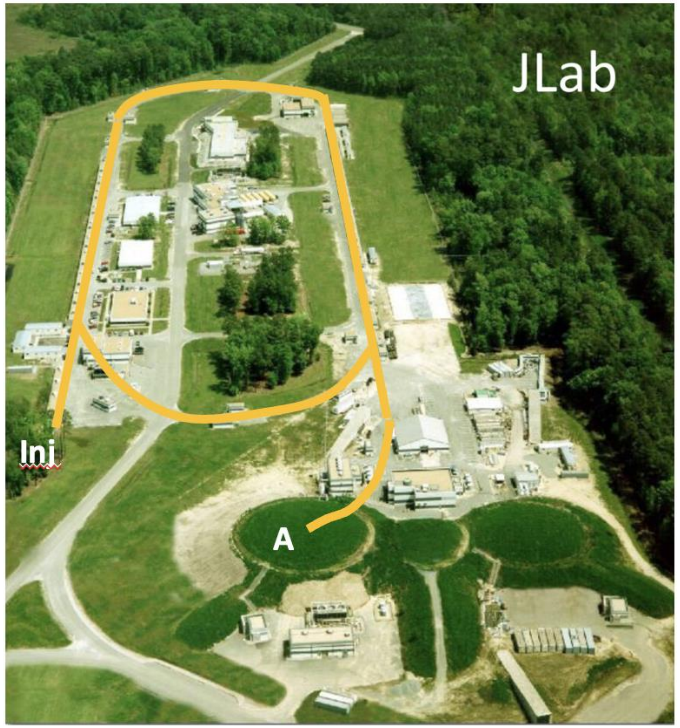
Neutral weak form factors and nuclear equation of state



Ciprian Gal

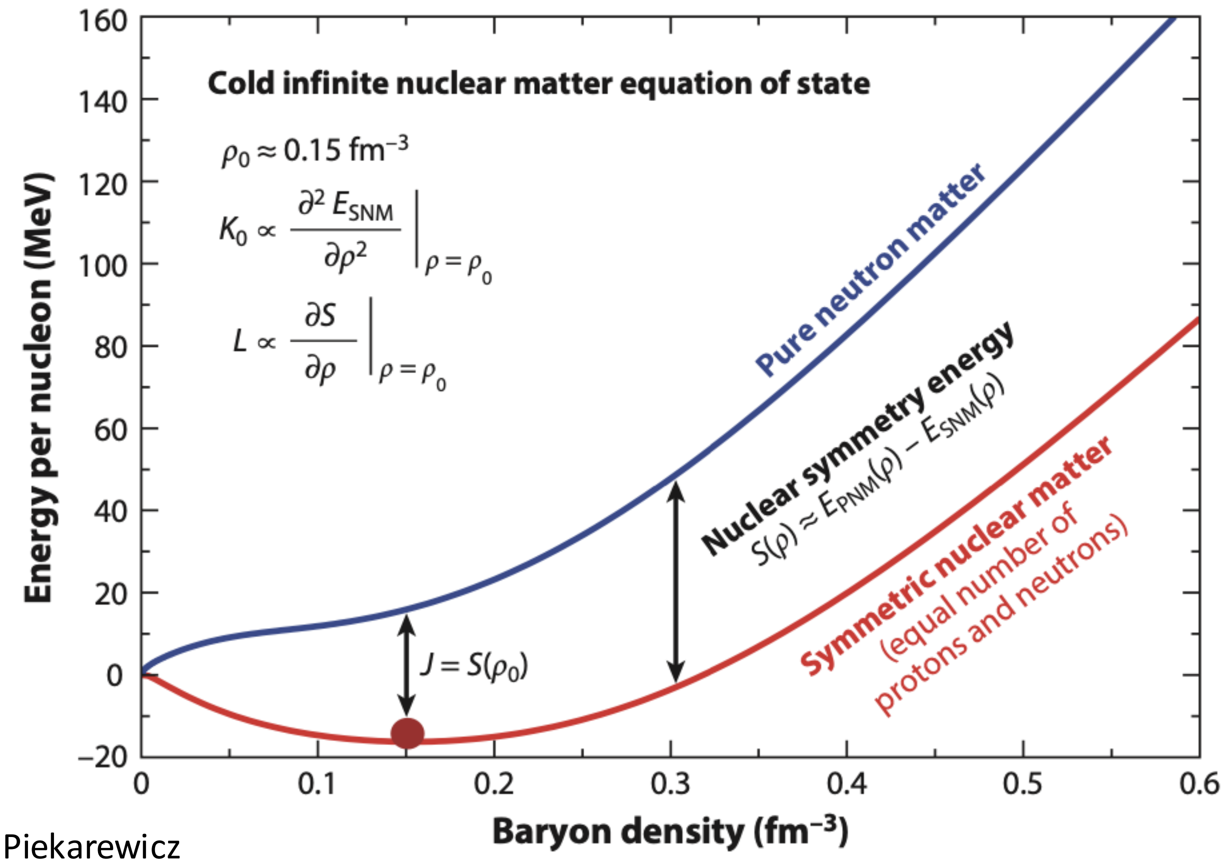
on behalf of the PREX and CREX collaborations

Many thanks for many collaborators for discussions, text, plots, slides …

PREX: ***Phys.Rev.Lett.*** **126 (2021) 17, 172502**
CREX: ***Phys.Rev.Lett.*** **129 (2022) 4, 042501**

Jefferson Lab

EOS of neutron rich matter



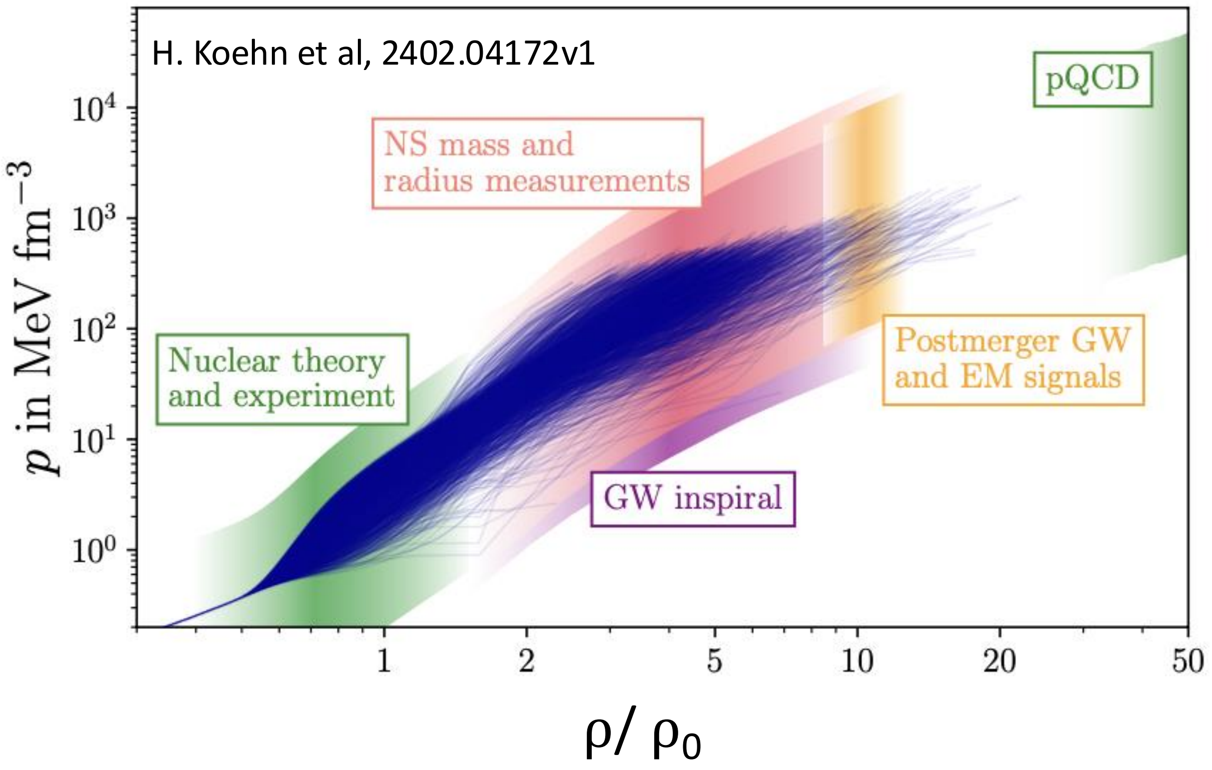
J. Piekarewicz

$$\frac{E}{A}(\rho,\alpha) - M \equiv \mathcal{E}(\rho,\alpha) = \mathcal{E}_{\rm SNM}(\rho) + \alpha^2 \mathcal{S}(\rho) + \mathcal{O}(\alpha^4)$$

$$\mathcal{S}(\rho) = J + L\frac{(\rho-\rho_0)}{3\rho_0} + \ldots.$$

- Similar to the ideal gas law the nuclear EOS gives the pressure inside nuclear matter as a function of energy density
- Historically separated into symmetric nuclear matter (p=n) and corrections
  - The slope of the symmetry energy (L) is a critical parameter

EOS of neutron rich matter

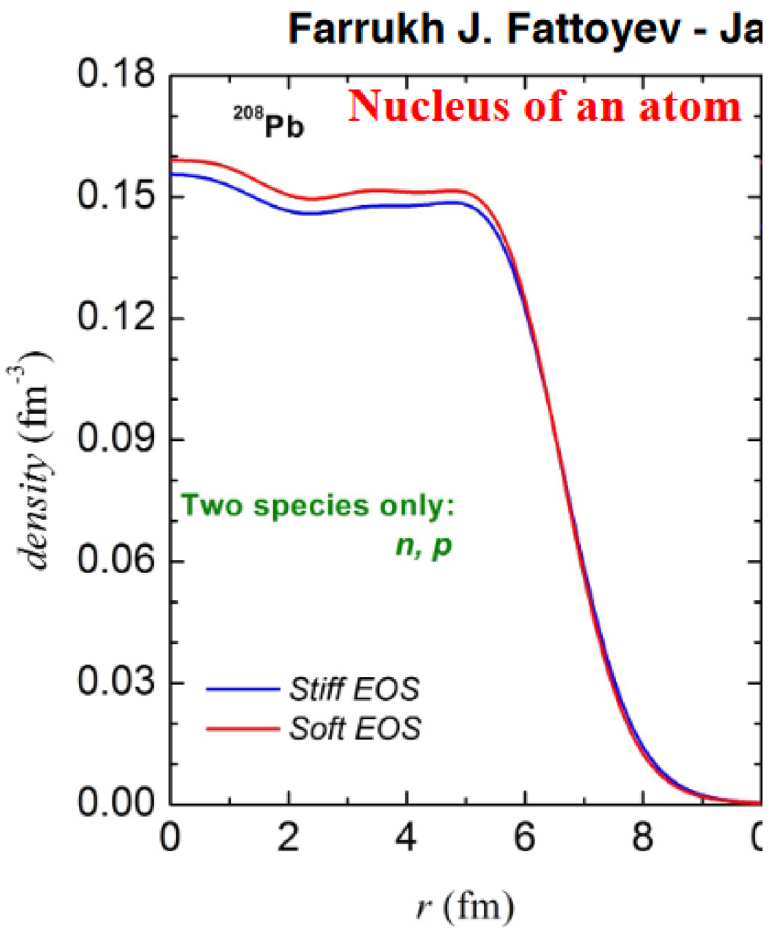


$$\frac{E}{A}(\rho,\alpha) - M \equiv \mathcal{E}(\rho,\alpha) = \mathcal{E}_{\mathrm{SNM}}(\rho) + \alpha^2 \mathcal{S}(\rho) + \mathcal{O}(\alpha^4)$$

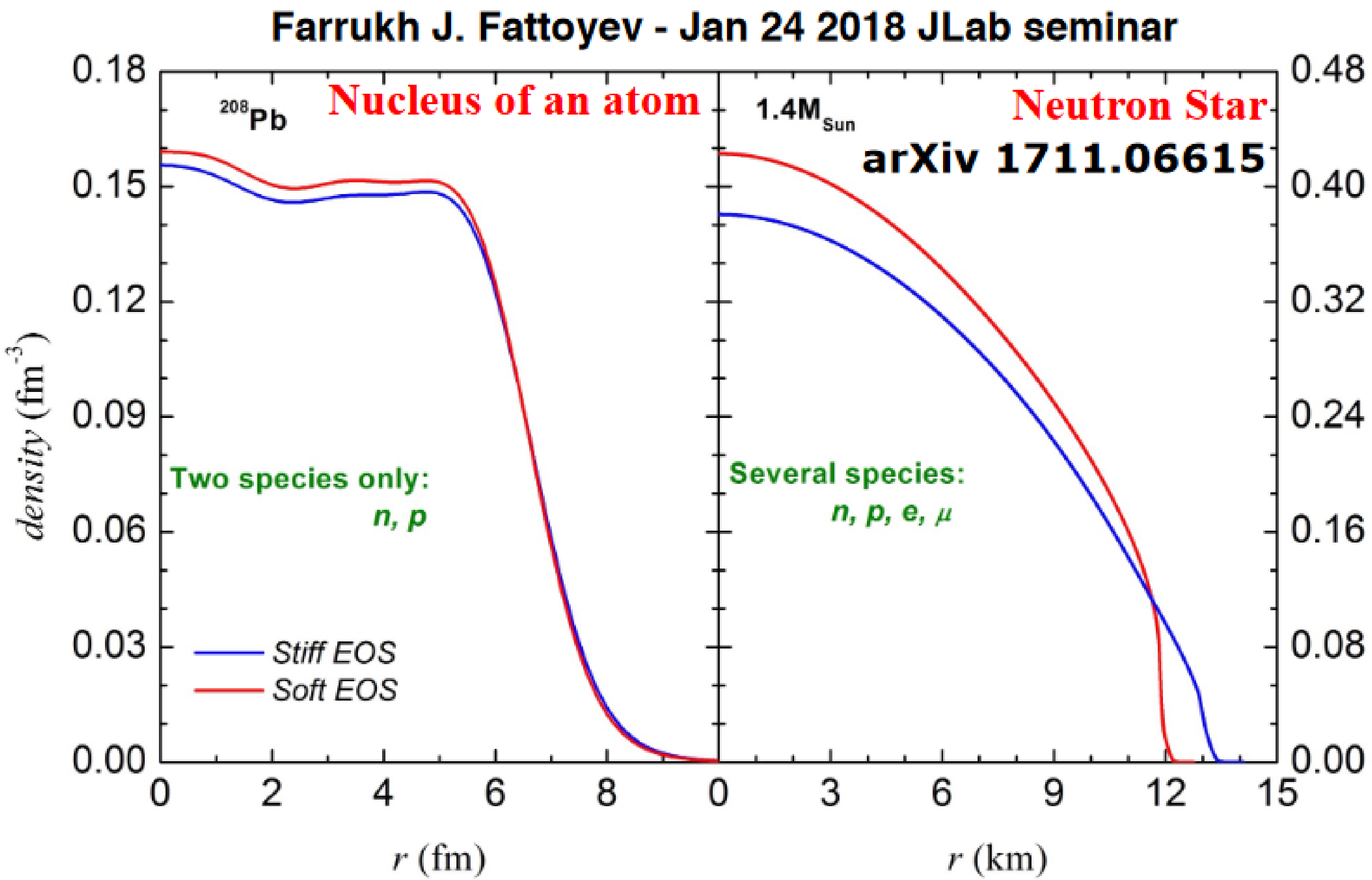
$$\mathcal{S}(\rho) = J + L\frac{(\rho - \rho_0)}{3\rho_0} + \ldots .$$

