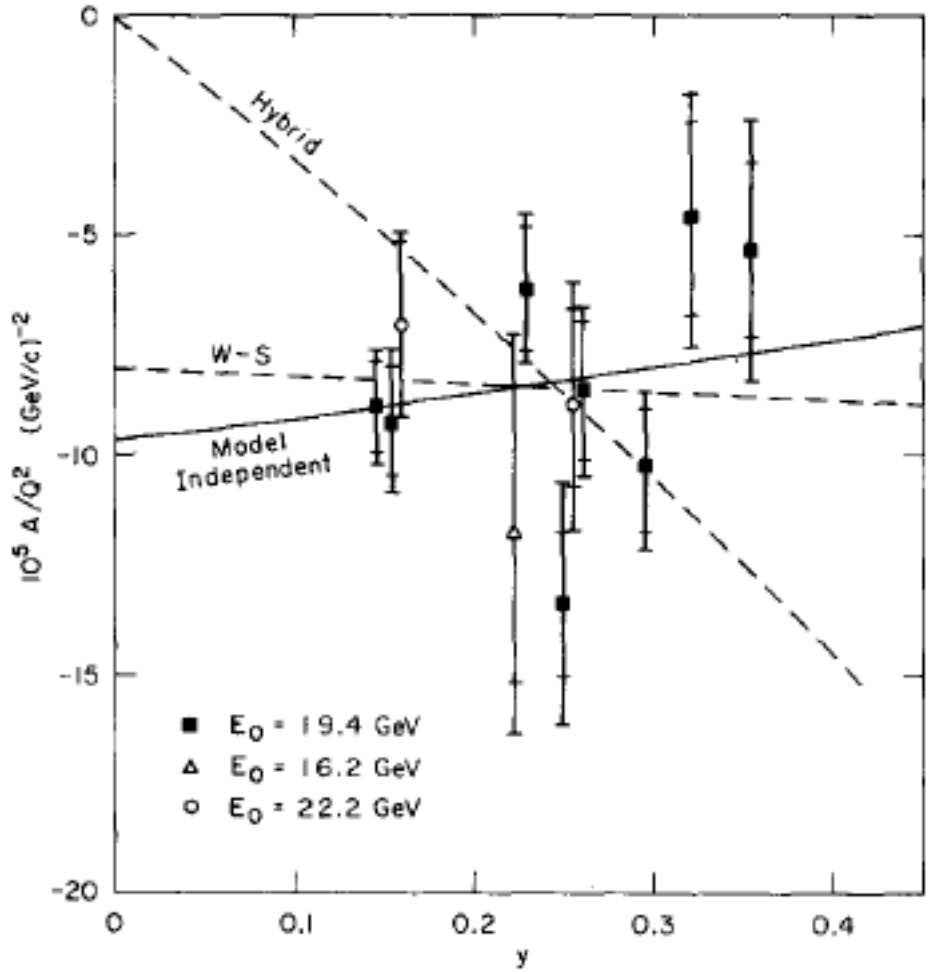
"strain" boosts polarization, but introduces anisotropy in response





Remarkable progress for these remarkable devices: APS Lawrence award in part for this work to M. Poelker.

Data: Non-zero Parity Violation



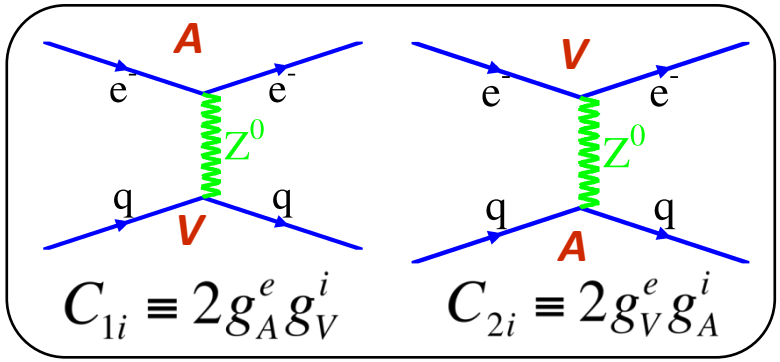
1. Obtained correct $\sin^2\theta_W$.
2. Ruled out hybrid model

After this experiment, the Weinberg-Salam model became the Standard Model

PVDIS Theory

$$A_{\rm iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r}$$

$$= -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right) \frac{2C_{1u} - C_{1d}\,(1+R_s) + Y\,(2C_{2u} - C_{2d})\,R_v}{5 + R_s}$$



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

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x,Q^2) = \sigma^l/\sigma^r \approx 0.2$$

$$C_{1u} = -\tfrac{1}{2} + \tfrac{4}{3}\sin^2\theta_W \approx -0.19$$

$$C_{1d} = \tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W \approx 0.35$$

$$C_{2u} = -\tfrac{1}{2} + 2\sin^2\theta_W \approx -0.04$$

$$C_{2d} = \tfrac{1}{2} - 2\sin^2\theta_W \approx 0.04$$

Cahn and Gilman, PRD **17** 1313 (1978) polarized electrons on deuterium

Why Do More PVES Experiments?

Do Proton as well as Deuterium to measure all couplings: no need for Qweak!

$$A^{DIS} \propto n^u q^u C_{1u} + n^d q^d C_{1d}$$

Won't work

1. Small change: $2C_{1u}-C_{1d} \rightarrow 4C_{1u}-C_{1d}$
2. Need PDF's (which cancel for D)

Experiments at Nuclear Physics Facilities are Competitive

Use Elastic scattering

(Coherent from all quarks)

$$A^{DIS} \propto n^u q^u C_{1u} + n^d q^d C_{1d}$$ ← Incoherent

$$A^{El} \propto q^{tot}(n^u C_{1u} + n^d C_{1d})$$ ← Coherent

$n^u = n^d$: $A \sim C_{1u} + C_{1d} \sim \sin^2\theta_W$

$n^u = 2n^d$: $A \sim 2C_{1u} + C_{1d} \sim 1 - 4\sin^2\theta_W$

Off to MIT-Bates: ^{12}C: 1977

Theory is simple and clean;

Hadronic Physics cancels

(Feinberg)

$$A \propto C_{1u} + C_{1d} \propto \sin^2 \theta_W$$

Problems:

1. Why would anyone want polarized electrons at Bates
2. Standard Model tests aren't part of Nuclear Physics

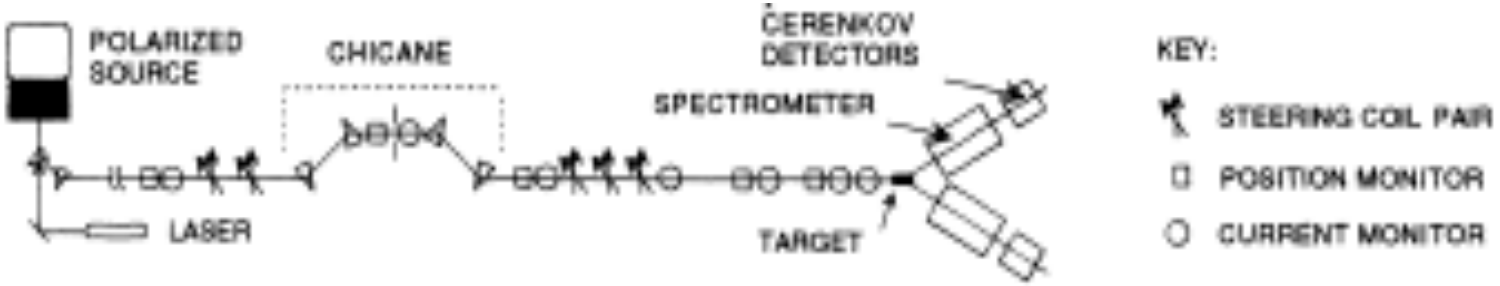


FIG. 1. Schematic diagram of the apparatus. The beam energy was measured in the chicane.

Solution: 2013-DOE Review

Why didn't DOE sent this to MIT in 1977?

Enclosure 3

TABLE 1: DISTRIBUTION OF RESEARCH EFFORT (FRACTIONAL FTE) AMONG GROUP'S ACTIVITIES

Subfield: Medium energy (ME)

For current members of the group, please indicate the fractional FTE devoted to each category. All of the following personnel who receive funding from the grant should be listed: Faculty (tenured and tenure track); Research Scientists; Post-docs; and Graduate Students.

	Nucleon structure / spin physics	PVES*	Hadron spectroscopy	SM** tests / BSM*** search	Other within ME	Other subfields in NP	Other non-NP effort	Total FTE (sum=1)
Faculty								
A. Einstein	0.3		0.2				0.5	1.0
Res. Scientists								
J. Watt	0.5		0.5					1.0
Post-docs								
E. Rutherford	0.5	0.5						1.0
Grad. students								
E. Windsor			0.5	0.5				1.0
J. Maxwell		0.5				0.5		1.0
Total	**1.3**	**1.0**	**1.2**	**0.5**		**0.5**	**0.5**	**5.0**

*PVES: Parity violating electron scattering **SM: Standard model ***BSM: Beyond standard model

Theory Gets More Complicated

$$A \propto \sin^2\theta_W \left[1 + \frac{G_E^s}{G_E^p} + \left(1 - \frac{F_n(Q^2)}{F_p(Q^2)} \right) \right]$$

Important at large Q^2 (He: HAPPEXII)

Important at large Z (^{208}Pb: PREx)

The 208 **P**b **R**adius **EX**periment

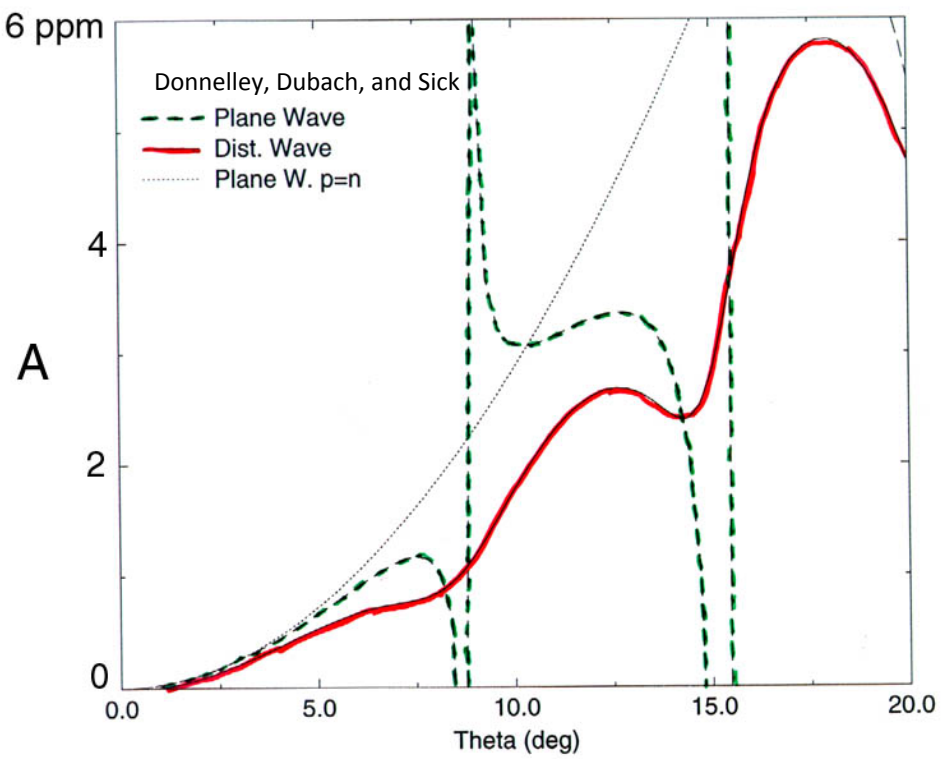
and Neutron Rich Matter
in the Heavens and on Earth

August 17-19 2008

Jefferson Lab

Newport News, Virginia

Need accurate calculation of distortion of incident wave (Horowitz).



