Parity-Violating Electron Scattering – Physics Overview

Mark Pitt, Virginia Tech

Intense Electron Beams Workshop
Cornell University, Ithaca, NY
June 17-19, 2015

Jefferson Lab
Thomas Jefferson National Accelerator Facility

U.S. DEPARTMENT OF ENERGY

Outline

- Parity-Violating Electron Scattering (PVES): Basics and Brief History
- Physics drivers for PVES – past and future experiments
  - Standard Model tests and beyond Standard Model reach
  - Neutron skin of heavy nuclei
  - Strange form factors
- Outlook and workshop goals for this topic

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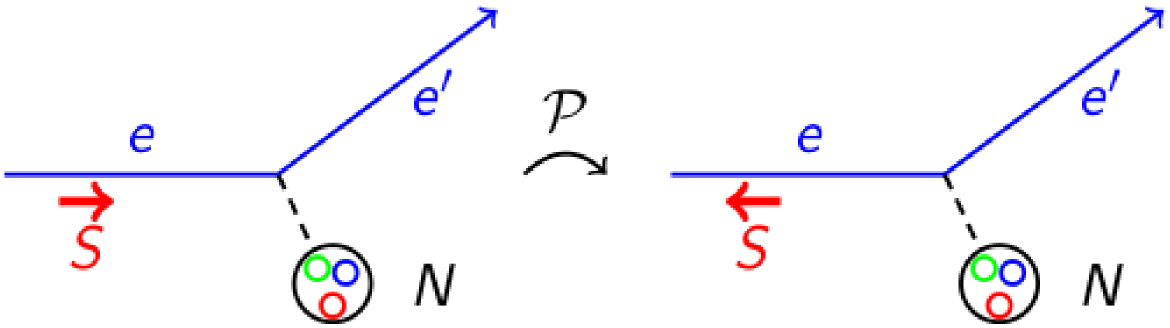
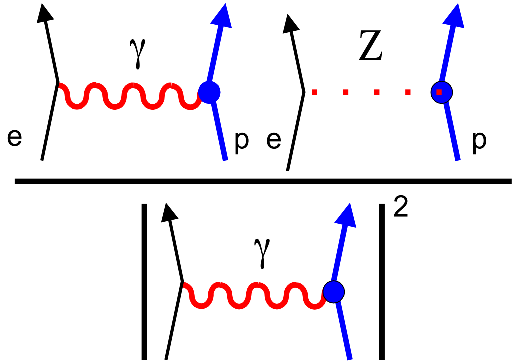
Parity-Violating Electron Scattering – The Basics



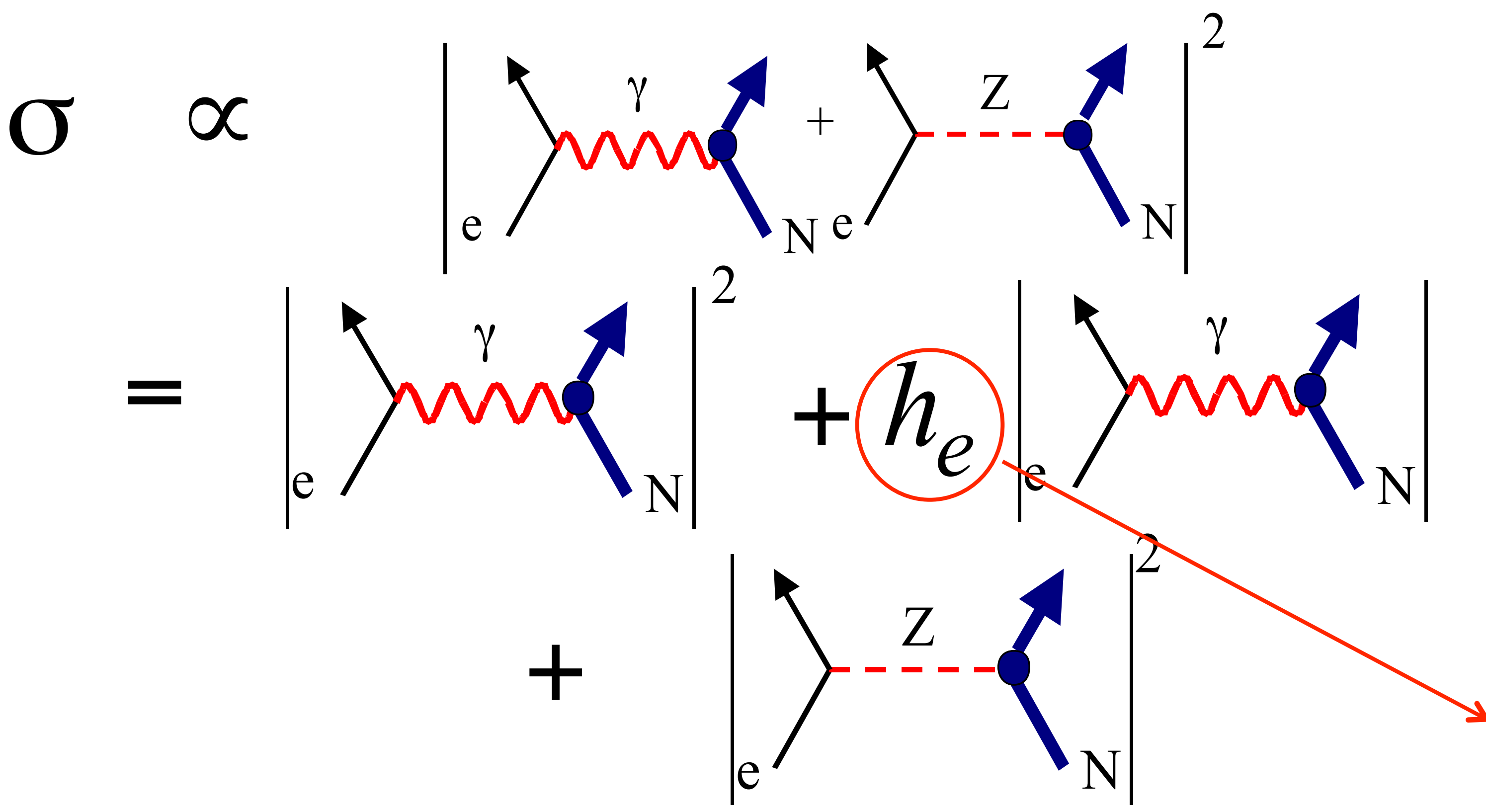
$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$

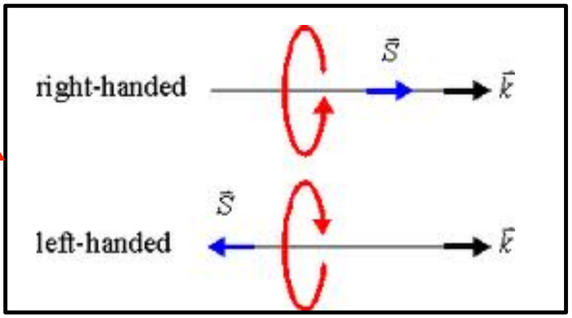


- Longitudinally polarized electrons on unpolarized targets – e, p, d, ^{4}He, ^{9}Be, ^{12}C, ^{208}Pb
- Measure small parity-violating cross section asymmetry (~ 20 ppb – 100 ppm)
- Elastic and deep inelastic kinematics
- Neutral weak current – Standard Model test and select hadronic physics topics

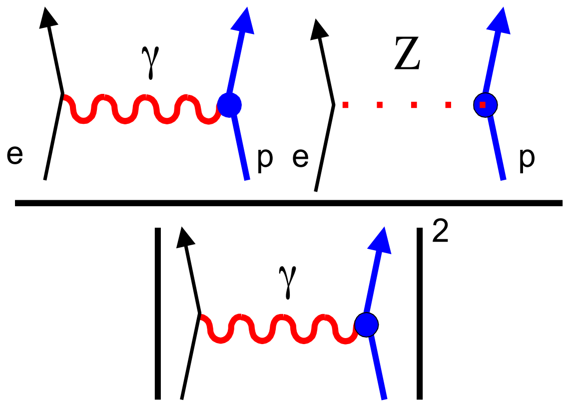
Parity-Violating Asymmetry –Accessing the Neutral Weak Sector

Exploit the interference between EM and weak interactions





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

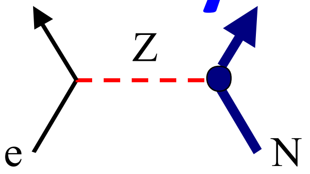


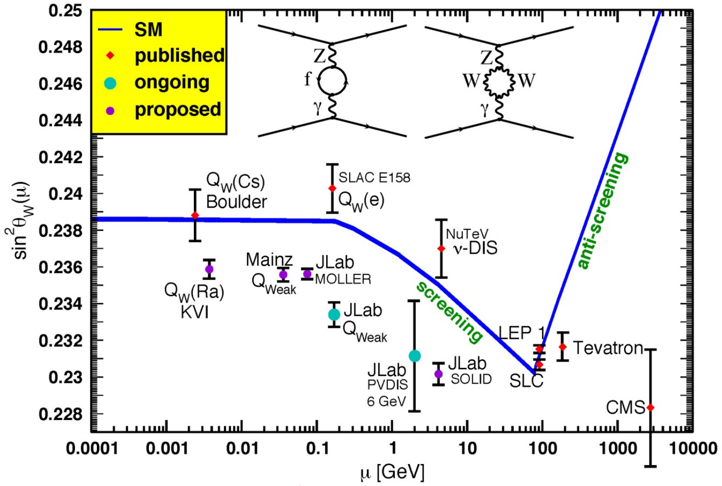
$$\propto \left[\frac{G_F}{\alpha}\right] Q^2 \approx 10^{-4} - 10^{-8}$$

Low energy PVES experiments – typically very small asymmetries, very large rates

Parity-Violating Electron Scattering – The Physics

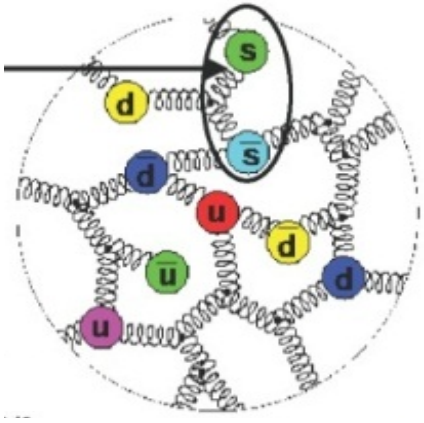
Neutral current matrix elements measured in PVES give access to Standard Model and hadronic physics topics



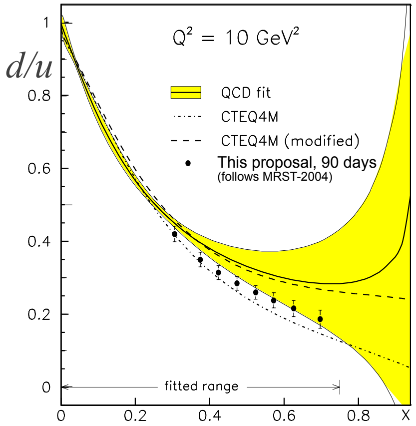


Standard Model Tests: sensitive to new physics from multi-TeV dynamics and MeV-scale mediators

Neutron skin in heavy nuclei: application to neutron rich matter equation of state and neutron stars



Strange form factors: contribution of strange quark sea to nucleon's electromagnetic properties

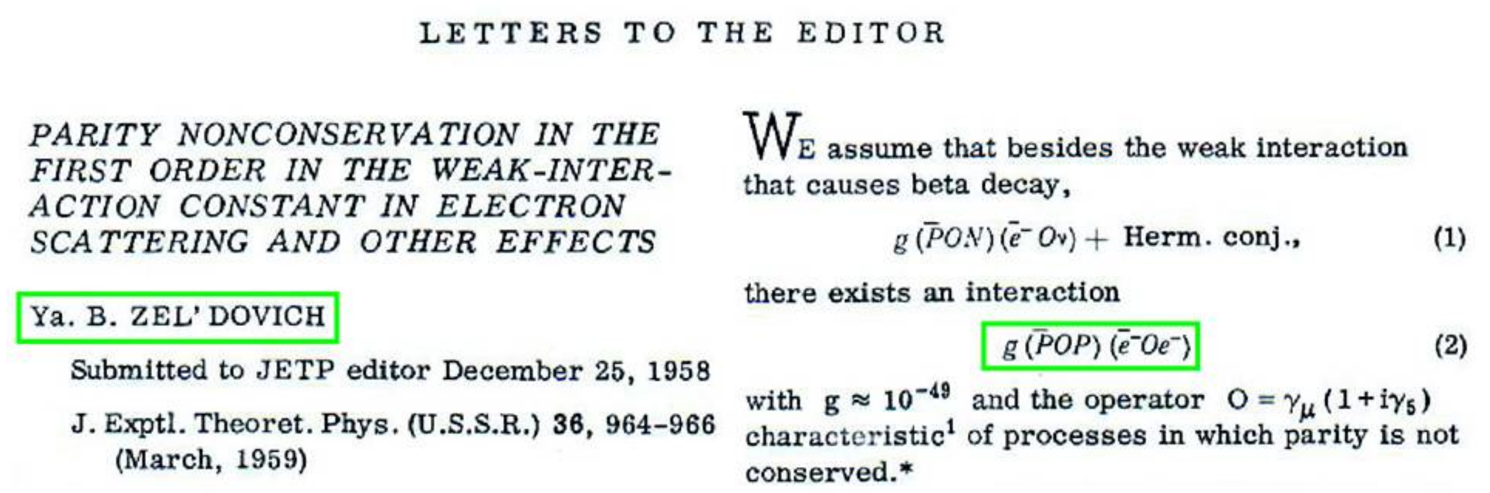


QCD valence quark structure of nucleons/nuclei: from parity-violating deep inelastic scattering (PVDIS)

PV Electron Scattering – First Suggestion

1956, 1957 – Lee, Yang, Wu: Parity Violation observed in charged weak current

1959: Zel'dovich suggests – What about neutral weak currents?



LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 964-966 (March, 1959)

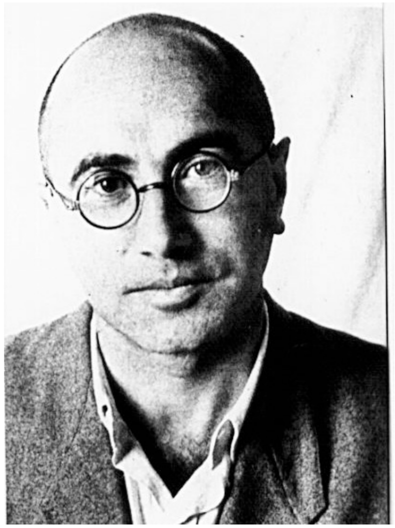
WE assume that besides the weak interaction that causes beta decay,

$$g(\bar{P}ON)(\bar{e}^- O\nu) + \text{Herm. conj.}, \qquad (1)$$

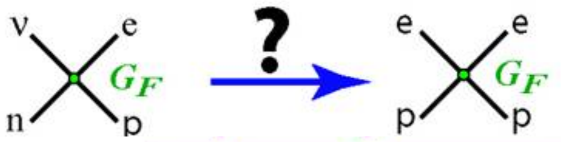
there exists an interaction

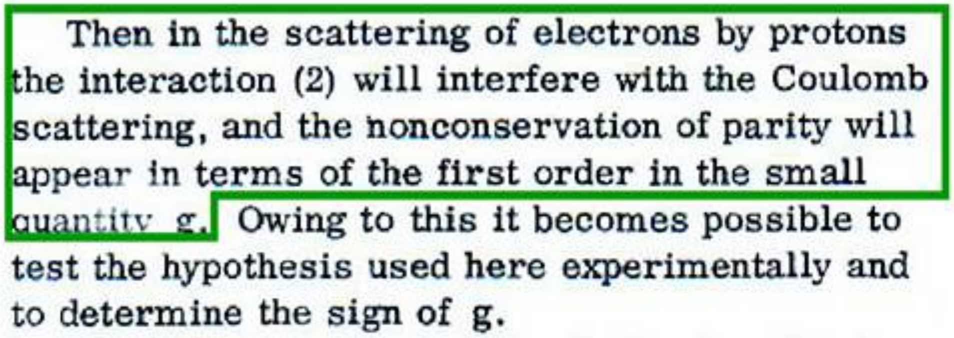
$$g(\bar{P}OP)(\bar{e}^- O e^-) \qquad (2)$$

with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

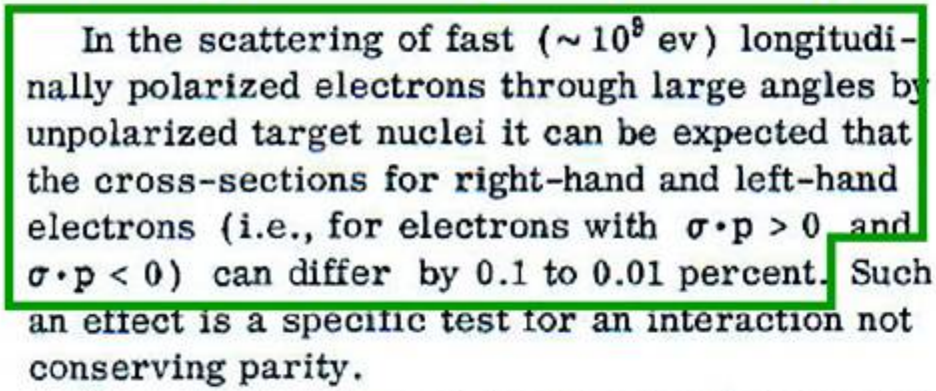


Zel'dovich '59:
- Is there a neutral analog to beta-decay?





Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.



In the scattering of fast ($\sim 10^8$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

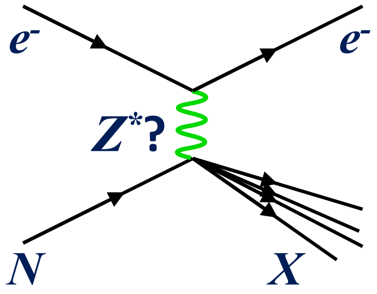
Expect EM/neutral weak interference – observable when scattering longitudinally polarized electrons on unpolarized target nuclei

First PV Electron Scattering Experiment – 1978 – SLAC E122

Charles Prescott and collaborators:

$\vec{e}^{\,-} + d \rightarrow e^- + X, \quad Q^2 \sim 1.6\ \mathrm{GeV}^2$

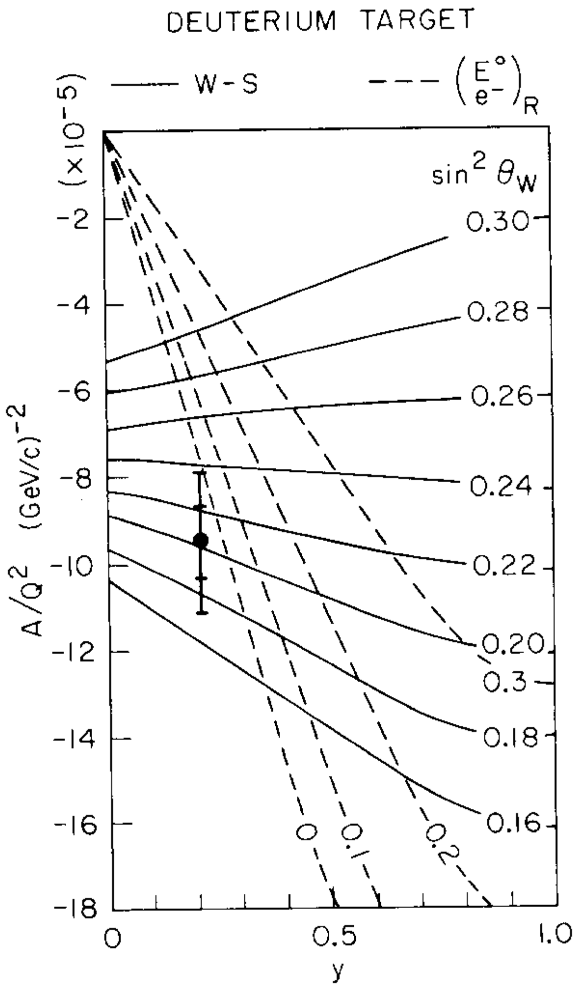
PV deep inelastic scattering at SLAC



- Weak neutral current observed in ν-e 1973
- Interference between EM and weak neutral current? Lack of signal in atomic PV expts. in mid-70's caused confusion
- E122 first result in 1978: $A = -(152 \pm 26) \times 10^{-6}$
  - ➢ first measurement of parity-violation in the neutral weak current

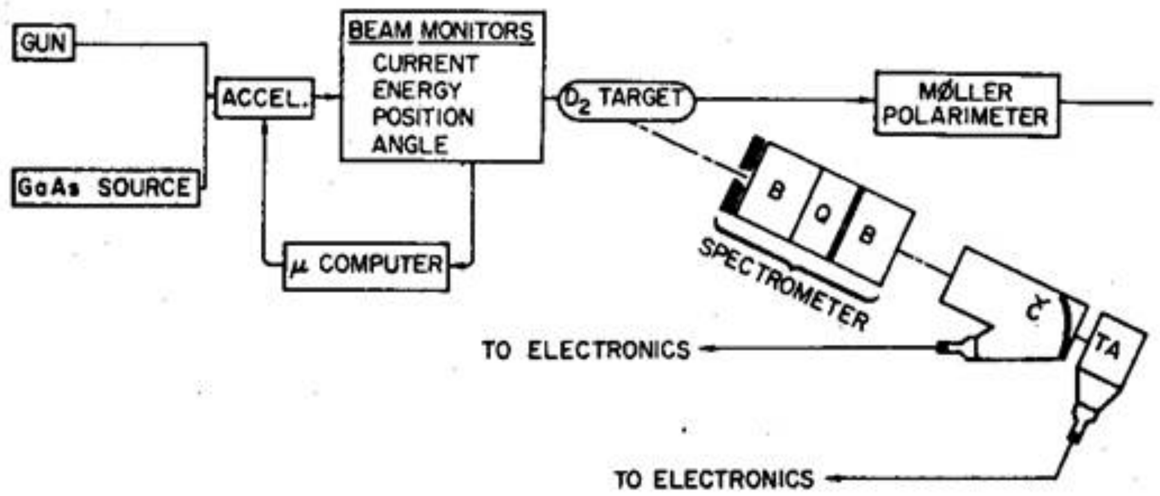
$\sin^2\theta_W = 0.224 \pm 0.020$ consistent with ν-e

> "Finally, parity-violation in the neutral currents was discovered at the expected level in electron-nucleon scattering at SLAC in 1978, and after that most physicists took it for granted that the electroweak theory is essentially correct."
>
> Steven Weinberg
>
> "The Making of the Standard Model" on the occasion of the CERN 30th anniversary celebration of discovery of neutral currents AND 20th anniversary celebration of discovery of W/Z bosons
>
> hep-ph/0401010



Prescott *et al.*, PLB 77, 347 (1978)
Prescott *et al.*, PLB 84, 524 (1979)

SLAC E122 - Seminal Technical Developments



Prescott *et al.*, PLB 77, 347 (1978)
Prescott *et al.*, PLB 84, 524 (1979)

E122 had essentially all the features that continue to be used in PV e-e, e-N

- **Polarized source:** photoemission from GaAs polarized source
- **Rapid, pseudo-random helicity reversal:** minimizes effects of drifts
- **Slow helicity reversal** – calcite prism, g-2 precession check
- **Accurate measurement and control of beam properties** (corrections procedure for helicity-correlated beam properties)
- **High power cryotarget** – 30 cm LD_2 target
- **Magnetic spectrometer** – isolates process of interest
- **Integrate phototube outputs** instead of pulse counting (~700 MHz instantaneous rates)
- **Beam polarimetry** – Moller polarimeter

See S. Baunack plenary talk and Grames, Covrig, Kargiantoulakis parallel talks

Key Beam Parameters of Published PVES Experiments

Experiment	Phys. Asym (ppm)	Beam Energy	Beam Current, Polarization	Target length and type
SLAC E122	-152 ± 15 ± 15	16 – 22 GeV	2-8 μA, 37%	30 cm LD_2
Bates C^{12}	1.62 ± .38 ± .05	250 MeV	30-60 μA, 37%	2.3 cm C
Mainz Be^9	-9.4 ± 1.8 ± 0.5	300 MeV	7 μA, 42%	1.3 cm Be
SAMPLE proton	-4.92 ± 0.61 ± 0.73	200 MeV	40 μA, 36%	40 cm LH_2
SAMPLE deuteron	-6.79 ± 0.64 ± 0.55	125, 200 MeV	40 μA, 36%	40 cm LD_2
A4 p @ .23 GeV^2 F	-5.44 ± 0.54 ± 0.26	854 MeV	20 μA, 80%	10 cm LH_2
A4 p @ .11 GeV^2 F	-1.36 ± 0.29 ± 0.13	570.4 MeV	20 μA, 80%	10 cm LH_2
A4 p @ .22 GeV^2 B	-17.23 ± 0.82 ± 0.89	315 MeV	20 μA, 70%	23 cm LH_2
HAPPEx – I	-15.05 ± 0.98 ± 0.56	3.3 GeV	35 μA, 70%	15 cm LH_2
HAPPEx – II H	-1.58 ± 0.12 ± 0.04	~3 GeV	~45 μA, 85%	20 cm LH_2
HAPPEx – II He	6.40 ± 0.23 ± 0.12	~3 GeV	~45 μA, 85%	20 cm LH_2
HAPPEx – III	-23.80 ± 0.78 ± 0.36	3.5 GeV	100 μA, 89%	25 cm LH_2
G0 forward	-1.51 ± 0.44 ± 0.28	3 GeV	40 μA, 74%	20 cm LH_2
G0 backward	-11.25 ± 0.86 ± 0.51	359, 684 MeV	60 μA, 86%	20 cm LH_2,LD_2
E158	-0.131 ± 0.014 ± 0.010	45,48 GeV	8-12 μA, 85%	156 cm LH_2
PREX – I	0.6571 ± .0604± .0130	1.06 GeV	70 μA, 90%	0.5 mm ^{208}Pb
PVDIS@6 GeV	-91 ± 3 ± 3	5 - 6 GeV	100 μA, 90%	20 cm LD_2
QWEAK	-0.279 ± 0.035 ± 0.031	1.165 GeV	180 μA, 89%	35 cm LH_2

Highest beam current employed to date: 180 , 89% pol. for Qweak at Jlab

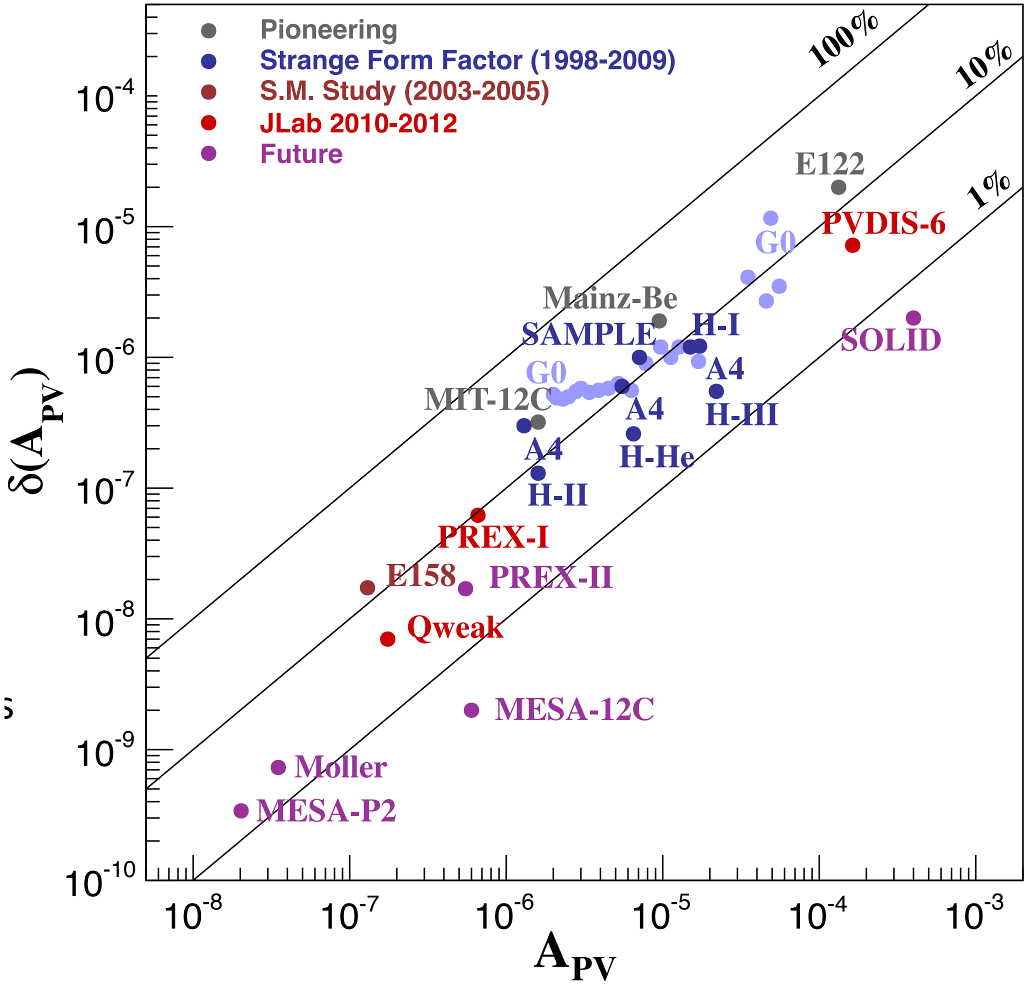
Several experiments in above list ran at E < 500 MeV

Parity-Violating Electron Scattering Experiments – A Brief History

Pioneering (1978) early SM test
SLAC E122 PVDIS – Prescott *et al.*
A = -152 ppm

Strange Form Factors
(1998 – 2009)
SAMPLE, G0, A4, HAPPEX
A ~ 1 – 50 ppm

Standard Model Tests
(2003 – present)
SLAC E158 Moller: A = - 131 ppb
JLAB Qweak: A ~ -230 ppb
→ smaller asymmetries,
smaller absolute and relative errors



Future: MOLLER, P2@MESA, SOLID, 12C@MESA, PREX-II, CREX

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Note: many of the proposed low energy experiments or ideas in the following slides are described in further detail in these recent conferences:

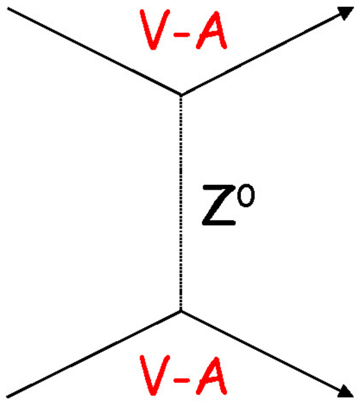
PEB13: Workshop to Explore Physics Opportunities with Intense, Polarized Electron Beams up to 300 MeV, MIT, Cambridge, MA, March 2013

