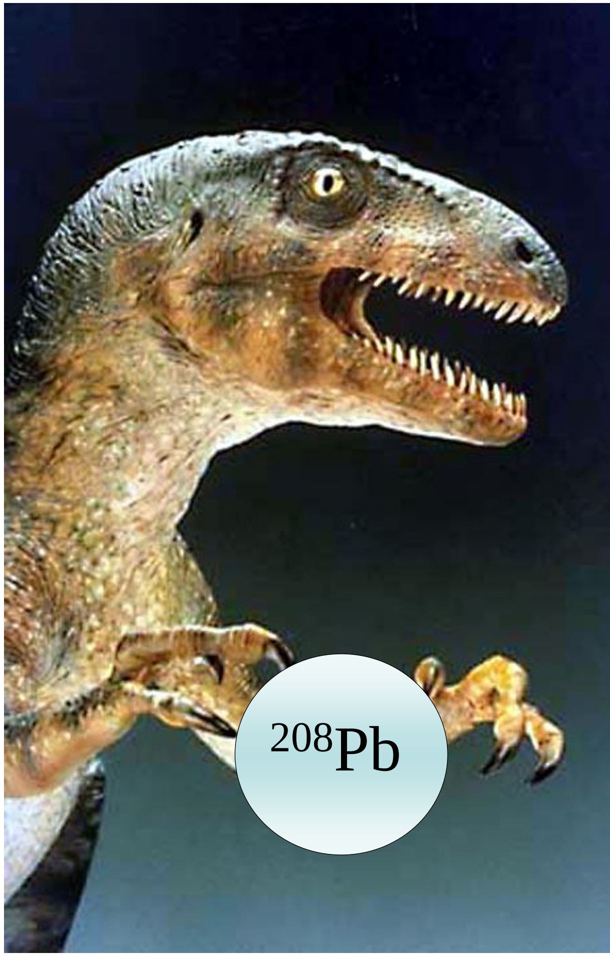
Lead (^{208}Pb) Radius Experiment : PREX

Elastic Scattering Parity Violating Asymmetry

E = 1 GeV, $\theta = 5^{0}$ electrons on lead



Spokespersons

- Krishna Kumar
- Robert Michaels
- Kent Pascke
- Paul Souder
- Guido Maria Urciuoli

Hall A Collaboration Experiment

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Electron - Nucleus Potential

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

electromagnetic

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

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott} |F_P(Q^2)|^2$$

Proton form factor

$$F_P(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_P(r)$$

axial

$$A(r) = \frac{G_F}{2\sqrt{2}} \left[(1 - 4\sin^2\theta_W) Z \rho_P(r) - N \rho_N(r) \right]$$

⇨ $A(r)$ is small, best observed by parity violation

⇨ $1 - 4\sin^2\theta_W << 1$ neutron weak charge >> proton weak charge

Neutron form factor

$$F_N(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_N(r)$$

Parity Violating Asymmetry

$$A = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_N(Q^2)}{F_P(Q^2)} \right]$$

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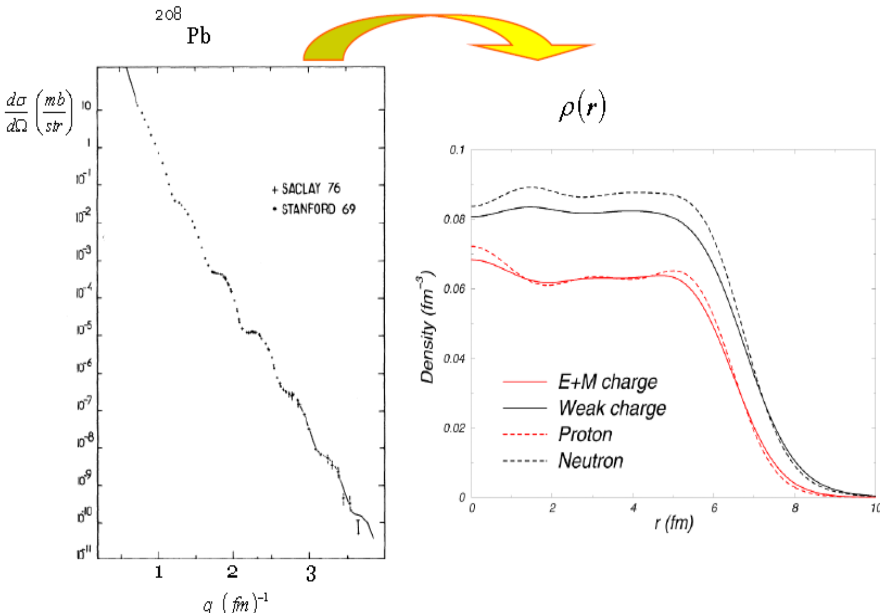
Reminder: Electromagnetic Scattering determines $\rho(r)$ (charge distribution)



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Z^0 of weak interaction : sees the neutrons

Analysis is clean, like electromagnetic scattering:

1. Probes the entire nuclear volume
2. Perturbation theory applies

	proton	neutron
Electric charge	1	0
Weak charge	0.08	1

Nuclear Structure: *Neutron density is a fundamental observable that remains elusive.*

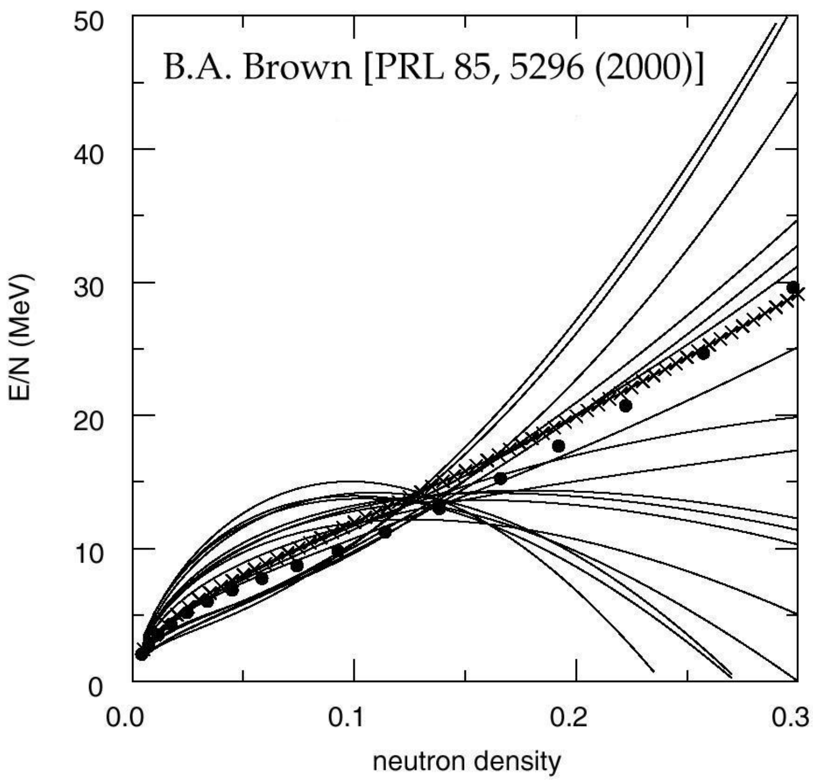

FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

Reflects poor understanding of symmetry energy of nuclear matter = the energy cost of $N \neq Z$

$$E(n,x) = E(n,x=1/2) + S_{\upsilon}(n)(1-2x^2)$$

n = n.m. density x = ratio proton/neutrons

- Slope unconstrained by data
- Adding R_N from ^{208}Pb will eliminate the dispersion in plot.

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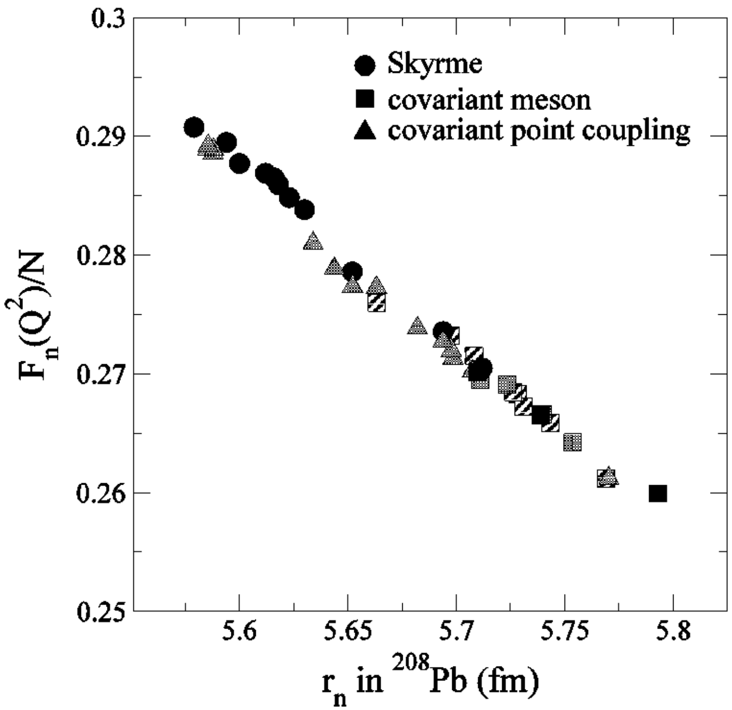
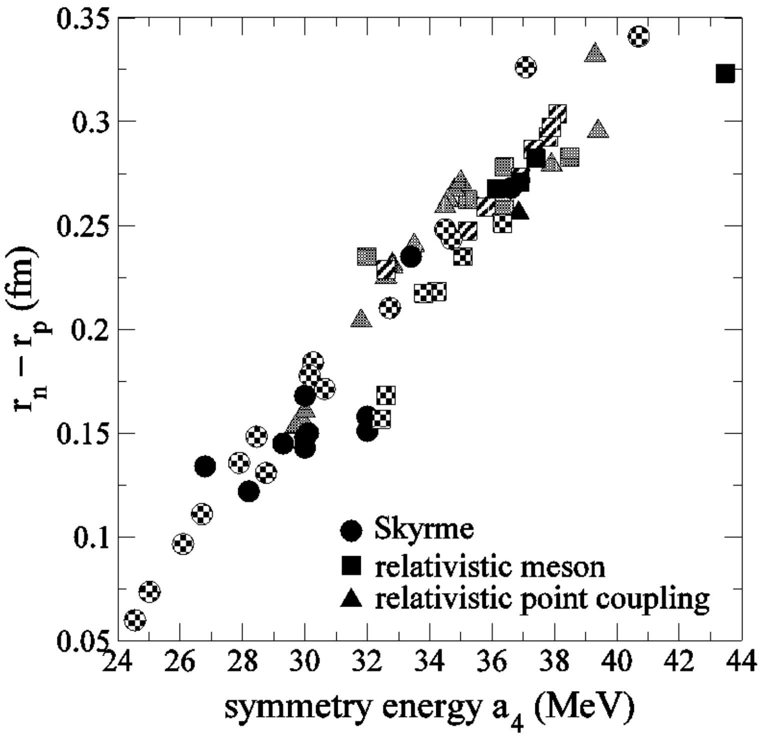
Measurement at one Q^2 is sufficient to measure R_N

Pins down the symmetry energy (1 parameter)





(R.J. Furnstahl)

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PREX & Neutron Stars

(C.J. Horowitz, J. Piekarweicz)

R_N calibrates EOS of Neutron Rich Matter

Crust Thickness

Explain Glitches in Pulsar Frequency ?

→

- Thicker neutron skin in Pb means energy rises rapidly with density → Quickly favors uniform phase.
- Thick skin in Pb → low transition density in star.

Combine PREX R_N with Obs. Neutron Star Radii

Phase Transition to "Exotic" Core ?

Strange star ? Quark Star ?

→

- The ^{208}Pb radius constrains the pressure of neutron matter at subnuclear densities.
- The NS radius depends on the pressure at nuclear density and above..
- If Pb radius is relatively large: EOS at low density is stiff with high P. If NS radius is small than high density EOS soft.
- This softening of EOS with density could strongly suggest a transition to an exotic high density phase such as quark matter, strange matter, color superconductor, kaon condensate…

Some Neutron Stars seem too Cold

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→

- Proton fraction Y_p for matter in beta equilibrium depends on symmetry energy S(n).
- R_n in Pb determines density dependence of S(n).
- The larger R_n in Pb the lower the threshold mass for direct URCA cooling.
- If R_n-R_p<0.2 fm all EOS models do not have direct URCA in 1.4 M– stars.
- If R_n-R_p>0.25 fm all models do have URCA in 1.4 M– stars.

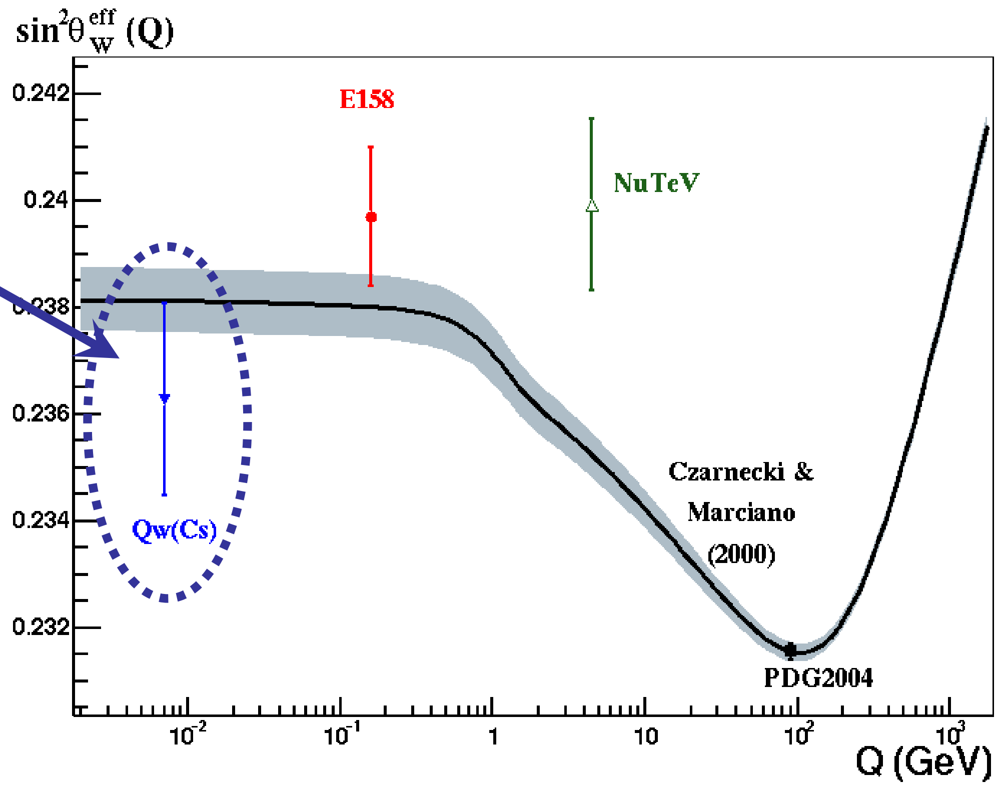
Atomic Parity Violation

- Low Q^2 test of Standard Model
- Needs R_N to make further progress.

