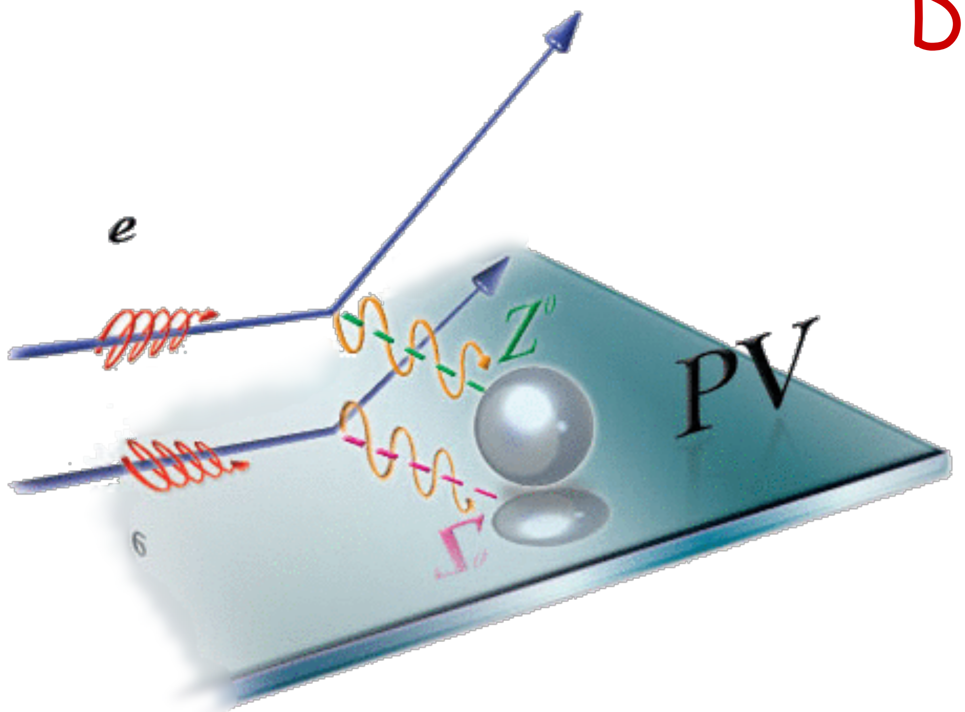
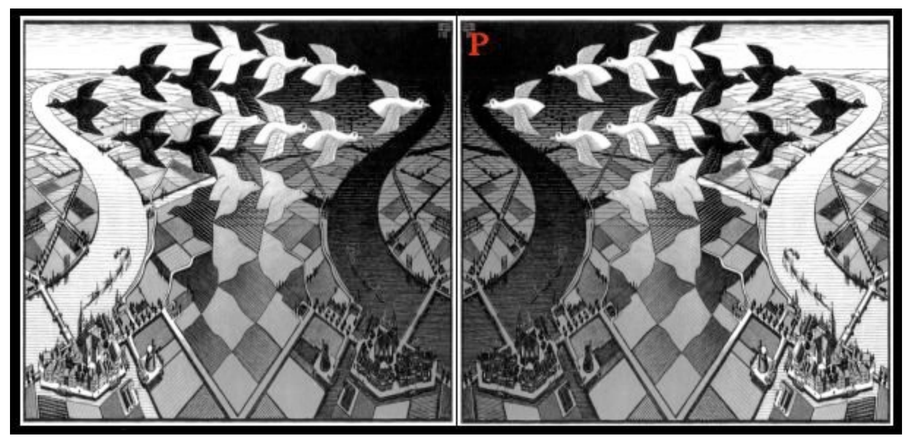
The QWeak experiment:
"tickling" the proton in the mirror world to test the Standard Model



David S. Armstrong

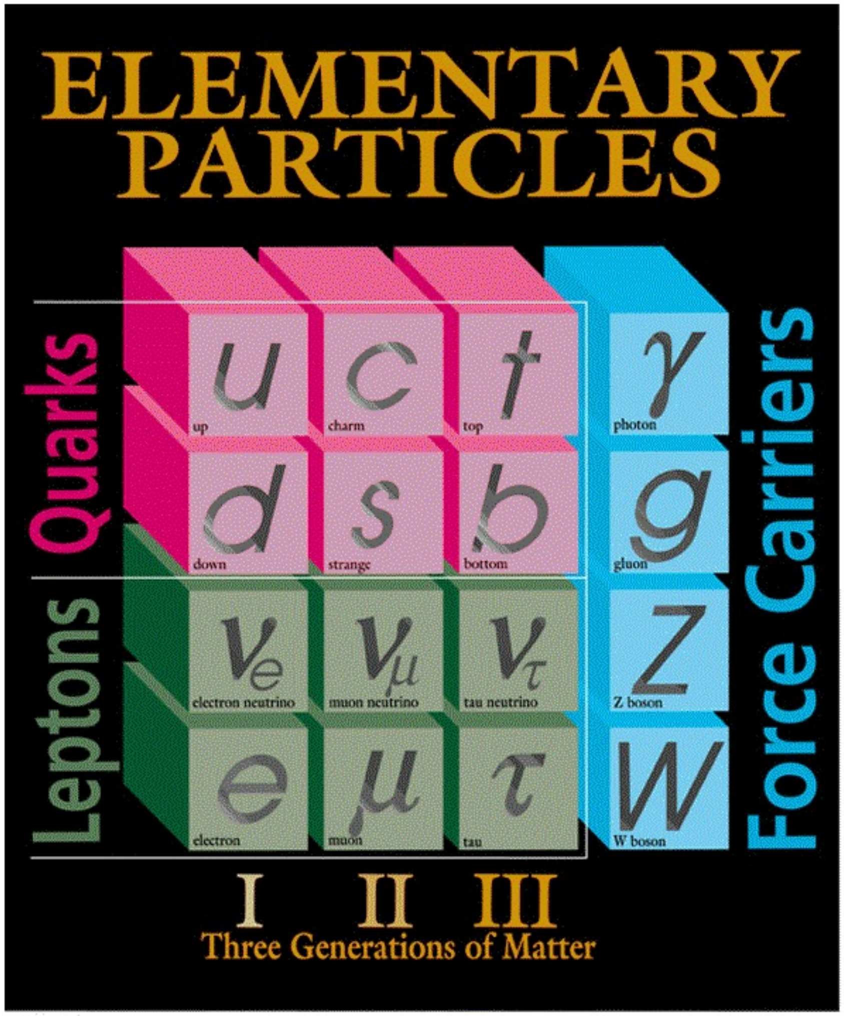


Physics 212
Feb 1 2021

The College of WILLIAM & MARY

Jefferson Lab

The Standard Model



Fermilab 95-759

- Building blocks are quarks and leptons

  point-like, spin $\frac{1}{2}$ particles
- Forces mediated by exchange of spin 1 particles:

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

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

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

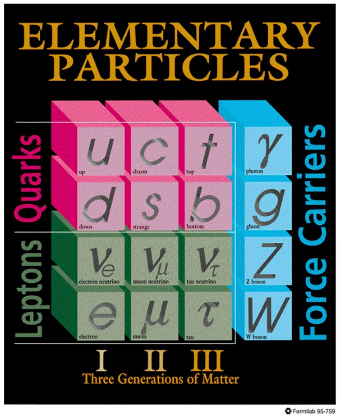
It is a rigorous, mathematically consistent theory that makes detailed and precise predictions of many phenomena… and, to date, it has *never had a prediction disproved by experiment!*

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?

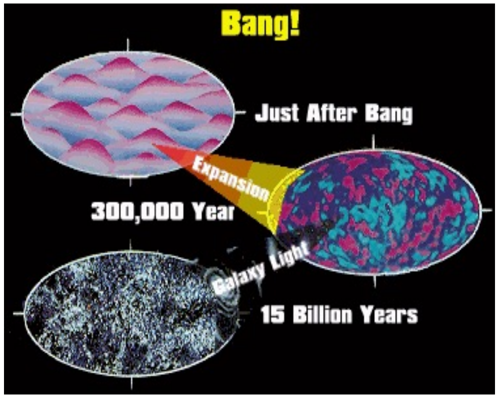
The Standard Model: Issues

- *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…)

- Insufficient CP violation to explain all the matter left over from Big Bang …or we wouldn't be here.



- Doesn't include gravity, dark matter, dark energy
  Big omission… gravity determines the structure of our solar system and galaxy; much of the universe seems to be in the form of dark matter and dark energy…

Suggests that our SM is only a low-order approximation of reality, just as Newtonian gravity is a low-order approximation of General Relativity.

Precision Tests of the Standard Model

- Received Wisdom: *Standard Model is the effective low-energy theory of underlying more fundamental physics – but how to find & identify this new physics?*

- Finding new physics: Two complementary approaches:

  - Energy Frontier (direct) : *eg.* LHC
  - Precision Frontier (indirect) : *(aka Intensity Frontier)*
    many examples… often at modest or low energy…

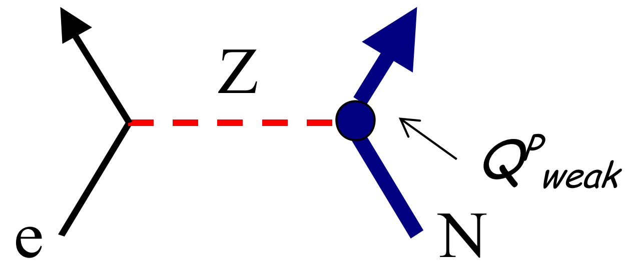
  here we focus on:

  Parity-violating electron scattering

Hallmark of Precision Frontier:

- Choose observables that are *zero* or *suppressed* in Standard Model
- One of these is the "weak charge" of the proton.

The weak charge of the proton: Q^p_{weak}



	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

Q^p_{weak}

“electromagnetic piece”

“weak interaction piece”

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
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& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
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\end{aligned}
$$

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):

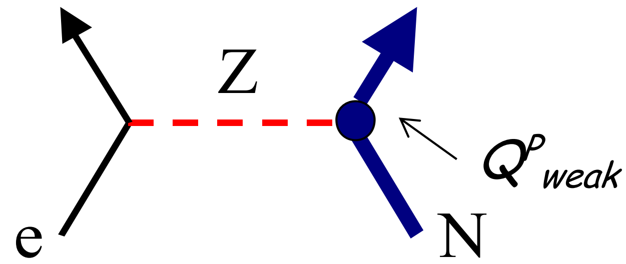
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

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



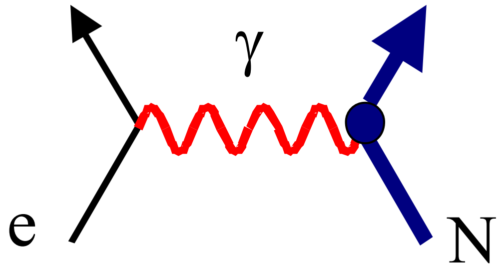
Q^p_{weak} $1 - 4\,sin^2(\theta_w) \approx 0.07$

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

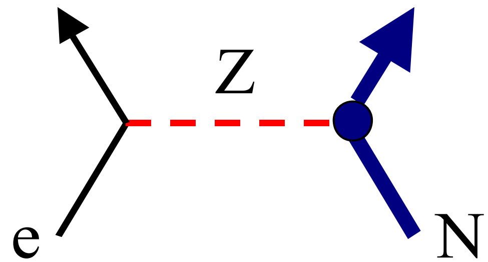
… never been measured before our experiment!

so, how can one measure the weak charge?

