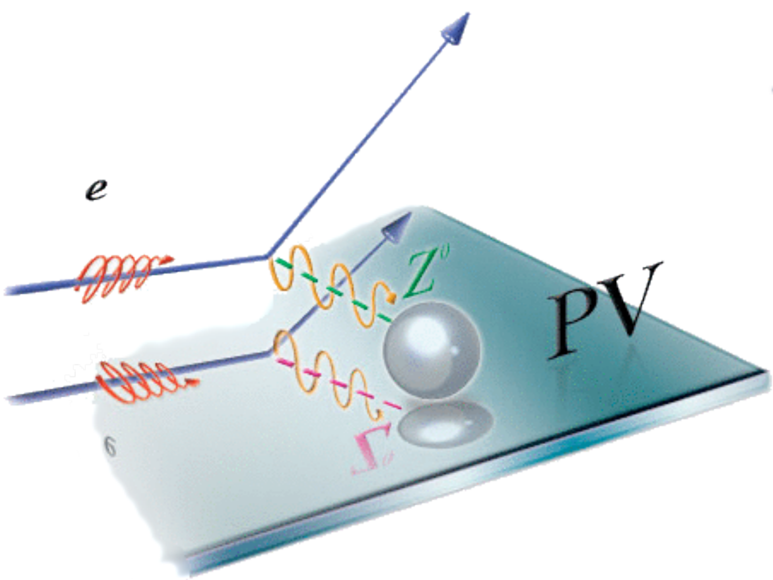
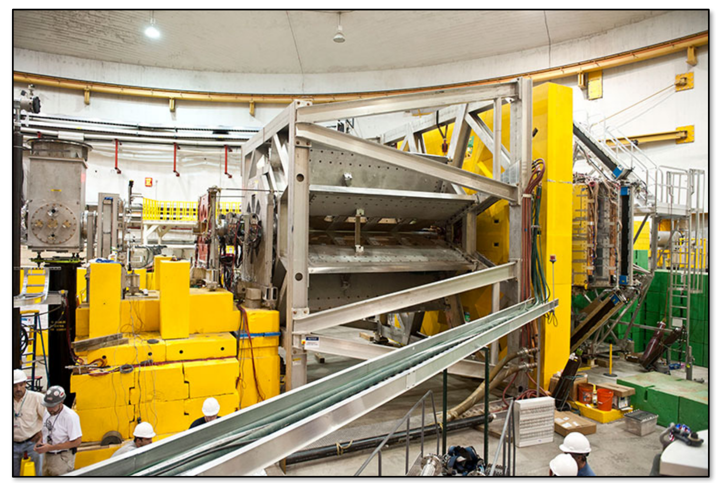
Looking for New Physics with the Weak Interaction: Recent Results from Qweak, and Future Perspectives

October 6, 2017

University of Virginia Bicentennial





Kent Paschke
University of Virginia

Outline

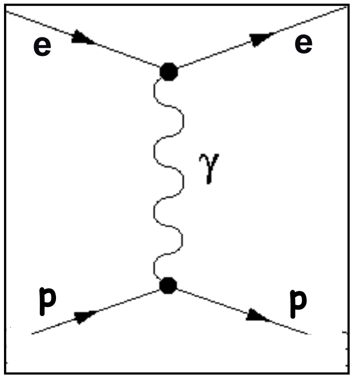
- Introduction to electron scattering
- Weak interaction, parity symmetry, and parity-violating electron scattering
- Peering beyond the SM at low energies
- The Qweak Experiment
- Results
- One more 3rd generation experiment: n-star in a terrestrial nucleus
- Next generation experiments
- Summary

Introduction to Electron Scattering

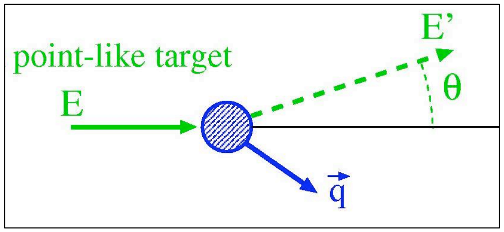
Introduction to electron scattering

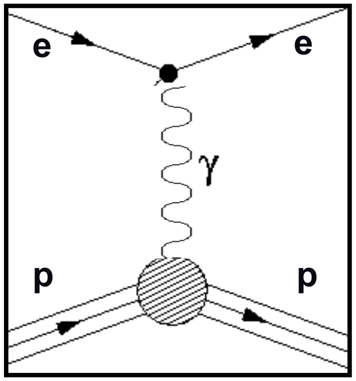
Electron scattering: electromagnetic interaction, described as an exchange of a virtual photon.

If photon carries low momentum
-> long wavelength
-> low resolution

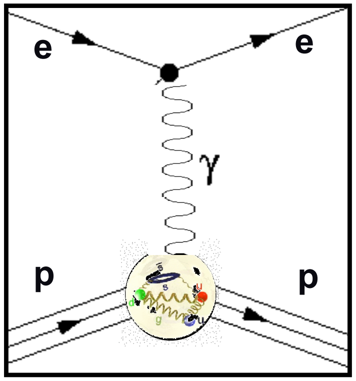


Q^2: 4-momentum of the virtual photon



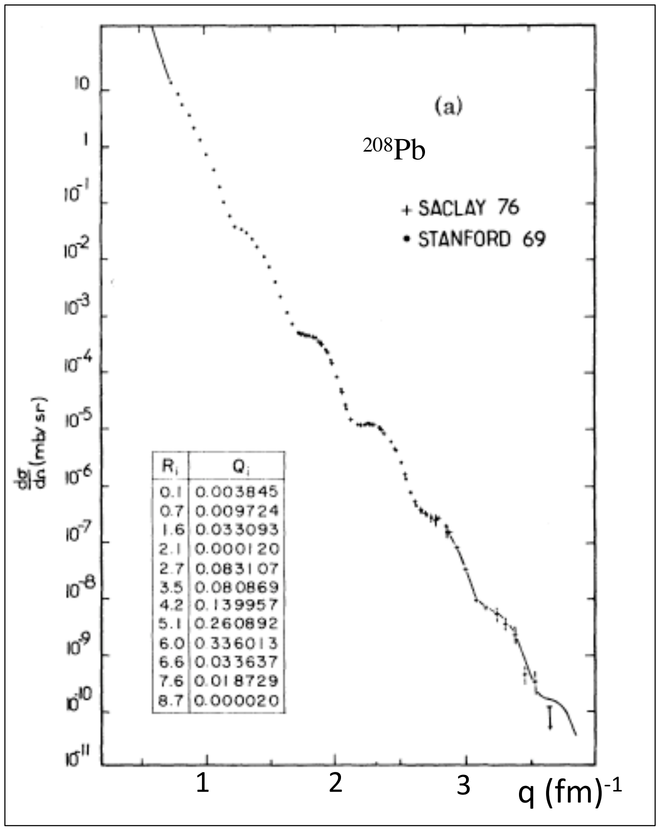


Increasing momentum transfer
-> shorter wavelength
-> higher resolution to observe smaller structures



Elastic Form Factors and Extended Targets

The point-like scattering probability for elastic scattering is modified to account for finite target extent by introducing the “form factor”



Assuming spherically symmetric (spin-0) target

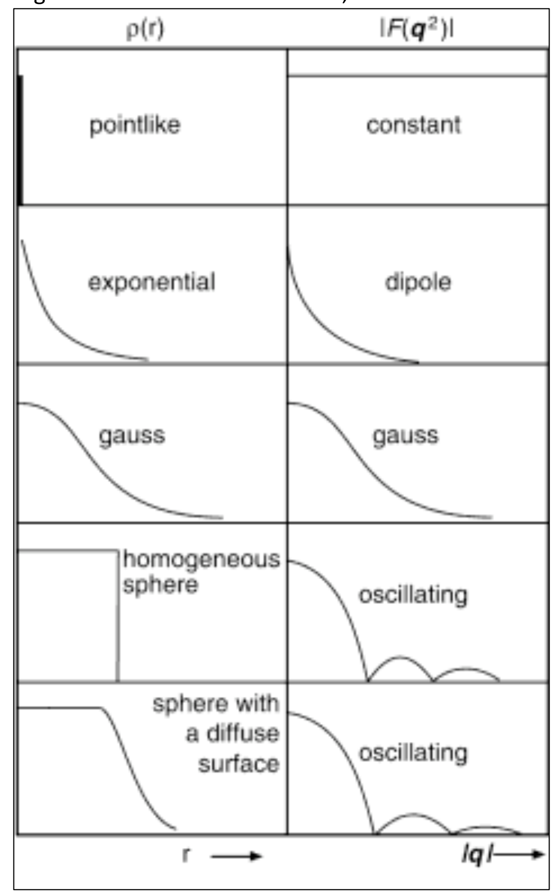
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Mott} |\, F(q)\,|^2$$

point-like target, electron spin

$$F(q) = \int e^{iqr}\rho(r)d^3r$$

Form factor is the Fourier transform of charge distribution

Figure from Particles and Nuclei, Povh *et al.*



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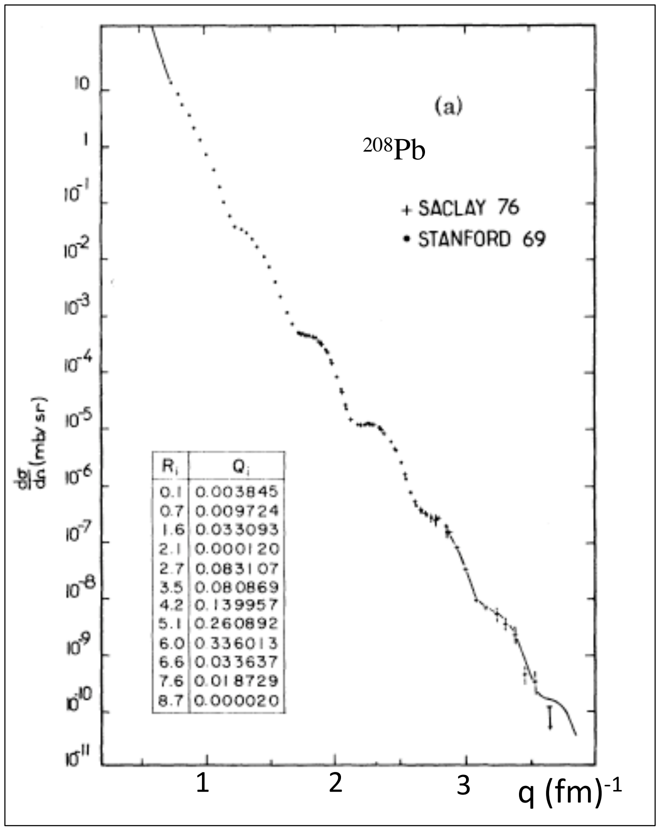

R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

Assuming spherically symmetric (spin-0) target

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} |F(q)|^2$$

point-like target, electron spin

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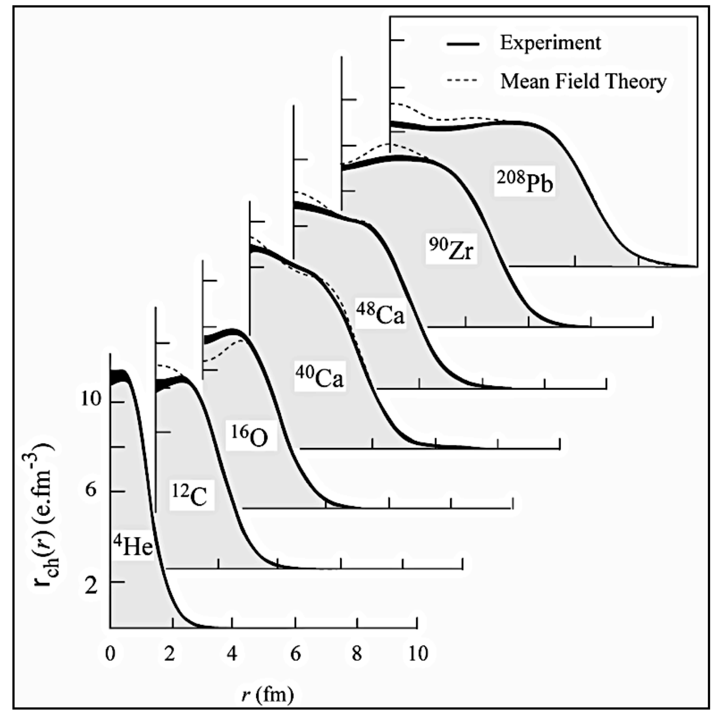


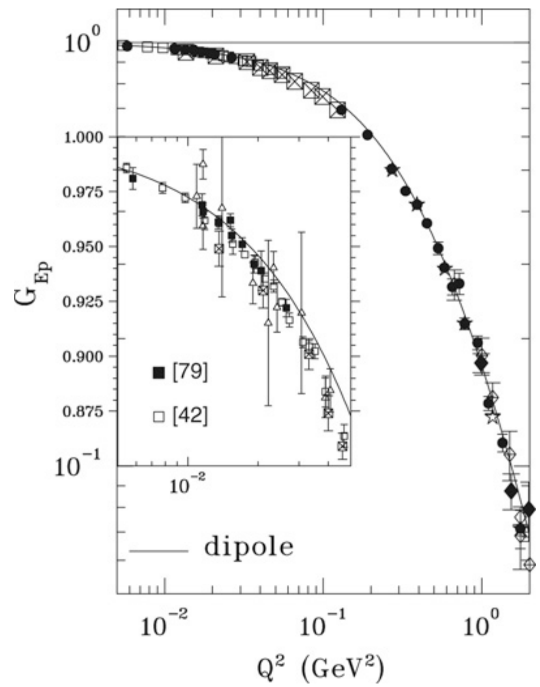
Elastic Electron-Nucleon Scattering

For targets with spin, must also account for magnetic moment

Electric and Magnetic form factors $G_E(Q^2)$ and $G_M(Q^2)$

$$\frac{d\sigma}{d\Omega}_{Rosenbluth} = \frac{d\sigma}{d\Omega}_{Mott}\left\{\frac{(G_E^2+\tau\, G_M^2)}{1+\tau}+2\tau\, G_M^2\tan^2(\theta/2)\right\}$$

Proton (and neutron magnetic) form-factors follow dipole form (exponential charge distribution)



With no structure

G_E = 1 (proton charge)

G_M = 1 (magnetic moment = μ_B).

At Q^2 = 0, the probe does not resolve the target

$G_E(0)$ = 1 (electric charge)

$G_M(0)$ = μ (magnetic moment in units of μ_B)

Weak Interaction, Parity Symmetry, and Parity Violating Electron Scattering

Weak Interaction and parity

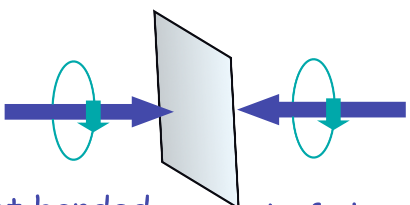
1930's - The weak nuclear interaction was needed to explain nuclear beta decay

1950's - Discovery of parity-violation by the weak interaction

Parity transformation

$$x, y, z \rightarrow -x, -y, -z$$

$$\vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{S} \rightarrow \vec{S}$$

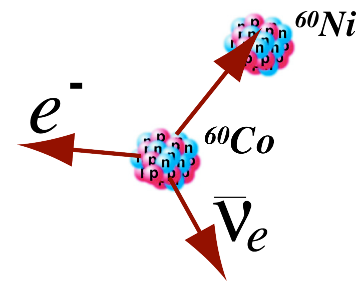


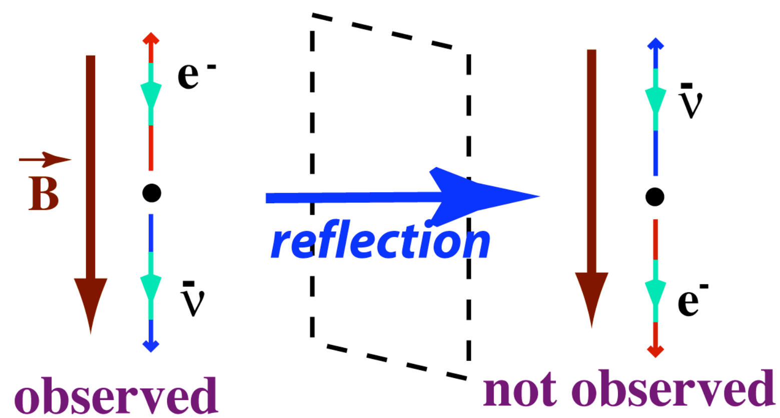
Parity transformation is analogous to reflection in a mirror:

. . . reverses momentum but preserves angular momentum

. . .takes right-handed (helicity = +1) to left-handed (helicity = -1).

