High Flux Parity Experiments at JLab:
PREX, CREX and MOLLER

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(for the PREX/CREX and MOLLER Collaborations)

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PREX, CREX and MOLLER

Outline

- Introduction to Parity-Violating Electron Scattering
  - Why PVES?
  - Experiment blueprint, ”how-to”, and technical progress
- PREX-II/CREX at Jefferson Laboratory
  - Experimental Concept and techniques
  - PREX-I result
- MOLLER at Jefferson Laboratory
  - Møller A_{PV} measurement
  - MOLLER motivation and ”reach”
  - Apparatus overview
- Summary and Future Plans

Why Parity-Violating Electron Scattering?

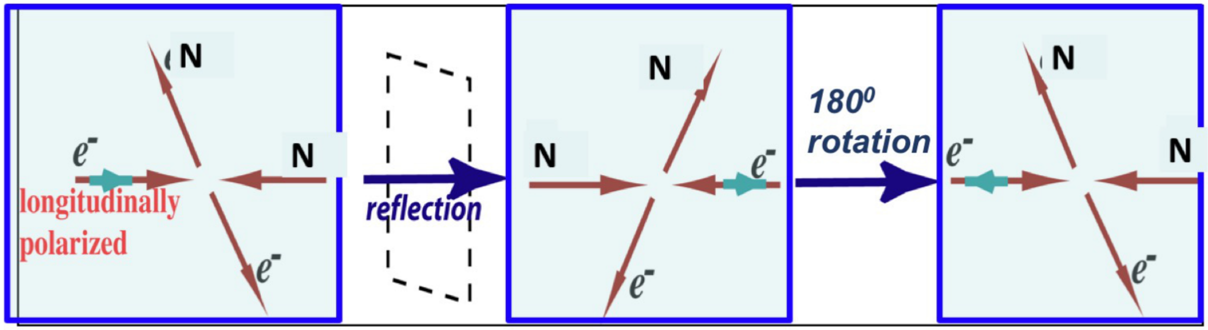
Provides model-independent determinations of nuclear and fundamental-particle weak-charge form factors and couplings with widespread implications for:

- Understanding nuclear and nucleon structure
  - Strange quark content of nucleon
  - Neutron radii of heavy nuclei $\longrightarrow$ density dependence of Symmetry Energy and EOS of nuclear matter; neutron stars; calibrate hadronic probe reactions on radioactive beams
- Search for physics Beyond the Standard Model (BSM)
  - Indirect searches using low energy ($Q^2 << M_Z^2$) precision electroweak tests at high intensity or precision frontier
  - complements direct searches at high energy frontier

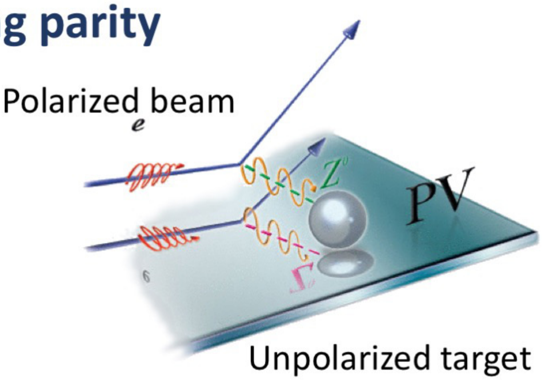
JLab PVES Programs: HAPPEX, G0, PVDIS, PREX, Qweak, CREX MOLLER, SoLID

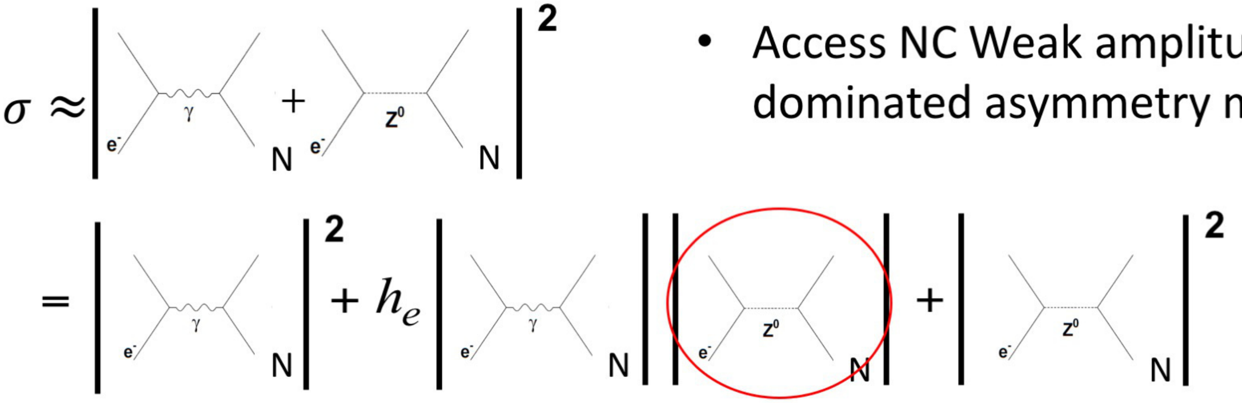
Parity-Violating Electron Scattering

Parity Transformation: Changing beam helicity equivalent to changing parity



Right-handed P-V Signature Left-handed





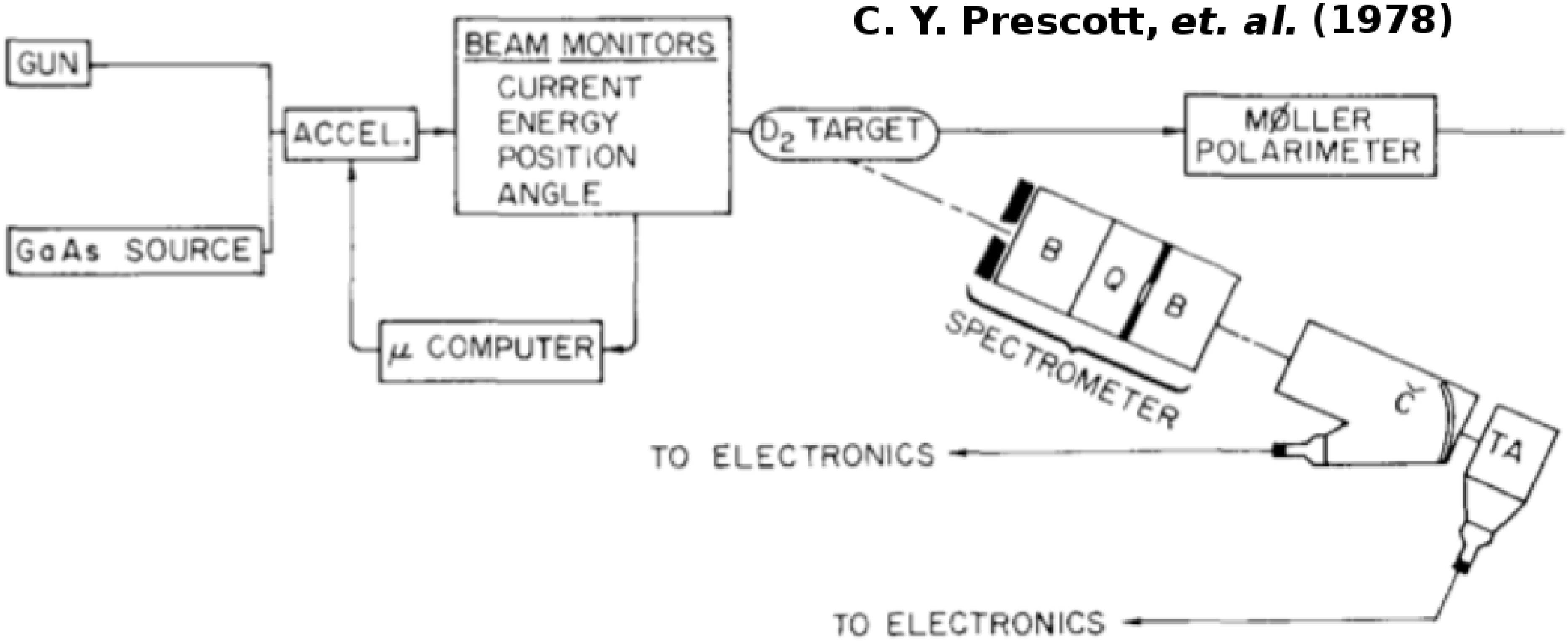
- Access NC Weak amplitude via EW interference-dominated asymmetry measurement

- Flip sign of longitudinal polarization
- Measure fractional rate difference or asymmetry

