Extracting neutron distributions using parity violating electron scattering

Chandan Ghosh (PREX/CREX collaboration)

2nd Nuclear Radius Extraction Collaboration (2026)

Jefferson Lab

April 14, 2026

U.S. DEPARTMENT OF ENERGY | Office of Science

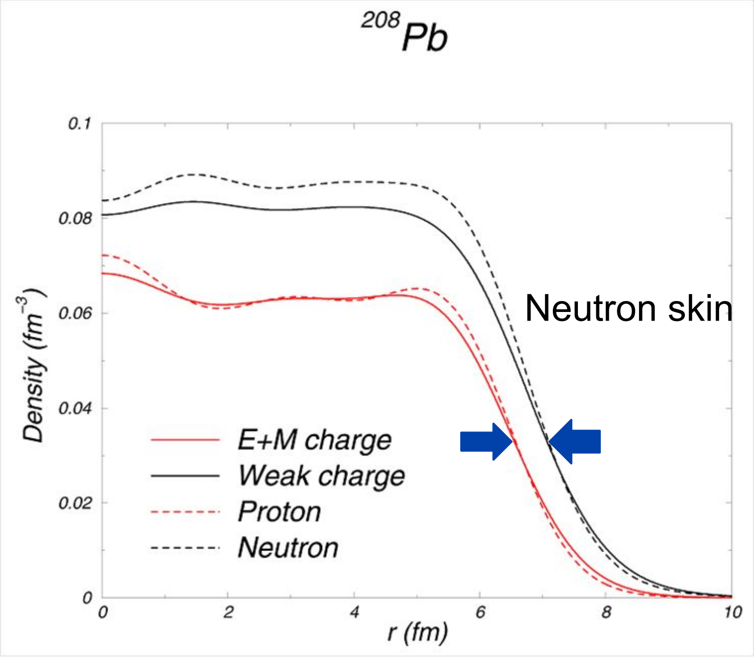
JSA

Outline

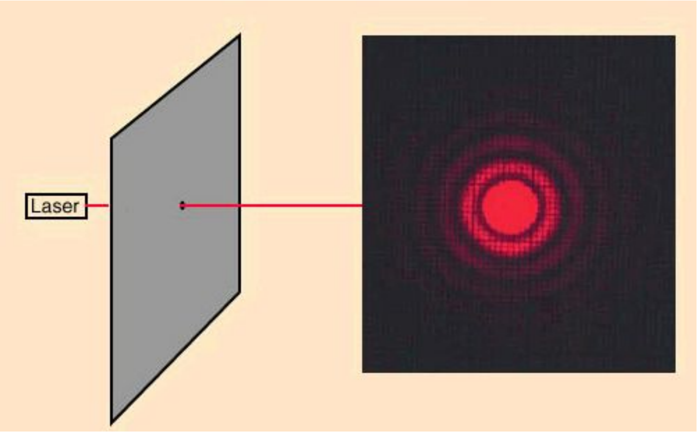
- Introduction: Radius measurement,

  parity-violating electron scattering
- Motivation of neutron skin measurements
- Experimental details
- Potential sources of error and their remedies.
- Results: PREX & CREX

