A Precision Measurement of the Neutron Radius in ^{208}Pb

Dustin McNulty
UMass
for the PREx Collaboration
mcnulty@jlab.org

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Outline

- Introduction:
  - Parity Violating Electron Scattering
  - Radial Densities of ^{208}Pb
- Theory Overview: Parity Violation and Form Factors
- PREx Measurement and Challenges
- Summary and Outlook

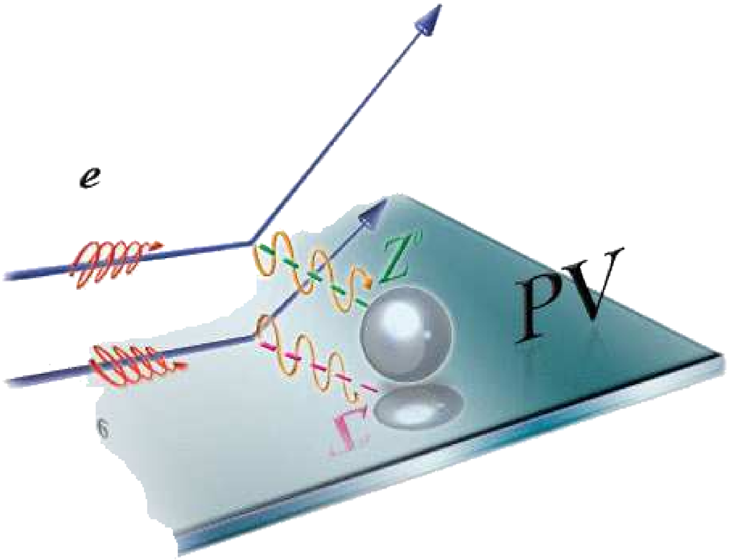
Introduction to PVES

- Parity Violating Electron Scattering (PVES) allows access to the weak nuclear charge distribution via an electroweak-interference dominated asymmetry measurement (A_{PV})
- Z^0 of weak interaction: Clean probe coupling primarily to neutrons
- Very challenging measurement requiring:

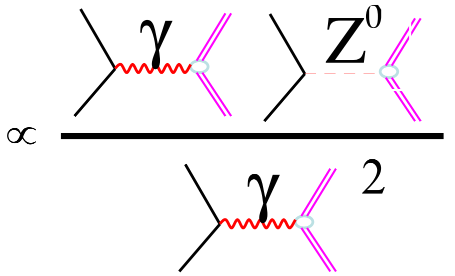
→ Precise matching of elec. beam charact. for Left vs. Right helicity states

→ Precision non-invasive, continuous beam polarimetry

→ Precision knowledge of Luminosity, Q^2, and spect. acceptances and bkgds

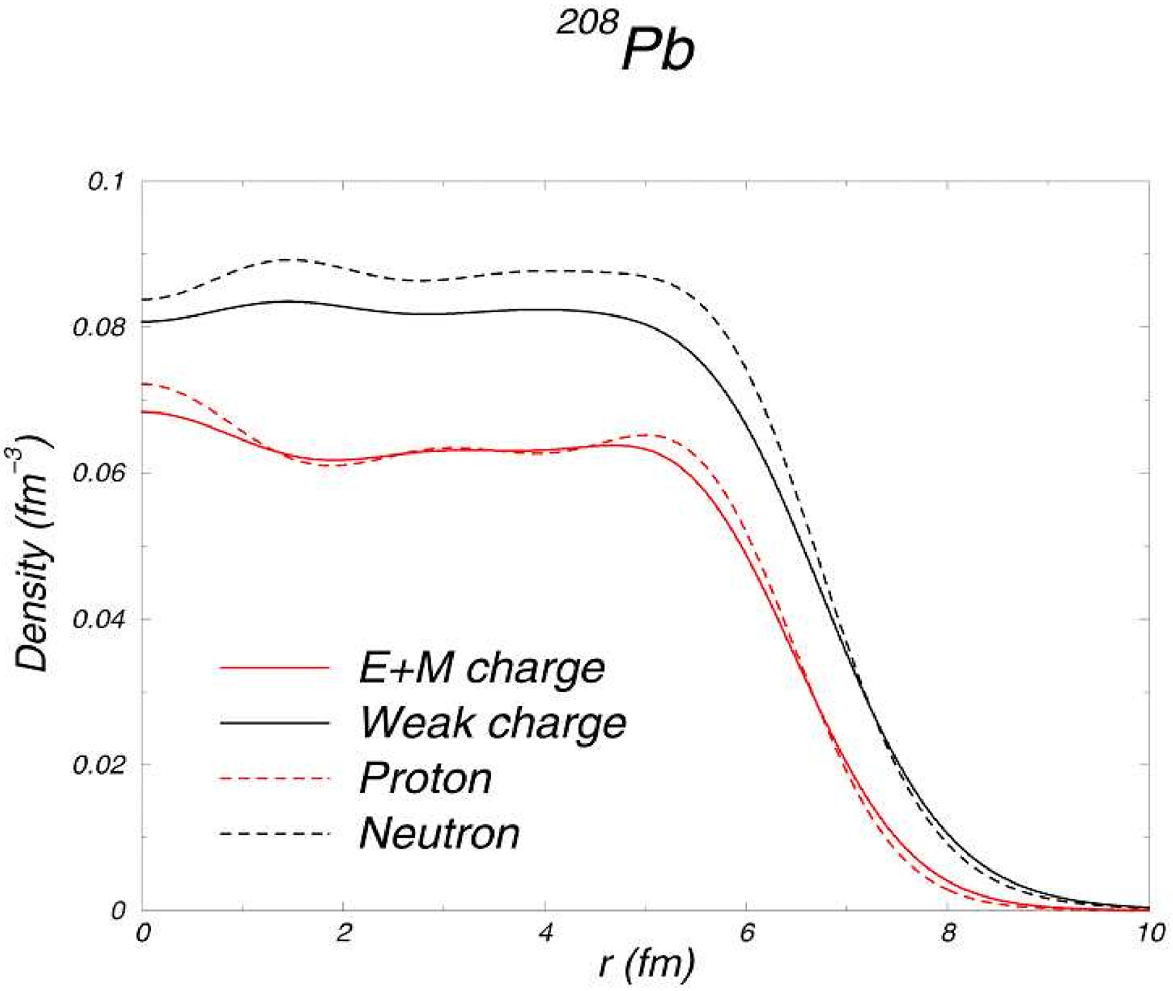


$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



$$\sim \frac{10^{-4} Q^2}{\mathrm{GeV}^2}$$

Radial Densities



- The size of a heavy nucleus is one of its most basic properties

Parity Violation and Nucleon Form Factors

- Isolate the weak interacting part of PV by measuring asymmetry:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-6} \tag{1}$$

- The potential between electron and nucleus can be written as:

$$\hat{V}(r) = V(r) + \gamma_5 A(r) \tag{2}$$

where $V(r) = \int d^3r' Z\rho(r')/|\vec{r} - \vec{r}'|,$ (3)

and $A(r) = \frac{G_F}{2^{3/2}}\left[(1 - 4\sin^2\theta_W) Z\rho_p(r) - N\rho_n(r)\right]$ (4)

- Since the weak charge of the proton is small ($\sin^2\theta_W \approx 0.23$), the axial potential depends mainly on the neutron density $\rho_n(r)$.

