Parity Violating Electron Scattering: Recent Results and Future Prospects

(Expanded version of CIPANP06 Plenary Talk)

Krishna Kumar

University of Massachusetts, Amherst

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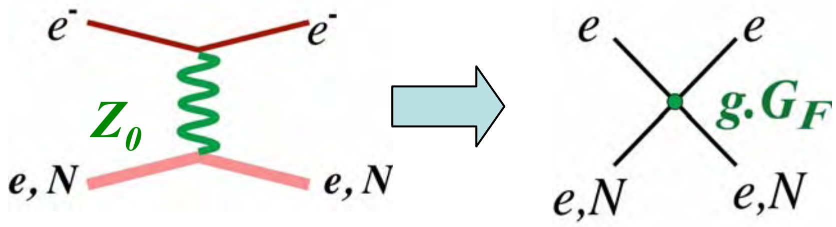
Jefferson Lab Users Meeting

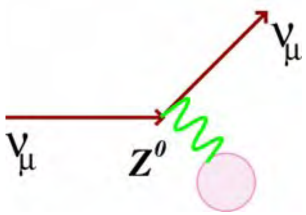
Weak Neutral Current (WNC) Interactions

Low energy WNC interactions ($Q^2 << M_Z^2$)



Historical Context:

- 1960s: An Electroweak Model of Leptons (and quarks)
  - **$SU(2)_L$ X $U(1)_Y$ gauge theory predicted the Z boson**
- 1973: antineutrino-electron scattering
  - **First weak neutral current observation**



- **Gargamelle observes one ν_μ e^- event**
- **First measurement of weak mixing angle**

- Mid-70s: Does the Weak Neutral Current interfere with the Electromagnetic Current?
  - **Central to establishing $SU(2)_L$ X $U(1)_Y$**

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad \begin{pmatrix}E^\circ\\ e\end{pmatrix}_r$$

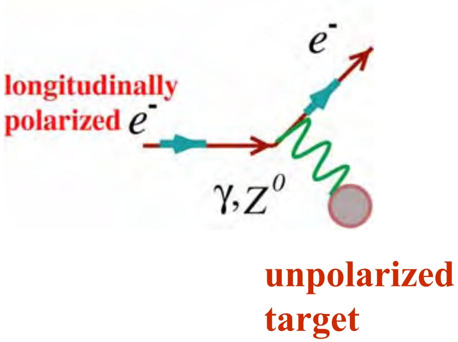
Parity is conserved

Consider fixed target electron scattering

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad (e)_r$$

Parity is violated

Parity-Violating (PV) Electron Scattering



$$\sigma \;\alpha\; |A_\gamma + A_{weak}|^2 \sim |A_{EM}|^2 + 2A_{EM}A^*_{weak} + \ldots$$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} g$$

$$g = g_A^e g_V^T + \beta\, g_V^e g_A^T$$

$$A_{PV} \sim 10^{-5} \cdot Q^2 \quad \text{to} \quad 10^{-4} \cdot Q^2$$

- g_V and g_A are function of $\sin^2\theta_W$
- β is a kinematic factor
- Q^2 is the 4-momentum transfer
- g^T affected by QCD physics

C.Y. Prescott et. al, 1978

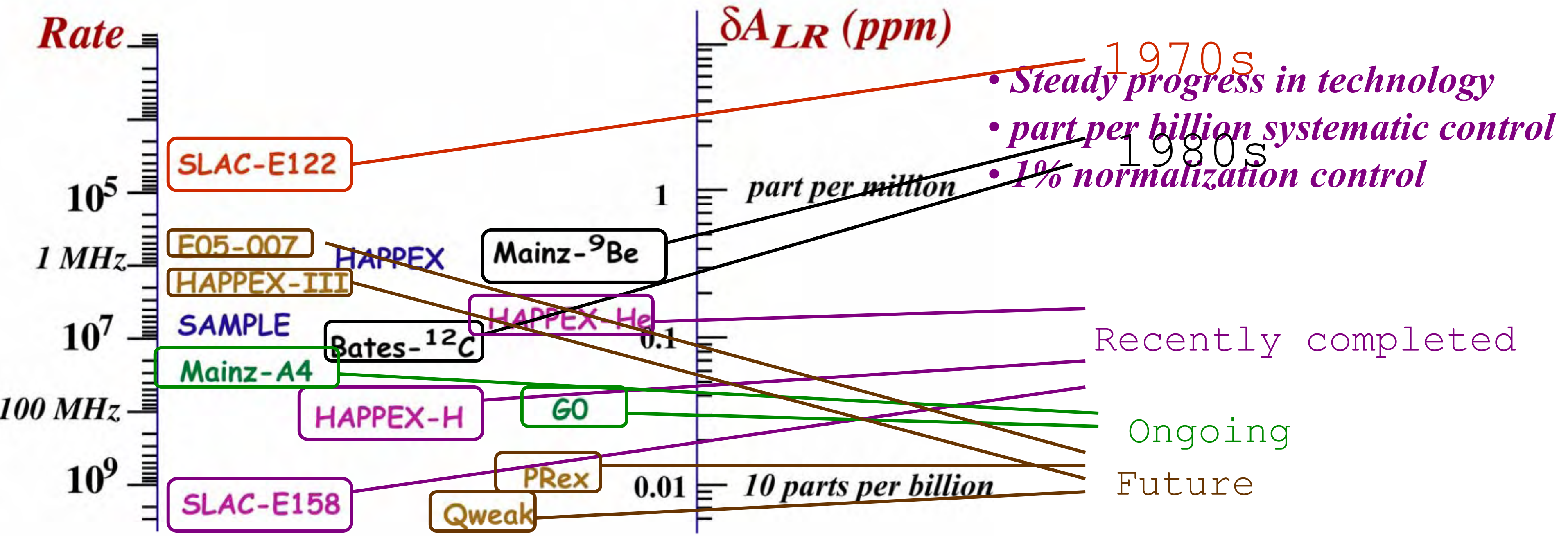
A_{PV} in Deep Inelastic Scattering off liquid Deuterium: $Q^2 \sim 1$ (GeV)^2

E122 at the Stanford Linear Accelerator Center (SLAC)

20 GeV polarized electron beam on a 30 cm LD_2 target

- Established experimental technique: $\delta(A_{PV}) < 10$ ppm
- Cleanly observed weak-electromagnetic interference
- Parity Violation in Weak Neutral Current Interactions
- $\sin^2\theta_W = 0.224 \pm 0.020$: same as in neutrino scattering

2006: MeV to TeV Physics



Parity-violating electron scattering has become a precision tool

Combined with judicious choices of kinematics and targets:

- ***Many-Body Nuclear Physics***
- ***Nucleon Structure Physics***
- ***Valence Quark Physics***
- ***Search for New TeV Physics***

Address fundamental physics issues over a range of energy scales

Outline

- **Strangeness in Nucleons**
  - New Results from HAPPEX at Jefferson Lab
  - Status and Plans for further measurements
- **The Neutron Skin of a Heavy Spinless Nucleus**
  - A planned measurement of elastic WNC amplitude off ^{208}Pb
- **Low Energy Weak Mixing Angle Measurements**
  - Final Result from the E158 Experiment at SLAC
  - Possible New Measurements at Jefferson Lab and an LC
- **PV Deep Inelastic Scattering at JLab at 11 GeV**
  - Potential of precision studies of nucleon structure at high x
- **Summary**

Nucleon Structure & Strangeness

QCD is intractable at low Q^2; what is its relationship to hadron structure?

Why don't sea quarks destroy Quark Model predictions?

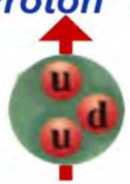
Strange quarks are relatively light;
What can we say about its role?

spin dependent deep inelastic scattering

$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L$$

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

Proton Spin



Experiments:
$\Delta\Sigma \sim 0.25$

+ *Hyperon decay*
+ *$SU(3)_f$ Symmetry:*

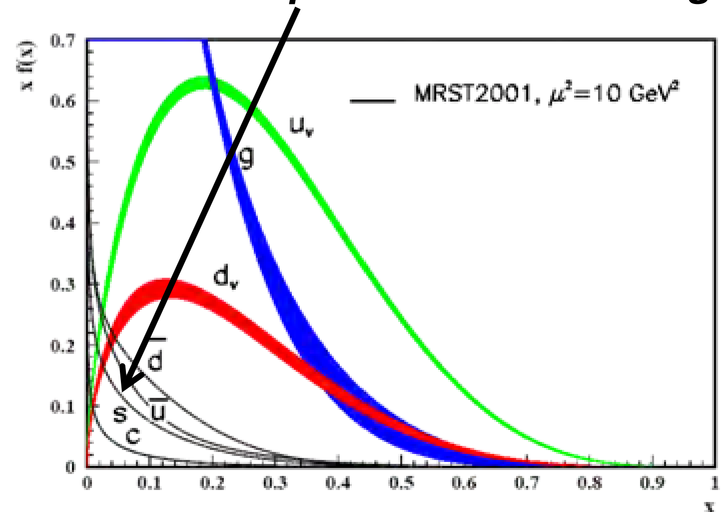
$\Delta s \sim -0.1$

$SU(3)_f$ symmetry-breaking introduces uncertainties

Semi-inclusive DIS (HERMES)
(Needs fragmentation functions)

$$"\Delta s" = \int_{0.023}^{0.30} \Delta s(x)\,dx = +0.03 \pm 0.03(\text{stat}) \pm 0.01(\text{syst})$$

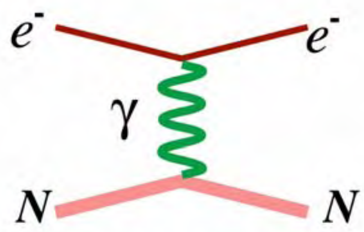
Neutrino deep inelastic scattering



πN scattering:
Strange mass: 0-20%

What about the nucleon's charge and magnetization distributions?

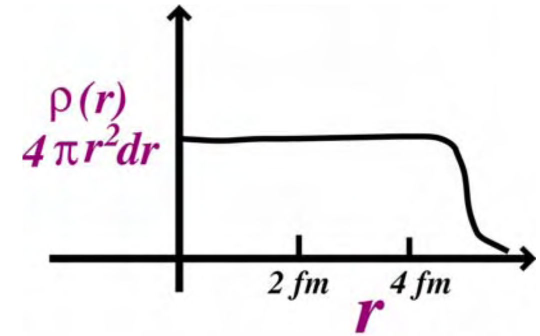
Elastic Electron Scattering 101



QED: precise predictions

Measure σ as a function of Q^2

Neglecting recoil and spin: Obtain Fourier transform of charge distribution



Nuclear charge distribution

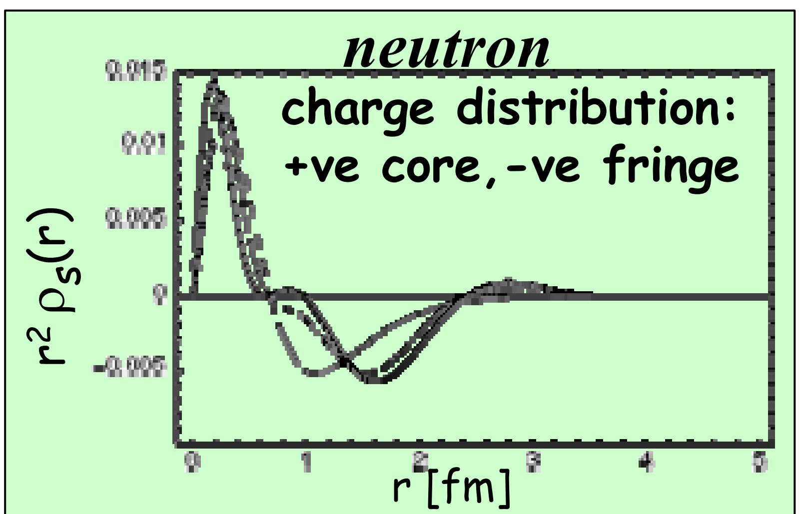
Nucleon charge and magnetization distributions:

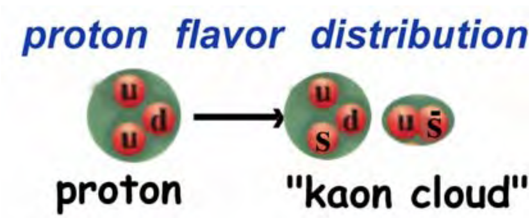
$G_E(Q^2)$, $G_M(Q^2)$

electric and magnetic form factors

$G_E^p(0) = 1$ $\qquad$ $G_M^p(0) = +2.79 \equiv \mu_p$

$G_E^n(0) = 0$ $\qquad$ $G_M^n(0) = -1.91 \equiv \mu_n$

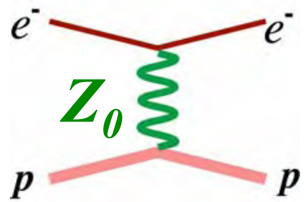




Is this a valid picture?

Need flavor-separation of G_E, G_M

Elastic Electroweak Scattering



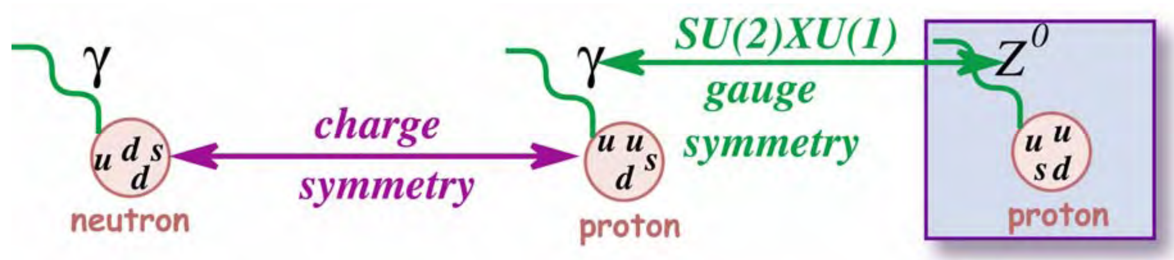
A_{PV} for elastic e-p scattering:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$

$$A_E = \varepsilon G_E^p G_E^Z, \quad A_M = \tau G_M^p G_M^Z, \quad A_A = -\left(1 - 4\sin^2\theta_W\right)\varepsilon' G_M^p G_A^e$$

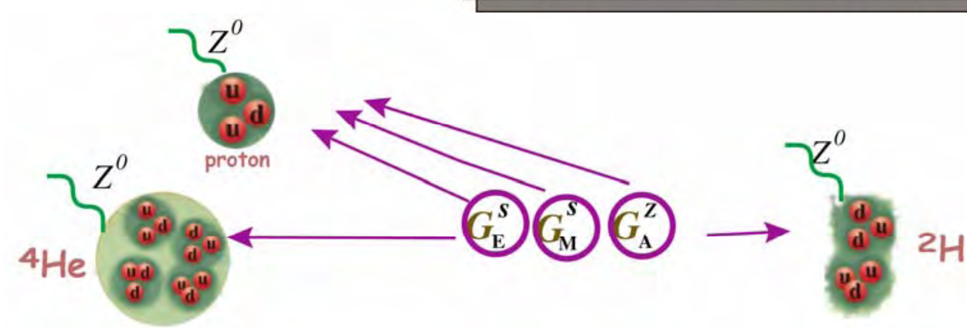
Forward angle — Backward angle

Kaplan & Manohar (1988)
McKeown (1989)



$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

$\Rightarrow$ $G_E^s(Q^2)$, $G_M^s(Q^2)$



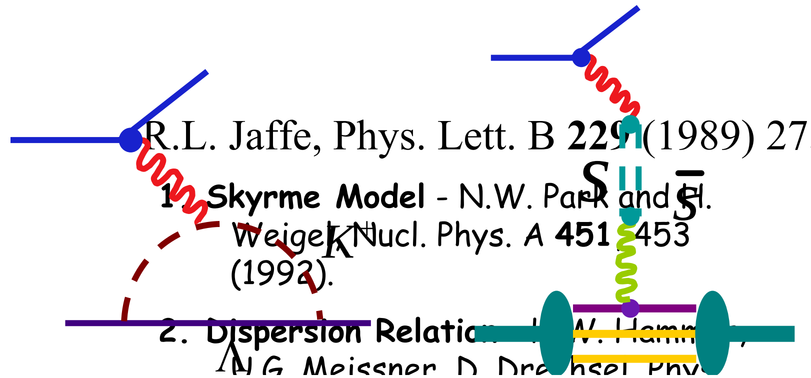
Helium: Unique G_E sensitivity
Deuterium: Enhanced G_A sensitivity

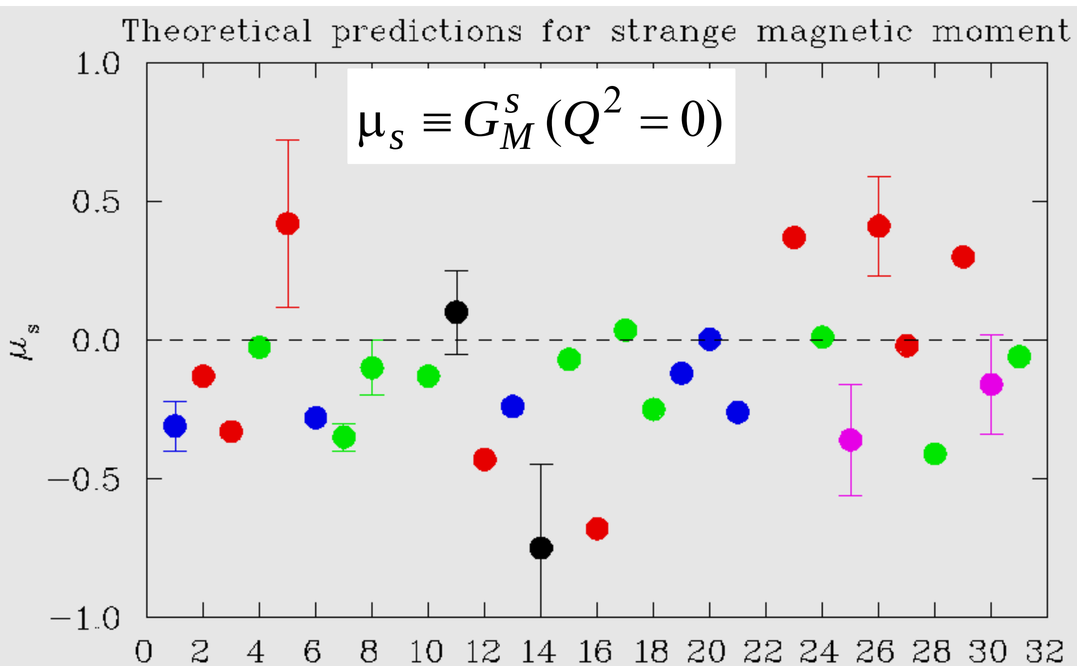
How Big Are G_E^s, G_M^s?