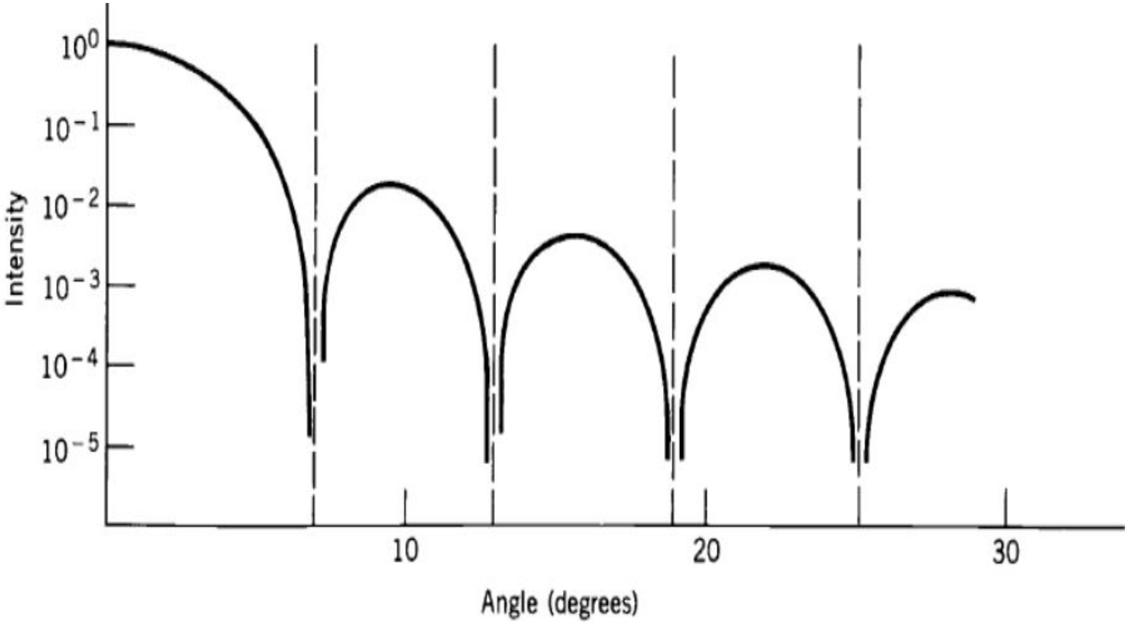
Summary



Diffraction of light through a pinhole



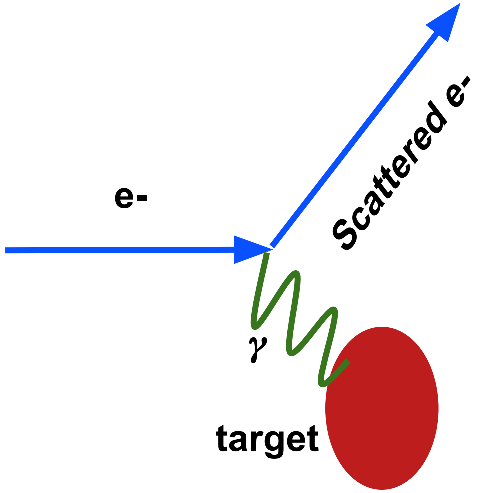
Intensity distribution



d **: diameter of the aperture**

Location of first minimum: $\sin\theta = \frac{1.22\lambda}{d}$

Scattering of a high energy electron from nucleus



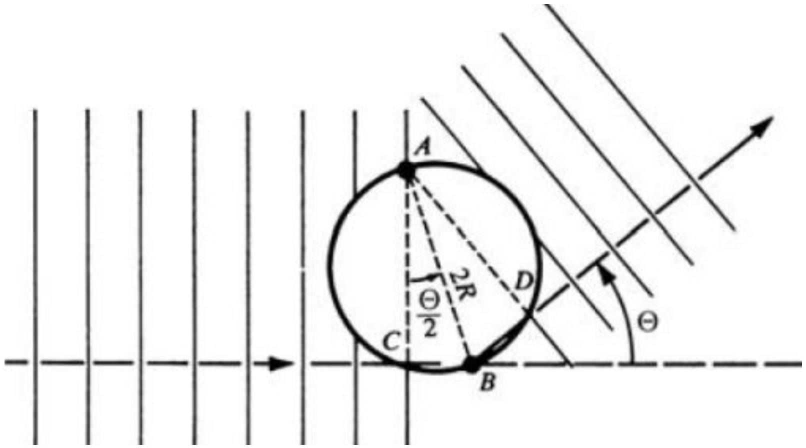
Particle-wave duality

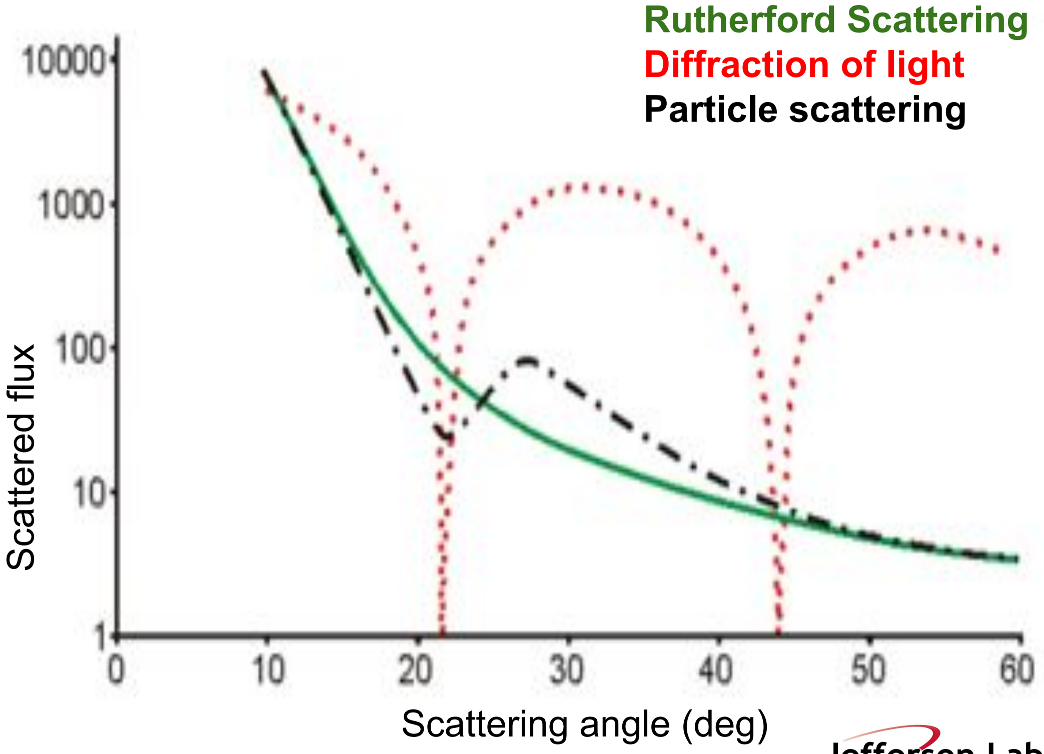
$$\lambda = \frac{h}{p}$$

$$h : Plank\ constant$$

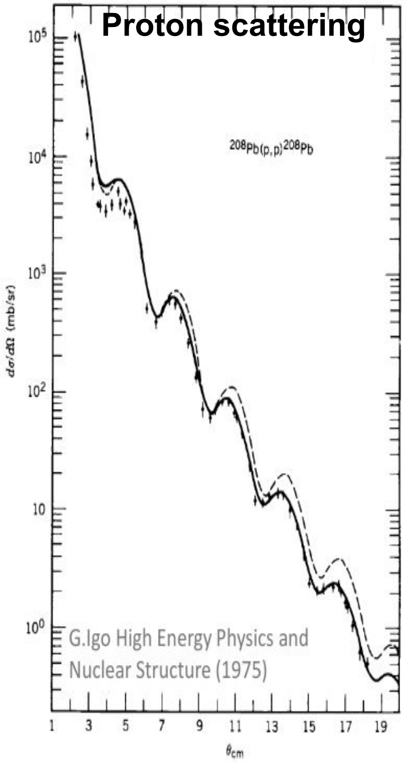
$$p : particle\ momentum$$

For 1 GeV electron,
the wavelength ~ 1.2 fm

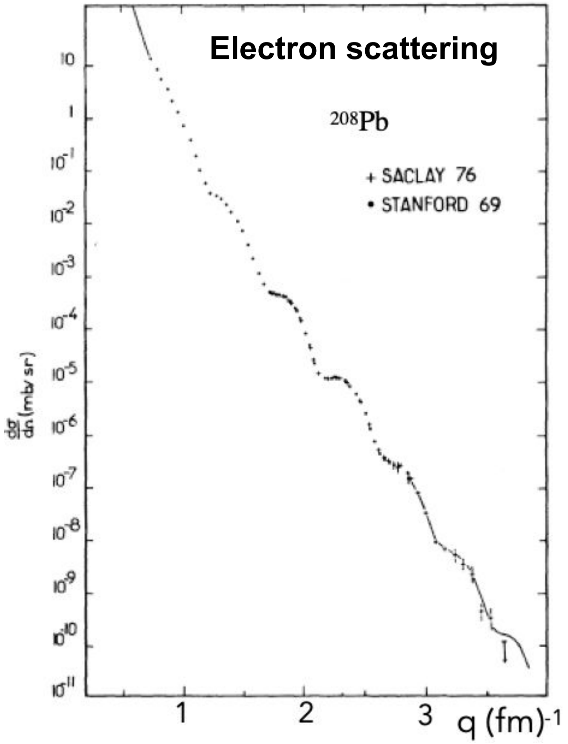


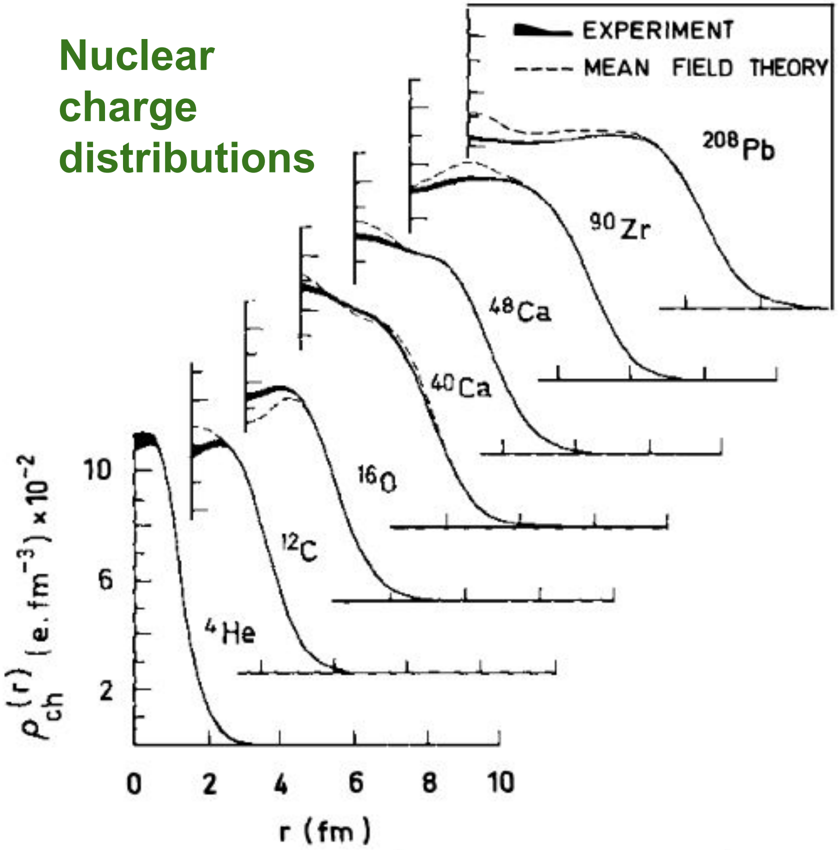


Electron scattering and nuclear structure



G.Igo High Energy Physics and Nuclear Structure (1975)





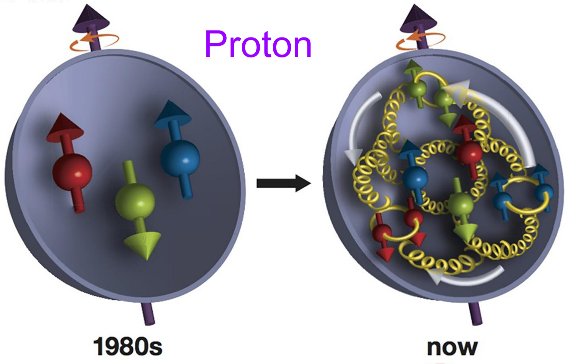
Nuclear charge distributions

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Mott} |\, F(q) \,|^2$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm Mott} = \frac{4Z^2\alpha^2E^2}{Q^4}$$

The form-factor is the Fourier transform of charge density

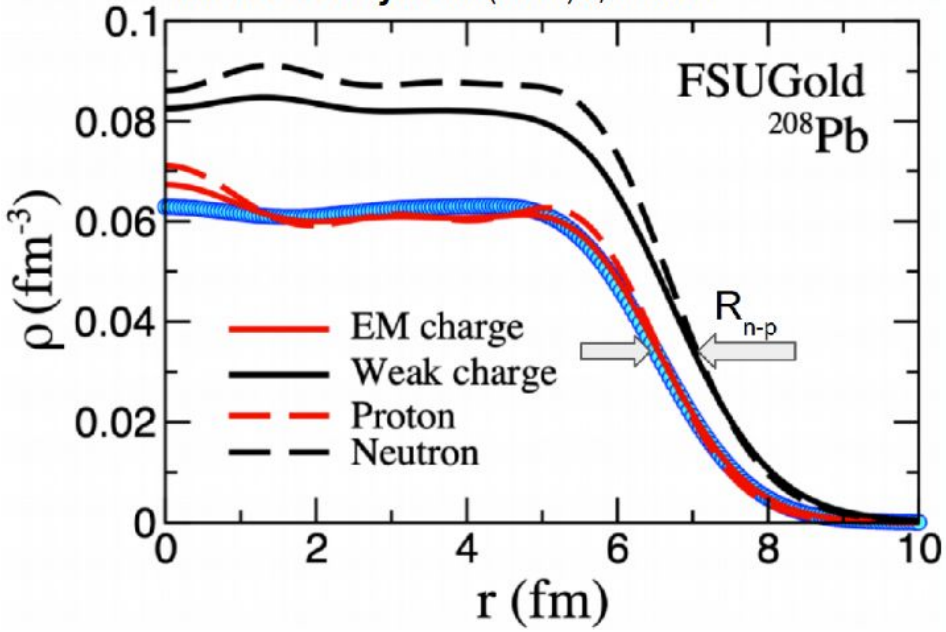
Electron is a better probe!!

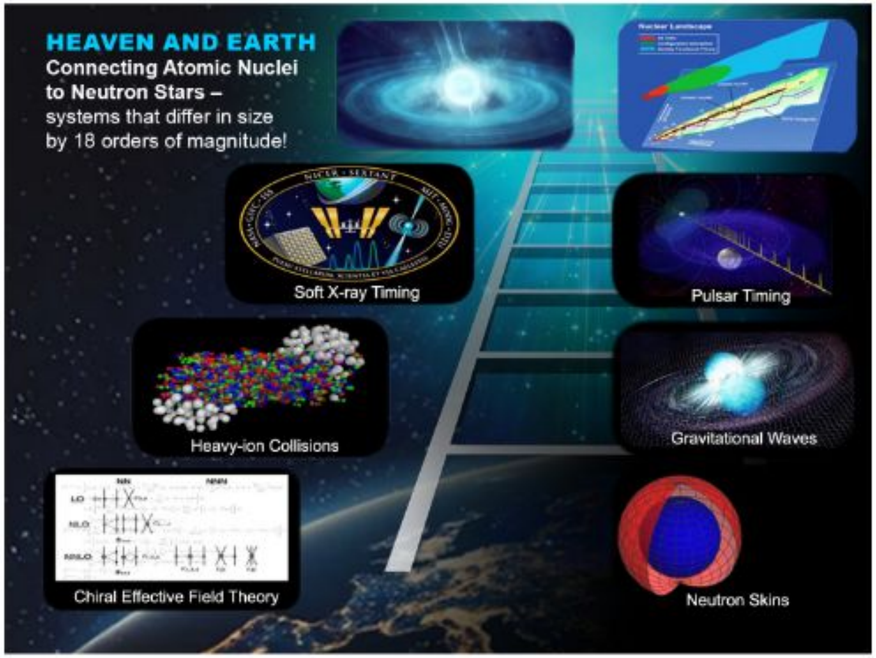


Weak charge distribution of heavy nuclei

Nuclear theory predicts a neutron "skin" on heavy nuclei

Thiel et al J.Phys.G 46 (2019) 9, 093003





HEAVEN AND EARTH
Connecting Atomic Nuclei to Neutron Stars – systems that differ in size by 18 orders of magnitude!

arXiv:2604.08286

Weak charge of the proton is heavily suppressed compared to the neutron

$$Q_w = (1 - 4sin^2\theta_w)Z - N$$

Neutron distribution matches the weak charge distribution

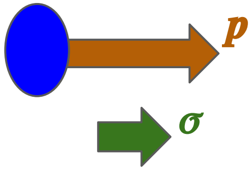
PREX- ^{208}Pb (82p+126n, n/p=1.54) Radius Experiment
CREX - ^{48}Ca (20p+28n, n/p=1.4) Radius Experiment

Parity-violation and Electron scattering (PVES)

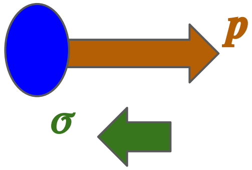
$$Helicity = \frac{\sigma.p}{|\sigma.p|}$$

σ - spin vector

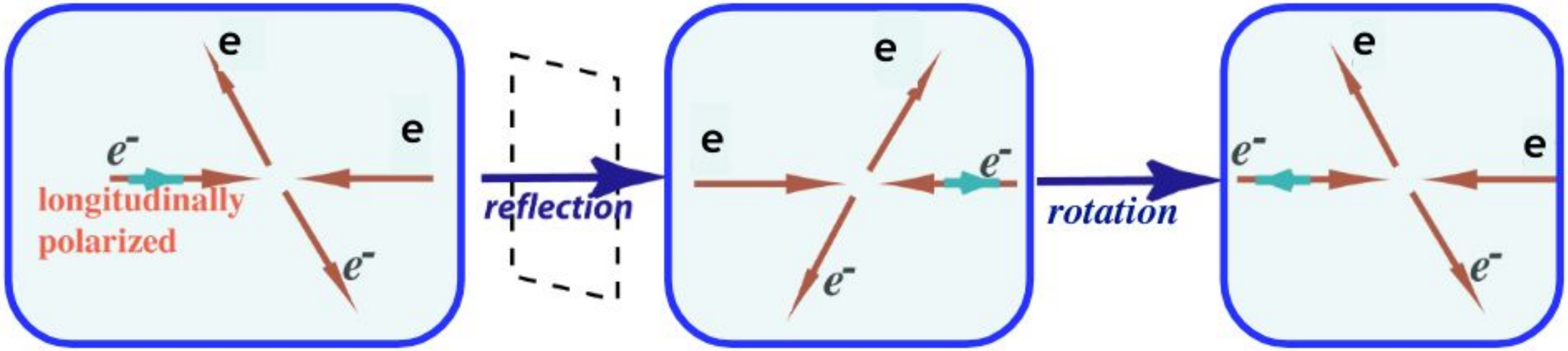
p - momentum vector



Helicity = Right (+)



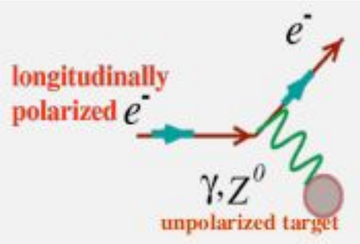
Helicity = Left (-)

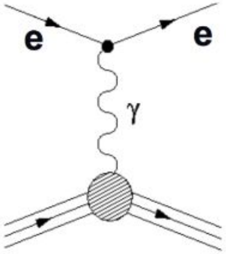


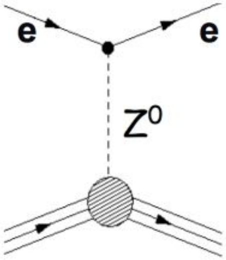
Helicity = Right (+)

Helicity = Left (-)

Parity-Violating Electron Scattering (PVES)





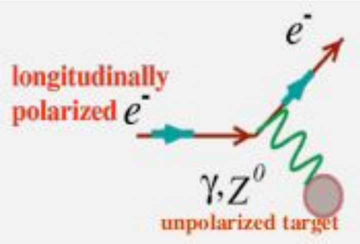


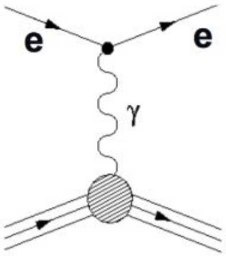
Looking for a needle!!

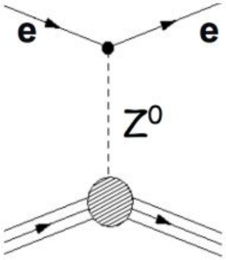
$$\sigma_{R(L)} = |A_\gamma + A_{Z^0}|^2 = |A_\gamma|^2 + 2|A_\gamma||A_{Z^0}| + |A_{Z^0}|^2$$

Interference of electromagnetic and weak neutral current amplitude

Parity-Violating Electron Scattering (PVES)







Looking for a needle!!

$$\sigma_{R(L)} = |A_\gamma + A_{Z^0}|^2 = |A_\gamma|^2 + 2|A_\gamma||A_{Z^0}| + |A_{Z^0}|^2$$

Interference of electromagnetic and weak neutral current amplitude

Looking for a needle with magnet!!

