山东大学
SHANDONG UNIVERSITY

PREX-II
JEFFERSON LAB, USA
SCIENCE FINDS A WAY

Probing neutron skin thickness with parity-violating electron scattering

PREX *CREX*

Jinlong Zhang (张金龙)

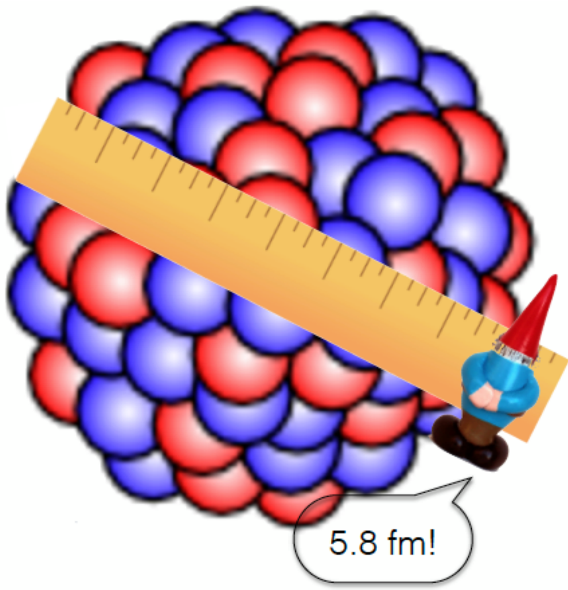
August 4, 2023

原子核结构与相对论重离子对撞前沿交叉研讨会 大连 2023-08

What's the size of nucleus?

- Proton distribution:
  - Owing to the electric charge, this has been accurately measured for many atomic nuclei
- Neutron distribution: poorly known
  - Primarily from hadron experiments (pN, HIC, Rare Isotope, electric dipole polarizability, etc), model dependent
  - Parity-violating electron scattering: via the weak charge

Charge type	Proton	Neutron
Electric	1	0
Weak	~0.07	-1



Weak interaction sees mostly neutrons !

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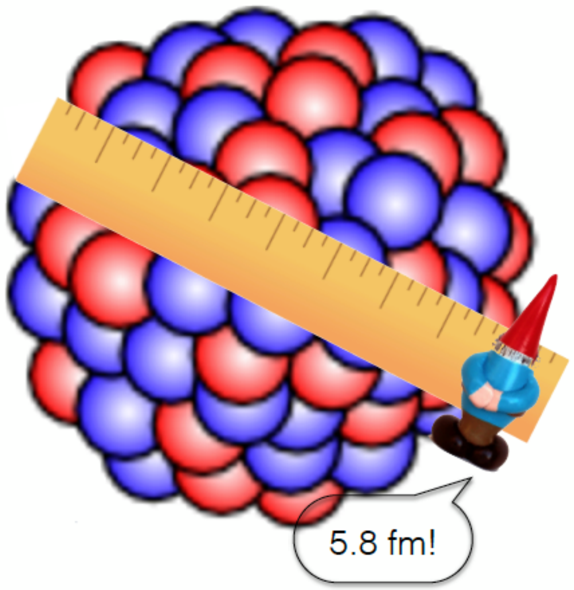
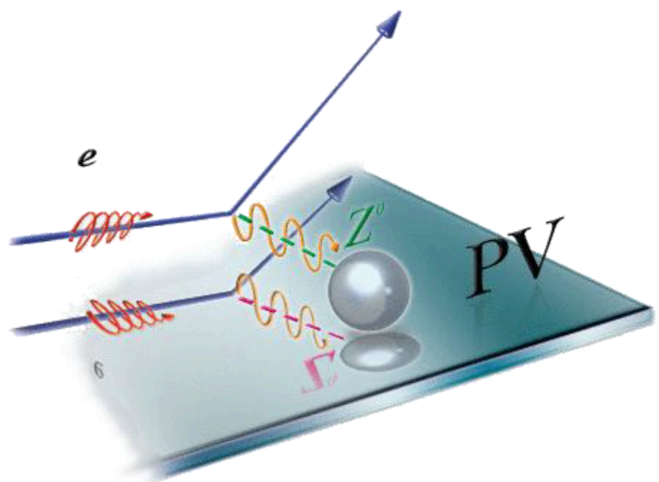
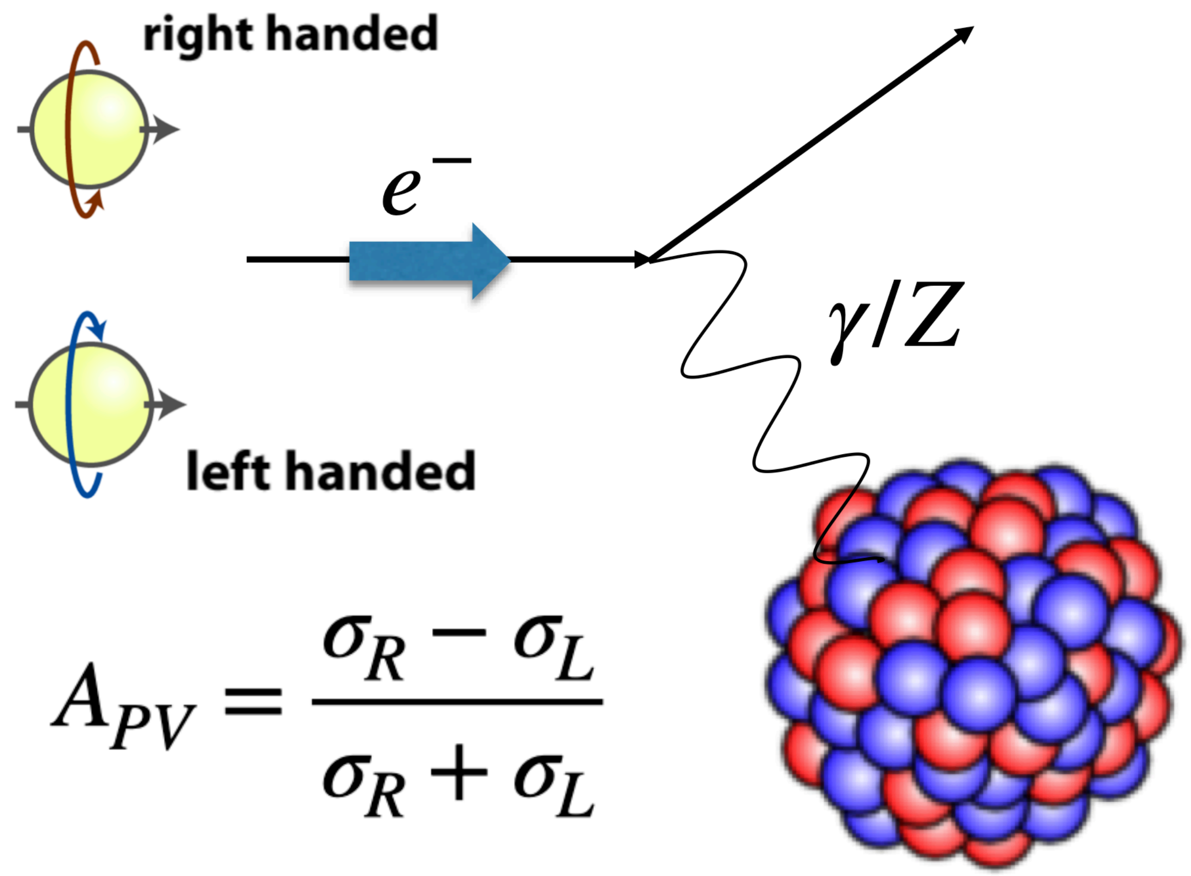


Weak interaction sees mostly neutrons !

Parity Violating Electron Scattering

Flip spin of electrons and look for difference in scattering rate





$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

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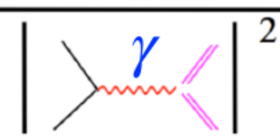
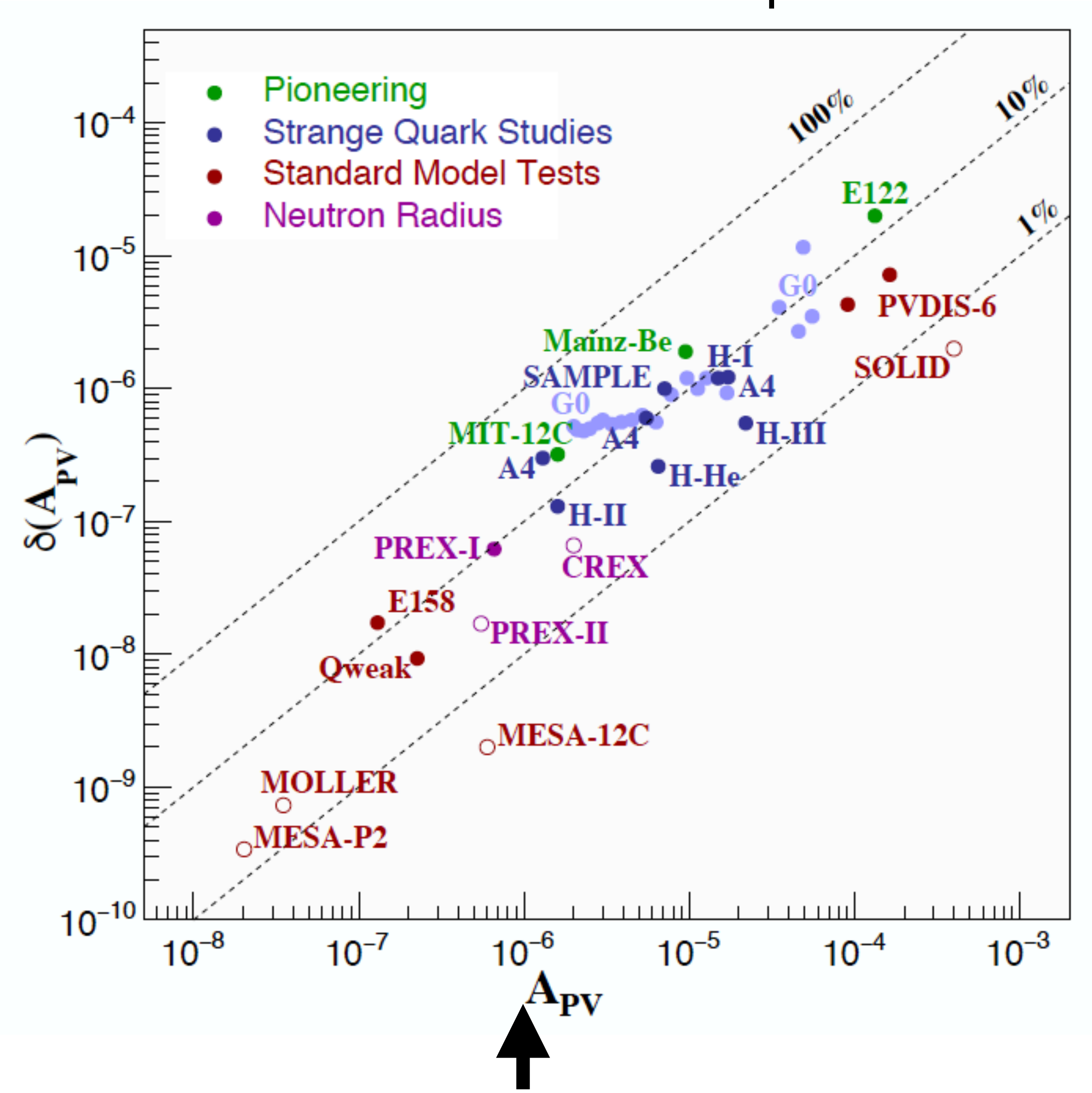


$$\propto \frac{|M_Z|}{|M_\gamma|} \approx \frac{G_F Q^2 Q_W}{4\pi\alpha\sqrt{2}Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)} \sim 10^{-4} \times Q^2$$

Clean and theoretically easy interpretation, but very challenging!

Parity Violating Electron Scattering

PVES Landscape



1,000,000 vs. 1,000,001 ppm (part per million)

- PVES has a long history of pushing the limits of precision and discovery
  - E122: (ΔA=10 ppm) 1978
    - pioneering experiment (already had most of the features of modern PVES experiments)
  - Strange form factor
    - G0, HAPPEX
  - Standard Model Tests
    - E158, PVDIS, Qweak
  - **Nuclear structure / neutron skin**
    - **PREX, PREX-II, CREX**
  - Future:
    - MOLLER, P2, SoLID

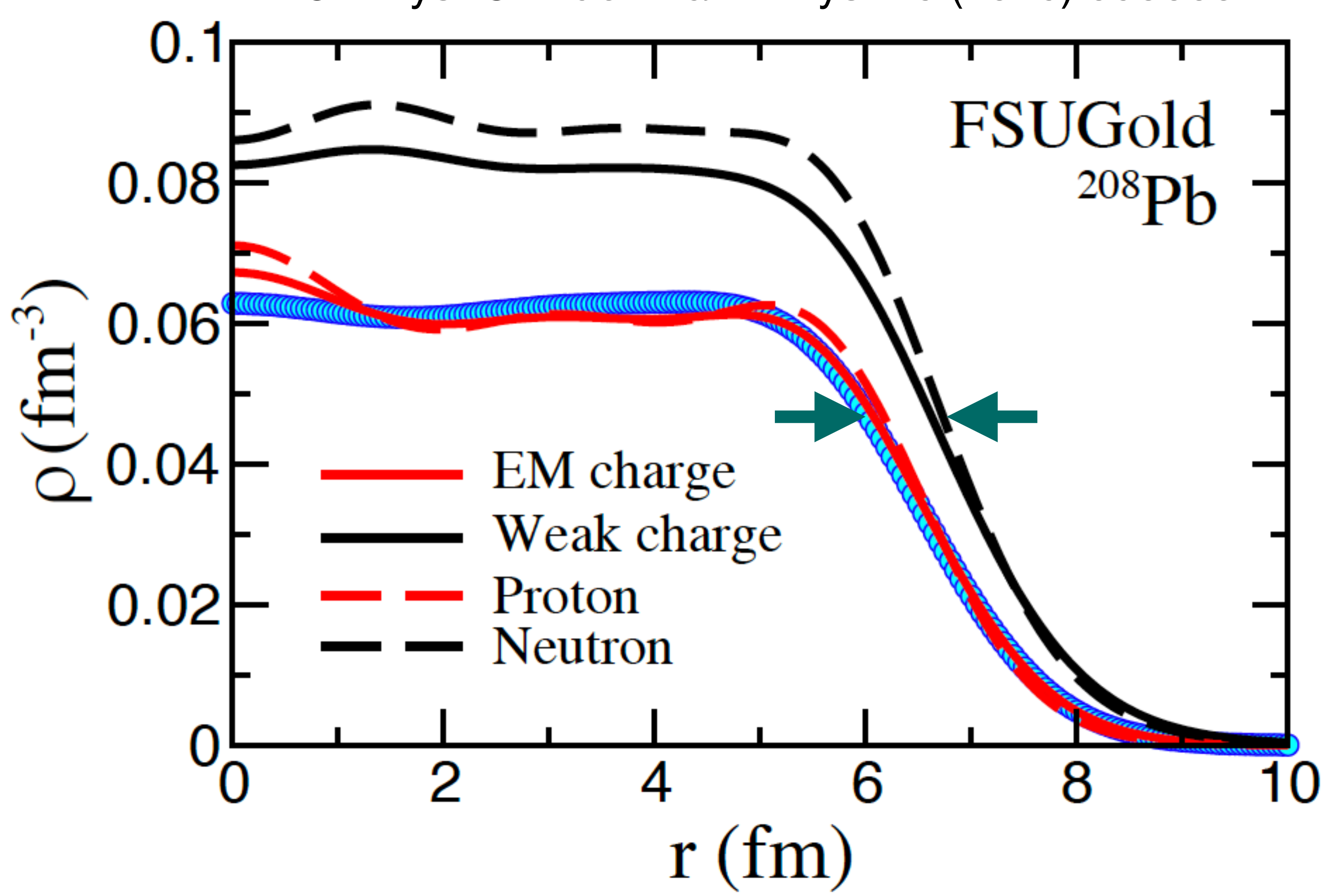
High statistics and excellent systematics control

Neutron Skin

Difference between **root-mean-squared** radii of neutron and proton.

$$\Delta r_{np} = R_n - R_p = \sqrt{< r_n^2 >} - \sqrt{< r_p^2 >}$$

J. Phys. G: Nucl. Part. Phys. 46 (2019) 093003



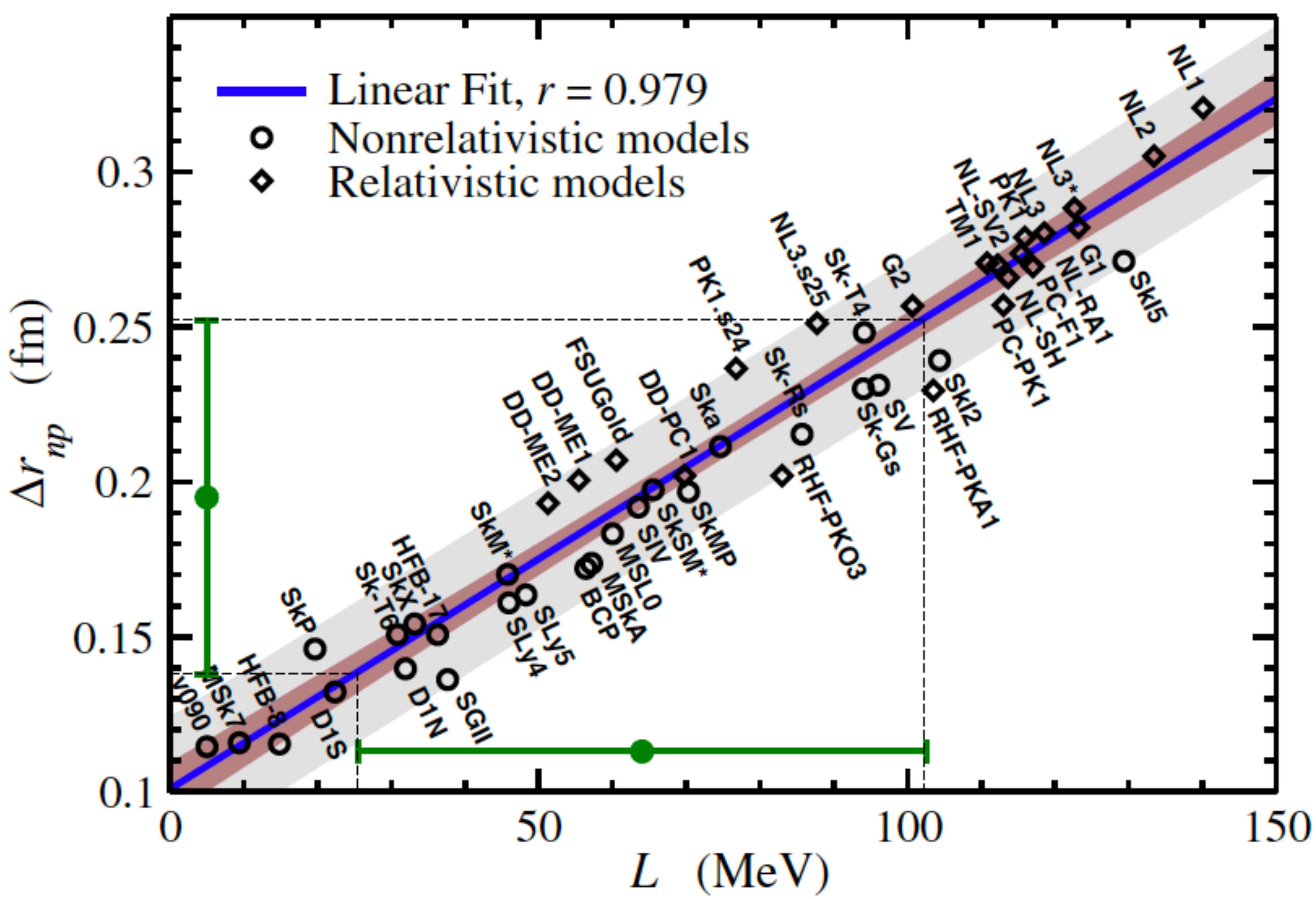
- For N=Z: the neutron and proton density distributions are expected to have a similar shape
- For N>>Z, the excess neutrons are pushed out to the periphery forming a **neutron skin**

See Liewen Chen's talk

Neutron Skin and Symmetry Energy

The extent of the neutron skin in a neutron rich nucleus is the result of balance between the surface tension and the slope of the symmetry energy.

