The Lead Radius Experiment PREX

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Outline

- Motivation
- Parity Violation at JLab
- PREx and Results
- Future Plans and Summary

Motivation: Nuclear Radii in Heavy Nuclei

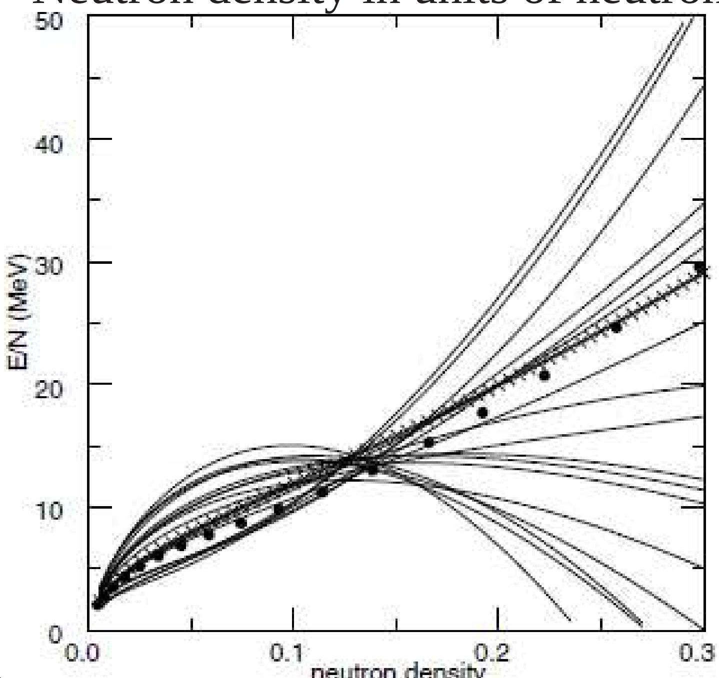
- Measurements are important for understanding the strong nuclear force
- Calculations are difficult due to non-pQCD regime and complicated due to many-body physics
- Interesting for:
  - →Fundamental nuclear structure
  - →Isospin dependence and nuclear symmetry
  - →Dense nuclear matter and neutron stars
- Proton radius is relatively easy - electromagnetic probes
- Neutron radius is difficult
  - →Weakly couples to electroweak probes
  - →Hadronic probes have considerable uncertainty
  - →Theory has range of R_n - R_p for Pb of 0 - 0.4 fm

Motivation: What do we learn from R_n?

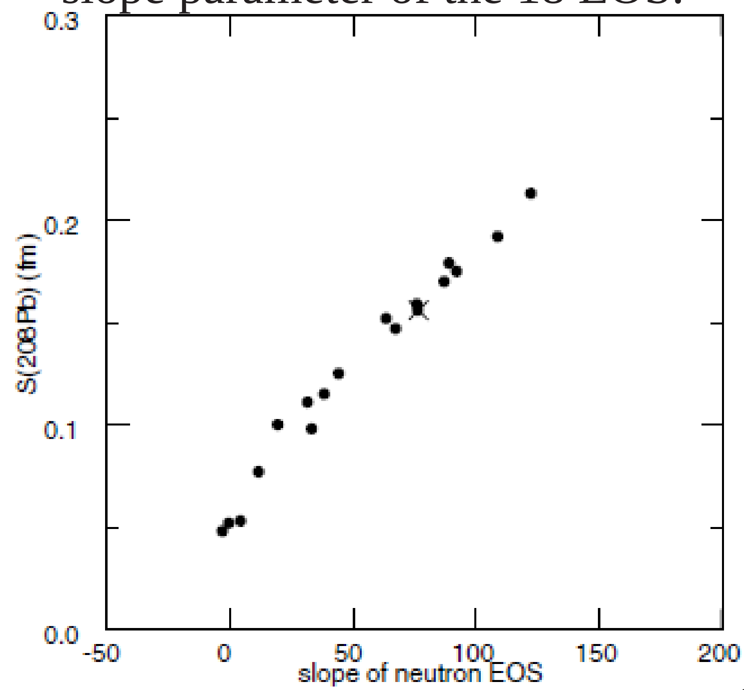
- Constraints on Eqn of State (EOS) and symmetry energy of neutron rich matter, where symm. energy is energy cost for asymmetric matter ($N \neq Z$)
- Slope of EOS can be used to constrain potential models

B.A. Brown, PRL 85, 5296 (2000)

Neutron EOS for 18 Skyrme sets. Dots are FP variational calcs; crosses are SkX. Neutron density in units of neutron/fm^3



Lead neutron skin vs. corresp. slope parameter of the 18 EOS.



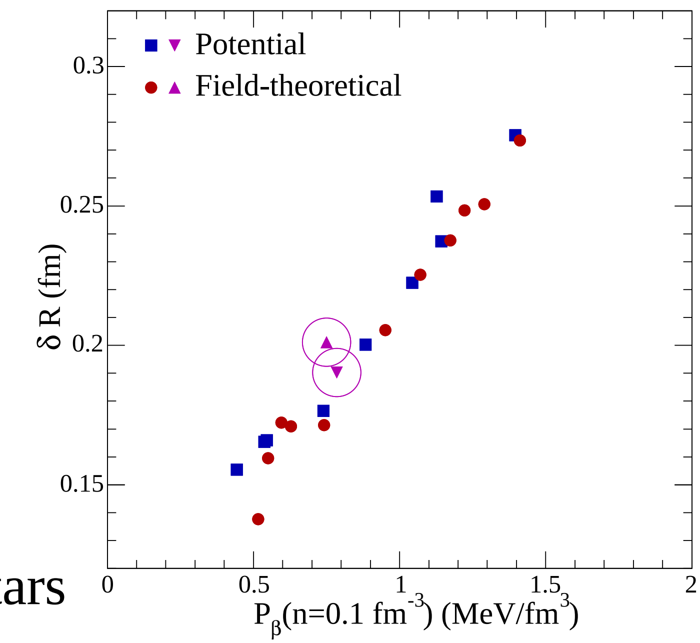
Motivation: Neutron Stars

- Neutron star structure is better understood with measurements of R_n
- Larger P pushes neutrons out against surface tension increasing R_n:

  $\longrightarrow$Thus measurement of R_n (and δR) could calibrate the pressure of neutron star matter at sub-nuclear densities

  $\longrightarrow$Combining δR with observed neutron star radius could allow access to pressure-density rel't inside neutron stars

A.W. Steiner *et al.*, Phys Rep 411, 325 (2005)



- Additionally, symmetry energy governs proton fraction

  $\longrightarrow$Direct URCA cooling depends on processes:

$$n \rightarrow p + e^- + \bar{\nu}$$

$$e^- + p \rightarrow n + \nu$$

$\longrightarrow$Larger symmetry energy gives larger proton fraction (need 11%)

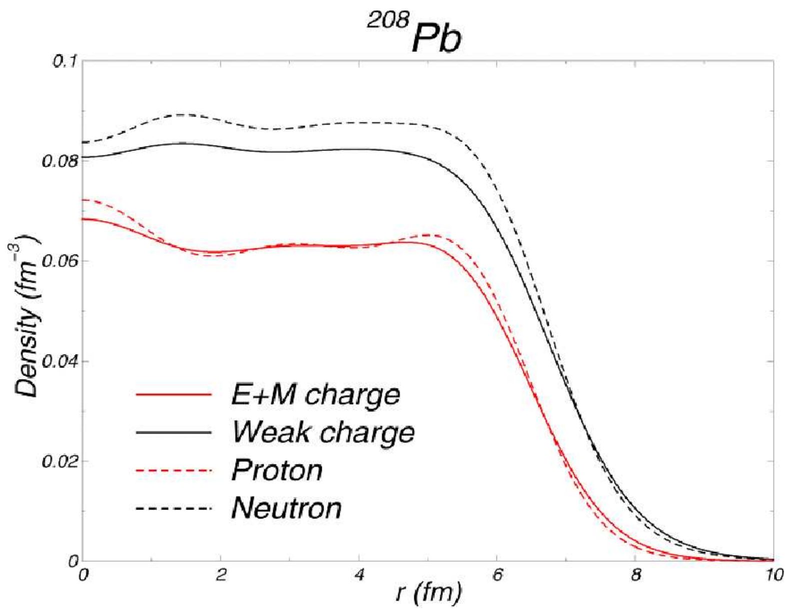
Methods used to Measure R_n

- Hadronic Probes
  - →Elastic pN, $\vec{p}$N, nN, $\pi^{\pm}$N
  - →π^0 photoproduction (Kruche, et al.)
  - →GDR
  - →Antiproton scattering
  - →Have theoretical uncertainty