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

Parity-Violating Electron Scattering (PVES)

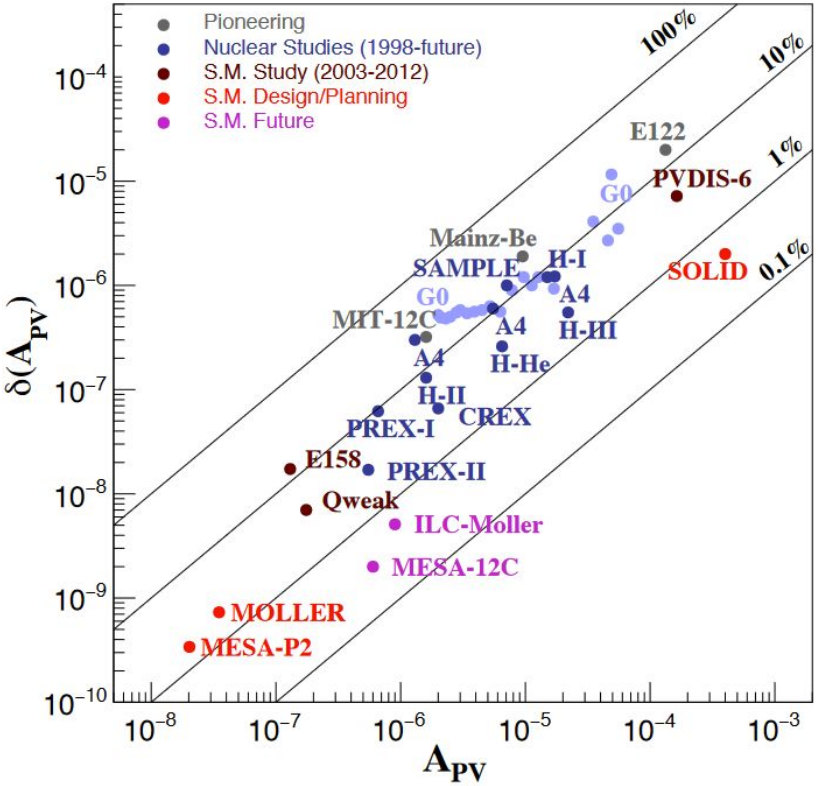
$$\sigma_{R(L)} = |A_\gamma + A_{Z^0}|^2 = |A_\gamma|^2 + 2|A_\gamma||A_{Z^0}| + |A_{Z^0}|^2$$

Steady improvements of parity experiments

$$\mathrm{A_{pv}} = \frac{\sigma_\mathrm{R} - \sigma_\mathrm{L}}{\sigma_\mathrm{R} + \sigma_\mathrm{L}}$$

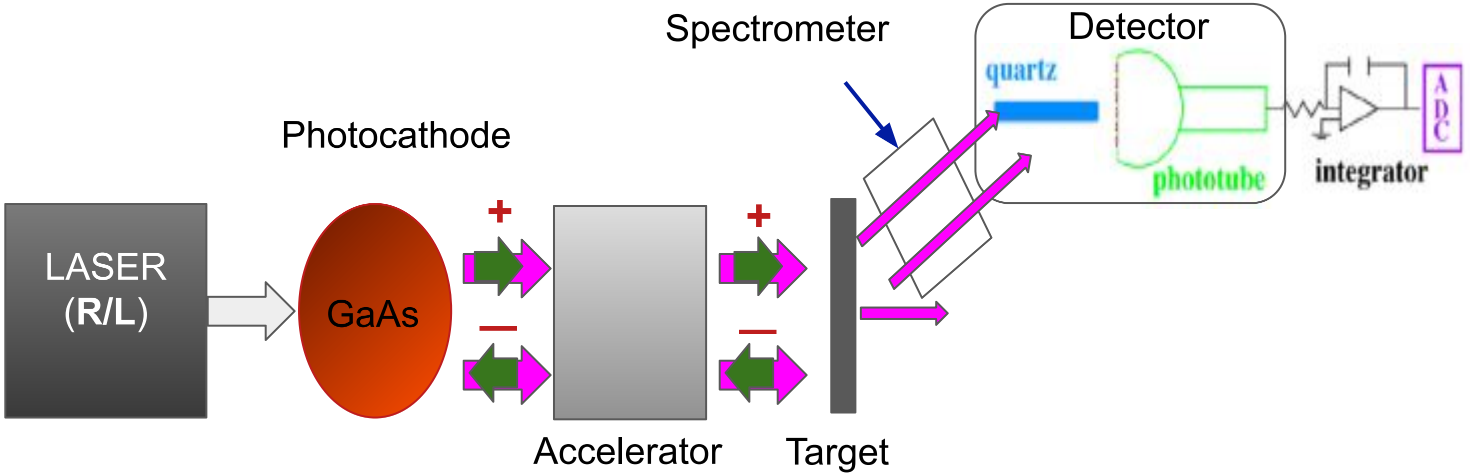
For spin 0 nuclei:

$$A_{PV} \approx -\frac{G_F Q^2 Q_W}{4\pi\alpha\sqrt{2}Z}\frac{F_W(Q^2)}{F_{ch}(Q^2)}$$



- ❖ PVES is used extensively to study nucleon, nuclear structures and for searches of new physics beyond the Standard model.

PVES experiment - in a single slide

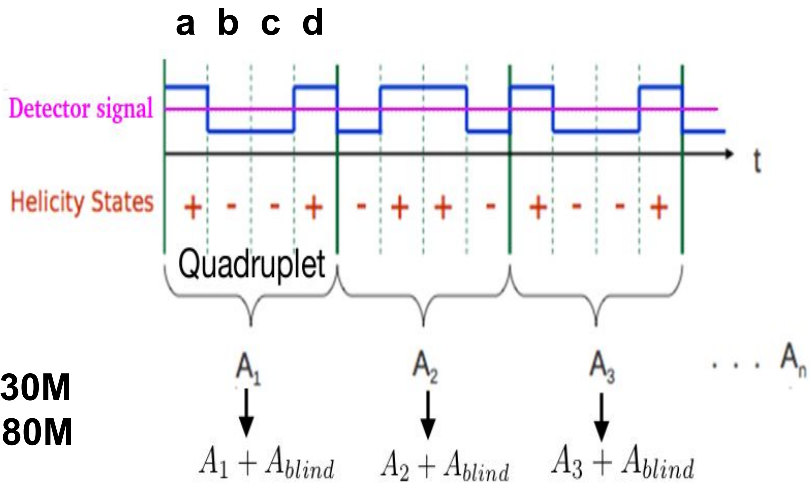


Rate~GHz

**"Rapid" and "random"
LASER polarization flip**

PREX:~50μA 950 MeV

CREX:~120μA 2.1 GeV

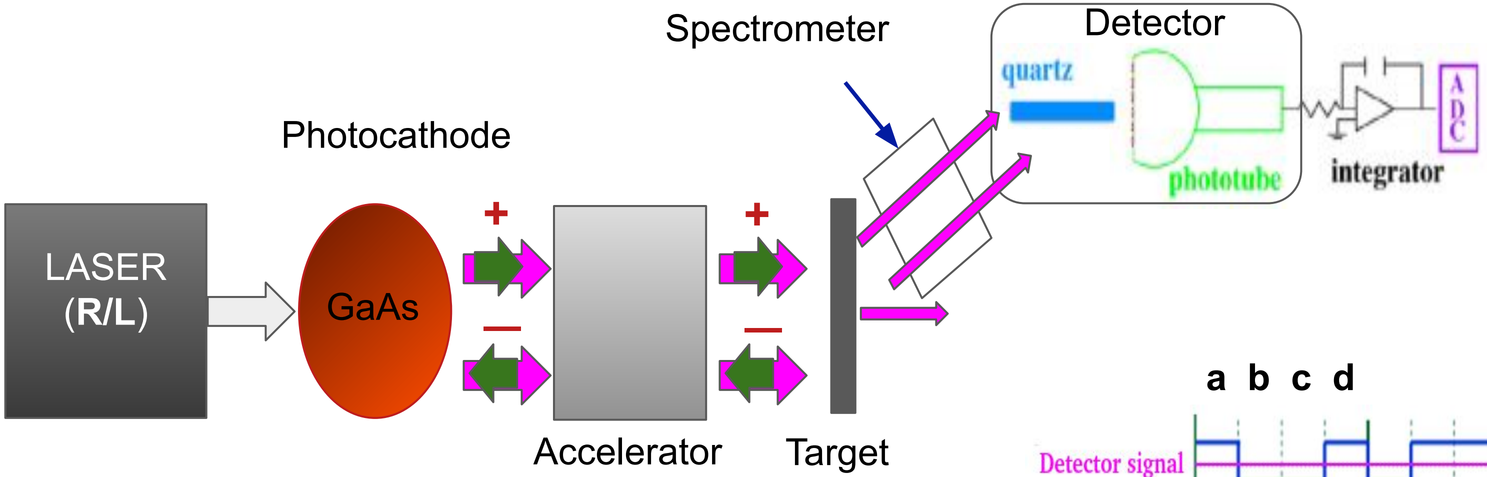


**PREX, n=30M
CREX, n=80M**

A1 = (a-b-c+d)/(a+b+c+d)

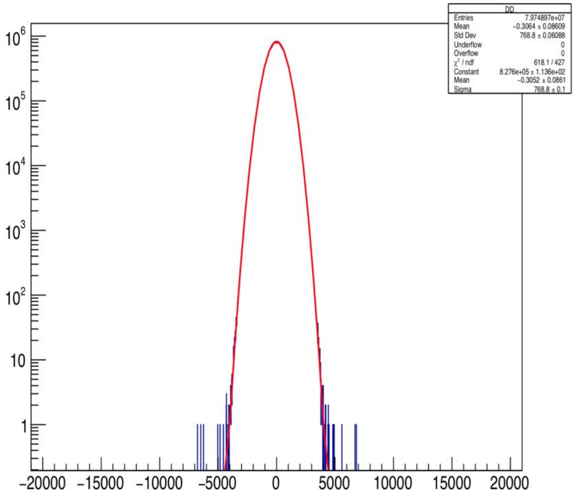
Data Blinding to eliminate personal bias

PVES experiment - in a single slide



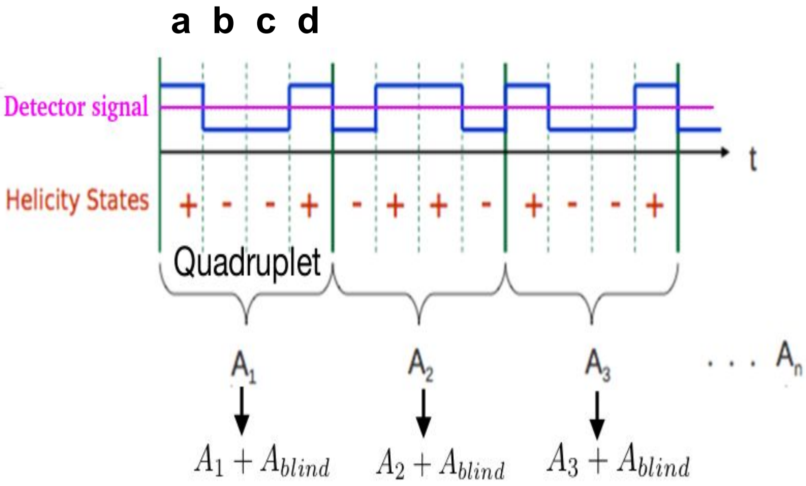
Rate~GHz

**“Rapid” and “random”
LASER polarization flip**



$$A \pm \sigma / \sqrt(n)$$

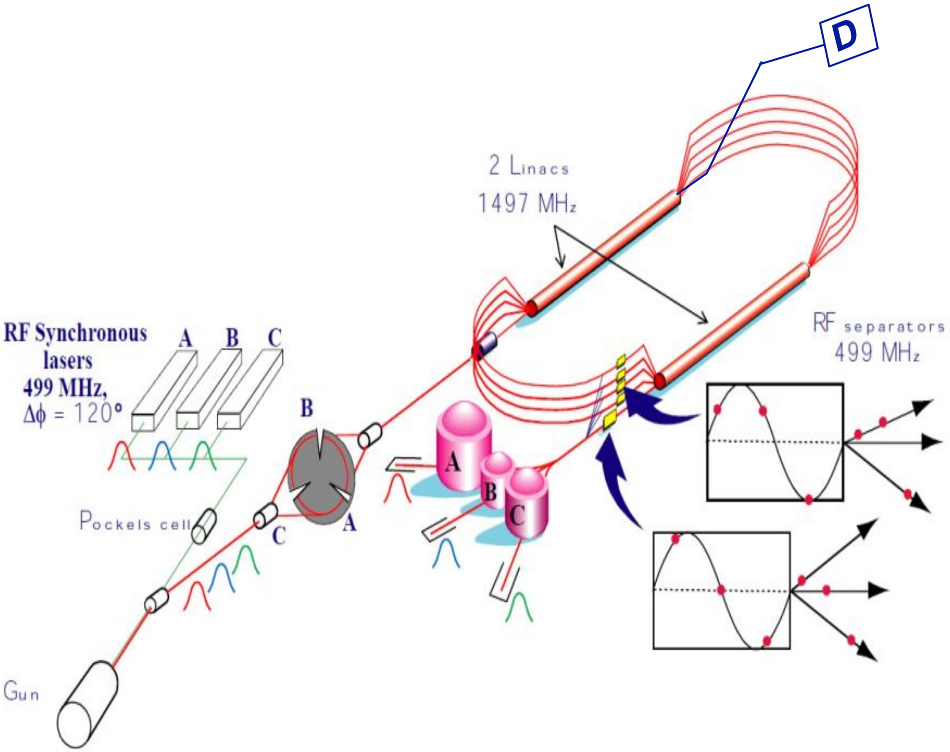
**PREX, n=30M
CREX, n=80M**



A1 = (a-b-c+d)/(a+b+c+d)

Data Blinding to eliminate personal bias

Jefferson Lab - is the best place for its excellent beam!!