- To get a full description of the EOS we need access to probes that are sensitive to different baryon densities
- Using the EOS one can relate phenomena at vastly different scales

Different systems: same EOS

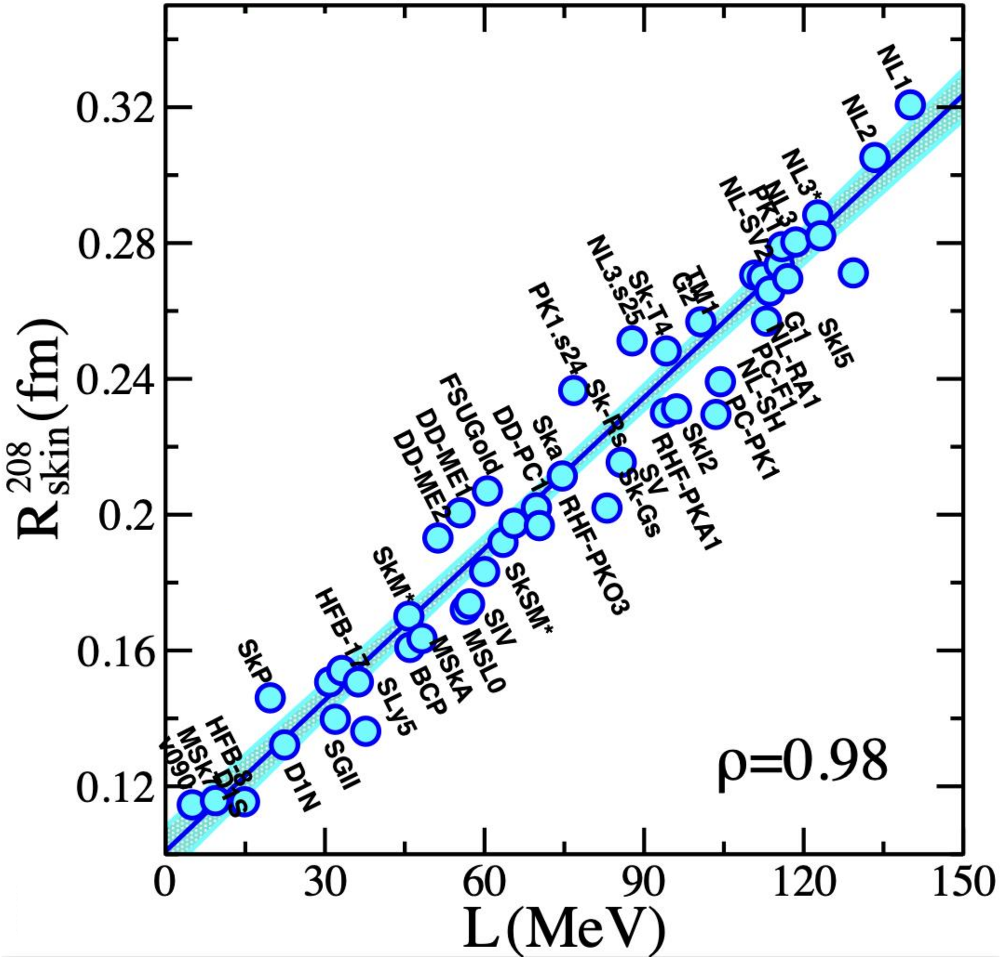


Different systems: same EOS



- While the ^{208}Pb nucleus and a neutron star are separated by 18 orders of magnitude in size they are largely made out of the same stuff and obey one equation of state (EOS)

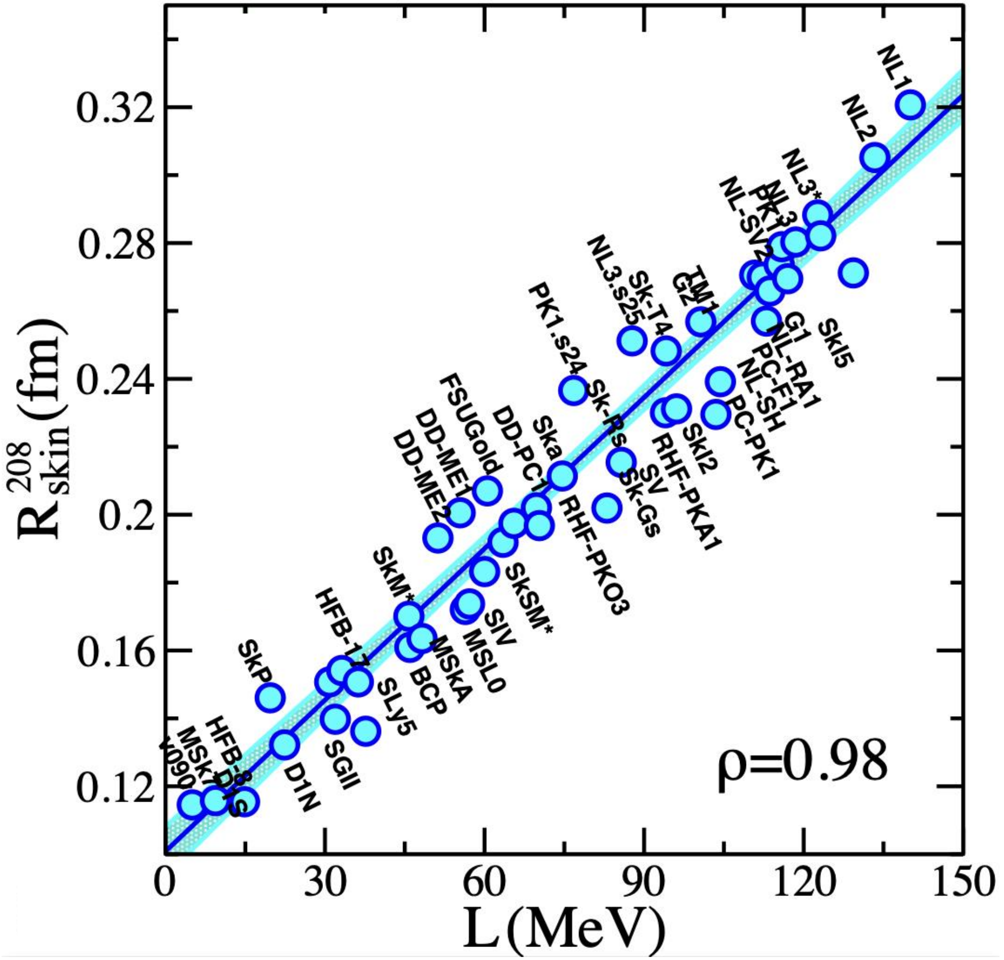
Getting L (the slope of symmetry energy)



J. Piekarewicz, 2403.16154v1

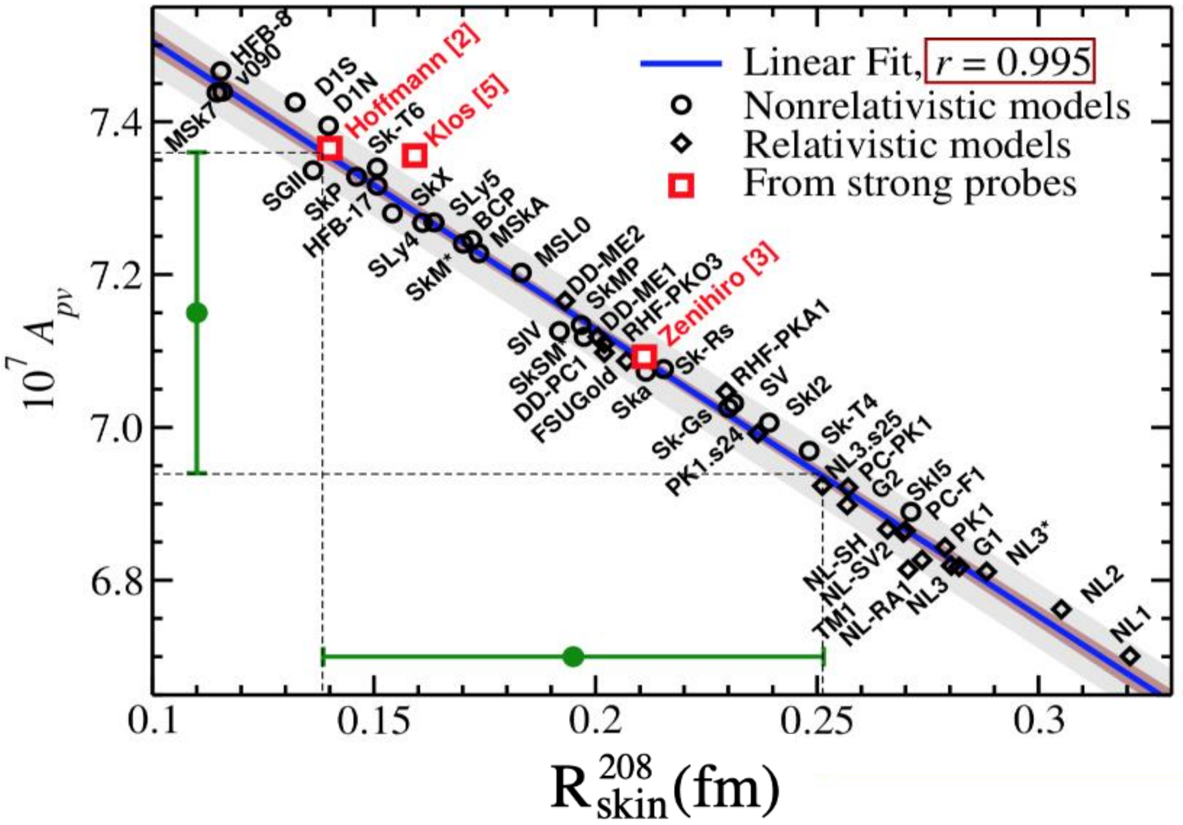
- Encoding the world knowledge on nuclear matter in the currently available models that describe them we can catch a glimpse of the underlaying correlations between different parameters and observables
- The neutron skin of lead-208 (and Ca-48) and the density dependence of the symmetry energy show a tight correlation

Getting L (the slope of symmetry energy)