Parity Violation and Nucleon Form Factors (cont.)

- The electromagnetic cross section for electron scattering:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}} |F_p(Q^2)|^2 \tag{5}$$

where $$F_p(Q^2) = \frac{1}{4}\int d^3r' j_0(qr)\rho_p(r) \tag{6}$$

is the form factor for protons from which one may determine R_p.

- One can also define a form factor for neutrons from which R_n may be determined:

$$F_n(Q^2) = \frac{1}{4}\int d^3r' j_0(qr)\rho_n(r) \tag{7}$$

- In the Born approx., the PV asymmetry involves the interference between V(r) and A(r):

$$A_{PV} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[4\sin^2\theta_W - 1 + \frac{F_n(Q^2)}{F_p(Q^2)}\right] \tag{8}$$

The Neutron and Weak Charge Radius

$$R_n^2 = \int d^3r\, r^2 \rho_n(r) \tag{9}$$

- But what we really measure is the weak charge density/radius:

$$R_W^2 = \frac{1}{Q_W}\int d^3r\, r^2 \rho_W(r) \tag{10}$$

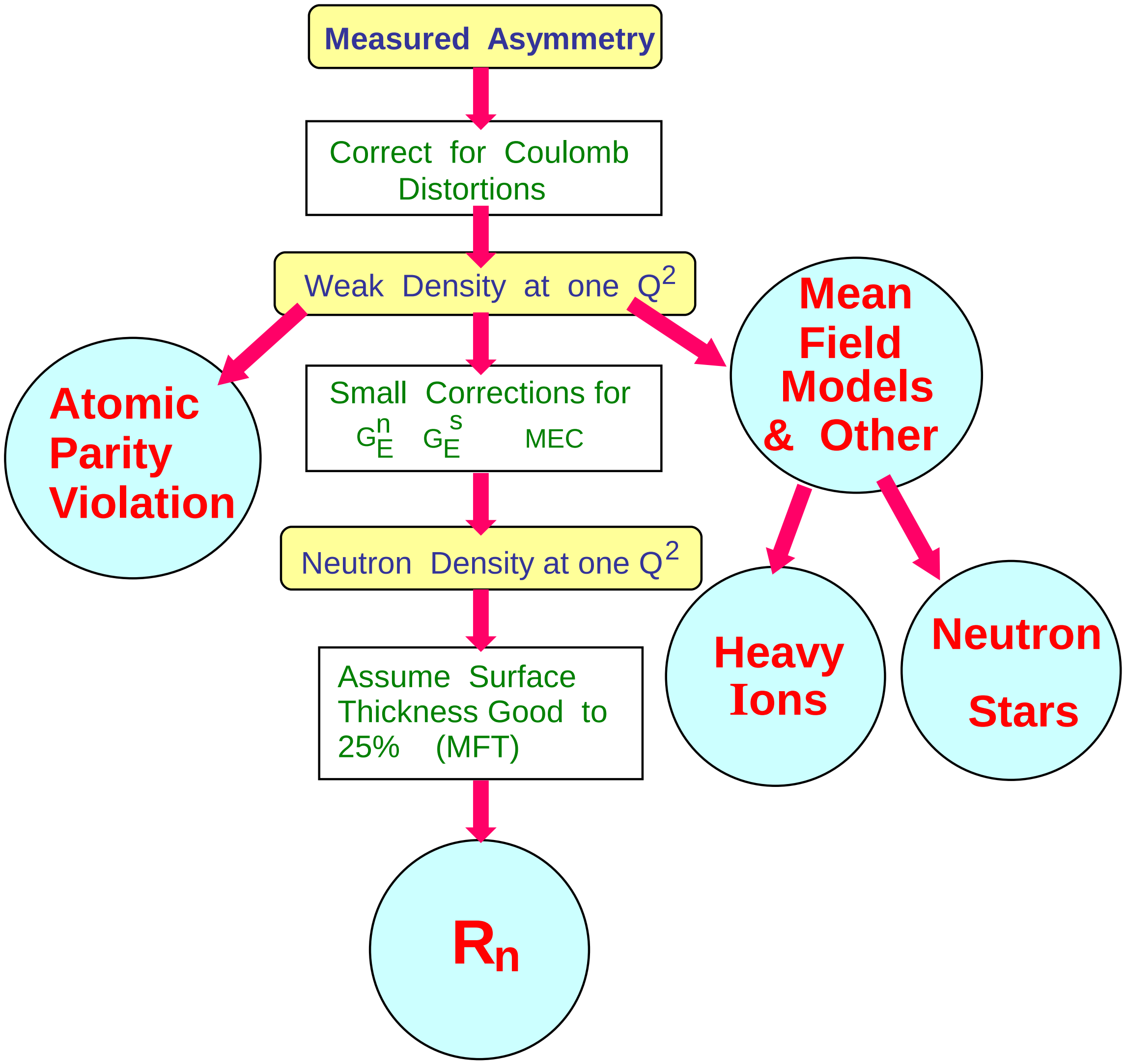
with $$\rho_W(r) = 4\int d^3r' [G_n^Z(r')N\rho_n(|\mathbf{r}-\mathbf{r'}|) + G_p^Z(r')Z\rho_p(|\mathbf{r}-\mathbf{r'}|)] \tag{11}$$

and $$G_{n:p}^Z = \frac{1}{4}(G_{n:p}^E - G_{p:n}^E) - \sin^2\theta_W G_{n:p}^E - \frac{1}{4}G_s^E. \tag{12}$$

- Under reasonable assumptions of strangeness and neutron form factors, one can show that R_n for a heavy nucleus directly follows R_W (within $\sim$1%)

$$R_n \approx R_W - 0.06\text{fm} \tag{13}$$

PREx Physics Impact



Measured Asymmetry

Correct for Coulomb Distortions

Weak Density at one Q^2

Small Corrections for G_E^n G_E^s MEC

Neutron Density at one Q^2

Assume Surface Thickness Good to 25% (MFT)