Elastic Nucleon Scattering at Mainz

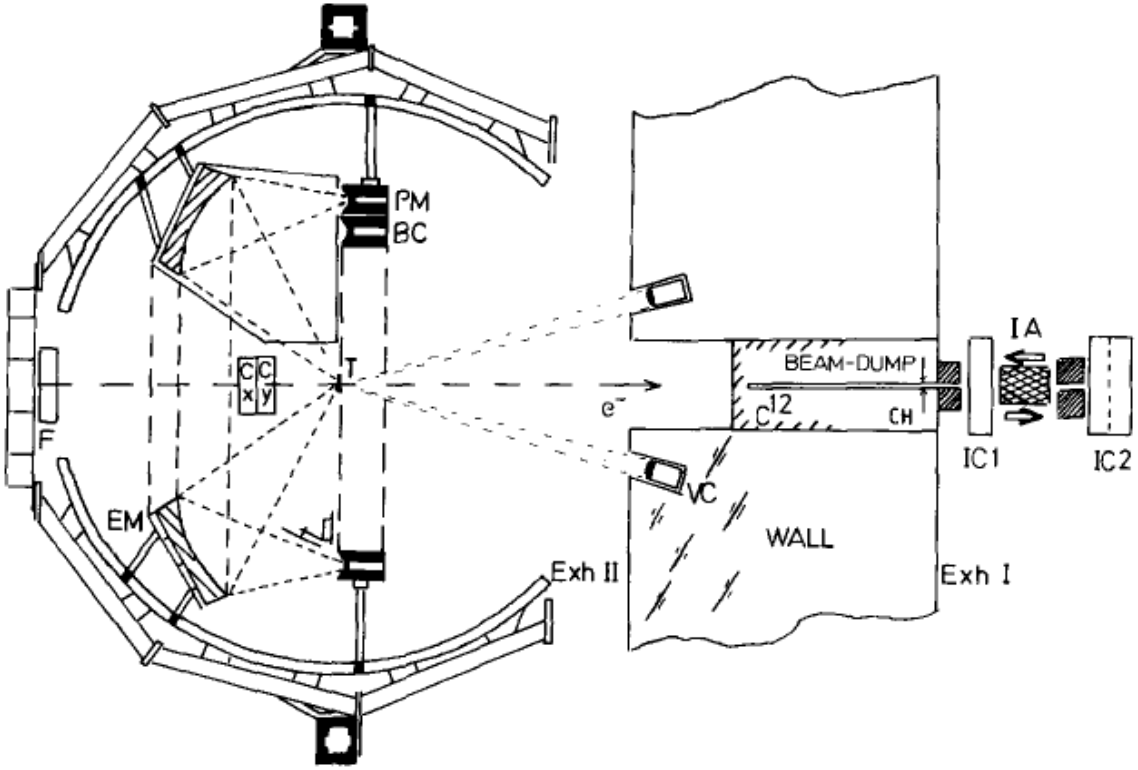


Fig. 6. Side view of the gas Čerenkov detector system and the Compton polarimeter: EM = elliptical mirrors, PM = photomultipliers, BC = background counters, VC = forward angle lucite Čerenkov detectors, T = ^{9}Be target ($m_p = 2.4$ g cm^{-2}), F = ferrite, C_x, C_y = position-sensitive cavities, CH = channel (∅ = 1 cm), IC1, IC2 = ionization chambers, IA = magnetized iron absorber.

Electroweak and Hadron Structure

$$A_{\rm PV} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{Z^0} - \mathcal{M}^r_{Z^0}}{\mathcal{M}_\gamma}$$

$$\propto -\left(\frac{G_{\rm F} Q^2}{4\pi\alpha}\right)\left(g_A^e g_V^T + \beta g_V^e g_A^T\right)$$

$A^{eP} = A_V + A_S + A_A$

g_V^T

$$A_{\rm V} = -a\rho'_{eq}\left[(1 - 4\hat{\kappa}'_{eq}\hat{s}^2_Z) - \frac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}\right] \quad (1)$$

$$A_{\rm S} = a\rho'_{eq}\frac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \quad (2)$$

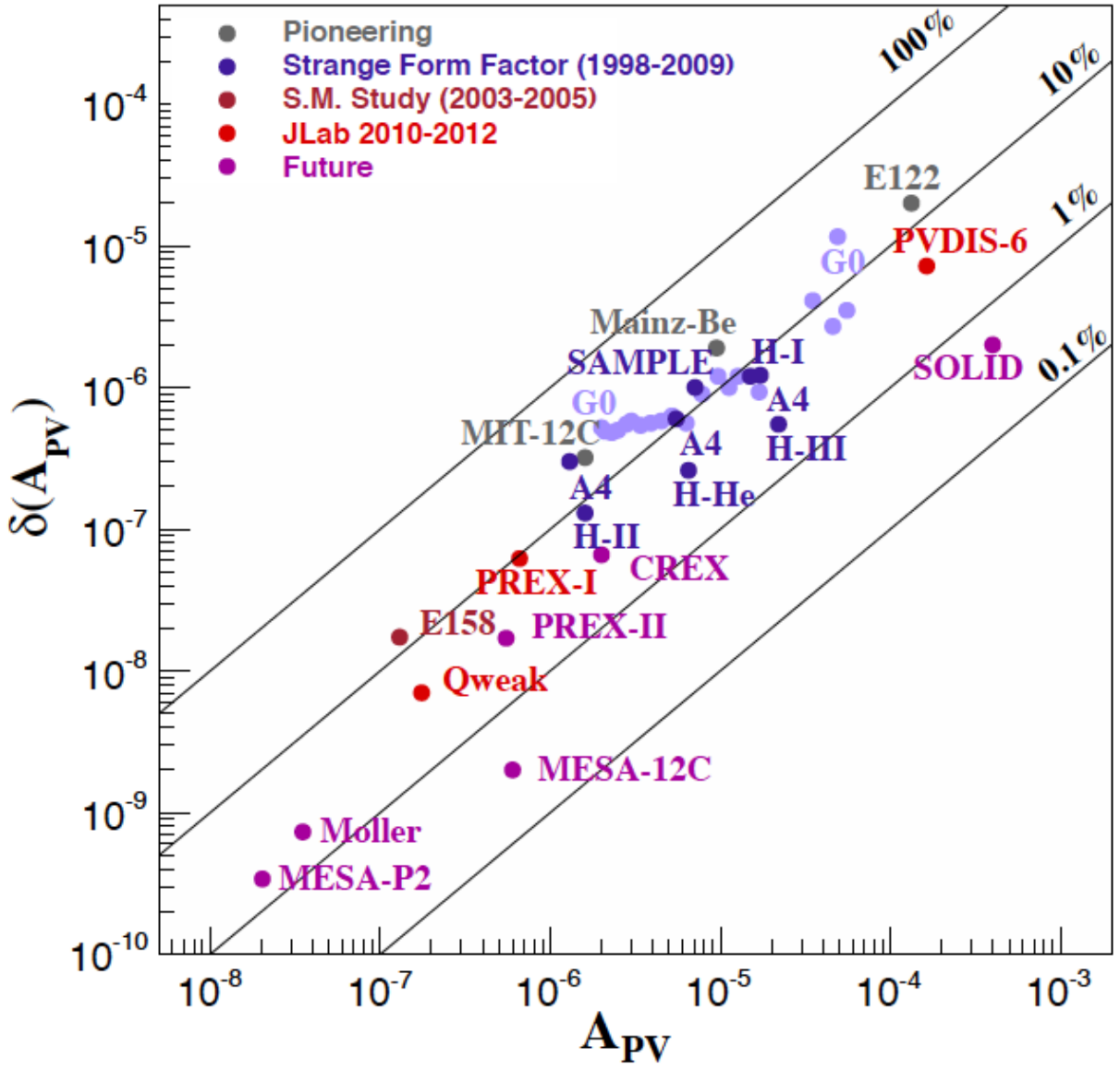
g_V^T

$g_A^e = 1$

$$A_{\rm A} = a\frac{(1 - 4\hat{s}^2_Z)\sqrt{1-\epsilon^2}\sqrt{\tau(1+\tau)}G_M^p \tilde{G}_A^p}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \quad (3)$$

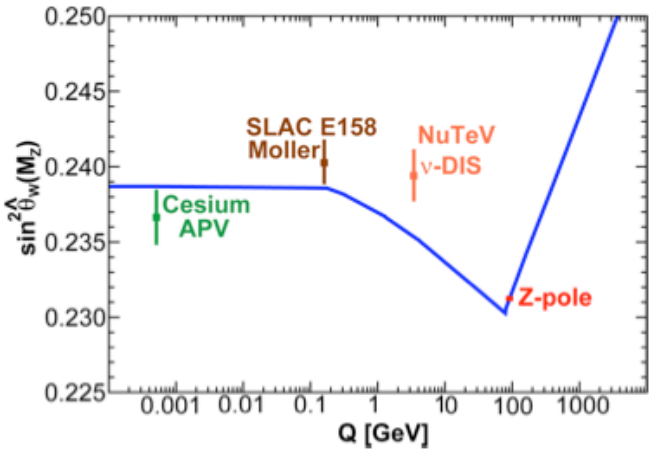
g_V^e β g_A^T

Many PVES Experiments Possible



Strange Quarks

Other Open Questions in Nucleonic Strangeness



NuTeV Anomaly

NuTeV published a 3σ deviation from the standard model

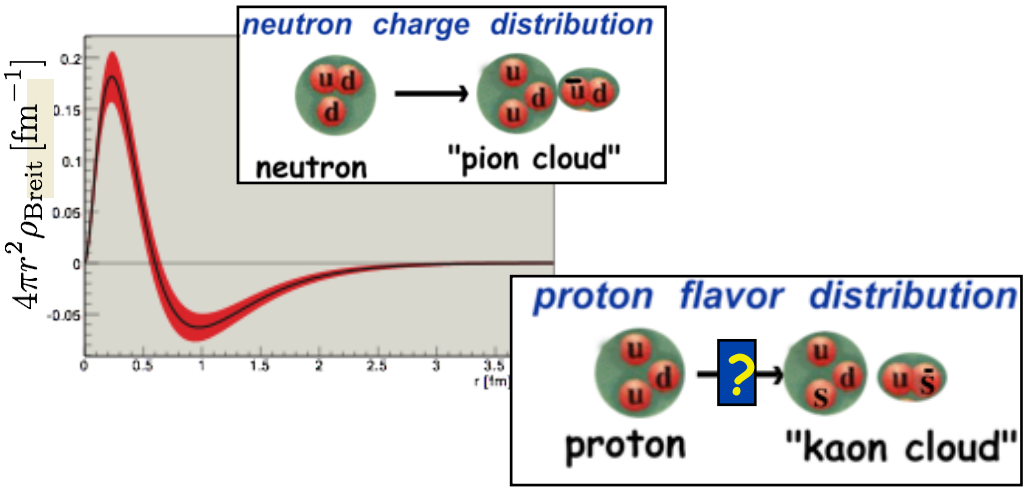
A leading hypothesis is that a signficant fraction is explained by an asymmetry in the strange sea: $s - \bar{s}$

Do the strange quarks in the sea play a significant role in the electric/magnetic charge distributions in the nucleon?