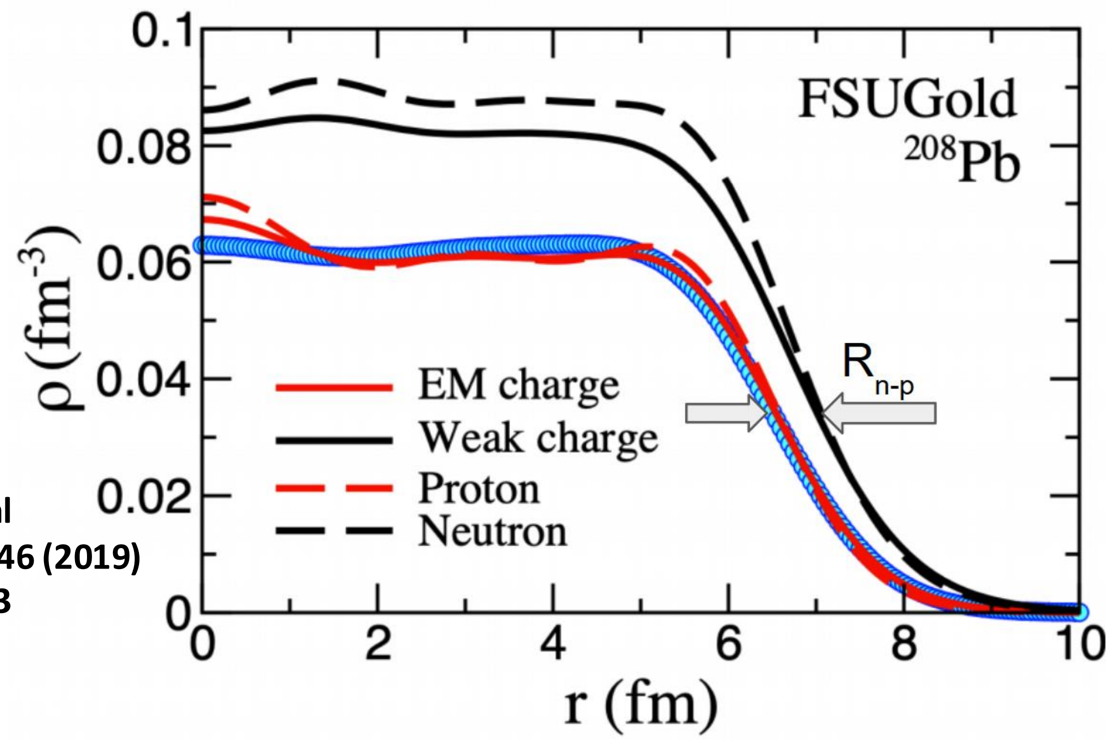
J. Piekarewicz, 2403.16154v1

A. Brown, PRL 85 (2000) 5296-5299
C. Horowitz, J. Piekarewicz, PRC 64 (2001) 062802

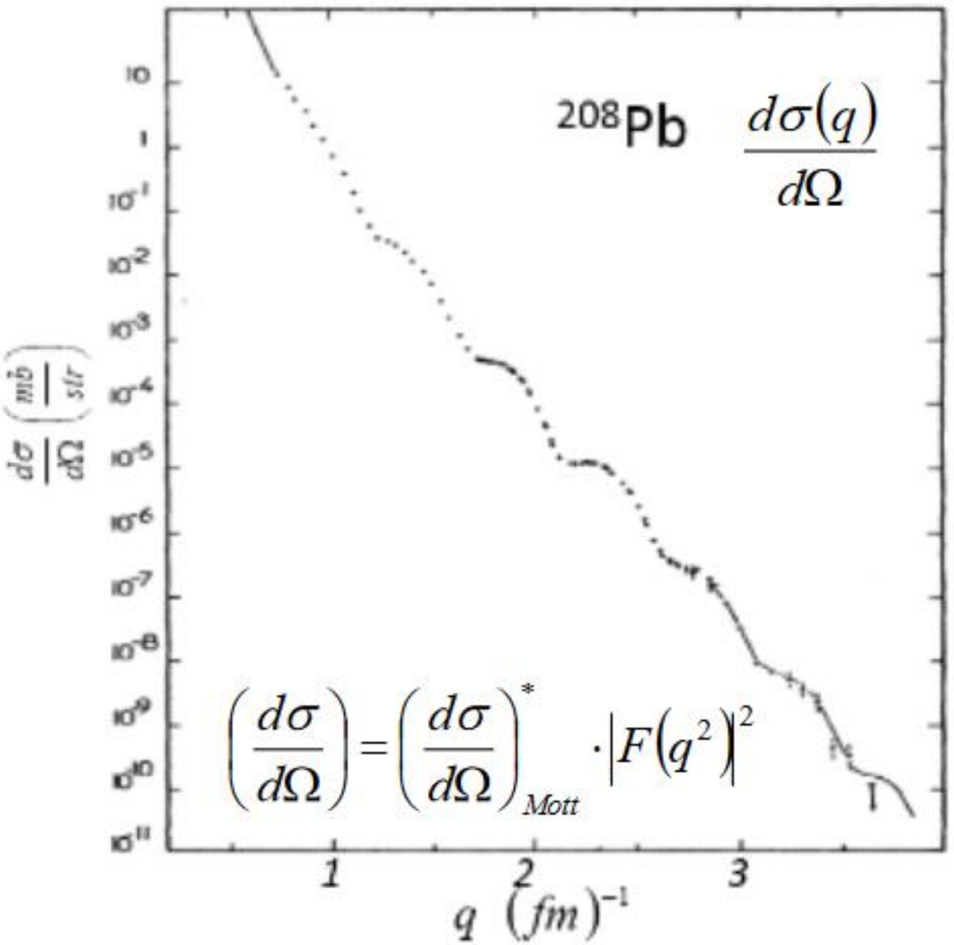


- The neutron skin shows a similarly tight correlation to the parity violating asymmetry in electron scattering

What are we looking for?

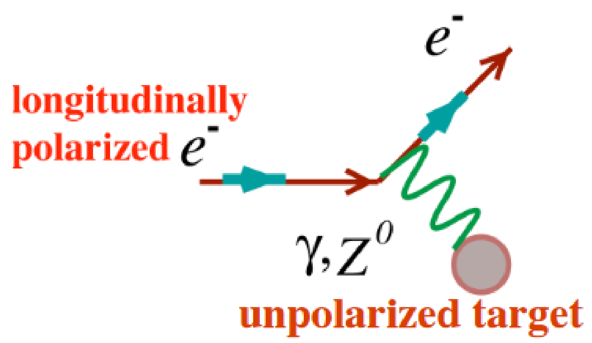


Thiel et al
J.Phys.G 46 (2019)
9, 093003



- The excess neutrons in ^{208}Pb are thought to form a skin on the outside of the nucleus
- Similar to how the Fourier transform of the electromagnetic form factor gives charge density so too measuring the weak form factor can give the weak distribution

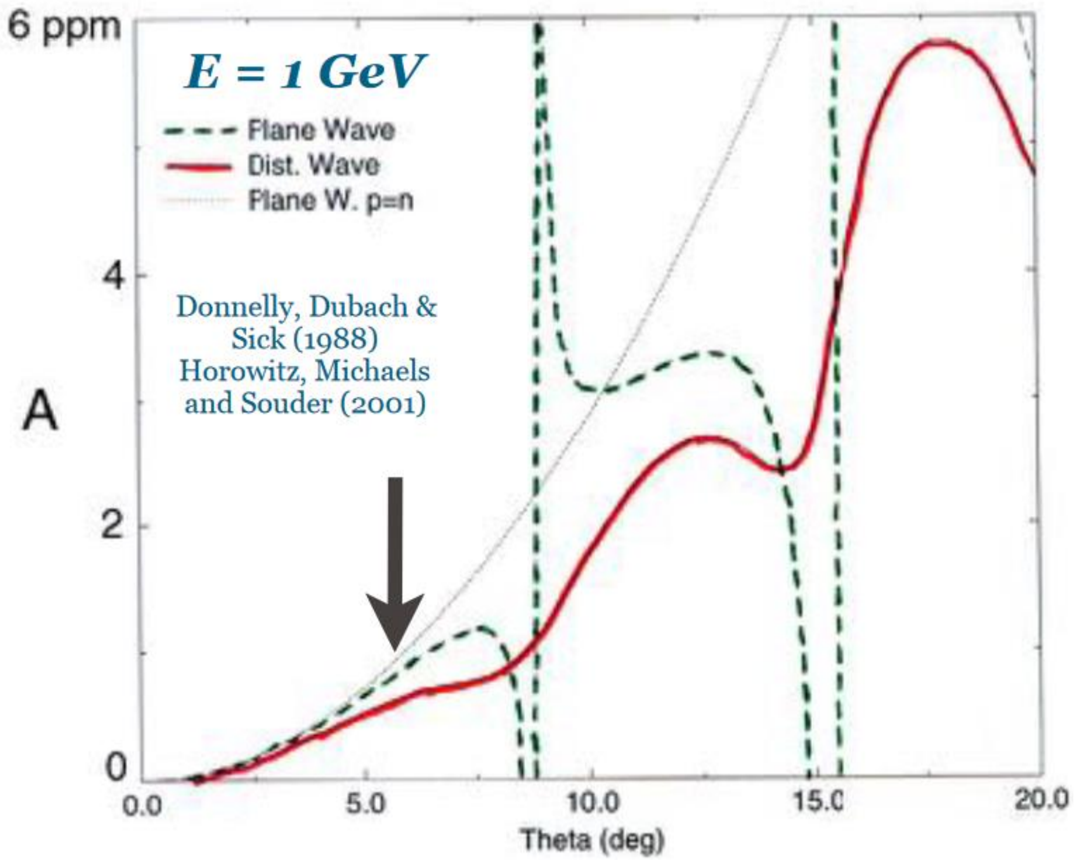
How can we find it?



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

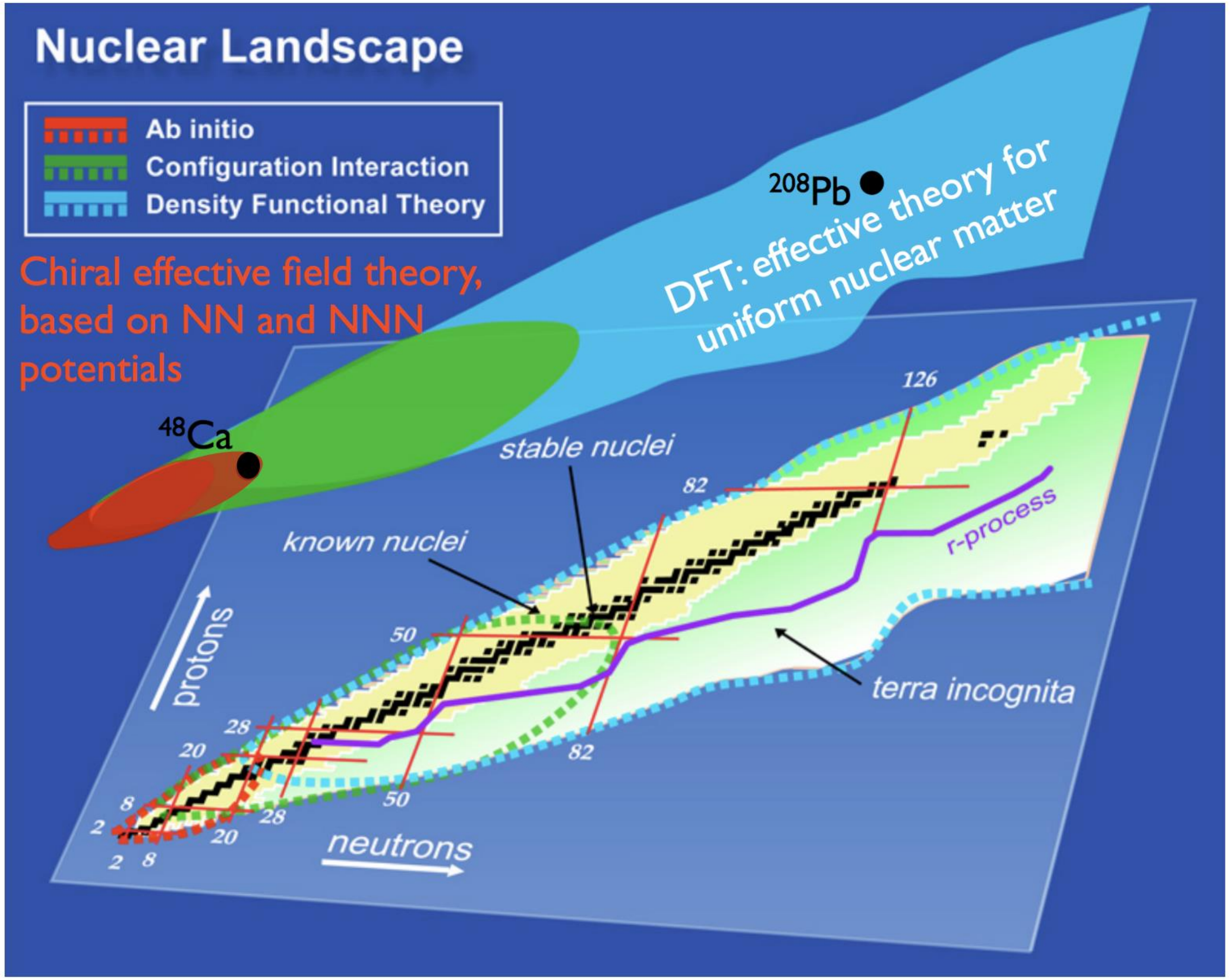
Born approximation:

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



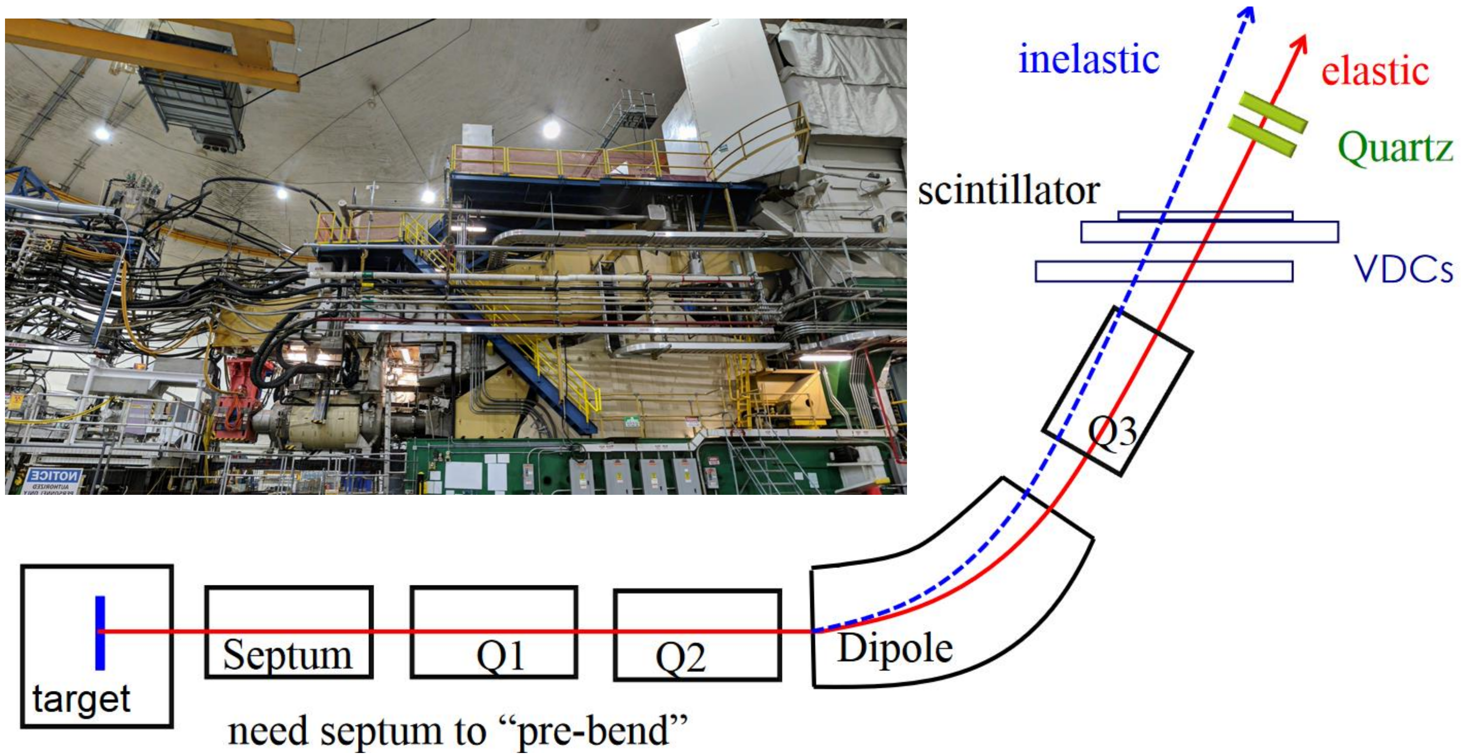
- The numerator is dominated by the gamma-Z interaction which picks up (almost exclusively) the weak charge of the neutron
- The denominator contains the parity conserving electro-magnetic interaction which is several orders of magnitude stronger than the electro-weak interference term
  - This leads to very small asymmetries that are on the level of parts-per-million