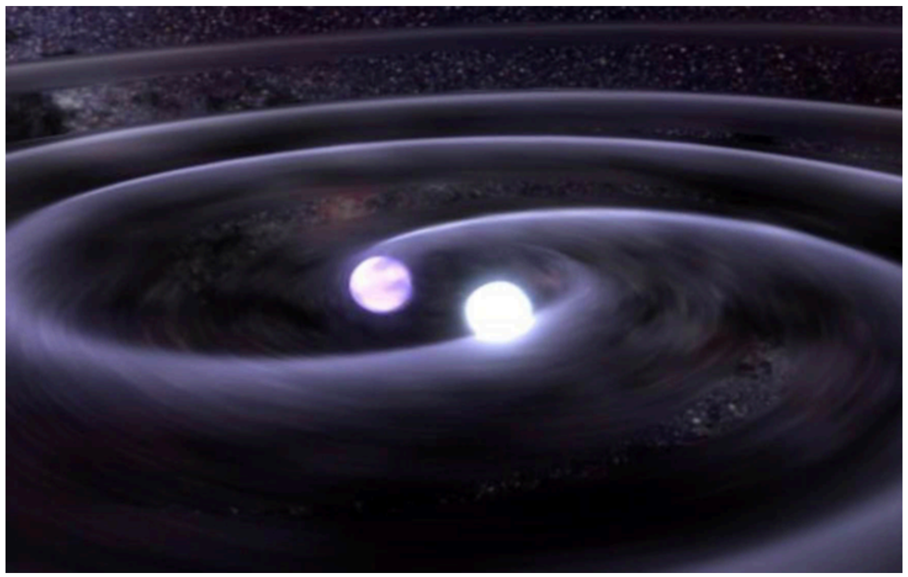
X. Roca-Maza (et al.) PRL 106 (2011) 252501



Δr_{np} calibrates the Equation of State of neutron rich matter, determining L constrains and guides models needed for heavy nuclei

Constraints deduced from Binary Neutron Stars

Binary Neutron Stars Merger



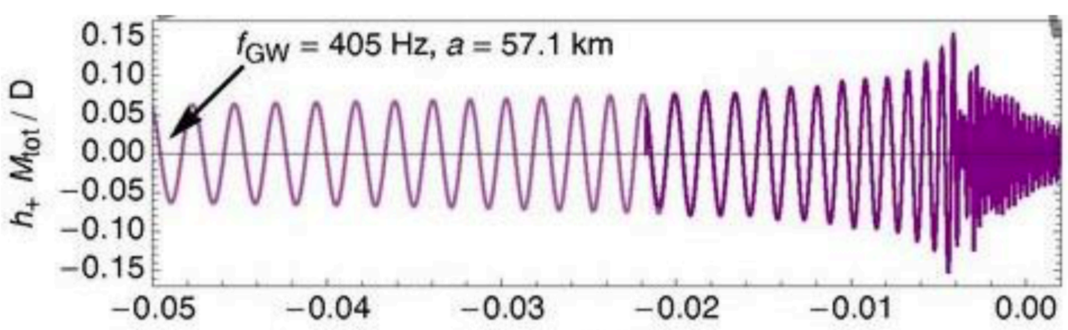


Image Credit: Jocelyn Read

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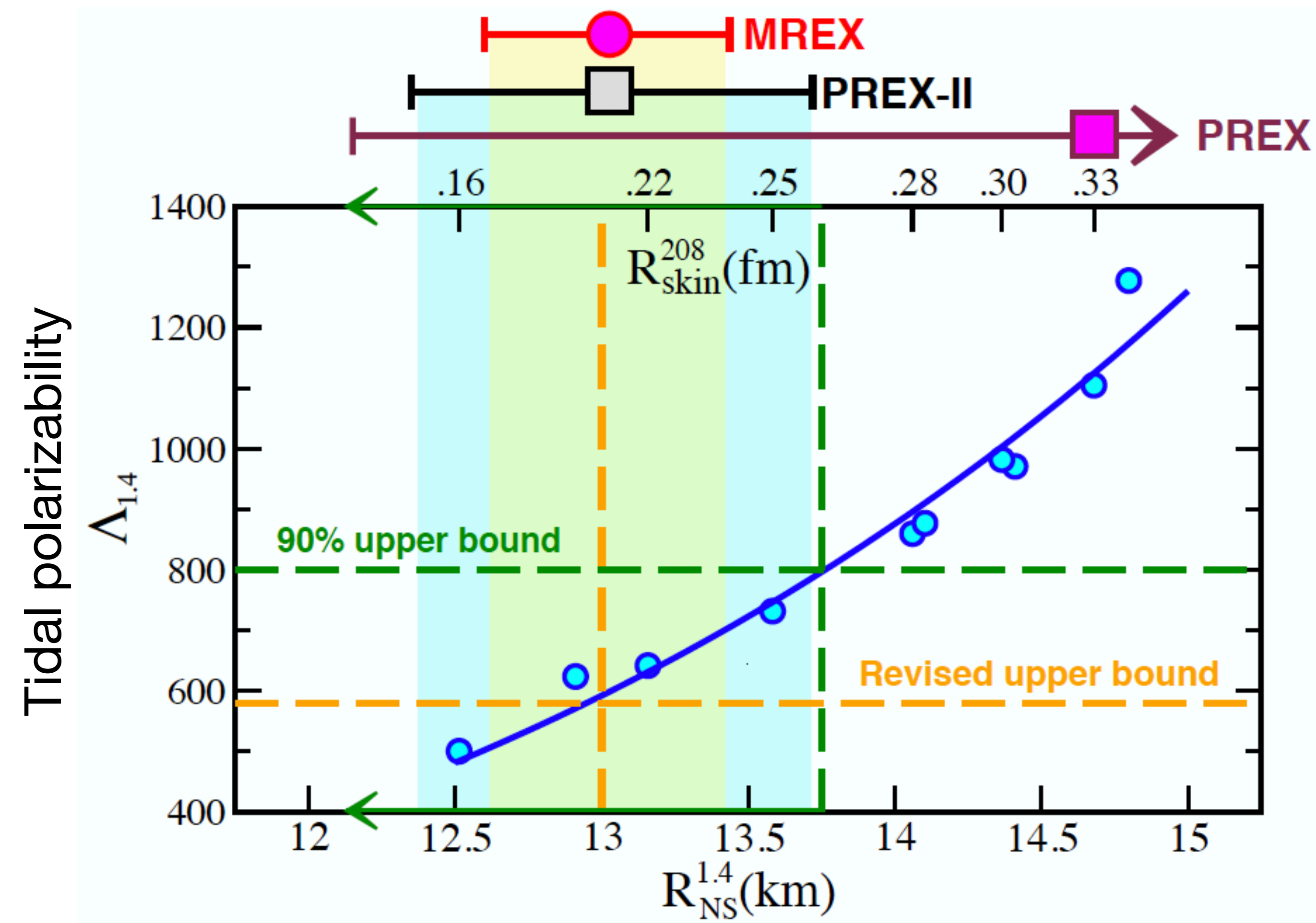


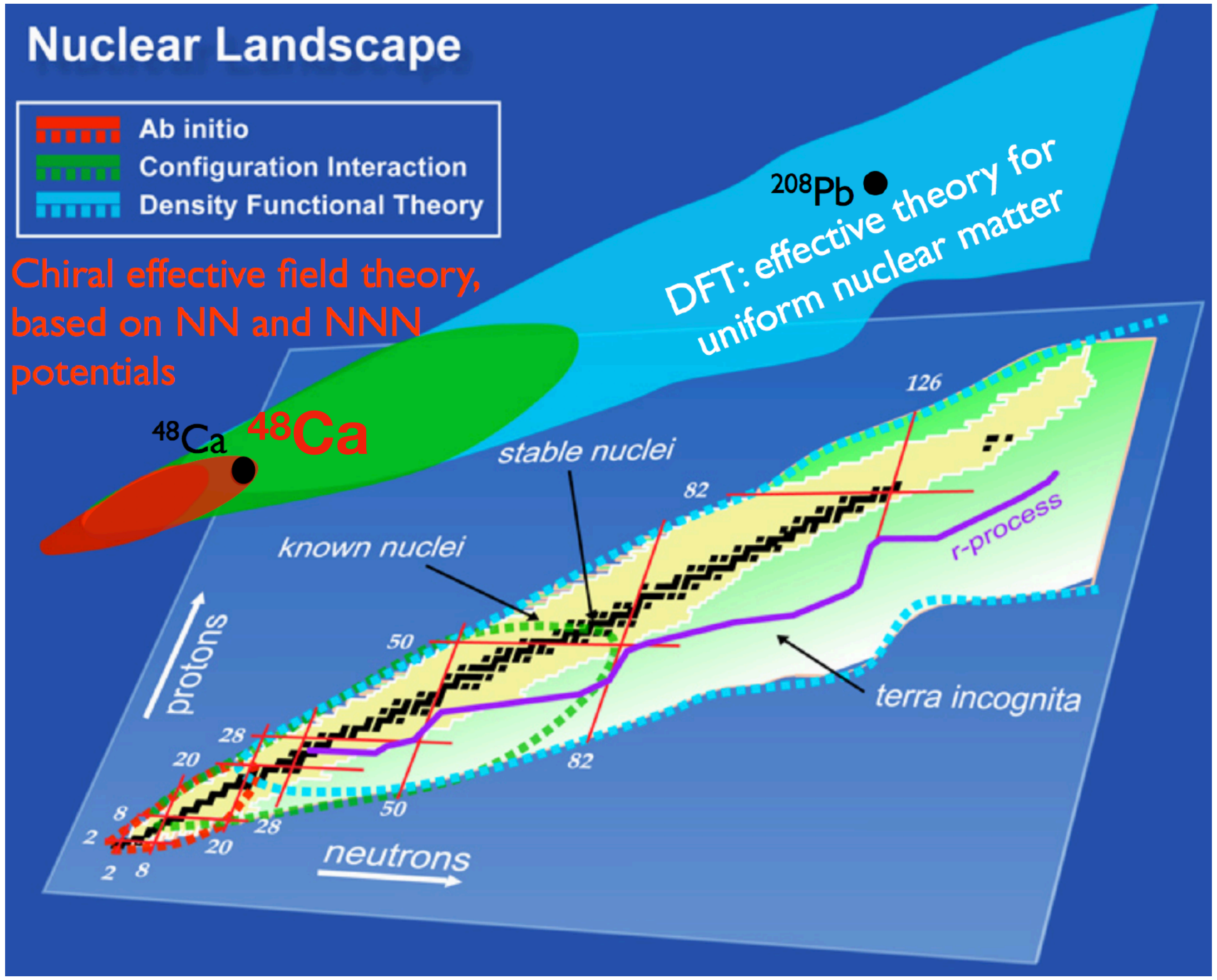
The induced quadrupole deformation will advance the orbit in this case and change the phase of rotation!

Binary Neutron Stars merger significantly limits the phase space for the neutron skin

Choice of Nuclei Target

Stable and Least theoretical uncertainties

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



PREX

^{208}Pb:

- in realm of uniform nuclear matter & Density Functional Theory
- serves as terrestrial laboratory to test neutron star structure

CREX

^{48}Ca:

- "*ab initio*" (exact microscopic) calculations of R_{skin} for ^{48}Ca have recently been available.

  G. Hagen et al., *Nature Physics 12, 186(2016).*

- bridge between "*ab initio*" models and effective theory (DFT)

From A_{PV} to Neutron Skin

Measured A_{PV}

↓

Known charge form factor → Coulomb correction

↓

Weak form factor $F_W(Q^2)$ and weak density $\rho_W(Q^2)$

↓

Corrections for Electric form factors

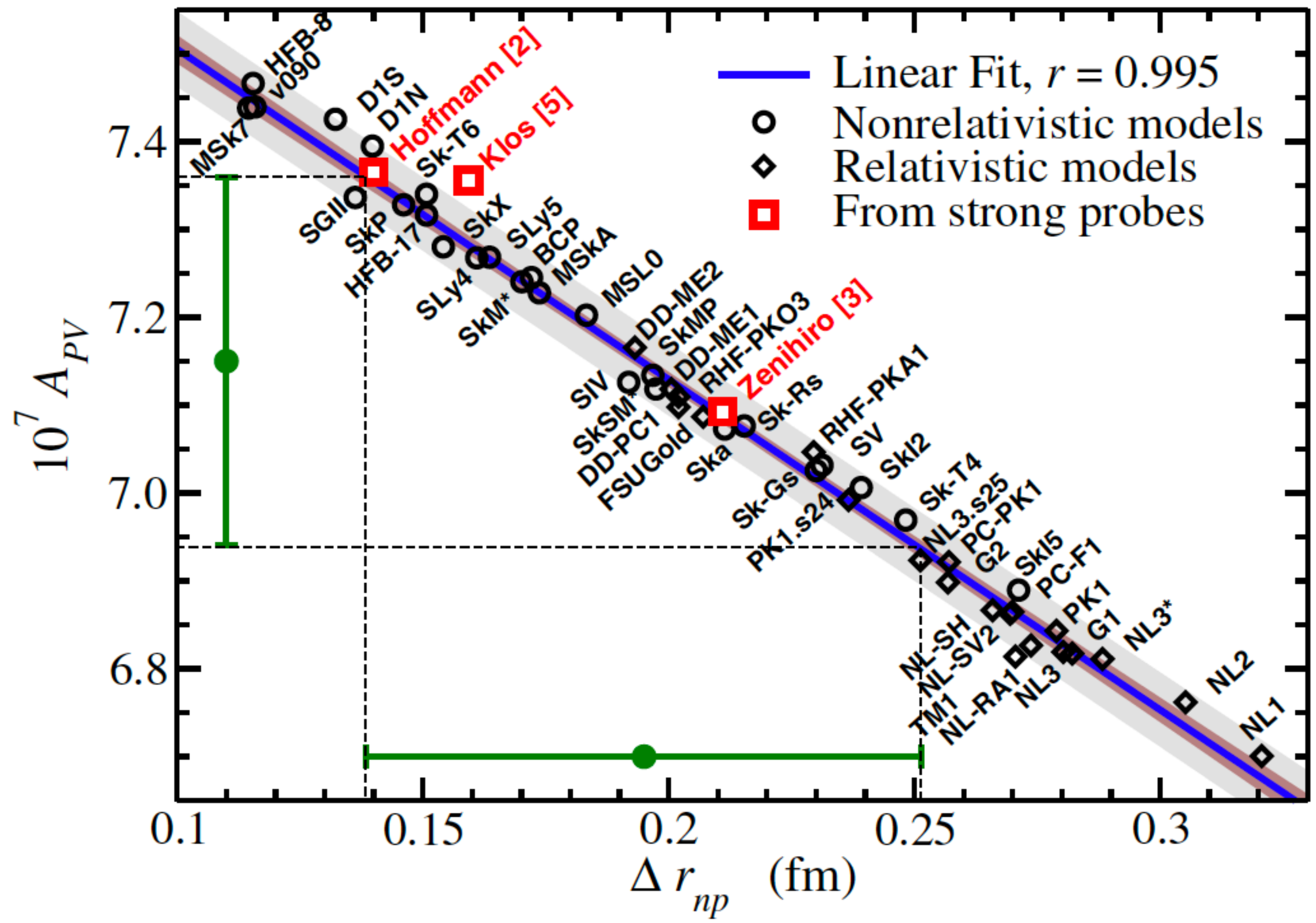
↓

Neutron density $\rho_n(Q^2)$ and neutron radius R_n

↓

Known proton radius R_p → **Neutron skin Δr_{np}**

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

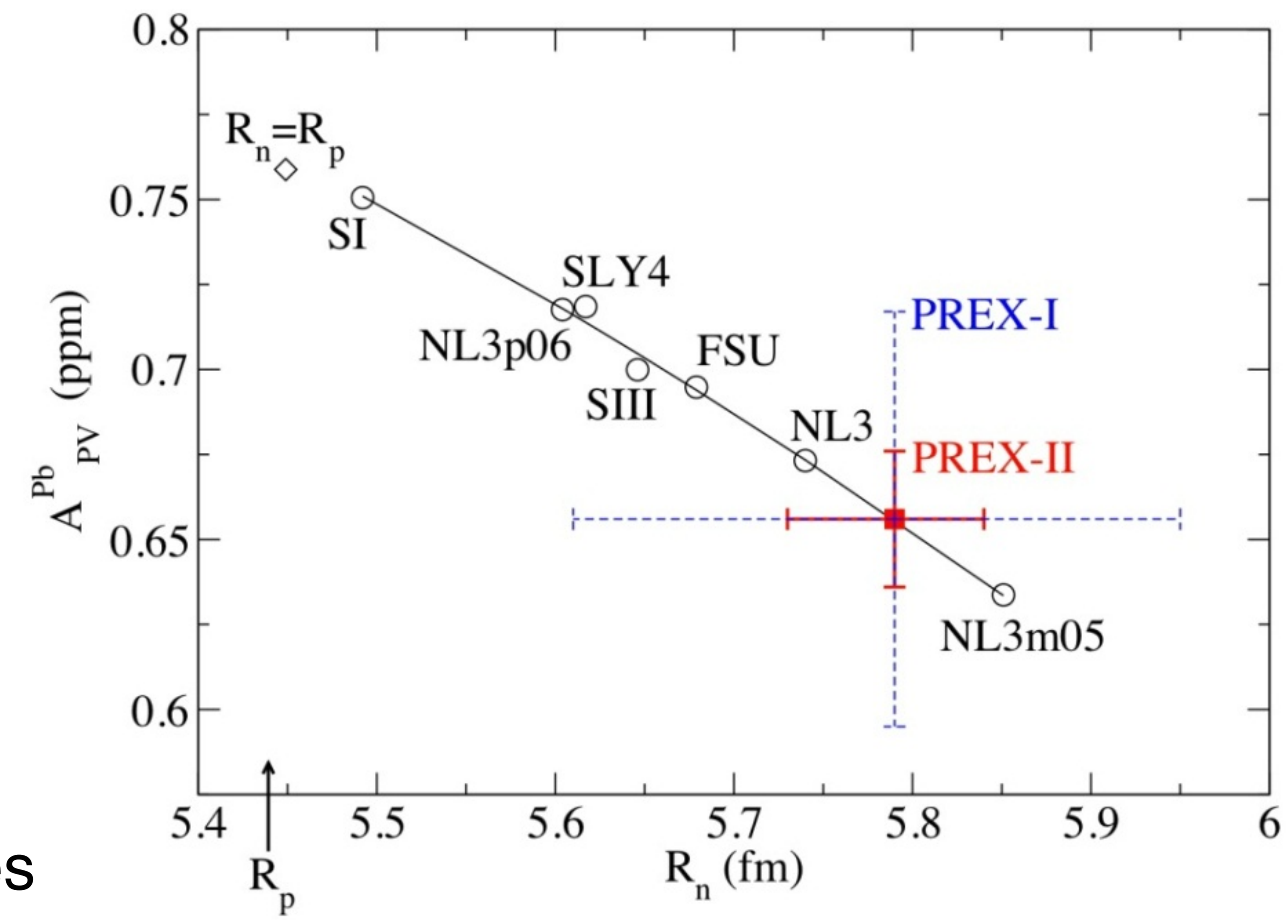


Robust correlation between ^{208}Pb A_{PV} and the neutron skin over existing nuclear structure models

