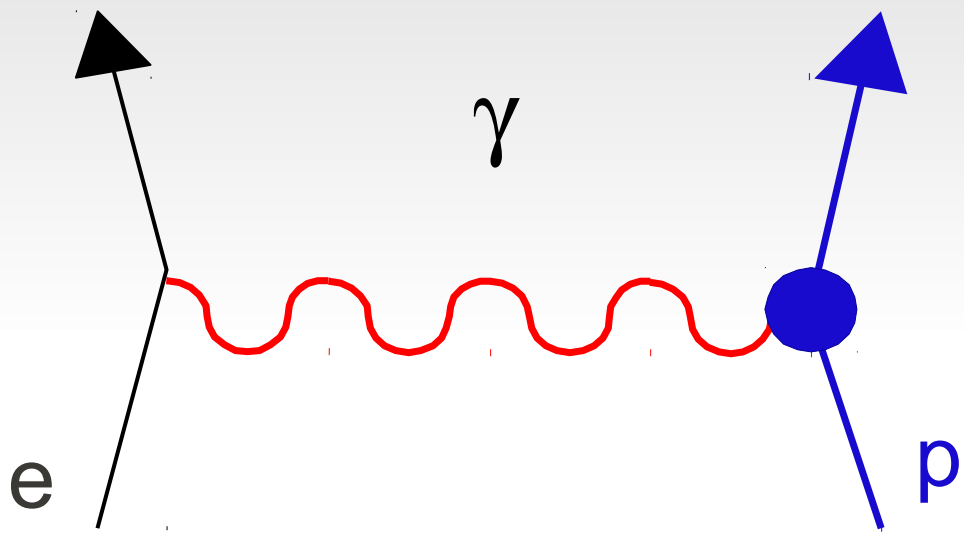
Parity-Violating Electron Scattering: Hadron Structure and New Physics

Jeff Martin
The University of Winnipeg

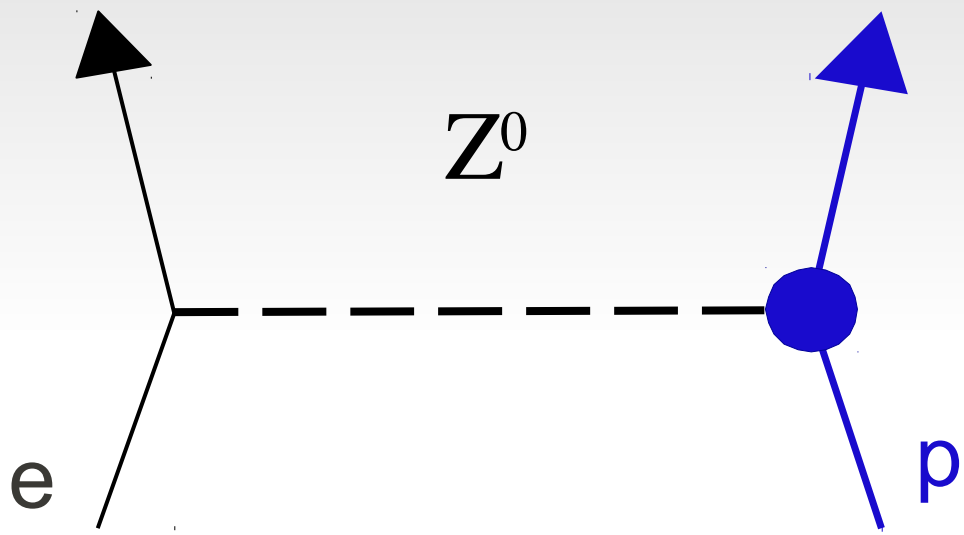
- Electron scattering
- Parity-violation
- Structure
- New Physics

”Regular” Electron Scattering



The EM interaction does not violate parity

Parity-violation in electron scattering?



Interference term in cross-section violates parity.

Structure

- Decomposition of the proton's electromagnetic form factors into contributions from up, down, and strange quarks.

Species	Charge	Weak Charge
u	$+\frac{2}{3}$	$1-\frac{8}{3}\sin^2\theta_W$
d	$-\frac{1}{3}$	$-1+\frac{4}{3}\sin^2\theta_W$
s	$-\frac{1}{3}$	$-1+\frac{4}{3}\sin^2\theta_W$

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

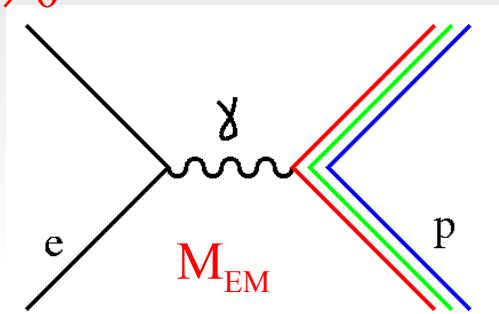
$$G_{E,M}^{\gamma,n} = \frac{2}{3}G_{E,M}^{d,p} - \frac{1}{3}G_{E,M}^{u,p} - \frac{1}{3}G_{E,M}^{s,p}$$

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

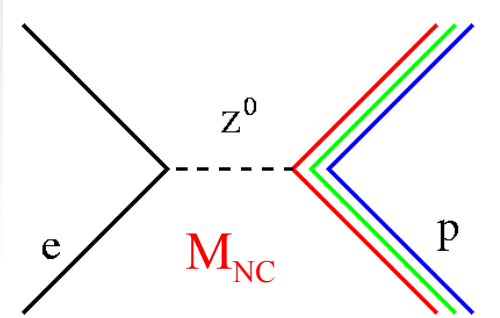
- And axial structure!

New Physics

As $Q^2 \rightarrow 0$



measures Q^p – proton's electric charge



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

At tree level in the standard model:

$$Q^p_{weak} = 1 - 4\sin^2\theta_W$$

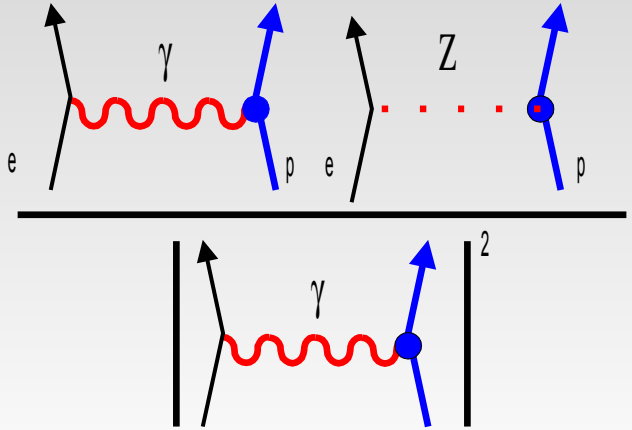
A sensitive, low-energy extraction of the weak mixing angle.

Structure

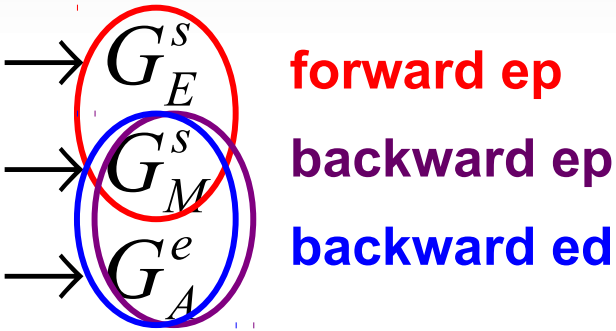
- Strange quark form factors
- Inelastic scattering, axial transition form factors
- Pb neutron skin
- (Transversely polarized beams)

Parity-violating Asymmetry

$$A=\frac{\sigma_R-\sigma_L}{\sigma_R+\sigma_L}=\left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E+A_M+A_A}{\varepsilon(G_E^p)^2+\tau(G_M^p)^2}=$$



$$A_E=\varepsilon(\theta)\,G_E^Z(Q^2)G_E^\gamma(Q^2)$$
$$A_M=\tau(Q^2)\,G_M^Z(Q^2)G_M^\gamma(Q^2)$$
$$A_A=-(1-4\sin^2\theta_W)\varepsilon'\,G_A^e(Q^2)G_M^\gamma(Q^2)$$



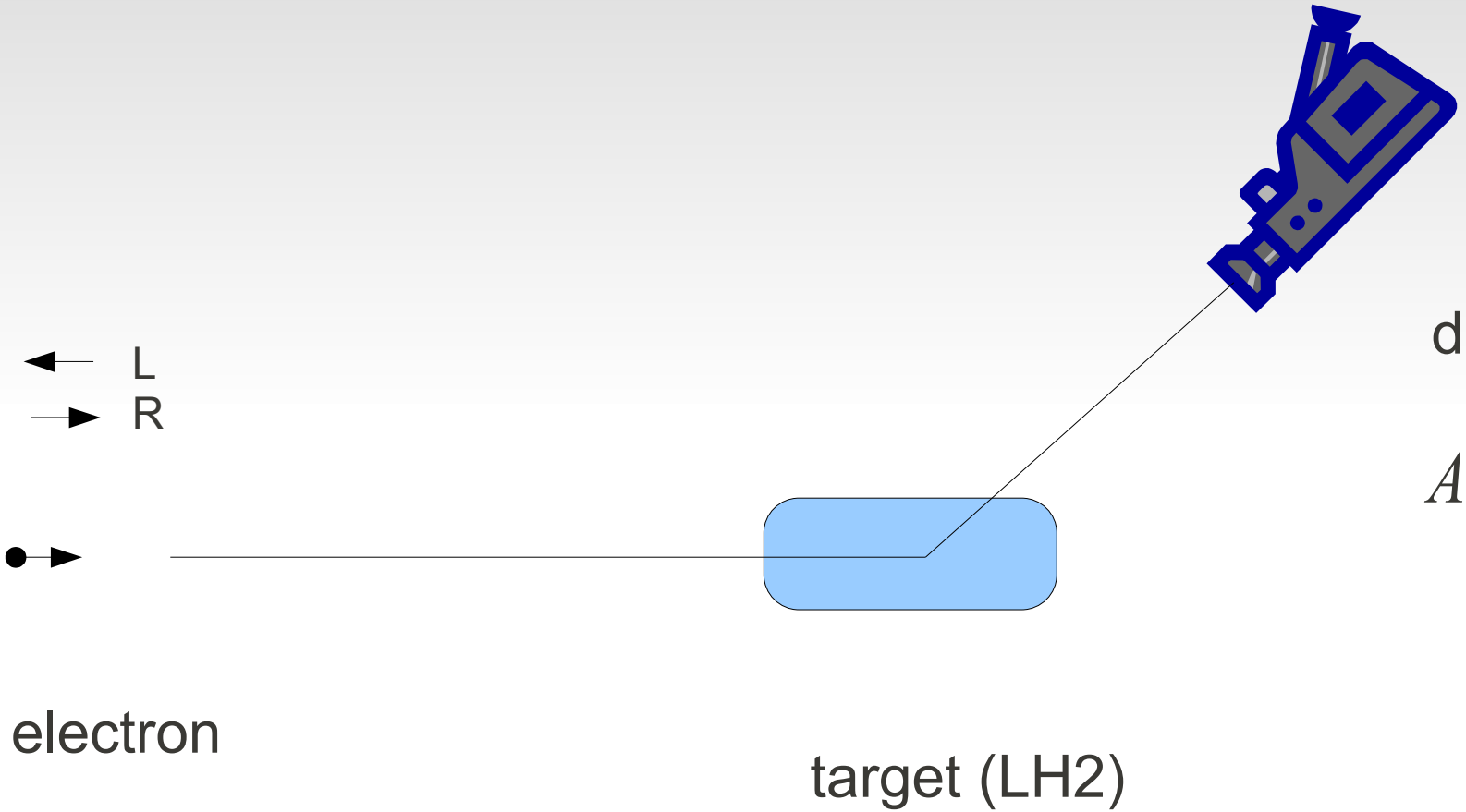
- Program of the last two decades:
  - Measure at forward and backward angles, on a variety of targets.

Strange-quark Experiments

- SAMPLE (MIT-Bates)
- HAPPEx I, II, and III (JLab)
- G0 (JLab)
- A4 (MAMI)

- A variety of techniques used to measure with (sub)ppm precision in a scattering experiment.
- Feedback to the injector on helicity-correlated beam properties measured in the experimental hall.