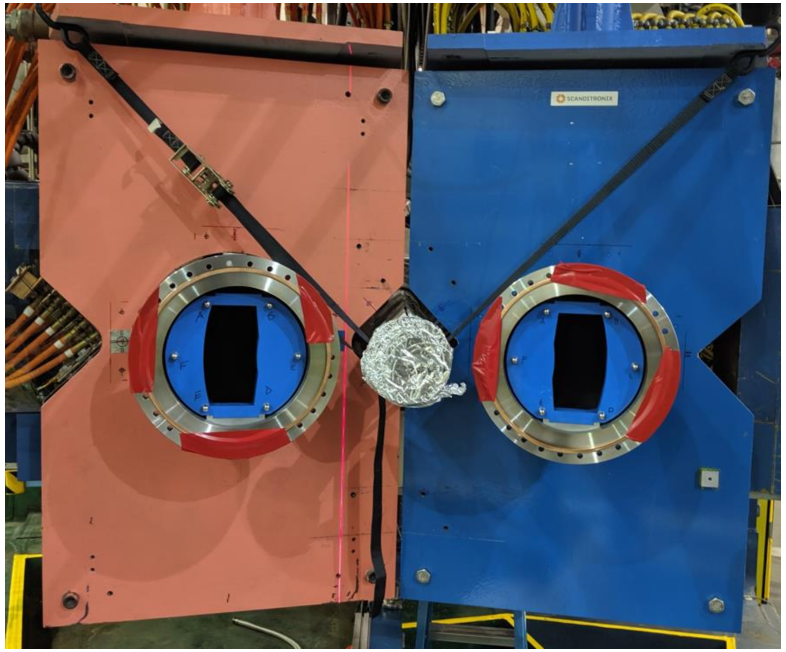
Selecting the targets

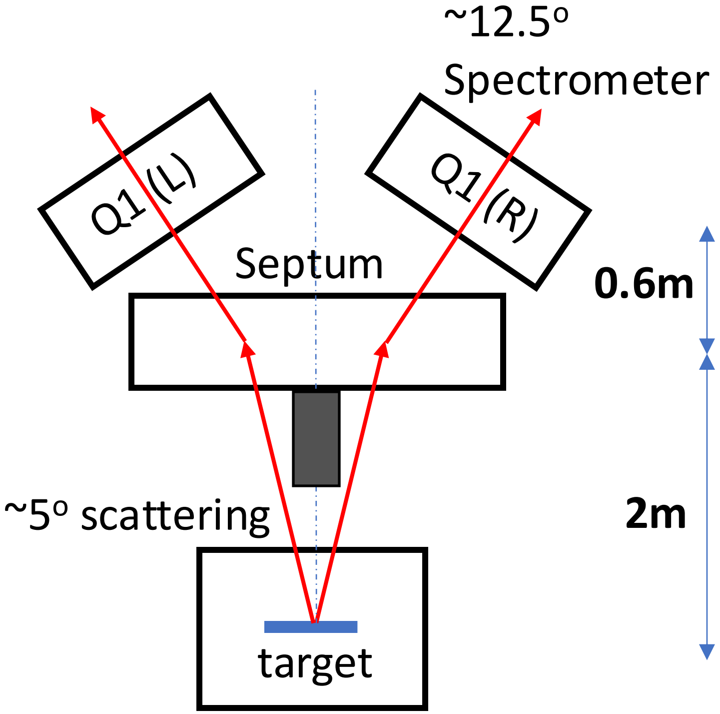


- Doubly magic nuclei
- Pb-208 provides a target that is as close as we can get to infinite nuclear matter
  - Theoretical corrections and uncertainties are small
- Ca-48 provides a somewhat different regime while retaining some of the theoretical cleanliness of lead

Magnet package



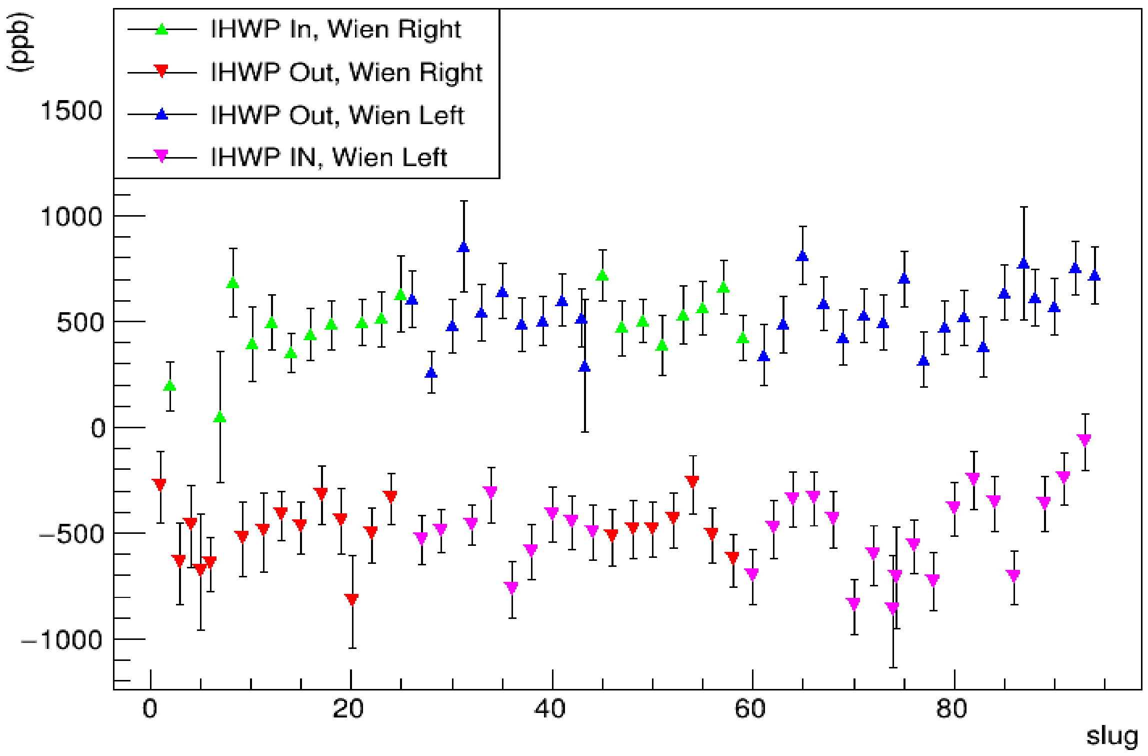




- The high resolution spectrometer (HRS) allows us to magnetically cleanly separate elastic and inelastic events
- The septum magnet provided the additional ~8 degree bend into the first set of Quads
  - The acceptance defining collimators physically allow an area only as big as your palm

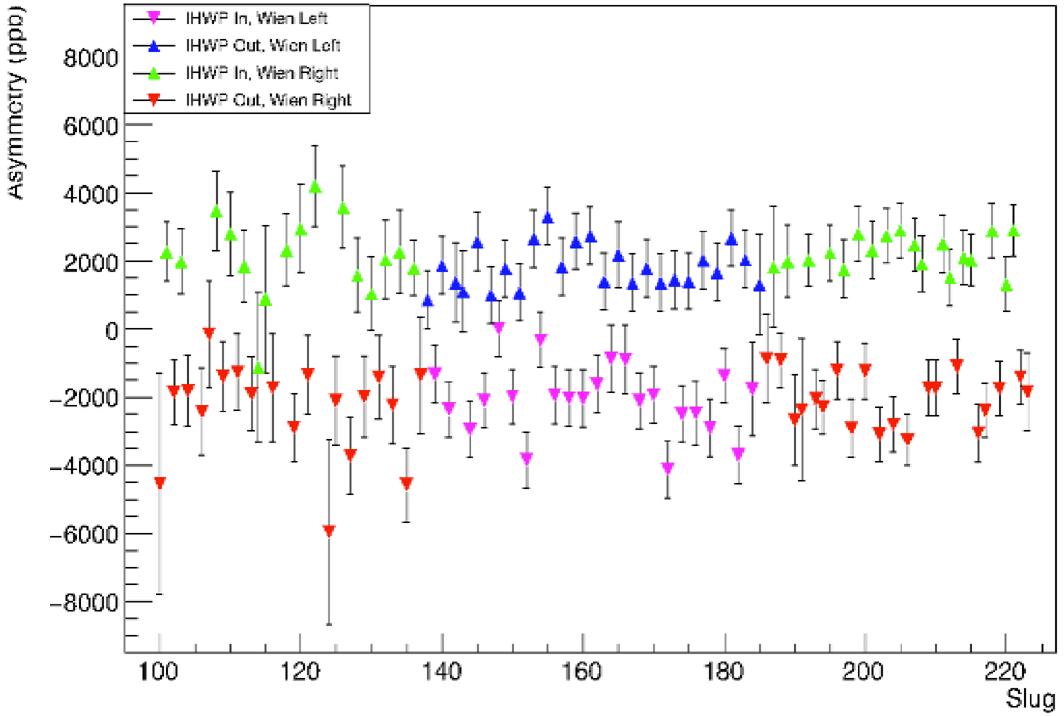
Statistics

PREX – 208-Pb



- Detector rate: 5GHz
- Asymmetry: 0.55 ppm

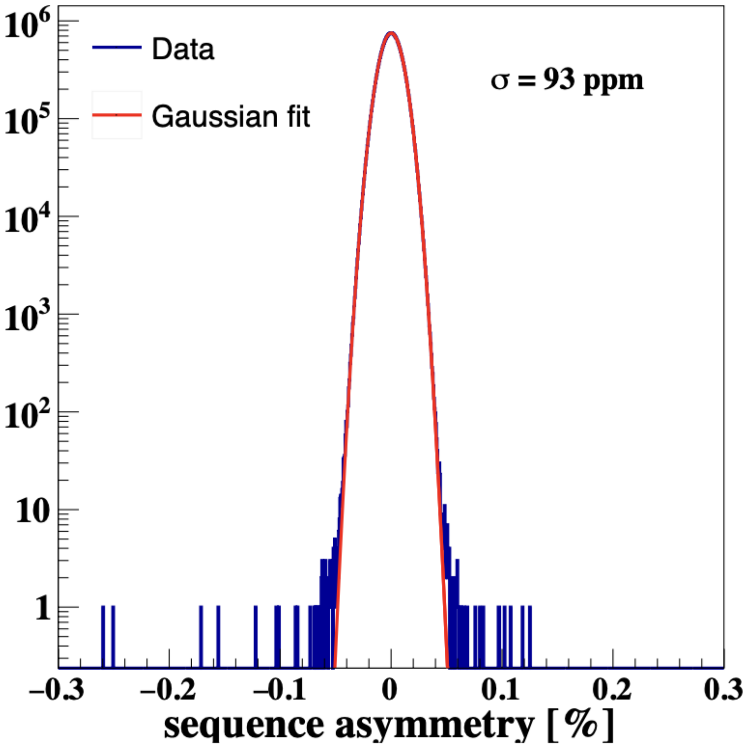
CREX – 48-Ca



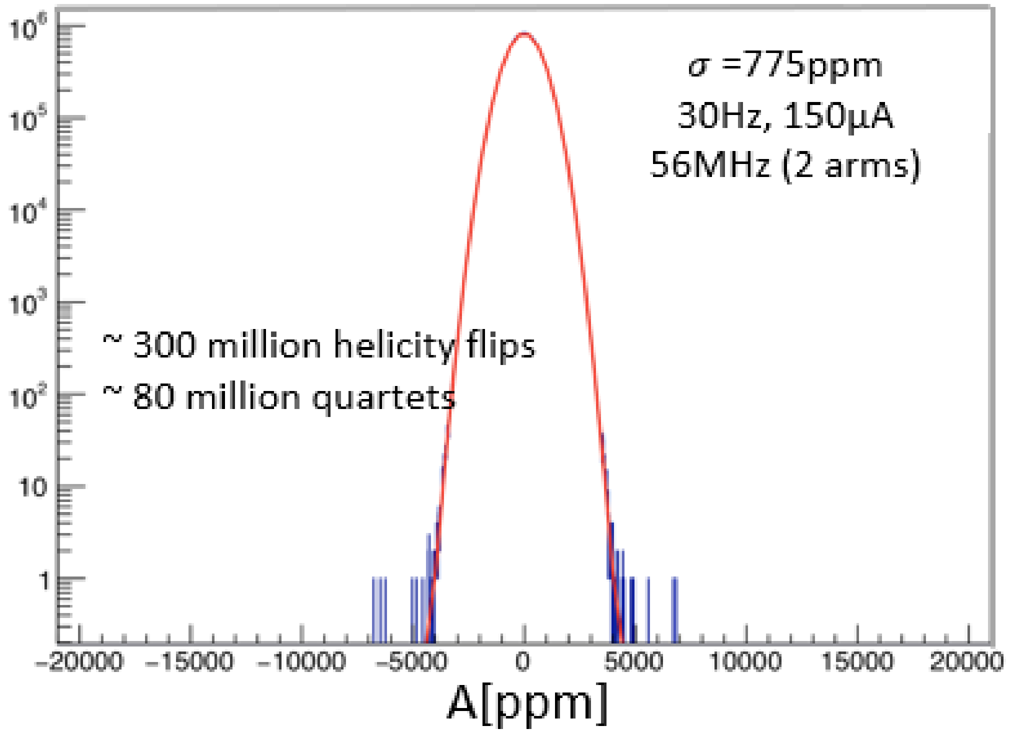
- Detector rate: 50MHz
- Asymmetry: 2 ppm

Statistics

PREX – 208-Pb



CREX – 48-Ca



- Both experimental widths are dominated by counting statistics after corrections

$$A_{PV} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

Systematics

PREX – 208-Pb

TABLE I. Corrections and systematic uncertainties to extract A_{PV}^{meas} listed on the bottom row with its statistical uncertainty.

Correction	Absolute [ppb]	Relative [%]
Beam asymmetry	-60.4 ± 3.0	11.0 ± 0.5
Charge correction	20.7 ± 0.2	3.8 ± 0.0
Beam polarization	56.8 ± 5.2	10.3 ± 1.0
Target diamond foils	0.7 ± 1.4	0.1 ± 0.3
Spectrometer rescattering	0.0 ± 0.1	0.0 ± 0.0
Inelastic contributions	0.0 ± 0.1	0.0 ± 0.0
Transverse asymmetry	0.0 ± 0.3	0.0 ± 0.1
Detector nonlinearity	0.0 ± 2.7	0.0 ± 0.5
Angle determination	0.0 ± 3.5	0.0 ± 0.6
Acceptance function	0.0 ± 2.9	0.0 ± 0.5
Total correction	17.7 ± 8.2	3.2 ± 1.5
A_{PV}^{meas} and statistical error	550 ± 16	100.0 ± 2.9

CREX – 48-Ca

TABLE I. A_{PV} corrections and corresponding systematic uncertainties, normalized to account for polarization and background fractions.