Different neuron skin thickness from different models, **experimental data needed.**

PREX-I (2010)

- Collected data at 2010
- 1.063 GeV electrons scattering from ^{208}Pb at 5 degree
- Initial goal: 3% precision
- Systematic uncertainties were well under control, however radiation issues limited the statistical uncertainty



A_{PV} = 0.657 ± 0.060(stat) ± 0.014(syst) ppm

First electroweak observation that there is a neutron skin around a heavy nucleus

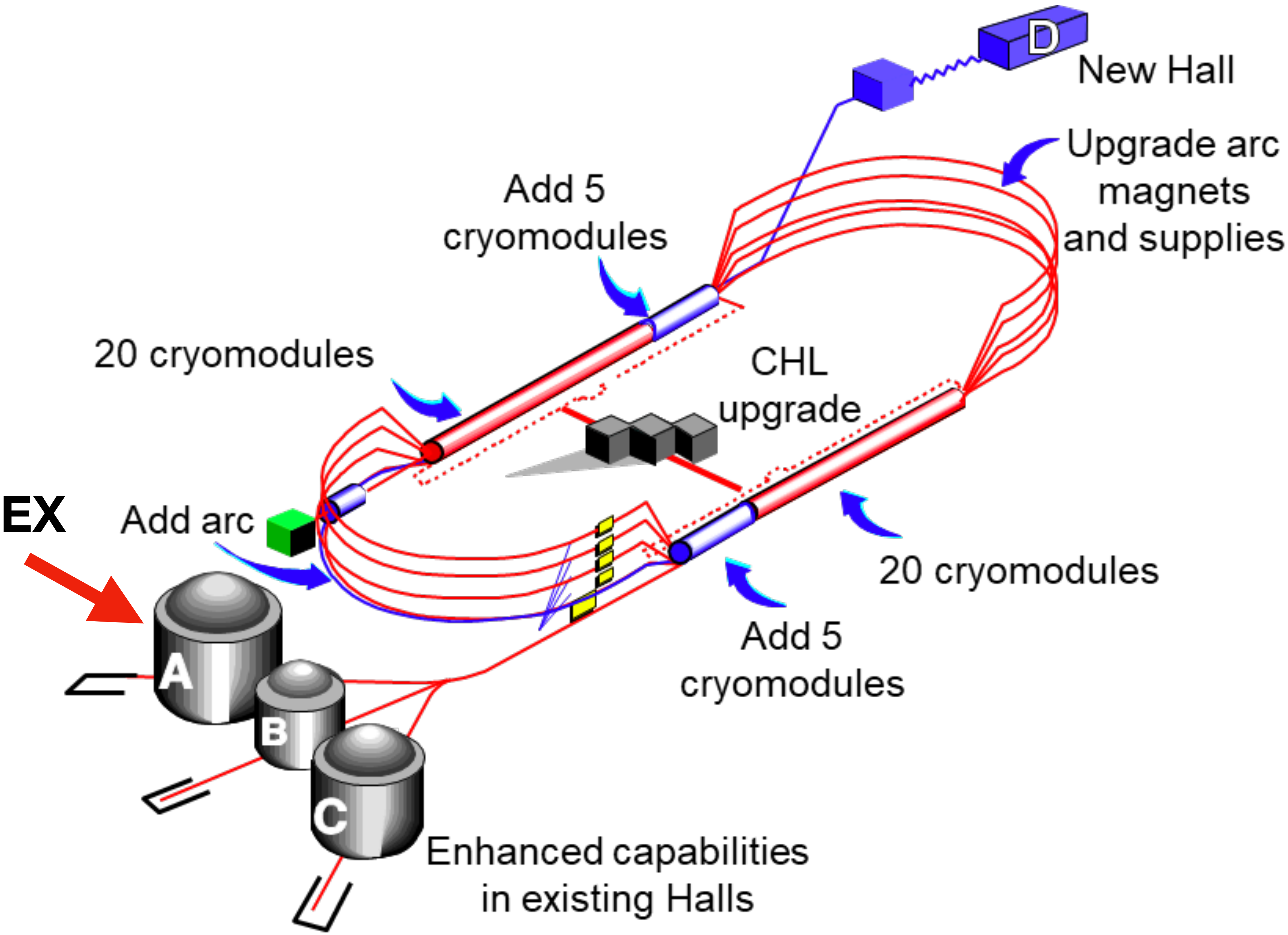
$$R_n - R_p = 0.33^{+0.16}_{-0.18} \text{ fm}$$

Precision of PREX-I did not allow to exclude many models, motivation for PREX-II.

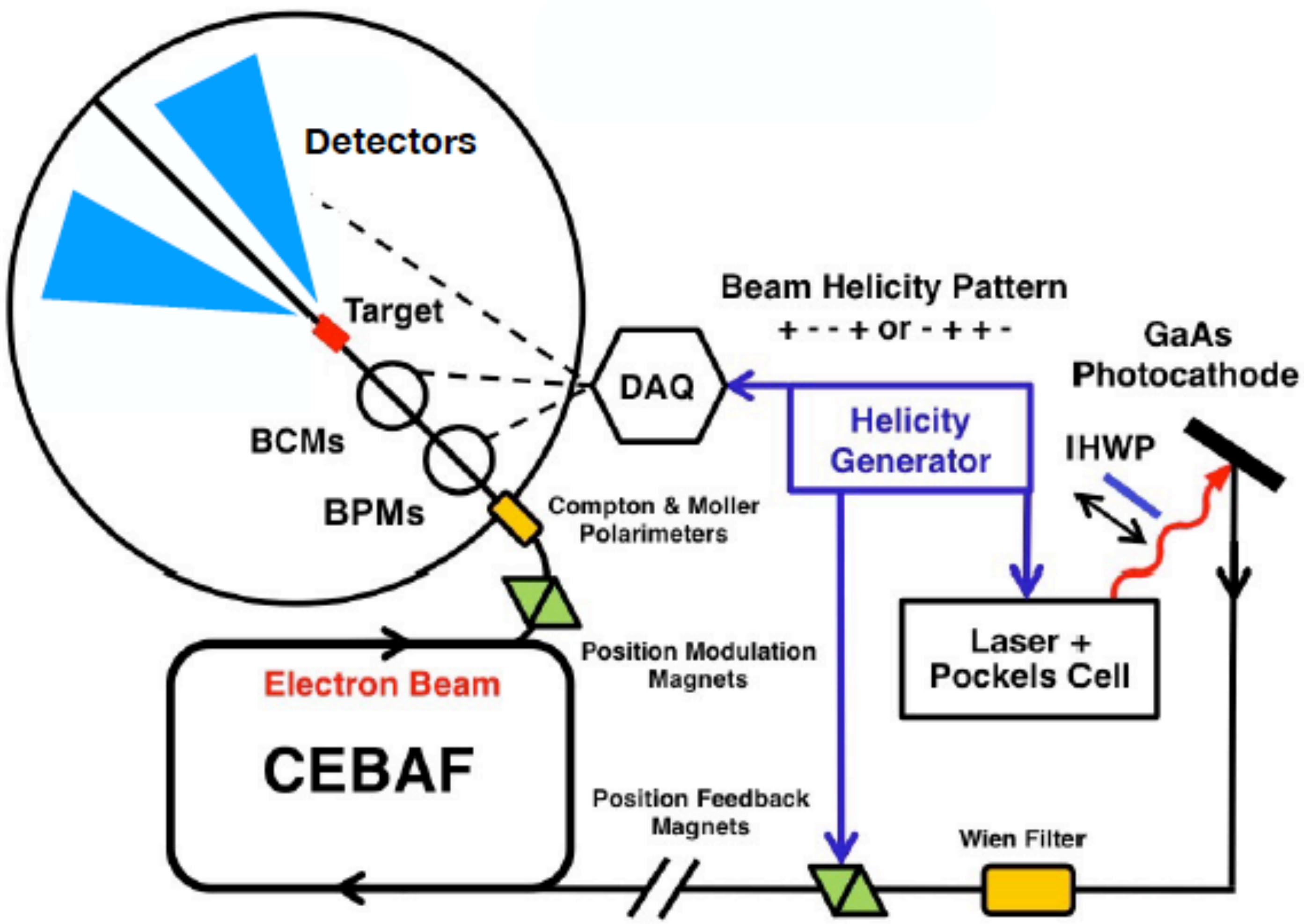
Continuous Electron Beam Accelerator Facility at Jefferson Lab

Continuous Electron Beam Accelerator Facility at Jefferson Lab

PREX/CREX

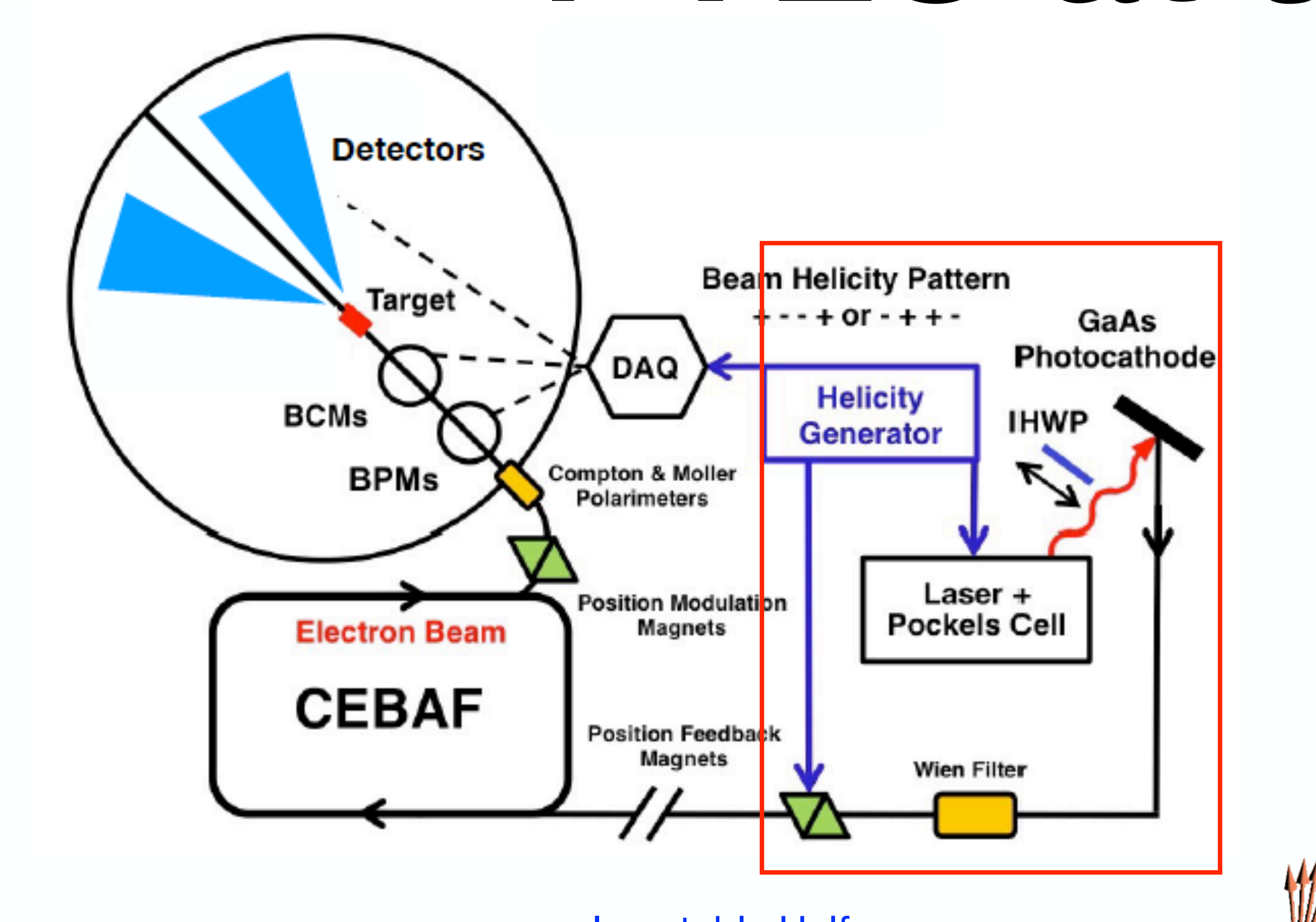


PVES at JLab



Detectors
Target
BCMs
BPMs
Compton & Moller Polarimeters
Beam Helicity Pattern
+ - - + or - + + -
DAQ
Helicity Generator
GaAs Photocathode
IHWP
Laser + Pockels Cell
Position Modulation Magnets
Electron Beam
CEBAF
Position Feedback Magnets
Wien Filter

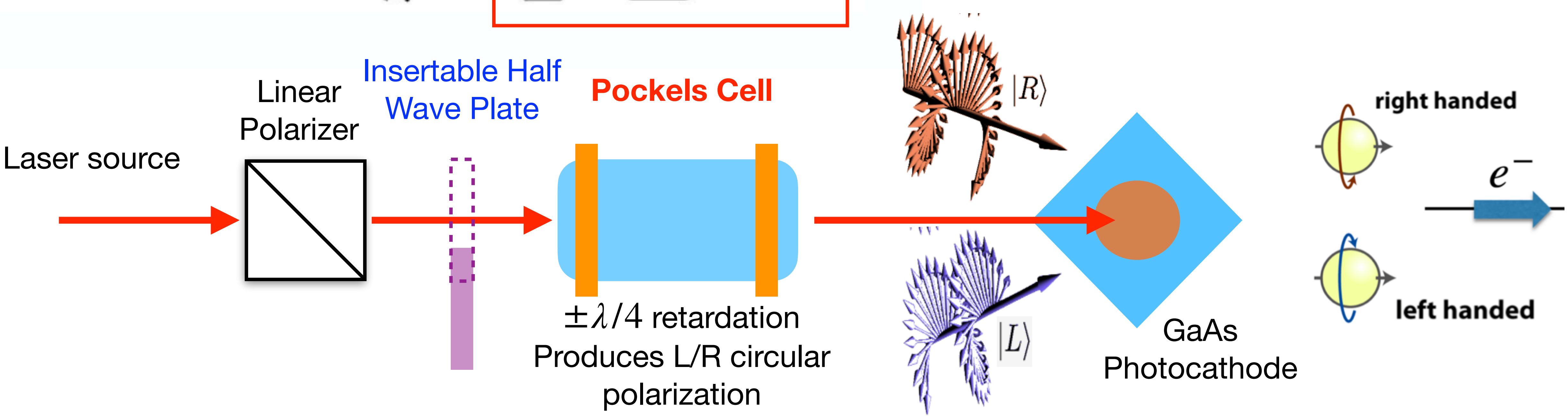
PVES at JLab



Injector:

- Up to 180 uA
- Polarization ~90%
- Up to 1kHz helicity flip

- Fast helicity flipping relies on **Pockels Cell**.
- Slow helicity flipping relies IHWP and Wien Filter



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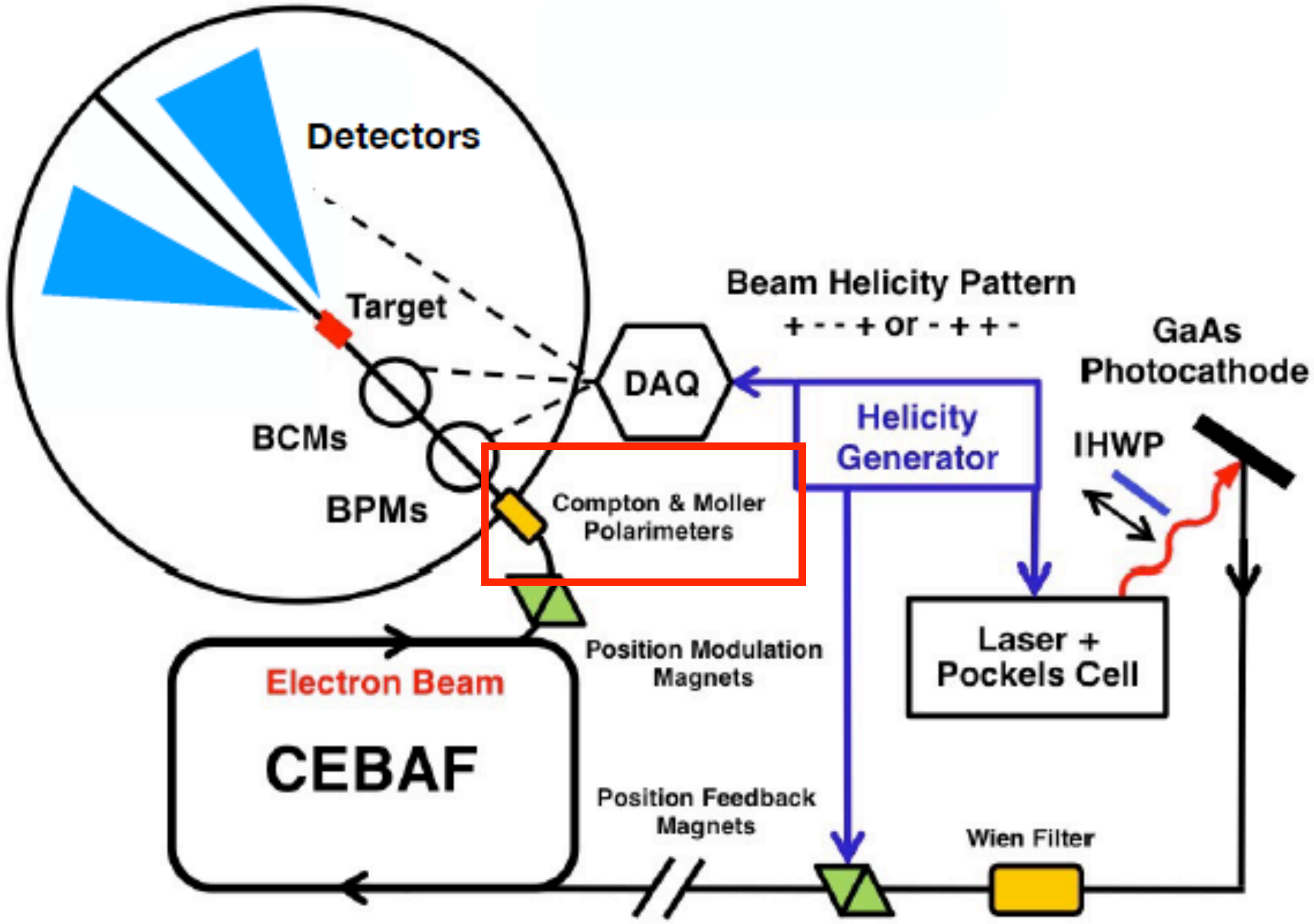