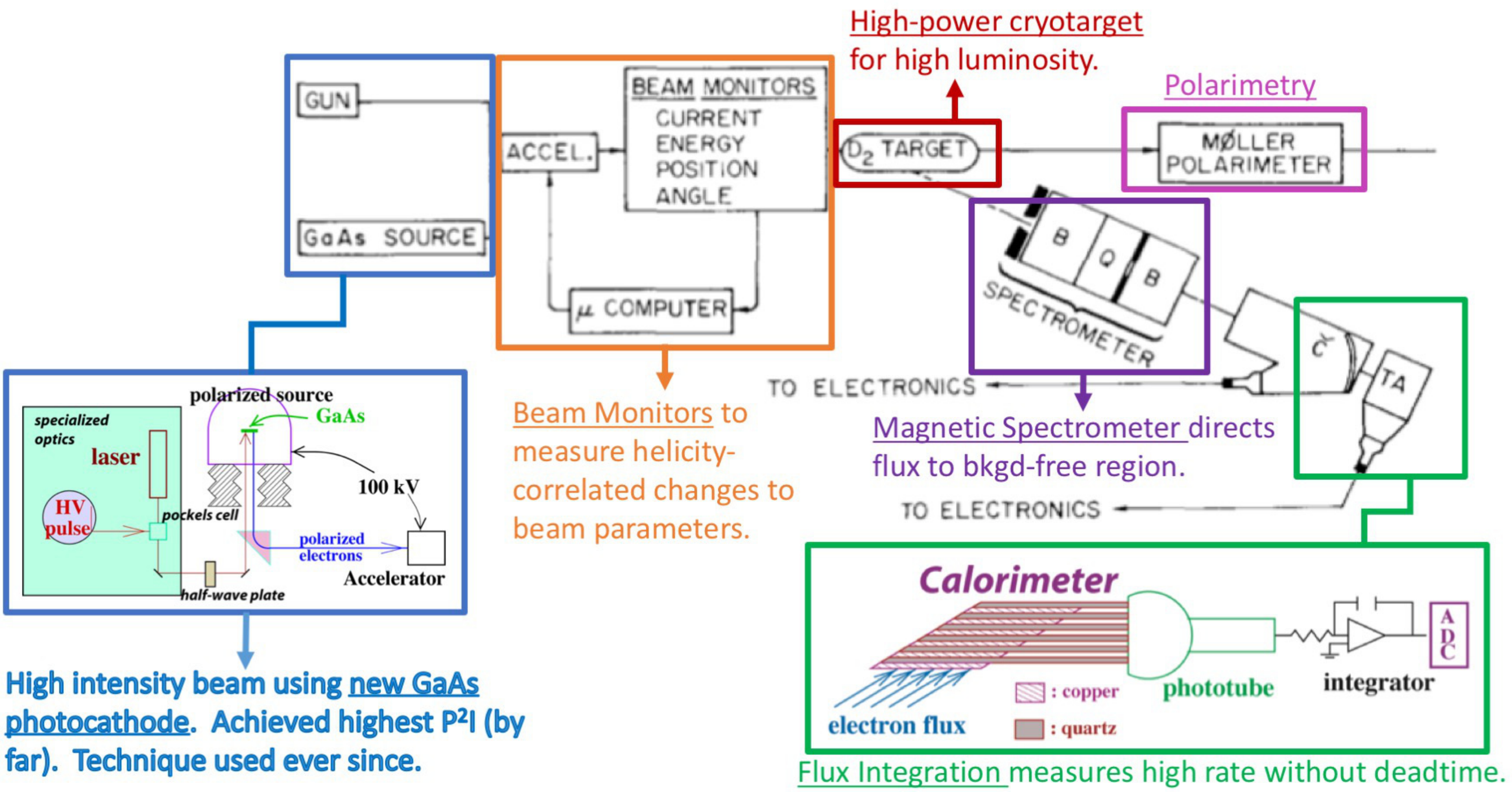
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{\boxed{M^{NC}_{Weak}}}{M_{EM}} \approx \frac{G_F Q^2}{4\pi\alpha} \sim 10^{-4} \cdot Q^2\ [/\mathrm{GeV}^2]$$

Blueprint of a PVES Experiment
(E122 at SLAC)

C. Y. Prescott, *et. al.* (1978)



Anatomy of a PVES Experiment (E122 at SLAC)



High-power cryotarget for high luminosity.

Polarimetry

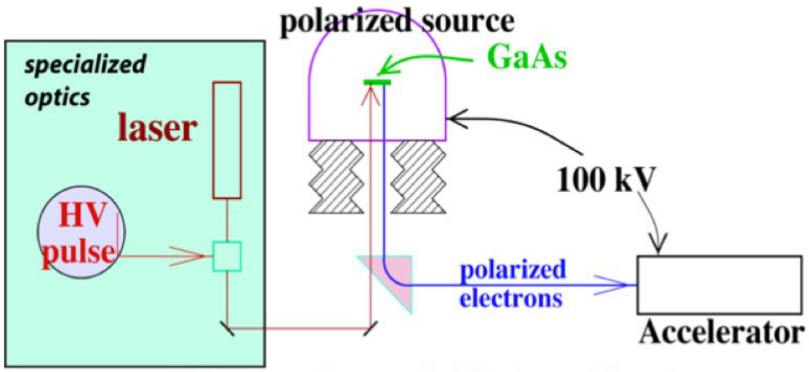
Beam Monitors to measure helicity-correlated changes to beam parameters.

Magnetic Spectrometer directs flux to bkgd-free region.

High intensity beam using new GaAs photocathode. Achieved highest P^{2}I (by far). Technique used ever since.

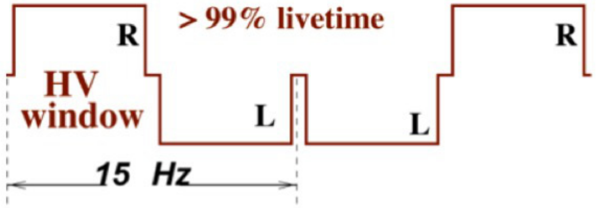
Flux Integration measures high rate without deadtime.

How to do a Parity Experiment



rapid, random, helicity flipping

Rapid, Random Helicity Flips



Measure flux F for each window

$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

Signal Average N Windows Pairs: $A \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}$

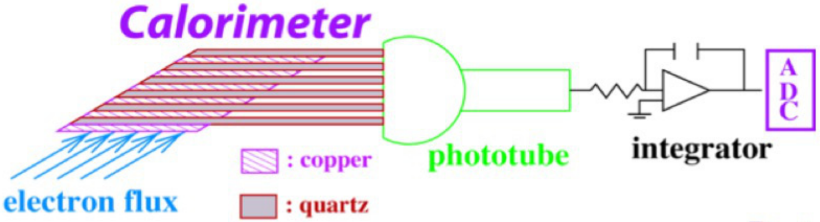
Flux Integration Technique:

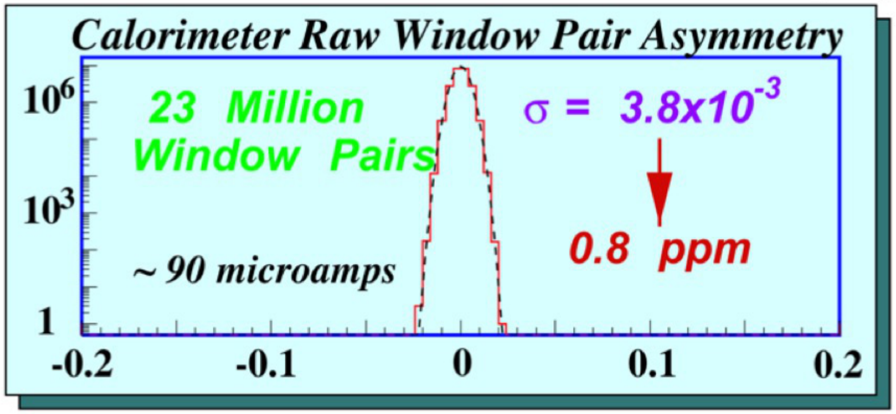
HAPPEX: 2 MHz $(A_{PV} \sim 15\text{ppm})$

