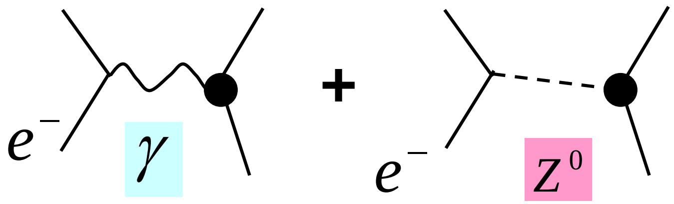
PREX and CREX

^{208}Pb ^{48}Ca

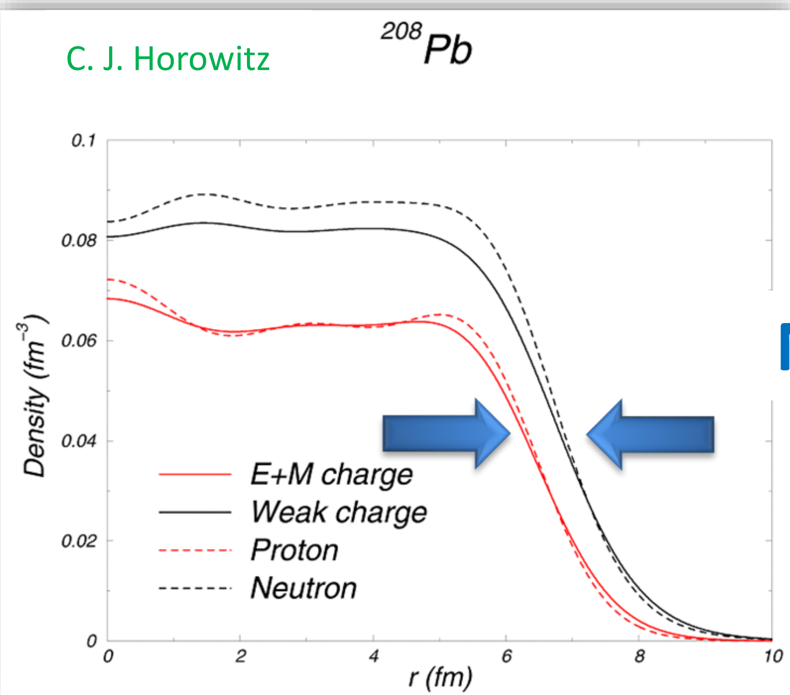
http://hallaweb.jlab.org/parity/prex

Robert Michaels
Jefferson Lab

NuSYM2018

$\sigma \approx \Big|$  $\Big|^2$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-4} \times Q^2 \sim 10^{-6}$$



Electroweak Asymmetry in Elastic Electron-Nucleus Scattering

Neutron Skin

$$R_n - R_p = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

Jefferson Lab
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PREX

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Robert Michaels	Jefferson Lab
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CREX

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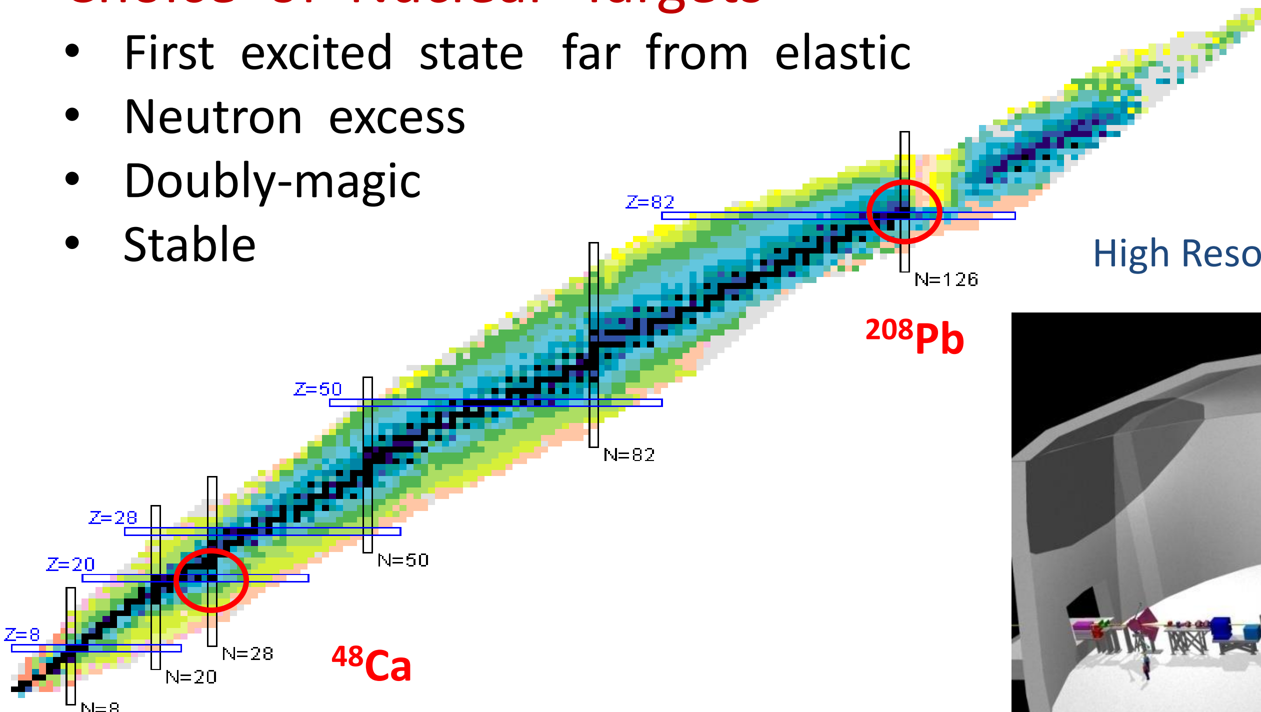
Neutron form factor

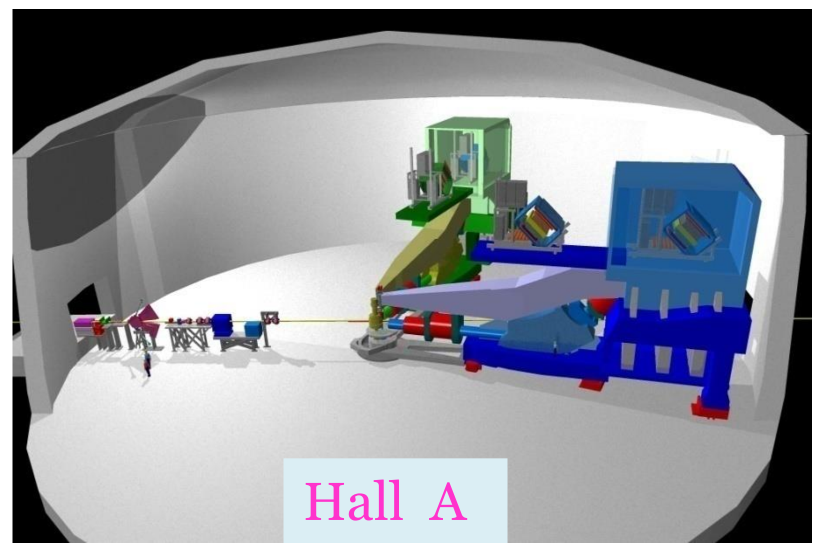
$$A \approx \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[1 - 4\sin^2\theta_W - \frac{F_N(Q^2)}{F_P(Q^2)} \right]$$