Polarimeters:

- Mott at Injector
- Compton and Moller at Hall
- ~1% level precision

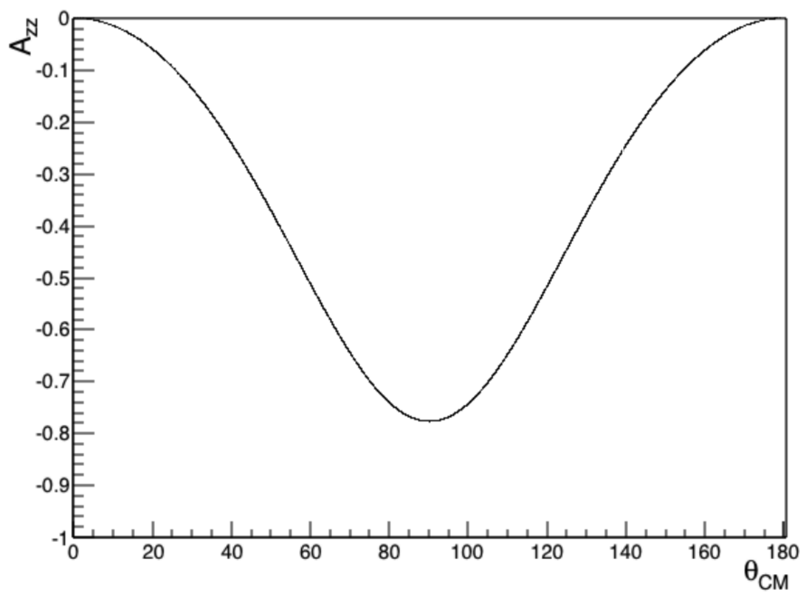
Moller Polarimetry

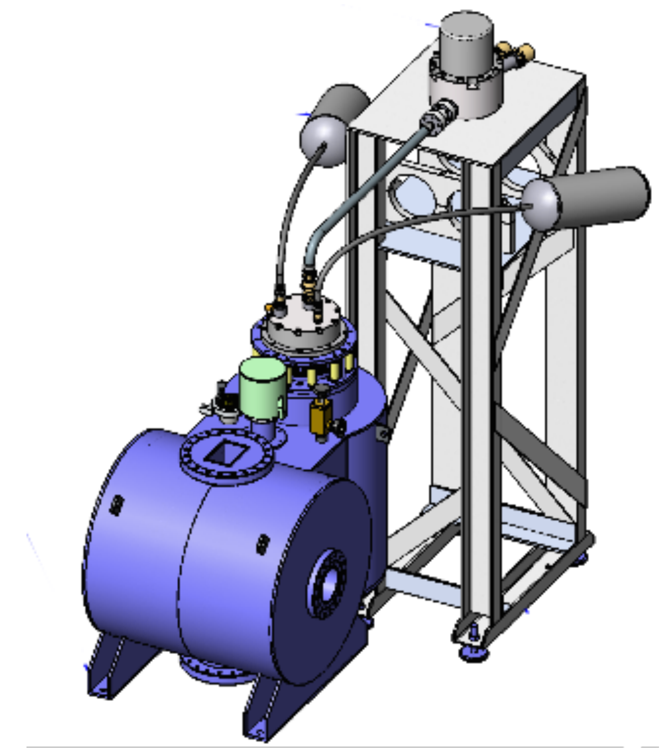
- Polarized cross section asymmetry of Moller scattering (elastic electron-electron scattering)
- Rapid, high precision measurement; **Destructive** only low beam current

$$\sigma \sim 1 + \sum_{i=X,Y,Z} (A_{ii} \cdot P_i^{targ} \cdot P_i^{beam})$$

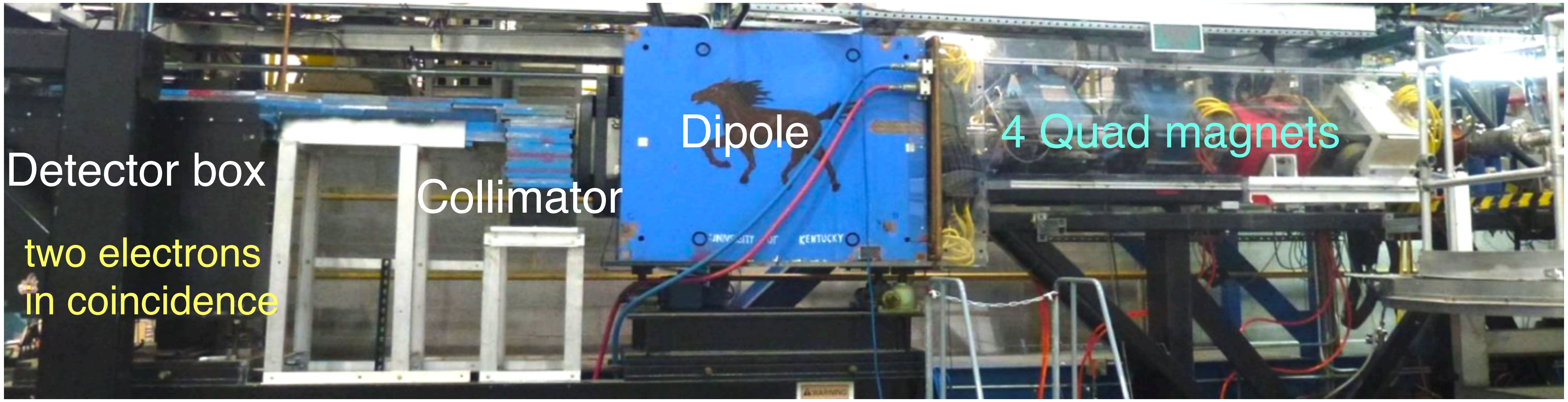
$$A_{ZZ} = -\frac{\sin^2\theta_{CM} \cdot (7+\cos^2\theta_{CM})}{(3+\cos^2\theta_{CM})^2}$$

Energy independent



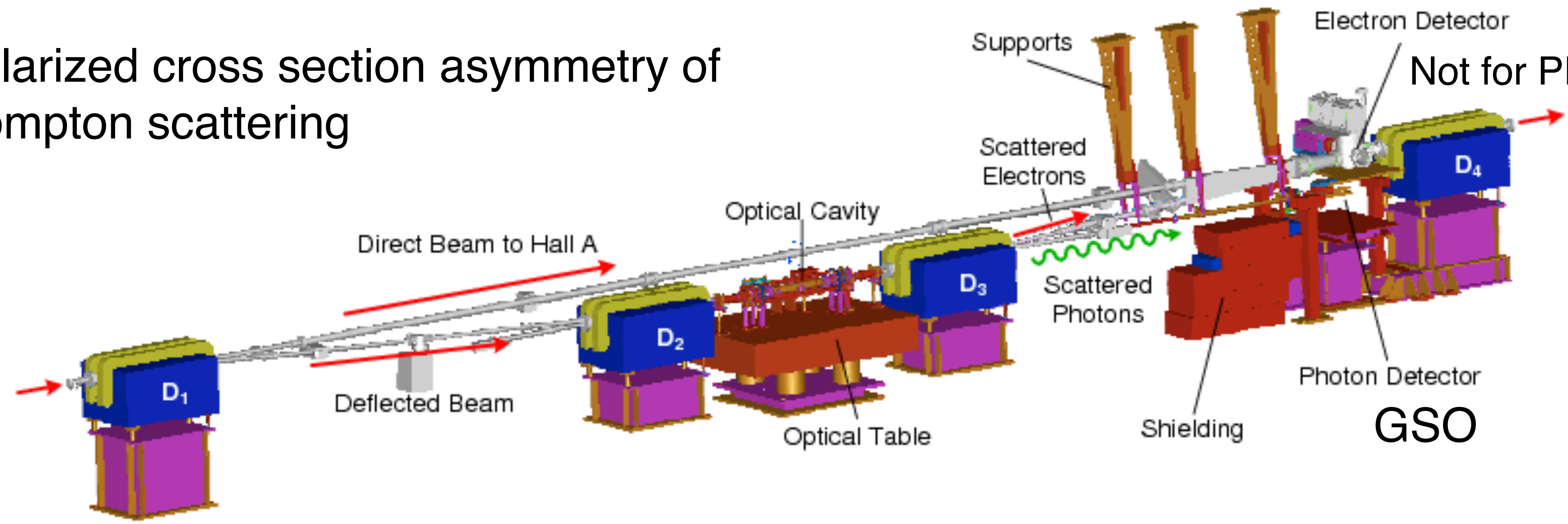


Iron Foil Target in high-field superconductor magnet.

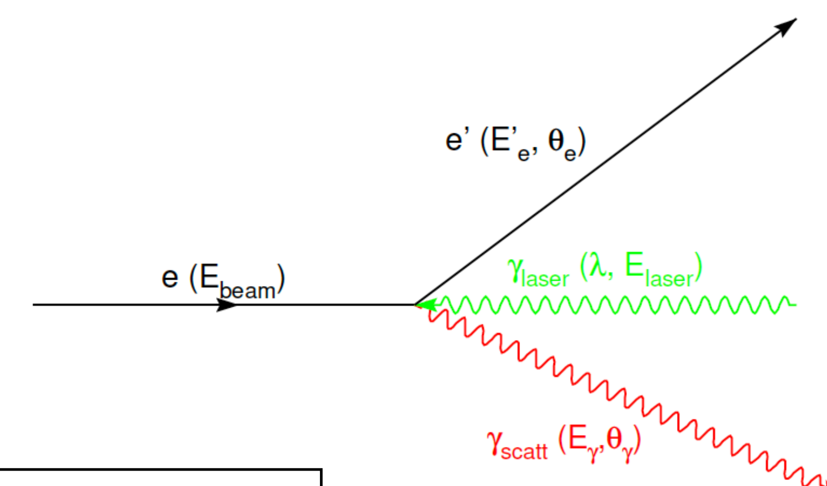


Compton Polarimeter

Polarized cross section asymmetry of Compton scattering

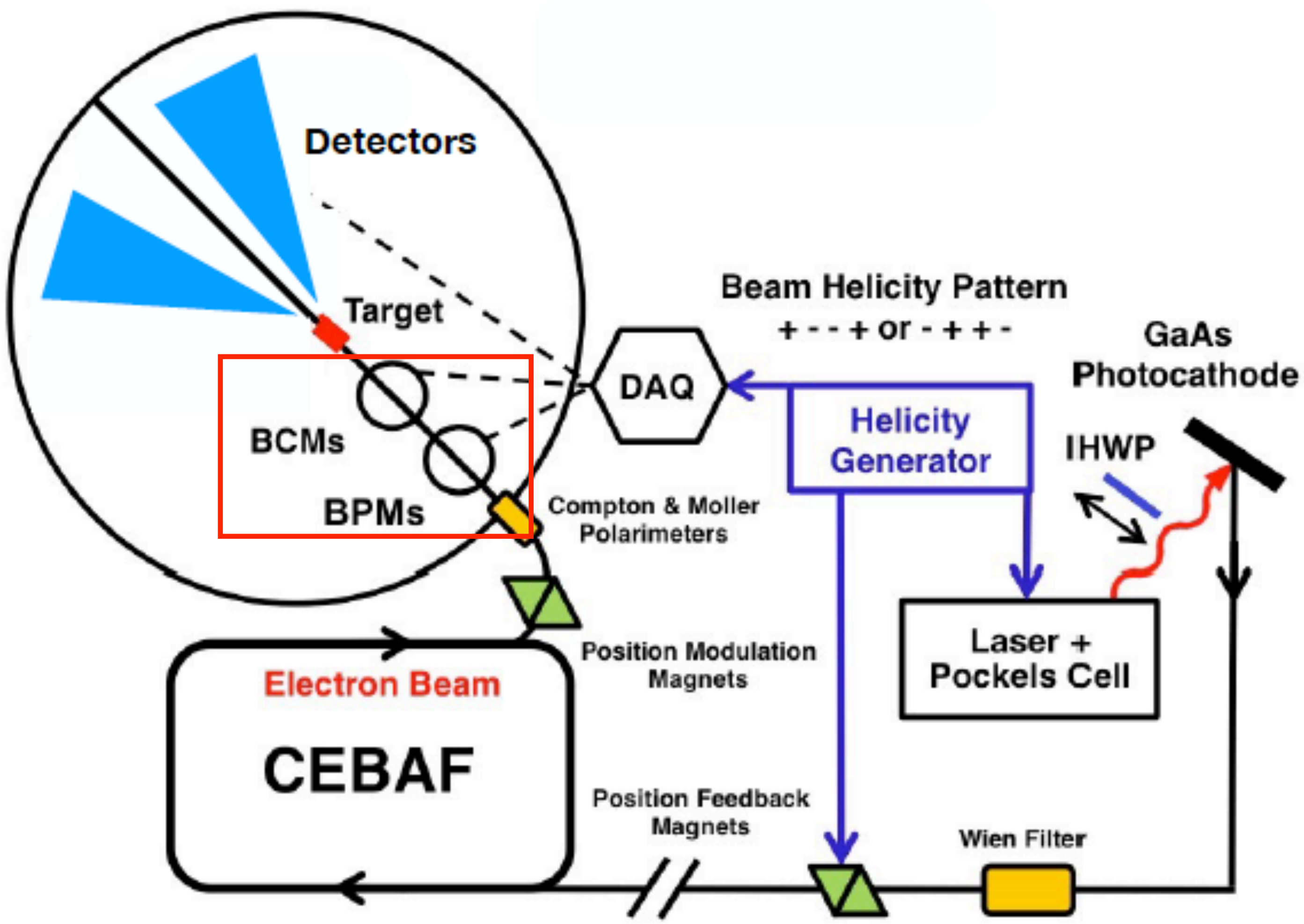


- 4-dipole chicane, **non-destructive** measurement: **continuous** monitoring of beam polarization
- Laser beam colliding with electron beam nearly head-on
- Integrating DAQ;
  GSO used to detect scattered photons;
  Diamond microstrips used to detect scattered electrons
- PREX2 will need 1% at 950 MeV
  CREX will need 0.8% at 2.22GeV



CREX Polarimetry Result:
Pe=87.09 +/- (0.44% dP/P)

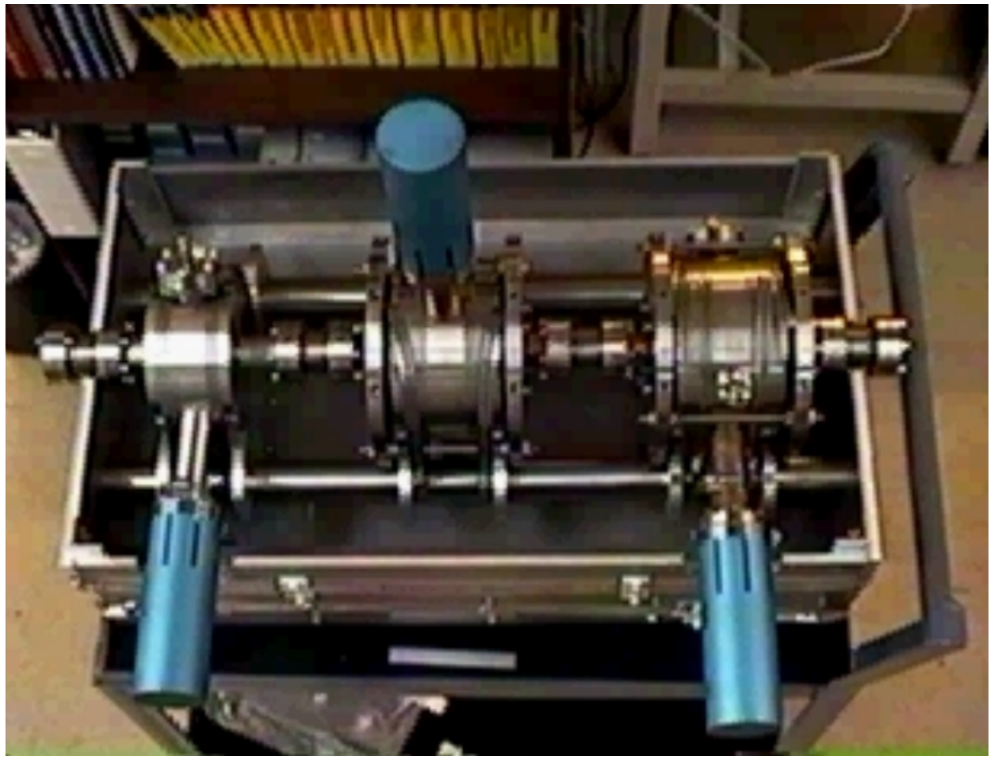
PVES at JLab

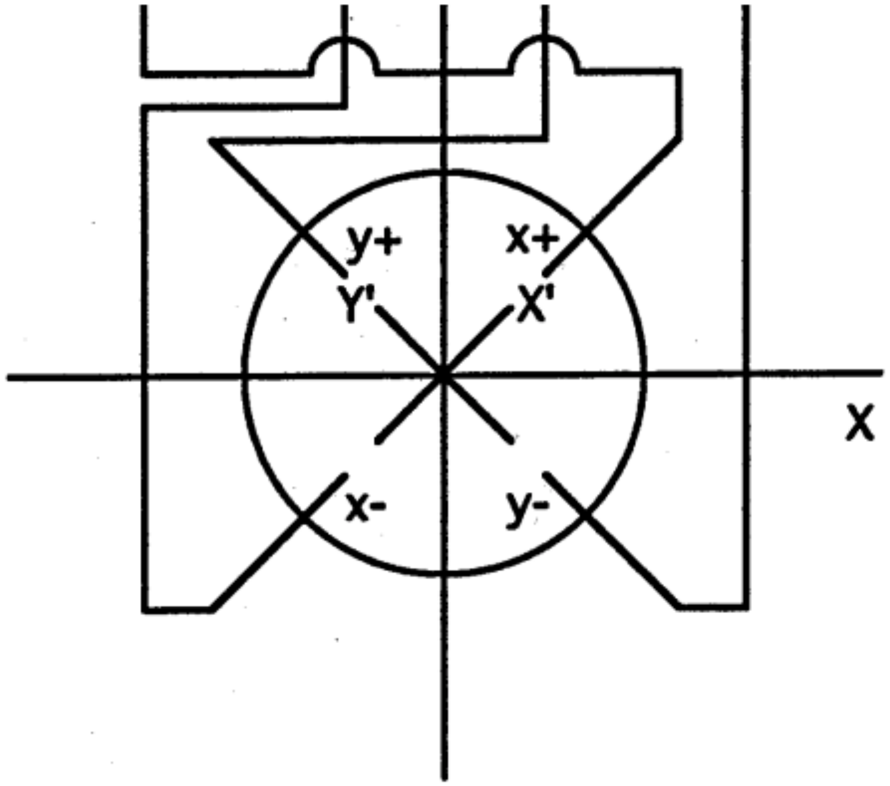


Beam monitoring:

- RF antenna or RF resonating cavities
- Charge ~30ppm, position ~1um
- Fast feed back to injector

