

Precision Electroweak Physics Using Parity Violation in Electron Scattering

Measurements of $\sin^2\theta_W$



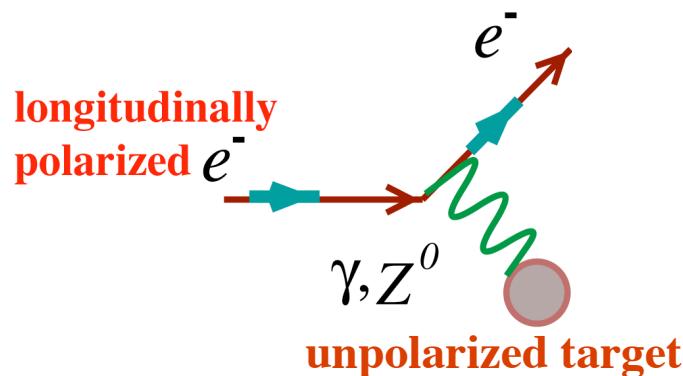
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 UNIVERSITY of VIRGINIA

Parity-Violating Electron Scattering

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

EDM, $g_\mu - 2$, weak decays, β decay, $0\nu\beta\beta$ decay, DM, LFV...

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



$$\begin{aligned}\sigma &\propto |A_\gamma + A_{\text{weak}}|^2 \\ &\sim |A_\gamma|^2 + 2A_\gamma(A_{\text{weak}})^* + \dots\end{aligned}$$

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

Many new physics models give rise to new neutral current interactions

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

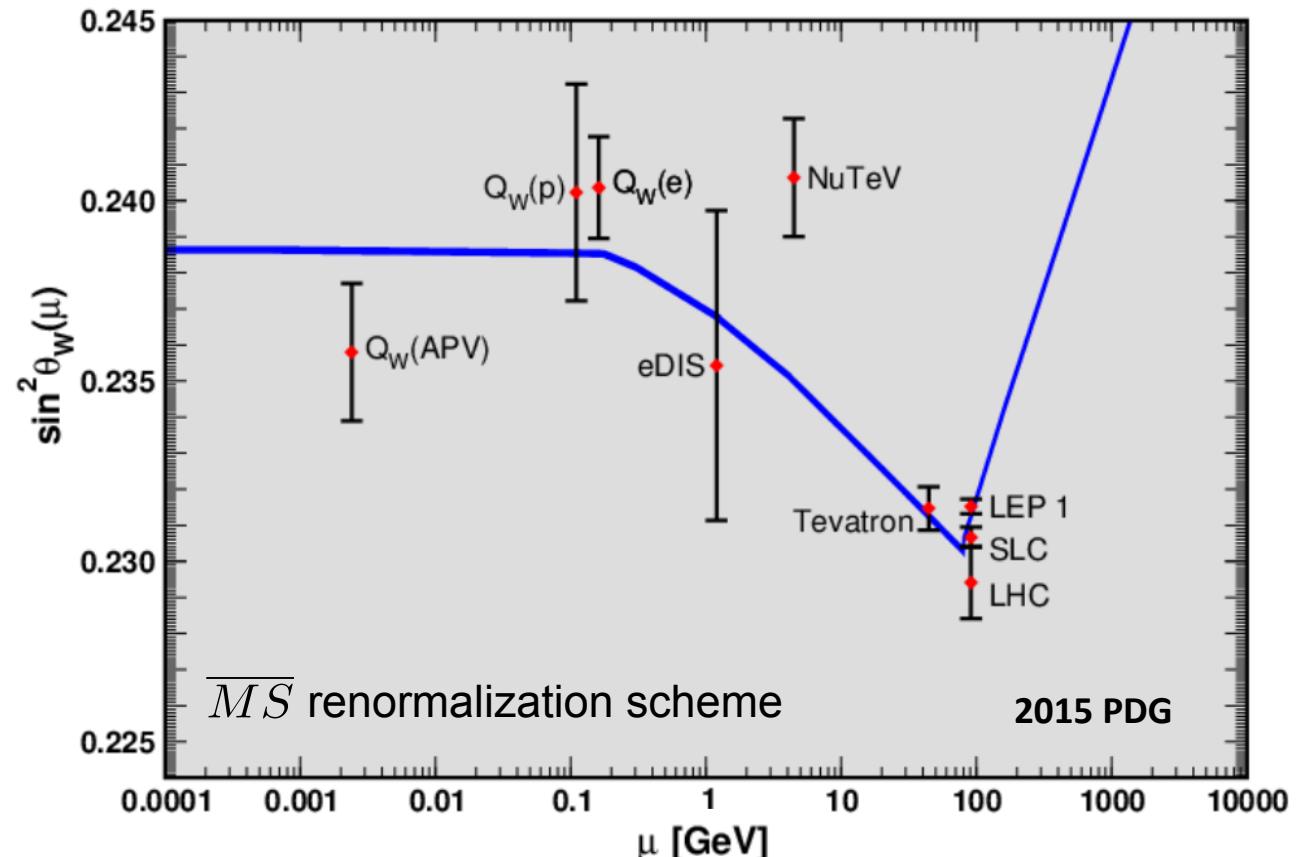
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{new}}$$

$$\left| A_\gamma + A_Z + A_{\text{new}} \right|^2 \rightarrow A_\gamma^2 \left[1 + 2 \left(\frac{A_Z}{A_\gamma} \right) + 2 \left(\frac{A_{\text{new}}}{A_\gamma} \right) \right]$$

Weak neutral current charge and $\sin^2 \theta_W$

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

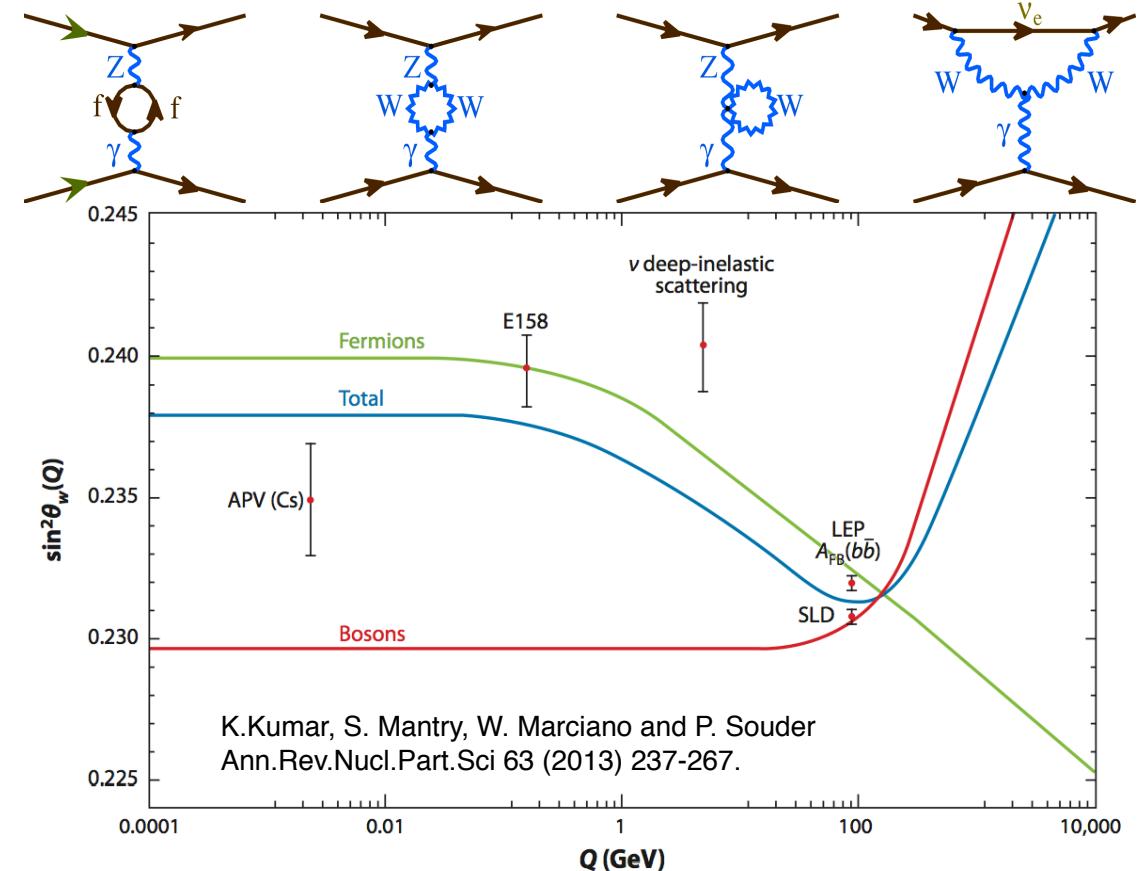
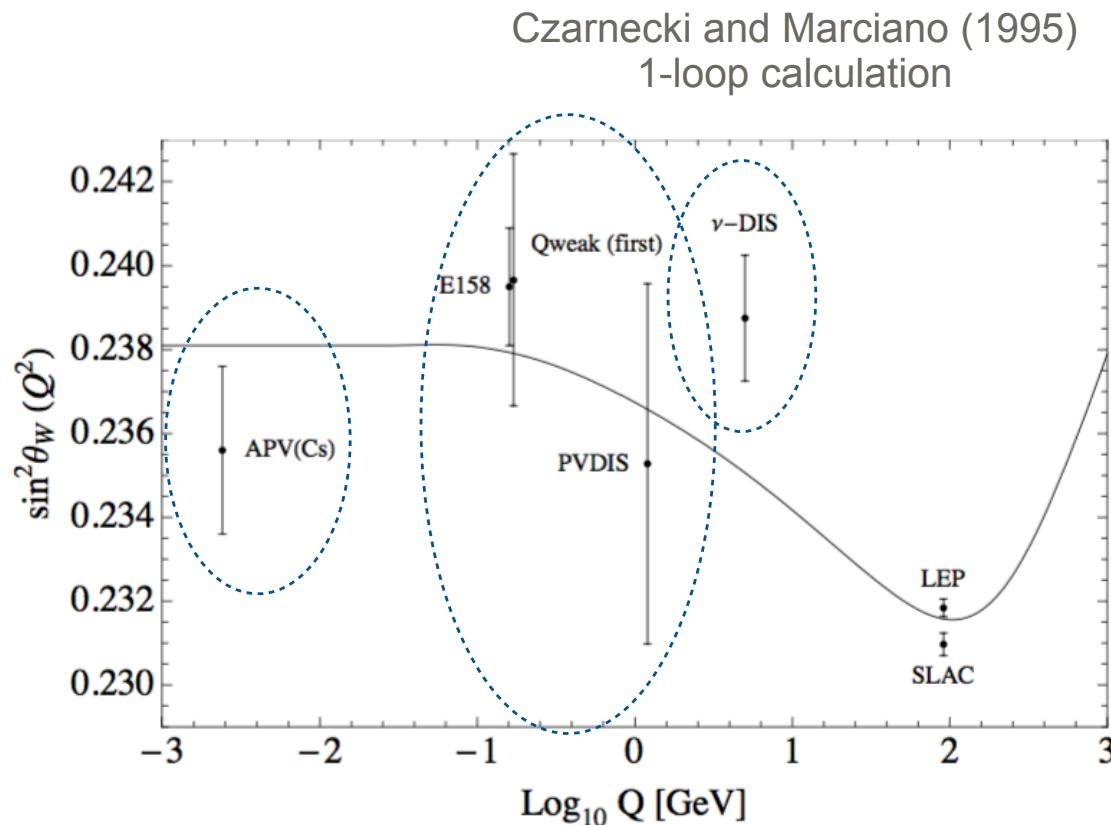
	EM Charge	WNC Vector Charge
u	$+\frac{2}{3}$	$1 - \frac{8}{3} \sin^2 \theta_W$
d	$-\frac{1}{3}$	$-1 + \frac{4}{3} \sin^2 \theta_W$
$p = 2u + d$	$+1$	$1 - 4 \sin^2 \theta_W$
$n = u + 2d$	0	-1
e	-1	$-(1 - 4 \sin^2 \theta_W)$



$$Q_W^p = 1 - 4 \sin^2 \theta_W \quad \sin^2 \theta_W \sim \frac{1}{4}$$

so Q_W^p and Q_W^e are strongly suppressed

Running of $\sin^2\theta_W$



- **Atomic Parity Violation (^{133}Cs)**
Theory challenging (atomic)
- **Neutrino DIS**
Controversial interpretation (QCD)

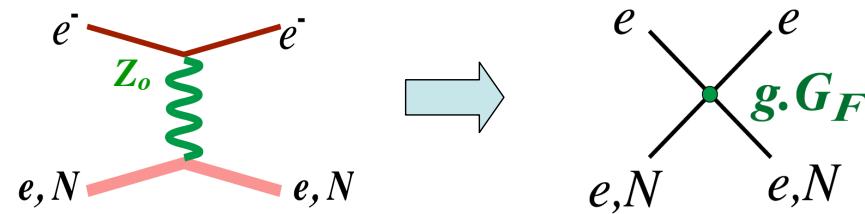
- **e-e & e-p PV Elastic Scattering**
statistics limited, theory robust
- **e-D PV-DIS**
axial-vector quark coupling

PVeS at low energies provides
a method for searching for
new neutral currents

Search for new neutral current contact interactions

Low energy WNC interactions ($Q^2 \ll M_Z^2$)

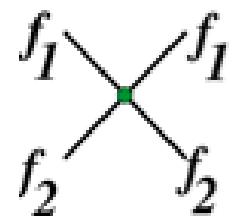
Heavy mediators = contact interactions



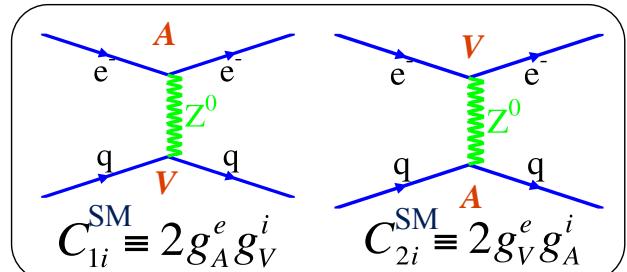
Consider $f_1 f_1 \rightarrow f_2 f_2$ or $f_1 f_2 \rightarrow f_1 f_2$

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

Eichten, Lane and Peskin, PRL50 (1983)
mass scale Λ , coupling g
for each fermion and handedness combination



Example:
Standard model
 $e\text{-}q$ or $e\text{-}e$
couplings



Conventional “mass limits” for new contact interaction:
assume coupling with compositeness scale $g^2=4\pi$.

precision measurement to test for new possible couplings

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

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

example: 4% measurement of $Q_W^p = 2C_{1u} + C_{1d}$
corresponds to a mass limit of 33 TeV

Erler et al., Ann.Rev.Nucl.Part.Sci. 64 (2014)

Can there be light new physics?

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

Hypothesis could explain $(g-2)_\mu$ discrepancy, 511keV line in galactic core, Pamela high energy positron excess

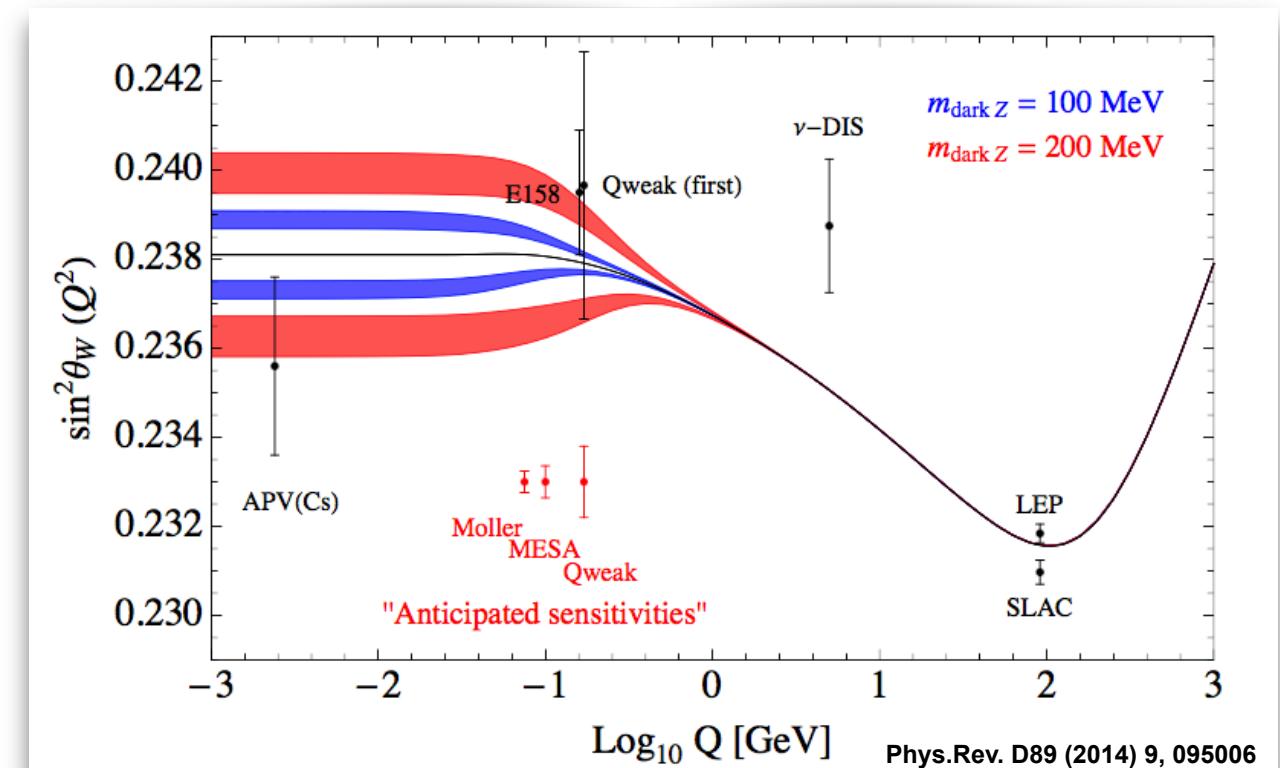
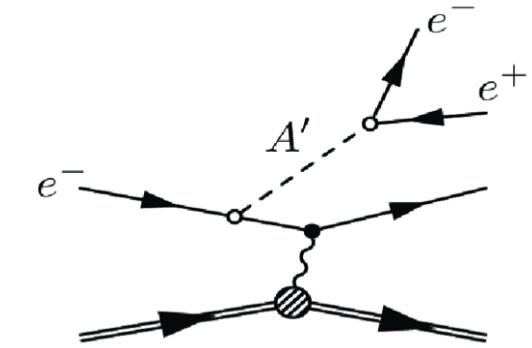
But what if the dark Z_d^0 had no couplings at all to the 3 known generations of matter?

Beyond kinetic mixing: introduce mass mixing with Z^0

$$M_0^2 = m_Z^2 \begin{pmatrix} 1 & -\varepsilon_Z \\ -\varepsilon_Z & m_{Z_d}^2/m_Z^2 \end{pmatrix}$$

$$\varepsilon_Z = \frac{m_{Z_d}}{m_Z} \delta$$

Requires $\delta < \sim 10^{-3}$ to have remained hidden at the Z-pole and in meson decay

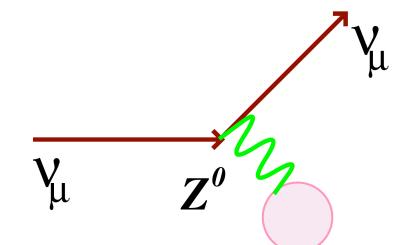


Complementary to direct heavy photon searches:
Lifetime/branching ratio/decay-mode model
dependence vs mass mixing assumption

Davoudiasl, Lee, Marciano
Phys. Rev. Lett. 109 (2012) 031802
Phys. Rev. D85 (2012) 115019
Phys. Rev. D89 (2014) 9, 095006
Phys. Rev. D92 (2015) 5, 055005

Weak Neutral Current Interactions

- 1950s: discovery of parity violation
- 1960s: An Electroweak Model of Leptons (and quarks)
 - $SU(2)_L \times U(1)_Y$ theory predicted the Z boson, introduced $\sin^2\theta_W$
- 1973: antineutrino-electron scattering
 - First weak neutral current observation at Gargamelle
- Mid-70s: Does the Weak Neutral Current interfere with the Electromagnetic Current?
 - Central to establishing $SU(2)_L \times U(1)_Y$

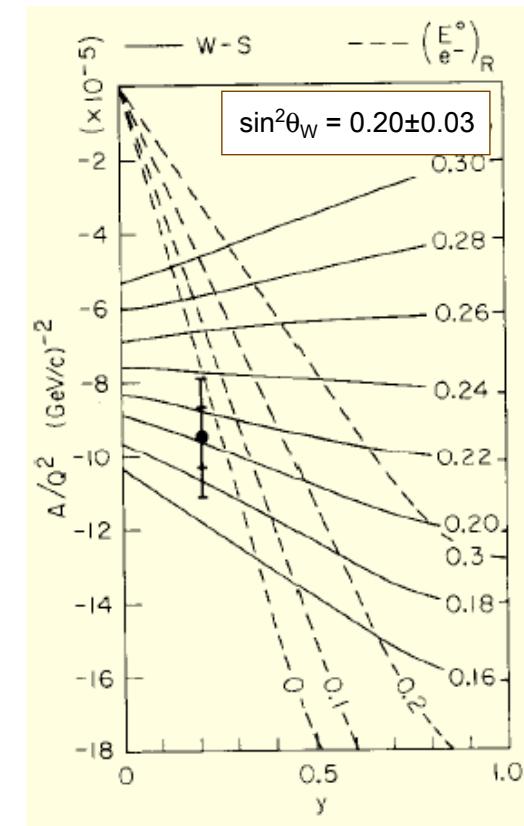


SLAC E122 (1978): First measurement of PV in electron scattering

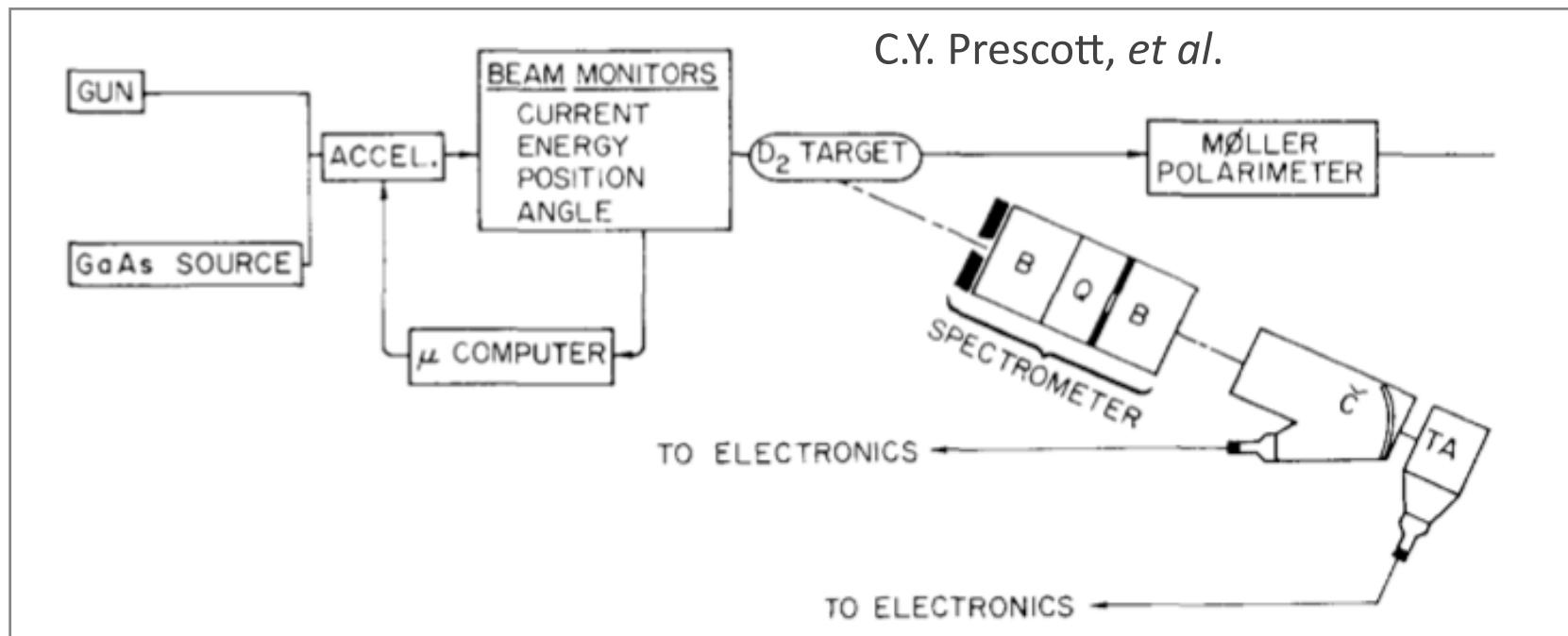
Parity Non-Conservation in Inelastic Electron Scattering, C.Y. Prescott et. al, 1978

- Showed electrons coupled to WNC
- Observed parity violation in WNC interactions
- $\sin^2\theta_W = 0.224 \pm 0.020$: consistent with neutrino scattering
- Central to establishing $SU(2)_L \times U(1)_Y$

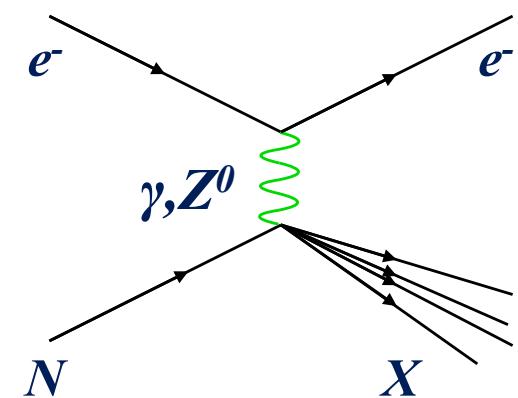
*Glashow, Weinberg, Salam Nobel
Prize awarded in 1979*