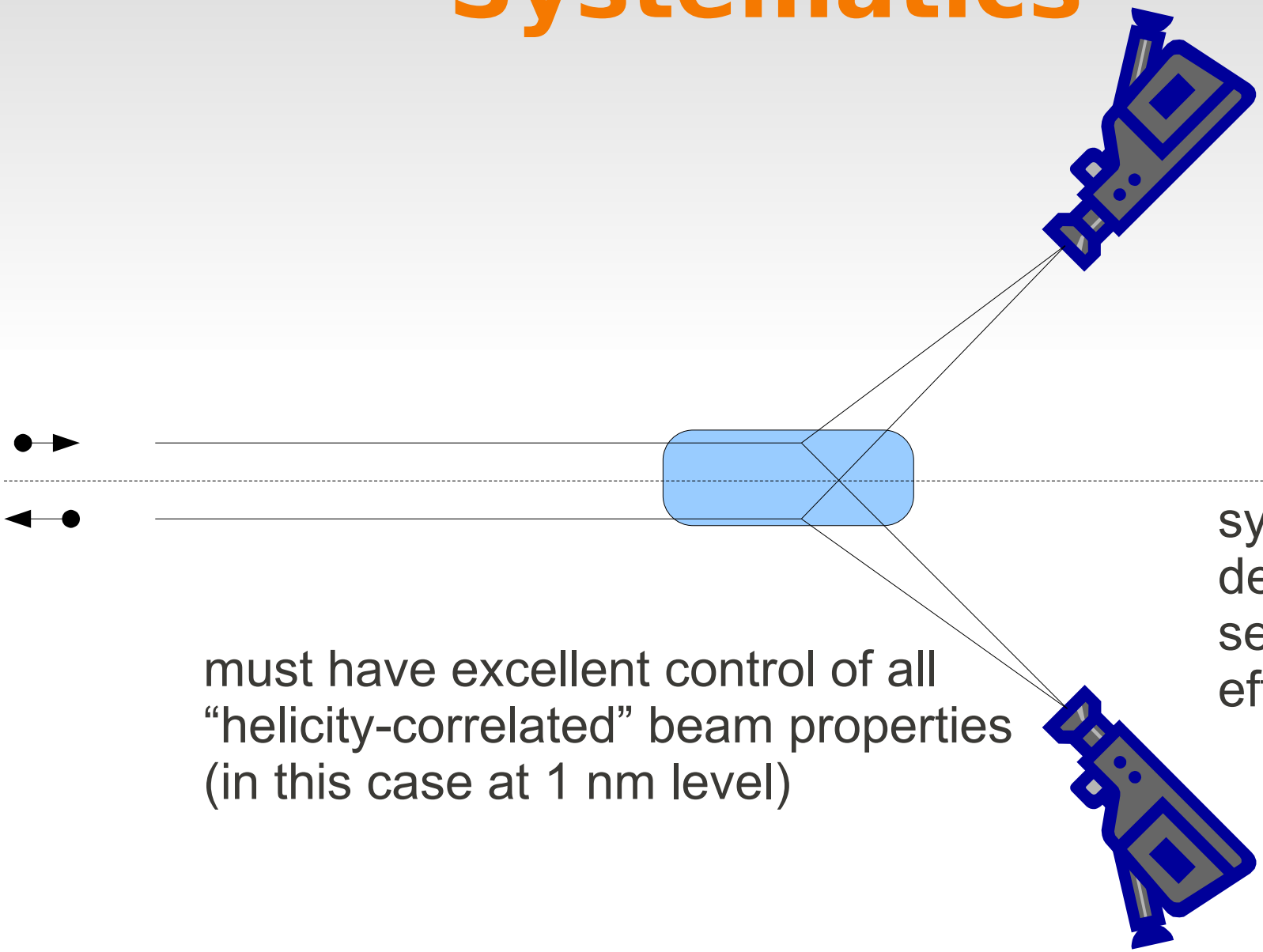
Basic Experiment



$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

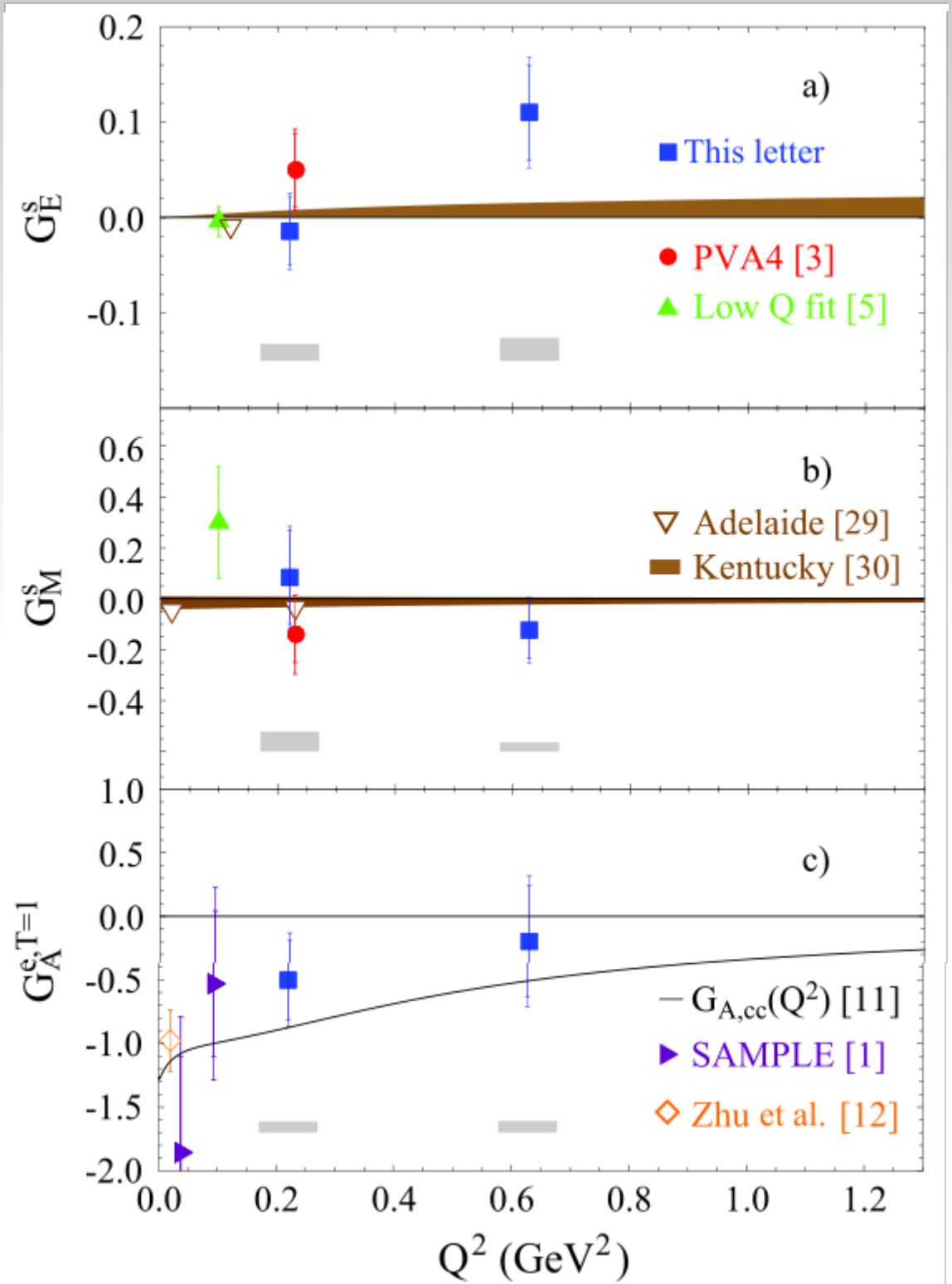
- High rates ~ MHz.

Helicity-Correlated Systematics



symmetry in detector to sense these effects

must have excellent control of all “helicity-correlated” beam properties (in this case at 1 nm level)



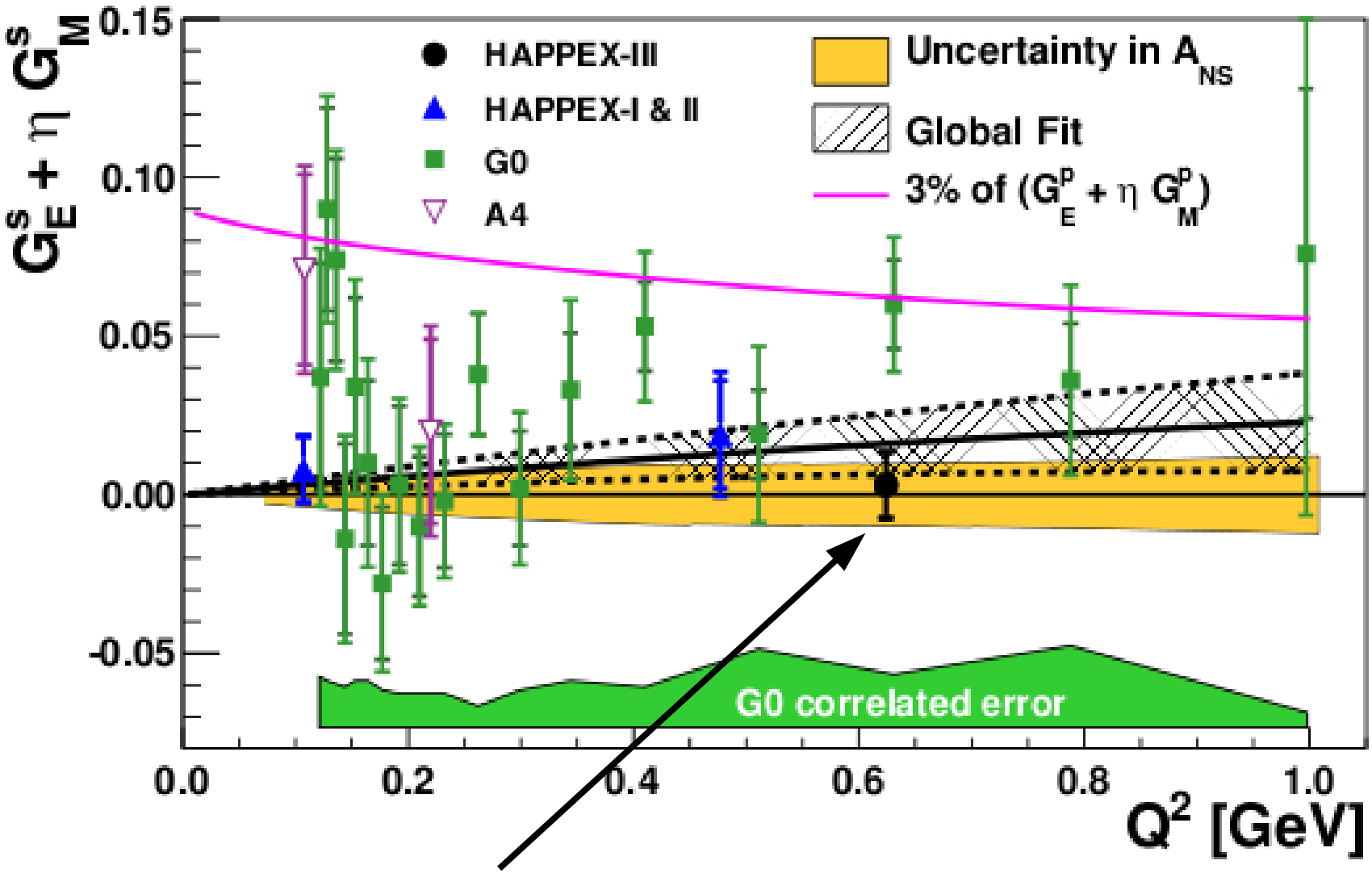
G0, A4, SAMPLE

Results as of last year

(HAPPEX on the next slide)