Beam Monitoring

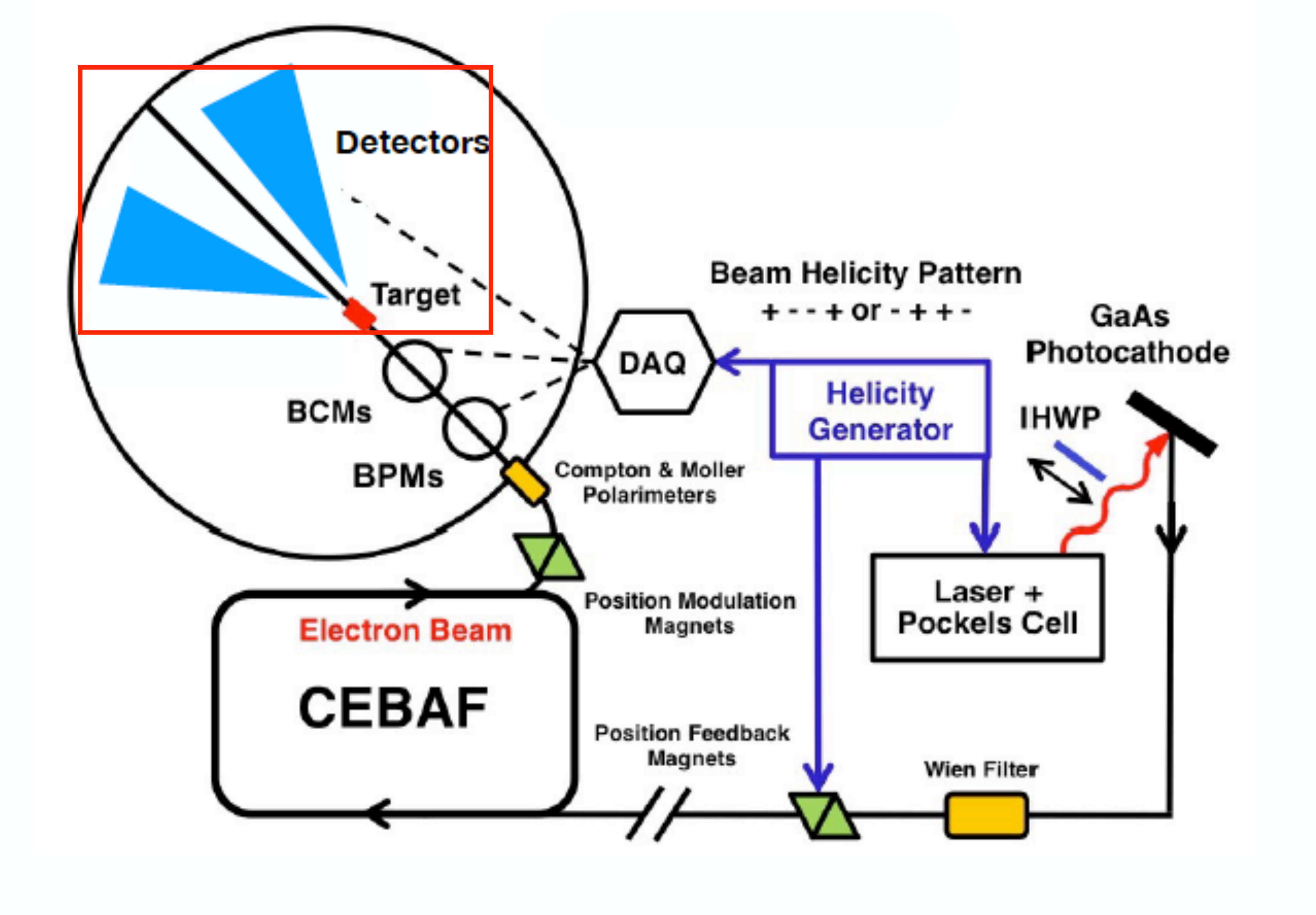




- Mostly use RF resonating cavities or RF antennas
  - can measure beam charge to about 30 ppm and positions to about 1 micron

- Electronics are used to **fast feedback** and reduce large helicity correlated beam asymmetries

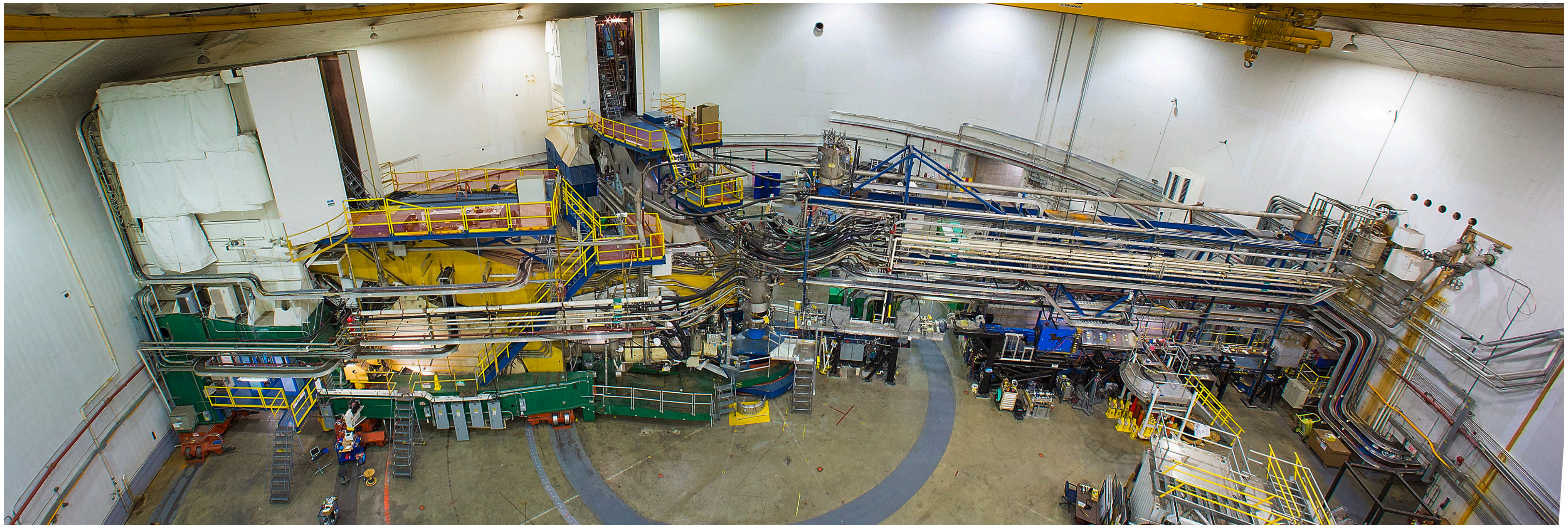
PVES at JLab

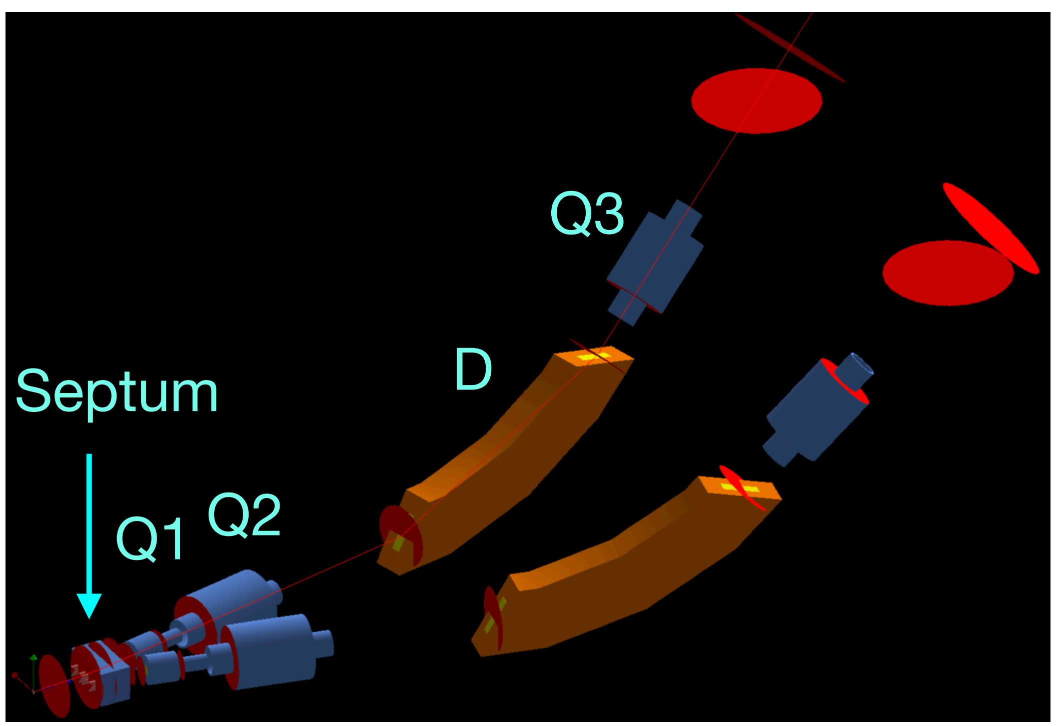


Spectometers:

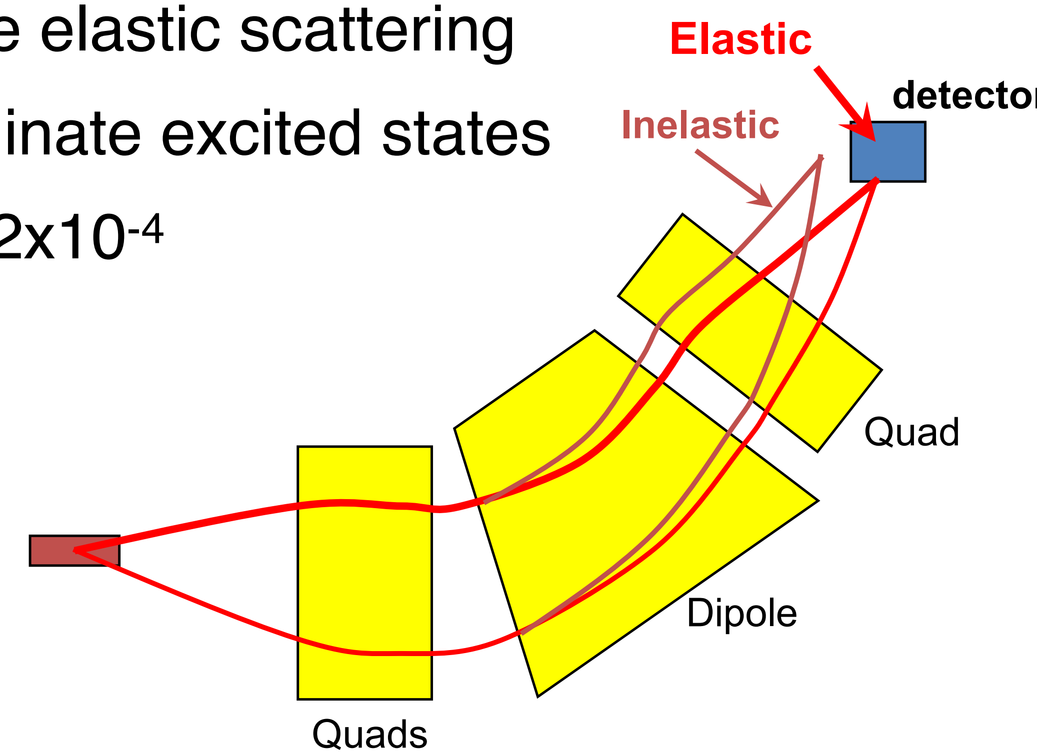
- HRS - High Resolution Spectrometers
- dp/p ~ $2x10^{-4}$

Hall A High Resolution Spectrometers

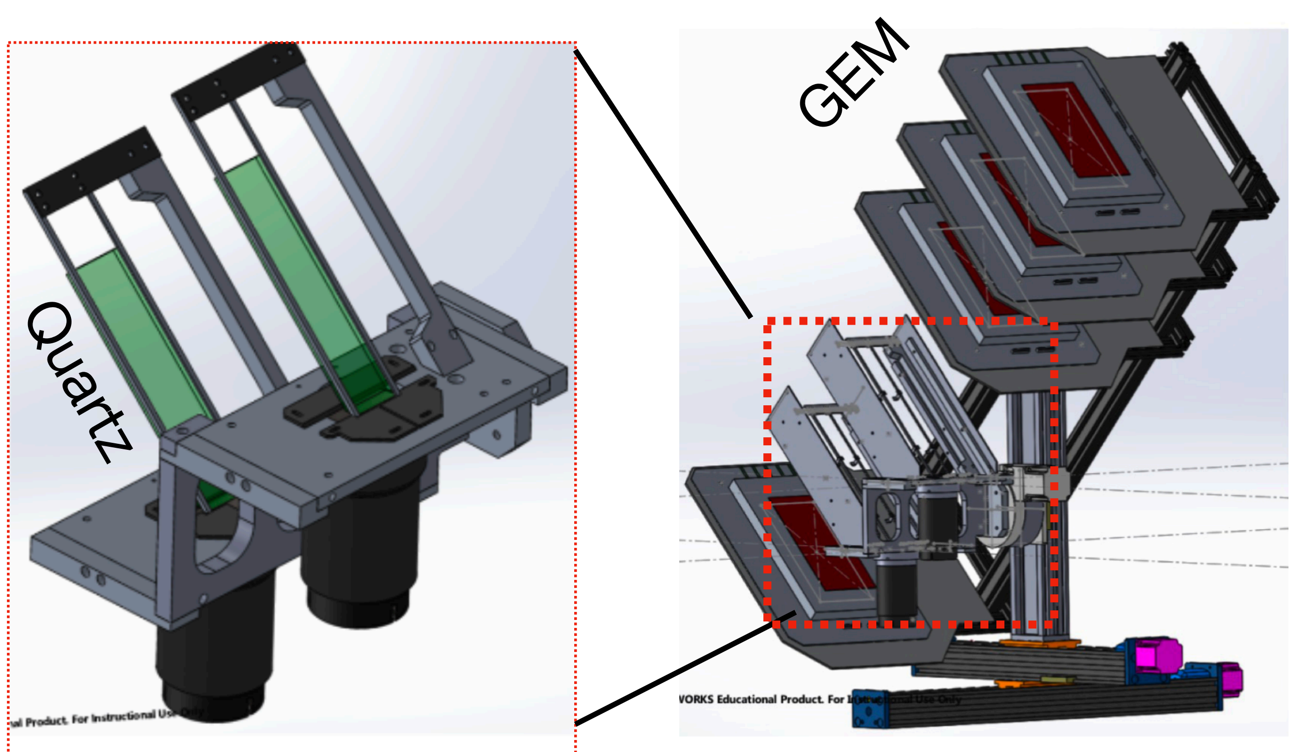




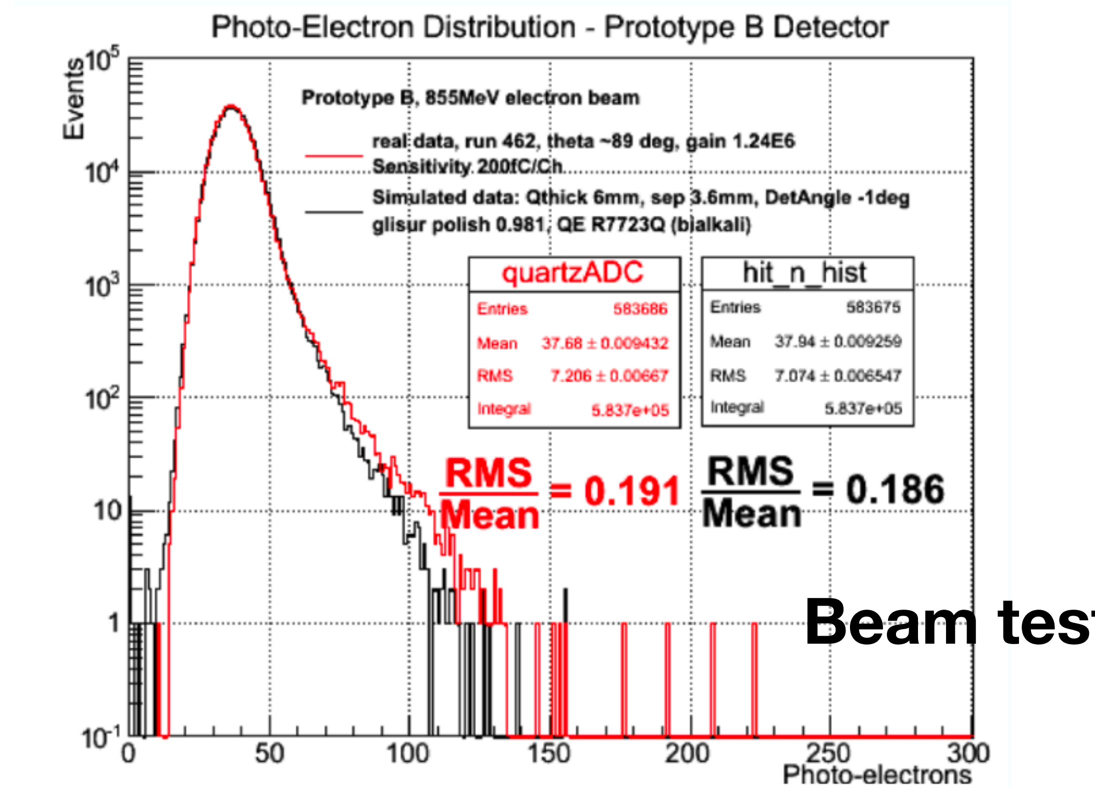
- Resolve elastic scattering
- Discriminate excited states
- $dp/p \sim 2x10^{-4}$



Main Detectors



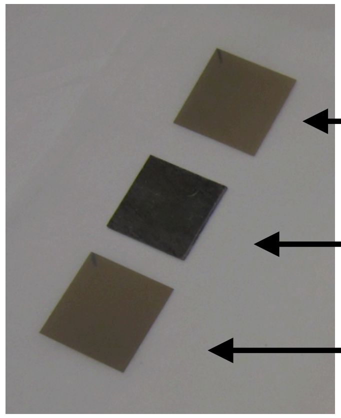
D. McNulty



- Fused silica Cherenkov radiator, 5mm thick 3.5x16 cm2 area, mated to a single PMT
  - Non-linearity of detector response was tested on the bench and with beam during the experiment
- GEMs for tracking runs (Q^2 measurement)

PREX/CREX Target

- Lead has low melting point, and low thermal conductivity
- Diamond foils have excellent thermal conductivity, Helium cooled
- ^{12}C is isoscaler, spin-0 (and well-measured) harmless background