Choice of Nuclear Targets

- First excited state far from elastic
- Neutron excess
- Doubly-magic
- Stable



High Resolution (10^{-4}) Spectrometers



Robert Michaels, NuSYM2018

Using Parity Violation

Electron - Nucleus Potential $\hat{V}(r) = V(r) + \gamma_5 A(r)$

electromagnetic

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

axial

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

^{208}Pb is spin 0

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

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

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

Proton form factor

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

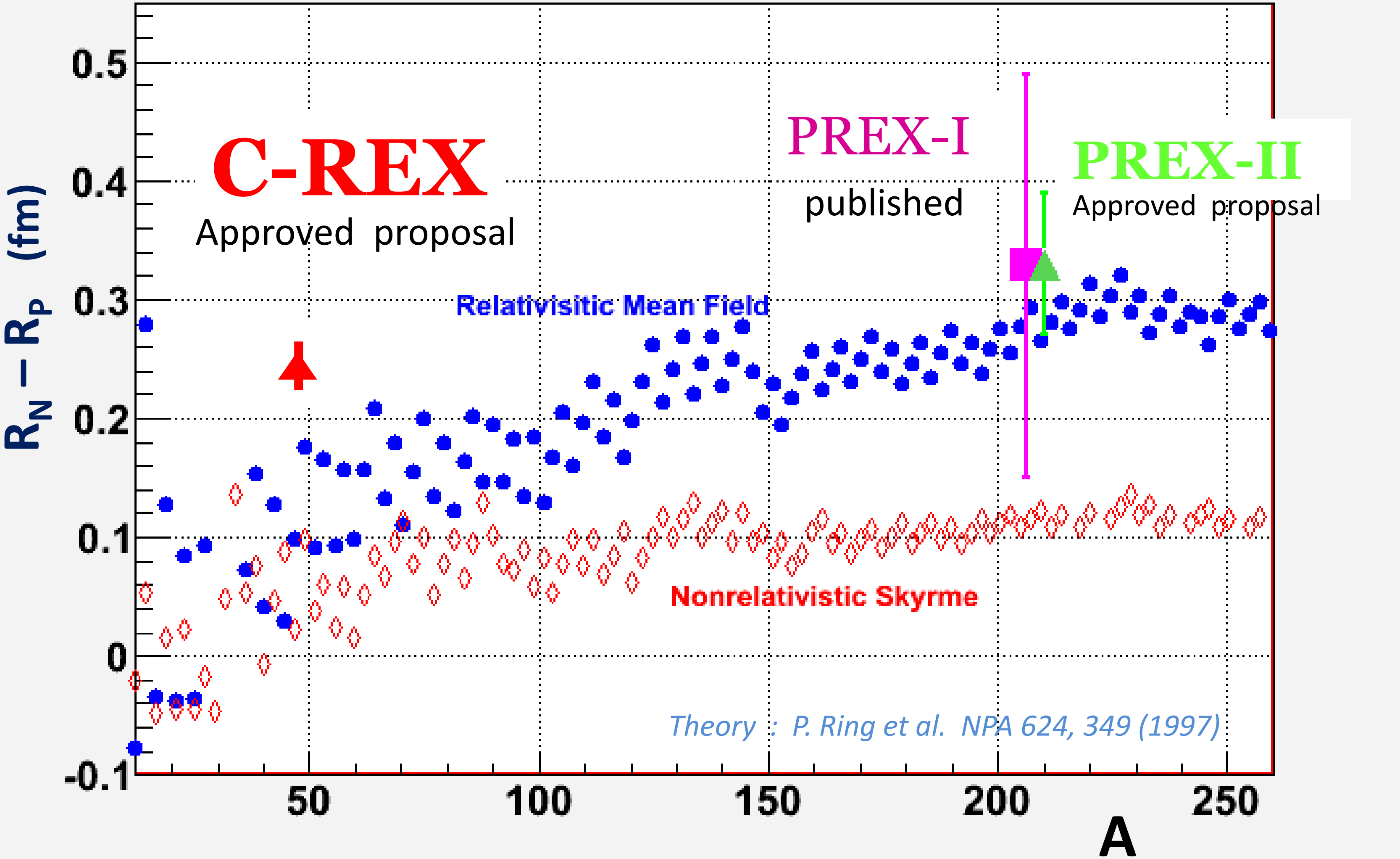
Neutron form factor

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

Parity Violating Asymmetry

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

Neutron Skin vs Mass Number A



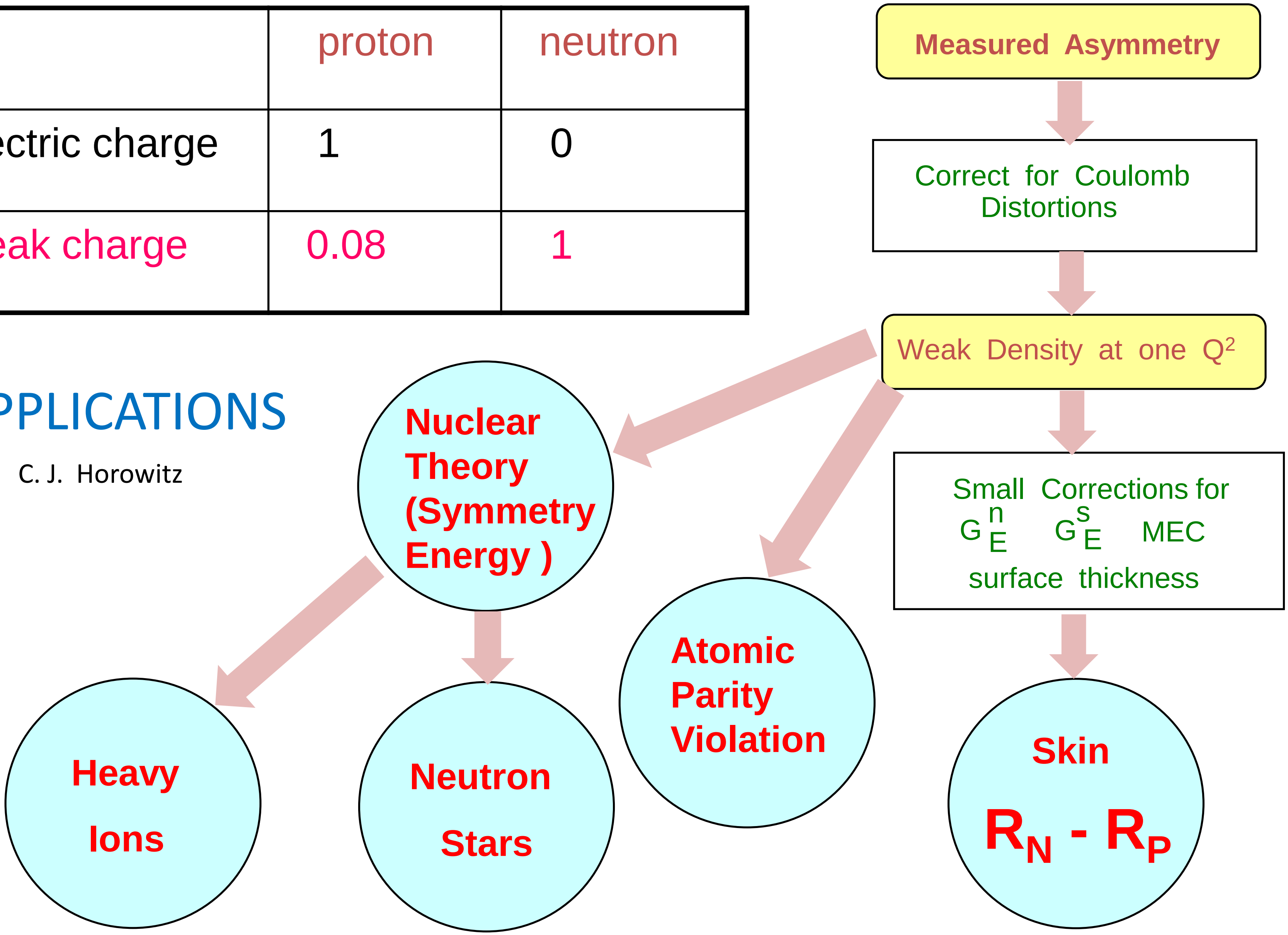
Weak Interaction: Sees the Neutrons

T.W. Donnelly, J. Dubach, I. Sick Nucl. Phys. A 503, 589, 1989

	proton	neutron
Electric charge	1	0
Weak charge	0.08	1

APPLICATIONS

C. J. Horowitz



Ways to Find

Neutron Distribution and Symmetry Energy

- Proton-Nucleus Elastic
- Pion, alpha, d Scattering
- Heavy ion collisions
- Rare Isotopes (dripline)

} Involve strong probes

- Pion Photoproduction
- Electric Dipole Polarizabilities
- Magnetic scattering

} Electromagnetic probes

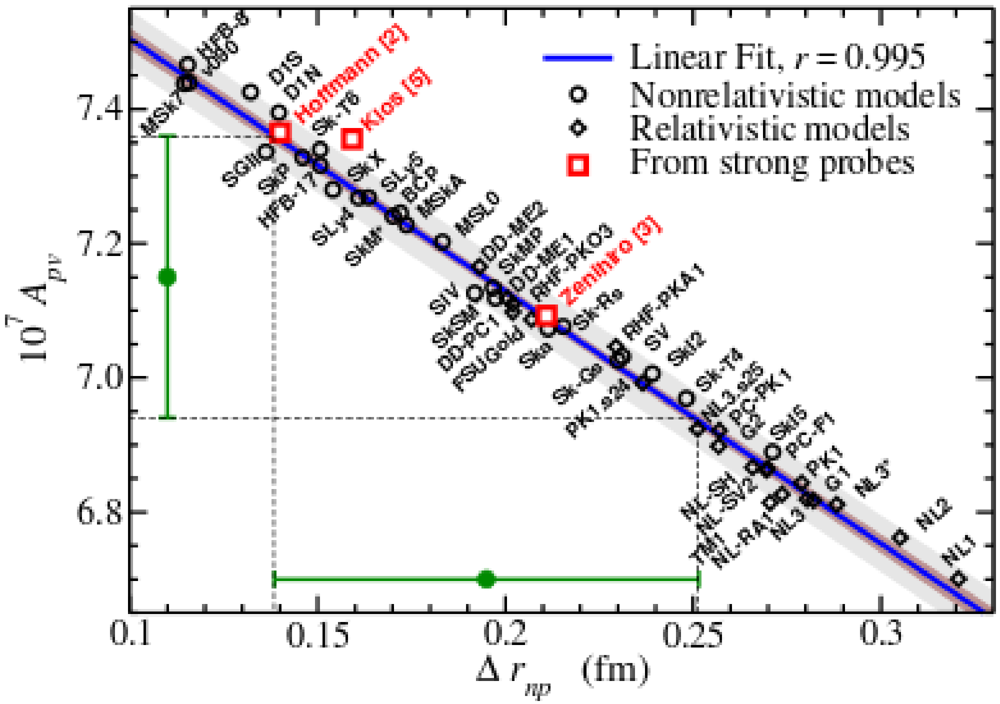
- PREX / CREX A_{PV}
- Neutrino-nucleus coherent