HAPPEX-II: 100 MHz $(A_{PV} \sim 1.5\text{ppm})$

PREX: 1 GHz $(A_{PV} \sim 0.5\text{ppm})$

MOLLER: 150 GHz $(A_{PV} \sim 0.035\text{ppm})$





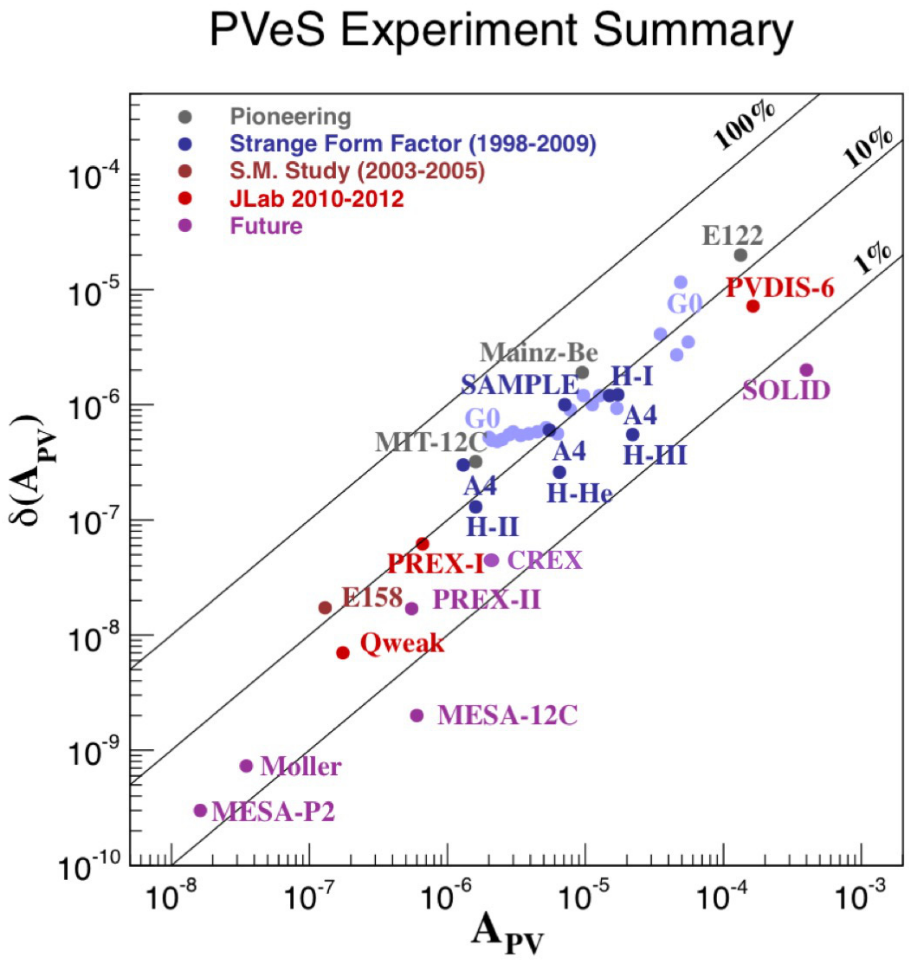
No non-gaussian tails to +/- 5σ

Detector signal noise dominated by electron counting statistics

3 Decades of Technical Progress

photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, rad-hard dets

1st generation
2nd generation
3rd generation
4th generation

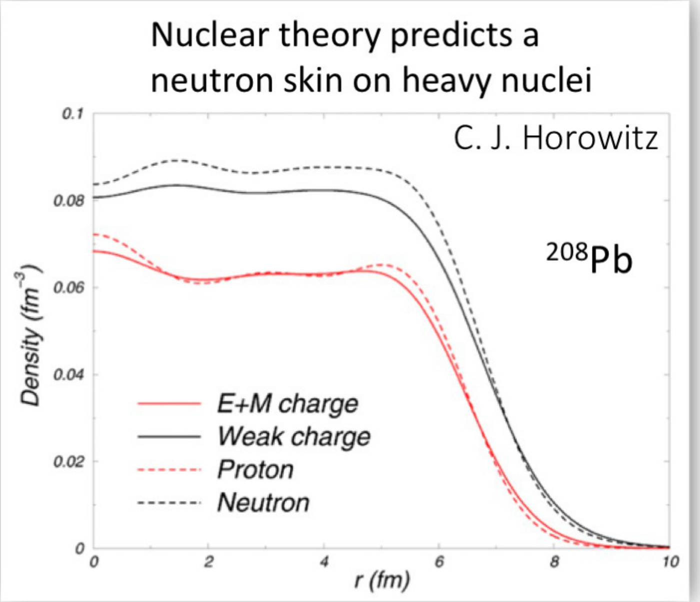


E122 – 1st PVES Expt (late 70's at SLAC)
Mainz & MIT-Bates in mid 80's
JLab program launched in mid 90's
E158 at SLAC meas PV Møller scattering

- Parity-violating electron scattering has become a precision tool

PREX/CREX Concept

(Probing the Weak Charge Distribution of N-rich Nuclei)



Nuclear theory predicts a neutron skin on heavy nuclei

Present knowledge of neutron distributions comes primarily from hadron scattering ⟶ model-dependent interpretation, large and uncontrolled uncertainties

- ❖ Parity violation can measure neutron and weak-charge form factors *model-independently* with *statistics-dominated uncertainty*

$$M_{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2) \quad \left(\text{EM amplitude accesses charge or proton form factor}\right)$$

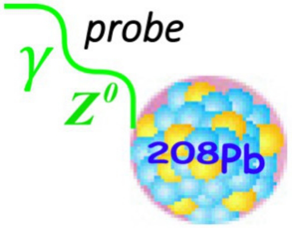
$$M^{NC}_{Weak} = \frac{G_F}{\sqrt{2}}\Big[\underbrace{(1 - 4\sin^2\theta_W)}_{Q^p{}_W \sim 0} F_p(Q^2) - \underset{\substack{\downarrow \\ Q^n{}_W \simeq -1}}{F_n(Q^2)}\Big]$$

	Proton	Neutron
Electric Charge	1	0
Weak Charge	~0.08	-1

- Neutron distribution not accessible to the charge-sensitive photon
- Z^0 couples primarily to neutron

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

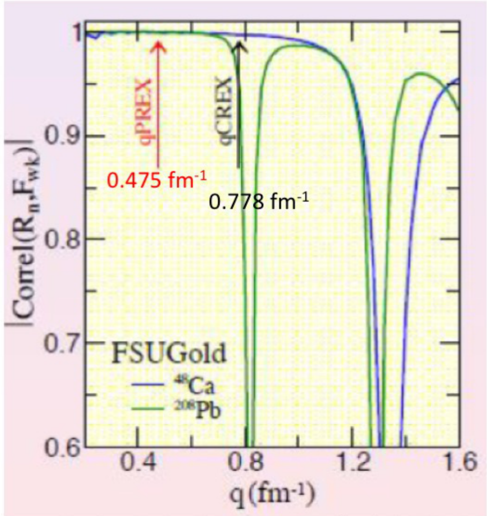
$$F_{n,p}(Q^2) = \frac{1}{4\pi}\int d^3r\; j_0(qr)\, \rho_{n,p}(r)$$



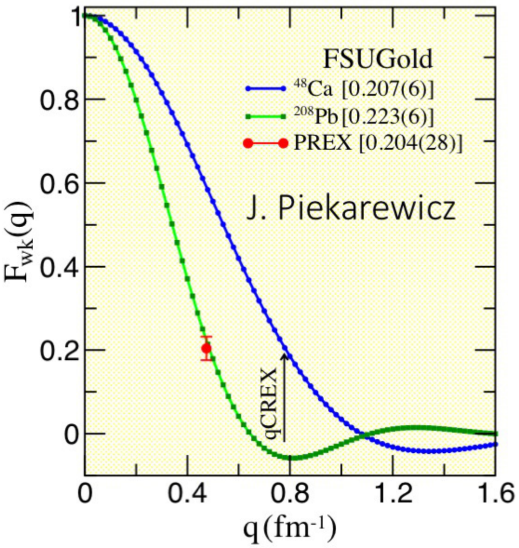
Clean neutron probe

PREX/CREX Concept

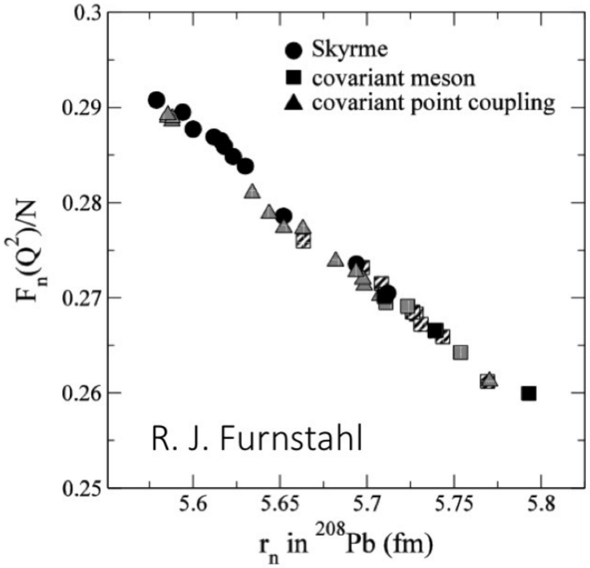
At low Q^2 there is a tight correlation between R_n and $F_{wk}(Q^2)$ $\Longrightarrow$ A single measurement of $F_{wk,n}(Q^2)$ translates to a measurement of R_n (via mean-field nuclear models)



Relativistic Mean-field EDF covariant analysis



J. Piekarewicz



R. J. Furnstahl

- Energy Density Functions (EDFs) characterized by a dozen free parameters that are calibrated to a host of well known properties of finite nuclei

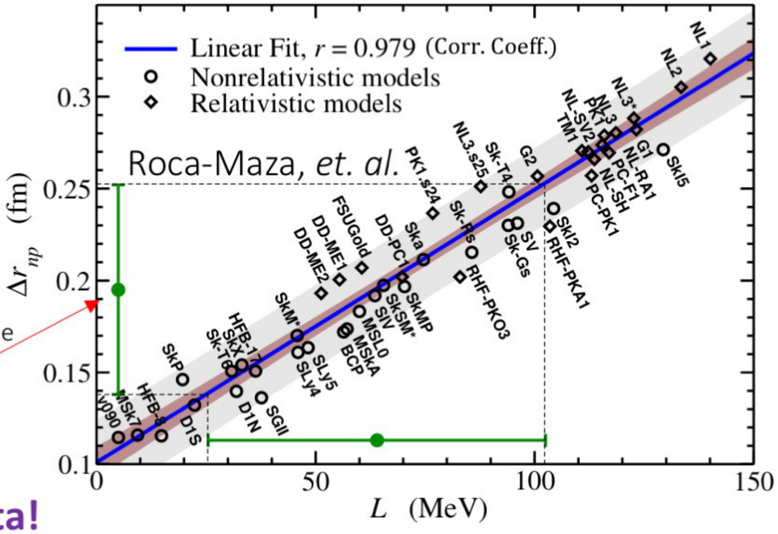
❖ There is a strong correlation between *Rn* and the density dependence or slope of the symmetry energy,

$$L = 3\rho_0 \left(\frac{\partial S}{\partial \rho}\right)_{\rho_0}$$

* See Javier Roca-Maza's talk about Neutron skin workshop at Mainz this afternoon at 5:30 PM

At present, L is ~completely unconstrained by "Real" data!