Strange Spin

Originally motivated by the "spin problem", but remains an important question in nucleon structure

The spin dependent neutralino-nucleon coupling depends on Δs



Extracting the Strange Vector Form Factor

Charge Symmetry

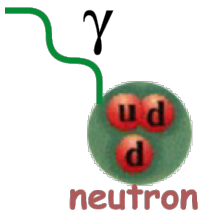
$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$

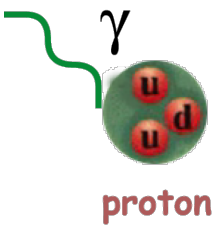
$$G_E^n = \frac{2}{3}G_E^{u,n} - \frac{1}{3}G_E^{d,n} - \frac{1}{3}G_E^s$$

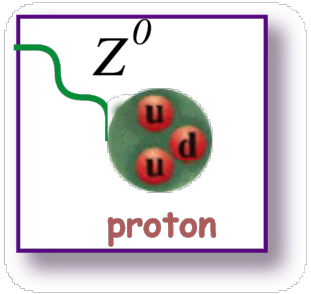
Two equations and three unknowns

Measure neutral weak proton vector form-factor

Three equations and three unknowns



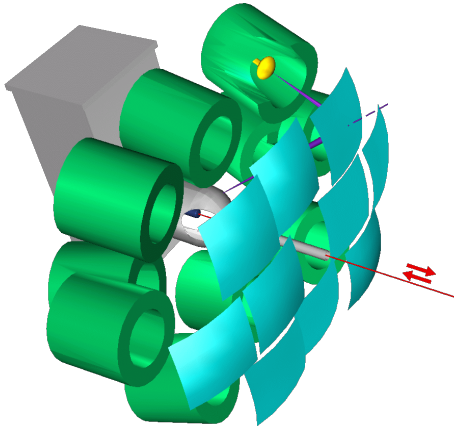




Measuring all three enables separation of up, down and strange contributions

The weak form factor is accessible via parity violation

Experimental Overview



SAMPLE

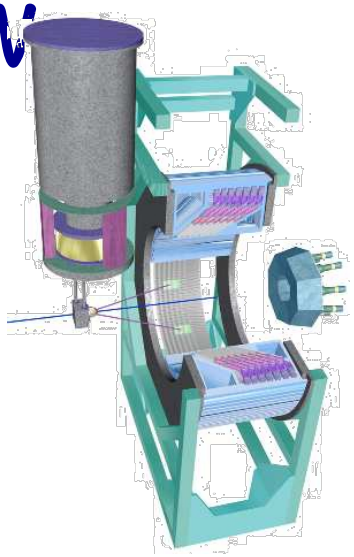
open geometry,
integrating,
back-angle only

A4

Open geometry

Fast counting calorimeter for background rejection

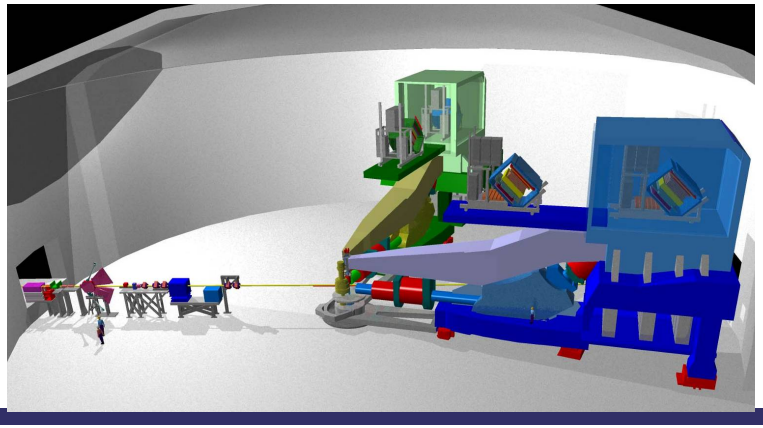
Forward and Backward angles



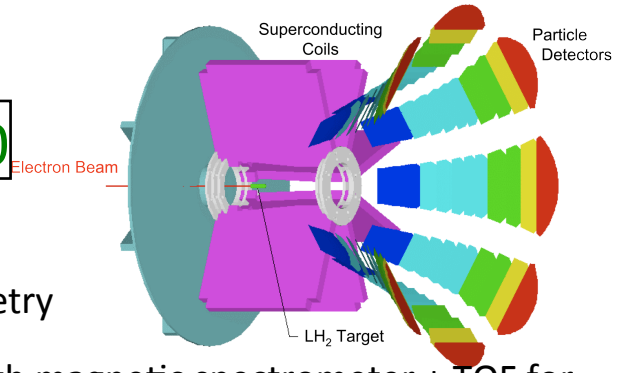
HAPPEX

Precision spectrometer, integrating

Forward angle, also ^{4}He at low Q^2



G0



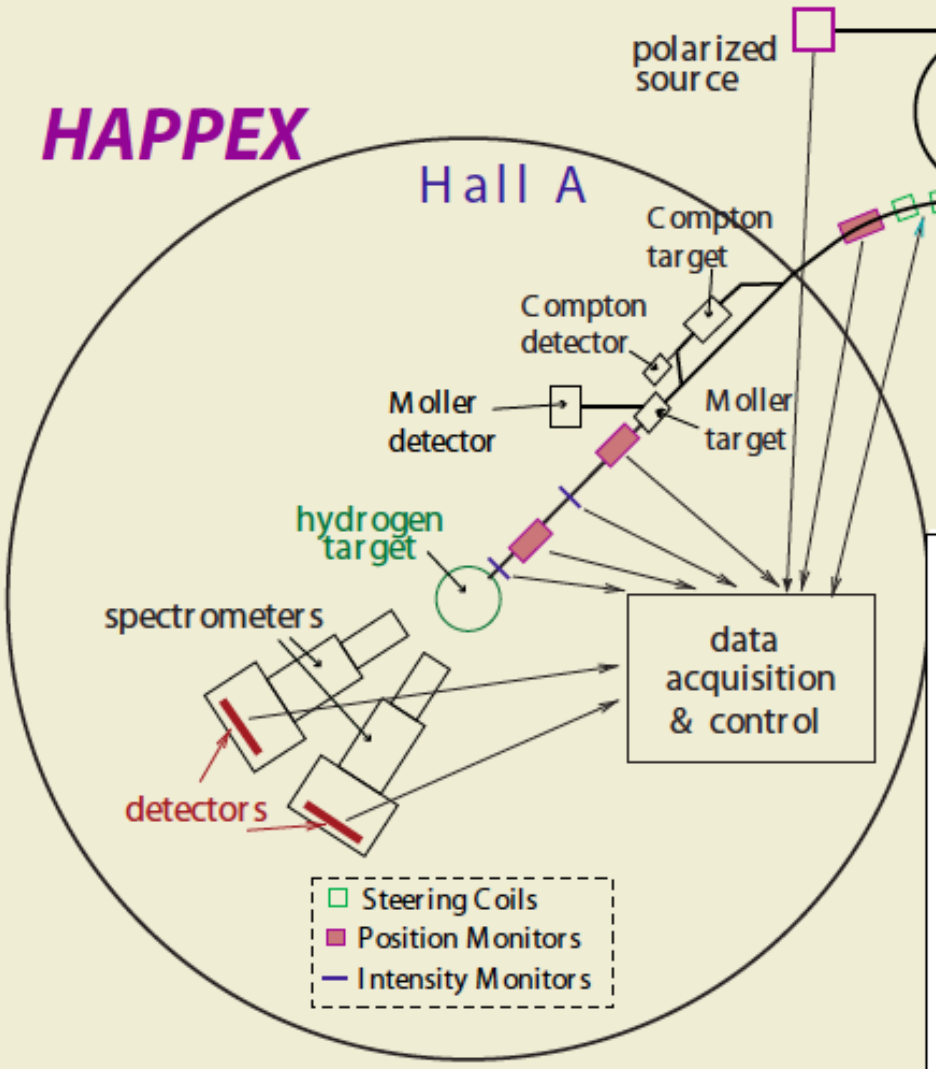
Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

Forward and Backward angles over a range of Q^2

First PVeS experiment at JLab

Hall A Proton Parity Experiment (E91-010)



98 Data A_{raw} = -5.64 ± 0.75 (ppm)

~ 95 uA, ~ 38% polarization

99 Data A_{raw} = -10.45 ±0.75 (ppm)

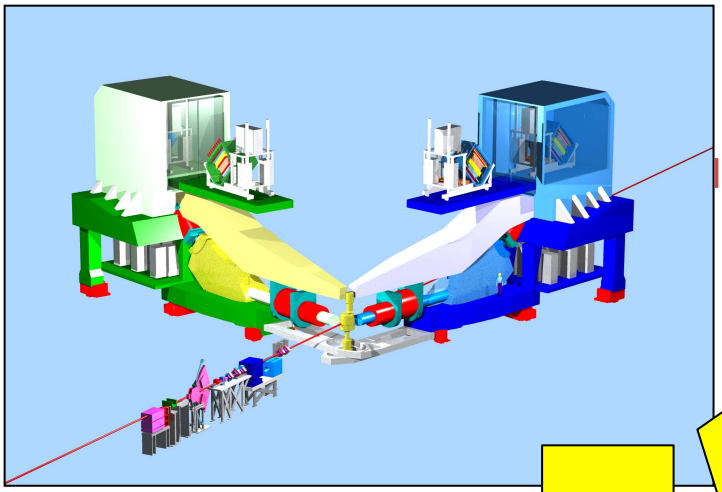
~ 40 uA, ~ 70% polarization

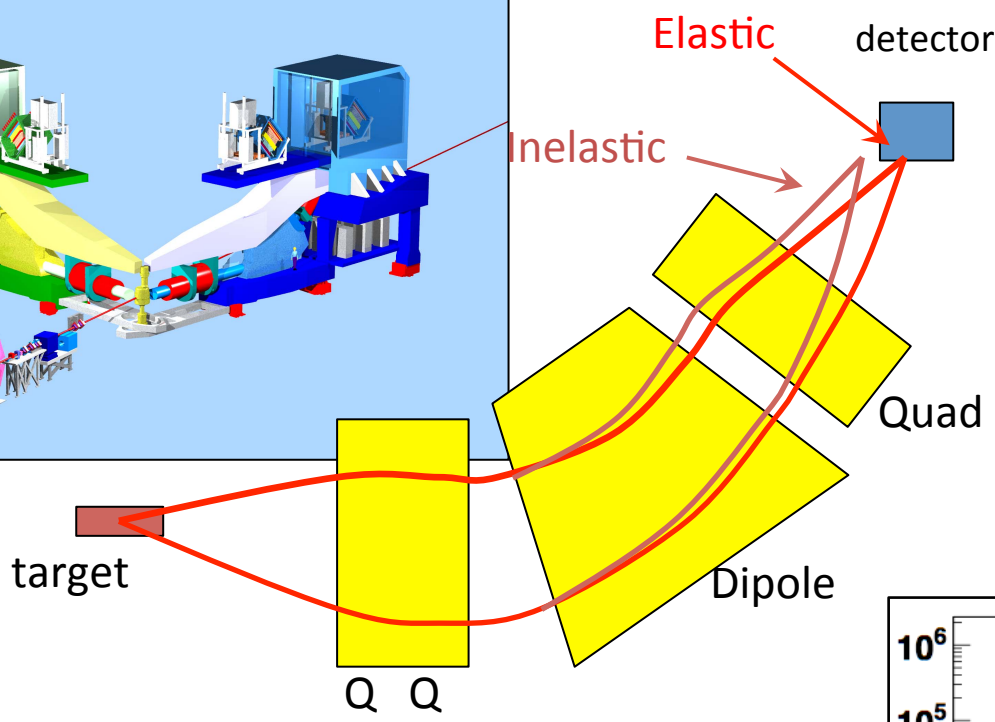
Pioneering new technologies at JLab

- High polarization from strained cathode
- Attention to polarized source and beam transport for precision and stability under helicity reversal
- Beam modulation to extract position/energy sensitivity
- Beam intensity asymmetry measurement and feedback
- Precision Compton polarimetry
- Low noise analog flux integration

Integrating in the High Resolution Spectrometers

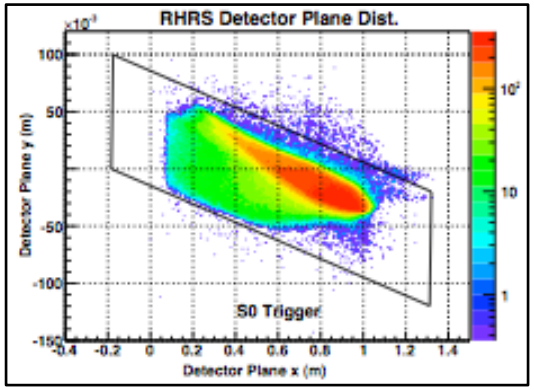
Techniques for high flux, to get few percent precision on 1-20 parts per million asymmetry





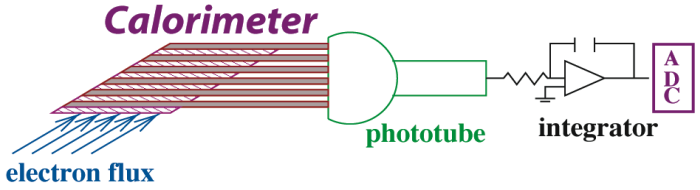
Very clean separation of elastic events by HRS optics