- Electroweak Probes
  - →Parity violating electron scattering
  - →Atomic parity violation
  - →“Clean” measurements, fewer systematics
  - →Technically challenging

Non-Parity Violating Electron Scattering

- Electron scattering γ exchange provides R_p through nucleus FF's



$\rightarrow$For spin 0 nucleus:

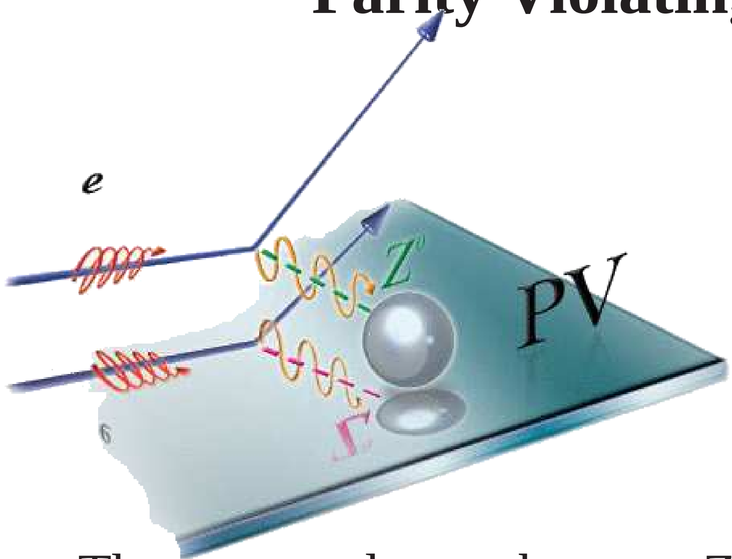
$$\frac{d\Omega}{d\sigma} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} |F(Q^2)|^2$$

$\rightarrow$In limit of small Q^2:

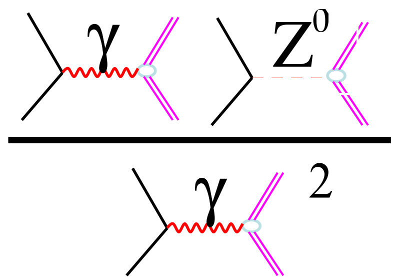
$$F(Q^2) \approx F(0) + \left.\frac{dF}{dQ^2}\right|_{Q^2=0} + \ldots = \int \rho(\vec{x}) d^3x - \frac{1}{6} Q^2 \langle r^2_{\text{charge}} \rangle$$

$\rightarrow$So small Q^2 measurements give density and RMS electromagnetic radius (dominated by R_p)

Parity Violating Electron Scattering



$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



$$\propto \frac{|\gamma + Z^0|}{|\gamma|^2} \sim \frac{10^{-4} Q^2}{GeV^2}$$

- The e^- can also exchange a Z^0 which is parity violating (PV)
- Z^0 primarily couples to the neutron, since:

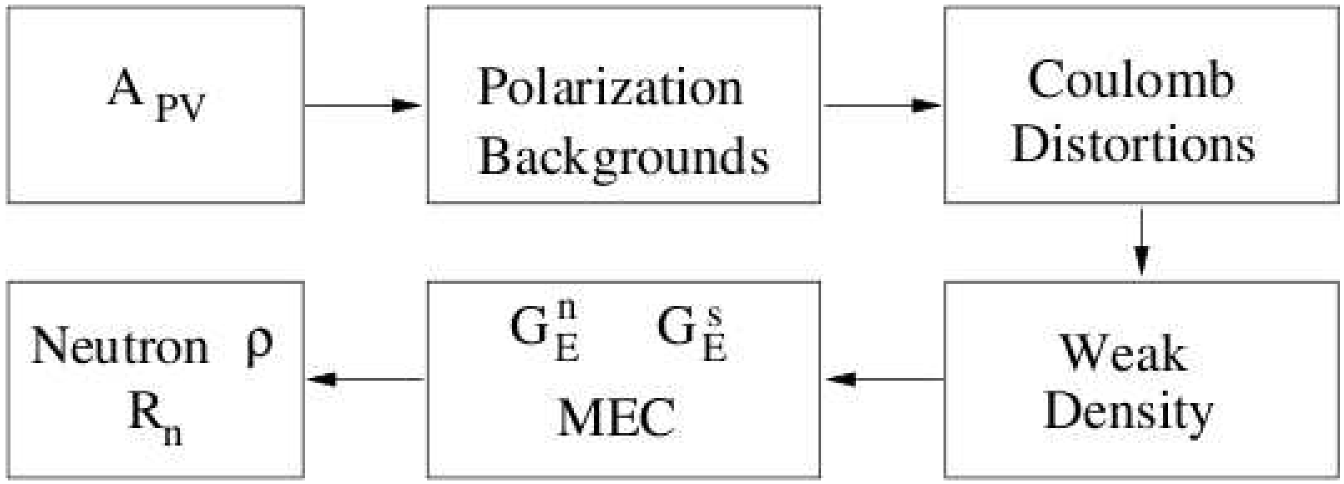
$$Q_{weak}^{proton} \propto 1 - 4\sin^2\theta_W \approx 0.076, \qquad Q_{weak}^{neutron} = -1$$

- Detectable in PV asymmetries of e^- with opposite helicities
- In Born approximation, $Q^2 \ll M_Z$, from γ - Z interference:

$$A_{PV} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[4\sin^2\theta_W - 1 + \frac{F_n(Q^2)}{F_p(Q^2)}\right], \quad F_n(Q^2) = \frac{1}{4}\int d^3r' j_0(qr)\rho_n(r)$$

- For fixed target experiment, typical $A_{PV} \sim 10^{-8} - 10^{-4}$

R_n Extraction



PV experiments are challenging for several reasons:

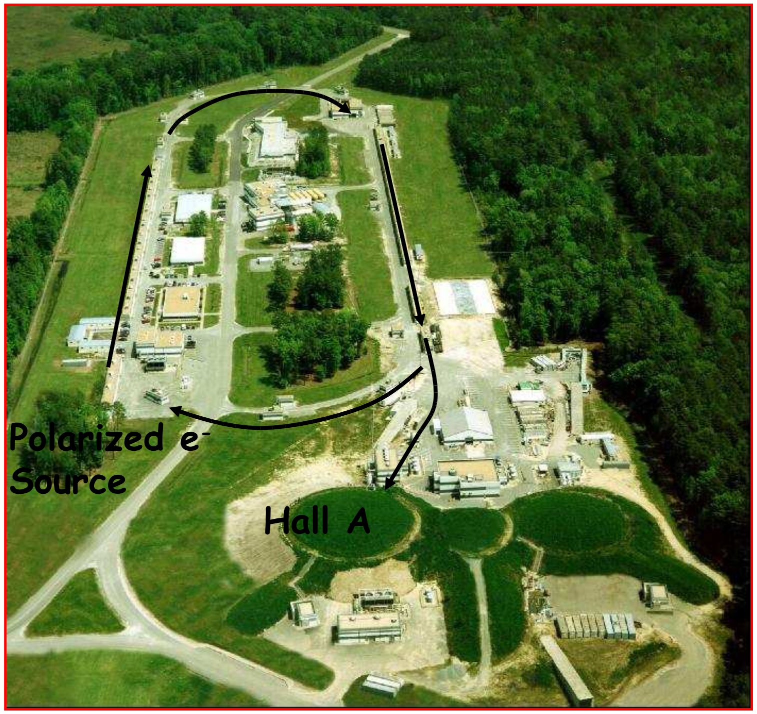
- Asymmetries are small, need lots of statistics
- Important control systematics

→Precise matching of e^- beam char. for Left vs. Right helicity states

→Precision non-invasive, continuous beam polarimetry

→Precision know. of Luminosity, Q^2, and spect. accept. and bkgds

JLab's CEBAF is Excellent Facility for PV Measurements



- High quality polarized beam, $P_e \sim 85$ - 90%
- PV experiments need quiet beam parms over helicity windows:

$\longrightarrow \Delta x < 10\mu m$

$\longrightarrow \Delta x' < 2\mu rad$

$\longrightarrow \Delta E < 10^{-3}$

PREx Measurement

PREx measures R_n of ^{208}Pb

- Lead is nice because:

$\longrightarrow$Excess of neutrons (44 more–with some expected to form a neutron-rich skin)

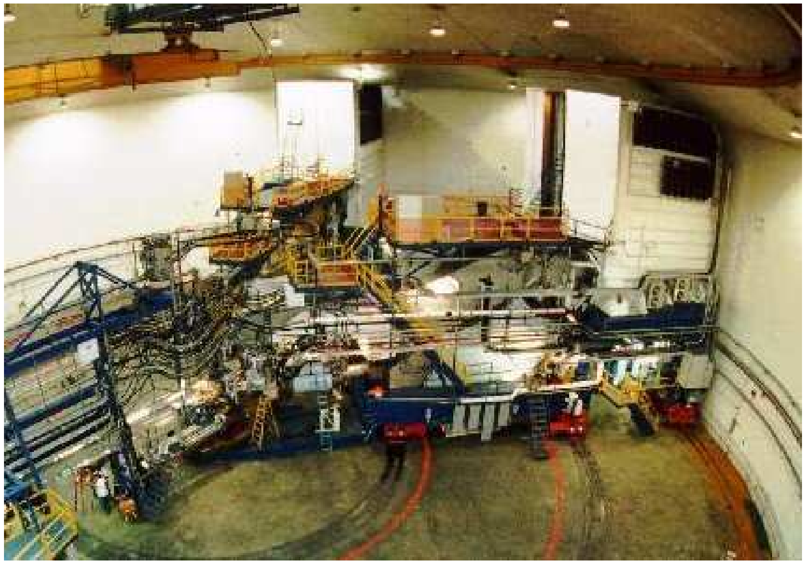
$\longrightarrow$Doubly magic nucleus (82 protons, 126 neutrons)

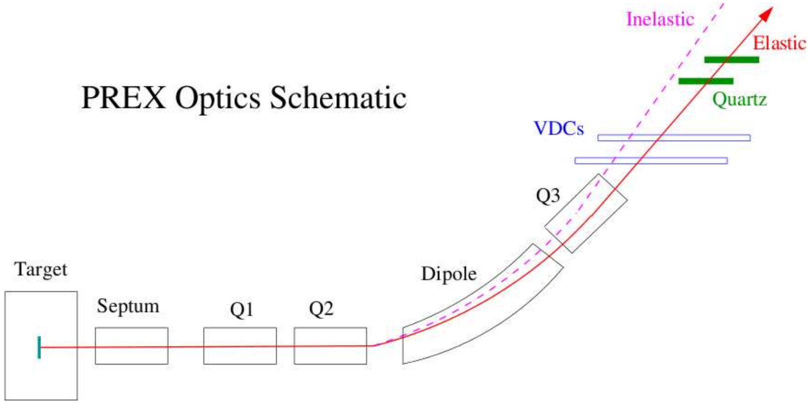
$\longrightarrow$Nearest excited state is 2.6 MeV from elastic peak (possible to exclude inelastics using HRS)

- Ran in Spring 2010 (approved 30 PAC days)
- E_e = 1.063 GeV, $\theta_e \approx 5^o$, $Q^2 \approx 0.009$ GeV^2
- $I_e \sim 50 - 75\mu$A
- Proposed uncertainty on A_{PV} of 3%, $R_n \sim 1\%$
- Uncertainty dominated by statistical error

Experimental Setup

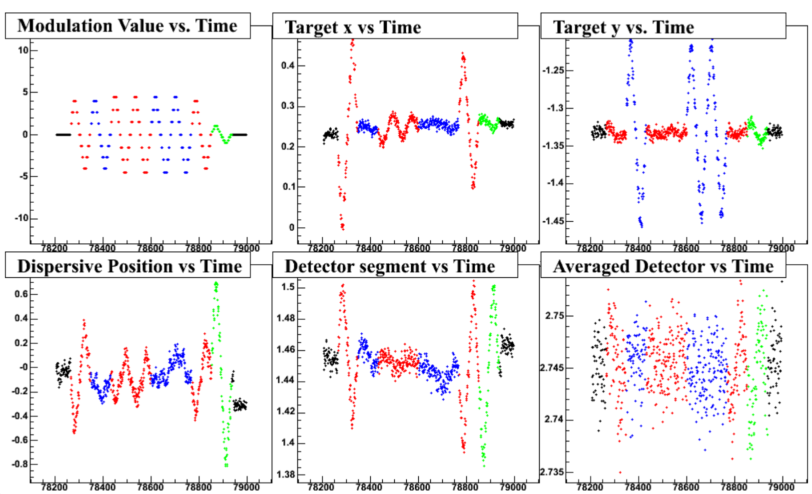
- Std. Hall A HRS Spects. with detector huts well shielded against bkgds.
- Running dual, symmetric arms cancels out A_{trans} and other systematics
- Use septum magnet to bend 5^o to 12.5^o
- Upgraded polarimetry (non-inv. Compton$\sim$ 1%, Inv. Moller$\sim$ 1%)
- 0.5mm thick Lead in between two 0.15mm Diamond targets ($\sim 1 \times 1$in^2) with cryogenically cooled frame; used fast rastered beam
- Quartz Cerenkov detectors with 18-bit integrating ADCs

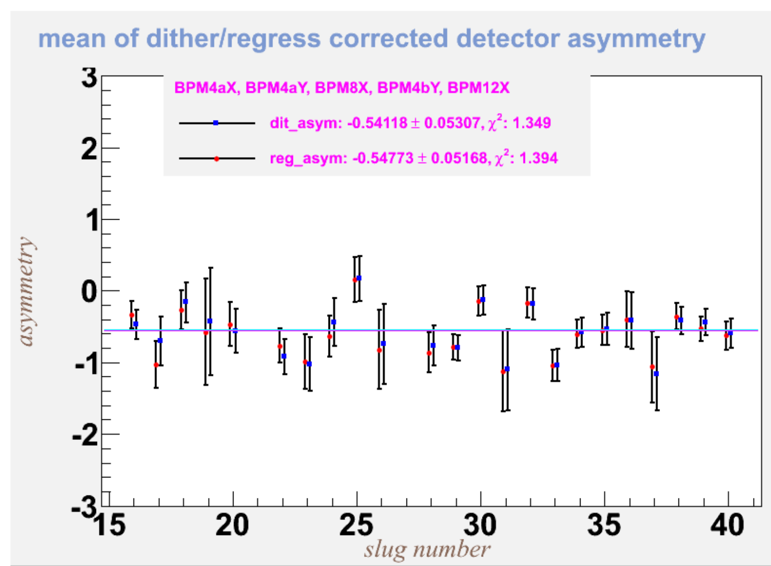




Data Quality and Analysis

- All asymmetries were blinded approximately 1σ
- Asym. widths are determined by statistics of photo-electrons, changes in beam parameters, electronic noise, etc.
- Integrated helicity pair-wise asymmetries are corrected for beam flucts. (using dithering/modulation system and standard regression)
- Measured asymmetries relatively stable over the run
- Slow helicity reversal with HWP and double-Wien successful in controlling systematics