} Weak interaction

- Theory → MFT fit mostly by data *other than* neutron densities

Neutron skin measured by A_{PV}

Robust correlation between ^{208}Pb A_{PV} and the neutron skin over existing nuclear structure models



X. Roca-Maza (et al.) PRL 106 (2011) 252501

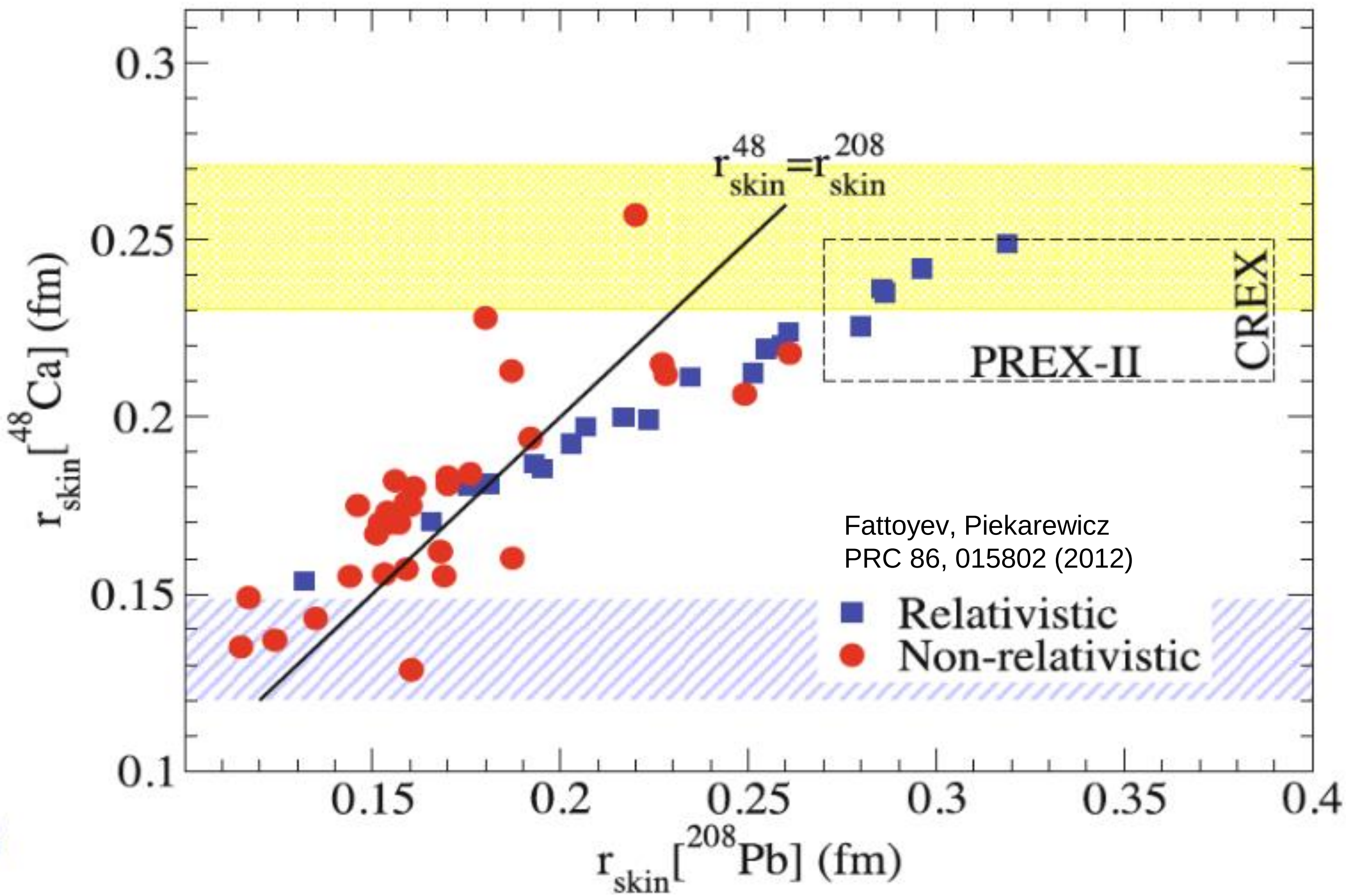
Apv in PVES provides a clean probe of the neutron distribution

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

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

"Ab Initio" (exact microscopic) calculations of R_{skin} for ^{48}Ca have recently been published.

Can be compared to Density Functional Theory (the red and blue points) and Dispersive Optical Model (DOM)



DOM

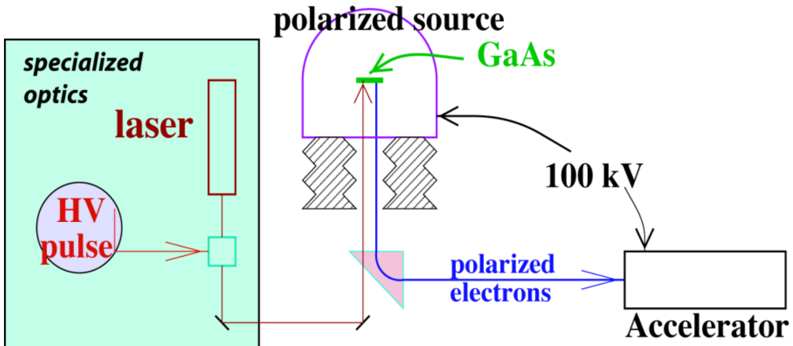
W. Dickhoff, et al.
PRL 119, 222503 (2017)

ab initio

G. Hagen, et al.
Nature 12, 186 (2015)

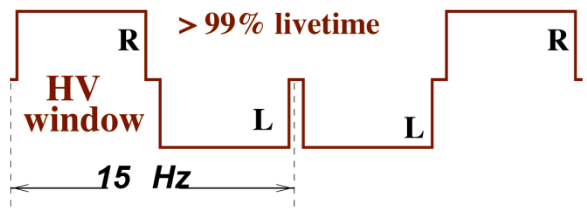
Parity Experiment Method

(integrating mode)



rapid, random, helicity flipping

Rapid, Random Helicity Flips



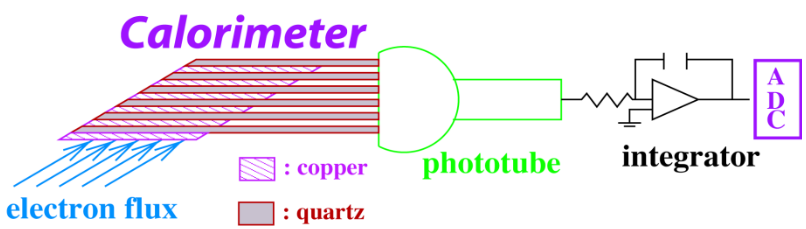
Measure flux F for each window

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

Flux Integration Technique:

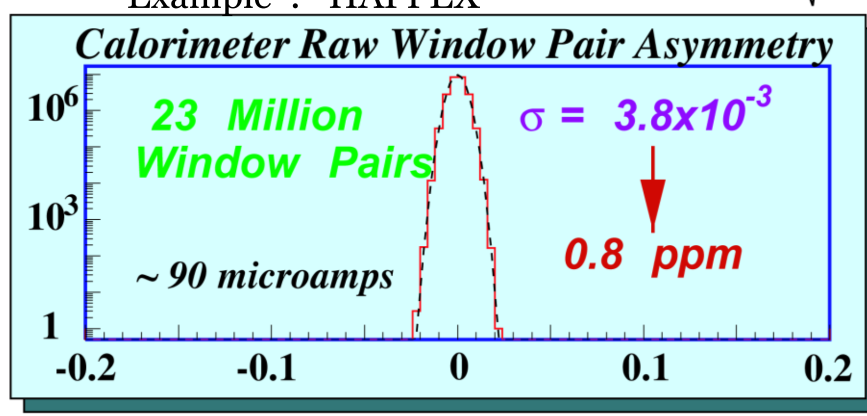
C-REX : 140 MHz

PREX: 500 MHz



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

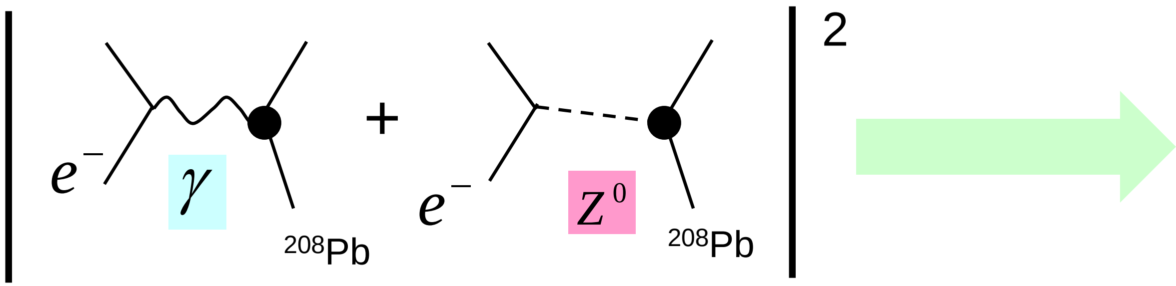
Example : HAPPEX



No non-gaussian tails to +/- 5σ

Parity Violating Asymmetry

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-4} \times Q^2 \sim 10^{-6}$$