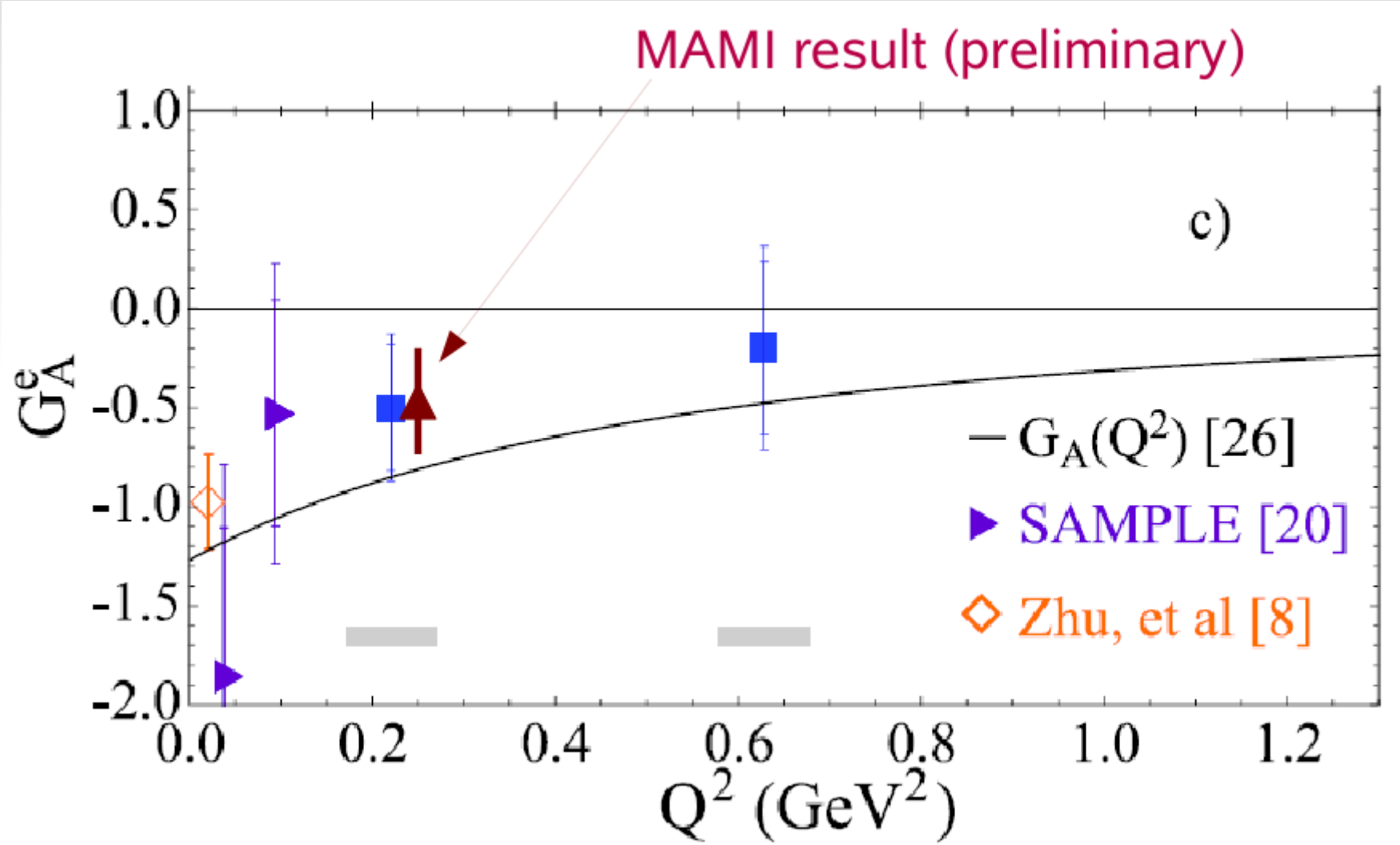
Note: G^s_E and G_A

New: HAPPEX III Results



See: M. Dalton, Session 1A, and global fit

New: A4 Experiment Preliminary LD2 results



- Thank you to S. Baunack.

Strange-quark Summary

- No large or obvious contributions of strange vector form factor in this range of Q^2. Contributions limited to the few percent level.
- Some enticing results on the axial form factor.
  - Is it being suppressed by electroweak radiative corrections?
- Results being analyzed by A4 at $Q^2 = 0.6$ GeV^2. Future running at $Q^2 = 0.1$ GeV^2 by A4.

Inelastic Scattering in the Resonance Region

- Determination of N->Delta axial transition form factors using PV electron scattering
- An interesting suggestion by Zhu et al (based partly on hyperon radiative decay) that the electroweak radiative corrections for this process might also be large.
- Zhu et al suggested the PV asymmetry could be as large as ± 5 ppm at $Q^2 = 0$ (that's very large, by my standards).

G0 Inclusive Pions Results

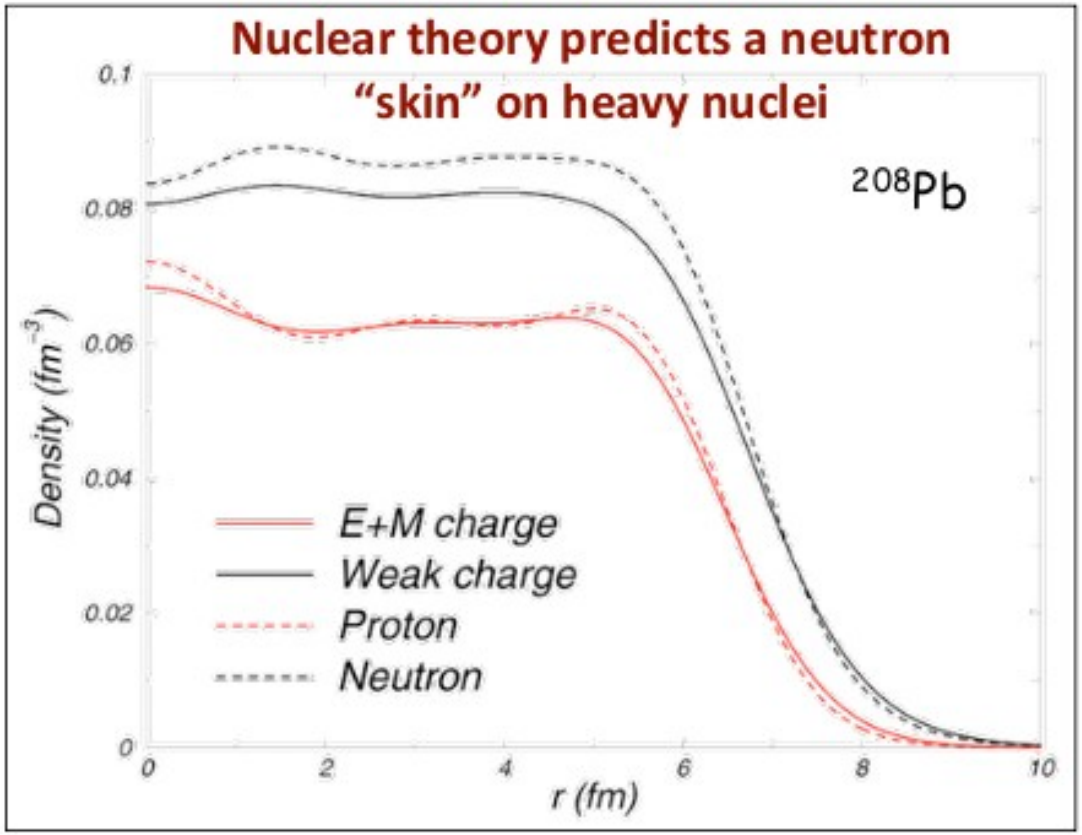
- Pion photoproduction asymmetry extracted:

$$A_{\gamma}^{-} = -0.36 \pm 1.06 \pm 0.37 \pm 0.03 \ ppm$$

A. Coppens, PhD thesis (U. Manitoba, 2010).
G0 Collaboration – in preparation.

- The possibility of an unexpectedly large PV asymmetry in pion photoproduction has been limited to the ppm level.
- More results, in inclusive electron scattering, expected from G0 (higher Q^2) and Qweak (lower Q^2) soon.

Weak Charge Distribution of Heavy Nuclei



Neutron distribution is challenging to interpret from strongly interacting probes (protons, pions, etc.), and is not accessible to the charge-sensitive photon.

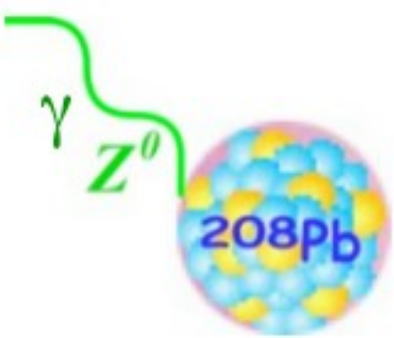
But the weak interaction sees the neutrons clearly:

	proton	neutron
Electric charge	1	0
Weak charge	~0.08	1

PREX (Pb-Radius EXperiment)

$Q^2 \sim 0.01\ \mathrm{GeV}^2$ ⇨ $A_{PV} \sim 0.6$ ppm

5° scattering angle ⇨ Rate ~1.5 GHz



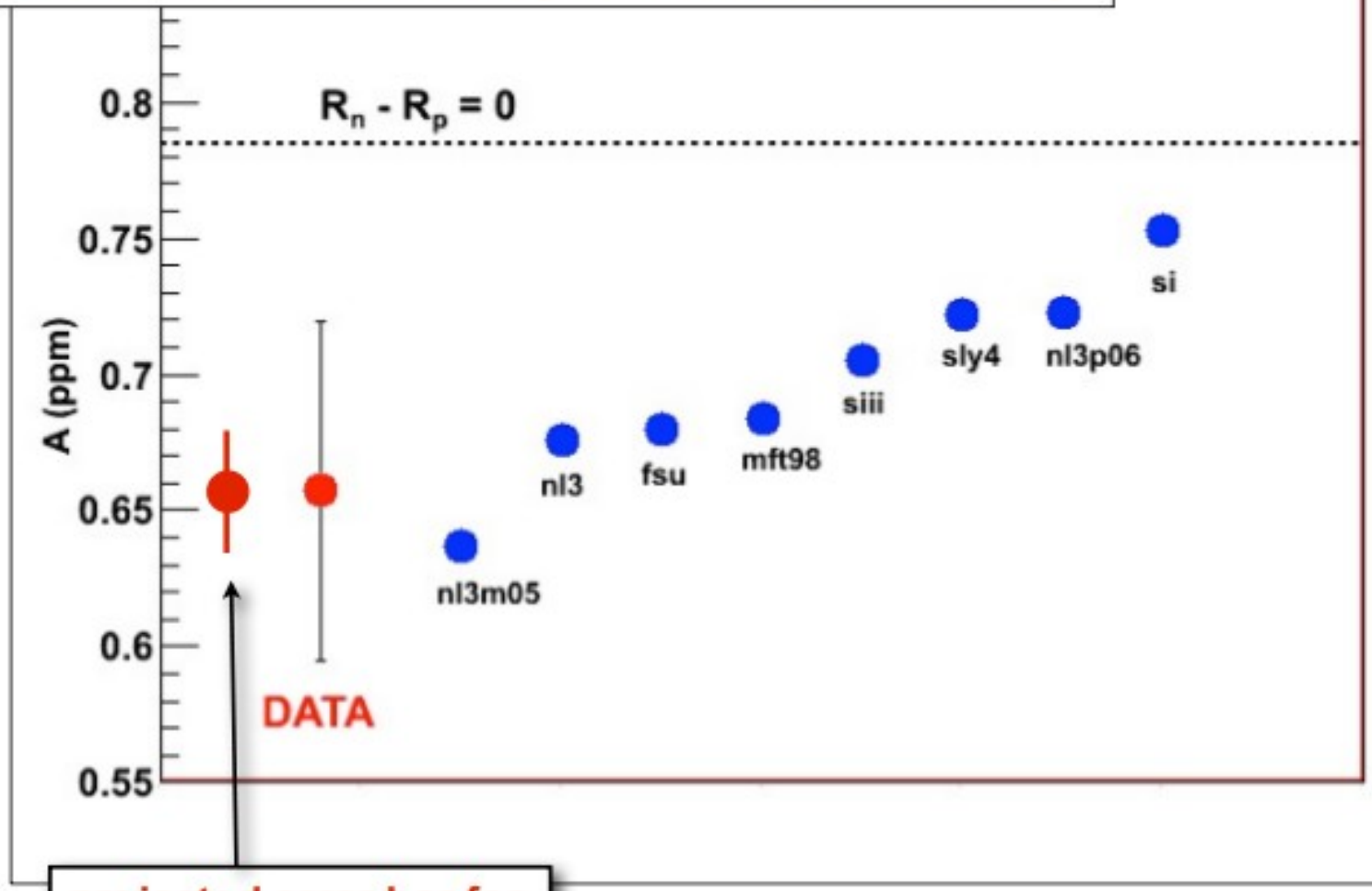
$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$$M_{PV}^{NC} = \frac{G_F}{\sqrt{2}}\left[\left(1 - 4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