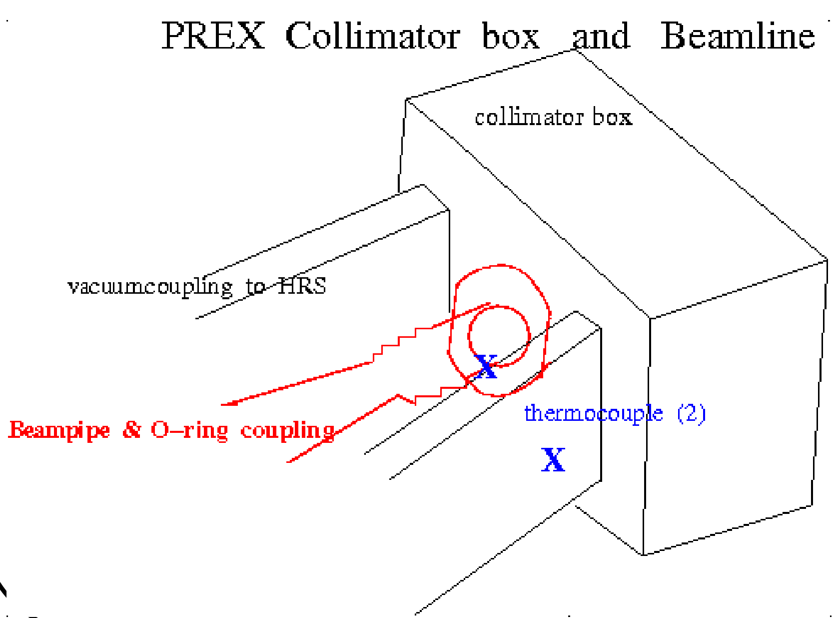


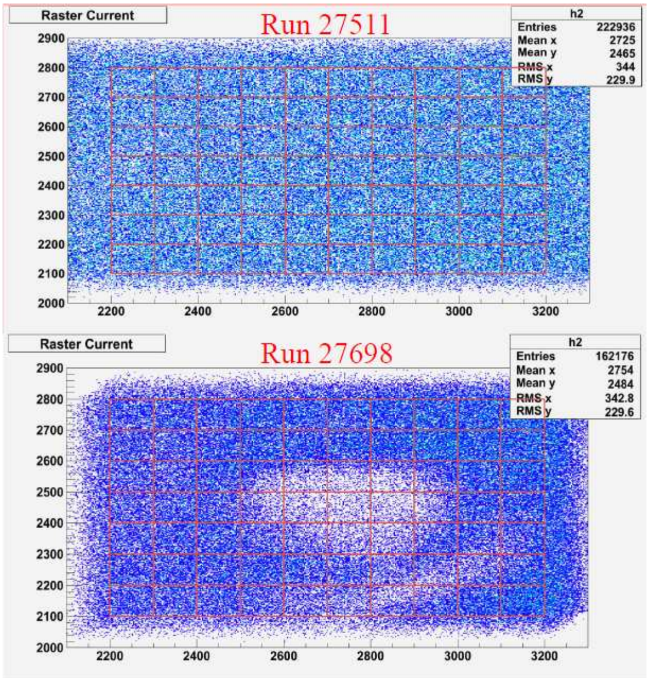
Experimental Issues

Several issues prevented full experimental program

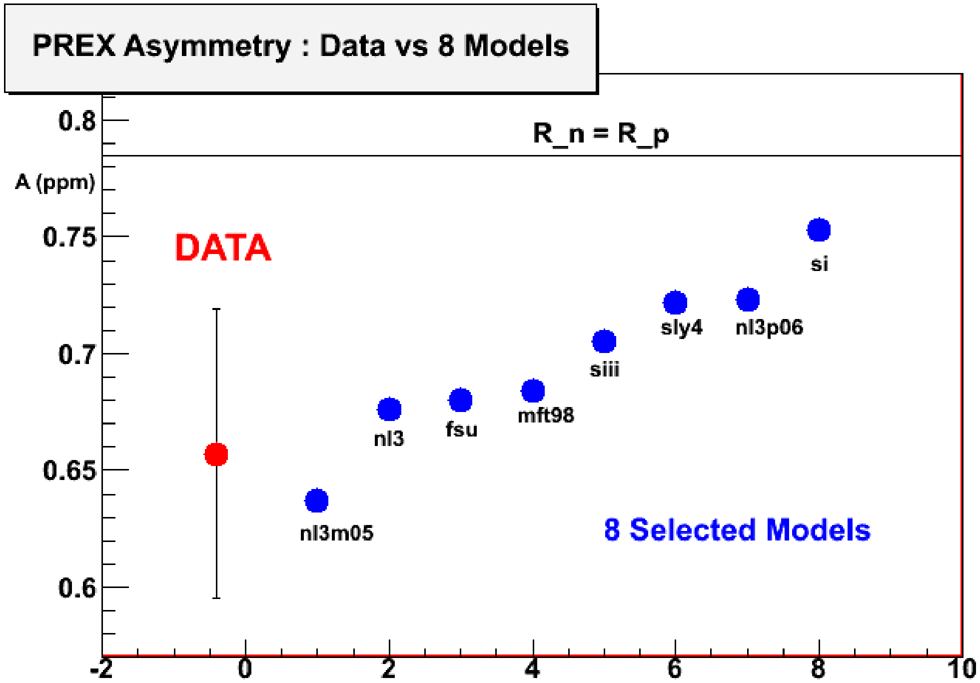
- Large amounts of rad. were dumped into the exp. hall damaging electronics
- Mistune of septum field – caused loss of some small angle statistics
- Destruction of scattering chamber rubber O-rings
- Targets were destroyed by beam over periods of time

(loss of material $\sim$ 10%); thicker diamond targets were more successful





Results



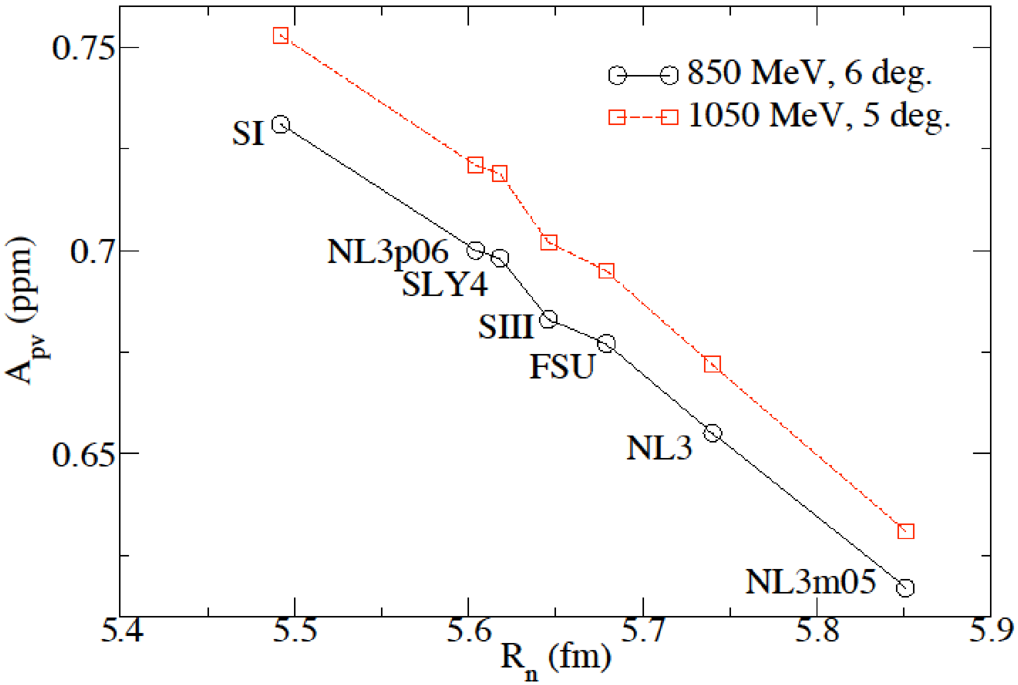
- Set 95% CL on existence of neutron skin
- $R_n = 5.78^{+0.15}_{-0.17}$ fm, $\delta R = R_n - R_p = 0.34^{+0.15}_{-0.17}$ fm

→Each model of neutron density is folded into numerical solution of Dirac eqn with Coulomb and weak axial potential

→Full acceptance (apertures, septum optics, detectors) applied to A_{PV}

- PRL forthcoming

Results



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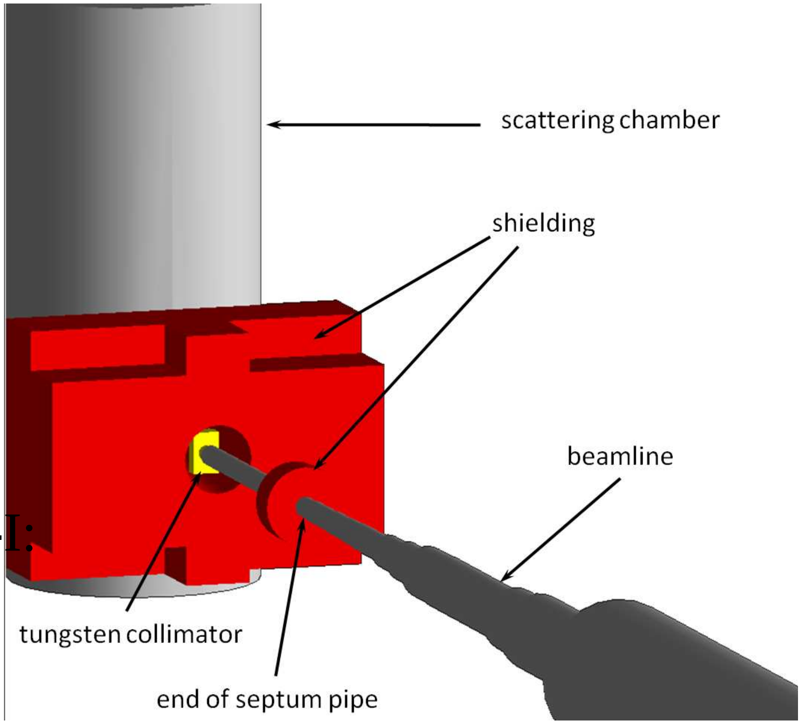
Result and Error Budget

$$A_{\mathrm{PV}} = 0.658 \quad \pm \quad 0.0604 \quad \pm 0.0130 \quad \mathrm{ppm}$$
$$\pm \quad 9.2\%(\mathrm{stat}) \quad \pm 2.0\%(\mathrm{syst})$$