Correction	Absolute [ppb]	Relative [%]
Beam polarization	382 ± 13	14.3 ± 0.5
Beam trajectory & 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 non-linearity	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%

- The parity violating asymmetry uncertainties are dominated by statistics

Results – weak form factors

PREX – 208-Pb

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

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

CREX – 48-Ca

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

Quantity	Value	± (stat)	± (sys)
$F_{\mathrm{W}}(q)$	0.1304	± 0.0052	± 0.0020

- The extraction of the weak form factors has minimal theoretical uncertainty

Results – weak form factors

PREX – 208-Pb

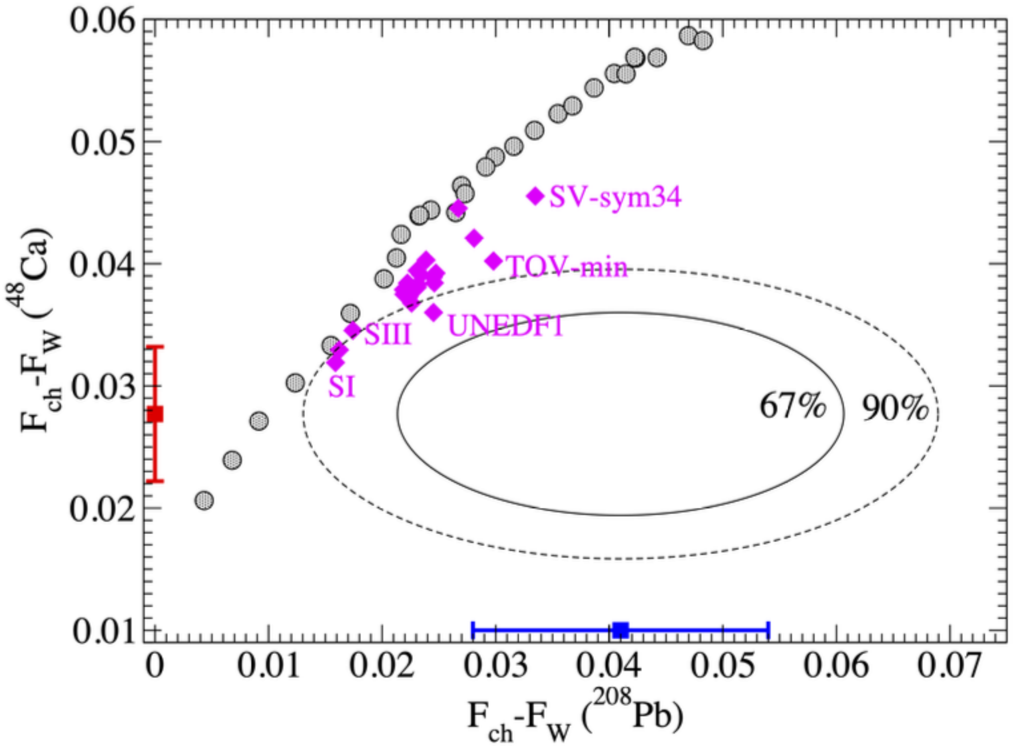
$$A_{PV}^{\text{meas}} = 550 \pm 16 \text{ (stat.)} \pm 8 \text{ (syst.) ppb}$$
$$F_W(\langle Q^2 \rangle) = 0.368 \pm 0.013 \text{ (exp.)} \pm 0.001 \text{ (theo.)}.$$

- The extraction of the weak form factors has minimal theoretical uncertainty
- The current models can't seem to be able to describe both of these results

CREX – 48-Ca

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

Quantity	Value ± (stat) ± (sys)
$F_W(q)$	0.1304 ± 0.0052 ± 0.0020



Results – neutron skins

PREX – 208-Pb

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

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

CREX – 48-Ca

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

Quantity	Value ± (stat) ± (sys)
$F_{\mathrm{W}}(q)$	0.1304 ± 0.0052 ± 0.0020

- While we could experimentally significantly improve the Pb-208 result the Ca-48 needs additional theoretical understanding in the extraction of the neutron skin

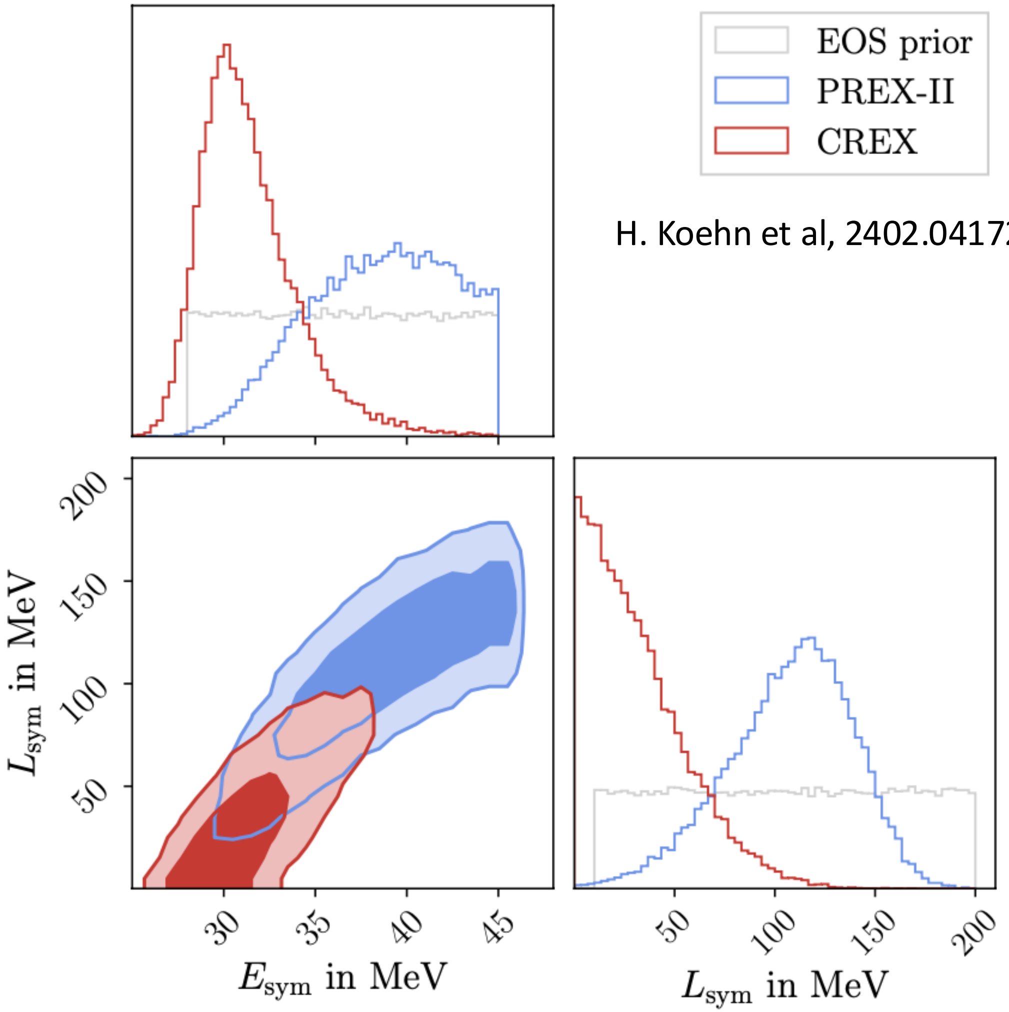
$$R_W = 5.795 \pm 0.082\ (\mathrm{exp.}) \pm 0.013\ (\mathrm{theo.})\ \mathrm{fm}$$

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

Quantity	Value ± (exp) ± (model) [fm]
$R_{\mathrm{W}} - R_{\mathrm{ch}}$	$0.159 \pm 0.026 \pm 0.023$
$R_n - R_p$	$0.121 \pm 0.026 \pm 0.024$

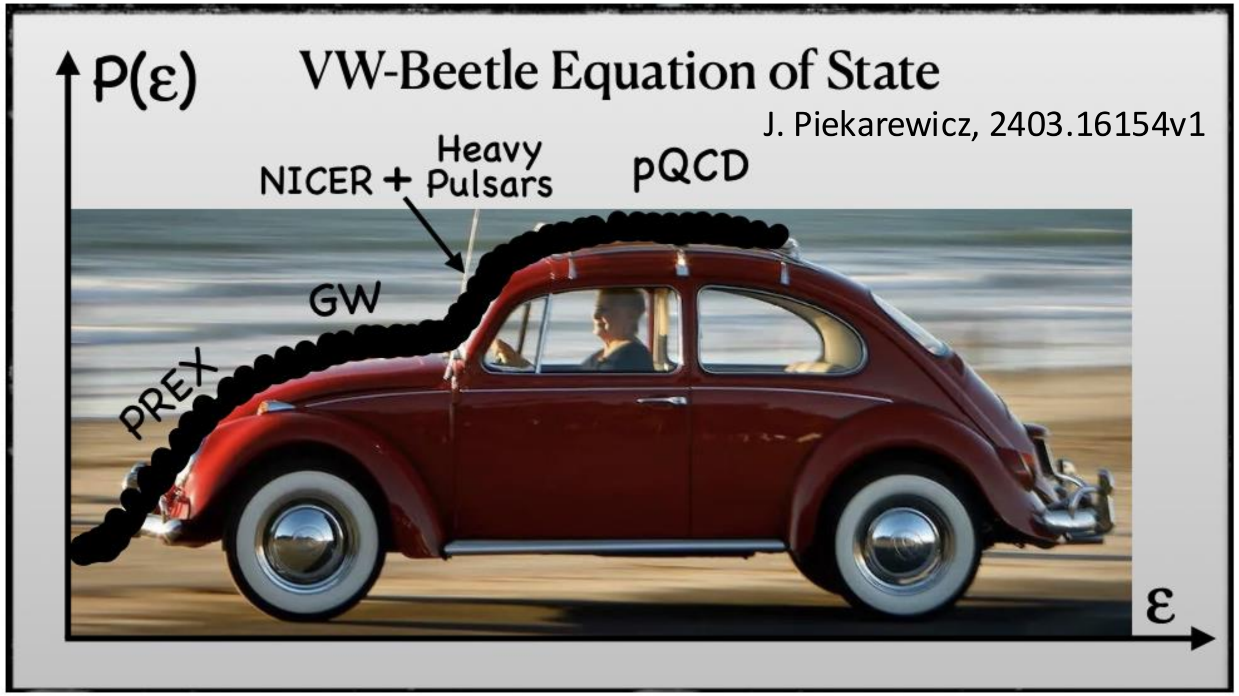
Impact on EOS

- A recent Bayesian analysis by Koehn and collaborators relied on the neutron skin extraction to look at the slope of the symmetry energy
- The results show a significant region of overlap in the posterior distributions in spite of the theoretical uncertainties for the Ca-48 result