Electroweak scattering of electrons



Electron scattering via electromagnetism



Electron scattering via weak interaction

10^6 times smaller amplitude at these energies

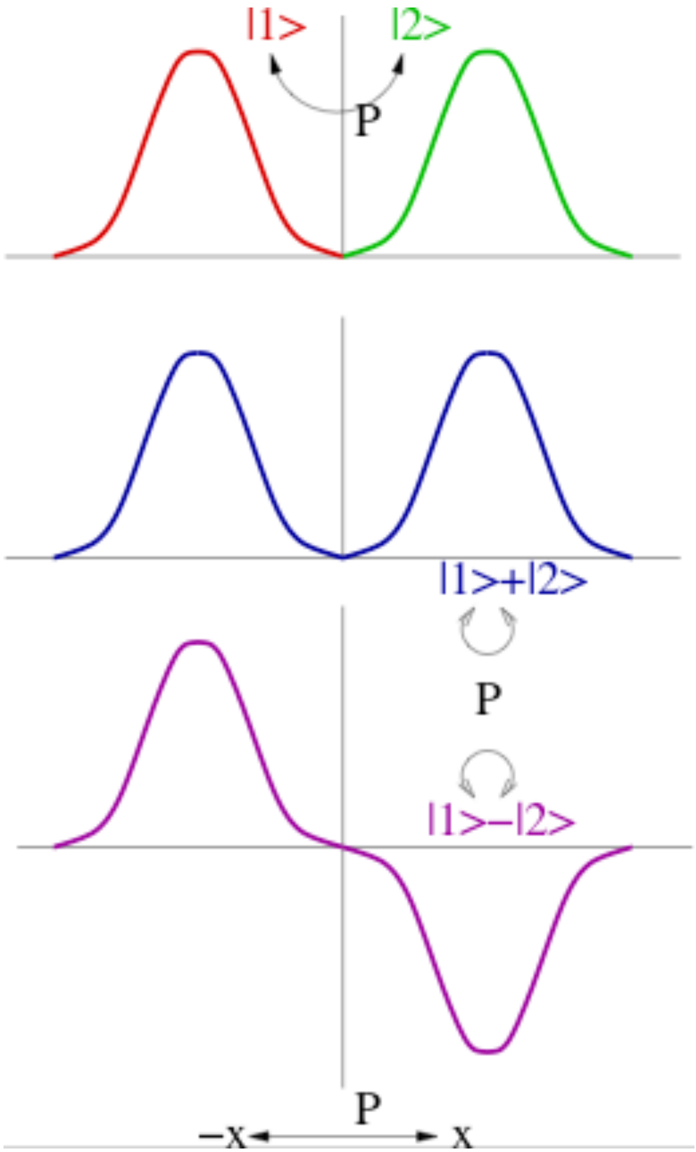
Final state is *identical* in the two cases…

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!

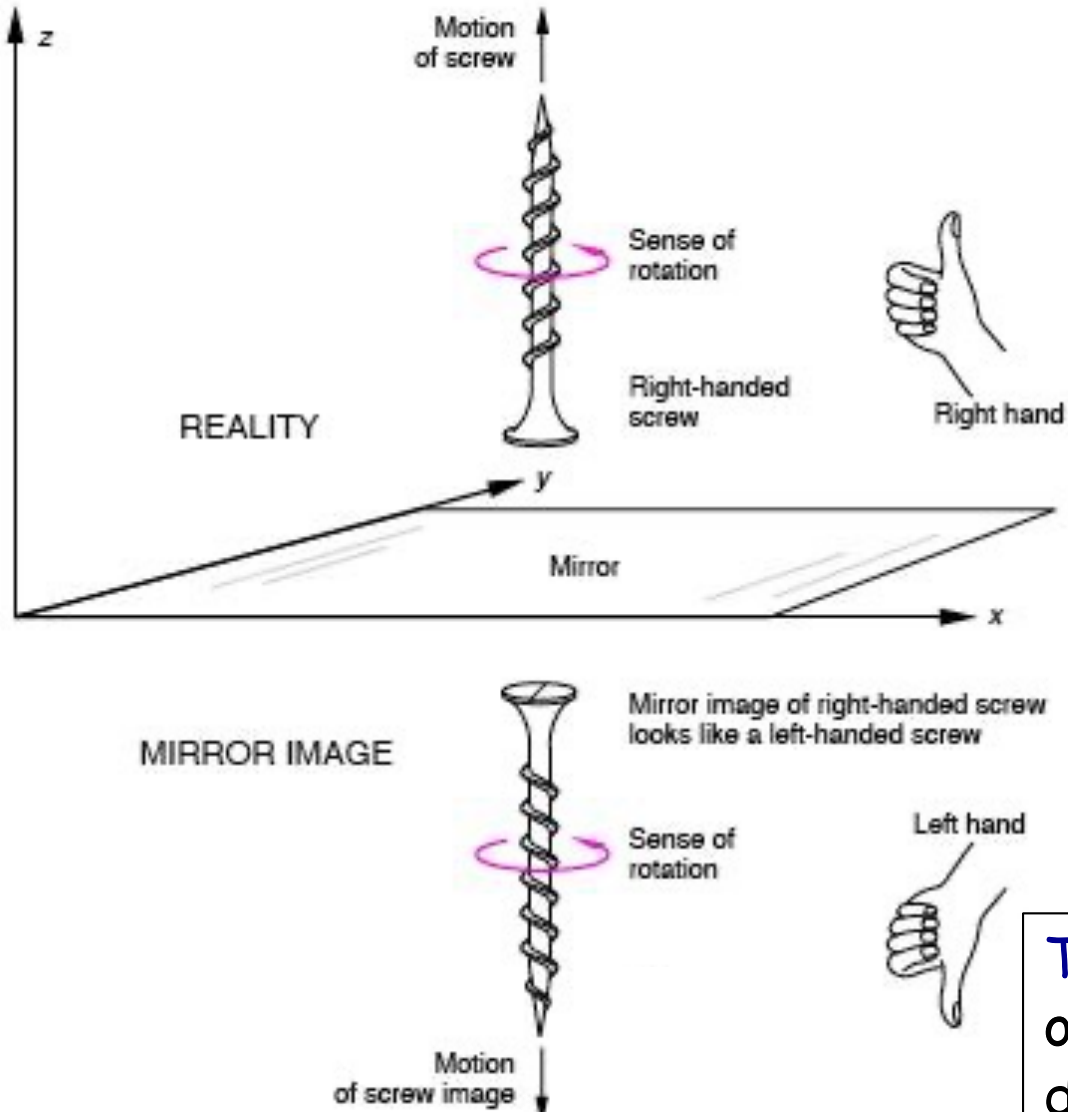
Parity



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

Parity operation inverts sign of all spatial coordinates

Parity and the Mirror World



Since: $\mathbf{L} = \mathbf{r} \times \mathbf{p}$

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

L does not

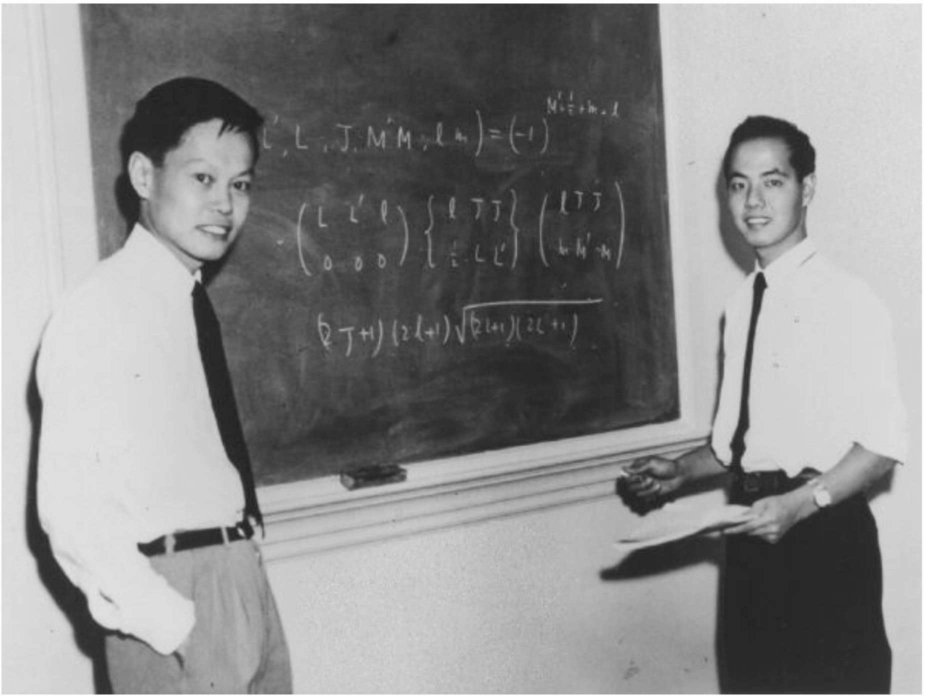
(it's an *axial* vector)

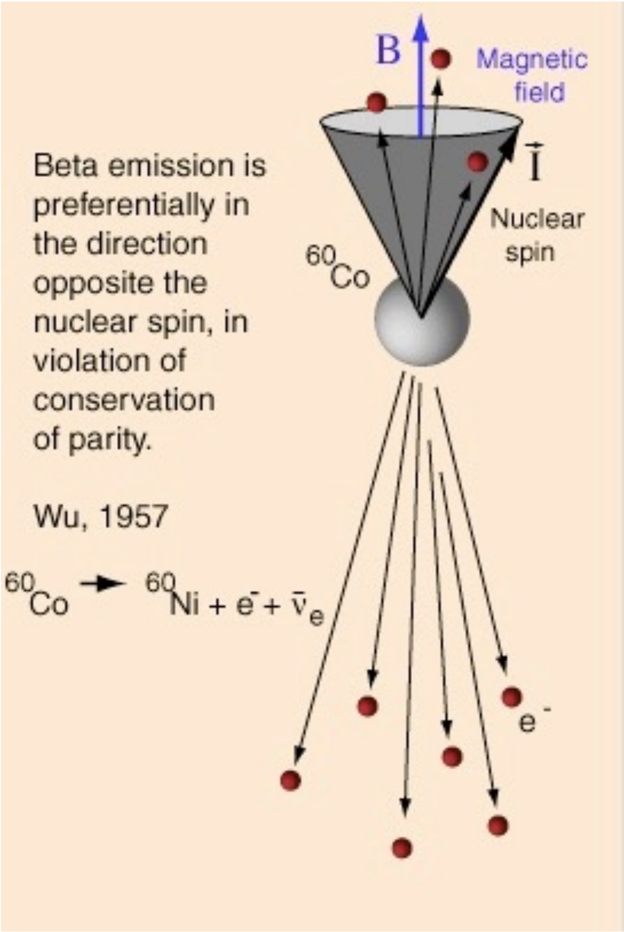
(x ➔ -x and y ➔ -y is same as a 180° rotation around z axis)

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

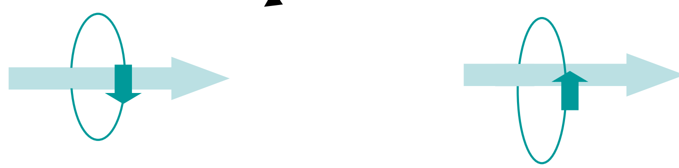
Hmmm….

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

Parity Violation – the mirror world

Electrons spin on their own axes:

either clockwise or counter-clockwise with respect to the direction of their motion: "right-handed" or "left-handed".



Mirror images!

Parity symmetry says: scattering must behave *same* as in a "mirror world" which interchanges right and left hands.

This is true for electromagnetism, but not for the Weak force (the universe is not ambidextrous!)