Isotope Chain Experiments
e.g. Berkeley Yb

$$H_{PNC} \approx \frac{G_F}{2\sqrt{2}} \int \left[-N \rho_N(\vec{r}) + Z \underbrace{(1 - 4\sin^2\theta_W)}_{\approx 0} \rho_P(\vec{r}) \right] \psi_e^{\dagger} \gamma^5 \psi_e \, d^3 r$$

APV



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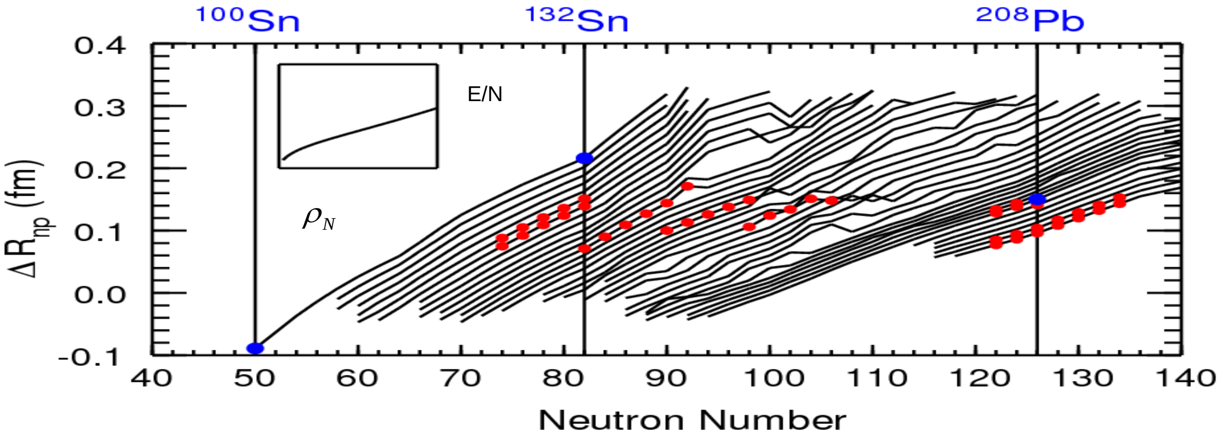
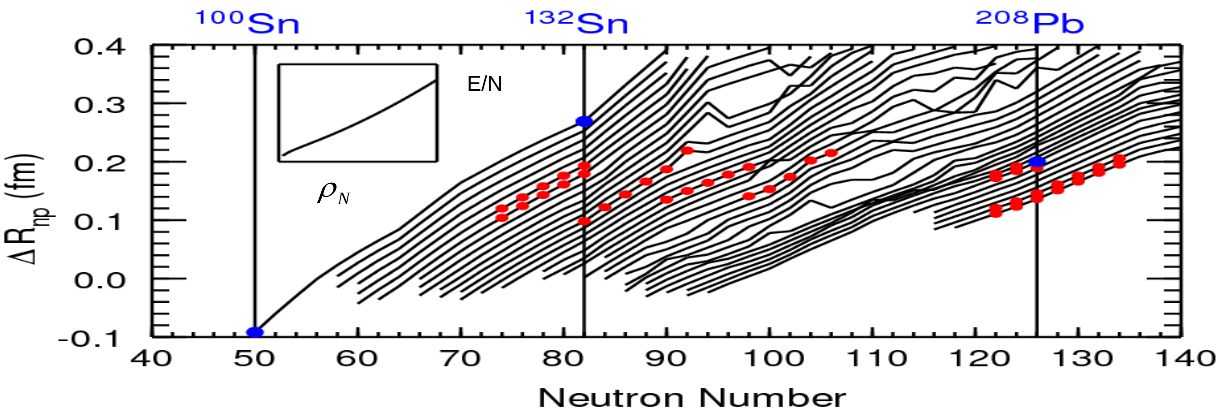
Neutron Skin and Heavy – Ion Collisions (Alex Brown)

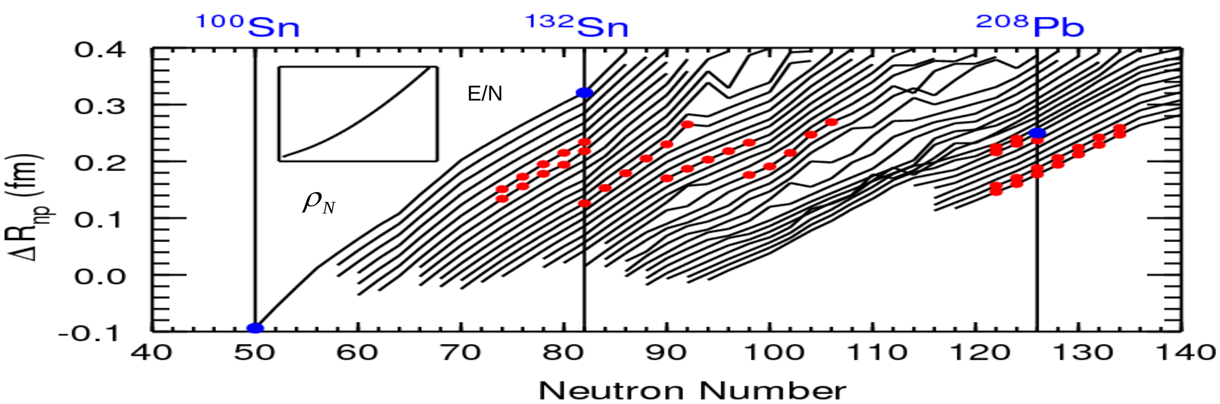
Skx-s15



Skx-s20



Skx-s25



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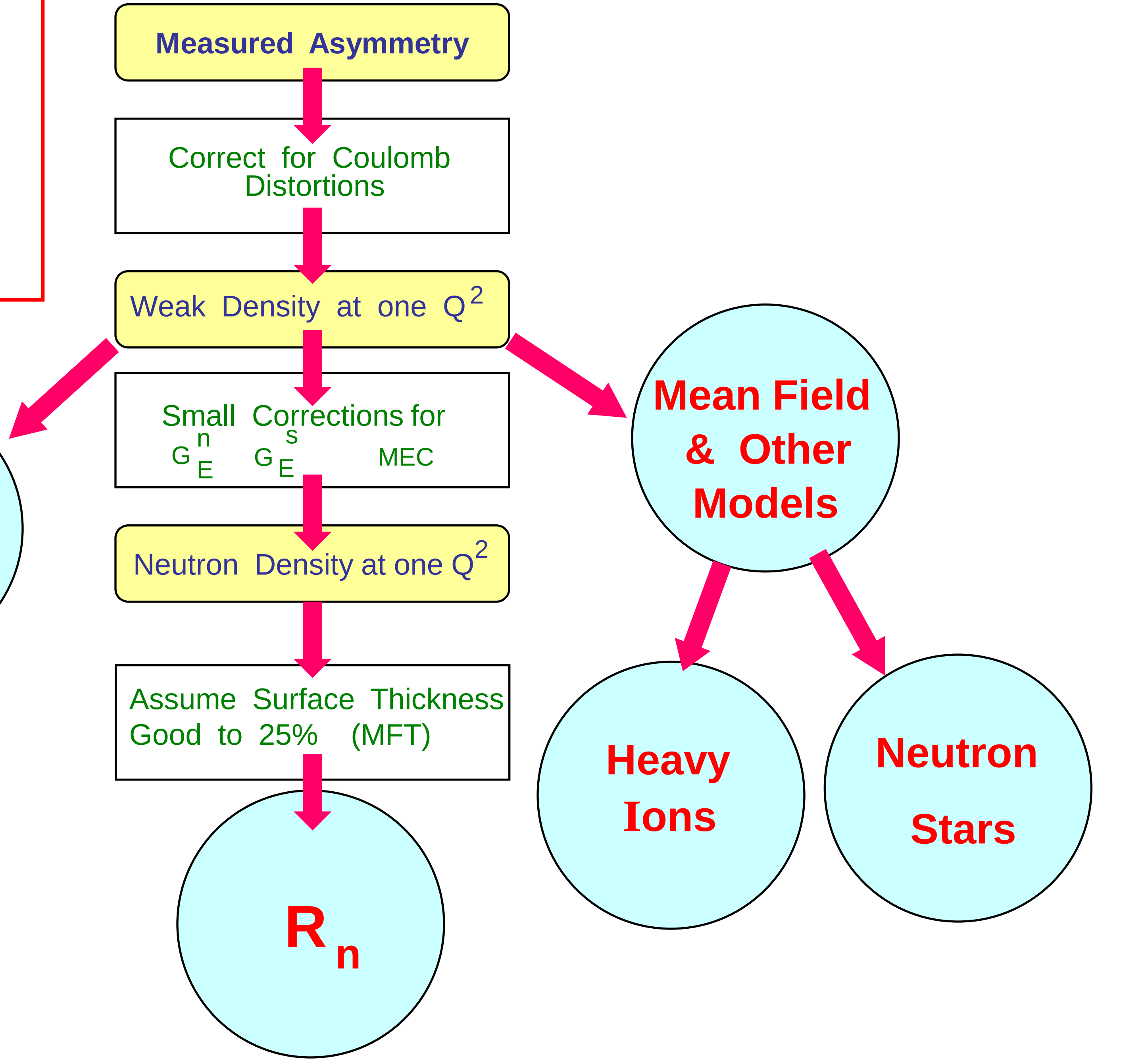
PREX Physics Impact



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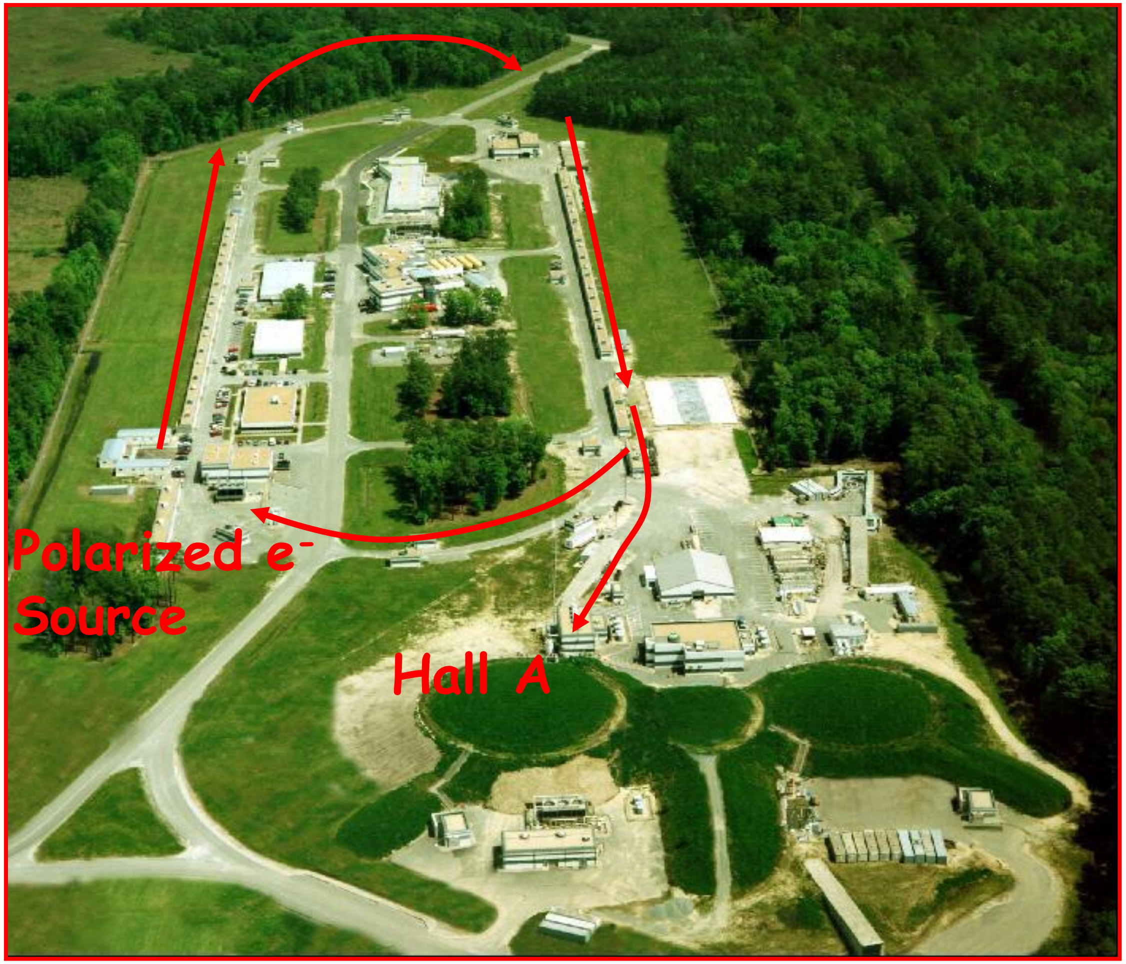
Hall A at Jefferson Lab



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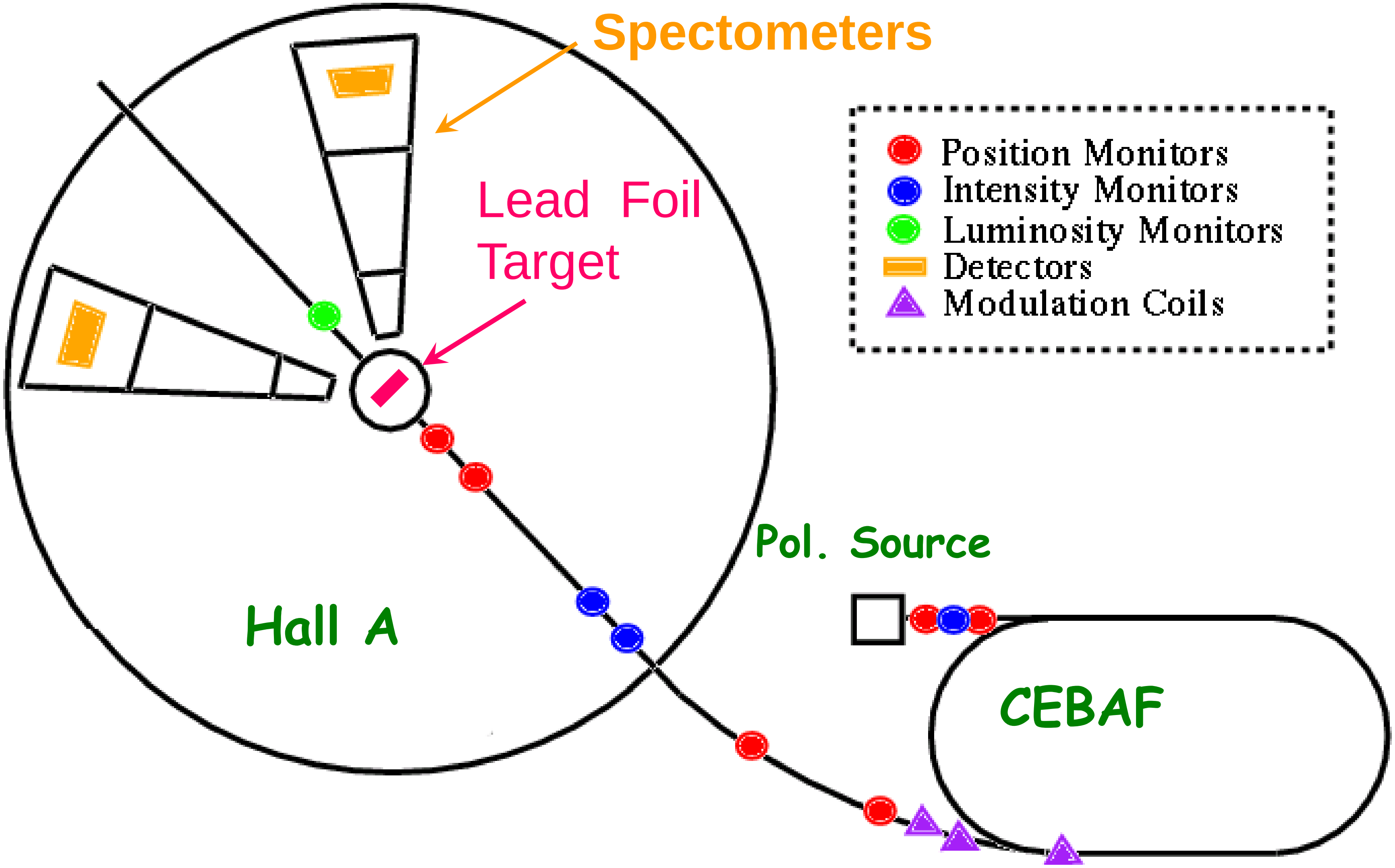
PREX in Hall A at JLab