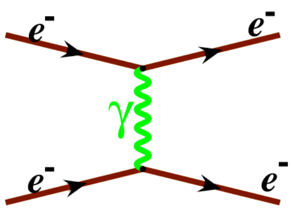
Weak decay of ^{60}Co Nucleus



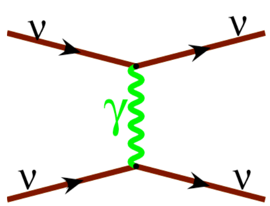


Charge and Handedness

Electric charge determines strength of electric force



observed



not observed

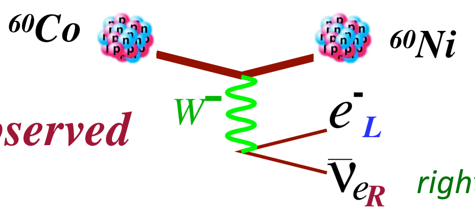
Neutrinos are "charge neutral": do not feel the electric force

	Left	Right
γ Charge	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$
W Charge	$T = \pm\frac{1}{2}$	zero

Weak charge determines strength of weak force

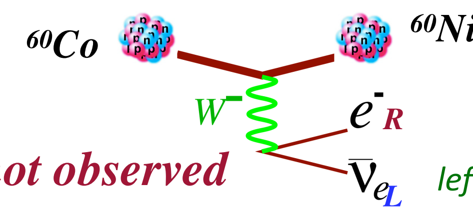
Left-handed particles (Right-handed antiparticles) have weak charge

Right-handed particles (left-handed antiparticles) are "weak charge neutral"



observed

right-handed anti-neutrino



not observed

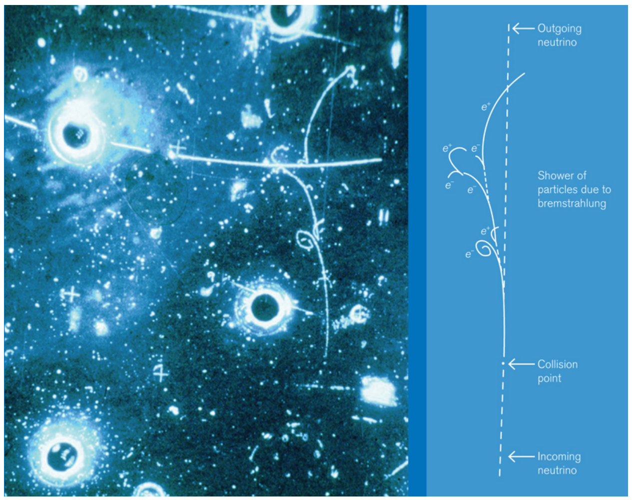
left-handed anti-neutrino

Electroweak Interaction

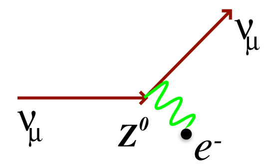
Until the 1970's, all known weak interactions could be explained by $W^{+/-}$ exchange

Weak neutral currents are proposed under electroweak unification (late '60s, Weinberg Salam Glashow, but others, also…)

⇒ The weak mixing angle θ_W introduced



Gargamelle bubble chamber uncovers ν_μ e^- events in 1973, more convincingly in 1976.



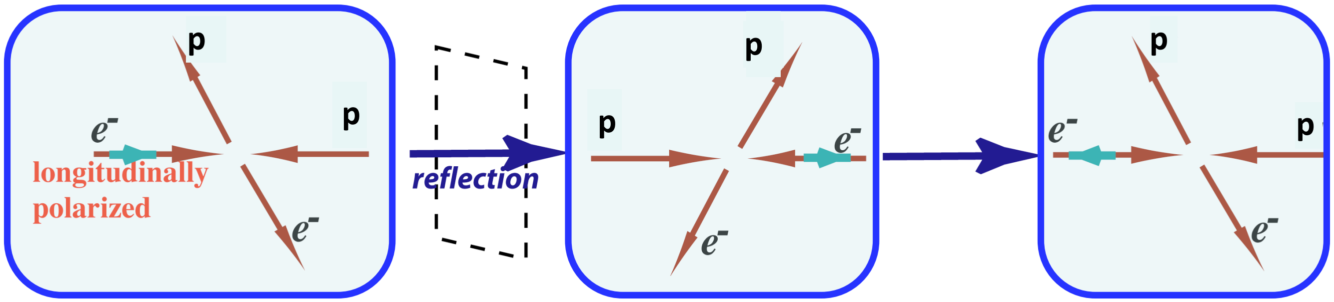
This demonstrated the existence of the neutral current (Z^0) but not its nature

- What is the gauge structure of the underlying theory?
- Is this the electroweak unification of GWS?
- Another EW unification?
- A new interaction?

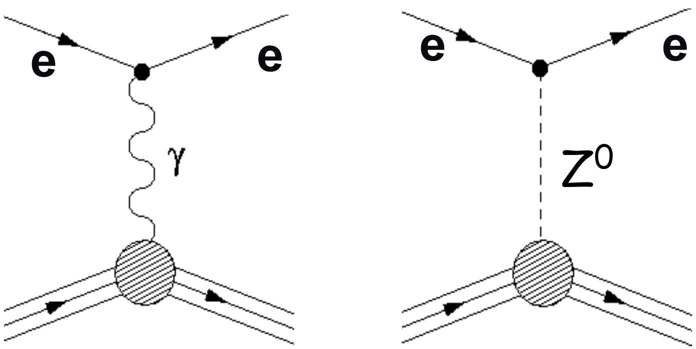
	Left	Right
γ Charge	$q=0,\pm1,\pm\frac{1}{3},\pm\frac{2}{3}$	$q=0,\pm1,\pm\frac{1}{3},\pm\frac{2}{3}$
W Charge	$T=\pm\frac{1}{2}$	zero
Z Charge		

Landmark experiment (late 1970s): parity-violating electron scattering

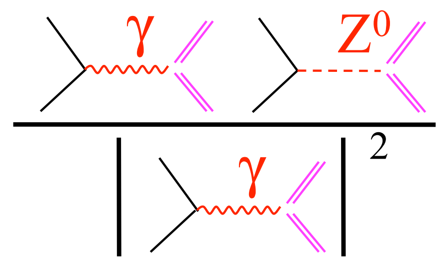
Electron Scattering and Parity-violation



- Incident beam is longitudinally polarized
- Change sign of longitudinal polarization
- Measure fractional rate difference



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



$$\propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|}$$

Scattering cross-section

$$\sigma = \left|\mathcal{M}_\gamma + \mathcal{M}_Z\right|^2$$

"Electroweak" models predicted
- interference of electromagnetic and weak amplitudes
- values for electron & quark weak neutral current coupling

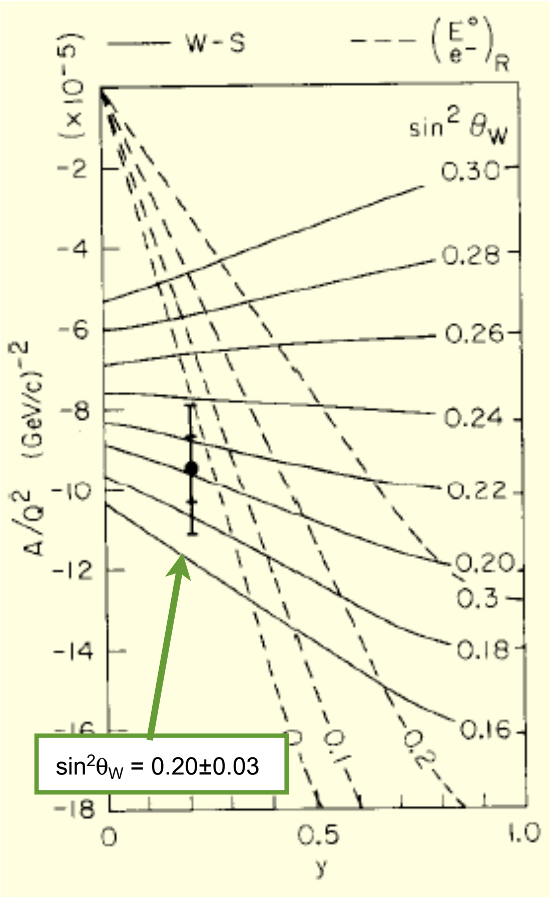
PVeS Verifies the "Standard Model" (1978)

Parity Non-Conservation in Inelastic Electron Scattering, ***C.Y. Prescott et. al, 1978***

A_{PV} ~ 100 ± 10 ppm

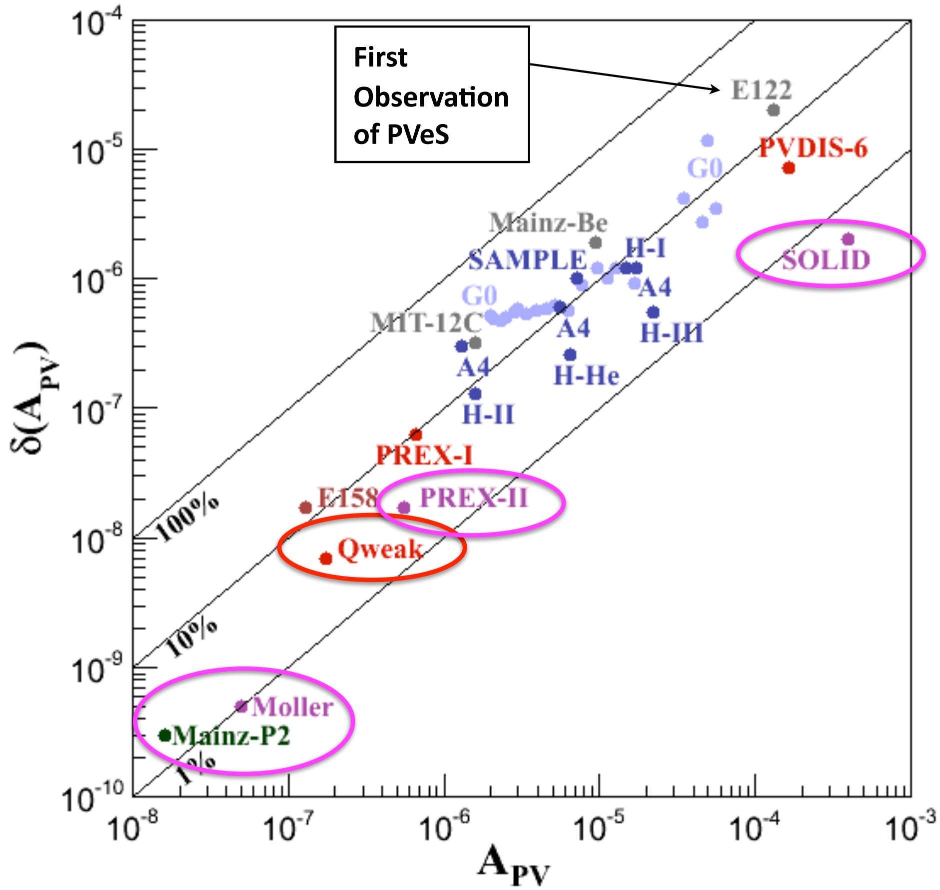
Definitive answer on gauge structure of electroweak interaction

	Left	**Right**
γ Charge	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$
W Charge	$T = \pm\frac{1}{2}$	**zero**
Z Charge	$T - q\sin^2\theta_W$	$-q\sin^2\theta_W$



The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Progress in PVeS studies



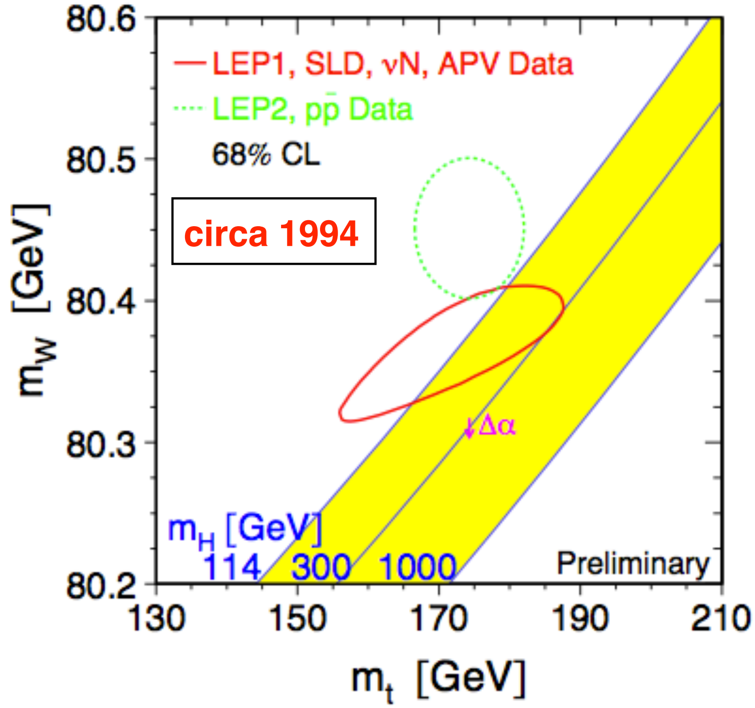
Broad program studying the structure of protons and nuclei, and searching for new (beyond Standard Model) physics

Beyond the Standard Model with Precision at Low Energies

Direct vs Indirect Searches

(according to Hans Christian Andersen)

Discovery of the Top



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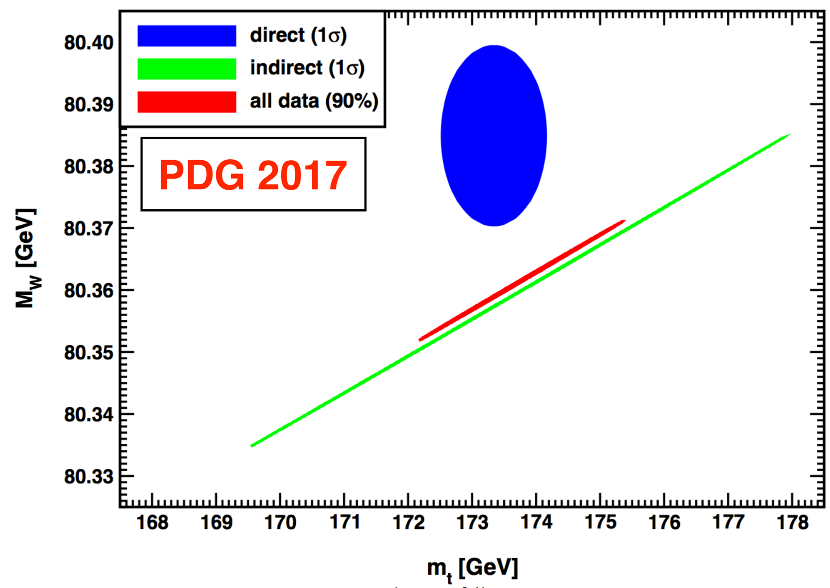


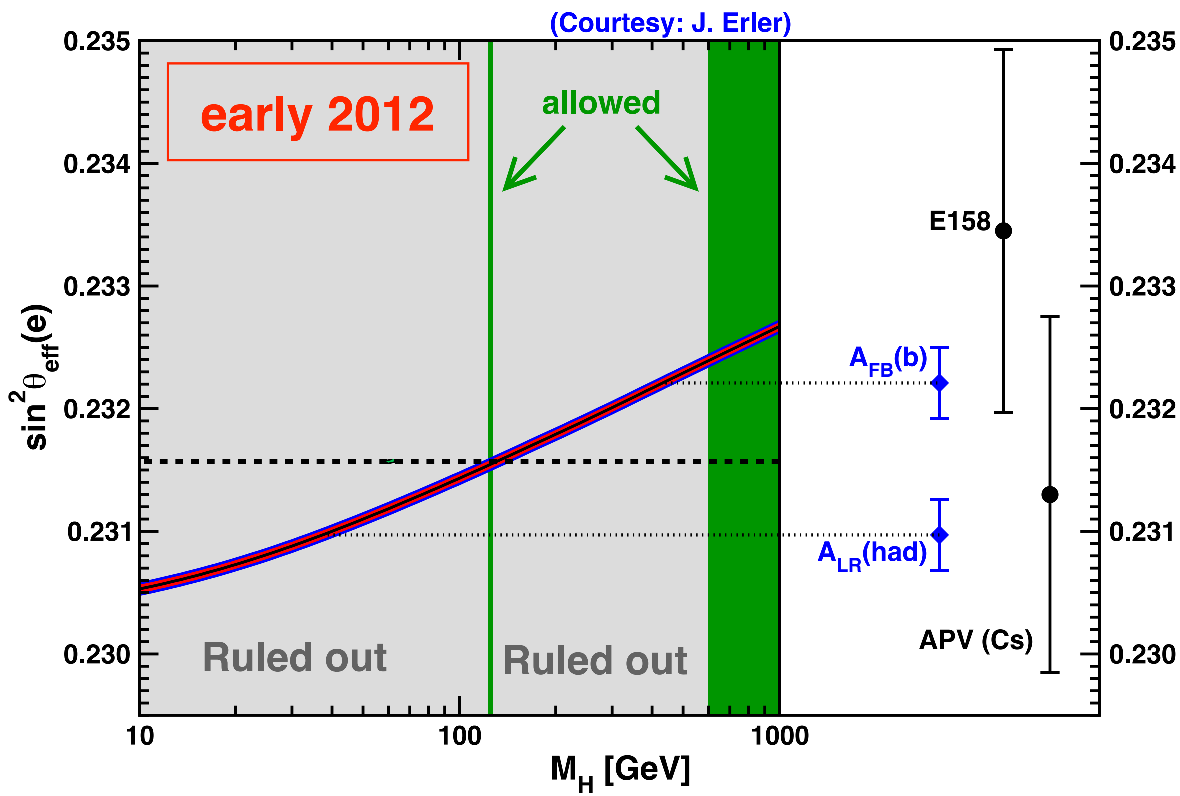
dating
hysics"

EW Standard Model has only three parameters, fixed by α_{EM}, G_F, and M_Z

Global fit over large precision data set to constrain additional parameters appearing in 1-loop corrections (H mass, fermion masses and mixing, and α_{strong})

Ultraprecise (0.1%) measurements of "derived" parameters ($\sin^2\theta_W$ and M_W) are the most sensitive consistency checks of the EW theory

The Higgs Boson and Electroweak Fit



Amazing consistency of the Standard Model prediction, between directly measured m_H, m_W, m_t, $\sin^2\theta_W$

New Physics with Precision at Low Energies

Low Q^2 offers complementary probes of new physics at multi-TeV scales

EDM, g_μ-2, weak decays, β decay, 0νββ decay, DM, LFV…

Parity-Violating Electron Scattering: *Low energy weak neutral current couplings (SLAC, Jefferson Lab, Mainz)*