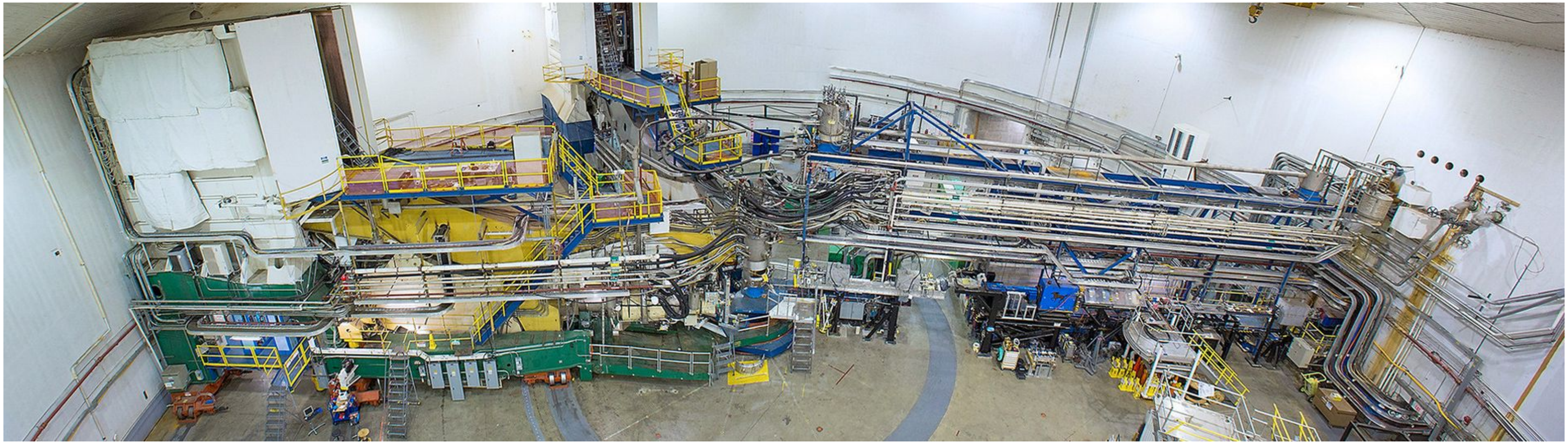


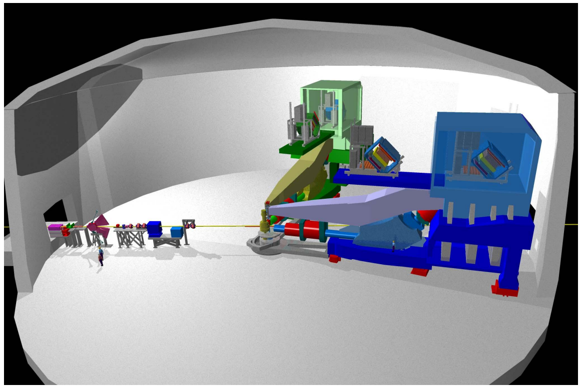
Evolutionary progression to extraordinary luminosity and electron beam stability with high longitudinal beam polarization

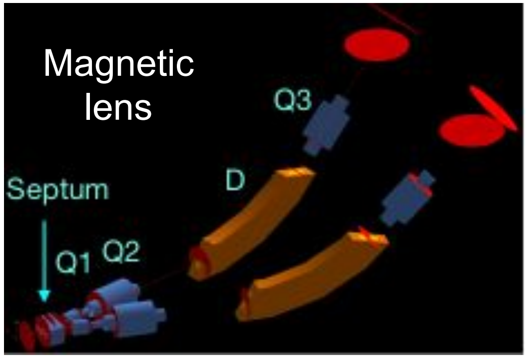
PREX-2 ran Jun-Sept 2019 - 114 C Charge

CREX ran Dec'19 to Sept'20 - 382 C Charge

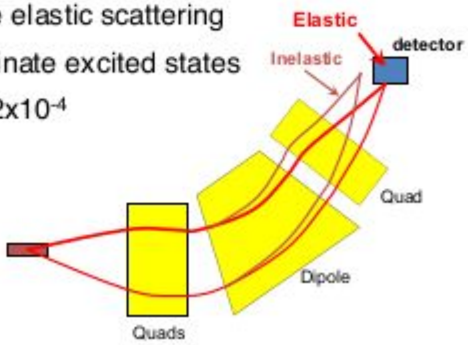
High resolution spectrometers



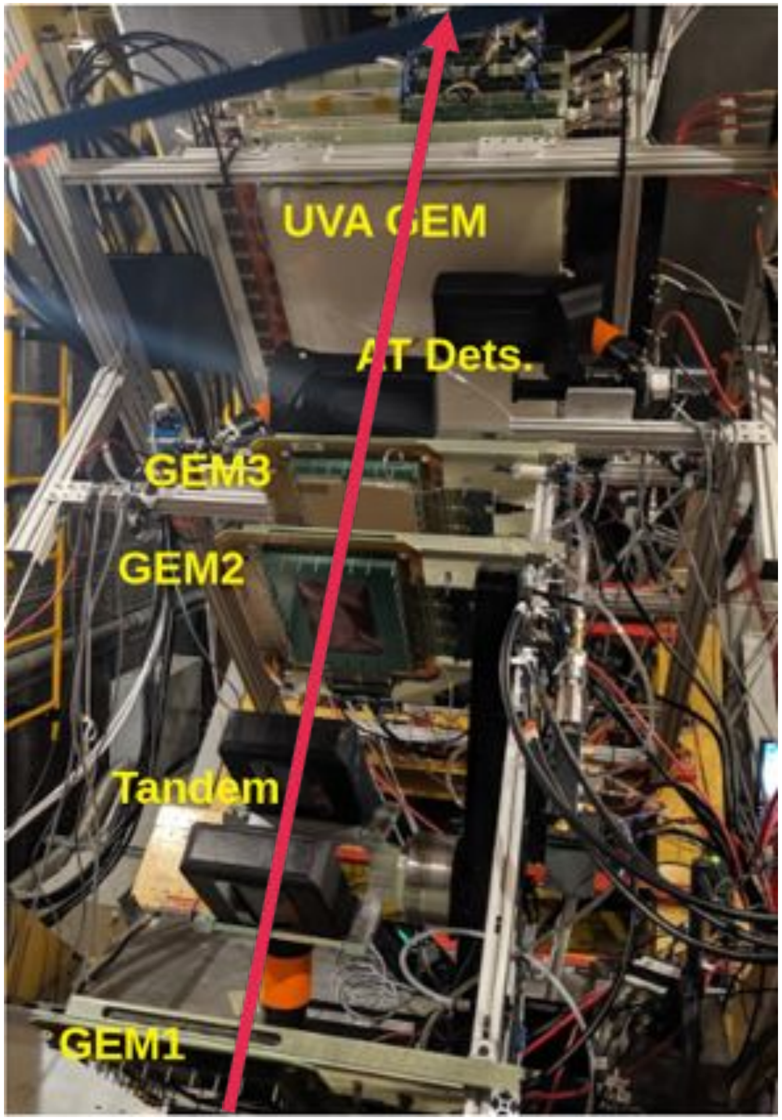




- Resolve elastic scattering
- Discriminate excited states
- dp/p ~ 2×10^{-4}



Detector Systems



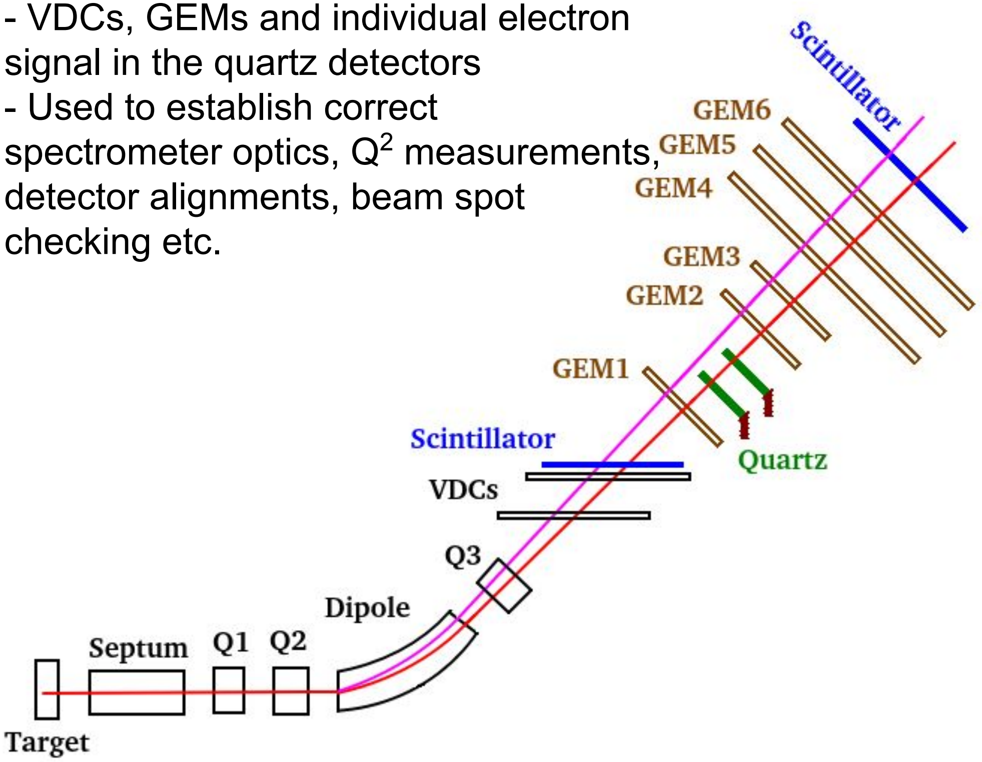
Integrating detectors:

- Charge integration method
  - 50 μA beam with helicity trigger
  - GHz electrons ~ 3x3 cm^2 area

-**Radiation hard** fused silica (Two in each HRS arm) - Cherenkov detectors

Counting detectors:

- 50 nA beam with scintillator triggers - few hundred Hz trigger rate
- VDCs, GEMs and individual electron signal in the quartz detectors
- Used to establish correct spectrometer optics, Q^2 measurements, detector alignments, beam spot checking etc.

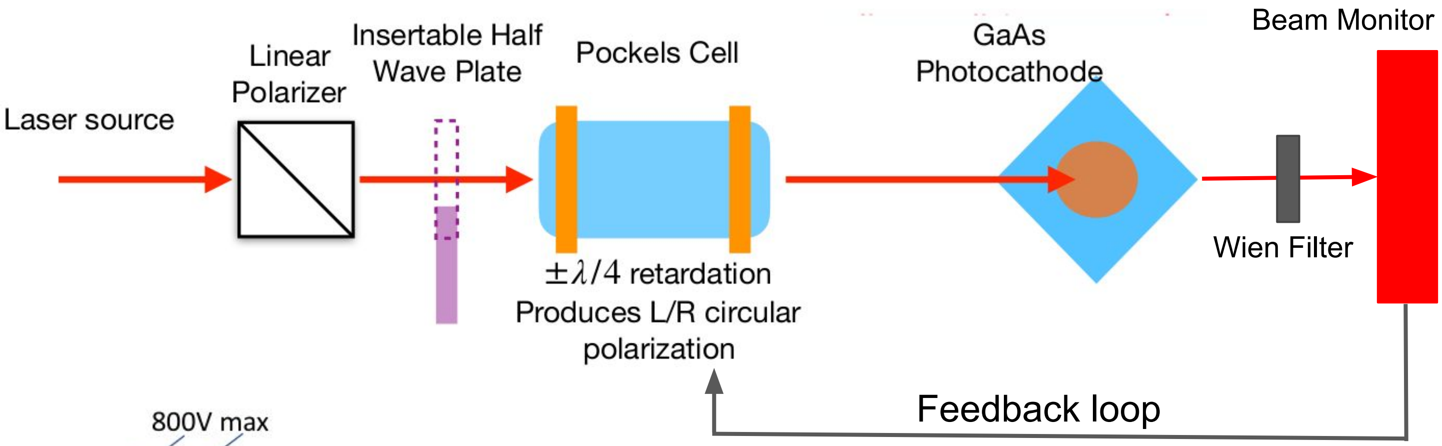


False asymmetry: Asymmetry not coming from our physics interest

Sources of Error/False Asymmetry

- Helicity dependent False Asymmetry: At the source, the number of electrons with positive and negative helicity (in subsequent windows) are not the same.