PREX Interpetation

First electroweak observation of the neutron skin of a heavy nucleus (CL =95%)



projected error bar for proposed follow up

Thank you, K. Paschke

Neutron Skin = R_N - R_P = 0.34 + 0.15 - 0.17 fm

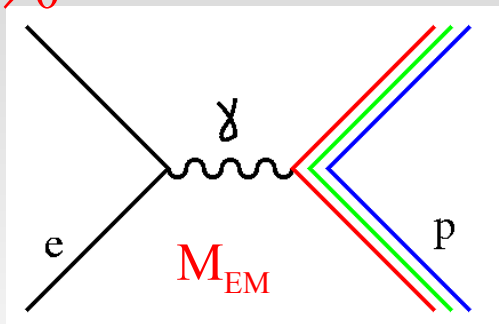
Preliminary estimate from C.J. Horowitz

Parity-Violating Electron Scattering

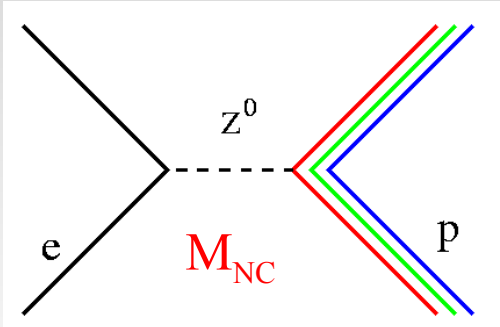
and New Physics

New Physics

As $Q^2 \rightarrow 0$



measures Q^p – proton's electric charge



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

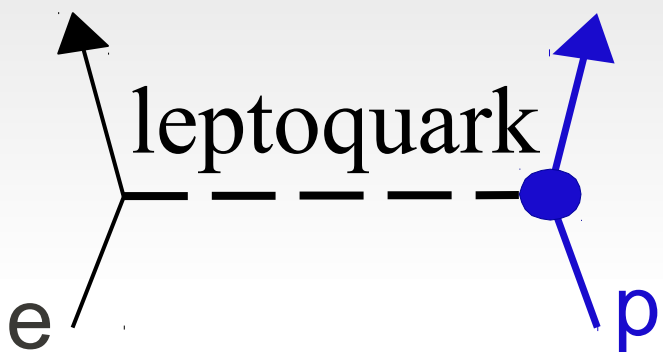
- Measure $\sin^2\theta_W$ using:
  - Moller (ee)
  - Elastic (ep)
  - Deep-inelastic (eq)

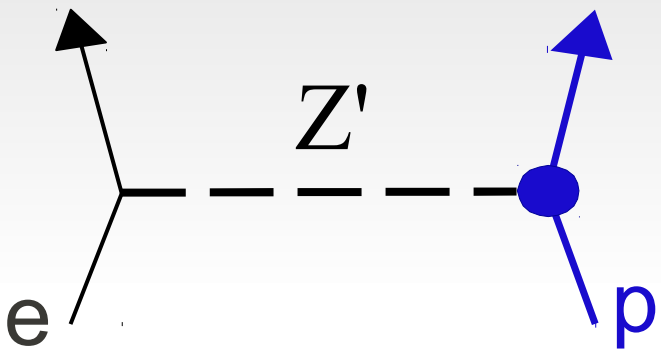
Species	Charge	Weak Charge
u	$+\frac{2}{3}$	$1-\frac{8}{3}\sin^2\theta_W$
d	$-\frac{1}{3}$	$-1+\frac{4}{3}\sin^2\theta_W$
s	$-\frac{1}{3}$	$-1+\frac{4}{3}\sin^2\theta_W$
p	1	$1-4\sin^2\theta_W$
e	-1	$-1+4\sin^2\theta_W$

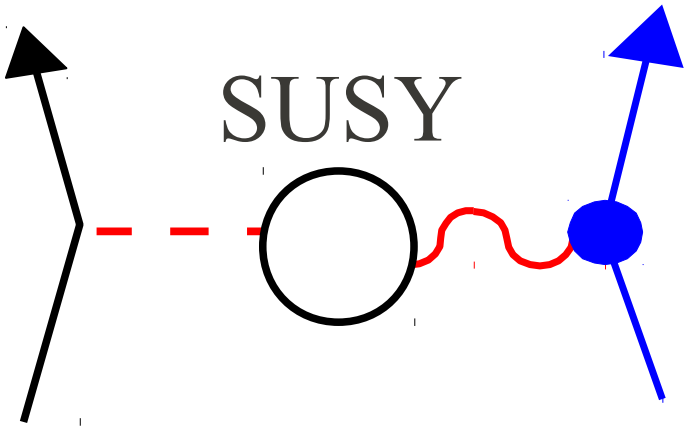
PV electron scattering to probe the weak charges of electrons, protons, and quarks

What New Physics?

- Z-exchange could compete with:

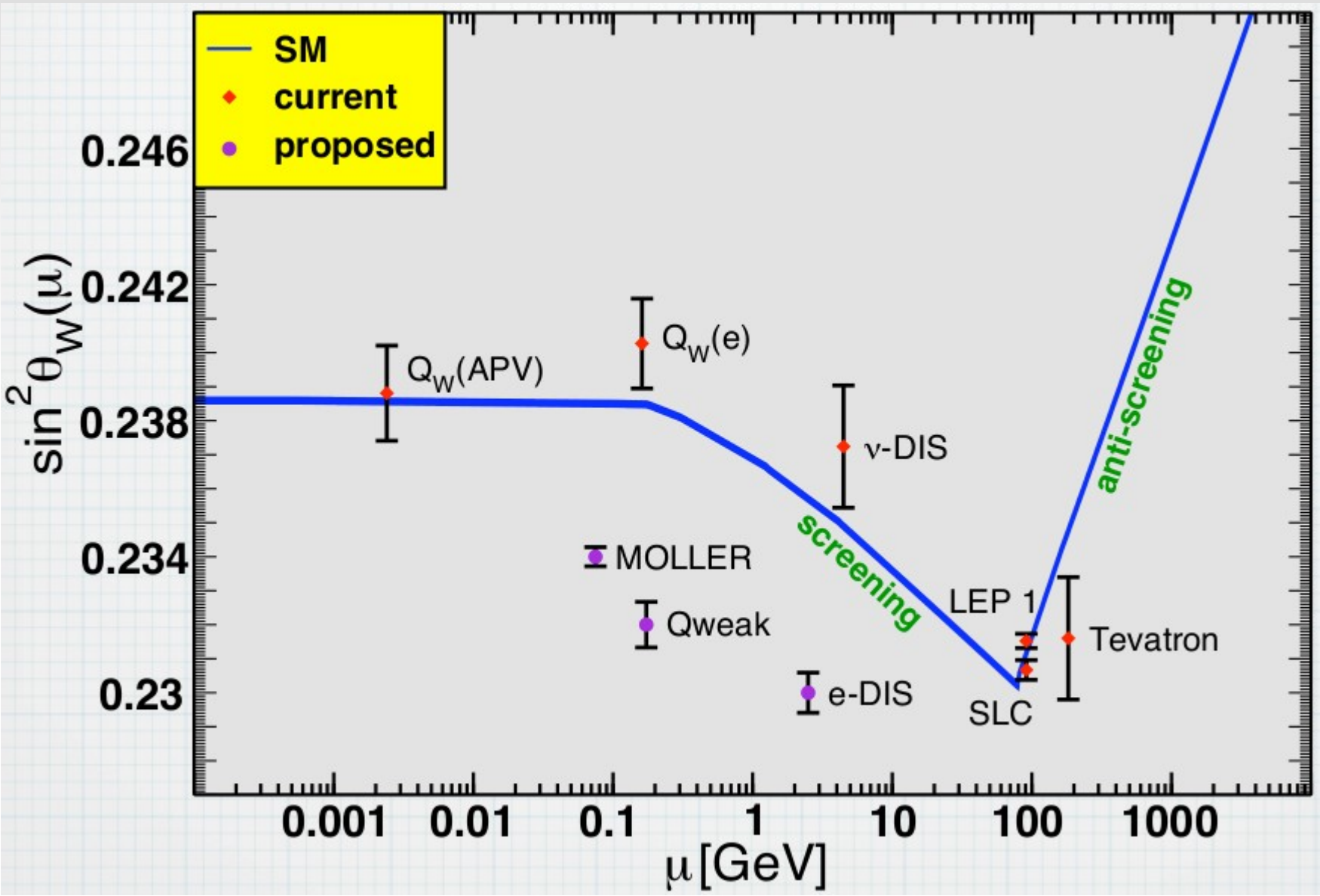






which would affect the running of $\sin^2\theta_W$ with energy.

Running of $\sin^2\theta_W$



From K. Kumar

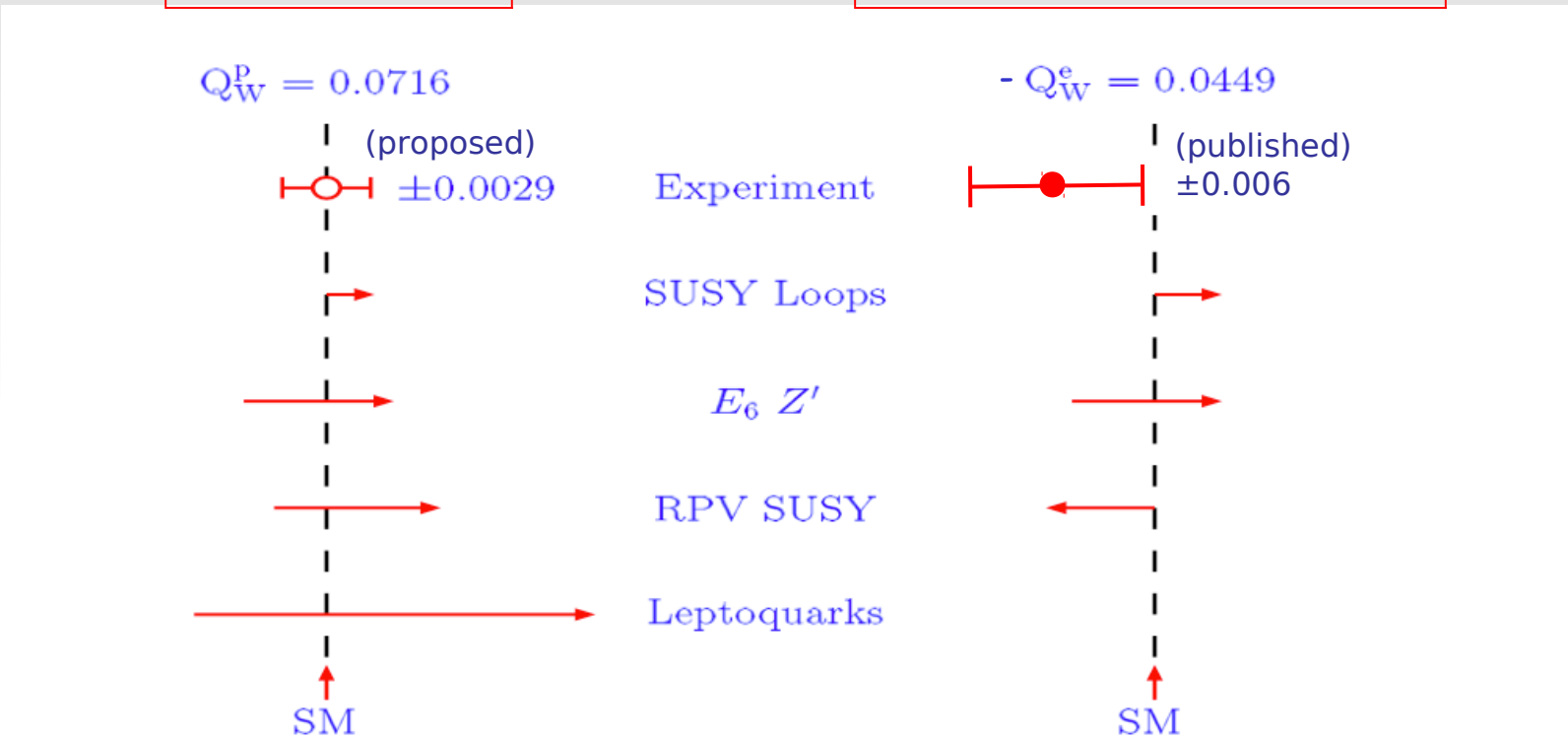
Experiments

- Past:
  - SLAC E122 – PV deep-inelastic scattering of D2
  - SLAC E158 – PV Moller scattering
- Present:
  - Qweak (PV Elastic ep at JLab)
  - PV DIS at 6 GeV (JLab)
- Future:
  - Moller (JLab 11 GeV)
  - SOLID (PV DIS at JLab 11 GeV)
  - P2 (PV elastic ep at MAMI)

Complementary Diagnostics for New Physics

JLab Qweak

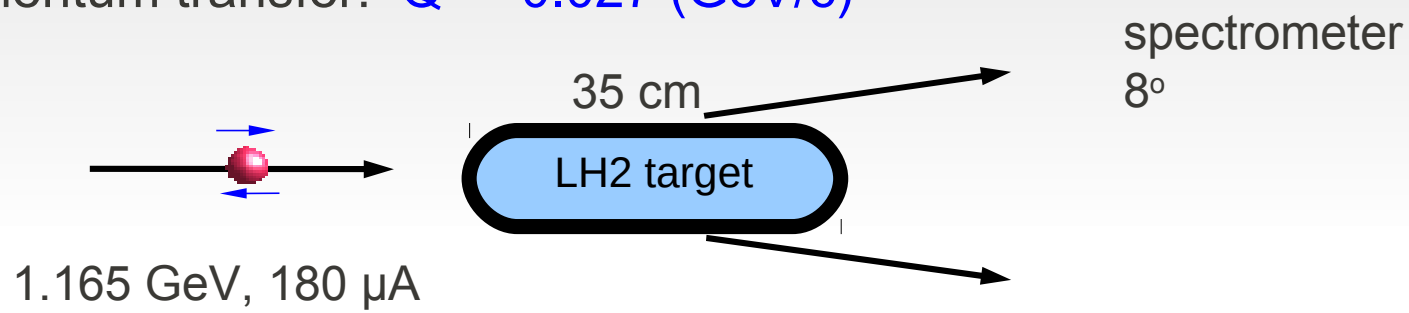
SLAC E158 (complete)