Arbitrary central value with PREX 0.06 fm proposed error bar



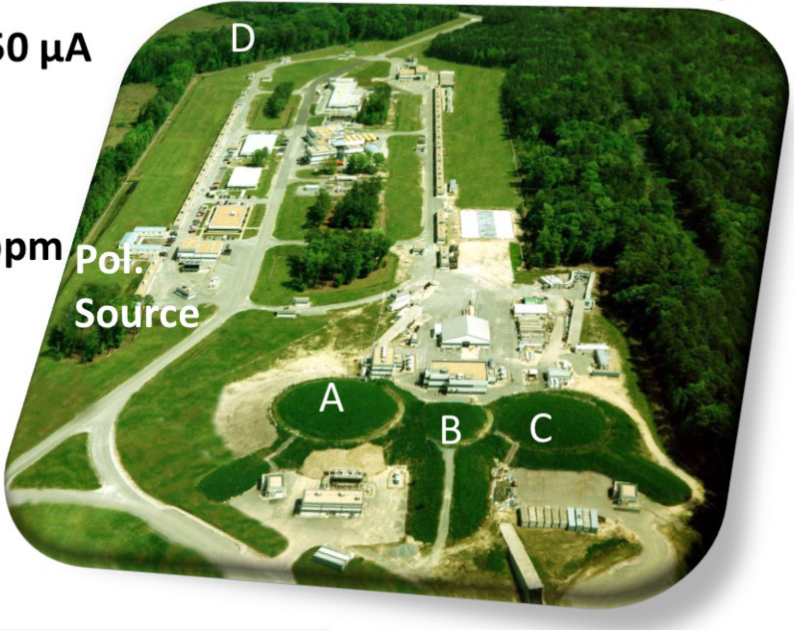
Roca-Maza, *et. al.*

PREX/CREX Overview

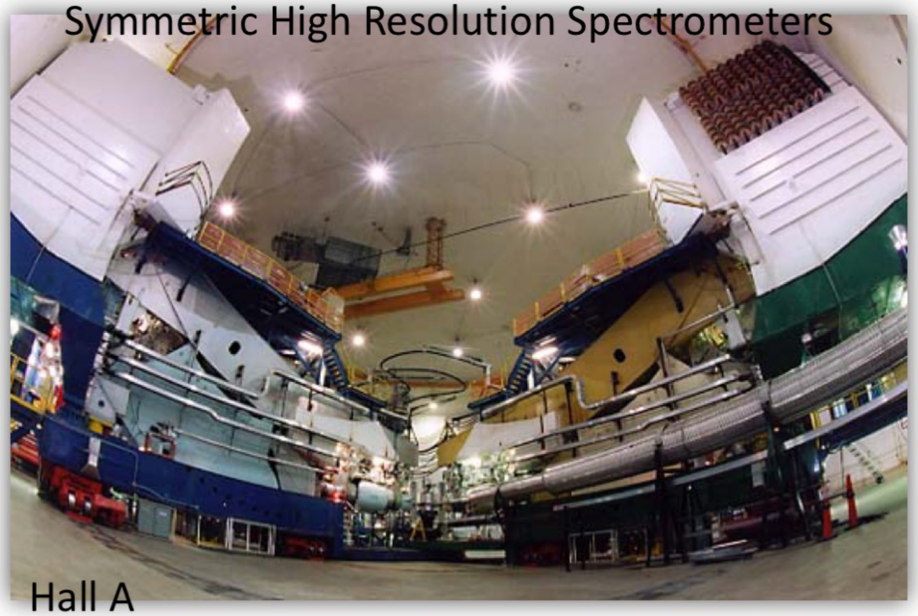
PREX/PREX-II:	**CREX:**
1 GeV electron beam, 50-70 µA	2.2 GeV electron beam, 150 µA
0.5 mm thick ^{208}Pb target	5 mm thick ^{48}Ca target
5° scattered electrons	4° scattered electrons
Q^2 =0.0088 GeV^2/c^2 , A_{PV}~0.5ppm	Q^2 =0.022 GeV^2/c^2, A_{PV}~2ppm
680 hours, ~35M pairs	840 hours, ~43M pairs
δA_{PV} ~ 15 ppb (3%)	δA_{PV} ~ 48 ppb (2.4%)

- high polarization, ~89%
- helicity reversal at 120 Hz
- new thin quartz detectors

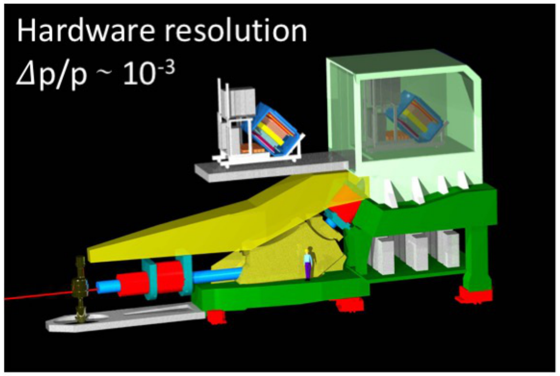
Jefferson Lab, Newport News, Virginia



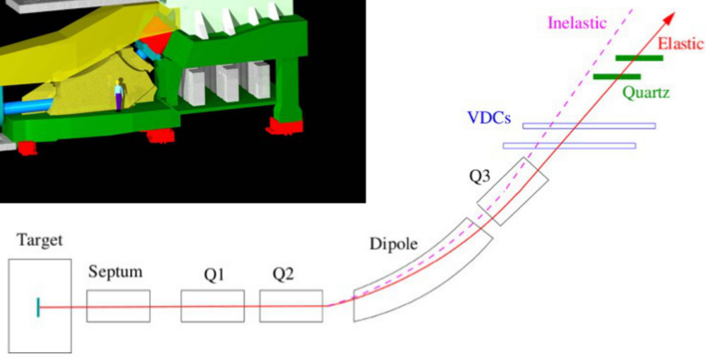
Symmetric High Resolution Spectrometers



Hall A



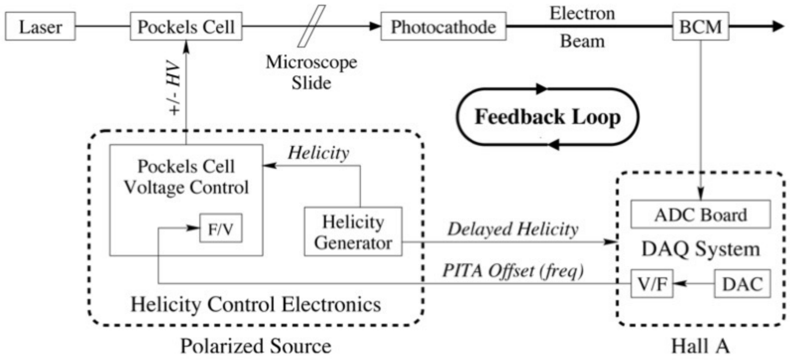
HRS and optics schematic



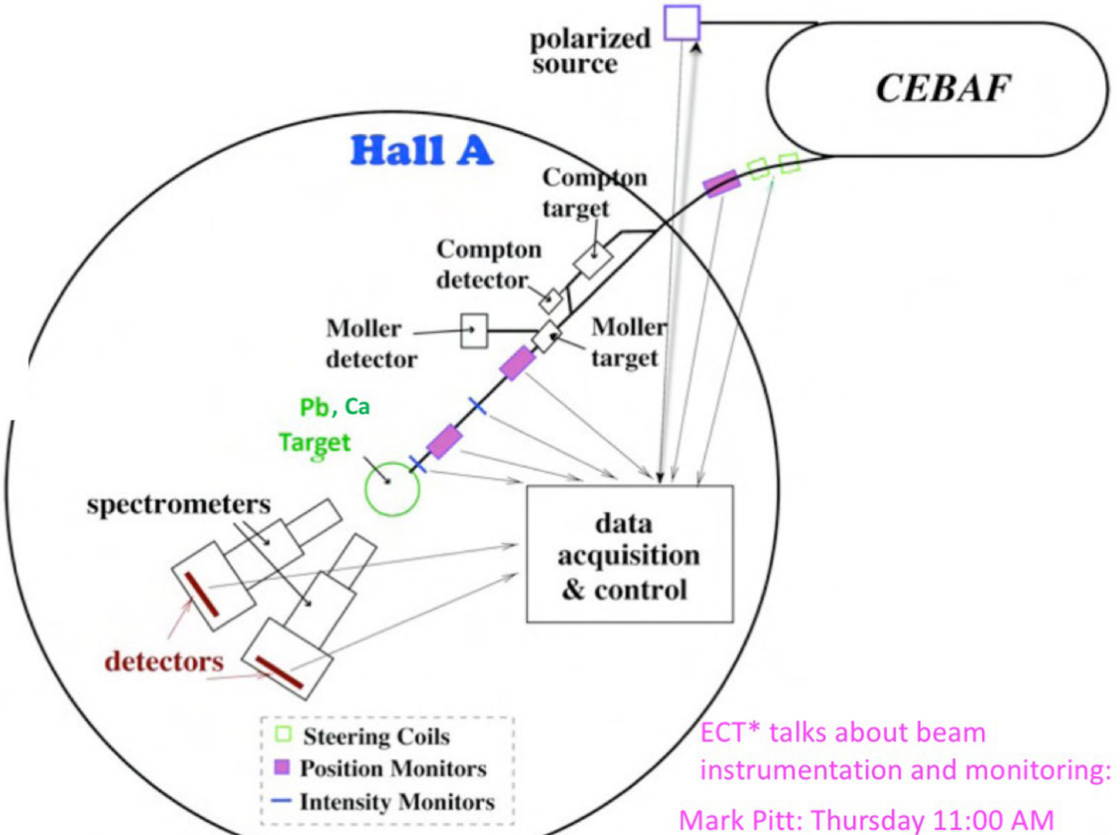
”Parity Quality” Beam Moniroring

(normalization and false-asymmetry systematics control)

- **Precision source-laser alignment**



- **Active feedback on charge asymmetry**
- **Precision beam position monitoring with active calibration of detector slopes (dithering)**
- **Two independent methods for “slow” helicty reversals:**
  1. **Insertable half-wave plate**
  2. **Double Wien filter**
- **Continuous beam polarization monitoring with Compton polarimeter**



Hall A Parity Quality Beam Monitoring Schematic

ECT* talks about beam instrumentation and monitoring:

Mark Pitt: Thursday 11:00 AM
Jürgen Diefenbach: Thurs 11:30 AM
Caryn Palatchi: Friday 10:30 AM

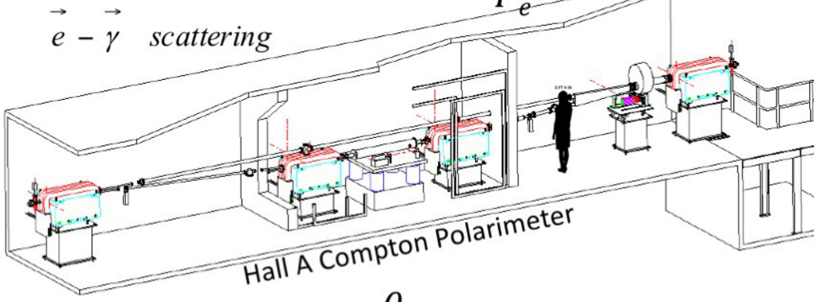
PREX-I Systematic Errors

PREX goal for ~ 2% total systematic error achieved!