Source of polarized electrons and control of false asymmetry


Laser source

Linear Polarizer

Insertable Half Wave Plate

Pockels Cell

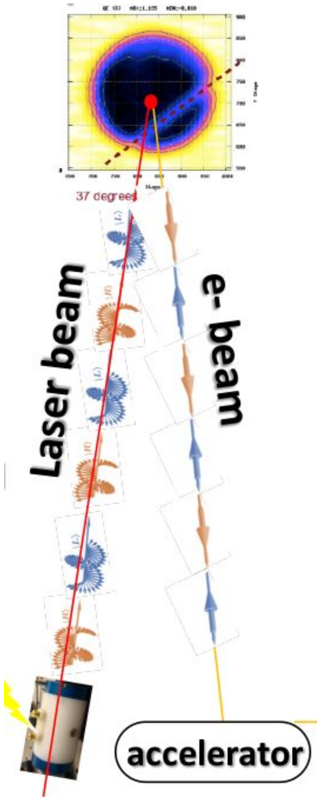
GaAs Photocathode

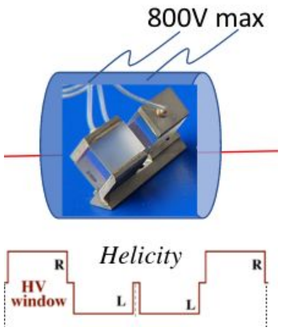
Beam Monitor

Wien Filter

±$\lambda/4$ retardation
Produces L/R circular polarization

Feedback loop

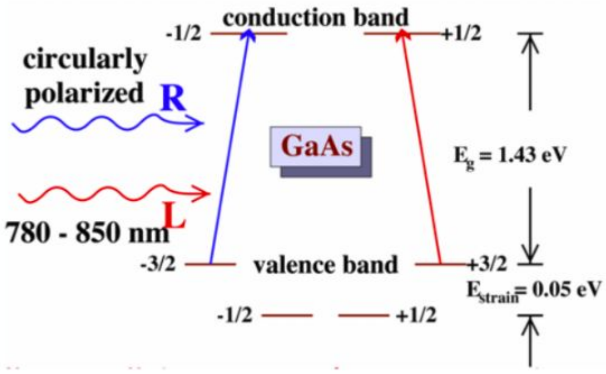




“Rapid” and “random” helicity flip
“Rapid” - to keep the beam condition “identical” for two opposite helicity states

“Random” - to cancel any correlated noise pickup

To cancel beam asymmetry
1. Fast - helicity flip - Pockels Cell
2. Slow-helicity reversal (every 6 hours) - Insertable Half wave plate
3. Double Wien rotation - Electromagnetically rotate electron’s spin -3 Wien flips



Sources of Error/False Asymmetry

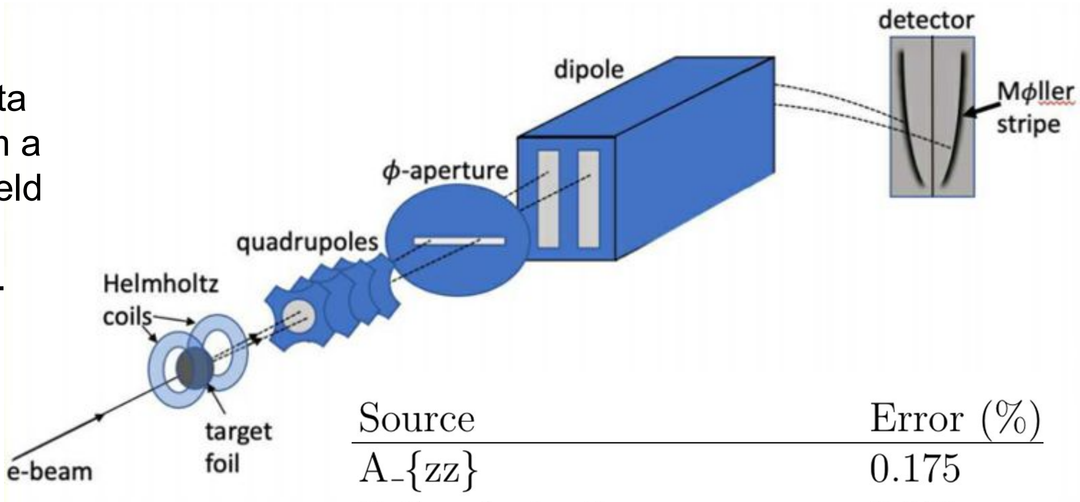
- Helicity dependent False Asymmetry: At the source, the number of electrons with positive and negative helicity (in subsequent windows) are not the same.
- Polarization: Beam is not 100% longitudinally polarized. The asymmetry with perpendicular beam polarization needs special measurements.

Needs Beam polarization measurements

1. **Moller Polarimeter**
2. **Compton Polarimeter**

Moller polarimeter

- Low current invasive measurements - Took fewer runs to cross-check with Compton data
- MOLLER -scattering of beam electrons from a magnetized Fe foil using a 3-4T magnetic field
- No significant fluctuation of measured polarization is observed over the run period.
- **Statistics: <0.25% per measurement**
- **Systematic: 0.85% relative uncertainty**



$$A_{beam} = A_{zz}\ P_{Fe\ foil}\ P_{beam}$$

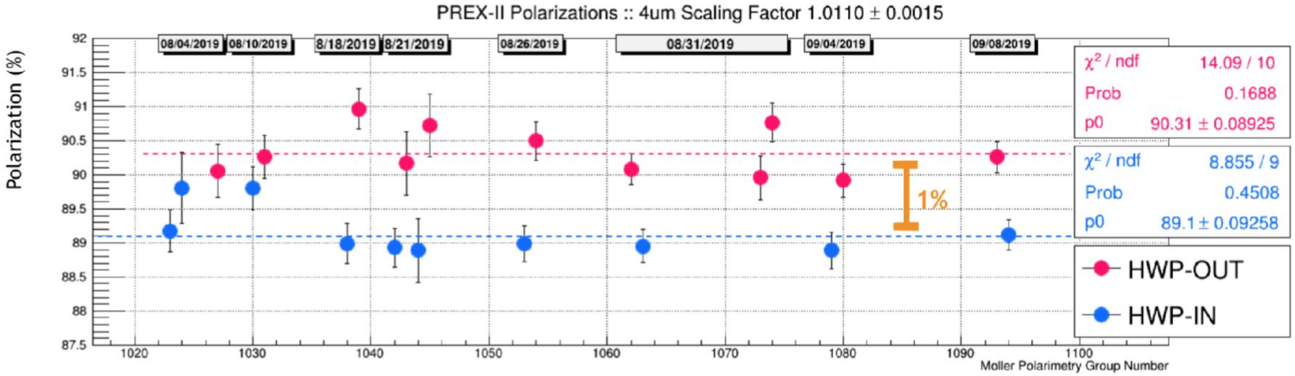
measured

from simulation

from theory assuming saturation

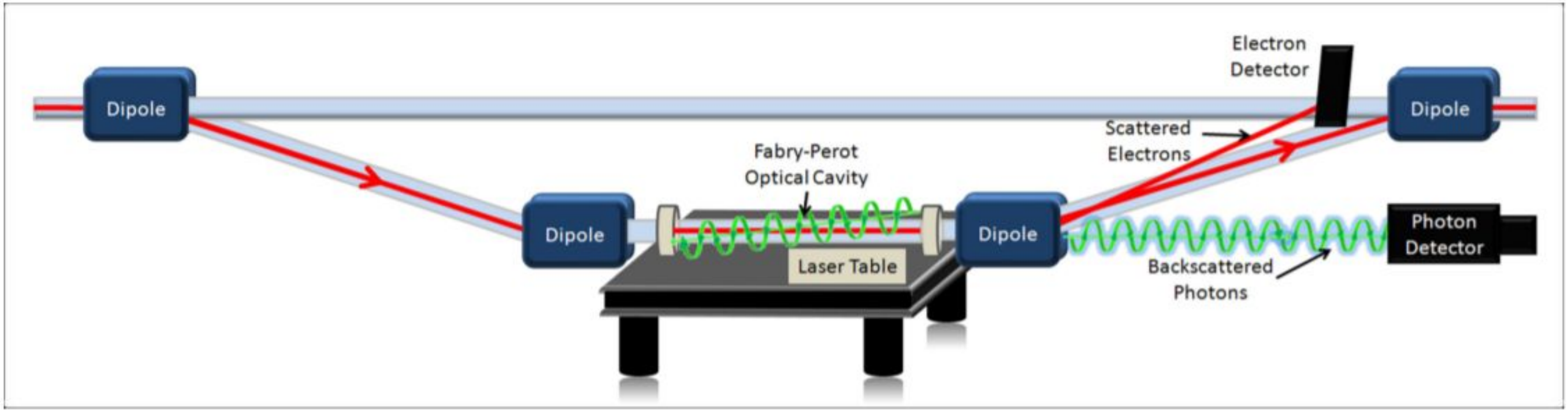
extracted

Source	Error (%)
A_{zz}	0.175
Foil polarization	0.571
Current bleedthrough	0.09
Laser polarization	0.07
High current extrapolation	0.51
Other	0.31
Total	**0.85**

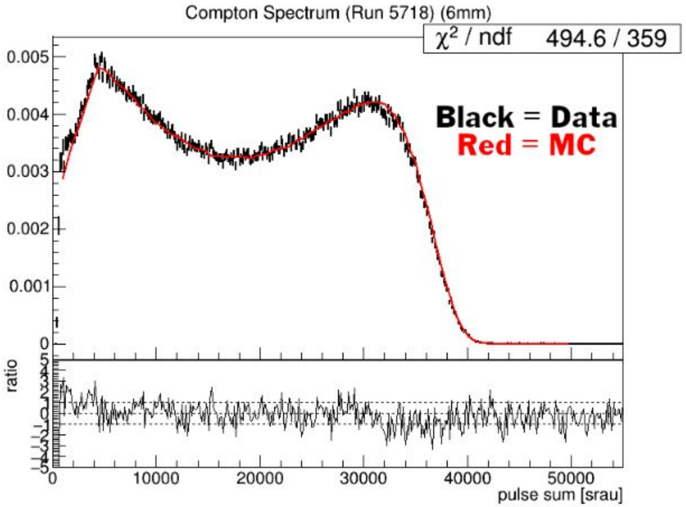


Average polarization - 89.7 (0.8)% - one of the sub-percent measurement at JLab

Compton Polarimeter

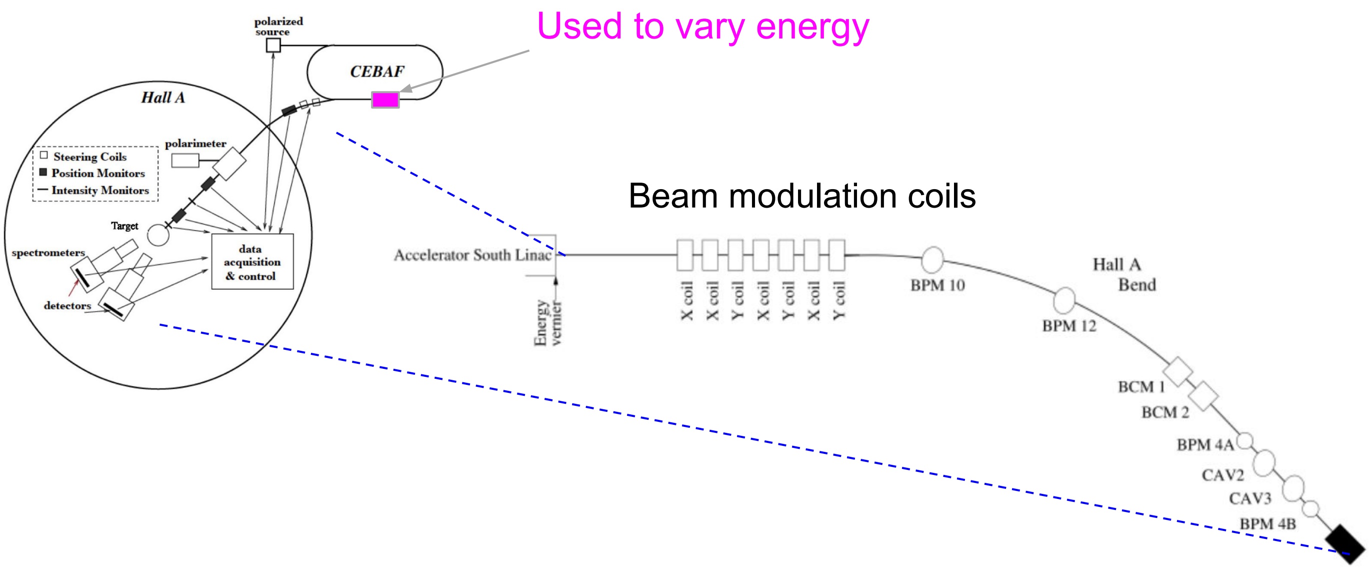


- Continuous, non-invasive measurement
- Polarimeter runs were taken continuously alongside the main detector data
- Utilized integrating technique with photon detector
- Evaluated systematic uncertainty