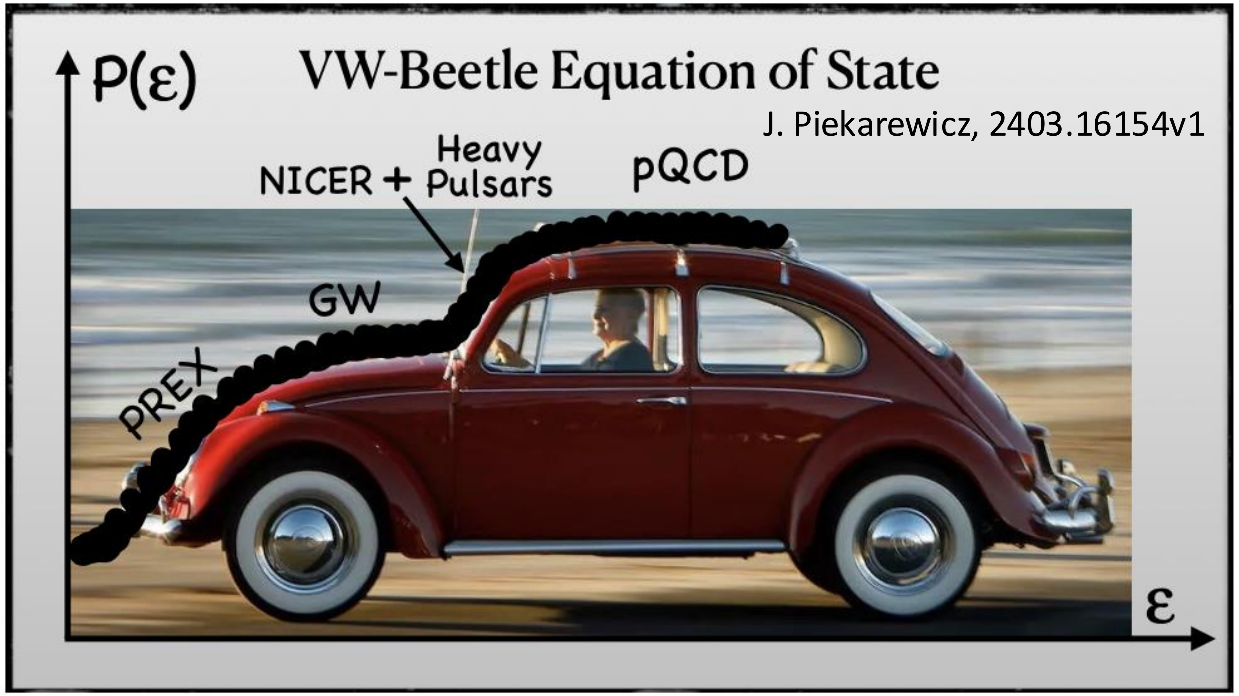
H. Koehn et al, 2402.04172v1

Conclusions and future

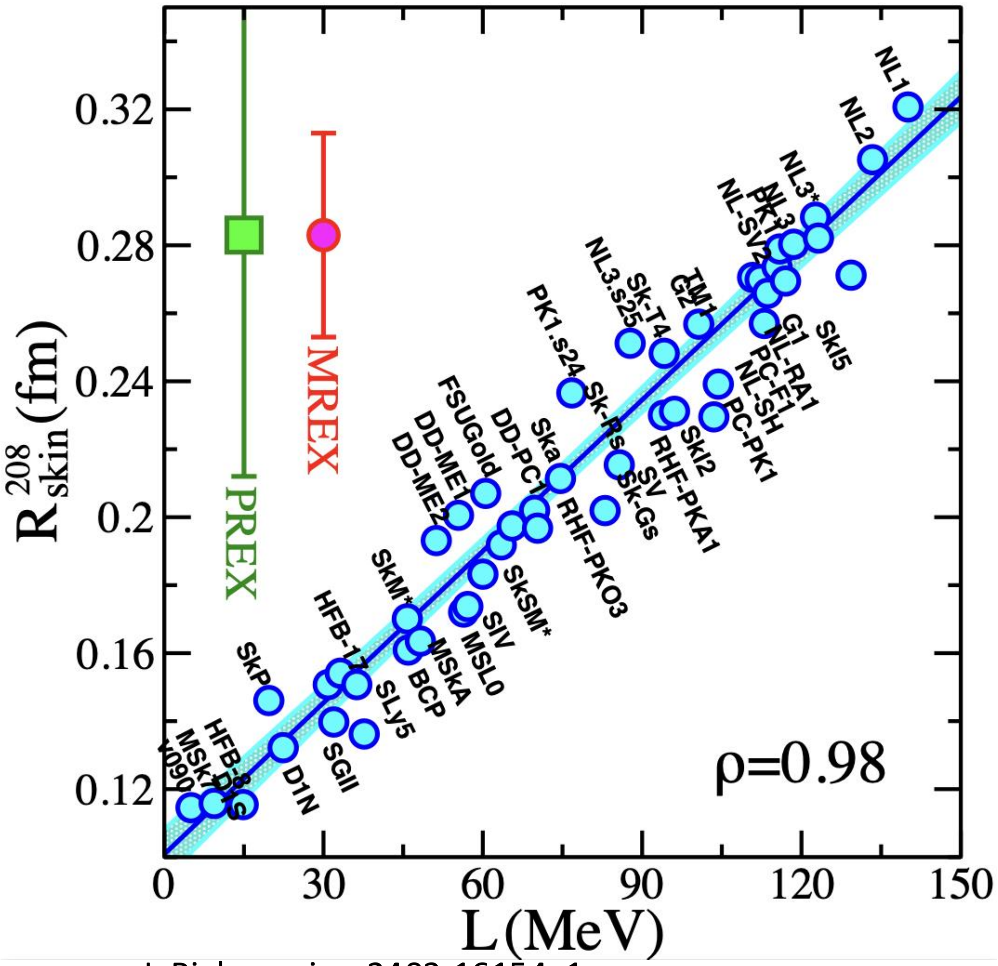


- The neutron rich EOS determined from both terrestrial and heavenly measurements bears an uncanny resemblance to a VW-Beetle

Conclusions and future



- The next measurements of Pb-208 promises to improve statistical precision by a factor of 2
  - still above the theoretical uncertainties even for the extraction of the neutron skin



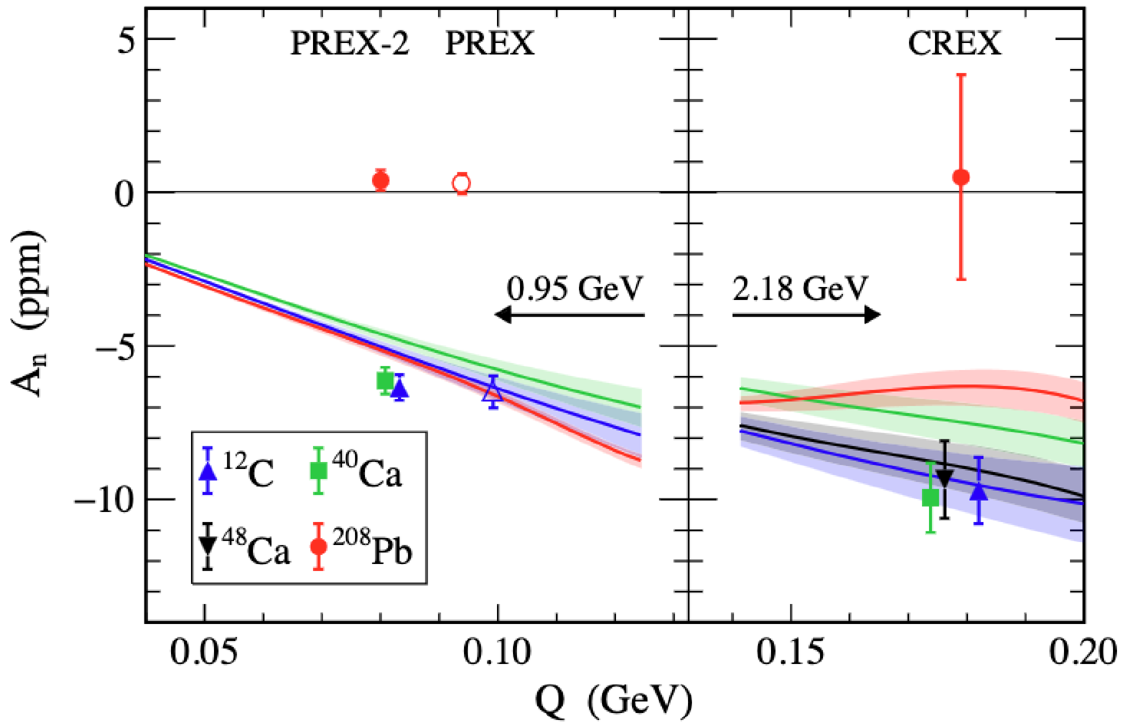
J. Piekarewicz, 2403.16154v1

Backups

A_T puzzle naïve suggestion

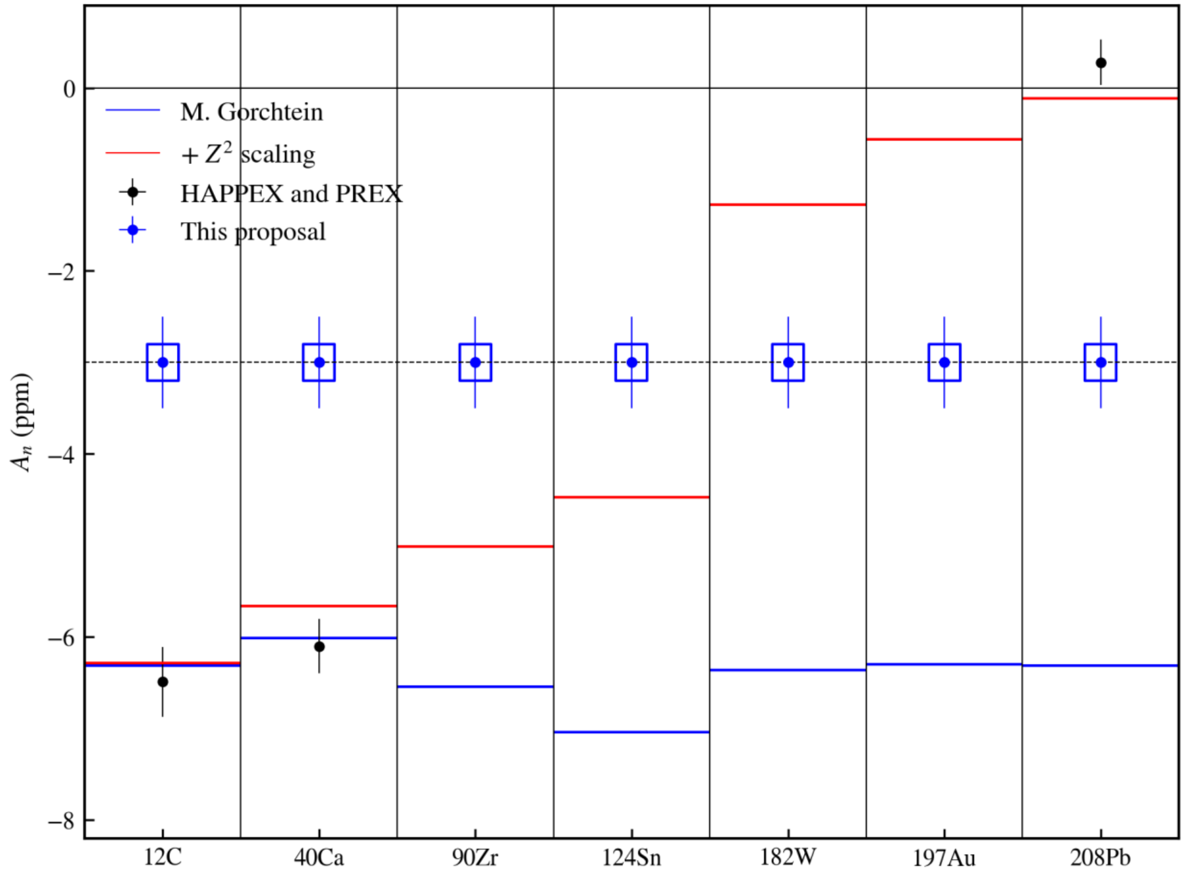
E_{beam} (GeV)	Target	A_n (ppm)	$A_{avg}^{Z\leq 20}$ (ppm)	$\frac{A_n - A_{avg}^{Z\leq 20}}{\text{uncert}}$
0.95	^{12}C	-6.3 ± 0.4	-6.2 ± 0.2	
0.95	^{40}Ca	-6.1 ± 0.3		
0.95	^{208}Pb	0.4 ± 0.2		$21\ \sigma$

- The lead results are in fact positive (by 2 sigma)
- One possible explanation would be that another physics process produces a transverse asymmetry with the opposite sign as the TPE that is present in high Z (or A) nuclei
  - We are in touch with theorists exploring this possibility



Pb208 results suggest there are missing contributions that are not accounted in the existing theoretical models

Projected results



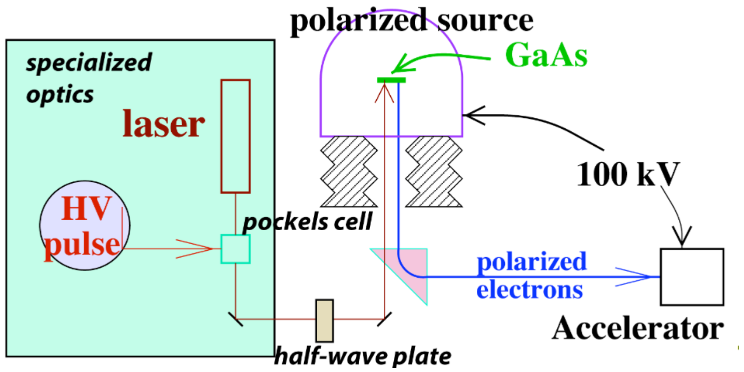
- TPE calculations suggest 6-7 ppm asymmetries for all targets at the proposed kinematics
- Empirical determination of asymmetry suppression assuming Z^2 corrections (https://arxiv.org/pdf/2111.04250)

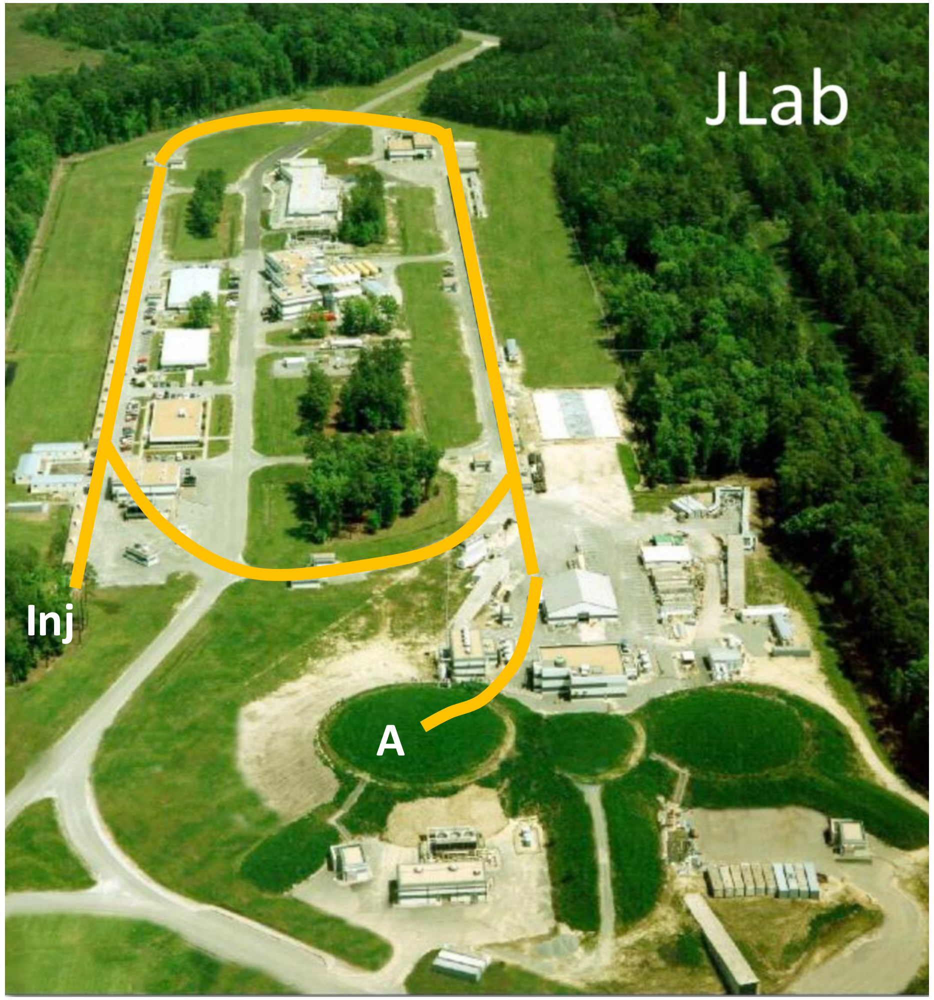
$$A_n \approx A_0(Q)(1 - C \cdot Z^2\alpha)$$

- Lack of data for Z > 40 makes it almost impossible to test models for the missing contributions
- The precision proposed in this experiment will allow studying the nuclear dependence of the asymmetry