E122 at SLAC (1978)

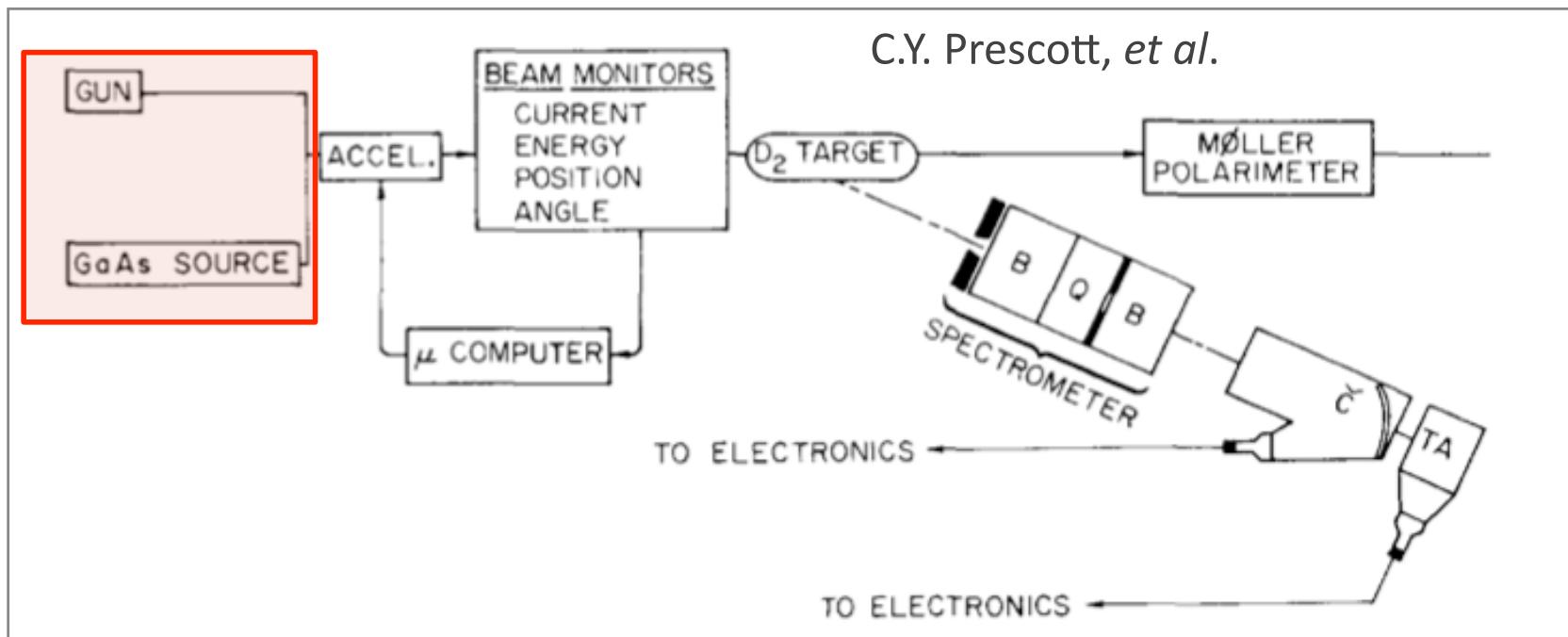


A_{PV} in Deep Inelastic Scattering from liquid Deuterium $Q^2 \sim 1 \text{ GeV}^2$

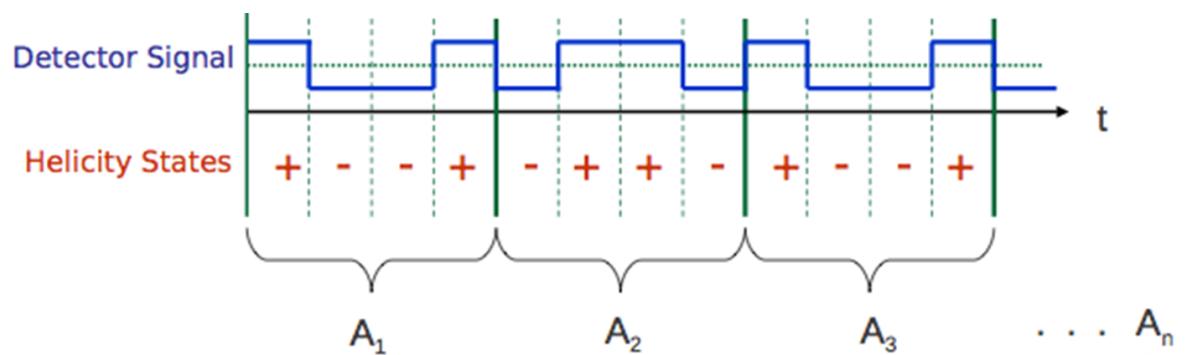


Inclusive measurement
detect scattered electron only

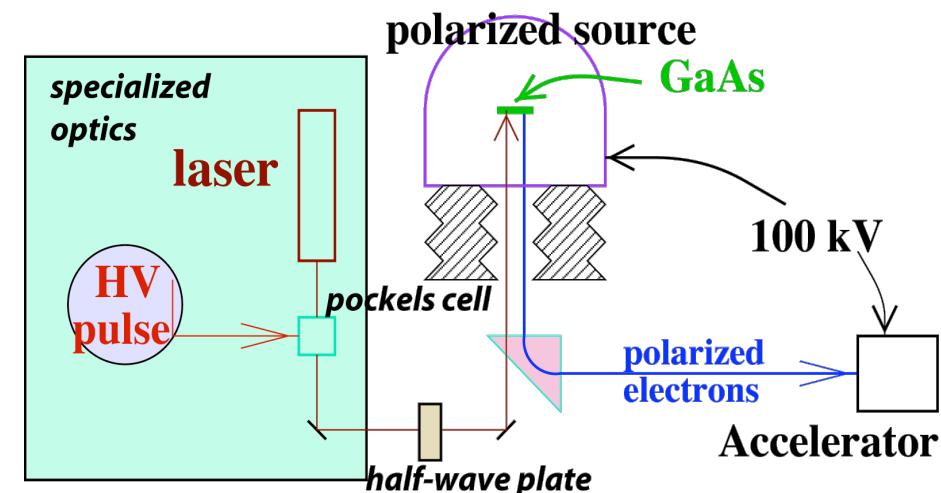
E122 at SLAC (1978)



- Rapid helicity-flip change sign of e^- polarization
 - electro-optic Pockels cell in laser optics
 - NOW: up to 1kHz measurement over helicity reversal

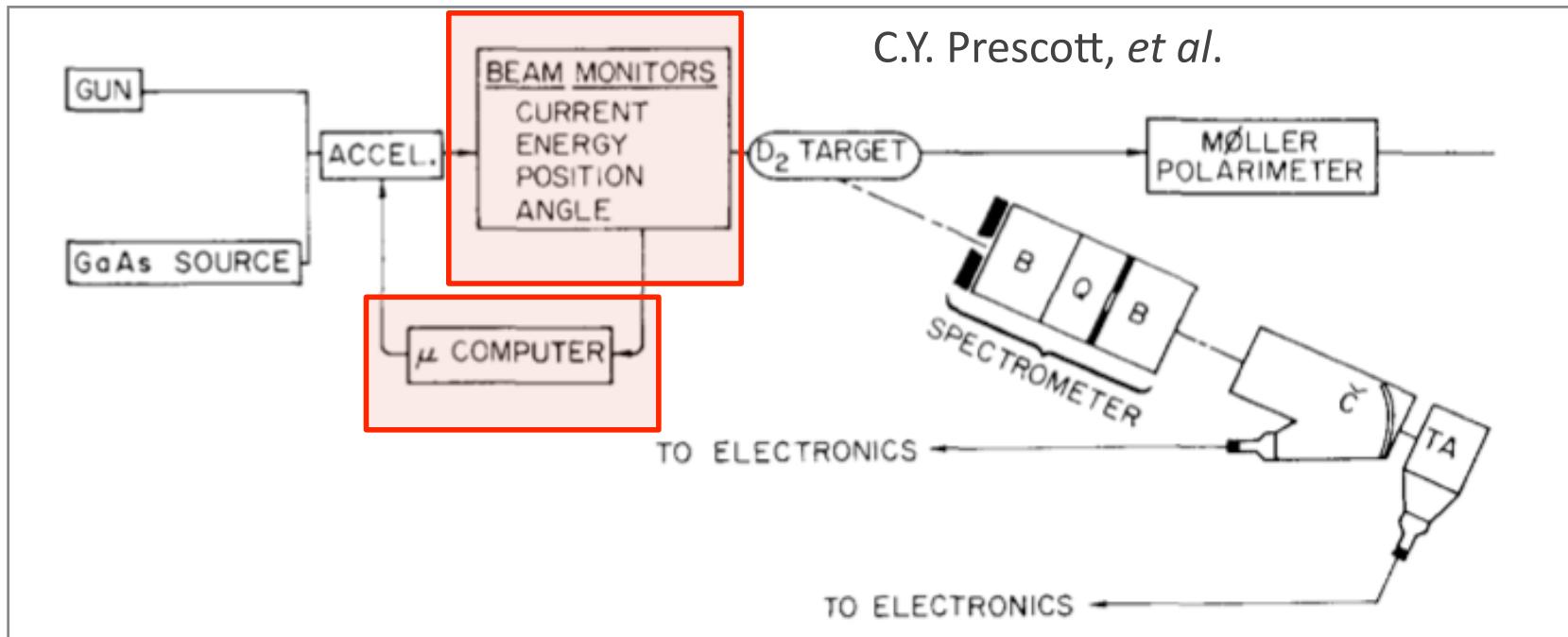


- High polarized luminosity from photoemission from NEA GaAs cathode
 - First developed for E122
 - NOW: superlattice cathodes for ~90% polarization, high QE and lifetime



- Helicity-correlated beam asymmetries
 - NOW: $A_Q \sim \text{few ppb}$, $\Delta x \sim 1\text{nm}$
 - both precision configuration and feedback

E122 at SLAC (1978)



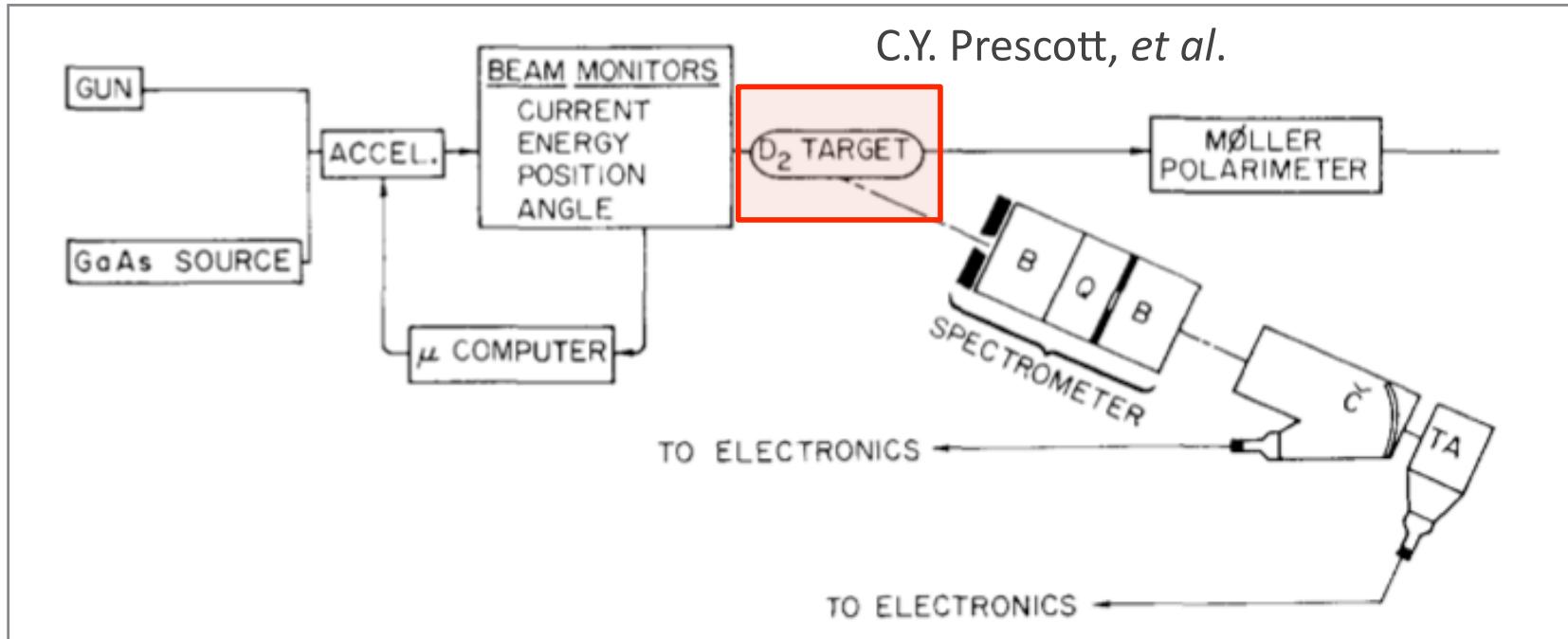
- **Beam Monitors**

- Measure helicity-dependent changes in current and position
- NOW: usually RF antenna or RF resonant cavity
- Precision Q ~ 30 ppm , x ~ 1 micron at 250 Hz

- **Fast Analysis**

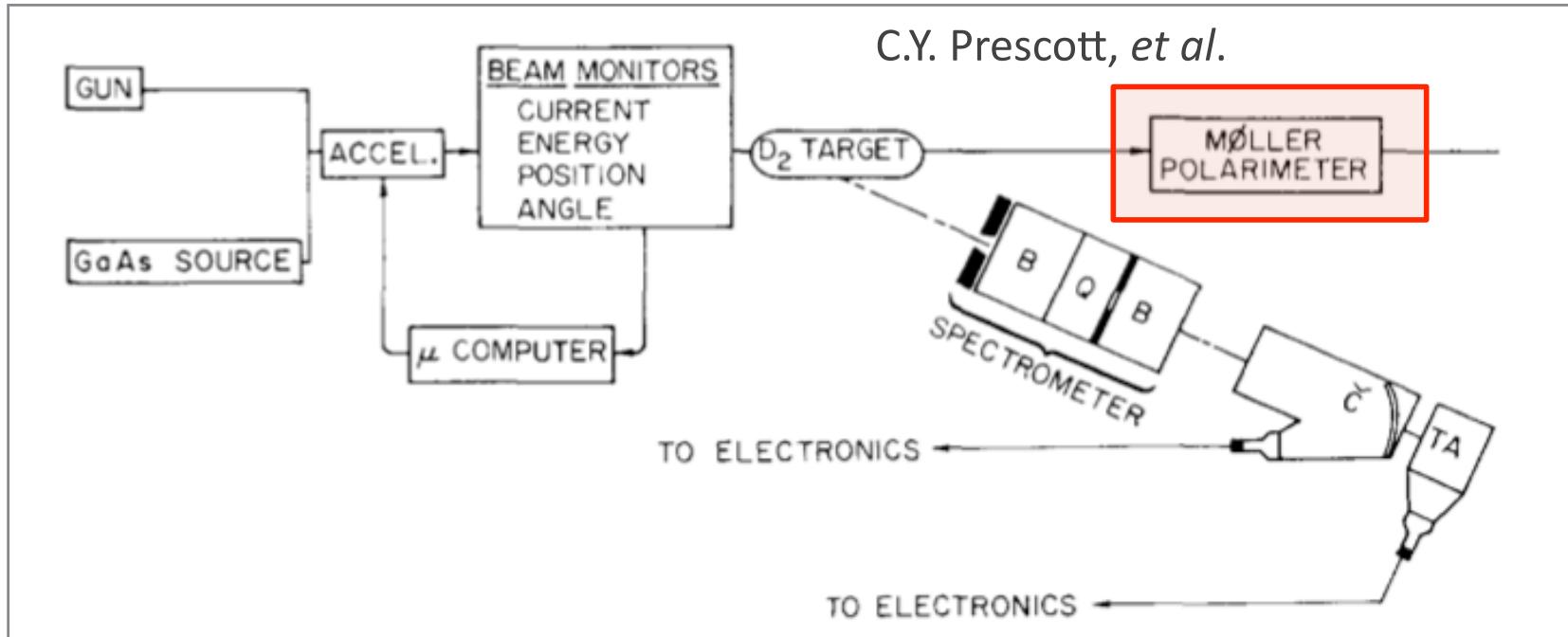
- Feedback to source to control beam asymmetries

E122 at SLAC (1978)



- **High-Power Cryogenic Target**
 - 30 cm long for high luminosity
 - NOW: power >2300 W, stability better than 40 ppm at 250 Hz
 - FUTURE: 1.5 meters, 4 kW, stability better than 25 ppm at 1kHz

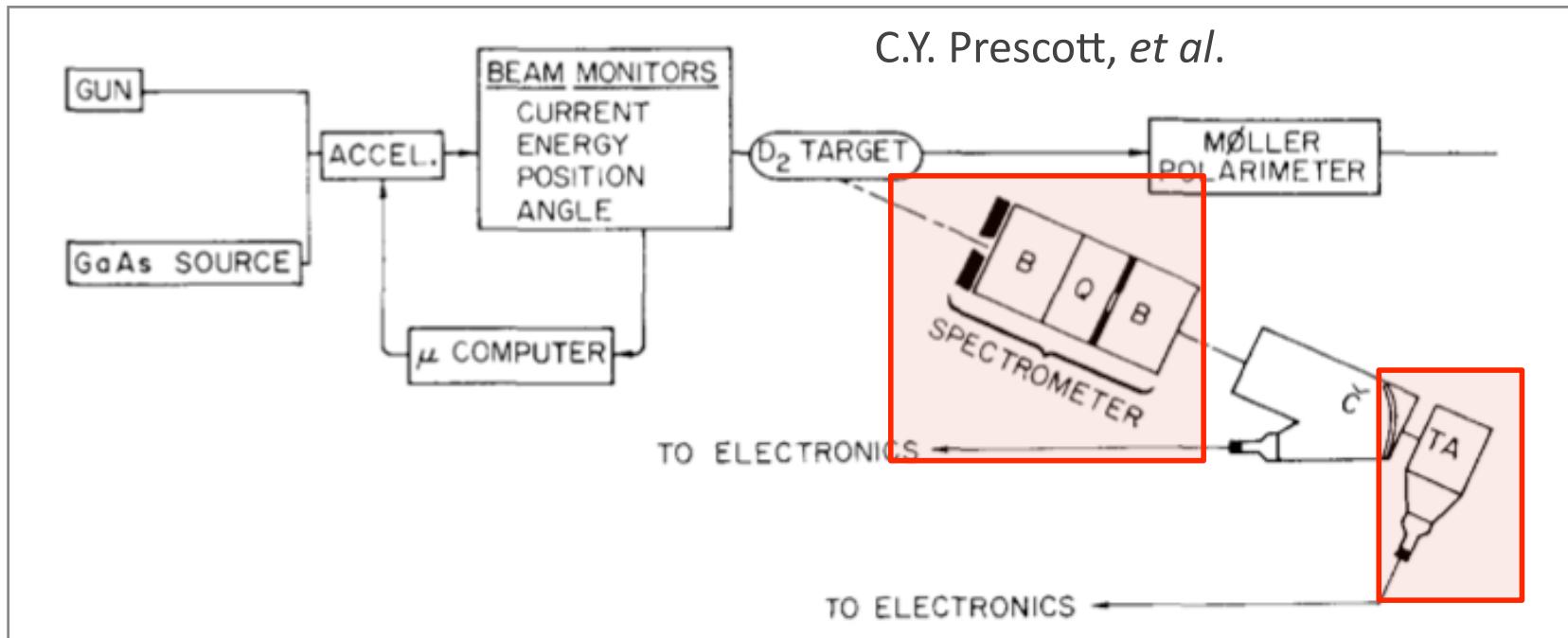
E122 at SLAC (1978)



- e-beam Polarimetry

- Møller polarimeter
- NOW: Mott ~1%, Møller ~1%, Compton ~0.7% (continuous)
- FUTURE: all three methods aim for 0.5%

E122 at SLAC (1978)

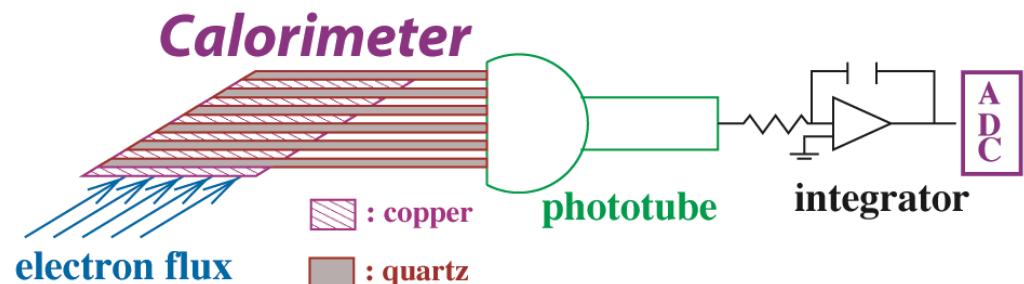


- **Magnetic Spectrometer**

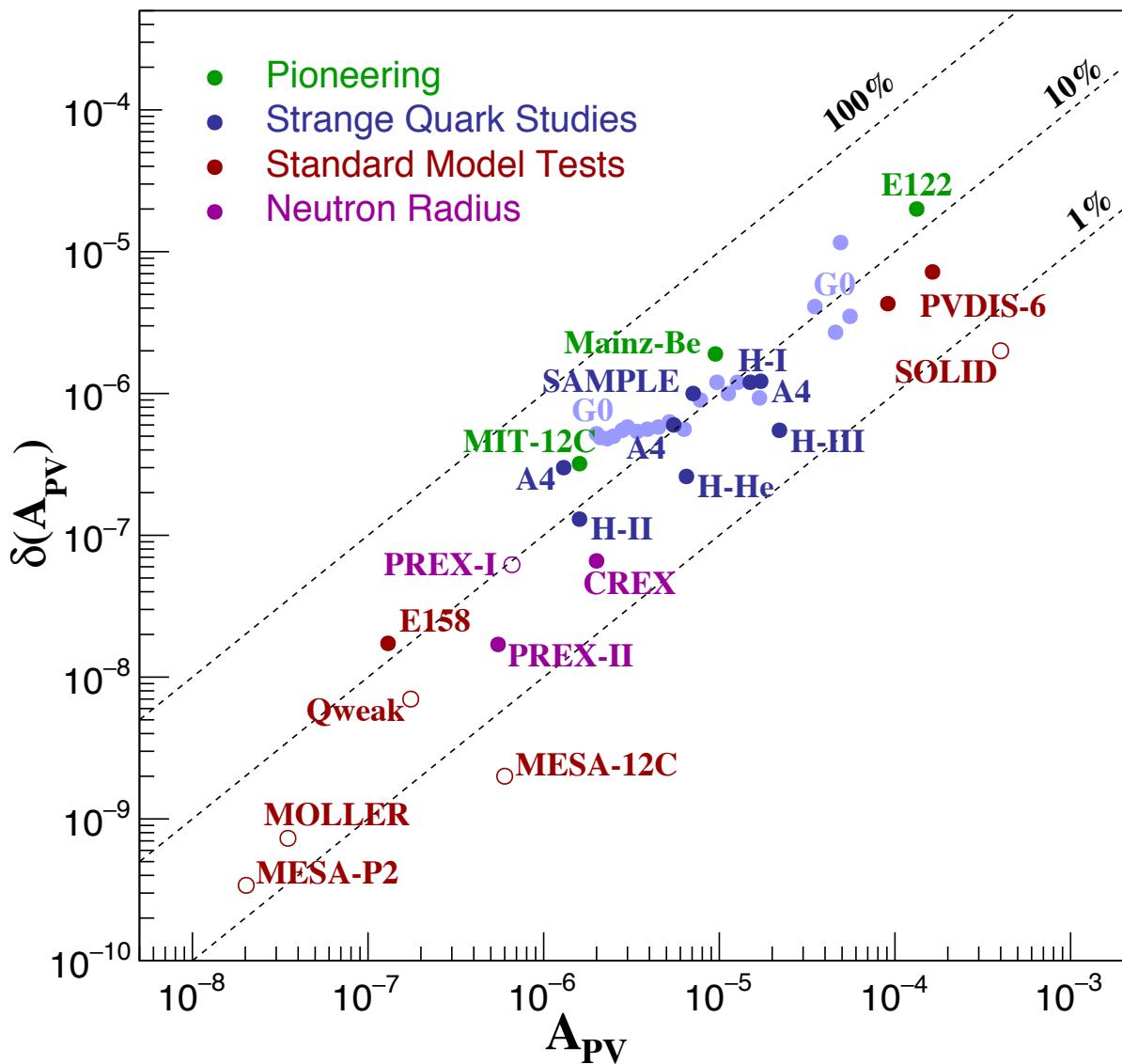
- directs scattered flux to background-free region
- defines / calibrates kinematic acceptance

- **Integrating Detection**

- integrate all signal during helicity window
- measures high rate (>100 kHz) with no deadtime
- NOW: ~6 GHz
- FUTURE: ~500 GHz



PVES has become a precision tool



Interplay between probing hadron structure
and electroweak physics

- Beyond Standard Model Searches
- Strange quark form factors
- Neutron skin of a heavy nucleus
- QCD structure of the nucleon

For future program:

- sub-part per billion statistical reach and systematic control
- 0.5% normalization control

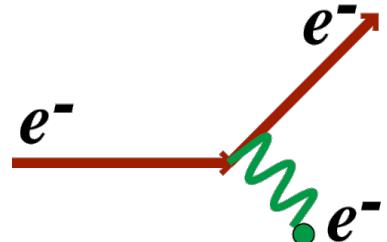
photocathodes, polarimetry, high power cryotargets,
nanometer beam stability, precision beam diagnostics,
low noise electronics, radiation hard detectors

PVES Searches for New Neutral Currents

SLAC-E122
Bates- ^{12}C
Mainz-Be

Cs APV
Weak vector
charge of
heavy nuclei

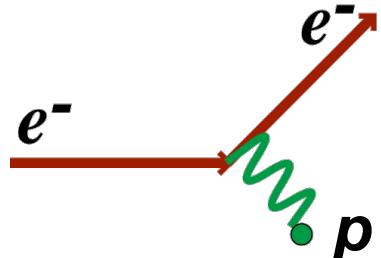
Møller (ee) scattering : Weak charge of the electron



SLAC-E158 1997-2004

MOLLER

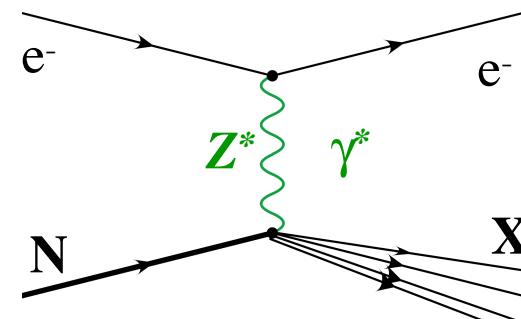
Elastic ep scattering : Weak vector charge of the proton



Qweak 2010-2012

P2@MESA

DIS from ^2H :
Weak Axial-Vector quark charge C_{2q}



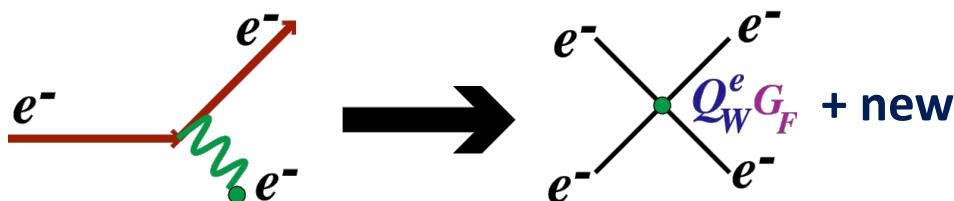
PV-DIS-6
2009

SOLID
EIC

SLAC-E158: Weak charge of the electron

1997-2004

Møller (ee) scattering

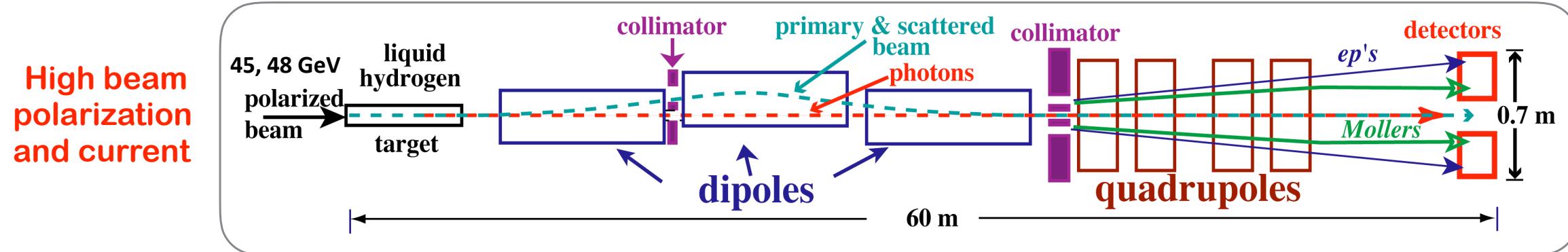


$$Q_W = 1 - 4 \sin^2 \theta_W$$

SM highly suppressed, so even a weakly-coupled or heavy new physics scenario can stand out

High-power
(1kW) LH_2 target,
18% radiator

Dipole chicane + quadrupole spectrometer
45, 48 GeV, 4-7 mrad scattering angle



First Measurement of the electron-electron weak interaction

$$A_{PV} = (-131 \pm 14 \pm 10) \text{ ppb}$$

$$\frac{\delta(\sin^2 \theta_W)}{\sin^2 \theta_W} \sim 0.5\%$$

LEP200
 $\Lambda_{VV}^{ee} \sim 17.7 \text{ TeV}$

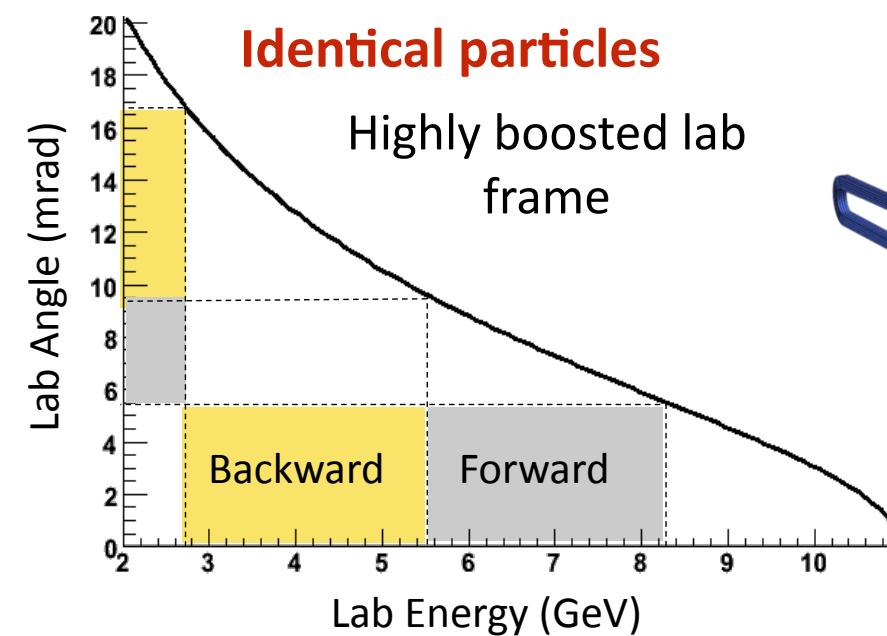
E158 Reach
 $\Lambda_{RR-LL}^{ee} \sim 17 \text{ TeV}$

Design for precision beyond E158

$$A_{PV} \propto E_{\text{lab}} Q_W^e, \quad \sigma \propto \frac{1}{E_{\text{lab}}}$$

Figure of Merit proportional to beam power
At 11 GeV, JLab luminosity and stability makes large improvement possible

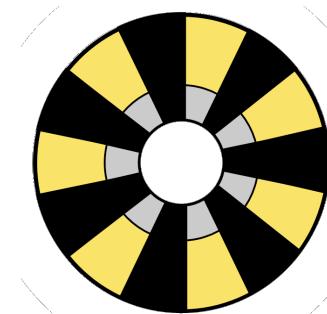
Figure of merit highest at $\theta_{CM} = 90^\circ$
Optimum Acceptance [90°,120°]



How do you maximize the azimuthal acceptance of the spectrometer?

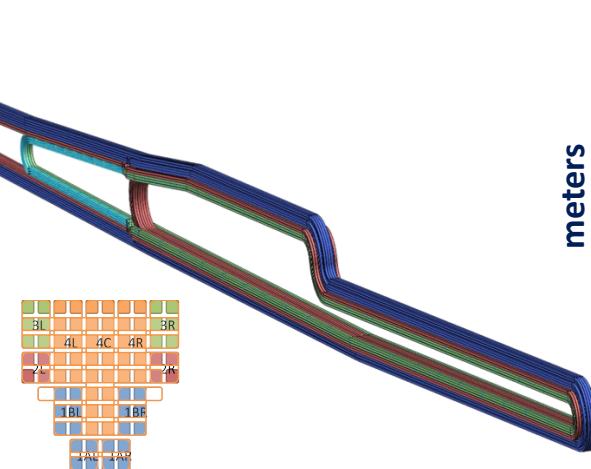
Idea: 50% Azimuth, 100% Acceptance

Odd number of octants: accept CM[60°,120°] so you always get one of the electrons from each event

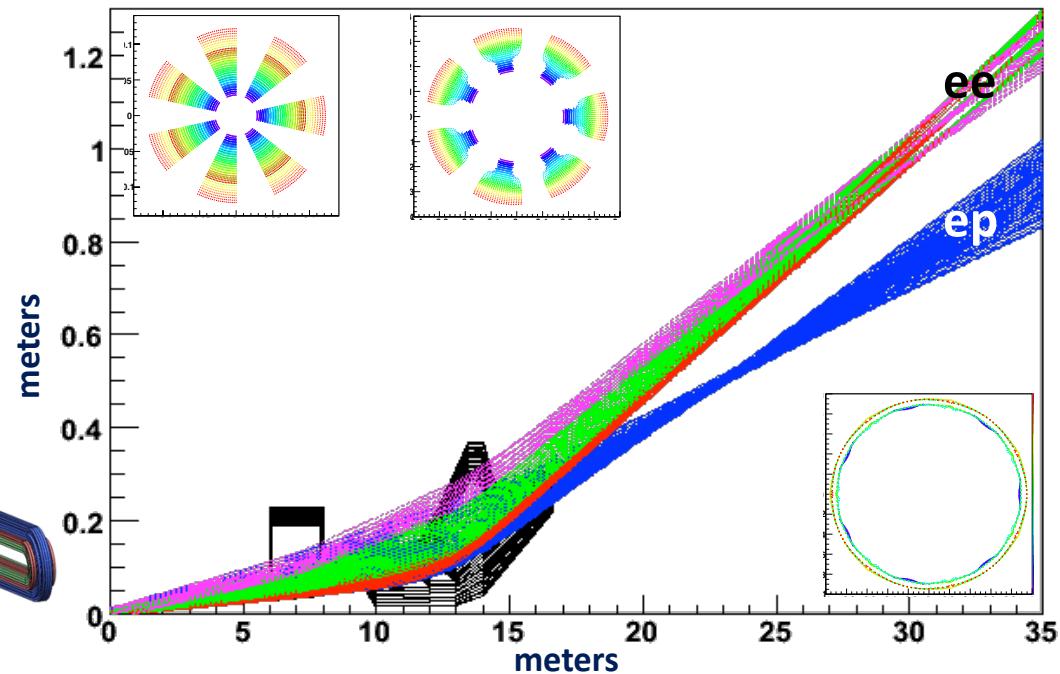


Toroid spectrometer

- $E' = 2.5-8.5$ GeV
- $\theta_{\text{lab}} = 0.3^\circ-1.1^\circ$
- Two resistive toroids

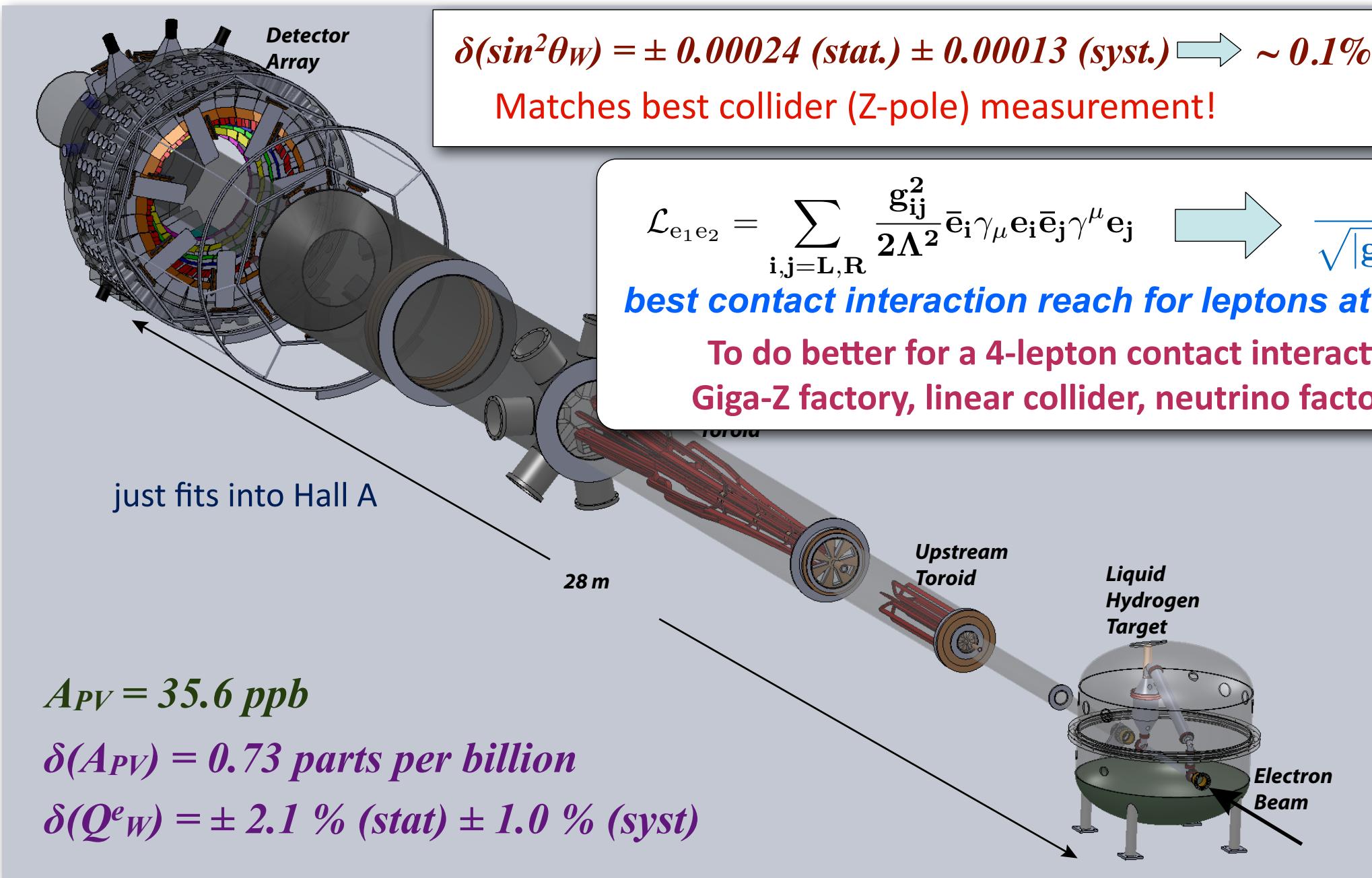


**Radial Fields defocus azimuthally.
Full detector ring**



MOLLER at 11 GeV JLab

improve on E158 by a factor of 5



MOLLER Status

Broad range of technical challenges

◎ Full Azimuthal coverage with to ~5° lab angle

- Magnet construction and engineering
- collimation
- backgrounds
- calibration procedures

◎ 1.5 m LH₂ target

- up to 5 kW power
- Boiling / density fluctuations <25ppm

◎ Polarized Source

- Flip at 2 kHz, 10 μ s deadtime
- beam position stable (<1nm) with reversal
- Improved slow reversal to cancel beam asymmetries

◎ Robust 0.4% beam polarimetry

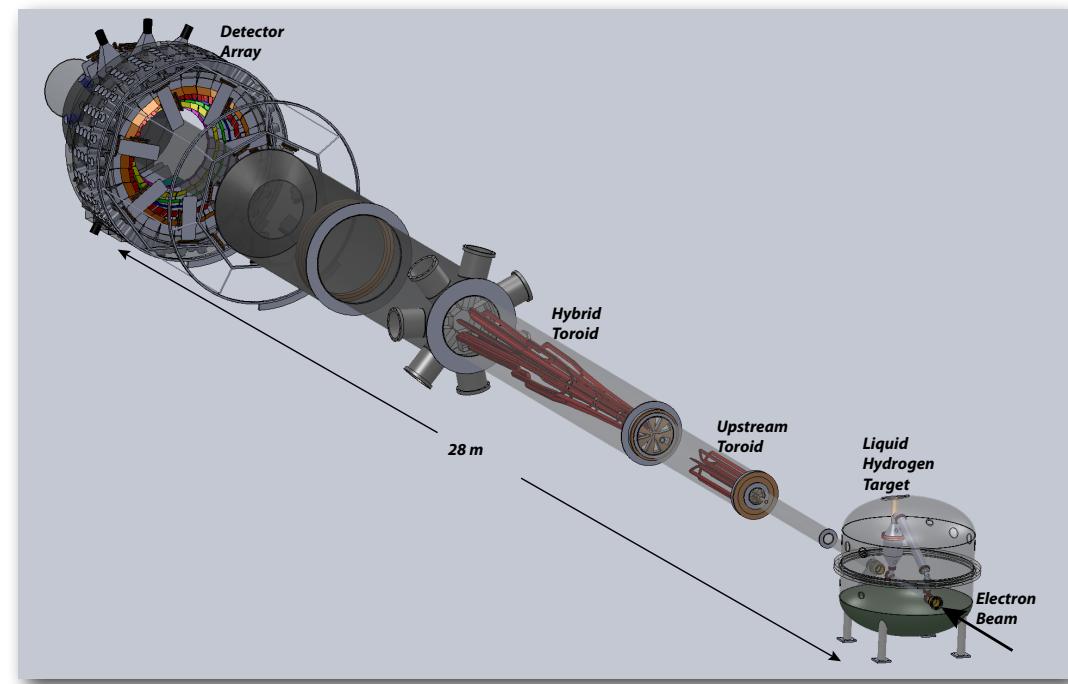
- Compton
- Iron foil and atomic hydrogen target Møller

◎ Detector development

- resolution, rad hard
- Ancillary (background and tracking)

Collaboration:

~100 scientists, ~ 30 institutions, expertise from Qweak, E158, HAPPEX, PREX, A4, G0



Outlook:

- 25M\$ MIE funding required
- Strong endorsement from recent DOE Science Review
- 2-3 years construction
- 3-4 years running

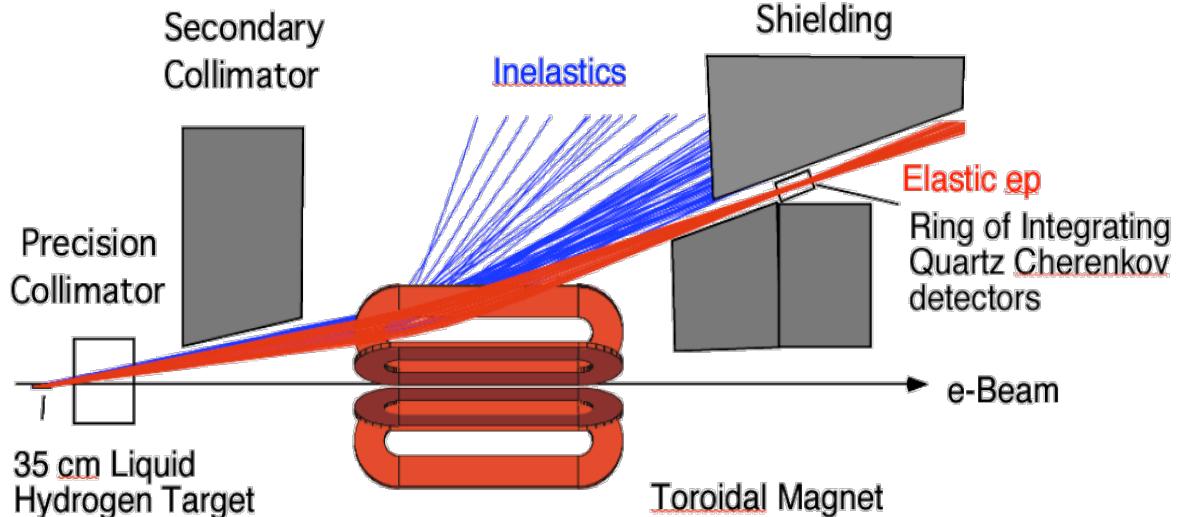
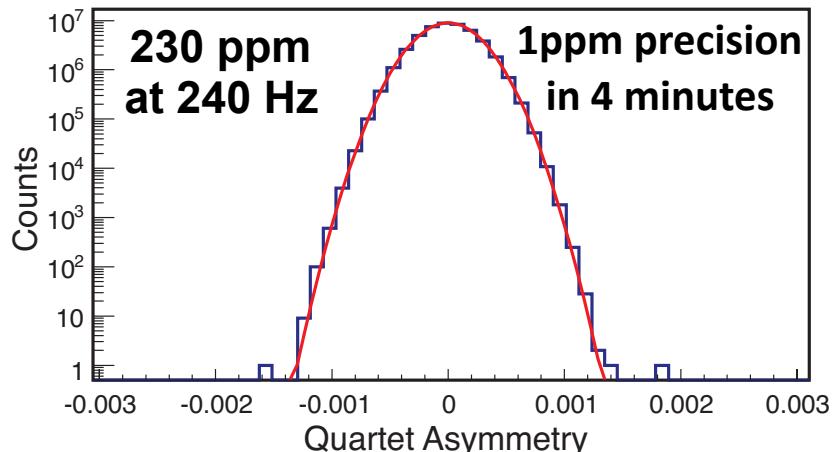
Proton Weak Charge: Qweak at JLab

Elastic ep scattering

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

$$Q_{\text{weak}}^p = 2C_{1u} + C_{1d} \propto 1 - 4 \sin^2 \vartheta_W$$

Q^2 : 0.025 GeV 2
 Beam Energy: 1.16 GeV
 θ Acceptance: 5.8°-11.6°
 Polarization: 89%
 Current: 180 μ A
Detected Rate: 6 GHz



At small angle and low Q^2 , form-factor and other contributions are small

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

“Run 0” results (about 1/25 of data set): PRL 111, 141803 (2013)

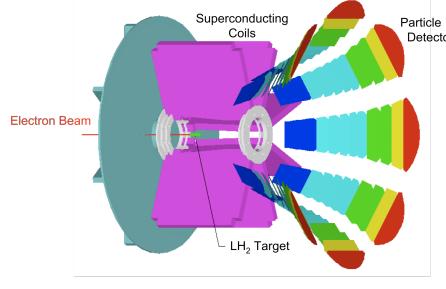
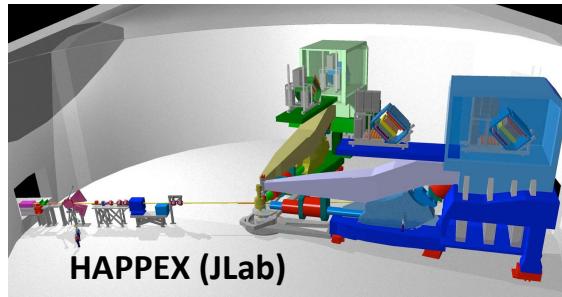
$$A_{PV} = -279 \pm 35 \text{ (stat)} \pm 31 \text{ (syst) ppb}$$

Qweak - Global Fit of PVES data

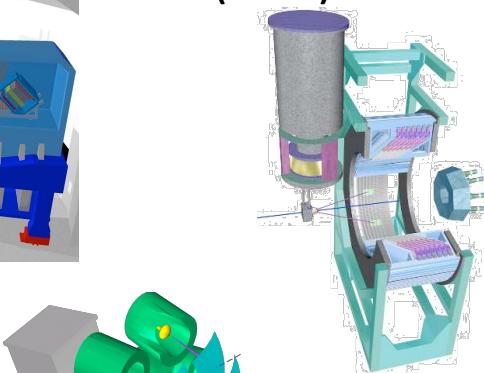
spin-1/2 target: electric and magnetic form-factors

$$G_{E,M}^Z = (1 - 4 \sin^2 \theta_W) G_{E,M}^P - G_{E,M}^N - G_{E,M}^S$$

Strange quark program probed over a range of low Q^2



A4 (Mainz)



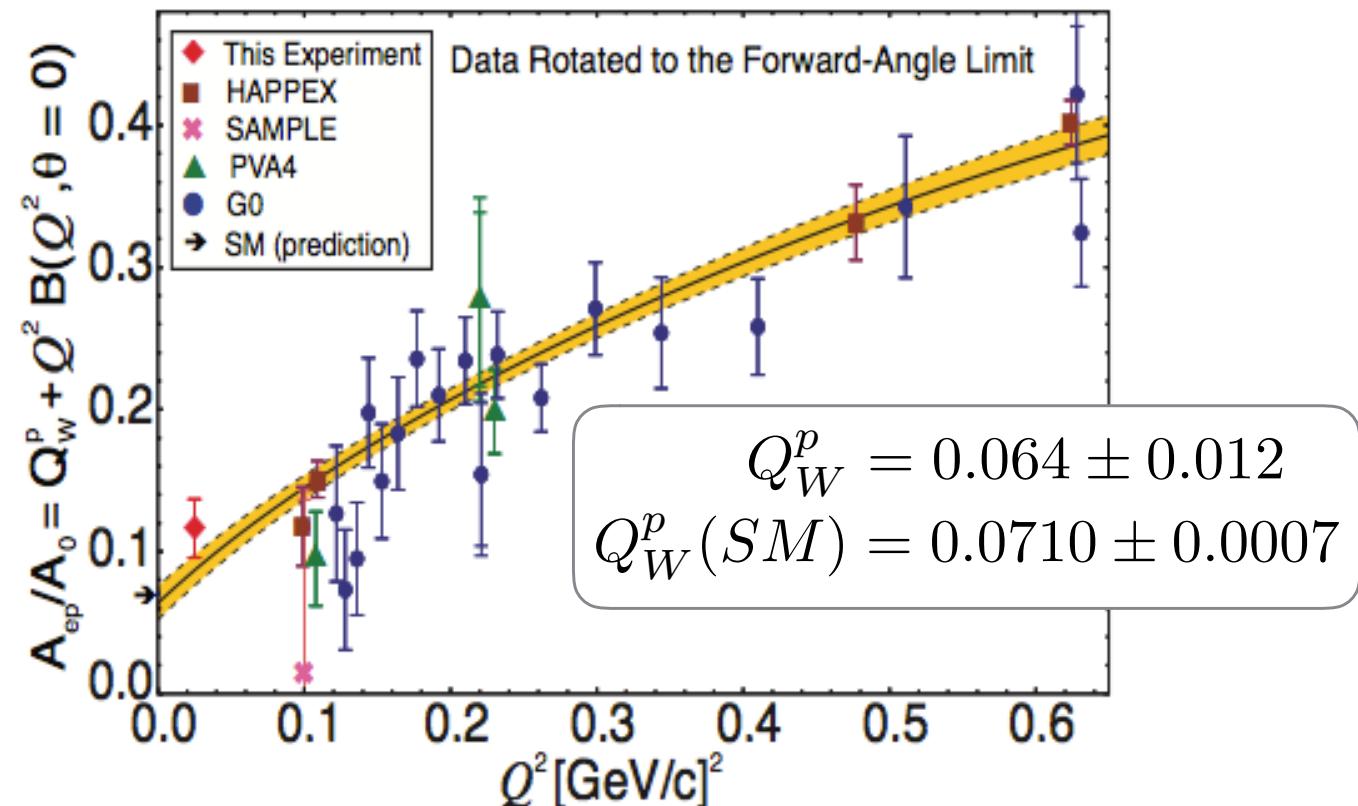
SAMPLE (Bates)