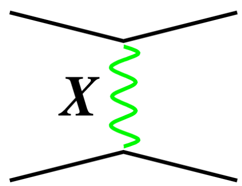
Many new physics models give rise to new neutral current interactions

Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

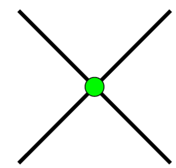
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{new}}$$

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

Heavy mediators = contact interactions



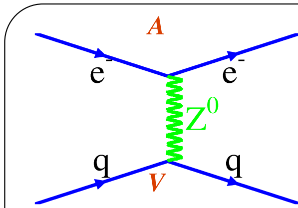
$$A_X \;\alpha\; \frac{1}{Q^2 - M_X^2} \sim \frac{4\pi}{\Lambda^2} \longrightarrow$$



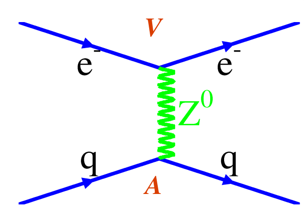
Contact interaction

for **each fermion** and **handedness** combination reach, characterized by mass scale Λ, coupling g

Example: Standard model *e-q* or *e-e* couplings

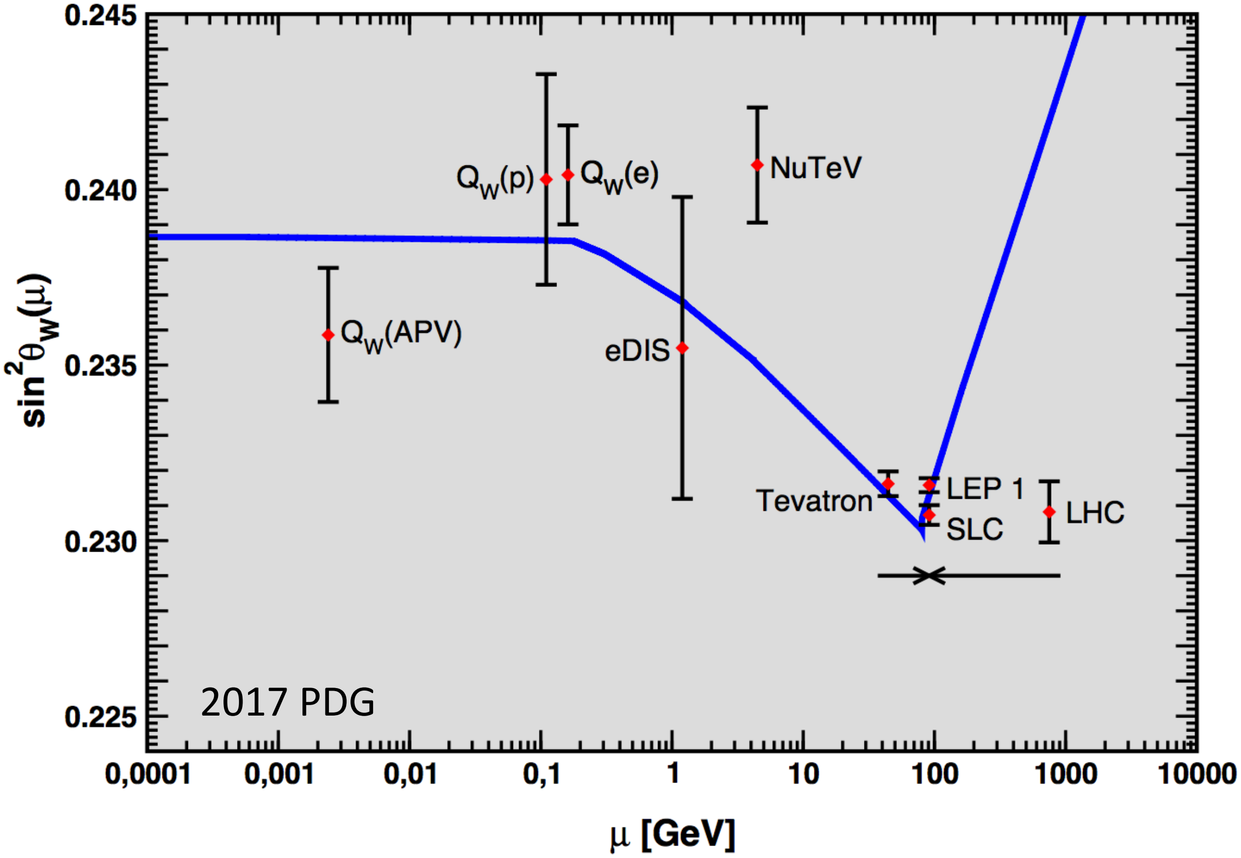


$$C_{1i}^{\mathrm{SM}} \equiv 2 g_A^e g_V^i$$



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

The Weak Mixing Angle



Renormalization scheme defines $\sin^2\theta_W$ at the Z-pole.

γ-Z mixing and other diagrams are absorbed into the coupling constant

At the Z-pole - measuring properties of the SM Z^0 boson

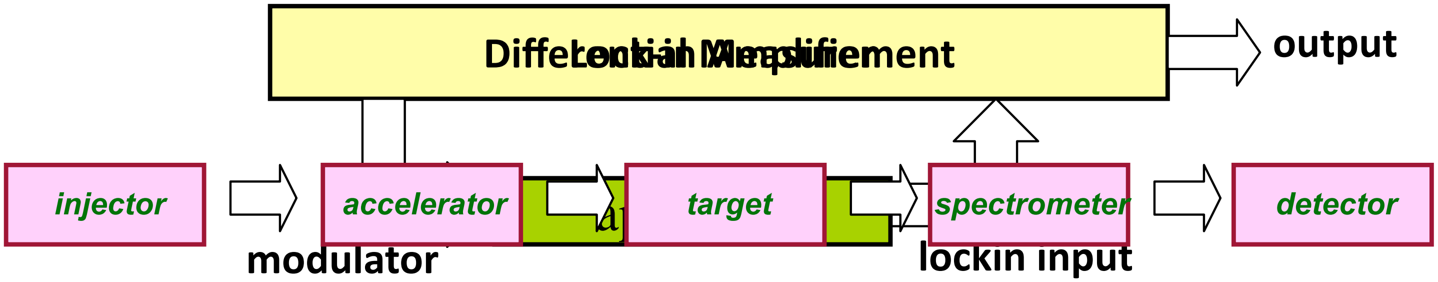
Off the Z-pole, low-energy measurements are sensitive to (new) parity-violating interactions

The QWeak Experiment

Measuring APV

Goal: 10^{-7} asymmetry measurement at the few percent level

How do you pick a tiny signal out of a noisy environment?



Measure fractional rate difference between opposing helicity states

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_R}$$

A_{measured} ~ -200 ppb with 4% precision
N ~ $1\text{x}10^{16}$ electrons!

High rates to get statistical precision, but also:

Control Noise - quiet electronics, luminosity stability

Low backgrounds - must be known PV asymmetry

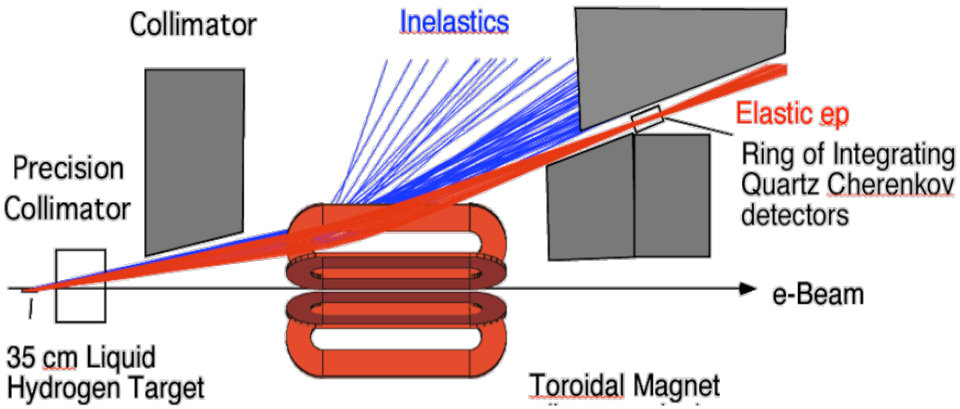
Polarimetry - Can't do better on A_{PV} than on P_{beam}

Kinematics - Interpretation requires Q^2 precision

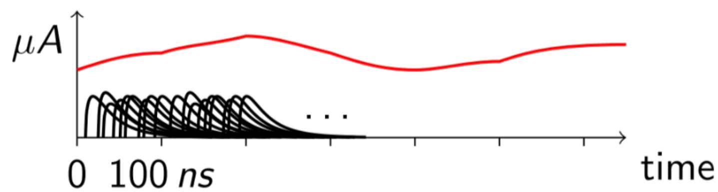
False Asymmetries - electronics, beam motion... ?

Measuring A_{PV}

Elastic signal focused on detector



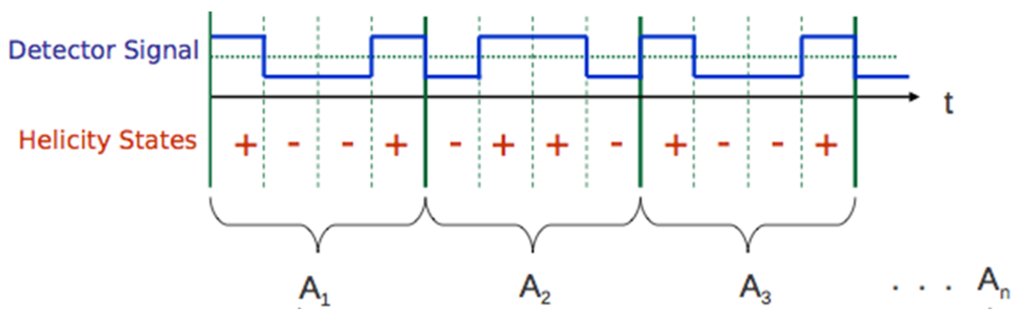
Analog integration of detector current

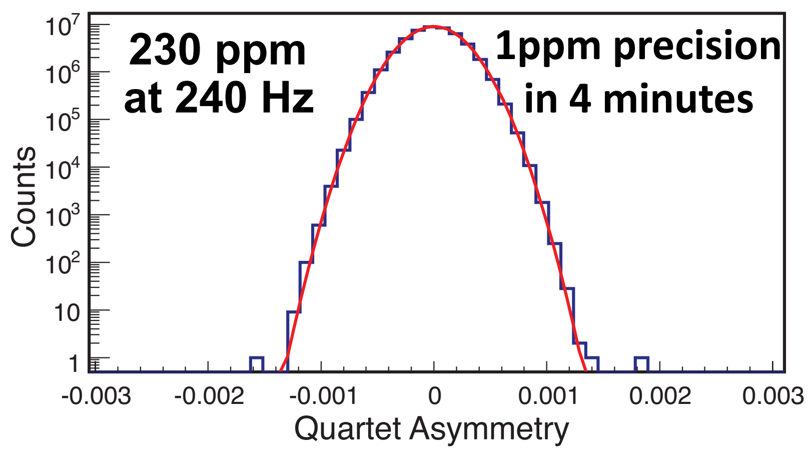


~6 GHz total rate

1 GeV, 180 μA, 1.5 years

Rapid (1kHz) measurement over helicity reversals to cancel noise



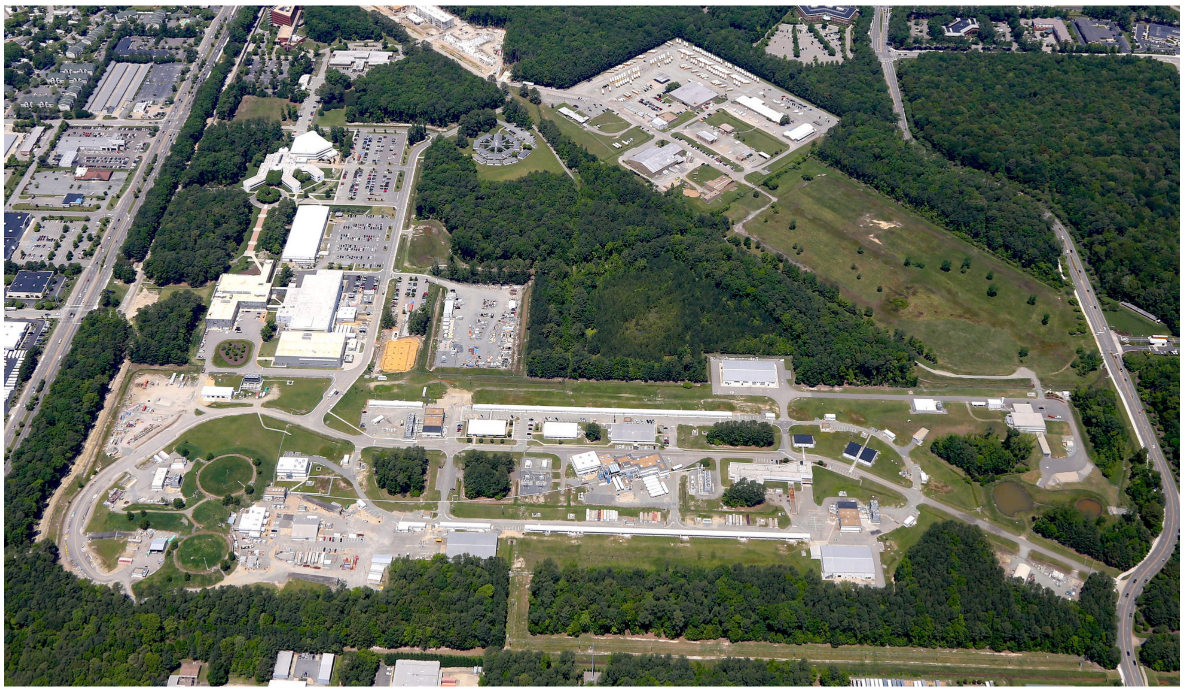


CEBAF at JLab

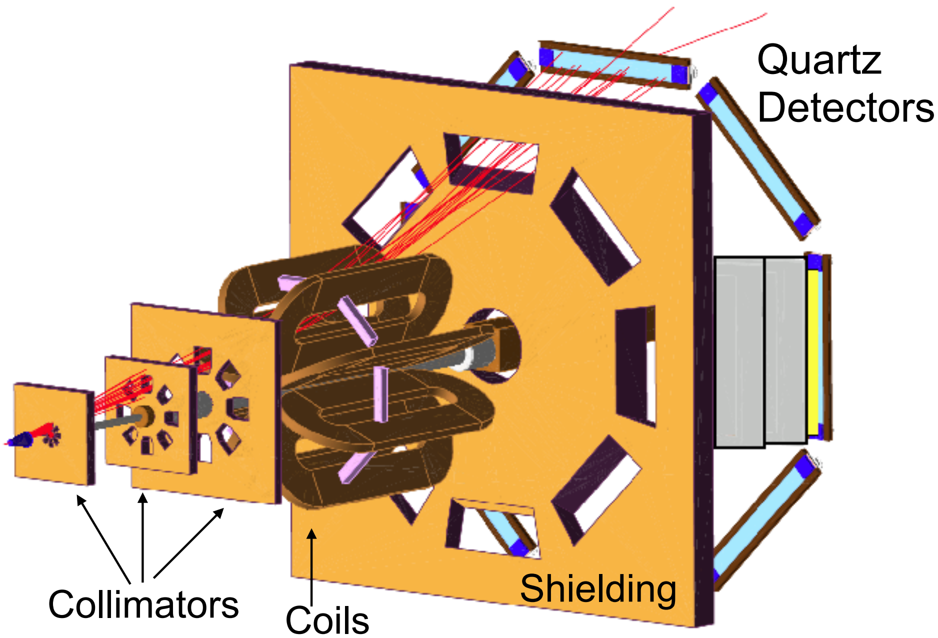
Superconducting, continuous wave, recirculating linac

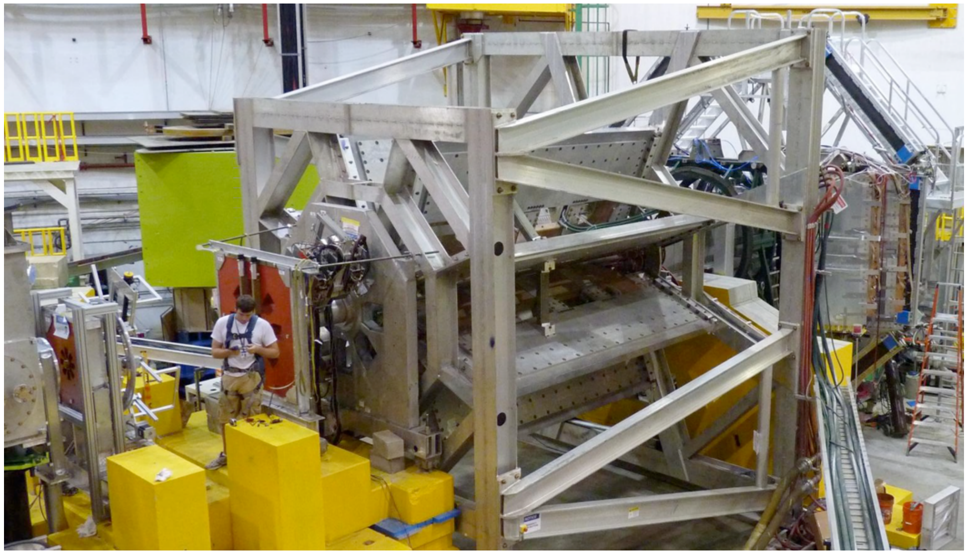
1500 MHz RF, with 3 interleaved 500 MHz beams