- Elastic, deep-inelastic (semi-leptonic) and Moller (pure leptonic) scattering experiments together make a powerful program to search for and identify new physics. Erler, Kurylov, Ramsey-Musolf, PRD **68**, 016006 (2003)

Qweak Experiment

- Elastic scattering at forward angle
- longitudinally polarized electrons
- rapid helicity-flip: 960 Hz
- low momentum transfer: $Q^2 = 0.027\ (GeV/c)^2$

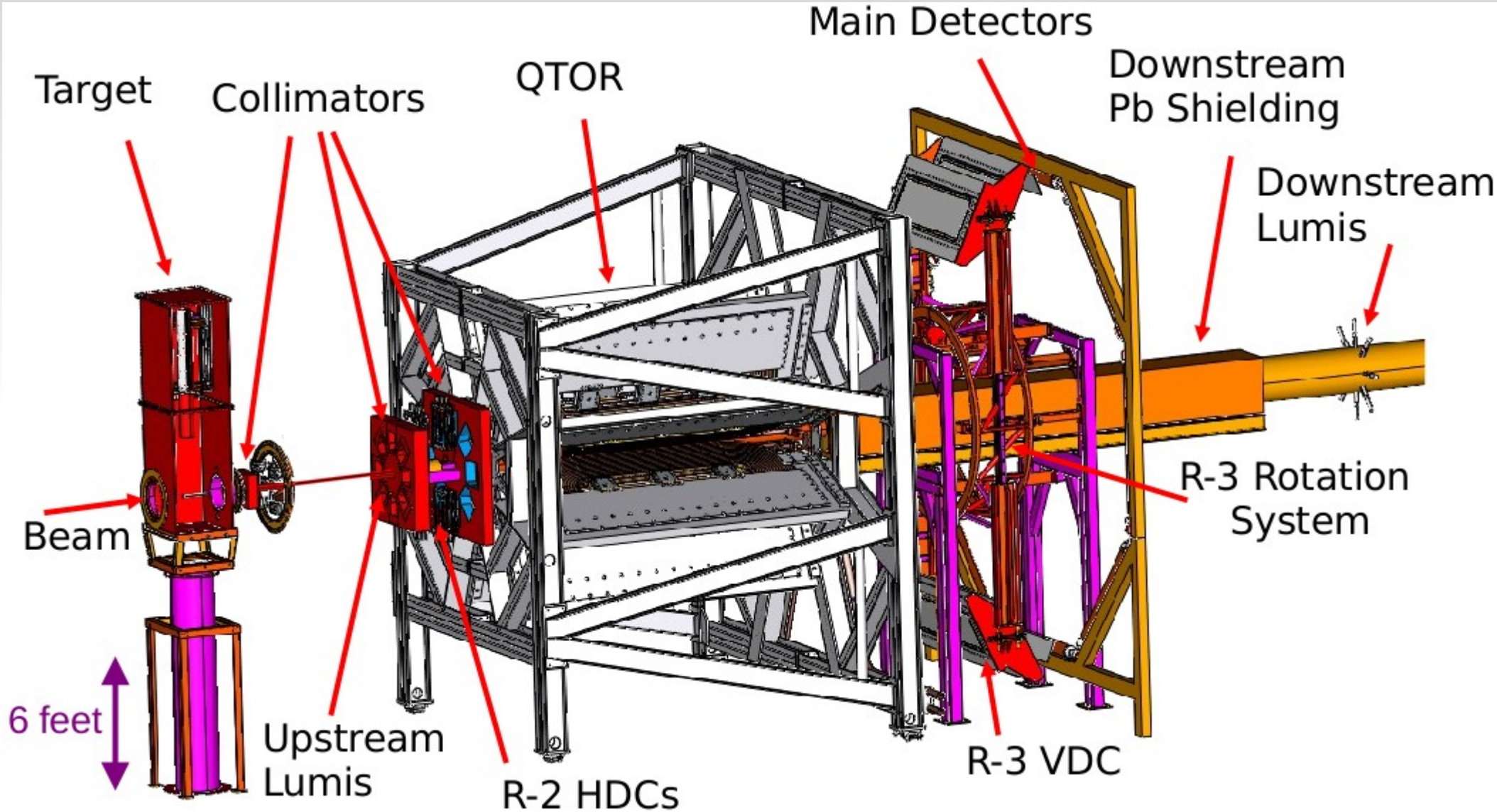


- Expect: $A_{PV} \approx -230$ ppb
- ≈ 5 ppb statistical error in ~2200 hours
- Use eight detectors, 800 MHz each, in "current integrating mode"

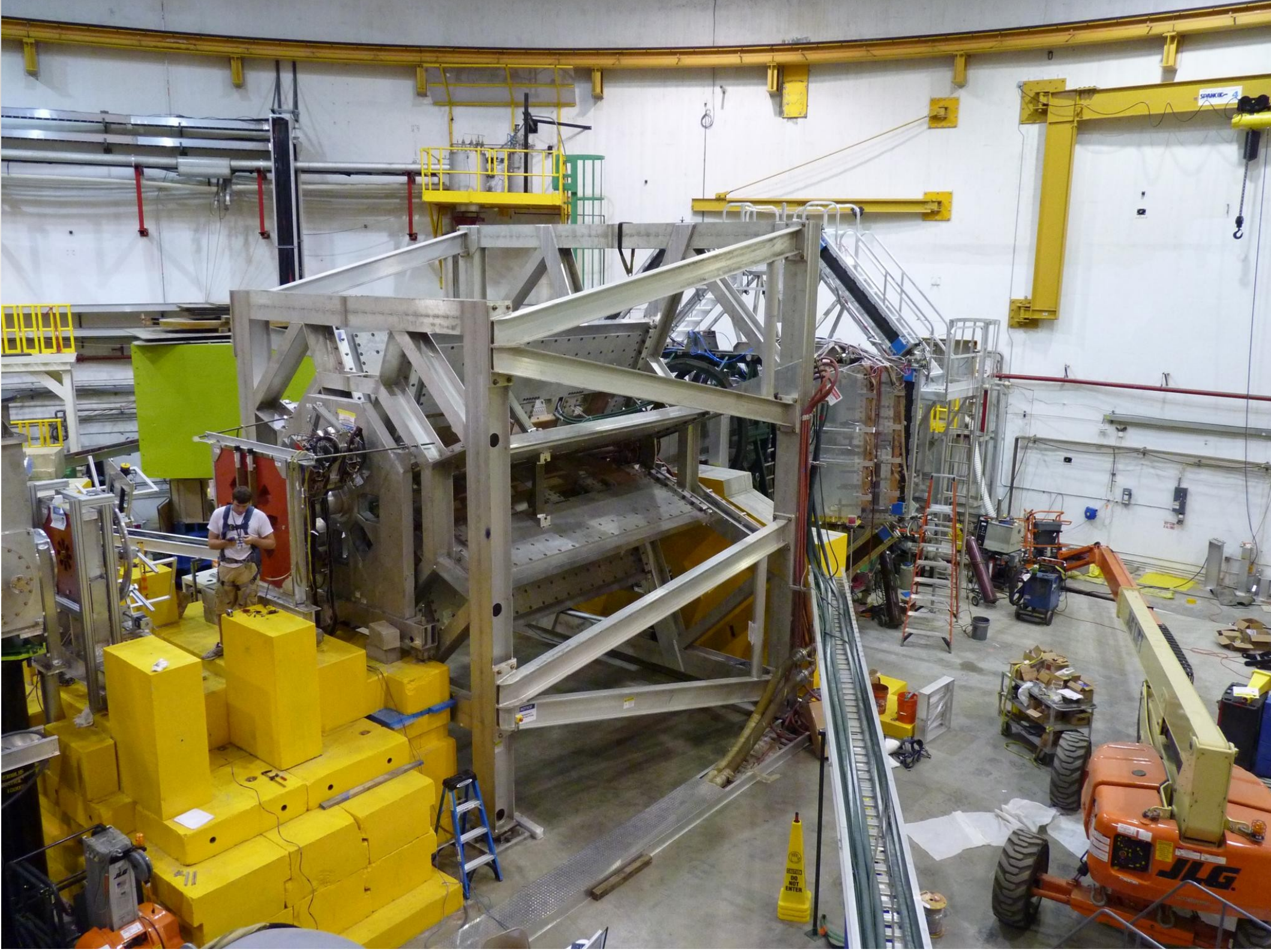
2.5% on A_{PV} 4% on Q_{weak} 0.3% on $\sin^2\theta_W$

See: R. Carlini, Session 3G

Qweak Experiment



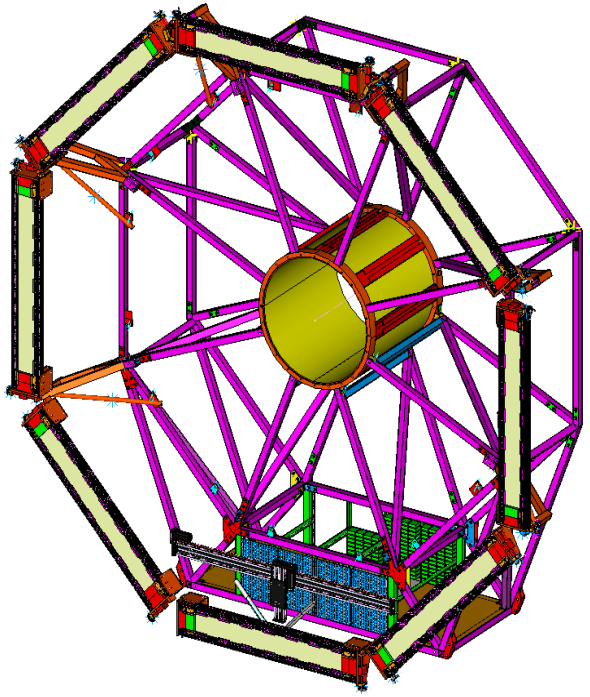
- Scanner detector for current mode tracking results
- New Compton polarimeter has produced %/hr relative measurements.


JLG
DO NOT ENTER

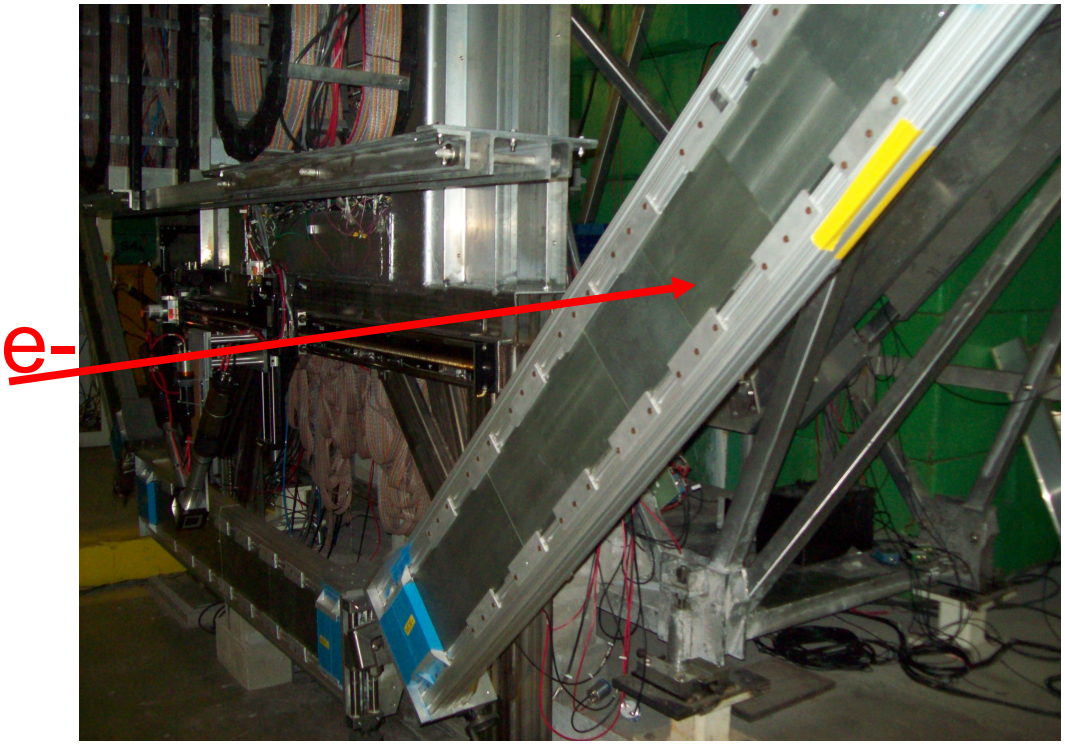
Main Detectors

Eight fused silica bars with dimensions 200 x 18 x 1.25 cm

- Cerenkov radiator
- low noise electronics; high precision ADCs
- radiation hard
- background insensitive
- preradiated to boost signal and kill backgrounds

