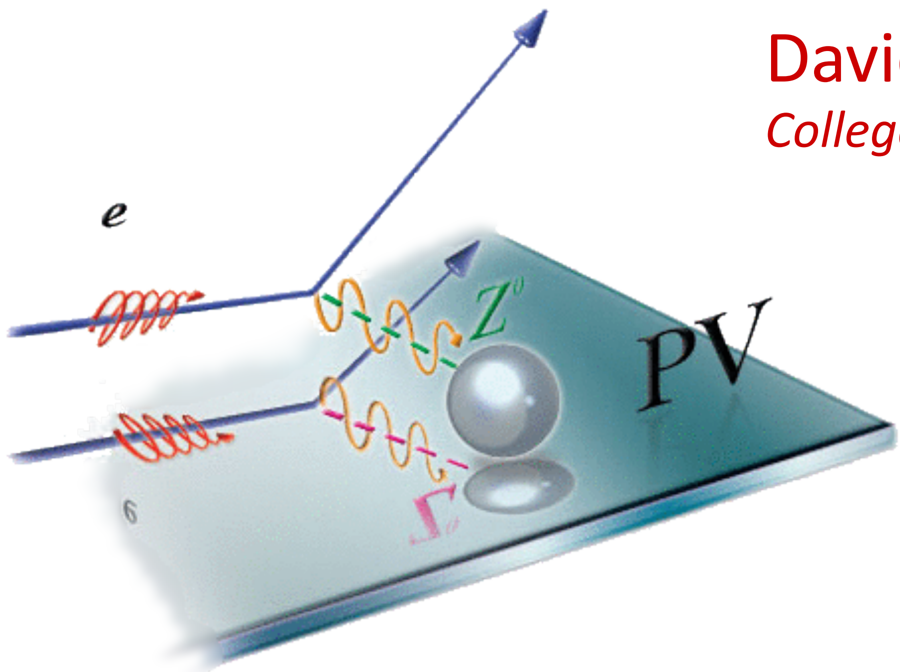
The Proton's Weak Charge



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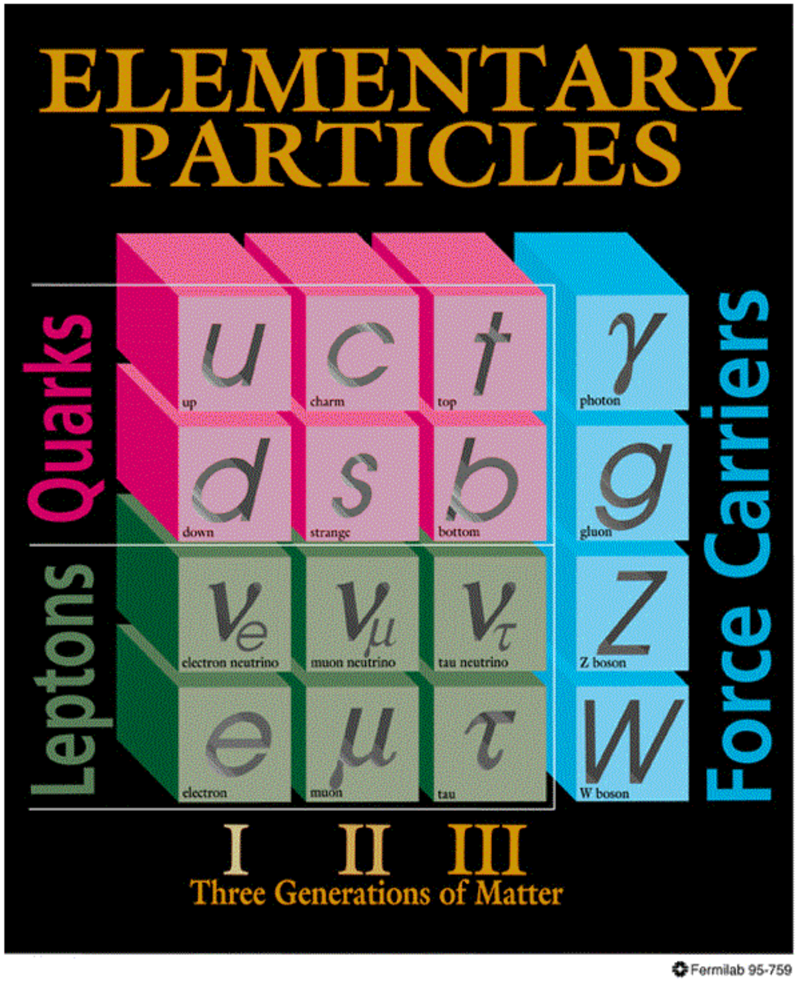
March 7 2014

The College of WILLIAM & MARY

Jefferson Lab

The Standard Model



- Building blocks are quarks and leptons

  point-like, spin ½ particles

- Forces mediated by exchange of spin 1 particles:

- neutral currents (γ ,Z, gluon)
- One charged current (W^{+-})
- One colored current (gluon)

The **Standard Model** is not just building blocks….

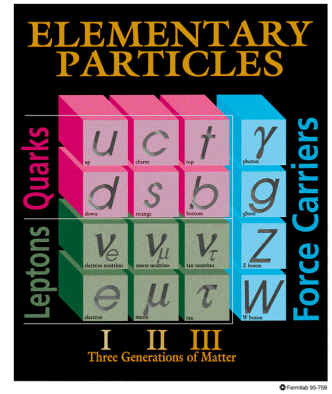
$$
\begin{aligned}
\mathcal{L} = \; & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R \sigma^\mu iD_\mu e_R + \bar{\nu}_R \sigma^\mu iD_\mu \nu_R + \text{(h.c.)} && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R \sigma^\mu iD_\mu u_R + \bar{d}_R \sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu \phi)} D^\mu \phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}
$$

It is a rigorous, mathematically consistent theory that makes detailed and precise predictions of many phenomena… and, to date, it has
never had a prediction definitively disproved by experiment!

The recent discovery of the Higgs Boson at the LHC at CERN (needed for this mathematical consistency) "completes" the Standard Model…

so what is left to study?

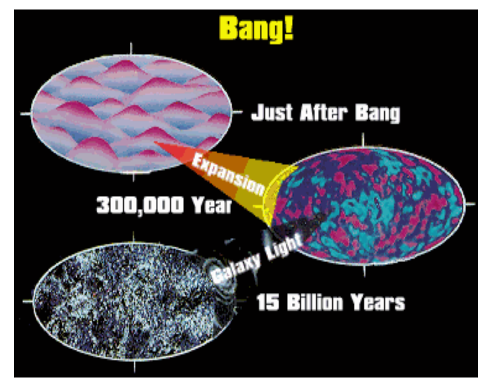
The Standard Model: Issues



- *Lots* of free parameters (masses, mixing angles, and couplings)
  How fundamental is that?

- **Why 3 generations of leptons and quarks?**
  Begs for an explanation
  (smells like a periodic table)

- **Hierarchy problem: the Higgs boson is much lighter than it "should" be**
  ($M_{Planck} \approx 1 \times 10^{19}$ GeV)



- Insufficient CP violation to explain all the matter left over from Big Bang …

- Doesn't include gravity, dark matter, dark energy….

Belief in a rational universe suggests that our SM is only a low-order approximation of reality, as Newtonian gravity is a low-order approximation of General Relativity.

Finding evidence for Physics Beyond the Standard model
– *the "Holy Grail" of modern subatomic physics…*

Search for physics *Beyond the Standard Model*

- Received Wisdom: Standard Model is incomplete, and is low-energy effective theory of more fundamental physics
- Low energy ($Q^2 \ll M^2$) precision tests: complementary to high energy measurements

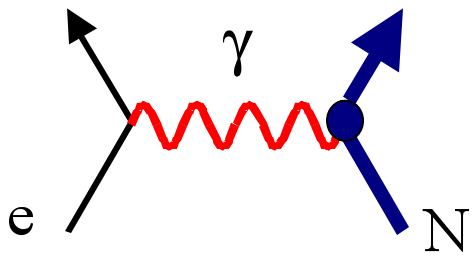
- ***Neutrino mass and their role in the early universe*** — $0\nu\beta\beta$ *decay*, θ_{13}, β *decay,…*
- ***Matter-antimatter asymmetry in the present universe*** — *EDM, DM, LFV,* $0\nu\beta\beta$, θ_{13}
- ***Unseen Forces of the Early Universe*** — *Weak decays,* ***PVES****,* g_μ*-2,…*

LHC new physics signals likely will need additional indirect evidence to pin down their nature

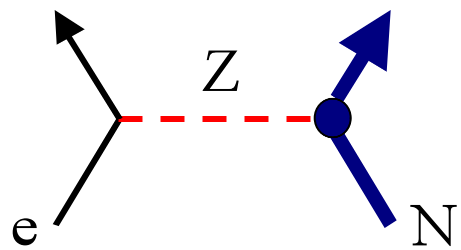
- ***Neutrons:*** *Lifetime, P- & T-Violating Asymmetries (LANSCE, NIST, SNS...)*
- ***Muons:*** *Lifetime, Michel parameters, g-2, Mu2e (PSI, TRIUMF, FNAL, J-PARC...)*
- ***PVES:*** *Low-energy weak neutral current couplings, precision weak mixing angle (SLAC, Jefferson Lab, Mainz)*
- ***Atoms:*** *atomic parity violation*

Ideal*: select observables that are zero, or significantly suppressed, in Standard Model*

Electroweak scattering of electrons



Electron scattering via electromagnetism



Electron scattering via weak interaction

10^6 times smaller amplitude at these energies

Final state is *identical* in the two cases…

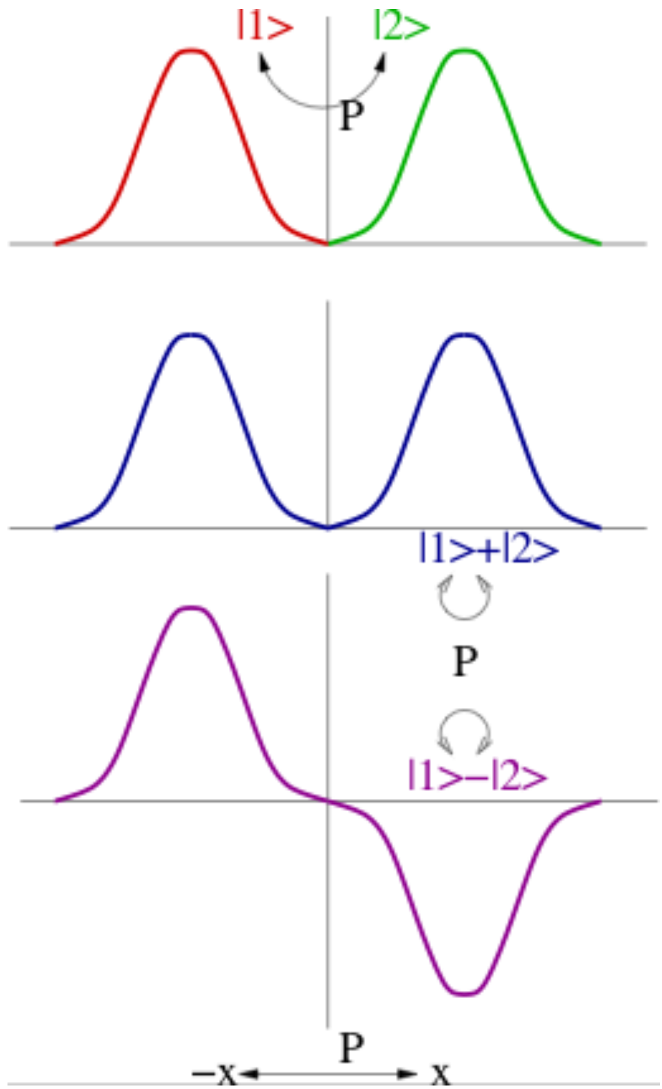
To detect the weak interaction, must exploit parity violation:

The Weak interaction is "left-handed" : it violates parity

(electromagnetism obeys this symmetry)