Hadronic corrections for QWeak constrained in fit of all PVES data over targets, E, θ , Q^2

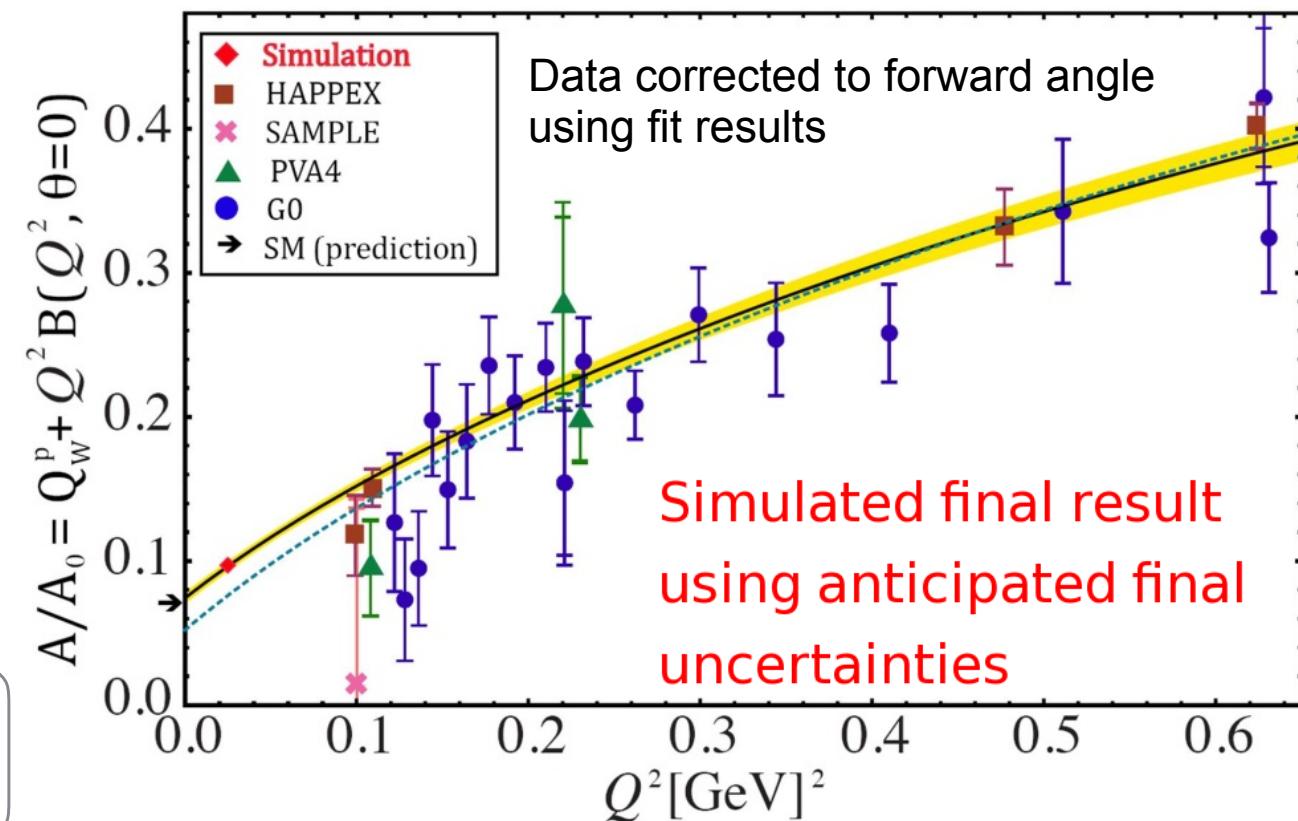
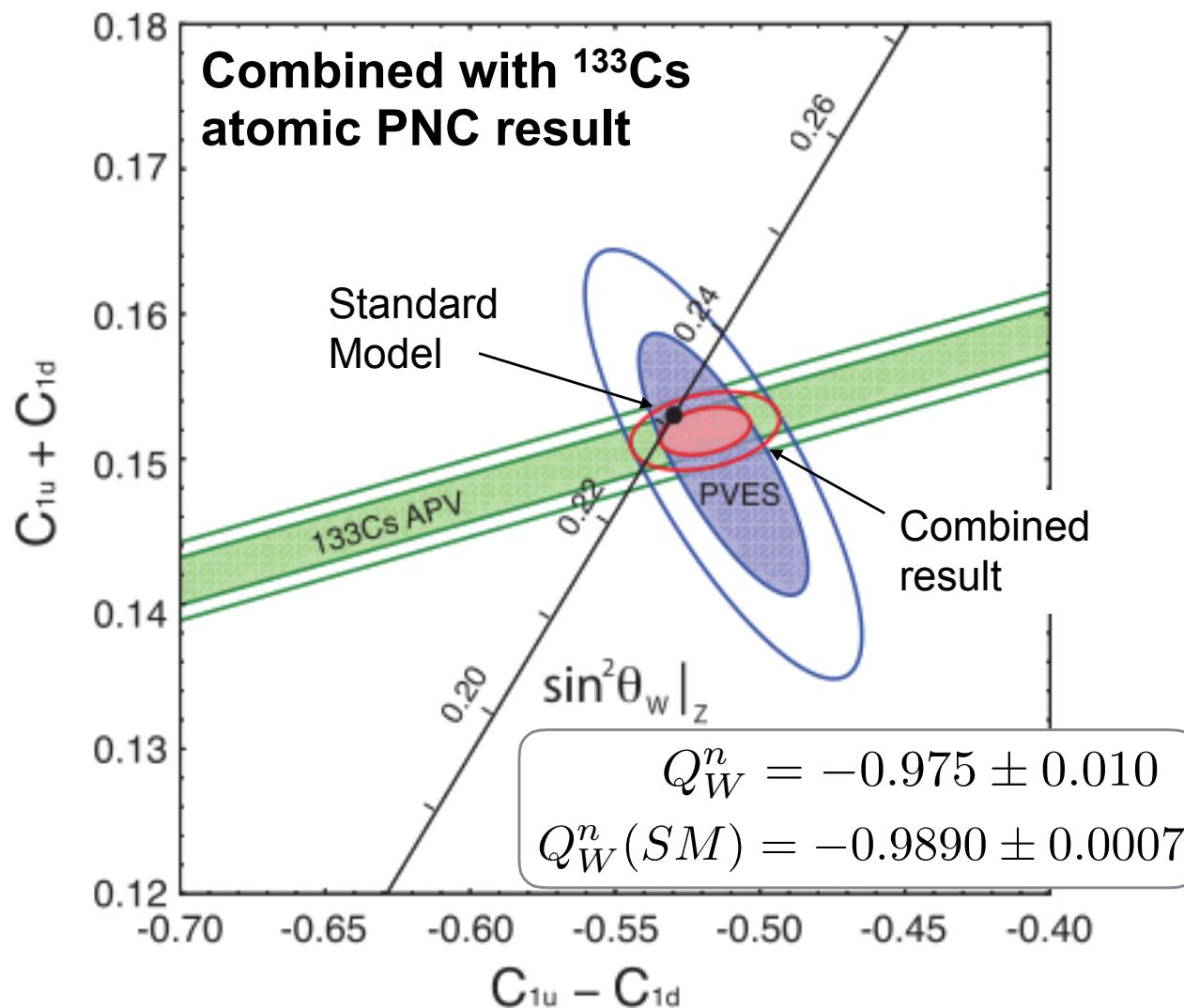
$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} [Q_W^p + Q^2 F(\theta, Q^2)]$$

Global fit, first results on Q_W^p

- All nuclear PVES data (hydrogen, deuterium, helium).
- 5 parameters (C_{1u} , C_{1d} , isovector axial FF, ρ_s , μ_s)
- Illustration shown here at forward angle.



Qweak Fit Result



P2 at MESA / Mainz

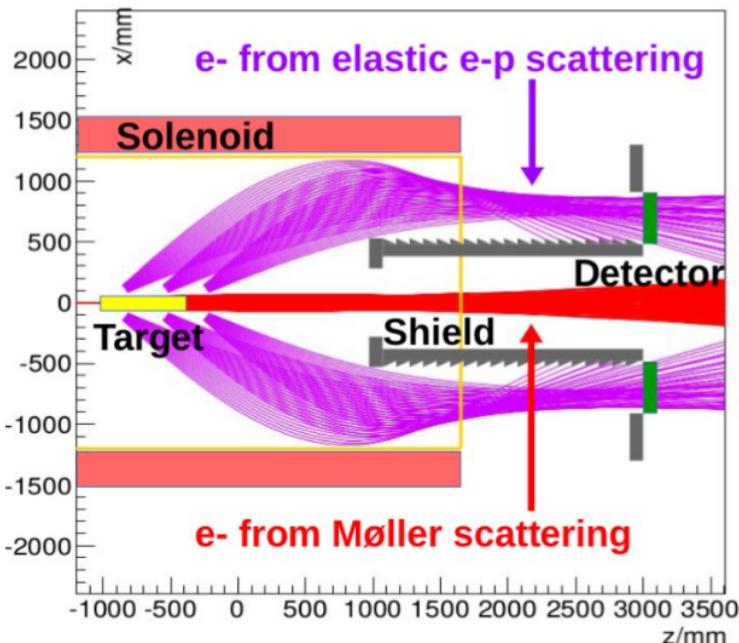
$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} [Q_W^p + Q^2 F(\theta, Q^2)]$$

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

Negligible for significantly lower Q^2

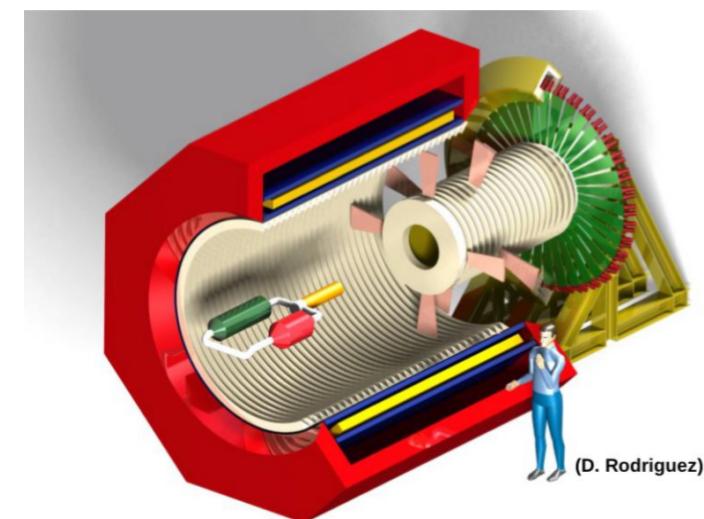
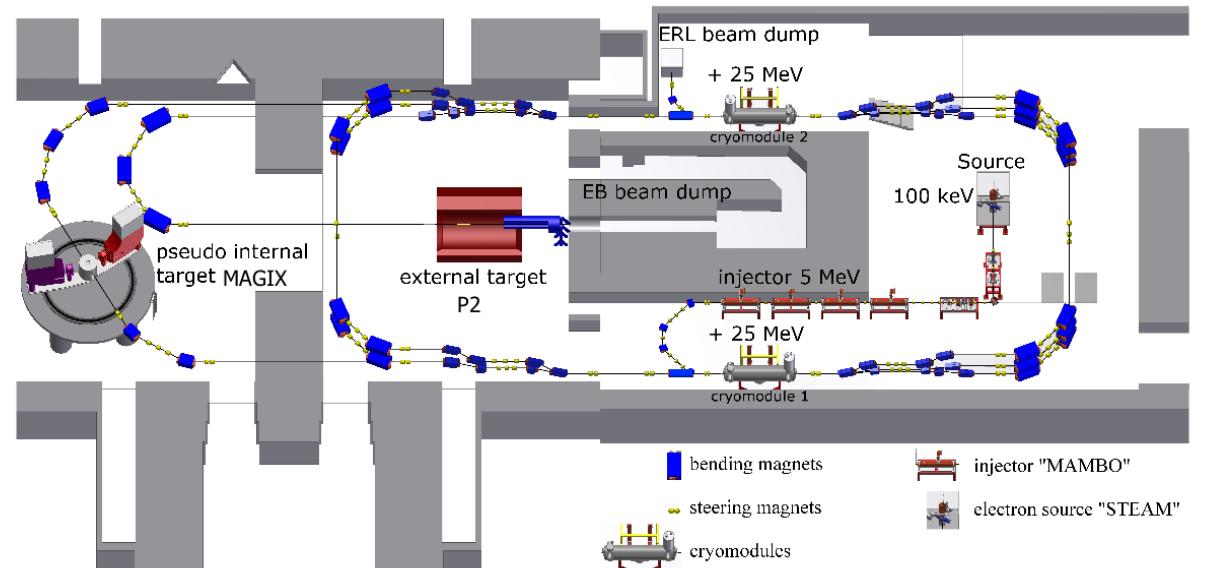
- rate up 80x, Q^2 down 5x: same FOM on A_{PV} and 2x FOM on Q_W^p
- reduced sensitivity to radiative corrections and proton structure

Solenoid Spectrometer



- $E_{beam} = 155 \text{ MeV}, 25-45^\circ$
- $Q^2 = 0.0048 \text{ GeV}^2$
- 60 cm target, 150 uA, 10^4 hours
- $A_{PV} = -29 \text{ ppb to } 1.5\%$ (**0.44ppb**)
- $\delta(\sin^2\theta_W) = 0.00031$ (**0.13%**)
- Development underway
- Installation starts in 2018
- Commissioning 2019

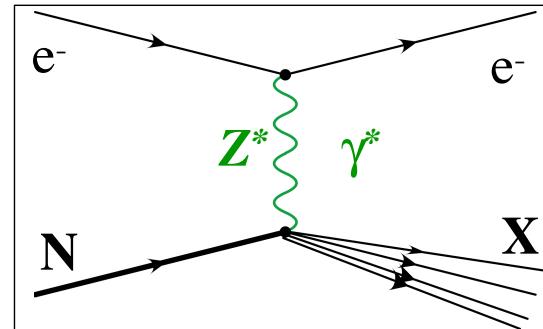
MESA: based on ERL but will also support a high-current extracted beam



Deep Inelastic Scattering

An isoscalar target like ^2H can access the axial-vector quark couplings C_{2q}

$$A_{\text{iso}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \sim - \left(\frac{3G_F Q^2}{\pi \alpha 10\sqrt{2}} \right) [2C_{1u} - C_{1d}] + Y [2C_{2u} - C_{2d}]$$



$$x \equiv x_{\text{Bjorken}}$$

$$y \equiv 1 - E'/E$$

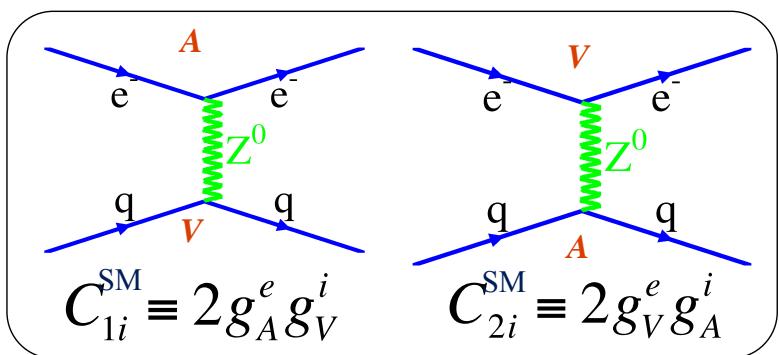
$$Y = \frac{1 - (1 - y)^2}{1 + (1 - y)^2 - y^2 \frac{R}{R+1}}$$

$$R(x, Q^2) = \sigma^l / \sigma^r \approx 0.2$$

At high x , sea quark contributions cancel out, A_D becomes independent of x & W , with well-defined SM prediction

$$R_s(x) = \frac{2S(x)}{U(x) + D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x) + d_v(x)}{U(x) + D(x)} \xrightarrow{\text{Large } x} 1$$

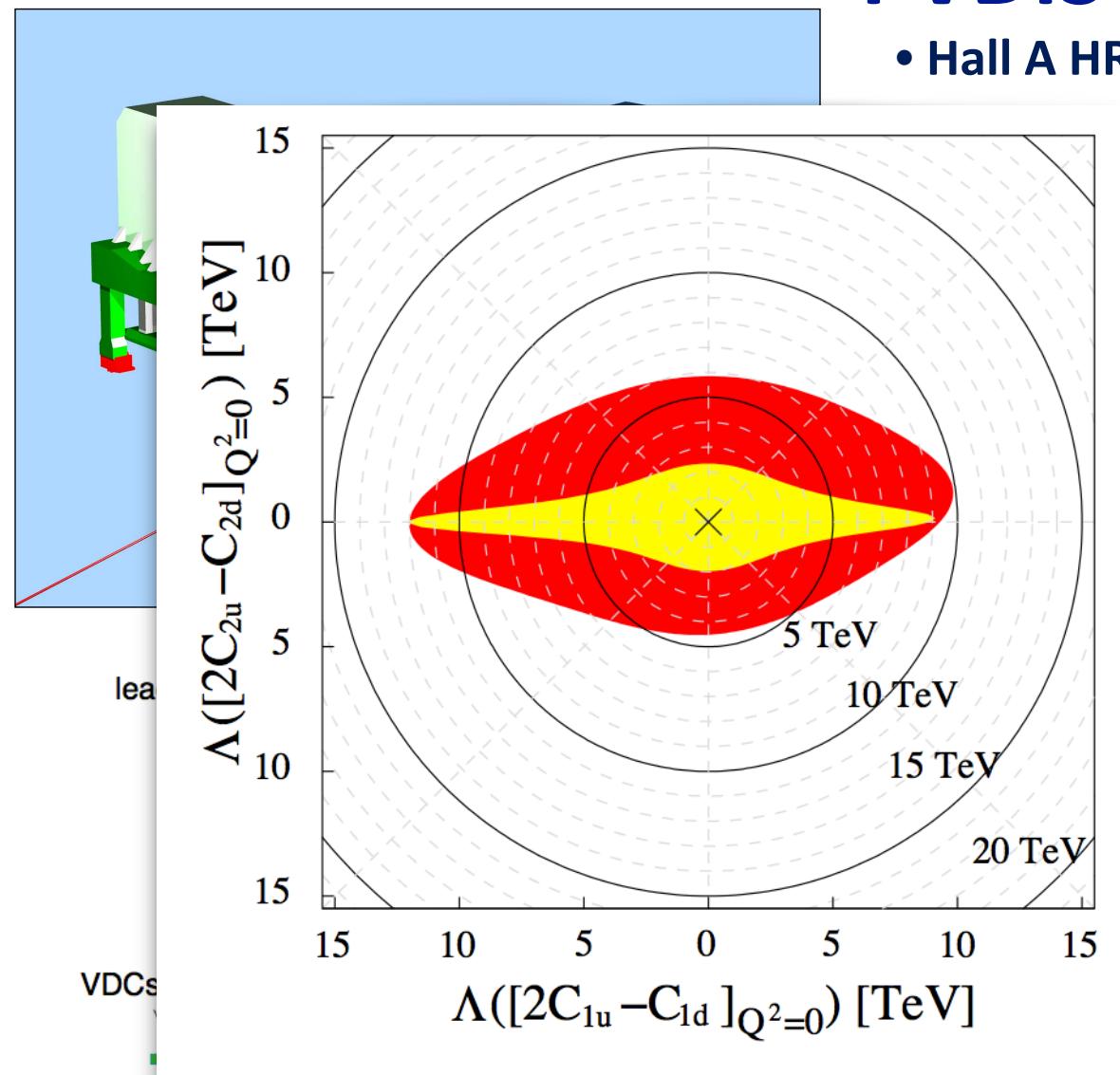


Hadronic effects may also be important

- sea quarks
- Charge symmetry violation
- Higher Twist

PVDIS-6 in Hall A

- Hall A HRS spectrometers



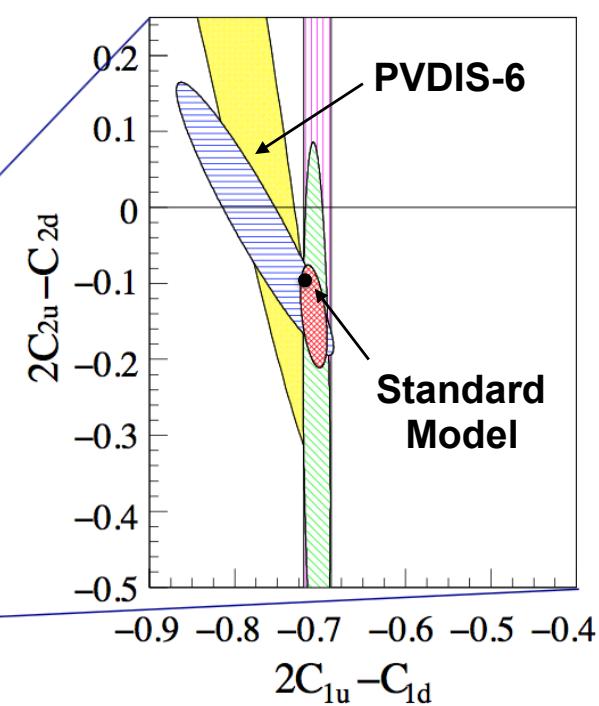
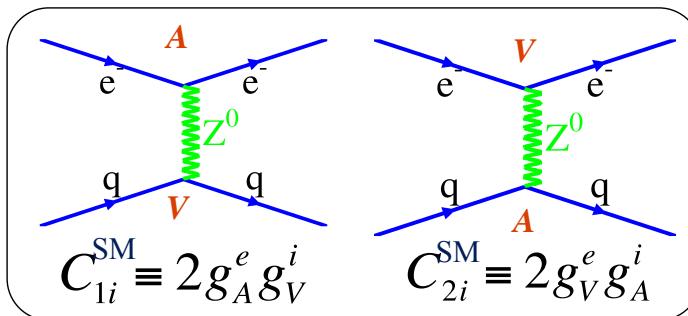
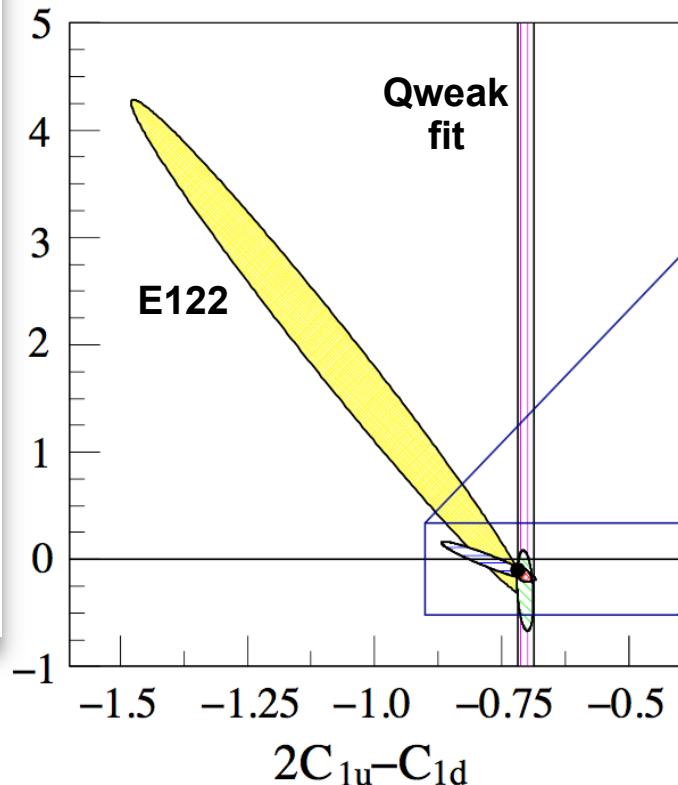
first experimental confirmation of non-zero
axial-vector quark WNC coupling

• 10% polarization, 6 GeV beam
• Timing DAQ - pion rejection,
• sc segmentation

Wang et al., Nature 506, no. 7486, 67 (2014);