Measure the *difference* in the scattering probability for right-handed and left-handed electrons → the Weak interaction component

$$\boxed{\text{Asymmetry} = A = \frac{N^R - N^L}{N^R + N^L}}$$

Effect is still tiny:
less than 1 ppm

(≈ 200 ppb)

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

2015 – 12 GeV upgrade

User group: 1500 physicists

Funded by U.S. DOE

Beam currents to 180 μA

CEBAF - Continuous Electron Beam Accelerator Facility

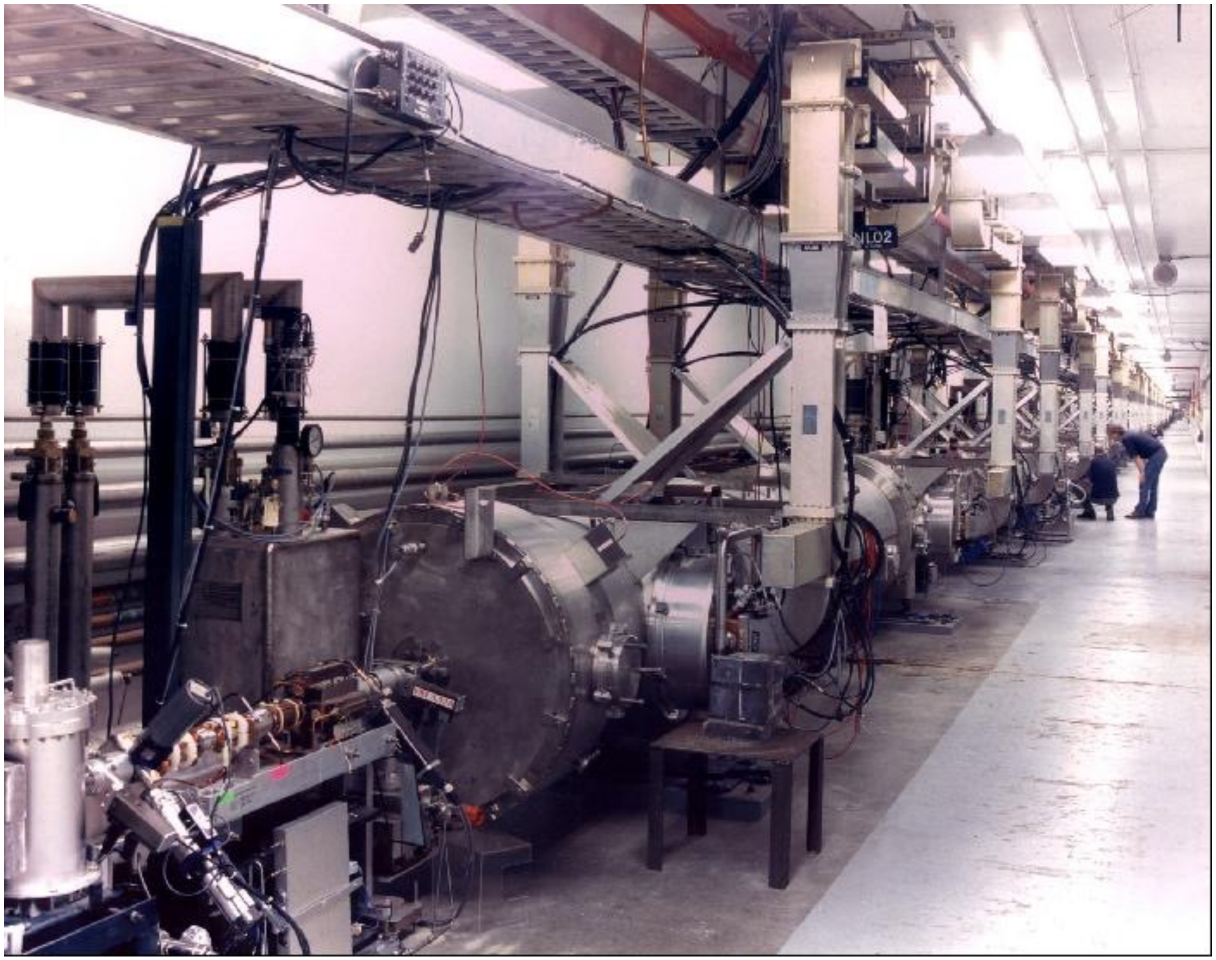
Up to 12 GeV beam energy

> 99.999% the speed of light

Electron's energy = rest mass of 12 protons…

(5 times around 7/8 mile track in 30 microseconds)

Accelerator requires 20 MW power



Bending magnets in arc

Linac tunnel

one million electrons every nanosecond

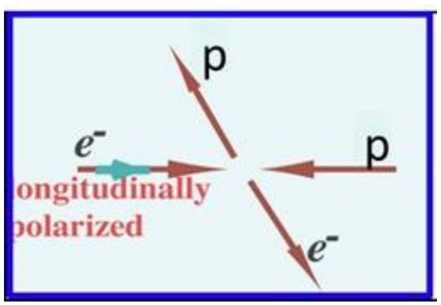
Probing the Weak Charge

The weak force is *unique*: it violates parity

To extract Q_W^p: measure the parity violating asymmetry in electron-proton scattering

$$\vec{e} + p \rightarrow e + p$$

Beam helicity change is equivalent to parity transformation



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35 cm LH2 target

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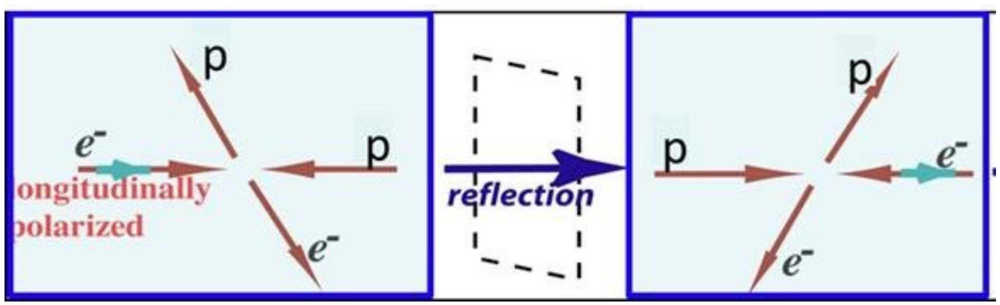

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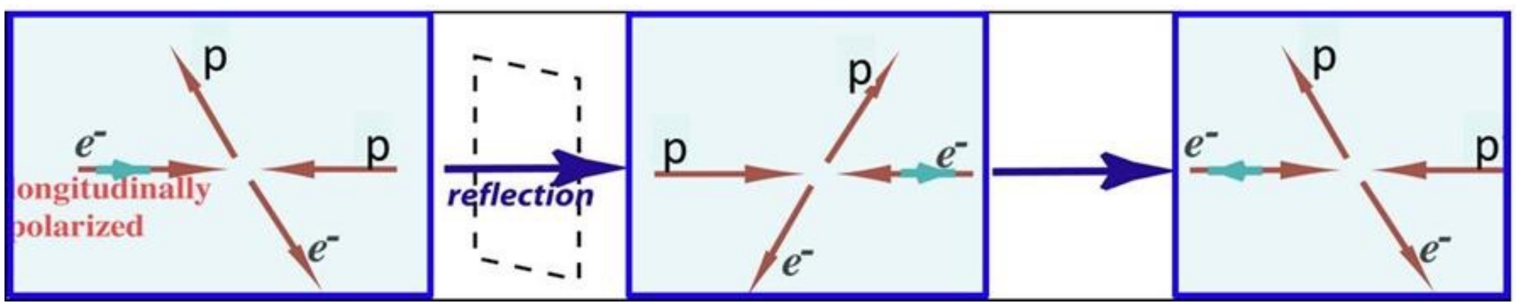

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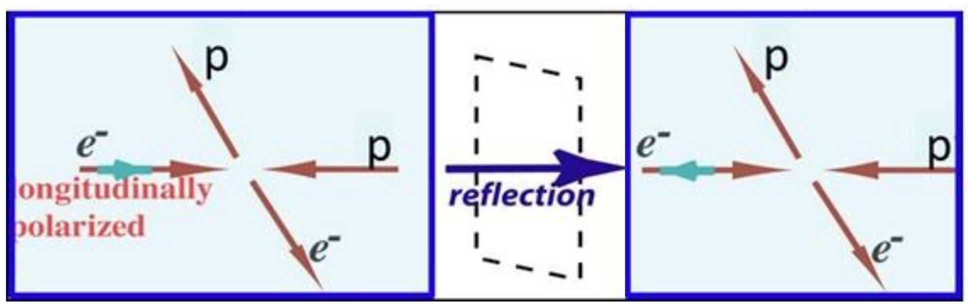
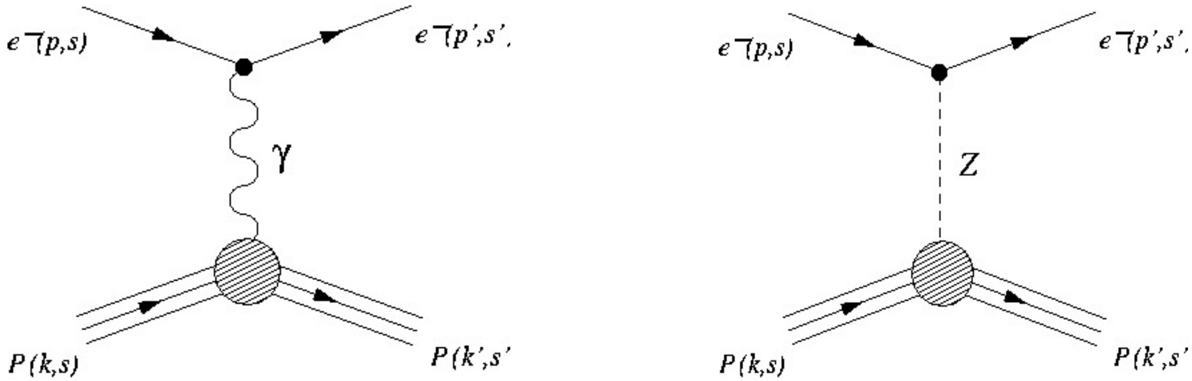


Rapid helicity reversal pattern (960 Hz) "quartets"

+−−+ −++−

Electroweak Interference



$$\boxed{\text{Probability} = |\text{Amplitude}|^2 = |M^\gamma|^2 + |M^Z|^2 + 2Re(M^\gamma)^* M^Z}$$

Interference allows us to access weak interaction

Extracting the weak charge

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

Hadronic structure enters here

Reduced asymmetry more convenient

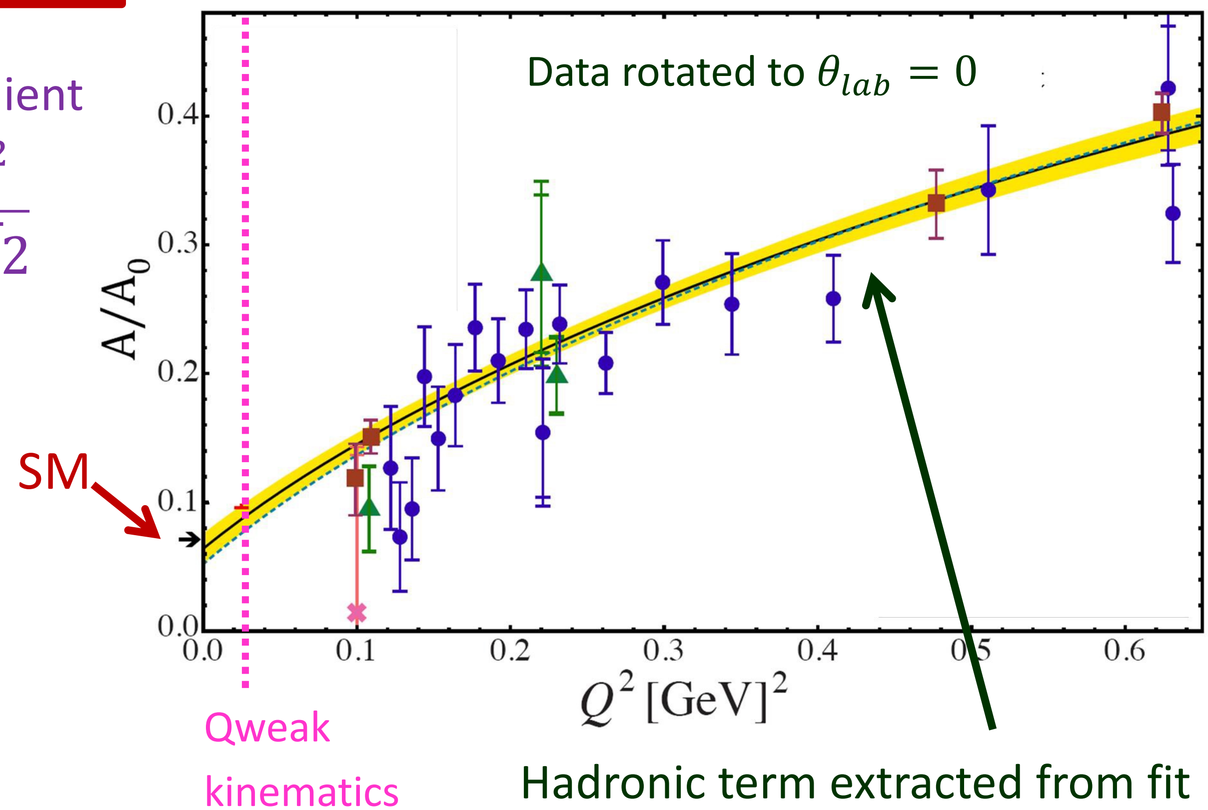
$$A_{red} = \frac{A_{PV}}{A_0} \qquad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

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

We measure A_{phys}^{PV}

at $Q^2 = 0.025\ GeV^2$.

