

PREX

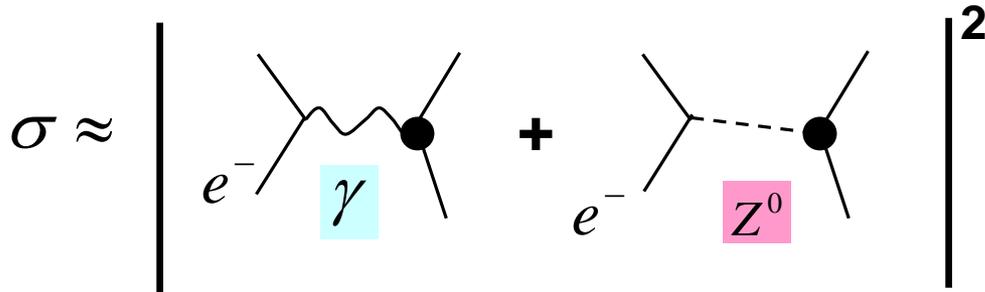
and

CREX

²⁰⁸Pb

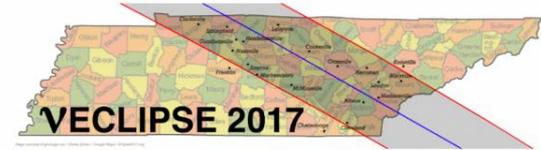
⁴⁸Ca

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



Robert Michaels

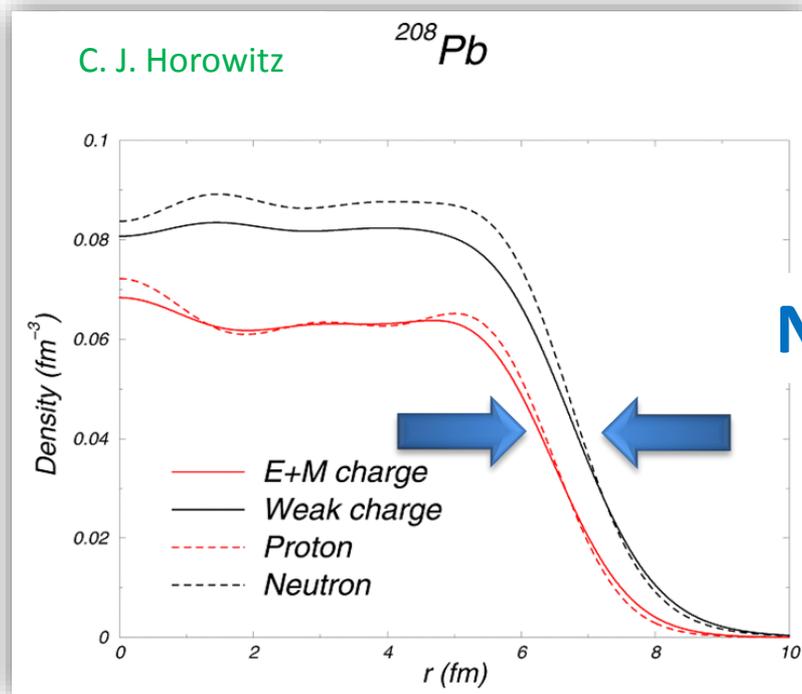
Jefferson Lab



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

Electroweak Asymmetry in
Elastic Electron-Nucleus
Scattering :

A measure of the
neutron distribution



Neutron Skin

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

PREX

Kent Paschke* UVa
 Krishna Kumar Stony Brook University
 Robert Michaels Jefferson Lab
 Paul Souder Syracuse Univeristy
 Guido Urcioli INFN Rome

* contact persons

J. Mammei, J. Birchall, M. Gericke, R. Mahurin, W.T.H. van Oers, S. Page
University of Manitoba

S. Riordan, P. Decowski, K. Kumar, T. Kutz, J. Wexler
University of Massachusetts, Amherst

K. Paschke, G.D. Cates, M. Dalton, D. Keller, X. Zheng
University of Virginia

P.A. Souder, R. Beminiwathra, R. Holmes
Syracuse University

R. Michaels, K. Allada, J. Benesch, A. Camsonne, J.P. Chen, D. Gaskell,
 J. Gomez, O. Hansen, D.W. Higinbotham, C.E. Keppel, J. LeRose, B. Moffit
 S. Nanda, P. Solvignon-Slifer, B. Wojtsekhowski, J. Zhang
Thomas Jefferson National Accelerator Facility

Konrad Aniol
California State University, Los Angeles

G.B. Franklin, B. Quinn
Carnegie Mellon University

D. Watts, L. Zana
The University of Edinburgh

P. Markowitz
Florida International University

CREX

Seamus Riordan* Stony Brook University
 Robert Michaels Jefferson Lab
 Kent Paschke UVa
 Paul Souder Syracuse Univeristy
 Dustin McNulty Idaho State University
 Juliette Mammei Manitoba University
 Silviu Covrig Jefferson Lab

P. Gueye
Hampton University

E. Cisbani, A. del Dotto, S. Frullani, F. Garibaldi
*INFN Roma gruppo collegato Sanità
 and Italian National Institute of Health, Rome, Italy*