PAVI14: From Parity Violation to Hadron Structure, Skaneateles, NY, July 2014

Standard Model Weak Neutral Current Couplings

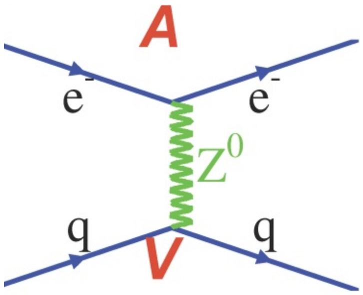
The Standard Model prescribes the couplings of the fundamental fermions to the Z boson:

fermions	$g_A^f = I_3$	$g_V^f = I_3 - 2Q\sin^2\theta_W$
ν_e, ν_μ	$\frac{1}{2}$	$\frac{1}{2}$
e-, μ-	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W$
u, c	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$



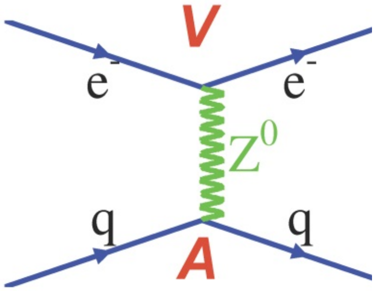
For low energy electroweak tests ($Q^2 << M^2_Z$), restrict to parity-violating e-q and e-e four-fermion contact interaction:

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}\left[\bar{e}\gamma^\mu\gamma_5 e\left(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d\right) + \bar{e}\gamma^\mu e\left(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d} d\gamma_\mu\gamma_5 d\right) + C_{ee}\bar{e}\gamma^\mu\gamma_5 e\left(\bar{e}\gamma_\mu e\right)\right]$$



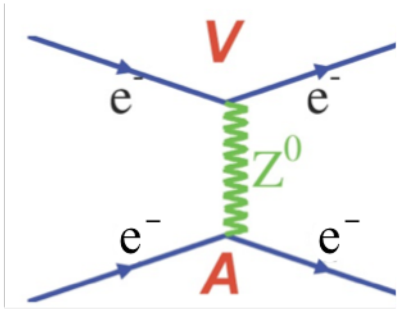
$$C_{1i} \equiv 2g_A^e g_V^i$$

quark vector: C_{1u}, C_{1d}



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

quark axial-vector: C_{2u}, C_{2d}



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

electron: C_{ee}

C_{1u} ,C_{1d} , C_{ee} : "Weak Charges": neutral current analog to the electric charges

The Hunt for New Physics

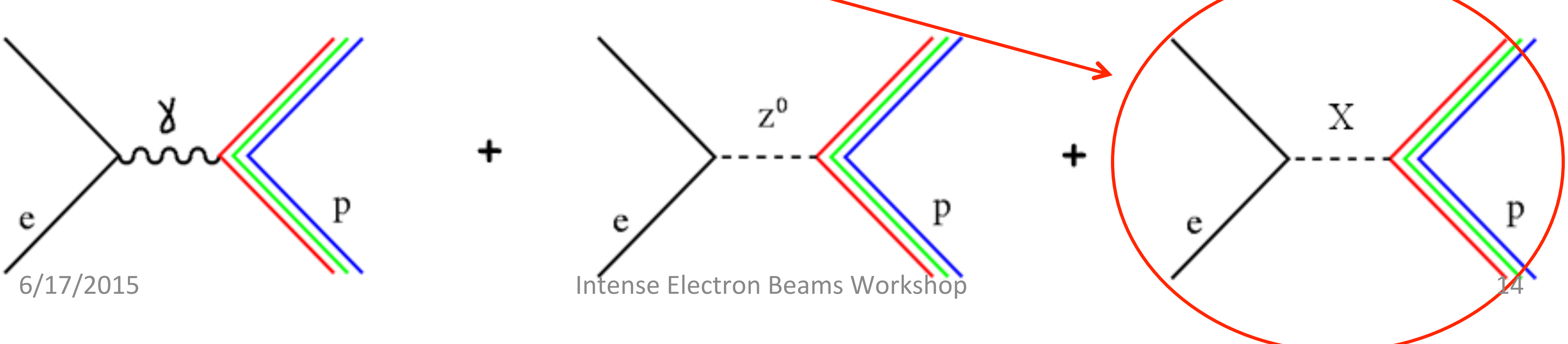
Two complementary approaches to searching for “New Physics”

“Energy frontier”
- like LHC – Large Hadron Collider

→ Make new particles (“X”) directly in high energy collisions

“Precision frontier”
- examples: Weak charge measurements at JLab, μ(g-2), EDM, ββ decay, n β decay, etc.

→ Look for indirect effect of new particles (“X”) made virtually in low energy processes



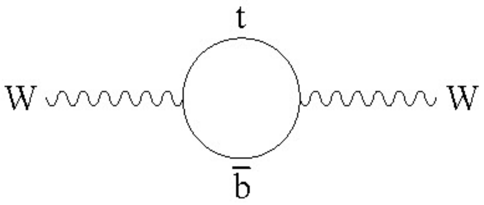
Historical Example: Top Quark

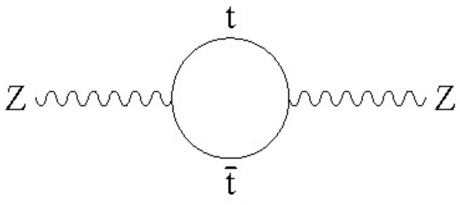
Past example of interplay between energy frontier and precision frontier

"Precision frontier"

Precision electroweak measurements (LEP at CERN and SLD at SLAC) were sensitive to "virtual top quarks" in loops

Prior to the direct top quark discovery, theorists predicted it would fall in a range from 145 GeV/c^2 - 185 GeV/c^2





"Energy frontier"

Top quark was produced directly at Tevatron at Fermilab in 1995

Direct production at energy frontier

Indirect evidence at precision frontier

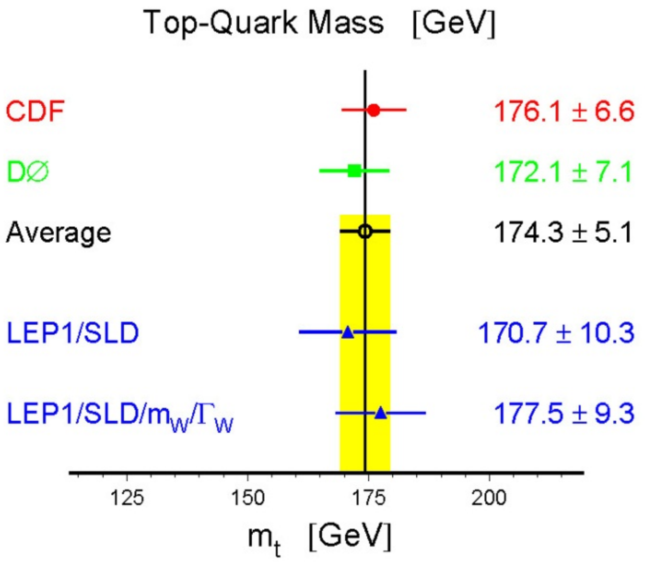


Figure 4. Measurements of the top quark mass at Fermilab (CDF and D0) and indirect predictions from precision measurements (LEP1, SLD and M_W).[3]

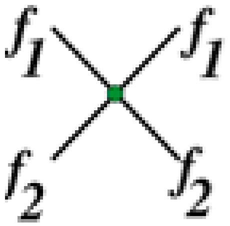
Sensitivity to New Physics at TeV Scales

Model-independent way to quantify effects of potential new high energy dynamics (ie. heavy Z's, compositeness, extra dimensions,…) is from expressing them in terms of neutral "contact" 4-fermi interactions:

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

Consider $f_1 f_1 \rightarrow f_2 f_2$ **or** $f_1 f_2 \rightarrow f_1 f_2$

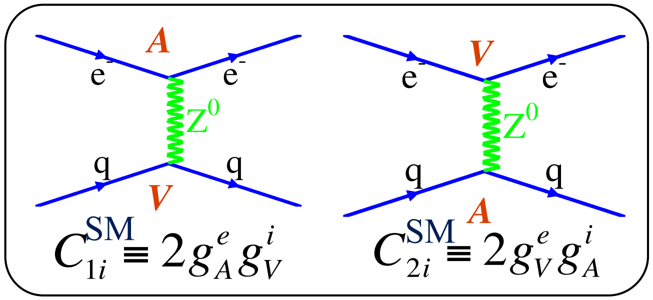
$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{i\,j}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$



Eichten, Lane and Peskin, PRL50 (1983)

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

Example:
Standard model
e-q couplings



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

precision measurement to test for new possible couplings

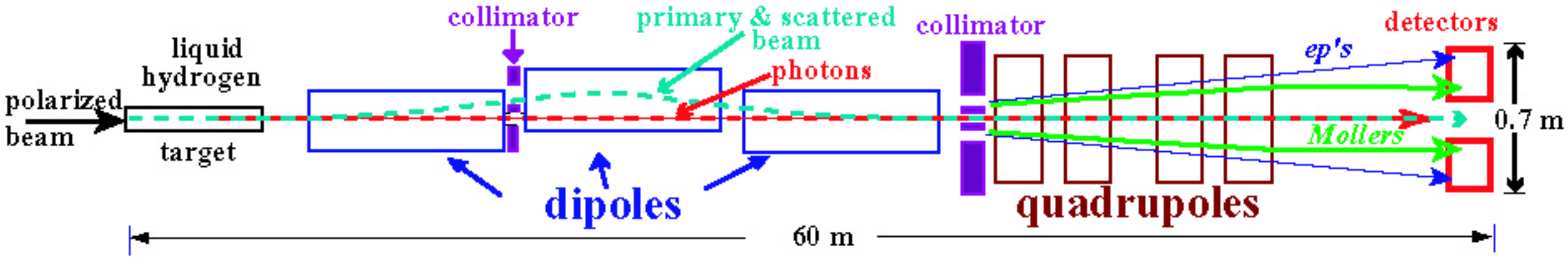
$$C_{1q} = (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

$$C_{2q} = (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

Precision of current and future low energy experiments →
mass reach of Λ/g in the multi-TeV region.

(See Erler, Horowitz, Mantry, Souder, Ann. Rev. Nucl. Part. Sci. **64** (2014) for detailed mass reach comparisons)

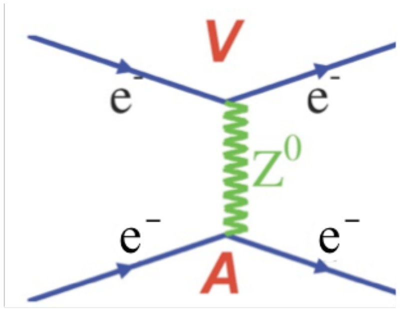
SLAC E158: First Measurement of Electron's Weak Charge



Parity-violating Møller scattering

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

$$A_{PV} = m_e E_{lab} \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4 sin^2\theta}{(3 + cos^2\theta)^2} Q_W^e$$



$$Q_W^e \equiv -2C_{ee} = -(1 - 4\sin^2\theta_W)$$

suppressed in SM

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

Q^2 ~ .026 GeV^2 θ ~ 4 – 7 mrad E ~ 48 GeV
at SLAC End Station A

Dipole chicane + QQQQ spectrometer + Cu-quartz shower detector

Results: PRL 95 081601 (2005)

A_{PV} = -131 ± 14 (stat) ± 10 (syst) ppb

Q^e_W=-0.0369 ± 0.0052

$\sin^2\theta_{eff}(Q^2=0.026\ \mathrm{GeV}^2)$ = 0.2397 ± 0.0010 ±0.0008

JLab Qweak: First Measurement of Proton's Weak Charge

$$Q_W^p \equiv -2\left[2C_{1u} + C_{1d}\right] = \left(1 - 4\sin^2\theta_W\right)$$

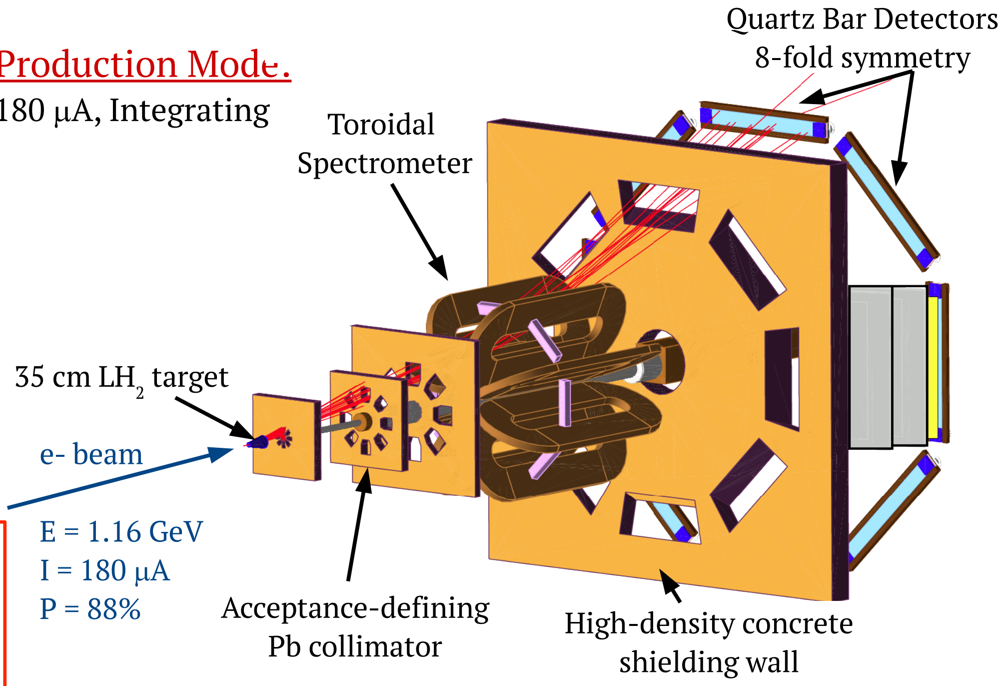
$$A \sim \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\ Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