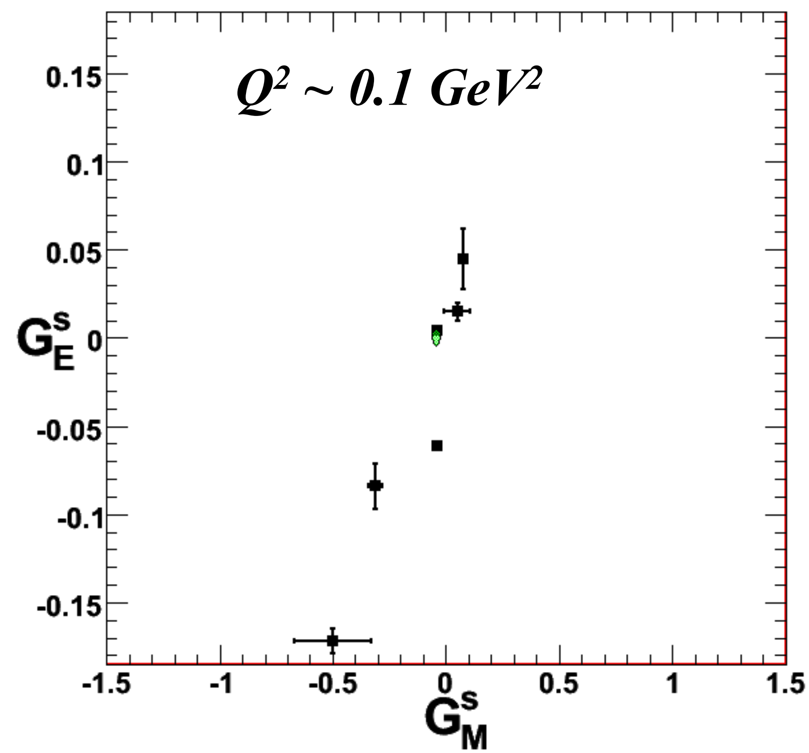
Experimental determination of non-zero G^s is unambiguous

Various theoretical estimates:

- *Vector Meson Dominance Models*
- *Quark models*
- *Dispersion Theory*
- *Lattice Gauge theory*
- *Chiral-Quark Soliton Model*

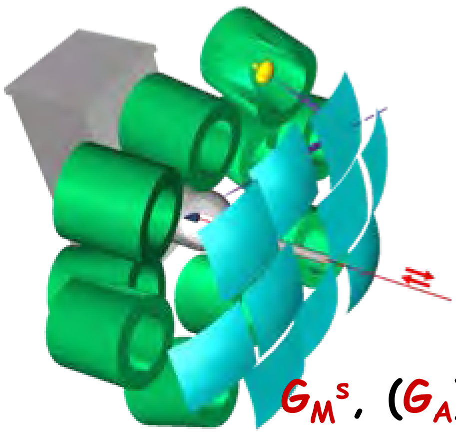






Little theoretical guidance on Q^2 dependence

Overview of Experiments

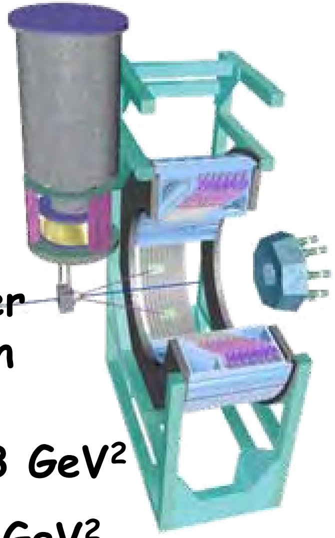


SAMPLE

open geometry, integrating

G_M^s, (G_A) at Q^2 = 0.1 GeV^2

A4



Open geometry

Fast counting calorimeter for background rejection

G_E^s + 0.23 G_M^s at Q^2 = 0.23 GeV^2

G_E^s + 0.10 G_M^s at Q^2 = 0.1 GeV^2

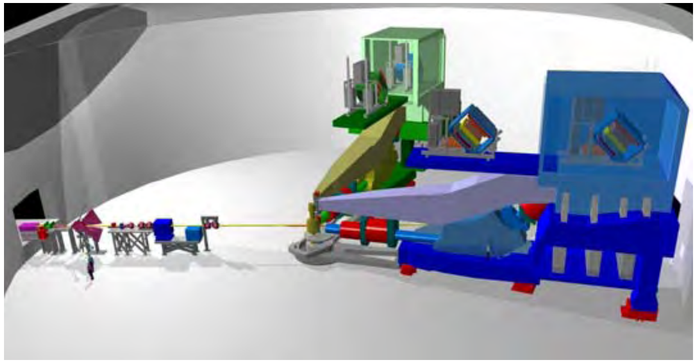
G_M^s, G_A^e at Q^2 = 0.1, 0.23, 0.5 GeV^2

HAPPEX

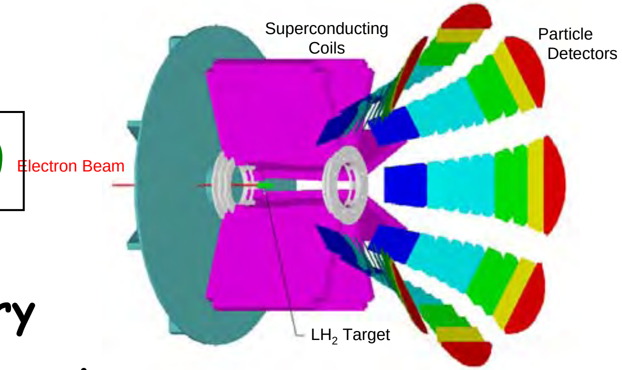
G_E^s + 0.39 G_M^s at Q^2 = 0.48 GeV^2

G_E^s + 0.08 G_M^s at Q^2 = 0.1 GeV^2

G_E^s at Q^2 = 0.1 GeV^2 (^{4}He)



G0



Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

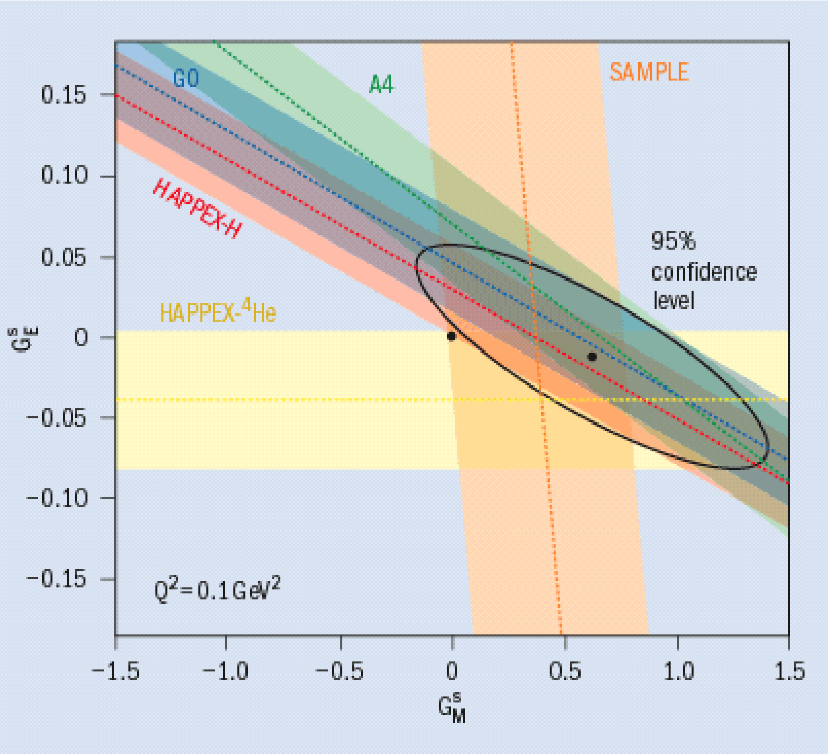
G_E^s + η G_M^s over Q^2 = [0.12,1.0] GeV^2

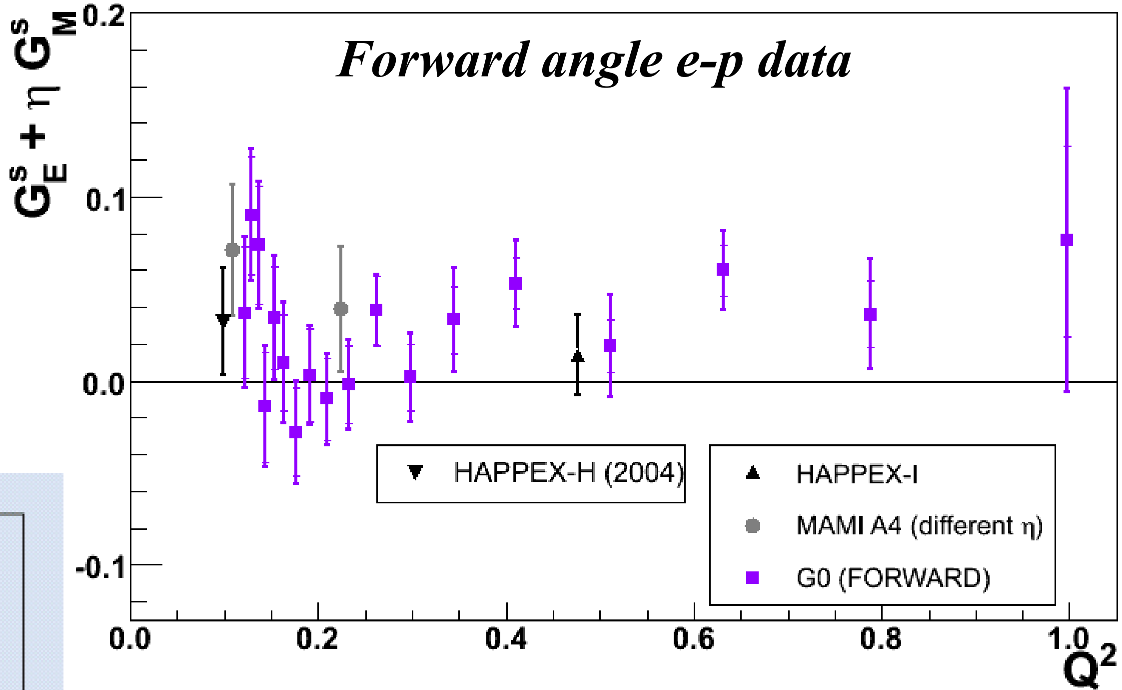
G_M^s, G_A^e at Q^2 = 0.23, 0.62 GeV^2

Status as of 2005

Over the past three years:
New data from A4, G0 and HAPPEX

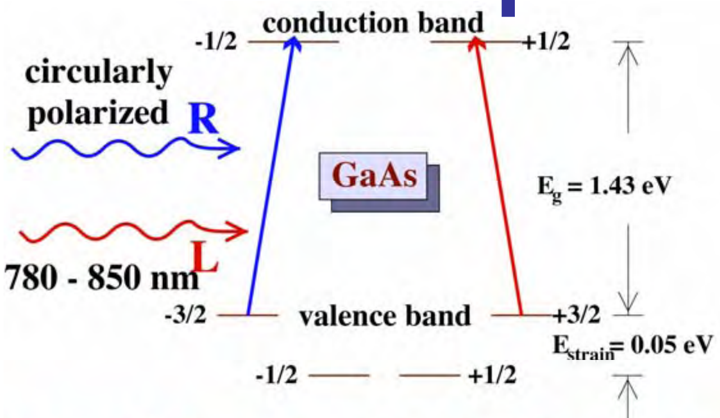
$Q^2 \sim 0.1\ GeV^2$



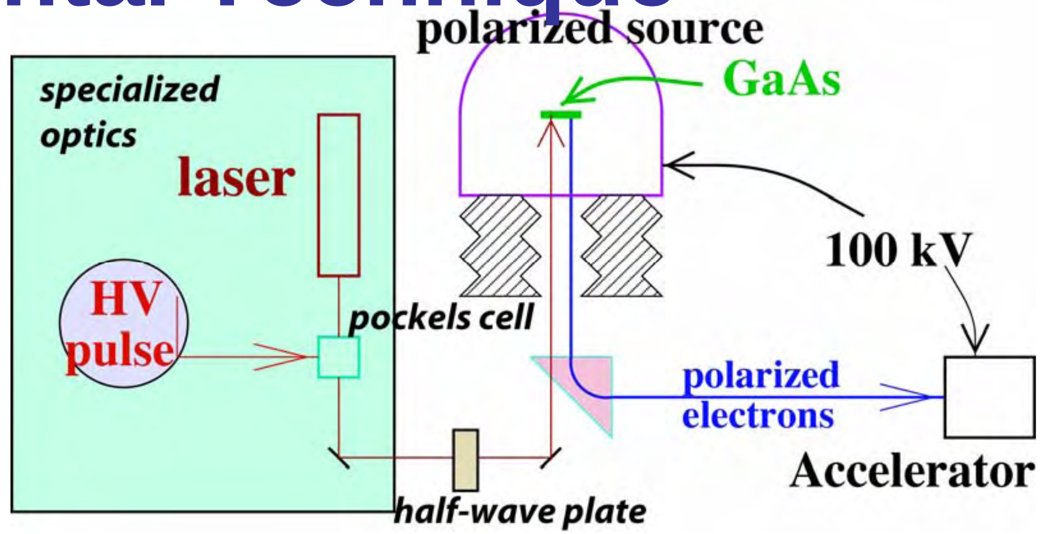


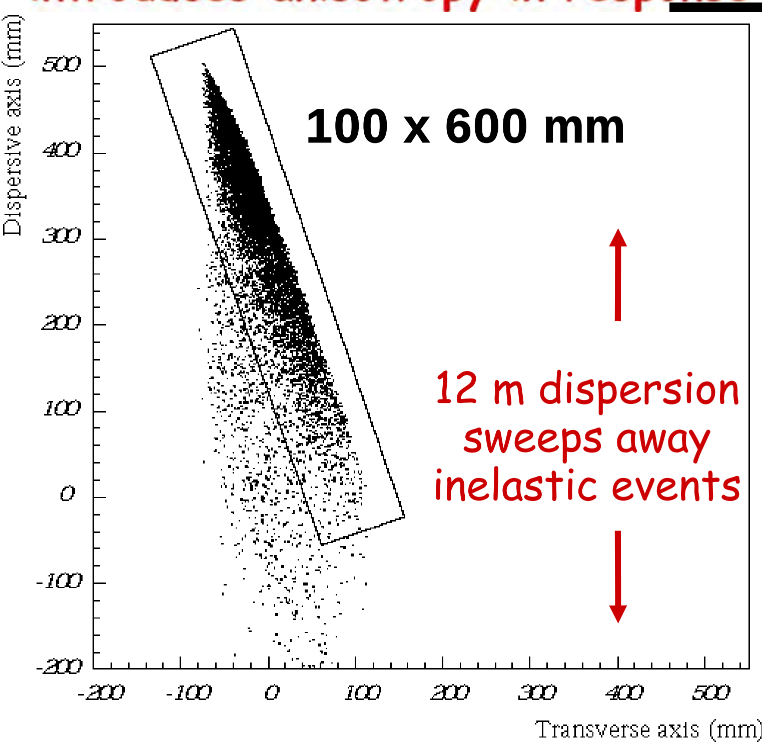
- ***Add SAMPLE & HAPPEX-He***
- ***Multiple constraints at $Q^2 \sim 0.1\ GeV^2$***
- ***Would imply 5-10% contribution to magnetic moment from strange quarks*** *(50-100% of isoscalar magnetic moment)*

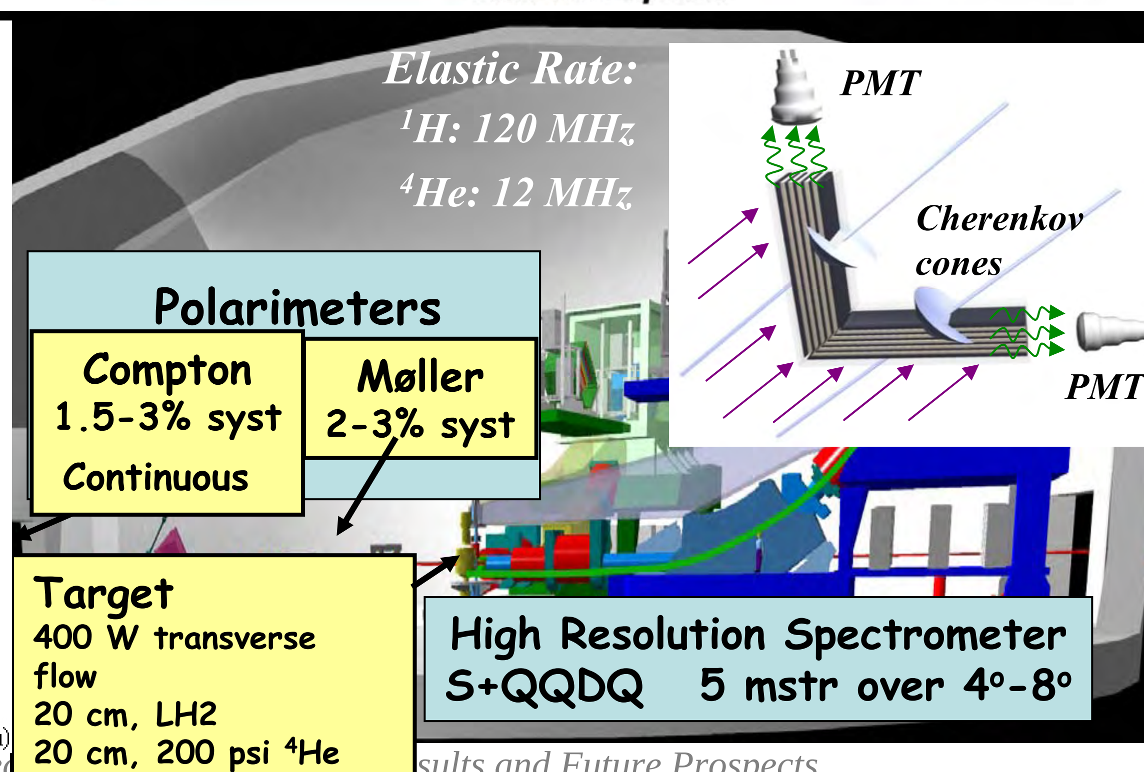
Experimental Technique



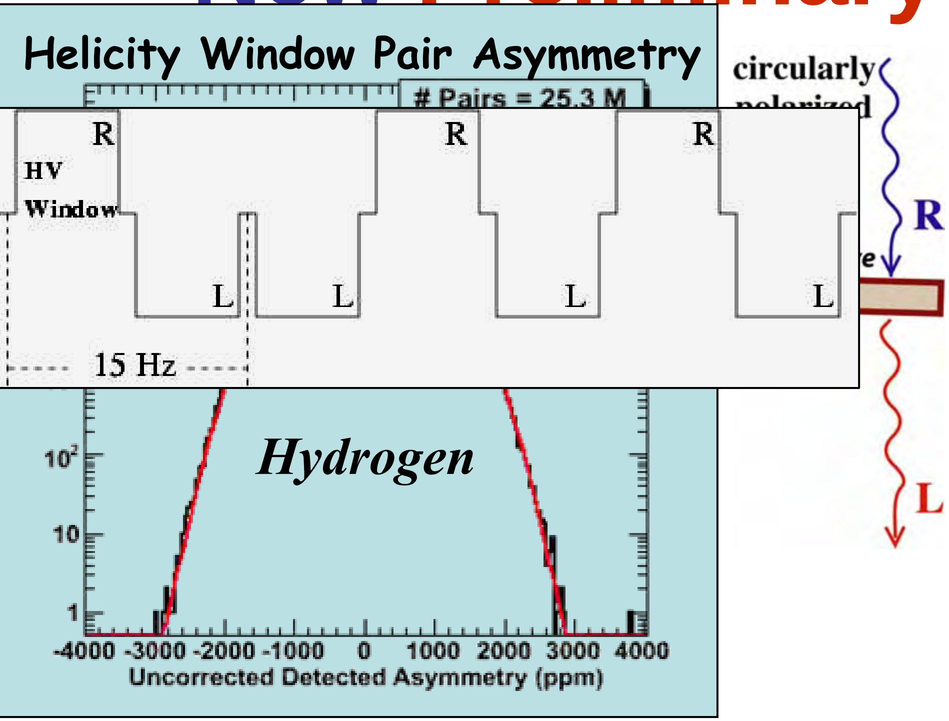
"strain" boosts polarization, but introduces anisotropy in response