M. Capogni
*INFN Roma gruppo collegato Sanità
 and ENEA Casaccia, Rome, Italy*

V. Bellini, A. Giusa, F. Mammoliti, G. Russo, M.L. Sperduto, C.M. Suter
INFN - Sezione di Catania

D. McNulty, P. Cole, T. Forest, M. Khandaker
Idaho State University

C.J. Horowitz
Indiana University

M. Mihovilović, S. Širca
Jožef Stefan Institute and University of Ljubljana, Slovenia

A. Glamazdin
Kharkov Institute of Physics and Technology

T. Holmstrom
Longwood University

S. Kowalski, R. Sitwal, V. Sulkosy
Massachusetts Institute of Technology

M. Shabestari
Mississippi State University

S.K. Phillips
University of New Hampshire

E. Korkmaz
University of Northern British Columbia

P. King, J. Roche, B. Waidyawansa
Ohio University

C.E. Hyde
Old Dominion University

F. Meddi, G.M. Urciuoli
Sapienza University of Rome and INFN - Sezione di Roma

A. Blomberg, Z.-E. Meziani, N. Sparveris
Temple University

M. Pitt
Virginia Polytechnic Institute and State University

D. Armstrong, J.C. Cornejo, W. Deconinck, J.F. Dowd, V. Gray, and J. Magee
College of William and Mary

D. Androic
University of Zagreb

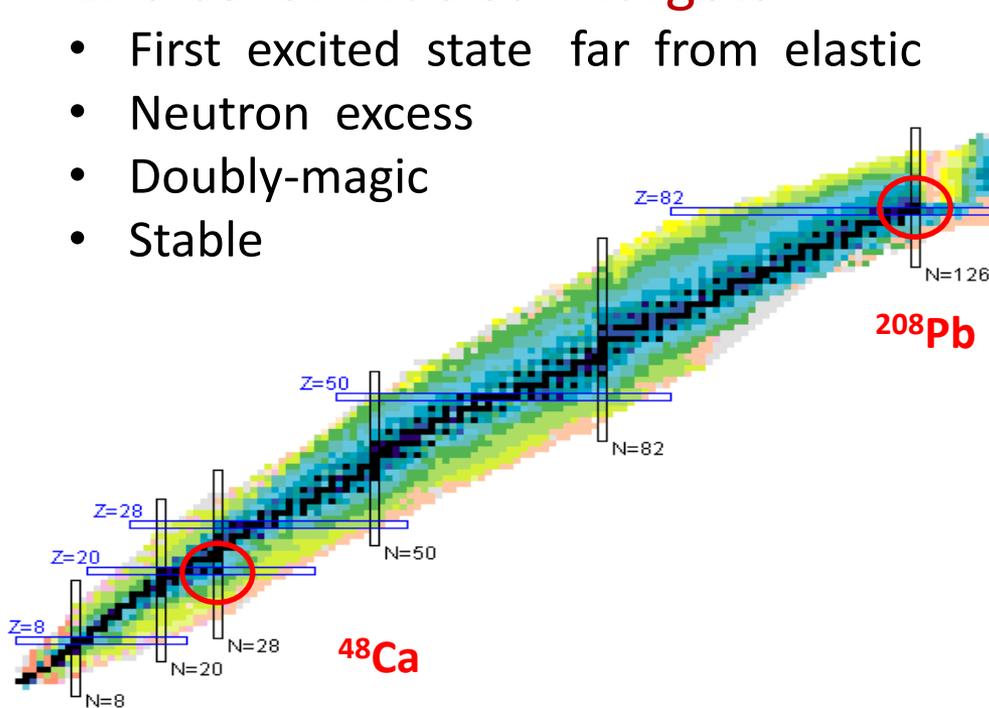
Neutron form factor

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

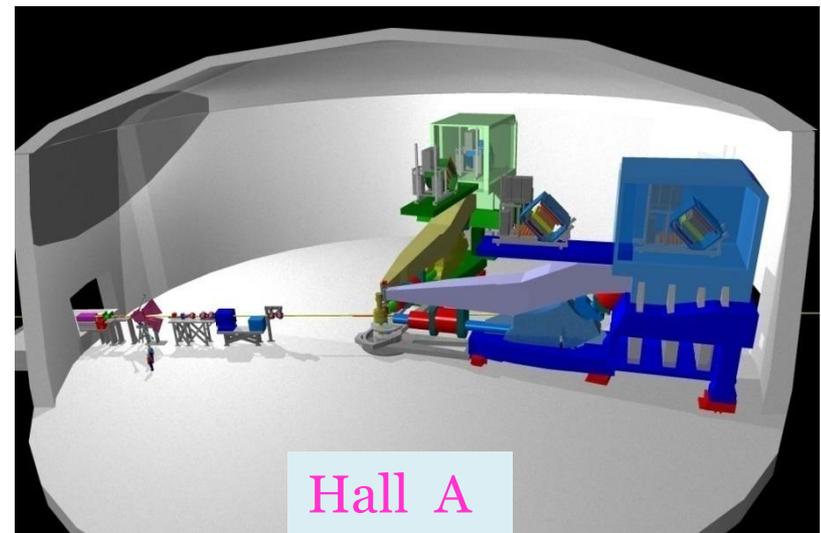


Choice of Nuclear Targets

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



High Resolution (10^{-4}) Spectrometers



Using Parity Violation

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

electromagnetic

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

^{208}Pb is spin 0

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

Proton form factor

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

Parity Violating Asymmetry

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

axial

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

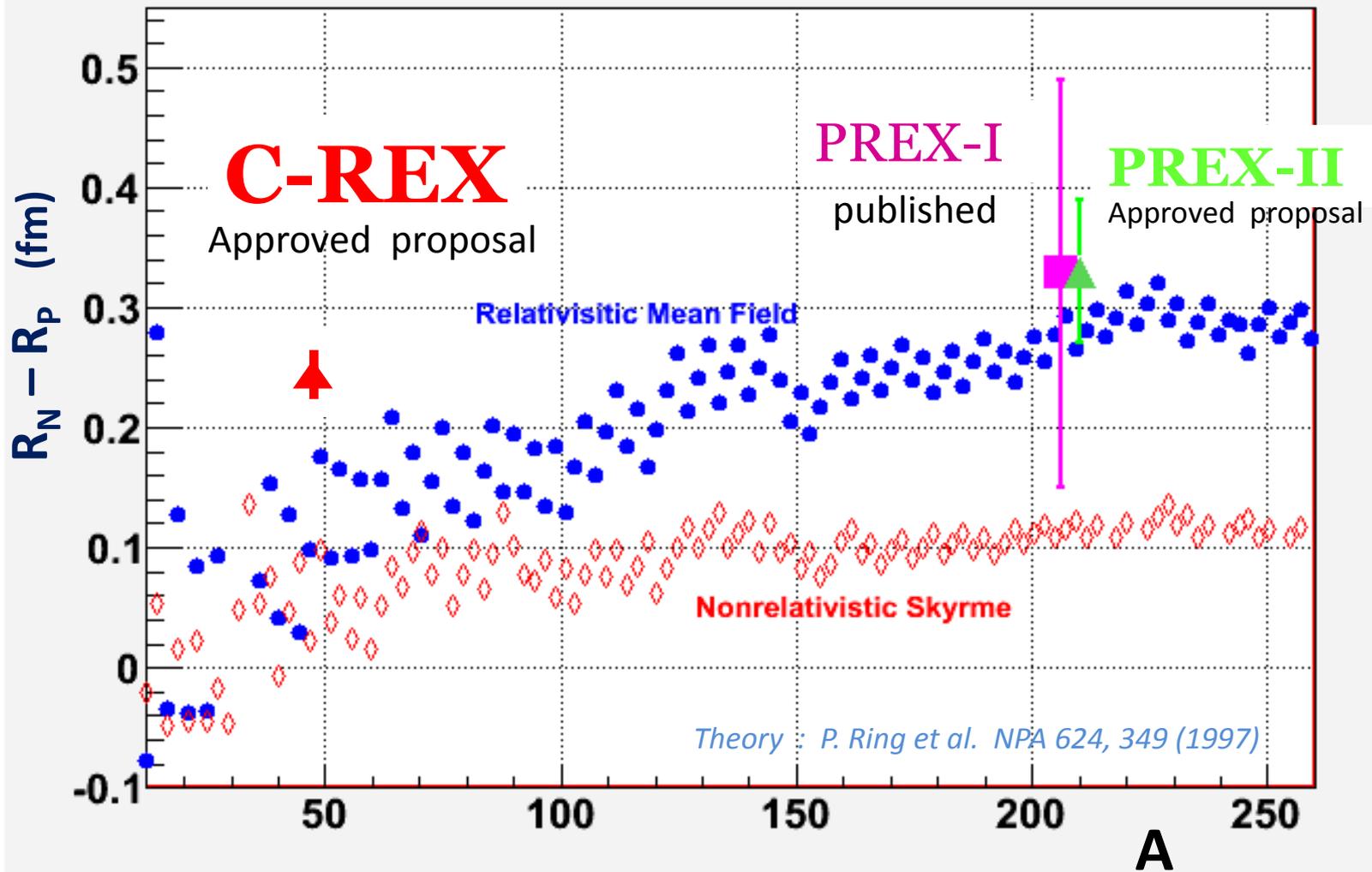
$A(r)$ is small, best observed by parity violation

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

Neutron form factor

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

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

Measured Asymmetry

Correct for Coulomb Distortions

Weak Density at one Q^2

Small Corrections for
 G_E^n G_E^S MEC
surface thickness

APPLICATIONS

C. J. Horowitz

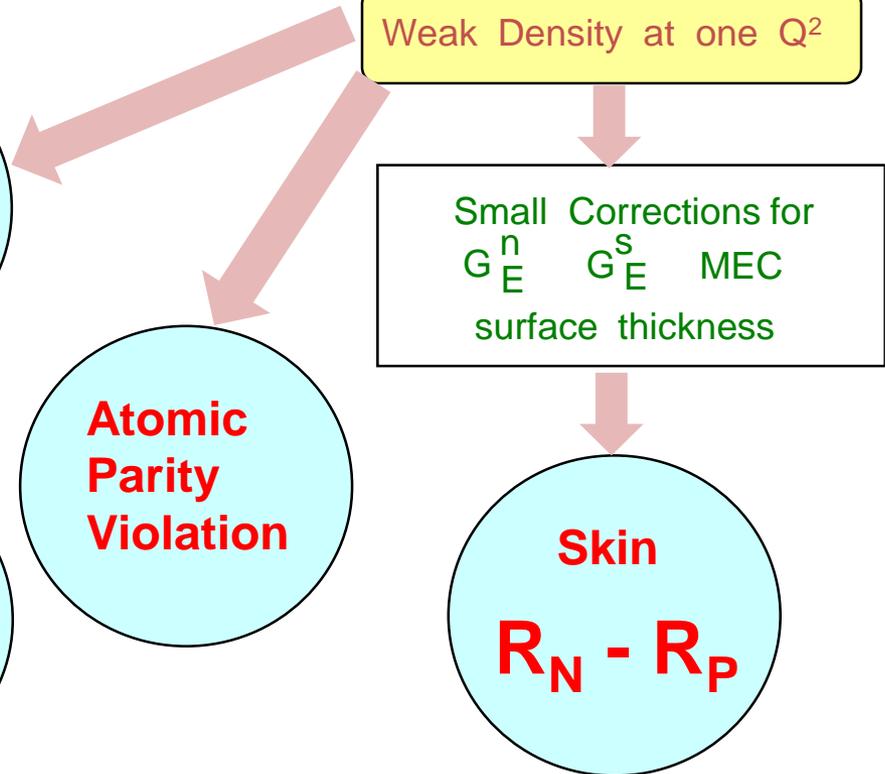
Nuclear Theory
(Symmetry Energy)