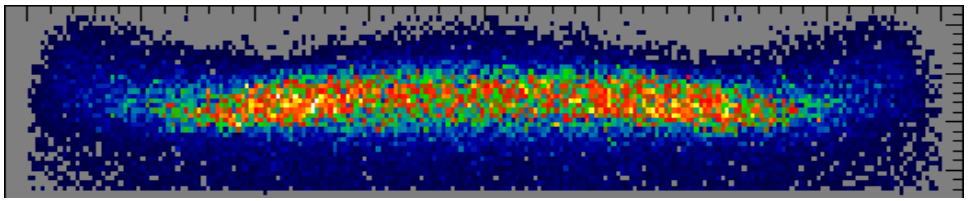


QTOR focuses the elastically scattered electrons onto each bar

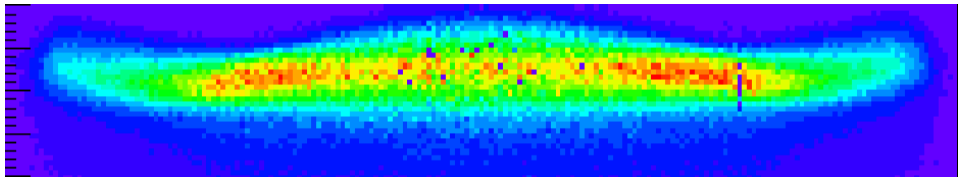


Scanner Rate map on MD face

Simulated



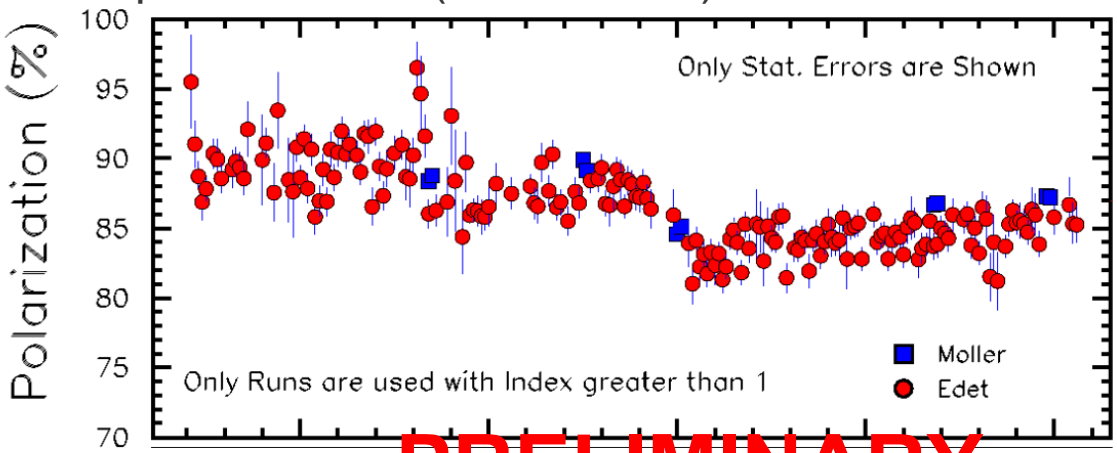
As measured



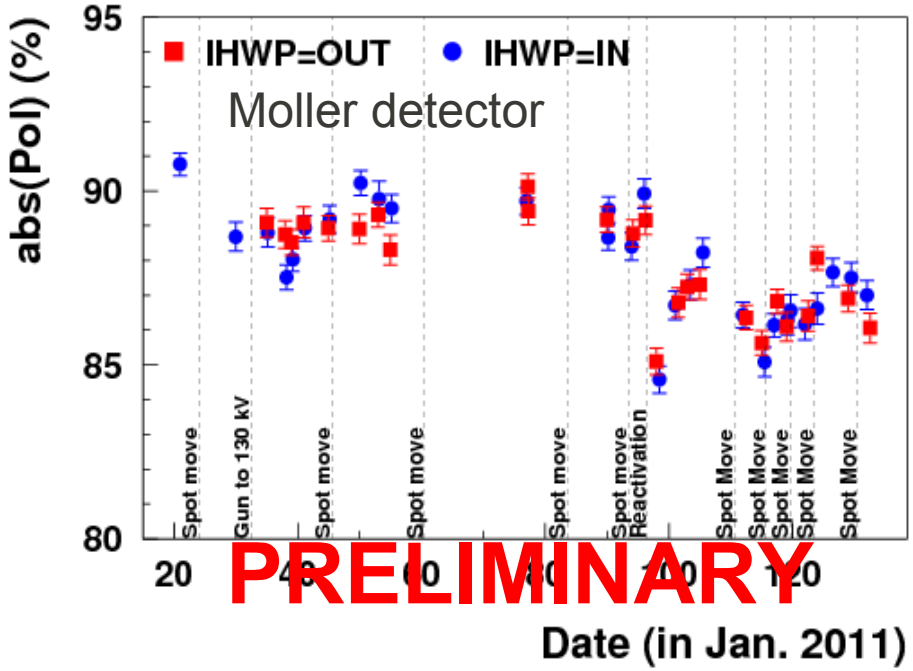
Polarimetry

Motivation:
1% measurement of polarization

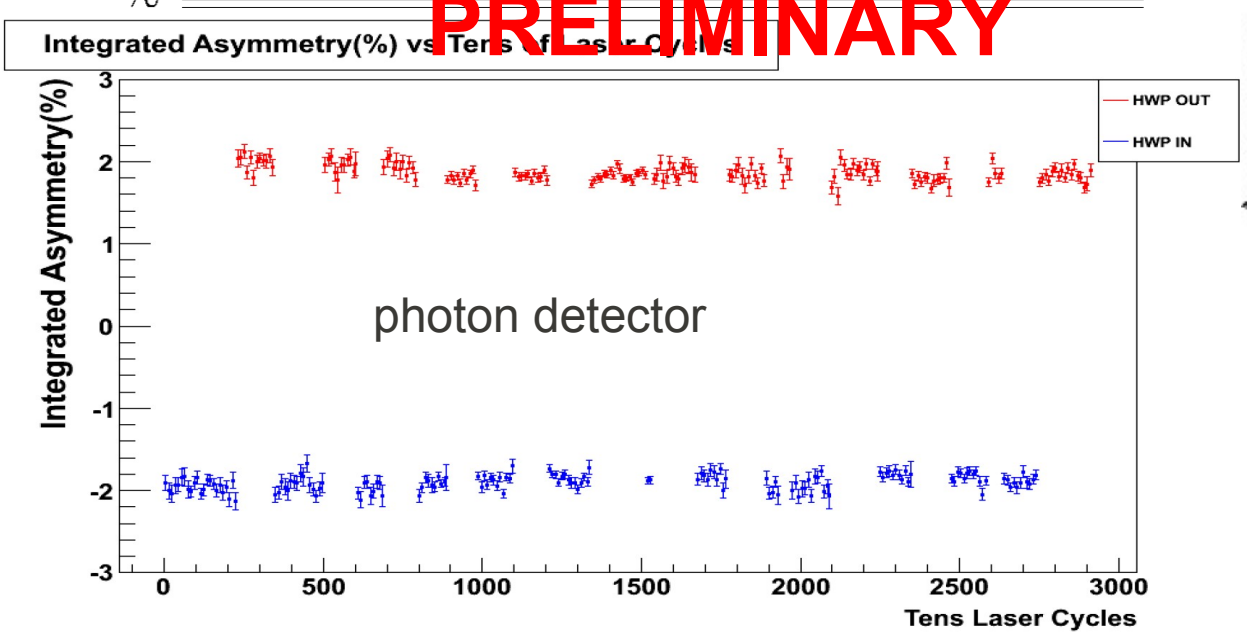
Moller (invasive)
Compton Photon (noninvasive)
Compton Electron (noninvasive)

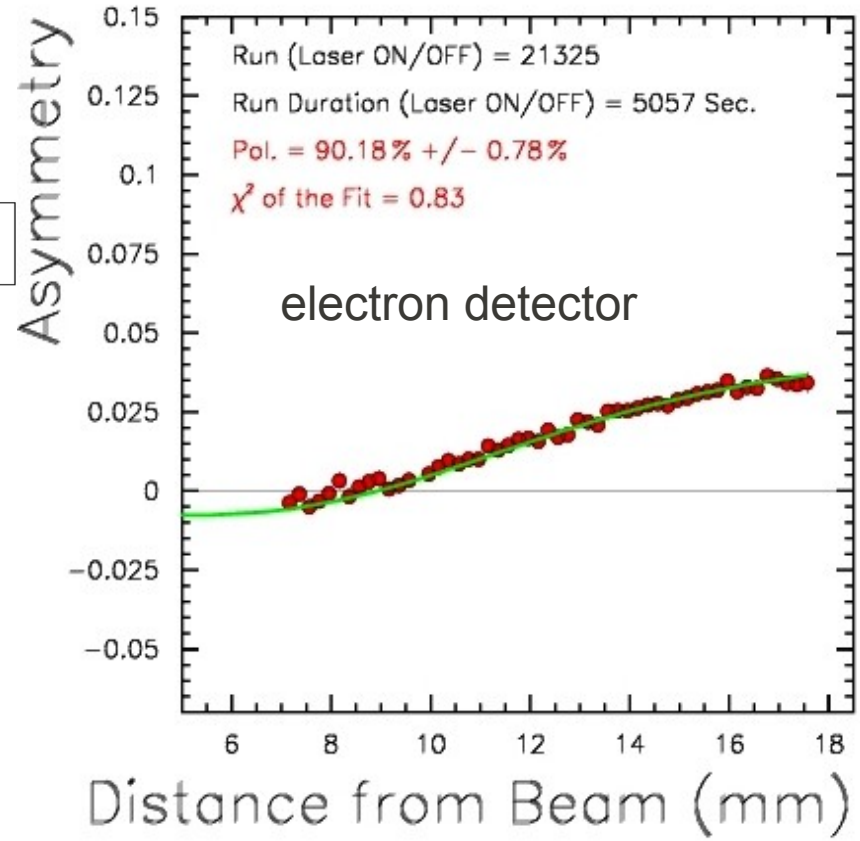


PRELIMINARY



PRELIMINARY





Qweak Status

- First commissioning beam July 2010
- Commissioning Fall 2010
- "Run I" Jan - May 2011
- "Run II" Nov 2011 - May 2012

Beam: routine data-taking at 165 μA , tests up to 180 μA (scheduled for 150 μA)
: ≈ 86-89% polarization
: helicity-correlated properties acceptable

Some teething pains: Target pump, Toroid power supply, beam dump vacuum,…

At present: have "in hand" ≈ 1/4 of proposed statistics

Initial Auxiliary measurements done:
- APV for Aluminum (target windows)
- APV for
- Parity-conserving transverse asymmetry

(each valuable and competitive measurements on their own)

See: R. Carlini, Session 3G

Electroweak Radiative Corrections

Source	Q^p_{Weak} Uncertainty
$\Delta \sin\theta_W (M_Z)$	±0.0006
$Z\gamma$ box	
$\Delta \sin\theta_W (Q)_{hadronic}$	±0.0003
WW, ZZ box - pQCD	±0.0001
Charge symmetry	0
Total	±0.0008

Erler, Kurylov, Ramsey-Musolf

PRD 68(2003)016006.