Right-handed and left-handed electrons scatter via neutral current with different probability…

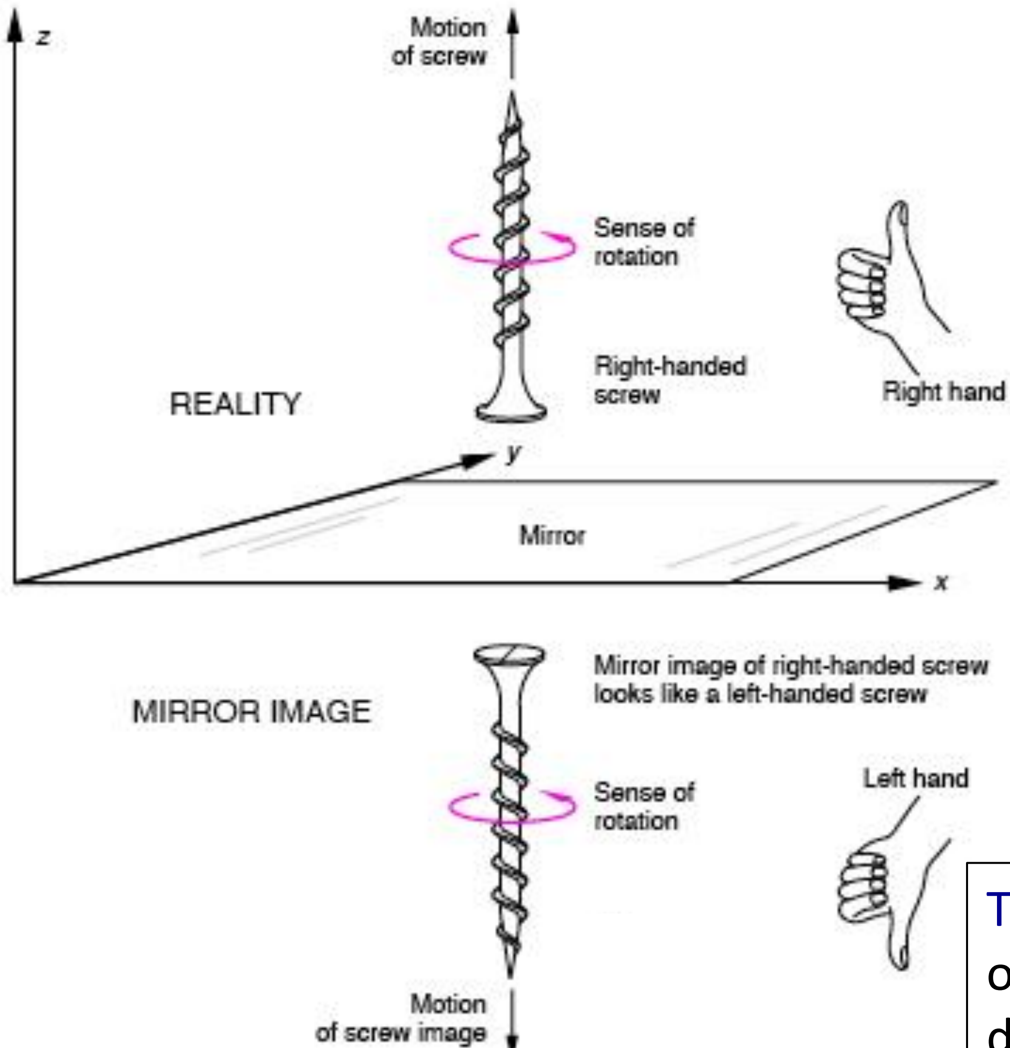
Parity



$$P : \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

Parity operation inverts sign of all spatial coordinates

Parity and the Mirror World



Since: **L** = **r** × **p**

r, **p** change sign under parity (vectors)

L does not

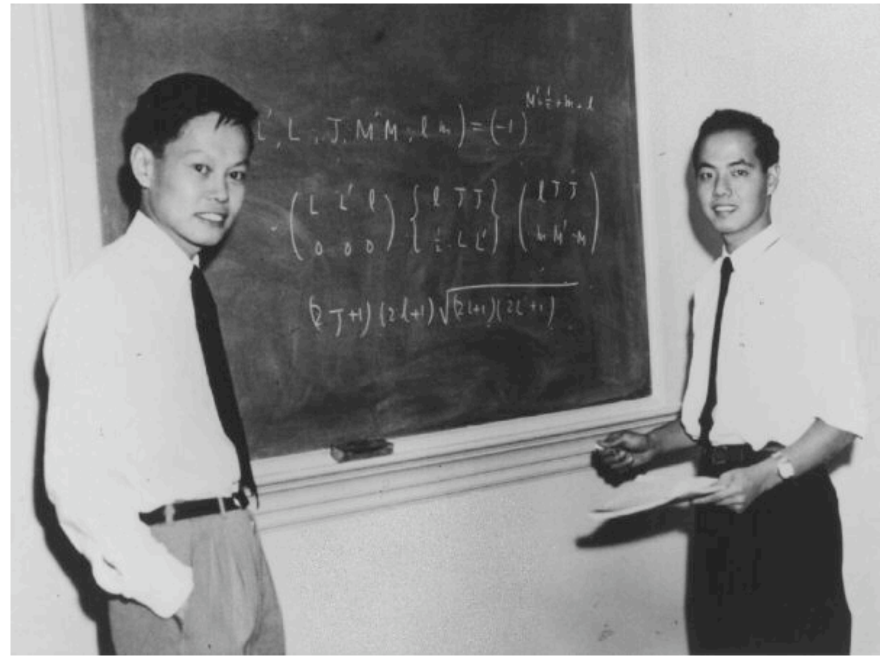
(it's an *axial* vector)

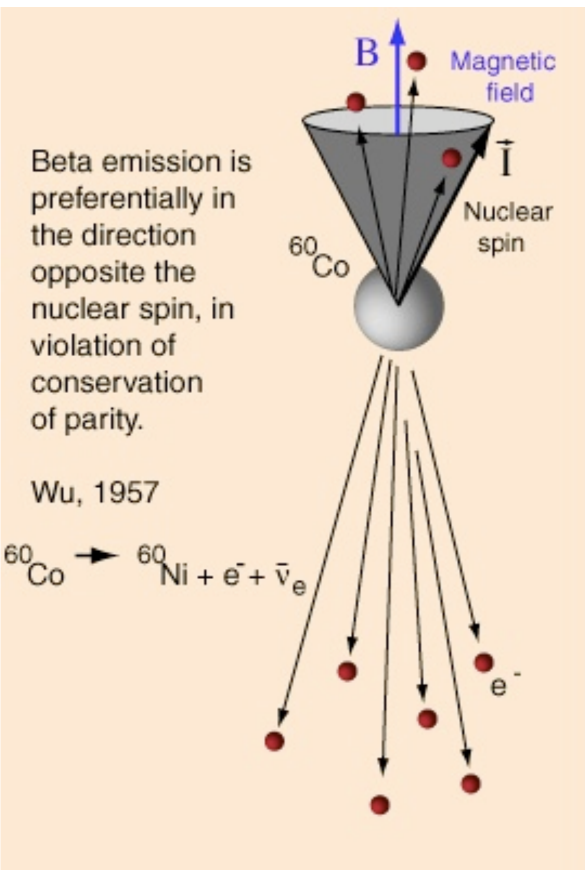
(x → -x and y → -y is same as a 180° rotation around z axis)

Thus: *if* parity symmetry is obeyed, reaction rate can't depend on σ•p
Right and left handed electrons should scatter the same

Parity Violation in the Weak Interaction

T.D. Lee and C.N. Yang suggested parity violation in the weak interaction (1956)



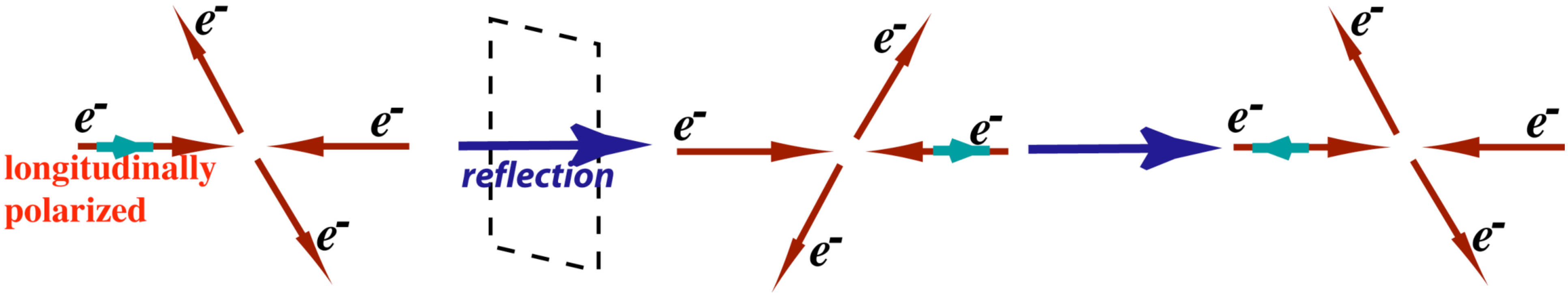


C.S. Wu and collaborators observed effect in nuclear beta decay later that year

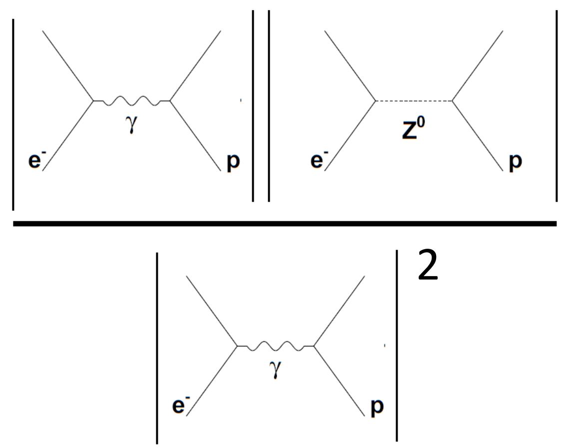
Hmmm….

aside: The reason that the weak interaction violates parity is not known… put in to Standard Model "by hand"

Parity-violating electron scattering



$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \propto$$



$$\propto \frac{|M_Z|}{|M_\gamma|}$$

Electroweak interference

$$A_{PV} \propto \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left(g_A^e g_V^T + \beta g_V^e g_A^T \right) \sim 10^{-4} Q^2 \left[\mathrm{GeV}^2 \right]$$

Electroweak Mixing

Two of the "bare" forces B, W, in the Standard Model "mix" in the observed universe to form the photon (electromagnetic force) and the Z boson (part of the weak interaction: weak neutral current):

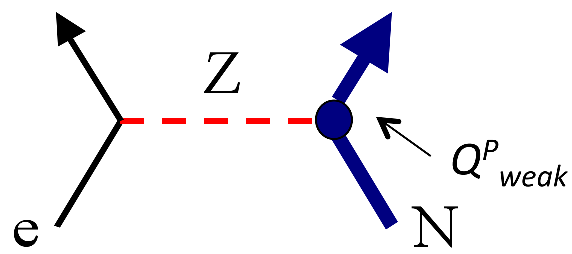
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

Mixing angle: $\sin\theta_W$ (*aka* "Weinberg angle").

This is one of the fundamental parameters of the Standard Model.

Precisely measured using high-energy processes

The weak charge of the proton



Q^P_{weak} $$1 - 4\,sin^2(\theta_w) \approx 0.07$$

Summary: proton's weak charge is both precisely predicted in the Standard Model, and suppressed – good place to look for "new Physics" i.e. physics beyond the Standard Model

… never before been measured!

so, how can one measure the weak charge?