Heavy Ions

Neutron Stars

Atomic Parity Violation

Skin
 $R_N - R_P$

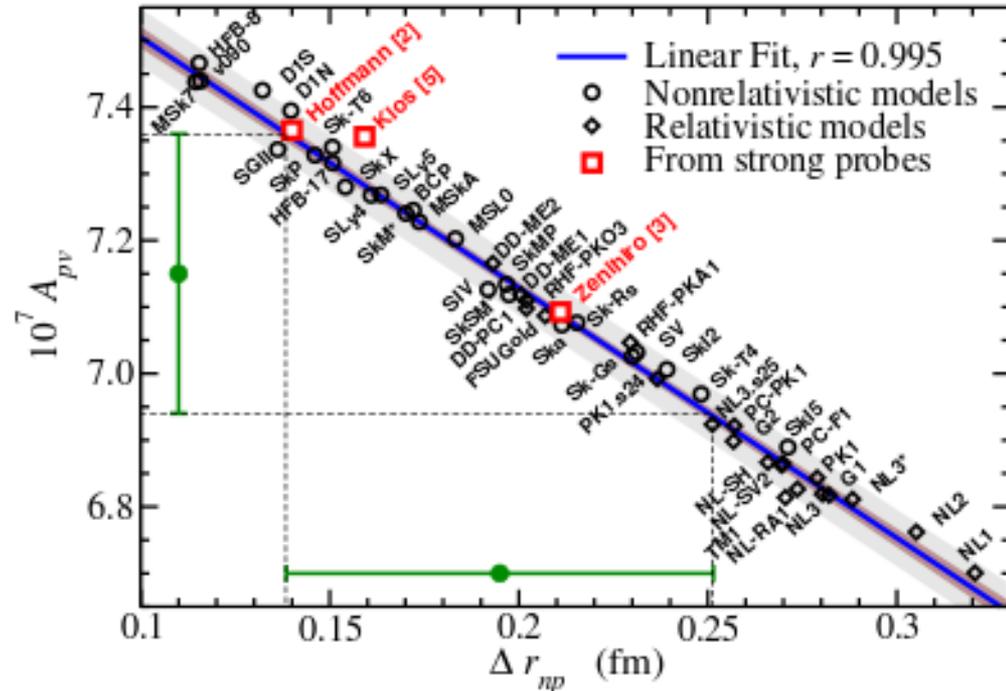


Ways to Find Neutron Distribution and Symmetry Energy

- 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

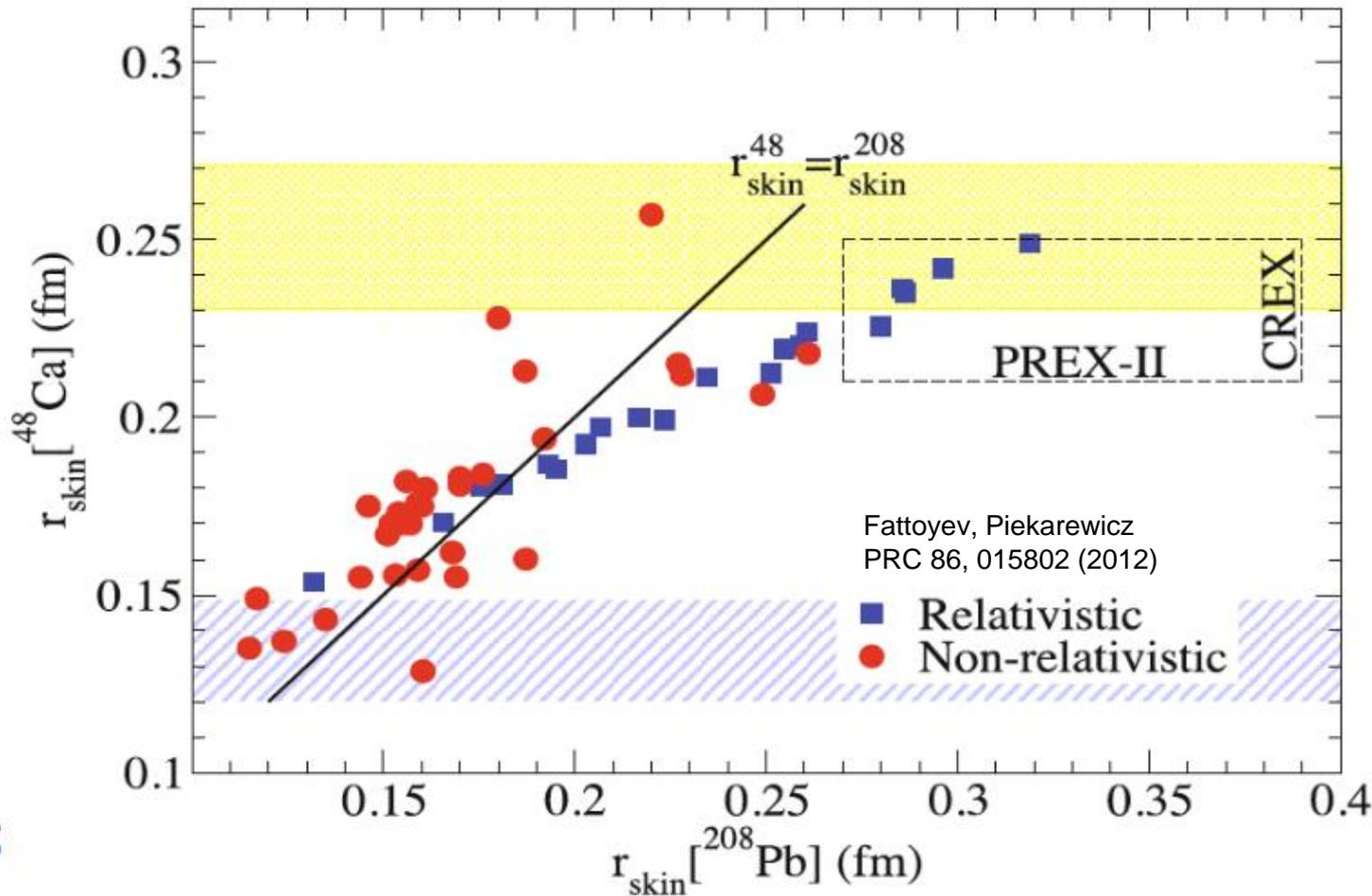
A_{PV} in PVES provides a clean probe of the neutron distribution

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

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

“Ab Initio” (exact microscopic) calculations of R_{skin} for ^{48}Ca have recently been published. G. Hagen et al., Nature Physics 12, 186 (2016).

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

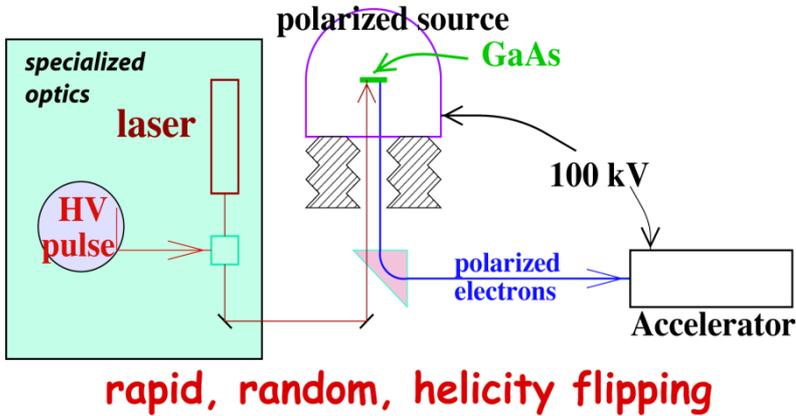


DOM
W. Dickhoff
[nucl-th] 1512.06823

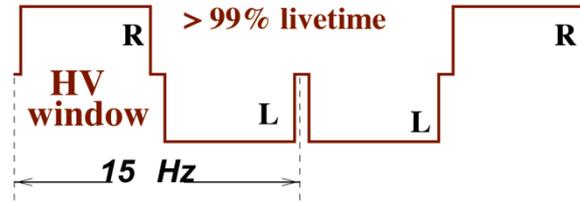
ab initio
G. Hagen, et al.
Nature 12, 186 (2015)

Parity Experiment Method

(integrating mode)



Rapid, Random Helicity Flips



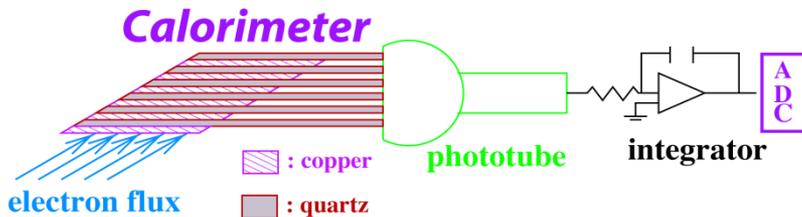
Measure flux F for each window

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

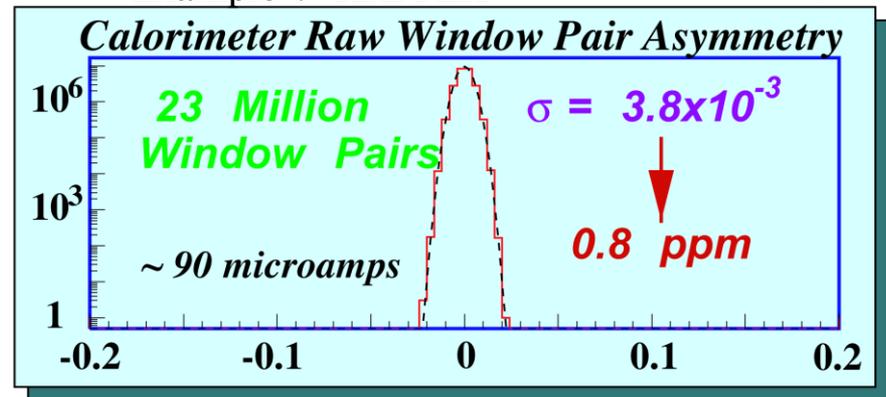
Flux Integration Technique:

C-REX : 140 MHz

PREX : 500 MHz



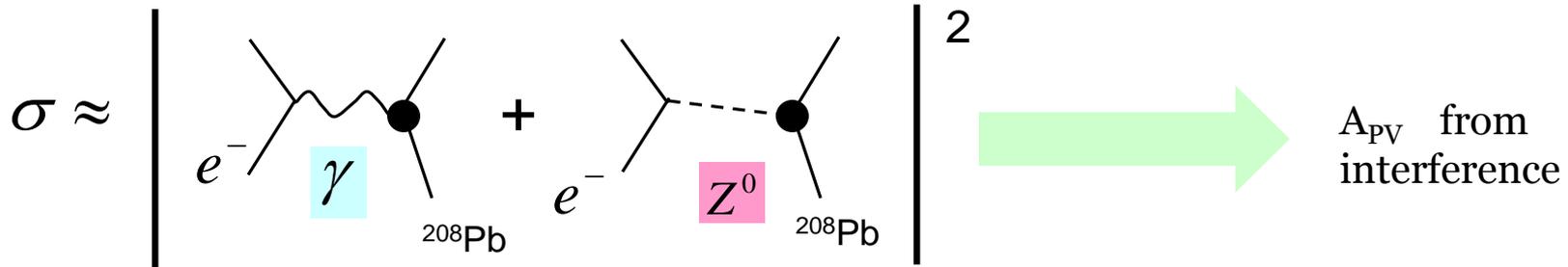
Signal Average N Windows Pairs: $A \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}$
Example : HAPPEX