"Cold" RF is makes a clean, quiet beam... perfect for precision experiments

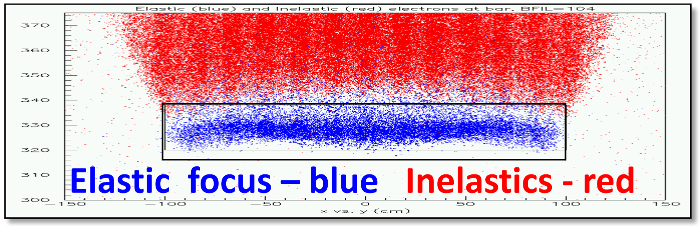


The Qweak Spectrometer



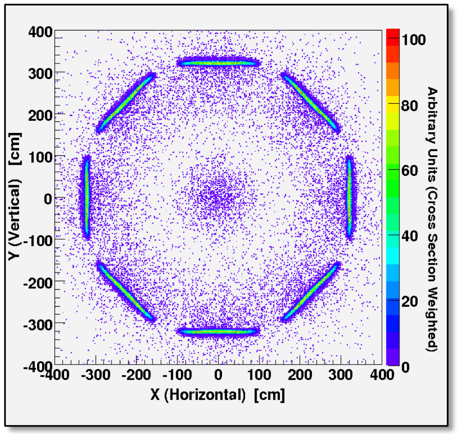


Toroidal Spectrometer separates elastics into each of 8 detectors

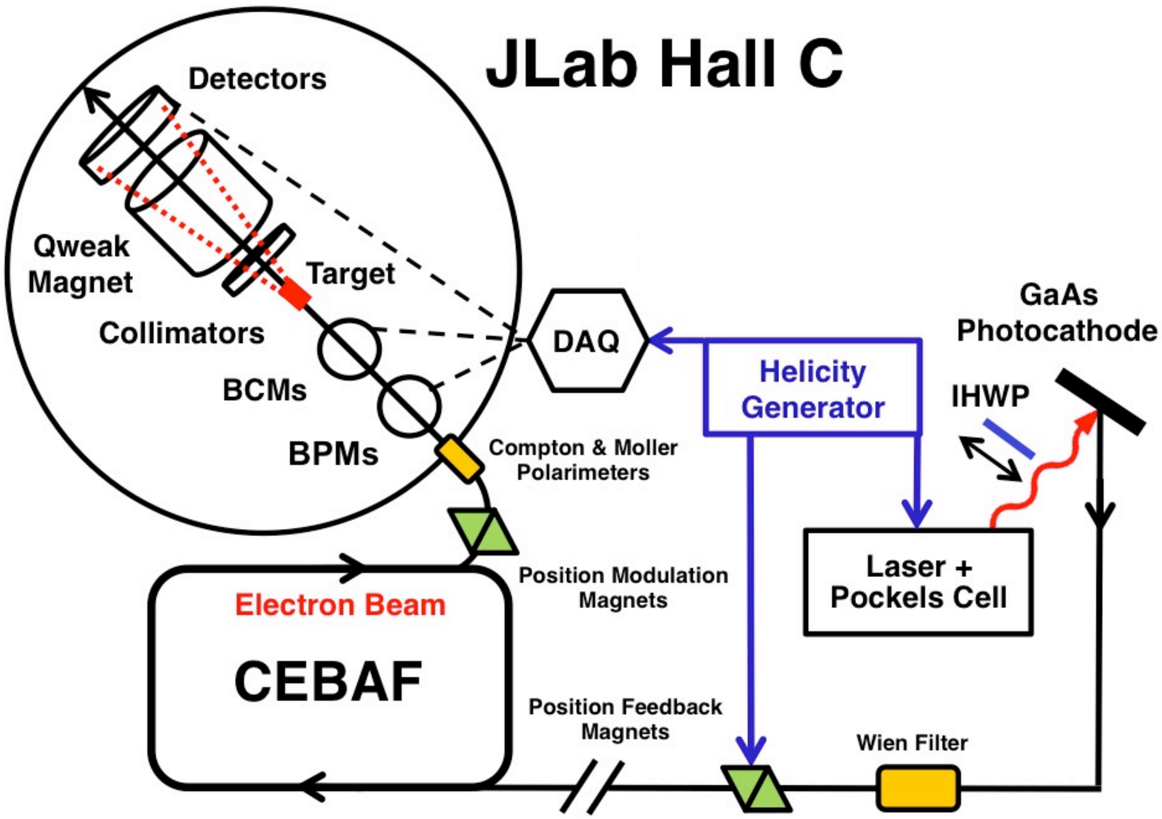


Each detector:

- 2 meters long
- lead radiator, fused silica
- Cerenkov light from shower
- collected by phototube at each end



The Entire Accelerator Complex is our Apparatus

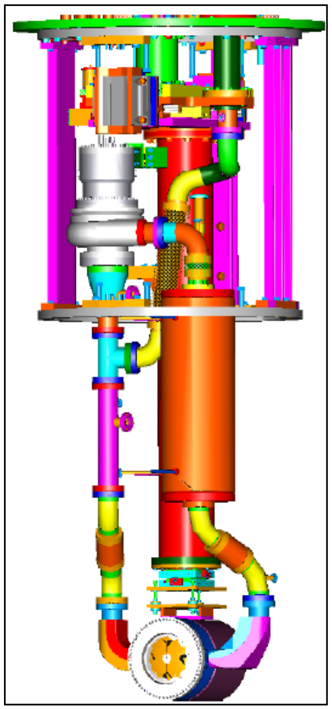


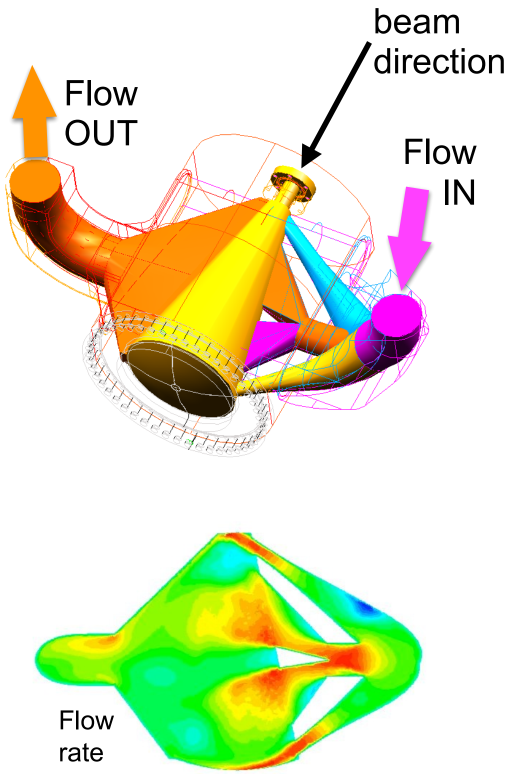
- Polarized Source Laser - rapid reversal, keep spin states the same intensity, position, shape…
- Spin Manipulation - crossed E and B fields, to rotate spin in low energy injector
- Position/Energy Modulation - for calibrating detector sensitivity
- Polarimeters
- Precise monitors for beam current and position

Qweak Experimental Target

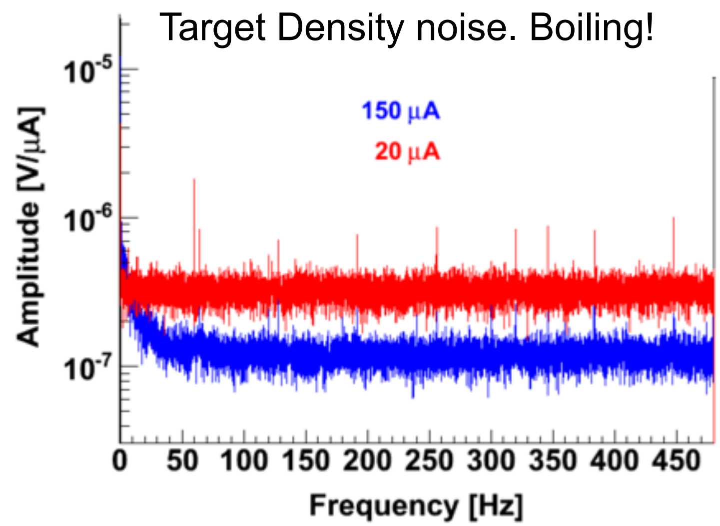
World's highest power and lowest noise cryogenic target

35 cm, 180 μA electron beam, 2.5 kW deposited power





Designed with CFD simulation



Fast helicity reversal (1 ms) cancelled density fluctuations

Density Variation: ~50 ppm over 4 ms at 180 μA

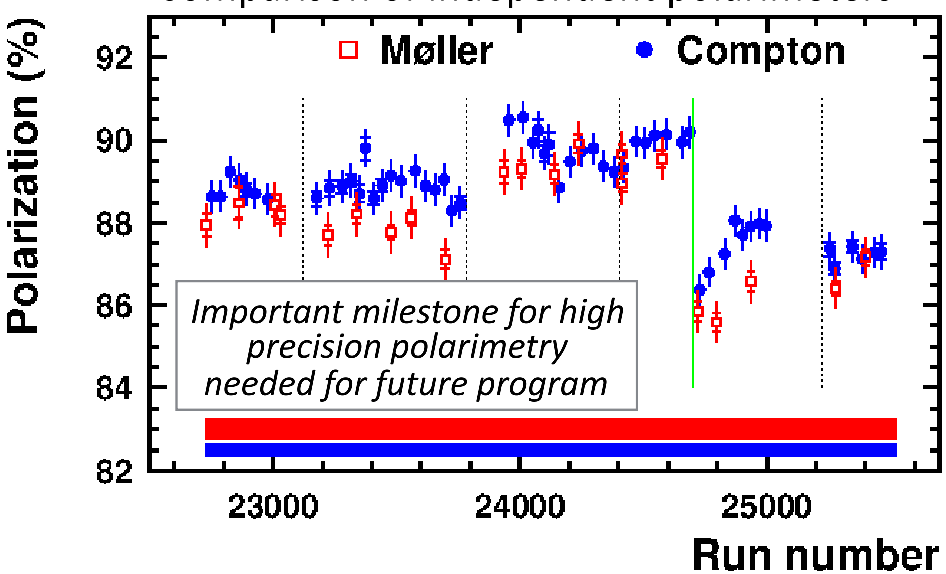
Polarimetry

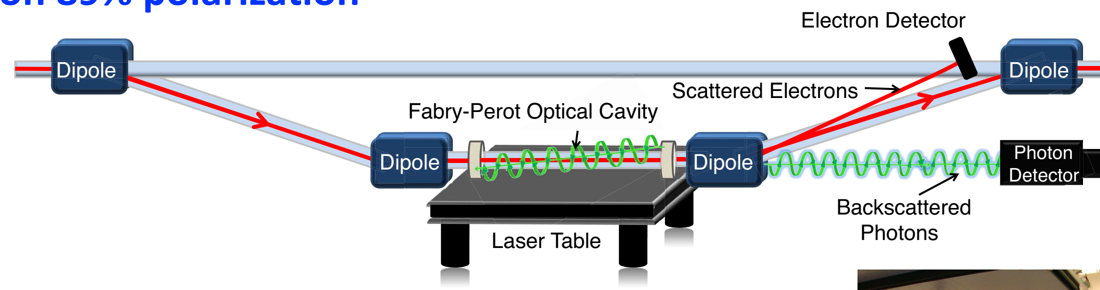
Moller: *ee* scattering off polarized iron foil
- 4T field, saturated iron
- experience with ~1% precision in Hall C
- modified spectrometer for 1 GeV
- invasive, low current only

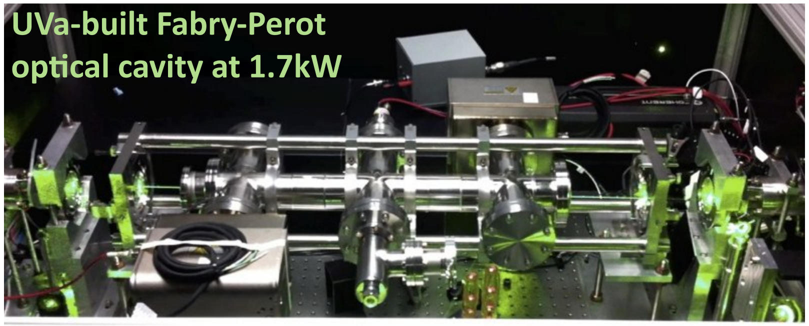
Compton: $e\gamma$ scattering with polarized green laser light
- new polarimeter
- low E_{beam}: low analyzing power, low scattering energies
- diamond microstrip detector
- *per mille* control of laser polarization inside cavity

Result: ~0.6% precision on 89% polarization

Comparison of independent polarimeters



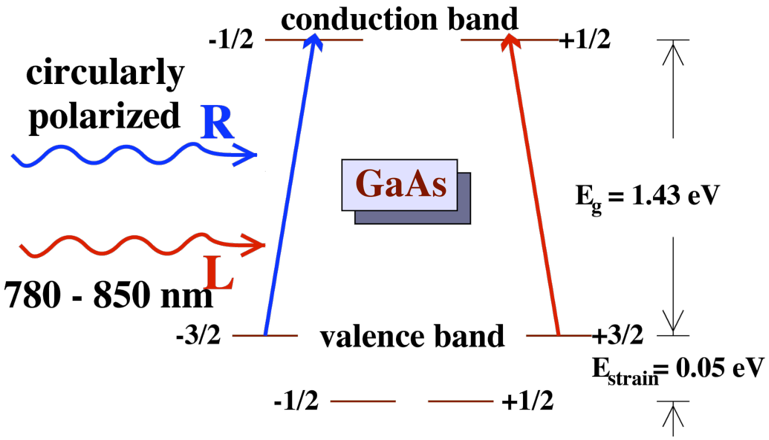




Physical Review X6 (2016) no.1, 011013

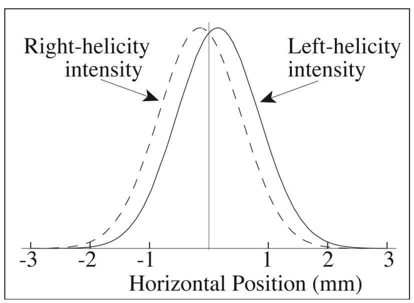
Don Jones

Polarized Electrons for Qweak

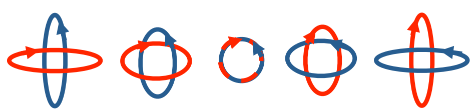


- High intensity, high polarization through photoemission from GaAs photocathode
- Rapid-flip of beam helicity by reversing laser polarization
- Pockels cell to flip laser polarization
- Beam must look the same for the two polarization states
- Photocathode has preferred axis: analyzing power for linear light

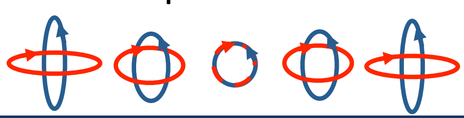
If on average linear polarization = 0, that doesn't mean that it is everywhere zero



A non-zero 1st moment creates a position difference



A non-zero 2nd moment creates a spot-size difference

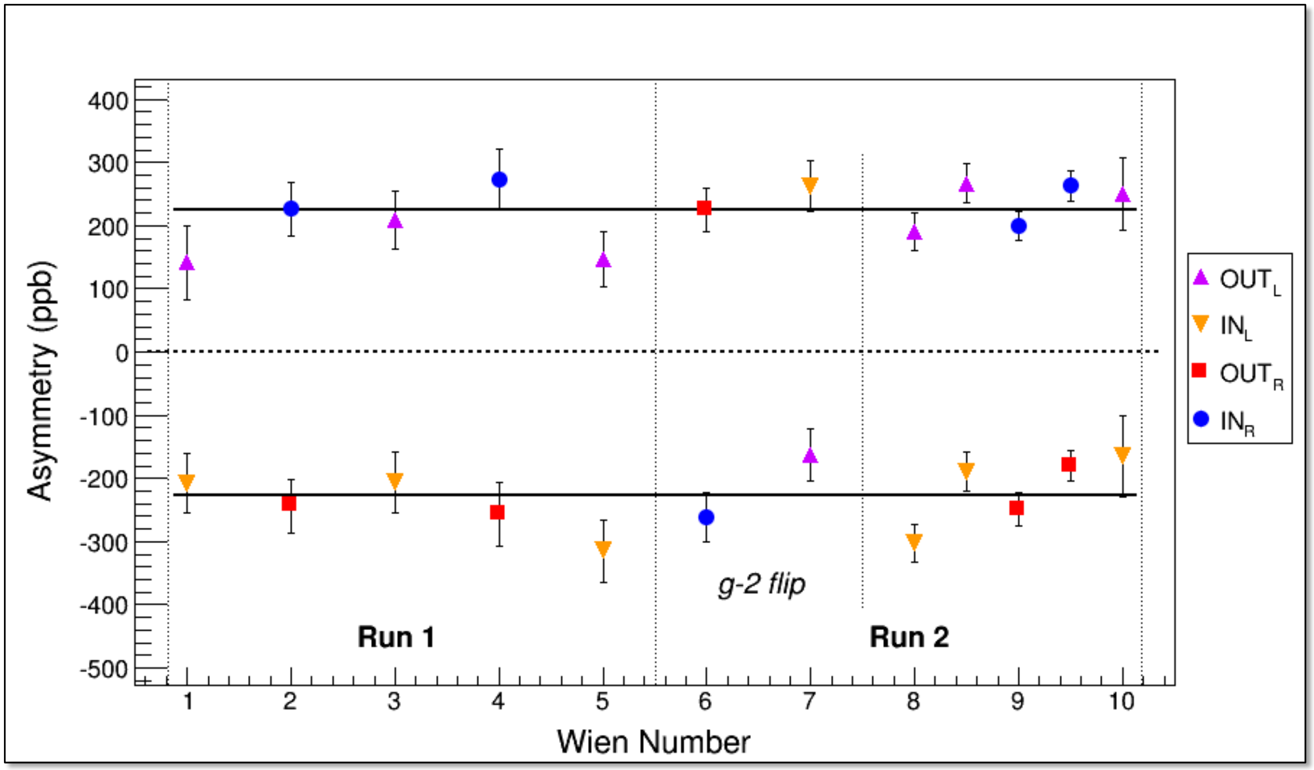


Average beam asymmetries were small over course of run

X	-2.7 nm
X'	-0.14 nrad
Y	-1.9 nm
Y'	-0.05 nrad
Energy	-0.6 ppb

Manolis Kargiantoulakis

Summary of Measurement



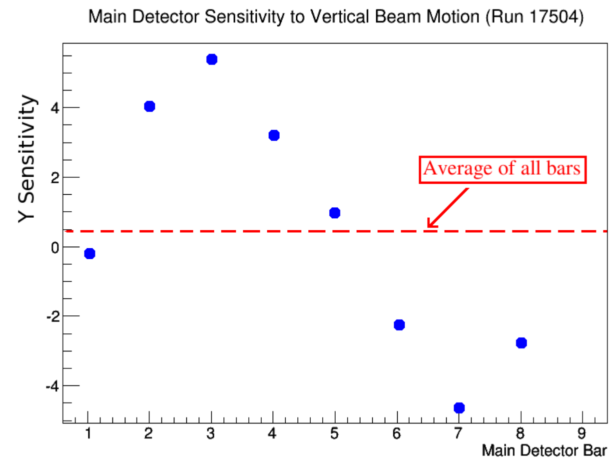
Various methods of polarization reversal