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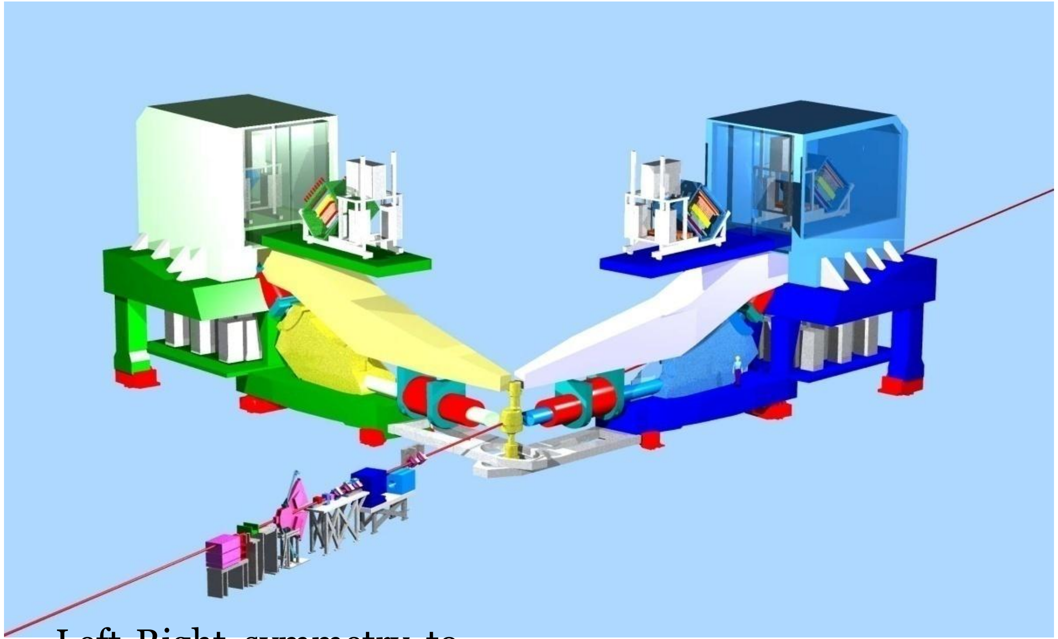
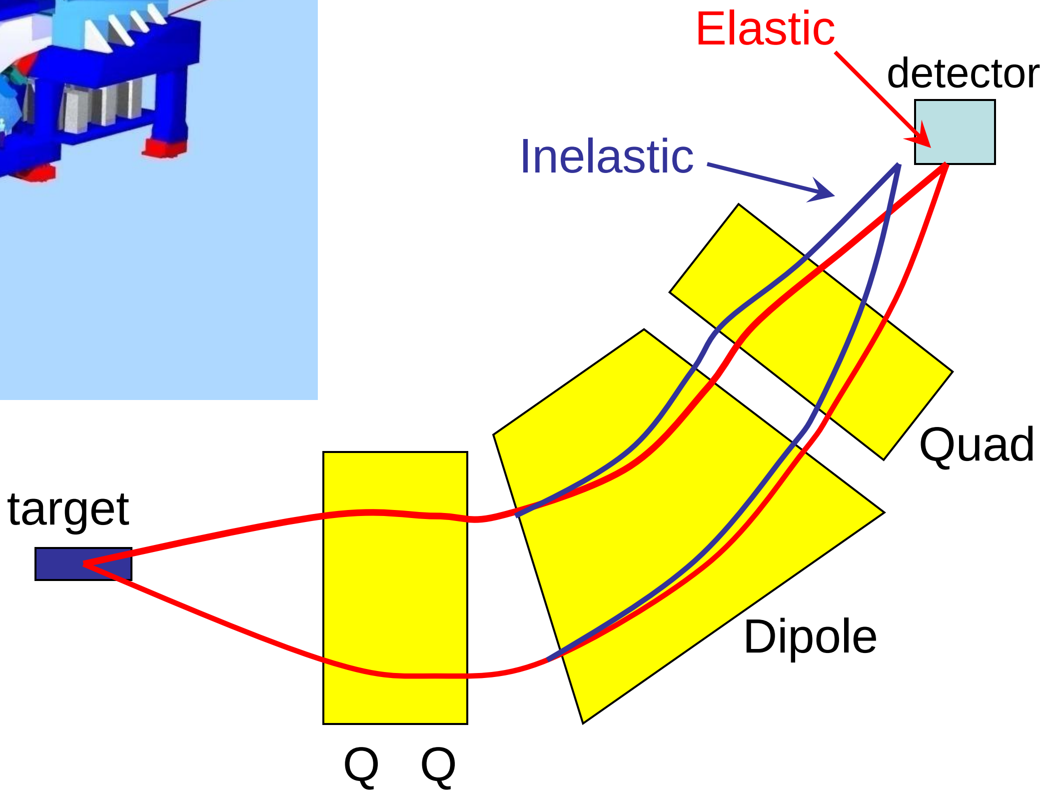
High Resolution Spectrometers



Left-Right symmetry to control transverse polarization systematic

Spectrometer Concept:

Resolve Elastic



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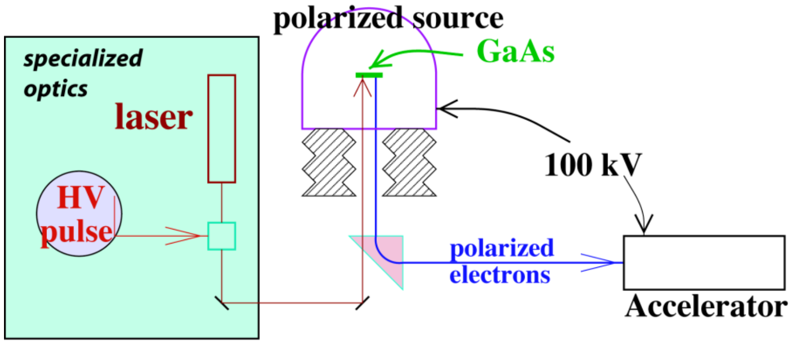
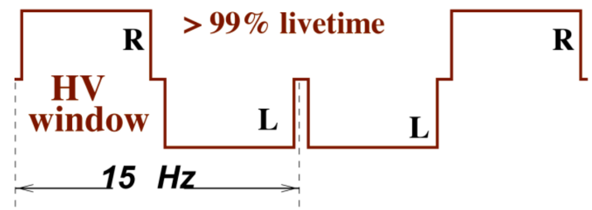
Experimental Method



rapid, random, helicity flipping

Rapid, Random Helicity Flips



Measure flux F for each window

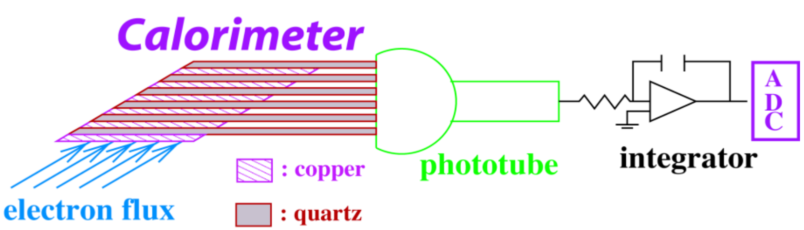
$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

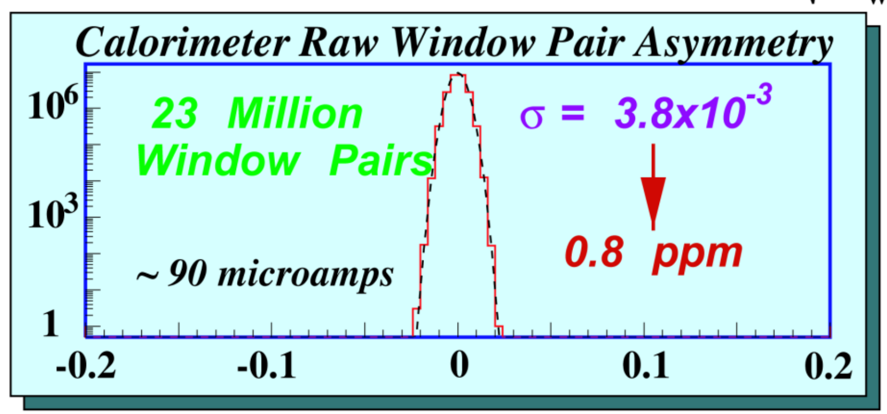
Signal Average N Windows Pairs: $\mathbf{A} \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}$

Flux Integration Technique:

HAPPEX: 2 MHz

PREX: 850 MHz





No non-gaussian tails to +/- 5σ

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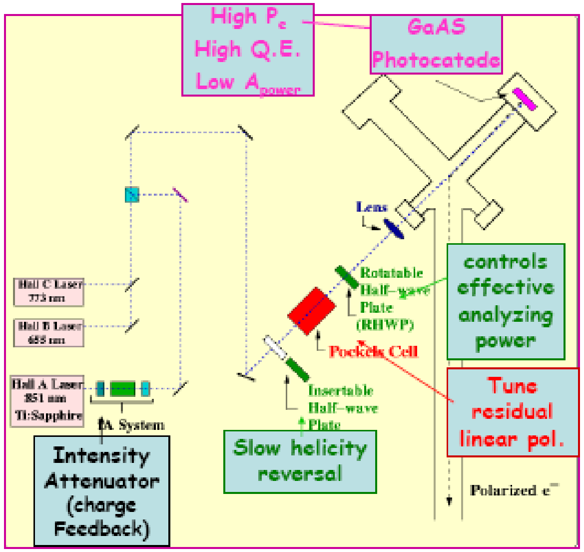
Consolidated techniques from the previous Hall A parity violating electron scatttering experiments (HAPPEX)

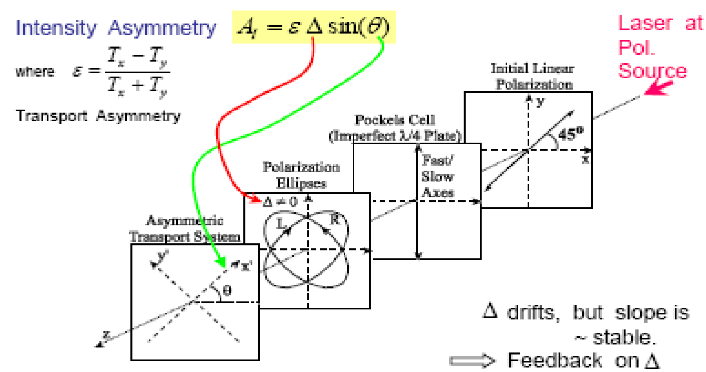
Polarized Source



- Optical pumping of solid-state photocathode
- High Polarization
- Pockels cell allows rapid helicity flip
- Careful configuration to reduce beam asymmetries.
- Slow helicity reversal to further cancel beam asymmetries

P I T A Effect

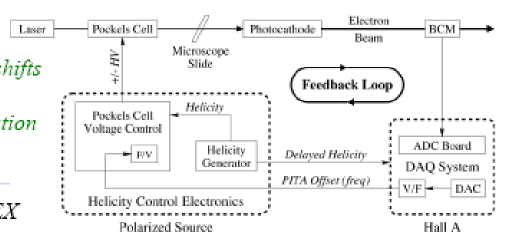
(Polarization Induced Transport Asymmetry)

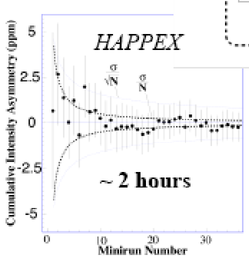


Δ drifts, but slope is ~ stable.
⟹ Feedback on Δ

Intensity Feedback

Adjustments for small phase shifts to make close to circular polarization





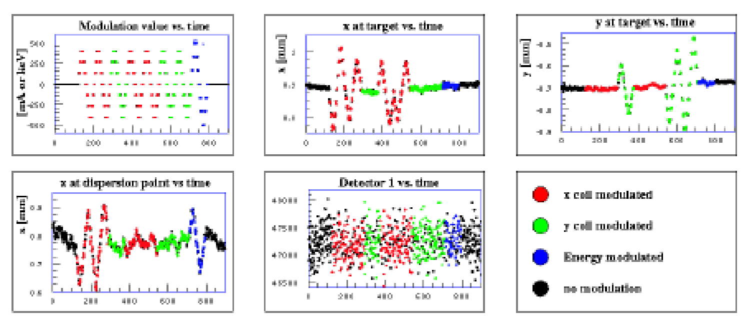
Low jitter and high accuracy allows sub-ppm Cumulative charge asymmetry in ~ 1 hour

In practice, aim for 0.1 ppm over duration of data-taking.

Beam Asymmetries

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

Slopes from
- natural beam jitter (regression)
- beam modulation (dithering)



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New for PREX

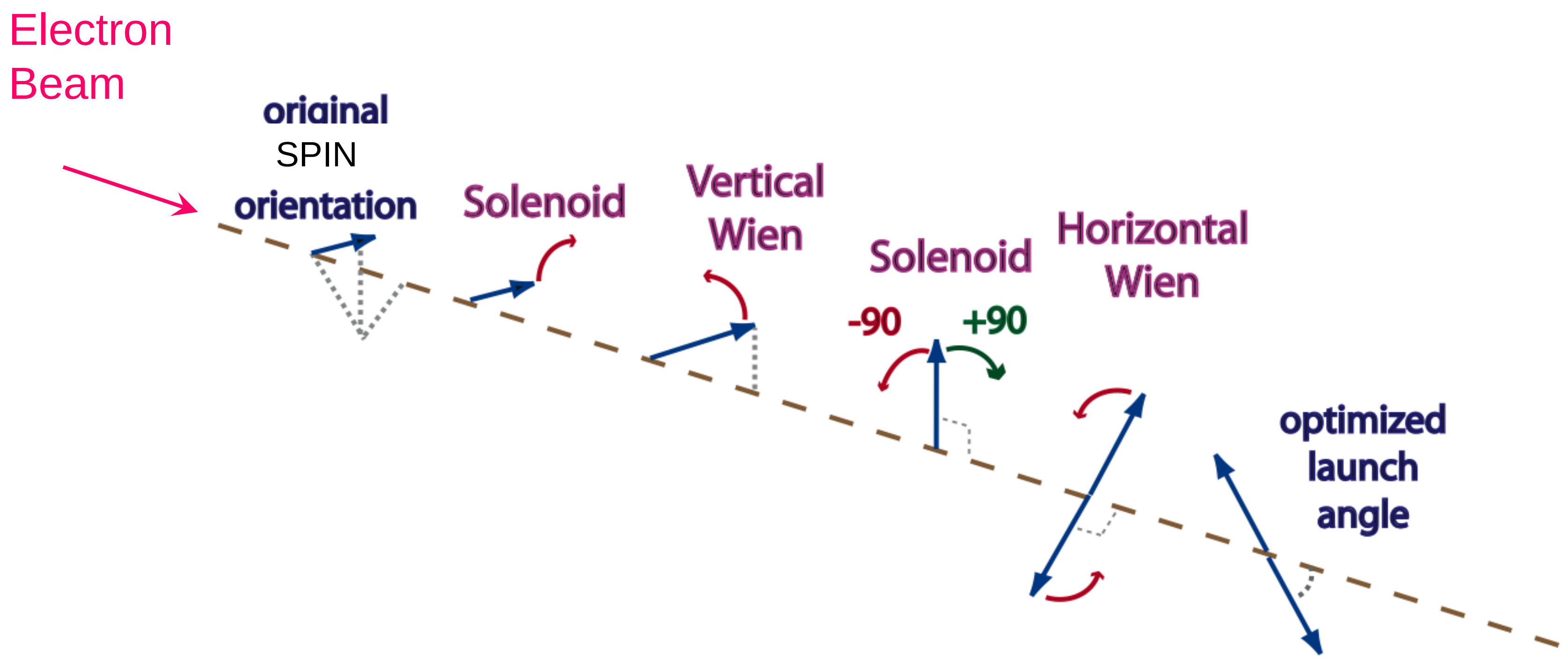
(to achieve a 2% systematic error)

Double Wien Filter

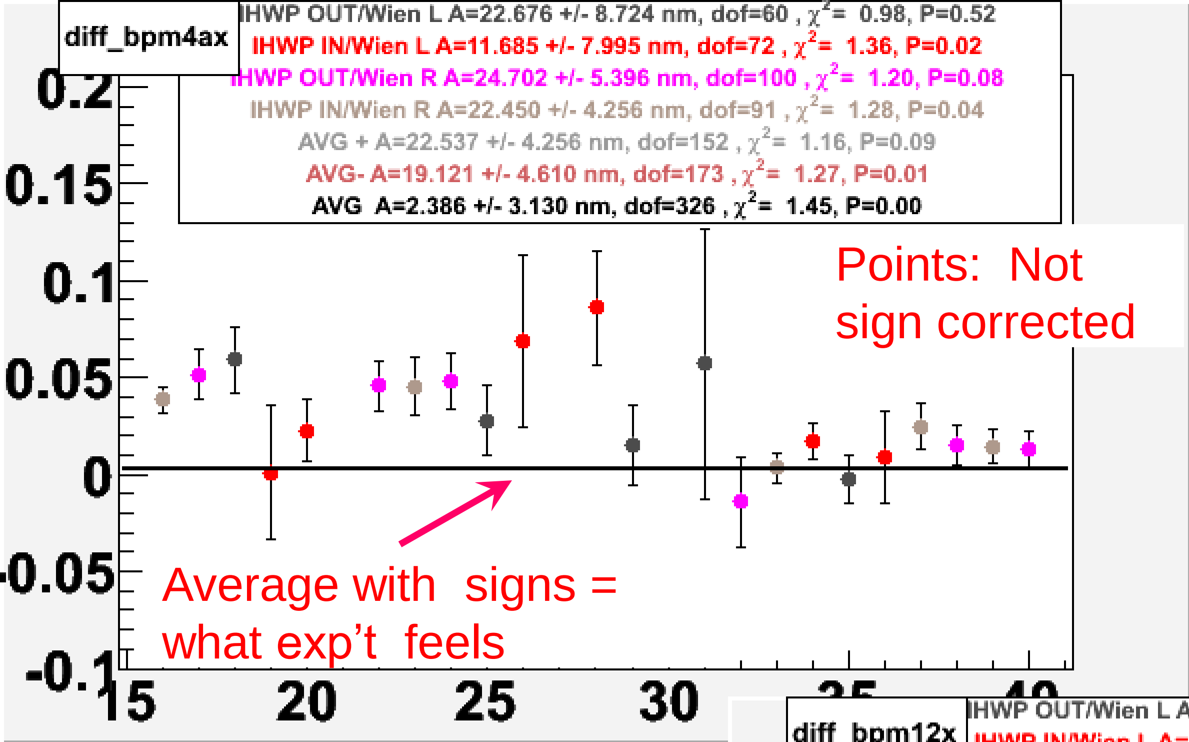
Crossed E & B fields to rotate the spin

- Two Wien Spin Manipulators in series
- Solenoid rotates spin +/-90 degrees (spin rotation as B but focus as B^2).