No non-gaussian tails to $\pm 5\sigma$

Parity Violating Asymmetry

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

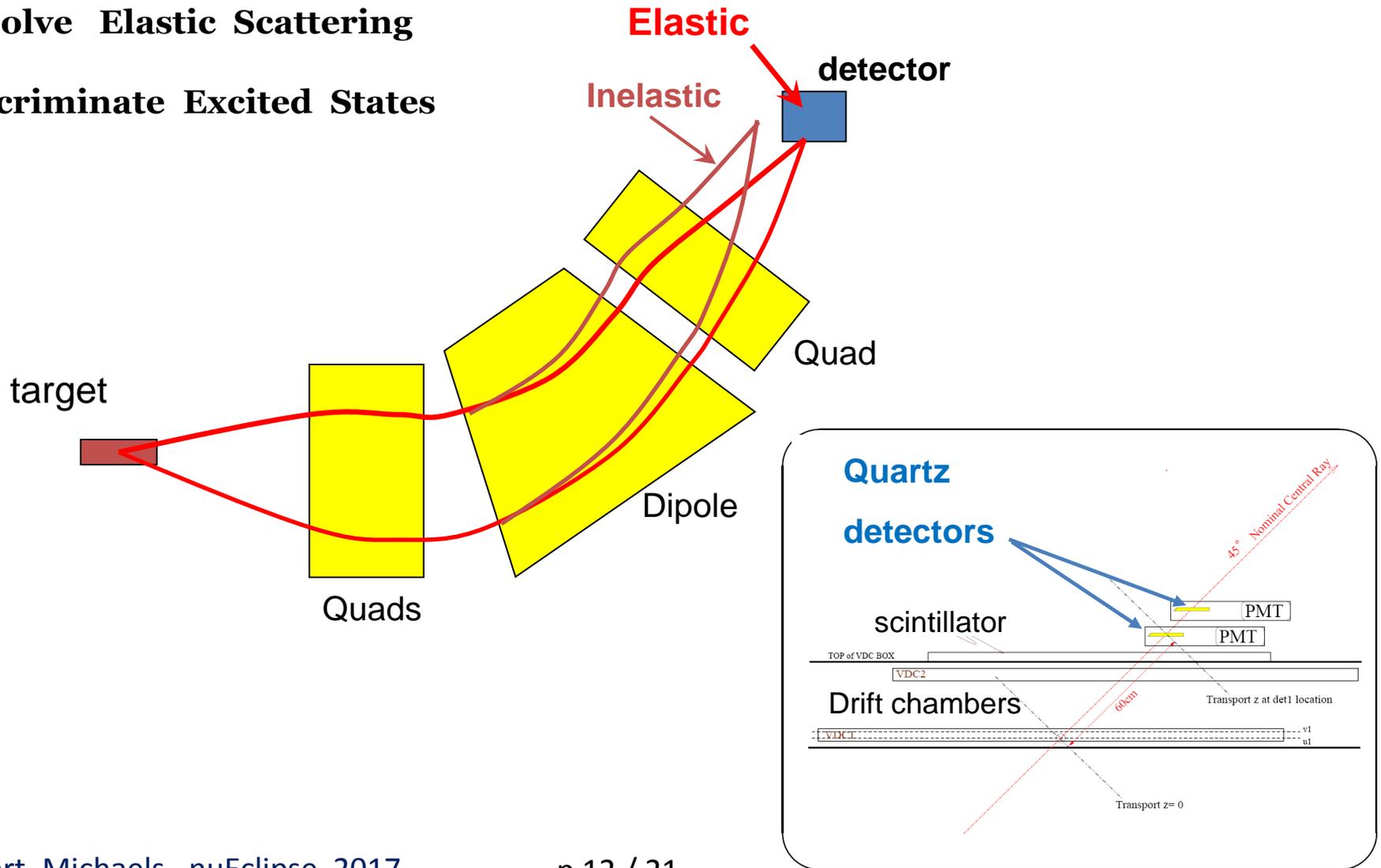


Applications of A_{PV} at Jefferson Lab

- 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**

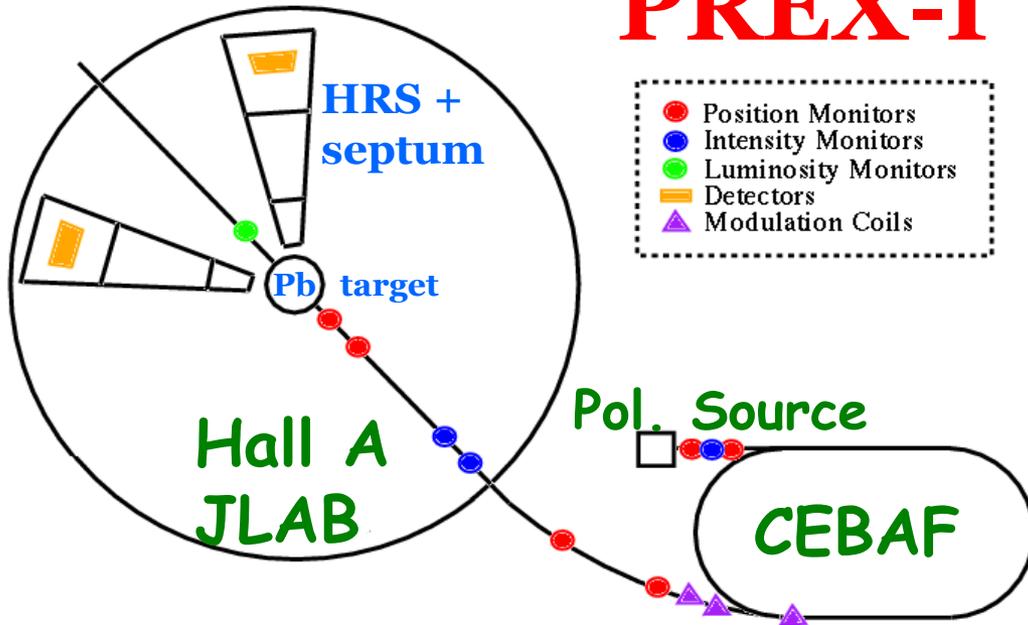
Hall A High Resolution Spectrometers

- Resolve Elastic Scattering
- Discriminate Excited States



PREX-I Results

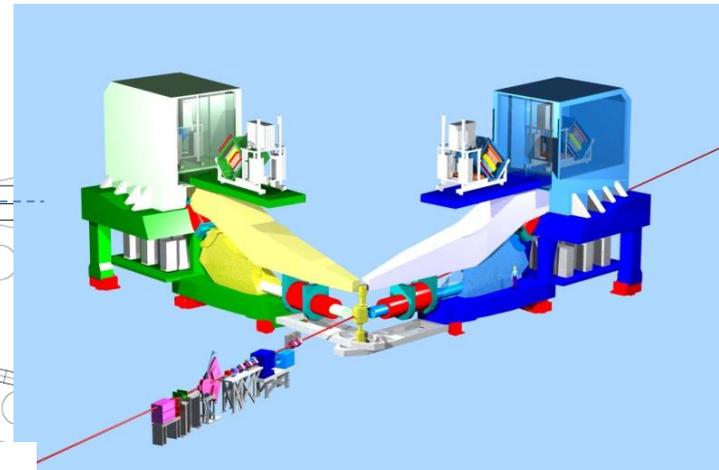
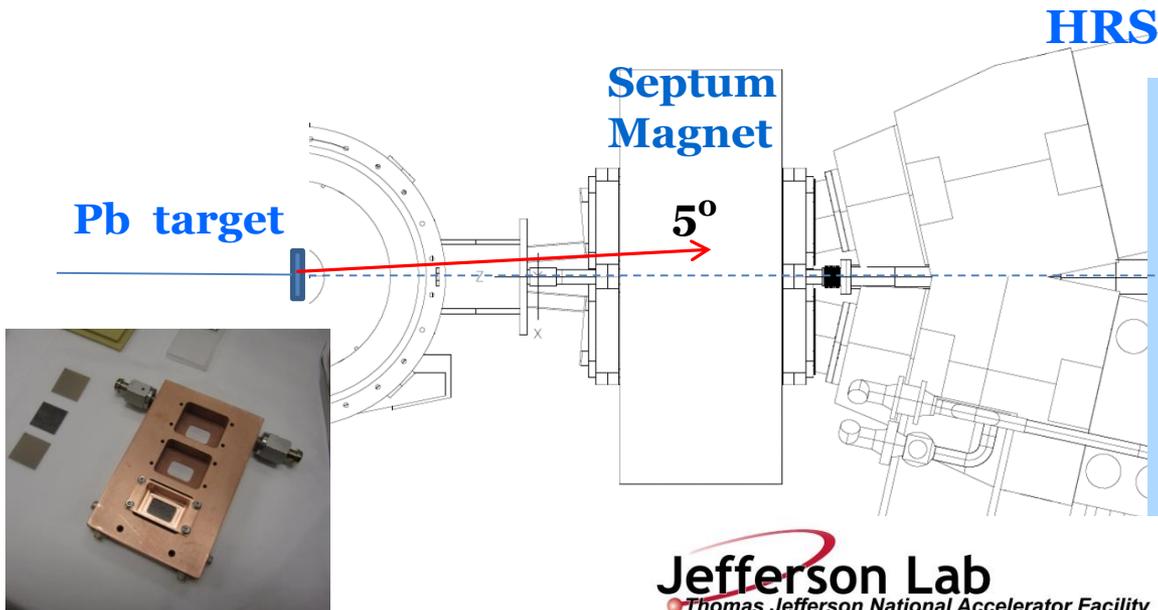
PRL 108 (2012) 112502