Qweak: Proton's weak charge

Q_W^p - Neutral current analog of electric charge

The Standard Model makes a firm prediction of Q_W^p

	EM Charge	Weak Charge
u	2/3	$1 - \frac{8}{3} sin^2(\theta_w) \approx 0.38$
d	-1/3	$-1 + \frac{4}{3} sin^2(\theta_w) \approx -0.69$
P (uud)	+1	$1 - 4\, sin^2(\theta_w) \approx 0.07$
N (udd)	0	-1

"Accidental suppression"
→sensitivity to new physics

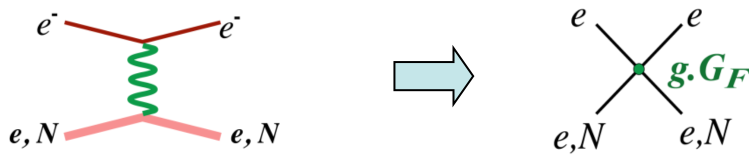
Note: $Q_W^n = -1$

Q-weak is particularly sensitive to the quark *vector* couplings (C_{1u} and C_{1d}) .

$$Q_W^p = -2(2C_{1u} + C_{1d})$$
$$Q_W^n = -2(C_{1u} + 2C_{1d})$$

Qweak: Proton's weak charge

For electron-quark scattering:



$$\frac{1}{Q^2 - M^2} \xrightarrow{Q^2 \ll M^2} \frac{1}{M^2}$$

Use four-fermion contact interaction to parameterize the effective PV electron-quark couplings (mass scale and coupling)

New physics:

$$\sigma \propto |M_\gamma + M_\mathrm{Z} + M_\mathrm{new}|^2$$
$$\sim |M_\gamma|^2 + 2M_\gamma M_\mathrm{Z}^* + 2M_\gamma M_\mathrm{new}^*$$

new Z', leptoquarks, SUSY ...

A 4% measurement of the proton's weak charge would probe TeV scale new physics

$$\frac{\Lambda}{g} \sim \left(\sqrt{2} G_F \Delta Q_W^p\right)^{-\frac{1}{2}} \sim \; O(\mathrm{TeV})$$

Erler, Kurylov, and Ramsey-Musolf, PRD 68, 016006 2003

Extracting the weak charge

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[Q_w^p + B(\theta, Q^2)Q^2\right]$$

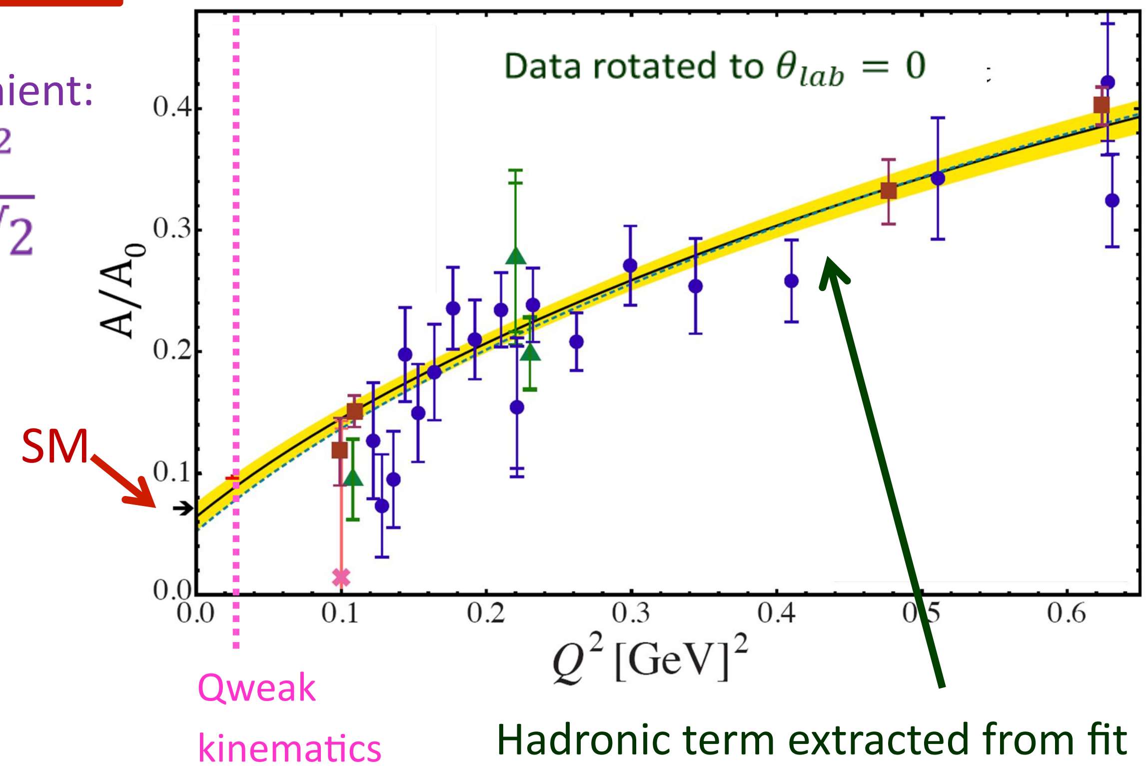
Hadron structure enters here: electromagnetic and electroweak form factors…

Reduced asymmetry more convenient:

$$A_{red} = \frac{A_{PV}}{A_0} \qquad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

One must extrapolate to $Q^2 = 0$.

We measure A_{phys}^{PV} at $Q^2 = 0.025\ GeV^2$.

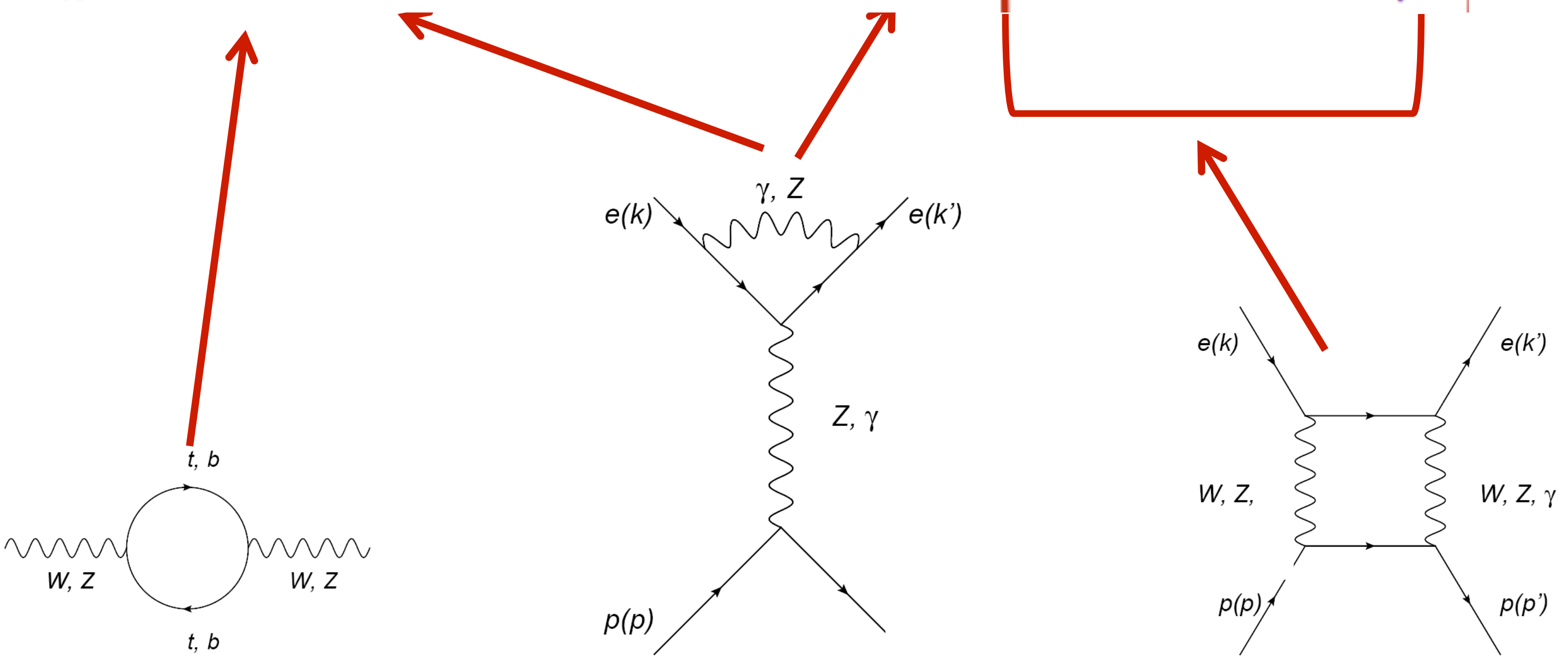


Previous experiments (strange form factor program: SAMPLE, HAPPEX, G0, PVA4 experiments at MIT/Bates, JLab and MAMI) explored hadron structure more directly; allow us to subtract our hadronic contribution

Electroweak Radiative Corrections

In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0.$

$$Q_W^p = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$



Full expression for Q_W^p has energy dependent corrections – need precise calculations

The $\Box_{WW}$ and $\Box_{ZZ}$ are well determined from pQCD ($\propto \frac{1}{q^2 - M^2_{W(Z)} + i\epsilon}$)

The $\Box_{\gamma Z}$ isn't pQCD friendly due to the photon leg ($\propto \frac{1}{q^2 + i\epsilon}$)

Electroweak Radiative Corrections

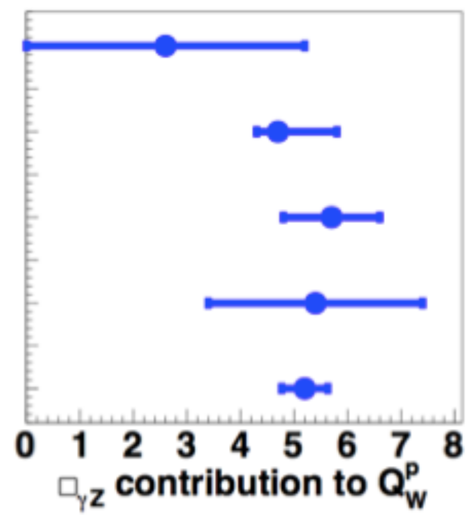
In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0.$

$$Q_W^p = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Uncertainty from these corrections on *current* results is irrelevant.

$\Box_{\gamma Z}$ contribution to Q_W^p (Qweak kinematics)