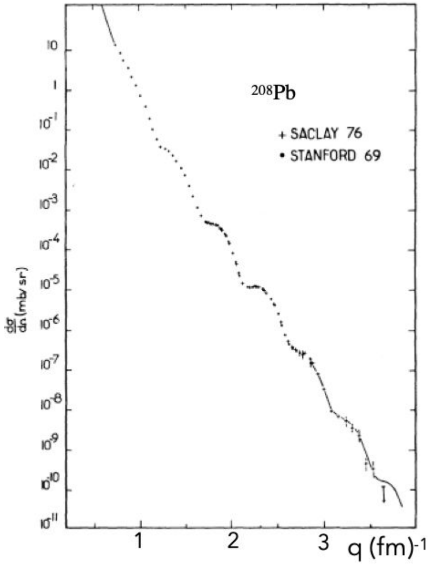


Sources of Error/False Asymmetry

- Helicity dependent False Asymmetry: At the source, the number of electrons with positive and negative helicity (in subsequent windows) are not the same.
- Polarization: Beam is not 100% longitudinally polarized. The asymmetry with perpendicular beam polarization needs special measurements.
- Beam motion: Beam- position, angle and energy are not identical between the two subsequent helicity windows - forced beam modulation

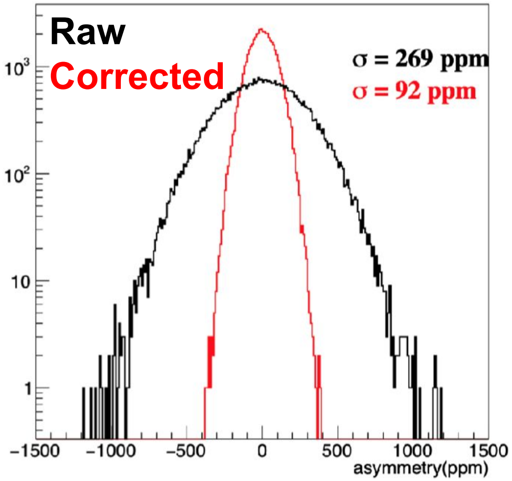

Used to vary energy

Beam modulation coils



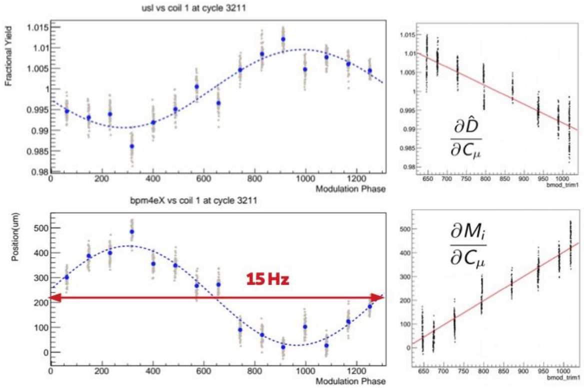
Blinded Data Analysis -Beam motion correction

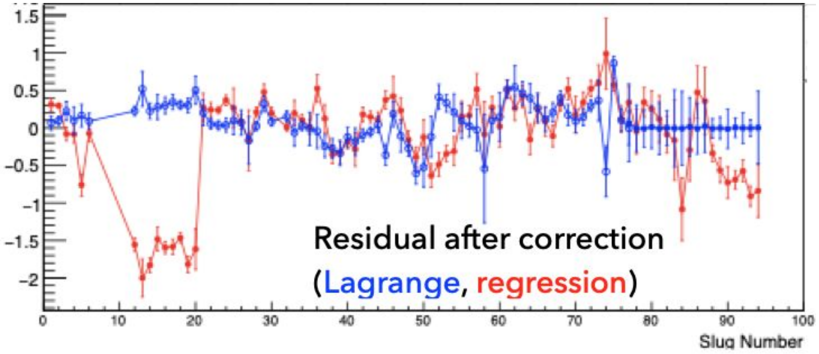
- Steep form-factor and very forward angle scattering make the observed yield difference very sensitive to beam corrections
- Beam jitter noise is several times greater than counting statistics



$$A = A_{raw} - A_Q - \sum_i \alpha_i \Delta x_i - \alpha_E A_E$$

❖ Multiple techniques are used to calibrate correction factors (α_i)
  - ➢ Regression: Natural beam motion
  - ➢ Beam modulation: use driven modulation
  - ➢ Lagrange multiplier: natural beam motion constrained by driven modulations





Residual after correction
(Lagrange, regression)

Main derived parameters:

Extracted quantities	PREX (^{208}Pb)	CREX (^{48}Ca)
Asymmetry (ppb)*	550 ± 16 (stat) ± 8 (syst)	2658.6 ± 106 (stat) ± 40 (syst)
Weak form factor*	0.368±0.013	0.1304±0.0056
Weak skin (fm)*	0.041 ± 0.013	0.0277 ± 0.0055
Neutron skin (fm)	***0.278±0.079***	***0.121 ± 0.035***

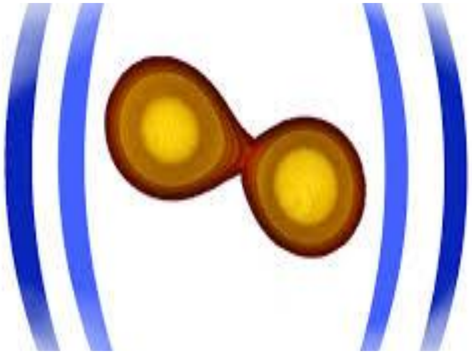
(*Model independent extraction)

- **Existing average skin thickness for ^{208}Pb using other probes~ *0.15* -0.20 fm**
- **Ab-initio prediction for ^{48}Ca skin thickness: $0.12 \lesssim R_{skin} \lesssim 0.15$ fm**

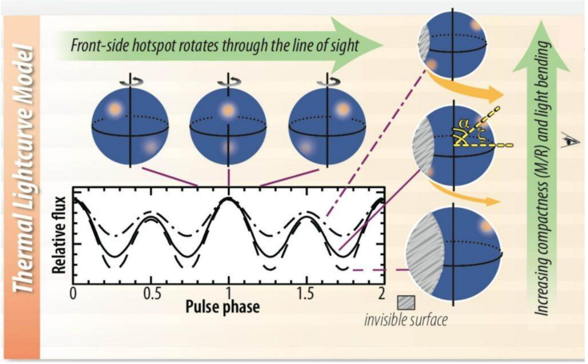
PREX: PRL 126 172502 (2021)
CREX: PRL 129 042501 (2022)

PREX-2 Result - Thicker Neutron Skin

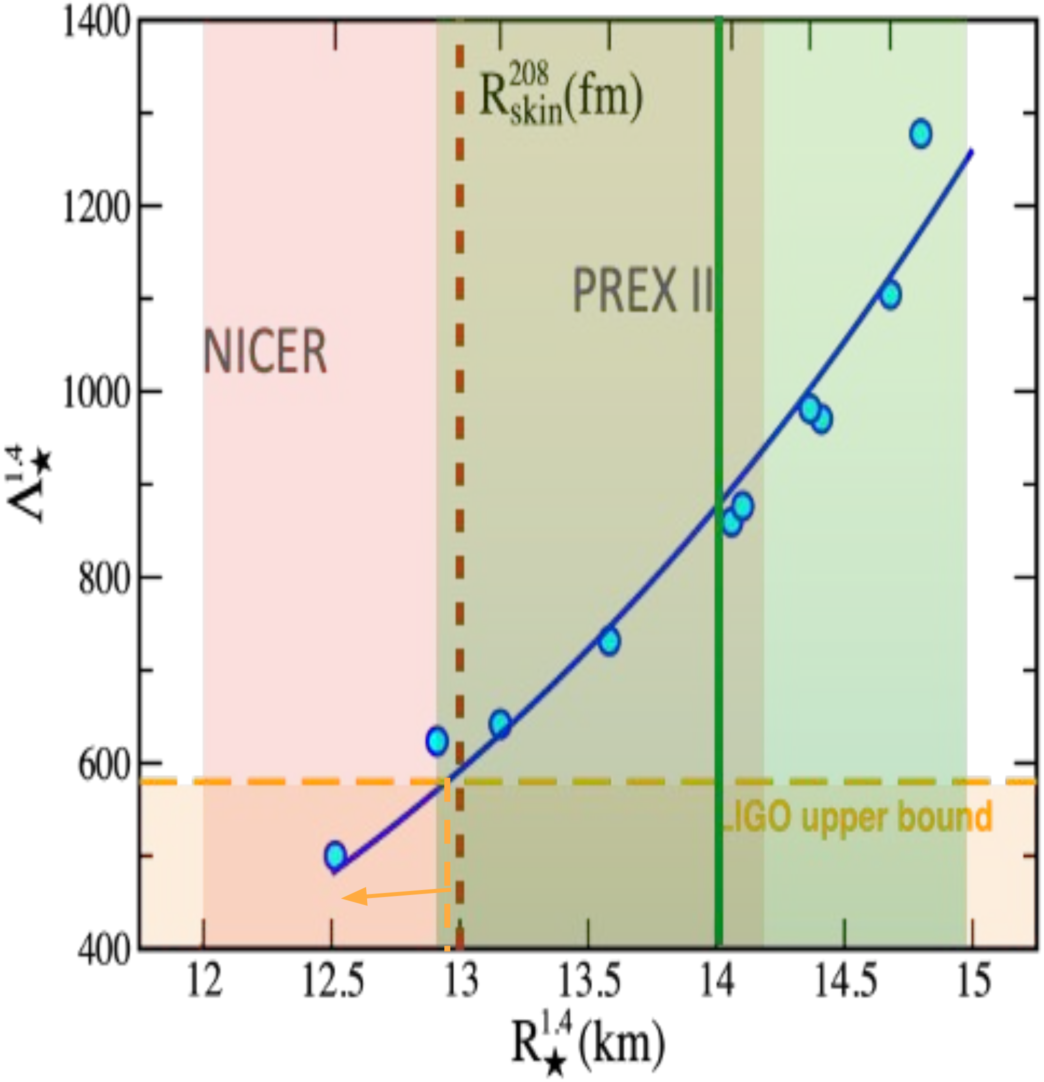
GW physics
GW170817



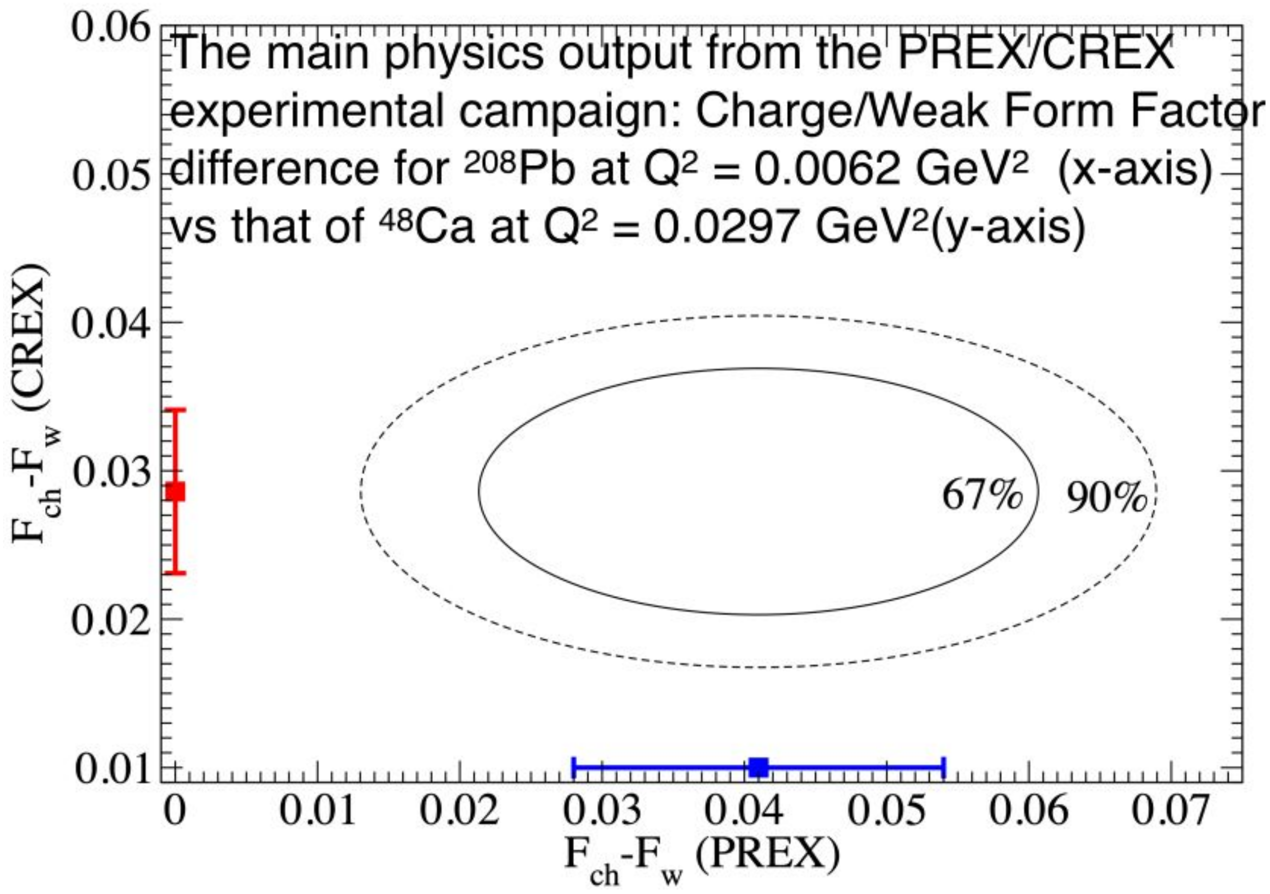
NICER
physics



There is a slight tension between our measurement, combined LIGO and NCER predictions when existing nuclear models are used for interpretations.