Physics Asymmetry

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

- **Statistics limited (9%)**
- **Systematic error goal achieved! (2%)**



Parity Quality Beam : Unique Strength of JLab

Helicity – Correlated Position Differences

$$\langle X_R - X_L \rangle \text{ for helicity } L, R$$

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

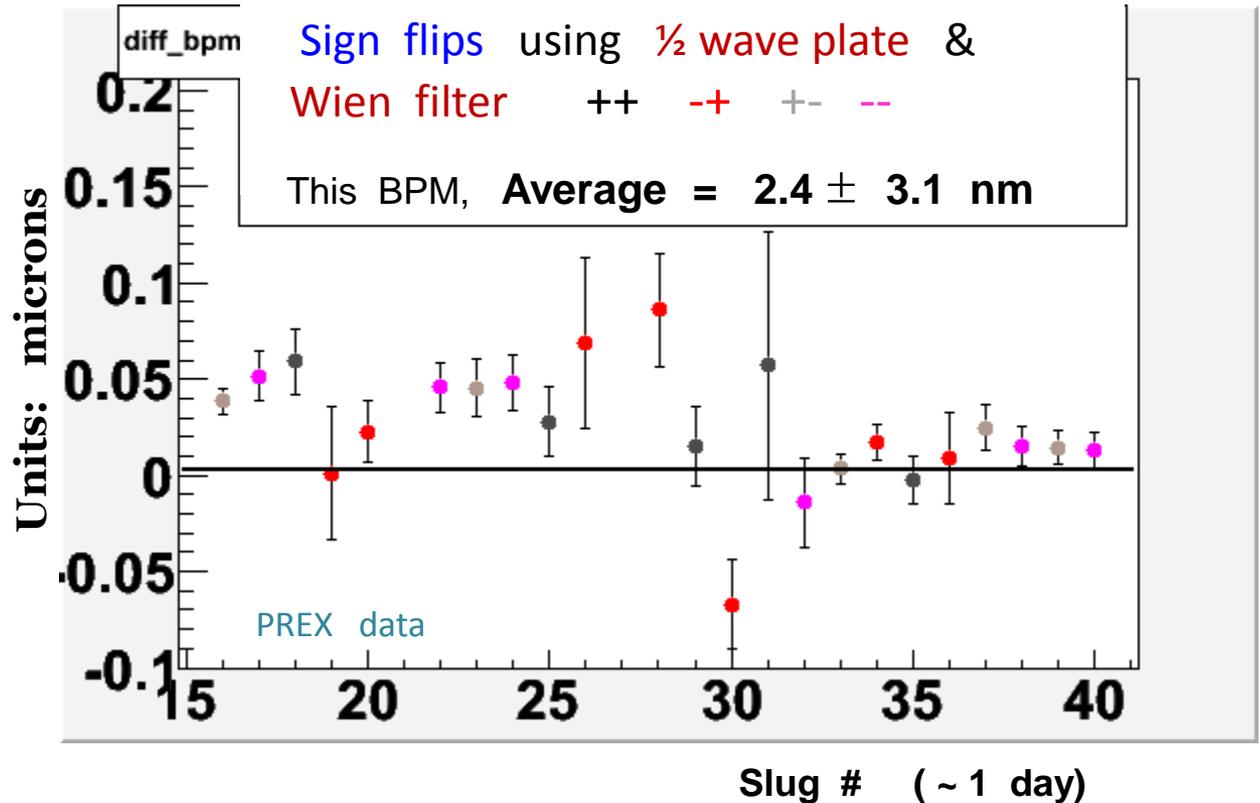
Plotted below

Measured separately

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

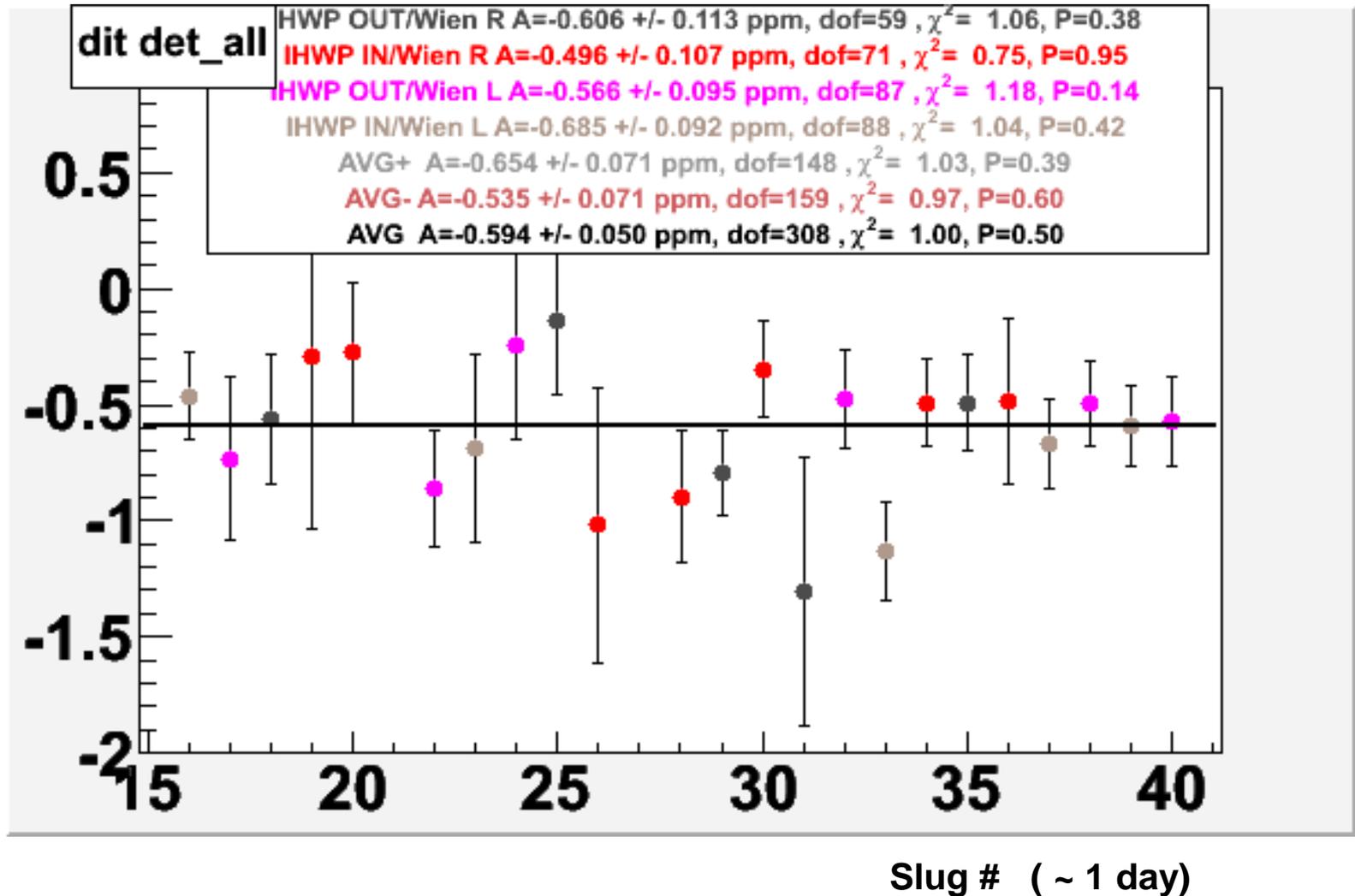
Sign flips provide
further suppression :
Average with signs =
what experiment feels

achieved
< 5 nm



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

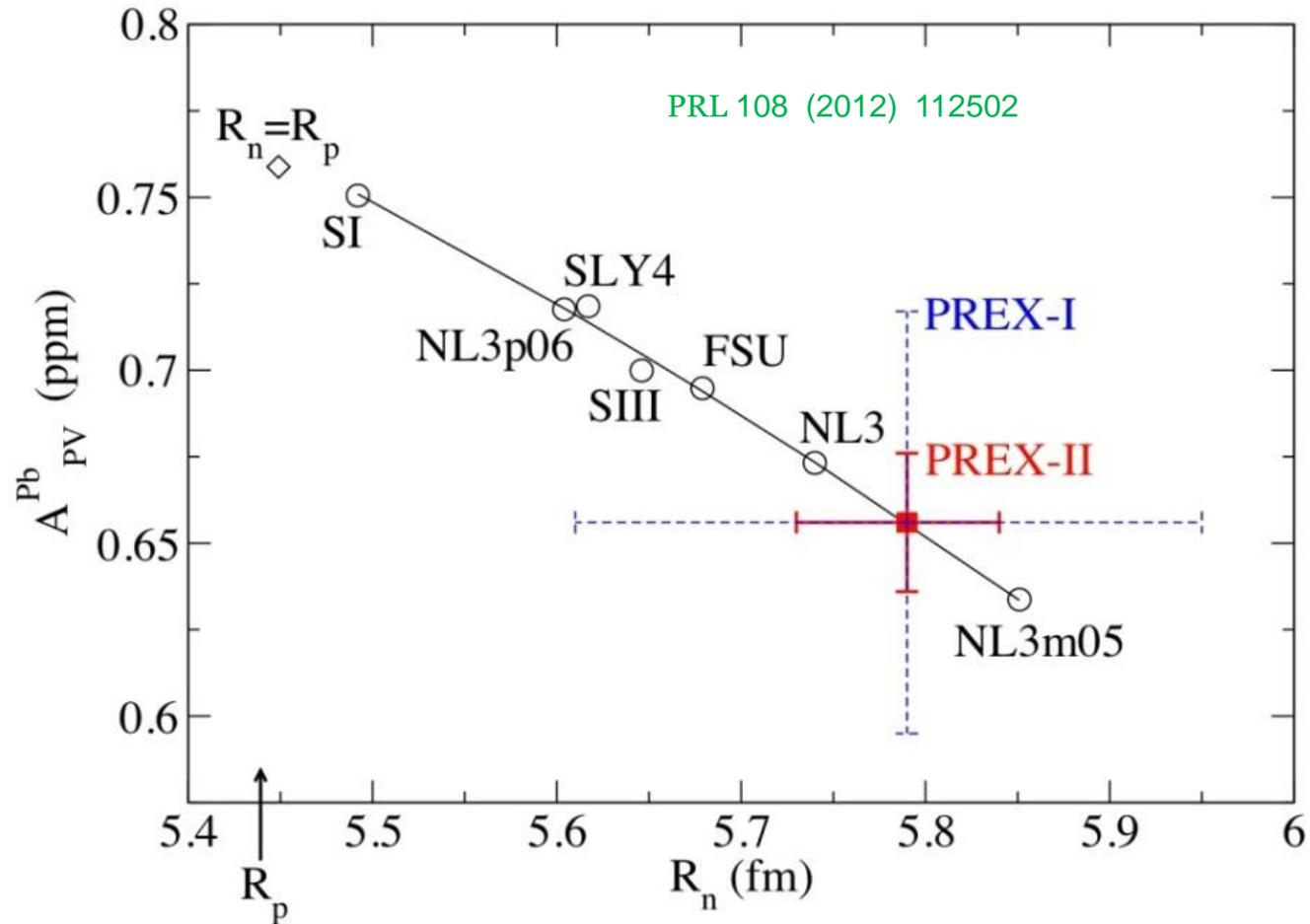
A
(ppm)