$\sigma \approx$ 

A_{PV} from interference

Applications of A_{PV} at Jefferson Lab

- Nucleon Structure

  Strangeness $\bar{s}s$ in proton (HAPPEX, G0 expts)

- Test of Standard Model of Electroweak $\sin^2 \theta_W$

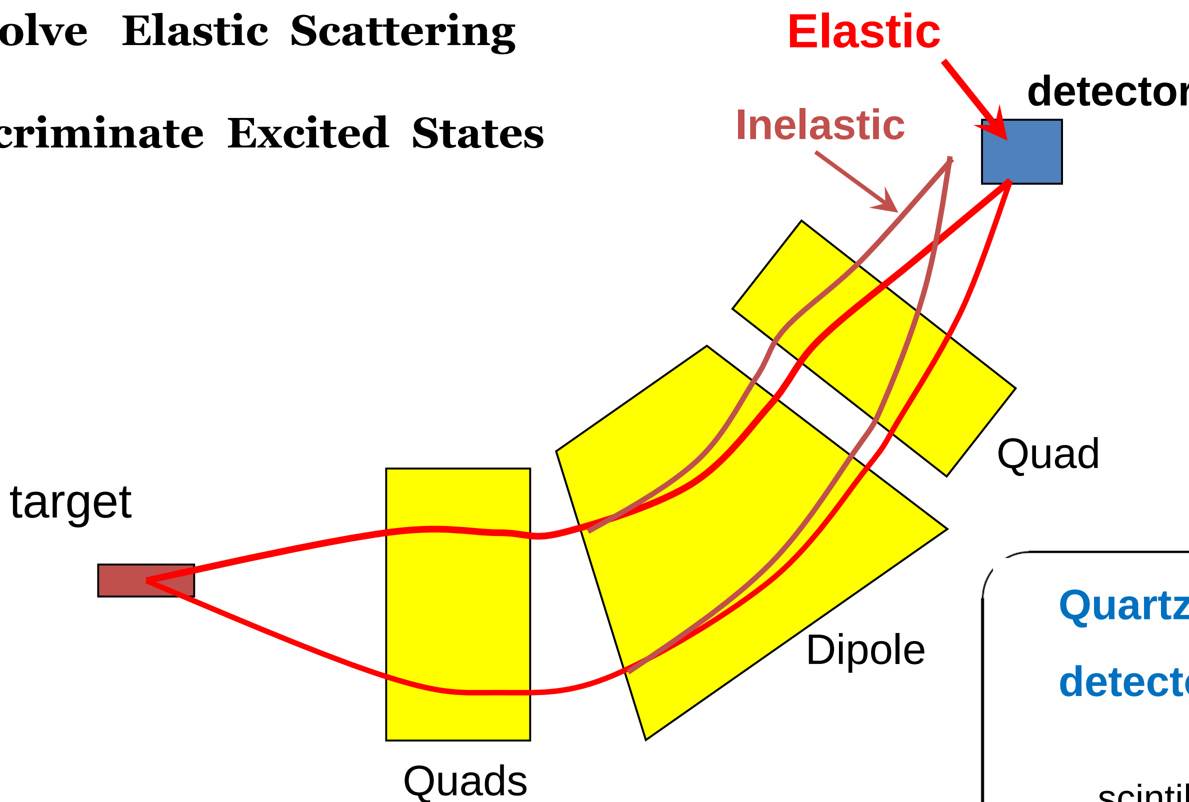
  e – e (MOLLER) or e – q (PVDIS)

  elastic e – p at low Q^2 (QWEAK)

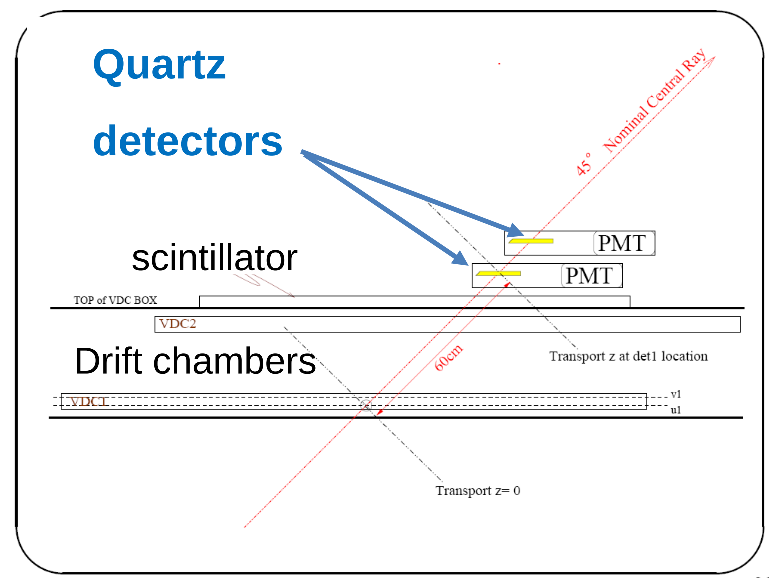
- *Nuclear Structure (neutron density) :* *PREX* & *CREX*