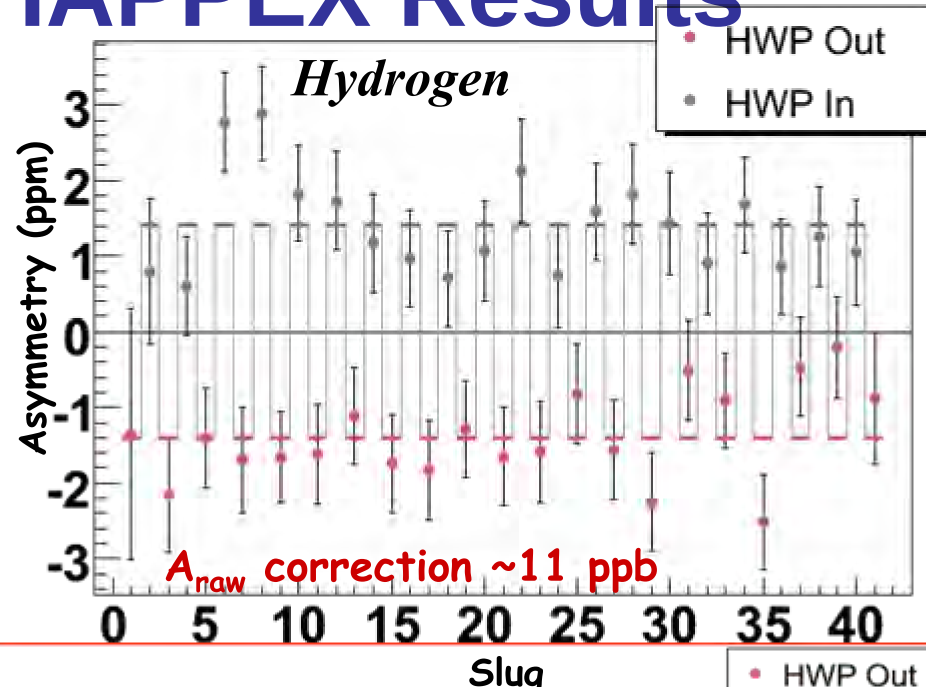


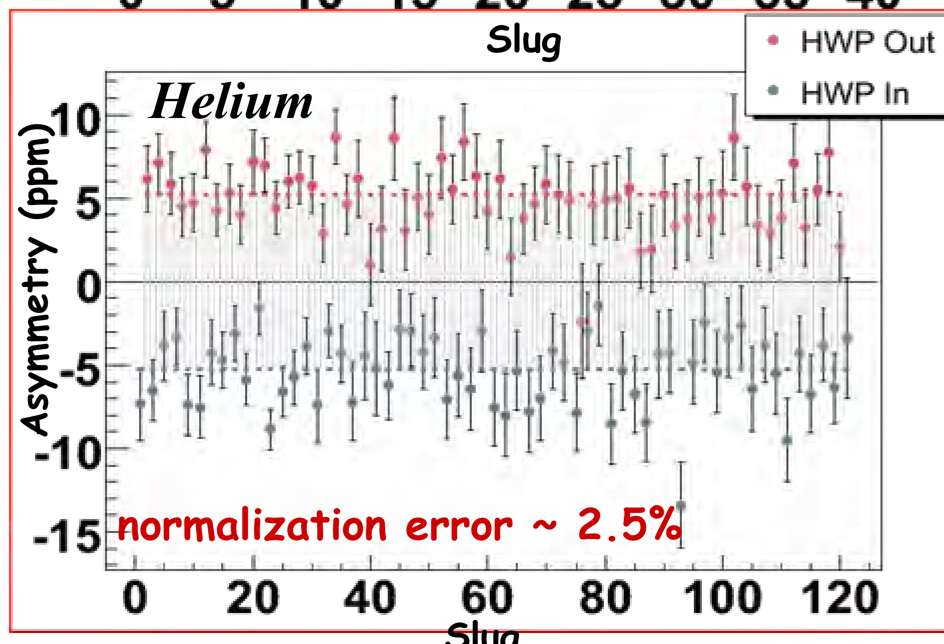




New Preliminary HAPPEX Results







Hydrogen

Systematic control ~ 10^{-8}

A_{PV} = -1.60 ± 0.12 (stat) ± 0.05 (syst) ppm

$A(G^s=0)$ = -1.640 ppm ± 0.041 ppm

Helium

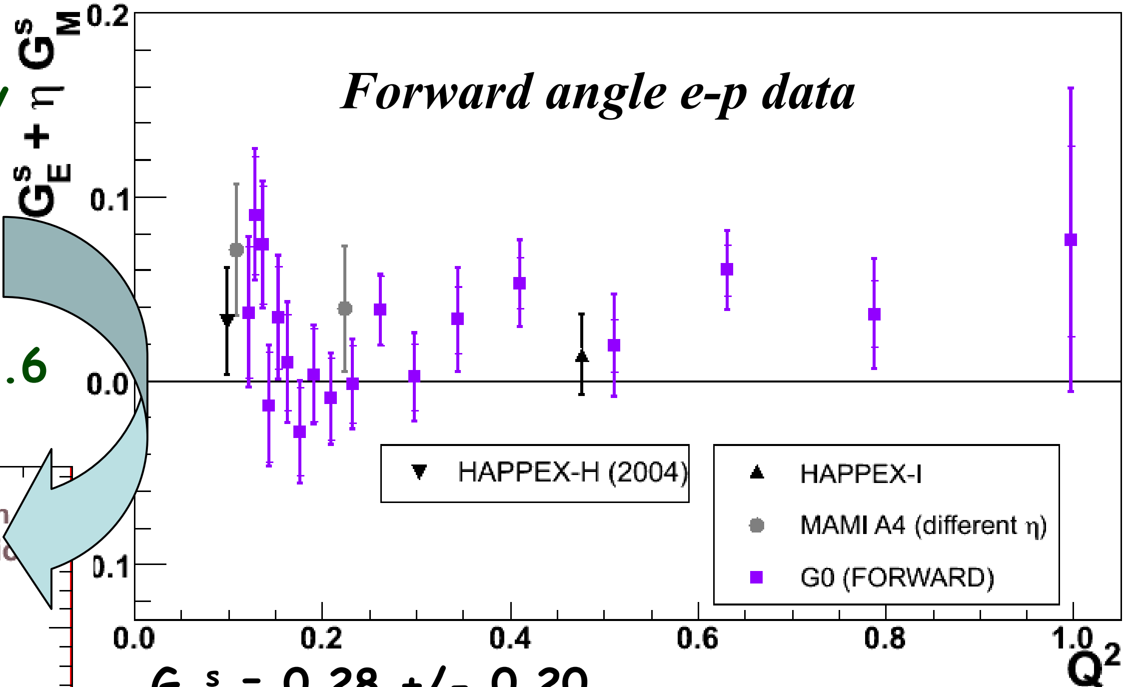
Normalization control ~ 2%

A_{PV} = +6.43 ± 0.23 (stat) ± 0.22 (syst) ppm

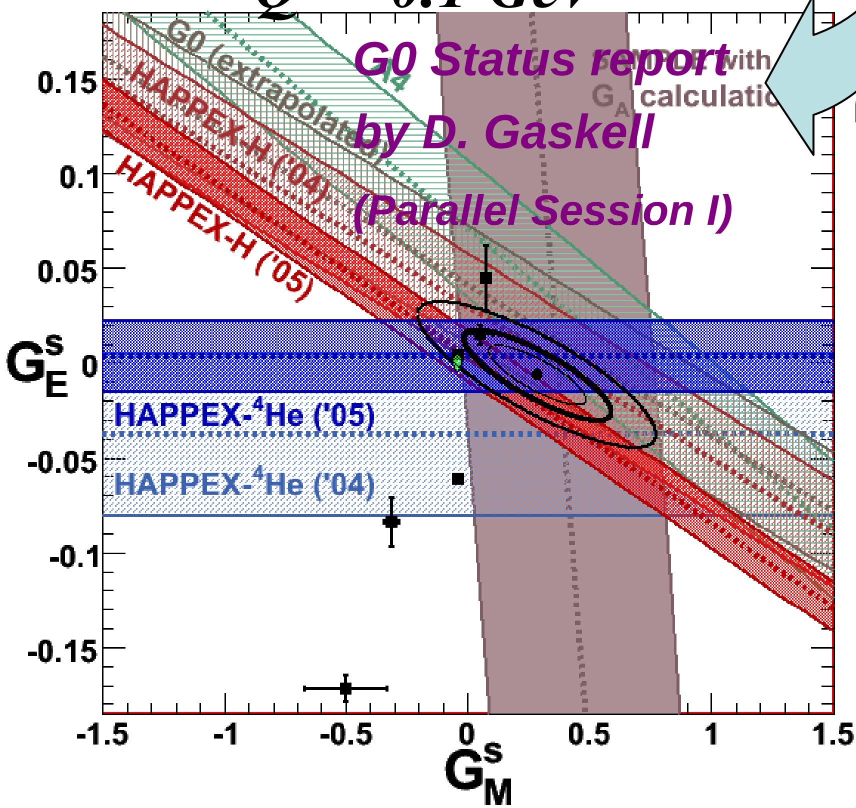
$A(G^s=0)$ = +6.37 ppm

Implications and Outlook

- Rapid variation at low Q^2 unlikely
- Await backward angle measurements from A4, G0
- Deuterium running will provide constraints on G_A
- One high precision point at $Q^2 \sim 0.6$



$Q^2 \sim 0.1$ GeV^2



G0 Status report by D. Gaskell (Parallel Session I)

$G_M^s = 0.28 \pm 0.20$

$G_E^s = -0.006 \pm 0.016$

~3% ± 2.3% of proton magnetic moment

(<20% of isoscalar magnetic moment)

~0.2 ± 0.5% of electric distribution

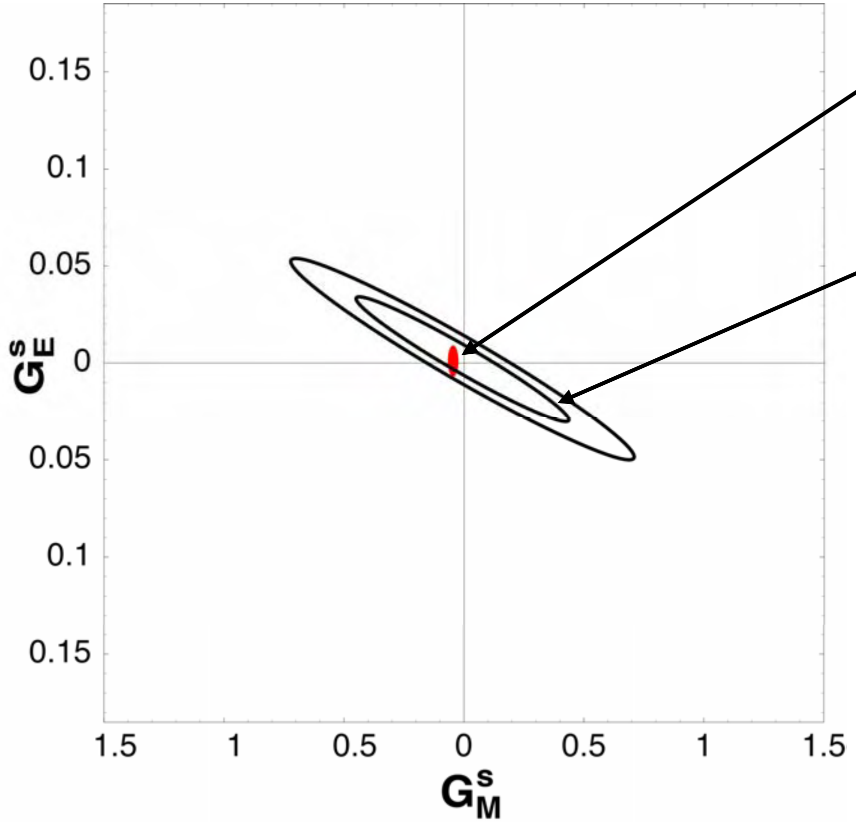
HAPPEX-only fit suggests something even smaller:

$G_M^s = 0.12 \pm 0.24$

$G_E^s = -0.002 \pm 0.017$

- *Approved program well-matched to ultimate sensitivity of the technique*
- *Models dealing with "sea" properties are extremely challenging*
- *Experimentally, a 20-year old quest nearing completion*
- *Ultimate insight: unquenched Lattice QCD calculations with light chiral quarks*

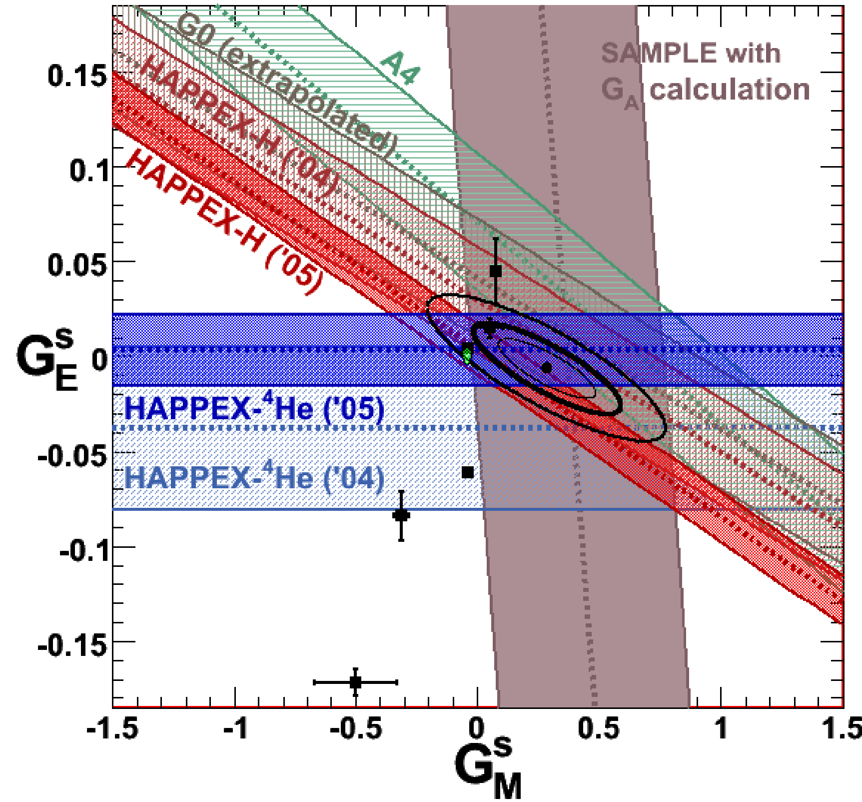
An Alternate Fit to Data $Q^2 \sim 0.1\ GeV^2$



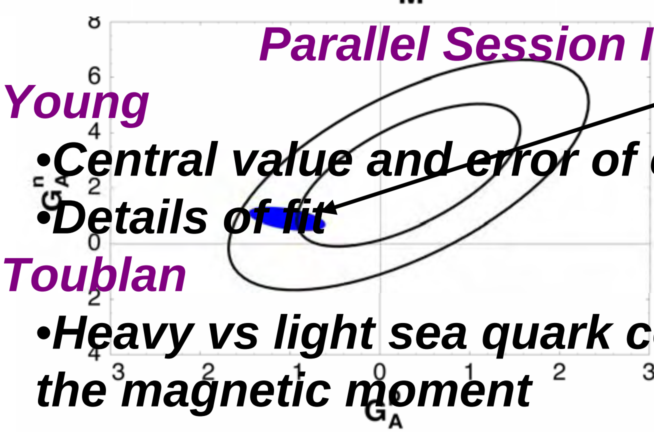
Leinweber et al, Phys. Rev. Lett. **94**, 212001 (2005) & hep-lat/0601025

Young et al, nucl-ex/0604010

- *Fit to all proton data up to $Q^2 \sim 0.3\ GeV^2$*
- *Specific choices of Q^2 dependence*
- *Similtaneously fit axial form factor*



Parallel Session I



Zhu et. al.

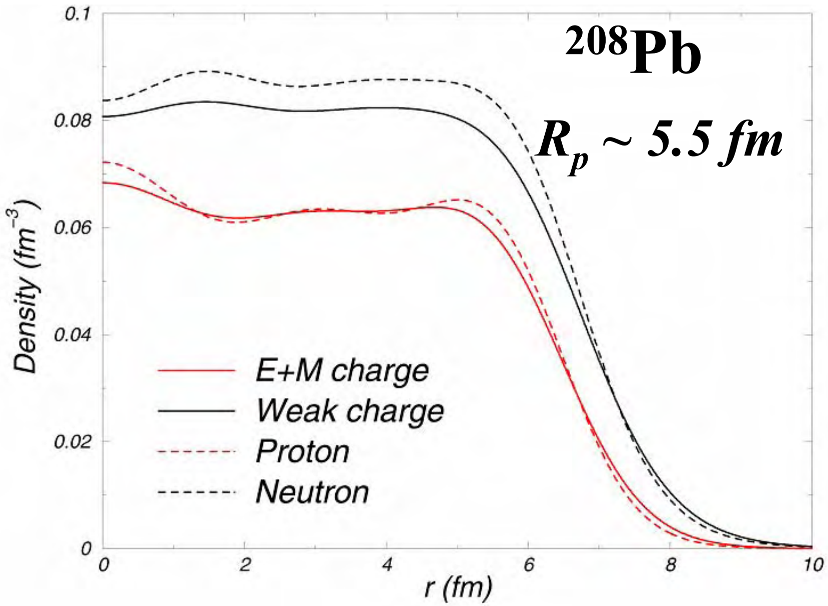
R. Young

- *Central value and error of calculation*
- *Details of fit*

D. Toublan

- *Heavy vs light sea quark contribution to the magnetic moment*

Probing Neutron-Rich Matter



•The proton distribution of heavy nucleus: mapped via electron scattering

•The neutron distribution:

- *•probed with hadrons*
- *•highly model-dependent*
- *•neutron "skin" ~ 0.1 - 0.3 fm?*

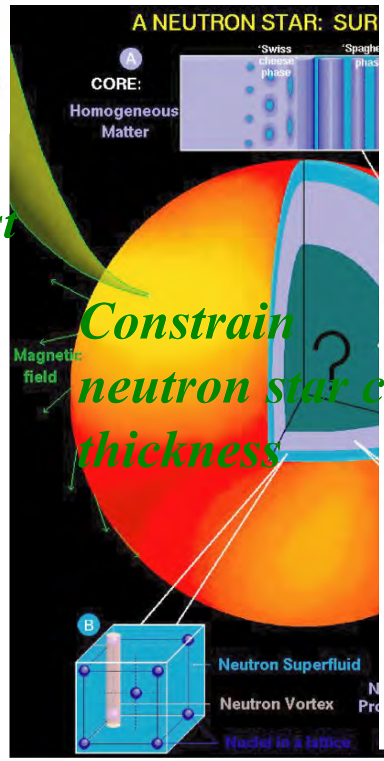
•Neutron density a fundamental observable:

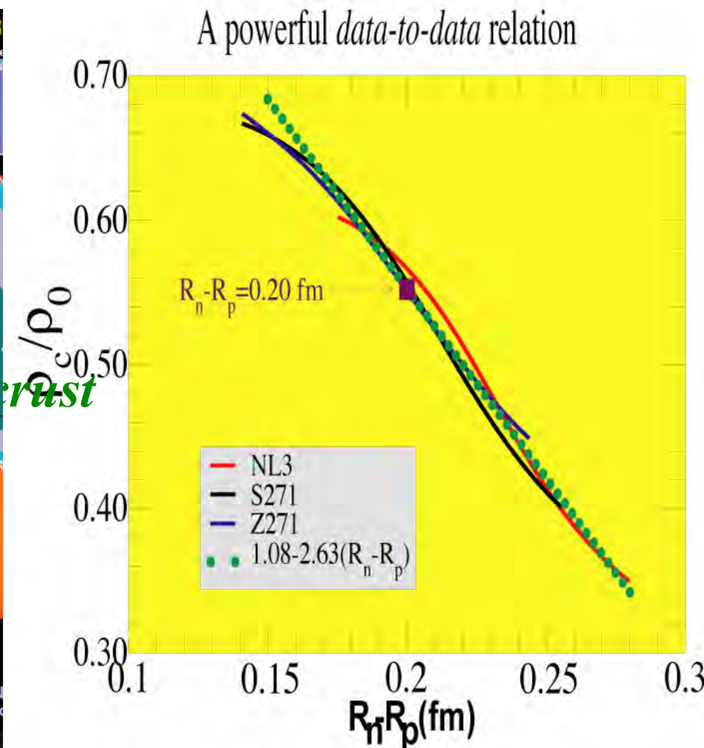
- *•Impacts a variety of physics*

•^{208}Pb neutron skin and neutron star crust made of similar material

• At what radius does transition from liquid to non-uniform matter take place?

•Mean Field theory predicts correlation between neutron star transition density and ^{208}Pb neutron skin





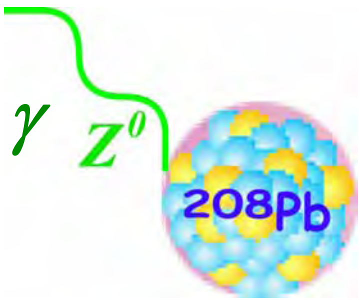
PREx at Jefferson Lab

$\delta(A_{PV}) \sim 3\%$ → $\delta(R_p\text{-}R_n) \sim 1\%$

$Q^2 \sim 0.01\ GeV^2$ → $A_{PV} \sim 0.5$ ppm

$Q^p_{EM} \sim 1$ $\quad Q^n_{EM} \sim 0$

$Q^n_W \sim 1$ $\quad Q^p_W \sim 1 - 4\sin^2\theta_W$

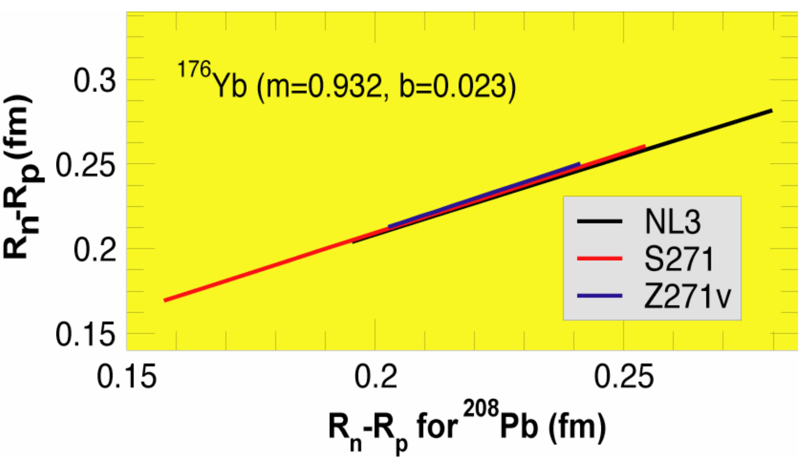


A technically demanding measurement:

- Rate ~ 2 GHz
- Separate excited state at 2.6 MeV
- Stat. Error ~ 15 ppb
- Syst. Error ~ 1 to 2 %

Tentatively scheduled to run in 2008

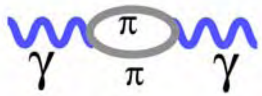
Constrain neutron halo for Atomic Parity Violation Expts

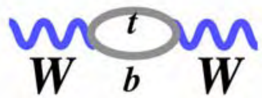


- *Tight control of beam properties*
- *New "warm" septum*
- *High power Lead target*
- *New 18-bit ADC*
- *New radiation-hard detector*
- *Polarimetry upgrade*

Beyond Standard Model @ Low Q^2

α_{QED} G_F





M_Z

σ_Z M_W A_f

- Precise predictions @ 0.1%
- Indirect access to TeV scale

- *World electroweak data has marginal χ^2, but no discernable pattern*
- *Data used to put limits on energy scale of new physics effects*

- *Parity-conserving contact interactions probed at 10-20 TeV level*
- *Parity-violating contact interactions probed at few TeV level*

$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g\, G_F} \longrightarrow \begin{array}{c} \delta(g)/g \sim 0.1 \\ \Lambda \sim 10\ \text{TeV} \end{array}$$

$$\frac{\delta(\sin\theta_W)}{\sin^2\theta_W} \lesssim 0.01$$

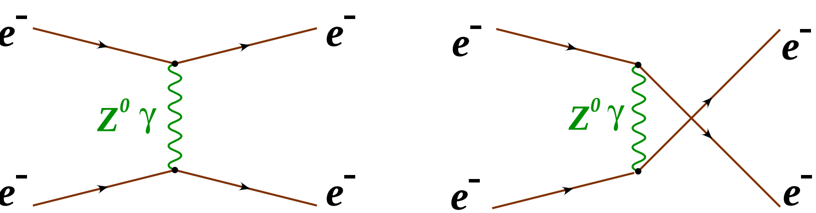
$Q^2 \sim M_Z^2$ on resonance: A_Z imaginary $\longrightarrow A_Z^2\left[1+\frac{A_X^2}{A_Z^2}\right]$

no interference!