Asymmetry leads to R_N

PREX-I has established a neutron skin
at $\sim 95\%$ CL

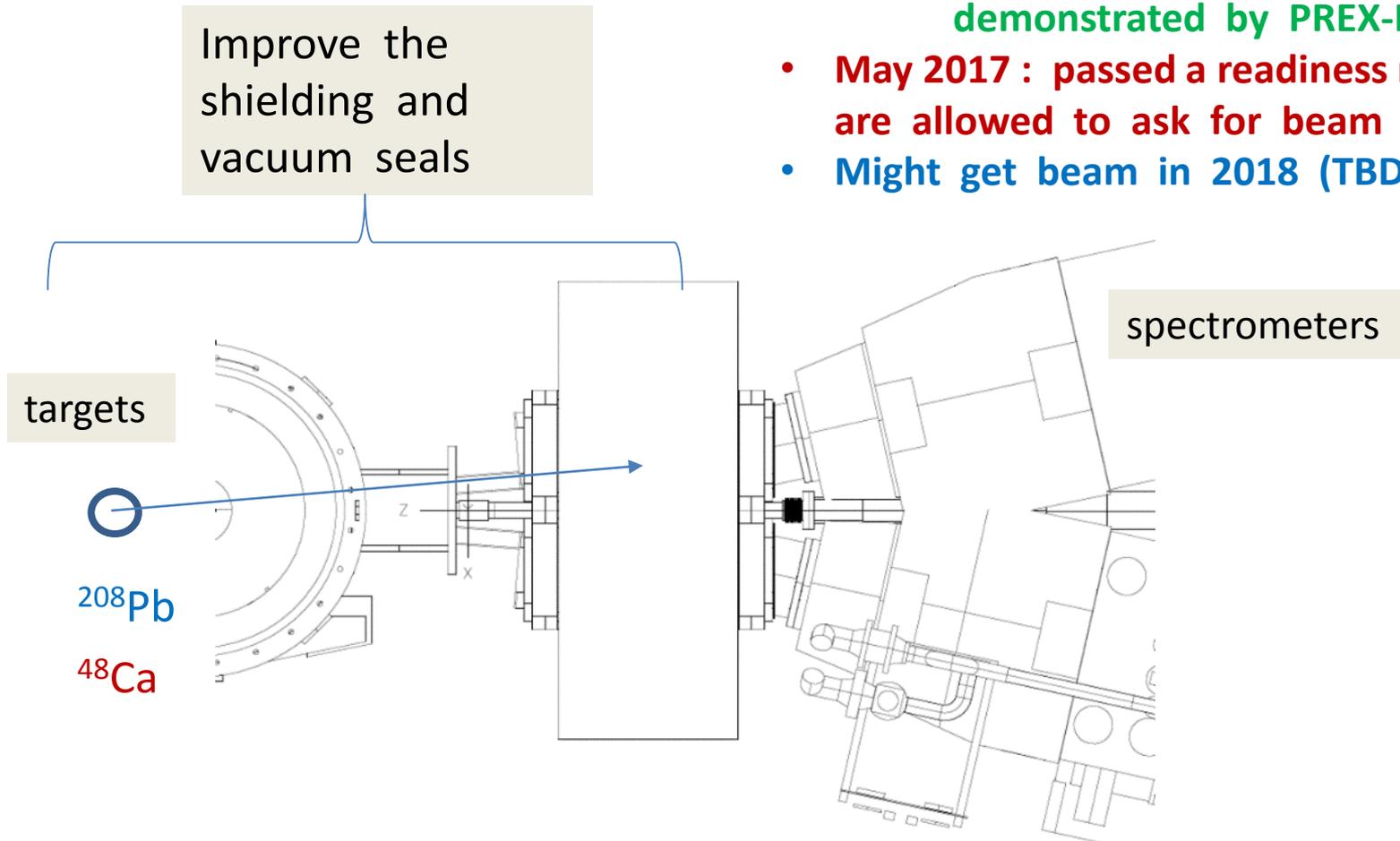
$$\text{Neutron Skin} = R_N - R_P = 0.33 + 0.16 - 0.18 \text{ fm}$$



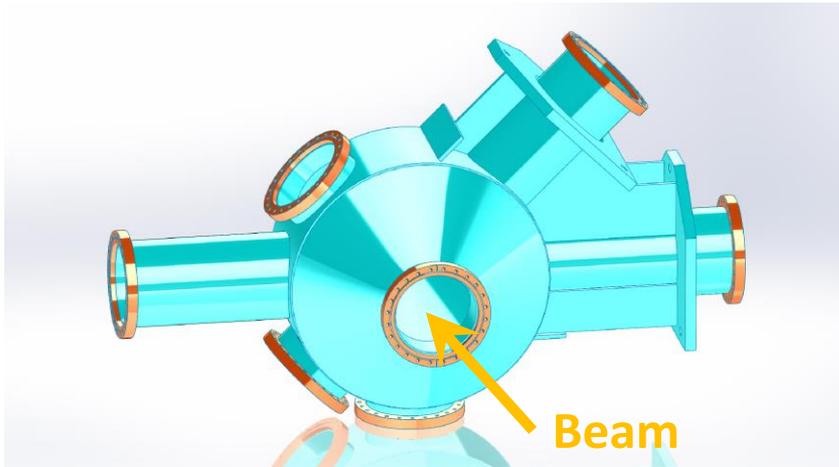
PREX-II and C-REX

Status

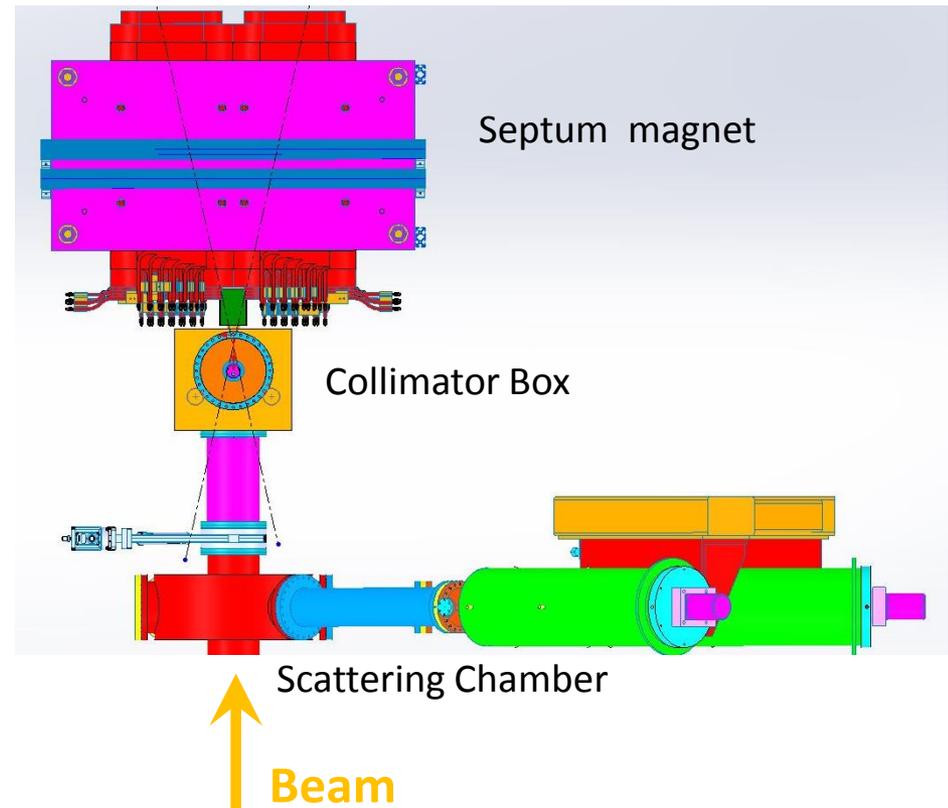
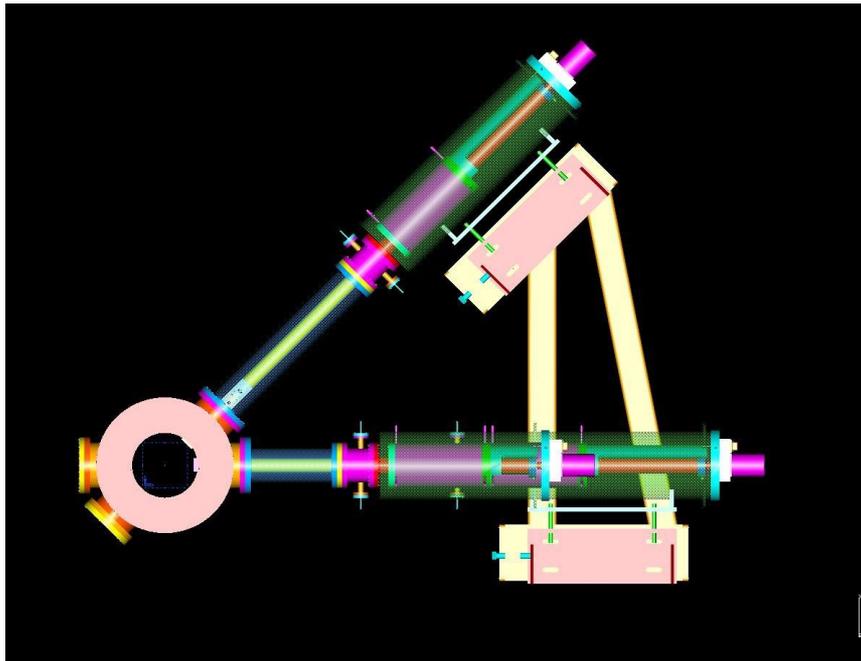
- Experiments approved
 - PREX-II A rating 35 days
 - C-REX A- rating 45 days
- Systematic Error Goals for PREX-II demonstrated by PREX-I
- May 2017 : passed a readiness review, are allowed to ask for beam time
- Might get beam in 2018 (TBD)