R_n

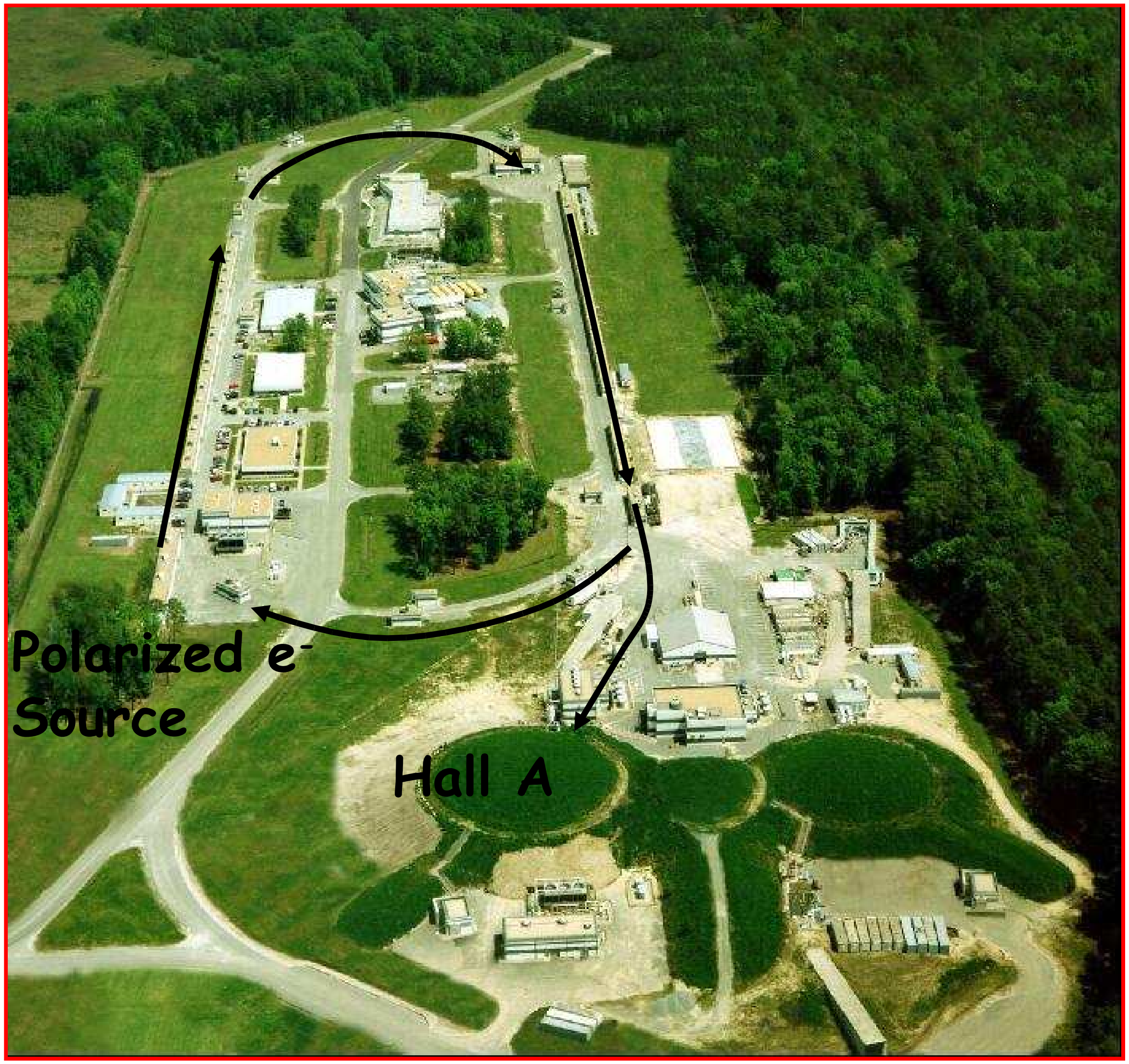
Atomic Parity Violation

Mean Field Models & Other

Heavy Ions

Neutron Stars

Jefferson Lab's CEBAF and Hall A



PREx Measurement (Spring 2010)

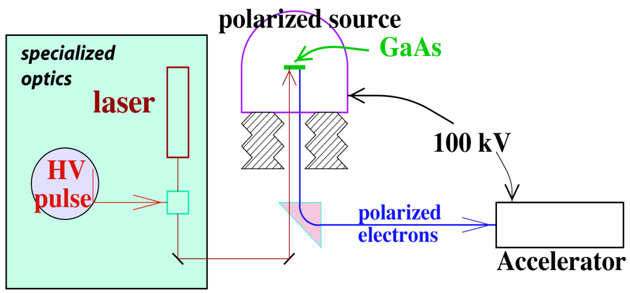
- $A_{PV} \sim 0.6$ ppm, $Q^2 \sim 0.01$ GeV
- $E_{beam} = 1.05$ GeV, 5.0° scattering, ~ 2 GHz Rate
- Statistical error goal $\sim$ 20 ppb ($\delta A/A \sim 3\%$)
- Systematic Error $\lesssim 2$ %

Physics Extracted

- Weak charge density
- Neutron density
- Neutron radius ($\sim$ 1 % level) and skin (R_n - R_p)

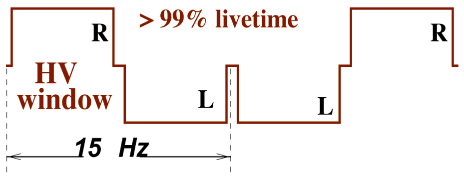
→With broad-based fundamental nuclear physics applications: Neutron stars, atomic PNC, heavy ion beams.

Experimental Method



rapid, random, helicity flipping

Rapid, Random Helicity Flips



Measure flux F for each window

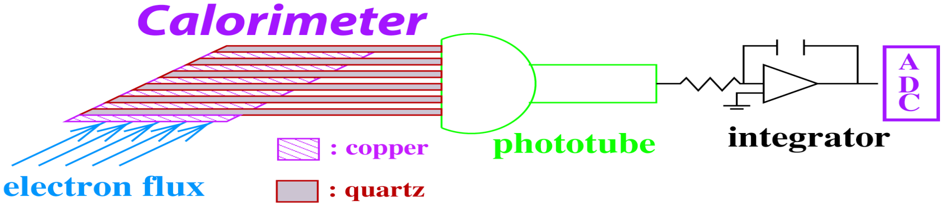
$$A_{\text{window pair}} = \frac{F_R - F}{F_R + F}$$

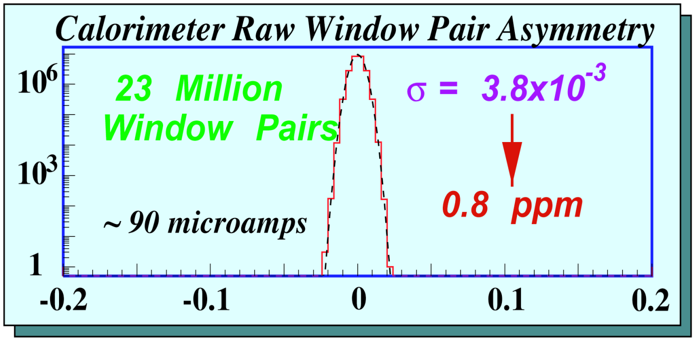
Signal Average N Windows Pairs: $A \pm \frac{\sigma(A}{\sqrt{N_{wi}}}$

Flux Integration Technique:

HAPPEX: 2 MHz

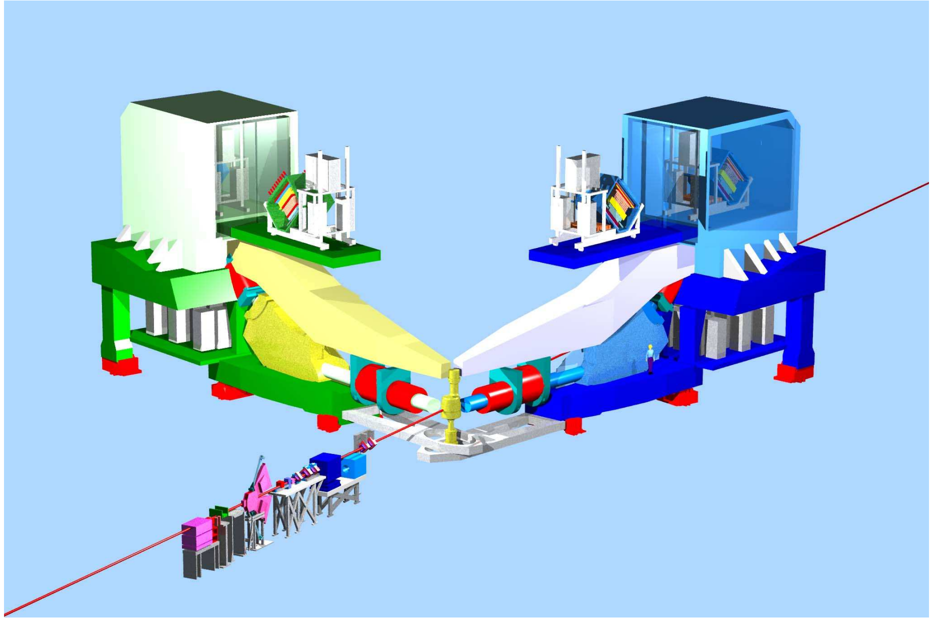
PREX: 850 MHz





No non-gaussian tails to +/- 5σ

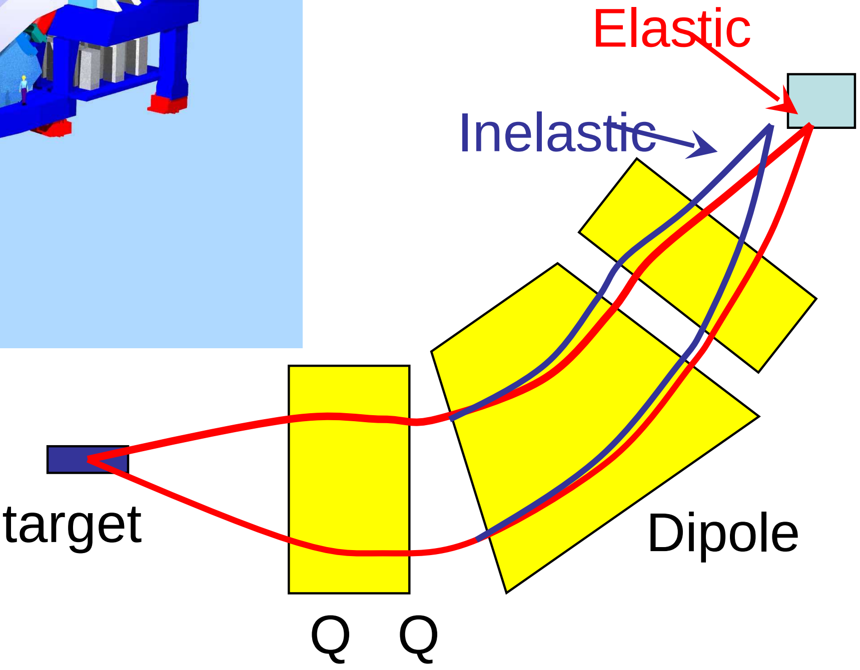
High Resolution Spectrometers



Left-Right symmetry to control transverse polarization systematic

Spectrometer Concept:

Resolve Elastic



Experiment Challenges

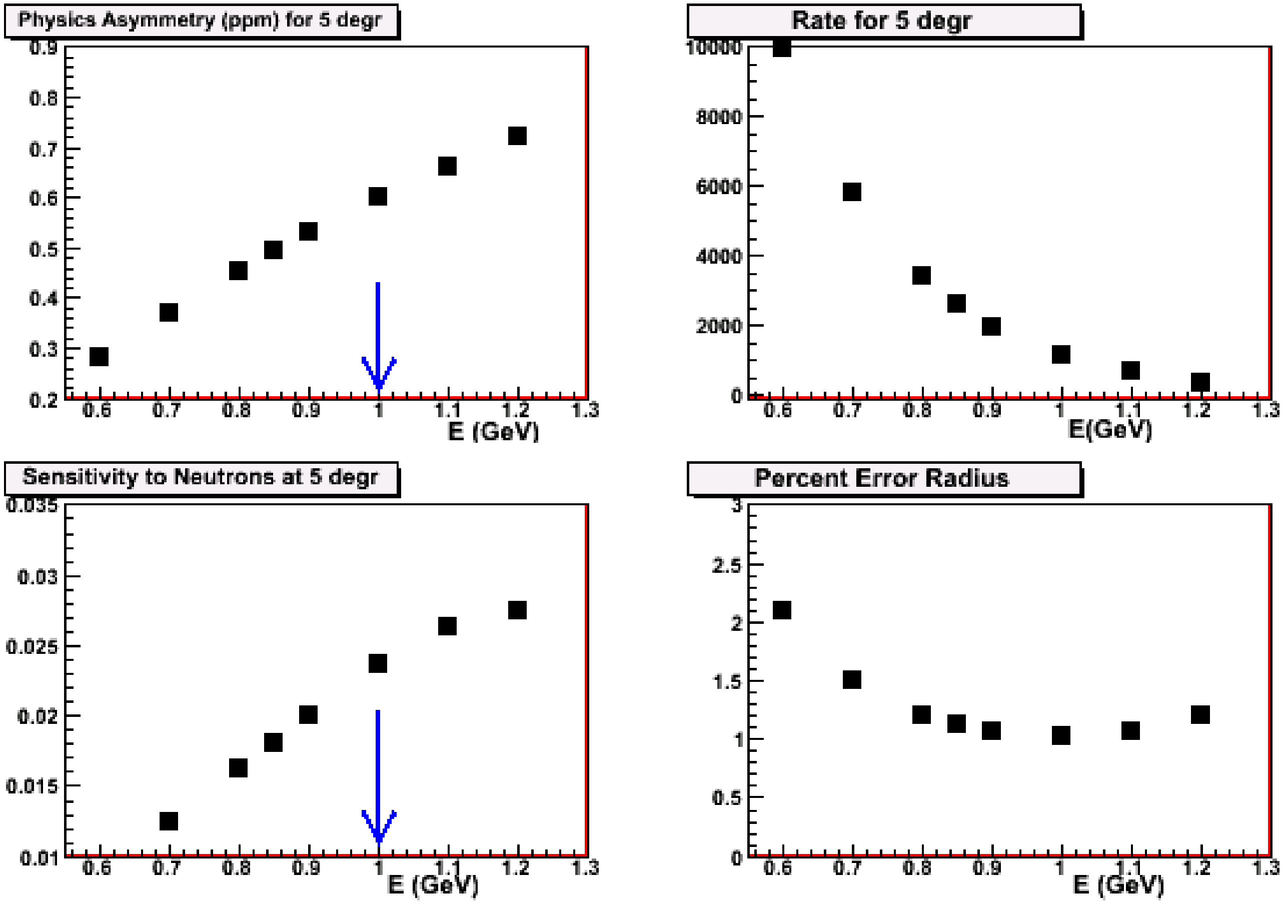
- Precision Measurement of Q^2
  - →Requires beam monitoring at 0.05 μA using new BCMs
  - →$\pm 0.02^\circ$ accuracy in spectrometer angles
- Precision beam polarimetry at 1GeV beam energy
  - →Upgrade Compton polarimeter: new cavity, e^- and γ detectors
- Unprecedented control over helicity correlated 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