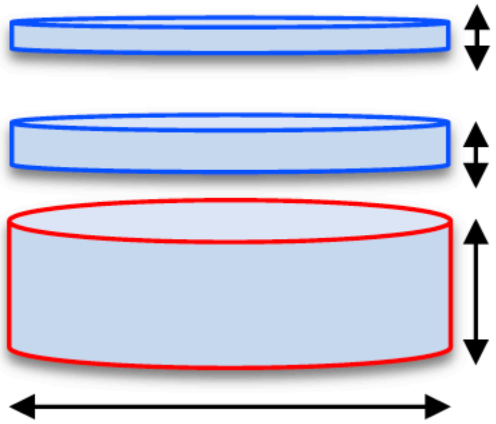
Diamond

Lead

Diamond

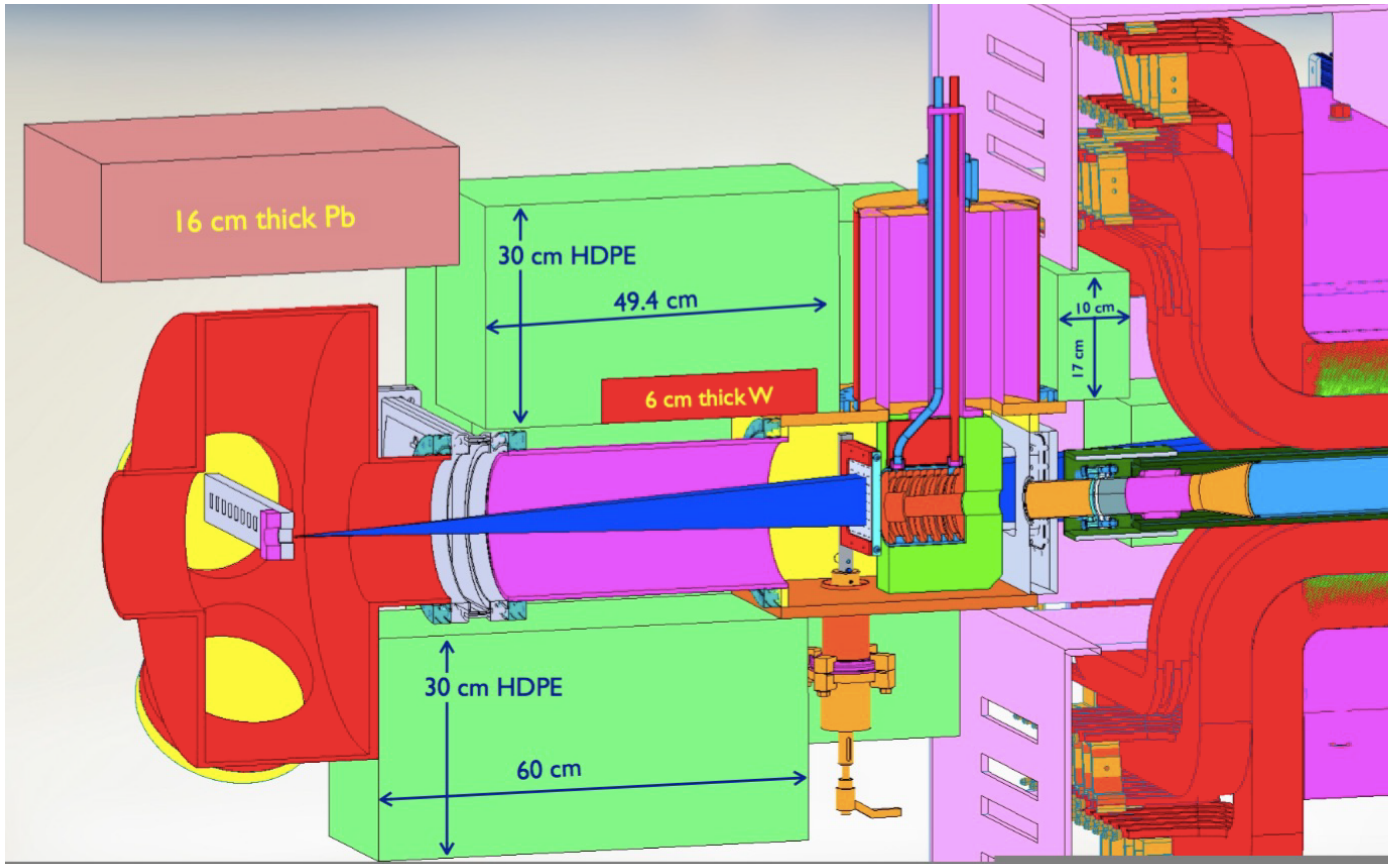
Cryogenic production target ladder

- ~5.7 mm thick
- ~91.7% ^{48}Ca, ~7.96% ^{40}Ca



Radiation Shielding

PREX-I distributed significant power in the hall, damaging vacuum and electronics



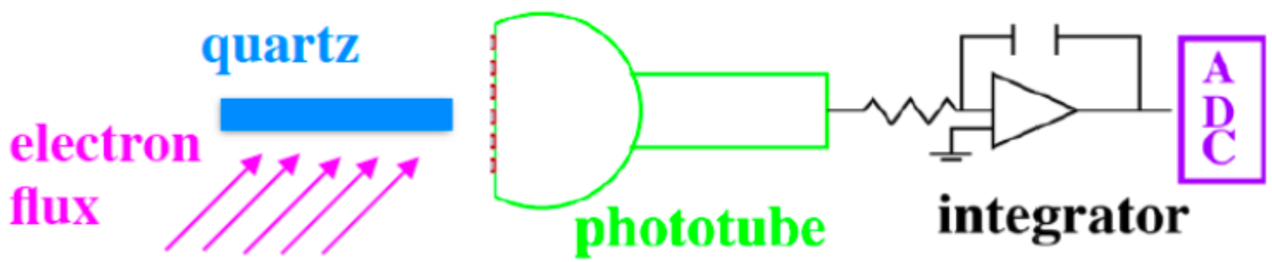
	PREX-I	PREX-II	CREX
Power in collimator (W/μA)	9.7	**28.8**	6.8
Power in hall (W/μA)	18.0	**3.0**	~1.5

Solution: Localize power in hall at collimator, and shield it

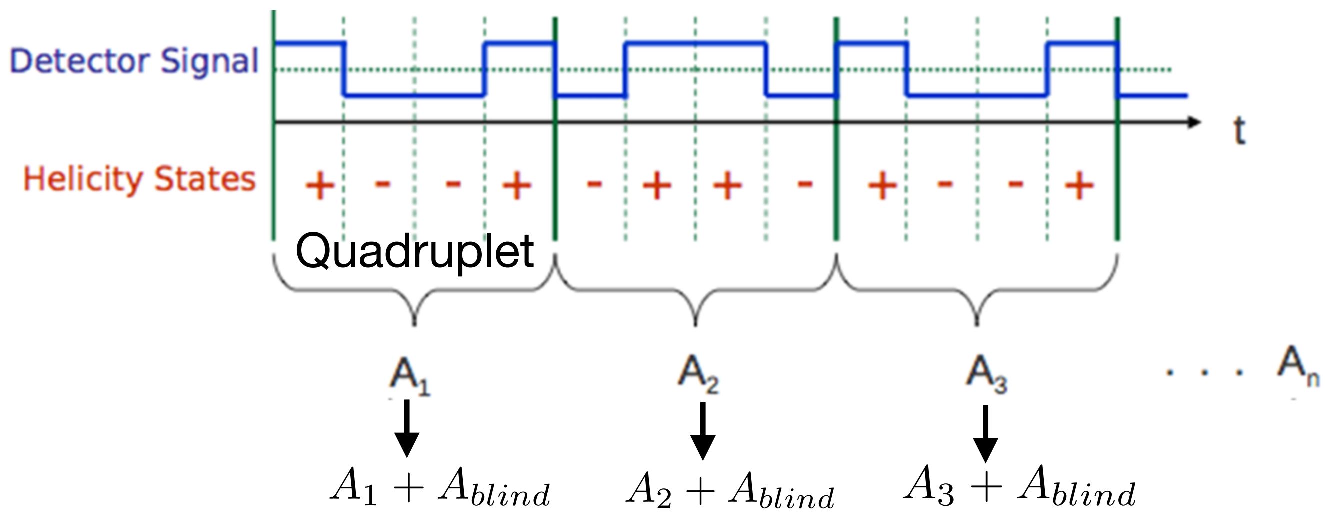
- Heavy concrete shielding over the target and collimator region to reduce the boundary dose
- Collimation and shielding protect sensitive electronics inside the hall

Integrating DAQ

Flux integration Technique



CREX rate: 500 MHz
PREX rate: 2GHz



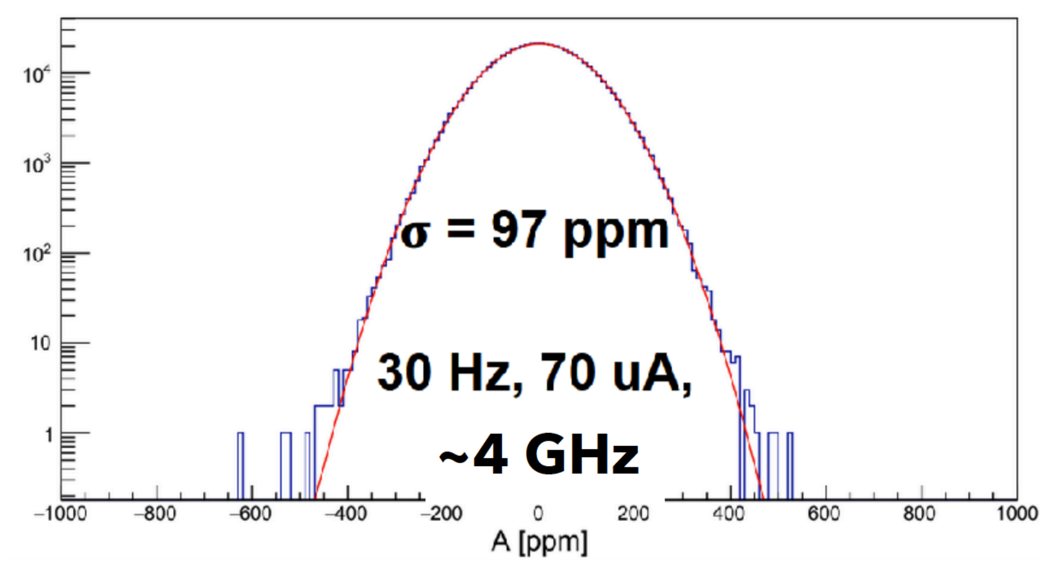
$$A_i = sign_1 \times \frac{D_1/I_1 - D_2/I_2 - D_3/I_3 + D_4/I_4}{D_1/I_1 + D_2/I_2 + D_3/I_3 + D_4/I_4}$$

D: detector signal, I: beam current

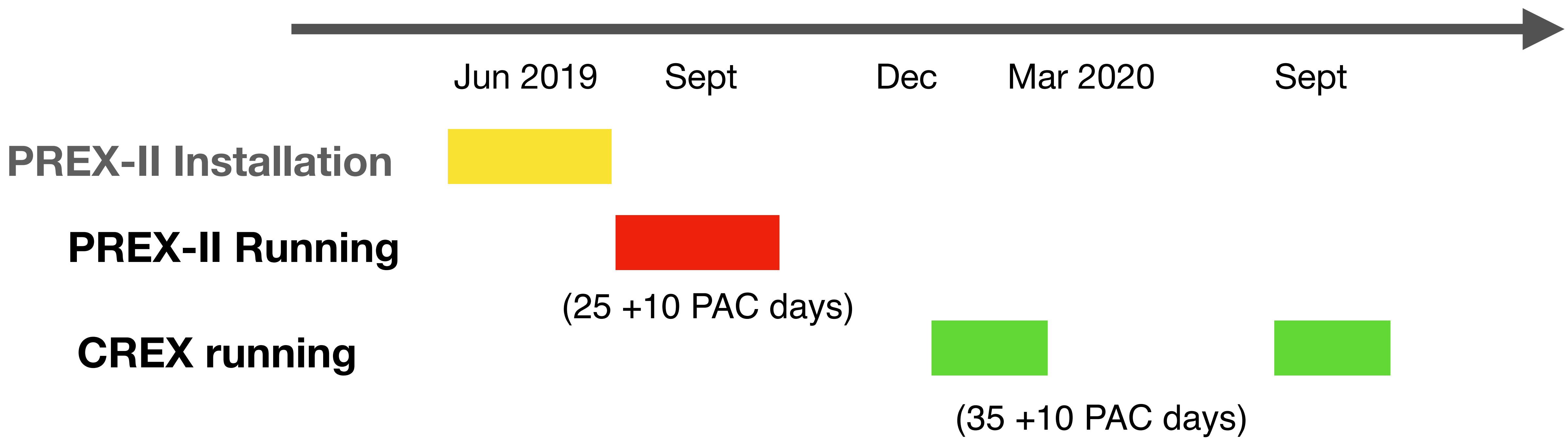
Continuous Wave (CW) laser which flips helicity fast enough to make sure that experimental conditions do not change from one helicity signal to the other

Integrating, not counting (total number of detected electrons was ~6e+15

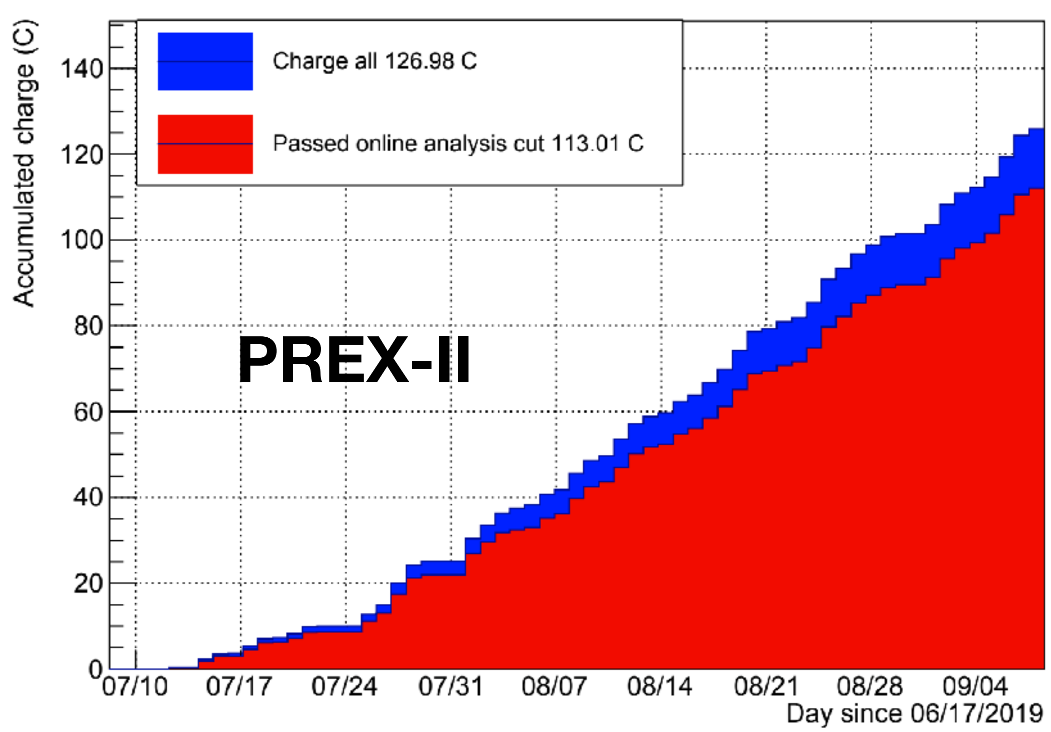
dominated by counting statistics fairly



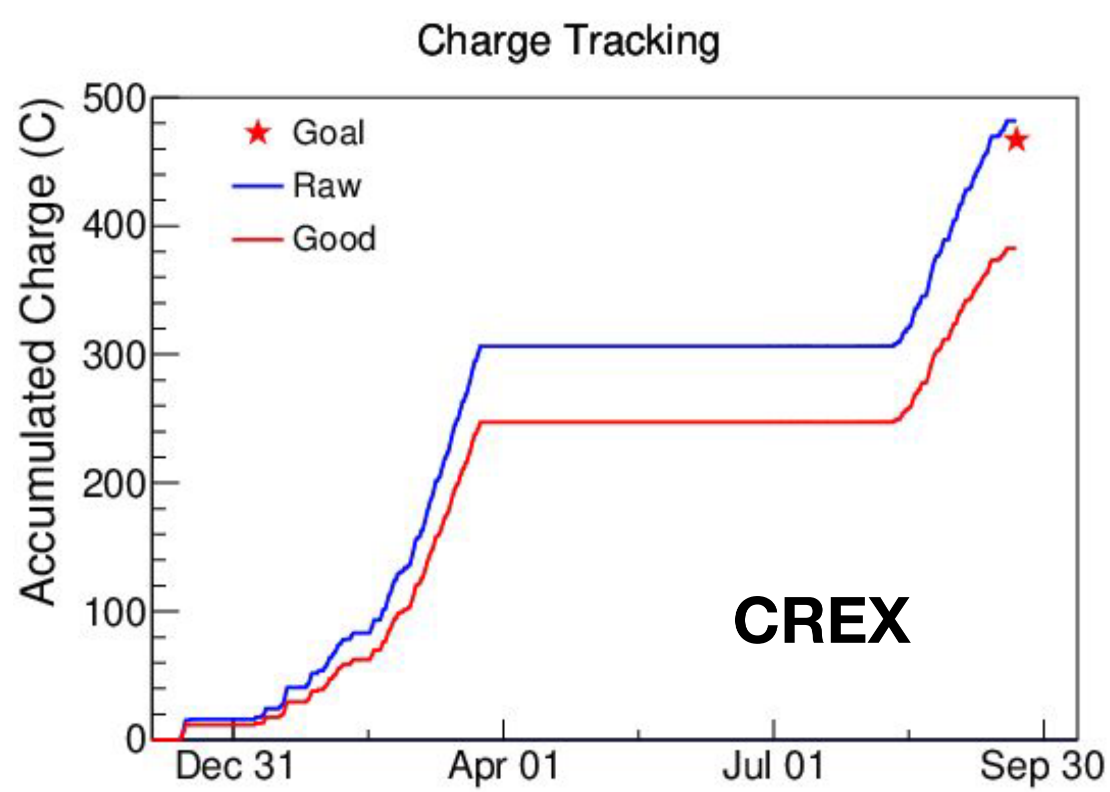
Time Line



Jun 2019
Sept
Dec
Mar 2020
Sept
PREX-II Installation
PREX-II Running
(25 +10 PAC days)
CREX running
(35 +10 PAC days)