The SLAC E158 Experiment

-Violating Left-Right Asymmetry In Fixed Target Møller Scatt

Goal: error small enough to probe TeV scale physics



$$A_{PV} \propto m_e E_{lab} (1 - 4\sin^2 \vartheta_W)$$

$$A_{PV} \approx -4 \times 10^{-9} \times E_{beam} \times P_{beam}$$

E158 Collaboration

- Berkeley
- Caltech
- Jefferson Lab
- Princeton
- Saclay
- SLAC
- Smith
- Syracuse
- UMass
- Virginia

8 Ph.D. Students
60 physicists

2001: Engineering run
2002-2003: Physics runs
2004: First PRL
2005: Final result

End Station A at SLAC

Precision beam monitoring

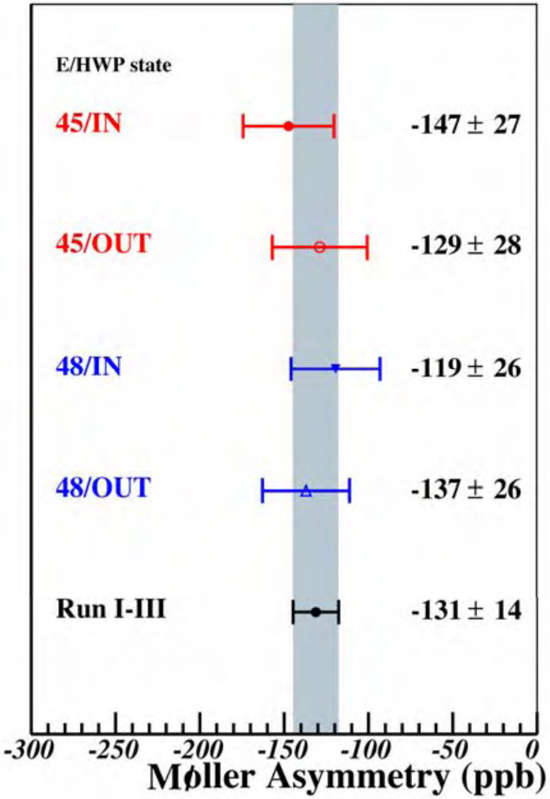
154 cm target
L ~ 10^{38} cm^{-2}s^{-1}

Novel small-angle spectrometer

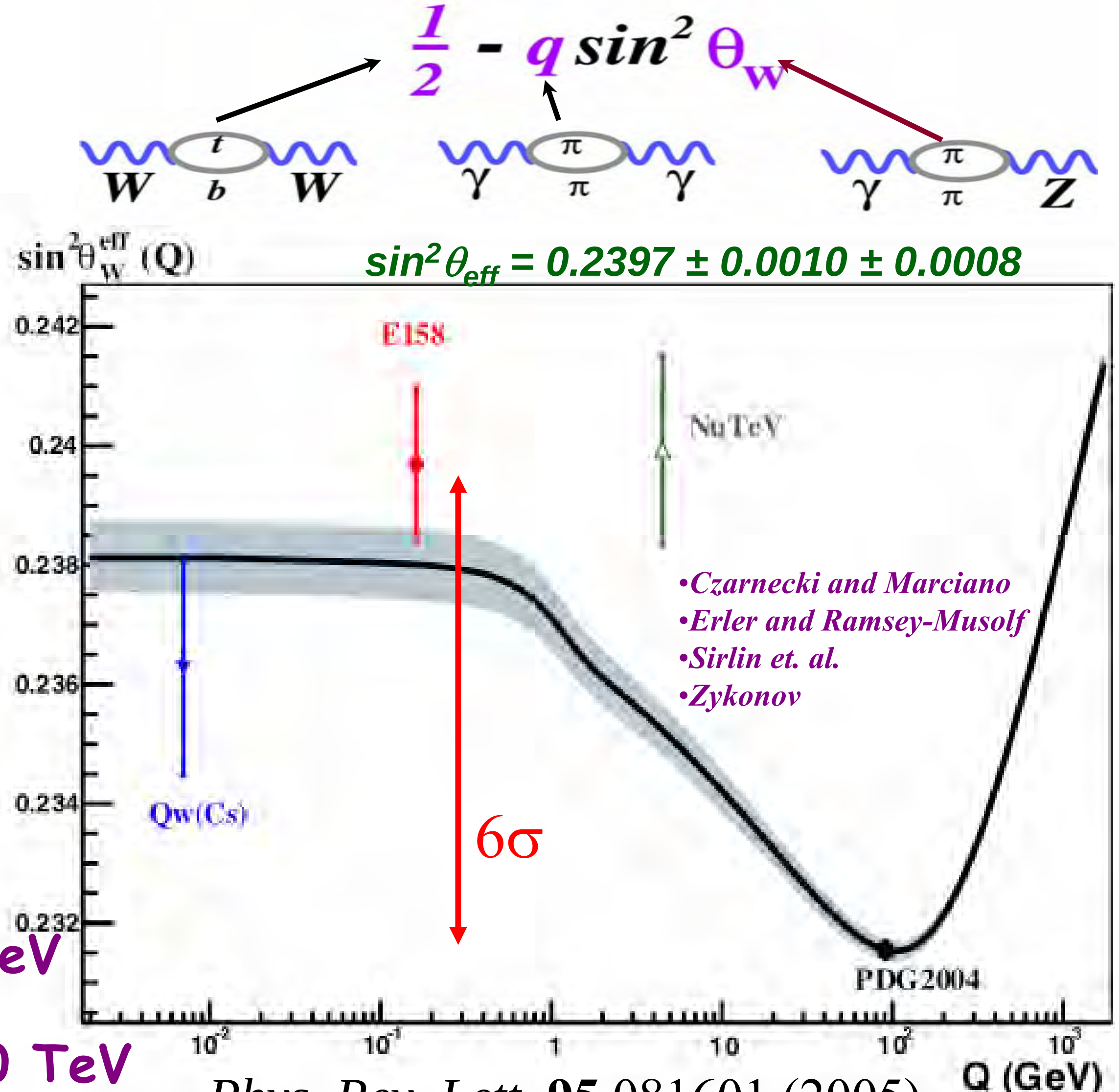
Radiation-hard, ultra-quiet detector

SLAC E158 Main Result

End of the SLAC Fixed Target Program



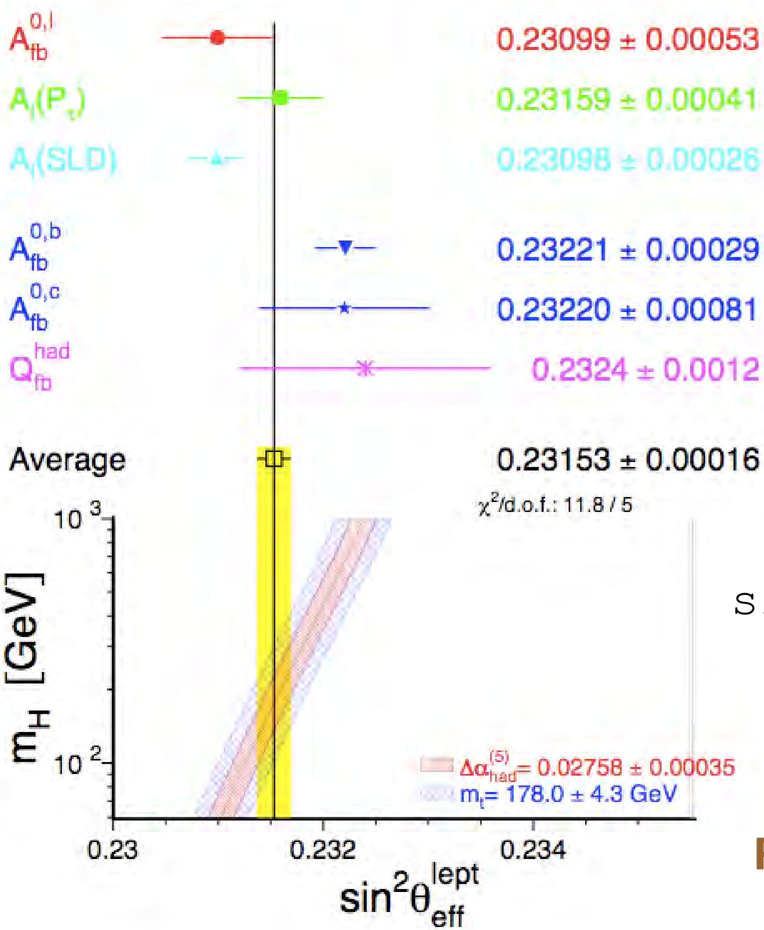
$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$



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

* Limit on Λ_{LL} ~ 7 or 16 TeV
* Limit on SO(10) Z' ~ 1.0 TeV
* Limit on lepton flavor violating coupling ~ $0.01G_F$

Weak Mixing Angle at HIGH Q^2



The Average: $\sin^2\theta_W$ = 0.23122(17)

$\Rightarrow$ m_H = 89 $^{+38}_{-28}$ GeV

$\Rightarrow$ S = −0.13 ± 0.10

3σ apart

Rules out Technicolor!

Favors SUSY!

Marciano, CIPANP06

EW & BSM Session

A_{LR}

(also APV in Cs)

$\sin^2\theta_W$ = 0.2310(3)

↓

m_H = 35 $^{+26}_{-17}$ GeV

S= −0.11 ± 17

Rules out the SM!

A_{FB} (Z→ bb)

(also Moller @ E15

$\sin^2\theta_W$ = 0.2322(3)

↓

m_H = 480 $^{+350}_{-230}$ GeV

S= +0.55 ± 17

Rules out SUSY!

Favors Technicolor

- ***Tevatron & LHC will make some improvements on M_W***
- ***$\sin^2\theta_W$ improvements at hadron colliders very challenging***
- ***Must wait for "Giga-Z" option of ILC or Neutrino Factory***

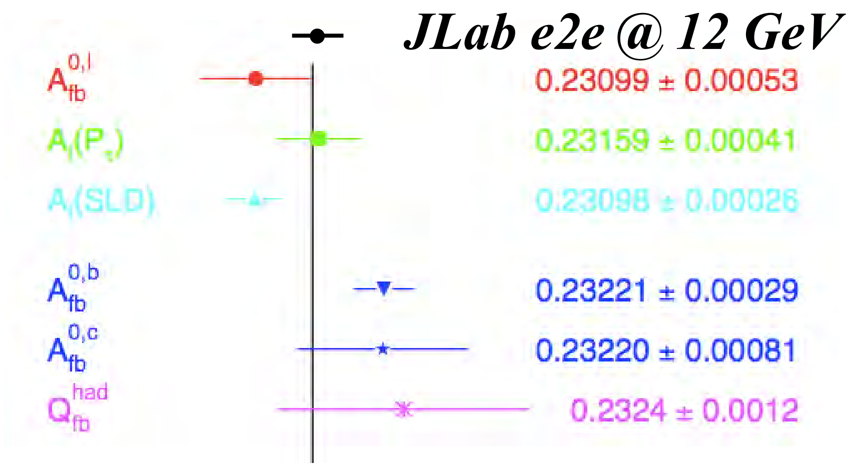
Future Possibilities (Purely Leptonic)

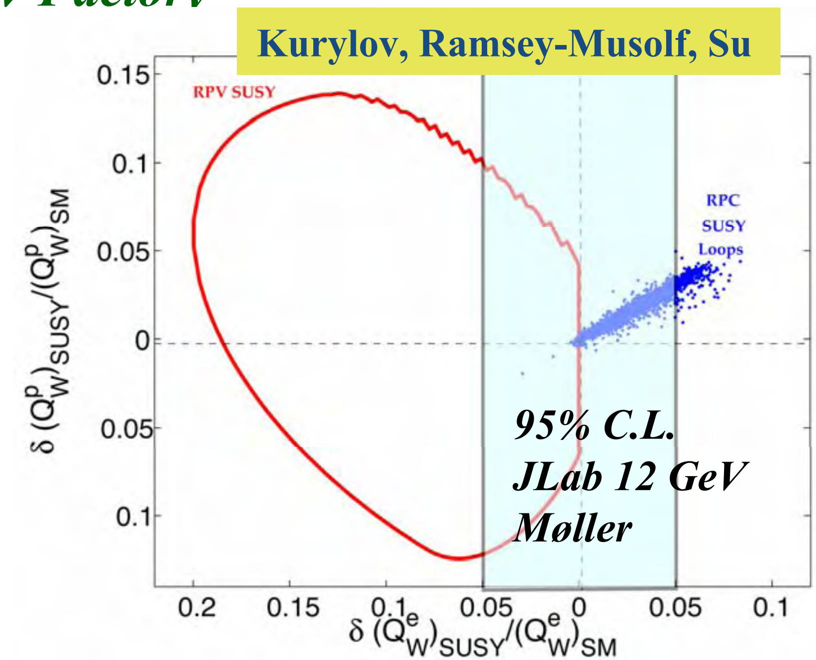
ν-e in reactor *can test neutrino coupling: $\sin^2\theta_W$ to ± 0.002*

Møller at 11 GeV at Jlab

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

- *Comparable to single Z pole measurement: shed light on disagreement*
- *Best low energy measurement until ILC or ν-Factory*
- *Could be launched ~ 2012*



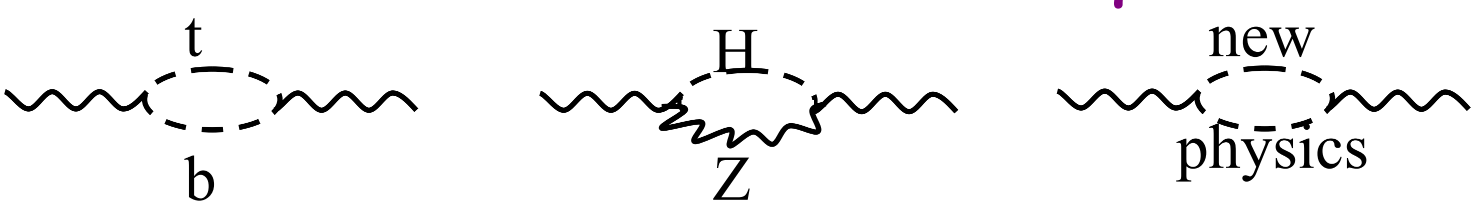


Does Supersymmetry (SUSY) provide a candidate for dark matter?

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

Ultrahigh Precision at ILC

Measure contribution from scalars to oblique corrections



$$\frac{\delta m_H}{m_H} \approx 10\% \text{ for } \delta \sin^2\theta_W \approx 0.00004$$ (world average ~0.00016)

Critical crosscheck

A_{LR} and M_W at future colliders:
Systematics extremely challenging!

Energy scale to 10^{-4}, polarimetry to 0.15%

Møller scattering at the ILC

$$\sigma \propto \frac{1}{E_{lab}}$$ → *Figure of Merit rises linearly with E_{lab}*

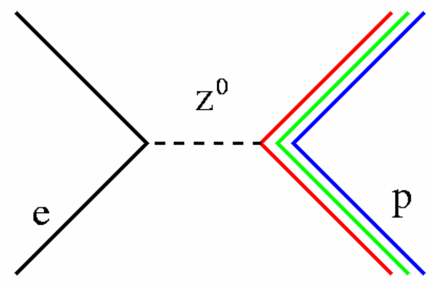
- *Fixed target has advantages for systematics*
- *Could work with ILC "exhaust" beam*

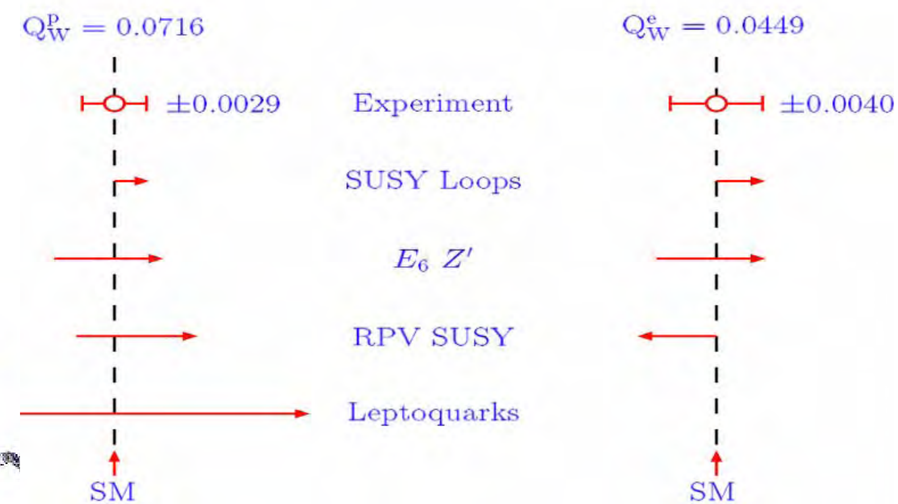
K.K, Snowmass 96	E158	LC
Energy (GeV)	48	250-500
Intensity/pulse	4.5×10^{11}	14×10^{11}
Pulse Rate (Hz)	120	120
P_e	85%	90%
Time (s)	4×10^6	2×10^7
A_{LR} (ppm)	0.15	1-2
δA_{LR} (ppm)	0.015	0.008
$\delta \sin^2(\theta_W)$	0.001	0.00008

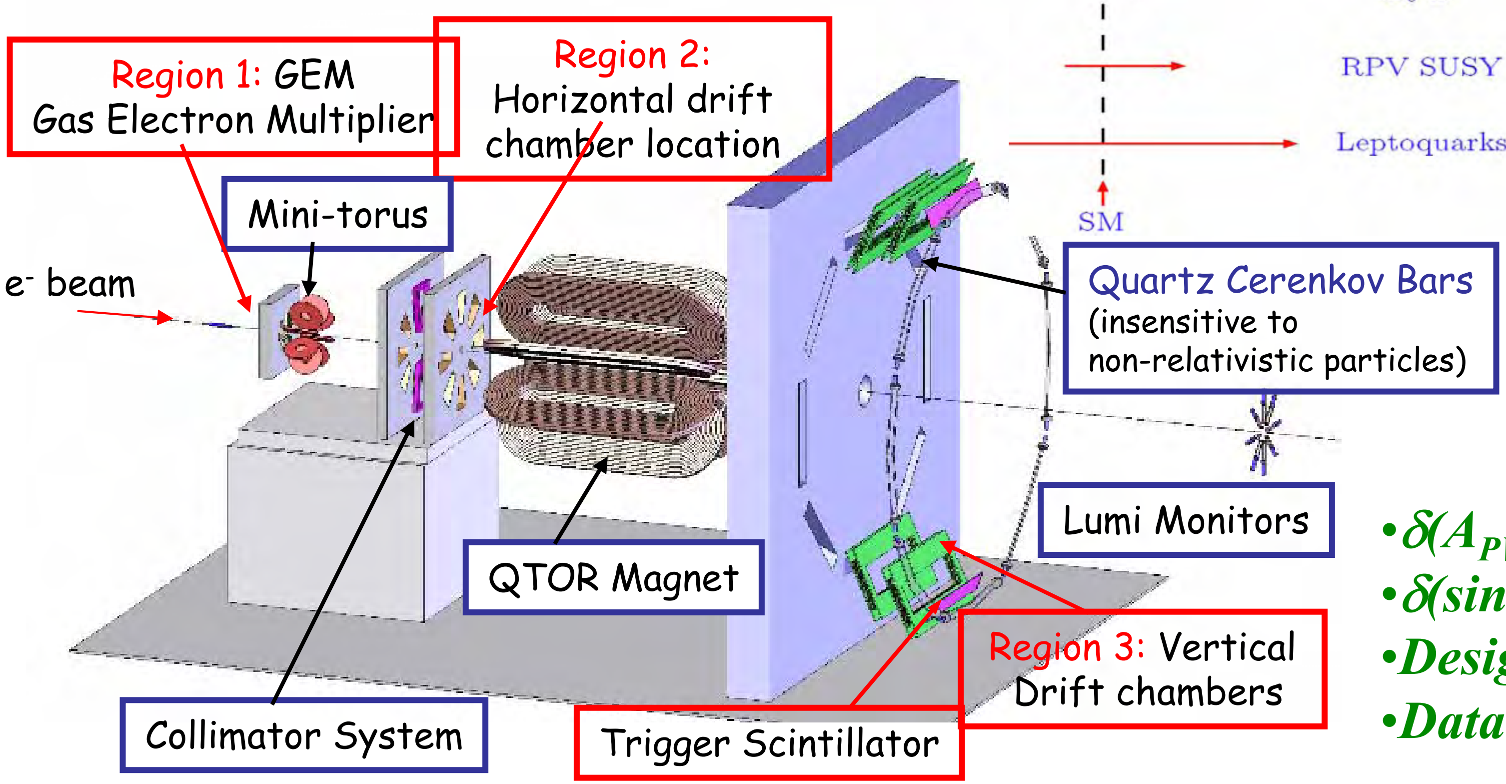
Qweak at JLab

A_{PV} in elastic e-p scattering

Physics Asymmetry: $A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2 Q^p_{weak} + Q^4 B(Q^2)\right]$

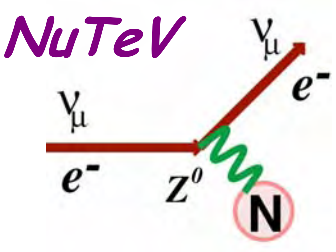




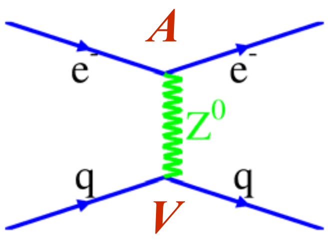


- ***$\delta(A_{PV}) \sim 3\%$***
- ***$\delta(\sin^2\theta_W) \sim \pm 0.0007$***
- ***Design under way***
- ***Data ~ 2009***

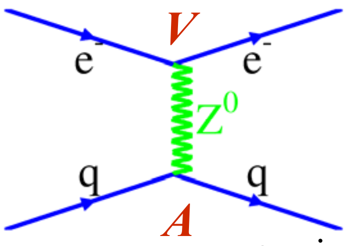
Future Measurements (Semi-leptonic)