Systematic Error	Absolute (ppm)	Relative (%)
Polarization	0.0083	1.3
Detector Linearity	0.0076	1.2
Beam current normalization	0.0015	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2	0.0028	0.4
Target Backing	0.0026	0.4
Inelastic States	0	0
TOTAL	0.0140	2.1

Crucial normalizations:

- **Polarization**: enters result directly → $A_{PV} = \frac{A_{raw}}{P_e}$



Use Compton Polarimetry for non-invasive, continuous measurement

*See Bob Michaels talk on Friday at 9:00 AM

- **4-momentum transfer**: $Q^2 = 4EE'\sin^2\frac{\theta}{2}$

Calibrations:

E (beam energy): spin precession in the machine

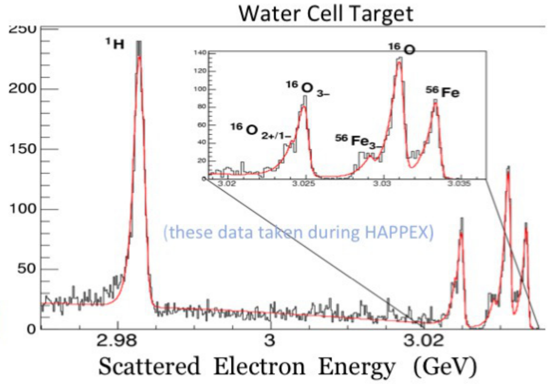
E' (scattered energy): NMR probe in HRS B-field

θ (scattered angle): surveyed to ~1 mrad and measured to 0.2% absolute using water cell target

Absolute angle calibration via nuclear recoil variation

$$\delta E_{\text{loss}} \approx \frac{\theta^2}{2}\frac{E^2}{M_A}$$

Q^2 distributions obtained by dedicated low-rate runs with tracking detectors triggered on quartz pulse-height (0.4% overall error on Q^2)

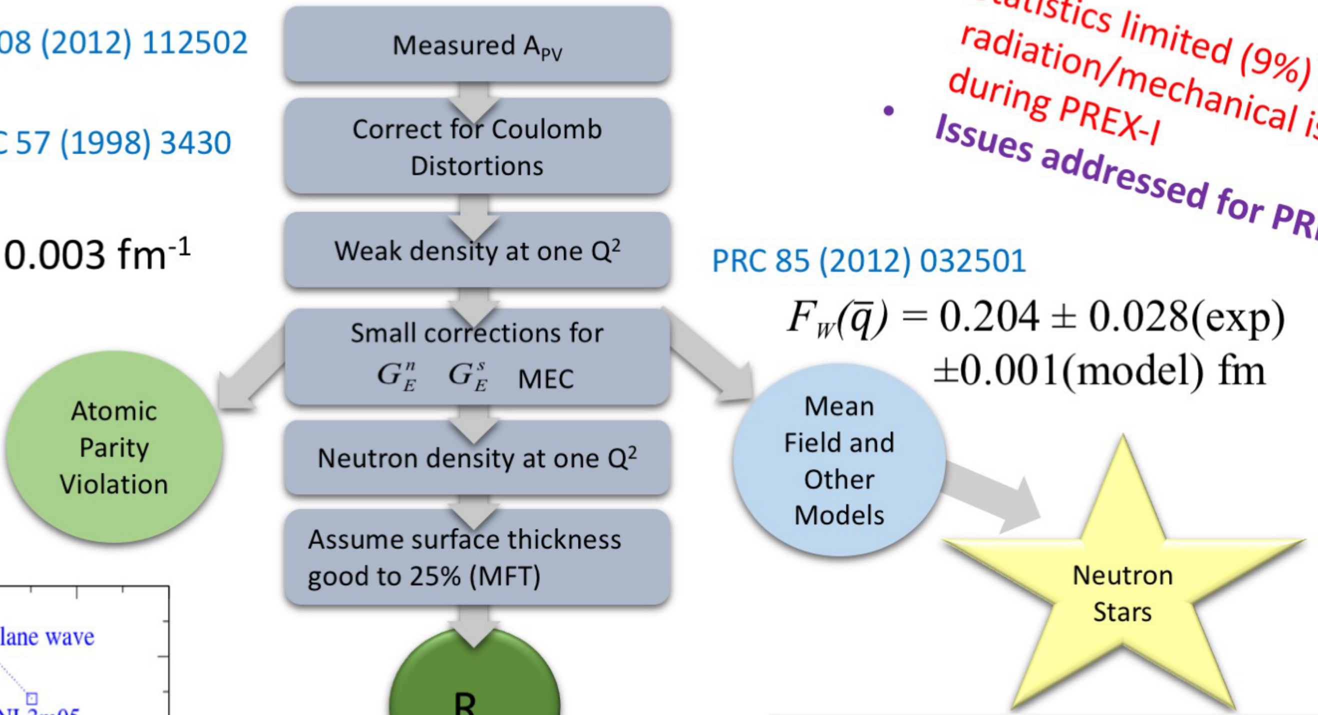


(these data taken during HAPPEX)

PREX-I Final Result

$$A_{PV} = 0.656 \pm 0.060(\mathrm{stat}) \pm 0.014(\mathrm{syst})\ \mathrm{ppm}$$

- Statistics limited (9%) due to radiation/mechanical issues during PREX-I
- Issues addressed for PREX-II



PRL 108 (2012) 112502

Measured A_{PV}

PRC 57 (1998) 3430

Correct for Coulomb Distortions

$\bar{q} = 0.475 \pm 0.003\ \mathrm{fm}^{-1}$

Weak density at one Q^2

PRC 85 (2012) 032501

$$F_W(\bar{q}) = 0.204 \pm 0.028(\mathrm{exp}) \pm 0.001(\mathrm{model})\ \mathrm{fm}$$

Small corrections for G_E^n G_E^s MEC

Atomic Parity Violation

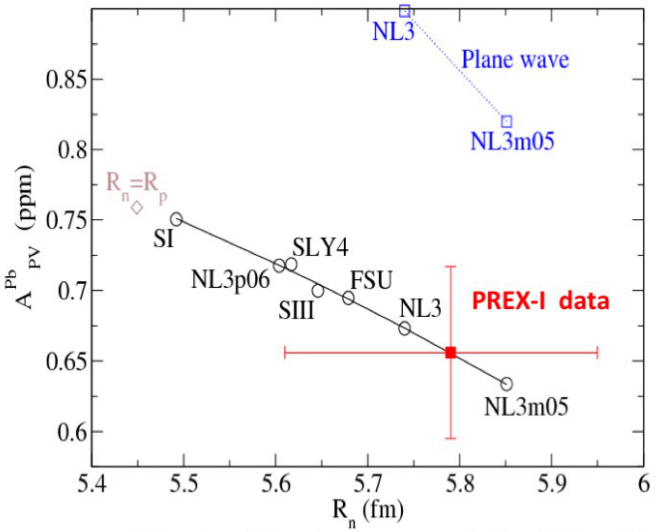
Mean Field and Other Models

Neutron Stars

Neutron density at one Q^2

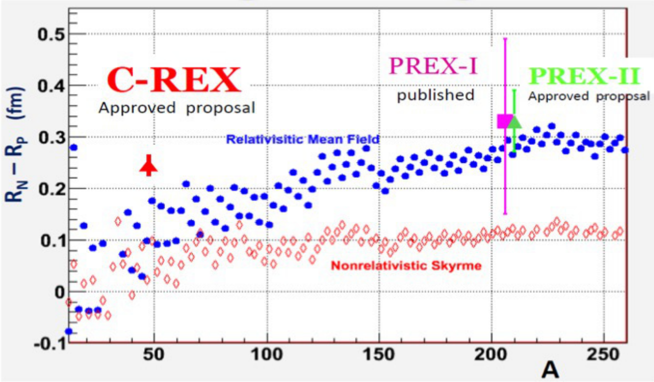
Assume surface thickness good to 25% (MFT)

R_n



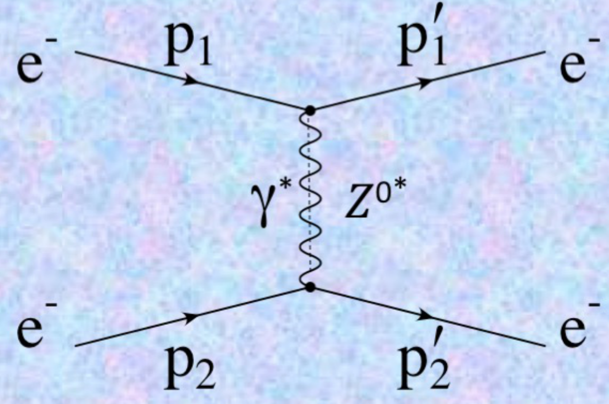
$$R_n = 5.751 \pm 0.175(\mathrm{exp}) \pm 0.026(\mathrm{model}) \pm 0.0005(\mathrm{strange})\ \mathrm{fm}$$

$$R_n - R_p = 0.33^{+16}_{-18}\ fm$$

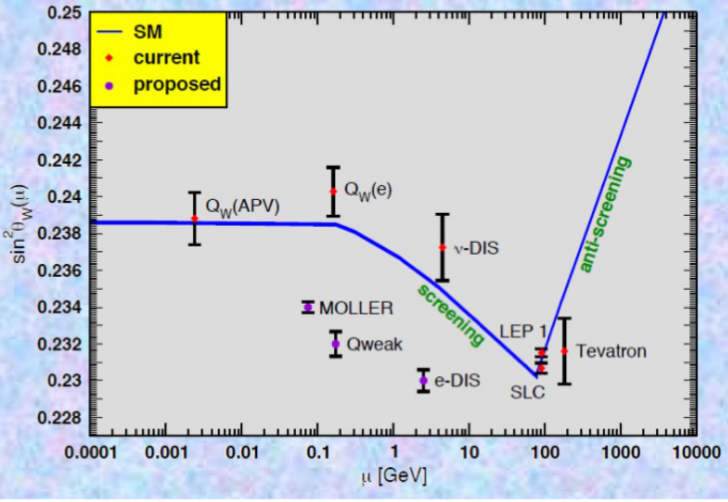


First electroweak indication of a neutron skin of a heavy nucleus (CL ~90–95%)