1 GeV² $A_{PV} = -91.1 \pm 3.1 \text{ (stat)} \pm 4.3 \text{ (syst) ppm}$

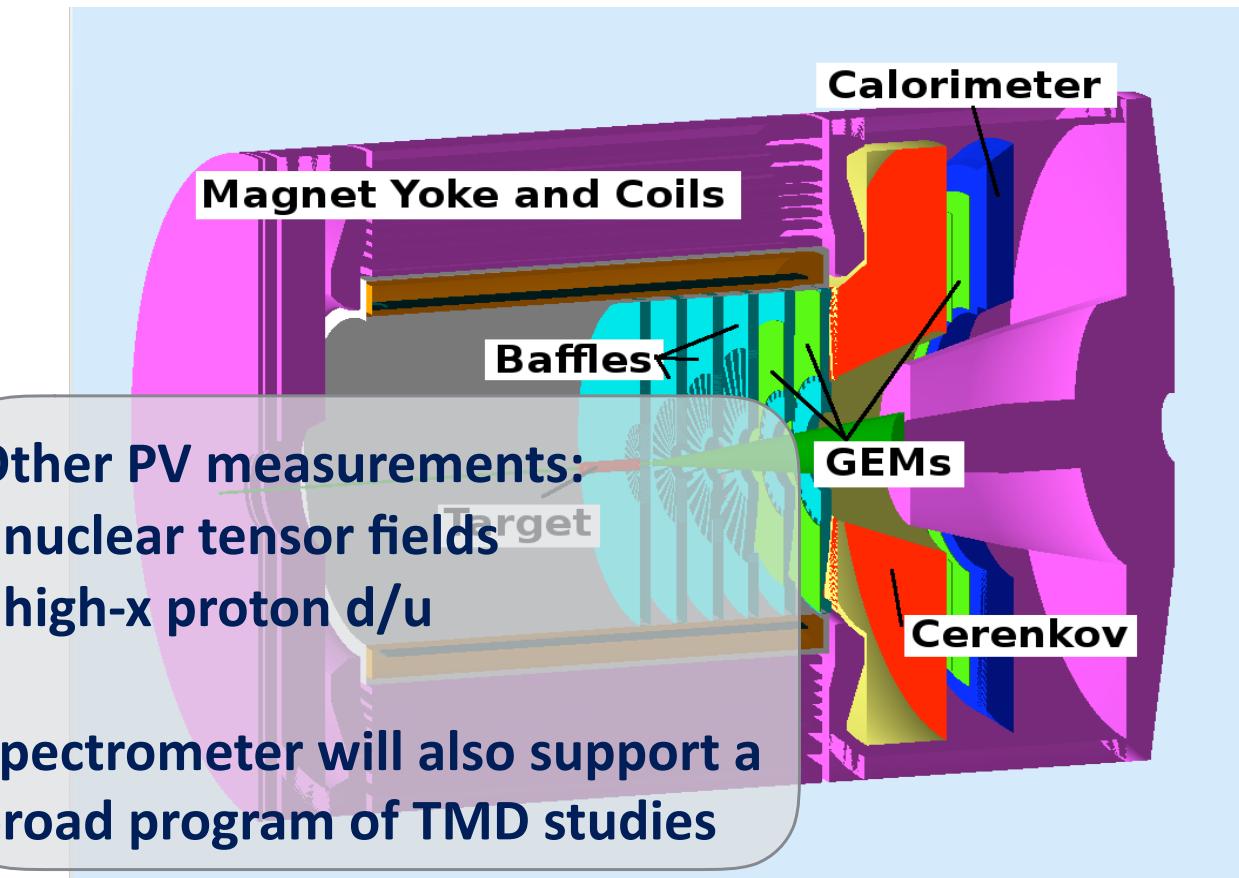
9 GeV² $A_{PV} = -160.8 \pm 6.4 \text{ (stat)} \pm 3.1 \text{ (syst) ppm}$



Phys. Rev. C91 (2015) 4, 045506

SOLID

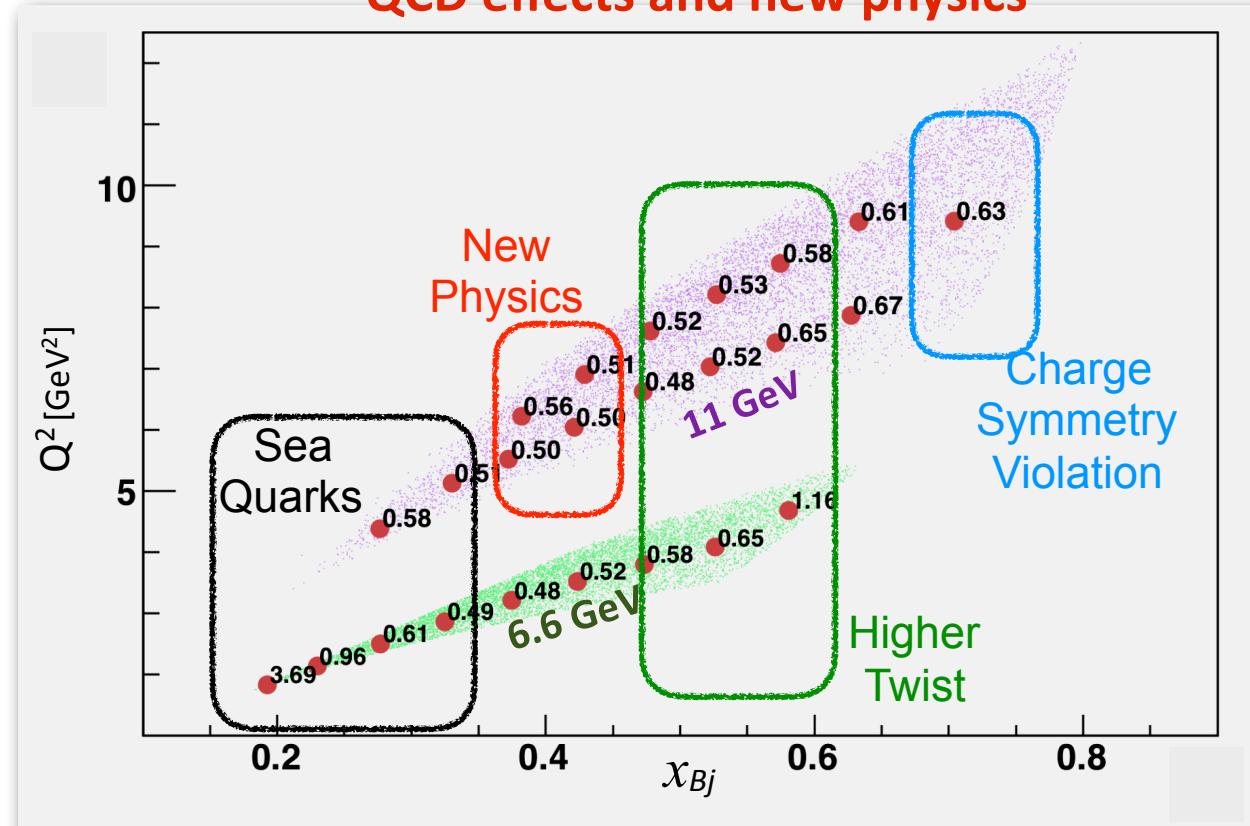
Strategy for high precision: controlling hadronic contributions
requires precise kinematics and broad range



- high luminosity, large acceptance
- repurpose the CLEO solenoid
- $20^\circ - 35^\circ$, $E' \sim 1.5 - 5$ GeV $\delta p/p \sim 2\%$

- some regions 10's of kHz/mm²
- GEM tracking
- Cerenkov + segmented calorimeter

Variations over x , Q^2 can discriminate
QCD effects and new physics



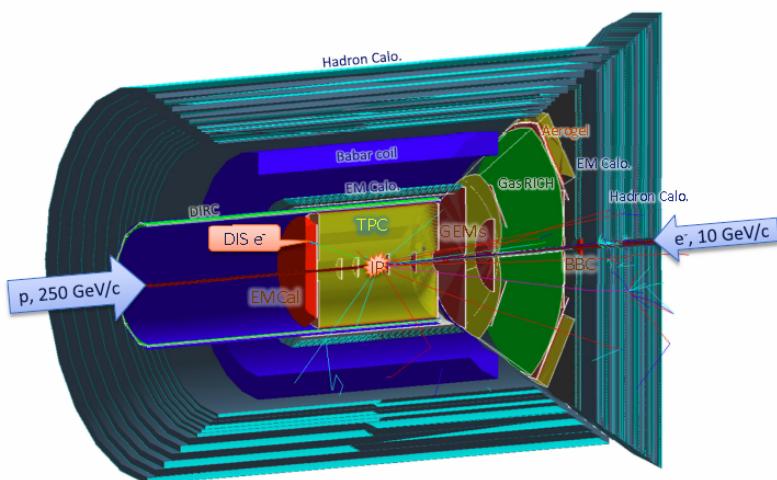
Requires 0.4% e^- - polarimetry

PV-DIS at EIC

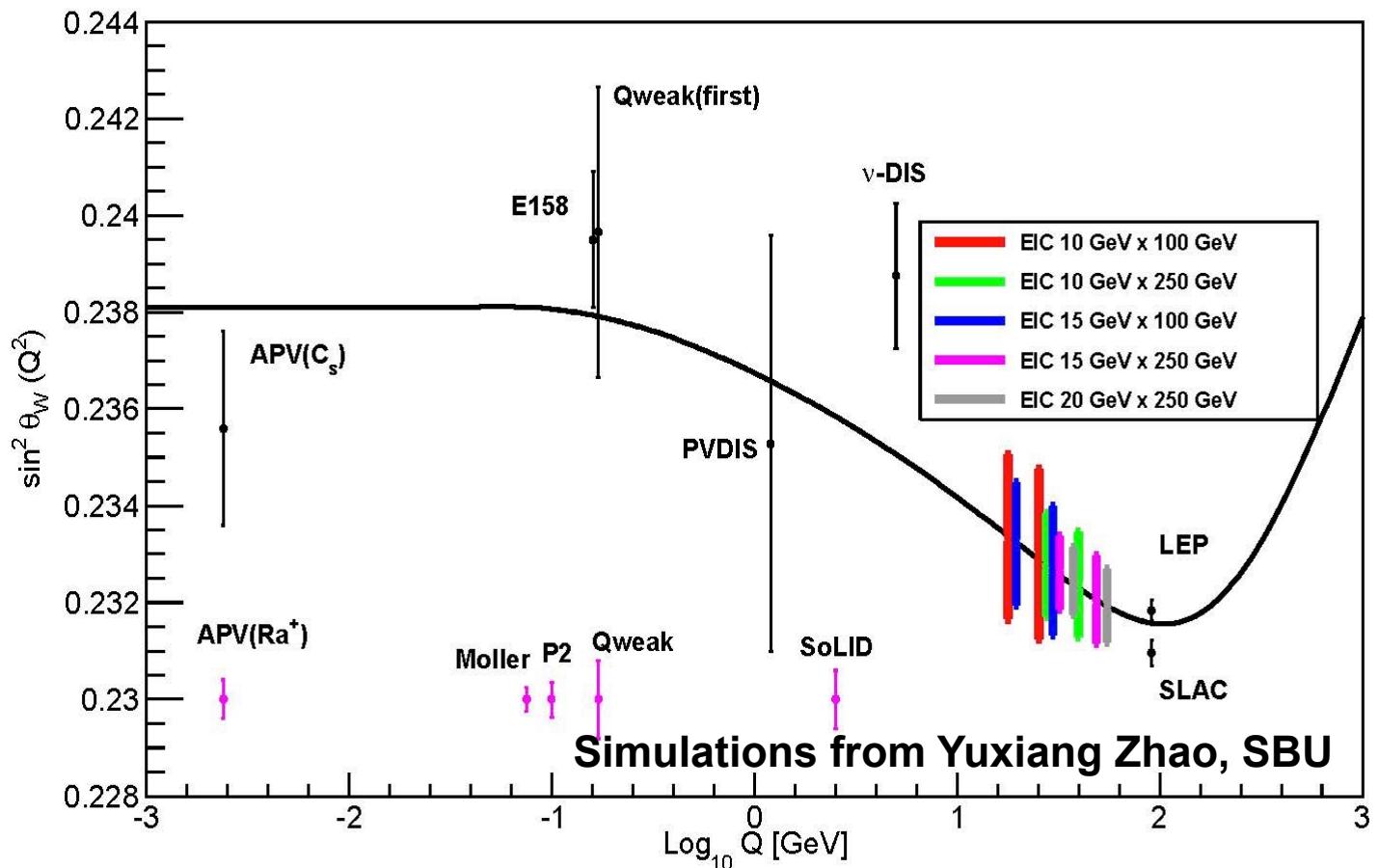
EIC can access interesting Q^2 region with PV-DIS - no past or planned measurements

Assumptions:

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

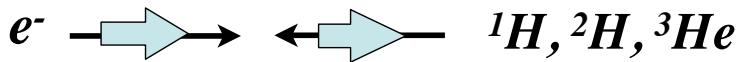


Simulated using “Day-1 EIC detector” described in ePHENIX LOI



- Polarimetry $\sim 0.5\%$ for highest energy, luminosity
- Differential luminosity precision $\sim 5 \times 10^{-4}$

Electroweak Structure Functions



polarized electron, unpolarized hadron

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \left[g_A \frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V \frac{f(y)}{2} \frac{F_3^{\gamma Z}}{F_1^\gamma} \right]$$

unpolarized electron, polarized hadron

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \left[g_V \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A f(y) \frac{g_1^{\gamma Z}}{F_1^\gamma} \right]$$

proton

$$F_1^{\gamma Z} \propto u + d + s$$

$$F_3^{\gamma Z} \propto 2u_v + d_v$$

$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$

$$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$$

deuteron

$$F_1^{\gamma Z} \propto u + d + 2s$$

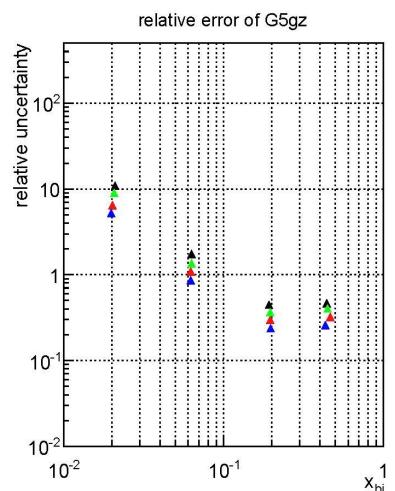
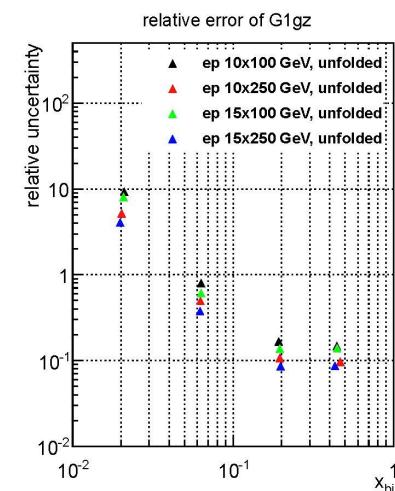
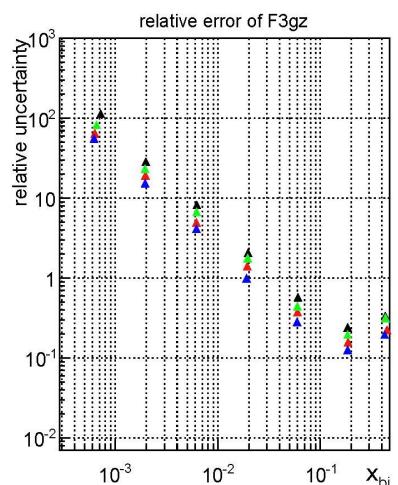
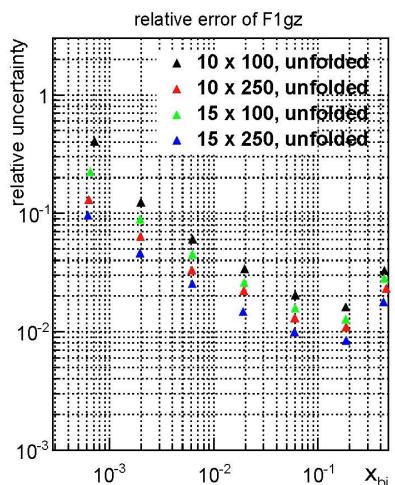
$$F_3^{\gamma Z} \propto u_v + d_v$$

$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$

$$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$$

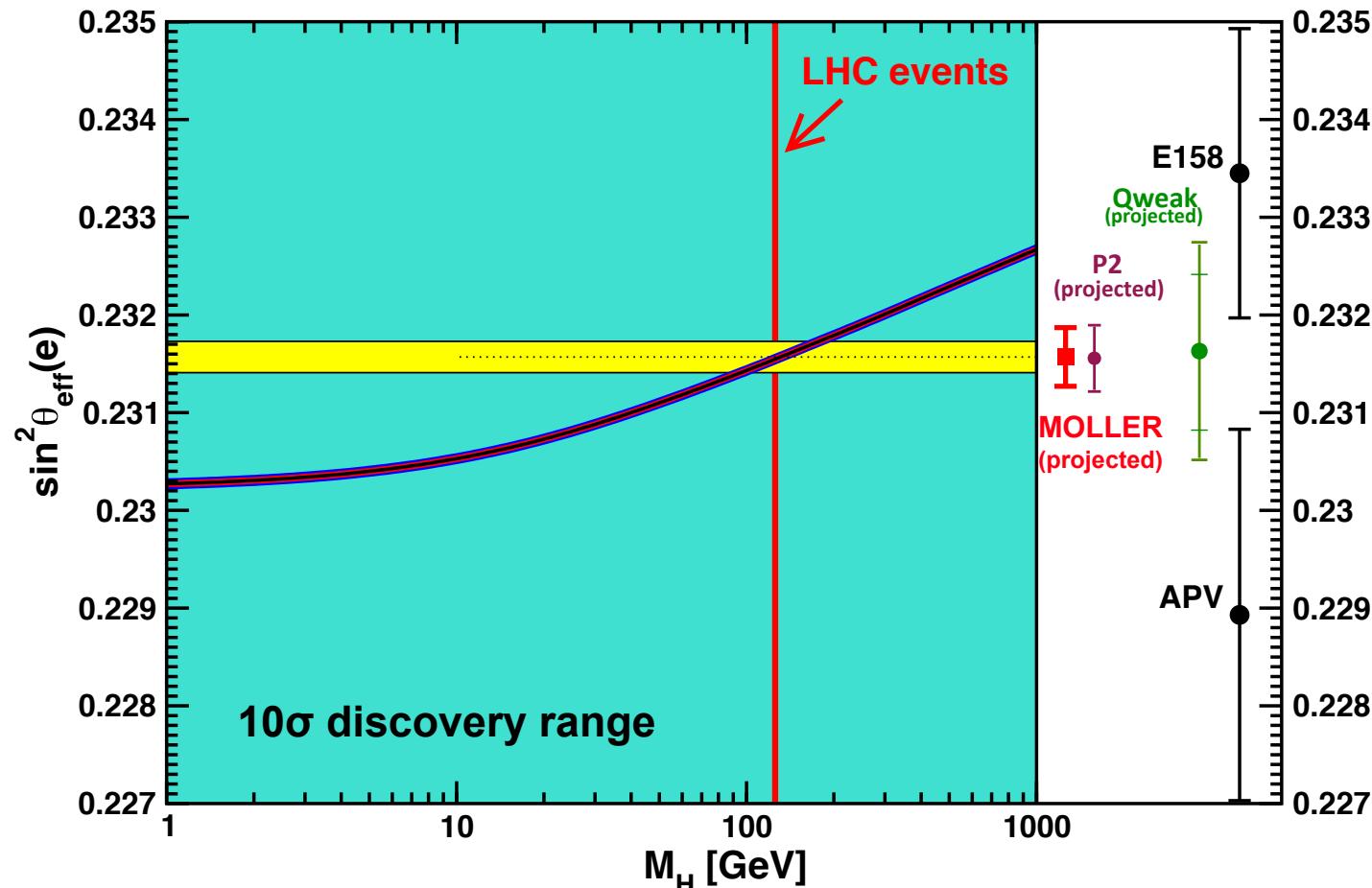
Assuming integrated luminosity $\sim 500 \text{ fb}^{-1}$

- “Non-small x”
- few % on $F_1^{\gamma Z}$
- 10% on $g_1^{\gamma Z}$

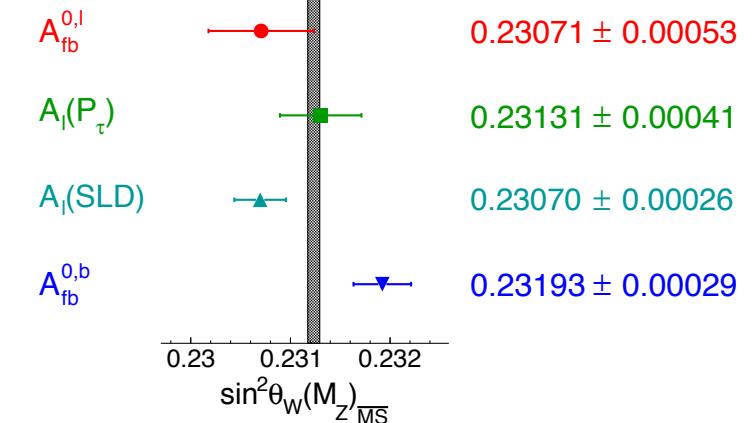


Simulations from Yuxiang Zhao, SBU

Precision Mixing Angle at Low Q^2



Z resonance measurements:
no interference term



Future projections, similar time scale:

MOLLER: ~ 0.00028

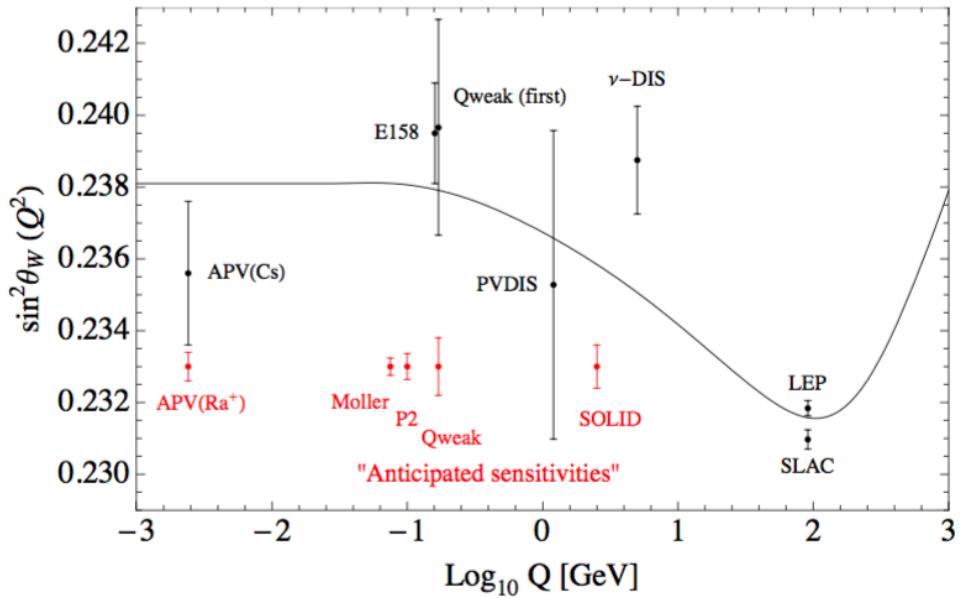
Mainz P2: ~ 0.00032

Final Tevatron: ~ 0.00046

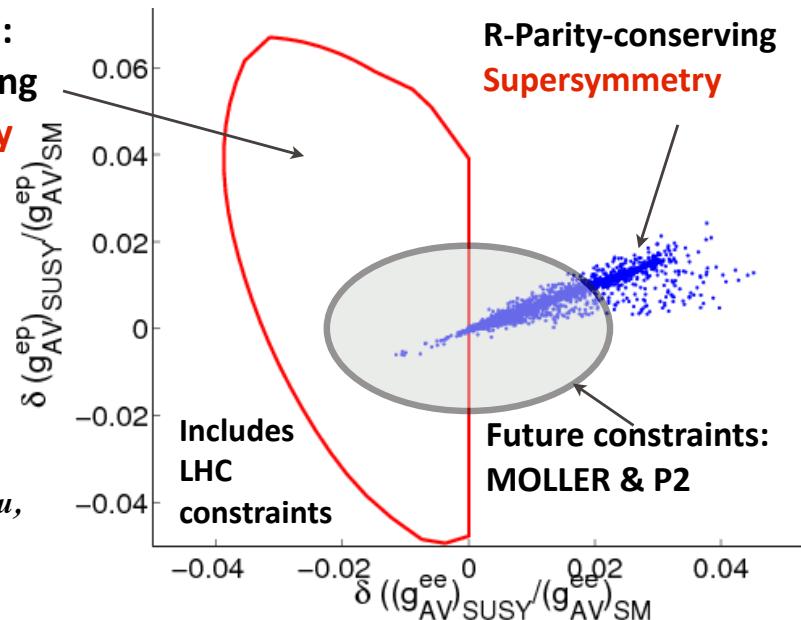
LHC 14 TeV, 300 fb^{-1} : ~ 0.00036

Note: systematics-dominated
(pdf uncertainties)