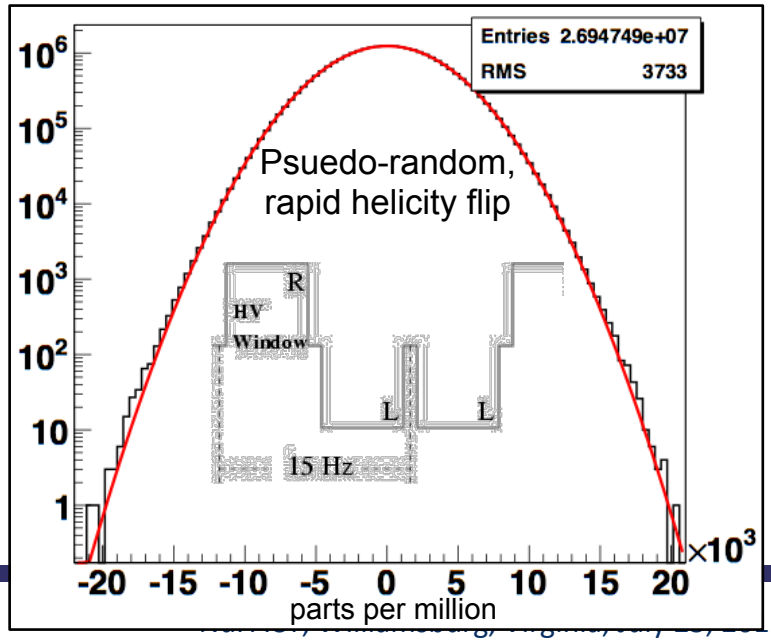
no PID needed; detector sees only elastic events



Lead - Lucite Cerenkov Shower Calorimeter

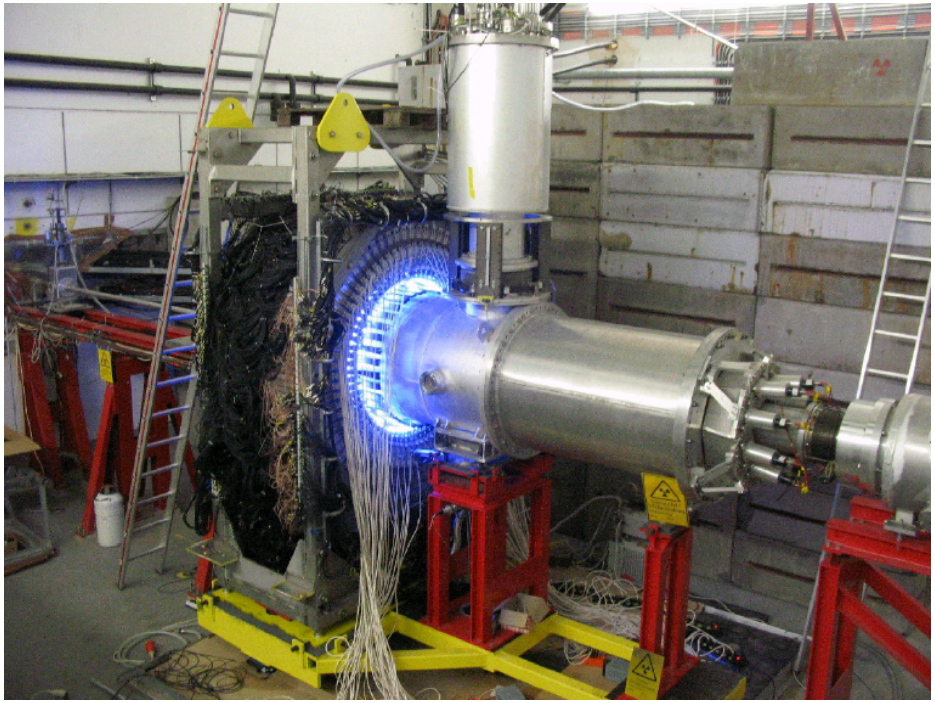
- phototube current integrated over fixed time periods

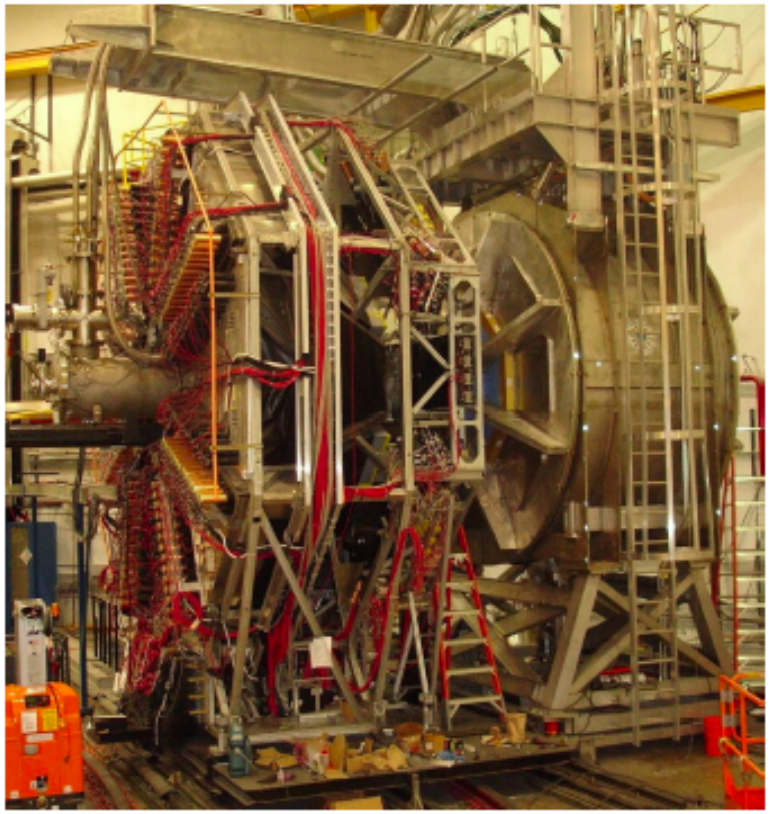




A4, G0 Apparatus

Counting





PbF calorimeter
(no magnet)

Toroidal magnet,
scintillation detectors

The Axial Term and the Anapole Moment

G0 Collaboration, Phys.Rev.Lett. 104 (2010) 012001

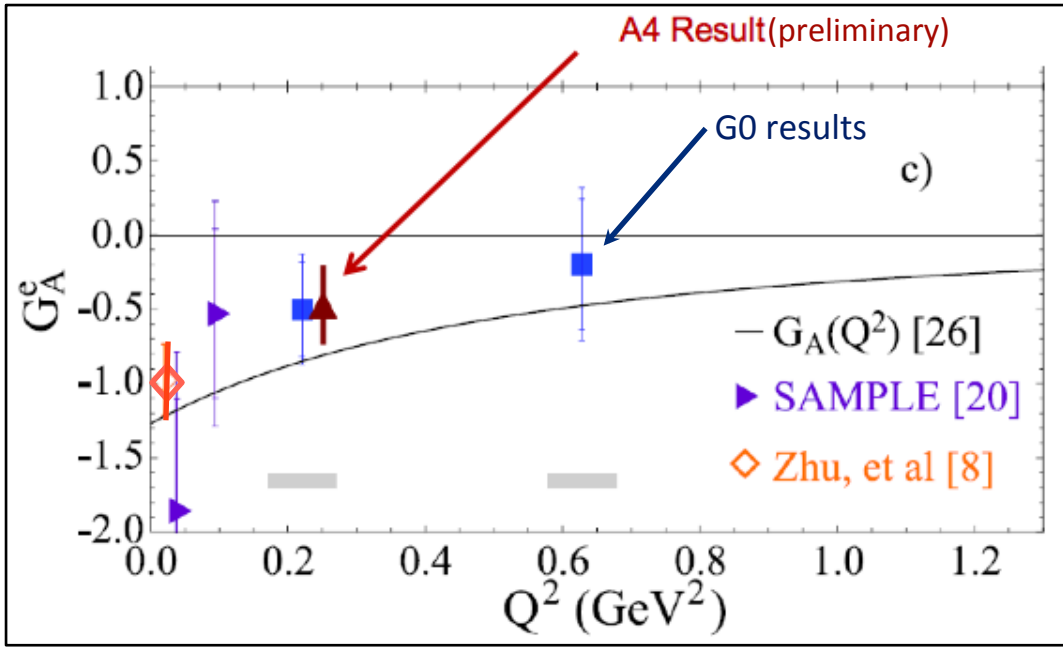
Anapole Moment Correction:

Multiquark weak interaction in $R_A^{(T=1)}$, $R_A^{(T=0)}$

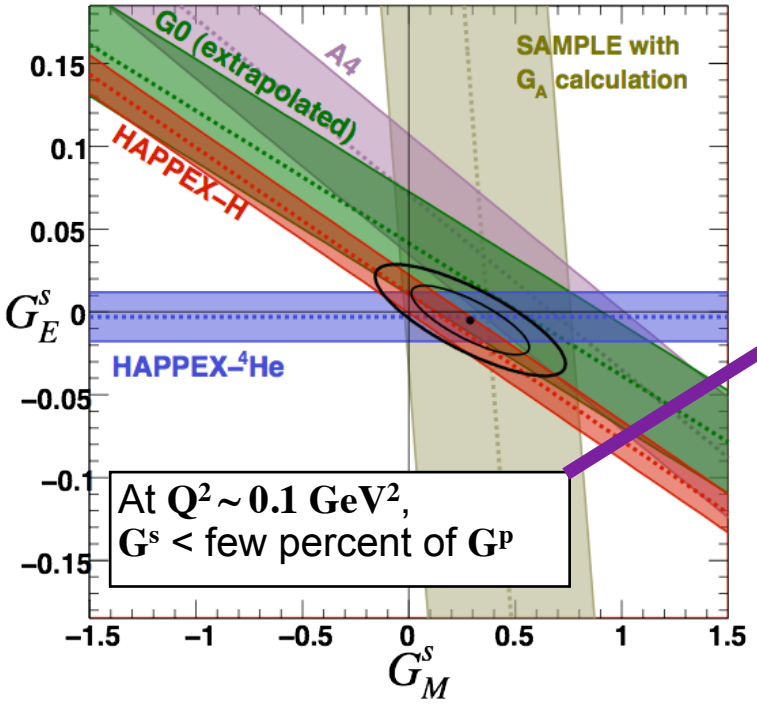
$$\tilde{G}_A^{p,n} = -\tau_3\left(1 + R_A^{T=1}\right)G_A^{(3)} + \sqrt{3}R_A^{T=0}G_A^{(8)} + \Delta s$$

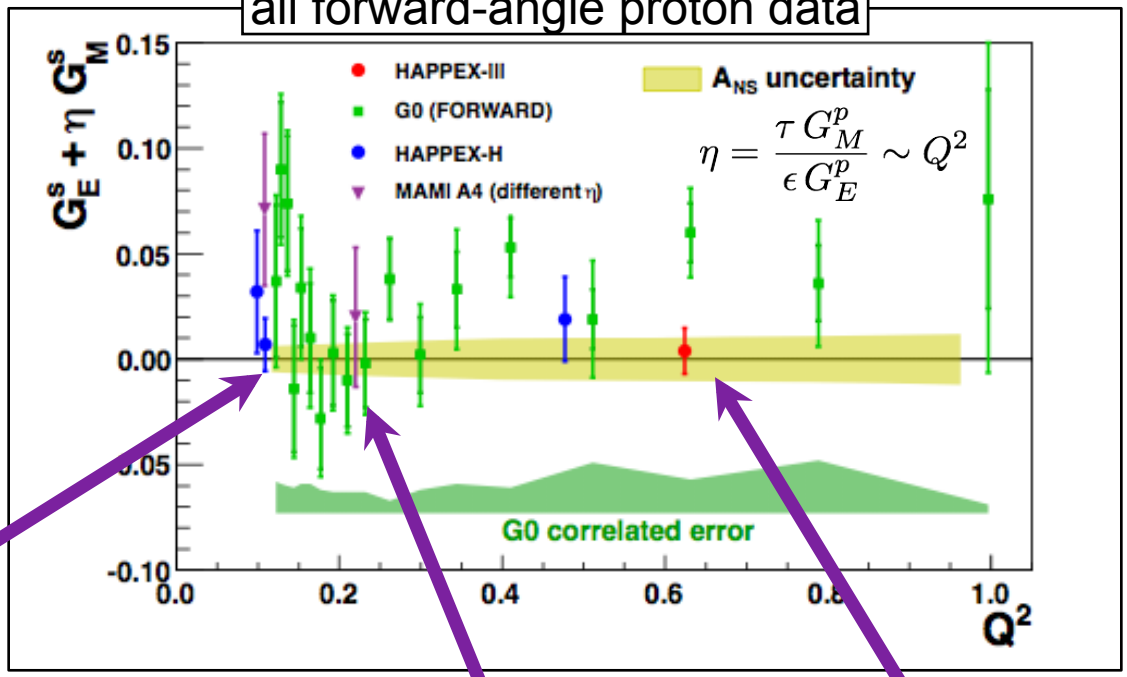
Difficult to improve on theoretical bound