(1/25th of total dataset) – published in PRL **111**, 141803 (2013)

$$A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{syst})\ \text{ppb}$$

$$\left\langle Q^2 \right\rangle = 0.0250\ \ (\text{GeV}/c)^2$$

$$Q_W^p(\text{PVES})\ = 0.064 \pm 0.012$$



Production Mode:
180 μA, Integrating

Quartz Bar Detectors
8-fold symmetry

Toroidal
Spectrometer

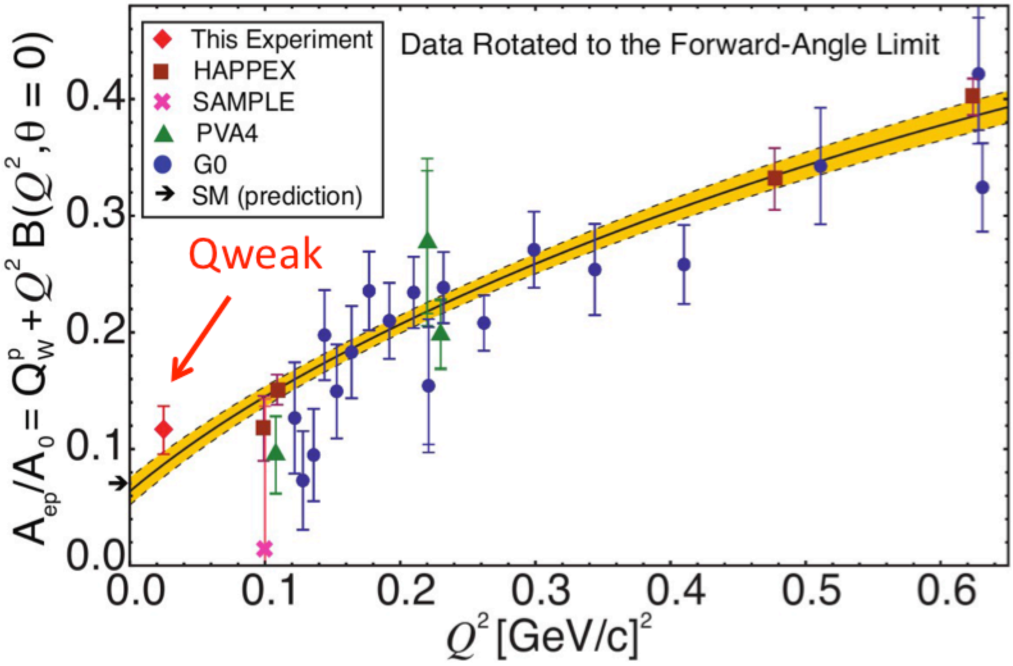
35 cm LH_2 target

e- beam

E = 1.16 GeV
I = 180 μA
P = 88%

Acceptance-defining
Pb collimator

High-density concrete
shielding wall

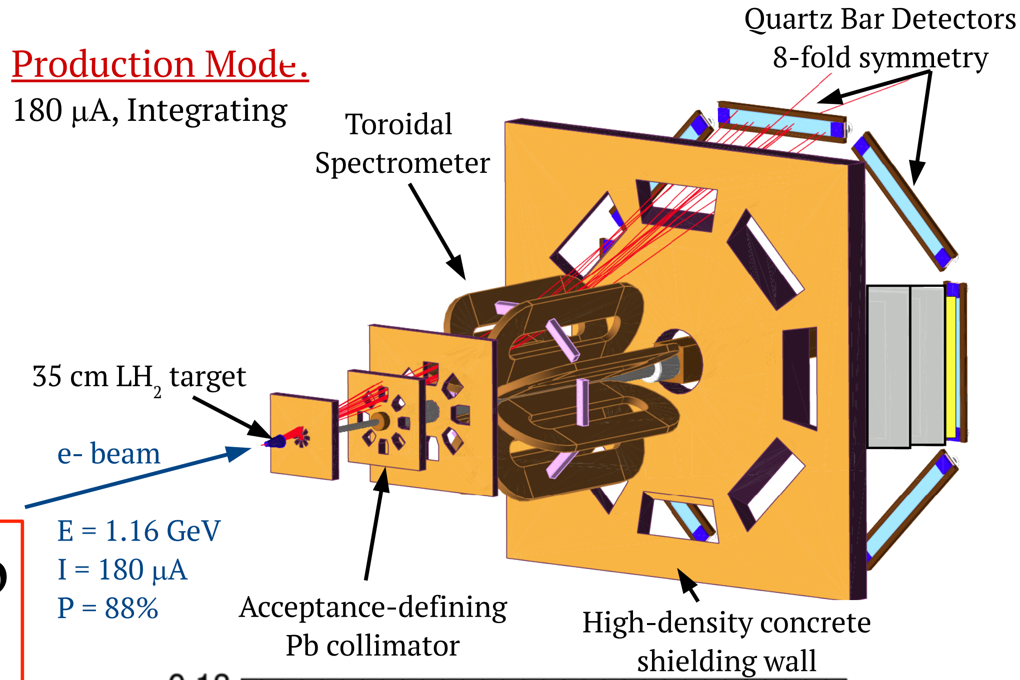


JLab Qweak: First Measurement of Proton's Weak Charge

$$Q_W^p \equiv -2\left[2C_{1u} + C_{1d}\right] = \left(1 - 4\sin^2\theta_W\right)$$

$$A \sim \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

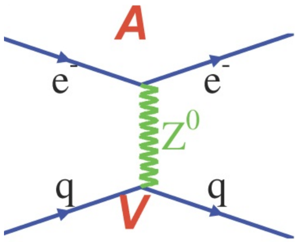
(1/25th of total dataset) – published in PRL **111**, 141803 (2013)



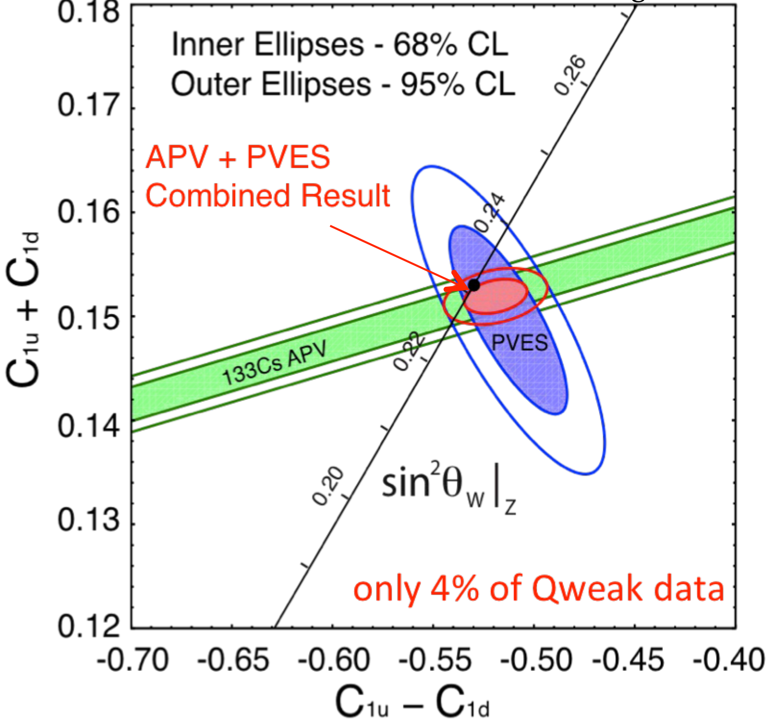
$$A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{syst})\ \text{ppb}$$

$$\langle Q^2 \rangle = 0.0250\ (\text{GeV}/c)^2$$

$$Q_W^p(\text{PVES}) = 0.064 \pm 0.012$$



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



Full dataset being analyzed; final results soon

See R. Carlini talk

JLab PVDIS – Recent C_{2u}, C_{2d} Determination

Nature 506, 67–70 (06 February 2014)

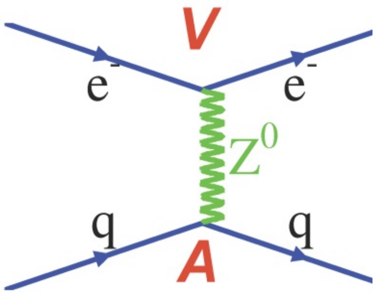
The Jefferson Lab PVDIS Collaboration

See also News & Views, *Nature* 506, 43–44 (06 February 2014)

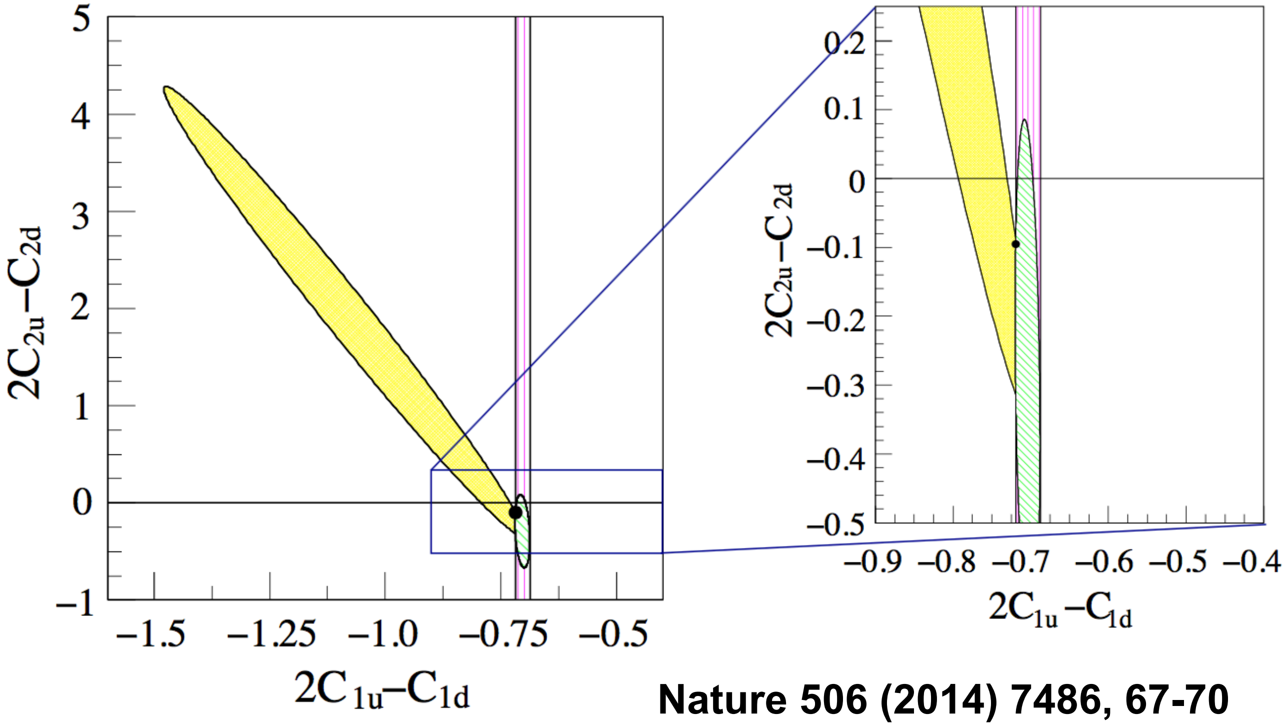
Measurement of the Parity-Violating Asymmetry in eD Deep Inelastic Scattering

- E = 6.067 GeV
- 20 cm liquid deuterium (LD_2) target
- 100 μA polarized beam with 90% beam polarization

- Two kinematic points:
  - $Q^2 = 1.1\ \mathrm{GeV}^2 \quad x_B = 0.24, \quad \theta = 12.90^\circ$
  - $Q^2 = 1.9\ \mathrm{GeV}^2 \quad x_B = 0.30 \quad \theta = 20.00^\circ$



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



Nature 506 (2014) 7486, 67-70
Phys.Rev. C91 (2015) 4, 045506

Significant improvement in knowledge of C_{2u}, C_{2d}

JLab PVDIS – Recent C_{2u}, C_{2d} Determination

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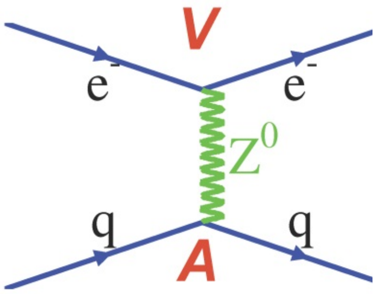

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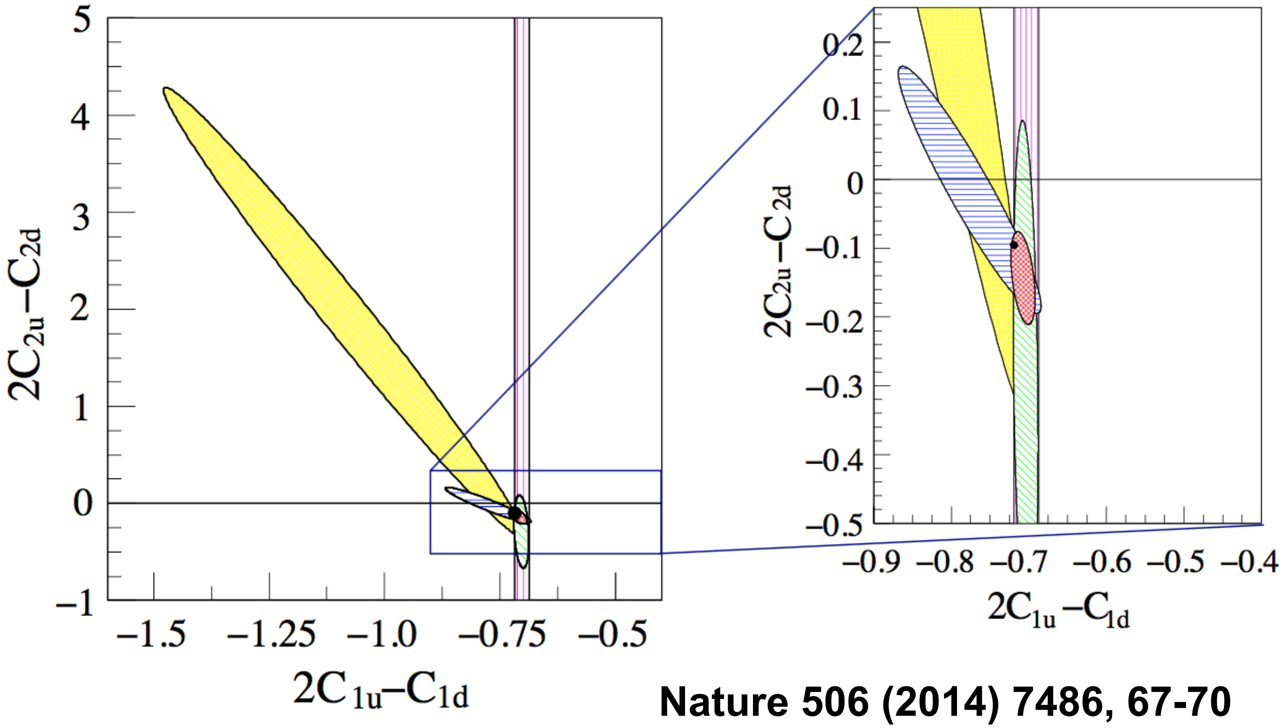
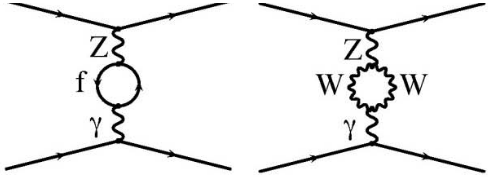


Nature 506 (2014) 7486, 67-70
Phys.Rev. C91 (2015) 4, 045506

Significant improvement in knowledge of C_{2u} , C_{2d}

Standard Model Test – "Running of $\sin^2\theta_W$"

"Running" of the weak mixing angle due to electroweak radiative corrections → Key prediction of the Standard Model