New Physics Complementarity



Allowed region:
R-Parity-violating
Supersymmetry



Erler and Su,
arXiv:1303.5522

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

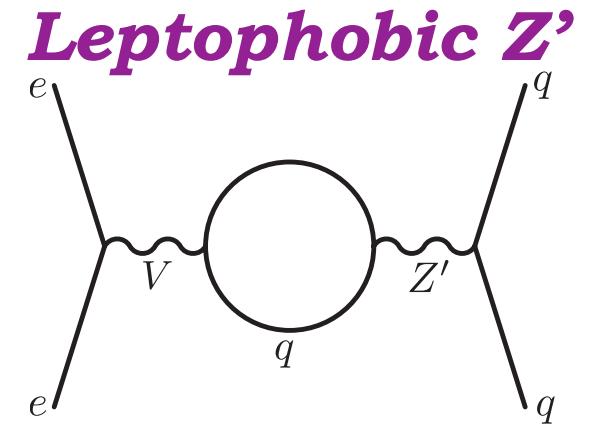
e^-e^- scattering
Lepton Number Violation
 $\Lambda > 5 \text{ TeV}$
Doubly-Charged Scalars
Significant reach beyond LEP-200

mass reach

(assumptions on isospin structure, strong coupling)

E158	~17 TeV
PV-DIS-6	~8 TeV
Qweak	~33 TeV
MOLLER	~39 TeV
P2	~49 TeV
SOLID	~22 TeV

Erler *et al.*,
Ann. Rev. Nucl. Part. Sci. 64 (2014)



SOLID can improve sensitivity:
100-200 GeV range

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

Summary

Fundamental symmetries at the intensity frontier is an important complement to energy frontier studies

- ◎ Future results to from Qweak, P2, SOLID, MOLLER
- ◎ Technical progress has enabled unprecedented precision
- ◎ search for new interactions from 100 MeV, to 10s of TeV
- ◎ Increasing precision on weak charges, with resolution on weak mixing angle at energy low scales comparable to Z-pole measurements
- ◎ EIC will open window to novel spin-dependent and spin-independent structure functions,
- ◎ and to precision weak mixing angle in an interesting Q^2 range

Large scale, flagship experiments for electron beam facilities
Interplay between nuclear and hadronic topics and fundamental symmetries

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

backup

New structure functions

--- γ -Z interference structure functions

pol. electron & unpol. nucleon:

$$A_{beam} = \frac{G_F Q^2}{2 \sqrt{2} \pi \alpha} [g_A^e \frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V^e \frac{Y_-}{2Y_+} \frac{F_3^{\gamma Z}}{F_1^\gamma}]$$

$$F_1^{\gamma Z} = \sum_f e_{q_f} (g_V)_{q_f} (q_f + \bar{q}_f)$$

$$F_3^{\gamma Z} = 2 \sum_f e_{q_f} (g_A)_{q_f} (q_f - \bar{q}_f)$$



unpol. electron & pol. nucleon:

$$A_L = \frac{G_F Q^2}{2 \sqrt{2} \pi \alpha} [g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+} \frac{g_1^{\gamma Z}}{F_1^\gamma}]$$

$$g_1^{\gamma Z} = \sum_f e_{q_f} (g_V)_{q_f} (\Delta q_f + \Delta \bar{q}_f)$$

$$g_5^{\gamma Z} = \sum_f e_{q_f} (g_A)_{q_f} (\Delta q_f - \Delta \bar{q}_f)$$

New structure functions

--- γ -Z interference structure functions

pol. electron & unpol. nucleon:

$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} [g_A^e \frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V^e \frac{Y_-}{2Y_+} \frac{F_3^{\gamma Z}}{F_1^\gamma}]$$

$$F_1^{p, \gamma Z} \approx \frac{1}{9}(u + \bar{u} + d + \bar{d} + s + \bar{s} + c + \bar{c})$$

$$F_1^{n, \gamma Z} \approx \frac{1}{9}(u + \bar{u} + d + \bar{d} + s + \bar{s} + c + \bar{c})$$

$$F_3^{p, \gamma Z} = \frac{2}{3}(u_V + c - \bar{c}) + \frac{1}{3}(d_V + s - \bar{s})$$

$$F_3^{n, \gamma Z} = \frac{2}{3}(d_V + s - \bar{s}) + \frac{1}{3}(u_V + c - \bar{c})$$

unpol. electron & pol. nucleon:

$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} [g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{2Y_+} \frac{g_1^{\gamma Z}}{F_1^\gamma}]$$

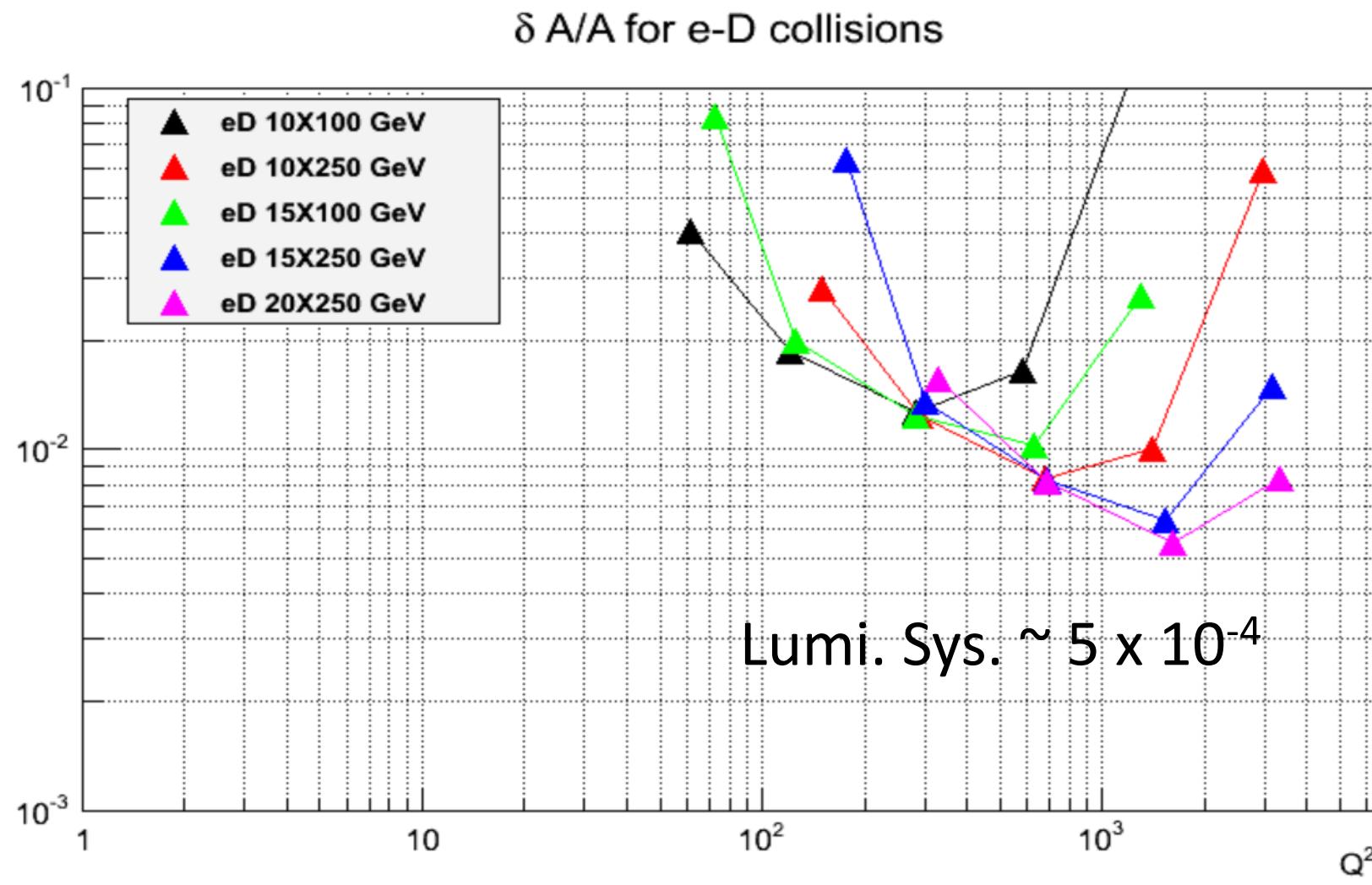
$$g_1^{p, \gamma Z} \approx \frac{1}{9}(\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} + \Delta c + \Delta \bar{c})$$

$$g_1^{n, \gamma Z} \approx \frac{1}{9}(\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} + \Delta c + \Delta \bar{c})$$

$$g_5^{p, \gamma Z} = \frac{1}{3}(\Delta u_V + \Delta c - \Delta \bar{c}) + \frac{1}{6}(\Delta d_V + \Delta s - \Delta \bar{s})$$

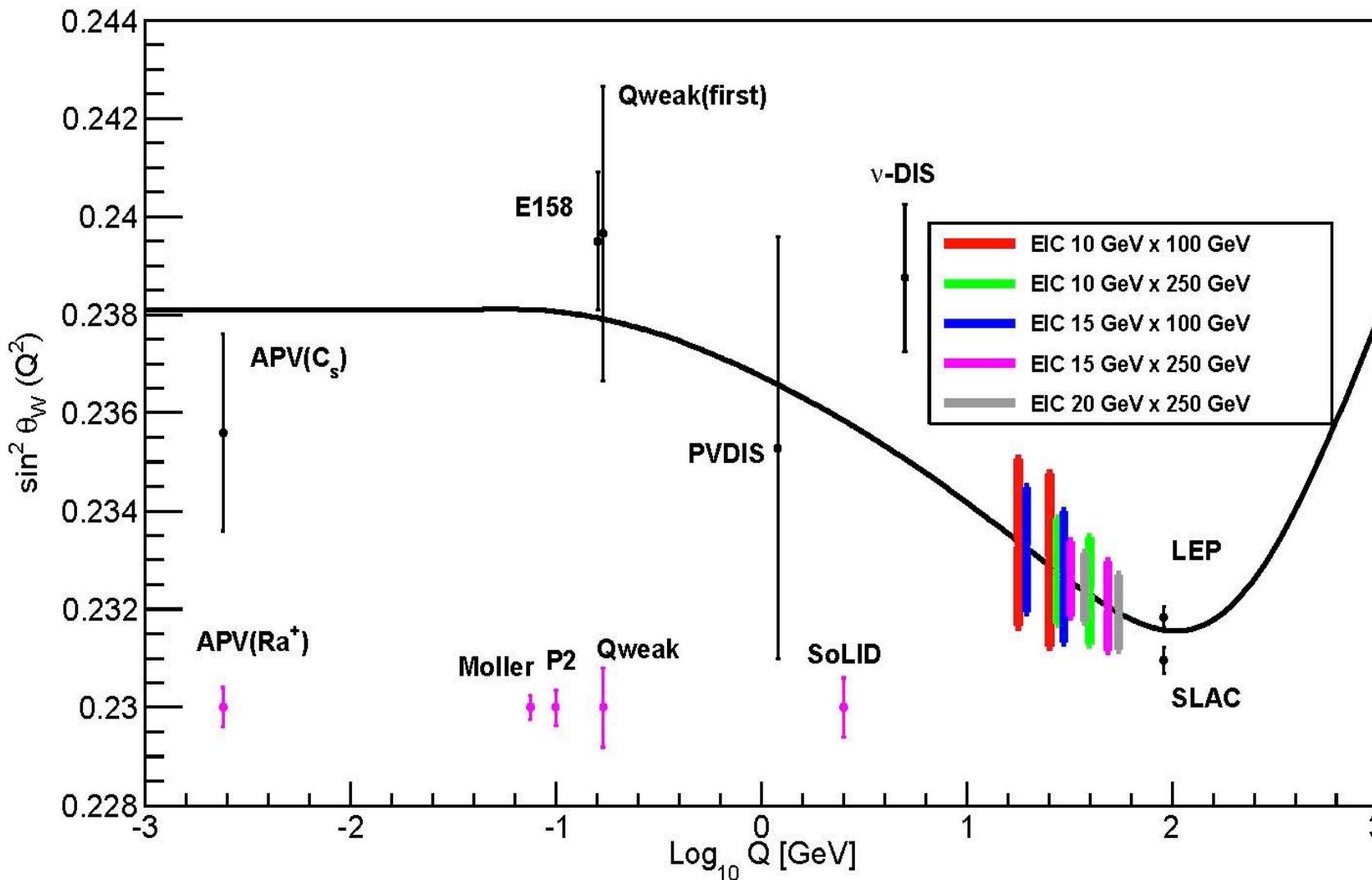
$$g_5^{n, \gamma Z} = \frac{1}{3}(\Delta d_V + \Delta s - \Delta \bar{s}) + \frac{1}{6}(\Delta u_V + \Delta c - \Delta \bar{c})$$

$\delta A/A$ for e-D collisions



- Polarimetry $\sim 1\%$ at the beginning and then 0.5% for higher energy and higher luminosity
- Alex's R&D proposal : target at 1%
- Experience:
Parity experiments drive the precision frontier of electron polarimetry: SLAC, PREX/CREX, MOLLER, SoLID

World data of $\sin^2 \Theta_w$ including EIC projections



- 200 days of dedicated run
- Can reach similar precision to SoLID measurement
- Interesting Q^2 region never been measured or planned

Tracking Calibration

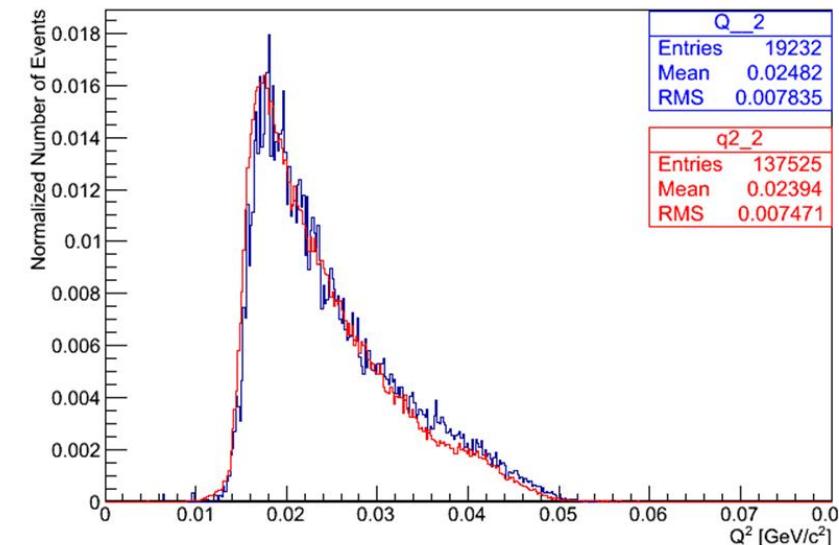
$\langle A(Q^2) \rangle$ is measured

$A(\langle Q^2 \rangle)$ is reported

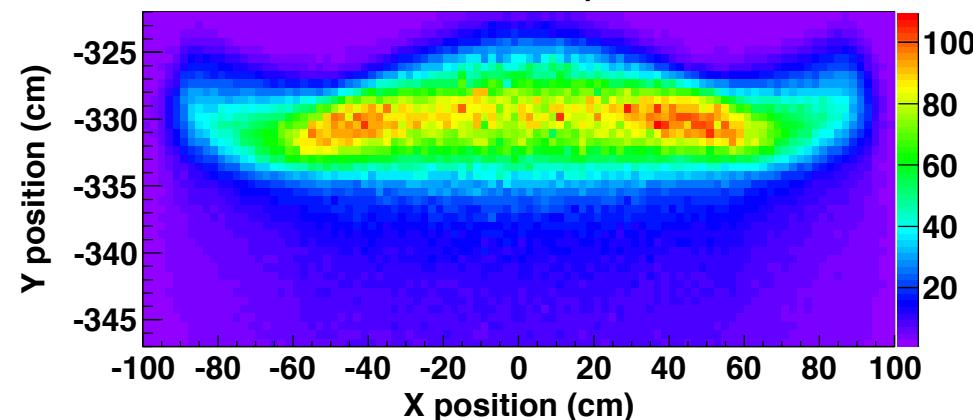
Simulation (using survey, field map)
estimates the Q^2 distribution.

Spatial distributions are verified against
tracking distributions

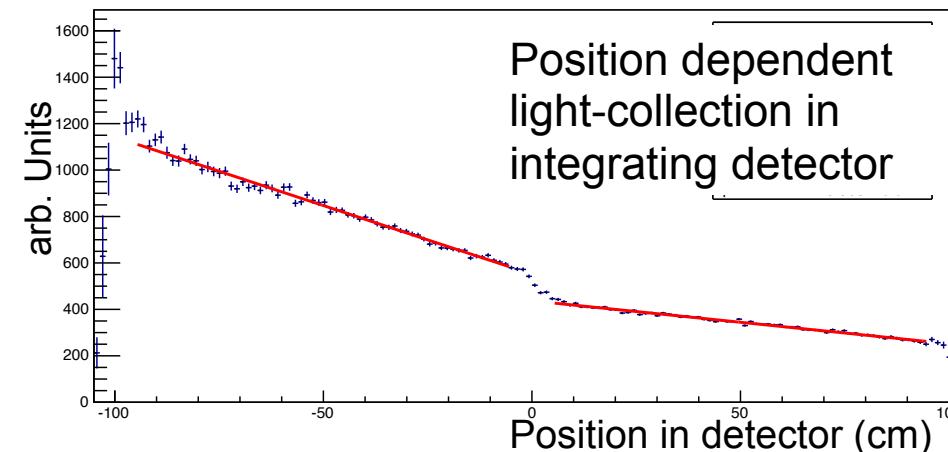
Q^2 distribution (simulation & data)



Hit distribution in quartz bar



Position dependent
light-collection in
integrating detector

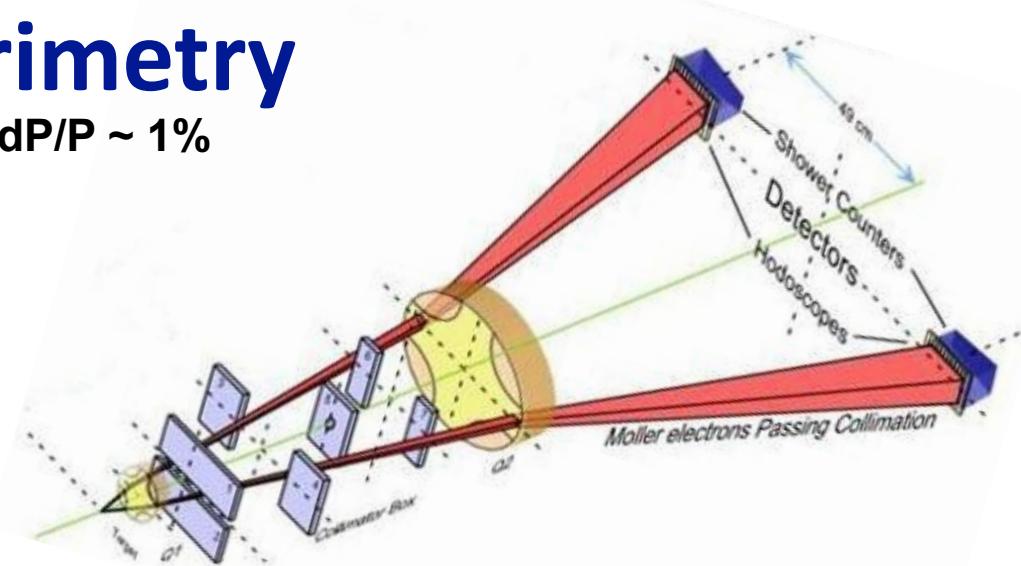


Polarimetry

Goal: $dP/P \sim 1\%$

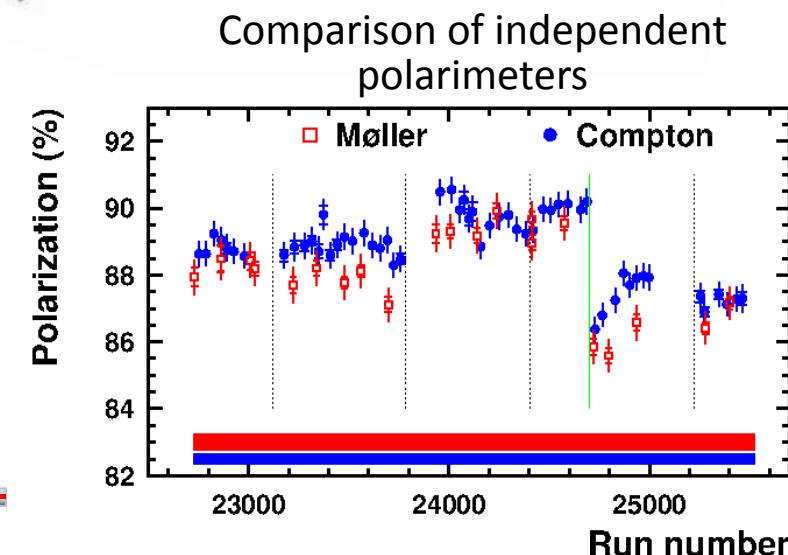
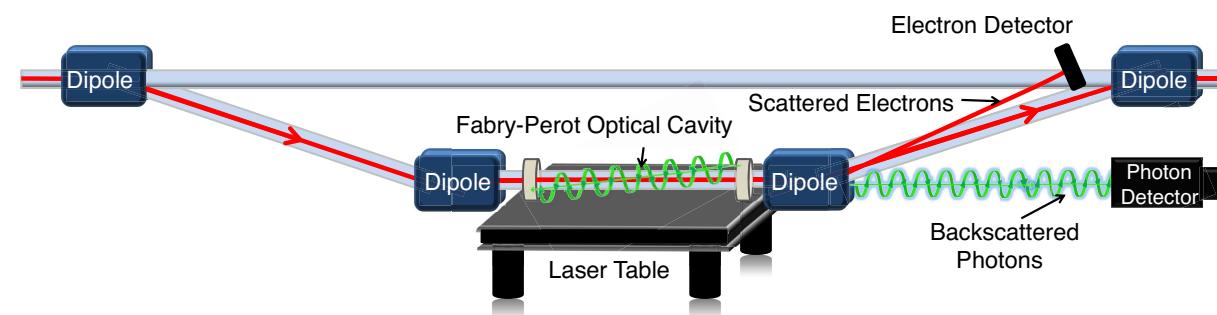
Møller: $e e$ scattering off polarized iron foil

- saturated iron
- experience with $\sim 1\%$ 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

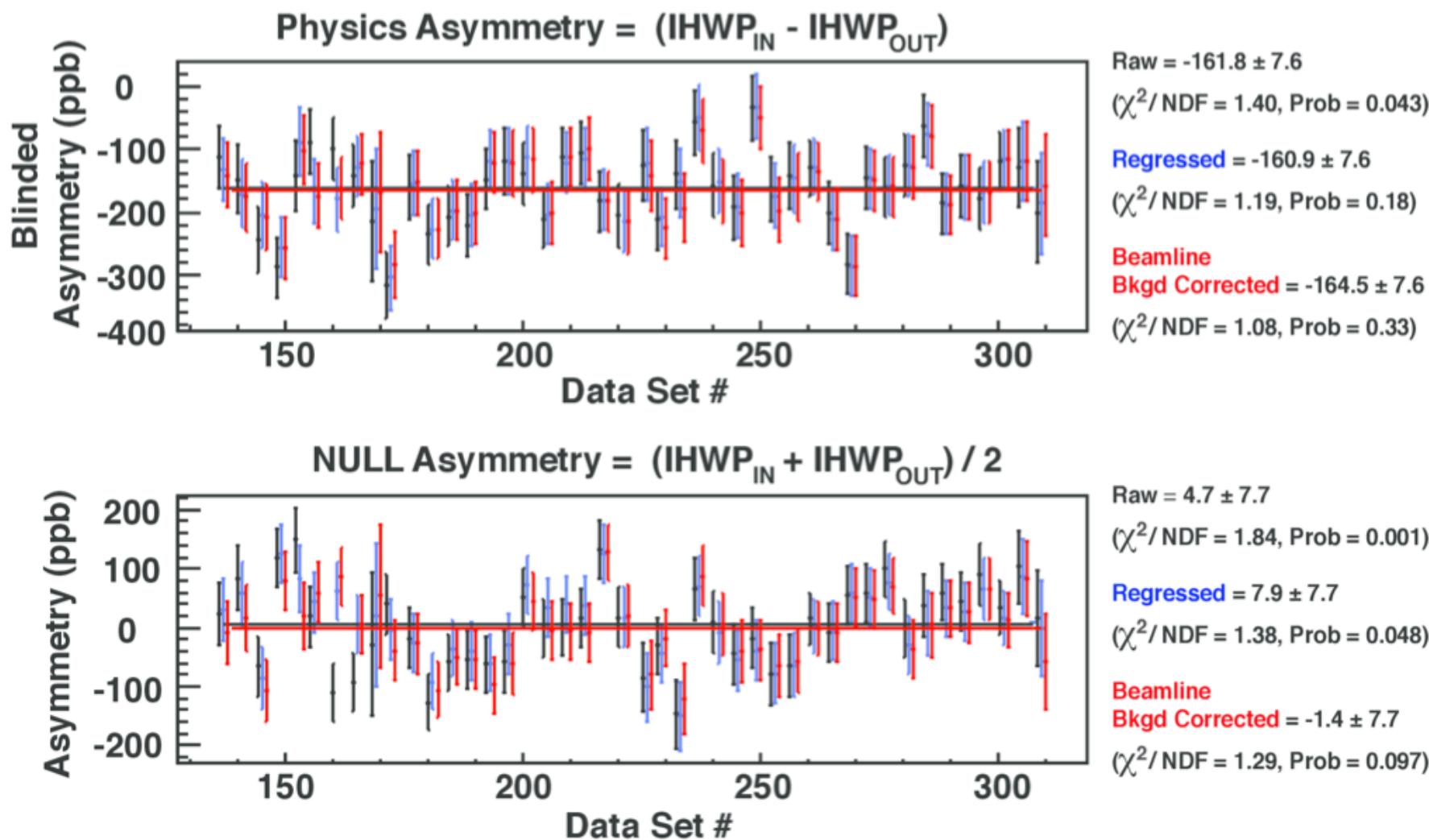


Important milestone for high precision polarimetry needed for future program

Physical Review X6 (2016) no.1, 011013

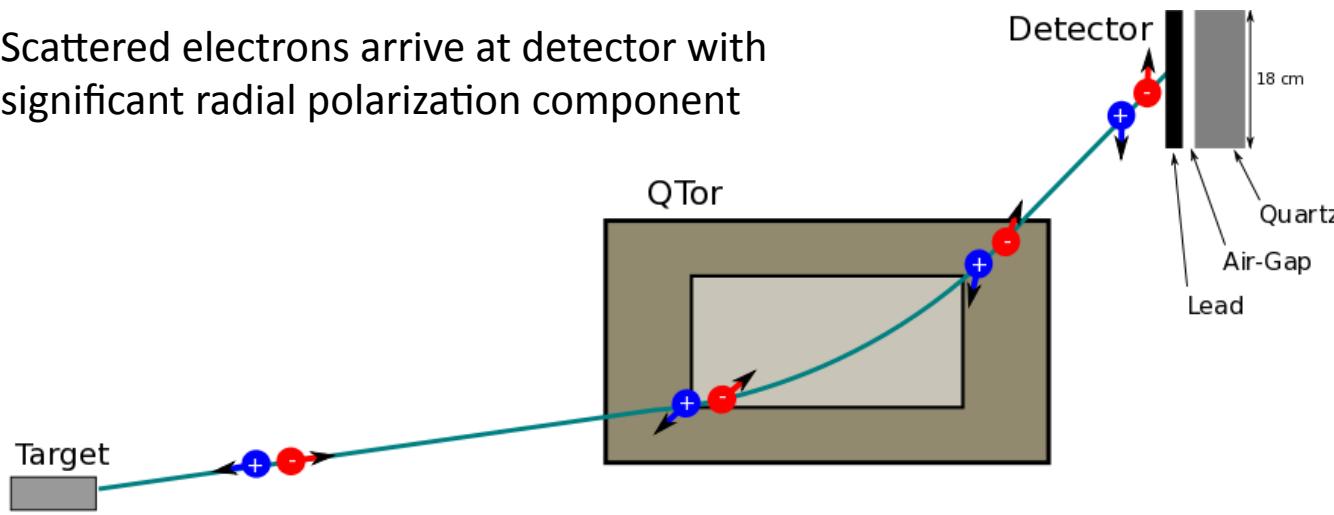
Qweak - Blinded Asymmetries (Run 2)

Measured asymmetry, Statistical uncertainty only.
Not scale corrected (P_{beam} , backgrounds, etc.)