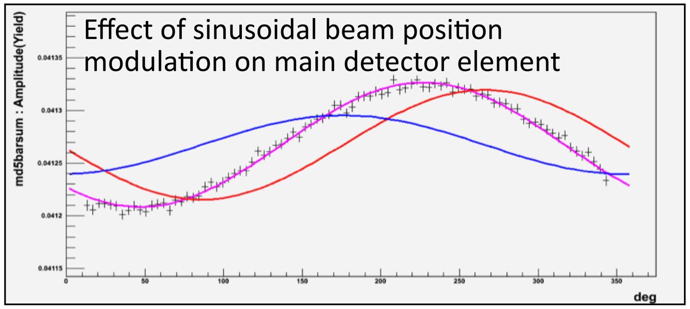
- Half-wave plate in source optics
- Injector spin manipulation
- energy (g-2 precession)

Beam Corrections

$$A_c = A_r - \sum \alpha_i \Delta x_i - \beta A_E$$

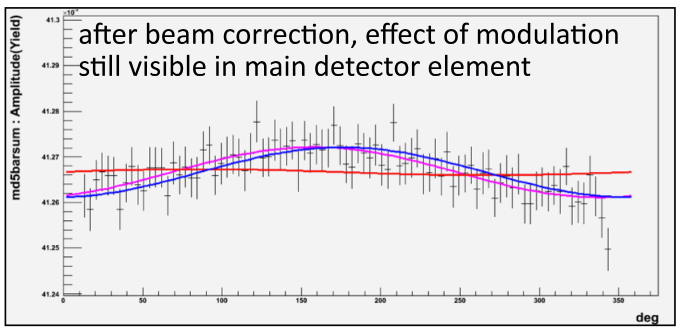
Measurement of the sensitivity of the Main Detector elements to beam motion. The spectrometer provides a high degree of cancellation for beam motion effects.





- Periodically run calibration routine, with sinusoidal modulation of the beam using dipole magnets
- Independently calibrate each degree of freedom

But, imperfect implementation led to inconsistent calibration information



In the end:

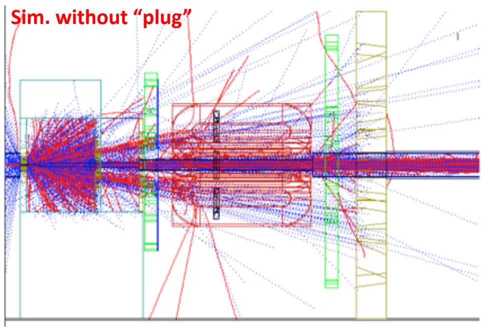
- gross inconsistencies removed from calibration
- small inconsistencies were shown to be harmless
- corrections were small, agreed between techniques

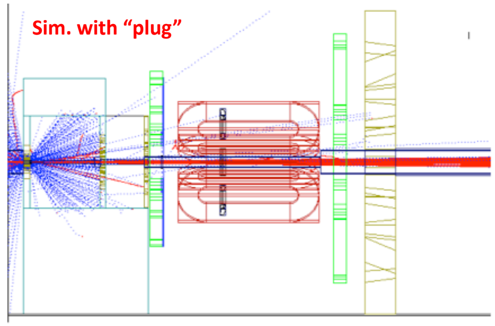
Net Correction: 3.5 ± 1.7 ppb

Don Jones

Beamline Backgrounds

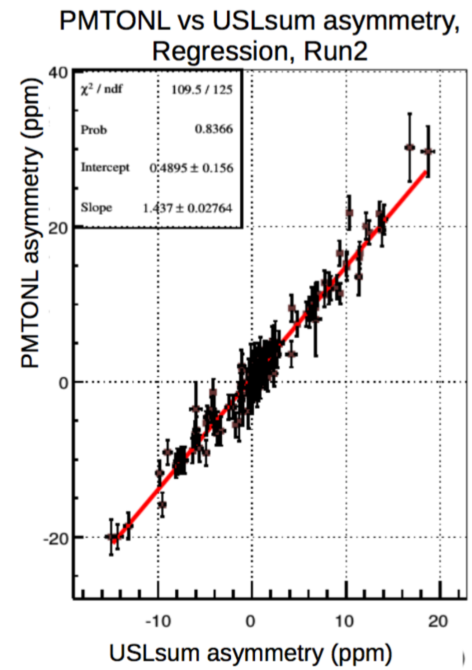
Scattering from the beampipe was recognized as a possible source of background





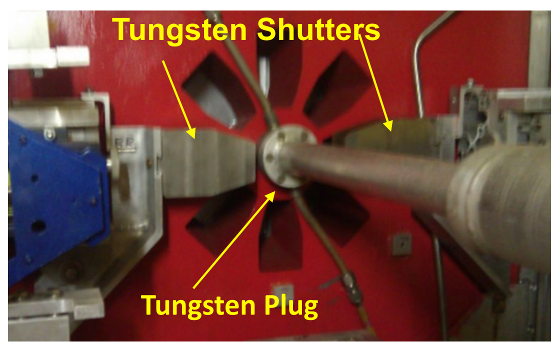
- But collimation didn't fully solve the problem.
- Radiators were added to the main detector to enhance hard scatters and cut soft backgrounds

Large asymmetries seen in both "small angle" and "background" monitors, were correlated with main detectors



Studies (included blocking octants):

- beamline background $f \sim 0.2\%$ in MD
- asymmetry due to beam halo
- asymmetry well measured by background detectors

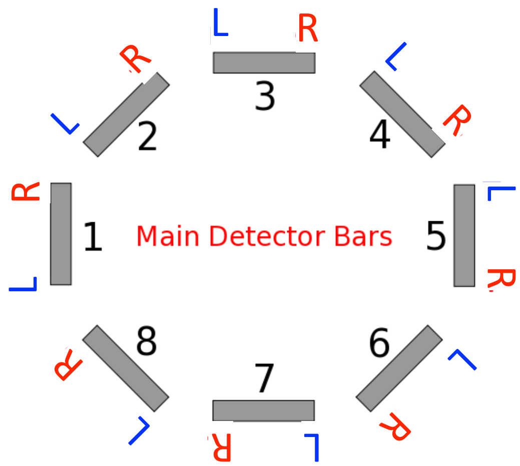


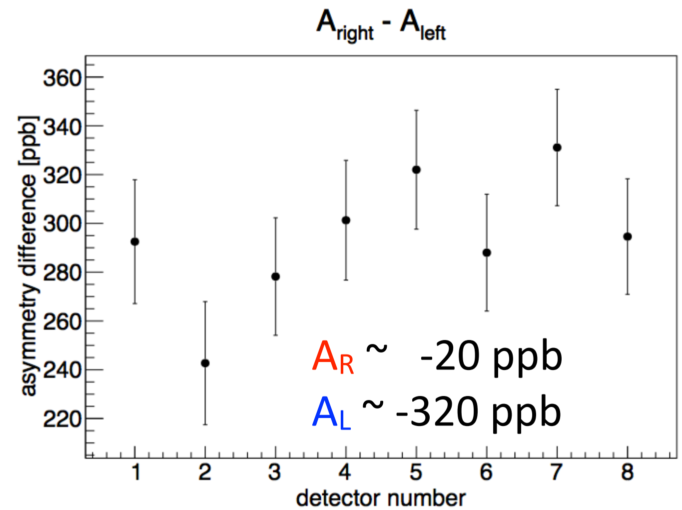
Scaling of backgrounds over the course of the run, and correlation with main detectors, were stable.

Net Correction: -1.2 ± 1.7 ppb

Manolis Kargiantoulakis

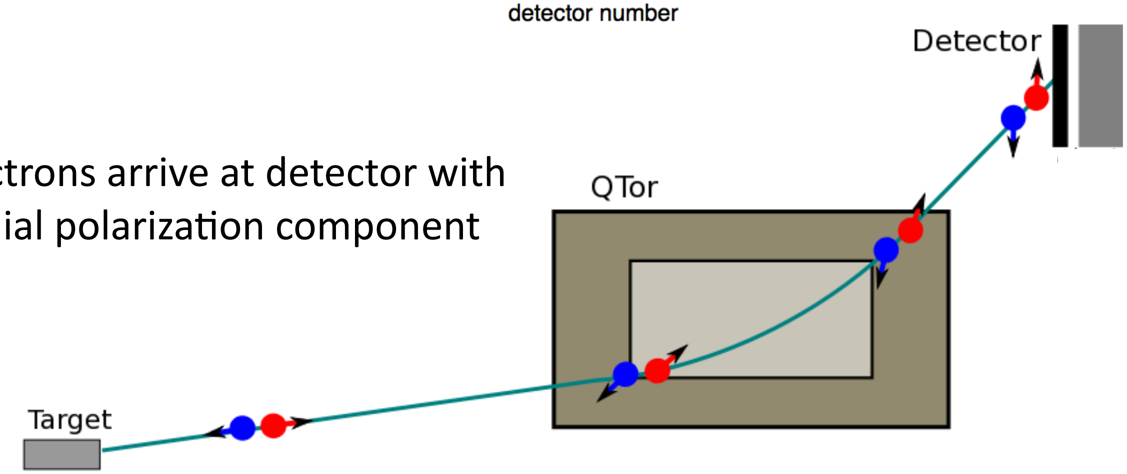
Detector Chriality?





Apparent polarization analyzing effect, so that PMTs on opposite ends of each detector bar see opposite sign asymmetry shifts

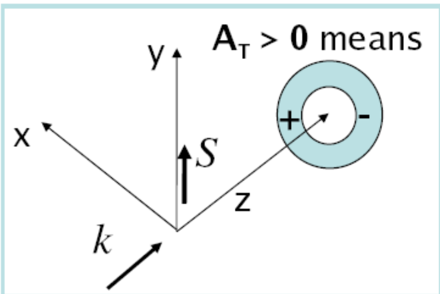
Scattered electrons arrive at detector with significant radial polarization component

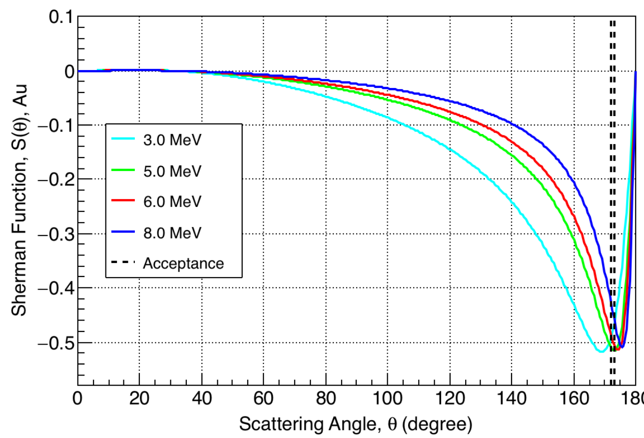


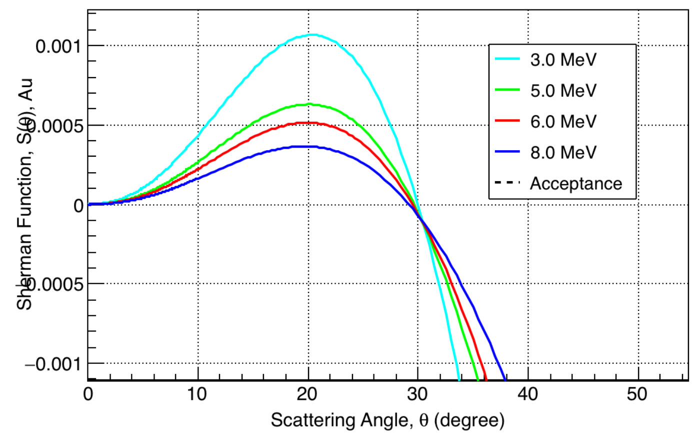
Polarization Sensitive Detector

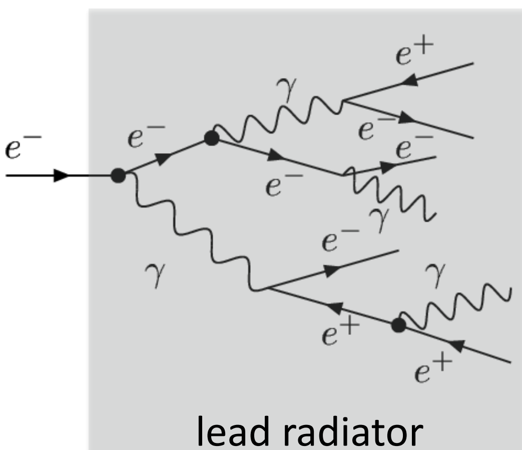
Mott scattering asymmetry: low energy phenomenon

$$A_T = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \propto \vec{S}_e \cdot \frac{\vec{k}_e \times \vec{k}_e'}{|\vec{k}_e \times \vec{k}_e'|}$$





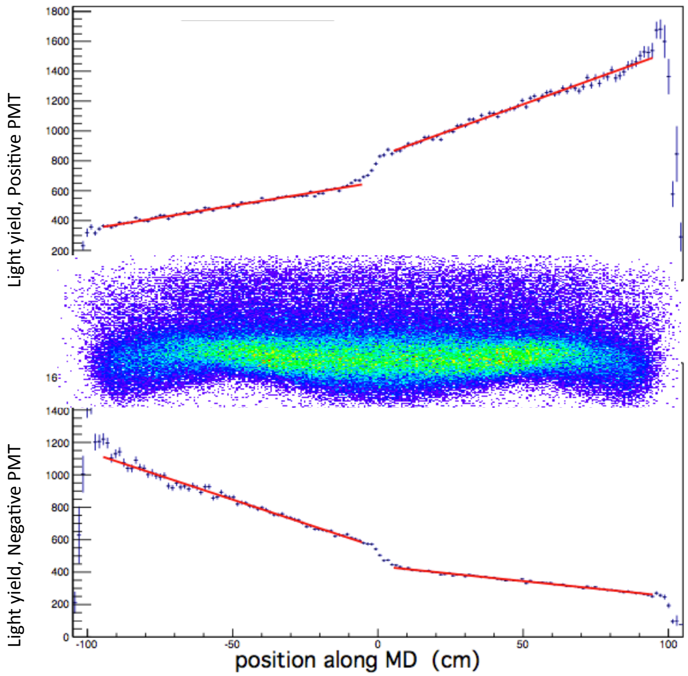


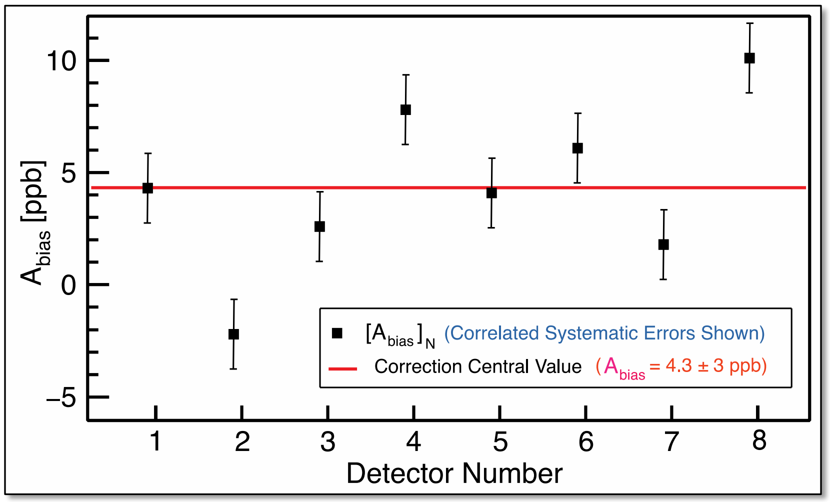


- The electron showering through lead radiator can become polarization-dependent via multiple scattering
- Only significant after is E<30 MeV or so, for large angles
- Cancellation between positive asymmetry for small angle scattering, negative for large angle scattering
- Electron ends up more likely to point toward one PMT, depending on its incident polarization

Estimated Residual Bias from Polarization Sensitive Detectors

- This should cancel: positive asymmetry in one PMT, negative in the other
- Quality of cancellation depends on imperfections in each bar optical properties and alignment
- Monte Carlo simulation of light collection used to estimate Abias for each bar, based on observed response and measured geometry