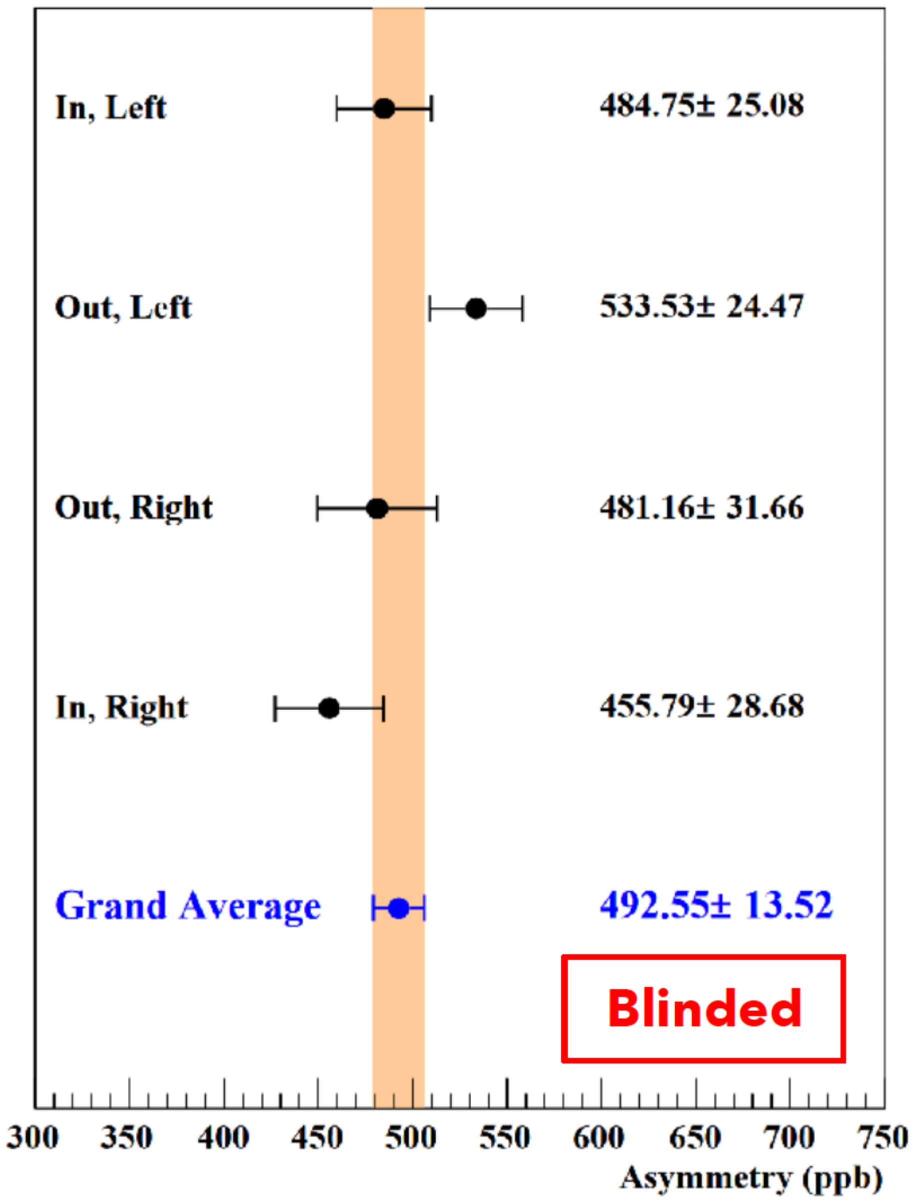


Accumulated charge (C)
Charge all 126.98 C
Passed online analysis cut 113.01 C
PREX-II
0
20
40
60
80
100
120
140
07/10
07/17
07/24
07/31
08/07
08/14
08/21
08/28
09/04
Day since 06/17/2019



Charge Tracking
Accumulated Charge (C)
Goal
Raw
Good
CREX
0
100
200
300
400
500
Dec 31
Apr 01
Jul 01
Sep 30

PREX-II Data Overview



$$A_{PV} = R_{acceptNorm} \frac{A_{corr}/P_e - \sum_i A_i f_i}{1 - \sum_i f_i}$$

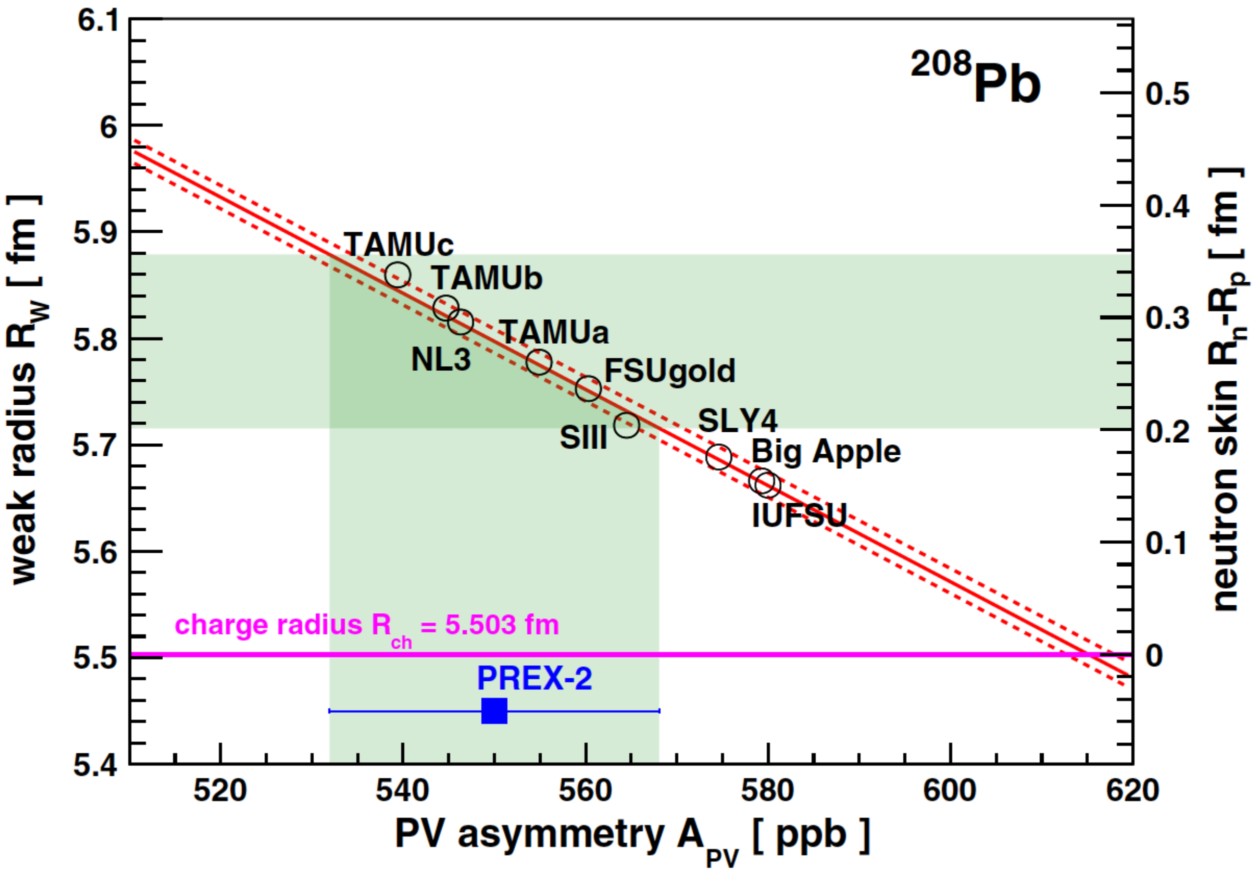
$$A_{corr} = A_{raw} + A_{beam} + A_{nonLin} - A_{blind}$$

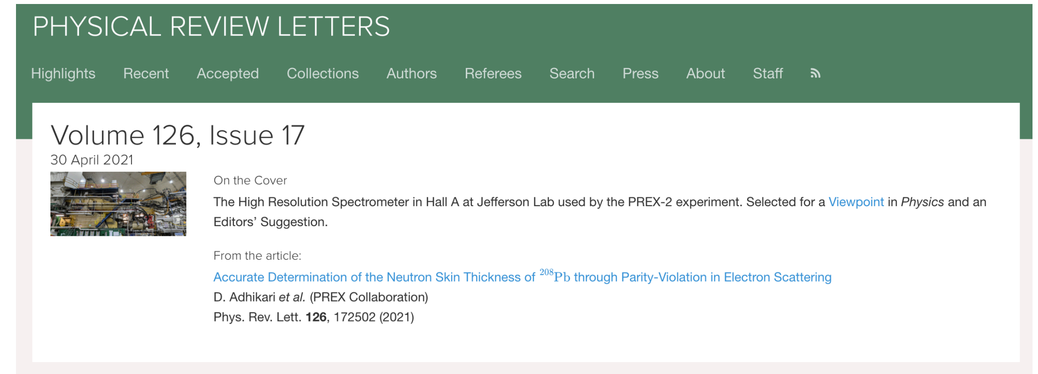
	A_{PV} uncertainty contribution [ppb]	A_{PV} uncertainty contribution [%]
Polarization	5.23	0.95%
Acceptance normalization	4.56	0.83%
Beam correction	2.98	0.54%
Non-linear detector response	2.69	0.49%
Carbon dilution	1.45	0.26%
Charge correction	0.25	0.04%
Inelastic contamination	0.12	0.02%
Total	**8.16**	**1.48%**

When taken all into account the experimental systematic uncertainty comes to just ~1.5% (2% in proposal)

Unblinded A_{PV}: (550.0 ± 16.1)ppb

PREX-II Result





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Volume 126, Issue 17

30 April 2021

On the Cover

The High Resolution Spectrometer in Hall A at Jefferson Lab used by the PREX-2 experiment. Selected for a Viewpoint in *Physics* and an Editors' Suggestion.

From the article:

Accurate Determination of the Neutron Skin Thickness of ^{208}Pb through Parity-Violation in Electron Scattering

D. Adhikari *et al.* (PREX Collaboration)

Phys. Rev. Lett. **126**, 172502 (2021)

$$A_{\mathrm{PV}}^{\mathrm{meas}} = 550 \pm 16\,(\mathrm{stat}) \pm 8\,(\mathrm{syst})\ \mathrm{ppb}$$

$$F_W(\langle Q^2 \rangle) = 0.368 \pm 0.013\,(\mathrm{exp}) \pm 0.001\,(\mathrm{theo})$$

$$R_W = 5.795 \pm 0.082(\mathrm{exp}) \pm 0.013(\mathrm{theo})\ \mathrm{fm}$$

$$R_n - R_p = 0.278 \pm 0.078(\mathrm{exp}) \pm 0.012(\mathrm{theo})\ \mathrm{fm}.$$

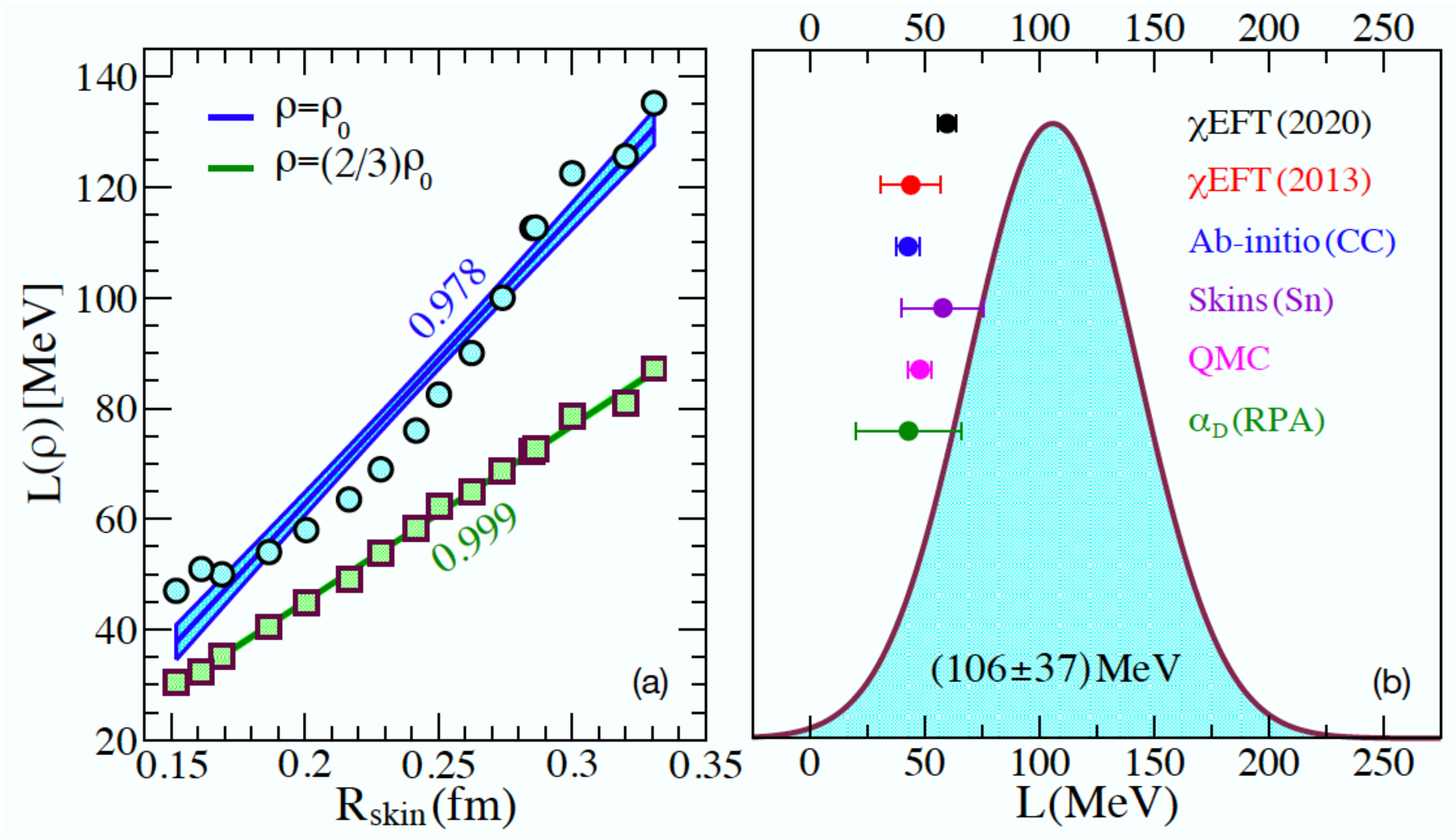
Combined PREX-I and PREX-II

^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ_W^0)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ_b^0)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

- Consistent with PREX-I
- Did better than originally proposed statistical (±3%) and systematic (±2%) uncertainty goals

Impact on symmetry energy slope

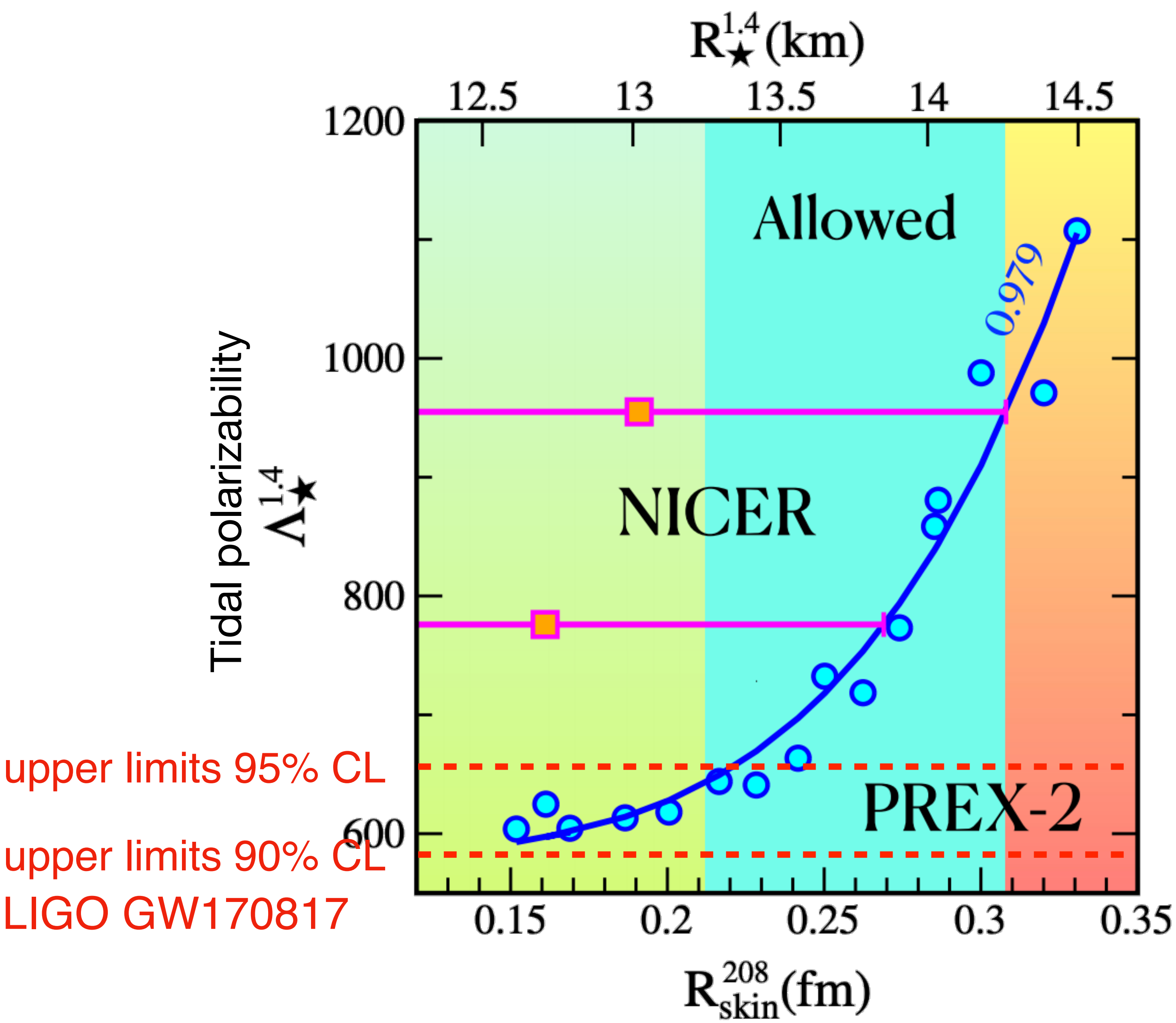
Reed, Horowitz et al. PRL 126, 172503 (2021)



PREX result indicating a larger L (stiff EOS)

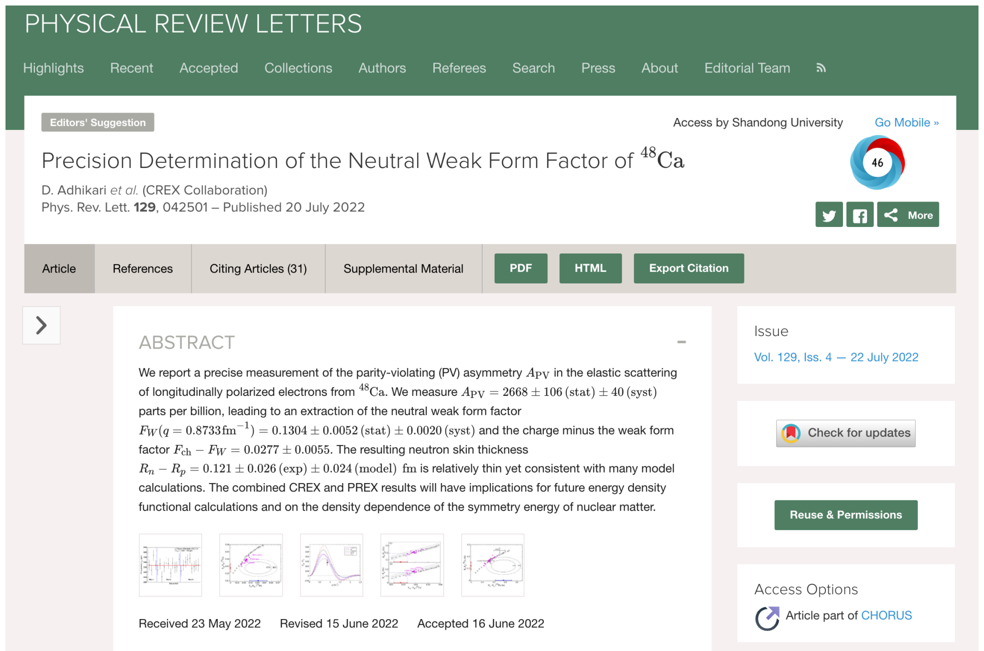
Implication on Neutron Star

Reed, Horowitz et al. PRL 126, 172503 (2021)



- NICER (NASA's neutron star Interior Composition ExporeR) is an X-ray telescope on the International Space Station
- LIGO GW170817 provided upper limits for tidal polarizability < 580 neutron star radius and accordingly for neutron skin as well.
- Consistent with NICER, but tension with LIGO

CREX Result



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Precision Determination of the Neutral Weak Form Factor of ^{48}Ca

D. Adhikari *et al.* (CREX Collaboration)

Phys. Rev. Lett. **129**, 042501 – Published 20 July 2022

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ABSTRACT

We report a precise measurement of the parity-violating (PV) asymmetry A_{PV} in the elastic scattering of longitudinally polarized electrons from ^{48}Ca. We measure $A_{PV} = 2668 \pm 106\,(\mathrm{stat}) \pm 40\,(\mathrm{syst})$ parts per billion, leading to an extraction of the neutral weak form factor $F_W(q = 0.8733\,\mathrm{fm}^{-1}) = 0.1304 \pm 0.0052\,(\mathrm{stat}) \pm 0.0020\,(\mathrm{syst})$ and the charge minus the weak form factor $F_{ch} - F_W = 0.0277 \pm 0.0055$. The resulting neutron skin thickness $R_n - R_p = 0.121 \pm 0.026\,(\mathrm{exp}) \pm 0.024\,(\mathrm{model})$ fm is relatively thin yet consistent with many model calculations. The combined CREX and PREX results will have implications for future energy density functional calculations and on the density dependence of the symmetry energy of nuclear matter.