Hall A High Resolution Spectrometers

- **Resolve Elastic Scattering**
- **Discriminate Excited States**

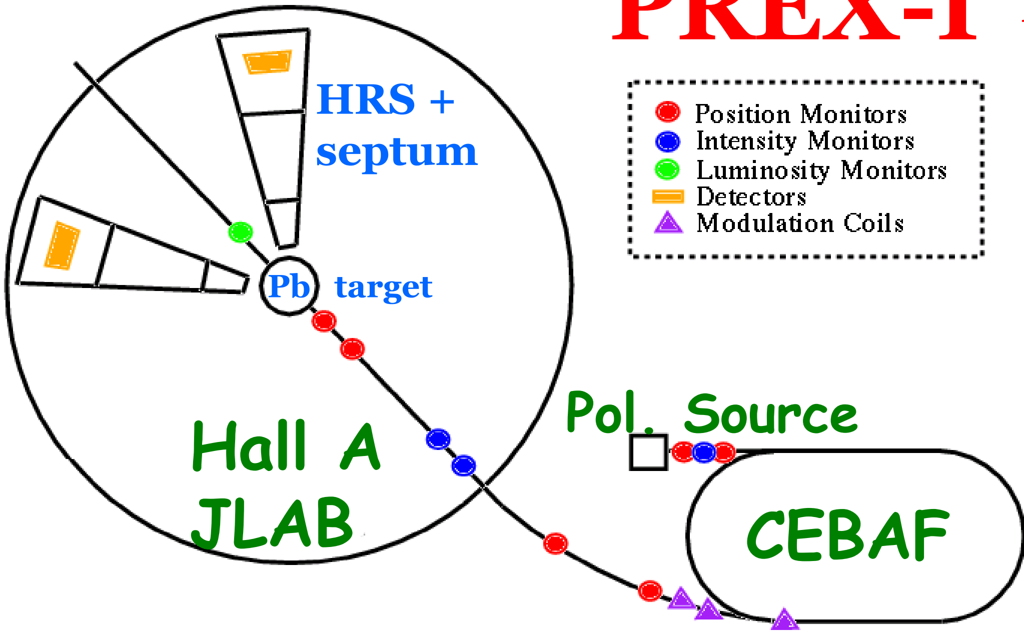


PREX	1.0 GeV	5^0
CREX	2.0 GeV	5^0



PREX-I Results

PRL 108 (2012) 112502

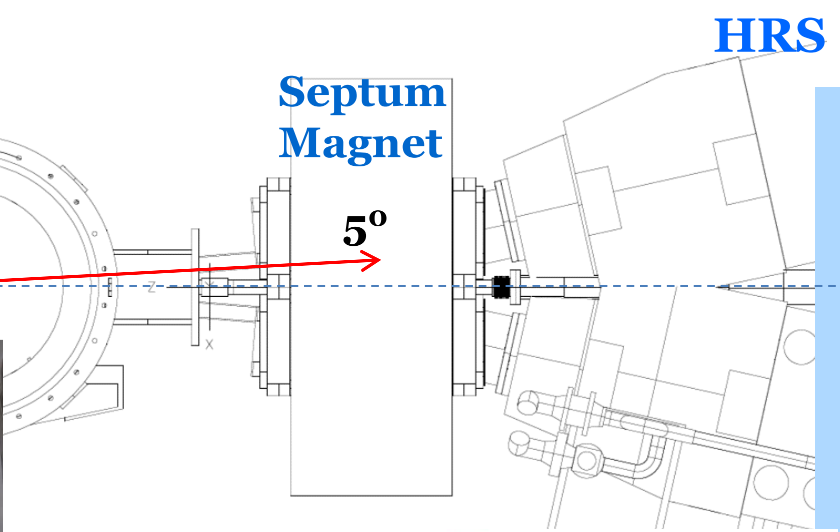


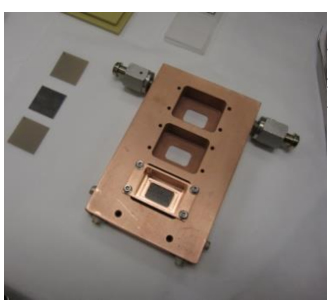
Physics Asymmetry

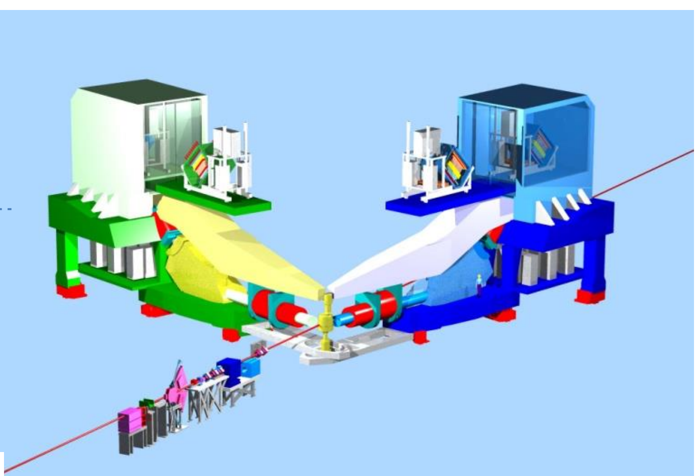
$$A = 0.656\ ppm \pm 0.060\,(stat) \pm 0.014\,(syst)$$

→ **Statistics limited (9%)**

→ **Systematic error goal achieved ! (2%)**







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Parity Quality Beam : *Unique Strength of JLab*

Helicity – Correlated Position Differences

$< X_R - X_L > \quad for \ helicity \ L, R$

Plotted below

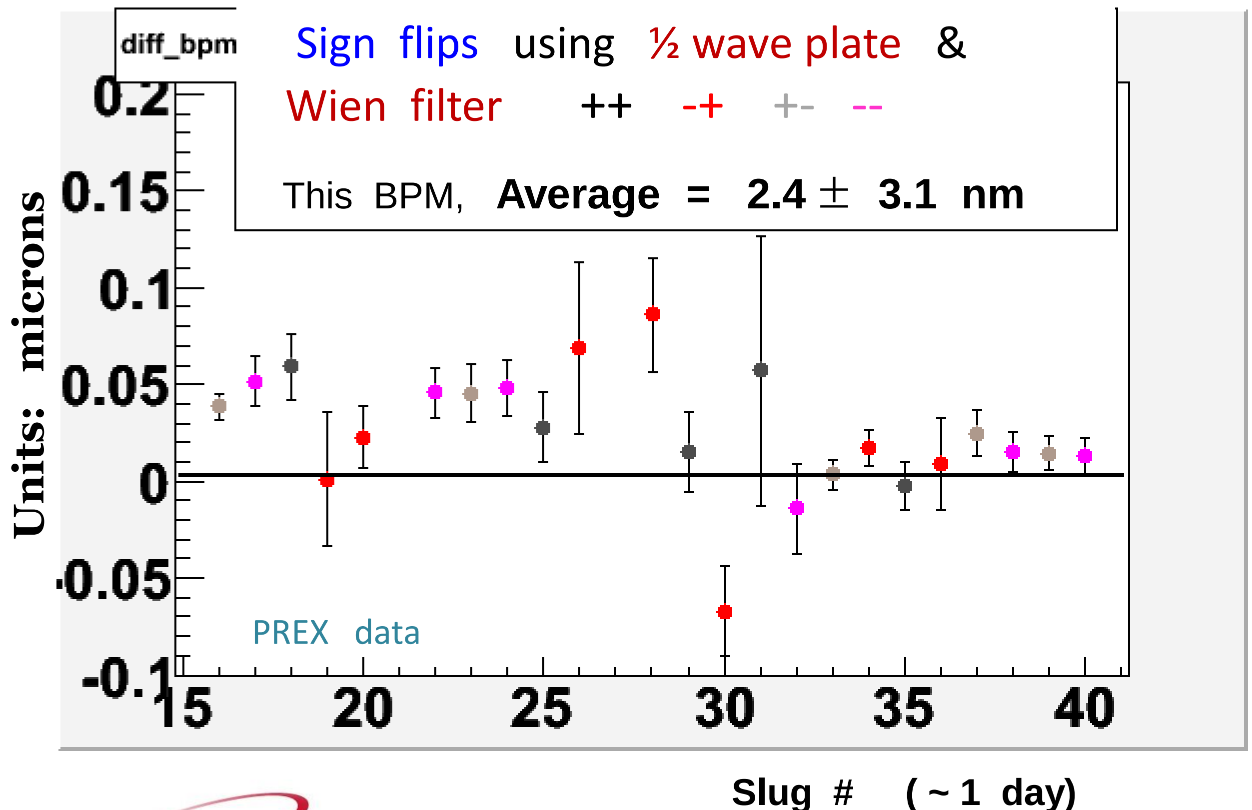
$$A_{raw} = A_{det} - A_Q + \alpha \, \Delta_E + \Sigma \beta_i \, \Delta x_i$$

Measured separately

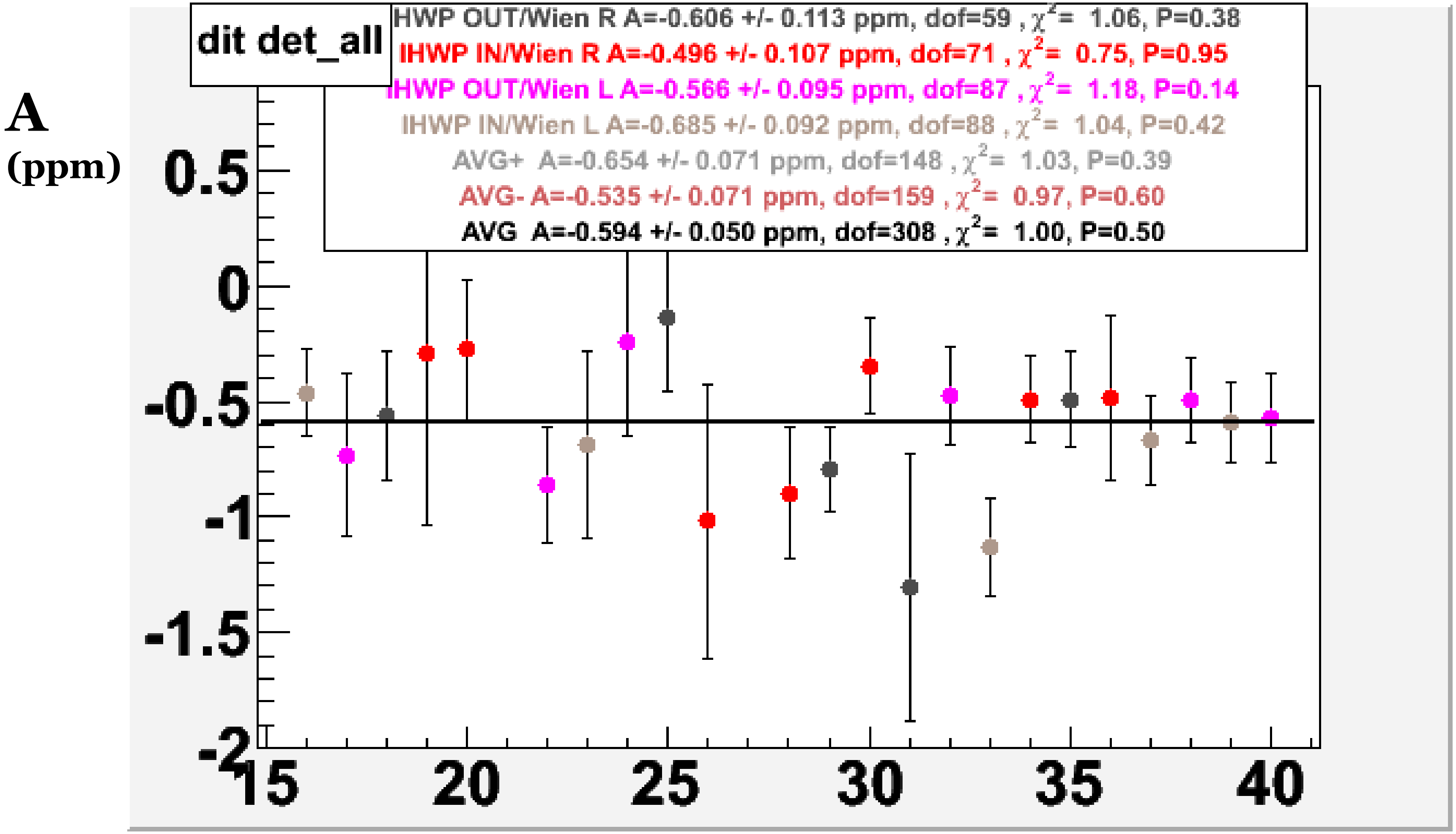
Points: Not sign-corrected.
20-50 nm diffs. with pol. source setup & feedback