The MOLLER Project at Jefferson Lab:



Measurement
of
Lepton
Lepton
Electroweak
Reaction

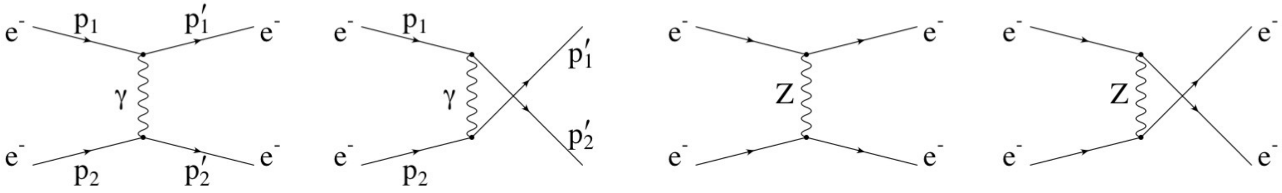


Møller Scattering A_{PV} Measurement

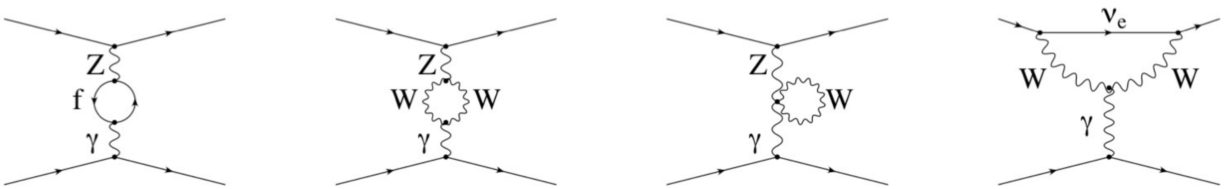
- MOLLER aimed at precision measurement of parity-violating asymmetry A_{PV} in polarized electron-electron scattering.
- Standard Model gives precise prediction for Møller A_{PV} –which can be measured as a test.

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{M_\gamma M_Z}{M_\gamma^2} = m_e E_{lab} \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4sin^2\theta_{lab}}{(3+cos^2\theta_{lab})^2} Q_W^e,$$

$$Q_W^e \equiv 4 \cdot g_V^e \cdot g_A^e = -(1 - 4sin^2\theta_W) \qquad (1)$$



Feynman diagrams for Moller Scattering at tree level



γ - Z mixing diagrams and W loops. “Hard” radiative corrections involving the massive vector bosons—modify the tree level prediction significantly.

The MOLLER A_{PV} Measurement

- At proposed kinematics: 11GeV $\mathrm{e}^{-}_{\mathrm{beam}}$(75$\mu$A, 80% P_e), and 5mrad $< \theta_{lab} <$ 20mrad:
  → Predicted $\langle A_{PV} \rangle$=36ppb at $\langle Q^2 \rangle$=0.0056 (GeV/c)^2
- For 49 (PAC) week run: $\delta A_{PV} = 0.74$ppb:
  → $\delta Q^e_W / Q^e_W = \pm 2.1\%(\mathrm{stat}) \pm 1.0\%(\mathrm{syst})$
  → $\delta\theta_{\mathrm{W}} = \pm 0.00026(\mathrm{stat}) \pm 0.00012(\mathrm{syst})$ ∼0.1% precision!

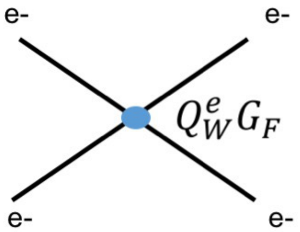
Challenging 4th generation measurement requiring:

- Unprecedented precision matching of electron beam characteristics for Left versus Right helicity states
- Precision non-invasive, redundant continuous beam polarimetry
- Precision knowledge of luminosity, spectrometer acceptance (Q^2) and backgrounds

MOLLER Reach

Weak charge measurement from purely-leptonic neutral current amplitudes

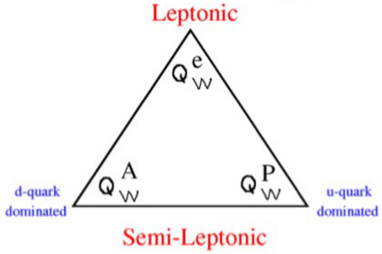
$$|A_\gamma + A_Z + A_{new}|^2 \longrightarrow A_\gamma\left[1 + 2\left(\frac{A_Z}{A_\gamma}\right) + 2\left(\frac{A_{new}}{A_\gamma}\right)\right]$$



$$\left.\begin{aligned} &Q^e_W \sim 0.045 \\ &\frac{\delta Q^e_W}{Q^e_W} \sim 2.4\% \end{aligned}\right\}$$

$$A_{new} \sim 10^{-3} \cdot G_F$$

Unprecedented sensitivity!



Other complementary semi-leptonic measurements:

- $\delta[Q_W(^{133}Cs)/A] \sim 0.6\ \% \Rightarrow A_{new} \sim 0.0033 \cdot G_F$
- Jlab Qweak: $\delta[Q^p_W] \sim 4\ \% \Rightarrow A_{new} \sim 0.003 \cdot G_F$
- $\delta[2C_{2u}\ \_\ C_{2d}] \sim 5\ \% \Rightarrow A_{new} \sim 0.004 \cdot G_F$

APV Future Cs meas.
*See Victor Flambaum's talk
Tuesday at 4:00 PM

Future Mainz P2:
Improve by 2x

SOLID: unique sensitivity
To axial quark couplings
*See Seamus Riordan's talk
today after lunch

MOLLER Reach

Search for Flavor-conserving BSM Neutral Currents

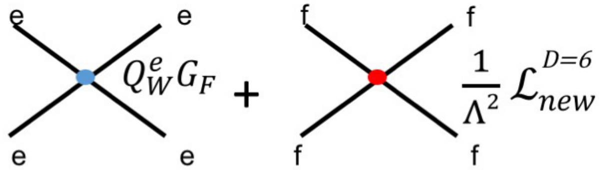
❖ Many new physics models require new neutral current interactions

- MOLLER searches for possible new interactions using purely leptonic PVES with *~no theoretical uncertainties*

Constraints on new 4-fermion contact interactions obtained using effective field theory dimension-6 operators

arXiv:1511.07434 (2015)

MOLLER sensitive to 4-fermion operators: $[O_{ee}]_{1111}$ and $[O_{\ell\ell}]_{1111}$



In this way, new physics can reveal itself through interference with SM physics (as long as $Q^2 << M_Z^2$ so that A_Z not imaginary)

$$|A_Z + A_{new}|^2 \longrightarrow A_z\left[1 + 2\left(\frac{A_{new}}{A_z}\right)\right]$$

- Where the new 4-fermion vector bosons incorporated into vertex corrections of SM interactions

For Example:

$$\mathcal{L}^{PV}_{e_1e_2} = \mathcal{L}^{PV}_{SM} + \mathcal{L}^{PV}_{new}$$

$$\mathcal{L}^{PV}_{new} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda_{ij}^2}\bar{e}_i\gamma_i e_i \bar{e}_j\gamma^j e_j$$

Eichten, Lane and Peskin, PRL50 (1983)

Couplings: g_{ij} $e_{L,R} = \frac{1}{2}(1 \mp \gamma_5)\psi_e$

MOLLER sensitivity:

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

Λ is the scale for new physics that sets the EFT expansion

MOLLER gives best contact interaction reach for leptons at low OR high energy!

(Need new lepton collider to do better!)

MOLLER Motivations

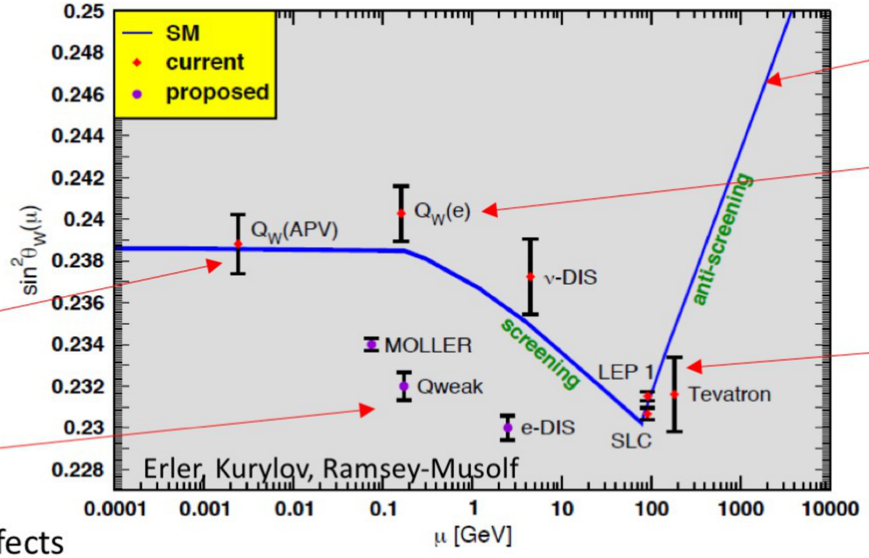
Ultra-precise (~0.1%) measurement of weak mixing angle will test SM

Running of $\sin^2\theta_W$: complicated and scheme-dependent – many orders in loops of all particles