A_{bias} = 4.3 ± 3.0 ppb

Asymmetry and Net Corrections

weight:	20%	80%
Quantity	Run 1	Run 2
$A_{\rm raw}$	-192.7 ± 13.2 ppb	-170.7 ± 7.3 ppb
$A_{\rm T}$	0 ± 1.1 ppb	0 ± 0.7 ppb
$A_{\rm L}$	1.3 ± 1.0 ppb	1.2 ± 0.9 ppb
$A_{\rm BCM}$	0 ± 4.4 ppb	0 ± 2.1 ppb
$A_{\rm BB}$	3.9 ± 4.5 ppb	-2.4 ± 1.1 ppb
$A_{\rm beam}$	18.5 ± 4.1 ppb	0.0 ± 1.1 ppb
$A_{\rm bias}$	4.3 ± 3.0 ppb	4.3 ± 3.0 ppb
P	$87.7 \pm 1.1\%$	$88.71 \pm 0.55\%$
f_1	$2.471 \pm 0.056\%$	$2.516 \pm 0.059\%$
A_1	1.514 ± 0.077 ppm	1.515 ± 0.077 ppm
f_2	$0.193 \pm 0.064\%$	$0.193 \pm 0.064\%$
f_3	$0.12 \pm 0.20\%$	$0.06 \pm 0.12\%$
A_3	-0.39 ± 0.16 ppm	-0.39 ± 0.16ppm
f_4	$0.018 \pm 0.004\%$	$0.018 \pm 0.004\%$
A_4	-3.0 ± 1.0 ppm	-3.0 ± 1.0ppm
$R_{\rm RC}$	1.010 ± 0.005	1.010 ± 0.005
$R_{\rm Det}$	0.9895 ± 0.0021	0.9895 ± 0.0021
$R_{\rm Acc}$	0.977 ± 0.002	0.977 ± 0.002
R_{Q^2}	0.9927 ± 0.0056	1.0 ± 0.0056

Raw Asymmetry ~ 175 ± 6.4 ppb

Aluminum windows, 2.5% background, but
A_{PV} = 1.5ppm (-7X the proton A_{PV}) so about 20% correction

Summary of Measurement

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

Quantity	Run 1 error (ppb)	Run 1 fractional	Run 2 error (ppb)	Run 2 fractional
BCM Normalization: A_{BCM}	5.1	25%	2.3	17%
Beamline Background: A_{BB}	5.1	25%	1.2	5%
Beam Asymmetries: A_{beam}	4.7	22%	1.2	5%
Rescattering bias: A_{bias}	3.4	11%	3.4	37%
Beam Polarization: P	2.2	5%	1.2	4%
Target windows: A_{b1}	1.9	4%	1.9	12%
Kinematics: R_{Q^2}	1.2	2%	1.3	5%
Total of others	2.5	6%	2.2	15%
Combined in quadrature	10.1		5.6	

APV and Extracting Qweak

A_{PV} depends on the proton form-factors

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}}\right] \frac{\epsilon G_E^{p\gamma} G_E^{pZ} + \tau G_M^{p\gamma} G_M^{pZ} - \frac{1}{2}(1-4\sin^2\theta_W)\epsilon' G_M^{p\gamma} \tilde{G}_A^p}{\epsilon (G_E^{p\gamma})^2 + \tau((G_M^{p\gamma})^2}$$

Axial Form Factor

Assuming charge symmetry, the weak form-factors relate to electromagnetic form factors of the proton and neutron

$$4G_{E,M}^{pZ} = (1-4\sin^2\theta_W) G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^{s}$$

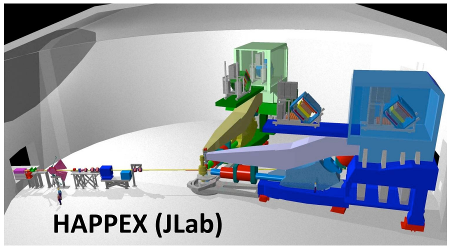
Proton Weak Charge

Electromagnetic Form Factors

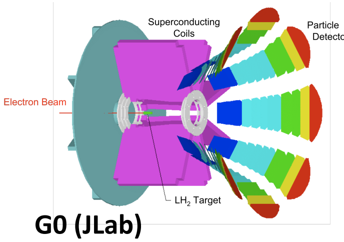
Strange Quark Form Factor

WNC elastic form-factors have been well studied in search of intrinsic nucleonic strangeness

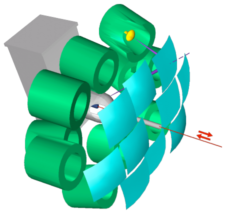
Results on strangeness is linked to which EMFF data you choose to believe (Ben Gilbert)



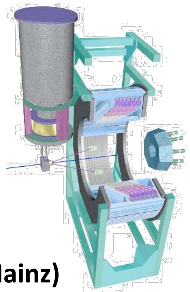
HAPPEX (JLab)



G0 (JLab)



SAMPLE (Bates)

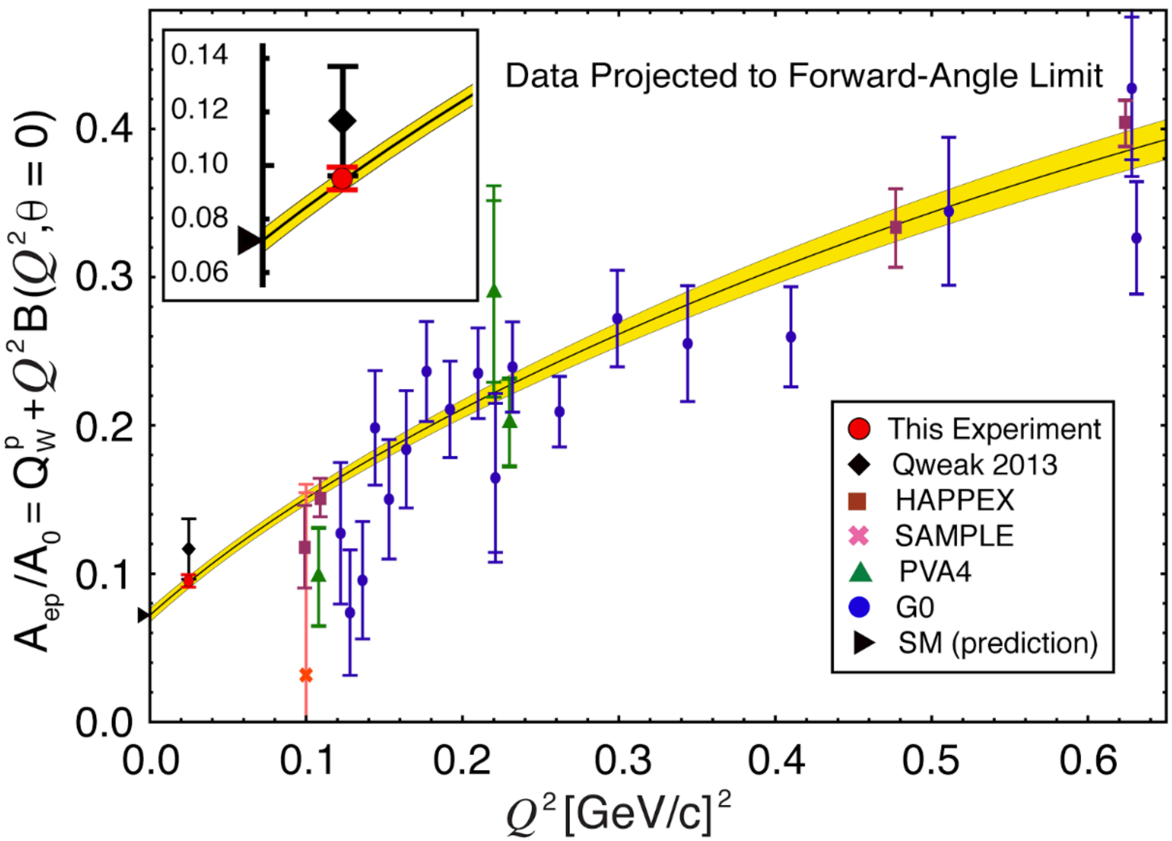


A4 (Mainz)

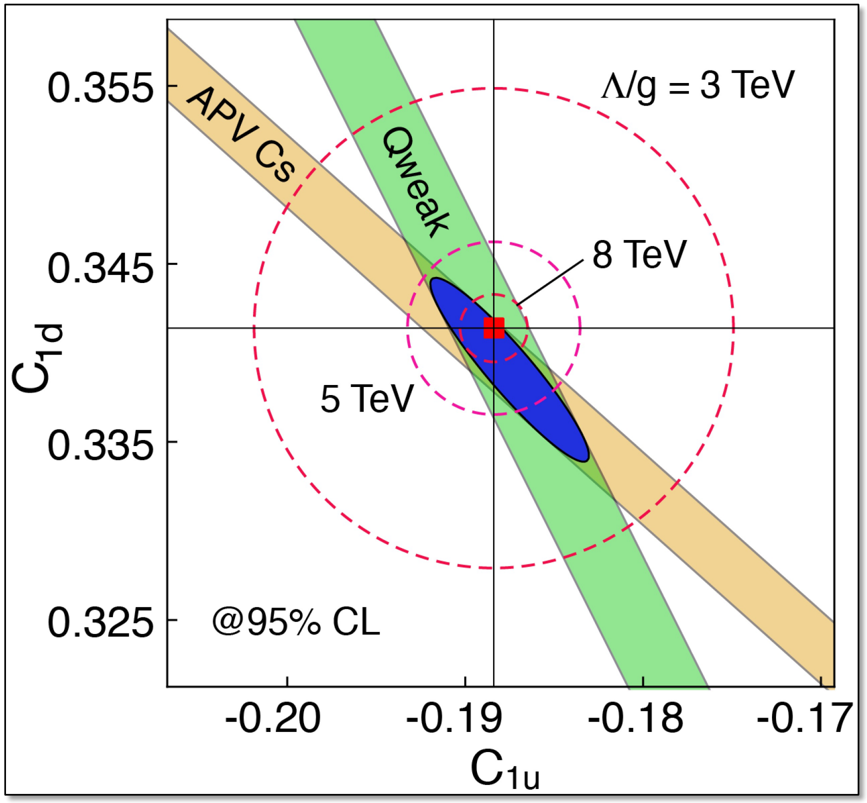
Extracting Qweak Results

Parameterization of electromagnetic form-factors

Fit for: weak charge, strangeness, axial form-factors



Weak Neutral Current Quark Vector Couplings



with usual convention for contact interactions

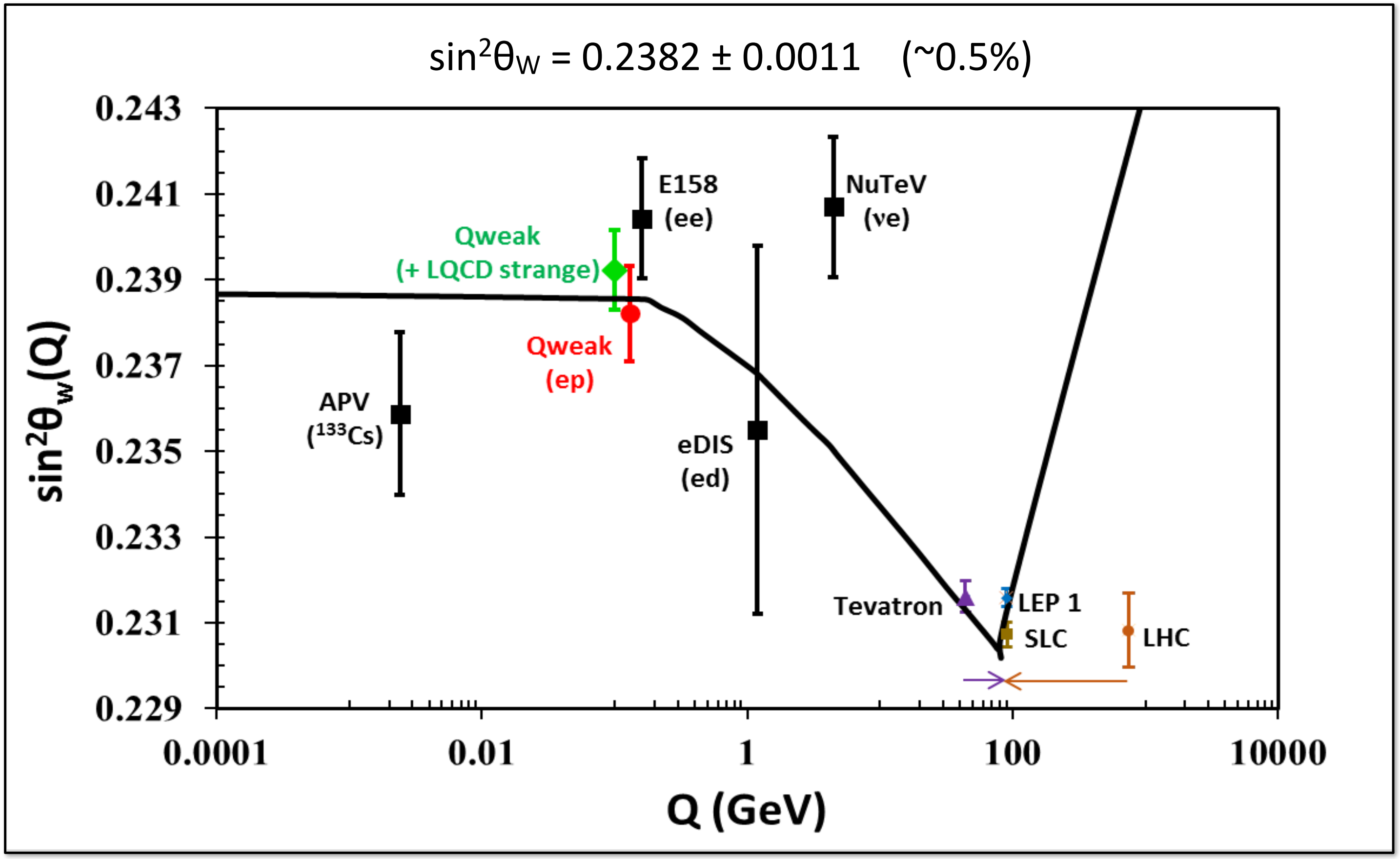
$$g = \sqrt{4\pi}$$

the exclusion limits are

$$\frac{\lambda}{g} \approx 7.5 \text{ TeV} \rightarrow \lambda \approx 27 \text{ TeV}$$

Fit with APV in ^{133}Cs (recent corrections from Flambaum)

Weak Mixing Angle



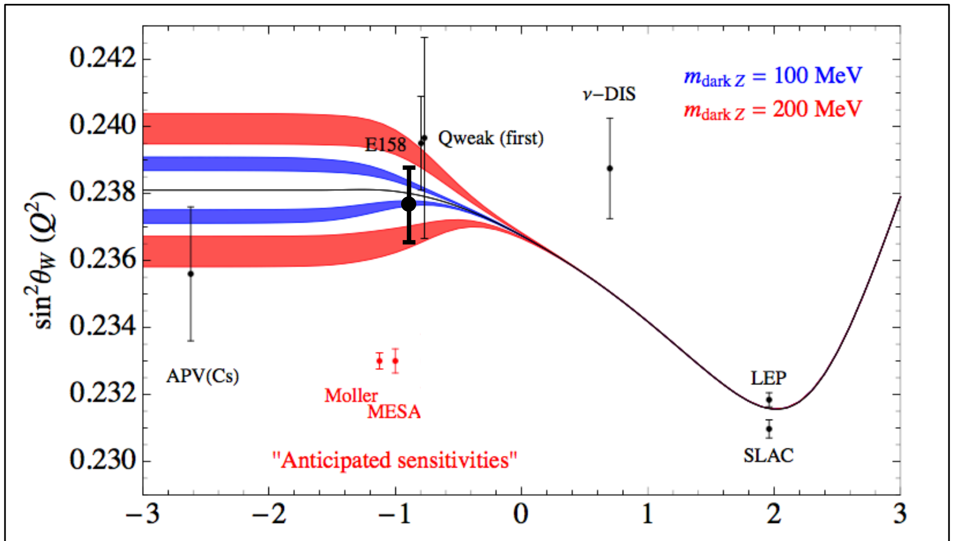
Solid Curve by: J. Erler, M. Ramsey-Musolf and P. Langacker

Dark Z

Dark photon, couples to Dark Sector massive particles but with small E&M couplings to known matter

511keV line in galactic core, Pamela high energy positron excess, $(g\text{-}2)_\mu$ discrepancy

New model: a dark Z_d^0 with no coupling to the 3 known generations of matter, but mass mixing with the Z^0