Sign flips provide further suppression : Average with signs = what experiment feels

achieved < 5 nm



PREX-I Asymmetry $(P_e \times A)$

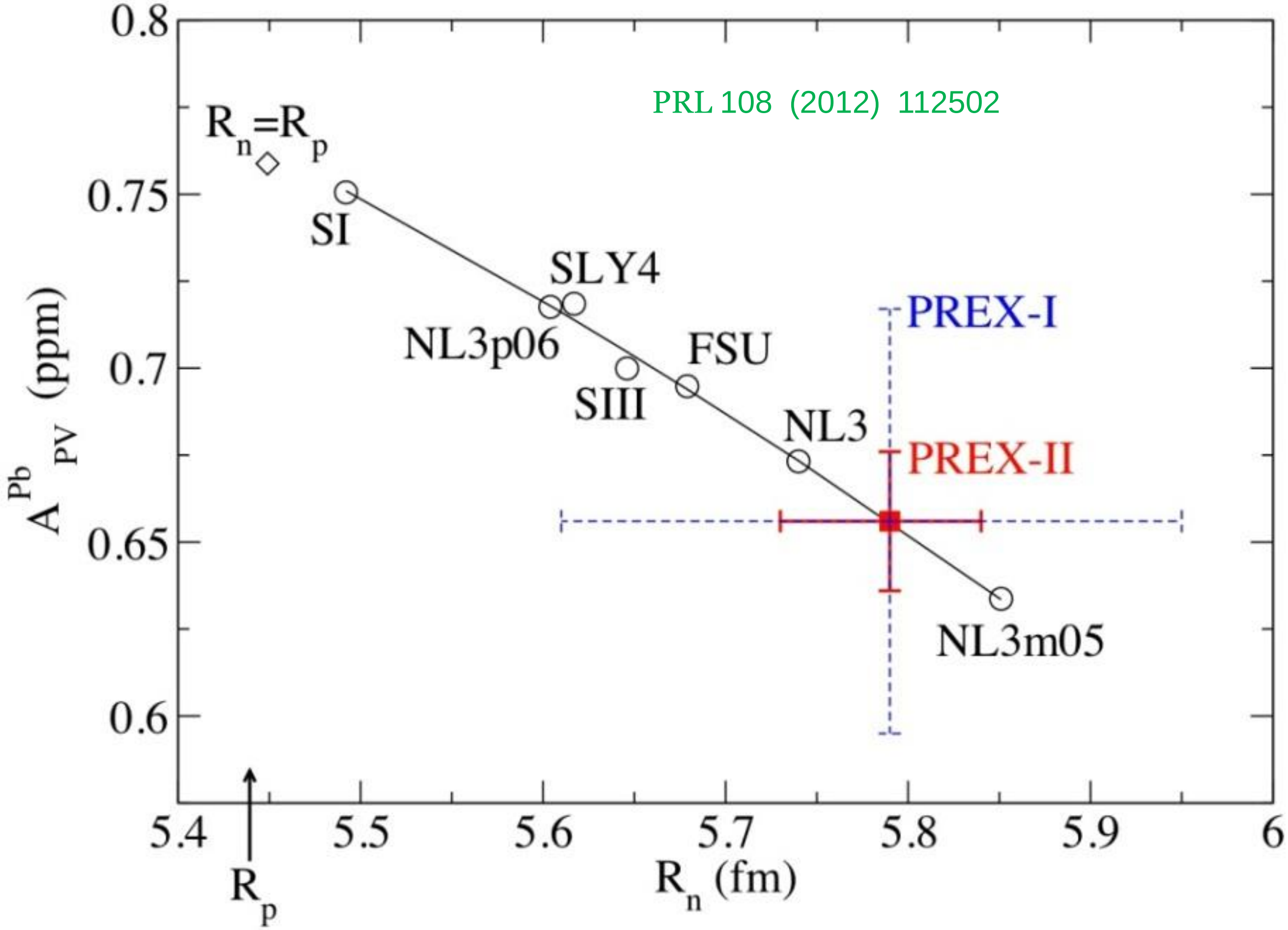


Slug # (~ 1 day)

Asymmetry leads to R_N

PREX-I has established a neutron skin at ~95 % CL

Neutron Skin = R_N - R_P = 0.33 + 0.16 - 0.18 fm



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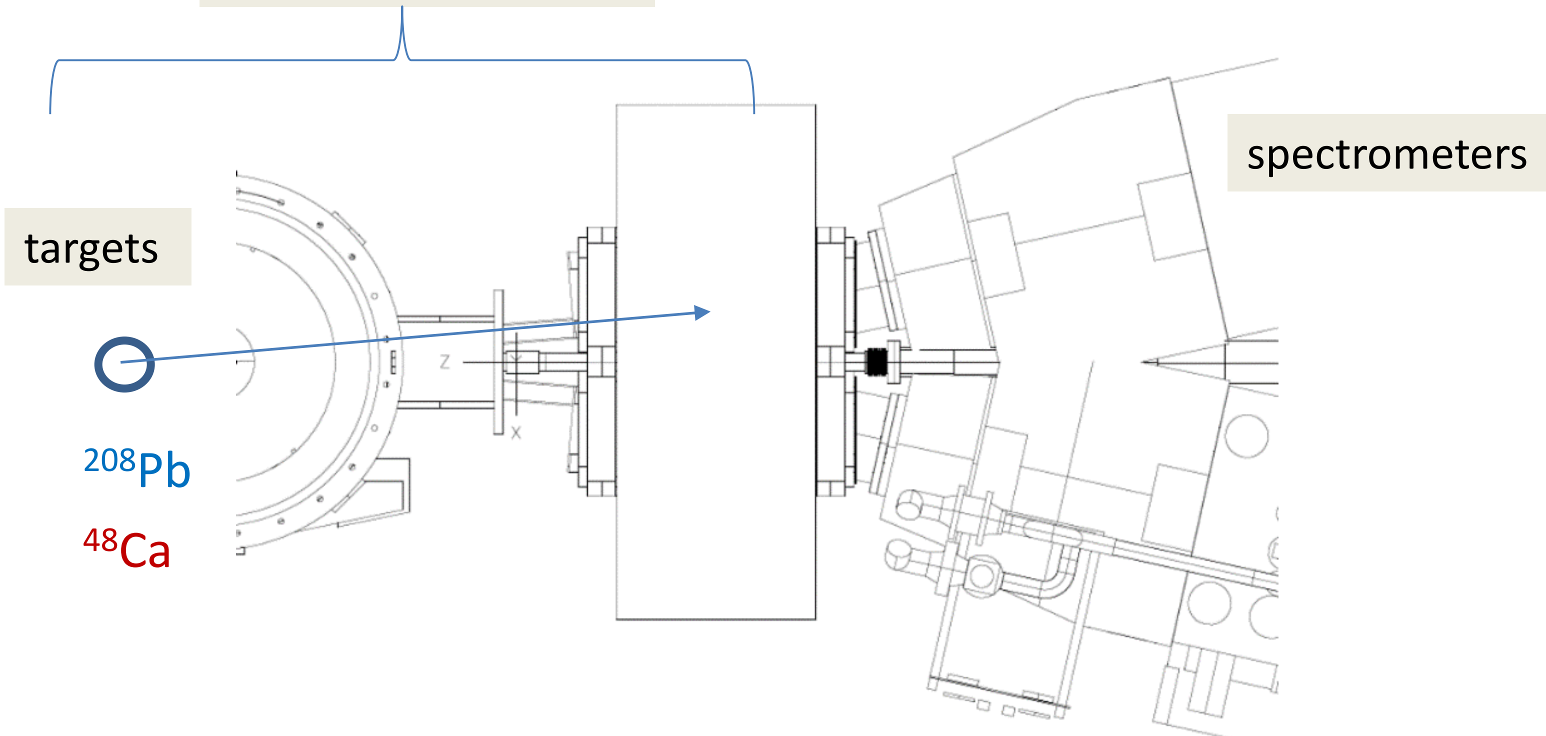
PREX-II and C-REX

Status

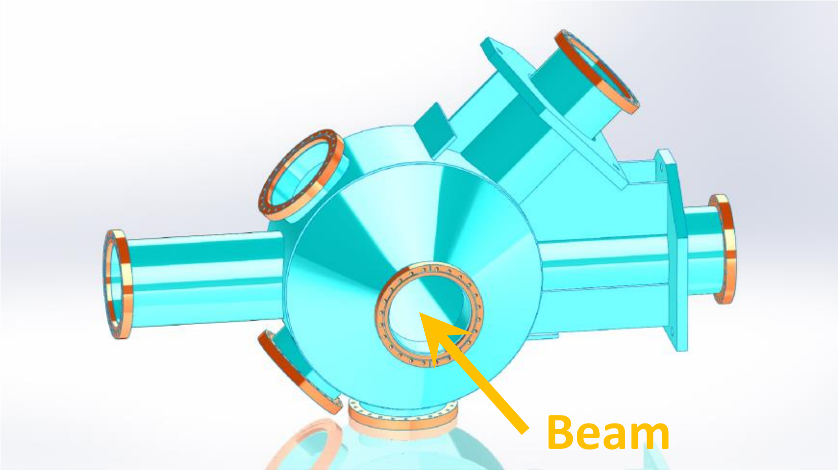
- **Experiments approved**
  - PREX-II A rating 35 days
  - C-REX A- rating 45 days
- **Systematic Error Goals for PREX-II demonstrated by PREX-I**
- **Scheduled to run in 2019**