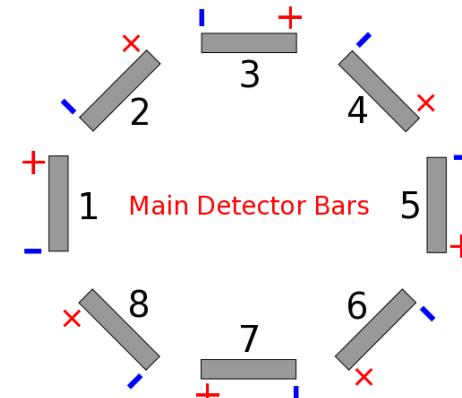
Polarization sensitive detector

Scattered electrons arrive at detector with significant radial polarization component



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

$$A_{PMTDD} = A_- - A_+$$

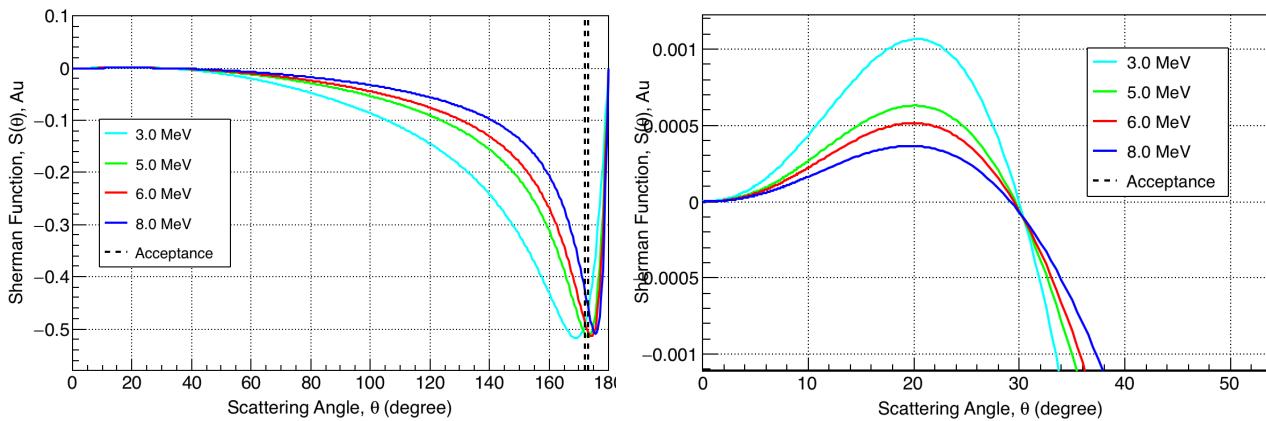
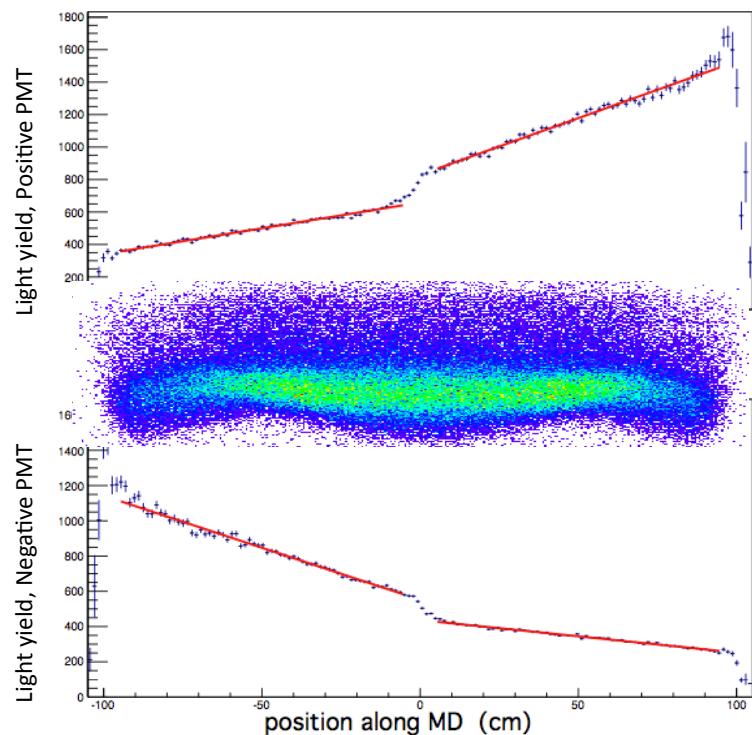


At first order, this cancels, since we measure an average of the two PMTs

$$A_{PV} = (A_- + A_+)/2$$

Polarization sensitive detector

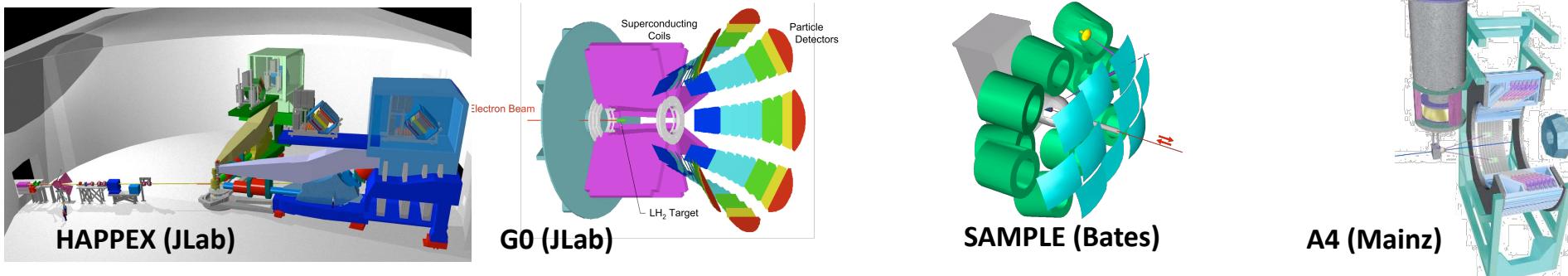
Mott scattering has asymmetry at low energy, so shower through radiator can become polarization-dependent



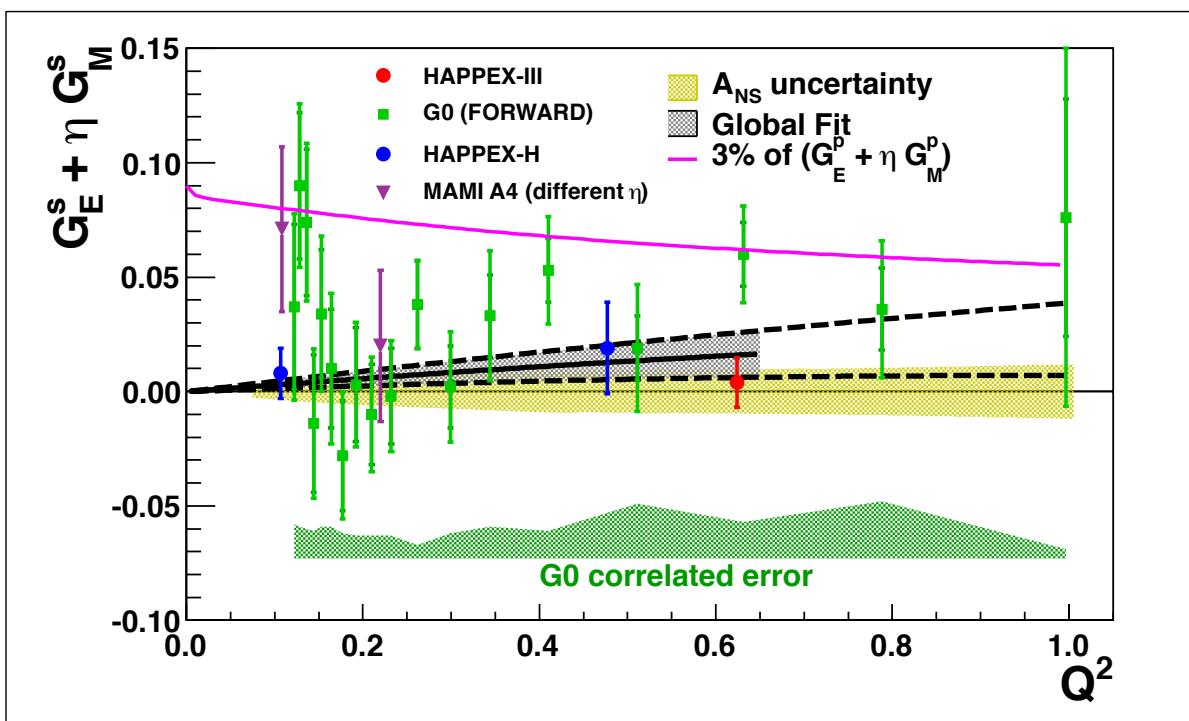
- Imperfect cancellation depends on imperfections in the bar light collection and alignment
- MC simulation is being used to investigate how precisely we know this cancellation

Last significant systematic uncertainty before result is complete

Weak Vector Form Factors at low Q^2



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



$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$

$$G_M^p = \frac{2}{3}G_M^{u,p} - \frac{1}{3}G_M^{d,p} - \frac{1}{3}G_M^s$$

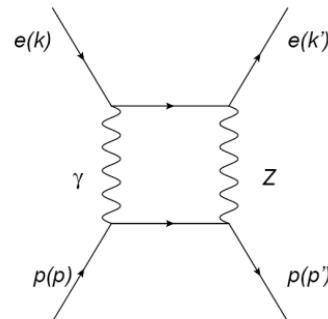
Probing over a range of low- Q^2 , strange effects are small (<3%) and consistent with zero.

Whatever the cause - proton structure effects in A_{PV} must go to zero at $Q^2 = 0$

Electroweak Corrections

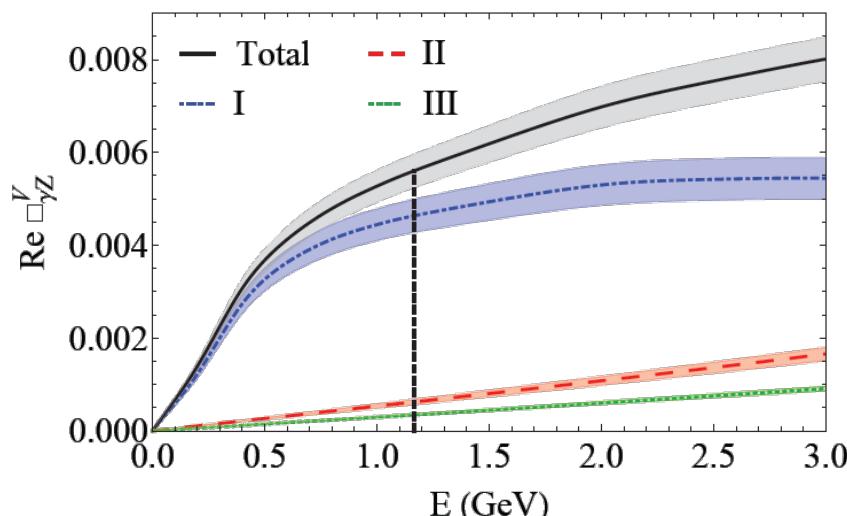
$$Q_W^p = [\rho_{NC} + \Delta_e] \left[1 - 4 \sin^2 \hat{\theta}_W(0) + \Delta'_e \right] + \square_{WW} + \square_{ZZ} + \square_{\gamma Z}$$

new (energy dependent) γZ box corrections must be considered



Authors	Vector Y-Z rad.
Gorchtein & Horowitz, PRL 102 , 091806 (2009)	0.0026 ± 0.0026
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

Significant theoretical work,
converging on precise calculation



γZ - box is E & Q^2 dependent

~7% correction at Q^2 weak kinematics,
but now well estimated

Similar corrections are required for all
data in the fit

First Results

Qweak had ~ 1 calendar year of beam split into 3 running periods

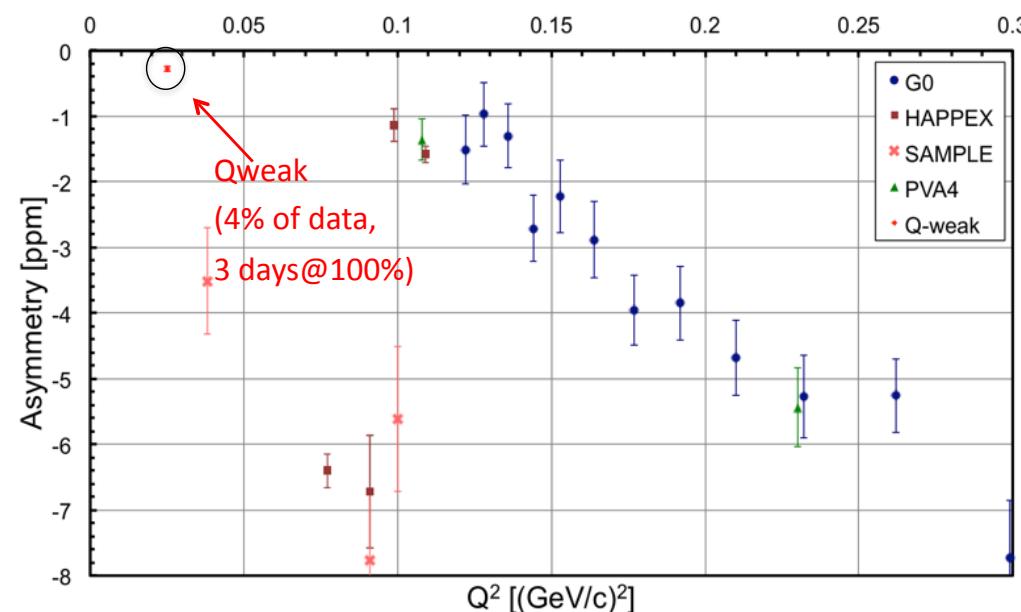
Each period had its own “blinding factor” for unbiased analysis

- Run 0: January – February 2011 (commissioning data)
- Run 1: February – May 2011
- Run 2: November 2011 – May 2012

“Run 0” results (about 1/25 of data set) were published in PRL in Oct. 2013

$$A_{PV} = -279 (35)(31) \text{ ppm}$$

$$Q^2 = 0.0250 \pm 0.0006 \text{ (GeV/c)}^2$$



Significant corrections:

- Aluminum background (3% fraction, but 10x the asymmetry.)
- Transverse polarization

These (and other ancillary measurements) are themselves valuable physics results

- Beam asymmetries
- Beamline background

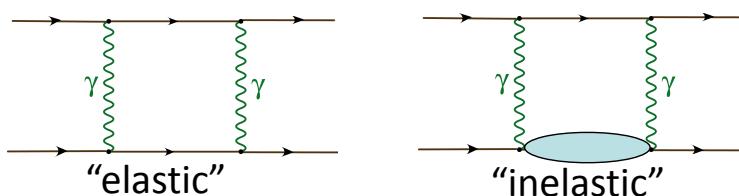
Required significant work to improve

All systematic errors reduced in final data set

Transverse Asymmetry

Beam-Normal Asymmetry in elastic electron scattering

Electron beam polarized transverse to beam direction



Interference between one- and two-photon exchange

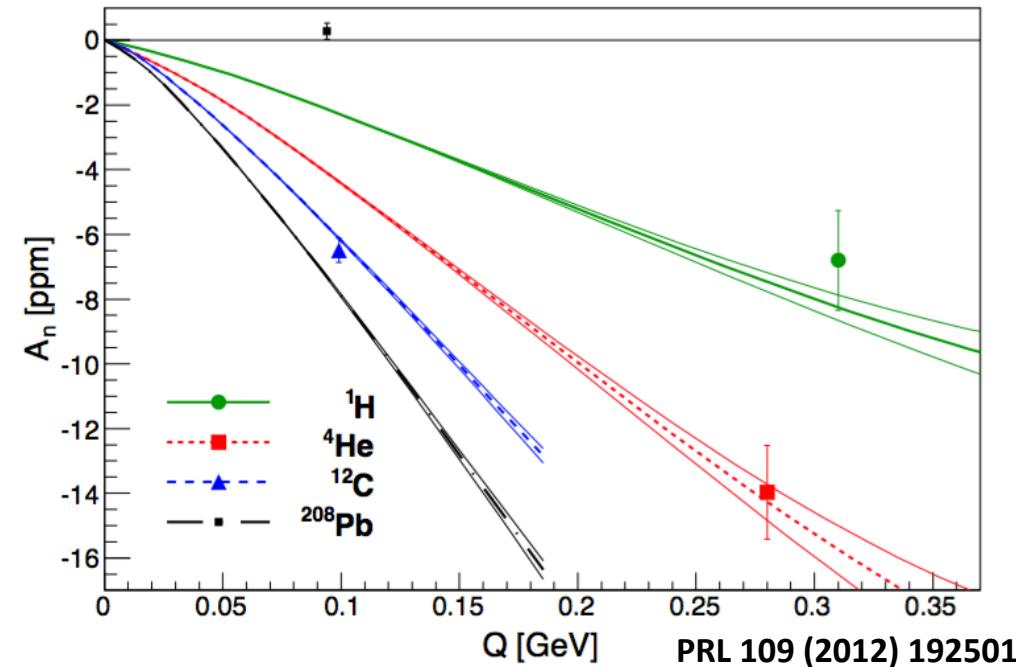
- Inelastic intermediate states enhance this asymmetry
- measured for several nuclei
- ~4ppm for Qweak
- Potential systematic error if poorly cancelled
- Well bounded by polarimetry, check on geometric averaging
- Measured also by Qweak, on hydrogen and Aluminum

$$A_T = \frac{2\pi}{\sigma^\uparrow + \sigma^\downarrow} \frac{d(\sigma^\uparrow - \sigma^\downarrow)}{d\phi} \propto \vec{S}_e \cdot (\vec{k}_e \times \vec{k}'_e)$$

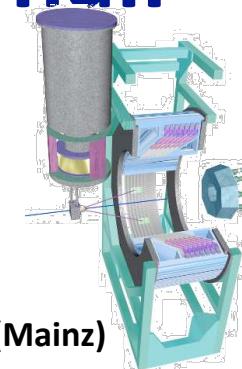
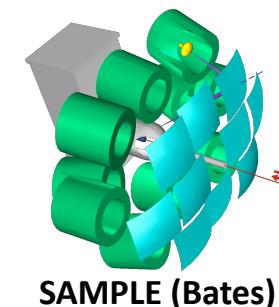
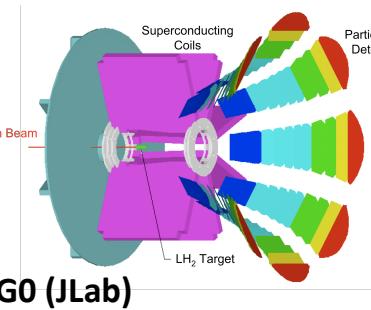
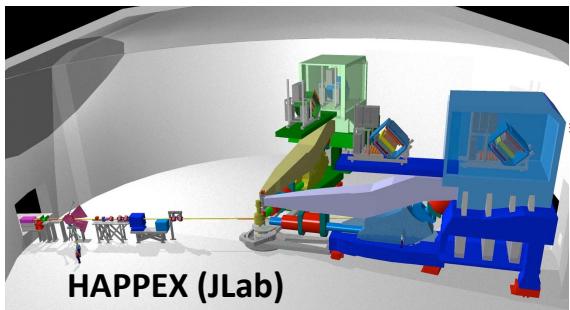
$$A_T \propto \frac{\alpha m_e}{\sqrt{S}}$$

Effect suppressed by

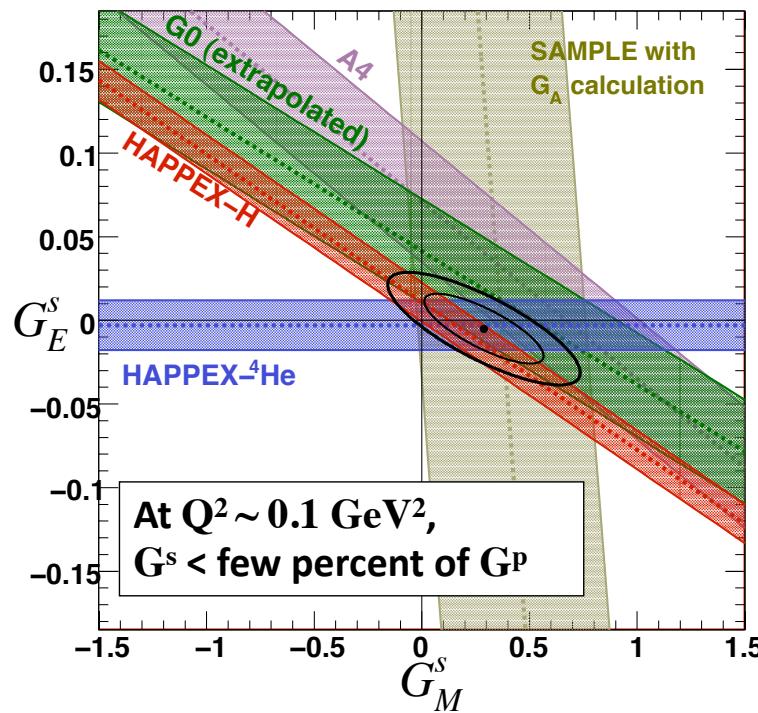
- α
- Lorentz boost



Strange Vector Form Factors Are Small



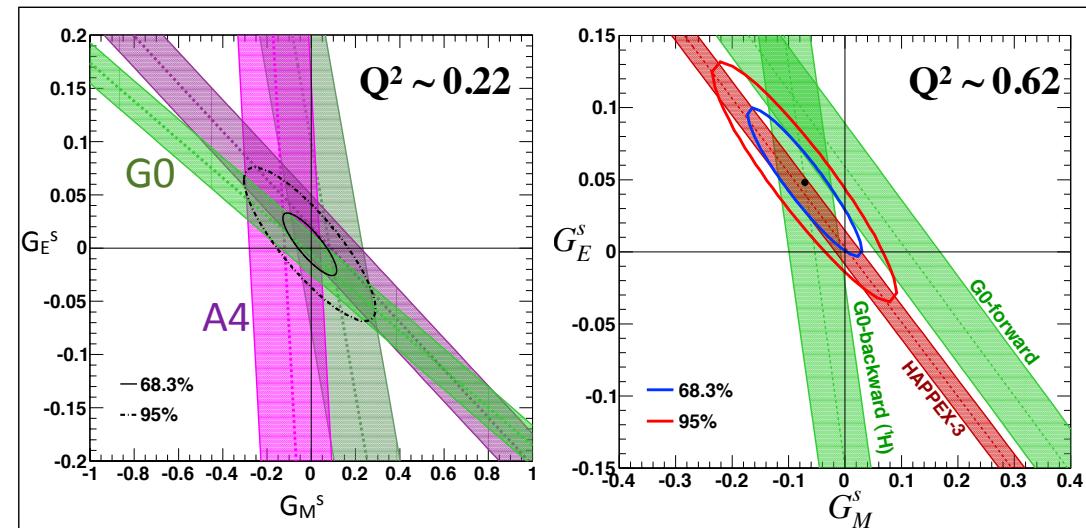
Form factors for elastic scattering



$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$

$$G_M^p = \frac{2}{3}G_M^{u,p} - \frac{1}{3}G_M^{d,p} - \frac{1}{3}G_M^s$$

Probing over a range of low- Q^2 , effects are small (<3%) and consistent with zero.