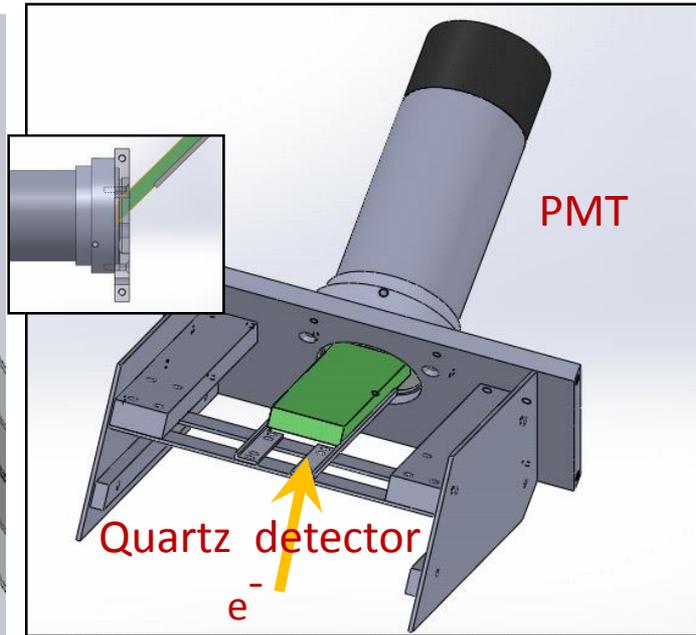
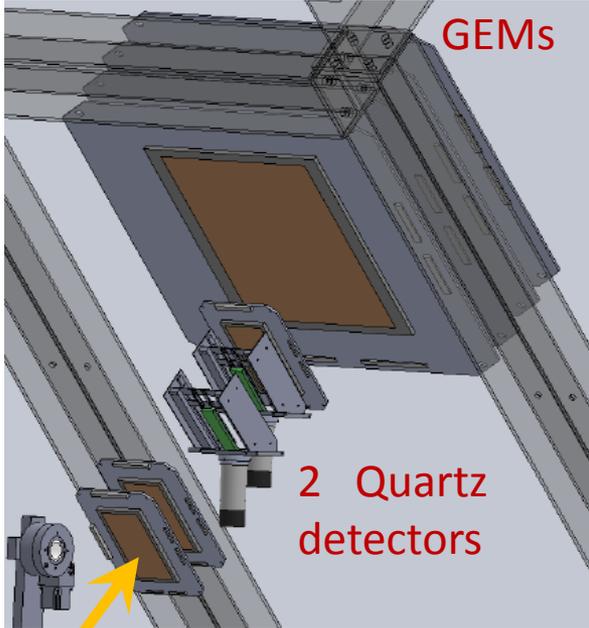
New PREX / CREX Scattering Chamber



- 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



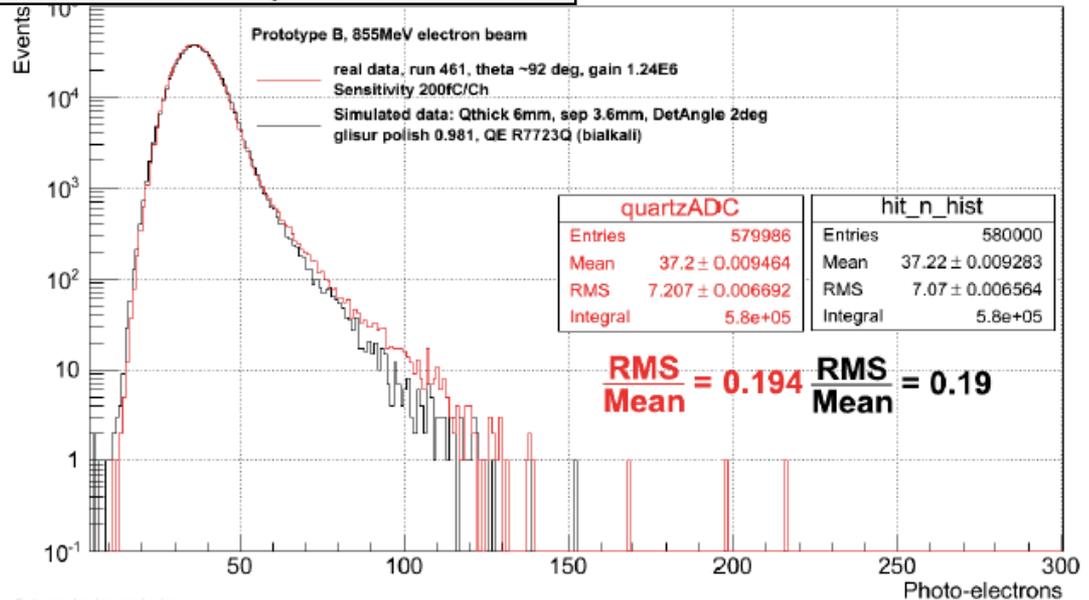
- Cherenkov radiation from electrons traversing thin quartz.
- Simulation and data benchmarked quartz properties
- Also, GEMs for high-rate tracking

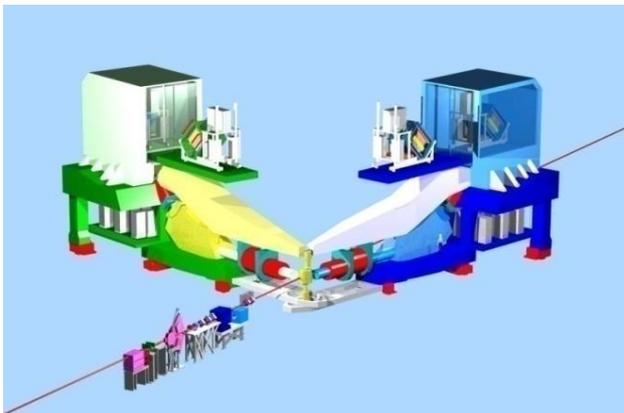
Electrons in HRS

Tested at Idaho and Stony Brook
Beam tests at Mainz

RMS/Mean ~ 19%

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

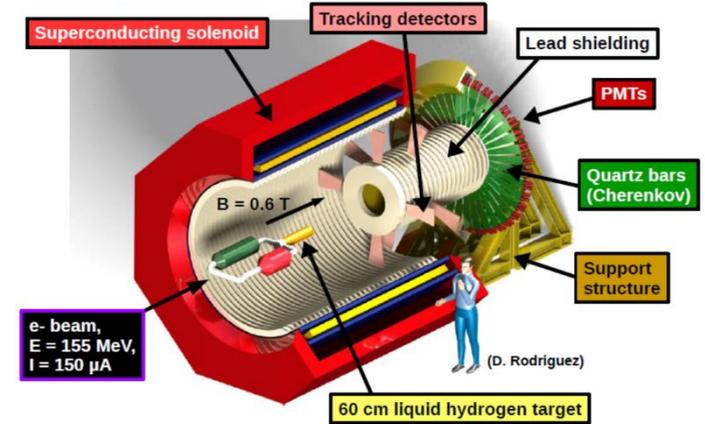




Future Weak Charge Scan ?

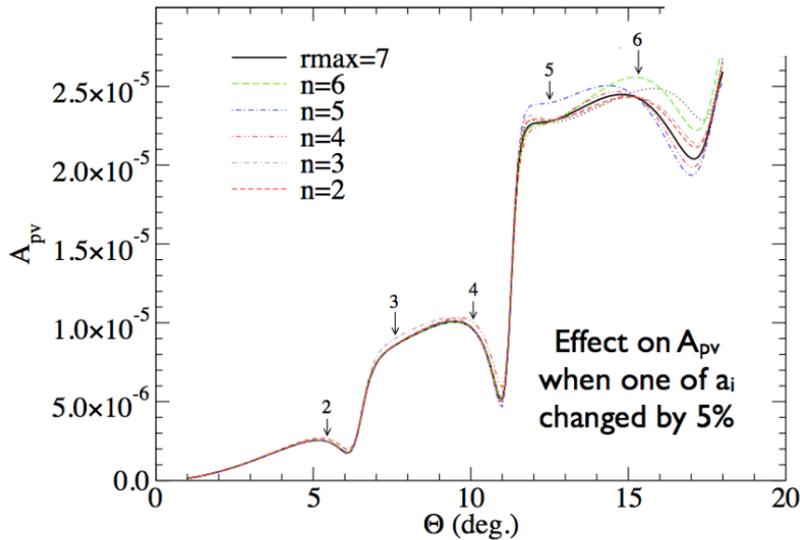
- Electron Scattering*
- lower Q^2 at Mainz
 - higher Q^2 at JLab