Flips spin without moving the beam !



Joe Grames, *et. al.*



Parity Quality Beam !

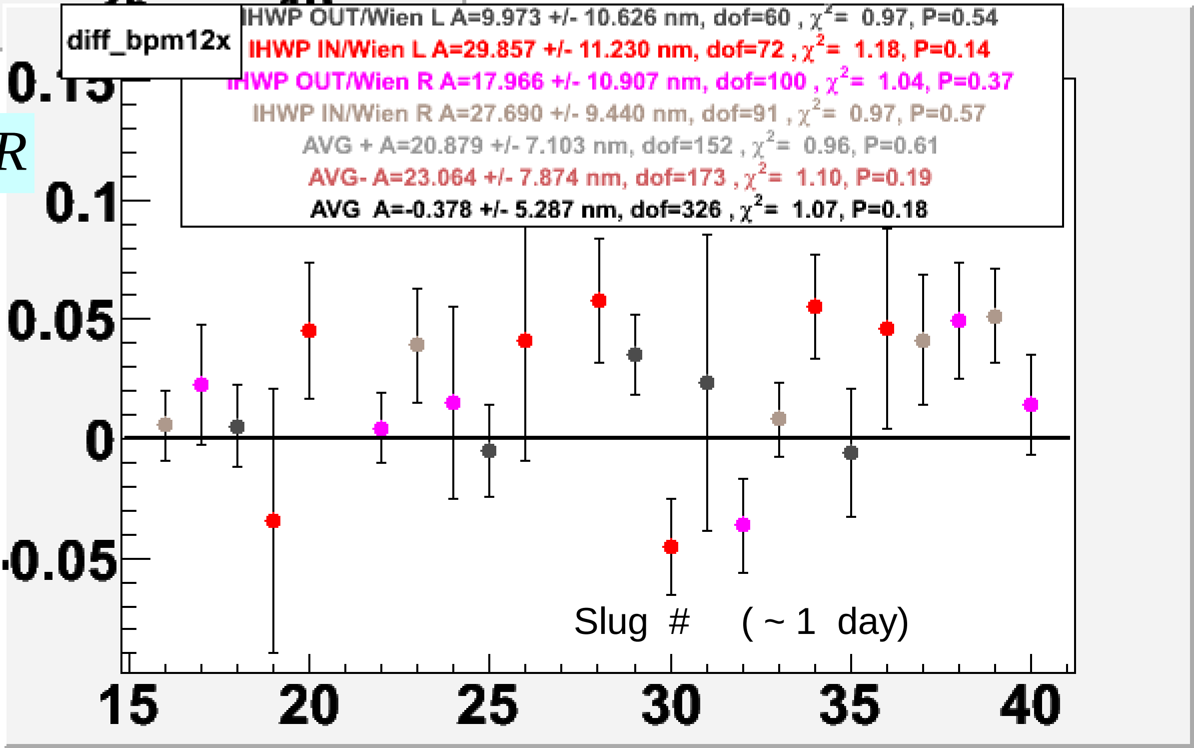
Helicity – Correlated Position Differences

< ~ 3 nm

Wien Flips helped !

$< X_R - X_L >$ *for helicity* L, R

Units: microns



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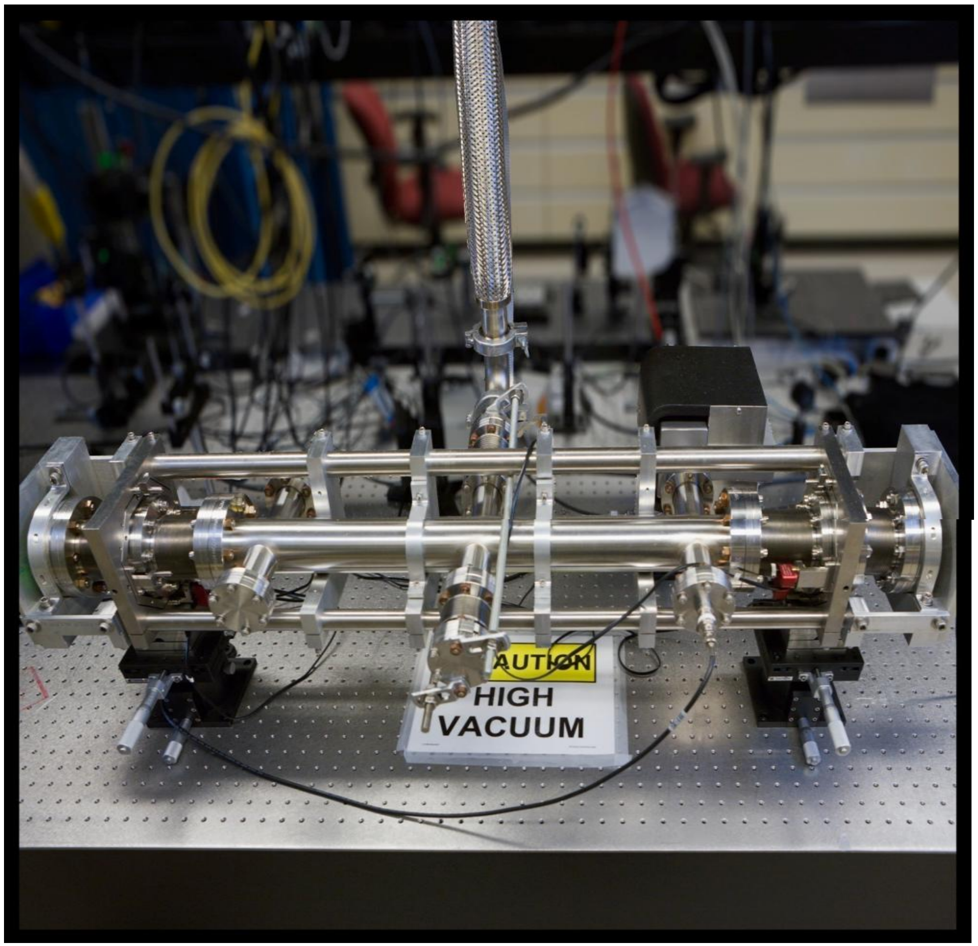
Upgraded Polarimetry

(Sirish Nanda et al.)

Compton Polarimeter (1 % Polarimetry)

Upgrades:

Laser → Green Laser



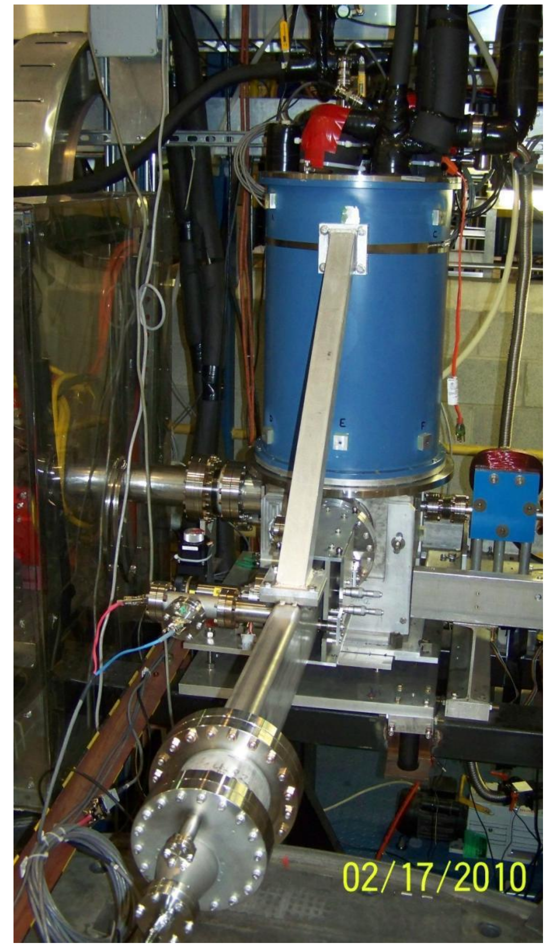
Moller Polarimeter (< 1 % Polarimetry)

Upgrades:

Magnet → Superconducting Magnet from Hall C

Target → Saturated Iron Foil Targets

DAQ → FADC



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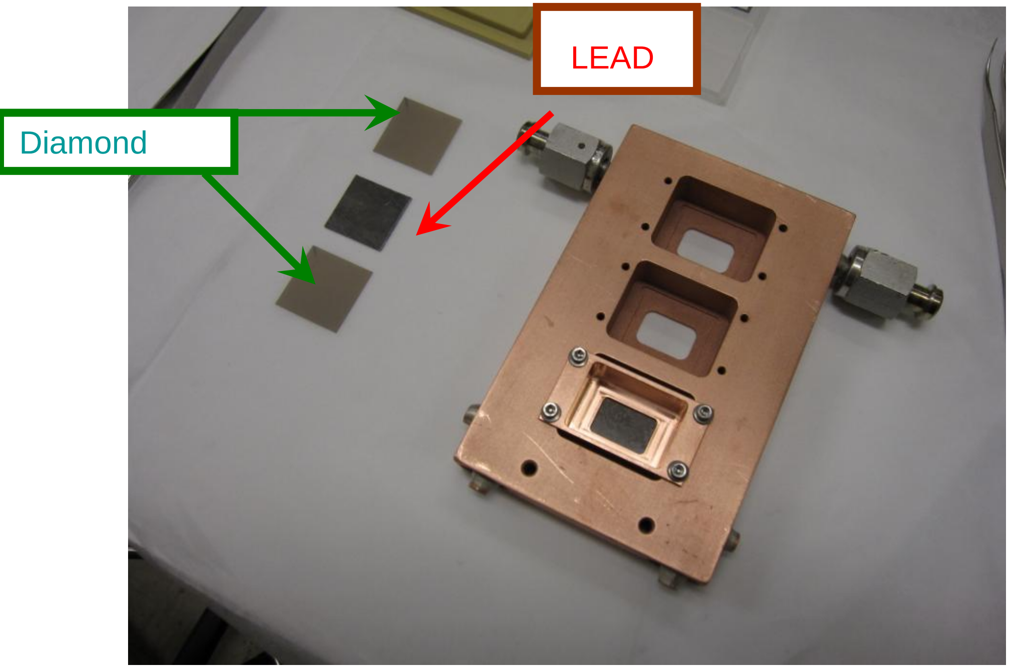
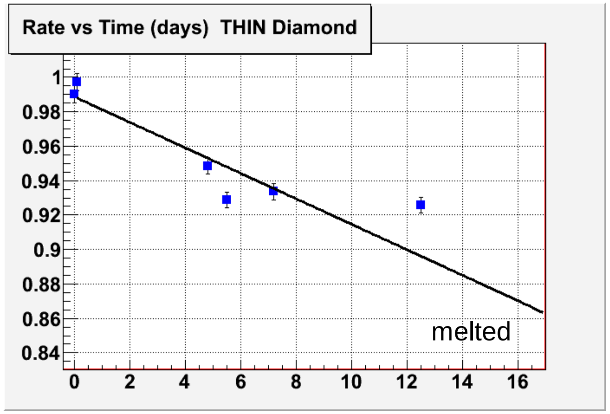
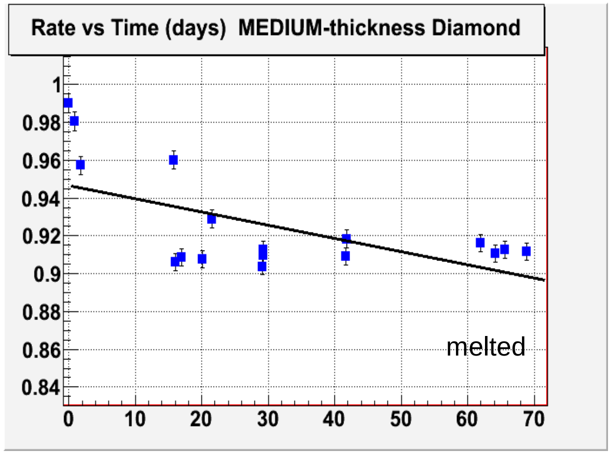
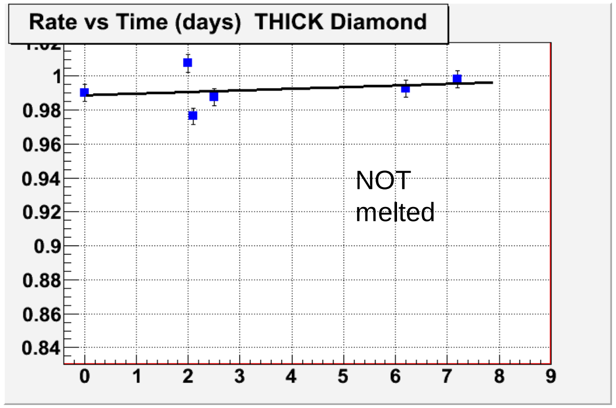
Lead Target

- Three bays
- Lead (0.5 mm) sandwiched by diamond (0.15 mm)
- Liquid He cooling (30 Watts)