Contributions	abs (ppm)	rel (%)
Polarization	0.0071	1.1%
Detector Lin.	0.0071	1.1%
Beam Corrections	0.0072	1.1%
Q^2	0.0028	0.4%
^{12}C Asymmetry	0.0025	0.4%
Transverse Pol.	0.0012	0.2%
BCM Lin.	0.0010	0.1%
Target Thick	0.0006	0.1%
Rescattering	0.0001	0.0%
Inelastic Cont.	0.0000	0.0%

Future Plans

- New proposal to complete measurement to be submitted to August PAC
  →Measurement of A_{PV} to 3% (combined with PREx-I) with 35 PAC days



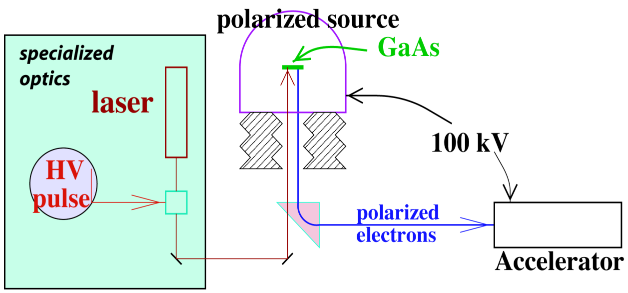
- Several improvements over PREx-I:
  →Improved metal O-rings
  →Additional radiation mitigation

- Must run at start of 12 GeV commissioning - 2014?
- Separate proposal for similar measurement on ^{48}Ca likely in future

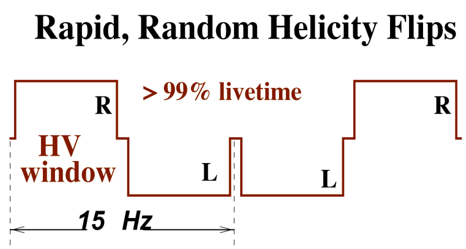
Summary

- PREx experiment ran March - June 2010 to measure R_n on ^{208}Pb
- After all corrections: A_{PV}^{Pb} = 0.658 ± 0.0604 (9.2%) ± 0.0130 (2.0%) ppm (statistics dominated uncertainty)
- From simple fit over models: $R_n = 5.78^{+0.15}_{-0.17}$ fm
- Neutron skin: R_n - R_p = $0.34^{+0.15}_{-0.17}$ fm
- Established existence of neutron skin with 95% CL
- PREx-II proposal, to reduce quoted uncertainty by factor of 3, to be considered by PAC in upcoming months
- PREx-II precision can better discriminate between models allowing predictions relevant for the description of neutron stars

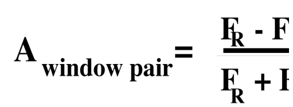
Experimental Method



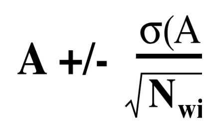
rapid, random, helicity flipping



Measure flux F for each window



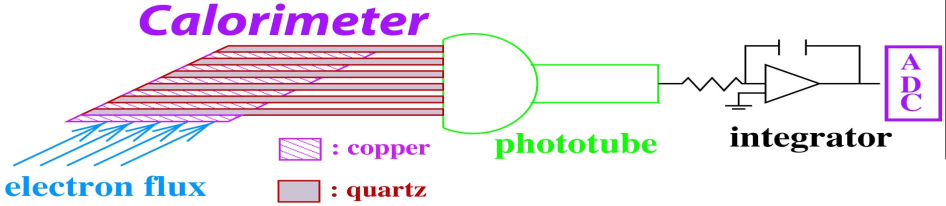
Signal Average N Windows Pairs:

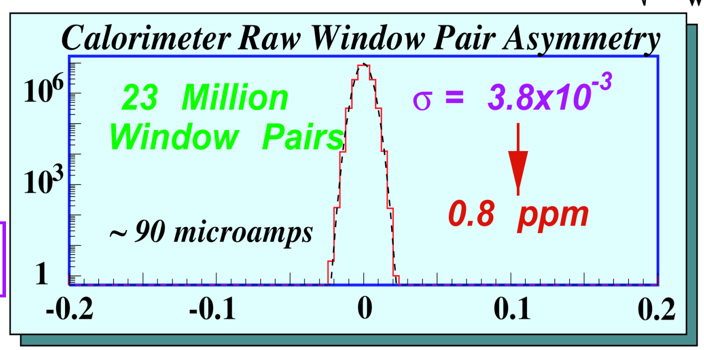


Flux Integration Technique:

HAPPEX: 2 MHz

PREX: 850 MHz





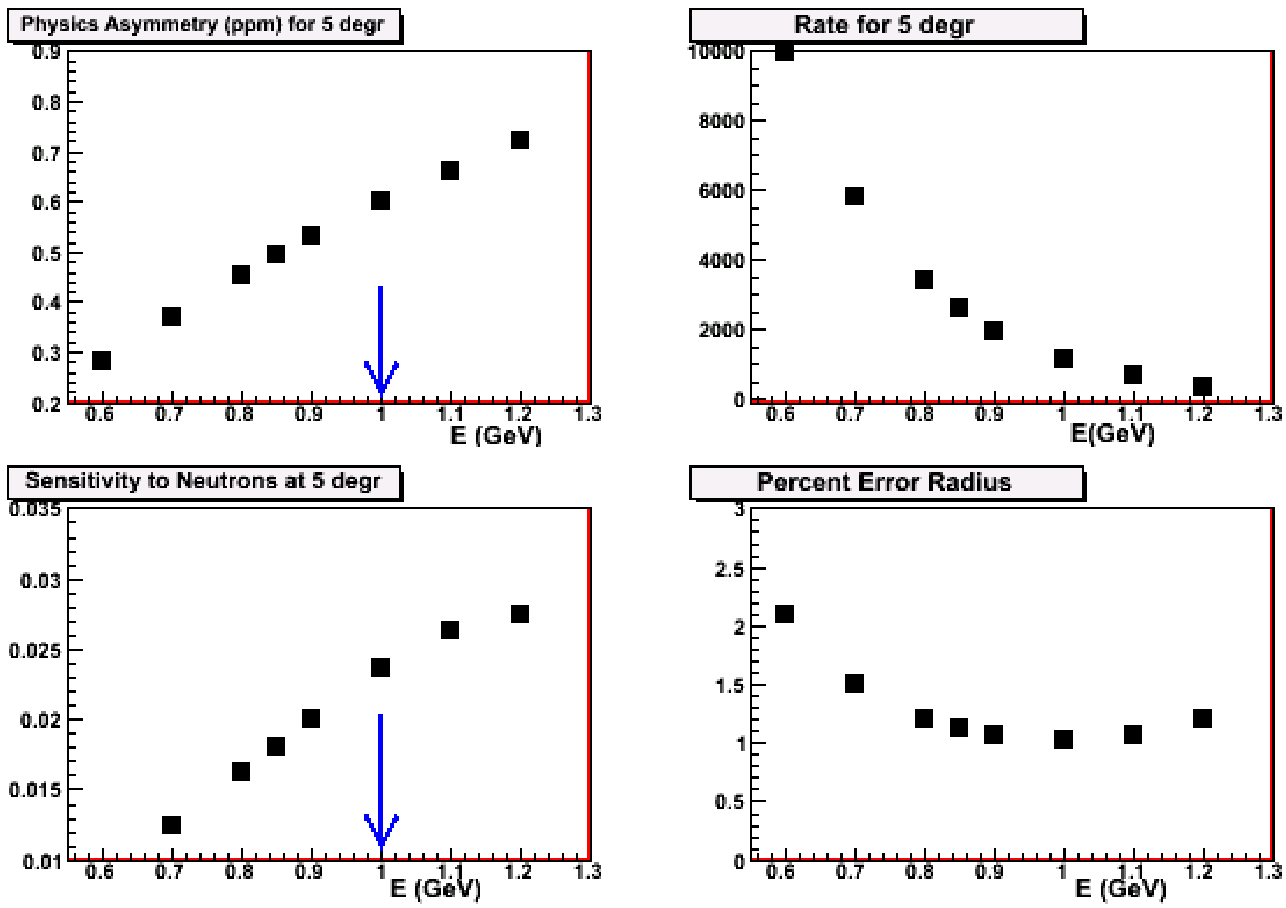
No non-gaussian tails to +/- 5σ

Extra Slide – Experiment Challenges

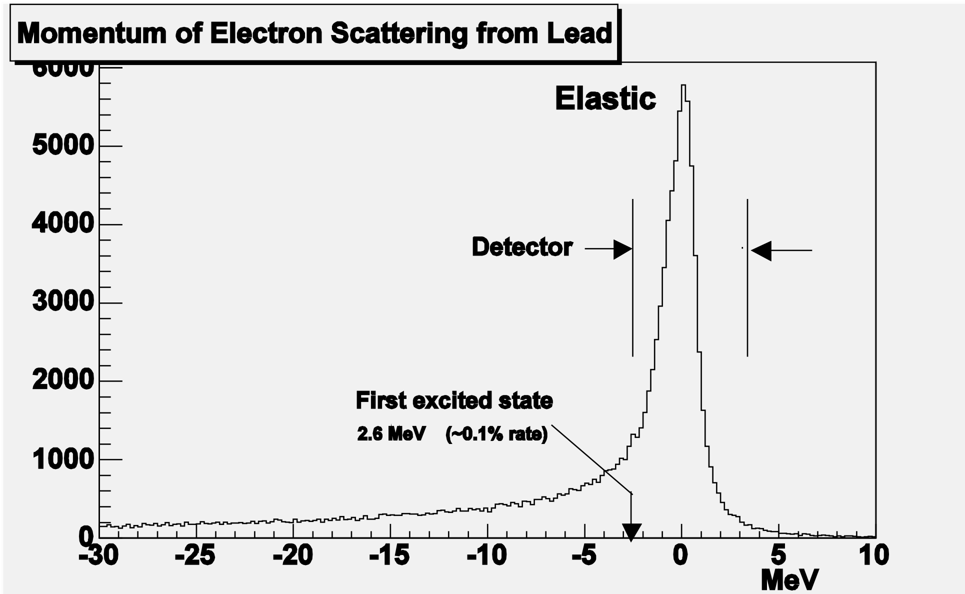
- Precision Measurement of Q^2
  - →Requires beam monitoring at 0.05 μA using new BCMs
  - →$\pm 0.02^\circ$ accuracy in spectrometer angles
- Precision beam polarimetry at 1GeV beam energy
  - →Upgrade Compton polarimeter: new cavity, e^- and γ detectors
- Unprecedented control over helicity correlated beam asymmetries
  - →$Q_{asym} \lesssim 100 \pm 10$ ppb
  - →Maintain beam position differences $\lesssim 1 \pm 0.1$ nm
  - →High precision beam trajectory corrections: cavity BPMs and new dithering system
- Require sub-100 ppm pulse-to-pulse electronics noise
  - →Employ new 18-bit ADCs (currently being commissioned)
  - →Improve Luminosity Monitor performance
- Keep all sources of systematics in check...for example
  - →Septum collimator alignments/acceptances
  - →Spect. optics tuning and prex detector size and positioning

Extra Slide – Figure of Merit for New Design

$$\mathrm{FOM} \times \varepsilon^2 = \mathrm{R} \times \mathrm{A}^2 \times \varepsilon^2 \quad (1)$$



Extra Slide – Integrate Elastic Peak

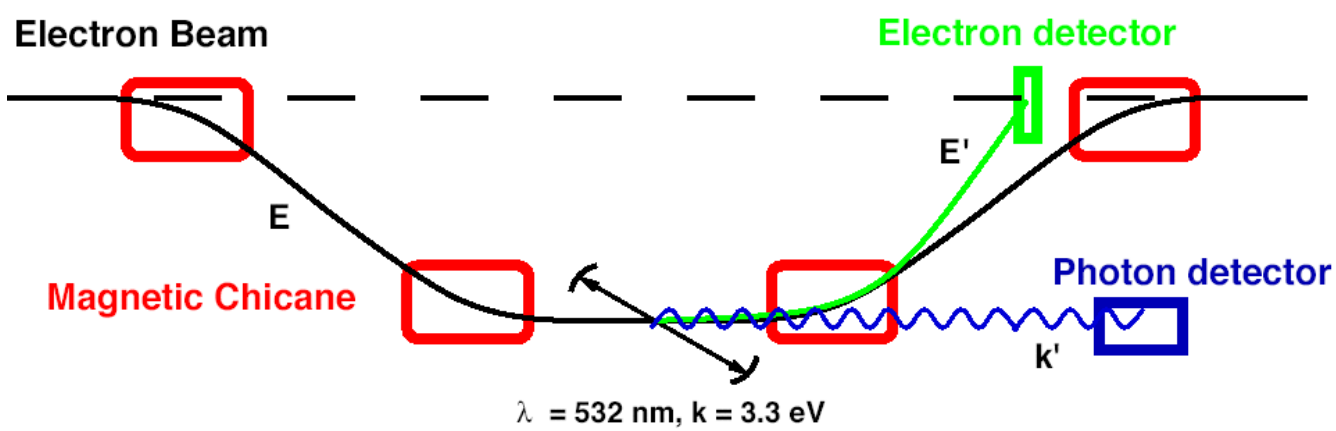


Extra Slide – Compton Beam Polarimetry

- Upgrade to green laser cavity and high resolution γ-detector

Compton Polarimetry

Goal : < 1% error



Extra Slide – Test Period Target Design

• 0.5mm, 10% X_0 isotopically pure (99.1%) ^{208}Pb foil sandwiched between 0.2mm thick diamond sheets