- *NuTeV motivates closer look at lepton-quark WNC couplings*
- *4 model-independent e-q couplings to nail down*
- *Implications for models of new TeV scale physics*

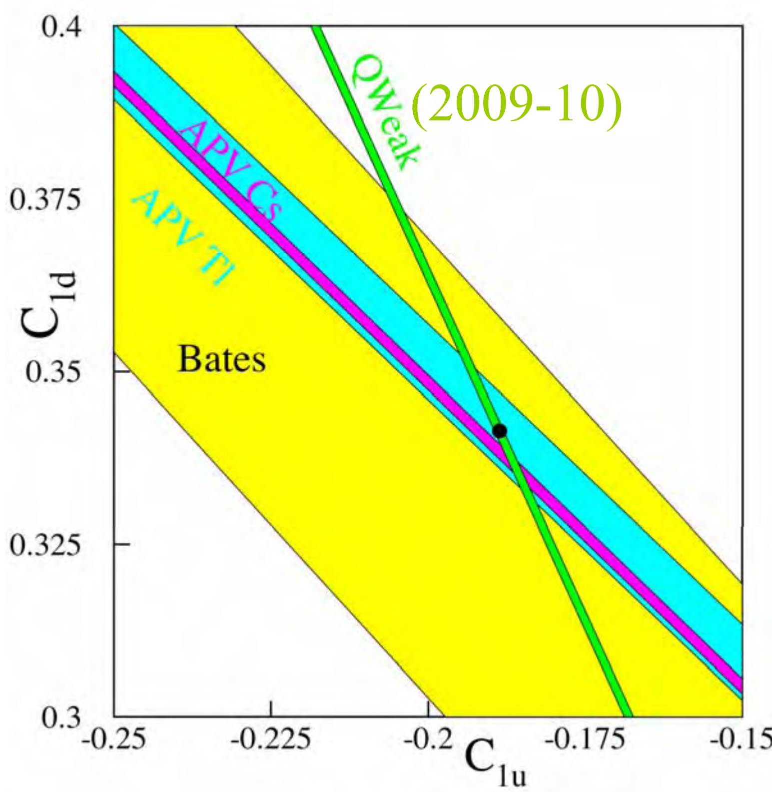


$$C_{1i} \equiv 2g_A^e g_V^i$$



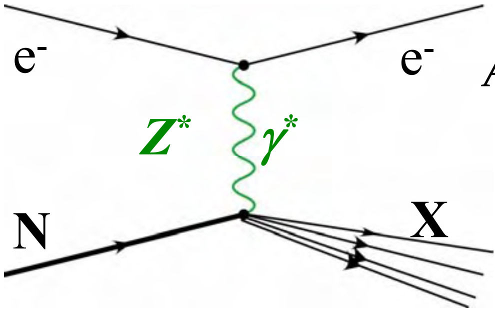
$$C_{2i} \equiv 2g_V^e g_A^i$$

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



- *C_{2i}'s small & poorly known: difficult to measure in elastic scattering*
- *PV Deep inelastic scattering experiment with high luminosity 11 GeV beam*

PV DIS at 11 GeV with an LD_2 target



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

$$a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \qquad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$

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

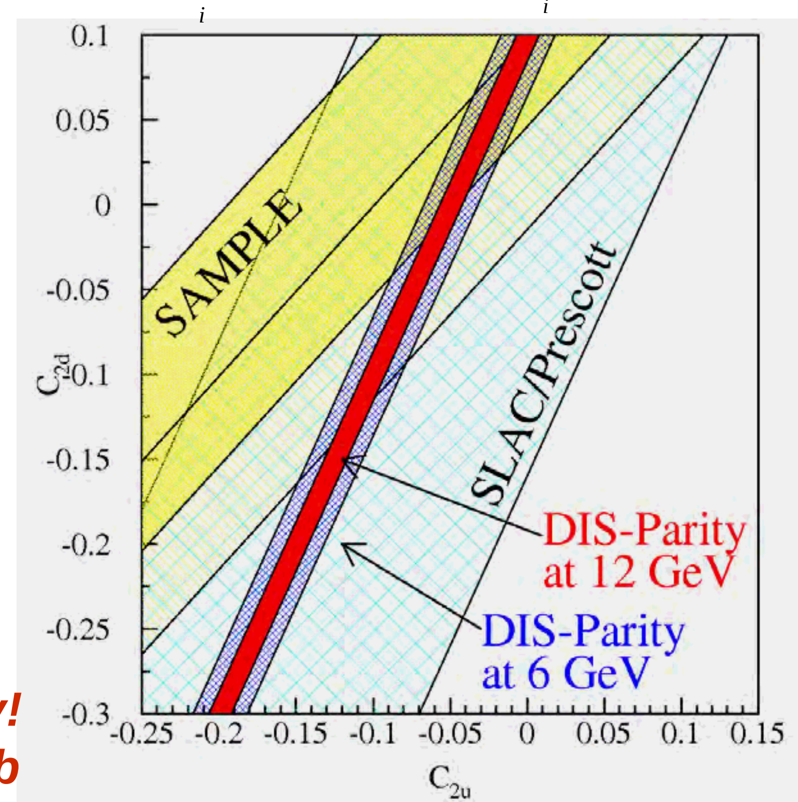
For an isoscalar target like ²H,
structure functions largely cancel in the ratio:

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

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

(Q^2 >> 1 GeV^2 , W^2 >> 4 GeV^2, x ~ 0.3-0.5)

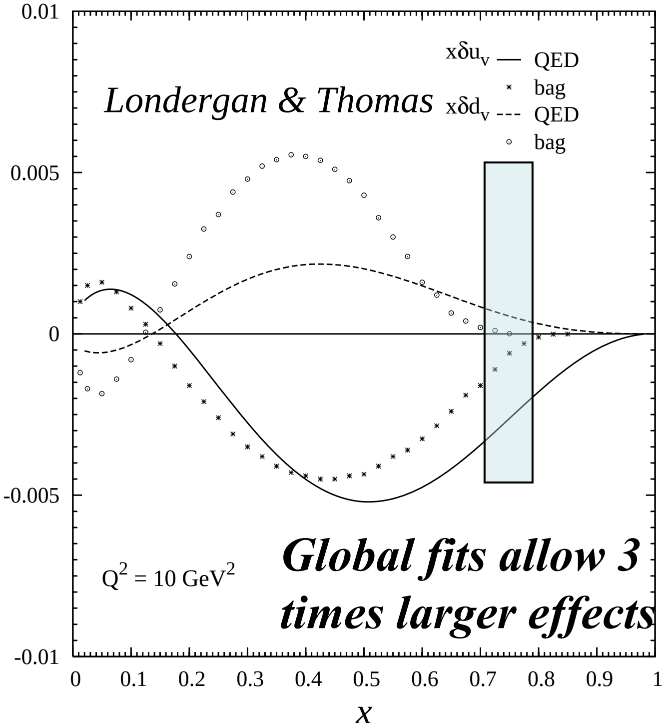
- ***Must measure A_{PV} to 0.5% fractional accuracy!***
- ***Luminosity and beam quality available at JLab***



- 6 GeV experiment launches PV DIS measurements at JLab
- 11 GeV experiment requires tight control of normalization errors
- Important constraint should LHC see anomaly
- Need to characterize nucleon structure at high-x to high precision

Precision High-x Physics with PV DIS

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



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

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

- *Direct observation of parton-level CSV: exciting!*
- *Implications for high energy collider pdfs*
- *Could explain significant portion of the NuTeV anomaly*

Need 1% A_{PV} measurement at x ~ 0.75

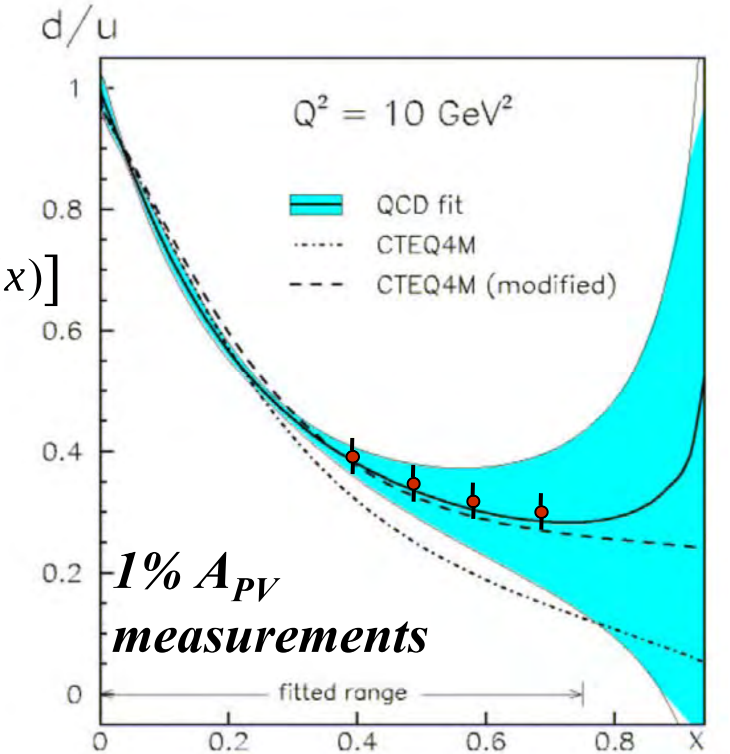
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

For hydrogen ^1H:

$$a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

Longstanding issue: d/u as x→1

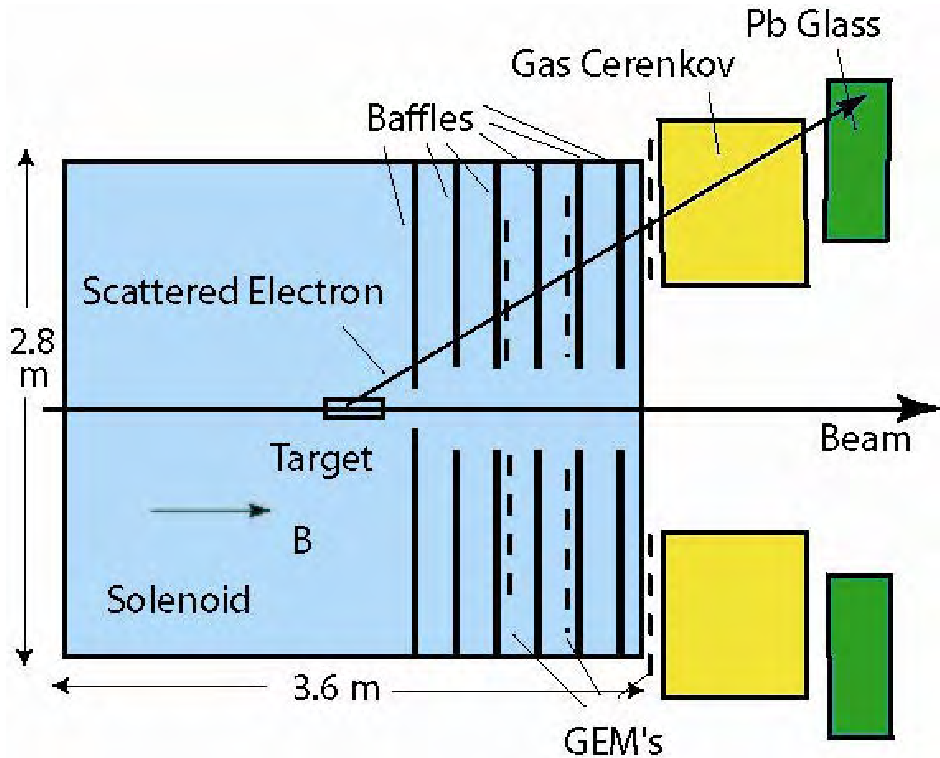
- *Allows d/u measurement on a single proton!*
- *Vector quark current! (electron is axial-vector)*



A Vision for Precision PV DIS Physics

- Hydrogen and Deuterium targets
- Better than 2% errors
  - It is unlikely that any effects are 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
  - (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
• online pion rejection of 10^2 to 10^3

Goal: Form a collaboration, start real design and simulations, and make pitch to US community at the next nuclear physics long range plan (2007)

Summary

- *New HAPPEX results on nucleon neutral weak form factors:*
  - *Helium:* G^s_E = +0.004 ± 0.014$_{(stat)}$ ± 0.013$_{(syst)}$ (Q^2 = 0.077 GeV^2)
  - *Hydrogen:* G^s_E+0.088G^s_M = +0.004±0.011$_{(stat)}$±0.005$_{(syst)}$±0.004$_{(FF)}$
  - *Final measurements to be completed within two years*

- *A clean measurement of the neutron's skin in ^{208}Pb: implications for neutron star formation and properties*

- *E158 has carried out a precision measurement of $\sin^2\theta_W$*
  - *A_{PV}: -131 ± 14 ± 10 ppb*
  - *Running of weak mixing angle established at 6σ*
  - *$\sin^2\theta_{eff}$ = 0.2397 ± 0.0010 ± 0.0008*
  - *New constraints on TeV scale physics*
- *Future experiments could improve sensitivity by ~ 2 to 6*
- *An "ultimate" measurement could be done at an LC*

- *New era of PV DIS measurements with JLab 12 GeV upgrade*

Search for CSV in PV DIS

$u^p(x) = d^n(x)?$

$d^p(x) = u^n(x)?$

- u-d mass difference
- electromagnetic effects

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

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

- *Direct observation of parton-level CSV would be very exciting!*
- *Important implications for high energy collider pdfs*
- *Could explain significant portion of the NuTeV anomaly*

For A_{PV} in electron-^{2}H DIS:

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

Sensitivity will be further enhanced if u+d falls off more rapidly than δu-δd as $x \rightarrow 1$

Strategy:

- ***measure or constrain higher twist effects at x ~ 0.5-0.6***
- ***precision measurement of A_{PV} at x ~ 0.7 to search for CSV***

d(x)/u(x) as x→1

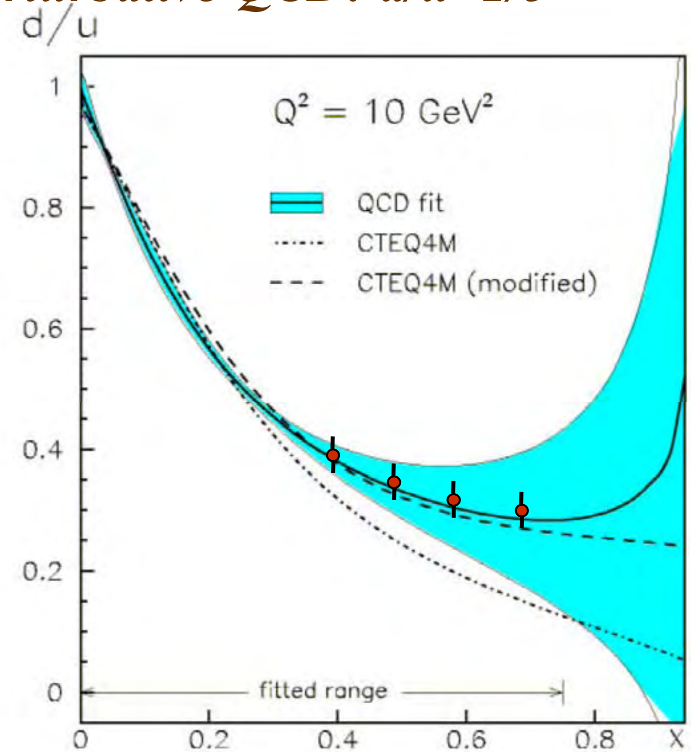
Proton Wavefunction (Spin and Flavor Symmetric)

$$|p\uparrow\rangle = \frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle - \frac{1}{3}|d\uparrow(uu)_{S=1}\rangle - \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

SU(6): d/u~1/2

Valence Quark: d/u~0

Perturbative QCD: d/u~1/5



Longstanding issue in proton structure

PV-DIS off hydrogen

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

$$a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

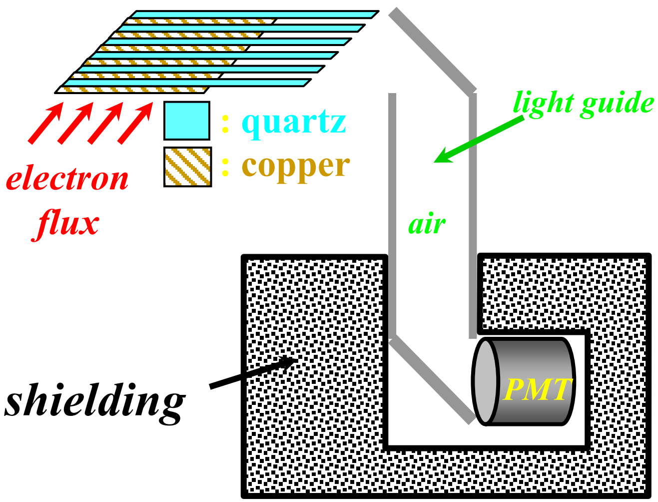
- *Allows d/u measurement on a single proton!*
- *Vector quark current! (electron is axial-vector)*

PV DIS and Nucleon Structure

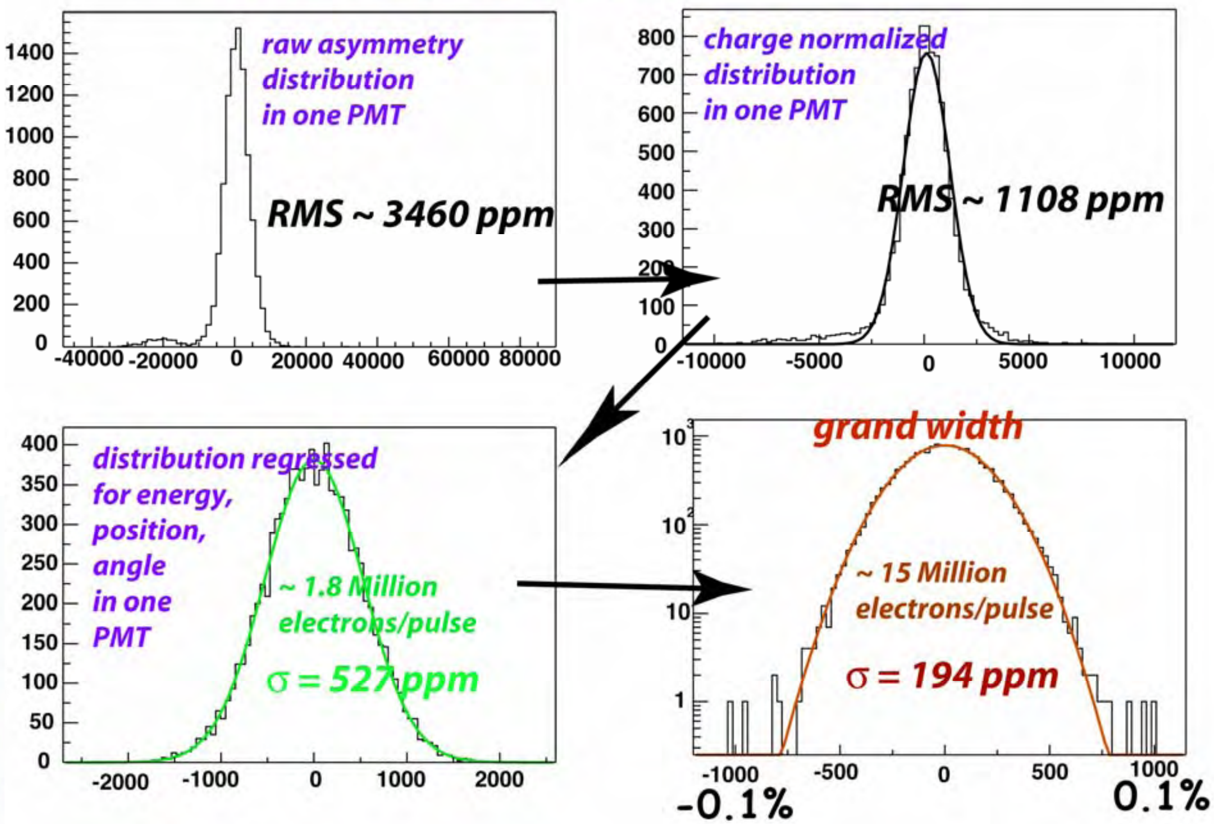
- Analysis assumed control of QCD uncertainties
  - **Higher twist effects**
  - **Charge Symmetry Violation (CSV)**
  - **d/u at high x**
- NuTeV provides perspective
  - **Result is 3σ from theory prediction**
  - **Generated a lively theoretical debate**
  - **Raised very interesting nucleon structure issues: cannot be addressed by NuTeV**
- JLab at 11 GeV offers new opportunities
  - **PV DIS can address issues directly**
    - ***Luminosity and kinematic coverage***
    - ***Outstanding opportunities for new discoveries***
    - ***Provide confidence in electroweak measurement***