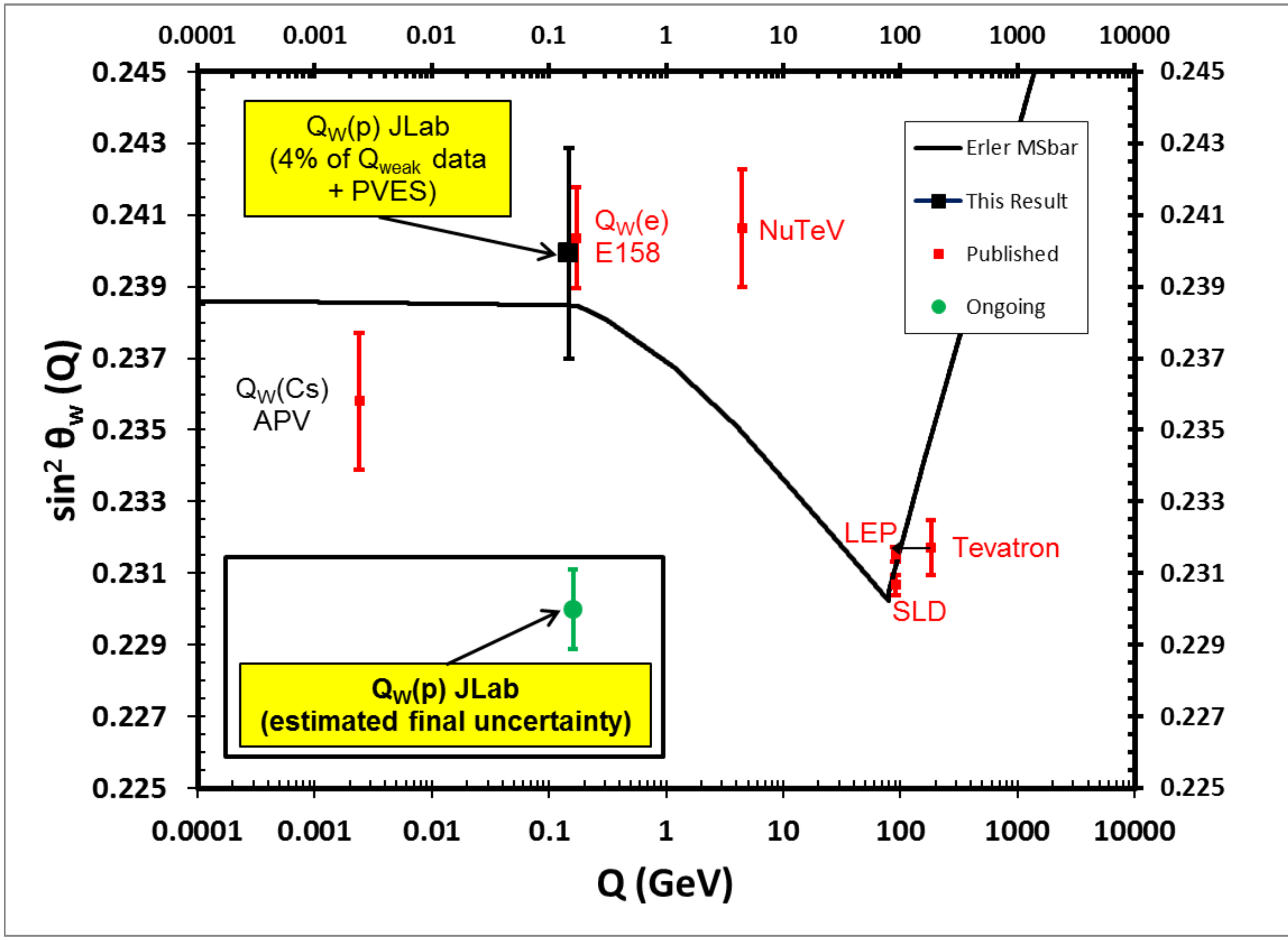


Any disagreement with SM prediction could be a signature of "New Physics"

Precise low energy measurements:

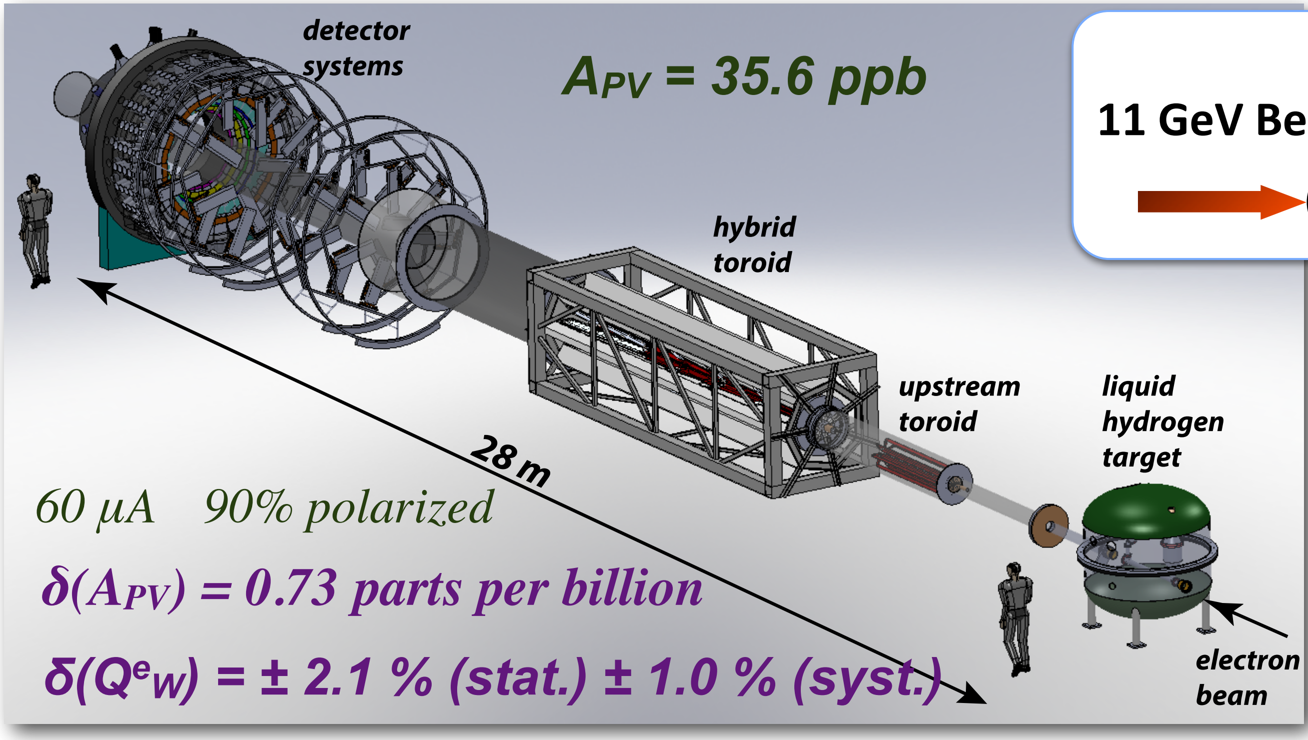
- E158 Moller
  electron's weak charge
- Cs Atomic Parity Violation
  mostly neutron weak charge
- Qweak's measurement of proton weak charge (when final)

Experiments being considered for E < 500 MeV have prospects of improving 2 out of these 3.



MOLLER Experiment at 11 GeV JLab

An ultra-precise measurement of the weak mixing angle using Møller scattering

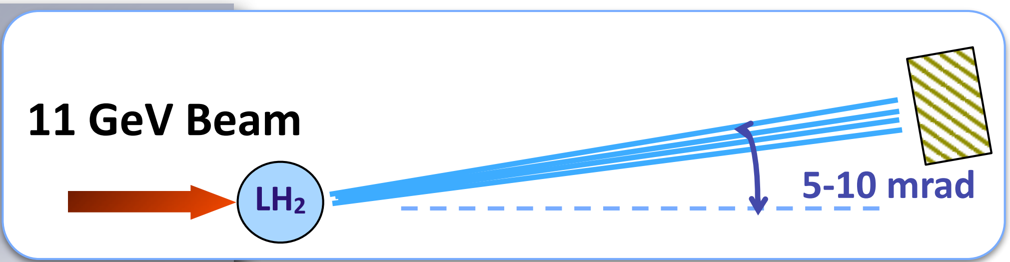


A_{PV} = 35.6 ppb

60 μA 90% polarized

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

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



Parity-violating Møller scattering

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

$$Q^e_W \equiv -2C_{ee} = -(1 - 4\sin^2\theta_W)$$

- Precision goal – 2.4% on electron's weak charge
  - factor of 5 improvement over E158
- 0.1% precision on $\sin^2\theta_W$ at low Q^2 – comparable to best collider determinations
- Sensitive to new neutral current amplitudes at ~ $10^{-3}\, G_F$

$$\Rightarrow \quad \frac{\Lambda}{\sqrt{|g^2_{RR} - g^2_{LL}|}} = 7.5\ \text{TeV}$$

Status:

- 120 collaborators, 30 institutions from US, Canada, Germany
- $20-25M MIE Proposal
- Very positive outcome of Sept. 2014 DOE NP Science Review
- 3-4 years construction
- 3 years running

See K. Kumar talk

P2 at Mainz MESA – Proton Weak Charge

$$\vec{e} + p \rightarrow e' + p \qquad Q_W^p \equiv -2\left[2C_{1u} + C_{1d}\right] = \left(1 - 4\sin^2\theta_W\right)$$

$$A \sim \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

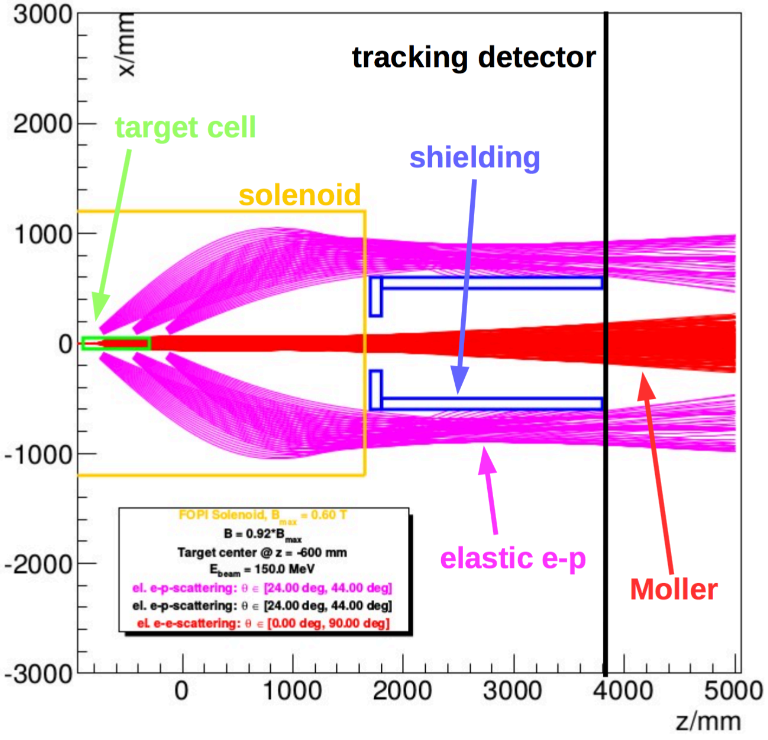
Run at low energy; reduce hadronic contributions and gamma-Z box radiative

- E_{beam} = 155 MeV, 25-45°
- $Q^2 = 0.0049\ \mathrm{GeV}^2$
- 60 cm LH_2 target, 150 µA, 10,000 hours
- Total rate ~ 0.5 THz
- A = - 28 ppb to 1.5%

- **Improve Jlab Qweak's determination of proton weak charge by factor of 2.5**

- **0.13% precision on $\sin^2\theta_W$**

spectrometer concept



FOPI Solenoid, B_{max} = 0.60 T
$B = 0.92{*}B_{max}$
Target center @ z = -600 mm
E_{beam} = 150.0 MeV
el. e-p-scattering: $\theta \in$ [24.00 deg, 44.00 deg]
el. e-p-scattering: $\theta \in$ [24.00 deg, 44.00 deg]
el. e-e-scattering: $\theta \in$ [0.00 deg, 90.00 deg]

Status:

- Collaborators from Germany and US
- Funding approval by DFG
- R&D in progress
- Aim to run from 2017-2020

See D. Becker talk

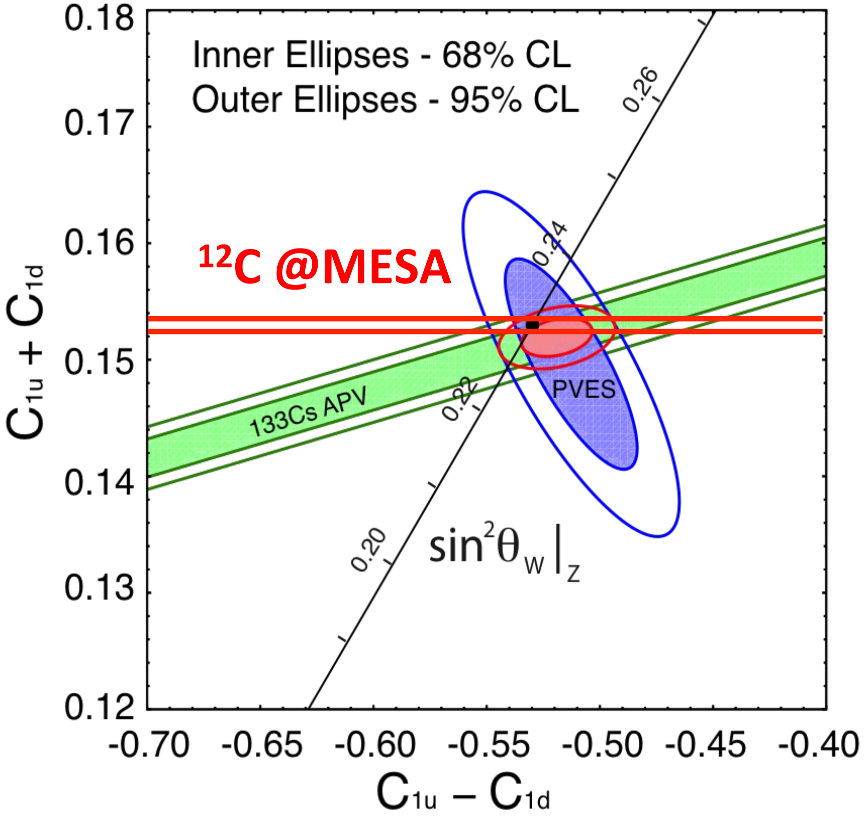
C12 @ P2 MESA – Weak Charge of the ^{12}C Nucleus

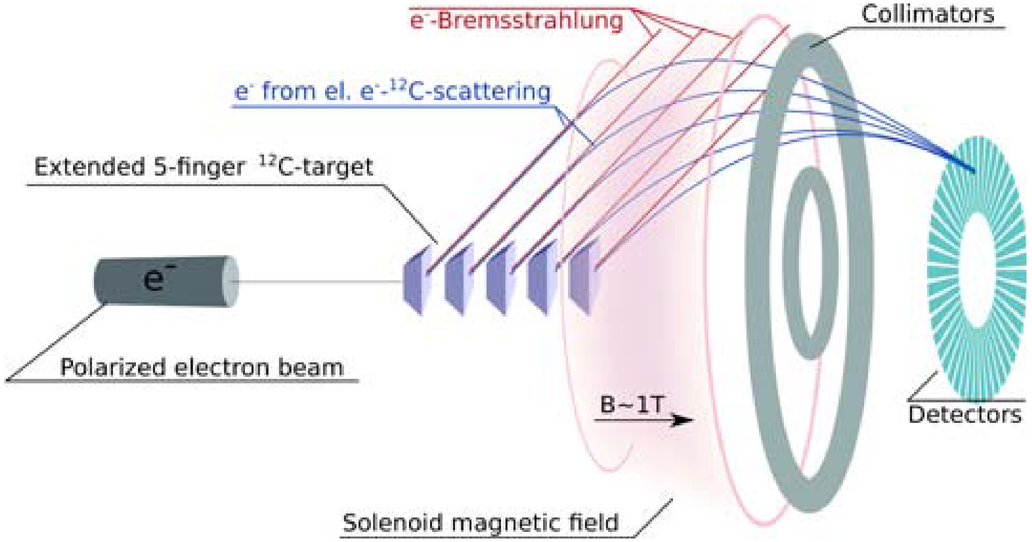
PV Elastic Electron Scattering
on J=0, T= 0 Nucleus:

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} \sin^2\theta_W$$

Bates ^{12}C (Souder, et al.) 1980's
Statistics limited A_{PV} = 1.62 ±0.38±0.05 ppm
$\delta(\sin^2\theta_W)/(\sin^2\theta_W) \sim 24\%$

C12@MESA: K. Gerz, PEB13
$\delta(\sin^2\theta_W)/(\sin^2\theta_W) \sim 0.3\%$
~ factor of 3 better than ^{133}Cs APV;
sensitive to nearly same C_{1u} ,C_{1d} combination

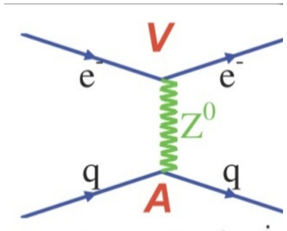




See K. Kumar, P. Souder, O. Moreno talks

SoLID at Jlab: Solenoidal Large Intensity Device

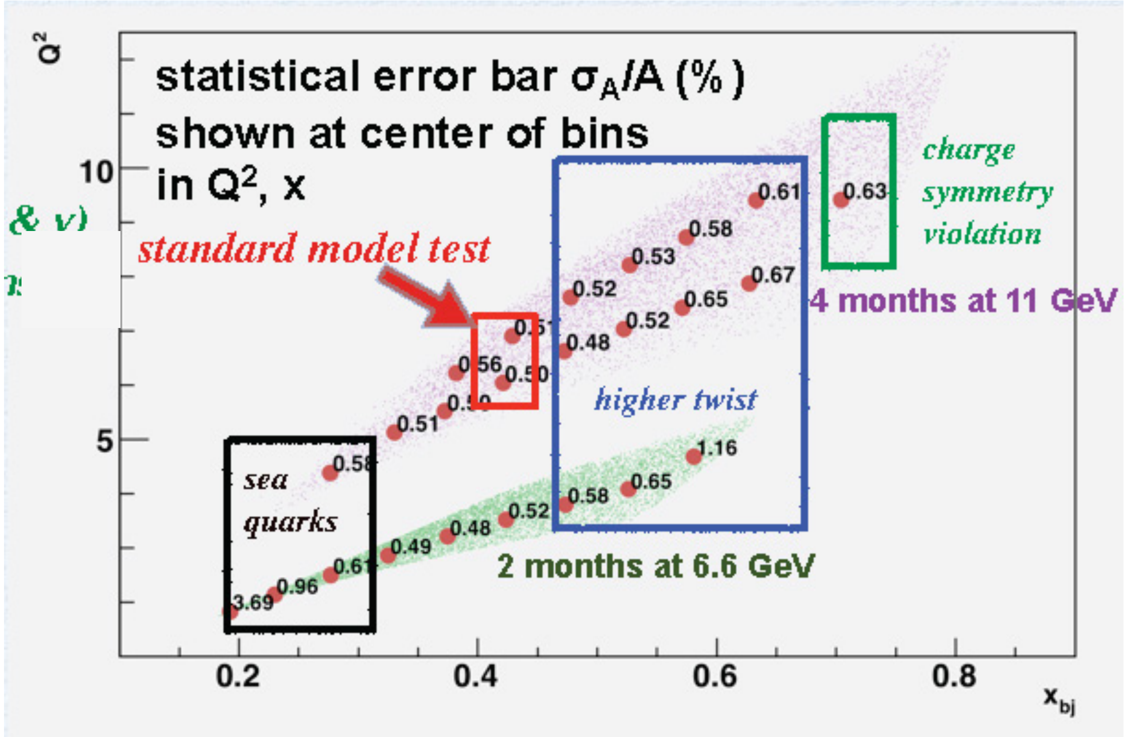
Parity-violating Deep Inelastic Scattering on H and D

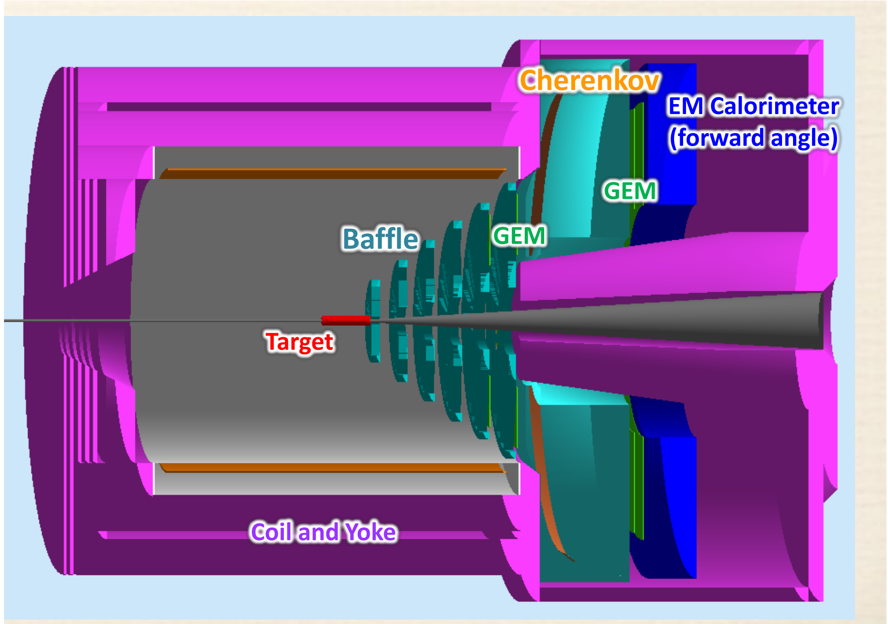


$$C_{2i} \equiv 2 g_V^e g_A^i$$

Strategy: sub-1% precision over broad kinematic range:

- Sensitive Standard Model Test (particulary axial-vector C_{2u} ,C_{2d})
- Detailed study of QCD hadronic structure contributions

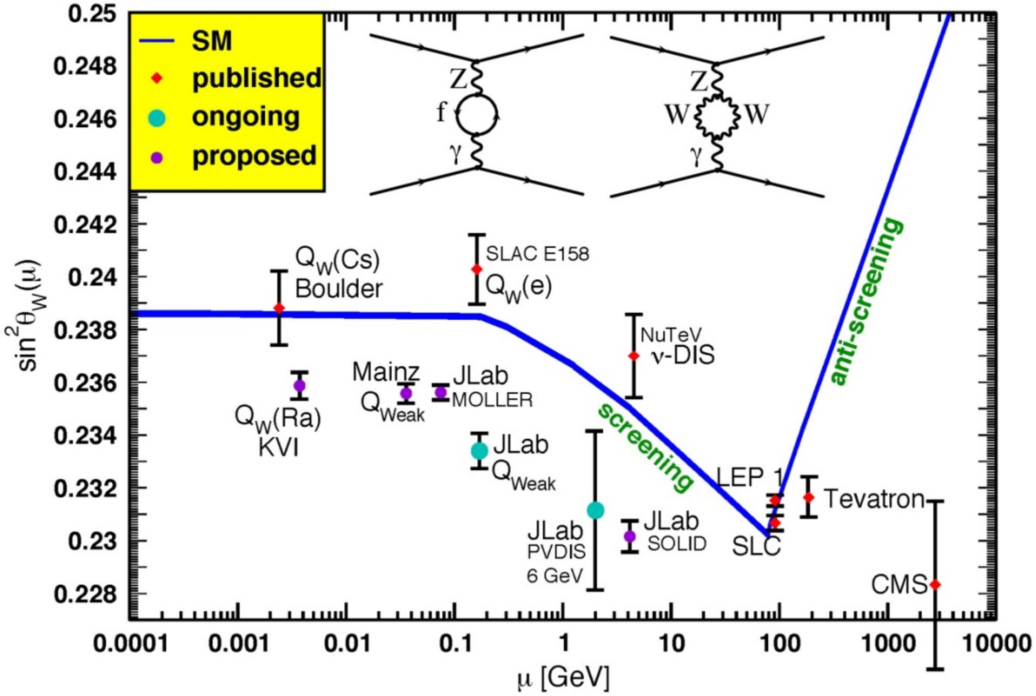


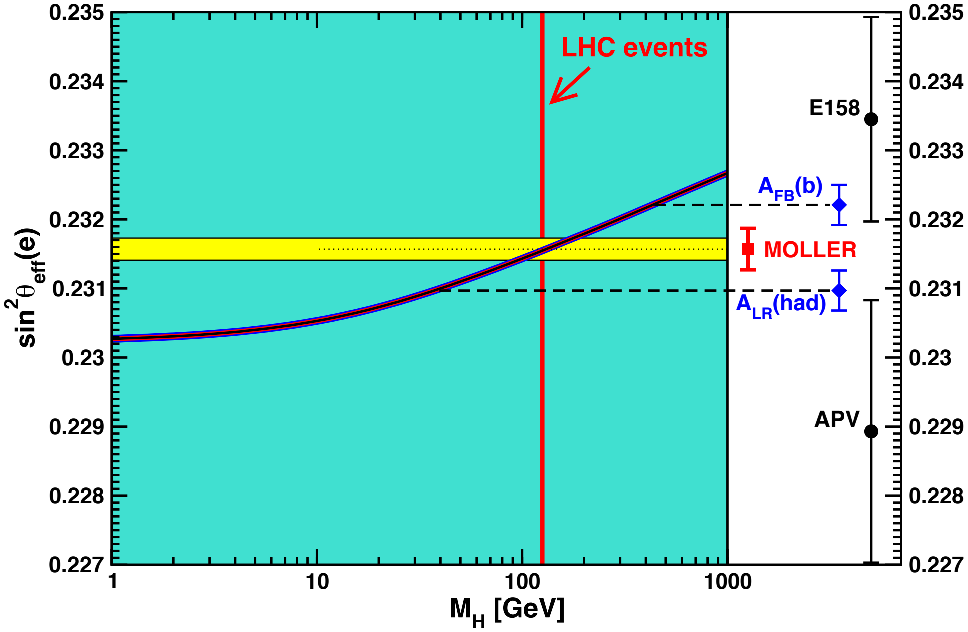


Status:

- Obtaining CLEO solenoid
- Good feedback from Feb. 2015 Director's review

Weak Mixing Angle – $\sin^2\theta_W$ - Future





- Two most precise values of $\sin^2\theta_W$ at Z pole (SLC A_{LR} and LEP A^b_{fb}) disagree by 3σ
- MOLLER goal is $\delta(\sin^2\theta_W) \sim \pm 0.00024\,(\text{stat.}) \pm 0.00013\ (\text{syst.})$
  - comparable sensitivity to these two most precise collider values (±0.00029)
  - precise enough that result will have an impact on the central value of the world average
- **The existing low energy data leave much discovery space for the much more precise future measurements – MOLLER, P2@MESA, C12@MESA, SOLID**

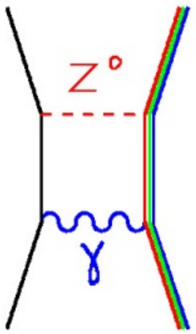
Energy Dependent Electroweak Radiative Corrections

→ For useful Standard Model test all electroweak radiative corrections need to be under good theoretical control

Proton weak charge: $Q_W^p = [1+\Delta\rho+\Delta_e]\left[(1-4\sin^2\theta_W(0))+\Delta_{e'}\right]+\Box_{WW}+\Box_{ZZ}+\Box_{\gamma Z}$

Most significant radiative correction: γ-Z Box Diagram

- significant theory effort in past several years



Authors	Vector Y-Z rad. corr. for Q_W_p
Rislow & Carlson, PRD **83**, 113007 (2011)	0.0057±0.0009
Gorchtein, Horowitz, Ramsey-Musolf, PRC 84, 015502 (2011)	0.0054±0.0020
Hall, Blunden, Melnitchouk, Thomas, Young, arXiv:1504.0397	0.0054±0.0004

See C. Carlson talk

Electron weak charge:

$$Q_W^e = \left\{1-4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\mathrm{MS}}}+\frac{\alpha(m_Z)}{4\pi\hat{s}^2}-\frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2}(1-4\hat{s}^2)[1+(1-4\hat{s}^2)^2]+F_1(y,Q^2)+F_2(y,Q^2)\right\}$$

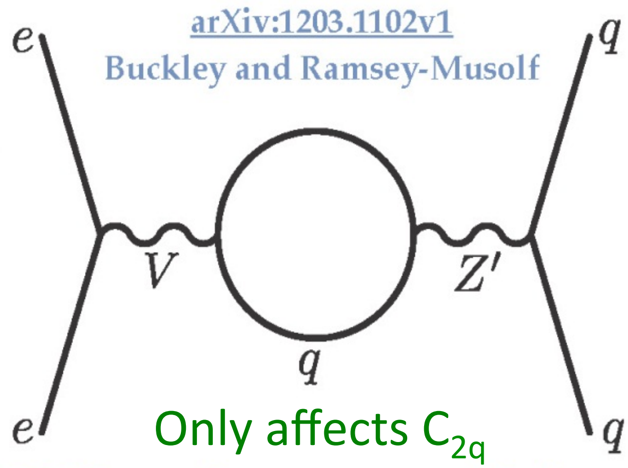
Purely leptonic process; electroweak radiative corrections under control at sub 1% level (1 loop, Czarnecki and Marciano, 2 loop: Aleksejevs, Barkanova)

BSM: Examples of TeV Scale New Physics Reach

Future low energy SM tests are quite complementary to each other in Beyond the Standard Model sensitivities

See K. Kumar talk

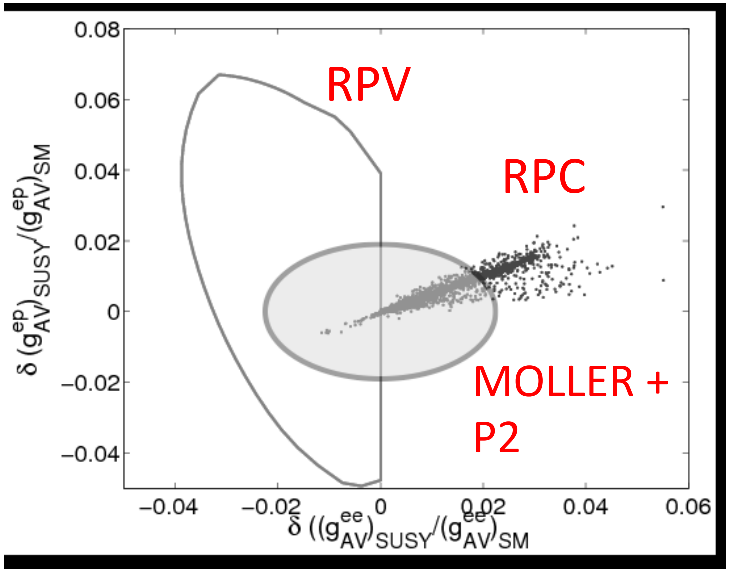
Leptophobic Z'



Only affects C_{2q}

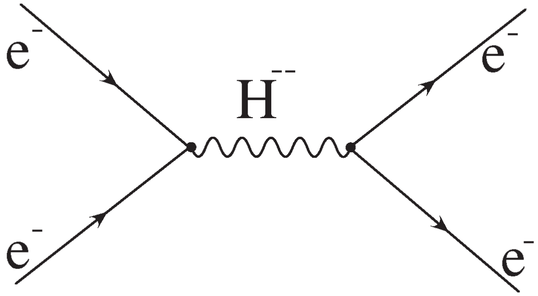
SOLID can improve sensitivity: 100-200 GeV range