(c.f. $Q^p_{weak} \approx 0.07$)

Estimates of $Z\gamma$ box diagram on Q^p_{weak} **(at our kinematics)**

Gorchtein & Horowitz **~ 7%**

Phys. Rev. Lett. 102, 091806 (2009)

Sibirtsev, Blunden, Melnitchouk, Thomas **$6.6^{+1.5\%}_{-0.6\%}$**

Phys. Rev. D 82, 013001 (2010)

Rislow and Carlson **8.0 ± 1.3%**

arXiv:1011.2397

Gorchtein, Horowitz, Ramsey-Musolf **7.6 ± 2.8%**

arXiv:1102:3910

See: C. Carlson, Session 1A

E08-011 Measurement of PV Asymmetry in e-D Deep Inelastic Scattering (PVDIS) Using a 6 GeV Beam at JLab

- e-D PVDIS asymmetry:

$$A_d = (540\ ppm)Q^2 \frac{2C_{1u}[1+R_C(x)] - C_{1d}[1+R_S(x)] + Y(2C_{2u} - C_{2d})R_V(x)}{5+R_S(x)+4R_C(x)}$$

Standard Model Neutral Weak Couplings: $C_{1q} = g_A^e g_V^q$ $\quad C_{2q} = g_V^e g_A^q$

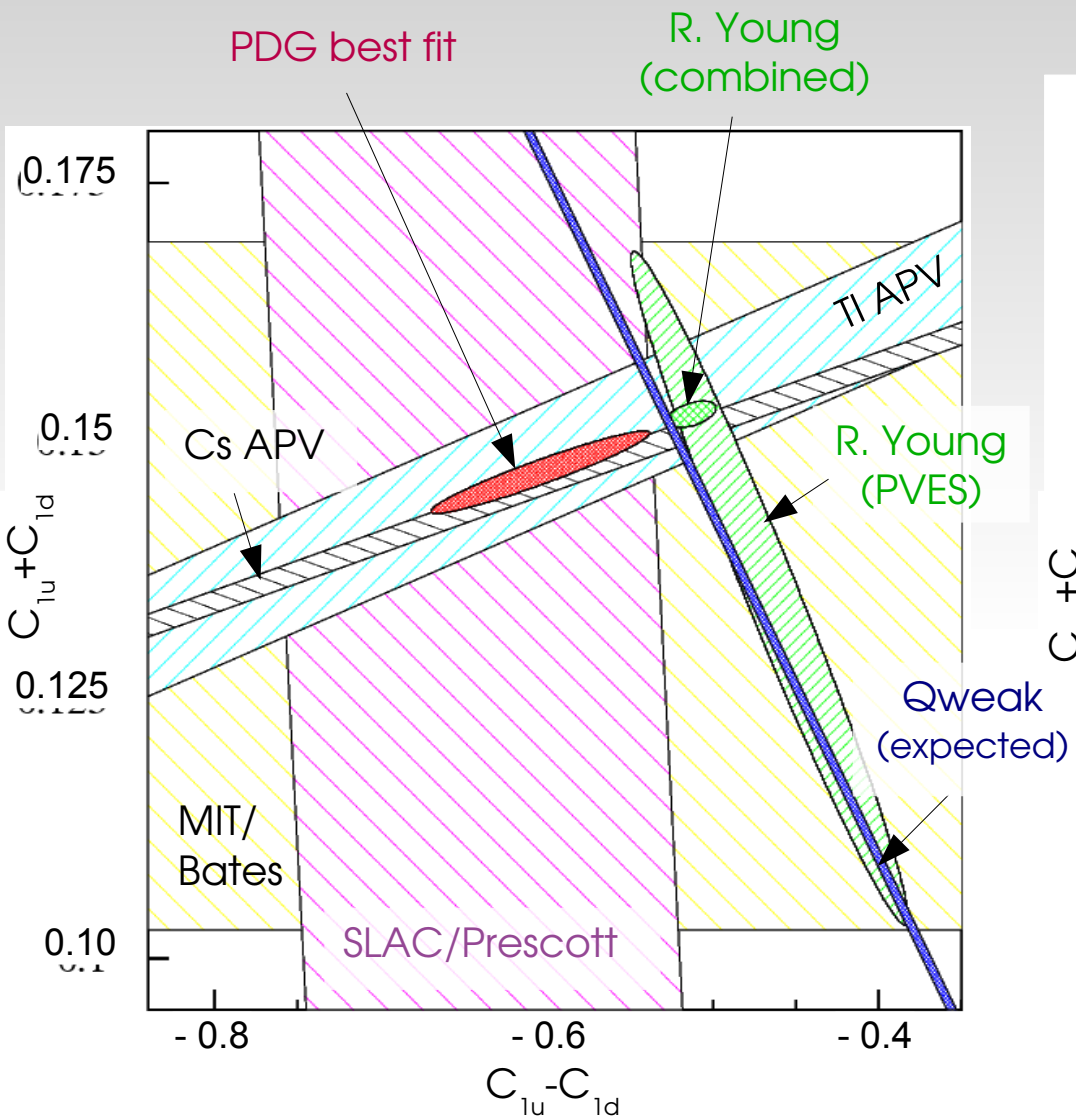
$$R_S(x) = \frac{2[s(x)+\bar{s}(x)]}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)} \quad R_C(x) = \frac{2[c(x)+\bar{c}(x)]}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)} \quad R_V(x) = \frac{u_V(x)+d_V(x)}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)}$$

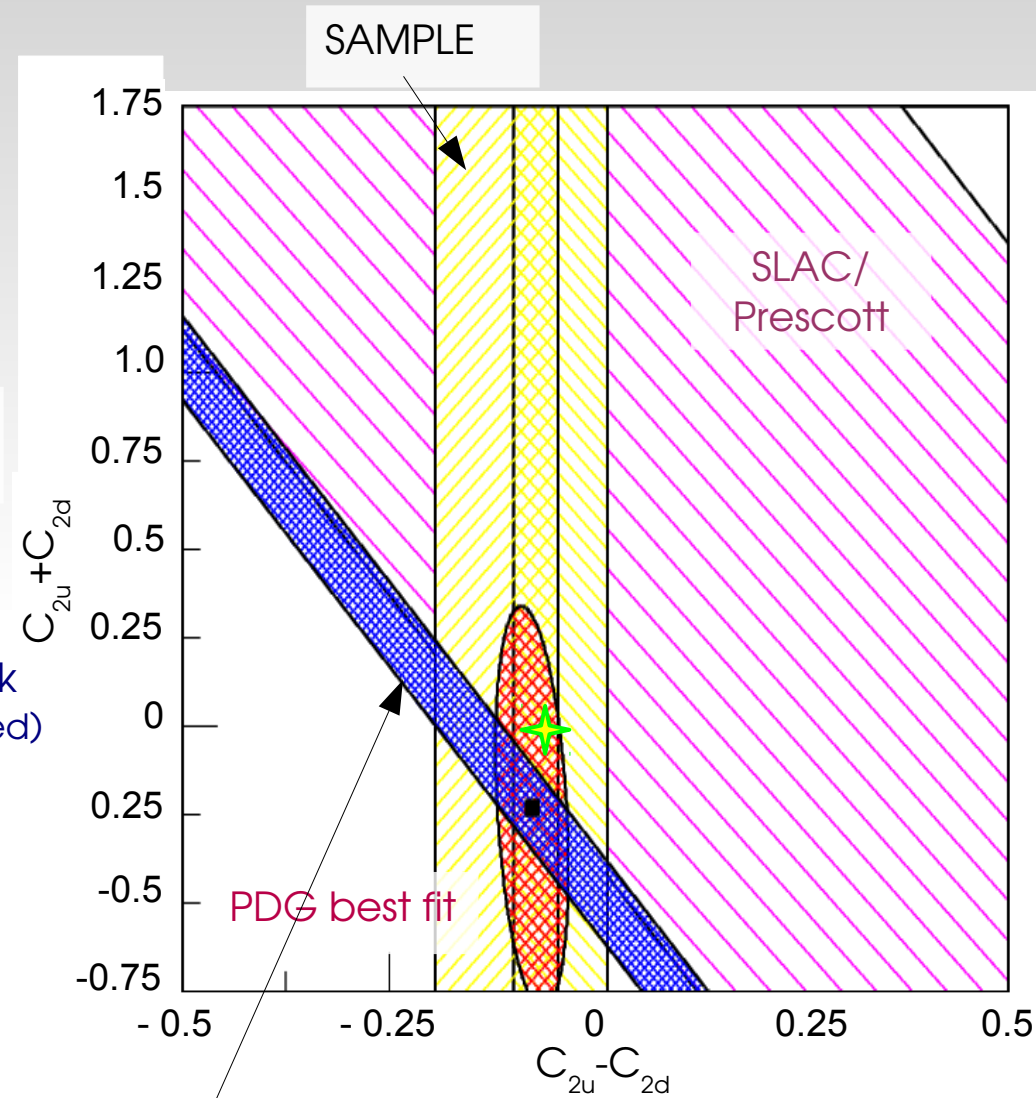
- E08-011: measured A_d at Q^2=1.1 and 1.9 GeV^2, to statistical precision of 3% and 4%, respectively.
  - 100 microA, 90% polarized beam
  - 20-cm LD2 target, two standard spectrometers collecting electrons independently.
  - Custom-built scaler-counting DAQ with hardware-based PID to accommodate ~500kHz rate
  - Ran in October-December 2009, expect to unblind the asymmetries by end of 2011.

Thank you, X. Zheng

See: Kai Pan, Session 1A

Expected Results on C_{2q} from E08-011 all are 1 σ limit





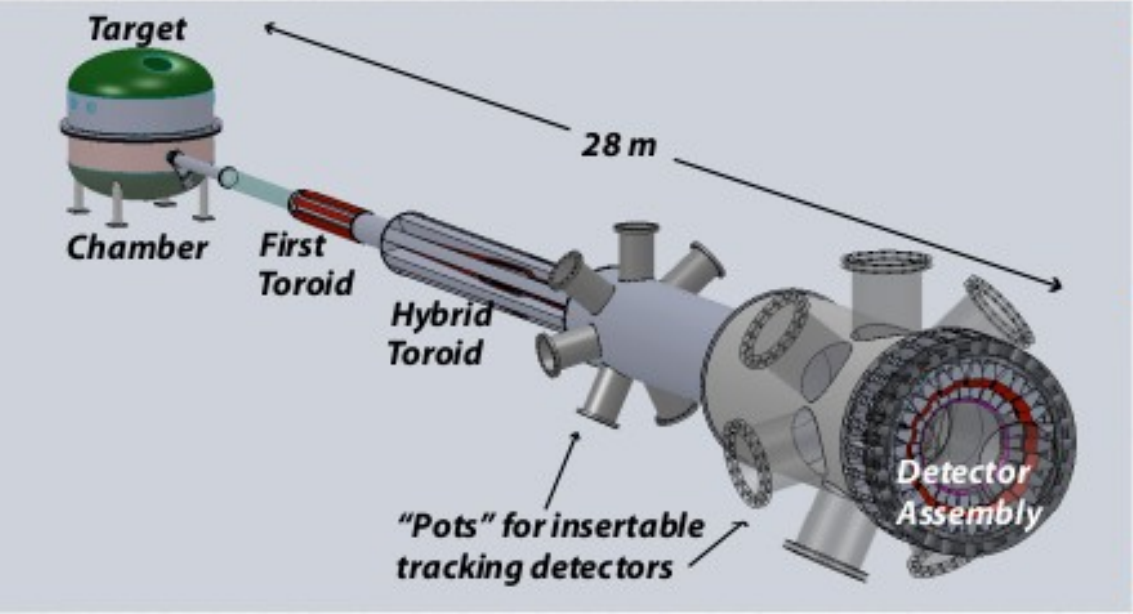
- Best world data: $\Delta(2C_{2u}-C_{2d}) = 0.24$

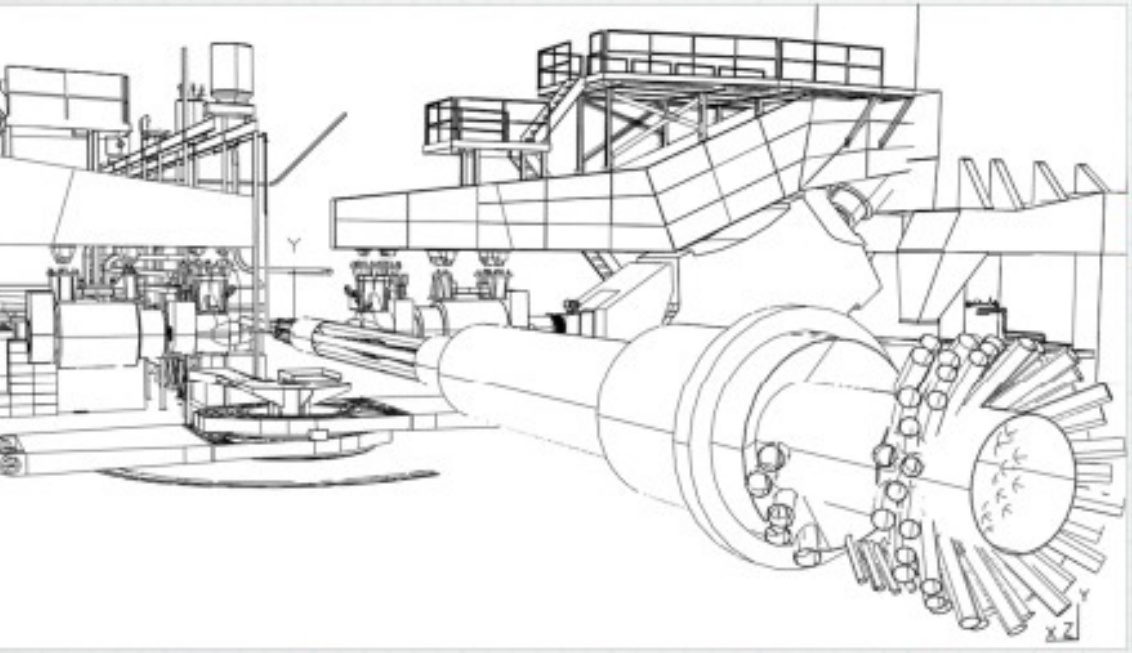
Expected: JLab 6 GeV PV-DIS E08-011 (assuming small hadronic effects and a 4% stat error on Ad)