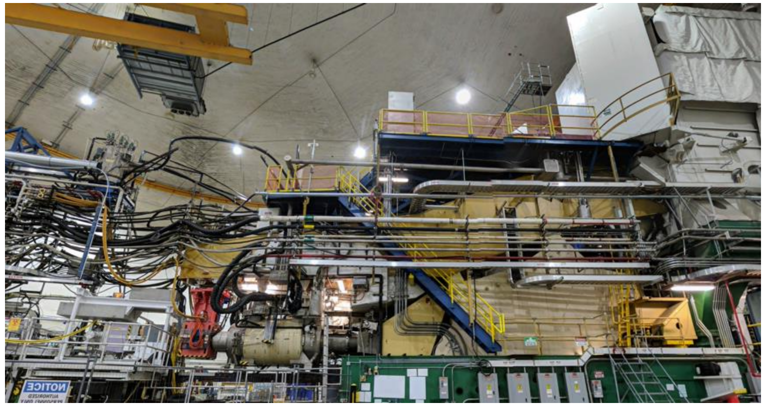
Accelerator/Experimental overview

Injector





Hall A



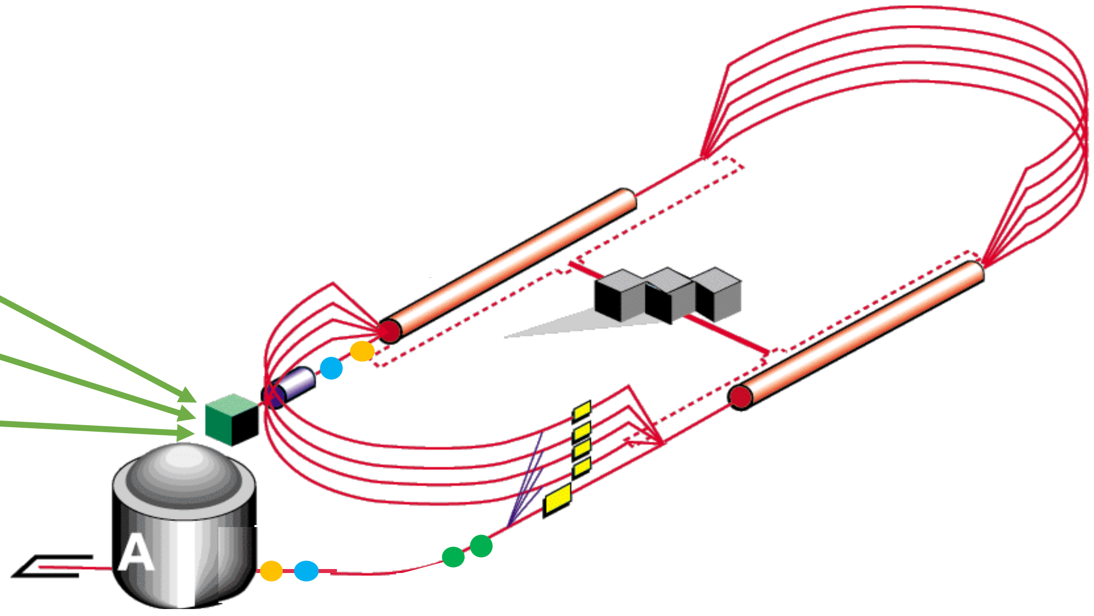
- CEBAF is the ONLY operating facility in the world where such an experiment could be attempted

Accelerator/Experimental overview

Injector laser setup crucial towards minimizing beam asymmetries

Pockels cell allowed us to flip the electron helicity at 120 or 240 Hz

Half Wave Plate allowed us to independently flip the laser polarization every few hours



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Double Wien allowed us to further electromagnetically flip the electron beam helicity every few weeks

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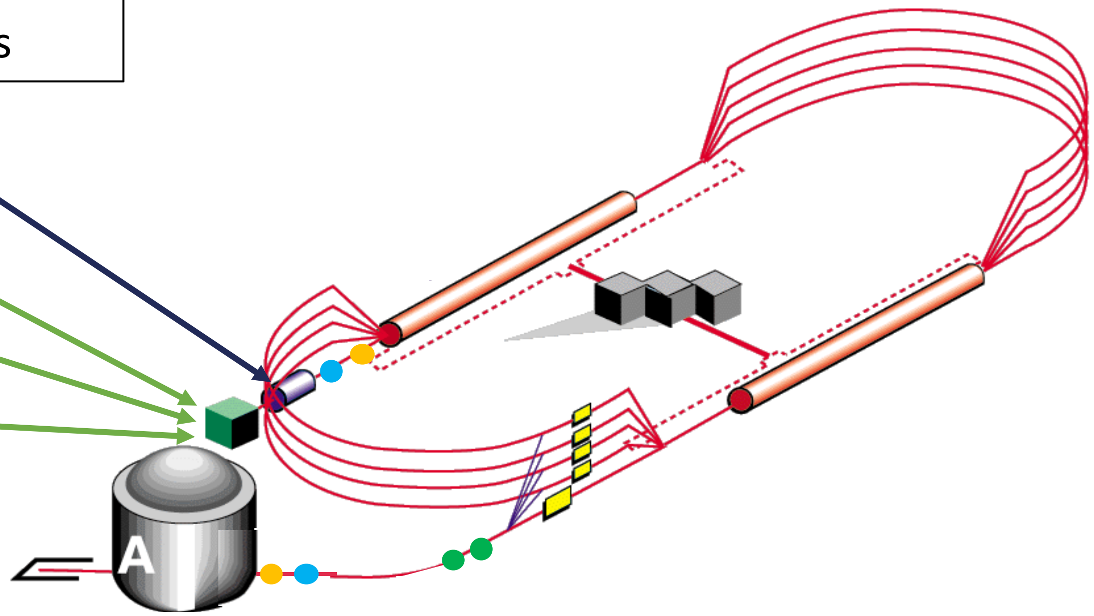

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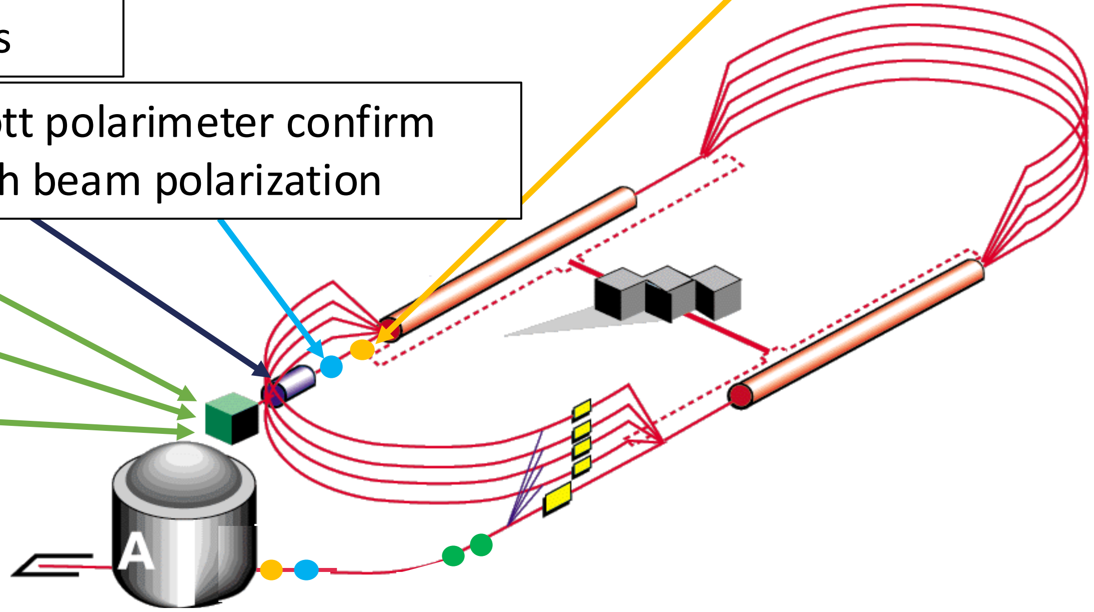
Mott polarimeter confirm high beam polarization

Beam monitors allowed for injector setup with small beam asymmetries



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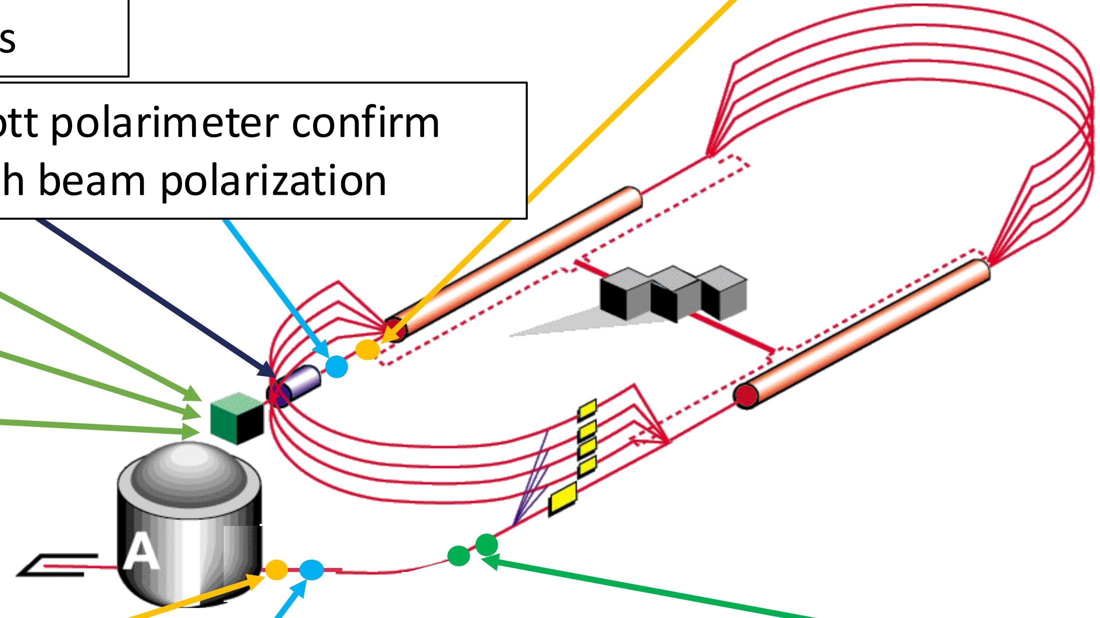


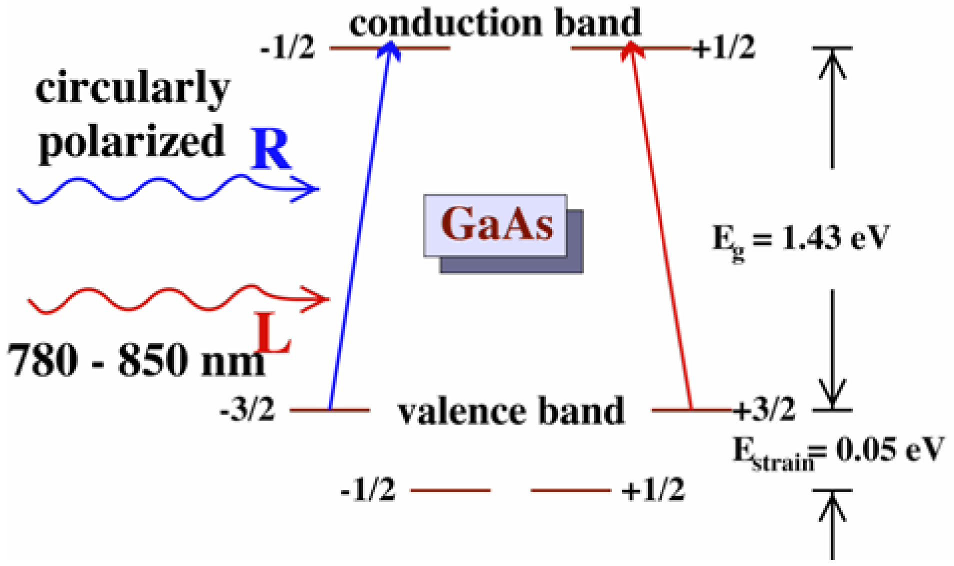
Beam monitors allow us to determine beam properties in front of the target

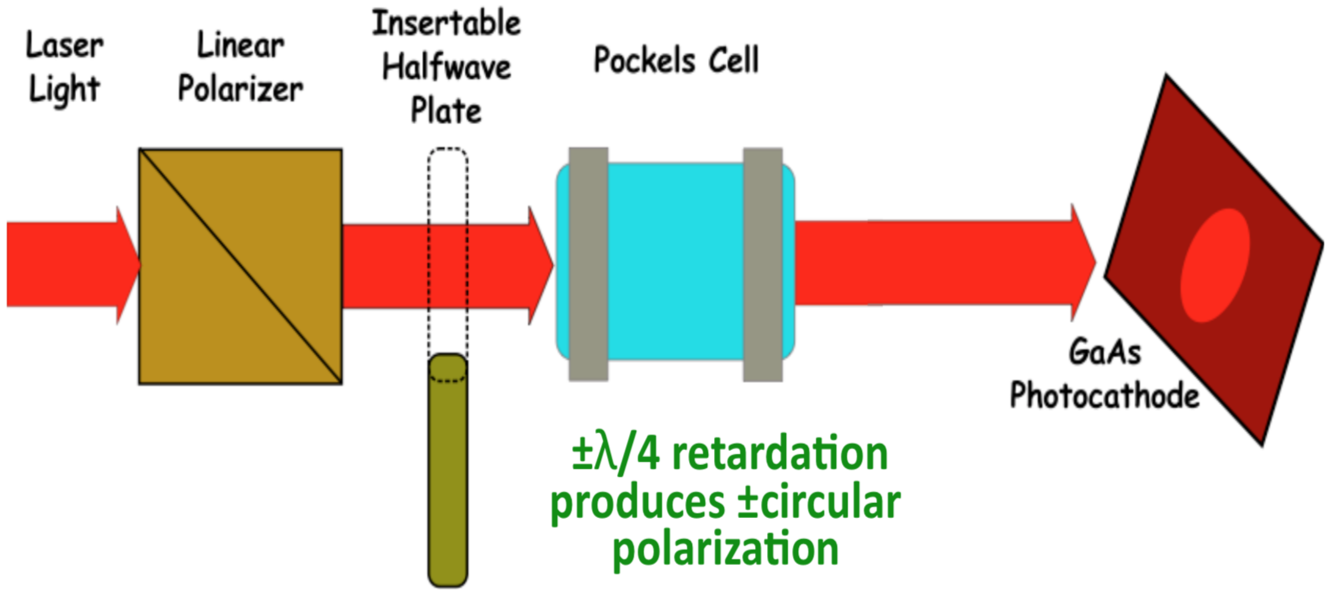
Polarimeters allow us to monitor polarization and check machine setup