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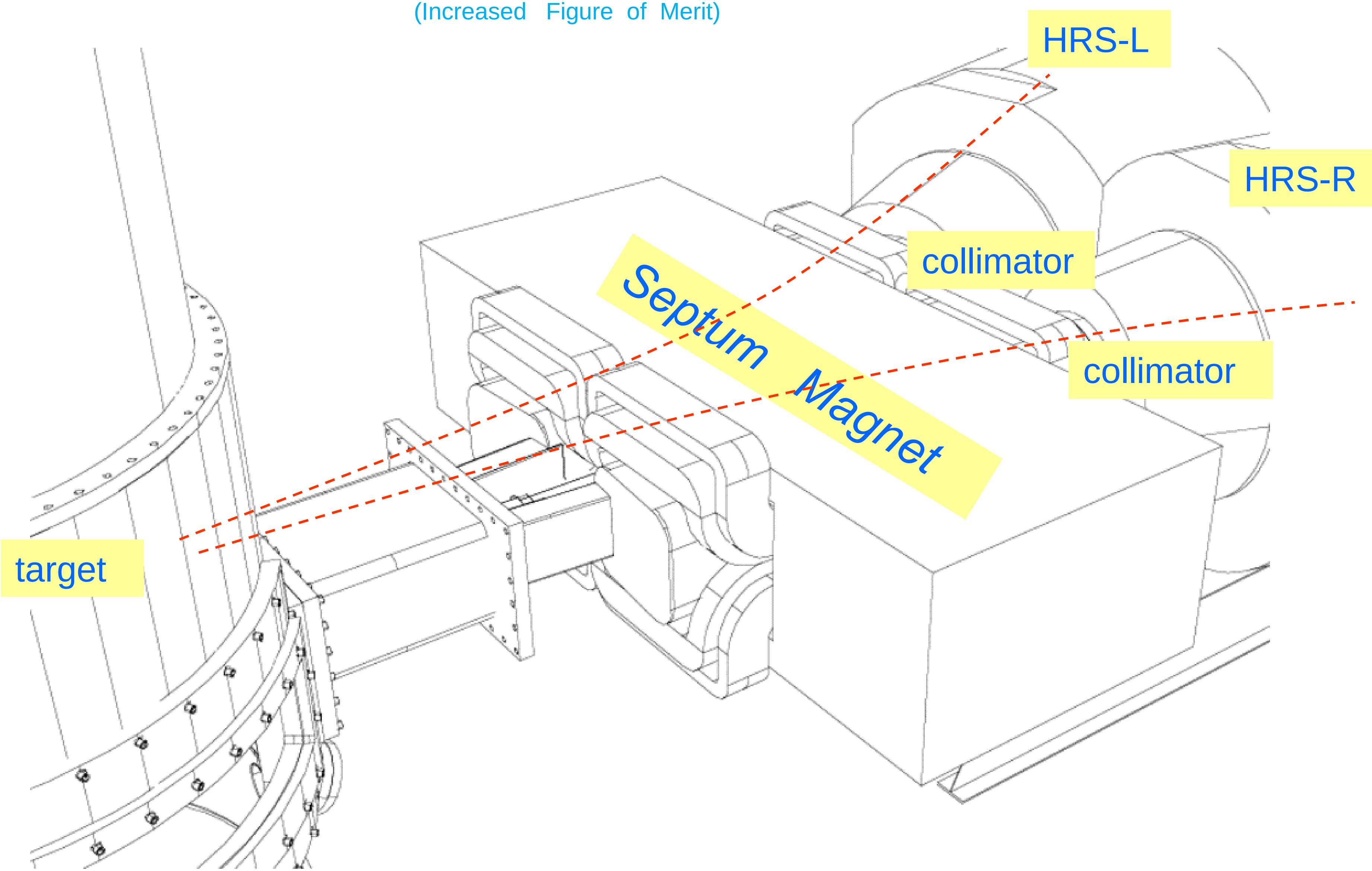
5^0 Septum magnet

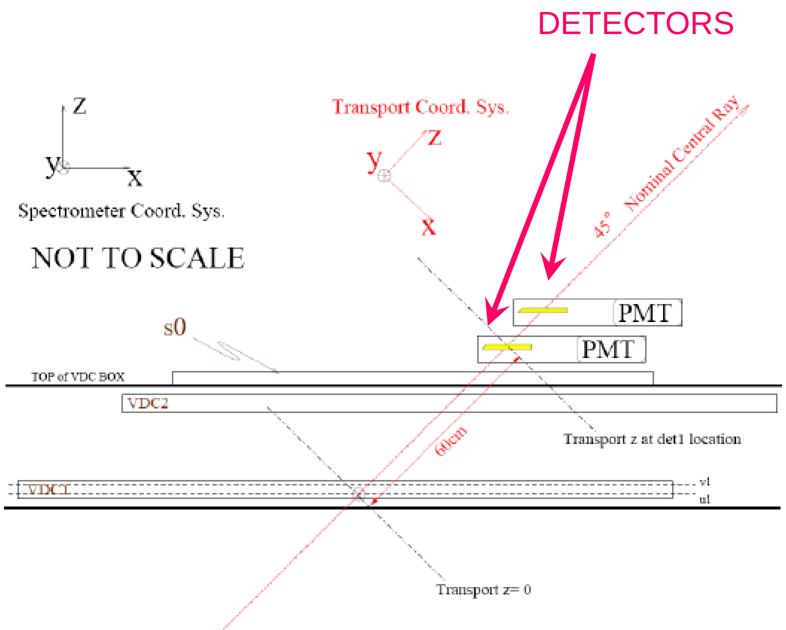
(augments the High Resolution Spectrometers)

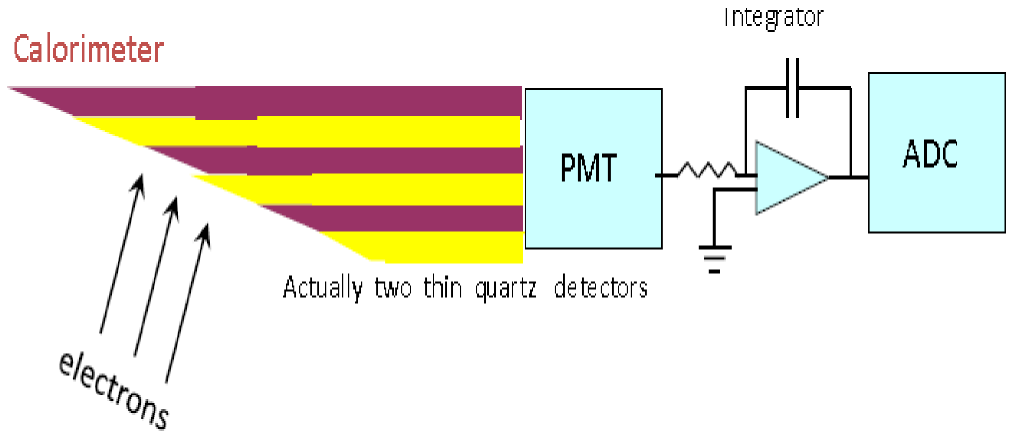
(Increased Figure of Merit)



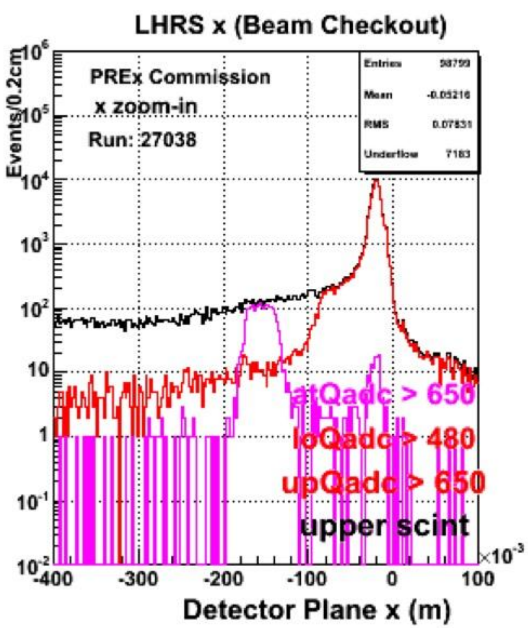
Integrating Detection

Deadtime free, 18 bit ADC with $< 10^{-4}$ nonlinearity.

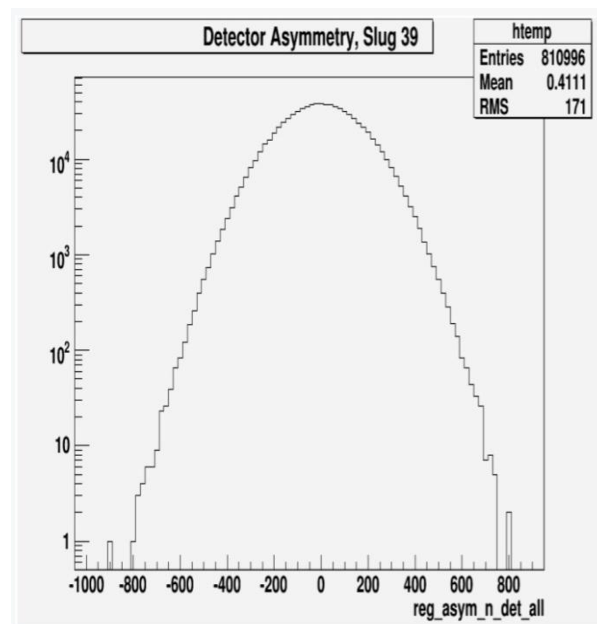




The x, y dimensions of the quartz determined from beam test data and MC (HAMC) simulations.
Quartz thickness optimized with MC.
.



New HRS optics tune focuses elastic events both in x & y at the PREx detector location



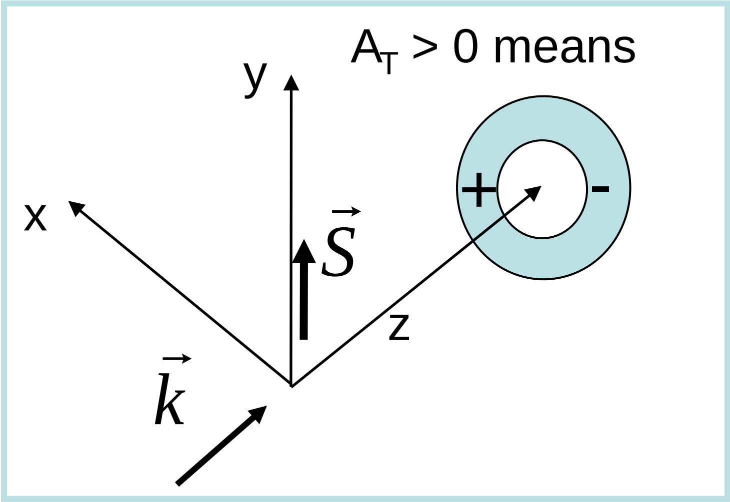
120 Hz pair windows asymmetry distribution.

No Gaussian tails up to 5 standard deviations.

Beam-Normal Asymmetry in elastic electron scattering

i.e. spin transverse to scattering plane

$$A_T \equiv \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto \vec{S}_e \bullet (\vec{k}_e \times \vec{k}'_e)$$



Possible systematic if small transverse spin component

New results PREX

Preliminary ! Publication in preparation

$$^{208}Pb: \quad A_T = +0.13 \pm 0.19 \pm 0.36 \ ppm$$

$$^{12}C: \quad A_T = -6.52 \pm 0.36 \pm 0.35 \ ppm$$

- Small A_T for ^{208}Pb is a big (but pleasant) surprise.
- A_T for ^{12}C qualitatively consistent with ^{4}He and available calculations (1) Afanasev ; (2) Gorchtein & Horowitz

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PREX Result

Systematic Errors

Error Source	Absolute (ppm)	Relative (%)
Polarization (1)	0.0071	1.1
Beam Asymmetries (2)	0.0072	1.1
Detector Linearity	0.0071	1.1
BCM Linearity	0.0010	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2 (1)	0.0028	0.4
Target Thickness	0.0005	0.1
^{12}C Asymmetry (2)	0.0025	0.4
Inelastic States	0	0
TOTAL	**0.0130**	**2.0**

(1) Normalization Correction applied

(2) Nonzero correction (the rest assumed zero)

$$A = 0.656\ ppm$$
$$\pm\ 0.060\,(stat) \pm 0.0140\,(syst)$$

→ Statistics limited (9%)

→ Systematic error goal achieved ! (2%)

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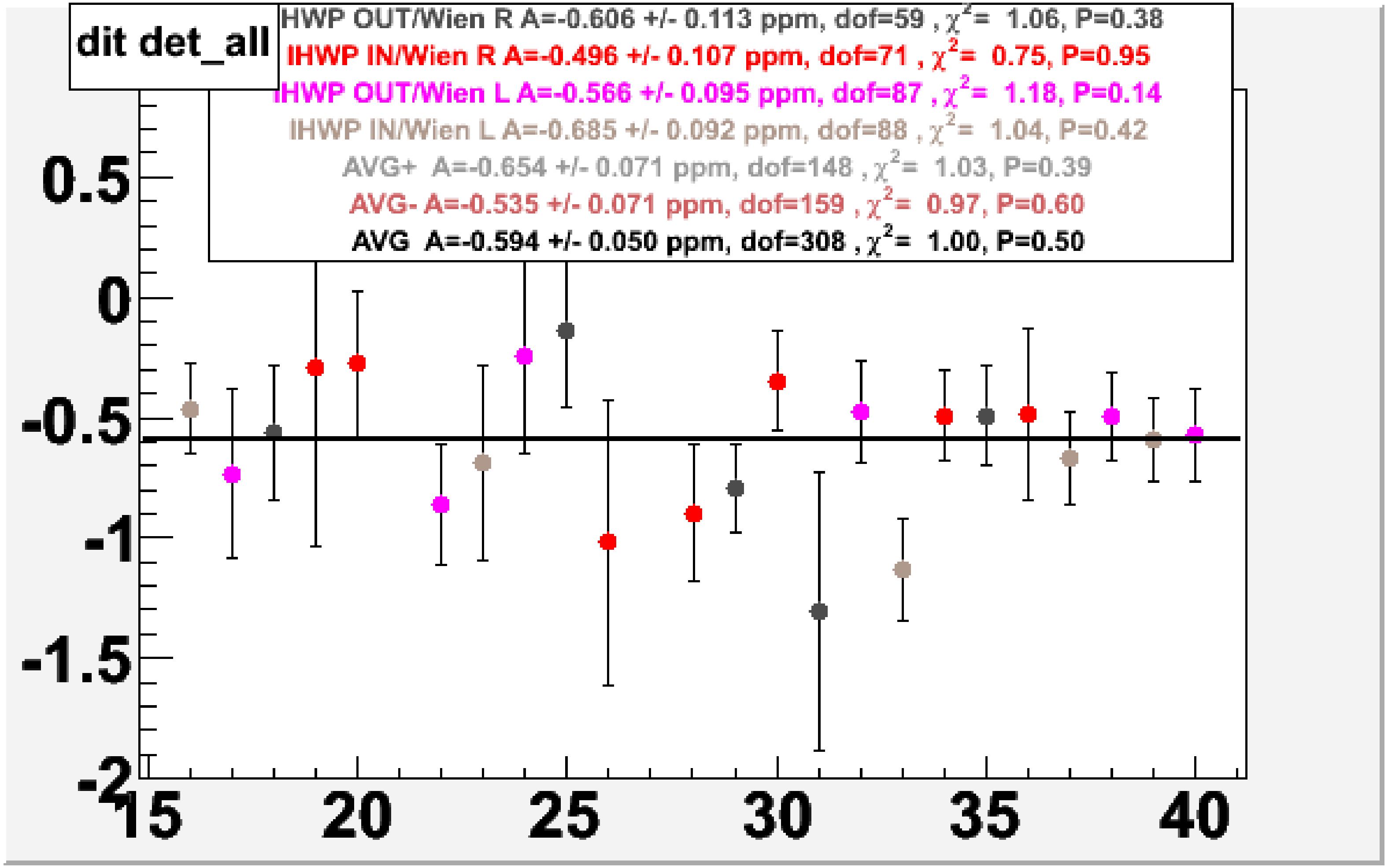
PREX Asymmetry (P_e x A)

ppm



Slug ~ 1 day

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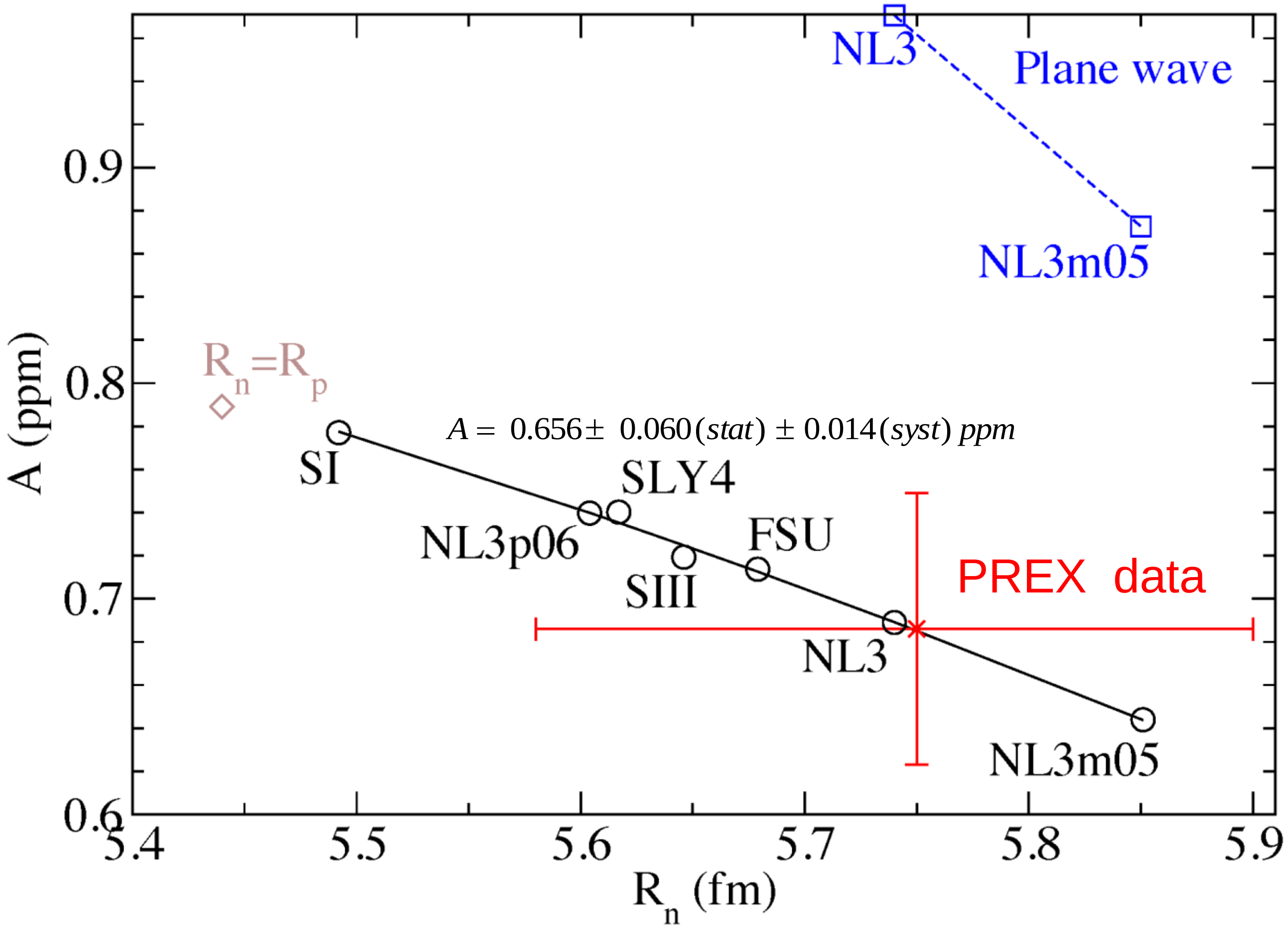
Asymmetry leads to R_N



$$R_N \approx 6.156 + 1.675 \bullet \langle A \rangle - 3.420 \bullet \langle A \rangle^2$$