E158 Analysis

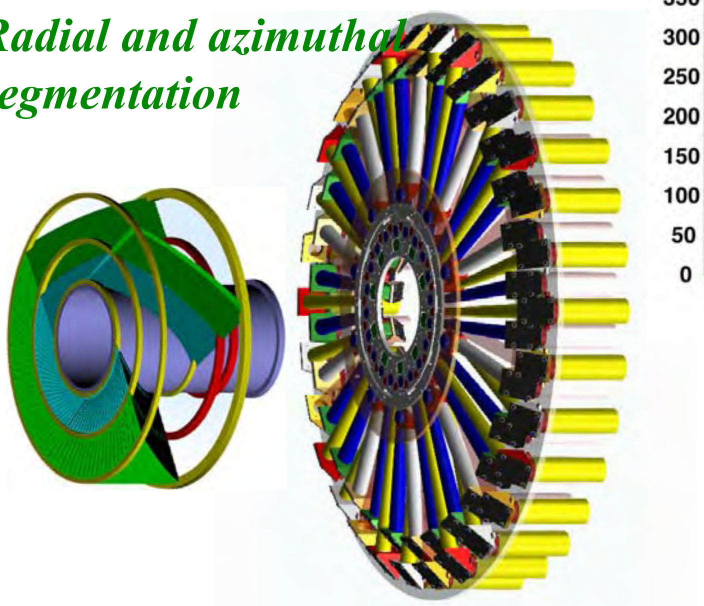
Basic Idea:



observed left-right asymmetry distribution



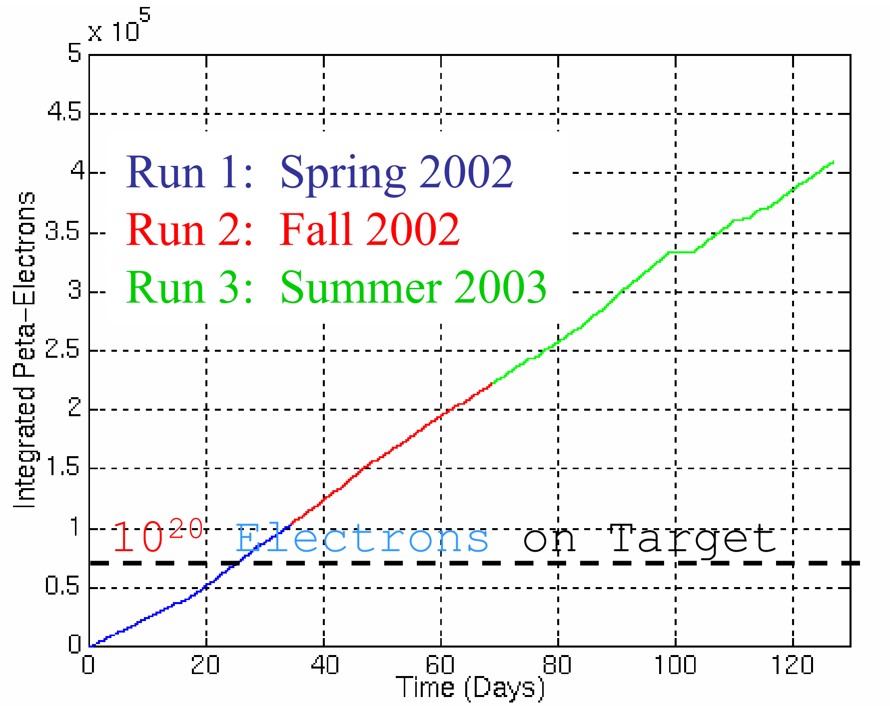
Radial and azimuthal segmentation



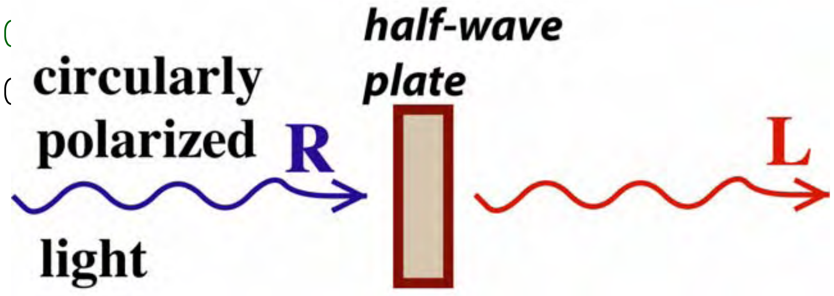
- Corrections for beam fluctuations
- Average over runs
- Statistical tests
- Beam polarization and other normalization

Physics Runs

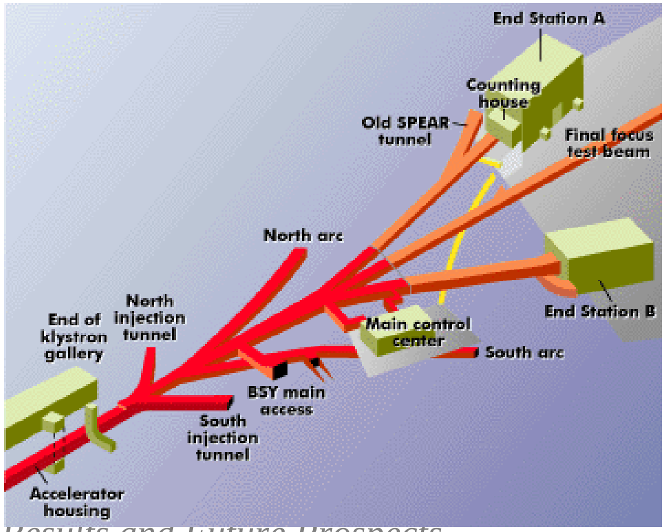
Run 1: Apr 23 12:00 - May 28 00:00, 2002
Run 2: Oct 10 08:00 - Nov 13 16:00, 20(
Run 3: July 10 08:00 - Sep 10 08:00, 2(



A_{PV} Sign Flips

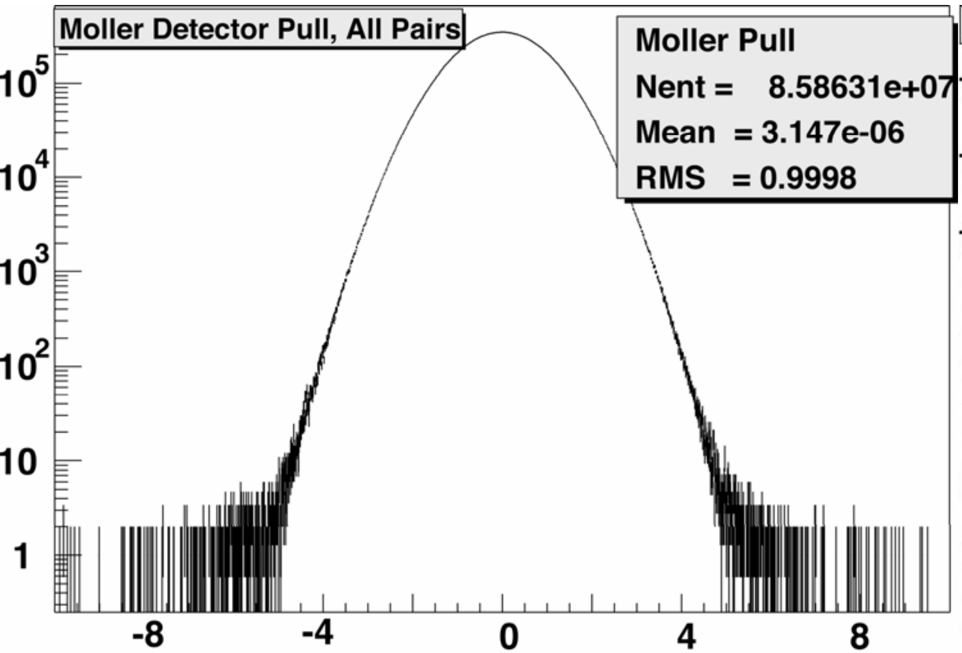


g-2 spin precession
45 GeV: 14.0 revs
48 GeV: 14.5 revs



Data divided into 75 "slugs":
- Wave plate flipped ~ few hours
- Beam energy changed ~ few days

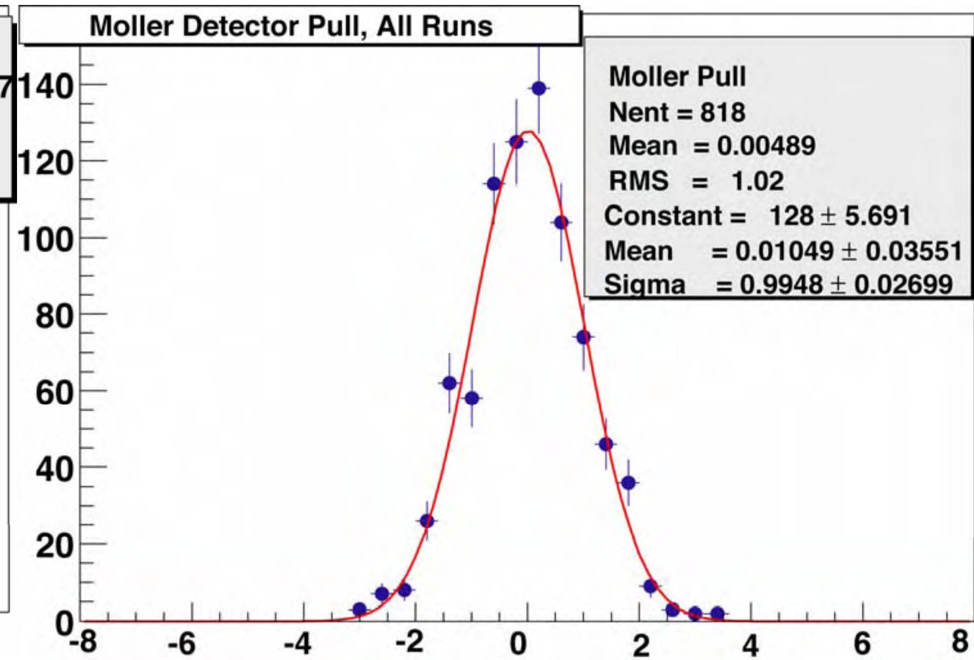
Raw Asymmetry Statistics



$$\frac{A_i - \langle \overline{A} \rangle}{\sigma_i}$$

$\sigma_i \approx 200$ ppm

$N = 85$ Million

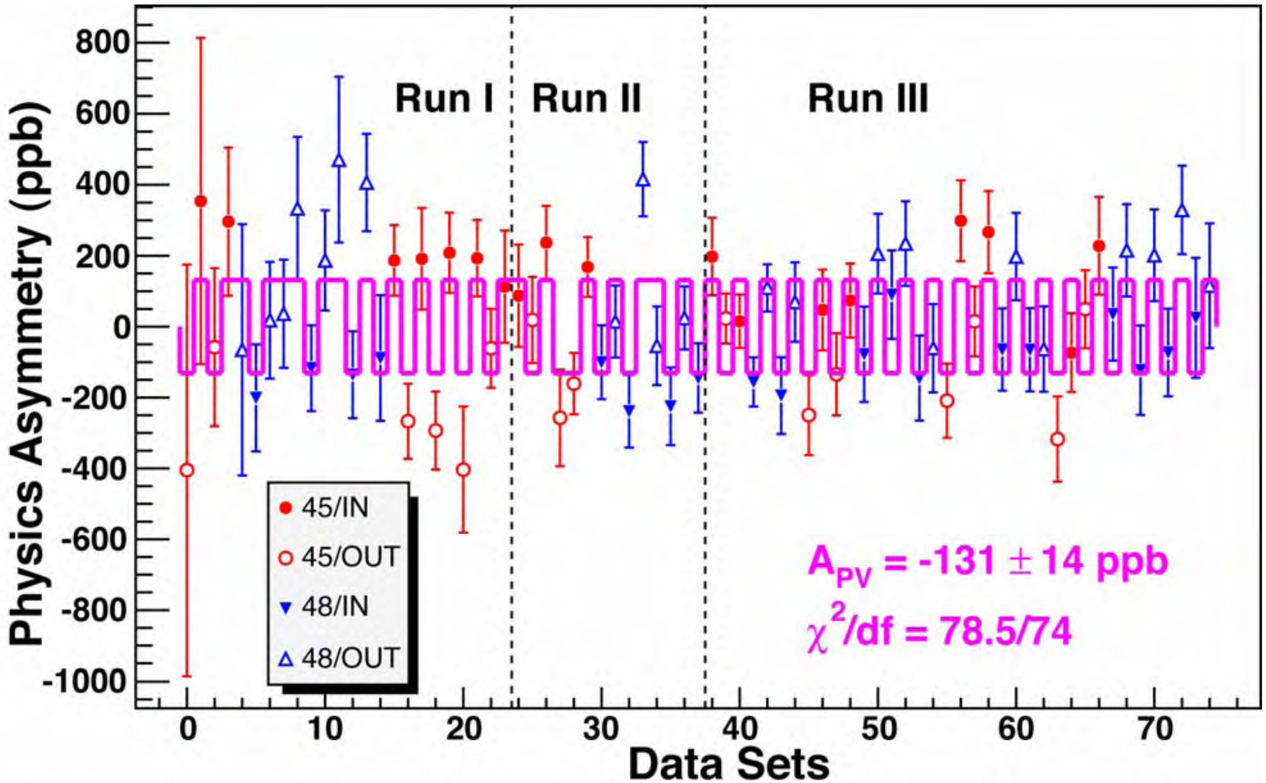


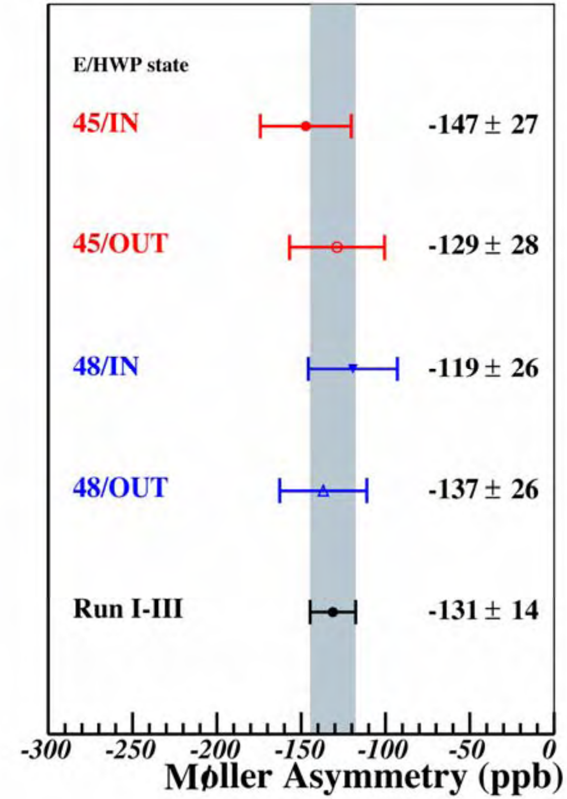
$$\frac{A_i - \langle \overline{A} \rangle}{\sigma_i}$$

$\sigma_i \approx 600$ ppb

$N = 818$

Final Analysis of All 3 Runs



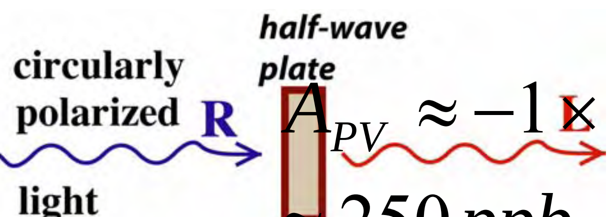


$$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$$

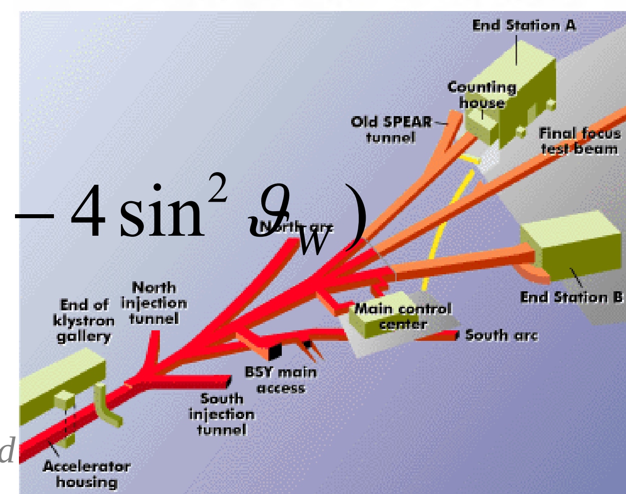
g-2 spin precession

45 GeV: 14.0 revs

48 GeV: 14.5 revs

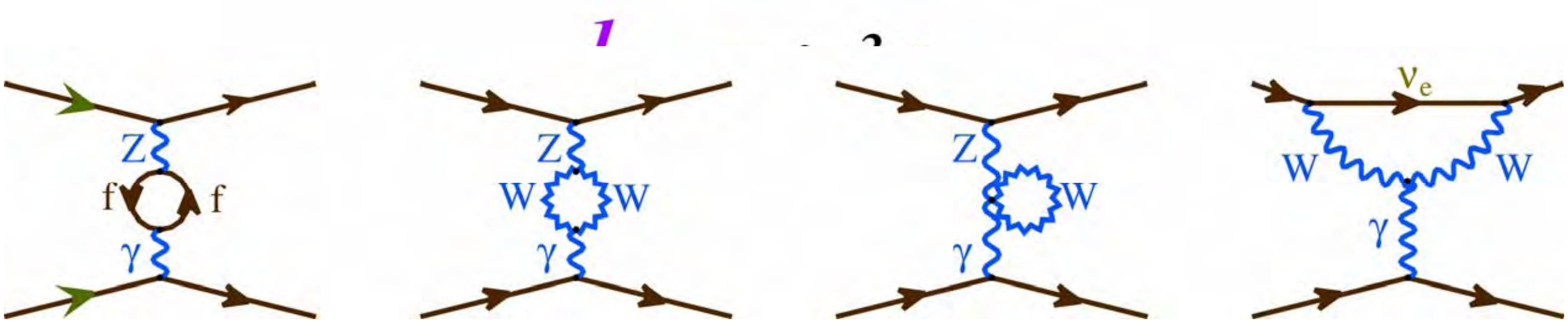


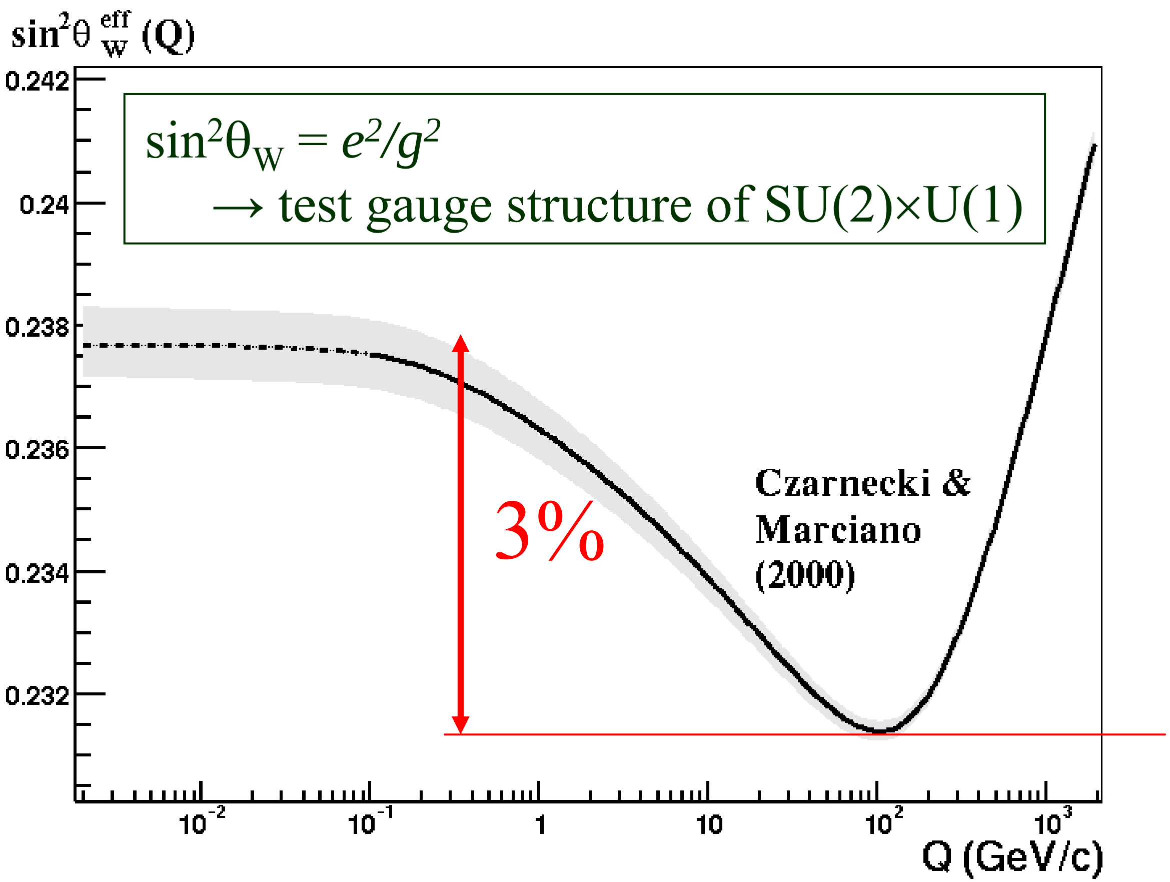
$$A_{PV} \approx -1 \times 10^{-7} \times E_{beam} \times P_{beam} \times (1 - 4\sin^2\vartheta_W) \approx 250\,ppb$$



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

Electroweak Physics





- ***Czarnecki and Marciano***
- ***Erler and Ramsey-Musolf***
- ***Sirlin et. al.***
- ***Zykonov***

Backgrounds & Normalization

Integrating calorimeter:

background dilutions and asymmetries must be separately measured or bounded.