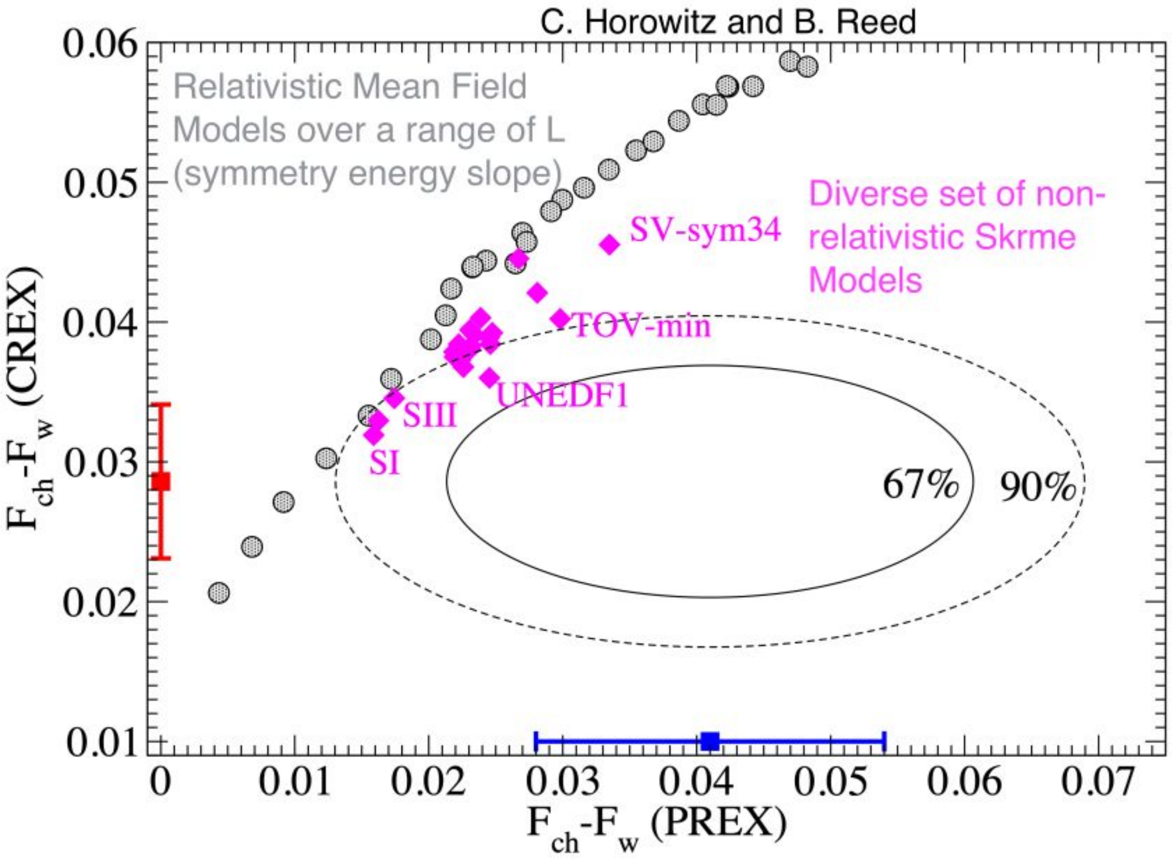
Combined PREX vs CREX weak-form factor



The main physics output from the PREX/CREX experimental campaign: Charge/Weak Form Factor difference for ^{208}Pb at $Q^2 = 0.0062$ GeV^2 (x-axis) vs that of ^{48}Ca at $Q^2 = 0.0297$ GeV^2(y-axis)

Combined PREX vs CREX weak-form factor

CREX result is consistent with a thin neutron skin prediction and is strongly inconsistent with predictions of a very thick skin



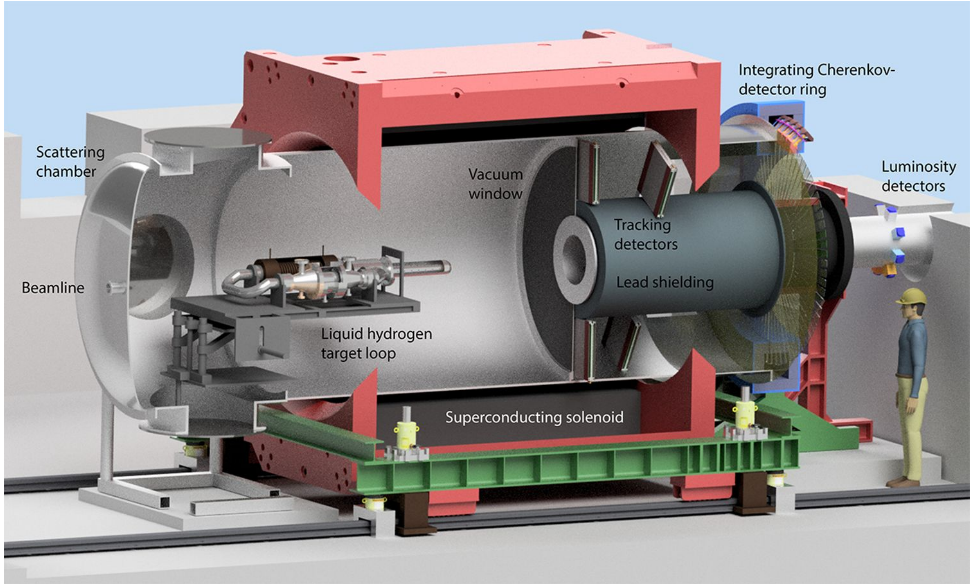
More theoretical work is required.

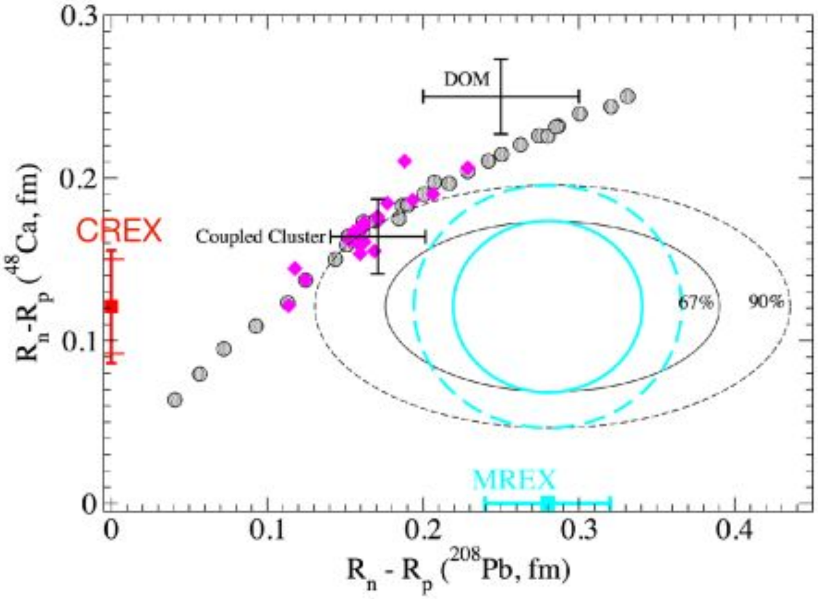
PREX: PRL 126 172502 (2021): 787 citations
CREX: PRL 129 042501 (2022): 380 citations

^{208}Pb neutron skin measurement at MESA, Mainz

Beam energy : 105/155 MeV
Time: 1500 h
~1.3% asymmetry measurement

MREX at Mainz: Will improve ^{208}Pb skin thickness by factor of 2 over PREX-2





Summary

- **Precise measurement of neutron distributions using parity-violating electron scattering**
  - Techniques
  - Potential sources of error

- **The larger neutron-skin of 208Pb nucleus - indicated stiffer EoS. Agrees with NICER, slight tension with LIGO**

- **PREX, along with CREX, puts questions about our understanding of nuclear interactions.**

- **Outcome of the future MREX measurement will be exciting**

Thank you for your attention

Backup

PREX-2 results

Measured the parity violating elastic scattering asymmetry of electrons from ^{208}Pb nucleus

A_{pv} = 550 ± 16 (stat) ± 8 (syst) ppb

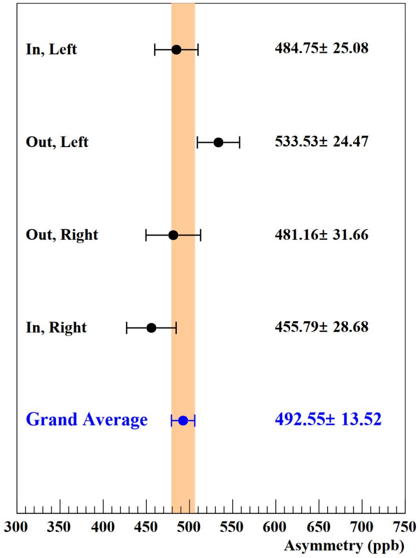
3.2% measurement

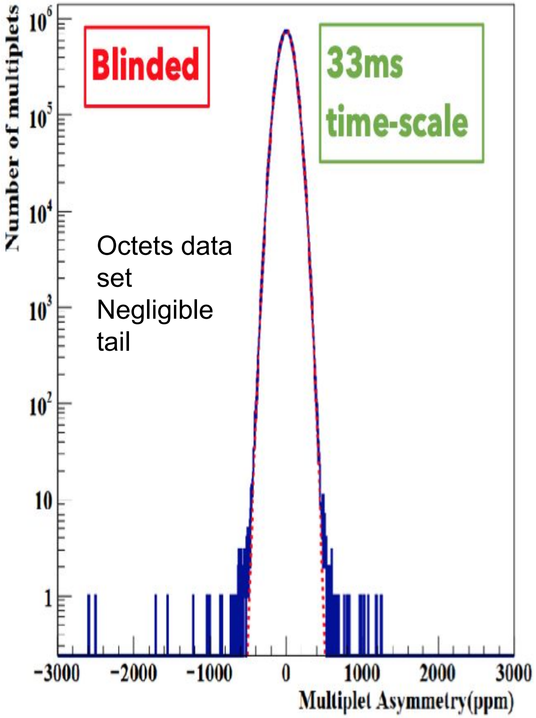
- **Implied neutron skin thickness**

R_n-R_p = 0.283 ± 0.071 fm

- **Density dependence of *S* - *L***

***L* = 106 ± 37 MeV - a stiff EOS**





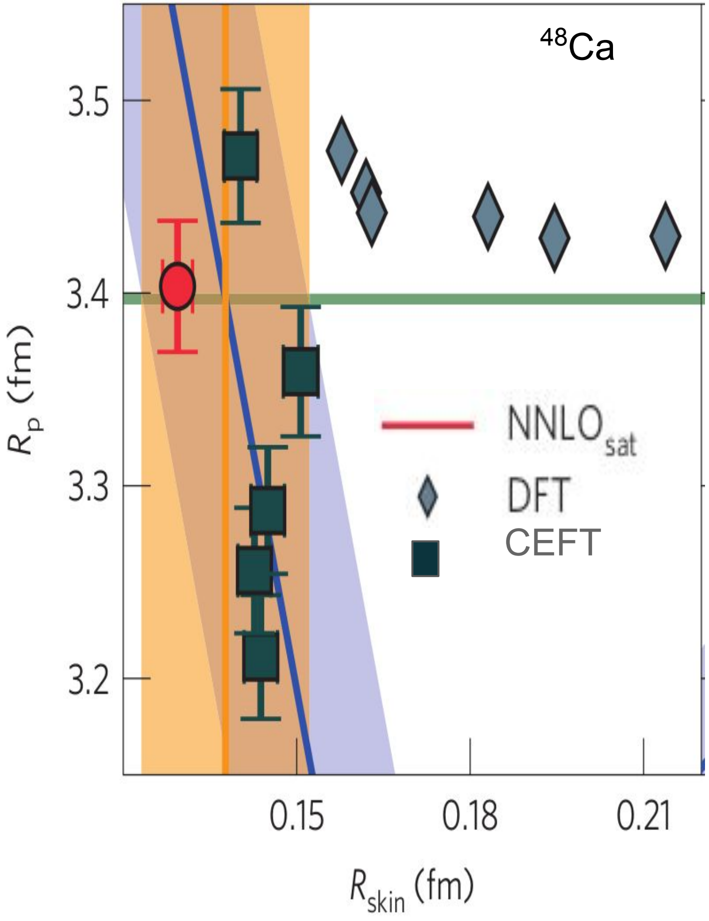
Octets data set
Negligible tail

Ab-initio calculations - computationally challenging

Numerically challenging -
Only possible for low- and medium-mass nuclei

Interactions are from Chiral Effective Field theory (including N-N and N-N-N interactions)
- Squares - CEFT with different interactions
- Circle - CEFT with NNLO corrections

Rhombus - DFT



Nature Physics 12, 186 (2016)