*See Rodolfo Ferro's talk today at 4:00 PM

6s ⟶ 7s ^{133}Cs atomic transition

Major improvements for near future

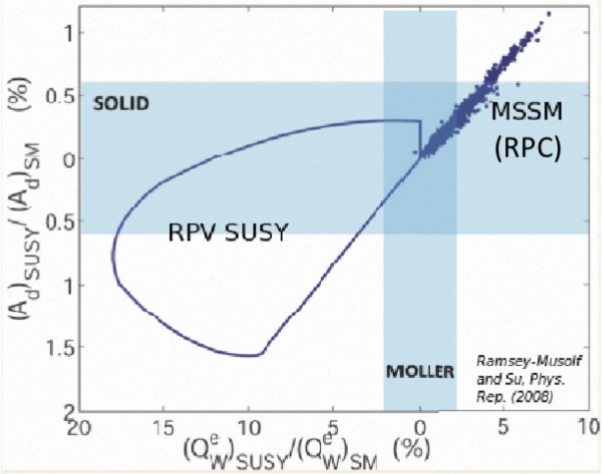


Electroweak fit with uncertainty

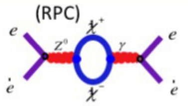
Parity violating Moller scattering (E158)

Collider experiments near Z-pole (most precise 0.1%)

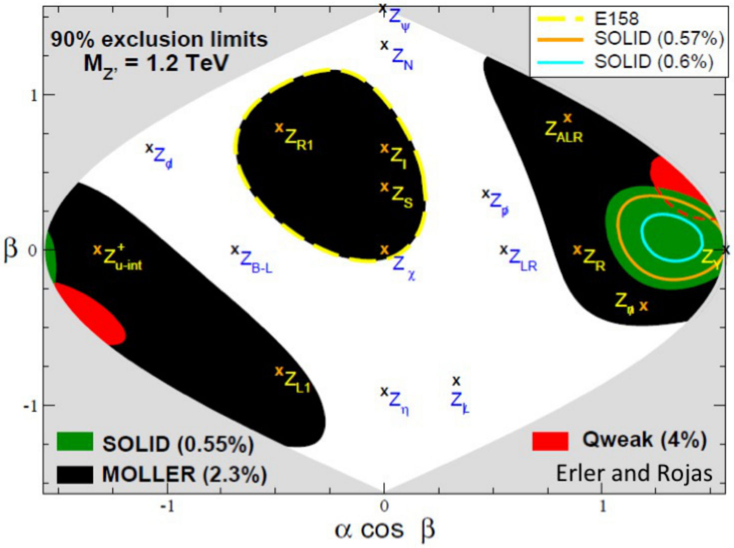
- ❖ Sensitivity to radiative loop effects of new particles predicted by MSSM



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



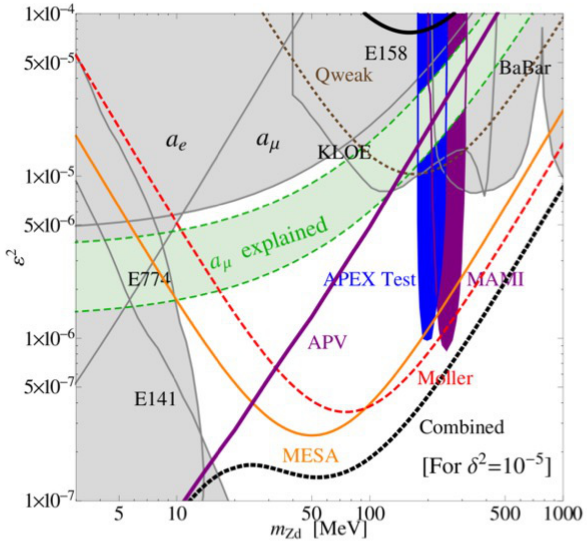
*See Shufeng Su's talk Tuesday at 5:30 PM



Erler and Rojas

- ❖ MOLLER can help discriminate between competing GUT models which predict new 1 – 2 TeV Z's

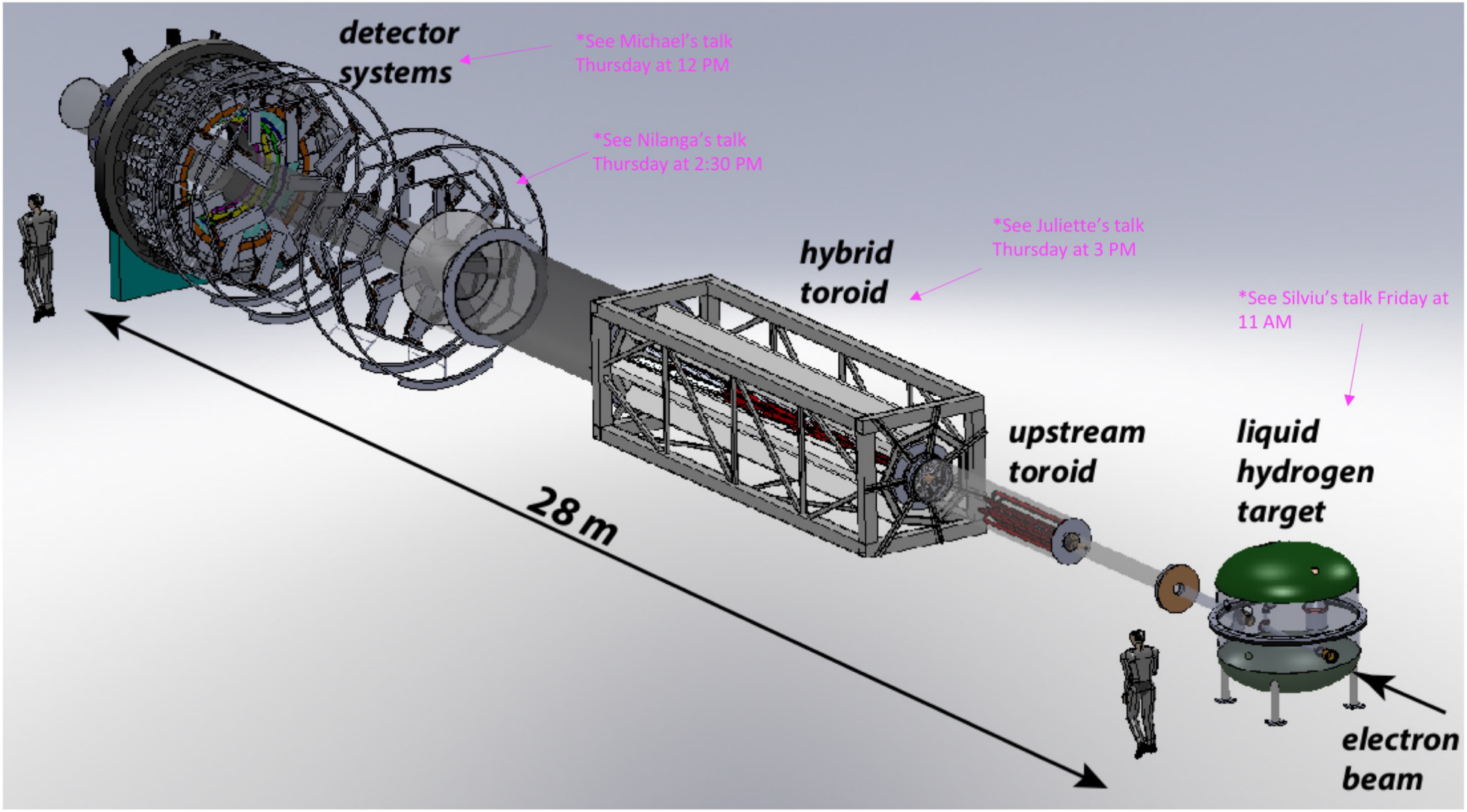
- ❖ Probe potential kinetic-mixing of super-light (10 to 500 MeV) dark Z bosons with SM Z



*See Hooman Davoudiasl's talk today at 4:45 PM

MOLLER Apparatus

(major new installation experiment for Hall A)



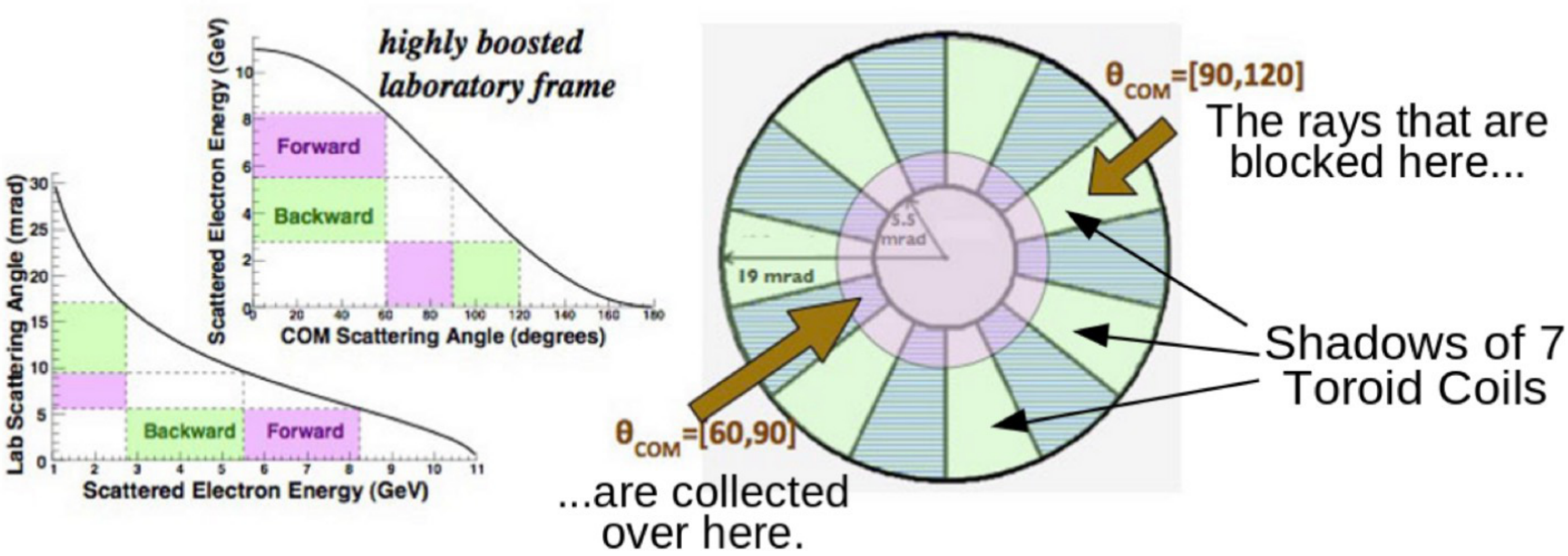
*See Michael's talk Thursday at 12 PM

*See Nilanga's talk Thursday at 2:30 PM

*See Juliette's talk Thursday at 3 PM

*See Silviu's talk Friday at 11 AM

Optimized Spectrometer (∼ 100% Acceptance)