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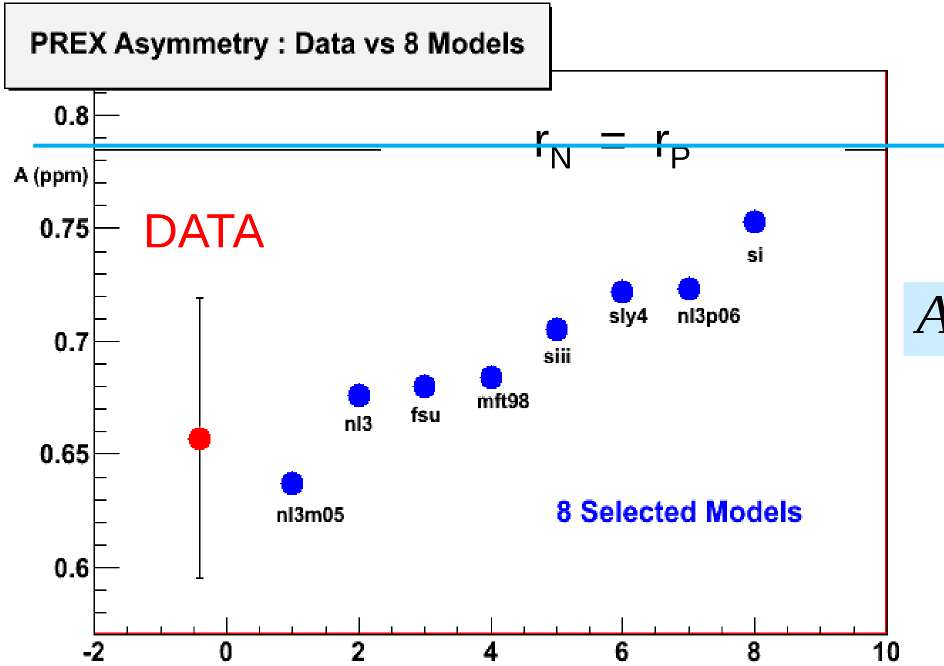
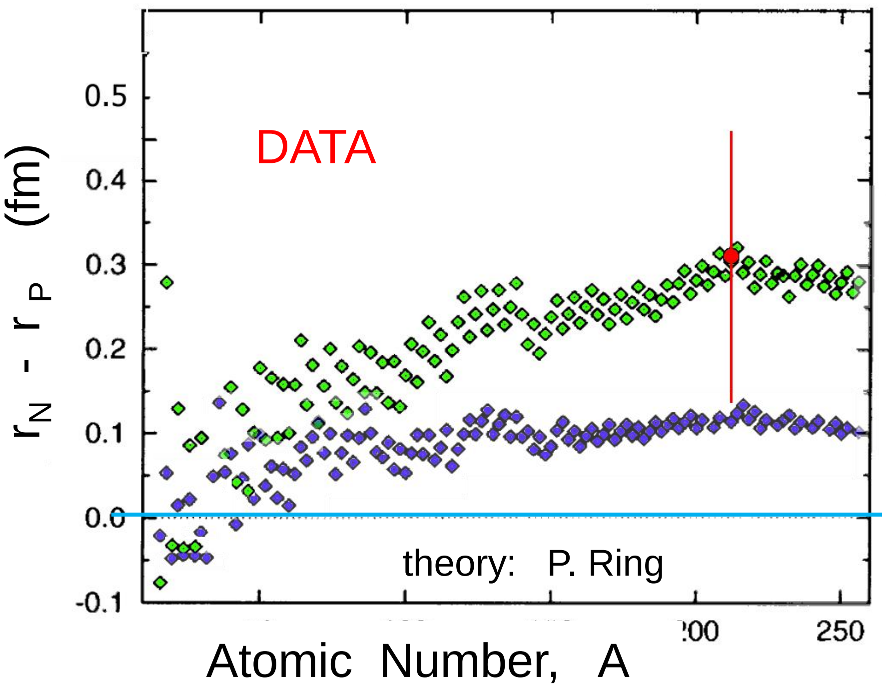


PREX Result, cont.

$$A = 0.656 \pm 0.060(stat) \pm 0.014(syst)\ ppm$$

↓

$R_N = 5.78 \ +0.16 \ -0.18$ fm



Neutron Skin = $R_N - R_P$ =

$0.33 \ +0.16 \ -0.18$ fm

Establishing a neutron skin at ~92 % CL

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^{208}Pb Radius from the Weak Charge Form Factor

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Measured Asymmetry

$$A = 0.656 \pm 0.060(stat) \pm 0.014(syst)\ ppm$$

Correct for Coulomb Distorsion

$$\rho_W = \frac{\rho_0}{1+e^{-\frac{r-R}{a}}}$$

$$F_W(q) = \frac{1}{Q_W}\int d^3r \frac{\sin(qr)}{qr}\rho_w(r)$$

Fourier Transform of the Weak Charge Density at $\bar{q}$ = 0.475 ± 0.003 fm^{-1}

$$F_W(\bar{q}) = 0.204 \pm 0.028(\exp) \pm 0.001(\text{mod})$$

Helm Model

$$R_W = 5.826 \pm 0.181(\exp) \pm 0.027(\text{mod})\ fm$$

Small Corrections for G_E^n G_E^s MEC

$$R_n^2 = \frac{Q_w}{q_n N} R_w^2 - \frac{q_p Z}{q_n N} R_{ch}^2 - \langle r_p^2 \rangle - \frac{Z}{N}\langle r_n^2 \rangle + \frac{Z+N}{q_n N}\langle r_s^2 \rangle$$

Assume Surface Thickness Good to 25% (MFT)

$$R_n^2 = 0.9525 \bullet R_w^2 - 1.671 \bullet \langle r_s^2 \rangle + 0.7450\ fm^2$$

R_N

$$R_n = 5.751 \pm 0.175(\exp) \pm 0.026(\text{mod}) \pm 0.005(str)\ fm$$

(To be compared with R_N = 5.78 + 0.16 - 0.18 fm)

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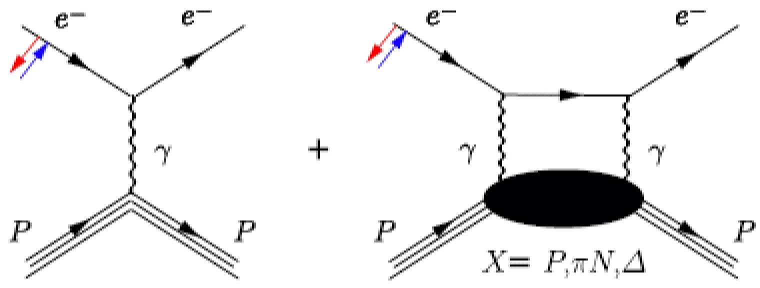
TRANSVERSE ASIMMETRY

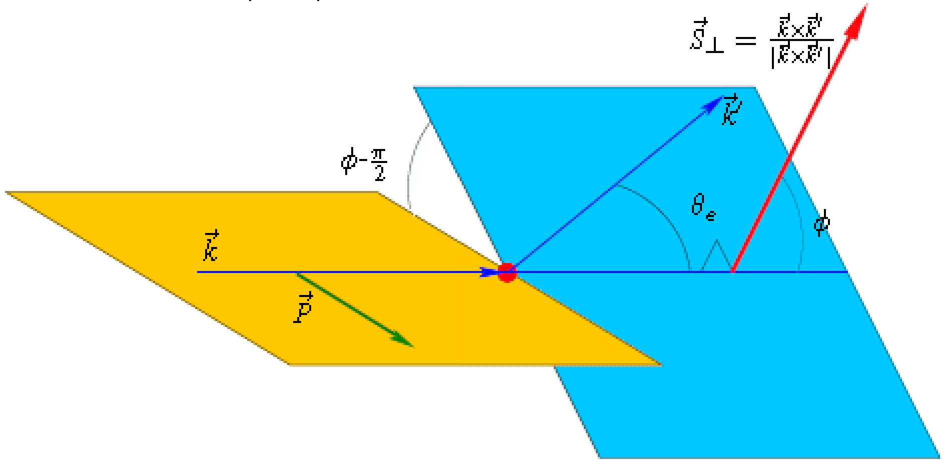
Two photon exchange



- $R = G_E^p / G_M^p$ discrepancy $\rightarrow$ 2γ exchange amplitude $A_{2\gamma}$
- Observable: Beam normal spin asymmetry BNSA
- BNSA sensitive to $Im(A_{2\gamma})$.

Asymmetry dependency on azimuthal angle

$$A_{\perp}^{m} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = A_{\perp}(\theta)\vec{P}_e \cdot \vec{S} = A_{\perp} \cos\phi$$



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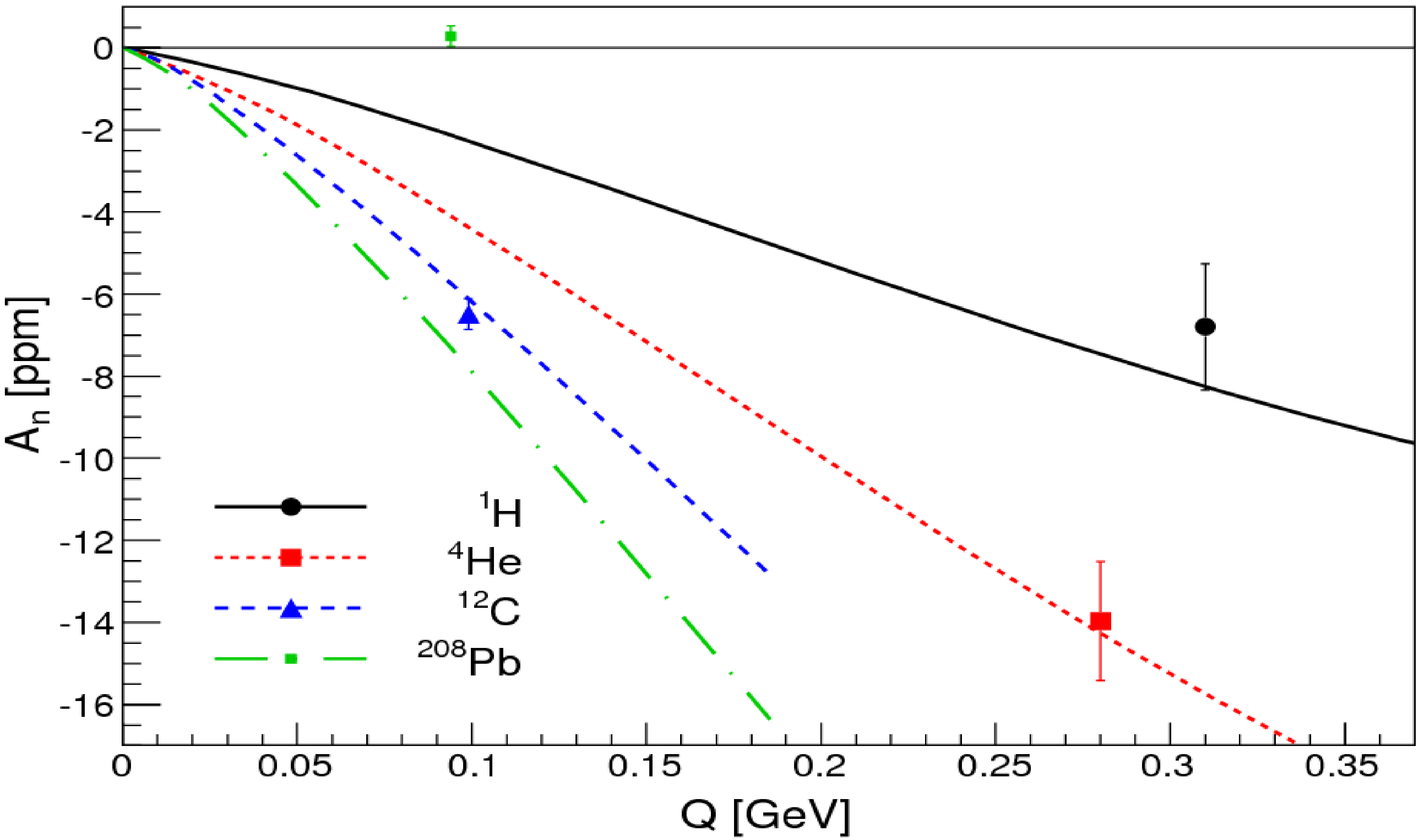

PREX measured A_n with ^{12}C and ^{208}Pb targets.