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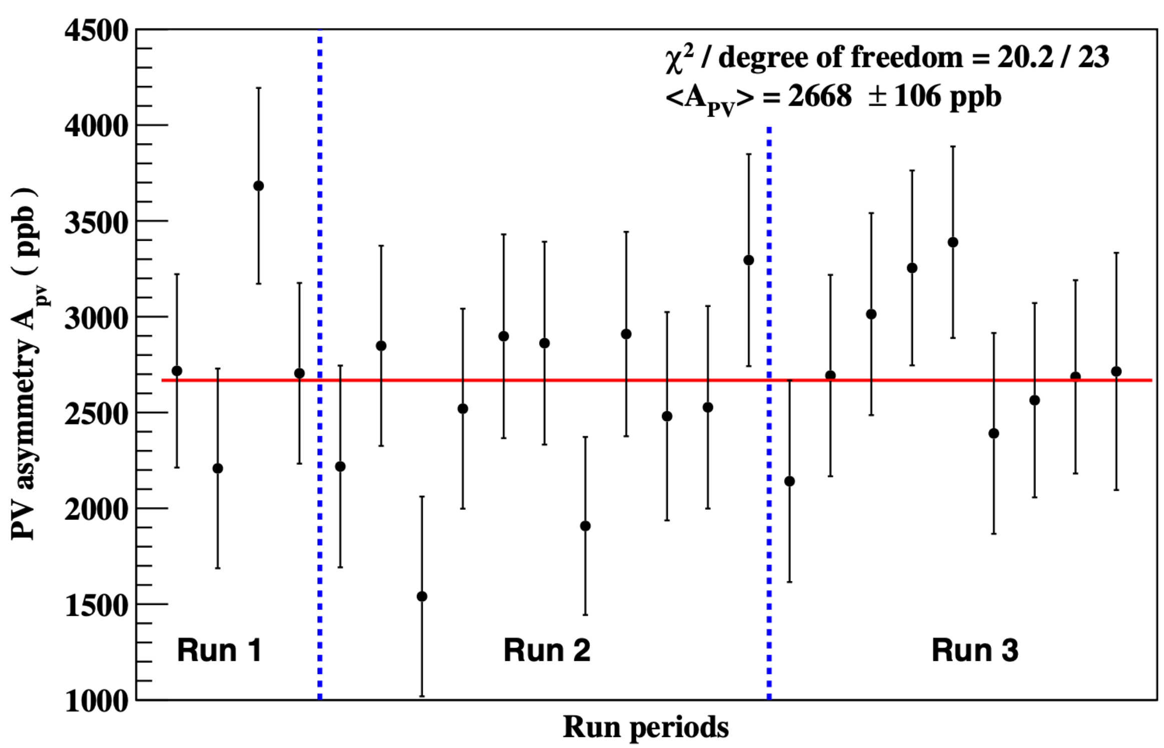
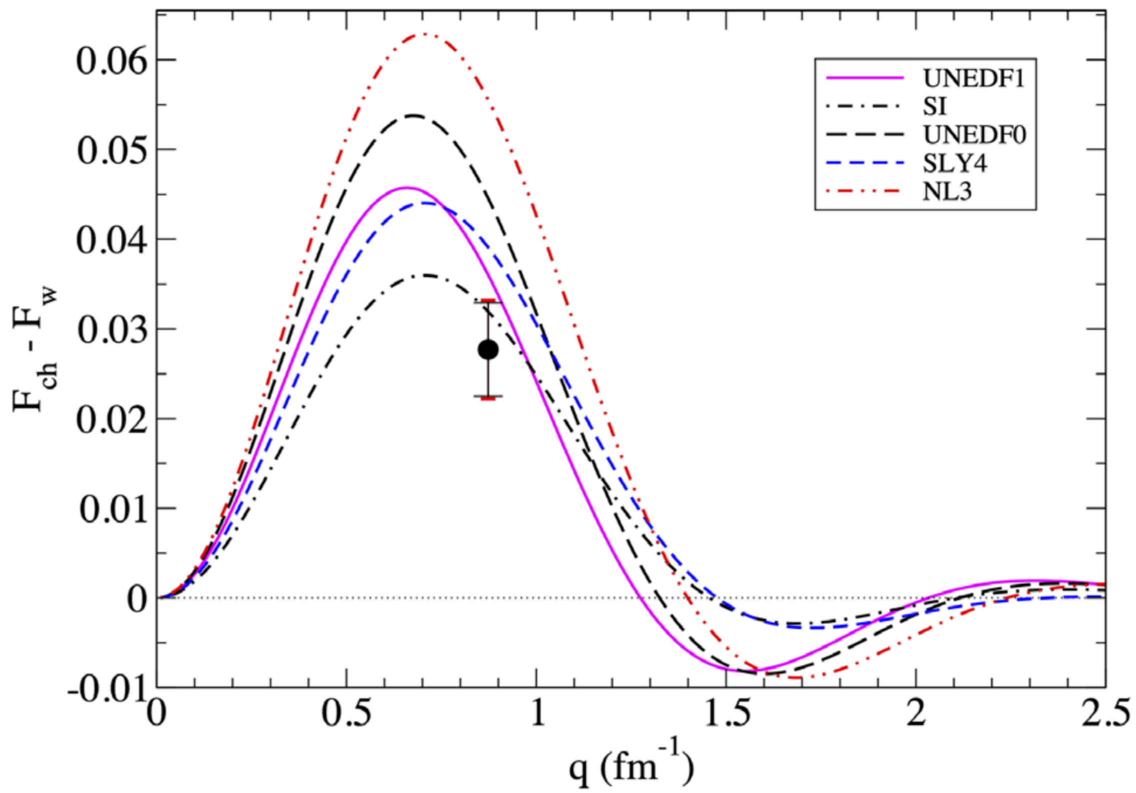
$$A_{PV} = 2668 \pm 106(\mathrm{stat}) \pm 40(\mathrm{syst})\ \mathrm{ppb}$$

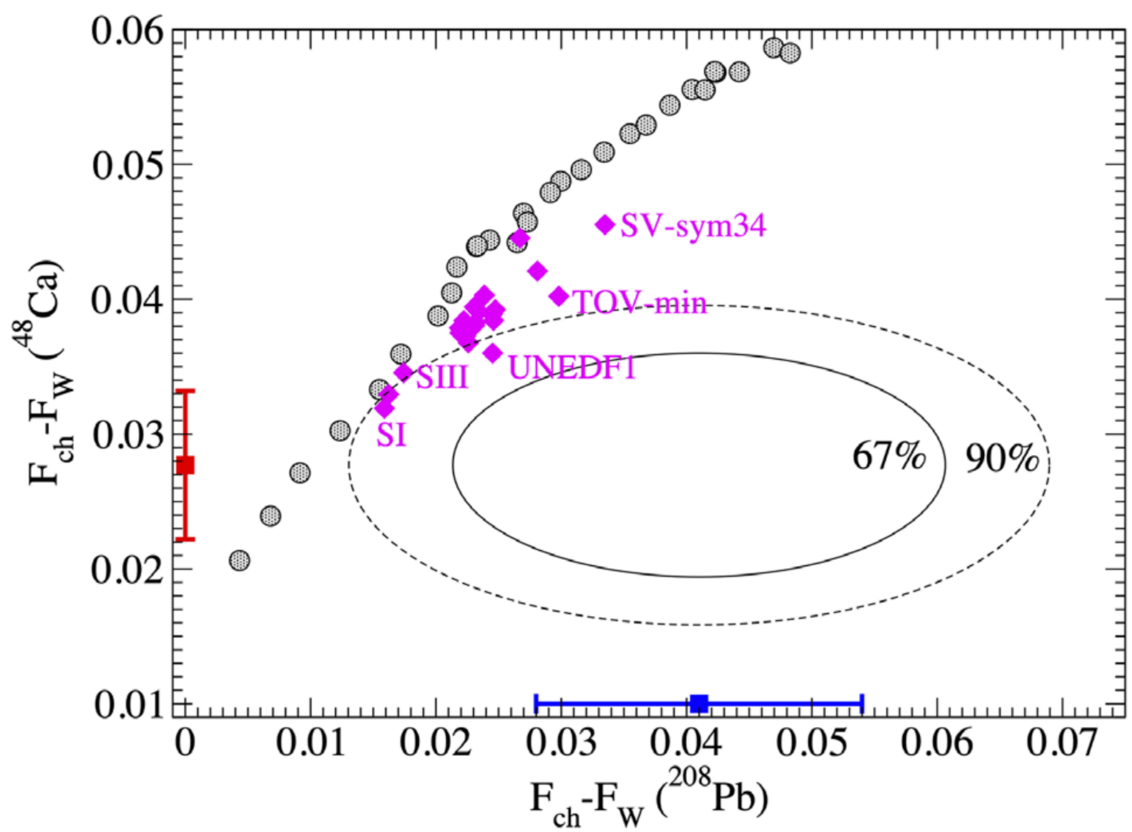
Correction	Absolute (ppb)	Relative (%)
Beam polarization	382 ± 13	14.3 ± 0.5
Beam trajectory and energy	68 ± 7	2.5 ± 0.3
Beam charge asymmetry	112 ± 1	4.2 ± 0.0
Isotopic purity	19 ± 3	0.7 ± 0.1
3.831 MeV (2^+) inelastic	-35 ± 19	-1.3 ± 0.7
4.507 MeV (3^-) inelastic	0 ± 10	0 ± 0.4
5.370 MeV (3^-) inelastic	-2 ± 4	-0.1 ± 0.1
Transverse asymmetry	0 ± 13	0 ± 0.5
Detector nonlinearity	0 ± 7	0 ± 0.3
Acceptance	0 ± 24	0 ± 0.9
Radiative corrections (Q_W)	0 ± 10	0 ± 0.4
Total systematic uncertainty	40 ppb	1.5%
Statistical uncertainty	106 ppb	4.0%



CREX results

Difference between charge and weak form factor

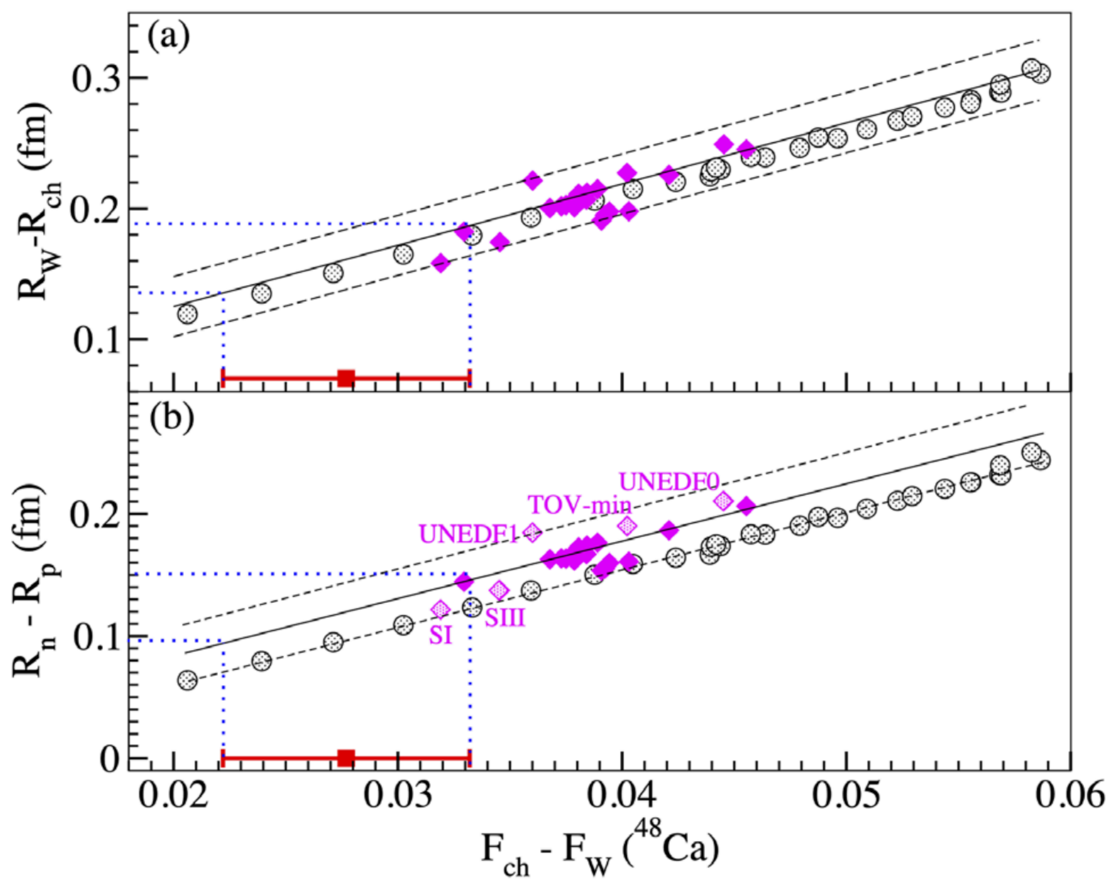


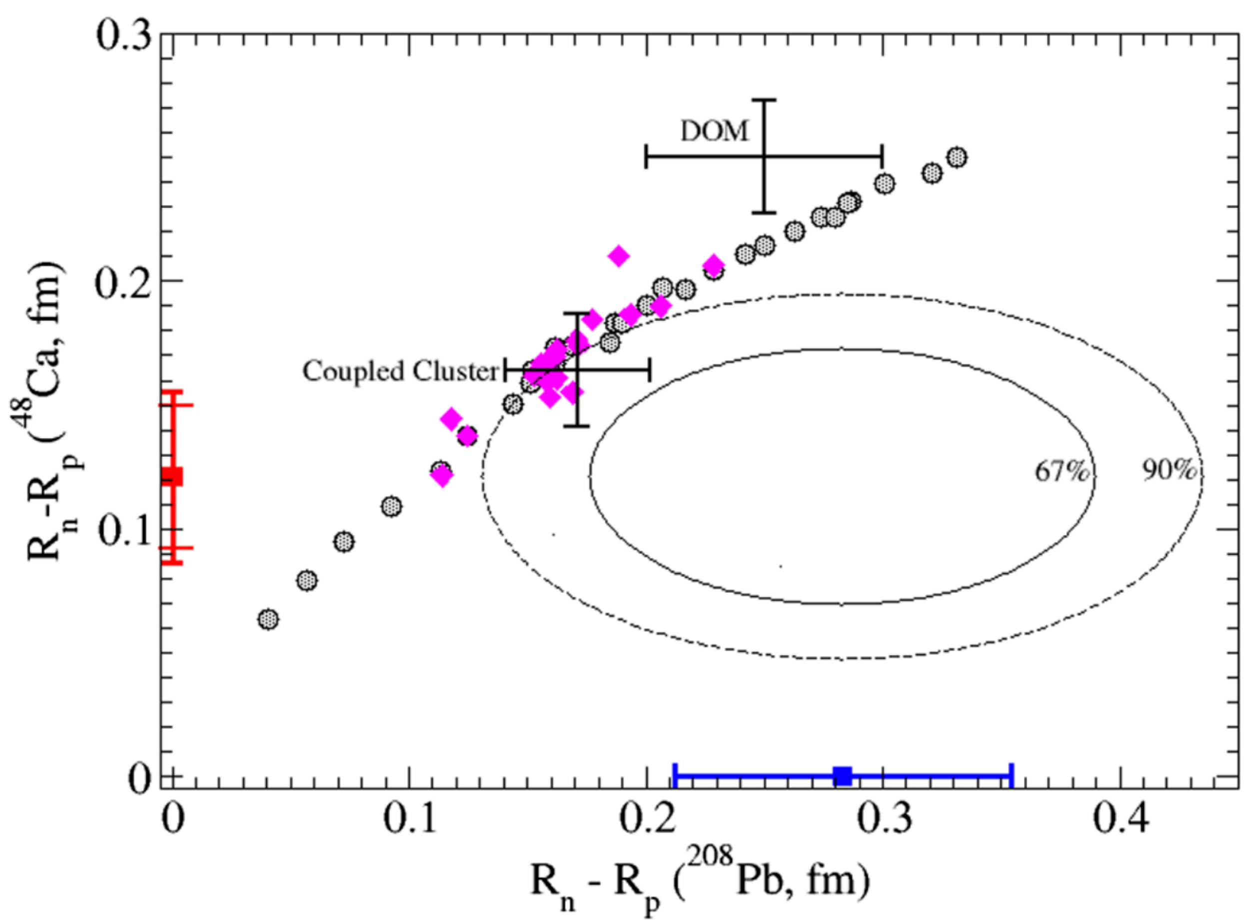


Quantity	Value ± (stat) ± (sys)
q	0.8733 fm^{-1}
$F_W(q)/F_{ch}(q)$	$0.8248 \pm 0.0328 \pm 0.0124$
$F_{ch}(q)$	0.1581
$F_W(q)$	$0.1304 \pm 0.0052 \pm 0.0020$
$F_{ch}(q) - F_W(q)$	$0.0277 \pm 0.0052 \pm 0.0020$

- Few models give consistent prediction for PREX and CREX

CREX results for neutron skin





- Model dependence in extracting neutron skin thickness

- Comparing to models
  - Pb-208 thick skin
  - Ca-48 thin skin

Collaboration

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Summary

- PREX-2 : Pb-208 **thick** neutron skin 0.283 (0.071) fm
  - Prefer to a larger L and larger neutron star
  - The final results were published in PRL as cover article in April 2021 and are already having an impact well beyond electron scattering community
- CREX: Ca-48 **thin** neutron skin 0.121 (0.035)fm
  - Model independent extraction for weak form factors
  - Model dependent extraction for neutron skin thickness, smaller than most model predictions
  - Provided tests of DFTs and microscopic calculations and thus provide valuable new insight into nuclear structure

Thank you for your attention!