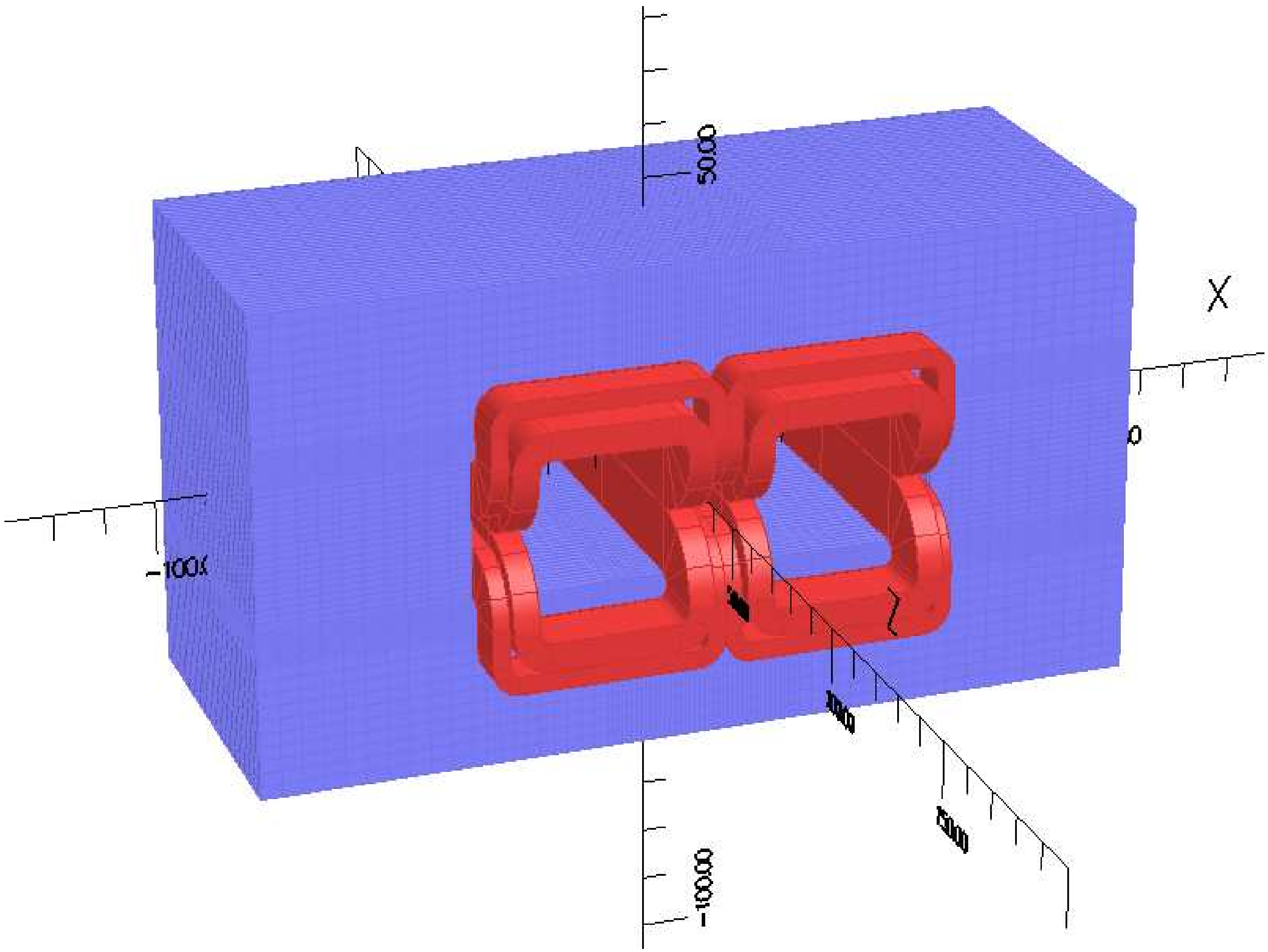
PREX target

(0.5mm)

e06007 targets

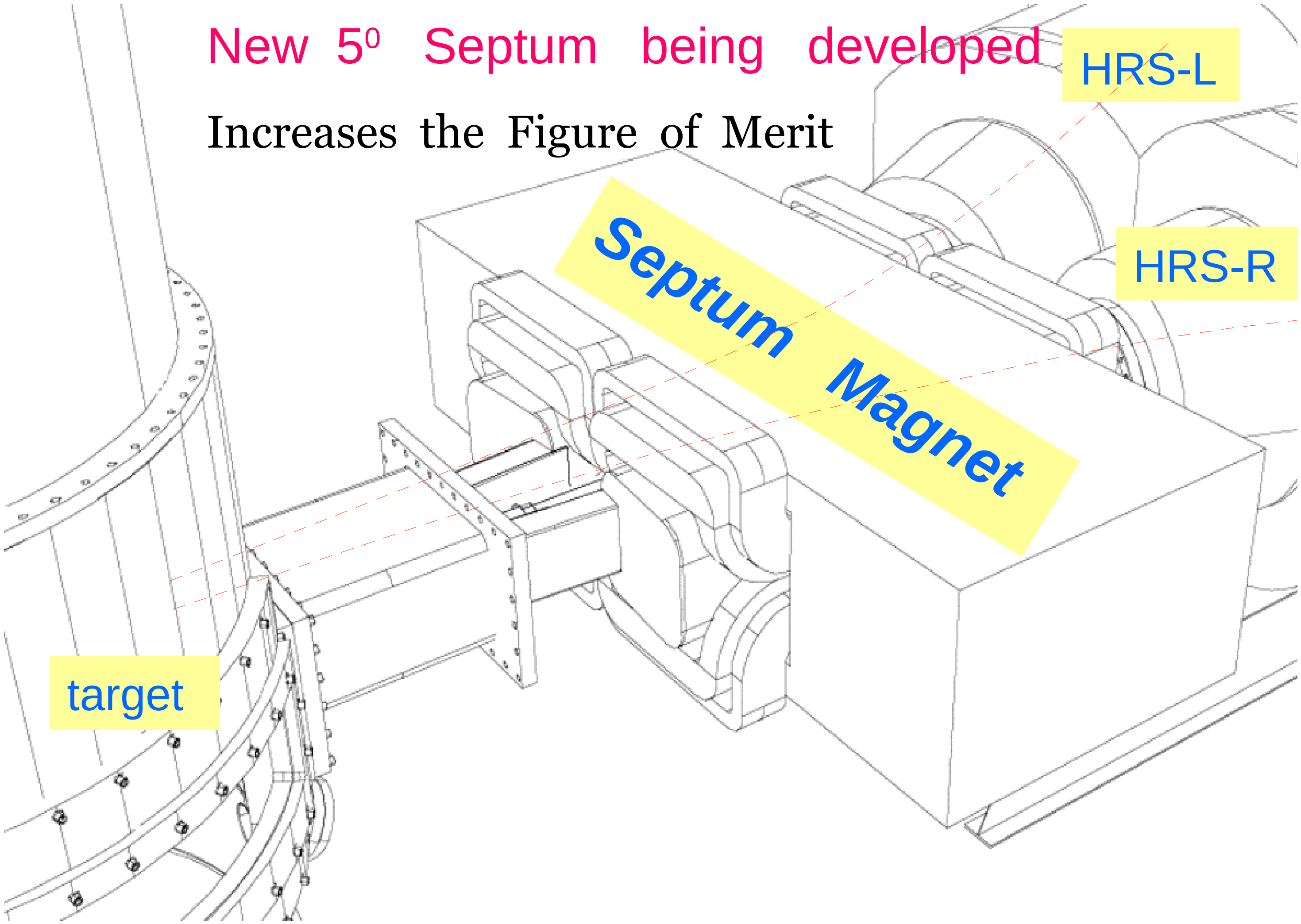
(tilted by 30deg)

Extra Slide – Warm Septum (Changed from 6° to 5°)