For ^{48}Ca, the ab-initio predictions

$0.12 \lesssim R_{skin} \lesssim 0.15$

❖ CREX is confronting the ab-initio calculations as I will show later in my talk

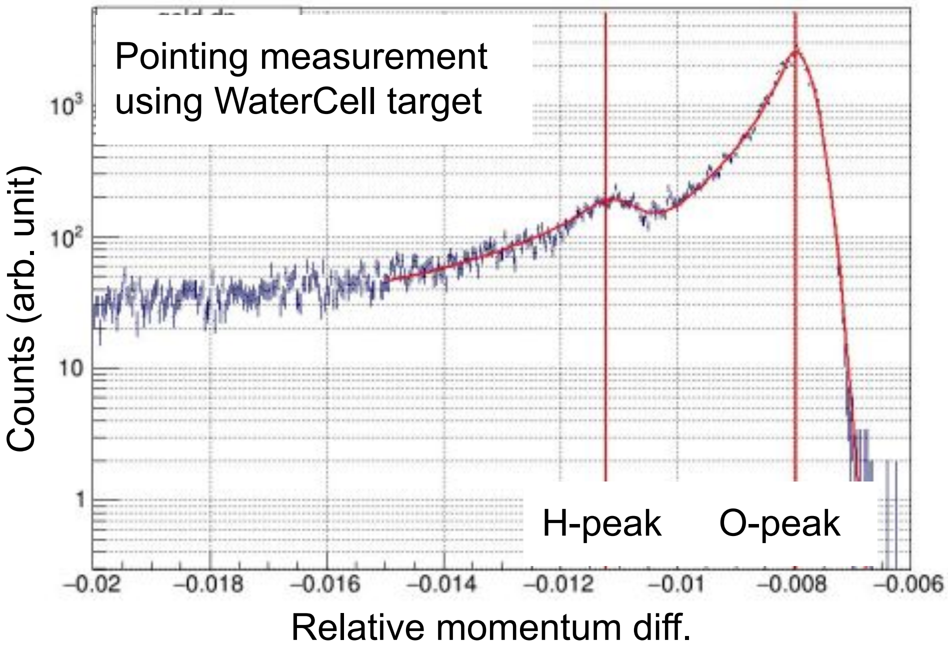
Q^2 measurement

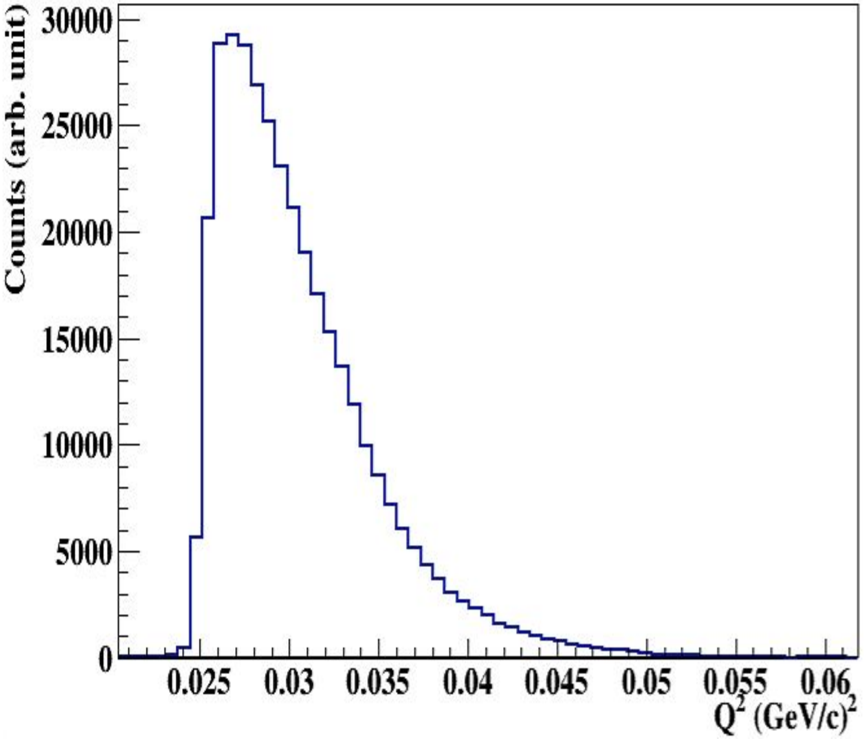
$$Q^2 = 2EE'(1 - cos\theta)$$

$$E, E' \equiv incident\ and\ scattered\ energy$$

$$\theta \equiv scattering\ angle$$

CREX:Q^2 = 0.0297 ± 0.0002 $(GeV/c)^2$





Measured angles with
± 0.02^0 precision

Equation of state of nuclear matter

- The Equation of State (EOS) of neutron-rich matter need to be understood.

$$\xi(\rho,\alpha) = \xi(\rho,\alpha=0) + S(\rho)\alpha^2 + \ldots$$

$$\rho \equiv density$$

$$\alpha \equiv \frac{N-Z}{A} - isospin\ asymmetry$$

$$S(\rho) \equiv symmetry\ energy - a\ parameter$$

$$which\ takes\ care\ of\ energy\ penalty\ due$$

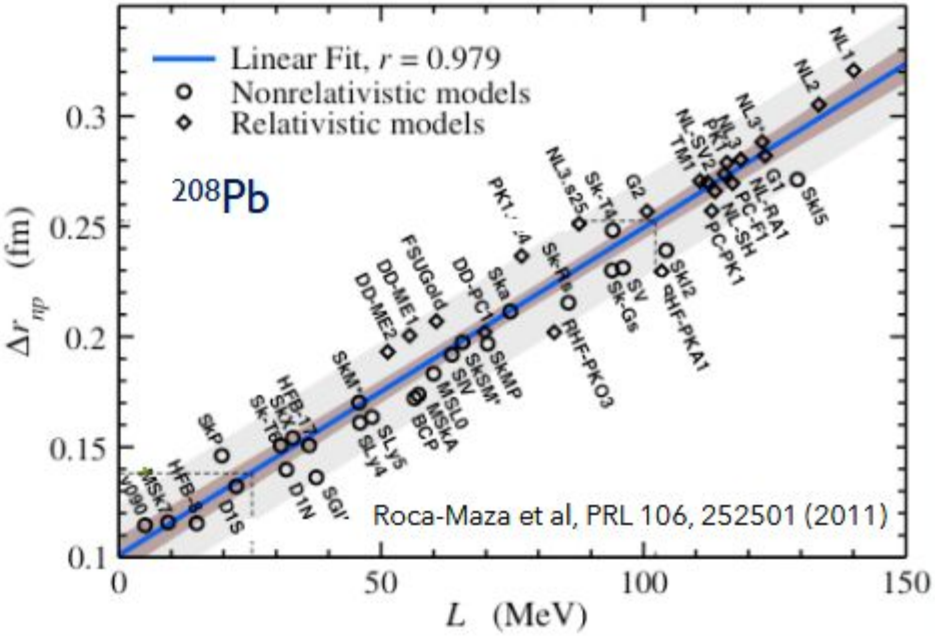
$$to\ isospin\ violation$$

- Slope of Symmetry energy -- $L \propto \frac{\delta S(\rho)}{\delta \rho}\Big|_{\rho_0}$

Large Variation of *L* parameter in the literature

- Large *L* - more energy required
  to add a new neutron - Stiff EOS; Small *L* - Soft EOS

Mean-field predictions show a clear correlation between neutron skin of a heavy nucleus and the density slope of the symmetry energy

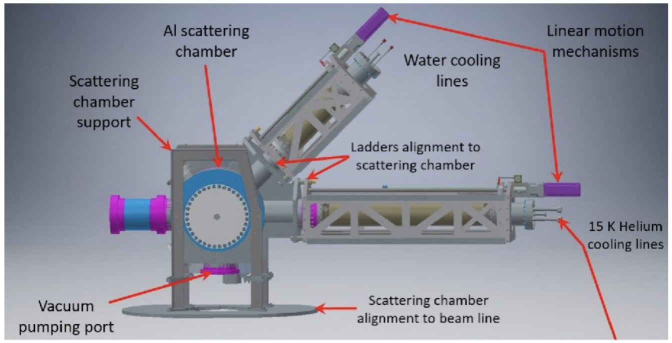


Roca-Maza et al, PRL 106, 252501 (2011)

PREX- ^{208}Pb (82p+126n, n/p=1.54) Radius Experiment
CREX - ^{48}Ca (20p+28n, n/p=1.4) Radius Experiment

Why ^{208}Pb and ^{48}Ca target?

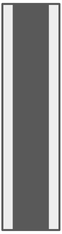
- ^{208}Pb (^{48}Ca) is doubly magic neutron rich nucleus - well studied both experimentally and theoretically.
- First excited state for ^{208}Pb (^{48}Ca) nucleus is separated by 2.6 (3.8) MeV - able to minimize in-elastic background

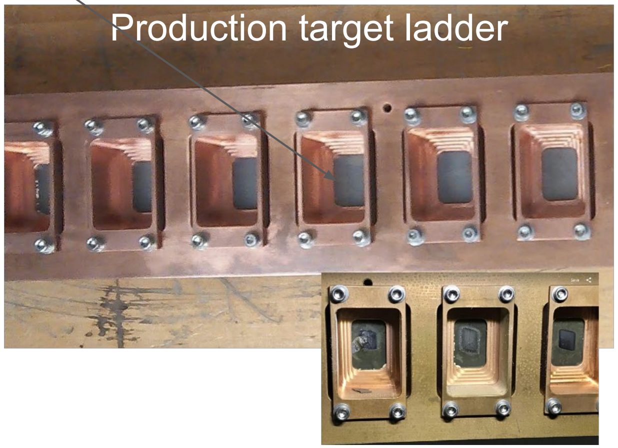


★ *n/p(^{208}Pb)=1.54*, n/p(^{238}U)=1.59,

★ First excited state - *^{208}Pb - 2.6 MeV*; ^{238}U- 44 keV

- Two target ladders - Production & optics
- **Diamond(0.2mm)-Lead(0.5mm)-Diamond(0.2mm) sandwich target**
- Production ladder is cryo-cooled
- Optics (45 deg) normal temperature - Water cell target, C-foil target
- **5.7 mm thick ^{48}Ca (91% enrich) target**





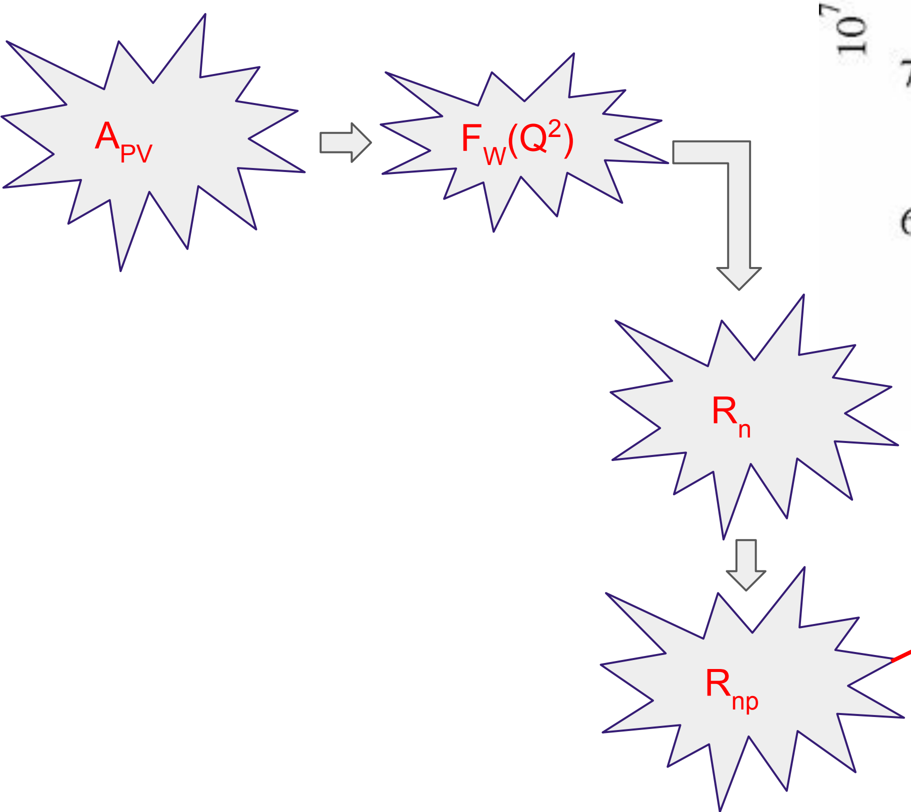
Based on PREX-1 experience, 10 isotopically enriched targets were installed; 6 of them are used

Used targets

PVES as clean probe for neuton distributions

For spin 0 nuclei:

$$A_{PV} \approx -\frac{G_F Q^2 Q_W}{4\pi\alpha\sqrt{2}Z}\,\frac{F_W(Q^2)}{F_{ch}(Q^2)}$$



A_{PV}

$F_W(Q^2)$

R_n

R_{np}

PRL 106, 252501 (2011)