Summary and Outlook

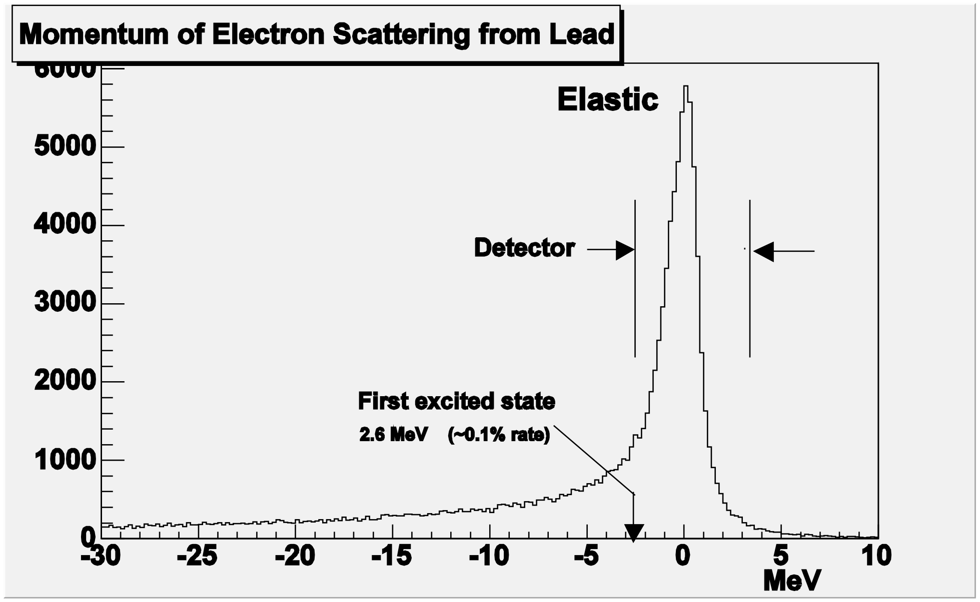
- PREx will measure directly the weak charge density of ^{208}Pb
- The data can be interpreted with as much confidence as that from electromagnetic scattering
- Interpretation is clean since theoretical corrections are either small or well understood
- The extracted neutron density and radius will provide unprecedented results with broad-based fundamental physics impact
- Changes in septum design ($6^\circ \rightarrow 5^\circ$) give optimized FOM at $E_{\mathrm{beam}} = 1.05$ GeV with increased R_n precision
- Steady progress is ongoing to meet the experimental challenges

Extra Slide – Figure of Merit for New Design

$$\mathrm{FOM} \times \varepsilon^2 = \mathrm{R} \times \mathrm{A}^2 \times \varepsilon^2 \qquad (14)$$



Extra Slide – Integrate Elastic Peak

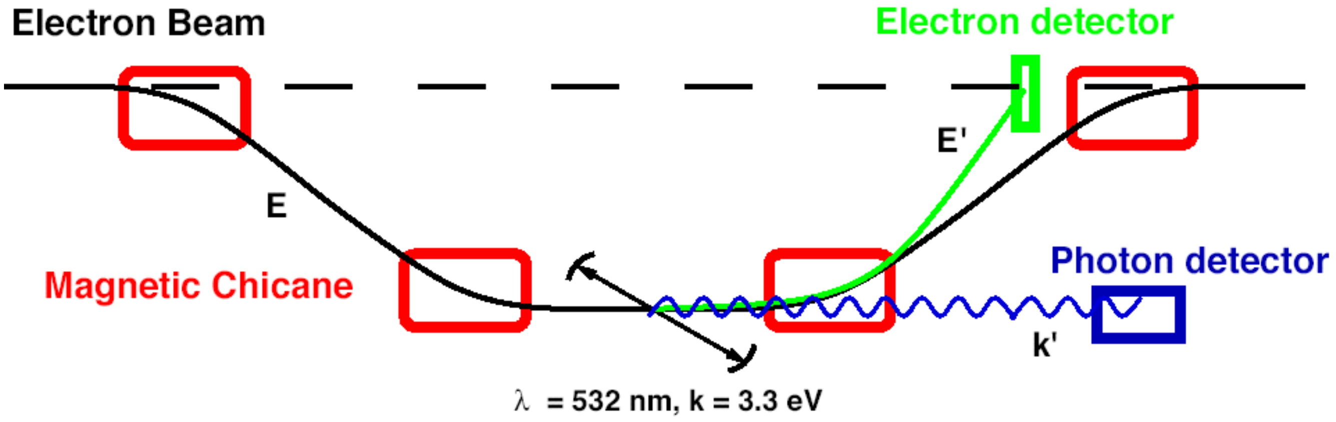


Extra Slide – Compton Beam Polarimetry

- 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

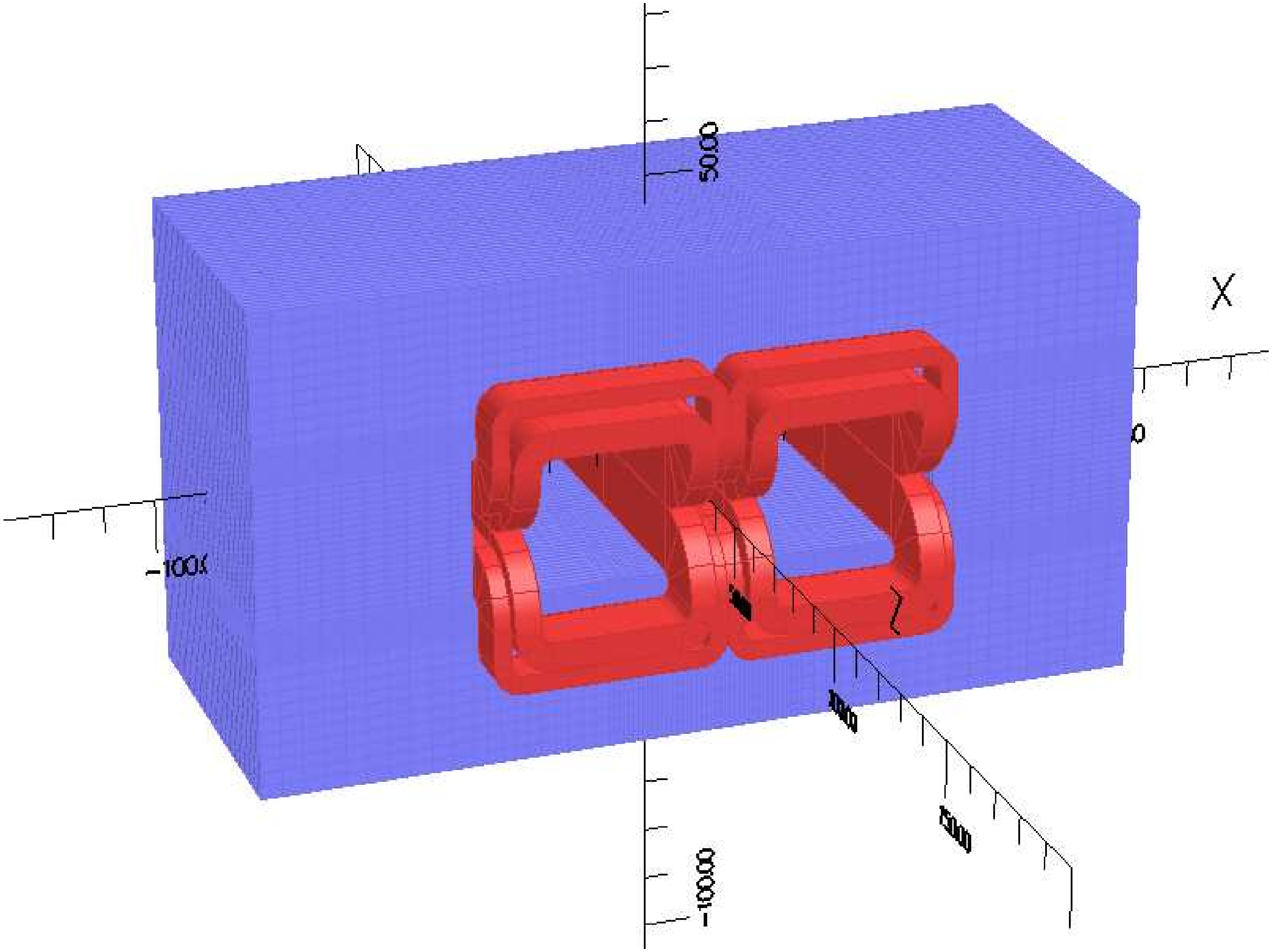
PREX target

(0.5mm)