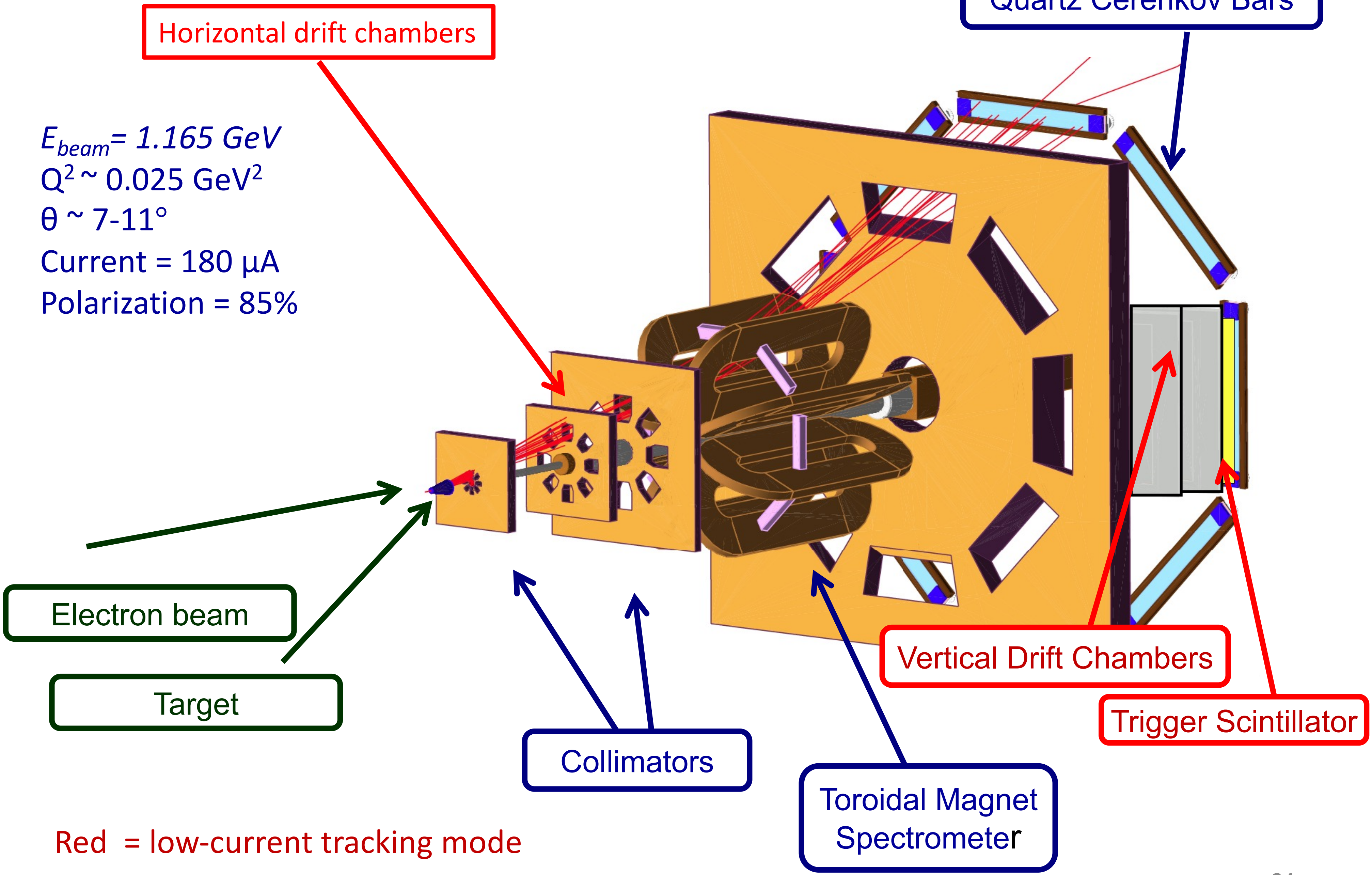
We just "tickle" the proton, not smash it…



Previous experiments explored hadronic structure more directly; help constrain our hadronic contribution

Q-weak Apparatus

E_{beam}= 1.165 GeV
$Q^2 \sim 0.025\ GeV^2$
$\theta \sim 7\text{-}11°$
Current = 180 μA
Polarization = 85%



Red = low-current tracking mode
Blue = production ("integrating") mode

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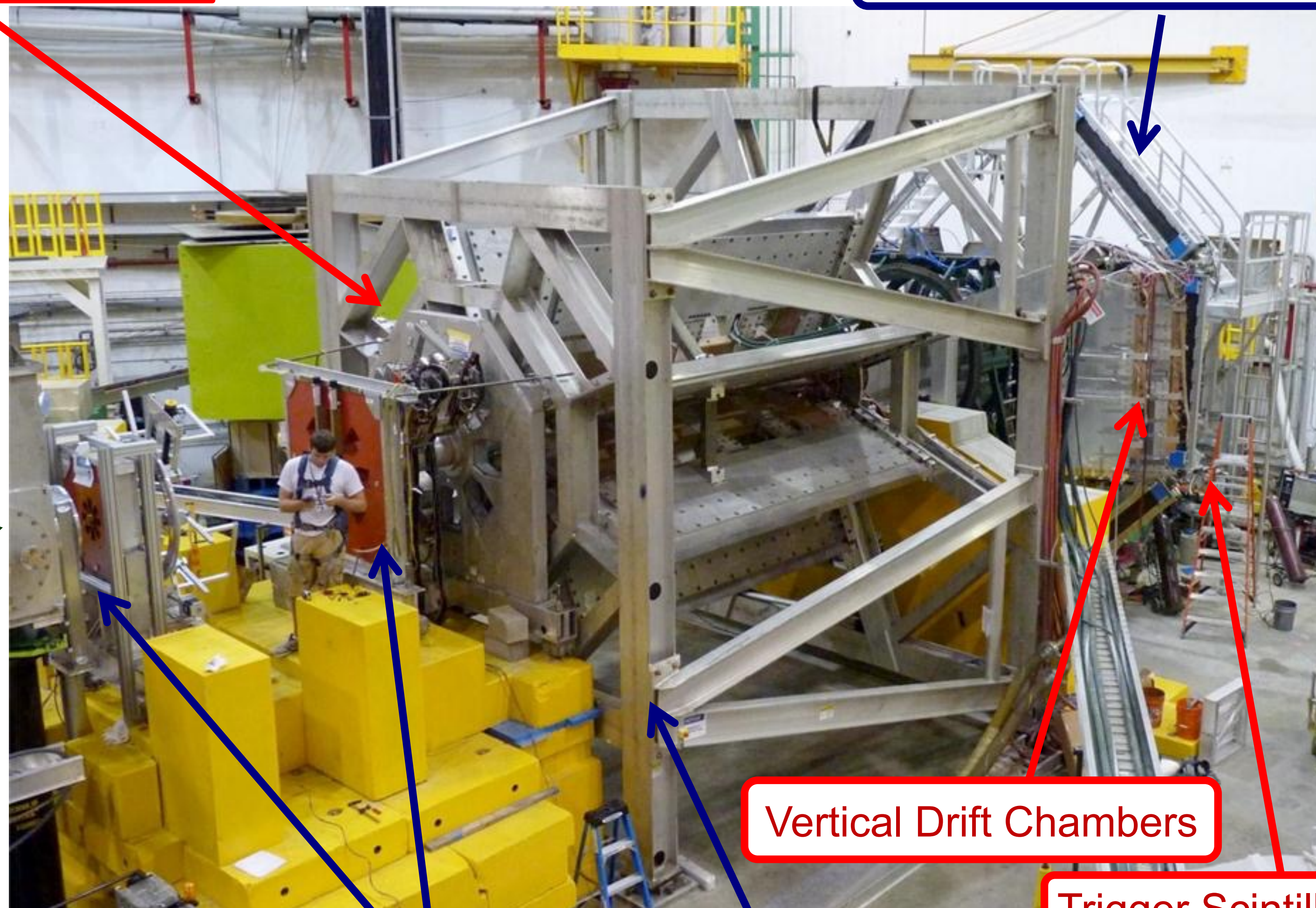

Red = low-current tracking mode
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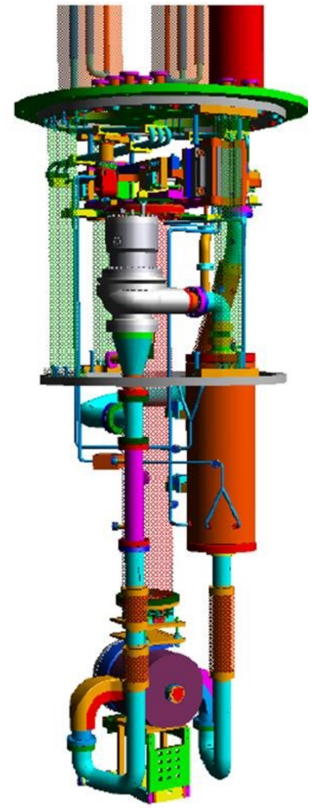
Qweak Target

35 cm long, 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!

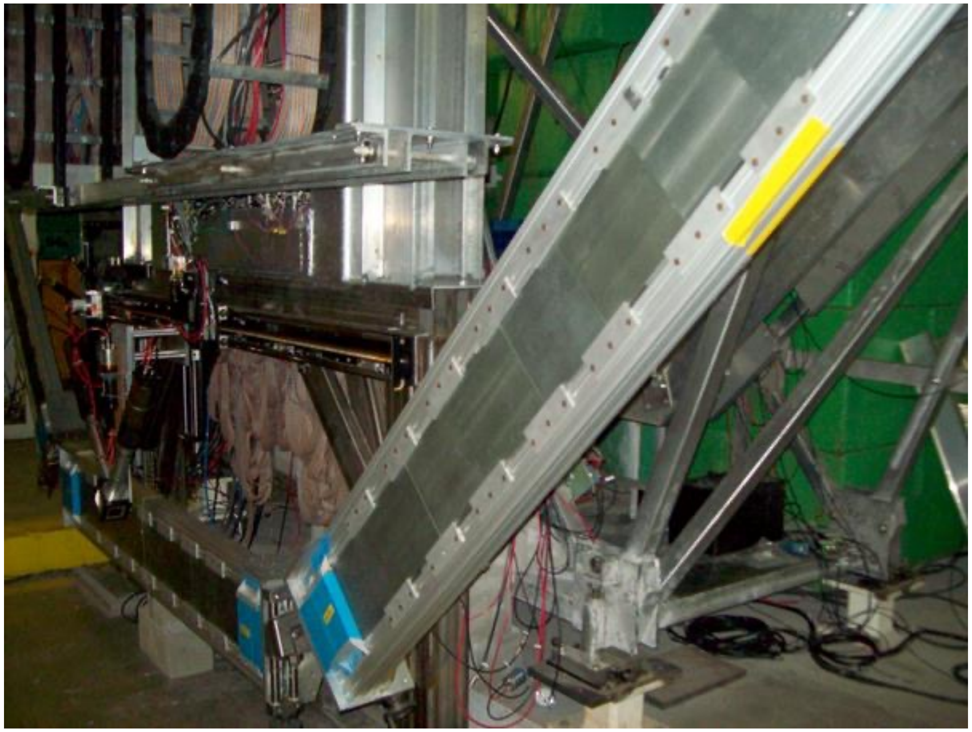


Main Detectors

- Main detectors

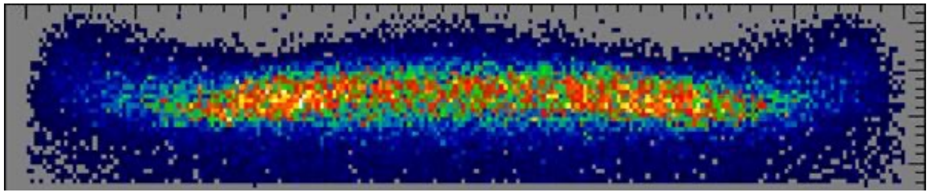
  The toroidal magnet focuses elastically scattered electrons onto each bar

  - 8 Quartz Cerenkov bars
  - Azimuthal symmetry
  - 2 cm lead pre-radiators reduce background