Whether strange quarks, charge symmetry breaking, axial contributions - proton structure effects in A_{PV} must go to zero at $Q^2 = 0$

The Axial Term and the Anapole Moment

Axial form-factors G_A^p, G_A^n

$$\tilde{G}_A^{p,n} = -\tau_3(1 + R_A^{T=1})G_A^{(3)} + \sqrt{3}R_A^{T=0}G_A^{(8)} + \Delta s$$

- Determined at $Q^2=0$ from neutron and hyperon decay parameters (isospin and SU(3) symmetries)
- Q^2 dependence often assumed to be dipole form, fit to ν DIS and π electroproduction
- Includes also Δs , fit from ν -DIS data (with significant uncertainties)

Anapole Moment Correction:

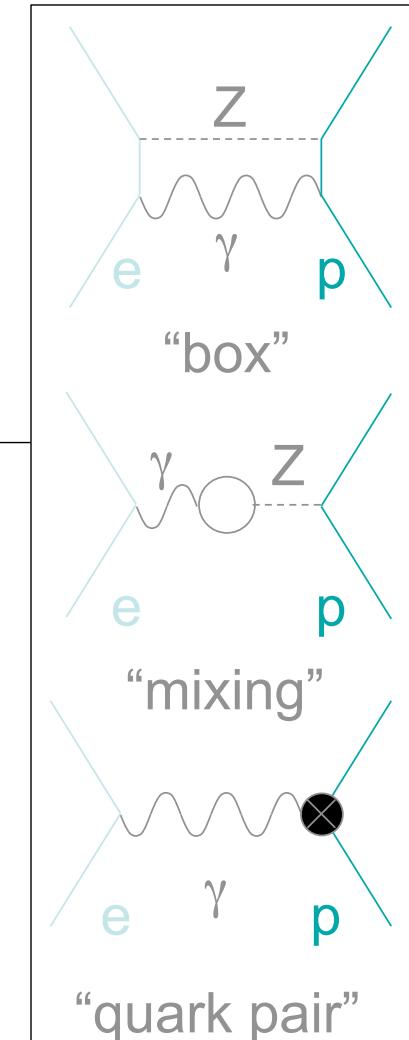
Multiquark weak interaction in $R_A^{(T=1)}, R_A^{(T=0)}$

Zhu, Puglia, Holstein, Ramsey-Musolf, Phys. Rev. D **62**, 033008

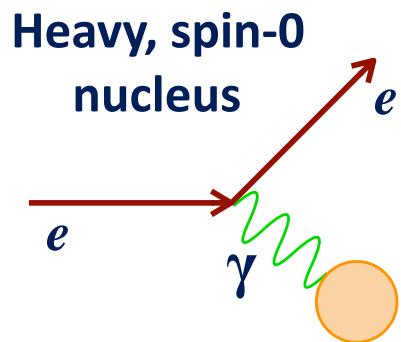
- Model dependent calculation, with large uncertainty (~30% on axial FF)
- Dominates Uncertainty in Axial Term

Difficult to achieve tight experimental constraint

Reduced in importance for forward-angle measurements



Elastic electron scattering

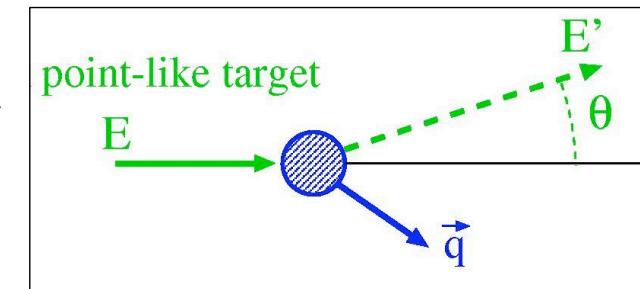


Q^2 : (4-momentum)² of the virtual photon

Improved resolution with increasing momentum transfer

$$Q^2 = 4EE' \sin^2 \frac{\theta}{2}$$

$$Q \approx \frac{hc}{\lambda}$$

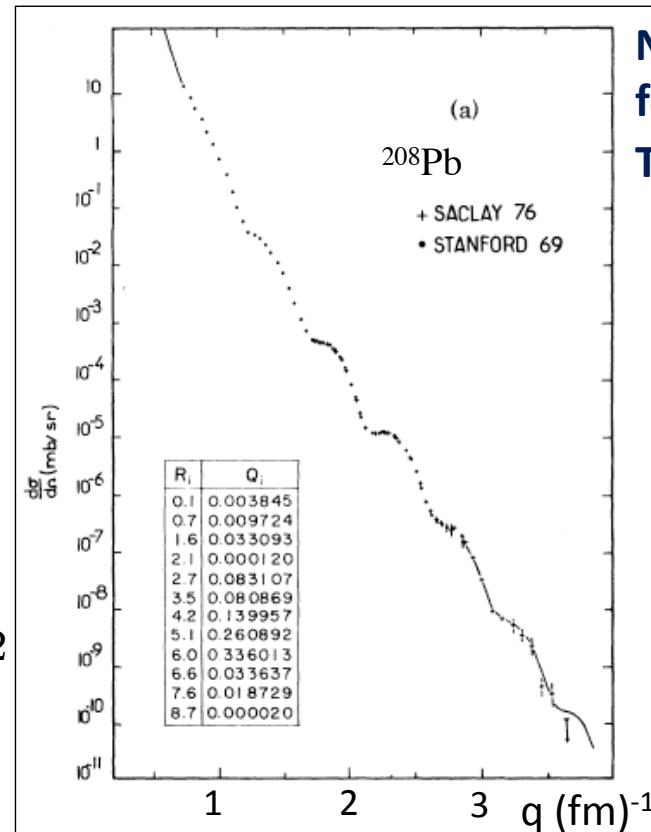


Differential cross-section

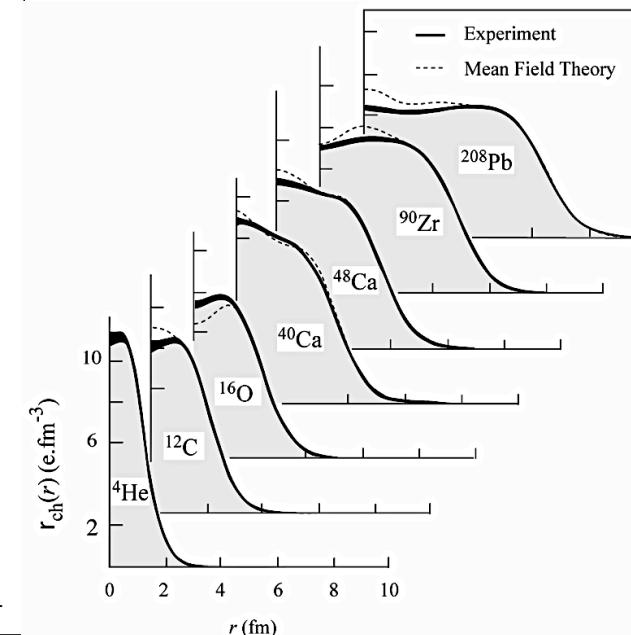
$$\left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} = \frac{4Z^2 \alpha^2 E^2}{Q^4}$$

As Q increases, nuclear size becomes important correction

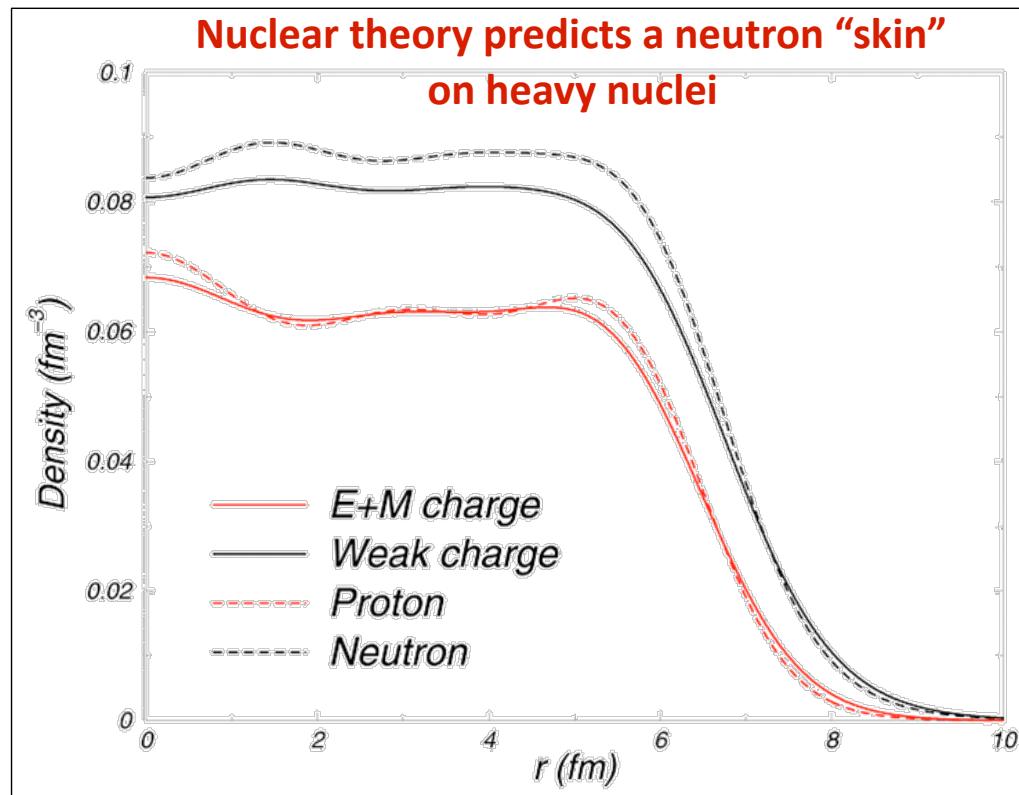
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} |F(q)|^2$$



Neglecting relativistic recoil, the form-factor $F(q)$ is the Fourier Transform of charge density



Weak Charge Distribution of Heavy Nuclei



Neutron distribution is not accessible to the charge-sensitive photon.

	proton	neutron
Electric charge	1	0
Weak charge	~ 0.08	1

for spin-0 nucleus

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

knowledge of r_n highly model dependent

Symmetry energy of nuclear matter =
the energy cost of $N \neq Z$

r_n calibrates the Equation of State of
neutron rich matter

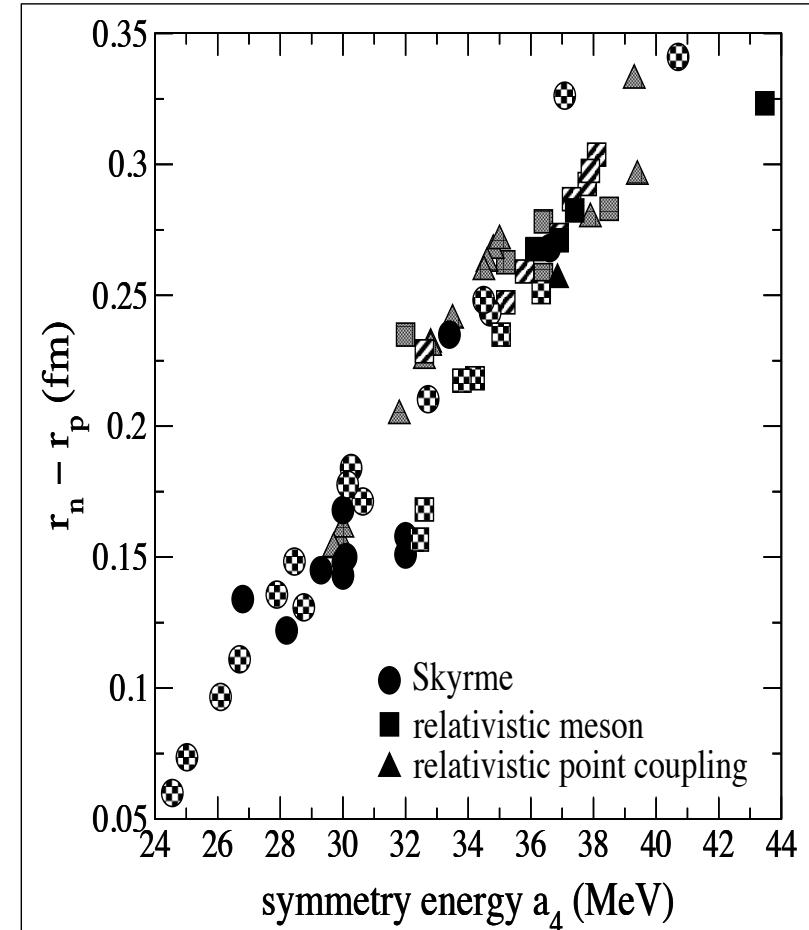
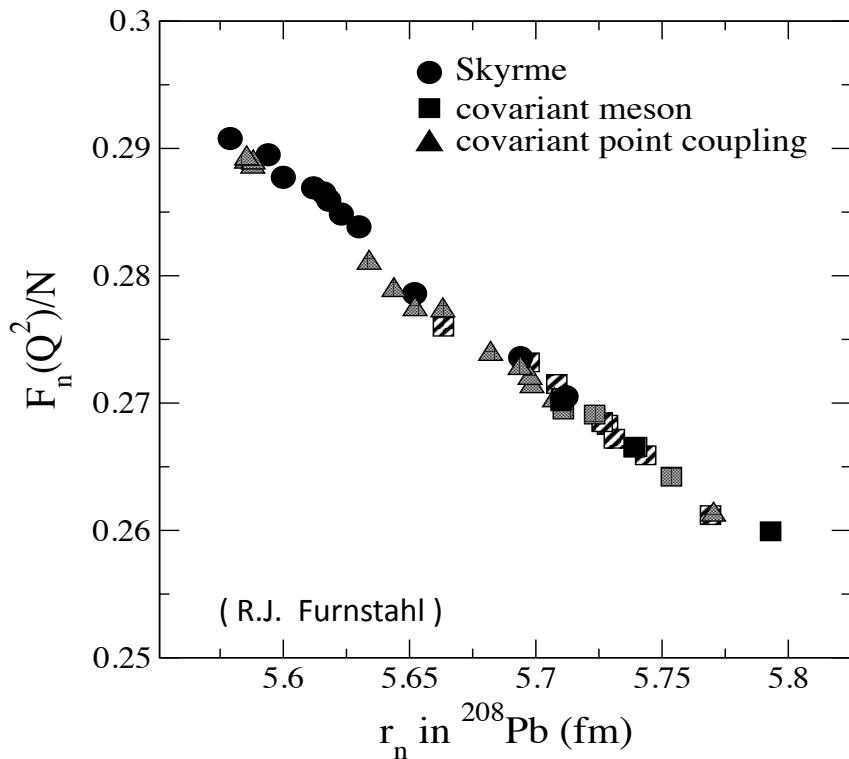
PVES provides a clean probe of the
neutron distribution

PREX: A_{PV} to 3% from ^{208}Pb
-> r_n to 0.06 fm

CREX: A_{PV} to 2.5% from ^{48}Ca
-> r_n to 0.02 fm

Weak Charge Distribution and Symmetry Energy

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



r_n in ^{208}Pb provides input to models to pin density dependence of symmetry energy

(see also M. Miorelli, Poster)

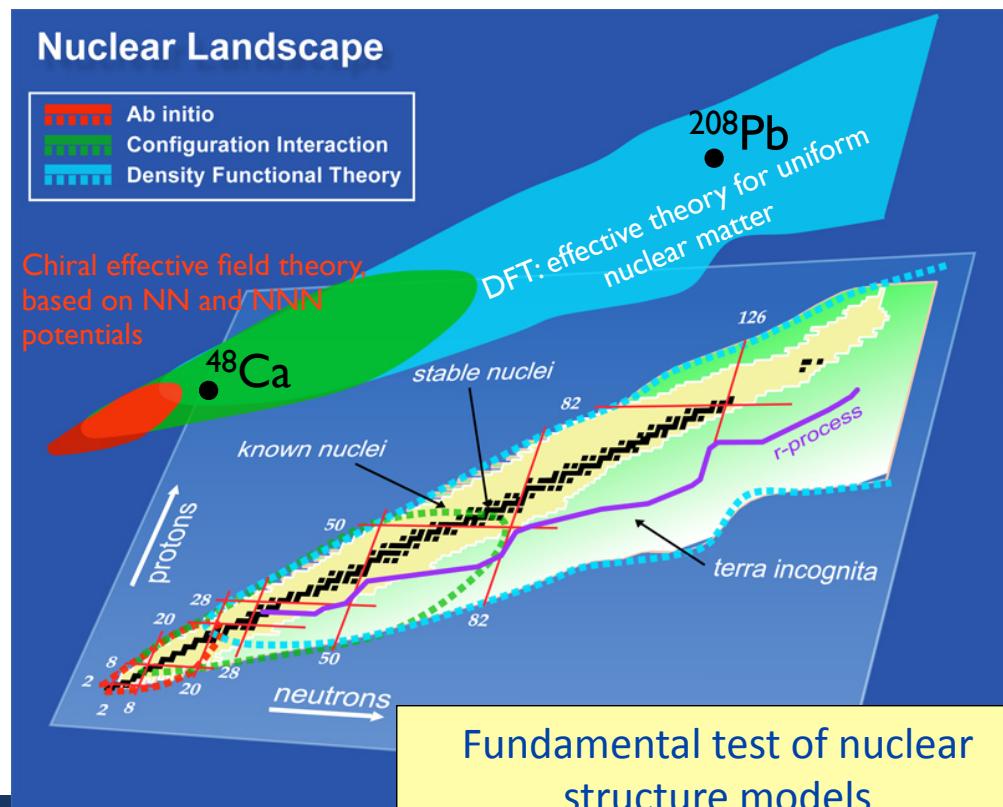
r_n and Nuclear Structure

^{208}Pb :

- uniform nuclear matter
- terrestrial laboratory to test n-star structure

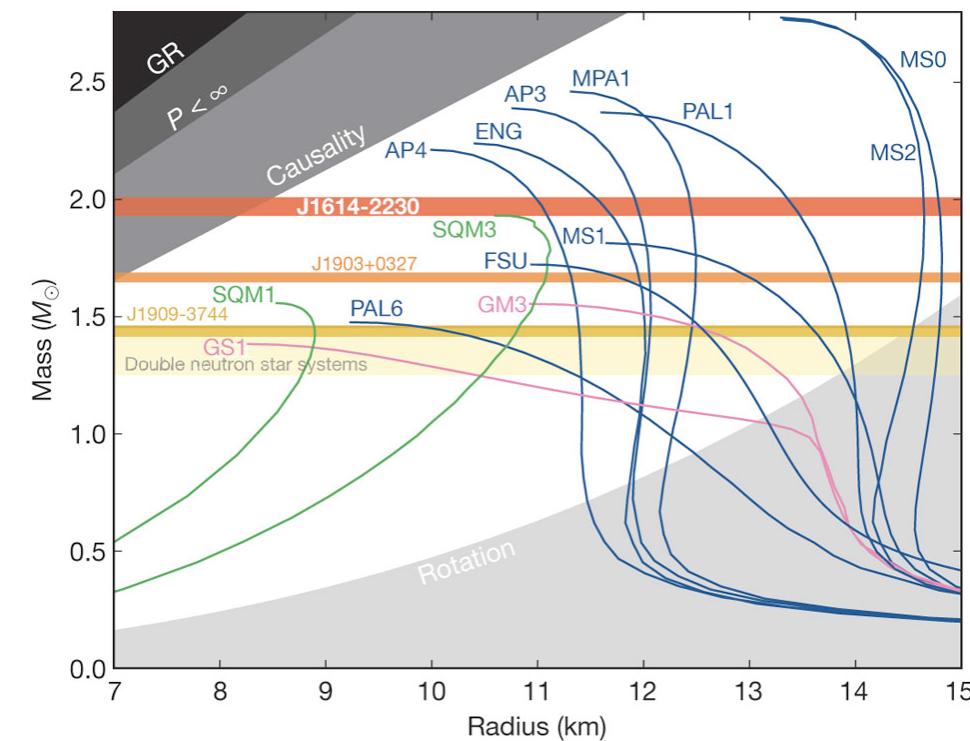
^{48}Ca :

- finite size effects.
- Within reach of microscopic calculations



- Important calibration point for FRIB studies
- $\rho(n)$ corrections to atomic PV

$^{208}\text{Pb } r_n$ crucial information for neutron star E.o.S.



- Mass/radius ratio, compare to observation
- cooling mechanisms (URCA or not)



neutron Skin at JLab

$Q^2 \sim 0.01 \text{ GeV}^2$

5° scattering angle

$A_{PV} \sim 0.6 \text{ ppm}$

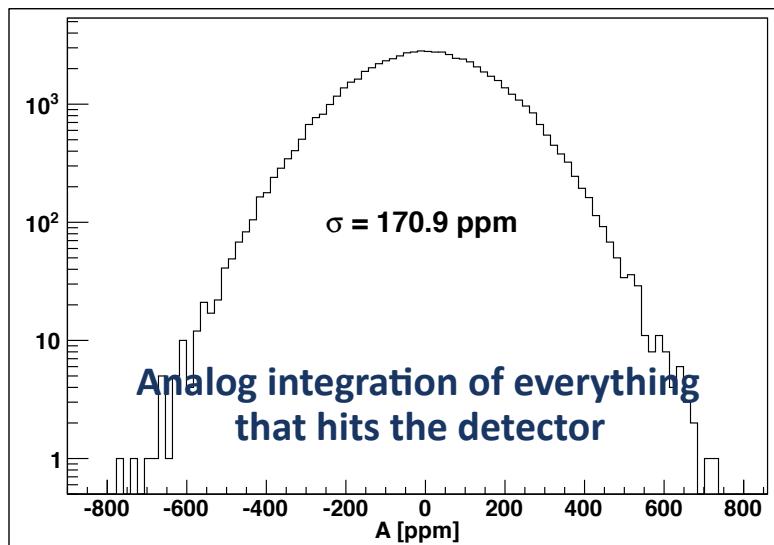
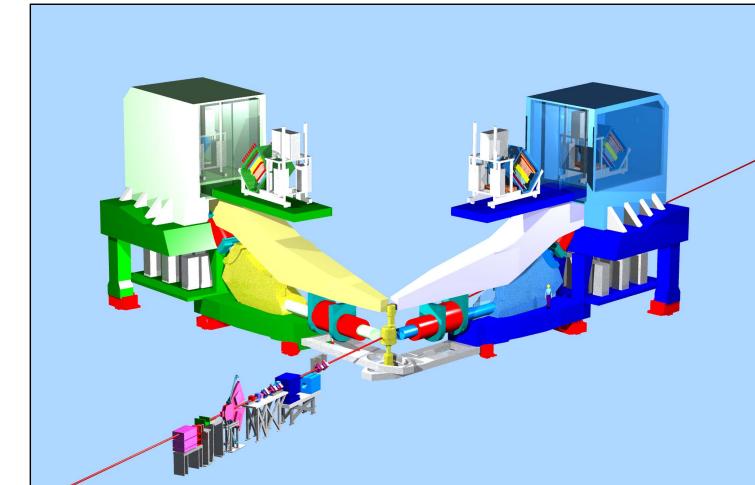
Rate $\sim 1.5 \text{ GHz}$

PREX-I (2012):

$A_{PV} = 0.657 \pm 0.060(\text{stat}) \pm 0.014(\text{sys}) \text{ ppm}$

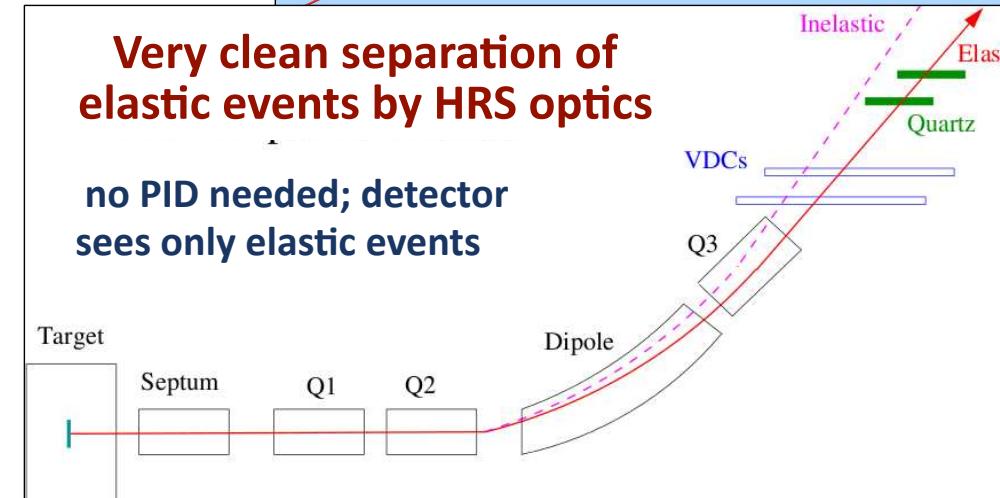
$r_n - r_p = 0.33 + 0.16 - 0.18 \text{ fm}$

- 0.5 mm ^{208}Pb foil, 70 μA
- 5° scattering
- $P_b \sim 90\% \pm 1\%$



Very clean separation of elastic events by HRS optics

no PID needed; detector sees only elastic events



2018: PREX (3% A_{PV} , r_n to 0.06 fm), CREX (2.5% A_{PV} , r_n to 0.02 fm)