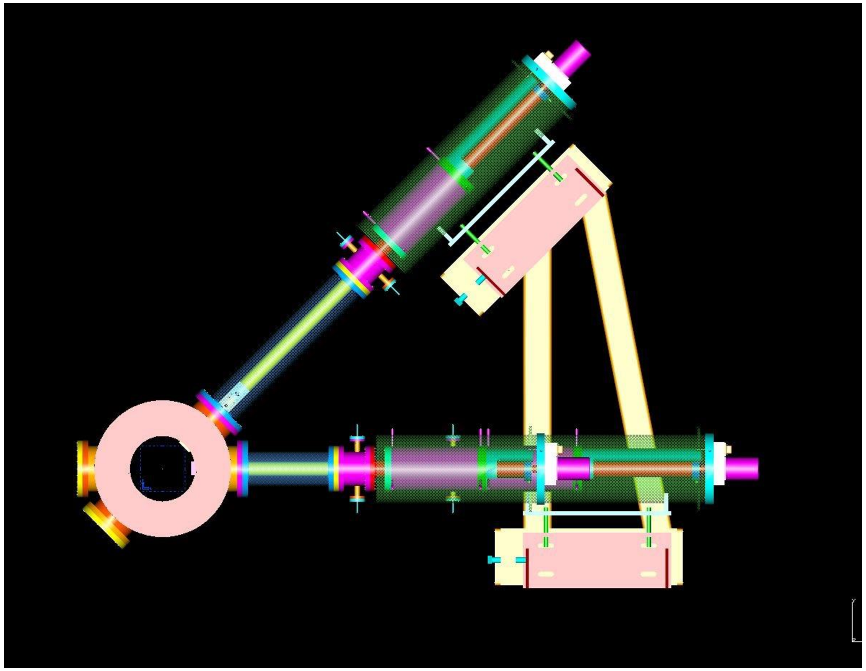
Improve the shielding and vacuum seals

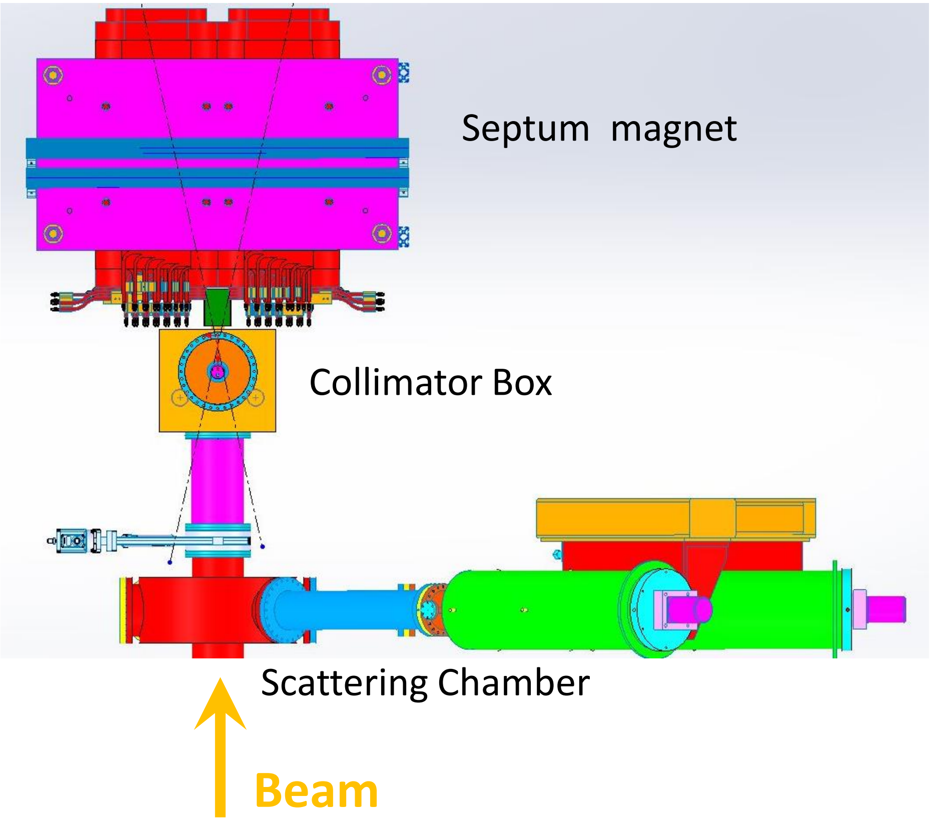


New PREX / CREX Scattering Chamber

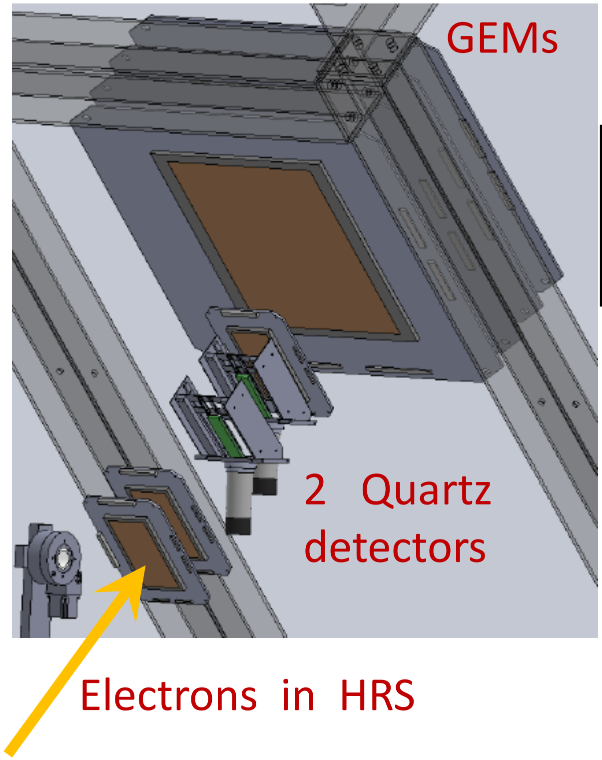
- One cryo-cooled production target ladder and one calibration-target ladder.
- Improved (hard) vacuum seals
- Run PREX and CREX with one installation
- Small chamber allows efficient shielding