- *Elastic and inelastic e-p scattering and radiative tail*
- *High energy pions*
- *High and low energy photons*
- *Neutrons*
- *Synchrotron radiation*

Total dilution: 9.3% in Run I, 7.6% in Run II & II

- ***Beam polarization measured using polarized foil target***
  - ***Same spectrometer used with dedicated movable detector***
- ***Energy scale and spectrometer alignment to determine*** $\langle Q^2 \rangle$
- ***Linearity of PMTs***

Largest systematic errors:

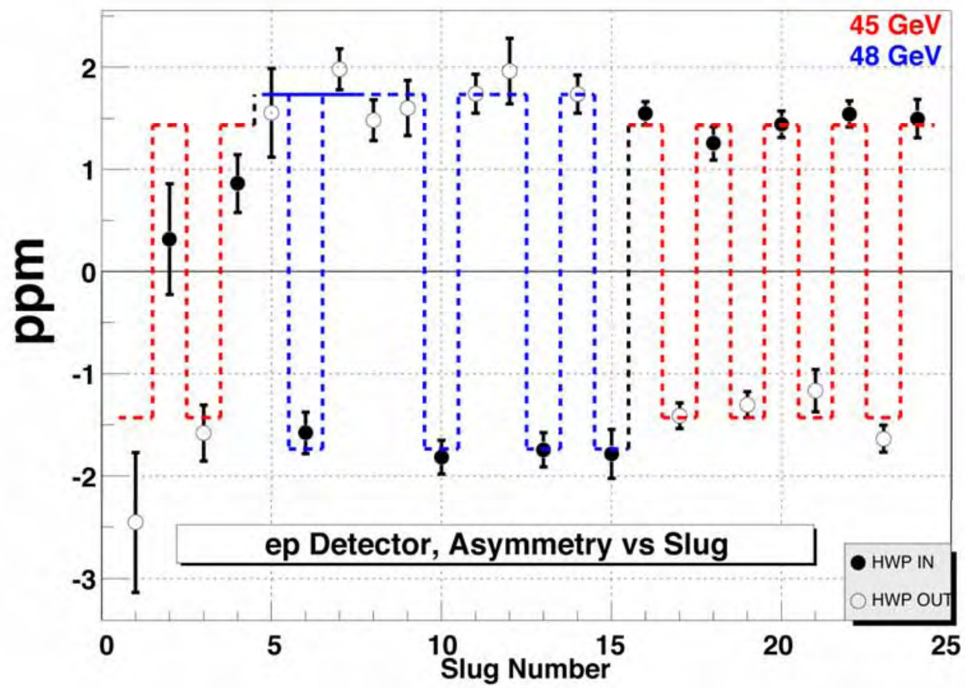
- Inelastic ep: -22 ± 4 ppb
- Beam polarization: 0.89 ± 0.04

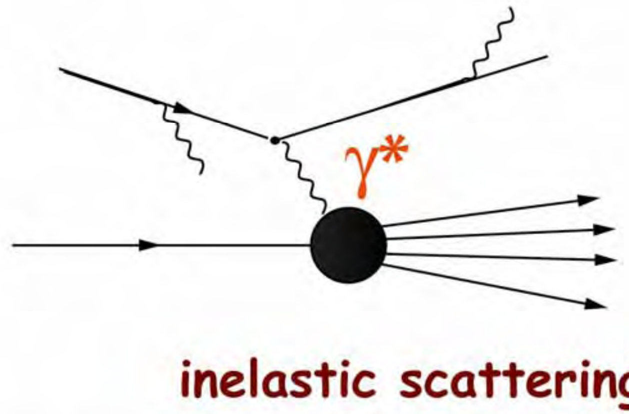
Summary of Corrections

Correction	f_{bkg}	$\sigma(f_{bkg})$	A_{corr} (ppb)	$\sigma(A_{corr})$ (ppb)
Beam first order	-	-	-10	1
Beam higher orders	-	-	0	3
Beam spotsize	-	-	0	1
Transverse asymmetry	-	-	-4	2
High energy photons	0.004	0.002	3	3
Synchrotron photons	0.002	0.001	0	1
Neutrons	0.003	0.001	-1	1
ep elastic	0.056	0.007	-7	1
ep inelastic	0.009	0.001	-22	4
Pions	0.001	0.001	1	1
TOTAL	0.075	0.008	-40	6

- Scale factors:
  - Average Polarization 89 ± 4% ⇦ New "NLC" cathode !
  - Linearity 99 ± 1%
  - Radiative corrections: 1.01 ± 0.01

“ep” Detector Data

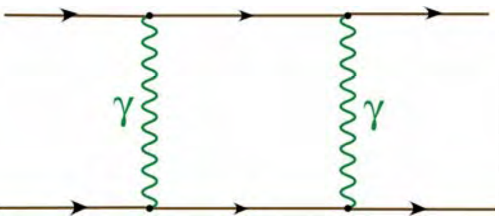




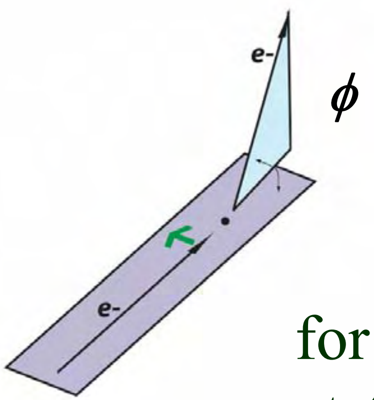
At low Q^2 : $A_{LR} \sim 10^{-4} * Q^2$

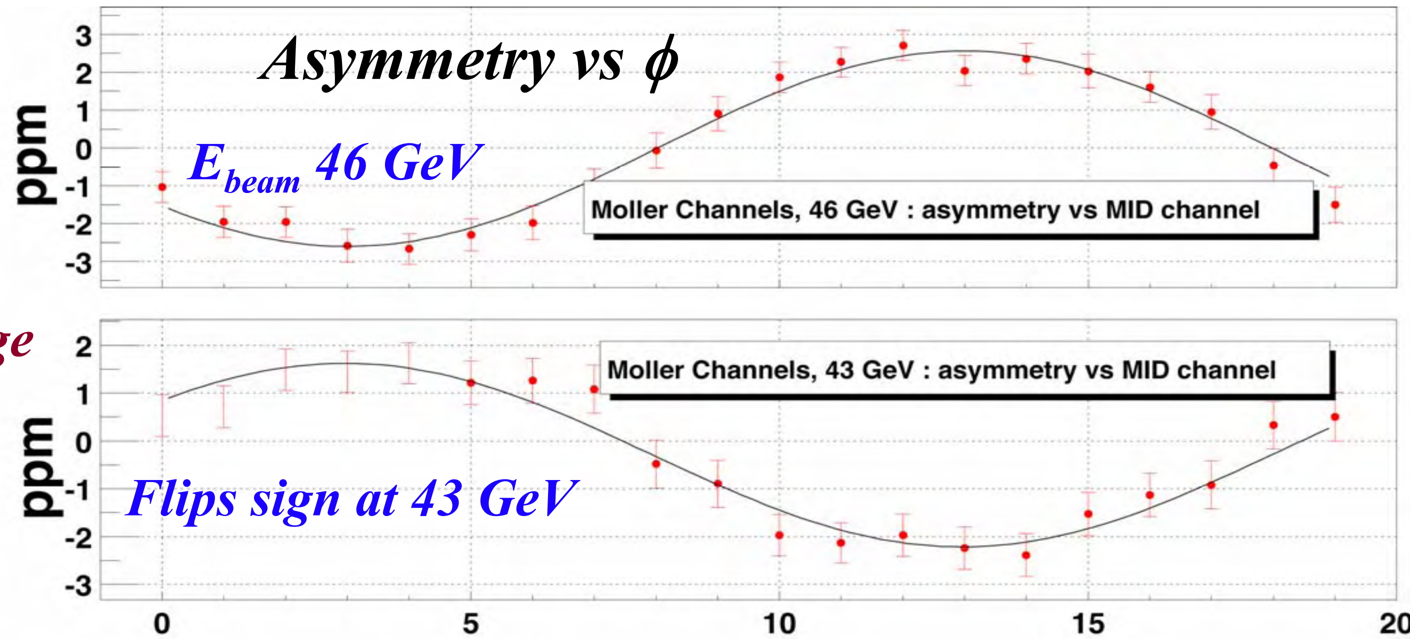
- *Radiative tail of elastic ep scattering is dominant background*
- *8% under Moller peak*
- *Additional 1% from inelastic e-p scattering*
- *Coupling is large: similar to 3 incoherent quarks: $0.8 \times 10^{-4} \times Q^2$*
- *Background reduced in Run II & III with additional collimation*

Transverse Asymmetry



Two-photon exchange
QED effect





for Møller scattering at 46 GeV

$$A_T \propto \frac{\alpha m_e}{\sqrt{s}} = -3.5\ \text{ppm} \bullet \sin\phi$$

Observe ~ 2.5 ppm up-down asymmetry w/ horizontal polarization
First measurement of single-spin transverse asymmetry in e-e scattering.

Theory References:

1. **A. O. Barut and C. Fronsdal, (1960)**
2. **L. L. DeRaad, Jr. and Y. J. Ng (1975)**
3. **Lance Dixon and Marc Schreiber (2004)**

Form Factors

$$J_\mu^{EM} = \sum_q Q_q \langle \overline{N} | \overline{u}_q \gamma_\mu u_q | N \rangle = \overline{N} \left[\gamma_\mu F_1^\gamma + \frac{i\sigma_{\mu\nu} q^\nu}{2M_N} F_2^\gamma \right] N$$

Adopt the Sachs FF: $G_E^\gamma = F_1^\gamma + \tau F_2^\gamma \qquad G_M^\gamma = F_1^\gamma + F_2^\gamma$

(Roughly: Fourier transforms of charge and magnetization)

NC probes same hadronic flavor structure, with different couplings:

$$G_{E/M}^\gamma = \frac{2}{3} G_{E/M}^u - \frac{1}{3} G_{E/M}^d - \frac{1}{3} G_{E/M}^s$$

$$G_{E/M}^Z = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G_{E/M}^u - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_{E/M}^d - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_{E/M}^s$$

$G^Z_{E/M}$ provide an important new benchmark for testing non-perturbative QCD structure of the nucleon

Charge Symmetry

One expects the neutron to be an isospin rotation of the proton*:

$$G^{p,u}_{E/M} = G^{n,d}_{E/M}, \qquad G^{p,d}_{E/M} = G^{n,u}_{E/M}, \qquad G^{p,s}_{E/M} = G^{n,s}_{E/M}$$

$$G^{\gamma,p}_{E/M} = \frac{2}{3}G^{u}_{E/M} - \frac{1}{3}G^{d}_{E/M} - \frac{1}{3}G^{s}_{E/M} \rightarrow G^{\gamma,n}_{E/M} = \frac{2}{3}G^{d}_{E/M} - \frac{1}{3}G^{u}_{E/M} - \frac{1}{3}G^{s}_{E/M}$$

$G^{\gamma,p}_{E,M}$, $G^{\gamma,n}_{E,M}$, $G^{Z,p}_{E,M}$	Charge symmetry →	$G^{u}_{E,M}$, $G^{d}_{E,M}$, $G^{s}_{E,M}$	Shuffle →	$G^{p}_{E,M}$, $G^{n}_{E,M}$, $G^{s}_{E,M}$

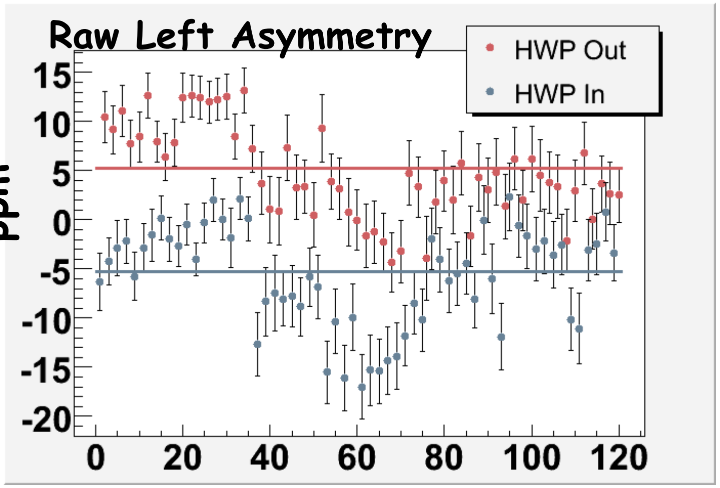
Well Measured ($G^{p}_{E,M}$, $G^{n}_{E,M}$)

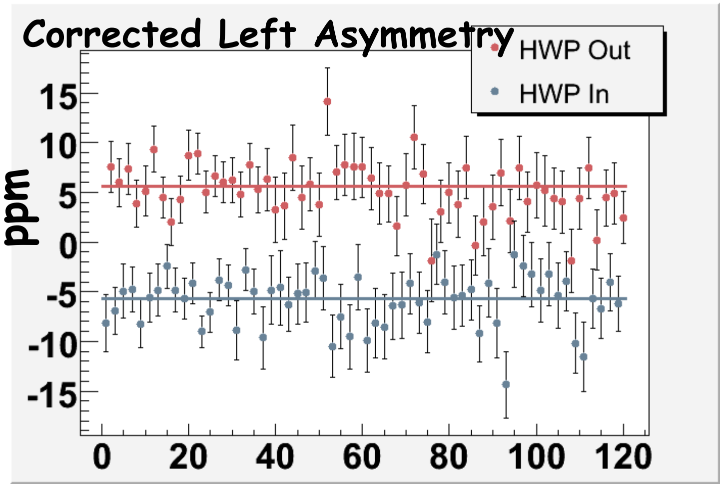
$\langle N|\ s\gamma^{\mu} s\ |N\rangle$ ($G^{s}_{E,M}$)

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{M_Z M_\gamma}{|M_\gamma|^2} = -\frac{G_F Q^2}{\sqrt{2}\pi\alpha} \mathrm{F}\left(G^{p}_{E/M}, G^{n}_{E/M}, G^{s}_{E/M}, G_A\right)$$

* See B. Kubis & R. Lewis nucl-th/0605006 & Randy Lewis' talk at this meeting

Beam Position Corrections, Helium





Beam Asymmetries

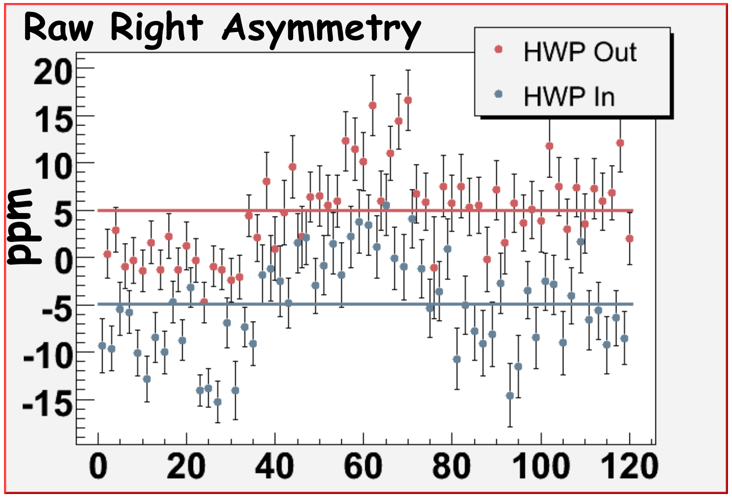
Energy: -3ppb

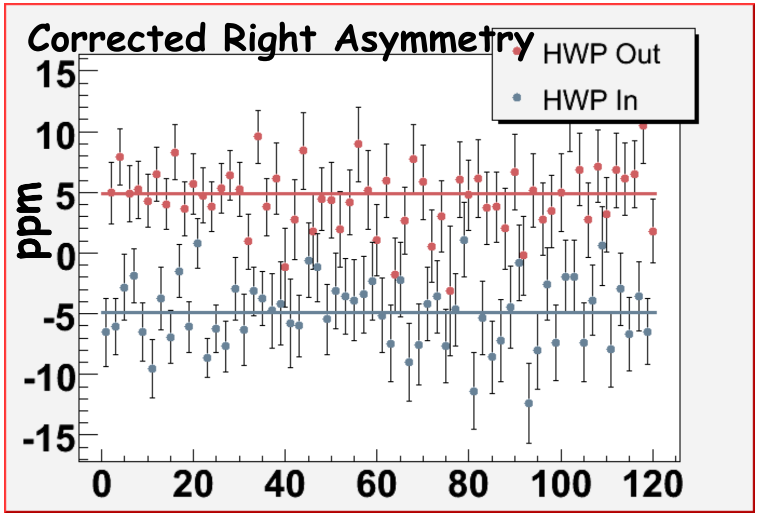
X Target: -5 nm

X Angle: -28 nm

Y Target :-21 nm

Y Angle: 1 nm





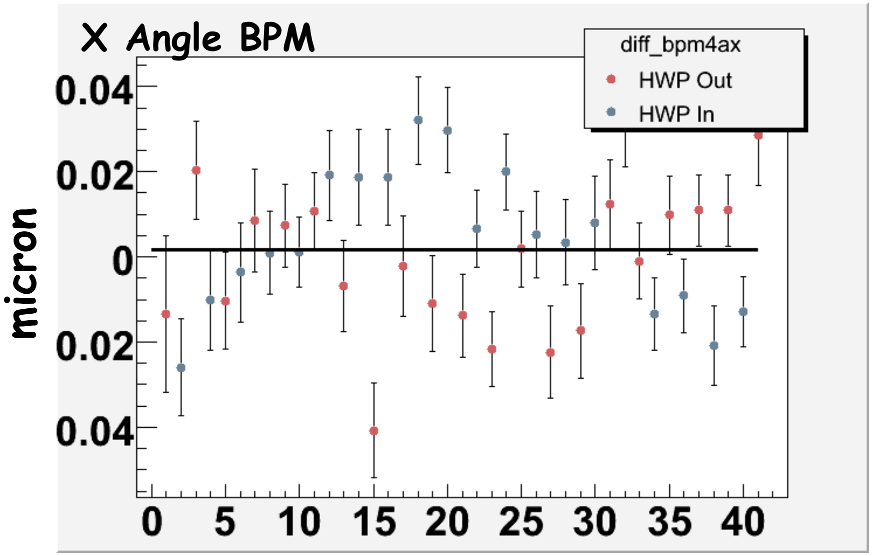
Total Corrections:

Left: -370 ppb

Right: 80 ppb

All: 120 ppb

Beam Position Corrections, Hydrogen



Surpassed Beam Asymmetry Goals for Hydrogen Run

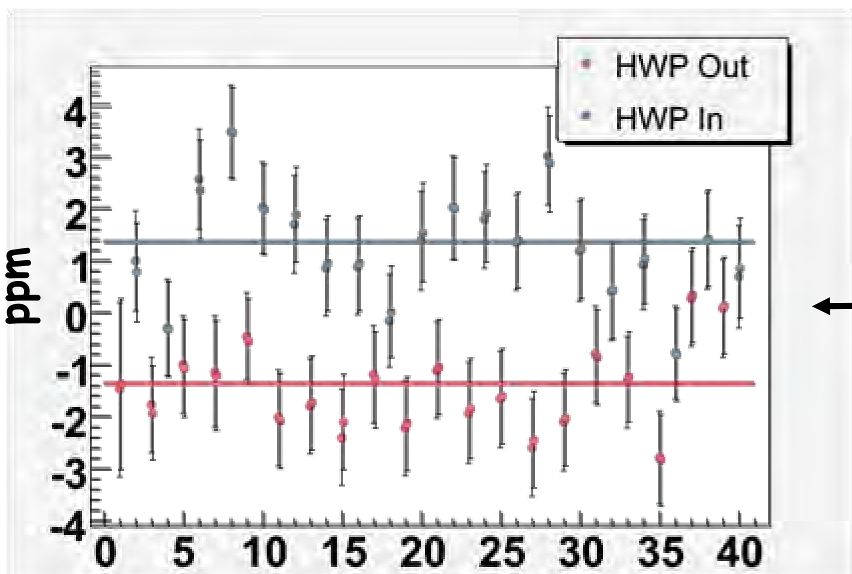
Energy: -0.25 ppb

X Target: 1 nm

X Angle: 2 nm

Y Target : 1 nm

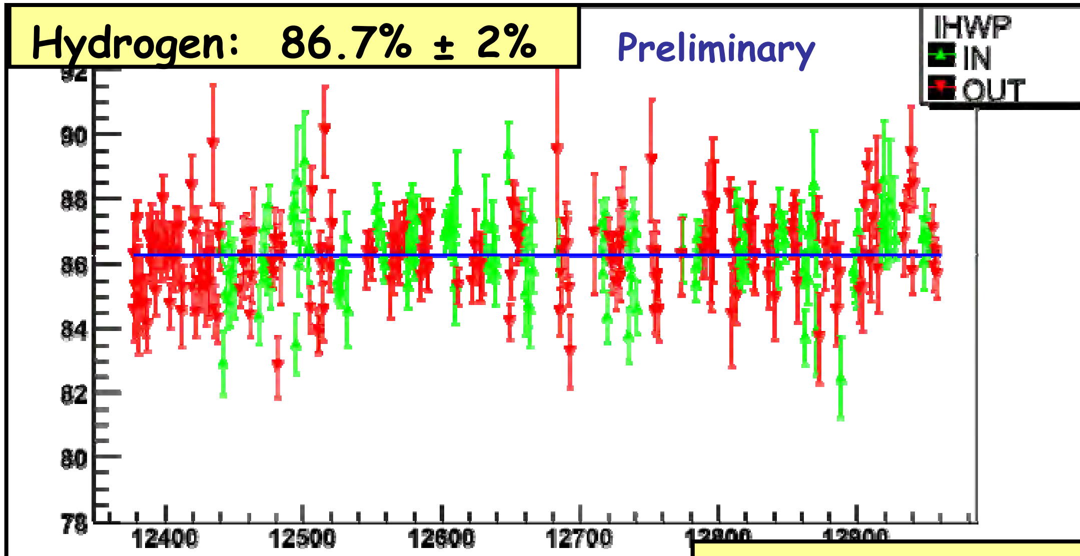
Y Angle: <1 nm



Corrected and Raw, Left arm alone, Superimposed!