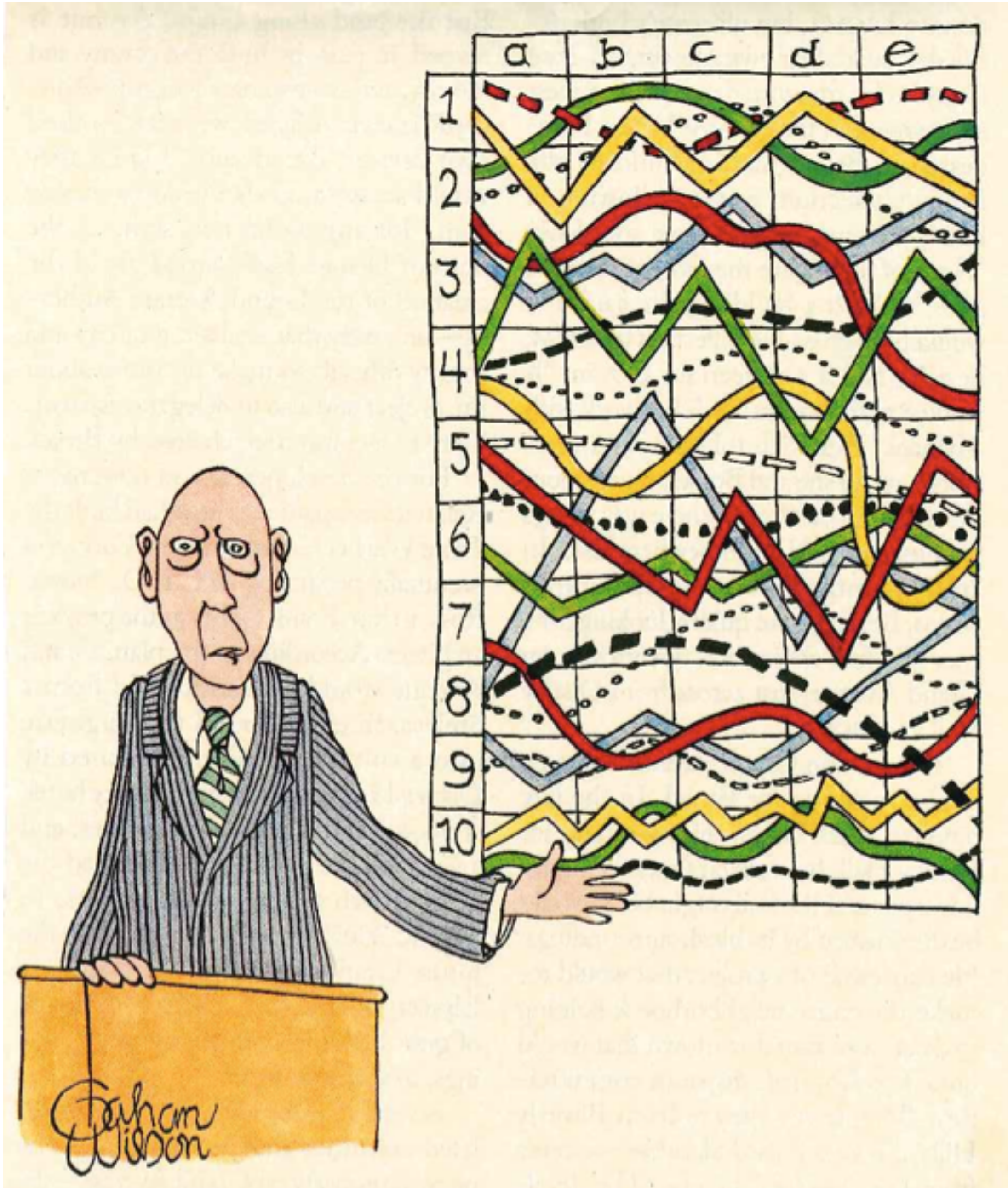
Gorchtein & Horowitz *PRL 102, 091806 (2009)*	0.0026 ± 0.0026
Sibirtsev, Blunden & Melnitchouk, Thomas *PRD 82, 013011 (2010)*	$0.0047^{+0.0011}_{-0.0004}$
Rislow & Carlson *PRD 83, 13007 (2011)*	0.0057 ± 0.0009
Gorchtein, Horowitz & Ramsey-Muslof *PRC 84, 015502 (2011)*	0.0054 ± 0.0020
Hall, Blunden, Melnitchouk, Thomas & Young *arXiv:1304:7877 (2013)* (calculation constrained by PVDIS data)	0.0052 ± 0.00043



Calculations are primarily dispersion theory type

error estimates can be firmed up with data!

Qweak: inelastic asymmetry data taken at W ~ 2.3 GeV, $Q^2 = 0.09\ GeV^2$



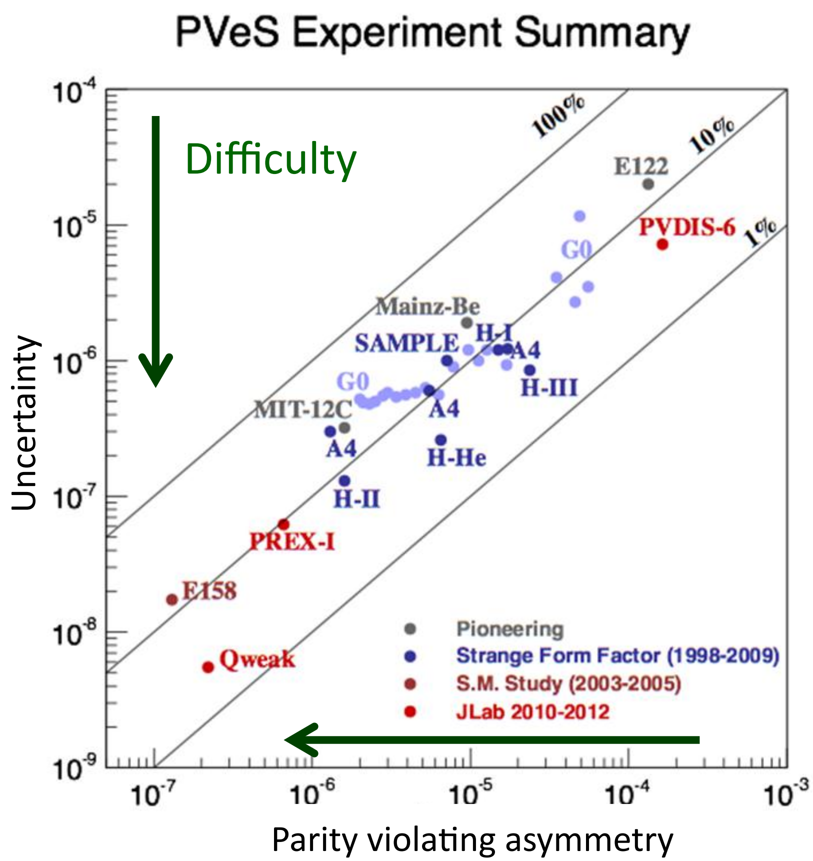
"I'll pause for a moment so you can let this information sink in."

Parity Violation Electron Scattering (PVES) Challenges

Qweak's goal: most precise (relative and absolute) PVES result to date.

PVES challenges:

- Statistics
  - High rates required
    - High polarization, current
    - High powered targets with large acceptance
- Low noise
  - Electronics, target density fluctuations
  - Detector resolution
- Systematics
  - Helicity-correlated beam parameters
  - Backgrounds (target windows)
  - Polarimetry
  - Parity-conserving processes



Small absolute *and* relative uncertainty (5ppb on A_{PV})

$\delta A_{PV} \approx \pm 2.1\%$

$\delta Q_W^p \approx \pm 4\%$

$\delta(\sin^2\theta_W) \approx \pm 0.3\%$

Meeting PVES Challenges

- Rapid helicity reversal (960 Hz)
- 180 μA beam current (JLab record)
- Small scattering angle: toroidal magnet, large acceptance
- GHz detected rates: data taking in integrating mode
- High power cryogenic target
- Exquisite control of helicity-correlated beam parameters
- Two independent high-precision polarimeters
- Radiation hard detectors
- Low noise 18-bit ADCs
- High resolution Beam Current monitors
- Four different kinds of helicity reversal
  Rapid (electron source), slow (insertable λ/2 plate) and ultra slow (wien-reversal and g-2 spin flip)

Thomas Jefferson National Accelerator Facility

Newport News Virginia

1980 – initial design

1987 – construction   started

1994 – first physics
experiments

1995 – design energy (4 GeV)

2000 – 6 GeV achieved

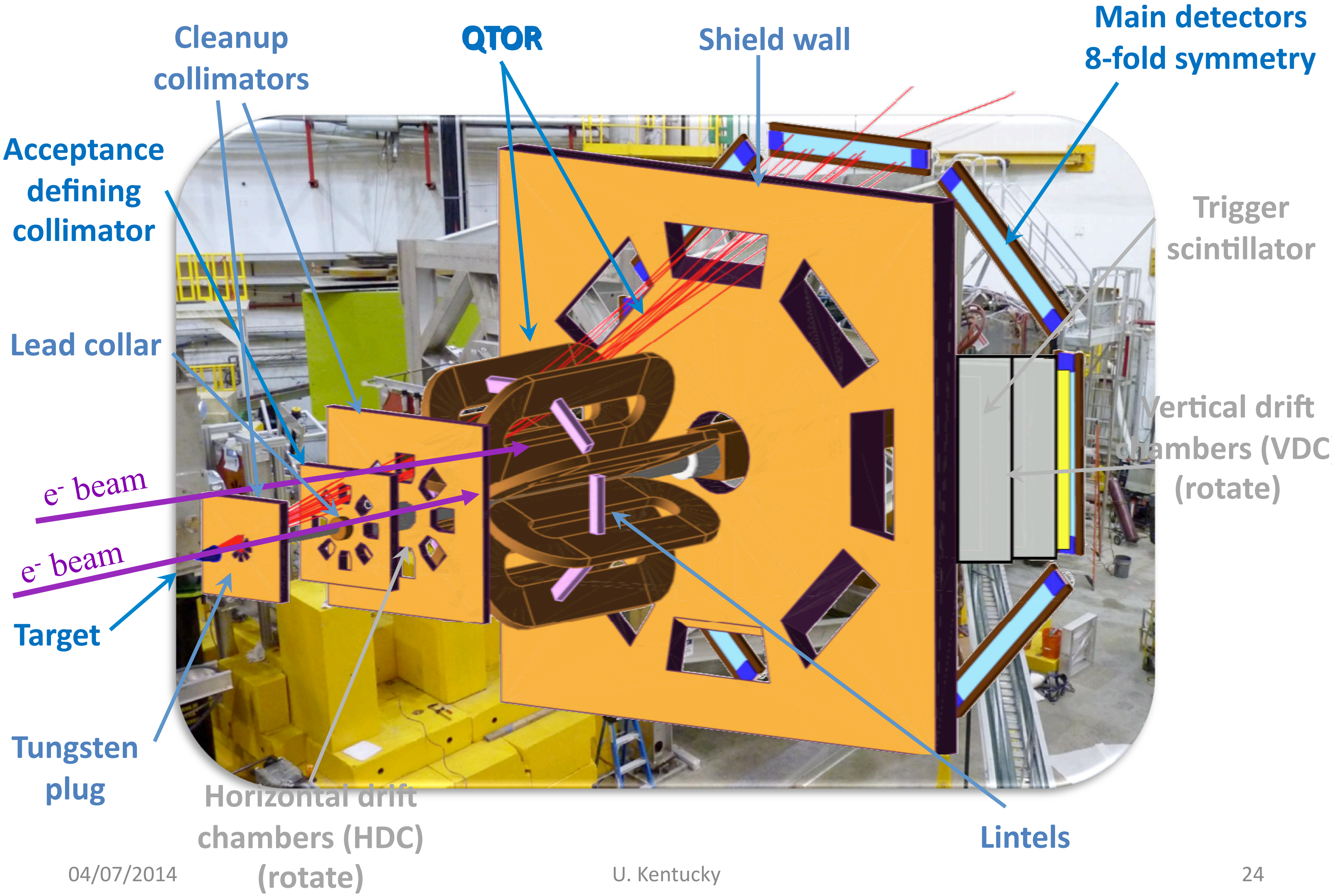
2014 – 12 GeV upgrade – first test
beam available

User group: 1500
physicists

Funded by U.S. DOE

Beam currents to 180 μA

The Qweak Apparatus



Qweak during construction

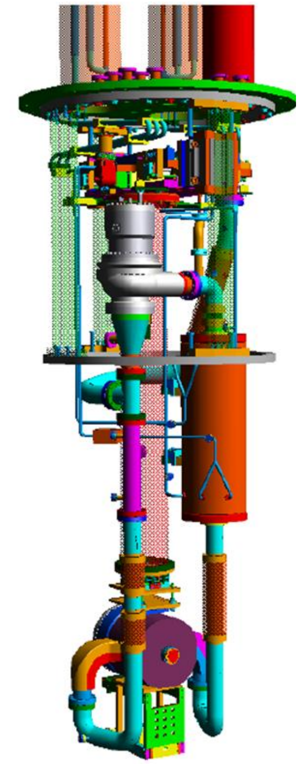
Qweak Target

35 cm, 2.5 kW liquid hydrogen target

World's highest powered cryotarget

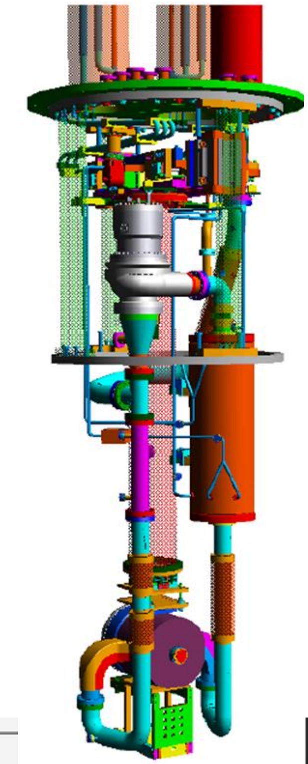
- Temperature ~20 K
- Pressure: 30-35 psia
- Beam at 150 – 180uA

Target boiling might have been problematic!