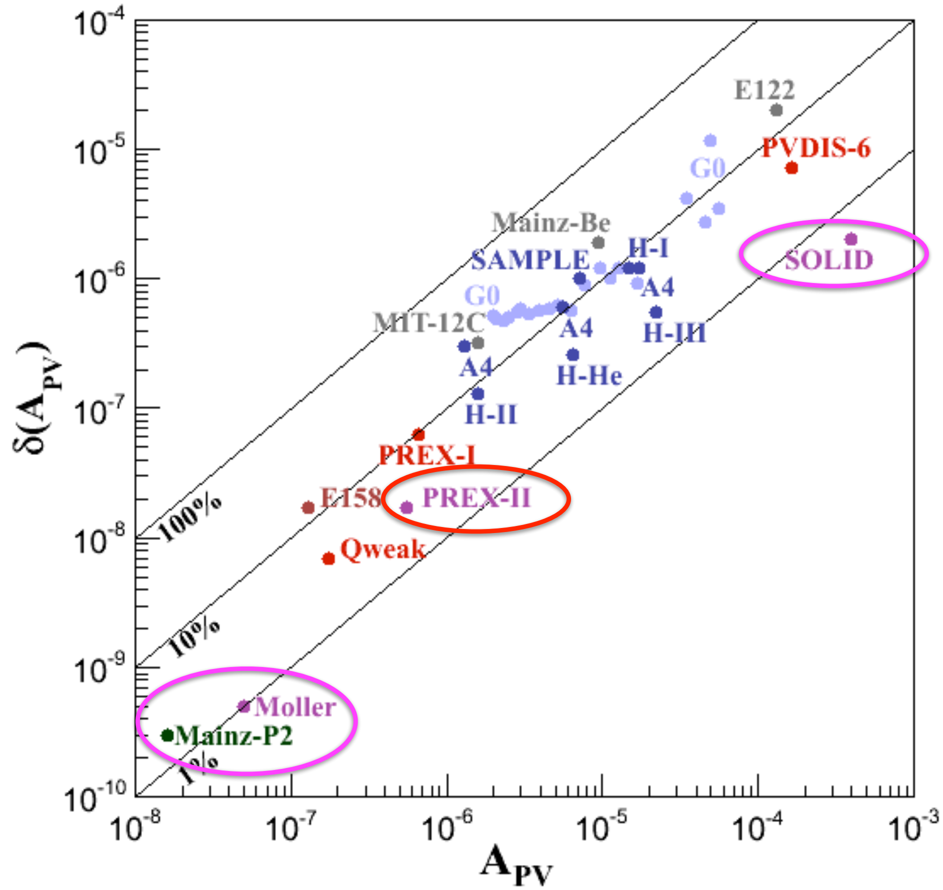


Phys.Rev. D89 (2014) 9, 095006

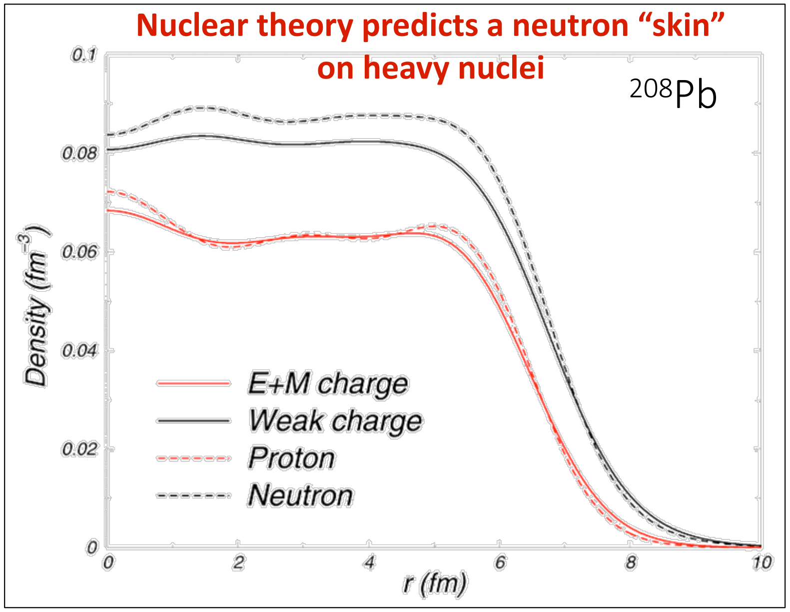
Davoudiasl, Lee, Marciano

Phys.Rev.Lett. 109 (2012) 031802
Phys.Rev. D85 (2012) 115019
Phys.Rev. D92 (2015) 5, 055005

Future PV


E122
PVDIS-6
G0
Mainz-Be
H-I
SAMPLE
SOLID
G0
A4
MIT-12C
A4
H-III
A4
H-He
H-II
PREX-I
E158
PREX-II
Qweak
100%
10%
1%
Moller
Mainz-P2
δ(A_PV)
A_PV
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3

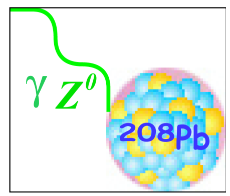
Weak Charge Distribution of Heavy Nuclei



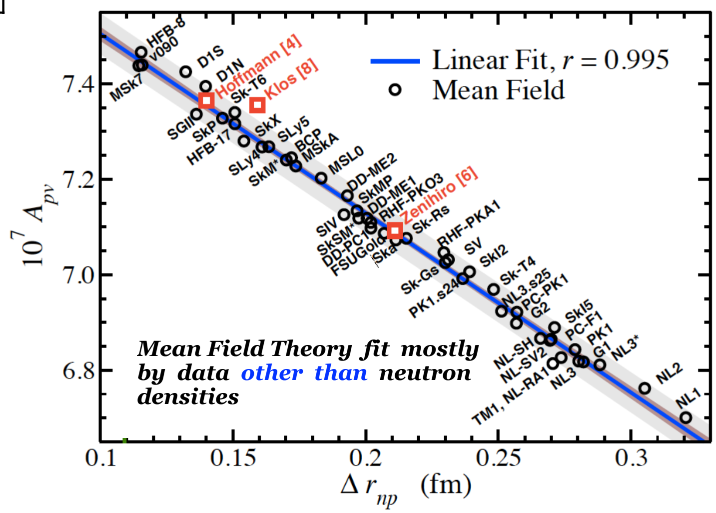
	proton	neutron
Electric charge	1	0
Weak charge	~0.08	1

for spin-0 nucleus

$$A_{\rm PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_W}{F_{ch}}$$



Mean-field model predictions of A_{PV} correlate with the neutron skin of a heavy nucleus



Rocal-Maza et al, PRL106, 252501 (2011)

- Neutron skin thickness is highly sensitive to the pressure in neutron-rich matter.
- The greater the pressure, the thicker the skin as neutrons are pushed out against surface tension.

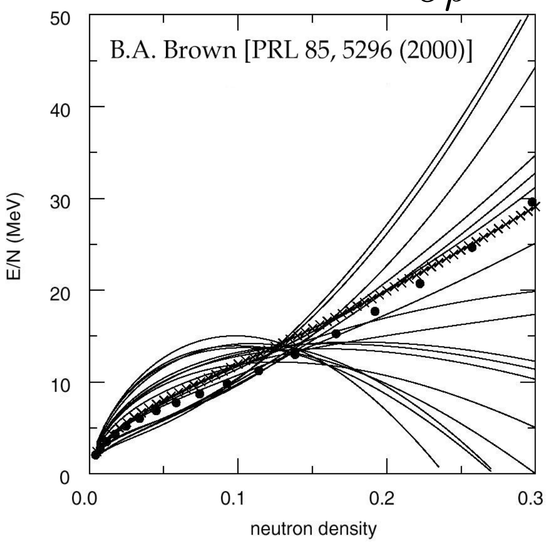
Knowledge of r_n highly model dependent, not well constrained by robust measurements

R_n of ^{208}Pb: Equation of state for neutron-rich nuclear matter

Density Dependence of Symmetry Energy

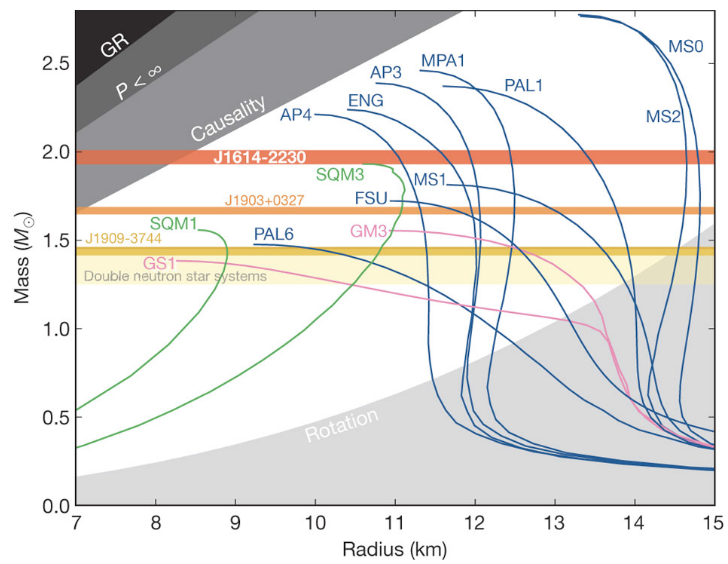
Energy penalty for breaking n=Z symmetry $S = \frac{E}{N}$

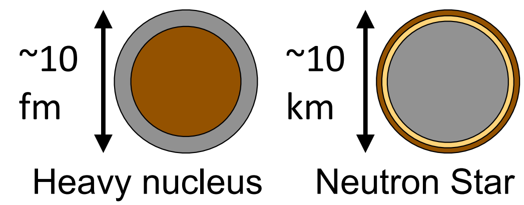
Slope at saturation density $L \propto \frac{\partial S(\rho)}{\partial \rho}|_{\rho_0}$



A_{PV} from ^{208}Pb provides a clean measure of L, testing the description of nuclear matter

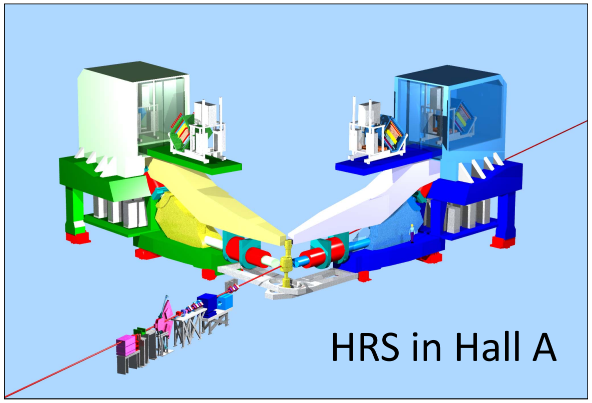
Isovector properties are not well measured.
Models informed mostly by measurements of properties sensitive to p+n.





- Stiffness vs core collapse
- Mass/radius
- cooling mechanisms (URCA or not)

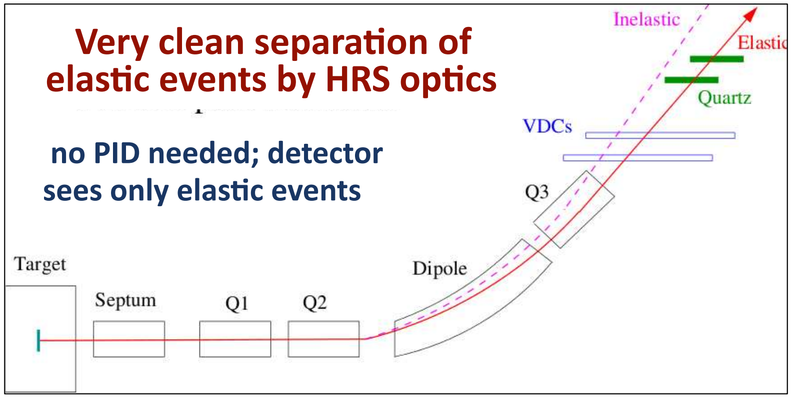
Measuring Neutron Skins at JLab

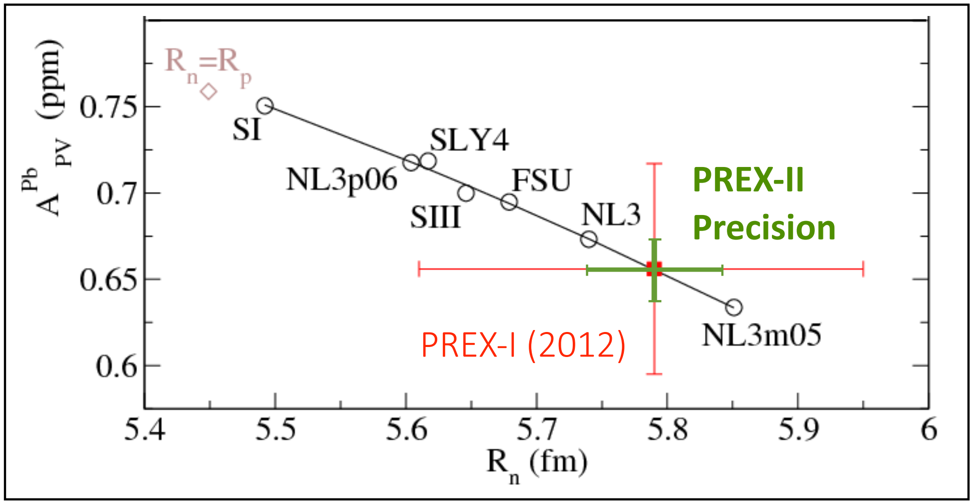


PREX (^{208}Pb)
- important check on nuclear structure data set
- uniform nuclear matter
- terrestrial laboratory for n-star matter

CREX (^{48}Ca)
- isovector probe in moderate size system
- finite size effects
- Within reach of microscopic calculations

Spring 2019:
PREX (3% APV, rn to 0.06 fm)
CREX (2.5% APV, rn to 0.02 fm)

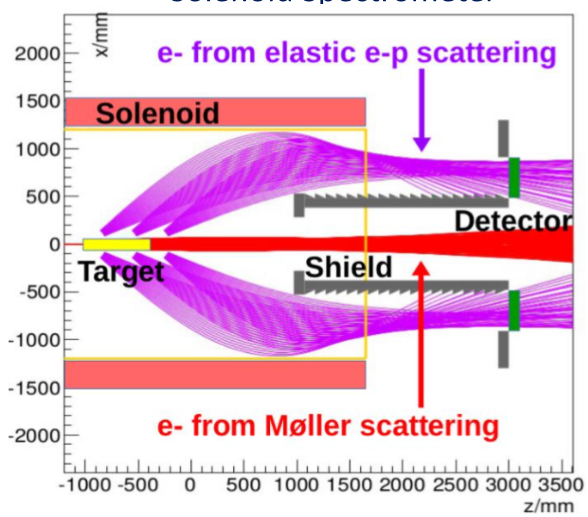


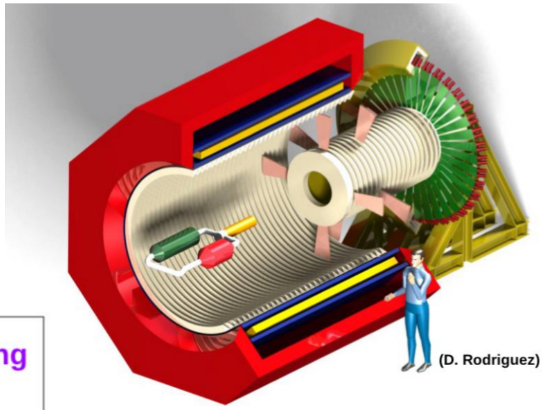


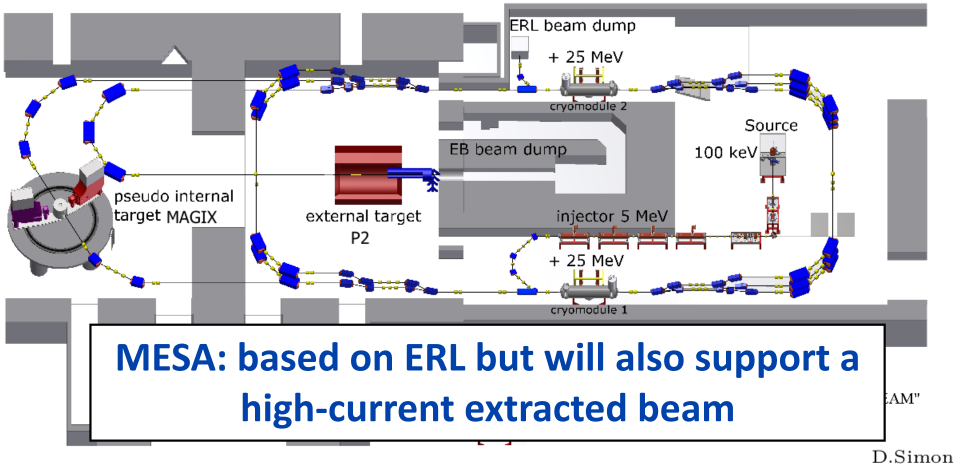
P2 at MESA / Mainz

Qweak: proton structure F contributes ~30% to asymmetry, ~2% to $\delta(Q_W^p)/Q_W^p$

Negligible for significantly lower Q^2







MESA: based on ERL but will also support a high-current extracted beam

- E_{beam} = 155 MeV, 25-45°
- Q^2 = 0.0048 GeV^2
- 60 cm target, 150 uA, 10^4 hours

- A_{PV} = -29 ppb to 1.5% (0.44ppb)
- **$\delta(\sin^2\theta_W)$ = 0.00031 (0.13%)**

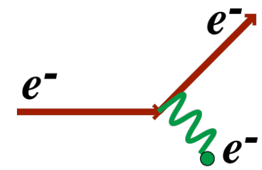
- **Development underway**
- **Funding approved**
- **start 2020+**

MOLLER at 11 GeV JLab

improve on E158 by a factor of 5

$\delta(\sin^2\theta_W) = \pm\, 0.00024\ (stat.) \pm 0.00013\ (syst.) \Rightarrow \sim 0.1\%$