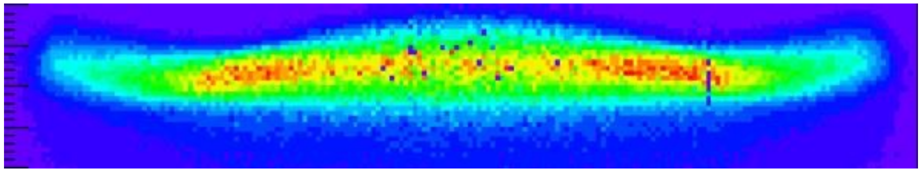


Close up of one detector in situ

Simulation of scattering rate MD face



Measured



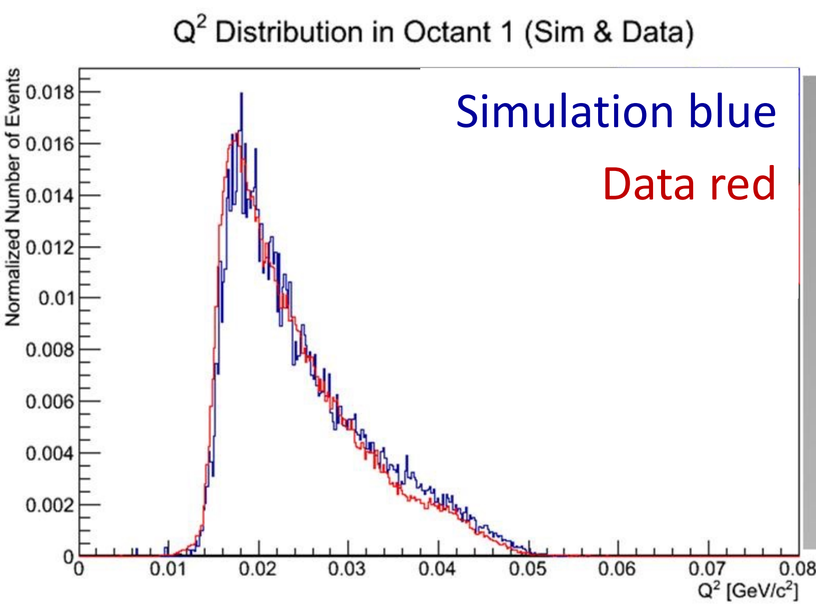
Q^2 determination

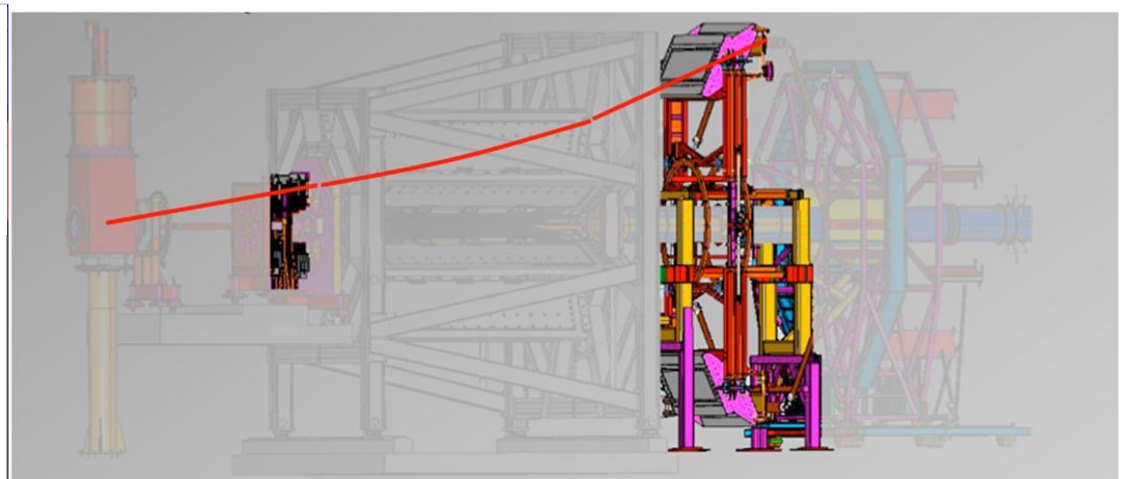
To determine Q^2, we go to "tracking" mode:

- Currents ~ 50 pA
- Use Vertical + Horizontal Drift Chambers
- Re-construct individual scattering events

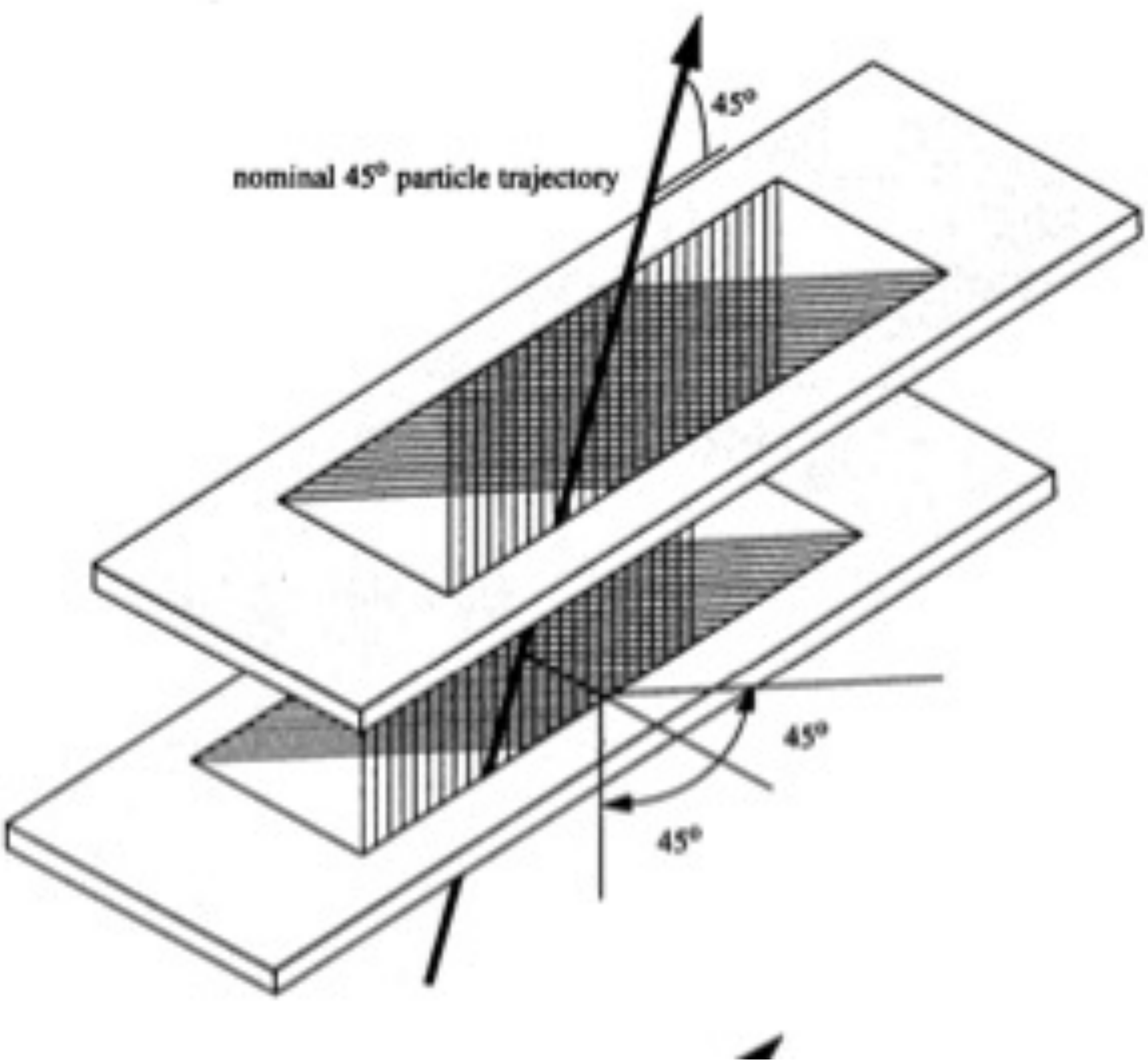
$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\{Q_w^p + B(\theta, Q^2)Q^2\}$$

)





Vertical Drift Chambers



Designed, built and tested at W&M

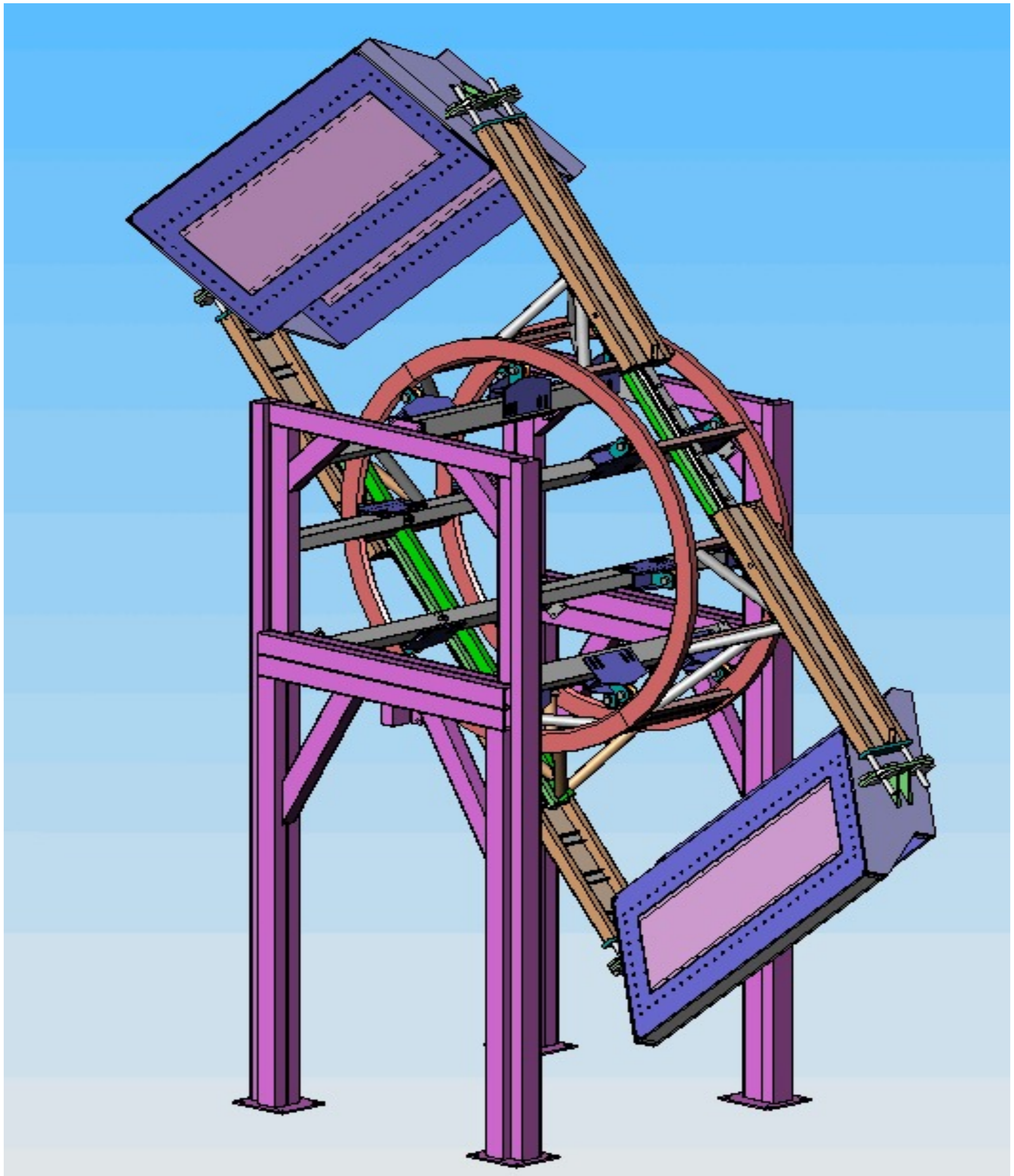
Two pairs of Ar/ethane gas-filled wire chambers

Each 3’ x 8’

558 wires/chamber:
25µm diameter Au-plated W
3800 V

Scattered electron ionizes gas, electron/ion pairs drift under electric field; time of arrival of electrons at wire – location of initial track.