Elastic Scattering

Deep-Inelastic Scattering

MOLLER Apparatus





* **Polarized Beam**
  - *Unprecedented polarized luminosity*
  - *unprecedented beam stability*
* **Liquid Hydrogen Target**
  - *5 kW dissipated power (2 X Qweak)*
  - *computational fluid dynamics*
* **Toroidal Spectrometer**
  - *Novel 7 "hybrid coil" design*
  - *warm magnets, aggressive cooling*
* **Integrating Detectors**
  - *build on Qweak and PREX*
  - *intricate support & shielding*
  - *radiation hardness and low noise*

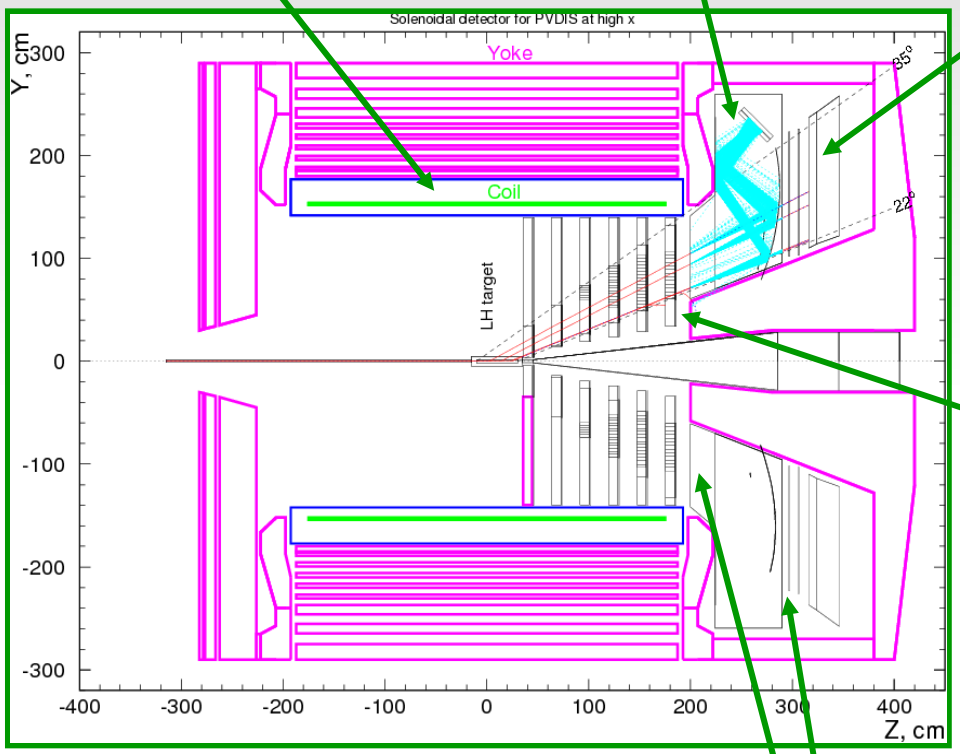
compact structure: plan to make apparatus and sheilding easily removable

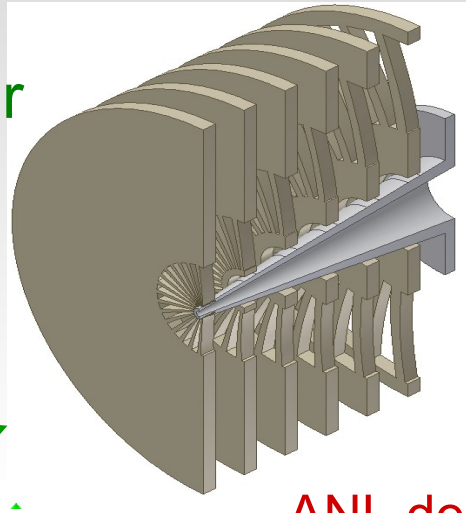
SoLID Spectrometer

Babar Solenoid

Gas Cerenkov

Shashlyk Calorimeter

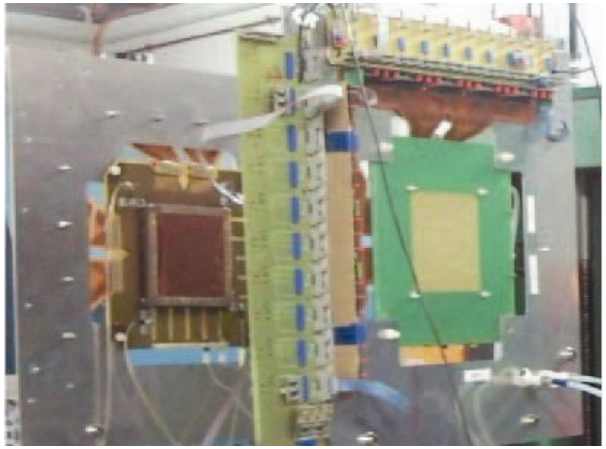




ANL design

Baffles

GEM's



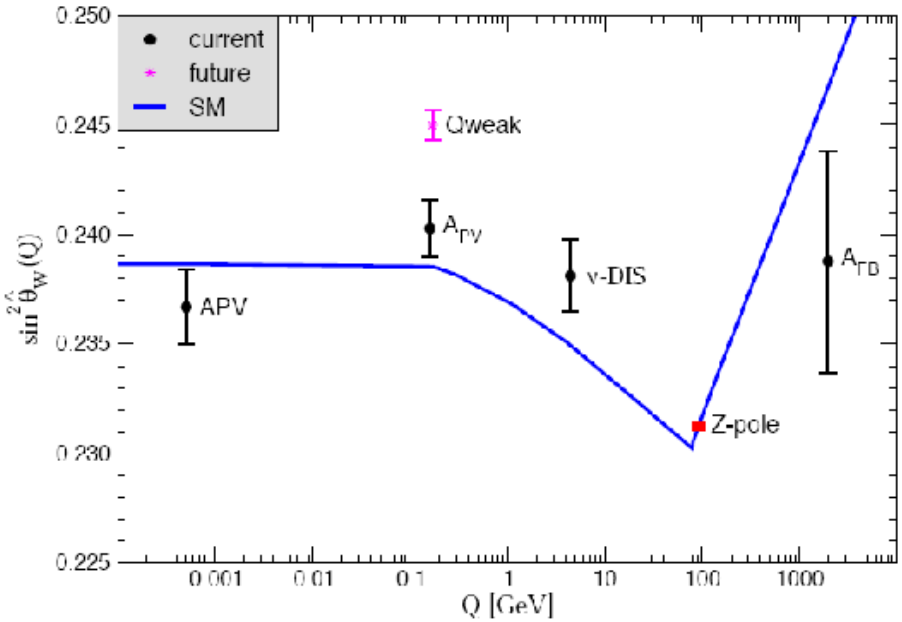
JLab/UVA prototype

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

See: P. Souder, Session 1A

New project: P2

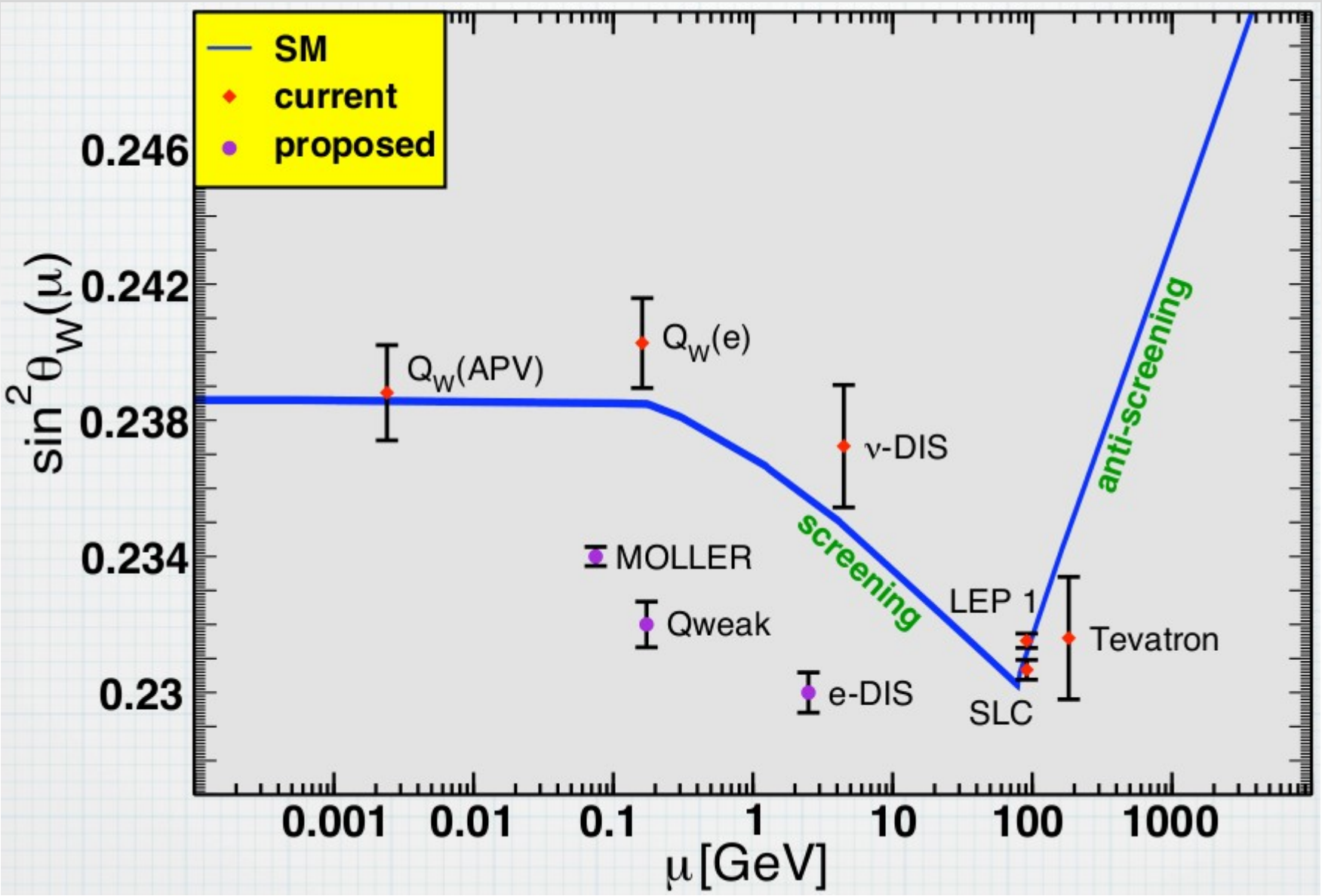
- Measurement of the weak charge of the proton at low $Q^2 \sim 0.0022$ GeV²
- New detector
- Enhanced polarimetry (*Brute force Moller, Double Mott => Mainz 0.5*)
- Beam energy 137 MeV (*low theoretical uncertainties due to two-boson-exchange*)
- Precision goal: $\Delta \sin^2\Theta_W = 0.0003$ (1‰)
- Time scale: 2015 - 2020



Being considered for MAMI accelerator at Mainz

Thank you, S. Baunack.

Outlook on $\sin^2\theta_W$



In different TeV-scale new physics scenarios, the future points could be scattered about, ...even appearing on different sides of the curve!

Summary

- Parity-violating electron scattering is a useful tool to study hadron structure and to probe new physics beyond the standard model.
- The field is in an exciting period where past investments in the use of this technique for structure studies are transitioning to precision measurements of standard model parameters.
- Complementary to other neutral-current techniques (please come to session 3G, this afternoon)
- There are many opportunities and a long-term future in this exciting field.

Acknowledgments

- Thank you to:
  - D. Armstrong, S. Baunack, P. King, K. Kumar, J. Leacock, F. Maas, K. Paschke, M. Pitt, P. Souder, and X. Zheng for providing slides and information.