P2 setup



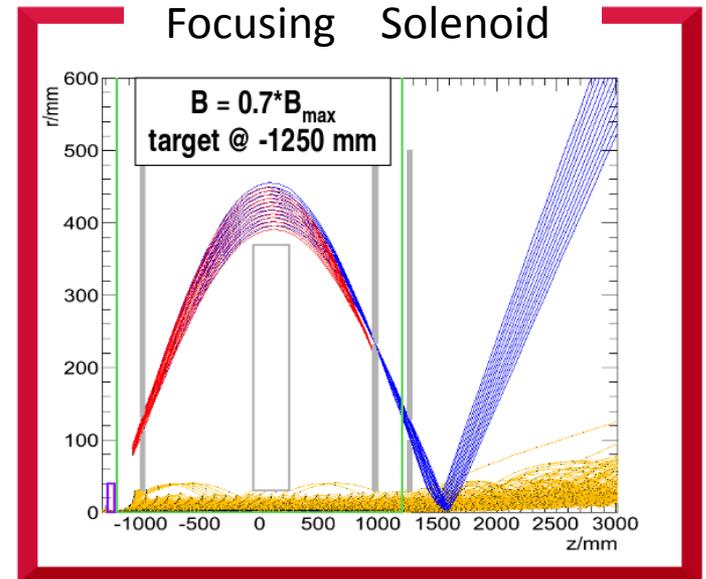
^{48}Ca at 2 GeV

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



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

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



M. Thiel, D. Becker, P. Souder

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

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
- Problems being fixed:
shielding, rad-hard vacuum seals.
- PREX-II & C-REX ready; possibly to run in 2018

Backup slides

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

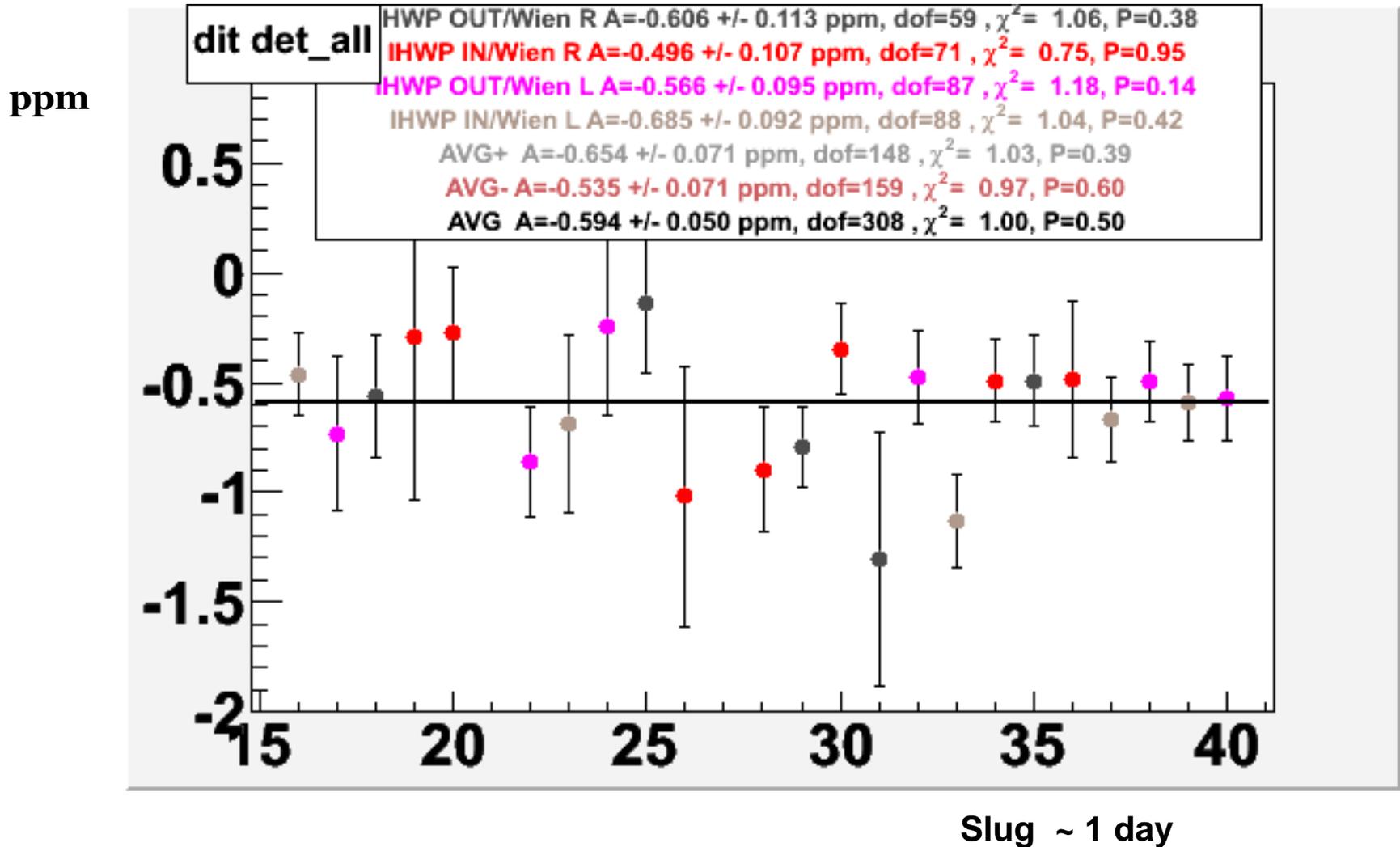
Charge Normalization	0.1%
Beam Asymmetries*	1.1%
Detector Non-linearity*	1.0%
Transverse Asym	0.2%
Polarization*	1.1%
Target Backing	0.4%
Inelastic Contribution	<0.1%
Effective Q ²	0.4%
Total Systematic	2%
Total Statistical	3%

*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%

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



Connecting low to medium to high density neutrons

Low density : nuclei

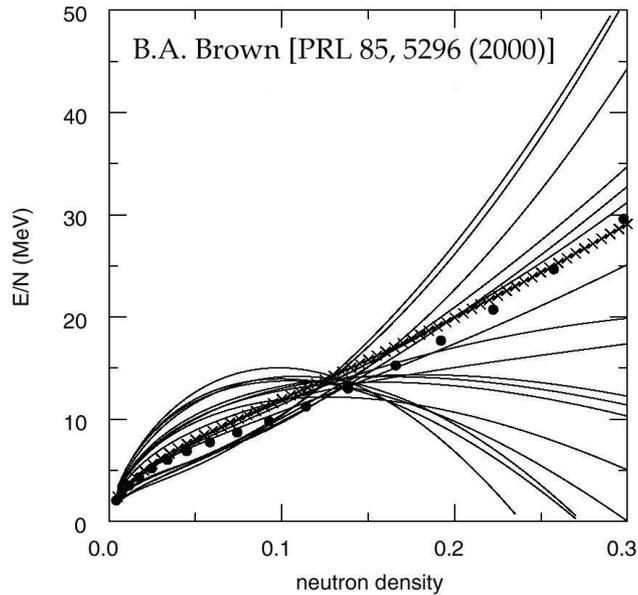
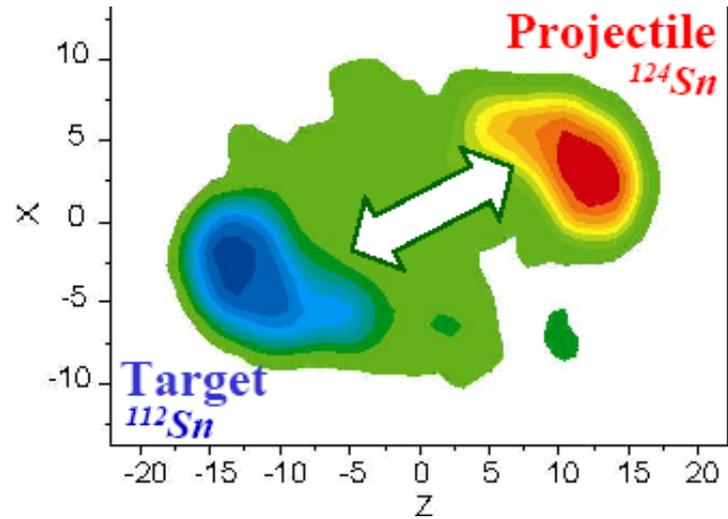


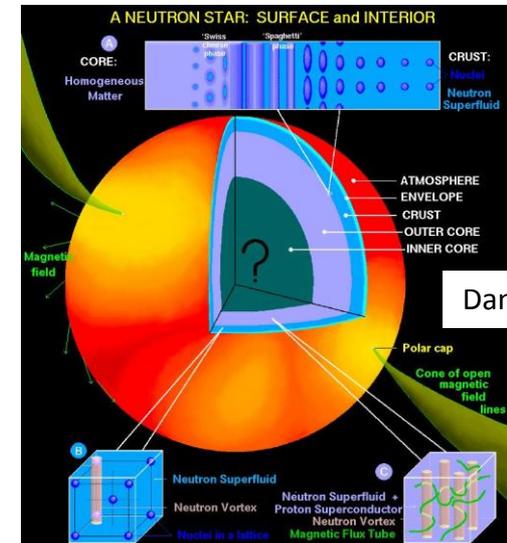
FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of $\text{neutron}/\text{fm}^3$.

Medium density :
Heavy Ion Collisions



Danielewicz, Lacey, and Lynch,
Science 298 (2002) 1592.

Highest density :
Neutron Stars



relationship to Neutron Stars



Crab Pulsar

Input :

- Eq. of state (EOS)

$$P(\rho)$$

pressure
density

PREX / CREX helps here

- Deduce Mass-Radius relationship, and other properties

Neutron skin is highly correlated with several **neutron star** properties

J. Piekarewicz, Rev. Nuc. Phys 10 (2016) 625