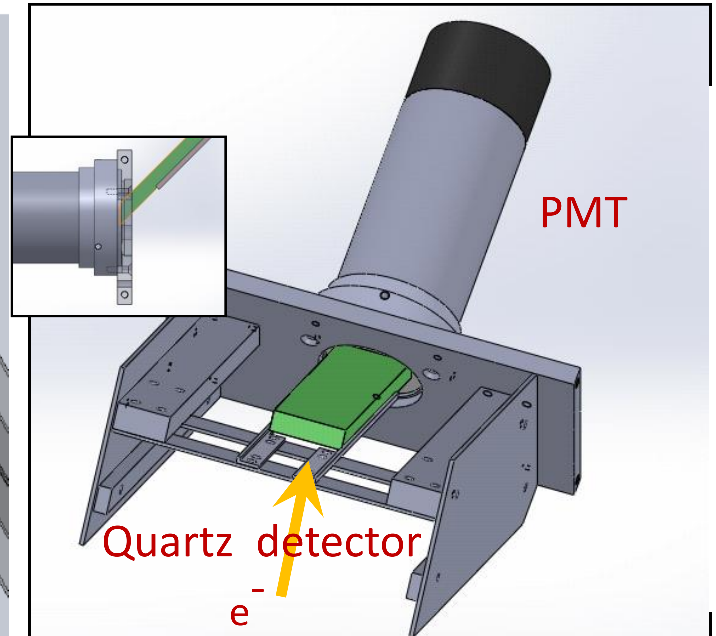






Detectors Developments



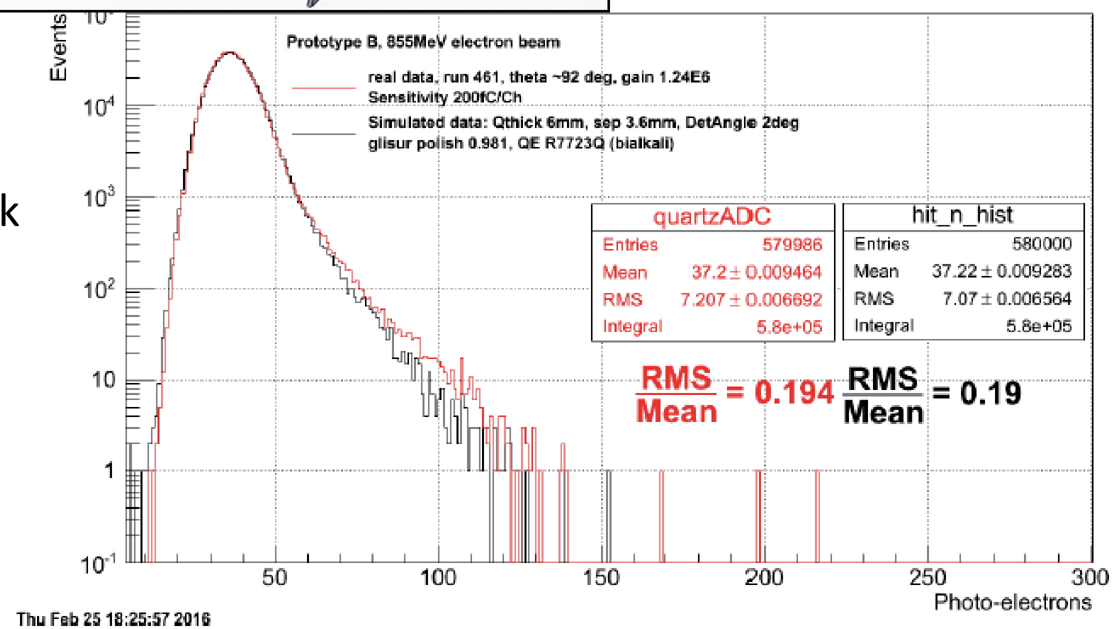


- Cherenkov radiation from electrons traversing thin quartz.
- Simulation and data benchmarked quartz properties
- Also, GEMs for high-rate tracking

Tested at Idaho and Stony Brook
Beam tests at Mainz

RMS/Mean ~ 19%

$$\sigma = \sigma_{stat}\sqrt{1+\sigma_{res}^2}$$



PREX / CREX Experiments

PREX-2: 3% stat, 0.06 fm
CREX: 2.4% stat, 0.02fm

PREX-I
E=1.1 GeV, 5°
A=0.6 ppm

Charge Normalization	0.2%
Beam Asymmetries	1.1%
Detector Non-linearity	1.2%
Transverse Asym	0.2%
Polarization	1.3%
Target Backing	0.4%
Inelastic Contribution	<0.1%
Effective Q^2	0.5%
Total Systematic	**2.1%**
Total Statistical	**9%**

Achieved, published

statistics limited result,
systematics well under control

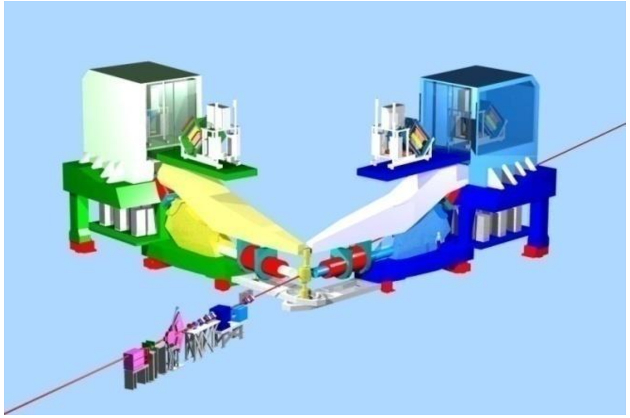
PREX-II
E=1.1 GeV, 5°
A=0.6 ppm
70 μA, 25+10 days

Charge Normalization	0.1%
Beam Asymmetries*	1.1%
Detector Non-linearity*	1.0%
Transverse Asym	0.2%
Polarization*	1.1%
Target Backing	0.4%
Inelastic Contribution	<0.1%
Effective Q^2	0.4%
Total Systematic	**2%**
Total Statistical	**3%**

*Experience suggests that leading systematic errors can be improved beyond proposal

CREX
E=1.9 GeV, 5°
A = 2.3 ppm
150 μA, 35 + 10 days

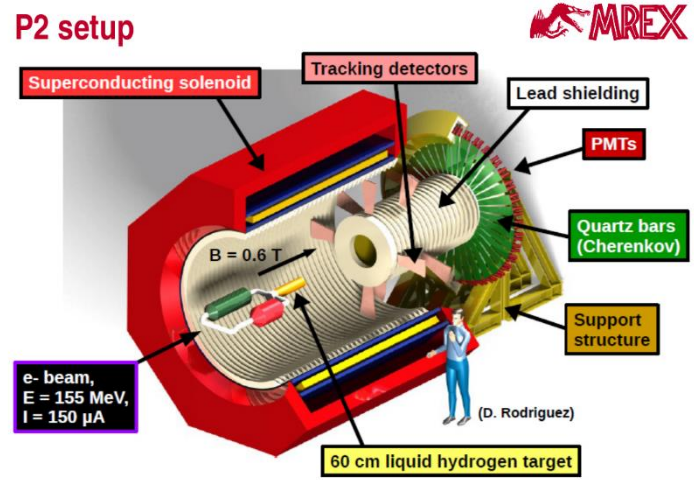
Charge Normalization	0.1%
Beam Asymmetries	0.3%
Detector Non-linearity	0.3%
Transverse Asym	0.1%
Polarization	0.8%
Target Contamination	0.2%
Inelastic Contribution	0.2%
Effective Q^2	0.8%
Total Systematic	**1.2%**
Total Statistical	**2.4%**



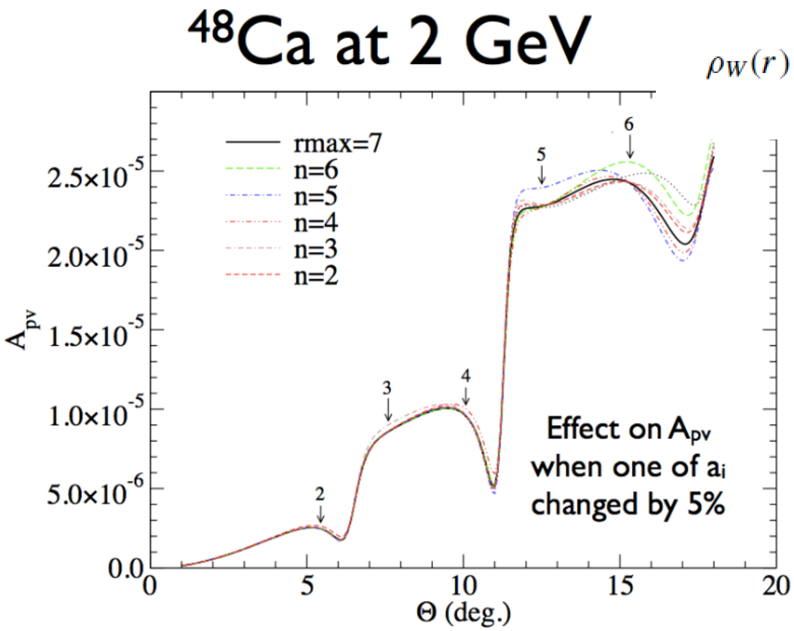
Future
Weak Charge
Scan ?

Electron Scattering

- *lower Q^2 at Mainz*
- *higher Q^2 at JLab*

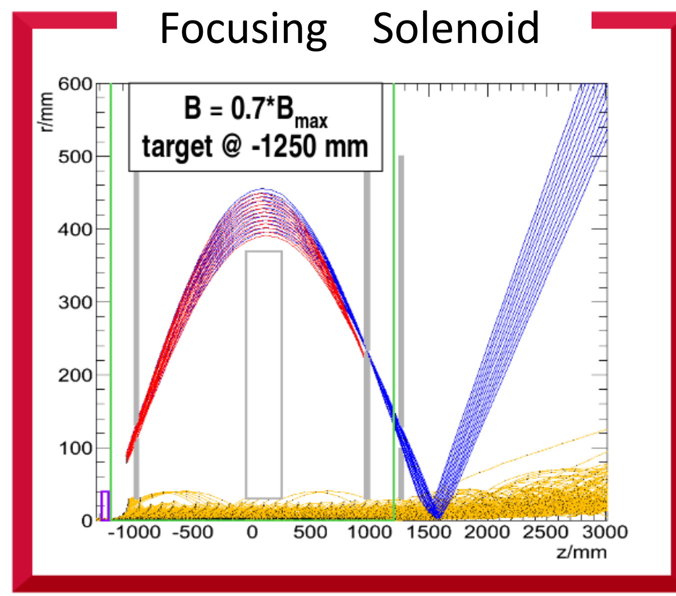


$$\rho_W(r) = \sum_{i=1}^{n_{\max}} a_i j_0(q_i r).$$



$$A_{pv} \equiv \frac{d\sigma/d\Omega_R - d\sigma/d\Omega_L}{d\sigma/d\Omega_R + d\sigma/d\Omega_L} \approx -\frac{G_F q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(q^2)}{Z F_{ch}(q^2)}$$

Z. Lin, S. Ban, C.J. Horowitz



M. Thiel, D. Becker, P. Souder

J. Phys. G39 014104 2012 ; PRC C92, 014313 2015

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PREX, C-REX : Summary

- Fundamental Nuclear Physics with many applications
- PREX-I : 9% stat. error in Asymmetry

  Goals: PREX-II ***3 %*** *0.06 fm , C-REX* ***2.4%*** *0.02 fm*
- Systematic Error Goals Achieved
- Apparatus is under construction.
- Scheduled to run in 2019