MD LH2 Asymmetry

Qweak Target



35 cm, 2.5 kW liquid hydrogen target

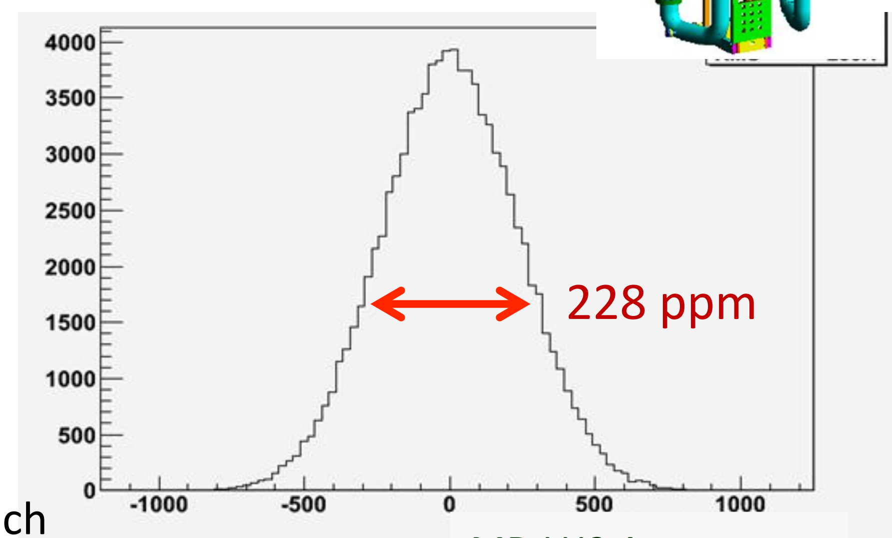
World's highest powered cryotarget

- Temperature ~20 K
- Pressure: 30-35 psia
- Beam at 150 – 180uA

Target boiling might have been problematic!

LH2 statistical width (per quartet):

- Counting statistics: 200 ppm
- Main detector width: 92 ppm
- BCM width: 50 ppm
- Target noise/boiling: 37 ppm



MD LH2 Asymmetry

This measurement is made 240 times per second /second – Repeated ≈5 billion times for each of 8 detectors

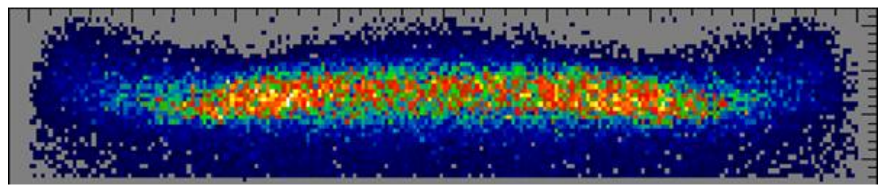
Main Detectors

- Main detectors

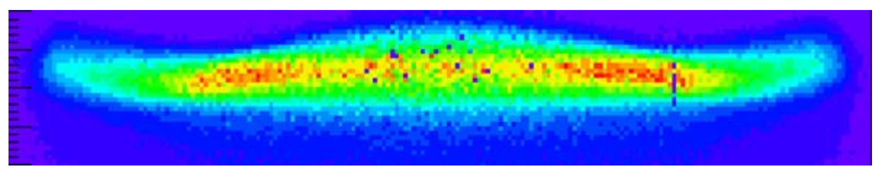
  Toroidal magnet focuses elastically scattered electrons onto each bar

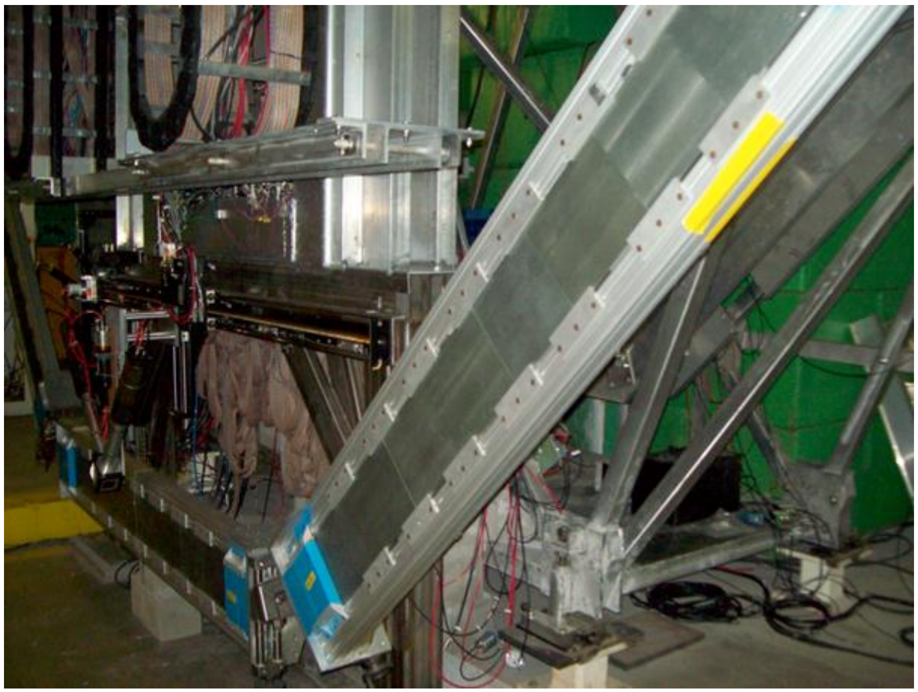
  - 8 Quartz Cerenkov bars
  - Azimuthal symmetry maximizes rates and reduces systematic uncertainties
  - 2 cm lead pre-radiators reduce background

Simulation of scattering rate MD face



Measured





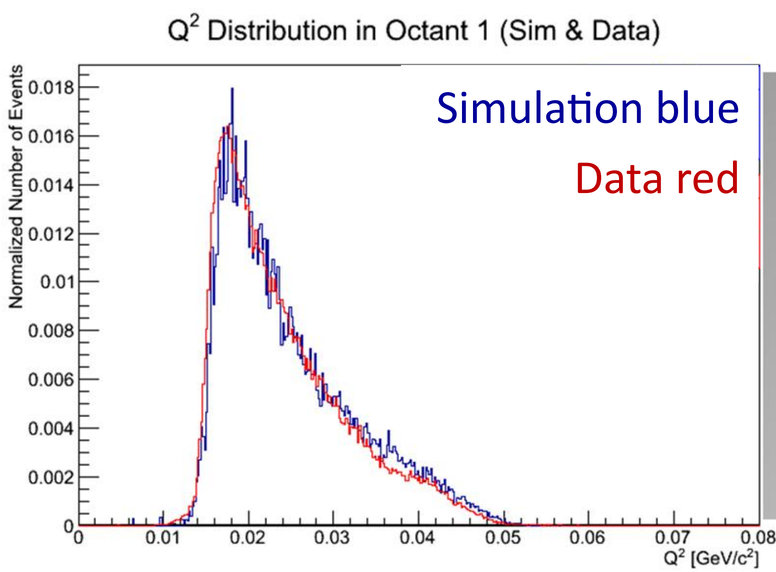
Close up of one detector *in situ*

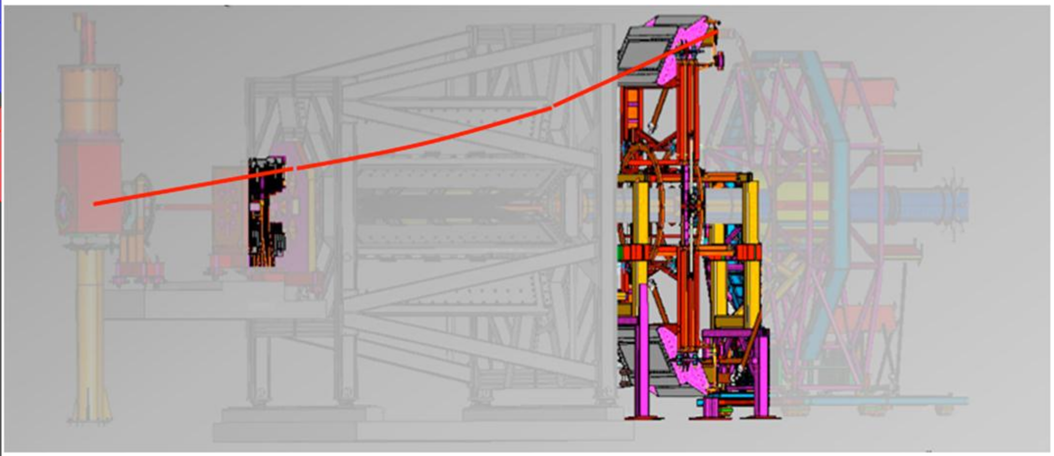
Kinematics (Q^2) determination

- To determine Q^2, we go to "tracking" mode:
  - Currents ~ 50 pA
  - Use Vertical + Horizontal Drift Chambers
  - Re-construct individual scattering events

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\{Q_w^p + B(\theta, Q^2)Q^2\}$$

Correct for radiative effects in target with Geant 4 simulations, benchmarked with gas-target & solid target studies





Beam Polarimetry

Polarization is our largest systematic uncertainty (goal: 1%)

This is a challenging goal; so we built a *second*, independent measurement device.

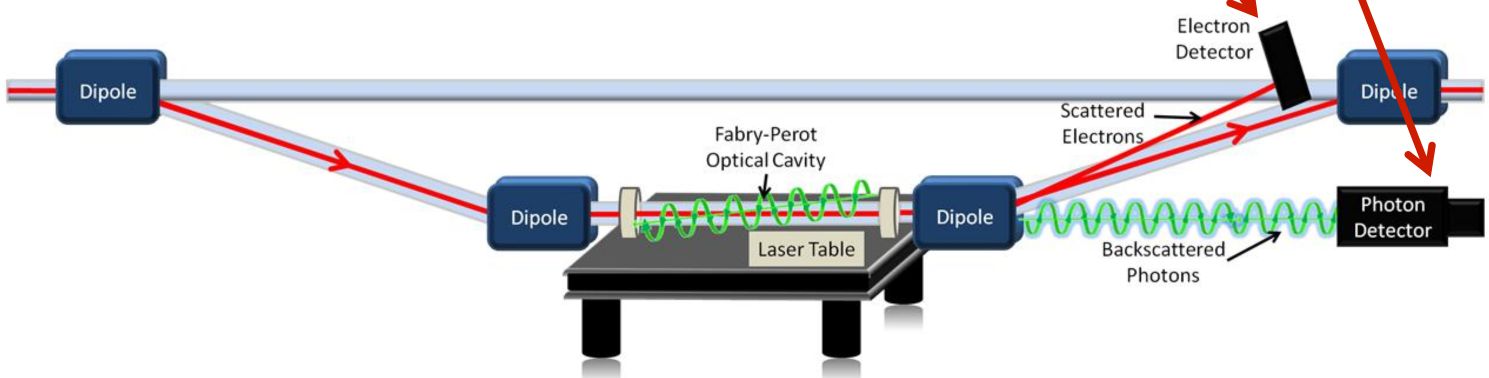
Møller polarimeter

- Precise, but invasive
- Thin, pure iron target
- Brute force polarization
- Limited to low current