RPC and RPV Supersymmetry



Includes LHC constraints;
Erler, Su arXiv: 1303.5522

Doubly Charged Scalars



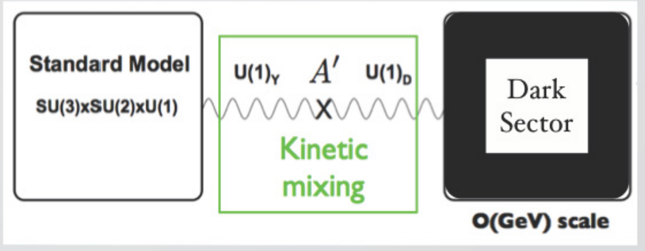
Naturally arise in many extended Higgs sector models; lepton number violating

MOLLER sensitivity: Λ > 5 TeV
(LEP-200 ~ 3 TeV)

BSM: Sensitivity to MeV Scale Mediators

"Dark photon" – possible portal for new force to communicate with SM

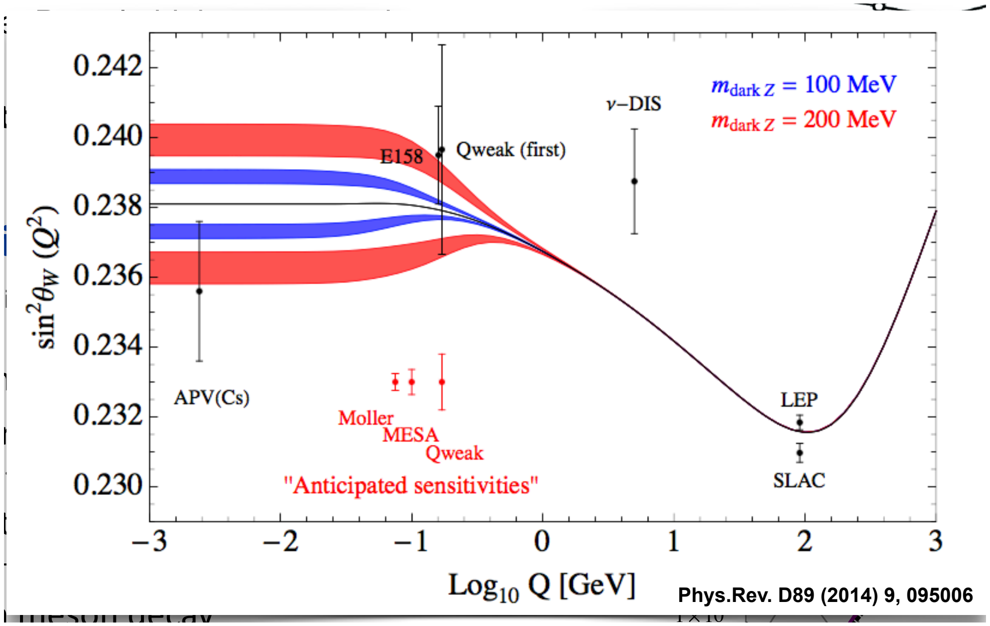
- Astrophysical motivation: observed excess in positron data
- Could explain muon g-2 anomaly



"Dark parity violation"

(Davoudiasl, Lee, Marciano, arXiv 1402.3620)

- Introduces a new source of low energy parity violation through mass mixing between Z and Z_d with observable consequences
- Complementary to direct searches for heavy dark photons
- Example: possible deviations of $\sin^2\theta_W$ for dark photons respecting kaon decay constraints ⟶



Phys.Rev. D89 (2014) 9, 095006

See H. Davoudiasl talk for further details

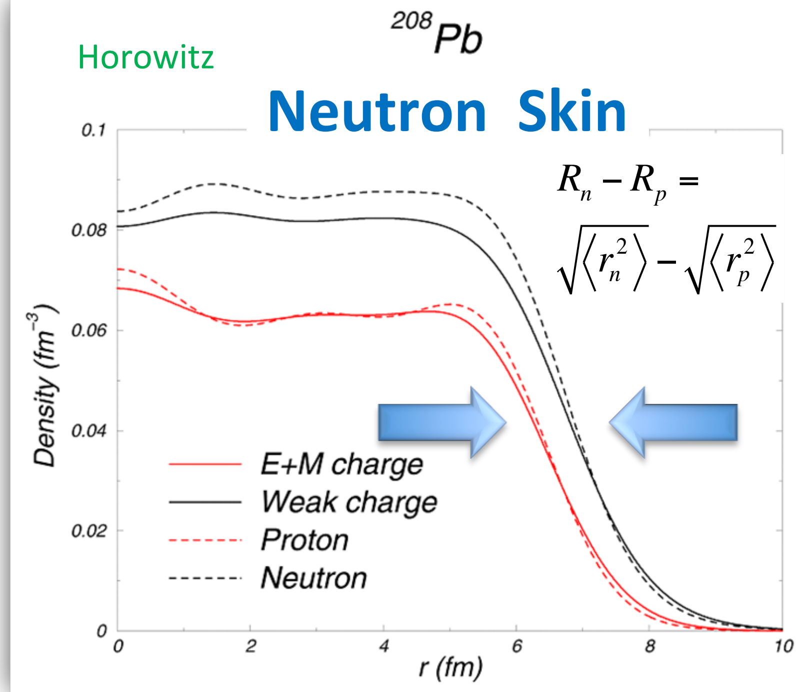
Outline

- Parity-Violating Electron Scattering (PVES): Basics and Brief History

- Physics drivers for PVES – past and future experiments
  - Standard Model tests and beyond Standard Model reach
  - Neutron skin of heavy nuclei
  - Strange form factors

- Outlook and workshop goals for this topic

Neutron Skin of Heavy Nuclei



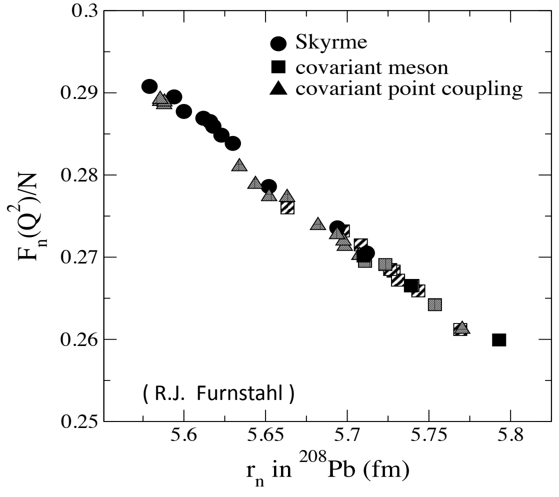
Nuclear theory predicts a neutron "skin" in heavy nuclei

Neutron distribution is not sensitive to the charge-sensitive photon

➔ access through weak charge distribution

	proton	neutron
Electric charge	**1**	**0**
Weak charge	**~0.08**	**1**

The single measurement of F_n translates to a measurement of r_n (via mean-field nuclear models)



For spin 0 nucleus:

$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\frac{F_n(Q^2)}{F_p(Q^2)} \right] \qquad F_{n,p}(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_{n,p}(r)$$

- Measurement of R_n in ^{208}Pb calibrates the equation of state in neutron rich nuclear matter (determines density dependence of symmetry energy)
- Applications to neutron stars, heavy ion physics, atomic parity violation

PREX and CREX at Jefferson Lab

Hall A at Jefferson Lab PV eN elastic

- PREX: ^{208}Pb
  - uniform nuclear matter, neutron star structure
- CREX: ^{48}Ca
  - finite size effects, within reach of microscopic calculations

Q^2 ~ 0.01 GeV^2 → **A_{PV} ~ 0.6 ppm**

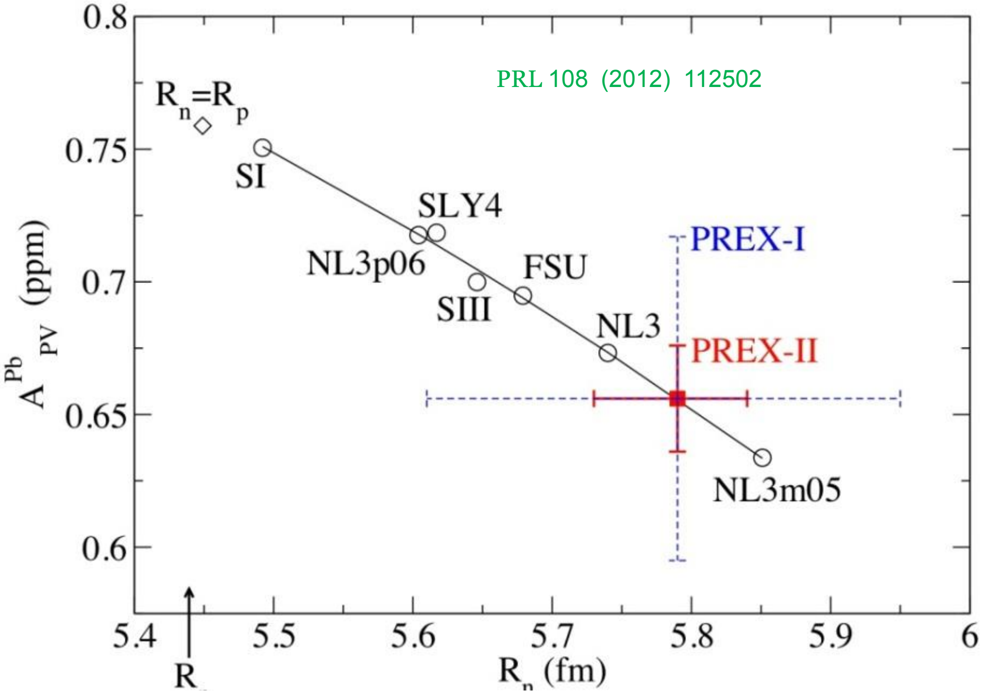
5° scattering angle **Rate ~1.5 GHz**

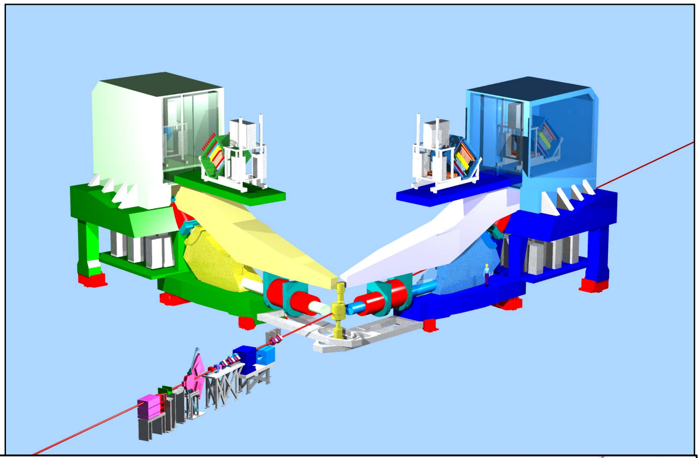
- **0.5 mm ^{208}Pb foil, 70 μA**
- **5° scattering**
- **P_b~ 90% +/- 1%**

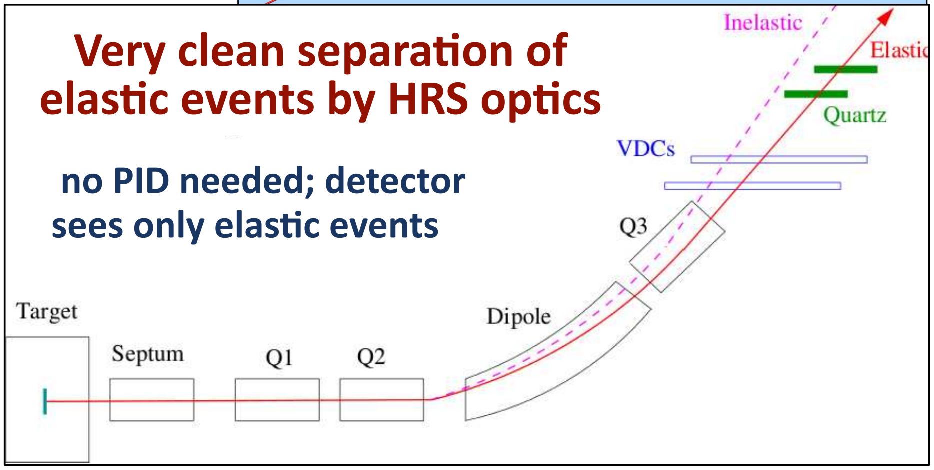
Asymmetry leads to R_N

PREX-I has established a neutron at ~95 % CL

Neutron Skin = R_N - R_P = 0.33 + 0.16 - 0.18 fm







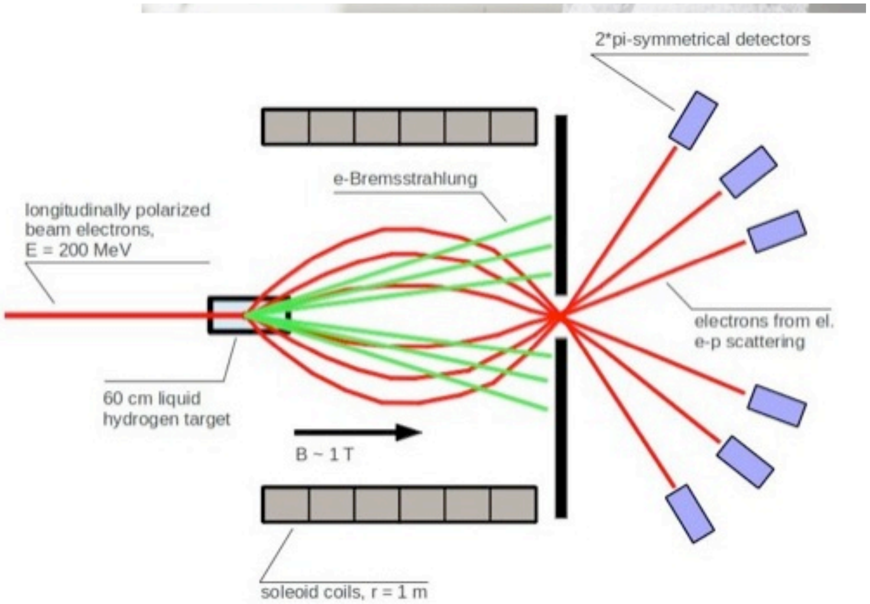
Very clean separation of elastic events by HRS optics

no PID needed; detector sees only elastic events

Summer 2017: PREX (3% A_{PV}, r_n to 0.06 fm), CREX (2.5% A_{PV}, r_n to 0.02 fm)

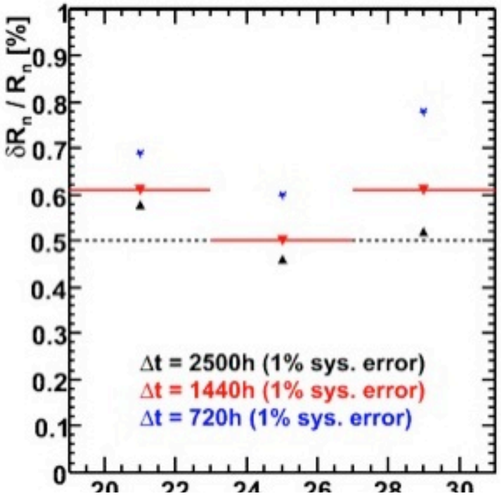
^{208}Pb at Mainz MESA

C. Sfienti, PEB13, PAVI14



E ~ 200 MeV

Both far and near detector setups in P2 solenoidal spectrometer give needed separation from ^{208}Pb first excited state



Same PREX Luminosity (0.25mm ^{208}Pb)

$\Delta\theta = 4^{\circ}$: Rate=9.75 GHz, $A_{PV} = 0.68 \times 10^{-6}$

1440h → $\delta A_{PV}/A_{PV} = 6.52 \times 10^{-3}$

→ $\delta R_n/R_n = 5.04 \times 10^{-3}$

(stat + syst 1%)