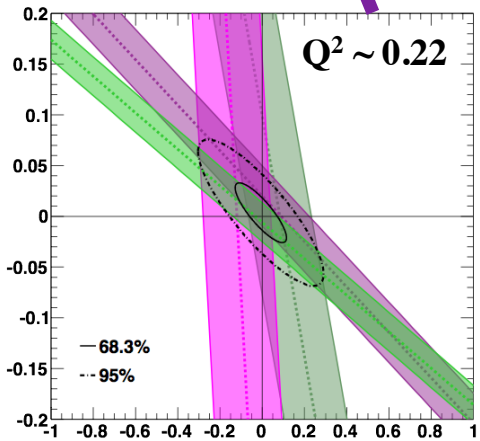
Uncertain Q^2 dependence

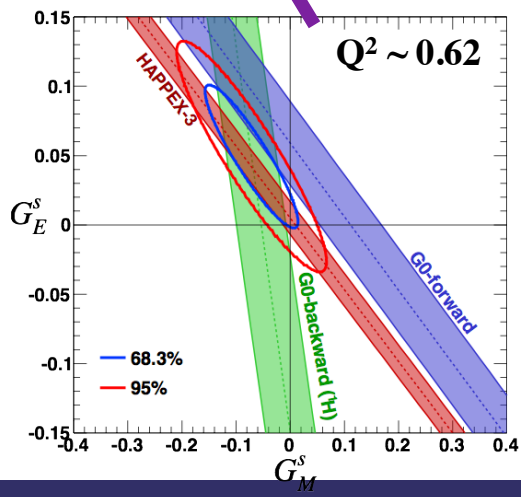


World data on G^s





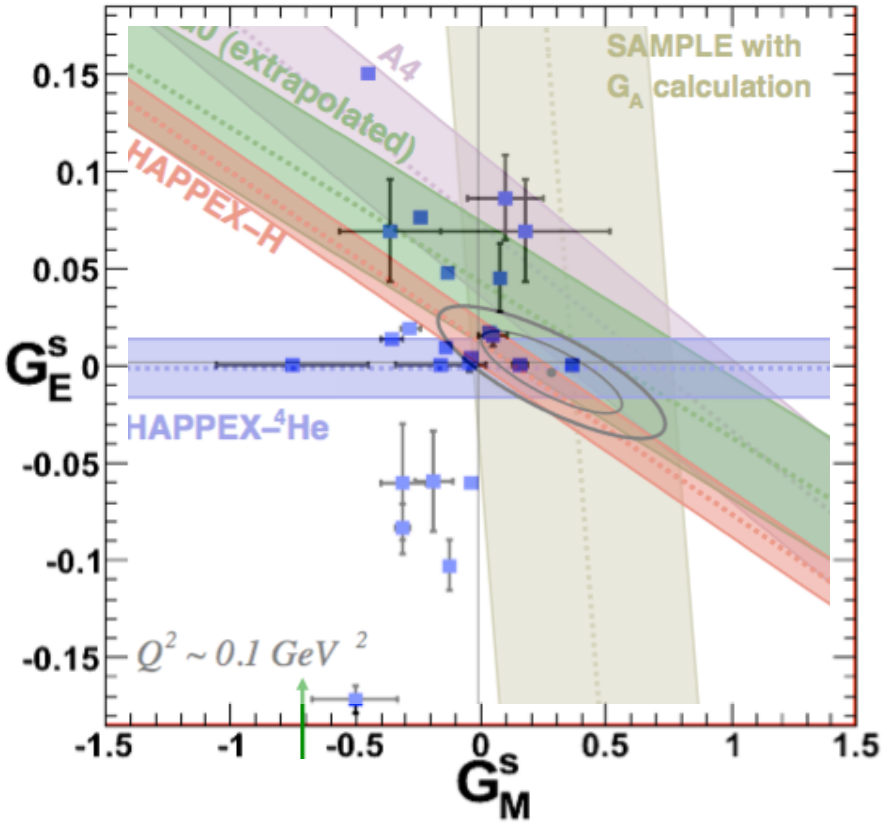




QCD models

Model guidance is unclear:

kaon loops, vector dominance, Skyrme model, chiral quark model, dispersion relations, NJL model,
quark-meson coupling model, chiral bag model, HBChPT, chiral hyperbag, QCD equalities, …



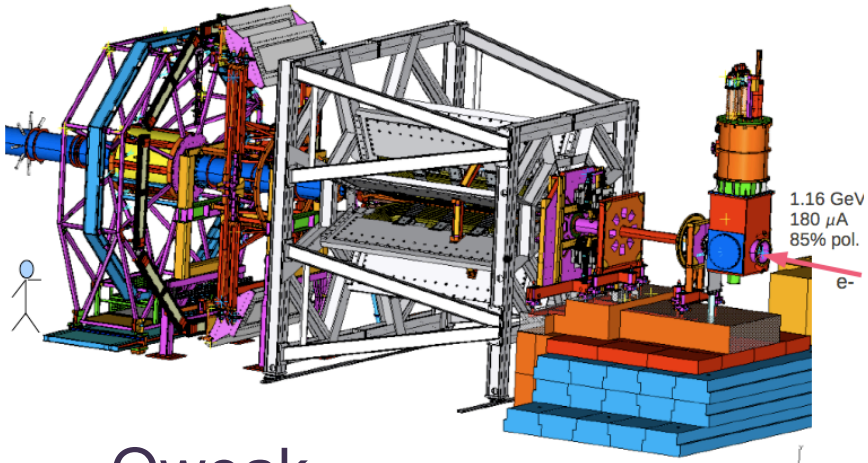
Recent significant progress in Lattice QCD:

- Dong, Liu, Williams PRD 58(1998)074504
- Lewis, Wilcox, Woloshyn PRD 67(2003)013003
- Leinweber, et al.,PRL 94(2005) 212001; 97 (2006) 022001
- Lin, arXiv:0707:3844
- Wang et al, Phys.Rev. C79 (2009) 065202
- Doi et al., Phys.Rev. D80 (2009) 094503

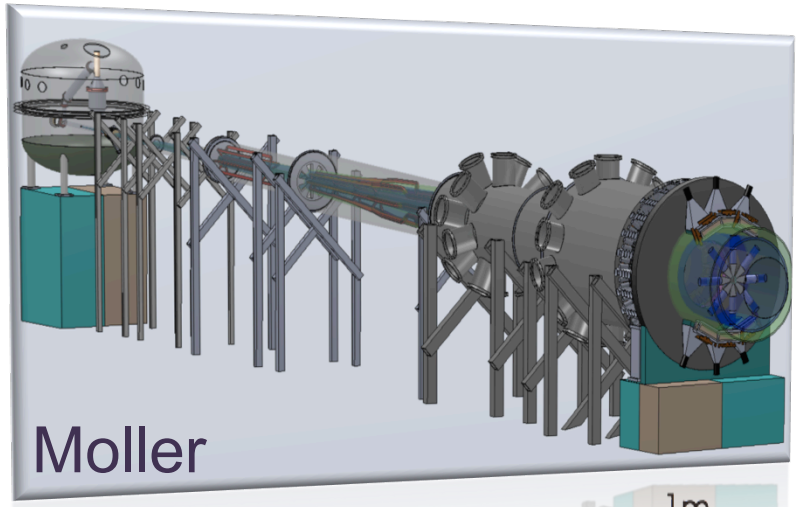
these all suggest very small effects with precision an order of magnitude beyond empirical constraints - predictions are experimentally indistinguishable from zero

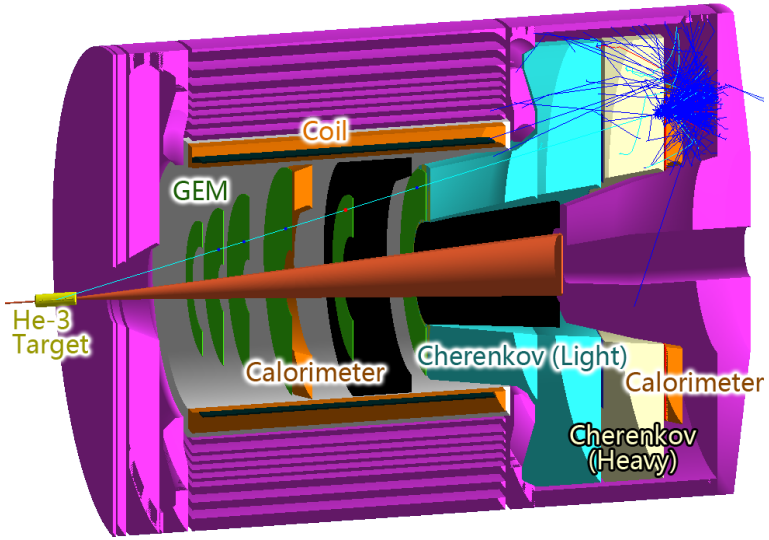
Future

Next Generation Spectrometers

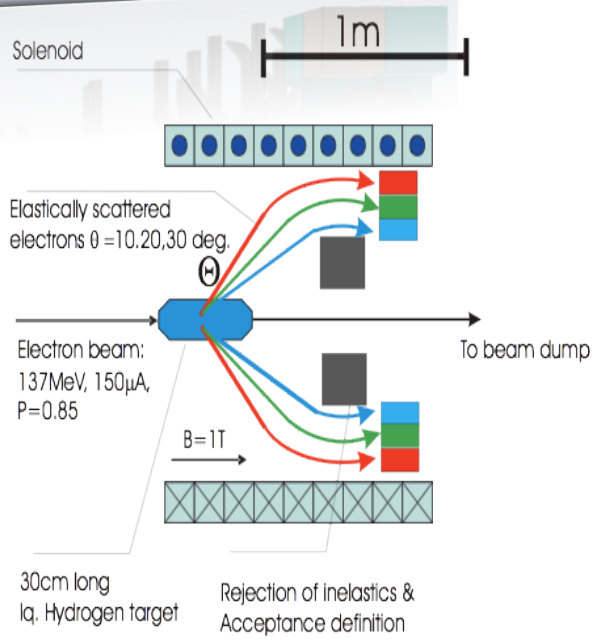


Qweak





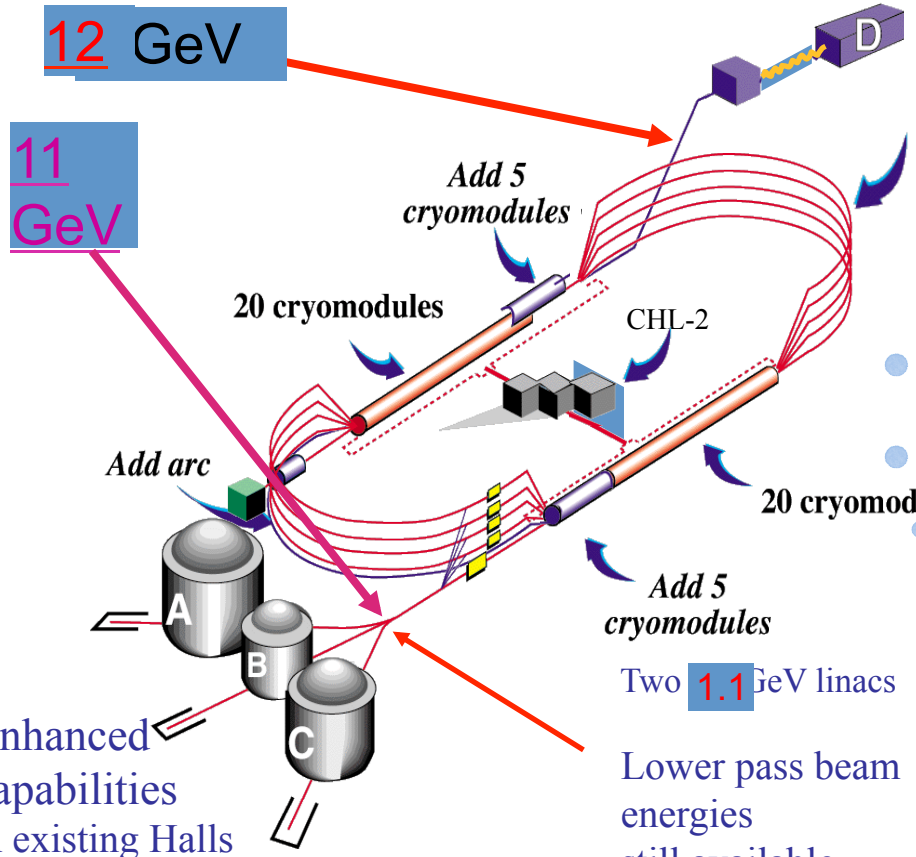
SOLID



P2

The 12 GeV Upgrade of JLab

First physics beams to Hall A in 2014

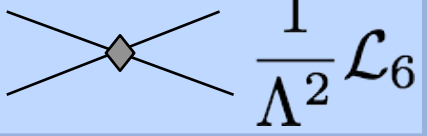


Fundamental Symmetries Opportunities

- Dark Photon Searches
- Parity Violation
- Search for new flavor-conserving neutral current interactions