e06007 targets

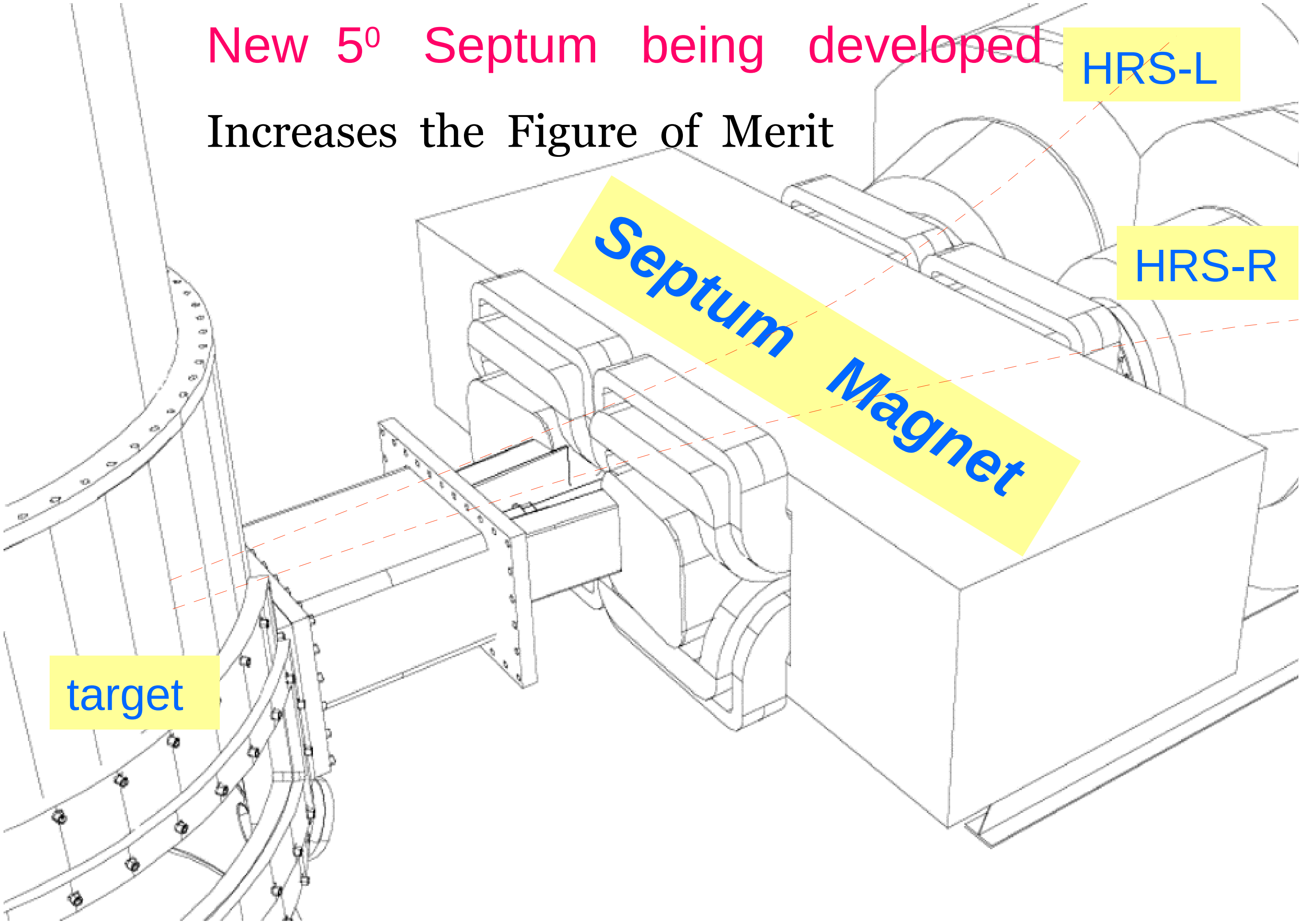
(tilted by 30deg)