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

Compton Polarimetry



Continuous, non-invasive

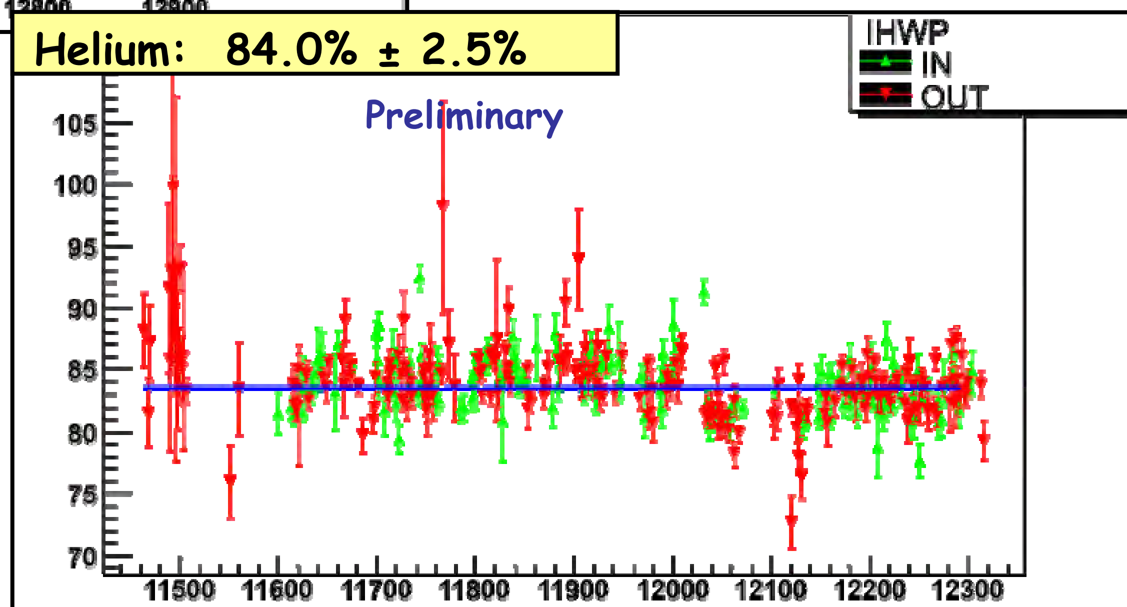
Here : Electron Detector analysis

Cross-checked with Møller, Mott polarimeters

also: independent electron analysis

Helium ran with lower beam energy, making the analysis significantly more challenging.

New developments in both photon and electron analyses in preparation: anticipate <2% systematic uncertainty



Miscellany

- ***Backgrounds:*** ***Bryan Moffit's talk***
  Dilutions: 2.2% (^{4}He) 0.8% (^{1}H)
  Systematic 60 ppb (^{4}He) 16 ppb (^{1}H)

- ***Q^2 & effective kinematics:*** ***□Q^2 < 1.0%*** ***Bryan Moffit's talk***

- ***Two-photon exchange corrections:***
  small ***Marc Vanderhaeghan's talk*** ***(no explicit correction made)***
- ***Transverse asymmetry:***
  measured directly in dedicated runs, □cancels in left-right sum;
  Systematic: 4 ppb (^{1}H) 8 ppb (^{4}He) ***Lisa Kaufmann's talk***

- ***Electromagnetic Form Factors:*** ***use Friedrich & Walcher parameterization, Eur. Phys. J. A, 17, 607 (2003), and BLAST data for G_E^n***
- ***Axial Form Factor:*** ***highly suppressed for ^{1}H (not present for ^{4}He)***
- ***Vector Electroweak Radiative Corrections:*** ***Particle Data Group***

- ***Blinded Analysis***

^{4}He: Nuclear Effects

O^{+} □ O^{+} T=0 transition

- **Any one-body electroweak operator O:** (eg Fetter and Walecka)

  <J,T|O|J,T> = □ □$_{J,T}$(□,□') <□'|O|□> |□> = complete set

  one-body density matrix element *(nuclear structure)* single-particle matrix element *(nucleon structure)*

- **Asymmetry involves ratio of weak/EM matrix elements (G_E^s and $G_E^{T=0}$);**
  Single term in J,T in transition; O same in weak and EM except for couplings
  □ **same one-body density matrix elements in numerator/denominator**
  □ **nuclear structure cancels, only nucleon form factors remain**

This result is EXACT, *if* :

- ^{4}He g.s. pure isospin state: Ramavataram, Hadjimichael, Donnelly PRC 50(1994)1174
- No D-state admixture: Musolf & Donnelly PL B318(1993)263
- Meson exchange corrections small: Musolf, Schiavilla, Donnelly PRC 50(1994)2173

- **Nuclear effects all << 1%, no explicit correction made.**

HAPPEx

Error Budget-Helium

2005

False Asymmetries	48 ppb
Polarization	192 ppb
Linearity	58 ppb
Radiative Corrections	6 ppb
Q^2 Uncertainty	58 ppb
Al background	32 ppb
Helium quasi-elastic background	24 ppb
Total	**216 ppb**

2004

False Asymmetries	103 ppb
Polarization	115 ppb
Linearity	78 ppb
Radiative Corrections	7 ppb
Q^2 Uncertainty	66 ppb
Al background	14 ppb
Helium quasi-elastic background	86 ppb
Total	205 ppb

Error Budget-Hydrogen

2005

False Asymmetries	17 ppb
Polarization	37 ppb
Linearity	15 ppb
Radiative Corrections	3 ppb
Q^2 Uncertainty	16 ppb
Al background	15 ppb
Rescattering Background	4 ppb
Total	**49 ppb**

2004

False Asymmetries	43 ppb
Polarization	23 ppb
Linearity	15 ppb
Radiative Corrections	7 ppb
Q^2 Uncertainty	12 ppb
Al background	16 ppb
Rescattering Background	32 ppb
Total	63 ppb

HAPPEX-II 2005 Preliminary Results

HAPPEX-^{4}He:

$Q^2 = 0.0772 \pm 0.0007\ (GeV/c)^2$

$A_{PV} = +6.43 \pm 0.23\ (stat) \pm 0.22\ (syst)\ ppm$

$A(G^s=0) = +6.37\ ppm$

$G^s_E = \quad 0.004 \pm 0.014_{(stat)} \pm 0.013_{(syst)}$

HAPPEX-H:

$Q^2 = 0.1089 \pm 0.0011\ (GeV/c)^2$

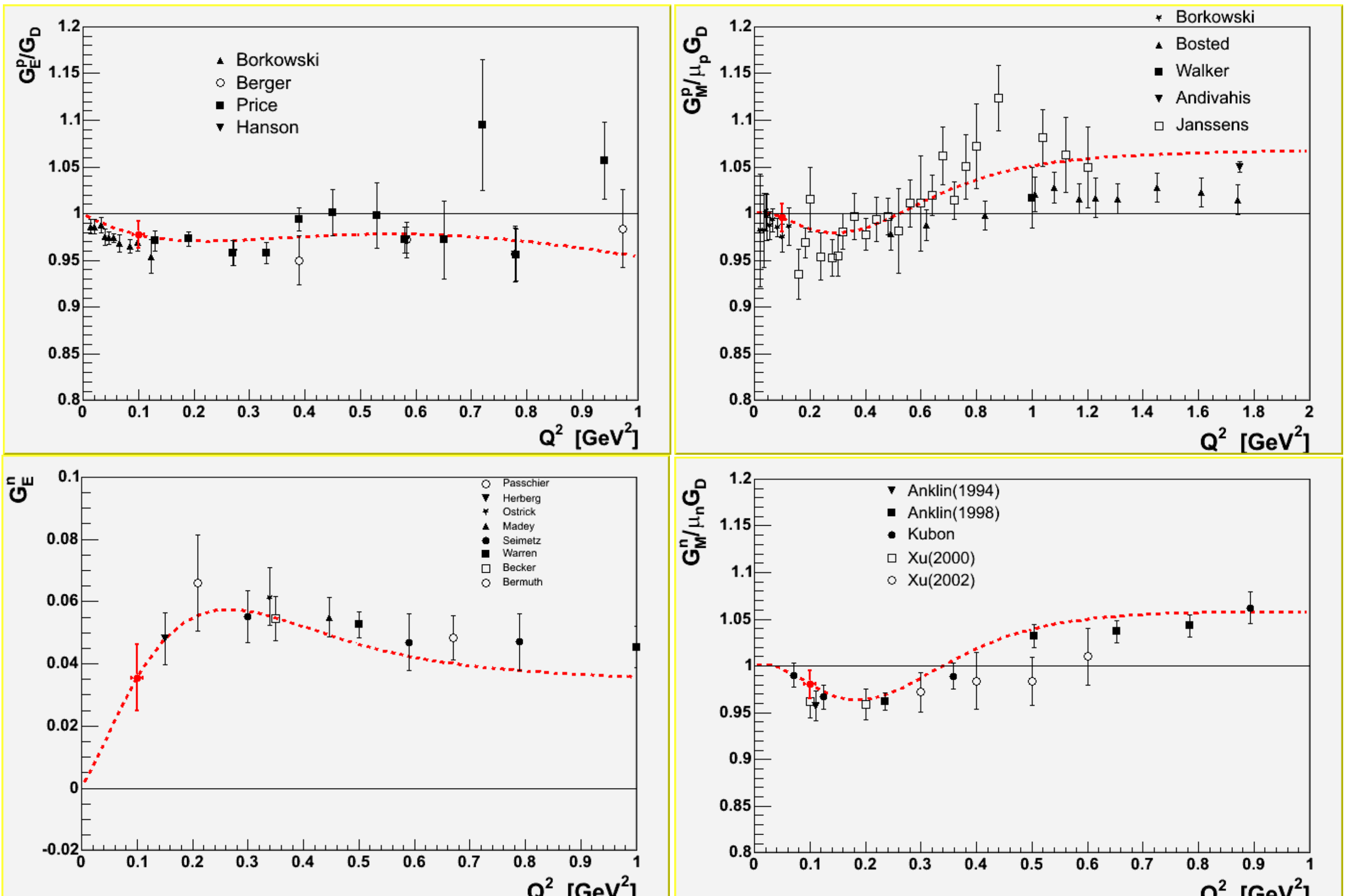
$A_{PV} = -1.60 \pm 0.12\ (stat) \pm 0.05\ (syst)\ ppm$

$A(G^s=0) = -1.640\ ppm \pm 0.041\ ppm$

$G^s_E + 0.088\ G^s_M = \quad 0.004 \pm 0.011_{(stat)} \pm 0.005_{(syst)} \pm 0.004_{(FF)}$

EM Form Factors

Electromagnetic form factors parameterized as by:
Friedrich and Walcher, Eur. Phys. J. A, **17**, 607 (2003)



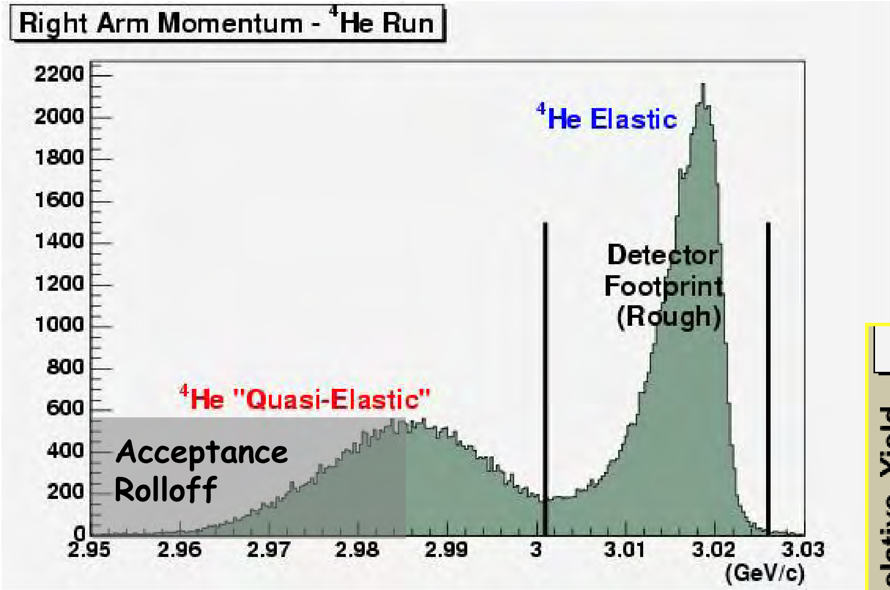
GEn from BLAST:

Claimed uncertainty at 7-8%

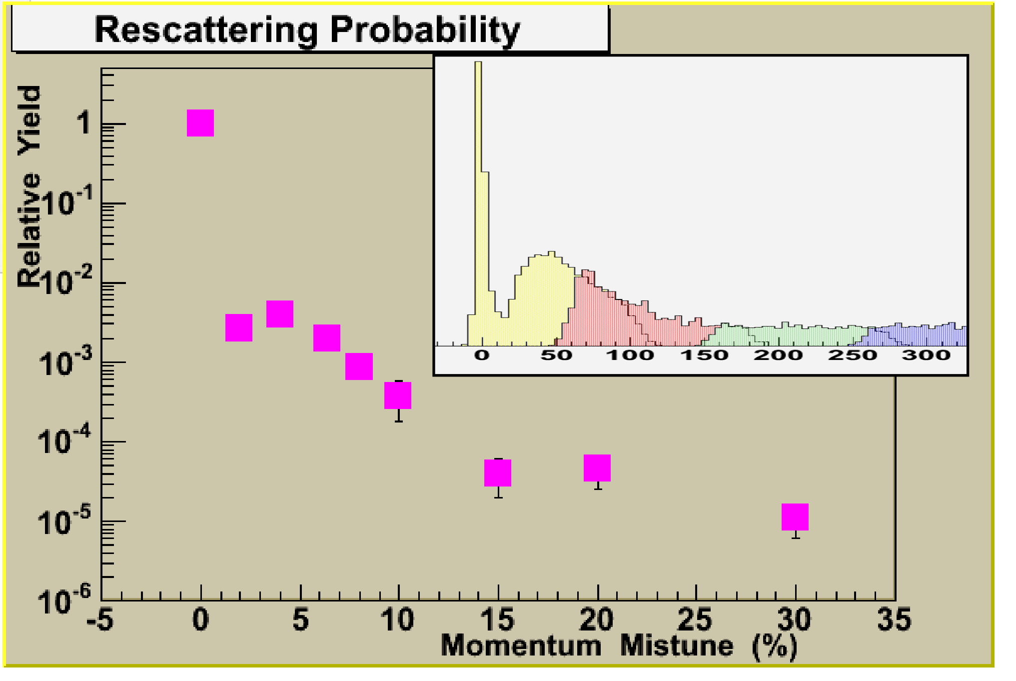
FF	Error
G_E^p	2.5%
G_M^p	1.5%
G_E^n	10%
G_M^n	1.5%
$G_A^{(3)}$	–
$G_A^{(8)}$	–

Background

Dedicated runs at very low current using track reconstruction of the HRS



Dipole field scan to measure the probability of rescattering inside the spectrometer



Helium
Helium QE in detector: 0.15 +/- 0.15%
Helium QE rescatter: 0.25 +/- 0.15%
Al fraction: 1.8 +/- 0.2%

Hydrogen:
Al fraction 0.75 +/- 25 %
Hydrogen Tail + Delta rescatter: <0.1%

Total systematic uncertainty contribution ~40 ppb (Helium), ~15ppb (Hydrogen)

Determining Q^2

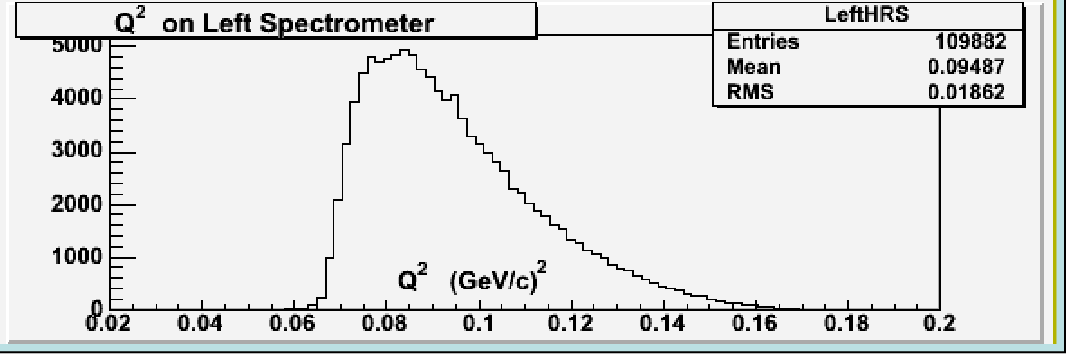
Asymmetry explicitly depends on Q^2:

$$A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left\{ \left(1 - 4\sin^2\theta_W\right) - \frac{\varepsilon G_E^p (G_E^n + G_E^s) + \tau G_M^p (G_M^n + G_M^s)}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \right\}$$

$$Q^2 = 2EE'\left(1 - \cos\theta\right)$$

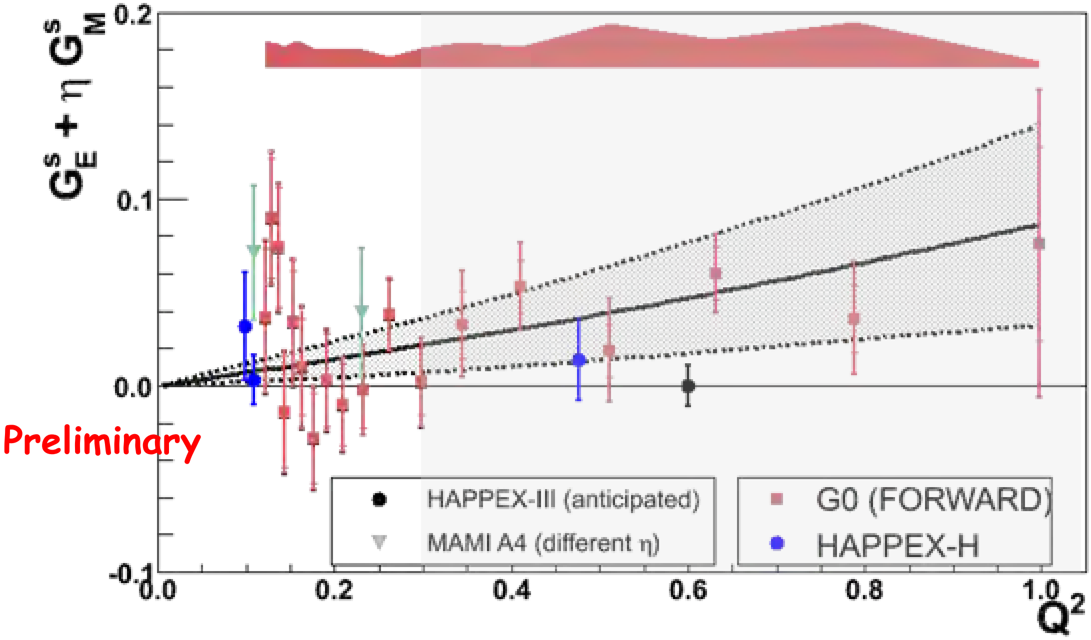
Goal: $\delta_{Q^2} < 1\%$

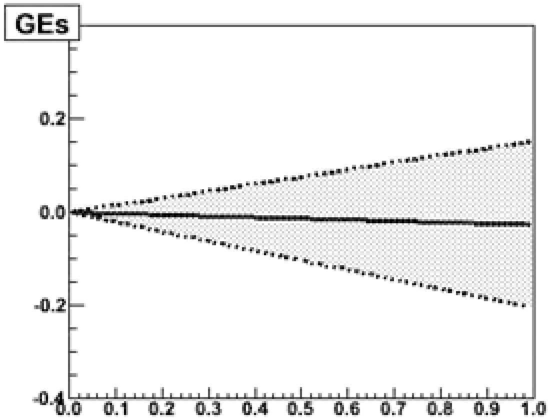
Q^2 measured using standard HRS tracking package, with reduced beam current

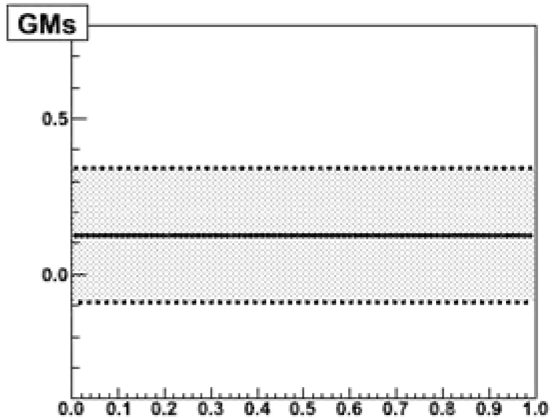


- Central scattering angle must be measured to $\delta\theta < 0.5\%$
- Asymmetry distribution must be averaged over finite acceptance

A Simple Fit (for a simple point)







Simple fit:

GEs = r_s*τ

GMs = mu_s

Includes only data $Q^2 < 0.3$ GeV^2

Includes SAMPLE constrainted with G_A theory and HAPPEX-He 2004, 2005

G0 Global error allowed to float with unit constraint

Nothing intelligent done with form factors, correlated errors, etc.

Quantitative values should NOT be taken very seriously, but some clear, basic points:

- **The world data are consistent.**
- **Rapid Q^2 dependence of strange form-factors is not required.**
- **Sizeable contributions at higher Q2 are not definitively ruled out. (To be tested by HAPPEX-III, G0 and A4 backangle.)**