HAPPEX and HAPPEX-II measured A_n with ^{1}H and ^{4}He targets

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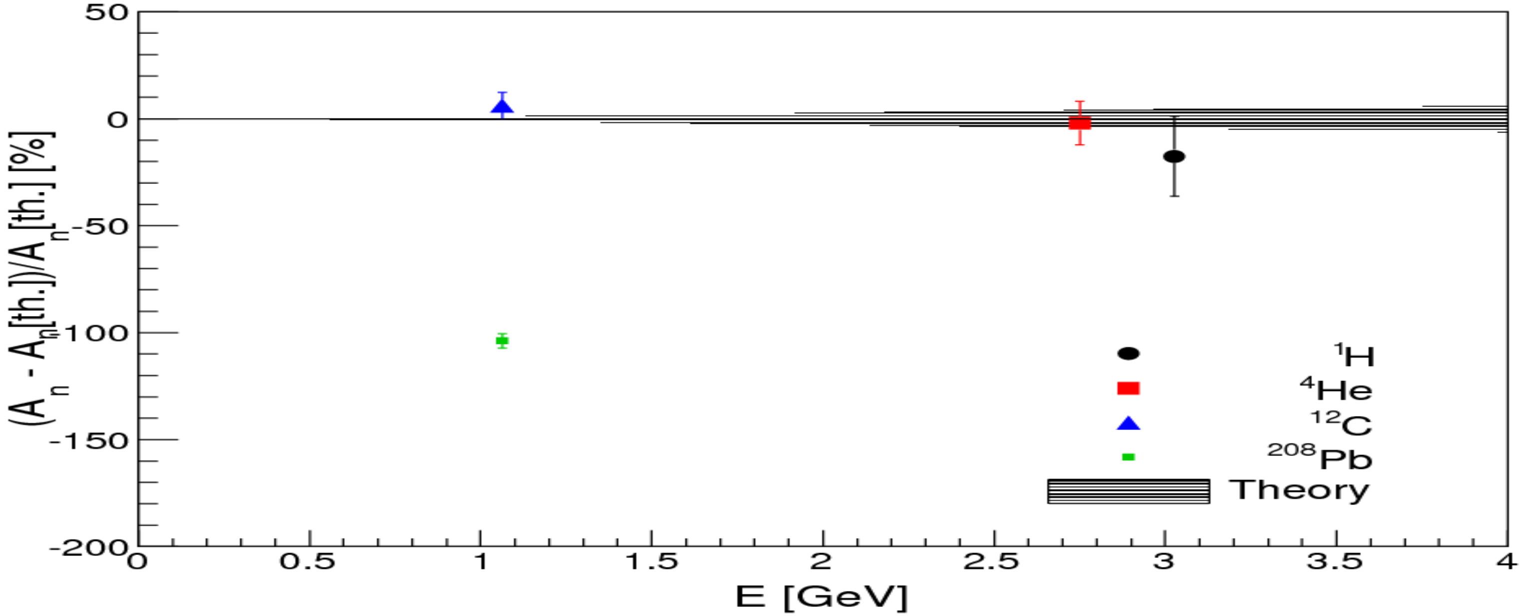
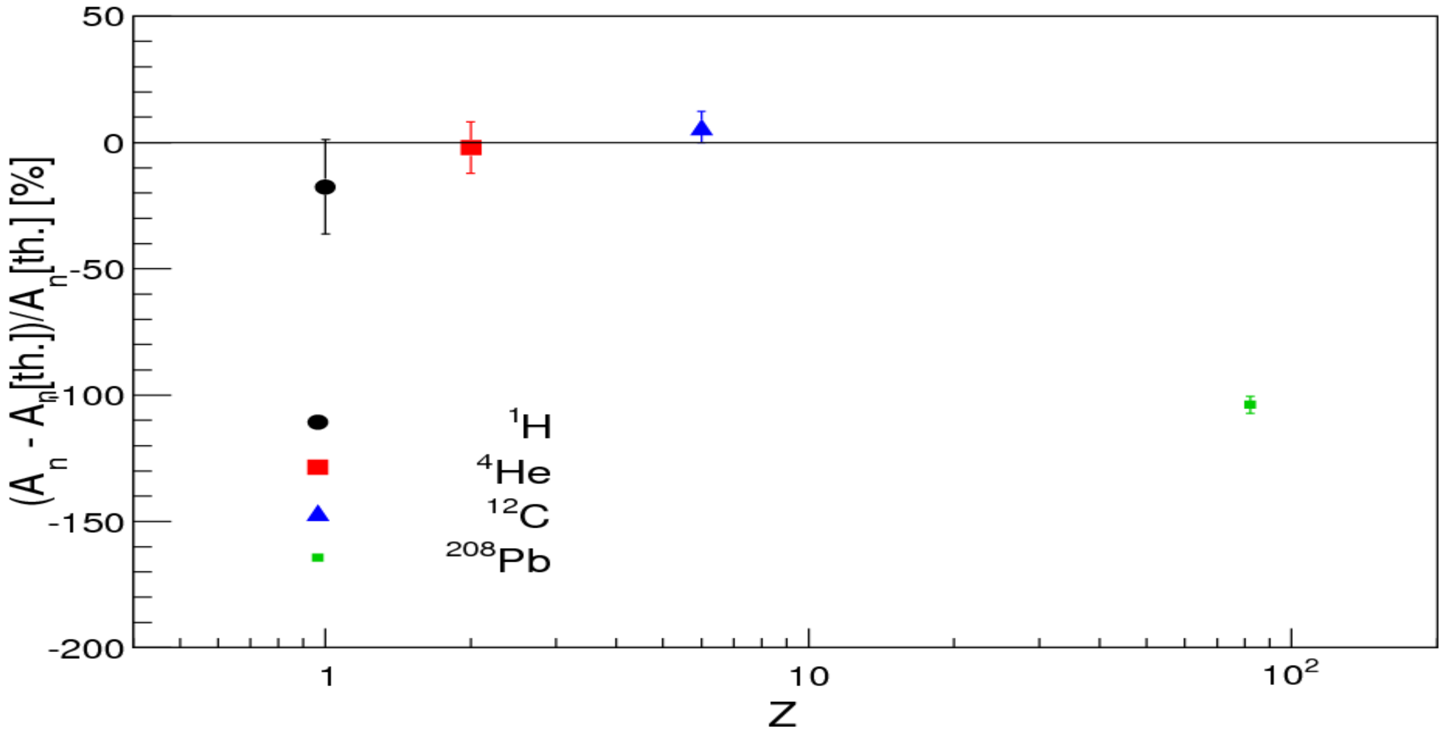


50
0
-50
-100
-150
-200
(A_n - A_n[th.])/A_n[th.] [%]
0
0.5
1
1.5
2
2.5
3
3.5
4
E [GeV]
¹H
⁴He
¹²C
²⁰⁸Pb
Theory



50
0
-50
-100
-150
-200
(A_n - A_n[th.])/A_n[th.] [%]
1
10
10²
Z
¹H
⁴He
¹²C
²⁰⁸Pb

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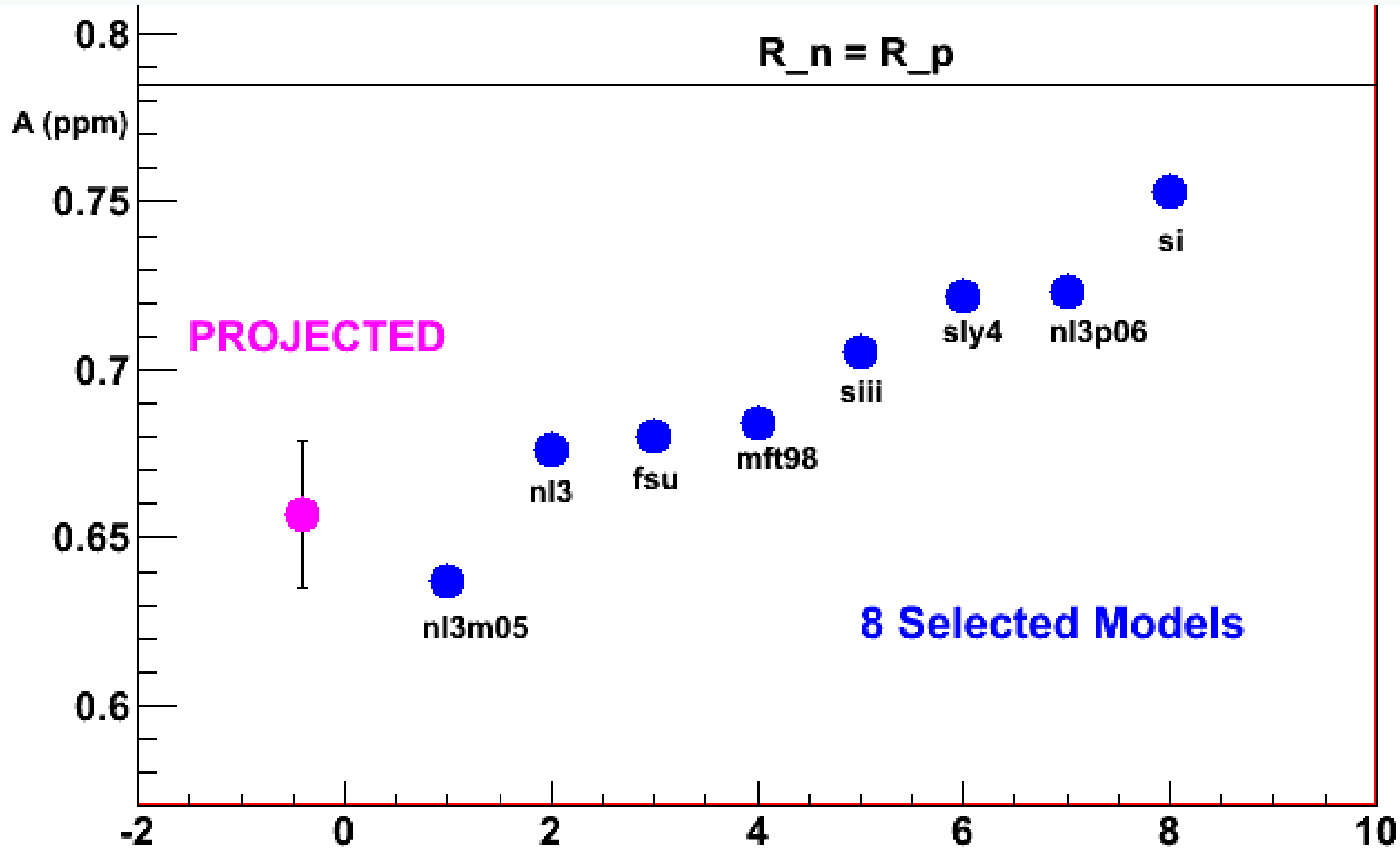
FUTURE: PREX-II

PREX-II Approved by PAC (Aug 2011)

"A" Rating 35 days run in 2013 / 2014



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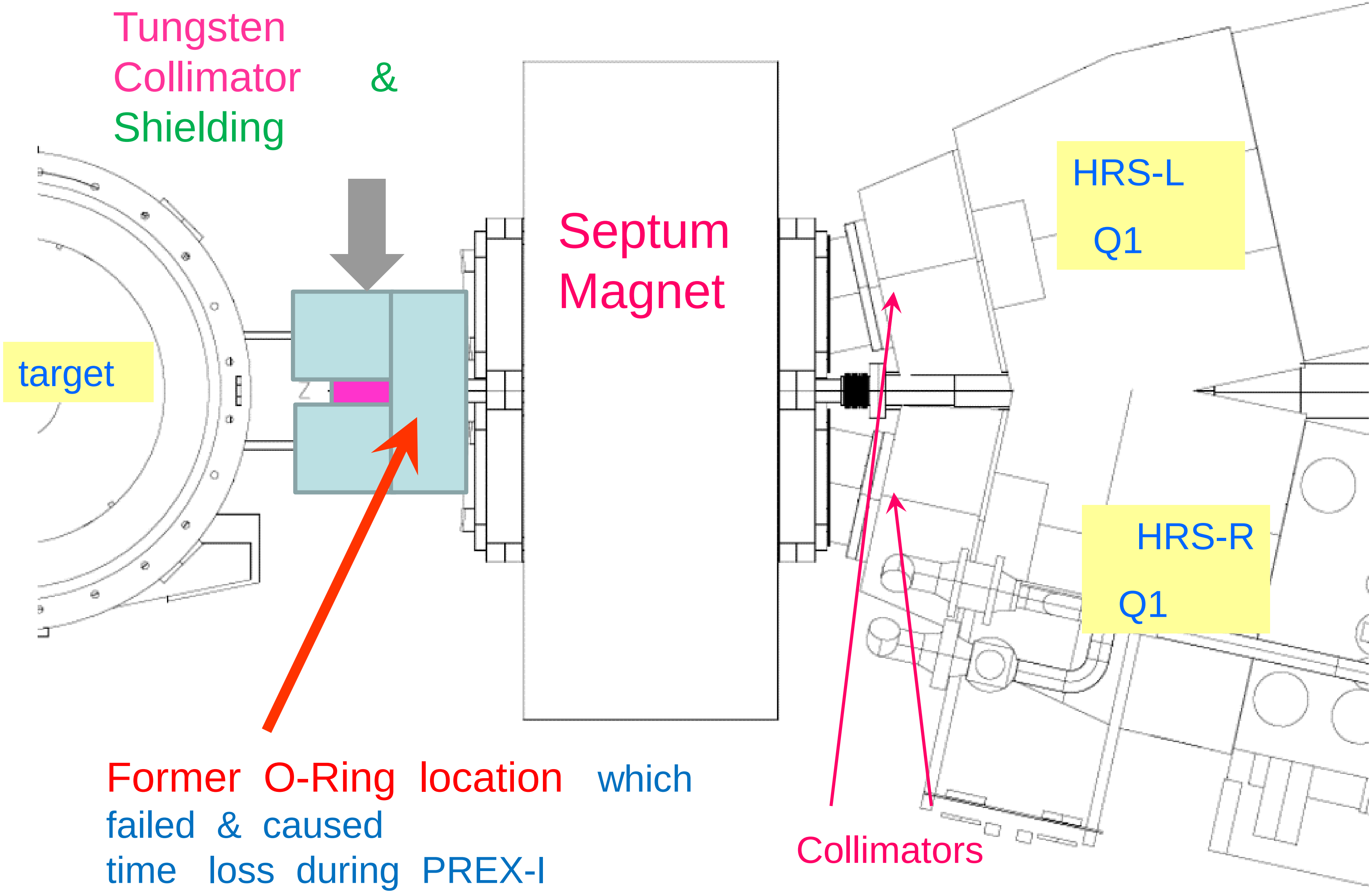
PREX Region After Target — Improvements for PREX-II



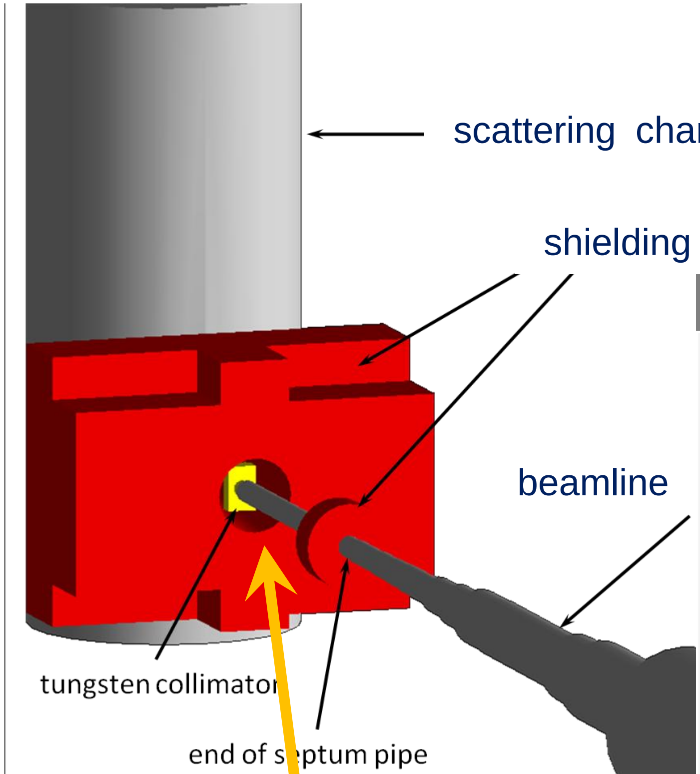
Former O-Ring location which failed & caused time loss during PREX-I