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

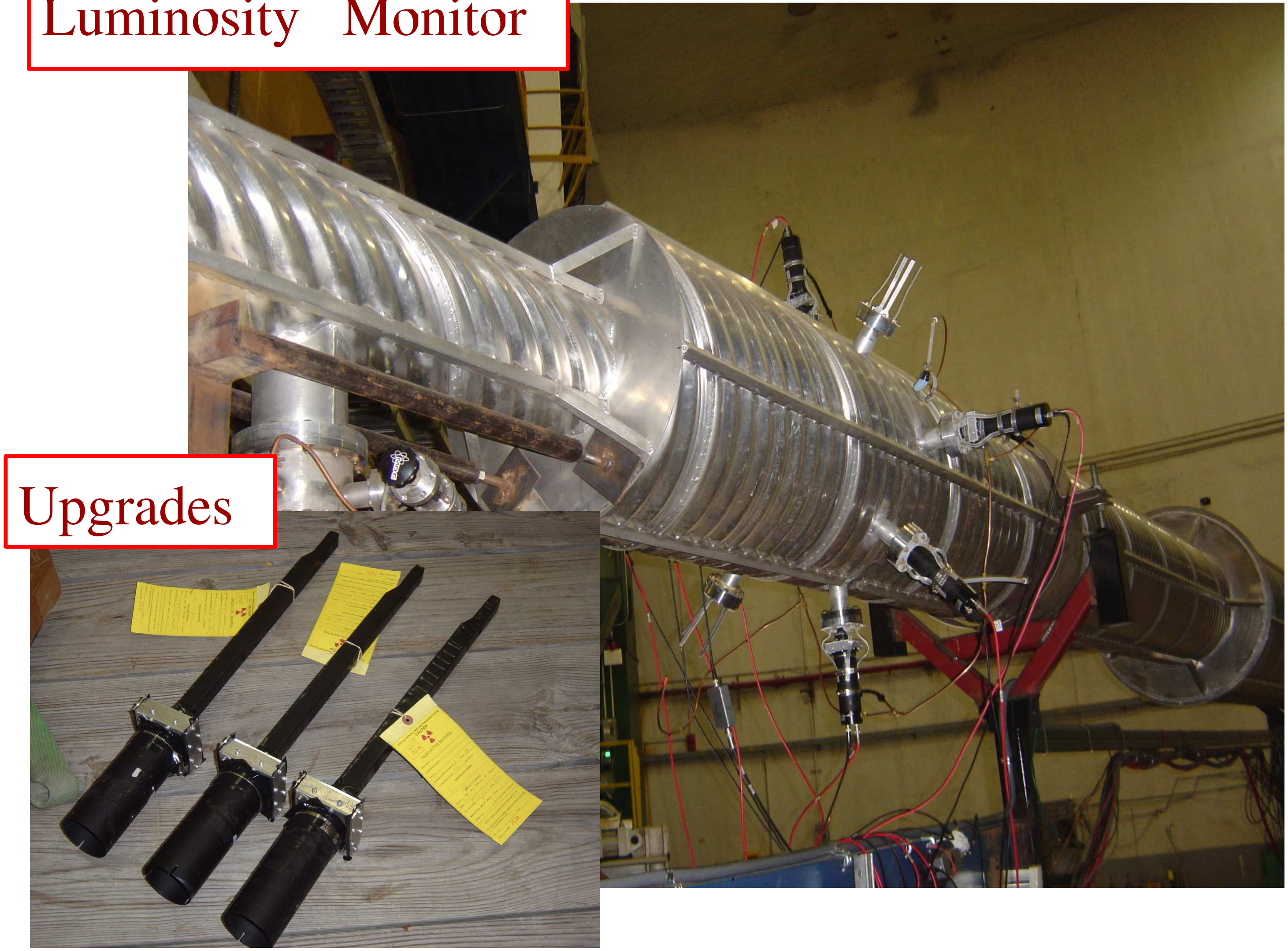


New 5^0 Septum being developed

Increases the Figure of Merit

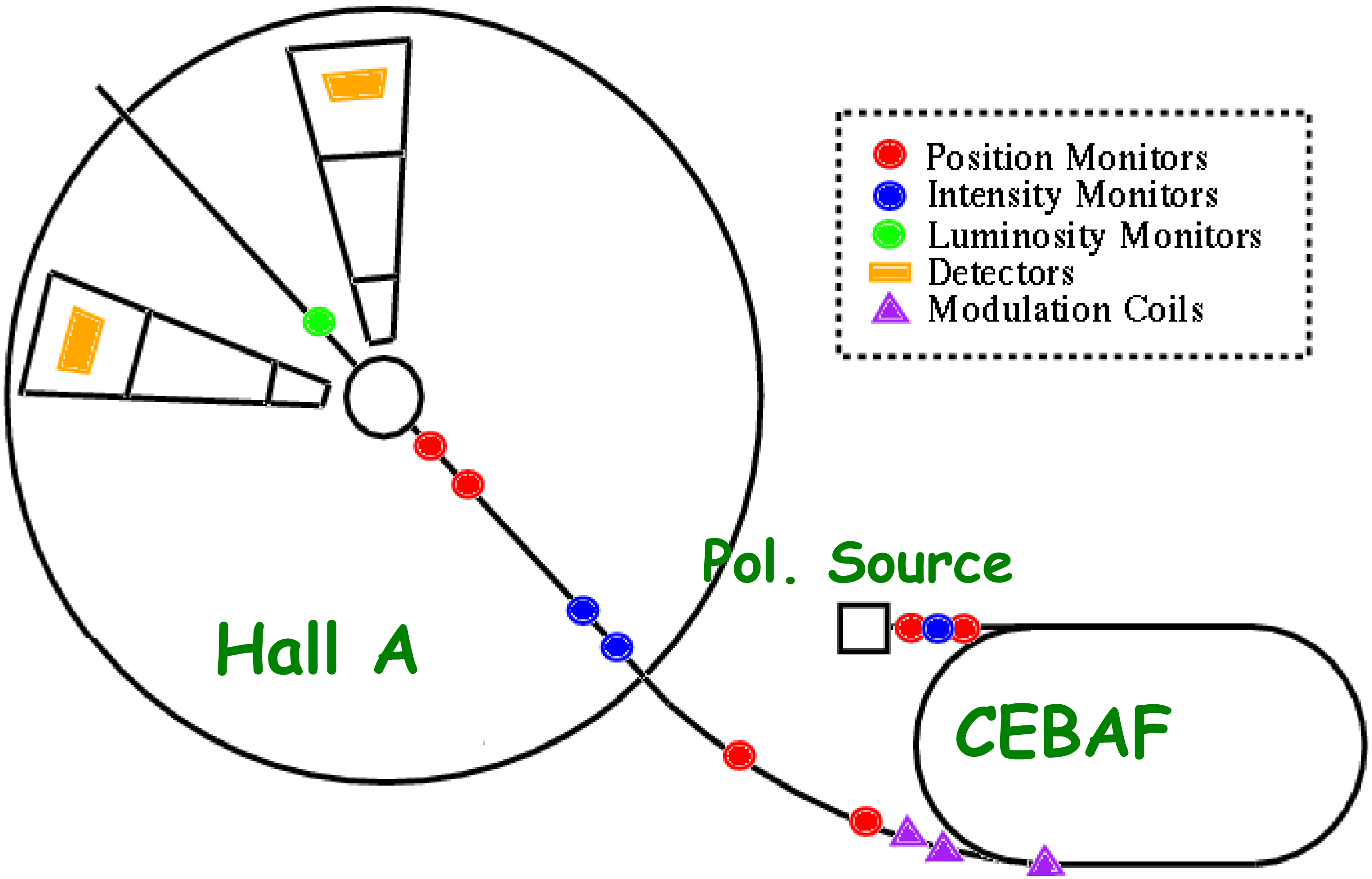


Luminosity Monitor

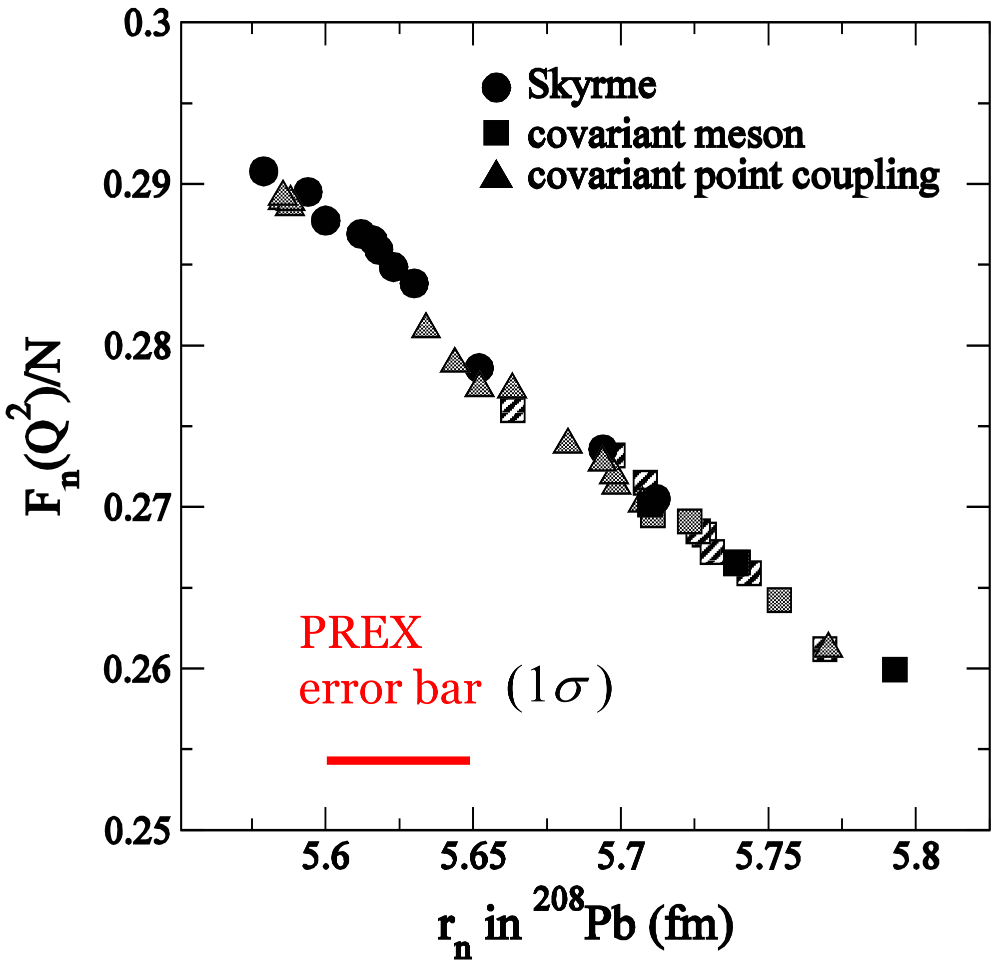


Upgrades