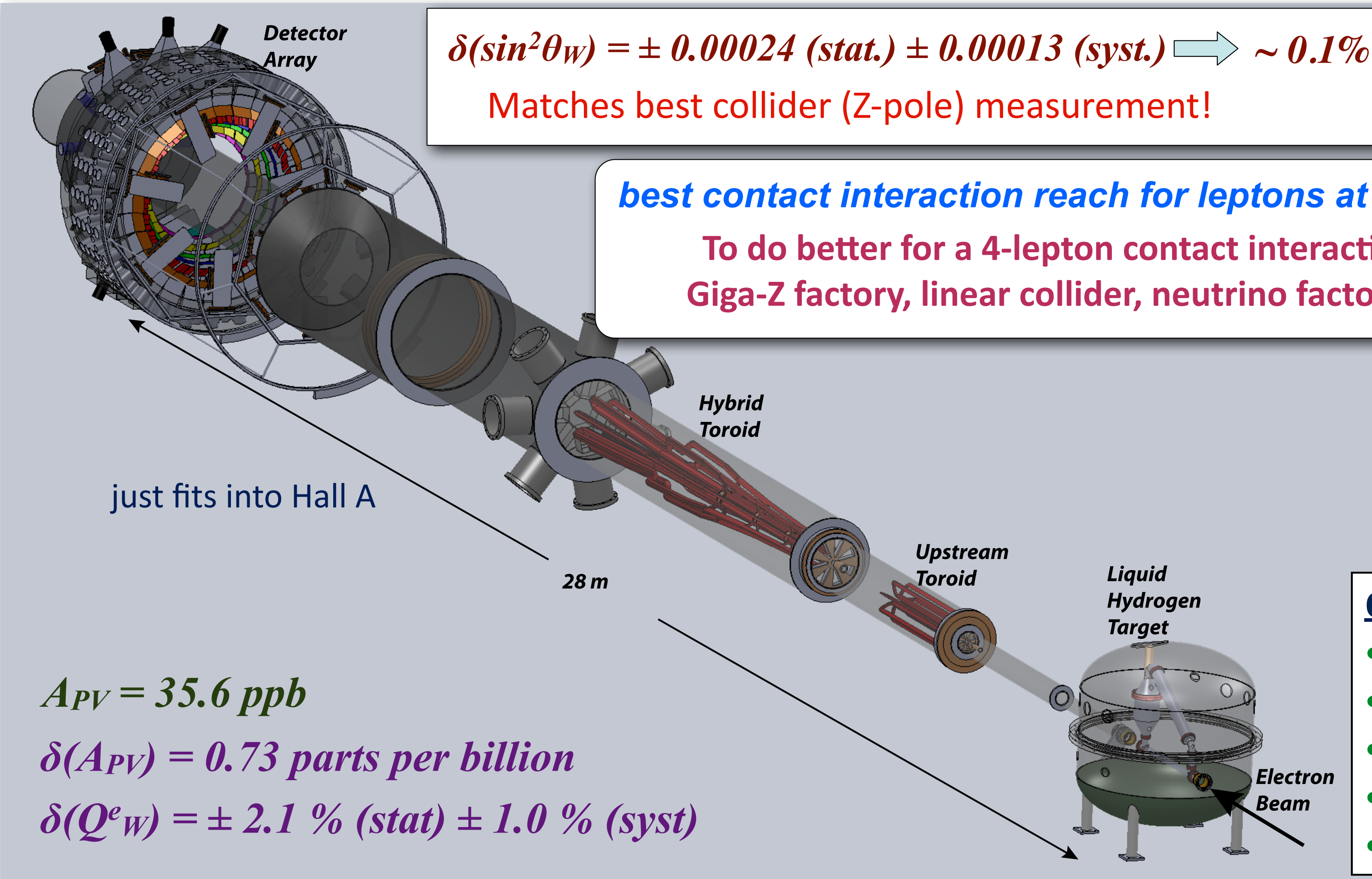
Matches best collider (Z-pole) measurement!



Q^e_W

best contact interaction reach for leptons at low OR high energy

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



$A_{PV} = 35.6\ ppb$

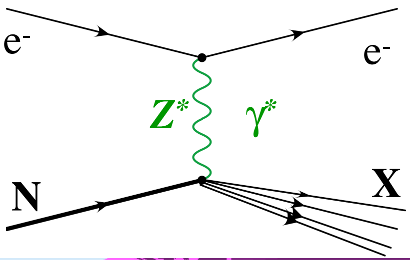
$\delta(A_{PV}) = 0.73$ *parts per billion*

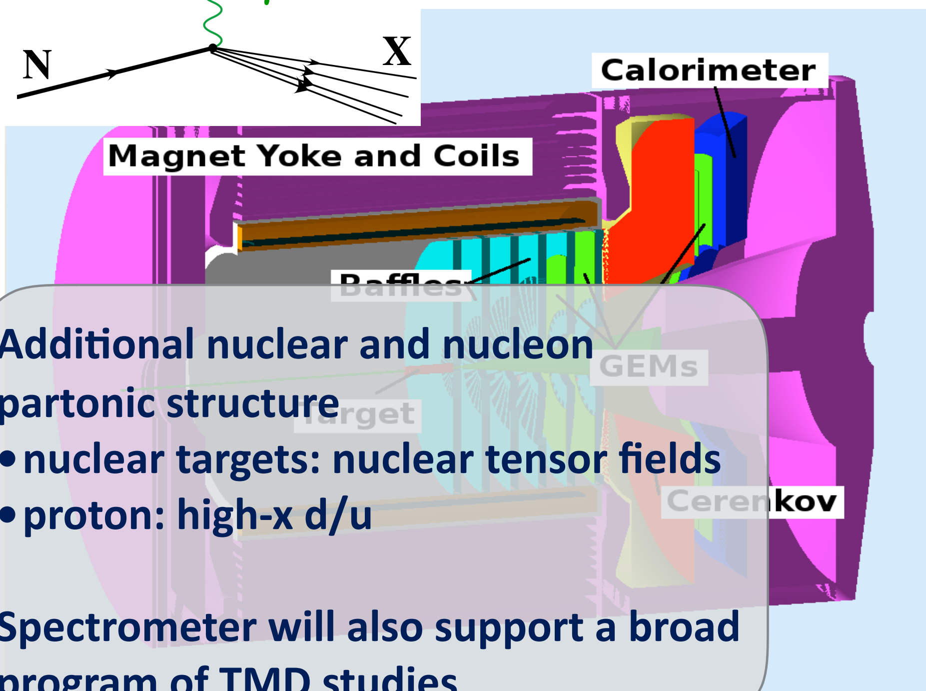
$\delta(Q^e_W) = \pm\, 2.1\ \%\ (stat) \pm 1.0\ \%\ (syst)$

Outlook:
- ~25M$ required
- CD0 approved
- (but project “paused”)
- 2-3 years construction
- 3-4 years running

SOLID

PV-DIS: controlling hadronic contributions requires precise kinematics and broad range





Additional nuclear and nucleon partonic structure

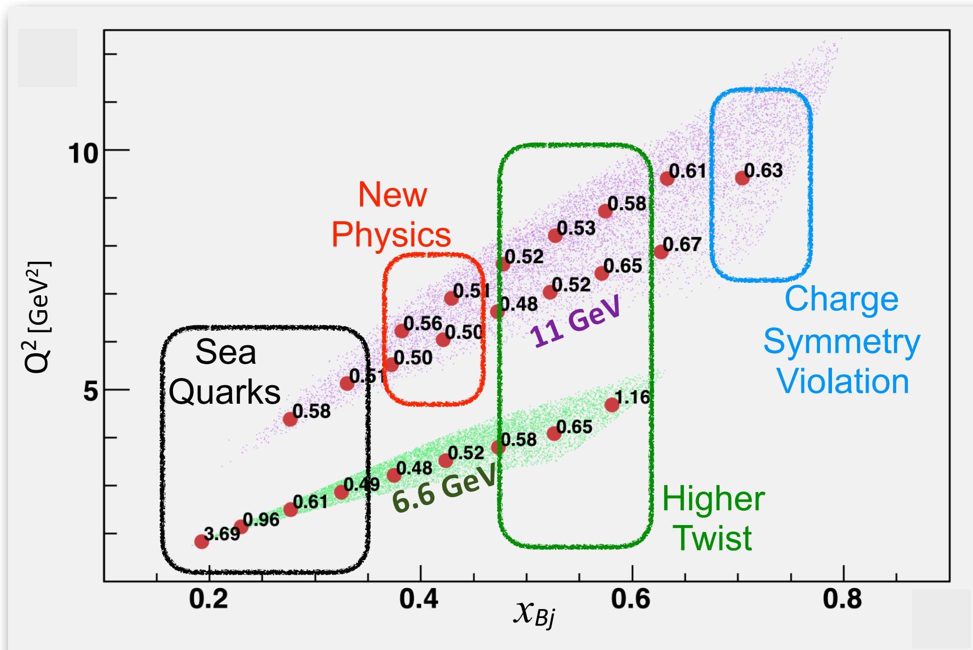
- nuclear targets: nuclear tensor fields
- proton: high-x d/u

Spectrometer will also support a broad program of TMD studies

- **high luminosity, large acceptance**
- **repurpose the CLEO solenoid**

__Strategy:__ **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

Requires 0.4% *e-* polarimetry

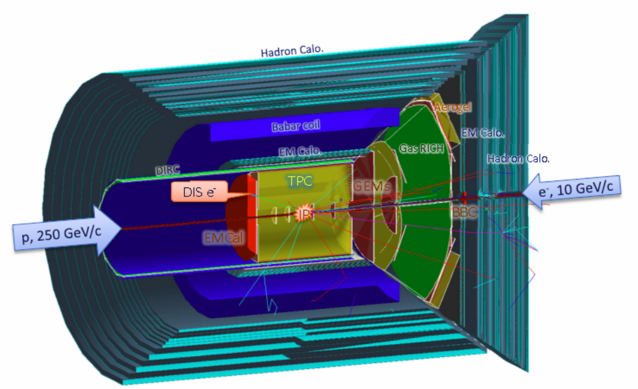


PV-DIS at EIC

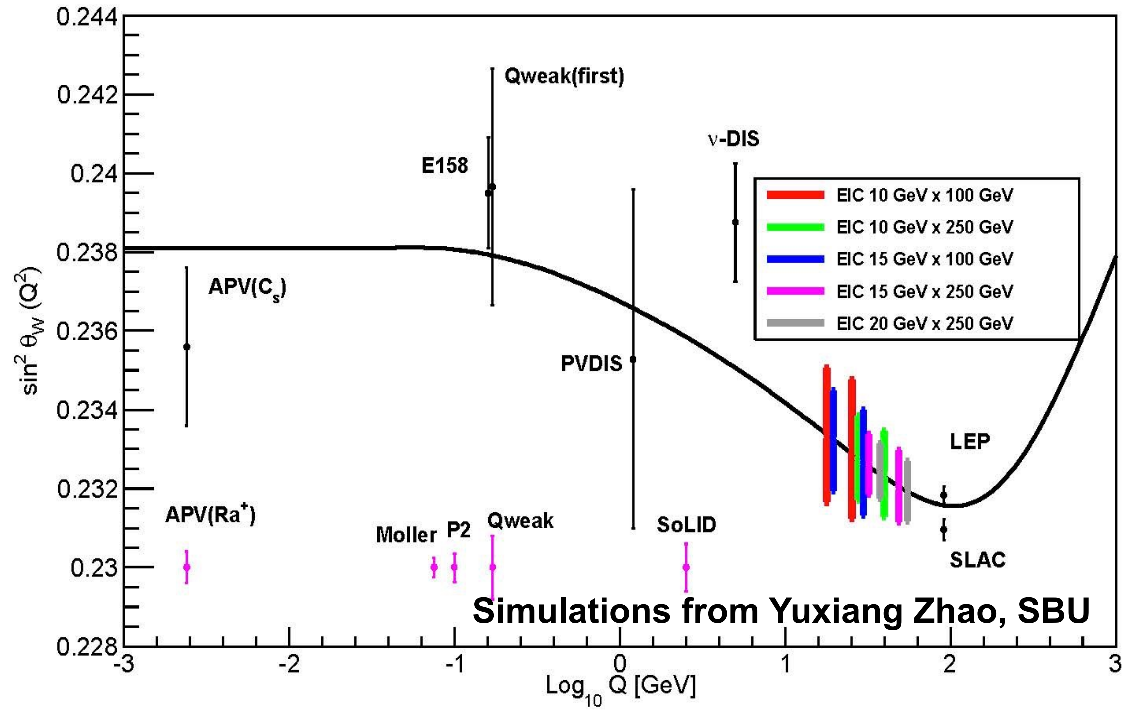
EIC can access interesting Q^2 region with PV-DIS - no past or planned measurements

Assumptions:

- Dedicated deuterium run
- This measure will average over ^2H polarization
- 200 days of beam time
- Int. Lumi. ~267 fb^{-1}(incl. eff.)



Simulated using "Day-1 EIC detector" described in ePHENIX LOI

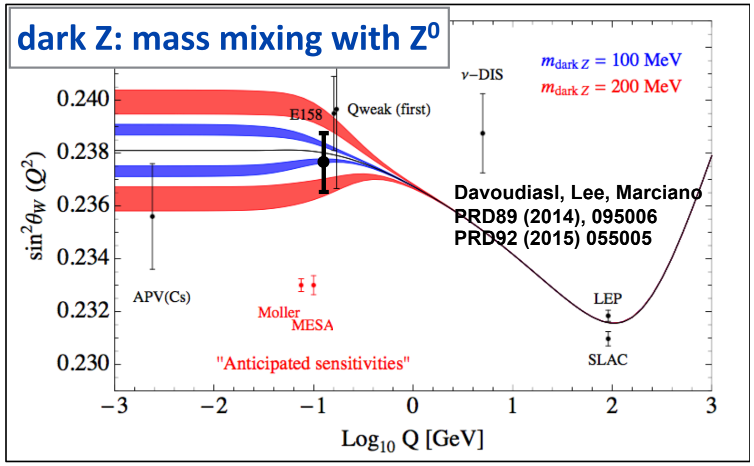


- Polarimetry ~0.5% for highest energy, luminosity
- Differential luminosity precision ~5×10^{-4}

New Physics Complementarity

Best Collider δ($\sin^2\theta_W$):
- A_l(SLD): 0.00026
- A_{fb}(LEP): 0.00029

Future projections, similar time scale:
- Final Tevatron: ~ 0.00046
- LHC 14 TeV, 300 fb^{-1} : ~ 0.00036
- Note: pdf uncertainties
- MOLLER: ~ 0.00028
- Mainz P2: ~ 0.00032



mass reach

assumptions on isospin structure, strong coupling

E158	~17 TeV
PV-DIS-6	~8 TeV
Qweak	~27 TeV
MOLLER	~39 TeV
P2	~49 TeV
SOLID	~22 TeV

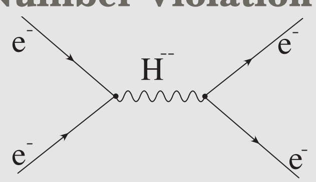
Erler *et al.*, Ann.Rev.Nucl.Part.Sci. (2014)

MOLLER: e^-e^- scattering

Lepton Number Violation

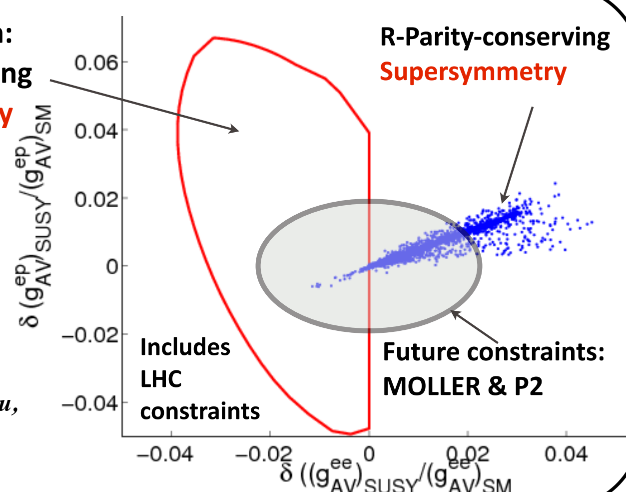
Λ > 5 TeV

Doubly-Charged Scalars



Significant reach beyond LEP-200

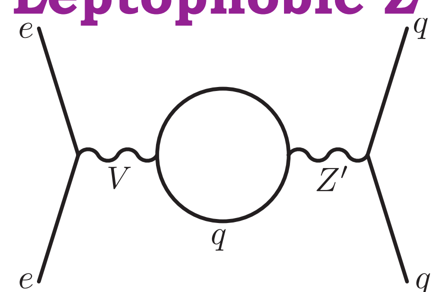
Allowed region: R-Parity-violating Supersymmetry



Erler and Su, arXiv:1303.5522

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

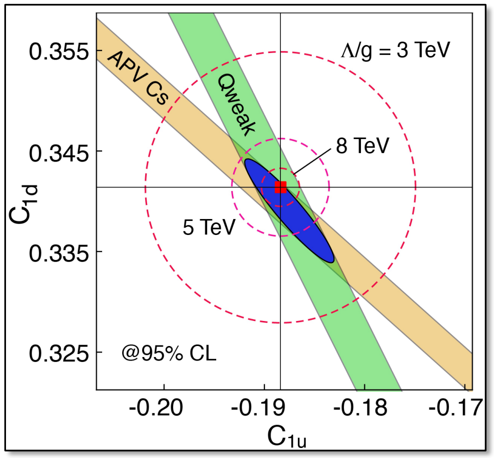
SOLID: Leptophobic Z'



SOLID: 100-200 GeV range

Buckley and Ramsey-Musolf
Phys.Lett. B712 (2012) 261-265

Summary



A measurement of the proton weak charge has been completed, providing a new tight constraint on possible new physics

New challenges arise with increasing precision. The experiments are hard, but worth it.

Unprecedented precision enabled by technological advances, preparing for the next generation of PVES experiments

Electroweak Physics with PVES is a powerful component of the low energy fundamental symmetries program

- P2, SOLID, MOLLER: Future Flagship experiments for electron beam facilities
- Search for new interactions from 100 MeV to 10s of TeV

Neutron skin provides a crucial check on nuclear structure theory

A rich experimental program is envisioned over the next 10 years at Jefferson Lab and Mainz MESA facility