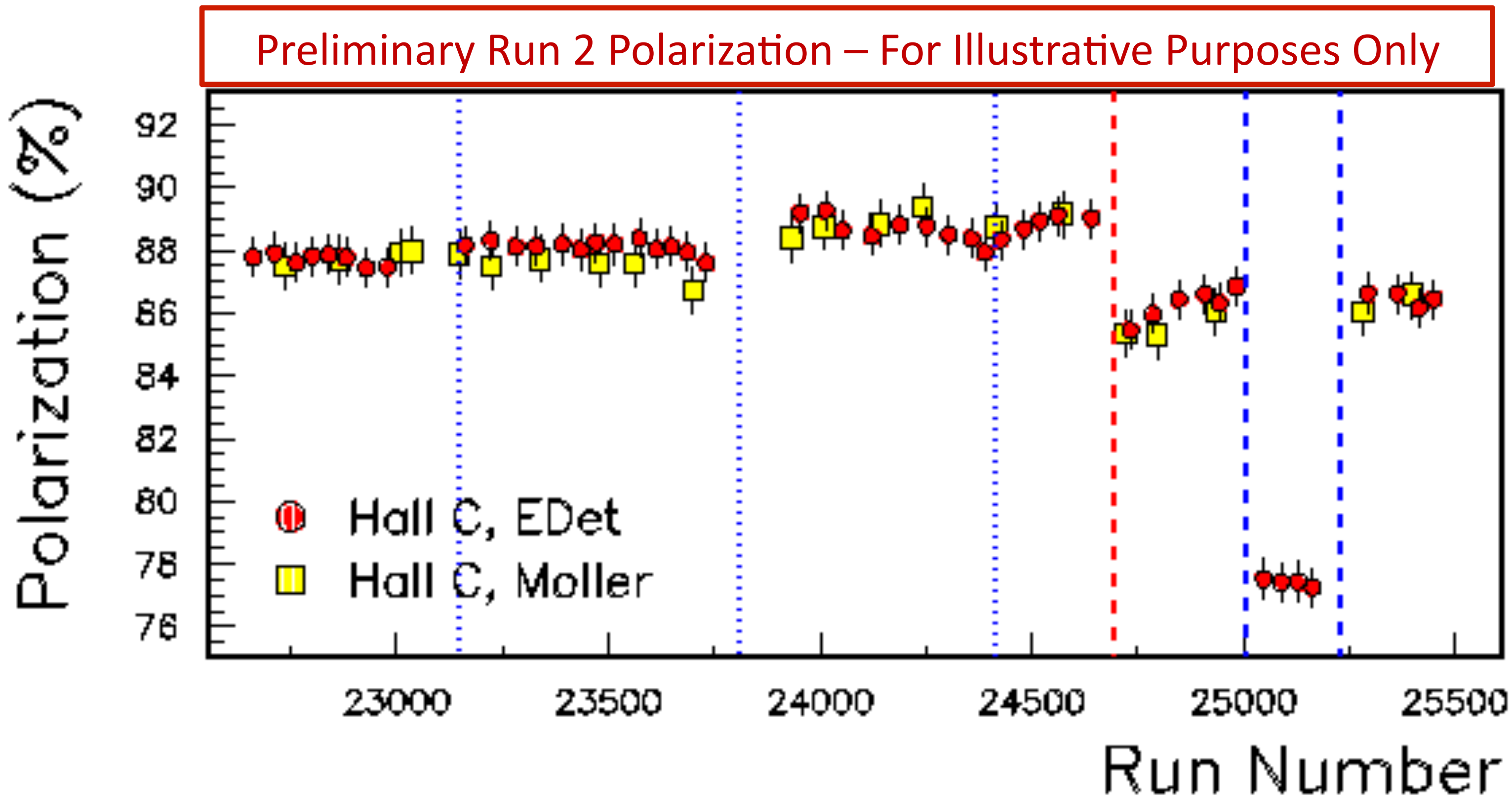
Compton polarimeter

- Installed for Q-weak
- Runs continuously at high currents
- Statistical precision: 1% per hour

We detect *both* recoil electron and photon.



Beam Polarimetry



Note the good agreement between both polarimeters

A suite of Auxiliary Measurements

Qweak has data (under analysis) on a variety of observables
of potential interest for Hadron physics:

- Beam normal single-spin asymmetry* for elastic scattering on proton
- Beam normal single-spin asymmetry for elastic scattering on ^{27}Al
- PV asymmetry in the $N \rightarrow \Delta$ region.
- Beam normal single-spin asymmetry in the $N \rightarrow \Delta$ region.
- Beam normal single-spin asymmetry near W= 2.5 GeV
- Beam normal single-spin asymmetry in pion photoproduction
- PV asymmetry in inelastic region near W=2.5 GeV (related to γZ box diagrams)
- PV asymmetry for elastic/quasielastic from ^{27}Al
- PV asymmetry in pion photoproduction

*: *aka* vector analyzing power *aka* transverse asymmetry;
generated by imaginary part of two-photon exchange amplitude

First result

Q-weak ran from Fall 2010 – May 2012 : four distinct running periods

- Hardware checkout (Fall 2010-January 2011)
- Run 0 (Jan-Feb 2011)
- Run 1 (Feb – May 2011)
- Run 2 (Nov 2011 – May 2012)

We have completed and unblinded the analysis of "Run 0" (about 1/25th of our total dataset).

$A_{PV}^{p} = -279 \pm 35(stat) \pm 29\ (sys)$ ppb

$\langle Q^2 \rangle = 0.0250 \pm 0.0006\ GeV^2$

$\langle E_{beam} \rangle = 1155\ MeV$

$\theta_{eff} = 7.90\,°$

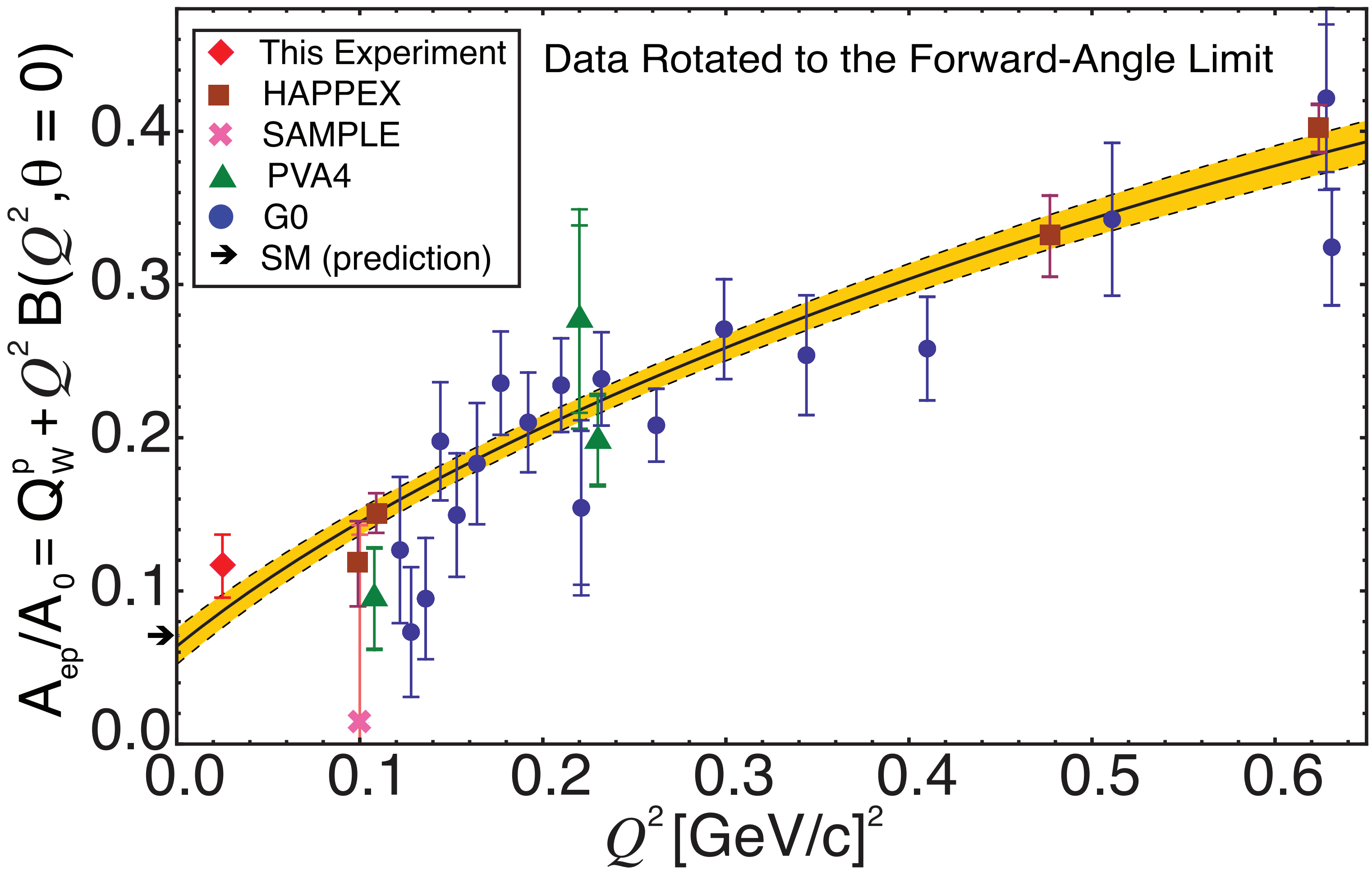
D. Androic *et al.* Phys. Rev. Lett. 111 (2013)141803.

Reduced Asymmetry

in the forward-angle limit (θ=0)

4% of total data

$$A_0 = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha} \qquad \overline{A^p_{\mathrm{LR}}} = \frac{A_{LR}}{A_0} \xrightarrow{\theta\to 0} [Q^p_W + Q^2 B(Q^2)]$$



Hadronic part extracted through global fit of PVES data.

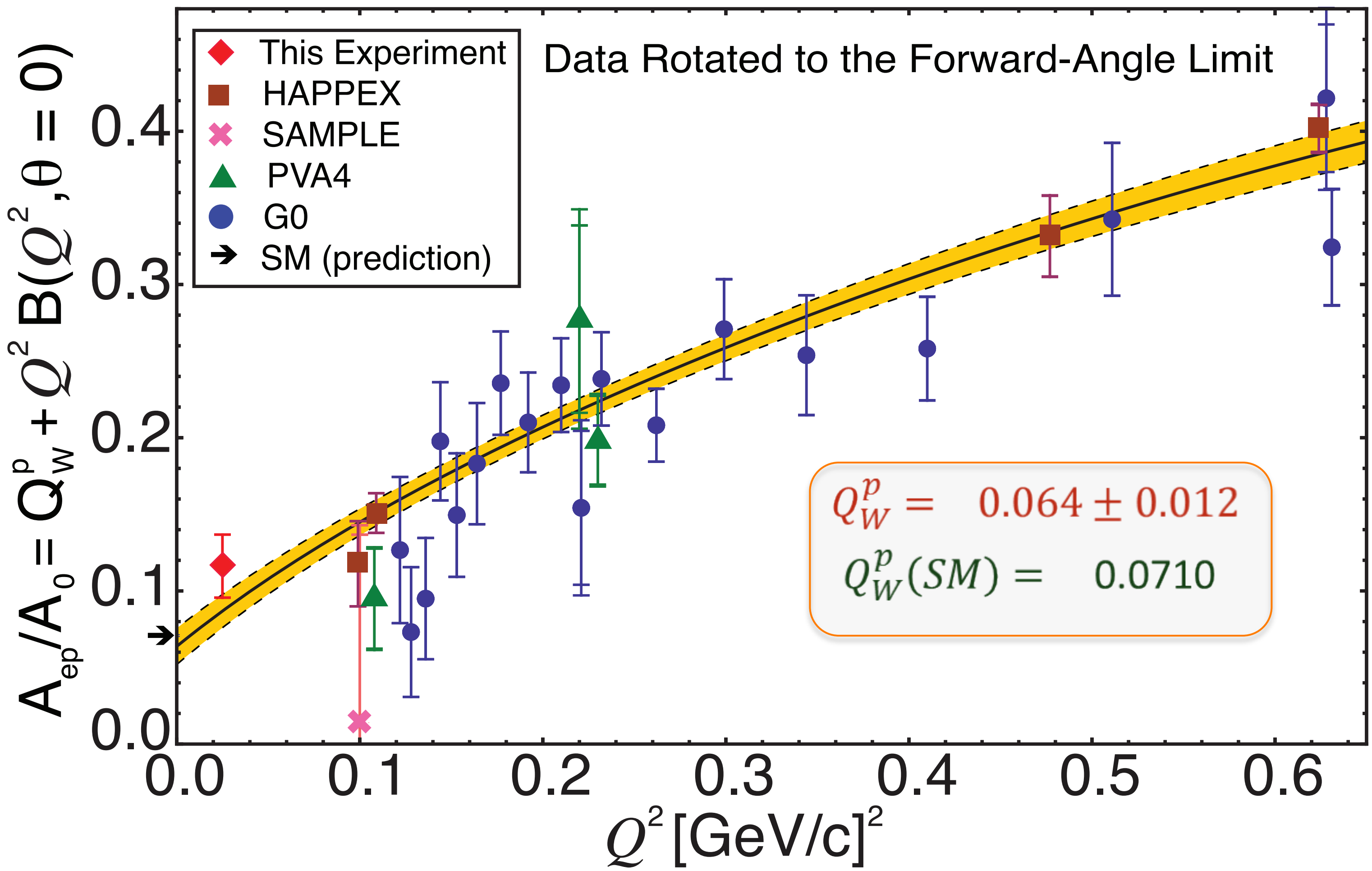
$$\overline{A^p}^{data}(\theta=0,Q^2) = \overline{A^p}^{data}(\theta^{data},Q^2)$$