VDC Rotator



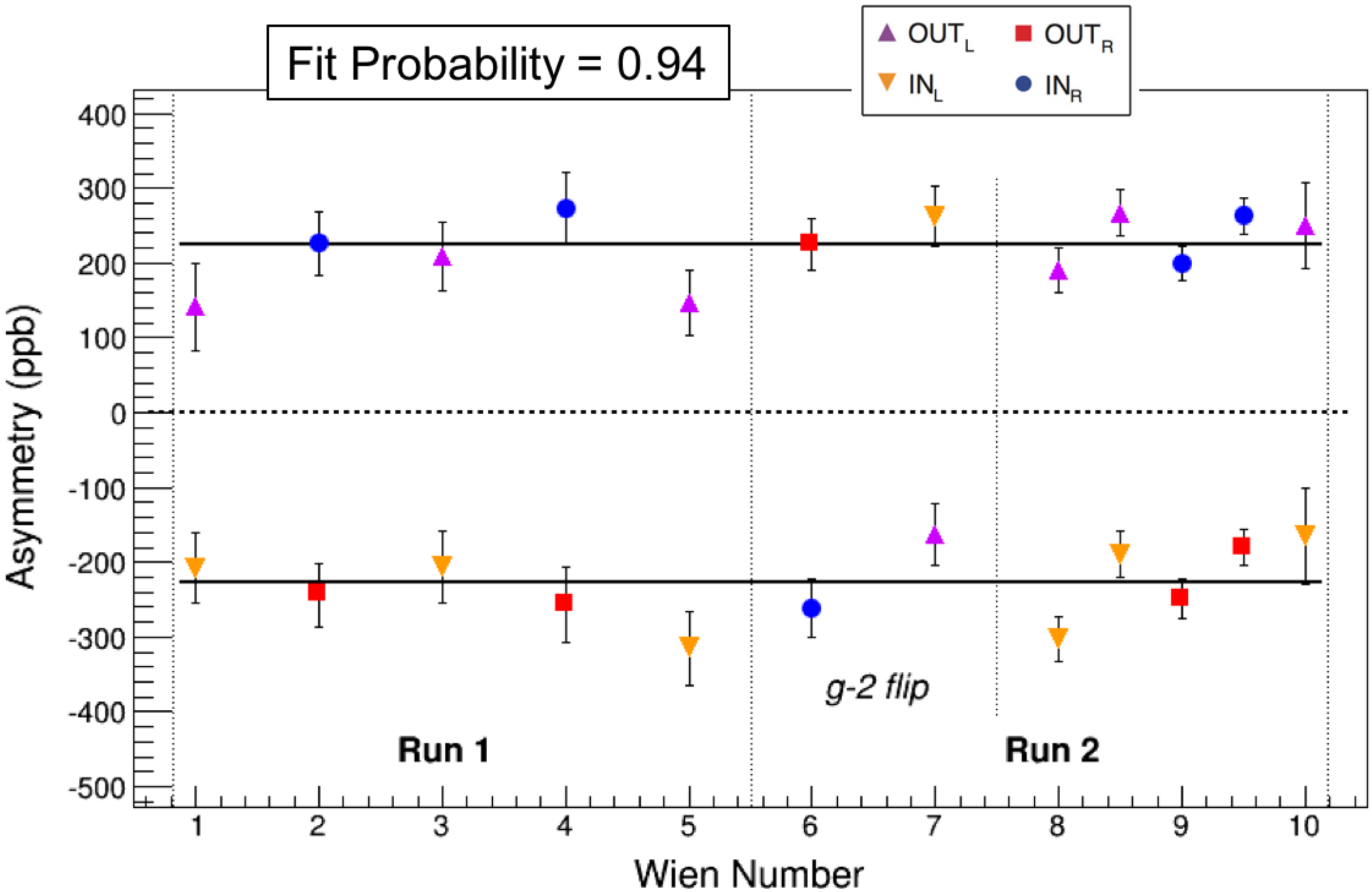
VDCs at JLab

Run periods

Q-weak ran from Fall 2010 – May 2012 in 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)

Behavior of Asymmetry under Slow Reversals



Three slow reversal types

IN/OUT: reversal of laser helicity (IWHP)

L/R: reversal of electron beam via Wien filter

g-2 flip: reversal of electron via spin precession in accelerator

The data behaved as expected under all three types of slow helicity reversal.

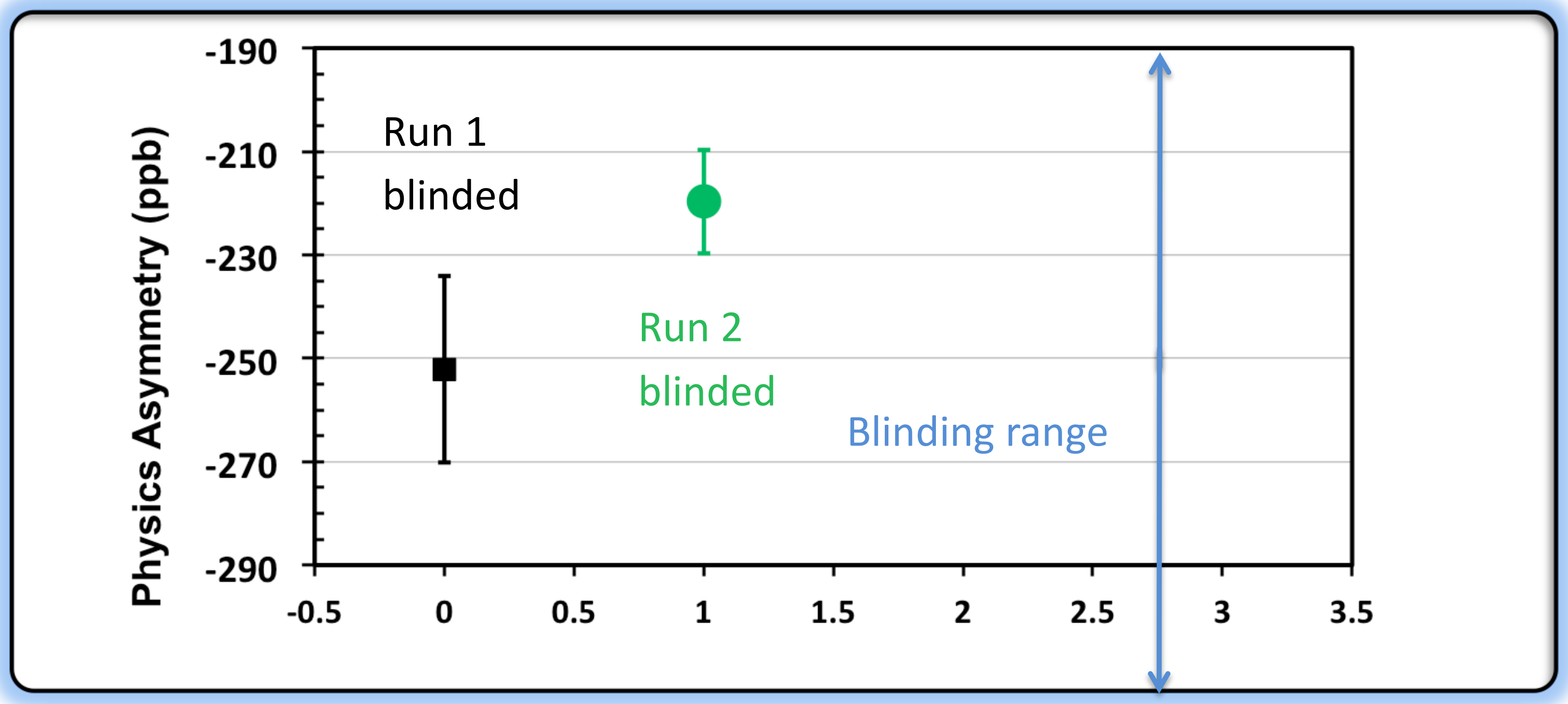
Combining the data without sign corrections gives

NULL average = -1.75 ± 6.51 ppb

- consistent with zero, as expected

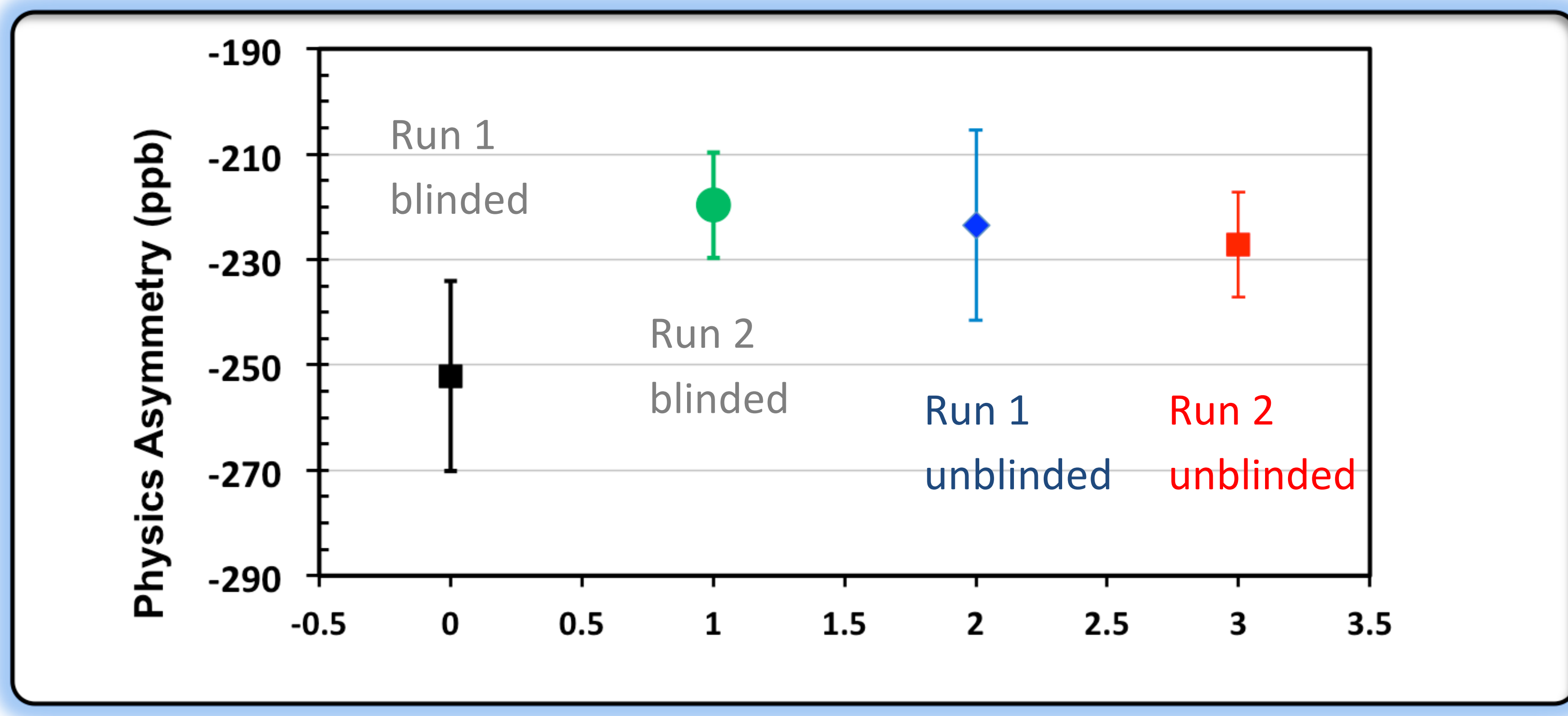
Blinded Analysis

Run 1 and 2 *each* had their own independent "blinding factor" (additive offset in range ± 60 ppb) to avoid analysis bias.