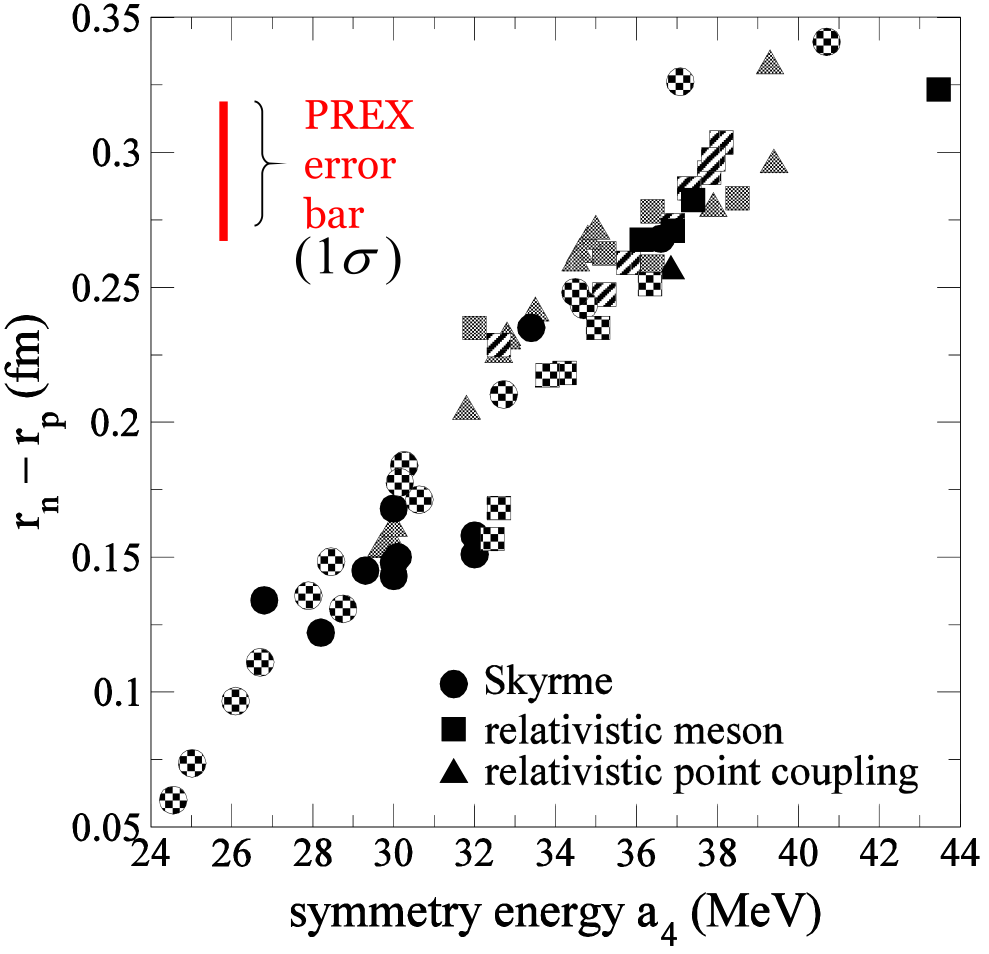
Extra Slide – Beamline Components



Measurement at a Single Q^2 Sufficient to Determine R_n



Symmetry Energy and the ^{208}Pb Neutron Skin



Neutron Equation of State

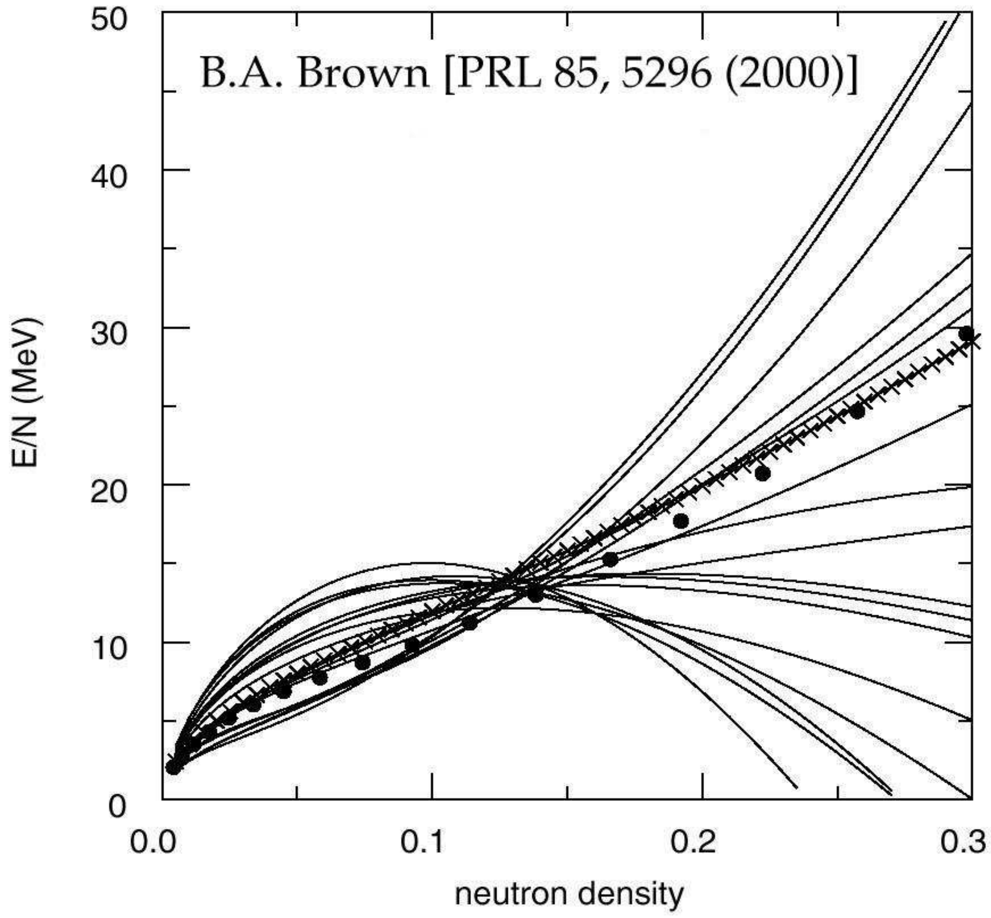


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.