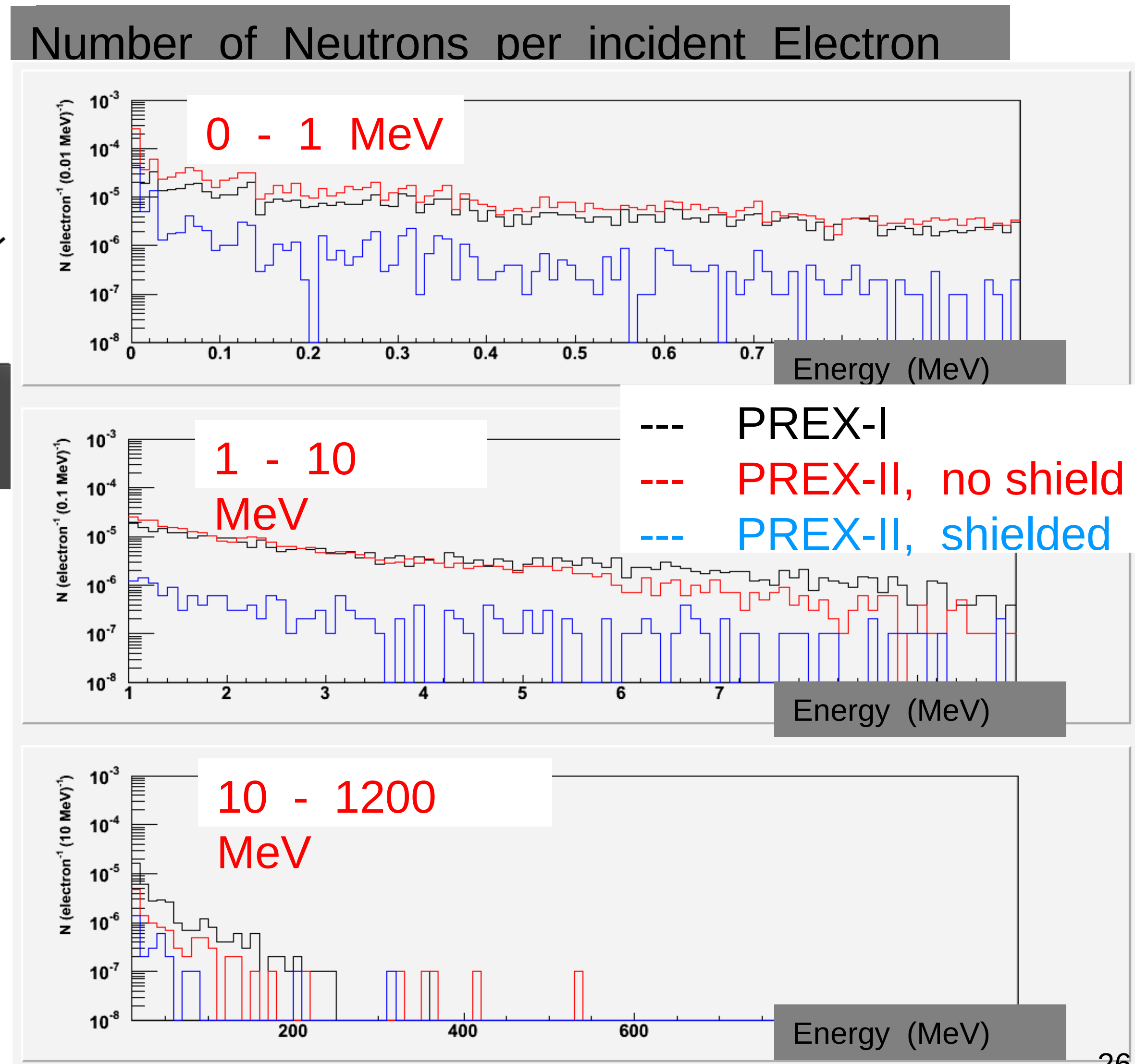
→ PREX-II to use all-metal seals

Geant 4 Radiation Calculations

J. Mammei, L. Zana

PREX-II shielding strategies





Strategy

- Tungsten (W) plug

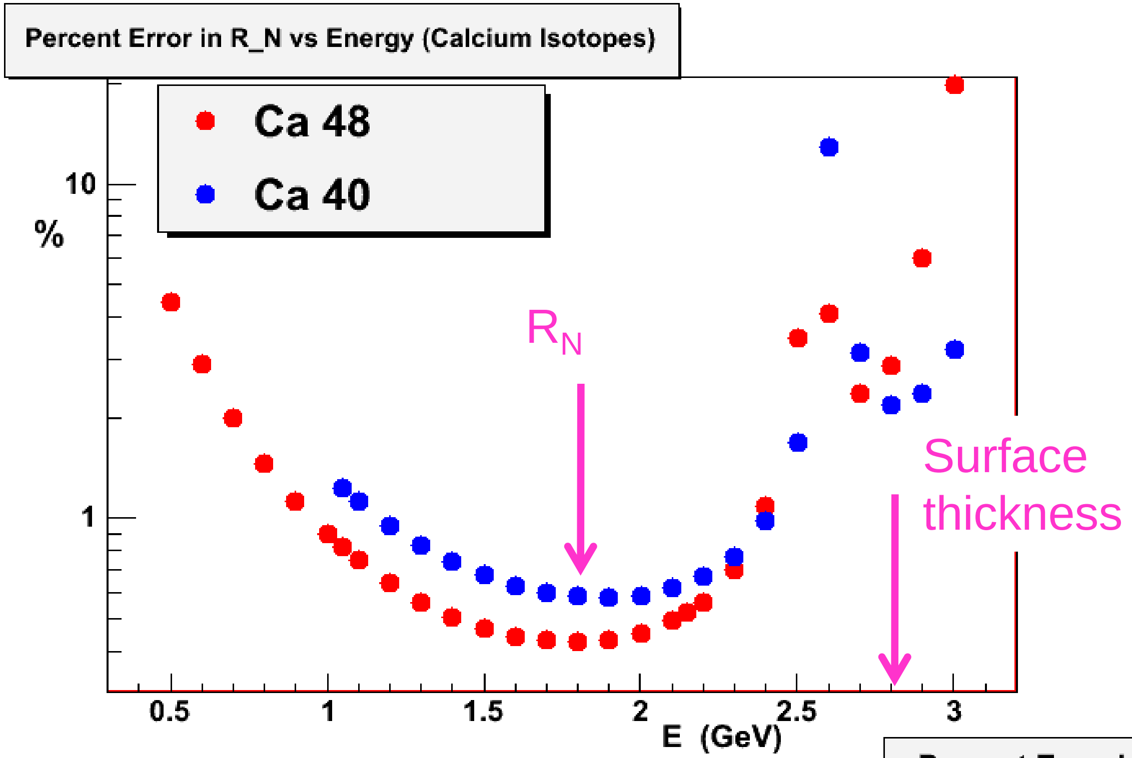
$$0.7^0 < \theta < 3^0$$

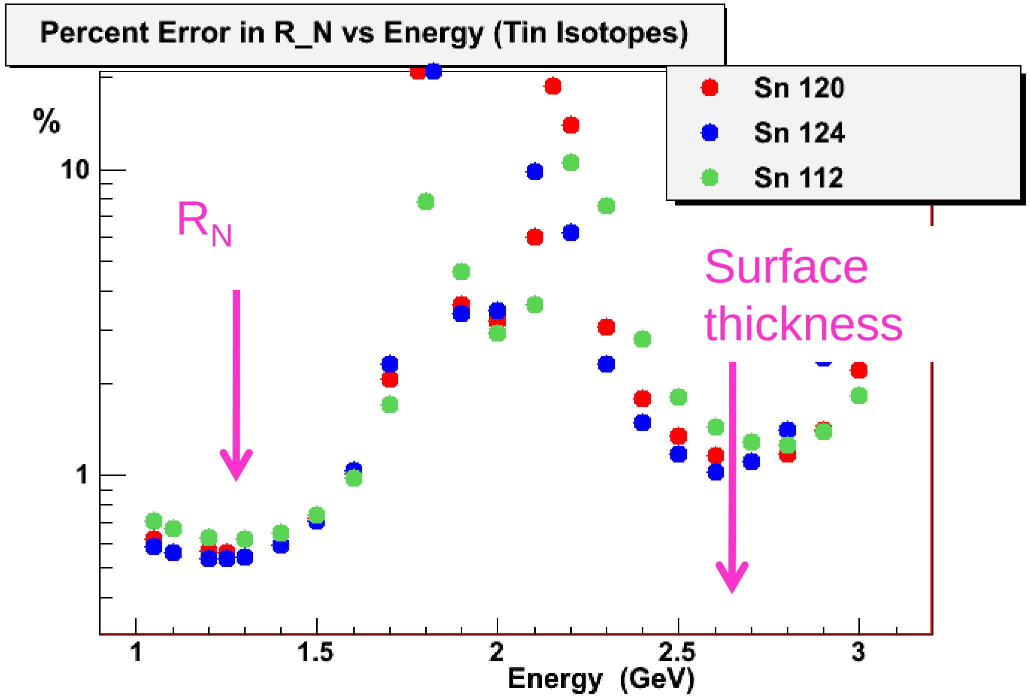
- Shield the W

- x 10 reduction in
  0.2 to 10 MeV neutrons

Other Nuclei ?

Shape Dependence ?





Parity Violating Electron Scattering Measurements of Neutron Densities

Shufang Ban, C.J. Horowitz, R. Michaels

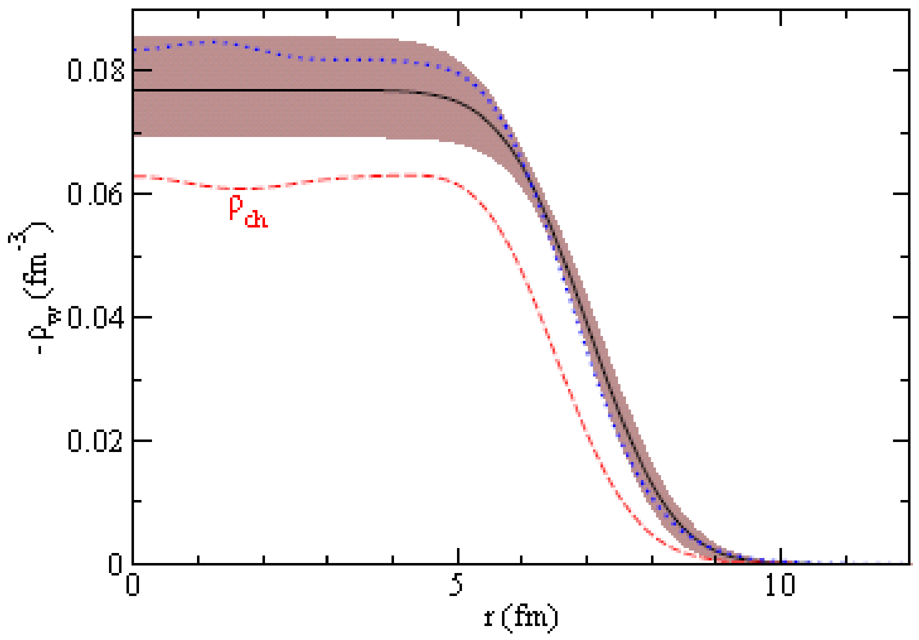
arXiv:1010.3246 [nucl-th]

G.M. Urciuoli

Summary

- Fundamental Nuclear Physics with many applications
- Because of significant time-losses due to O-Ring problem and radiation damage PREX achieved a 9% stat. error in Asymmetry (original goal was 3 %).
- PREX measurement of Rn is nevertheless the cleanest performed so far
- Several experimental goals (Wien filters, 1% polarimetry at 1 GeV, etc.) were all achieved.
- Systematic error goal was consequently achieved too.
- PREX-II approved (runs in 2013 or 2014) ➔ 3% statistical error

Spare



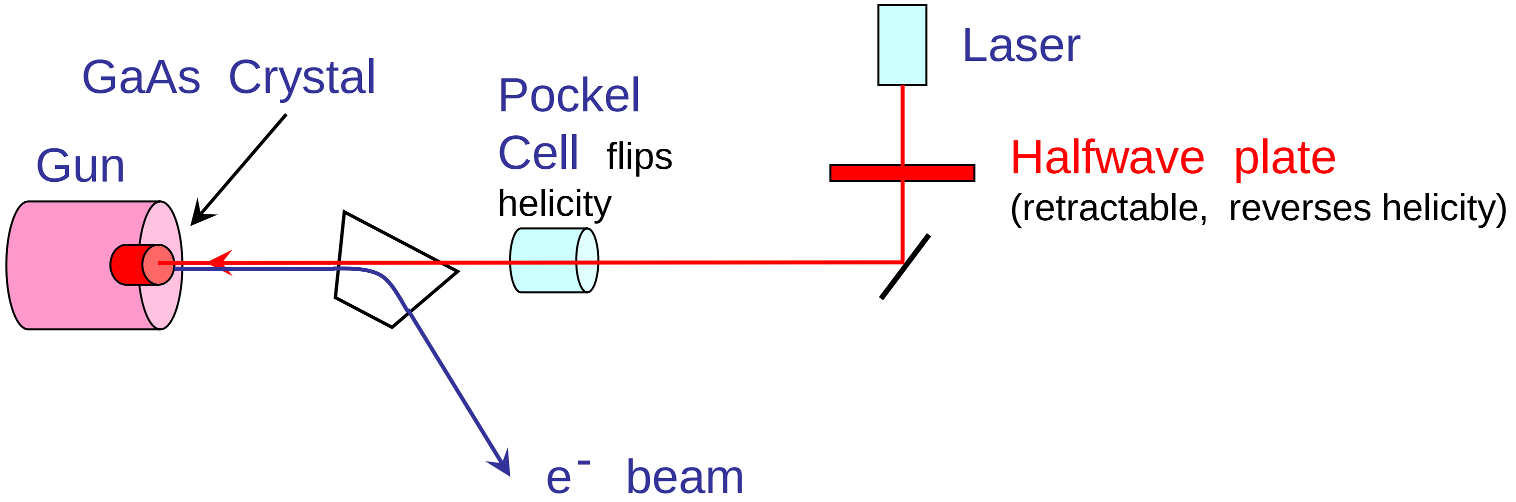
0.08
0.06
0.04
0.02
0
0
5
10
r (fm)
$-\rho_w$ (fm^{-3})
ρ_{ch}

Corrections to the Asymmetry are Mostly Negligible

- Coulomb Distortions ~20% = the biggest correction.
- Transverse Asymmetry
- Strangeness
- Electric Form Factor of Neutron
- Parity Admixtures
- Dispersion Corrections
- Meson Exchange Currents
- Shape Dependence
- Isospin Corrections
- Radiative Corrections
- Excited States
- Target Impurities

} Horowitz, *et.al.* PRC 63 025501

Polarized Electron Source



- Rapid, random helicity reversal
- Electrical isolation from rest of lab
- Feedback on Intensity Asymmetry

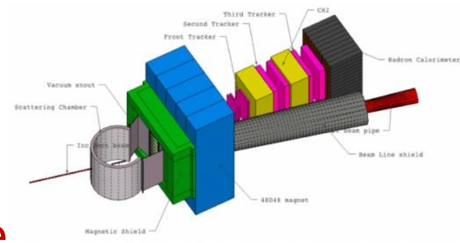
Future in Hall A at JLab

Early Experiments

g2p/GEp

12 mo. Shutdown

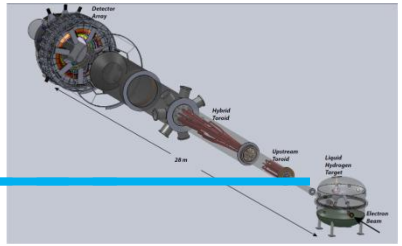
no promised beam



Commissioning

SuperBigbite

$



Beam 1st to Hall A

Moller

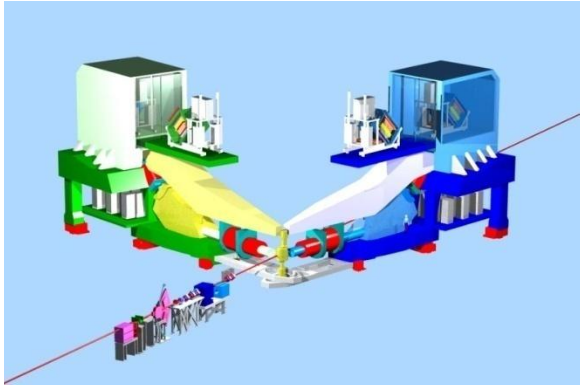
$$$

PREX – II ?

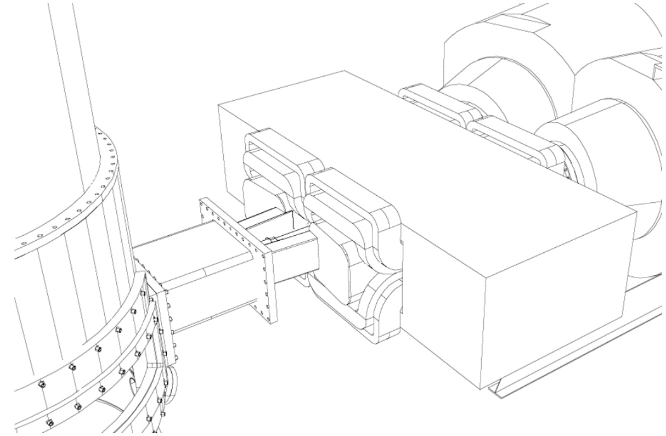
SOLID

$$$$

2011	2012	2013	2014	2015	2016	2017	2018



Possible Future PREX Program ?



Each point 30 days   stat. error only

Nucleus	E (GeV)	dR_N / R_N	comment
^{208}Pb	1	1 %	**PREX-II** (approved)
^{48}Ca	2.2 (1-pass)	0.4 %	natural 12 GeV exp't
^{48}Ca	2.6	2 %	surface thickness
^{40}Ca	2.2 (1-pass)	0.6 %	basic check of theory
tin isotope	1.8	0.6 %	apply to heavy ion
tin isotope	2.6	1.6 %	surface thickness

Not yet proposed. Just a "what if ?"

Shufang Ban, C.J. Horowitz, R. Michaels arXiv:1010.3246 [nucl-th]