Un-Blinded Results

Marvelous agreement between the two Runs
(several systematic corrections rather different in the two Runs)



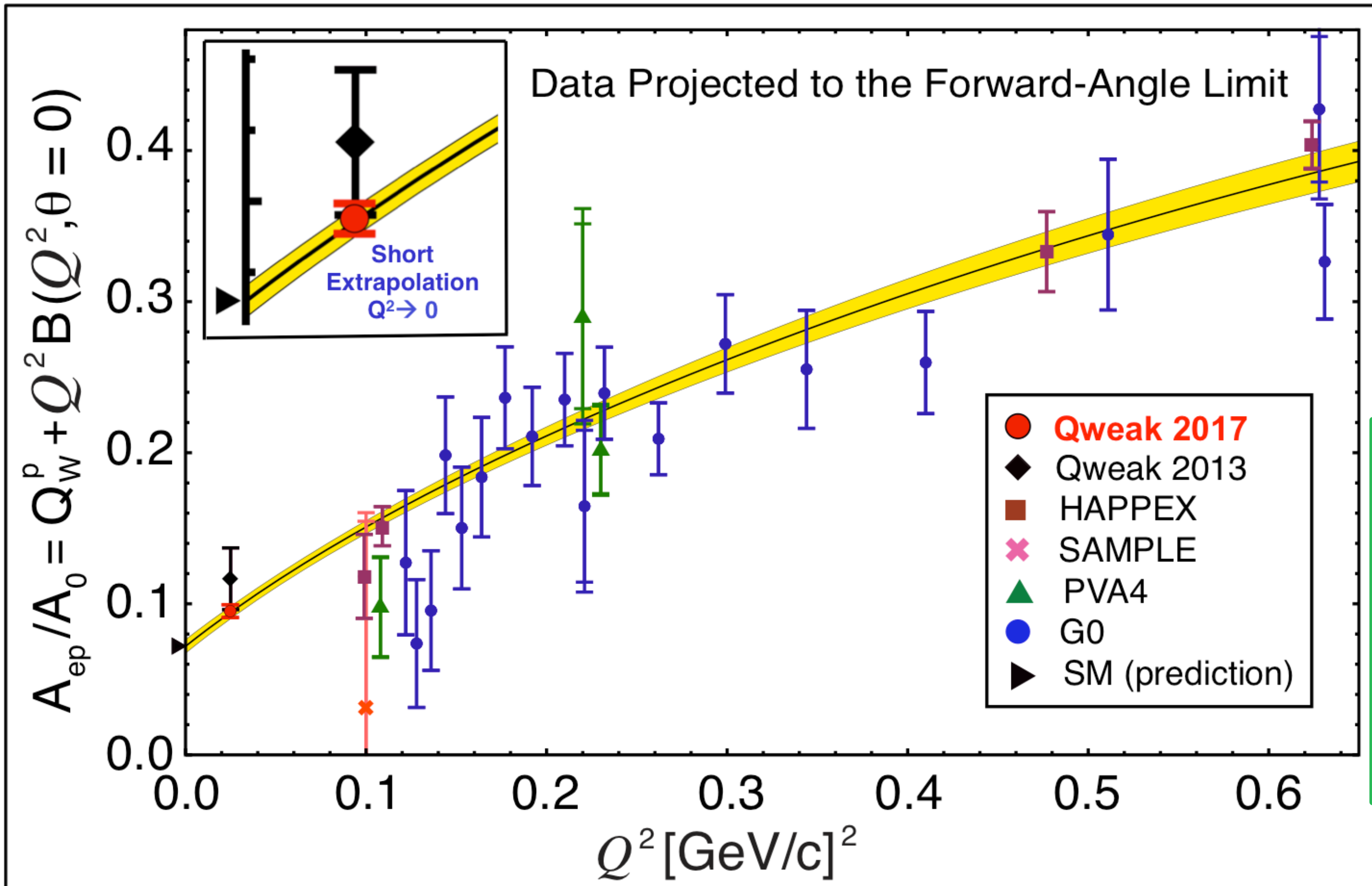
Period	Asymmetry (ppb)	Stat. Unc. (ppb)	Syst. Unc. (ppb)	Tot. Uncertainty (ppb)
Run 1	-223.5	15.0	10.1	18.0
Run 2	-227.2	8.3	5.6	10.0
Run 1 and 2 combined with correlations	-226.5	7.3	5.8	9.3

Extracting Weak Charge from Asymmetry Result

$$\boxed{A_{ep} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst})\ \text{ppb at } \langle Q^2 \rangle = 0.0249\ (\text{GeV}/c)^2}$$

Global fit of world PVES data up to $Q^2 = 0.63\ \text{GeV}^2$ to extract proton's weak charge:

$$A_{ep}/A_0 = Q_W^p + Q^2 B(Q^2, \theta), \qquad A_0 = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right].$$



33 entries in PVES (e-p, e-d, e-^{4}He) database

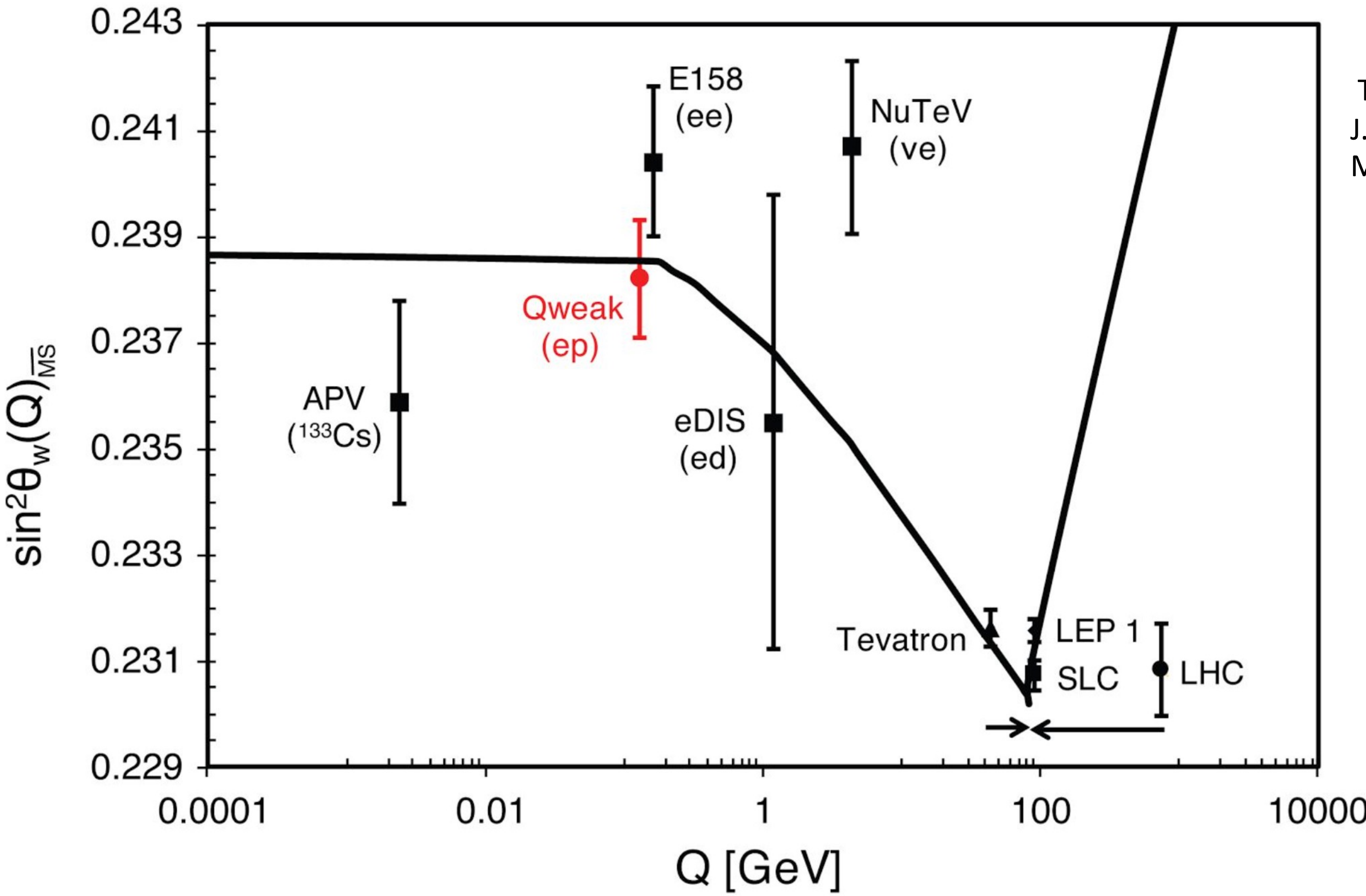
Standard Model:

$Q_W^p = 0.0708 \pm 0.0003$

Experiment:

$Q_W^p = 0.0719 \pm 0.0045$

Running of the Weak Mixing angle $\sin^2\theta_W$



Theory Solid Curve:
J. Erler, M. Ramsey-Musolf, P. Langacker

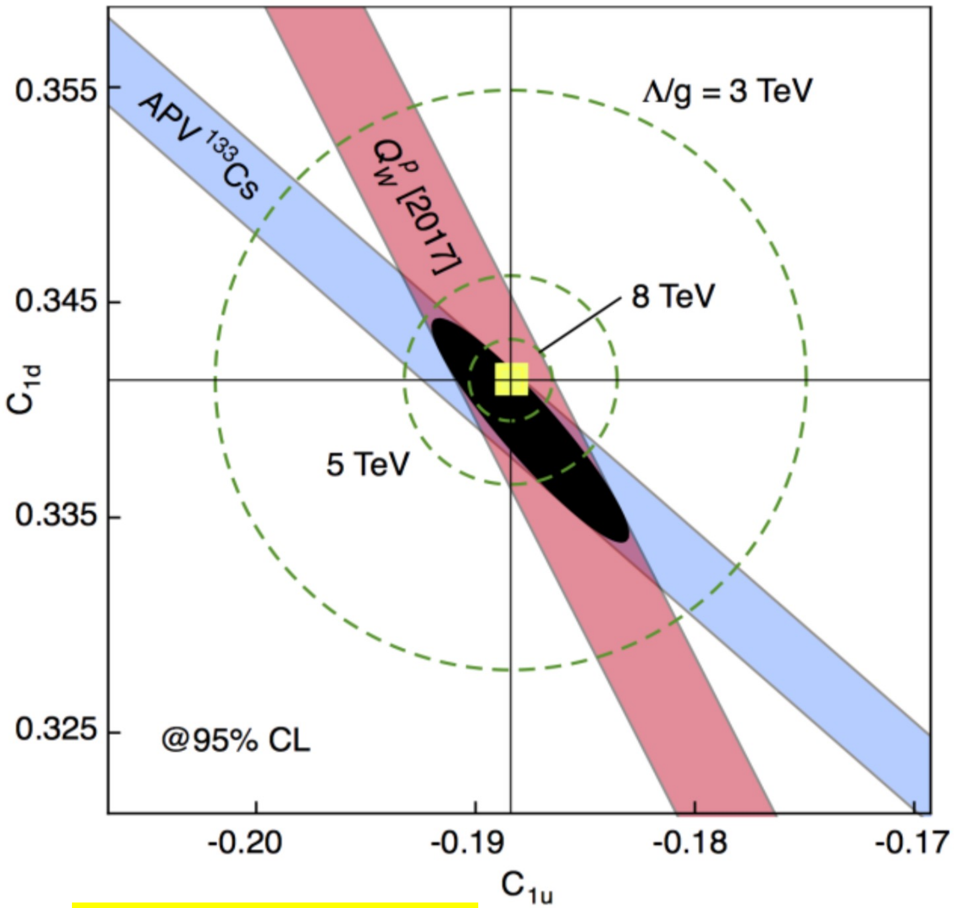
Limits on Semi-Leptonic PV Physics beyond the SM

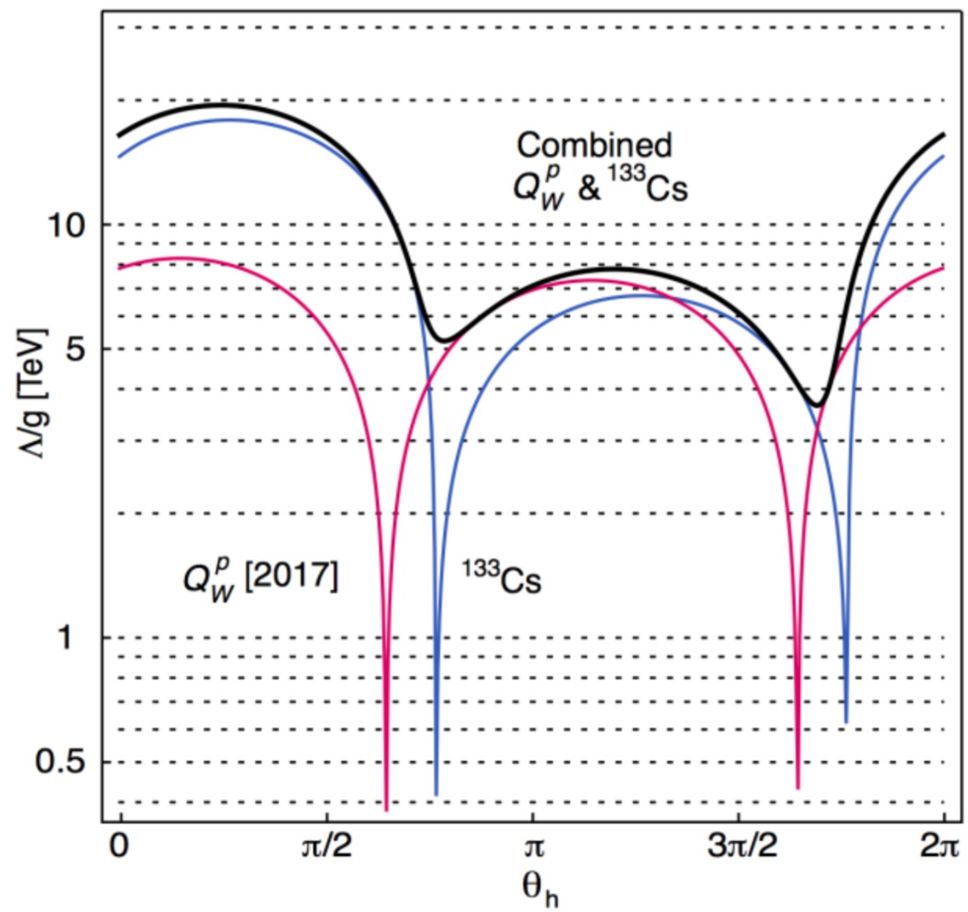
$$\boxed{Q_W^p = -2(2C_{1u} + C_{1d})}$$