See C. Horowitz talk for more ideas for Nuclear Weak Form Factors at low energies

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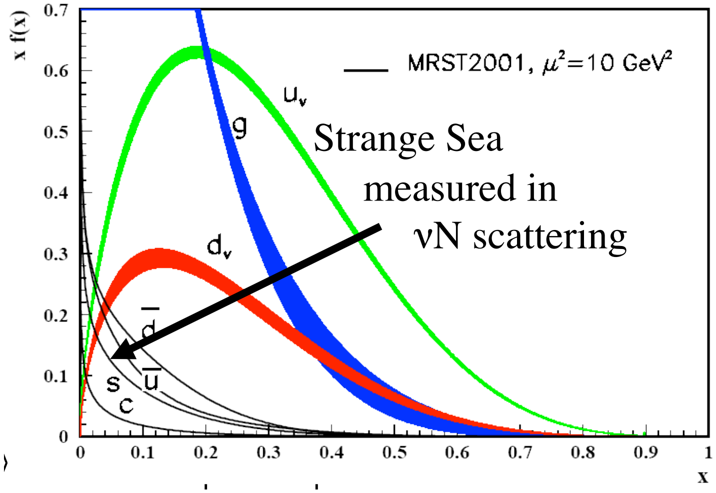
  - Strange form factors

- Outlook and workshop goals for this topic

Strange Form Factors

Strange quark sea contributes to nucleon momentum.

$$\int_0^1 x[s(x)+\bar{s}(x)]dx \sim 4\%$$



Strange Sea measured in νN scattering

Question from late 1980's:

How does it contribute to other nucleon properties?

mass, spin, electromagnetic form factors…

Parity violation in elastic e-p (and e-d, e -^{4}He)

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

$$\begin{aligned} A_E &= \varepsilon(\theta) G_E^Z(Q^2) G_E^\gamma(Q^2) \\ A_M &= \tau(Q^2) G_M^Z(Q^2) G_M^\gamma(Q^2) \\ A_A &= -(1-4\sin^2\theta_W)\varepsilon' G_A^e(Q^2) G_M^\gamma(Q^2) \end{aligned}$$

"Rosenbluth"-like separation to determine neutral weak form factors

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

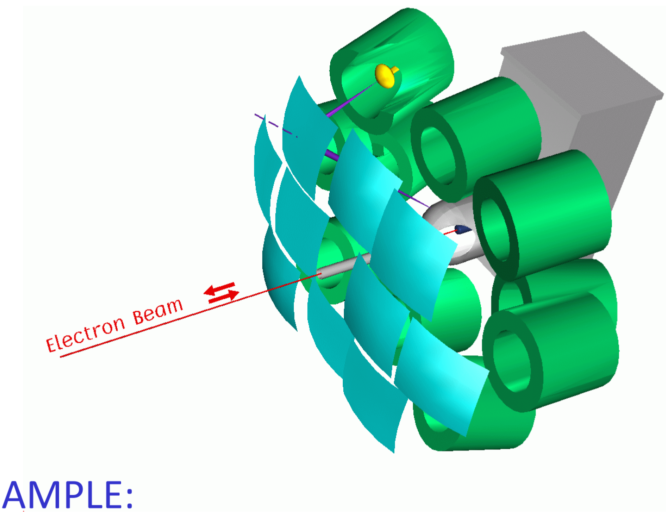
Obtain "strange" form factors:

$G_E^s(Q^2)$ Strange electric form factor: $s\bar{s}$ contribution to nucleon's spatial charge distribution

$G_M^s(Q^2)$ Strange magnetic form factor: $s\bar{s}$ contribution to nucleon's spatial magnetization distribution

Strange Form Factors – Worldwide Program

1992 – 2011: Worldwide program on strange form factors measured with PVES



SAMPLE:

Location: MIT-Bates

Targets: p,d

Kinematics: backward angle, Q^2 = .038,.10 GeV^2

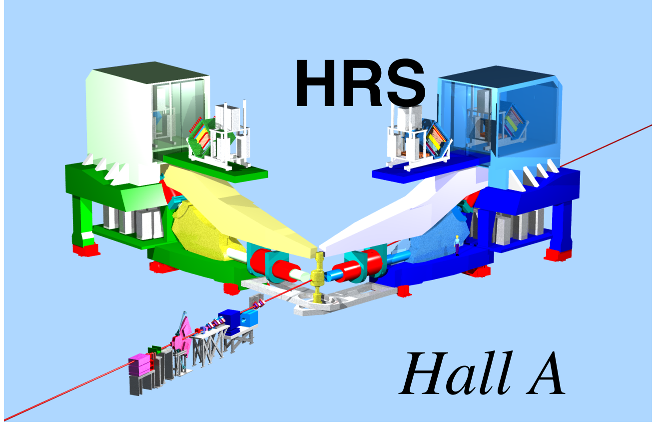
Mainz PV-A4:

Location: Mainz MAMI microtron

Targets: p,d

Kinematics: forward & backward angles

Q^2 = .11, .23, .62 GeV^2

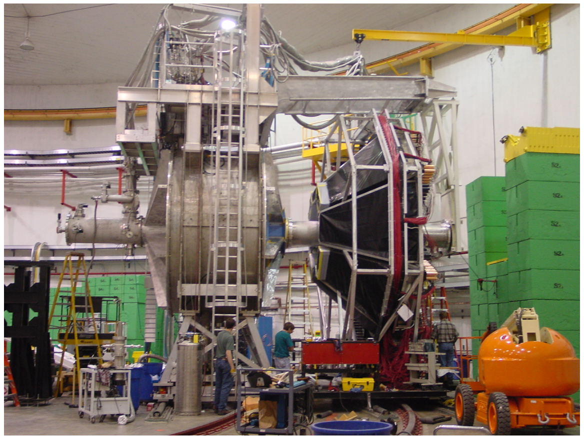


HAPPEx I, II, III:

Location: Jefferson Lab Hall A

Targets: p, ^{4}He

Kinematics: forward angle, Q^2 = .10,.48, .62 GeV^2



G^0:

Location: Jefferson Lab Hall C

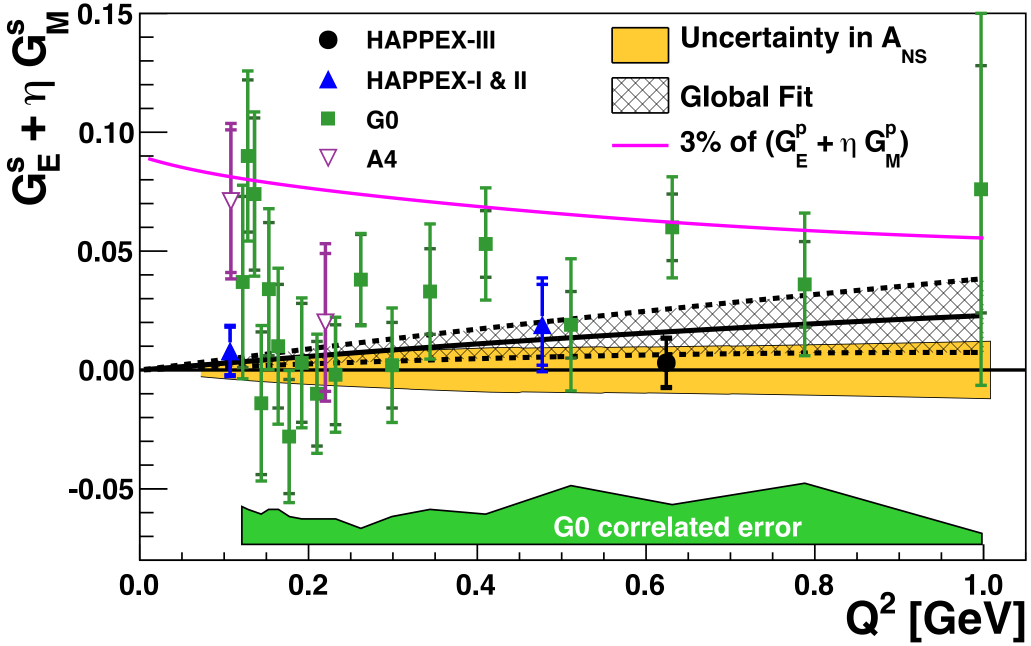
Targets: p, d

Kinematics: forward & backward angles

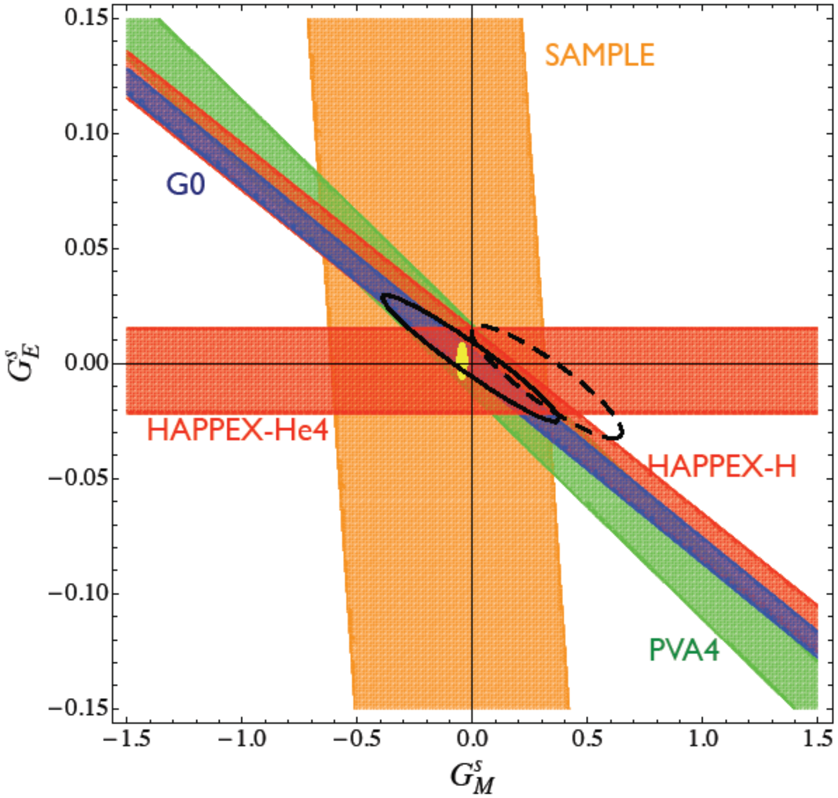
Q^2 = .1 – 1 GeV^2

Strange Form Factors – current situation

Worldwide forward angle results



Strange form factor separation at $Q^2 = 0.1$ GeV^2



Global fits:

- R.D. Young, *et al*. PRL **97**, 10200 (2006) ———
- J. Liu, *et al*. PRC **76**, 025202 (2007) -------

Lattice: D. Leinweber *et al*. PRL **94**, 212001 (2005) ●
D. Leinweber *et al*. PRL **97**, 022001 (2006)

Conclusion: Strange quark sea contributions to proton form factors are consistent with zero and not more than a few percent of the overall proton electromagnetic form factors.

Strange Form Factors – Measurements at Low Energy?

Are further strange form factor measurements warranted?

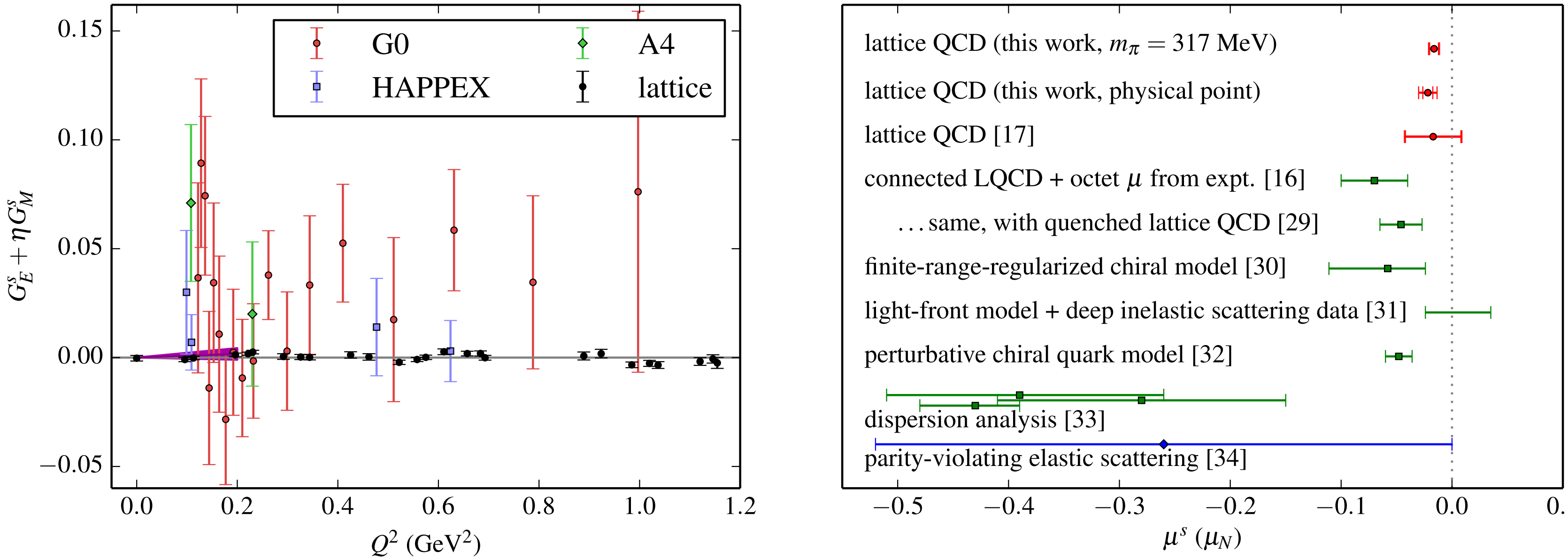
State-of-the-art lattice QCD calculations set the scale of what is interesting.

Recent lattice predictions for the strange magnetic moment:

$$G_M^s\ (Q^2=0) \equiv \mu_s = -0.07 \pm 0.03\ \mu_N$$ Green, *et al.*, arXiv:1505.01803

$$G_M^s\ (Q^2=0) \equiv \mu_s = -0.022 \pm 0.004 \pm 0.004 \pm 0.006\ \mu_N$$ Shanahan, *et al.*, PRL **114**, 091802 (2015)

Shanahan, *et al.*, PRL **114**, 091802 (2015)



Possible backangle measurements at low energies?

- ”A4 style” fast calorimeter during P2, θ ~ 140 – 150°, 150 MeV, 150 µA, 60 cm LH/D_2 targets, 1000 hours each ➔ $\delta G^s_M \sim \pm 0.05\ \mu_N$ (Baunack, PEB2013)
- “SAMPLE” style air Cerenkov, θ ~ 130 – 170°, not yet estimated

See K. Kumar talk for possibilities for strange radius at low energies

Summary

- Parity-violating electron scattering has proven to be an important tool
  - Provides stringent low energy tests of the Standard Model
  - Addresses nuclear/nucleon structure issues: strange form factors and neutron "skin"

- Workshop parameters: E < 500 MeV; appear to be many interesting prospects and maybe we will hear more at this workshop
  - Standard Model tests: Proton weak charge P2@MESA, C12 weak charge (12C@MESA) – nicely complementary to MOLLER and SOLID
  - Neutron skin: perhaps availability of a dedicated low energy machine makes it possible to measure nuclear weak form factors for a series of nuclei
  - Strange form factors: perhaps newly designed experiments could probe strange form factors at the level of precision suggested by lattice QCD