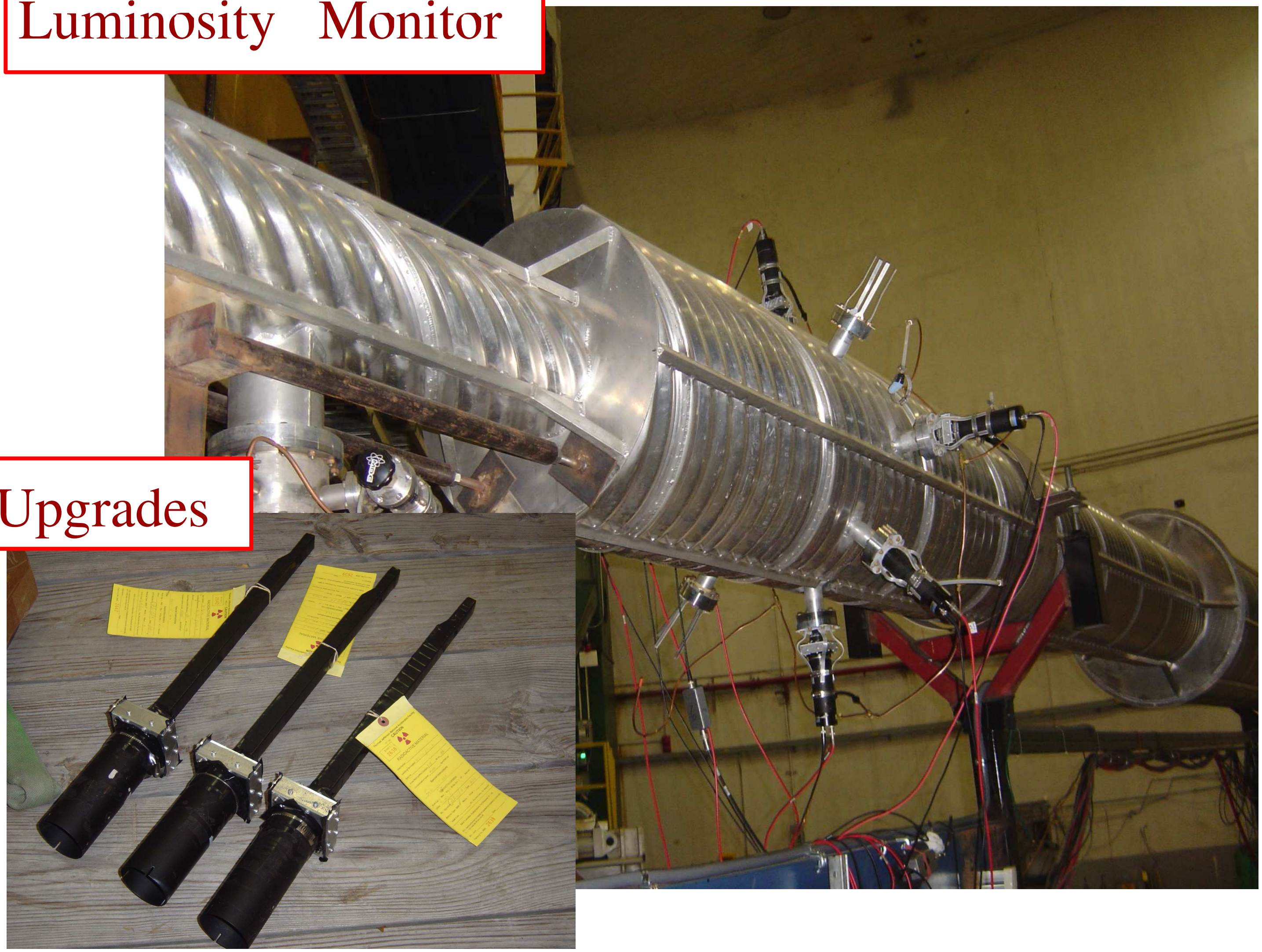
New 5^0 Septum being developed

Increases the Figure of Merit



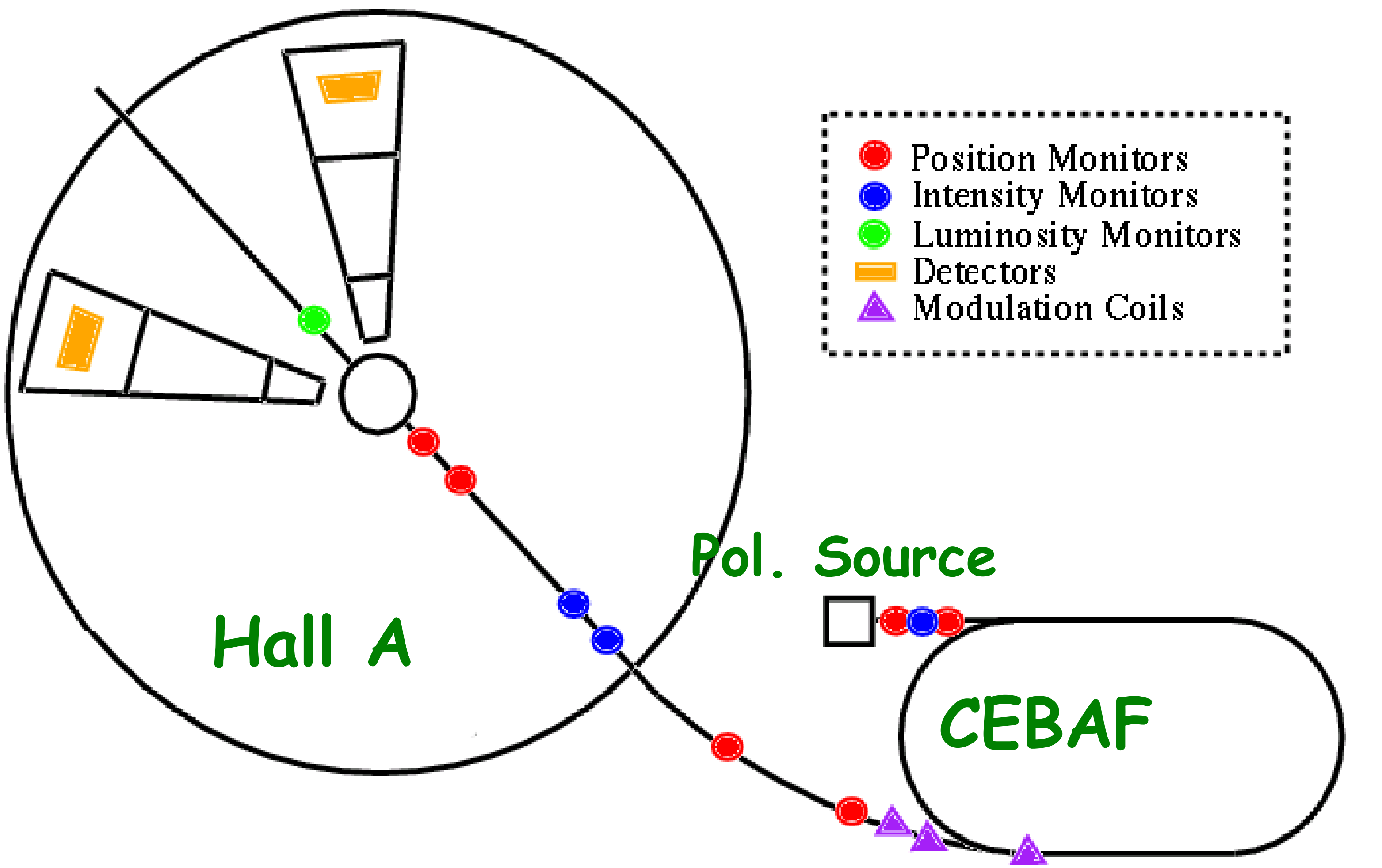
PREx Collaboration

Luminosity Monitor

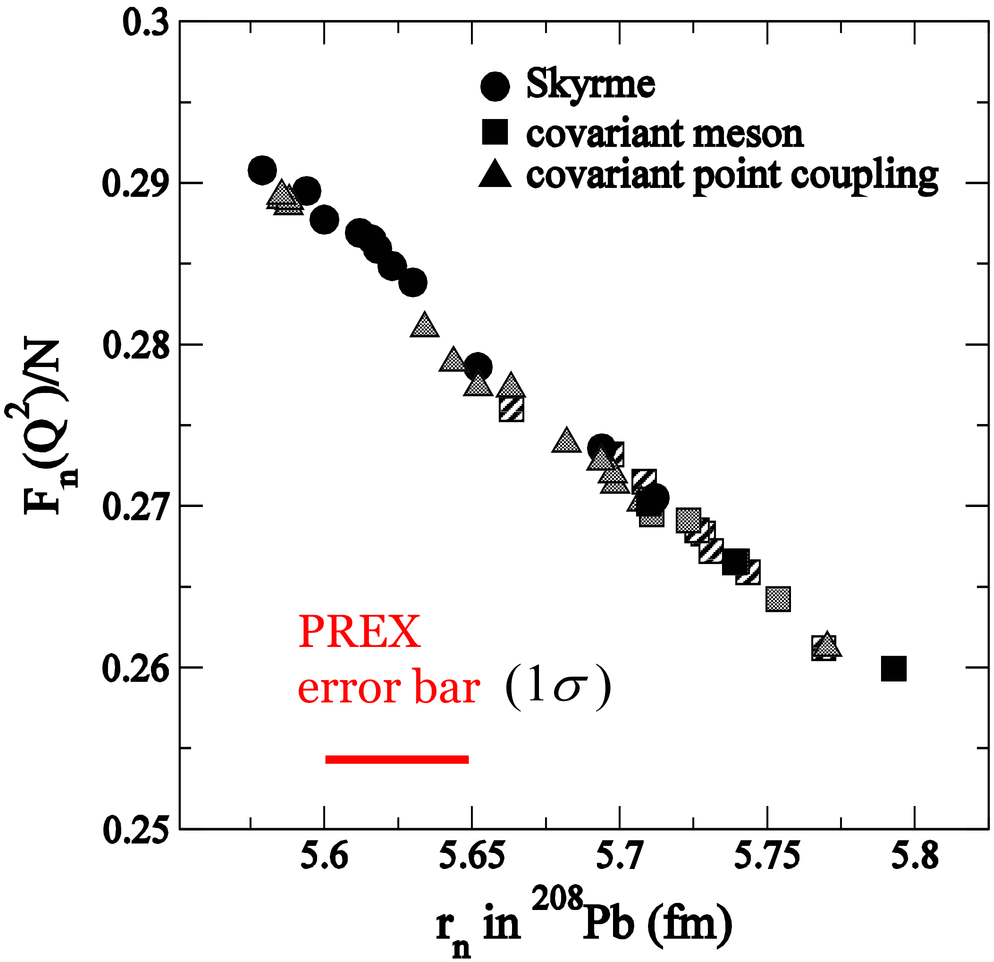


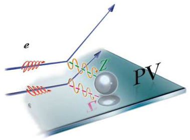
Upgrades

Extra Slide – Beamline Components



Measurement at a Single Q^2 Sufficient to Determine R_n





Symmetry Energy and the ^{208}Pb Neutron Skin