New Physics Ruled Out
@95% CL Below Mass Scale of Λ/g

$$\mathcal{L}_{\rm NP}^{\rm PV} = -\frac{g^2}{\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$



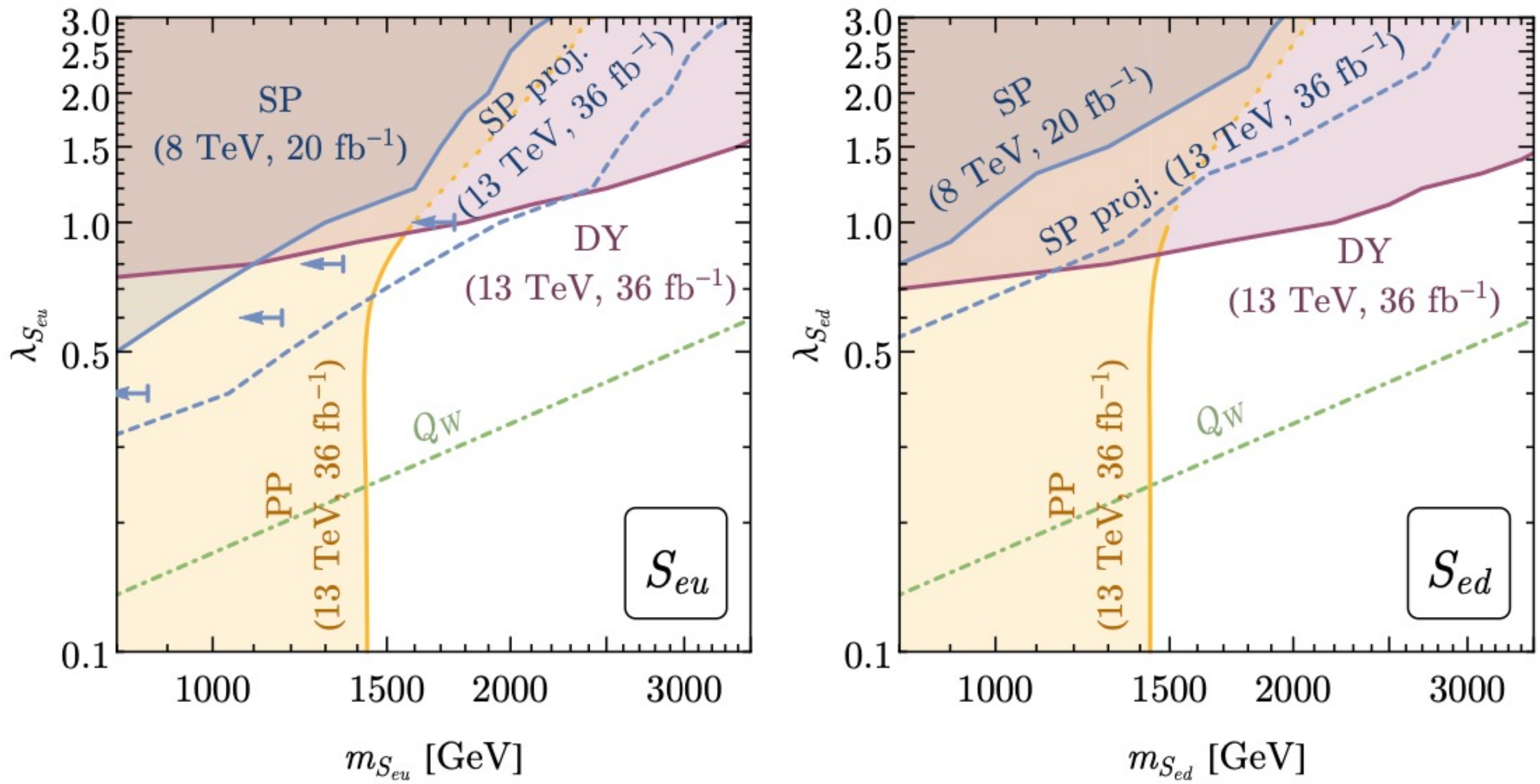


Yellow box: SM values

APV: atomic parity violation ^{133}Cs   C.S. Wood et al. Science **275**, 1759 (1997); Dzuba et al. PRL **109**, 203003 (2012)

Limits on Leptoquarks

An example of the impact on one class of "New Physics" beyond the Standard Model: "leptoquarks"



"The leptoquark Hunter's guide: large coupling"
M. Schmaltz, Y-M. Zhong *Journal of High Energy Physics* 01 (2019) 132

Qweak Collaboration

D.S. Armstrong, A. Asaturyan, T. Averett, J. Balewski, J. Beaufait, R.S. Beminiwattha, J. Benesch, F. Benmokhtar, J. Birchall, R.D. Carlini[1], J.C. Cornejo, S. Covrig, M.M. Dalton, C.A. Davis, W. Deconinck, J. Diefenbach, K. Dow, J.F. Dowd, J.A. Dunne, D. Dutta, W.S. Duvall, M. Elaasar, W.R. Falk, J.M. Finn[1], T. Forest, D. Gaskell, M.T.W. Gericke, J. Grames, V.M. Gray, K. Grimm, F. Guo, J.R. Hoskins, K. Johnston, D. Jones, M. Jones, R. Jones, M. Kargiantoulakis, P.M. King, E. Korkmaz, S. Kowalski[1], J. Leacock, J. Leckey, A.R. Lee, J.H. Lee, L. Lee, S. MacEwan, D. Mack, J.A. Magee, R. Mahurin, J. Mammei, J. Martin, M.J. McHugh, D. Meekins, J. Mei, R. Michaels, A. Micherdzinska, K.E. Myers, A. Mkrtchyan, H. Mkrtchyan, A. Narayan, L.Z. Ndukum, V. Nelyubin, Nuruzzaman, W.T.H van Oers, A.K. Opper, S.A. Page[1], J. Pan, K. Paschke, S.K. Phillips, M.L. Pitt, M. Poelker, J.F. Rajotte, W.D. Ramsay, J. Roche, B. Sawatzky,T. Seva, M.H. Shabestari, R. Silwal, N. Simicevic, G.R. Smith[2], P. Solvignon, D.T. Spayde, A. Subedi, R. Subedi, R. Suleiman, V. Tadevosyan, W.A. Tobias, V. Tvaskis, B. Waidyawansa, P. Wang, S.P. Wells, S.A. Wood, S. Yang, R.D. Young, S. Zhamkochyan

[1]Spokespersons [2]Project Manager Grad Students

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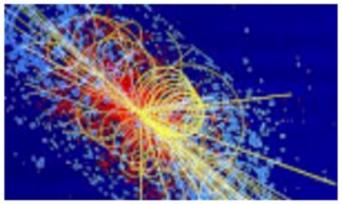

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The Weak Side of the Proton

A new result from the Q-weak experiment at the Department of Energy's Thomas Jefferson National Accelerator Facility provides a precision test of the weak force, one of four fundamental forces in nature.

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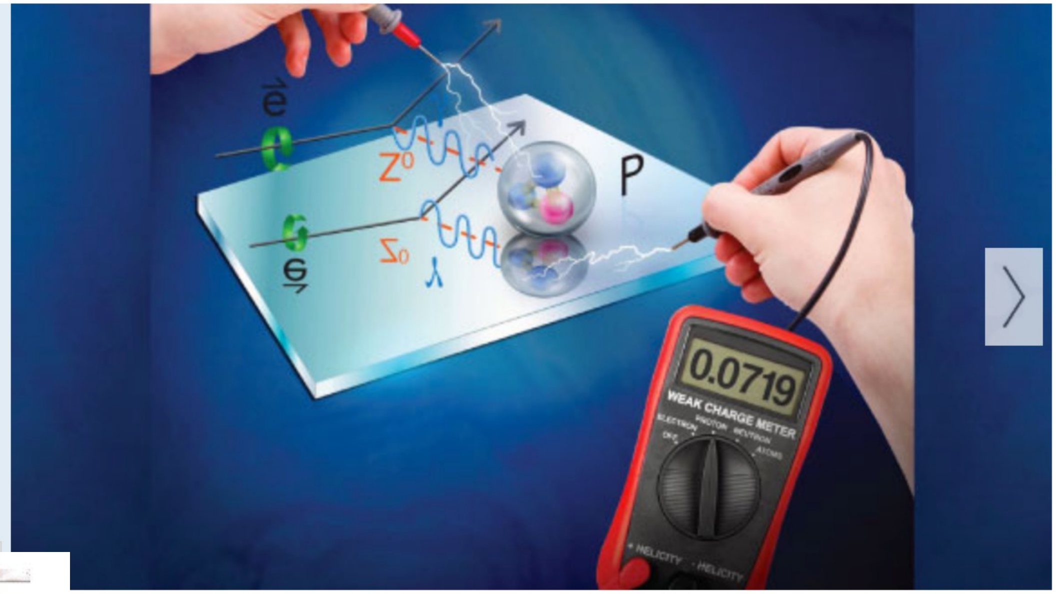

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Daily Press

MONDAY, MAY 21, 2018

JEFF LAB SHINES LIGHT ON UNIVERSE'S WEAK FORCE

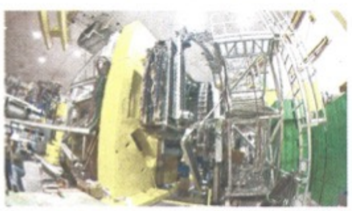
By Tamara Dietrich
tdietrich@dailypress.com

The weak force is one of four fundamental forces of nature that, together, prevent all matter in the universe from breaking up and floating away.

Three of those forces — electromagnetism, the strong force and the weak force — are accounted for in the Standard Model of particle physics, or the grand mathematical theory that scientists came up with in the 1970s to try to explain how the quantum world works. The fourth force is gravity.

But particle physicists around the globe are forever poking and prodding at the sub-atomic level to test the

See FORCE/Page 5



COURTESY OF JEFFERSON LAB

Shown is the detector system for measuring scattered electrons in the Q-weak experiment. The electromagnet is to the left of the yellow concrete shielding, and several of the eight sets of precision detectors for identifying the electrons are seen at center.

FORCE

Continued from 1

limits of that model, and to fill in where it falls short. It doesn't account, for instance, for gravity, dark energy or dark matter.

By design, the Standard Model doesn't only account for particles

"The holy grail of particle and nuclear physics is to look for forces or particles that are beyond the Standard Model of particle physics."

David Armstrong, chancellor professor of physics at the College of William and Mary in Williamsburg

tickled it," Armstrong said.

Moving forward

And so for two years, said Smith, they ran the experiment in 24-hour shifts on the floor, seven days a week, performing measurements millions of billions of times.

"We just gave it our all," Smith said.

Link

Physicists Just Measured One of the Four Fundamental Forces of Nature. Now They're Bummed.

The most precise measurement yet of the weak force shows no signs of new physics.

Live Science · May 9

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Summary

Precision measurement of proton's weak charge: $\boxed{Q_W^p = 0.0719 \pm 0.0045}$

Excellent agreement with Standard Model prediction = 0.0708

Constrains generic new parity-violating "Beyond the Standard Model" physics at TeV scale: Λ/g > 3.6 TeV (arbitrary u/d ratio of couplings)

D. Androic *et al.*, "Precision Measurement of weak charge of the proton" Nature 557, 207-211 (2018).

Now underway: we are building an experiment to measure the weak charge of the electron… hope to start taking data in 2025…

Thanks!