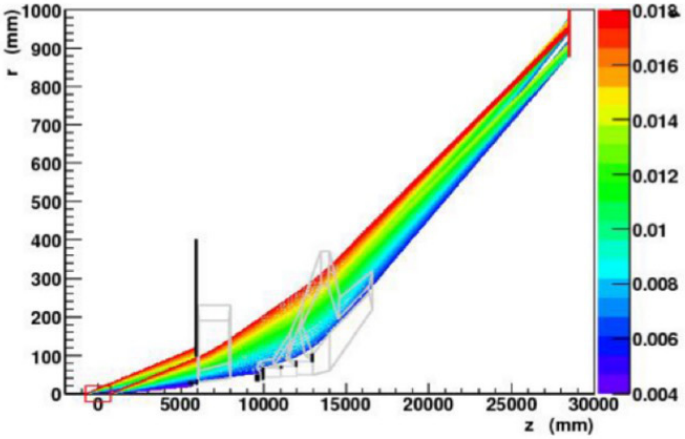
The rays that are blocked here...

Shadows of 7 Toroid Coils

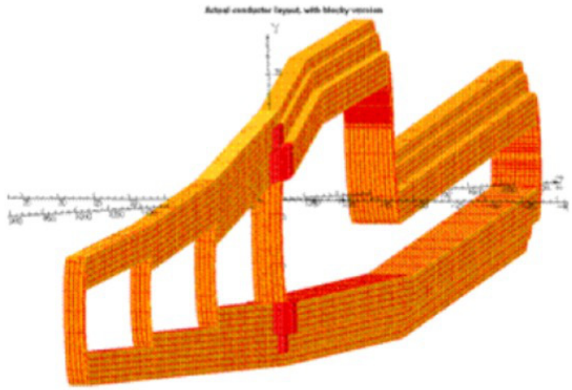
...are collected over here.

- The combination of a toroidal magnetic system with an odd number of coils together with the symmetric, identical particle scattering nature of the Møller process allows for ∼ 100% azimuthal acceptance

Toroid Design Concept



Projected radial coordinate of scattered Møller electron trajectories. Colors represent θ_{lab} (rad). Magnet coils (grey) and collimators (black) are overlaid.



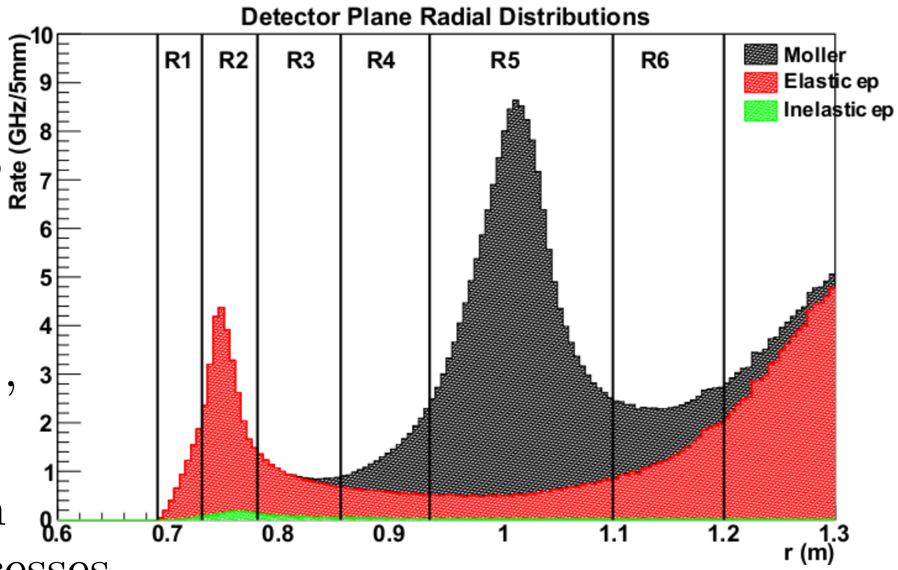
Single Hybrid coil shown with 1/10 scale in z direction. Note the 4 current returns give successively higher downstream fields.

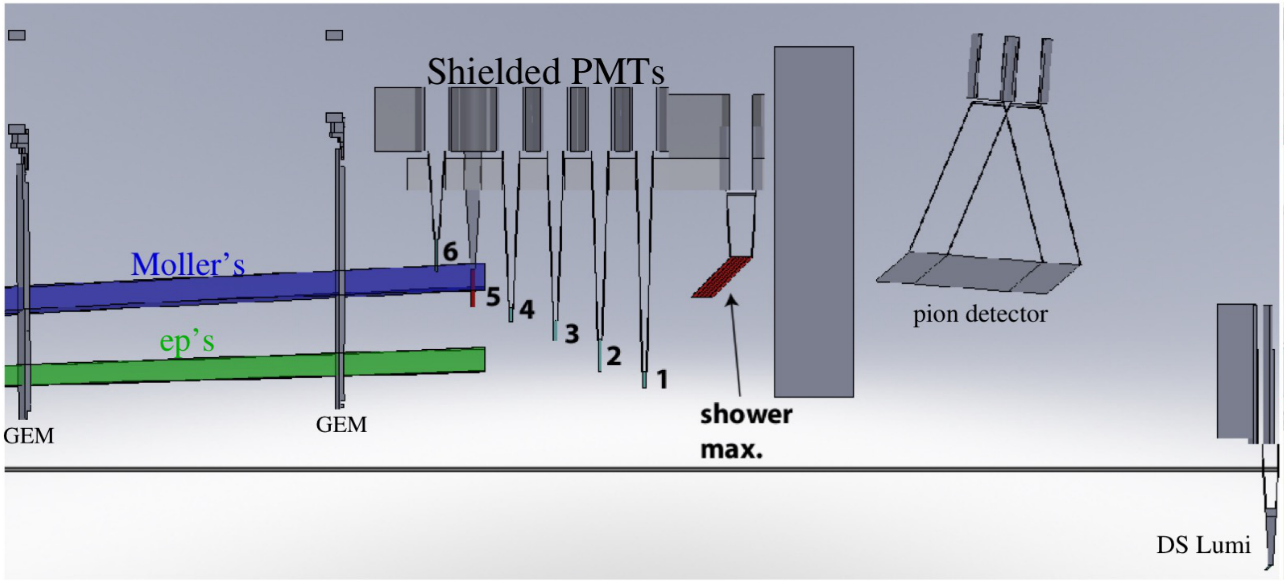
*See Juliette Mammei's talk Thursday at 3:00 PM

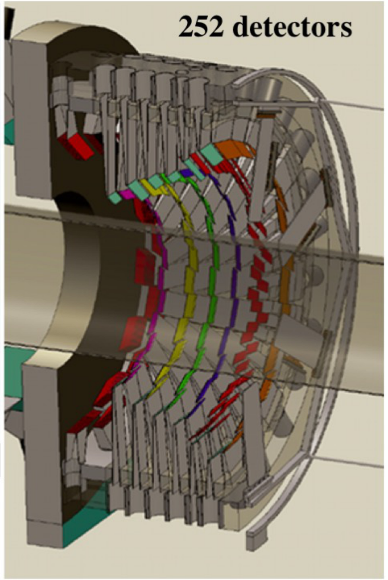
- Spectrometer employs two back-to-back toroid magnets and precision collimation:
  - Upstream toroid has conventional geometry
  - Downstream "hybrid" toroid novel design inspired by the need to focus Møller electrons with a wide momentum range while separating them from e-p (Mott) scattering background

MOLLER Integrating Detector Layout and Rates

- Spectrometer separates signal from bkgd and radially focuses at detector plane
- Rates for 11 GeV/75 μA (80% pol.) beam, 1.5m liquid hydrogen target. See fig. ⟶
- Six radial rings, 28 phi segments per ring*
- Ring 5 intercepts Moller peak (∼150 GHz), Ring 2 intercepts bkgd ”ep” peaks
- 250 quartz tiles: allow full characterization and deconvolution of bkgd and signal processes







*See Michael Gerick's talk Thursday at 12:00 PM

New Challenges

- 150GHz total detected Moller event rate
  → Must flip pockels cell at ∼2kHz
  → 80ppm pulse-to-pulse statistical fluctuations
    - Electronic noise and density fluctuations $< 10^{-5}$
    - Pulse-to-pulse beam monitoring res. a few microns at 1kHz
- 0.5nm/0.05nrad control of beam on target
  → Requires improvement on control of pol. src. laser transport
  → Improved methods of "slow helicity reversal" (double wien)
- Target requires ∼5kW of cooling power at 85μA I_{beam}
- Full azimuthal acceptance with θ_{lab} between 5 and 20mrad
  → Aggressive spectrometer design
  → Complex collimation and shielding issues
- Robust and redundant 0.4% beam polarimetry
  → Plan to pursue both Compton and atomic Hydrogen techniques

Summary and Future Plans

- PVES is a precision tool for measuring weak-charge distributions with implications for nuclear structure and BSM discovery

PREX/CREX:

- PREX achieved systematic error goal and PREX-II poised to reach full precision
- Latest Schedule: PREX-II and CREX to run concurrently in 2018 (at the earliest)

MOLLER

- JLab director's review at the end of the year
- Project cost estimated at ∼$25M
- We are assuming to enter the CD process in FY 2017
- Construct experiment in 2018 - 2020