- **MOLLER: electron-electron scattering**
- **SOLID: electron deep-inelastic scattering**

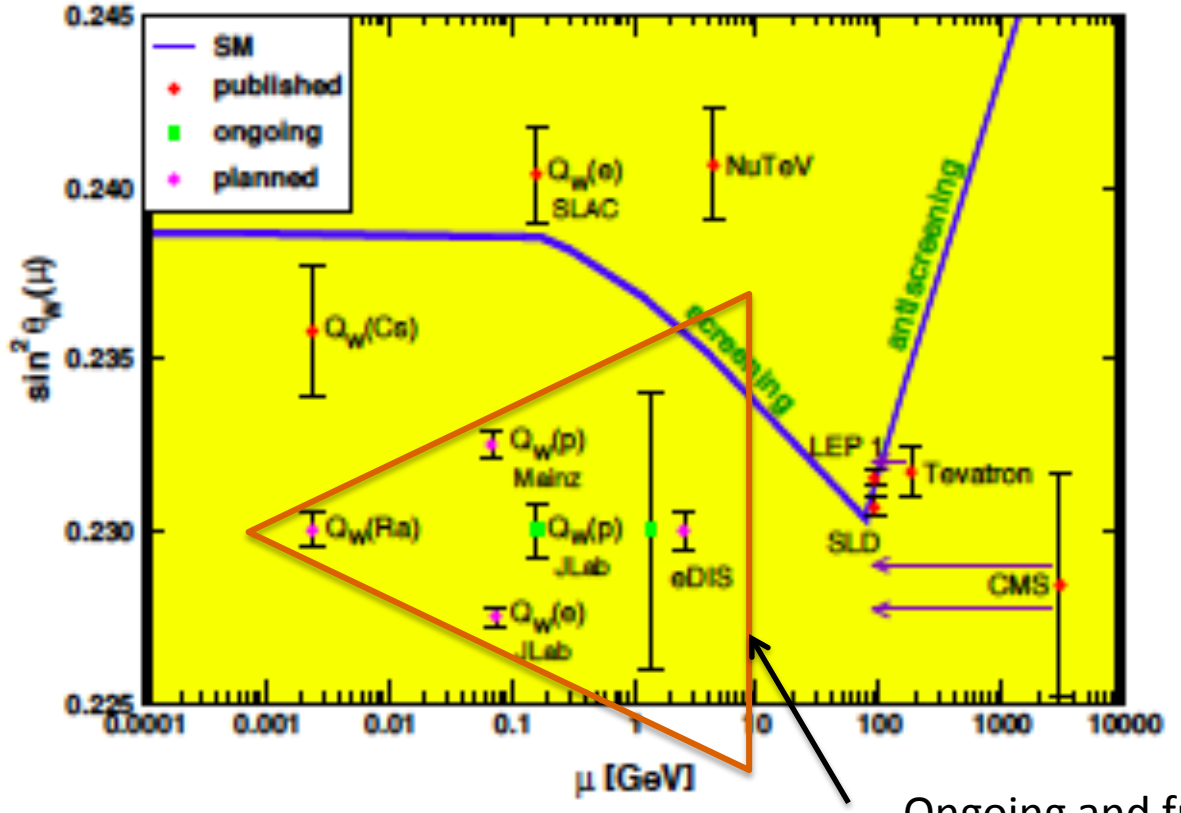
Look for tiny but measurable deviations from precisely calculable predictions for SM processes



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

Λ reach similar to LHC

Measurement of $\sin^2\theta_W$



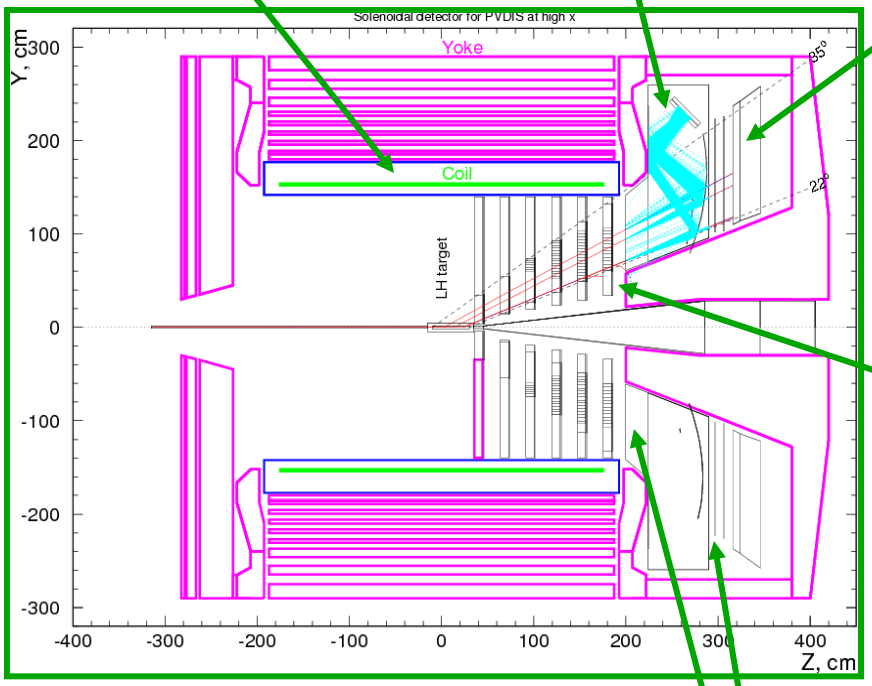
Ongoing and future

SoLID Spectrometer

CLEO Solenoid

Gas Cerenkov

Shashlyk Calorimeter



Baffles

GEM's

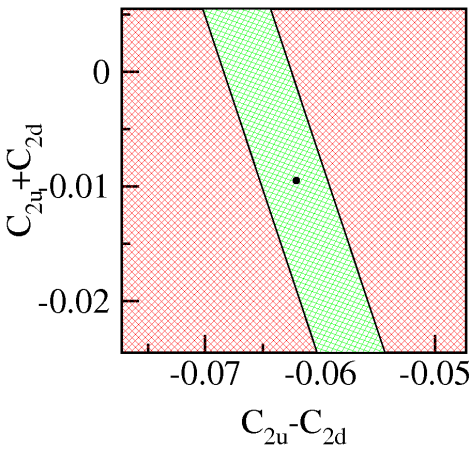
International Collaborators:
China (Gem's)
Italy (Gem's)
Germany (Moller pol.)

Motivation for PVDIS

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

Standard Model

$$b(x) = \frac{\sum_i C_{2i} Q_i f_i^-(x)}{\sum_i Q_i^2 f_i^+(x)}$$



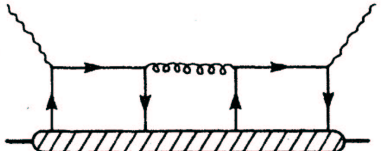
CSV at Quark Level

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

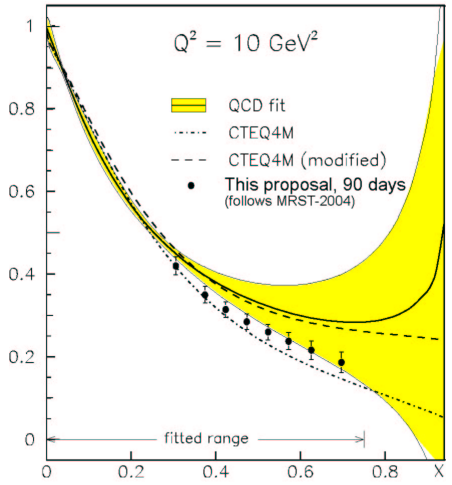
$$\delta d(x) = d^p(x) - u^n(x)$$

$$R_{CSV} = \frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.28\,\frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

Di-quarks in the nucleon (Q^2 Dependence)



d/u for Hydrogen



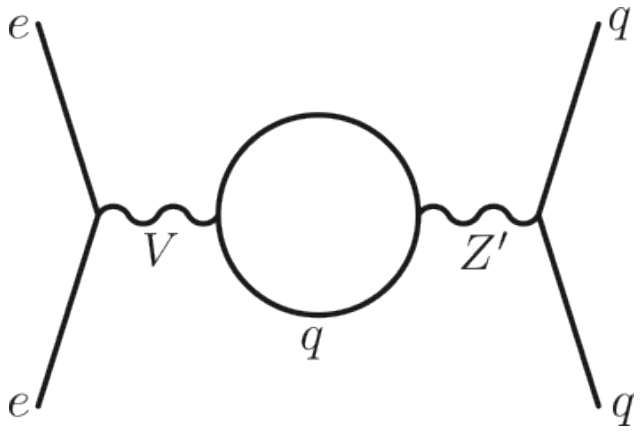
New Physics Examples

Leptophobic Z'

- *Virtually all GUT models predict new Z's*
- *LHC reach ~ 5 TeV, but....*
- *Little sensitivity if Z' doesnt couple to leptons*
- *Leptophobic Z' as light as 120 GeV could have escaped detection*

Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect ***C_{2q}'s***

SOLID can improve sensitivity:
100-200 GeV range

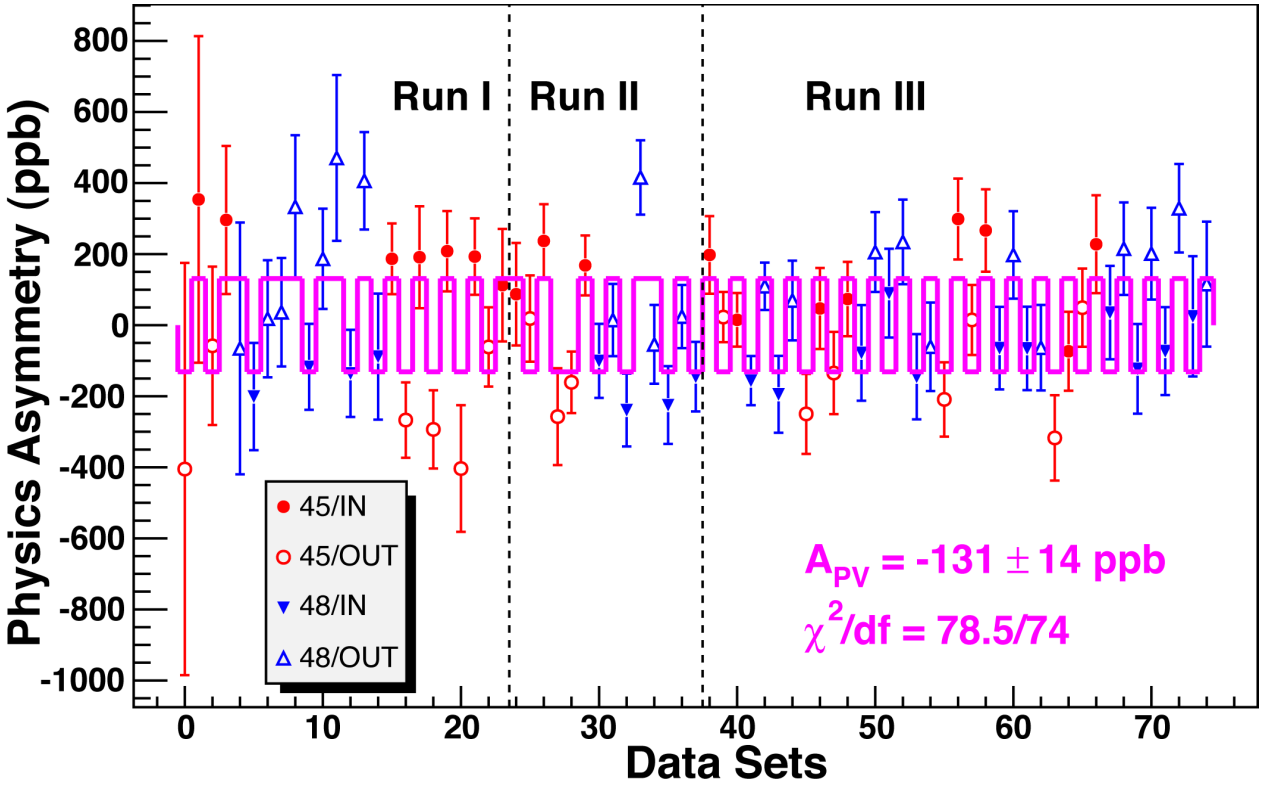


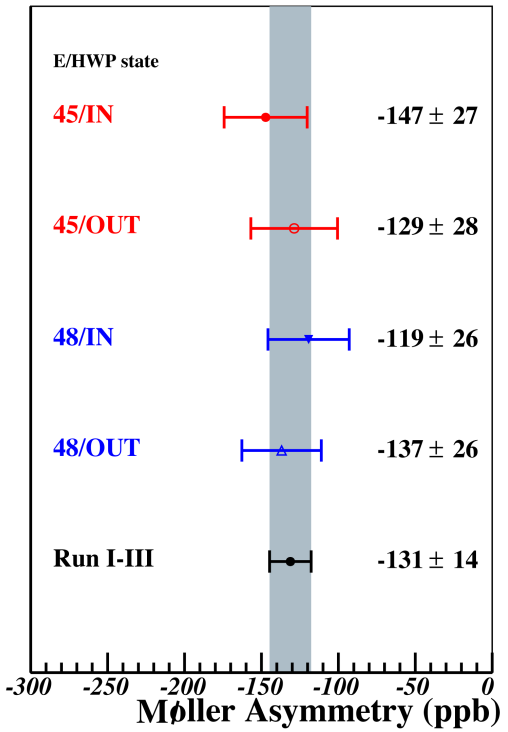
arXiv:1203.1102v1
Buckley and Ramsey-Musolf

SLAC E158: Tiny PV Asymmetry

Phys. Rev. Lett. **95,** 081601 (2005)

$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

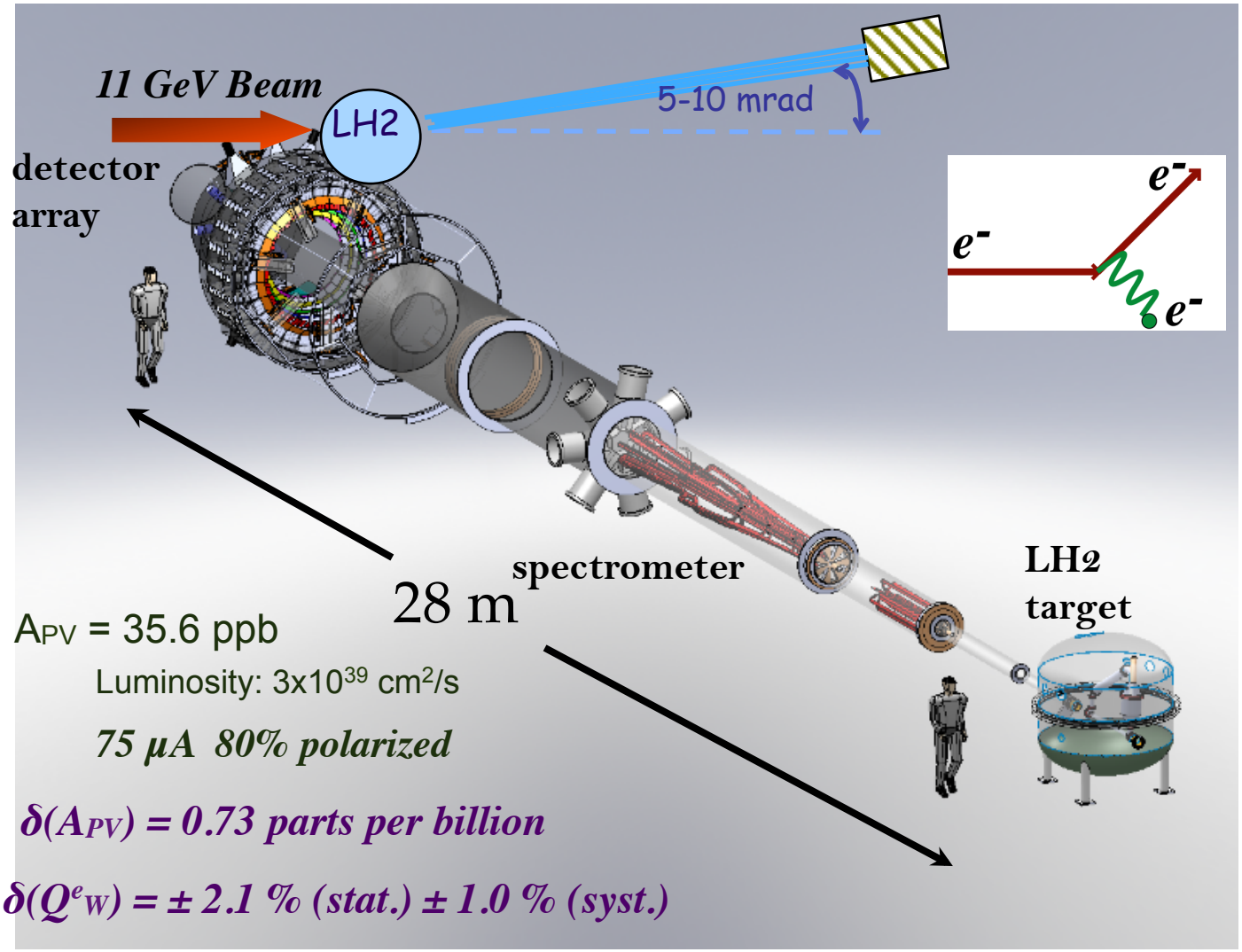




MOLLER at JLab

Measurement Of Electron Electron Electroweak Reaction

11 GeV Møller scattering



Goal for MOLLER

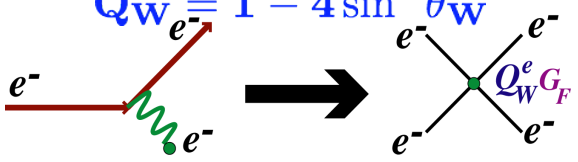
$\delta(\sin^2\theta_W) = \pm 0.00026\ (stat.) \pm 0.00012\ (syst.)$ ⇨ $\sim 0.1\%$

Matches best collider (Z-pole) measurements!

best contact interaction reach for leptons at low OR high energy

To do better for a 4-lepton contact interaction would require:
Giga-Z factory, linear collider, neutrino factory or muon collider

$$Q_W = 1 - 4\sin^2\theta_W$$



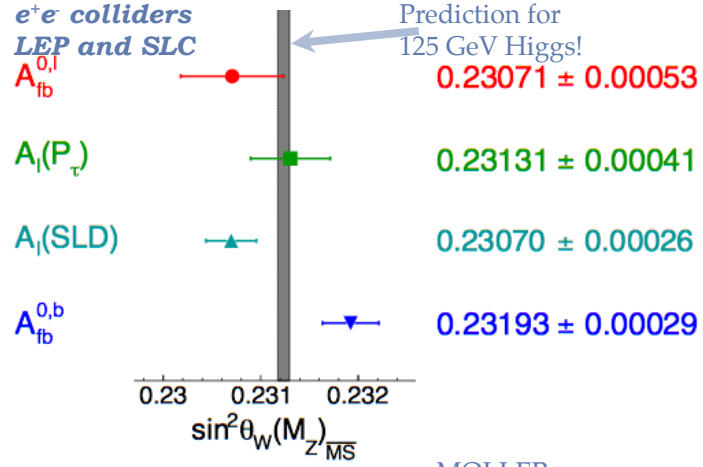
$$+ \quad \frac{1}{\Lambda^2}\mathcal{L}_6$$

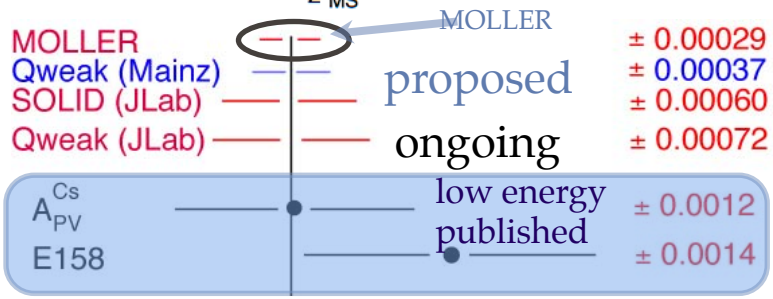
$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i \bar{e}_j\gamma^\mu e_j$$

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5\ \text{TeV}$$

Physics Examples: Beyond LHC

Z resonance measurements: little sensitivity to new contact interactions

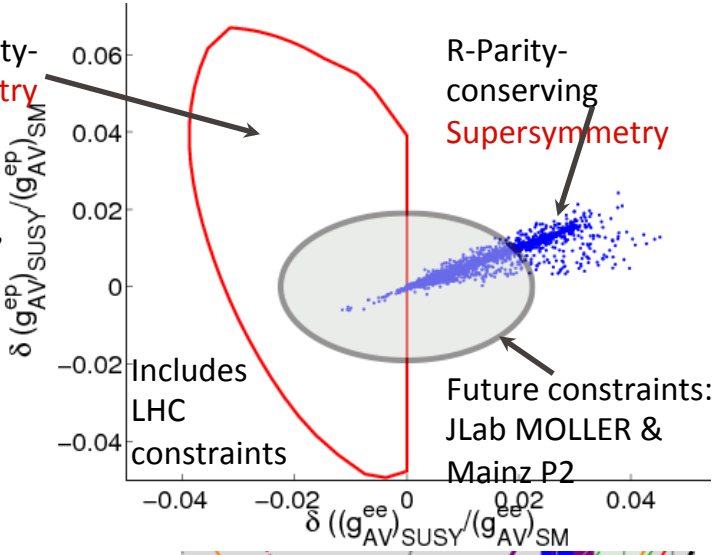




Allowed region: R-Parity-violating Supersymmetry

Ramsey-Musolf and Su, Phys. Rep. 456 (2008)