Reduced Asymmetry

4% of total data

in the forward-angle limit (θ=0)

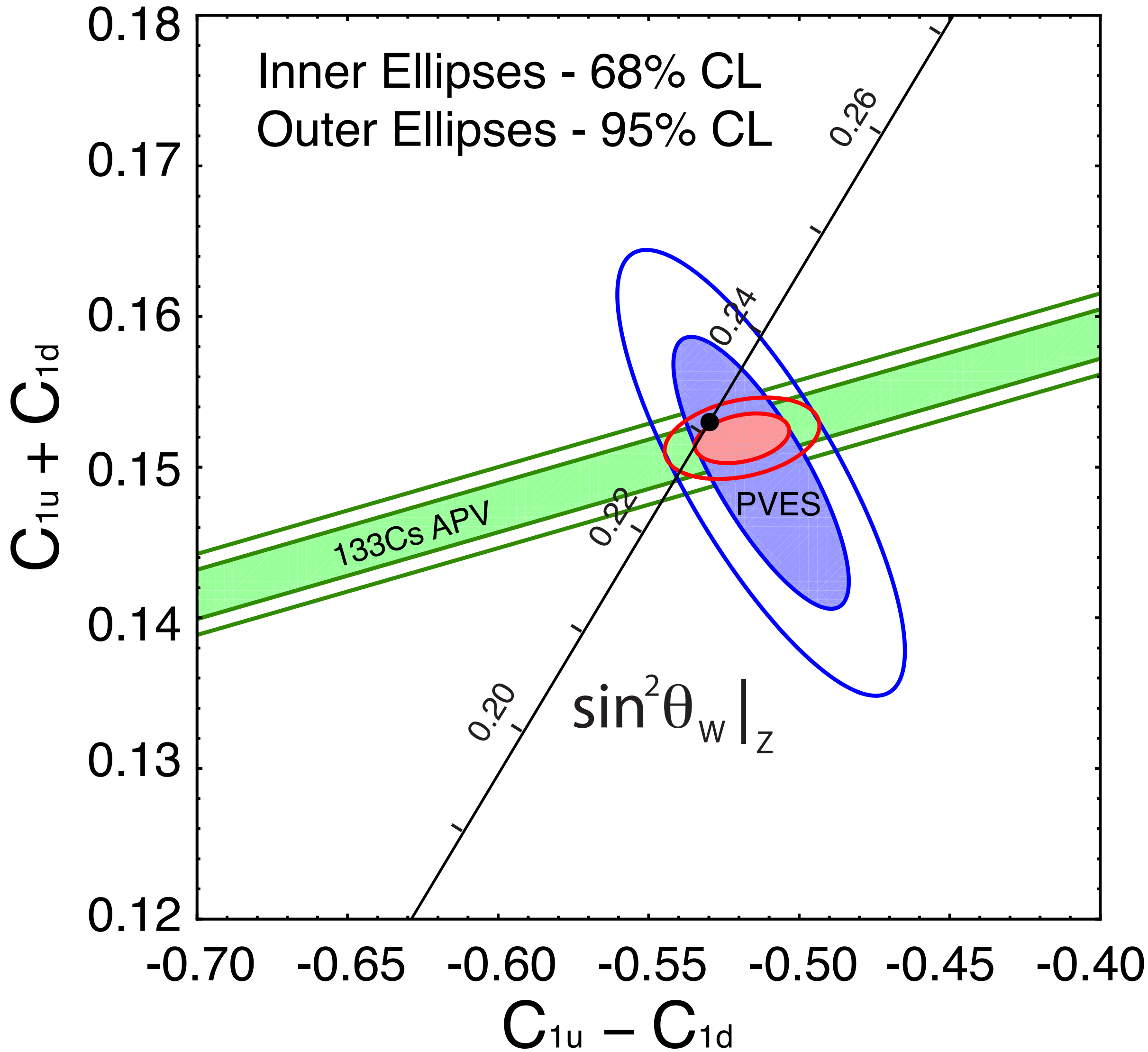
$$A_0 = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha} \qquad \overline{A^p_{\rm LR}} = \frac{A_{LR}}{A_0} \xrightarrow{\theta\to 0} [Q^p_W + Q^2 B(Q^2)]$$



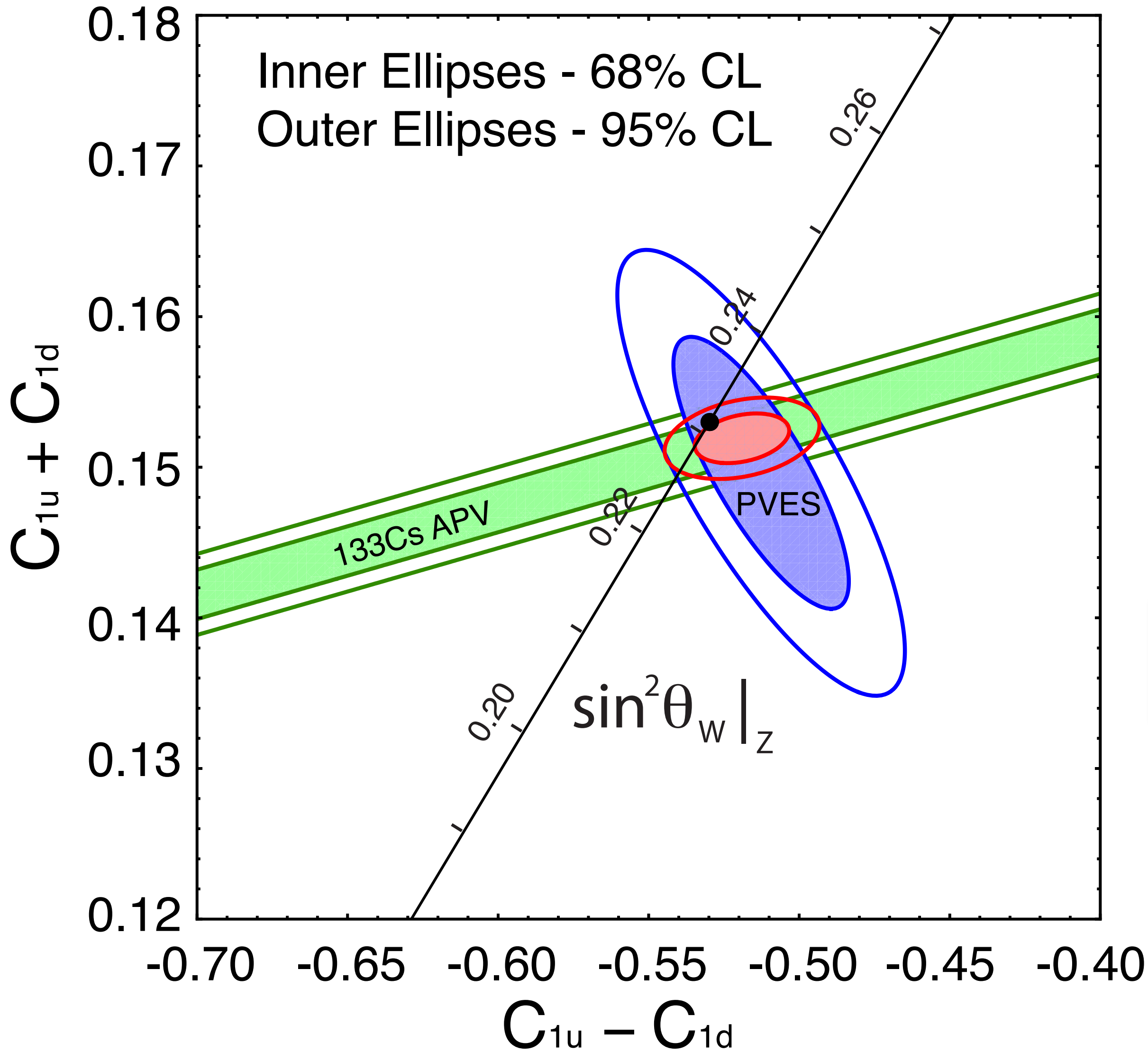
Hadronic part extracted through global fit of PVES data.

$$\overline{A^p}^{data}(\theta = 0, Q^2) = \overline{A^p}^{data}(\theta^{data}, Q^2)$$

The C_{1q} & the neutron's weak charge



The C_{1q} & the neutron's weak charge



Combining this result with the most precise atomic parity violation experiment we can also extract, for the first time, the neutron's weak charge:

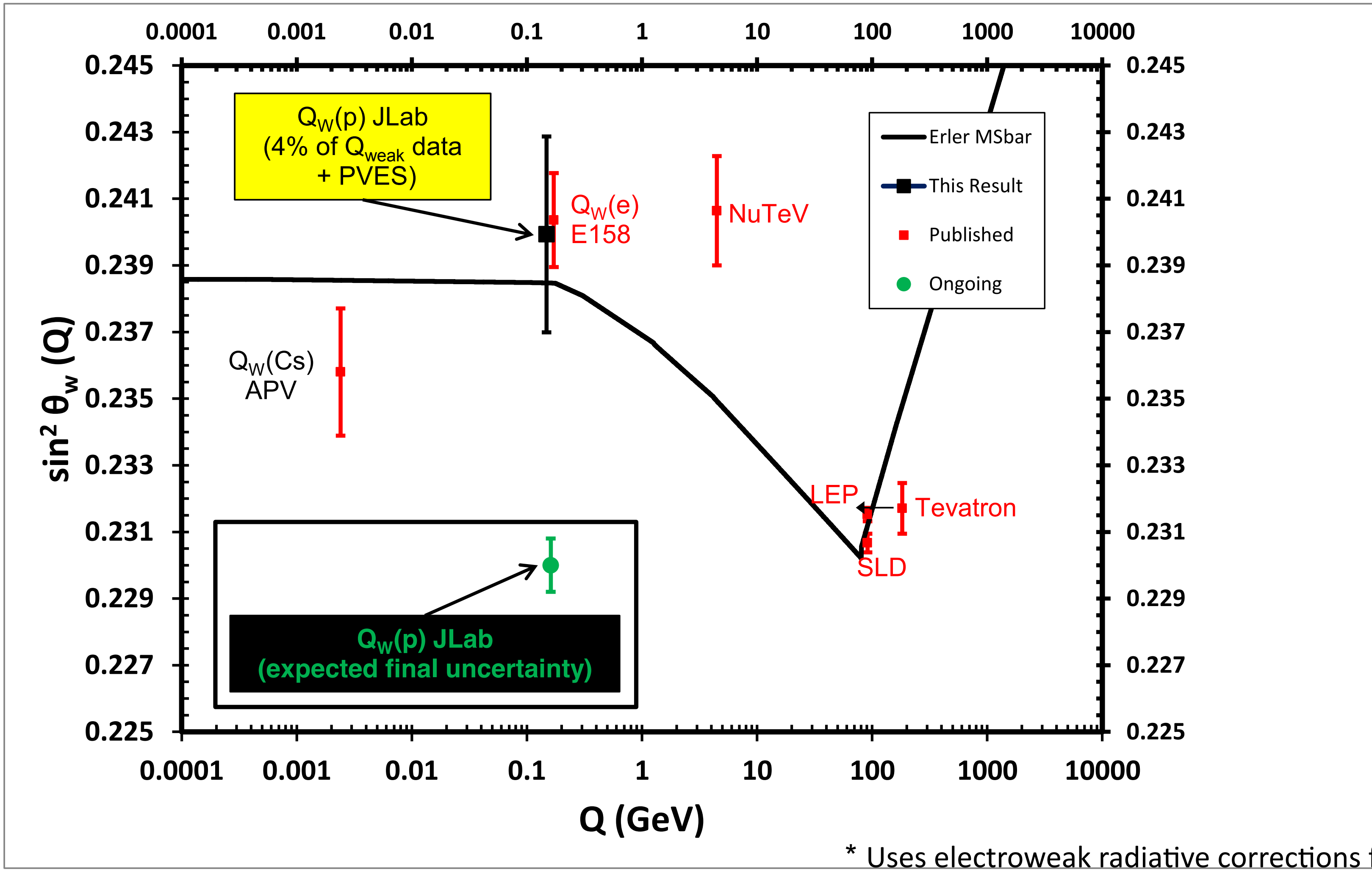
$$Q_W^n = -0.975 \pm 0.010$$

$$Q_W^n(SM) = -0.9890$$

Weak mixing angle result

4% of total data

Recall: in Standard Model, at tree-level, Q_W^p = $(1 - 4\sin^2\theta_W)$



* Uses electroweak radiative corrections from Erler, Kurylov, Ramsey-Musolf, PRD 68, 016006 (2003)

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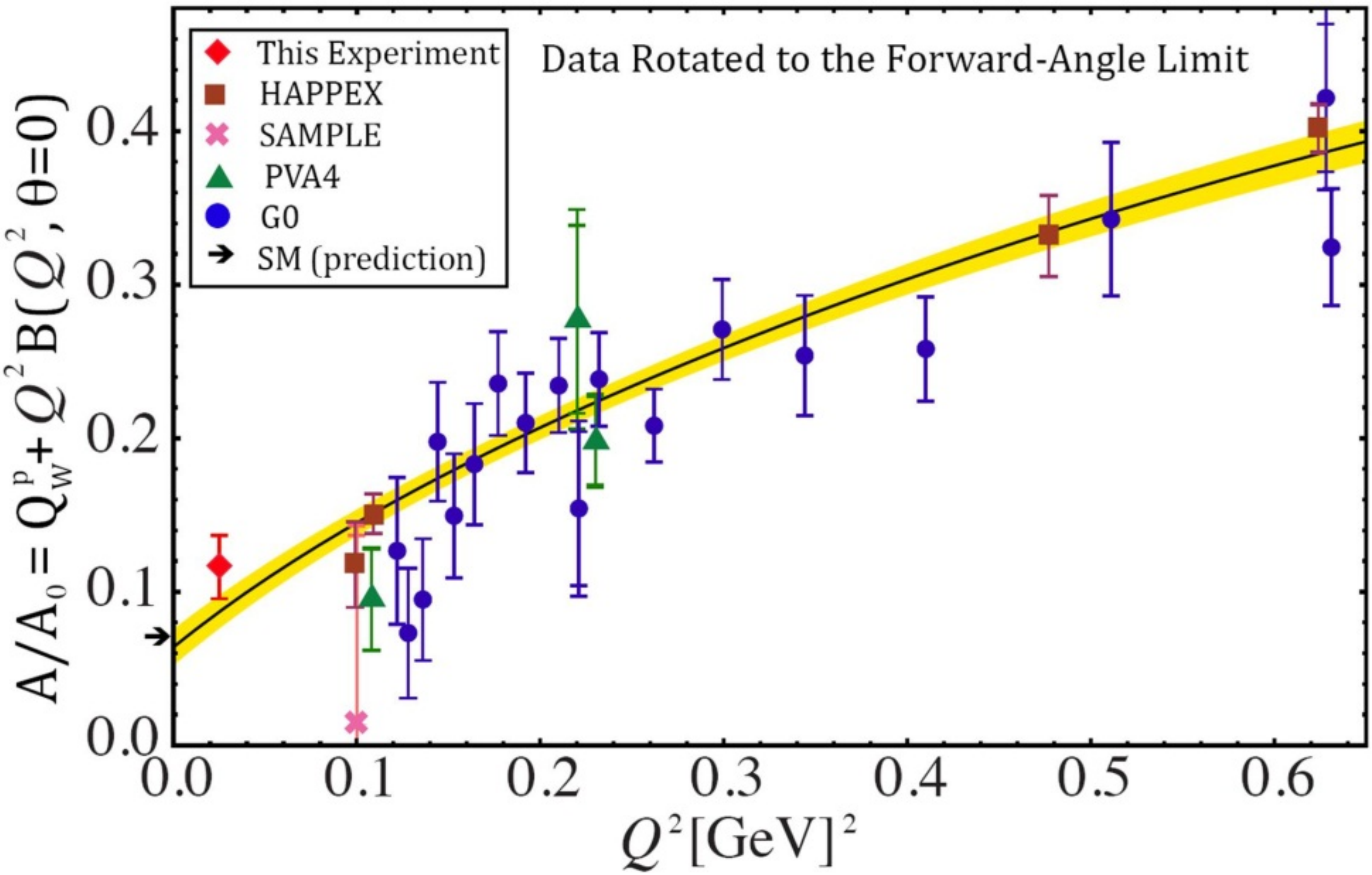
Experiment probes strength of the weak interaction

Sep 16, 2013 6 comments

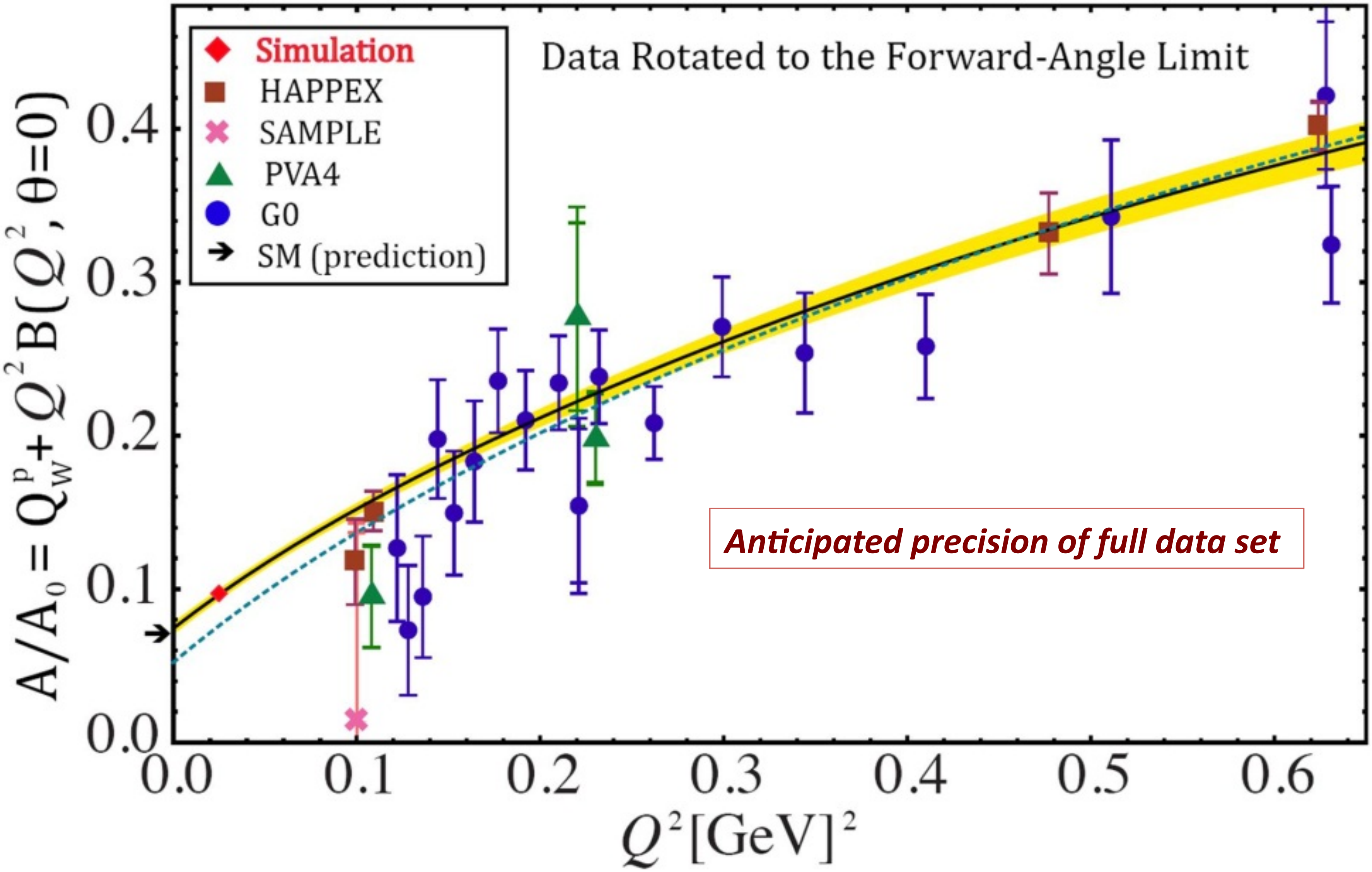
Q-weak at Jefferson Lab has measured the proton's weak charge

An international collaboration has made the first determination of the proton's "weak charge" – a quantity that is related to the strength of the weak interaction. The Q-weak experimental collaboration, working at Jefferson Lab in Newport News, Virginia, says that the small number of data analysed so far agree with predictions of the Standard Model of particle physics but that it believes a full analysis

"Teaser"


This Experiment
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)
Data Rotated to the Forward-Angle Limit
A/A0 = Q^p_W + Q^2 B(Q^2, θ=0)
0.0
0.1
0.2
0.3
0.4
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Q^2 [GeV]^2

"Teaser"



Simulation
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)
Data Rotated to the Forward-Angle Limit
Anticipated precision of full data set
$A/A_0 = Q_W^p + Q^2 B(Q^2, \theta=0)$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
$Q^2 [\mathrm{GeV}]^2$

"Teaser"

Determination of weak charge of the proton

- Assume agreement with Standard Model within ΔQ_W^p
- What are the limits on $\frac{\Lambda}{g}$?

Limits on new physics energy scale

$$\frac{\Lambda}{g} = \frac{1}{2}\left(\sqrt{2} G_F \Delta Q_W^p\right)^{-1/2}$$

- Limits from $\Delta Q_W^p = 0.005$: $\frac{\Lambda}{g} > 1.7\,\text{TeV}$ at $1\,\sigma$
- For comparison with LHC results: $g^2 = 4\pi^2$ or $g^2 = 4\pi$
- Lower limit $\Lambda > 5.4\,\text{TeV}$ at 95% C.L.

The Qweak Collaboration

97 collaborators **23 grad students**
10 post docs **23 institutions**

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[4] Massachusetts Institute of Technology
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[6] Ohio University
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[9] University of Virginia
[10] TRIUMF
[11] Hampton University
[12] Mississippi State University
[13] Virginia Polytechnic Institute & State Univ
[14] Southern University at New Orleans
[15] Idaho State University
[16] Louisiana Tech University
[17] University of Connecticut
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