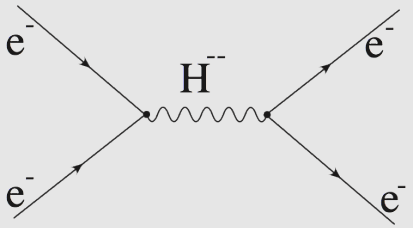
Erler and Su, arXiv:1303.5522



Lepton Number Violation

Λ > 5 TeV

Doubly-Charged Scalars



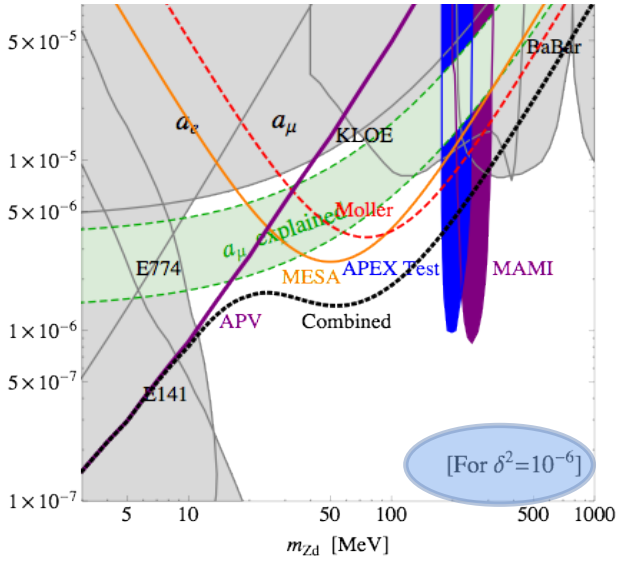
Significant reach beyond LEP-200

Dark Photons: Beyond kinetic mixing; introduce mass mixing with the Z^0

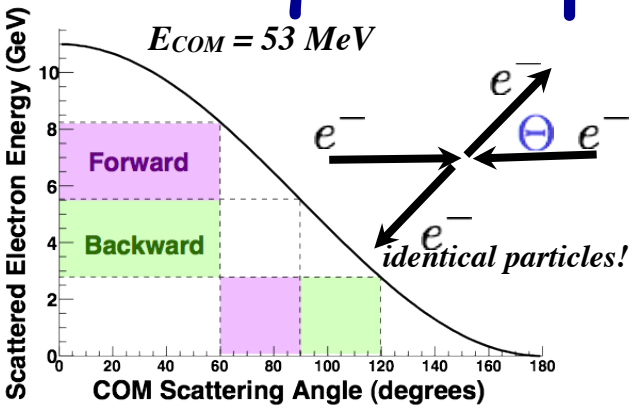
Davoudiasl, Lee, Marciano

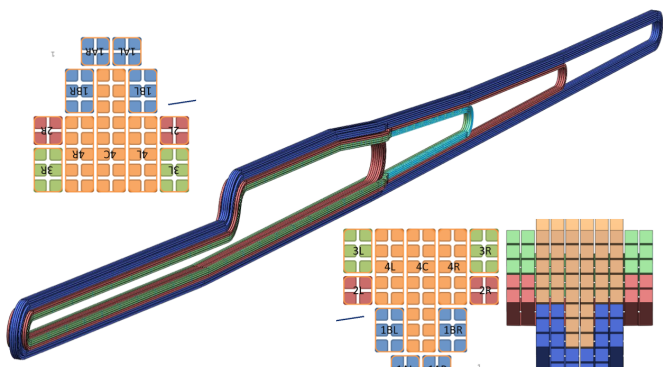
arXiv:1203.2947v2

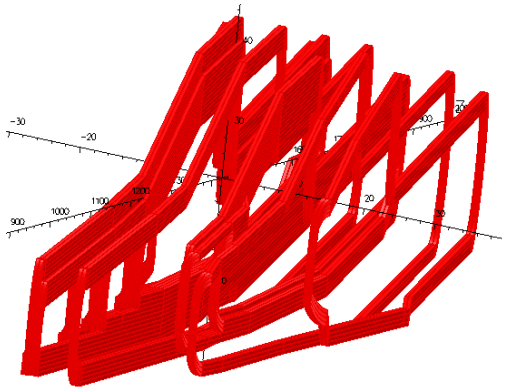
$$\epsilon_Z = \frac{m_{Z_d}}{M_Z}\delta$$



Unique Spectrometer Concept

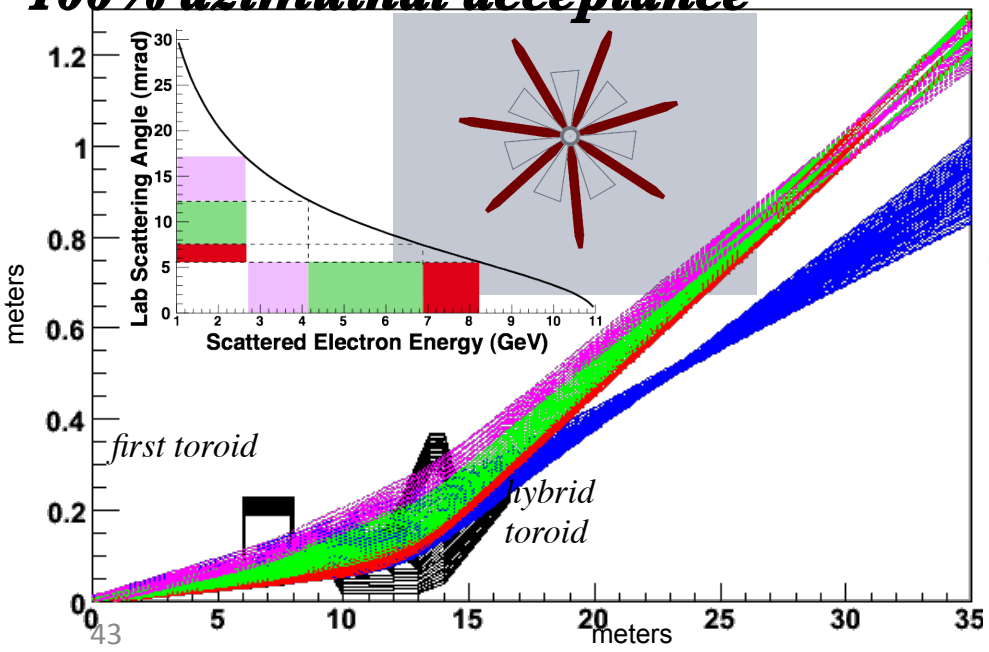




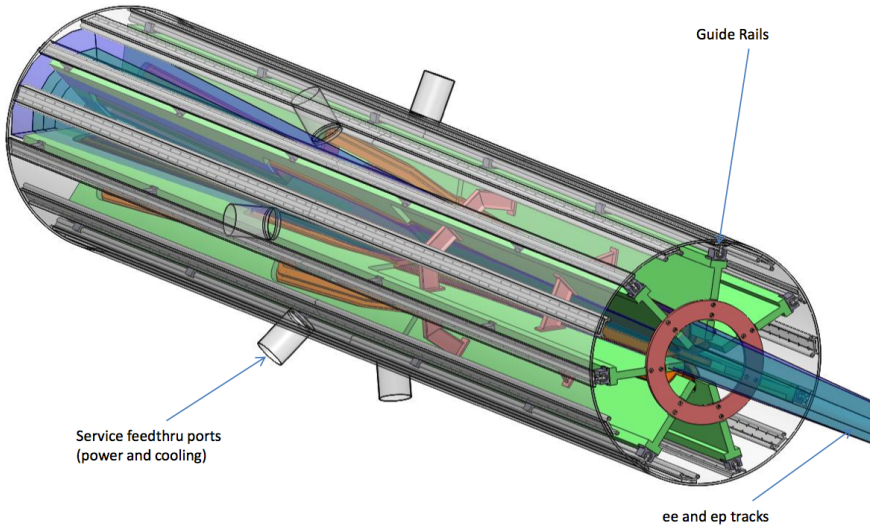


odd number of coils:

100% azimuthal acceptance



conceptual engineering design:
MIT-Bates, UMass, Manitoba



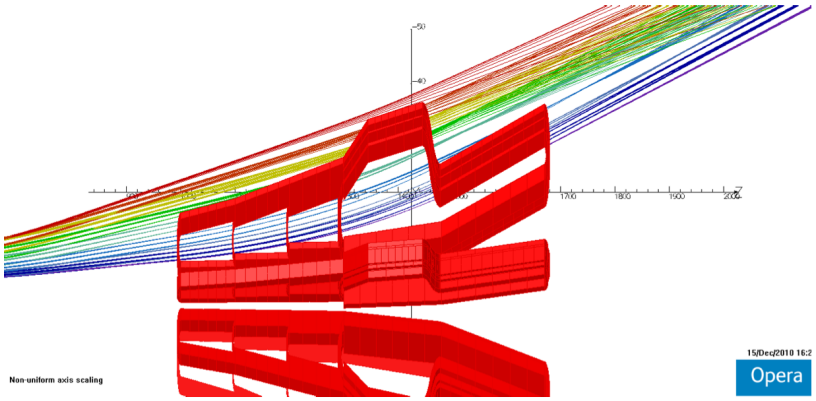
MOLLER Status

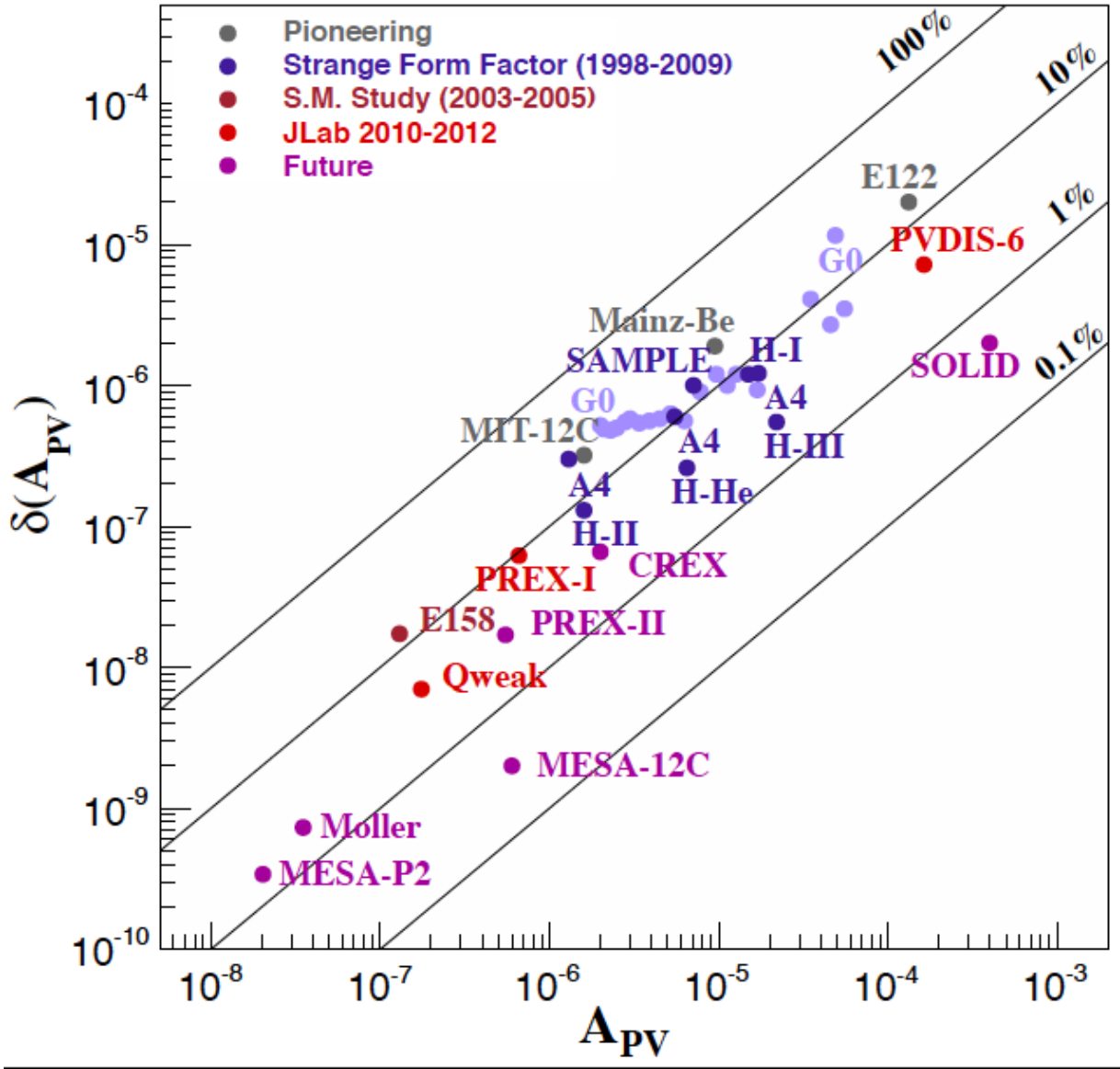
Director's Review chaired by C. Prescott: strong, positive endorsement

Technical Challenges

- **~ 150 GHz scattered electron rate**
  - Design to flip Pockels cell ~ 2 kHz
  - 80 ppm pulse-to-pulse statistical fluctuations
- **1 nm control of beam centroid on target**
  - Improved methods of "slow helicity reversal"
- **> 10 gm/cm^2 liquid hydrogen target**
  - 1.5 m: ~ 5 kW @ 85 μA
- **Full Azimuthal acceptance with θ_{lab} ~ 5 mrad**
  - novel two-toroid spectrometer
  - radiation hard, highly segmented integrating detectors
- **Robust and Redundant 04% beam polarimetry**
  - Pursue both Compton and Atomic Hydrogen techniques

- **MOLLER Collaboration**
  - ~ 100 authors, ~ 30 institutions
  - Expertise from SAMPLE A4, HAPPEX, G0, PREX, Qweak, E158
  - 4th generation JLab parity experiment



- **20M$ proposal to DoE NP**
- **3-4 years construction**
- **2-3 years running**

Summary of PVES Experiments