Beam modulation system allows us to span the phase space of beam motion

Injector setup

- The GaAs strained cathode acts as an analyzer and produces negative and positive helicity electrons with approximately 90% polarization
- The system relies on a Pockels Cell to produce quick changes between opposite circular polarization states
- Imperfections between the two polarization states will lead to beam asymmetries
  - Careful setup and constant monitoring is needed to mitigate any changes in the accelerator setup that introduce such asymmetries





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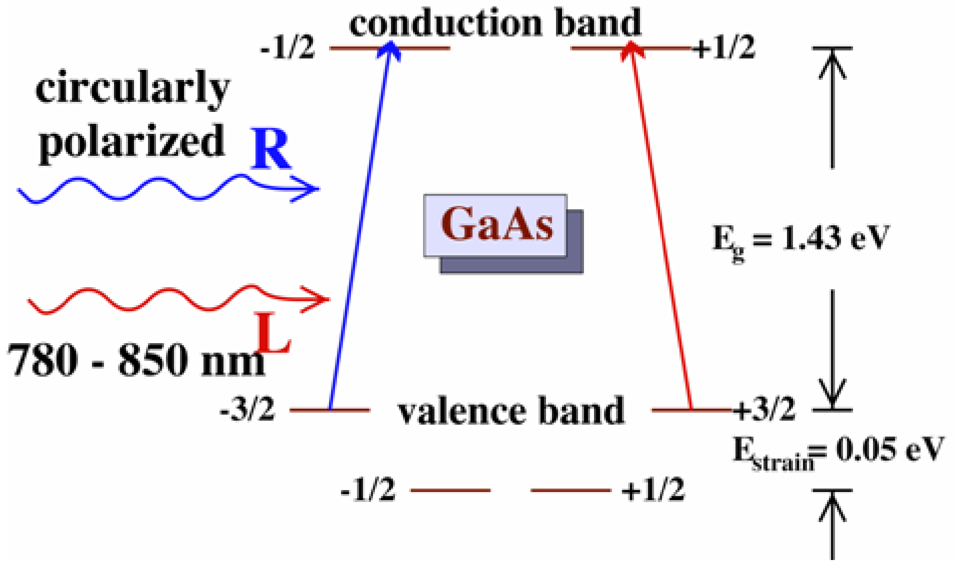
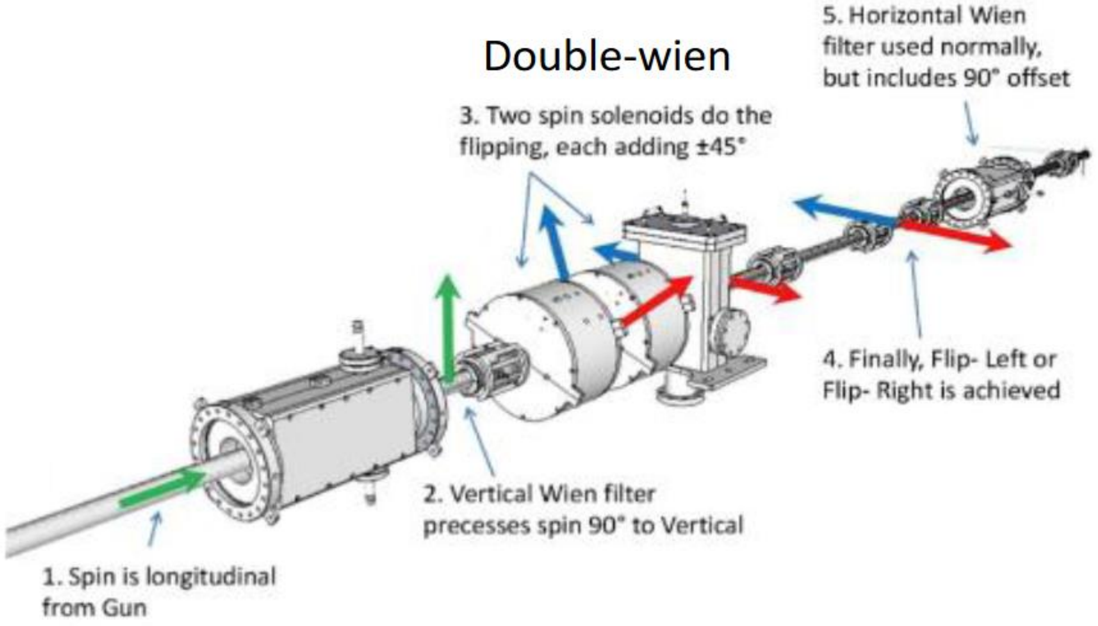
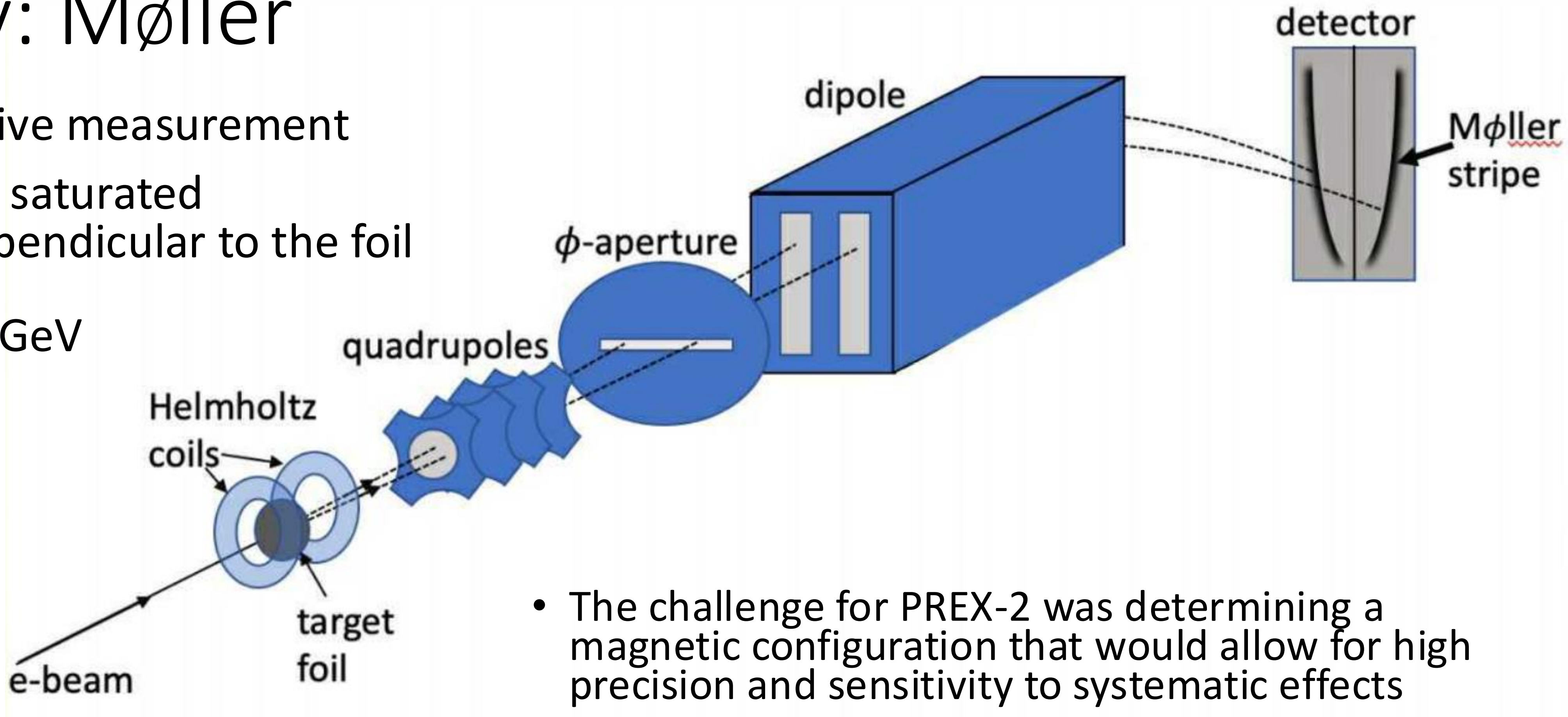
- The system relies on a Pockels Cell to produce quick changes between opposite circular polarization states
- Imperfections between the two polarization states will lead to beam asymmetries
  - Careful setup and constant monitoring is needed to mitigate any changes in the accelerator setup that introduce such asymmetries
- The double Wien allows us to change the helicity of the electron beam completely independently of the laser flips





Polarimetry: Møller

- Low-current, invasive measurement
- 3-4T field provides saturated magnetization perpendicular to the foil
- Redesigned for 11 GeV running



Average polarization:
(89.7 ± 0.8)%

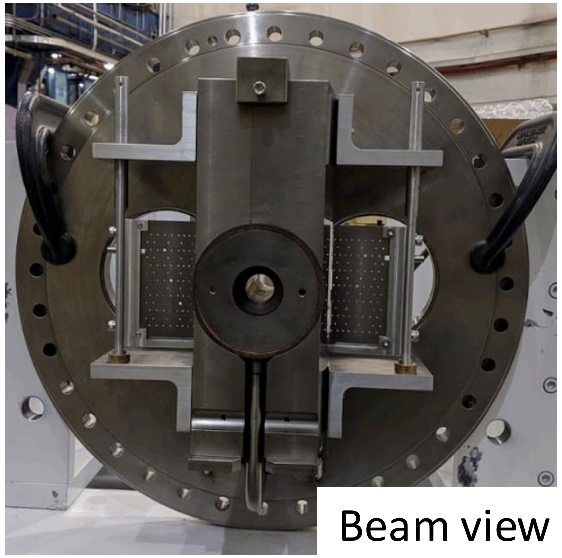
- One of the few sub percent polarization measurements at Jefferson Lab

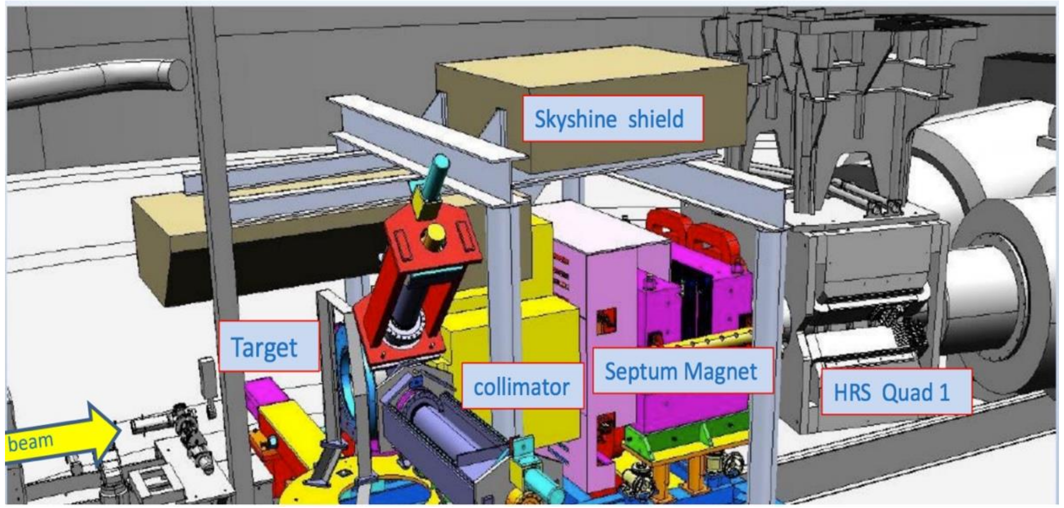
- The challenge for PREX-2 was determining a magnetic configuration that would allow for high precision and sensitivity to systematic effects
- Polarimeter runs were taken approximately every week and established no significant fluctuations in beam polarization over the course of the run
- While still under review the Compton polarimeter analysis showed similar consistency of the run from data taken concurrently with the main experiment

Shielding redesigned since PREX-1

- The experimental hall provides unique challenges for a high luminosity, high Z, low energy experiment
- Large angle scattered electrons need to be stopped close to the target and that region needs to be heavily shielded
- Electronics inside the hall need to be protected from both the electromagnetic and neutron radiation damage that will stop it from functioning properly

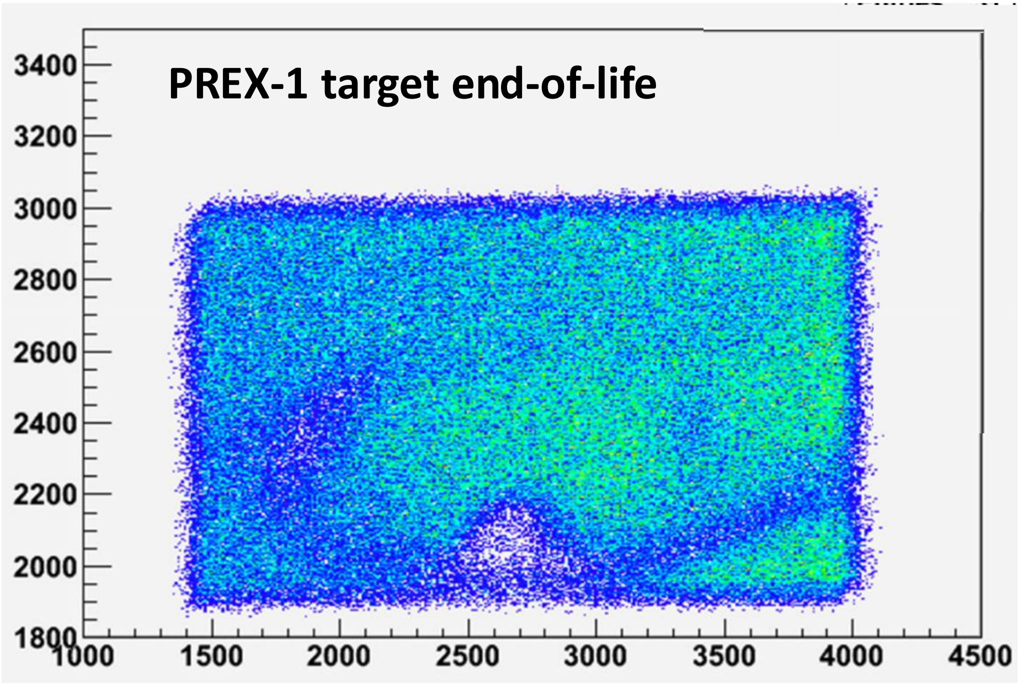

Side view

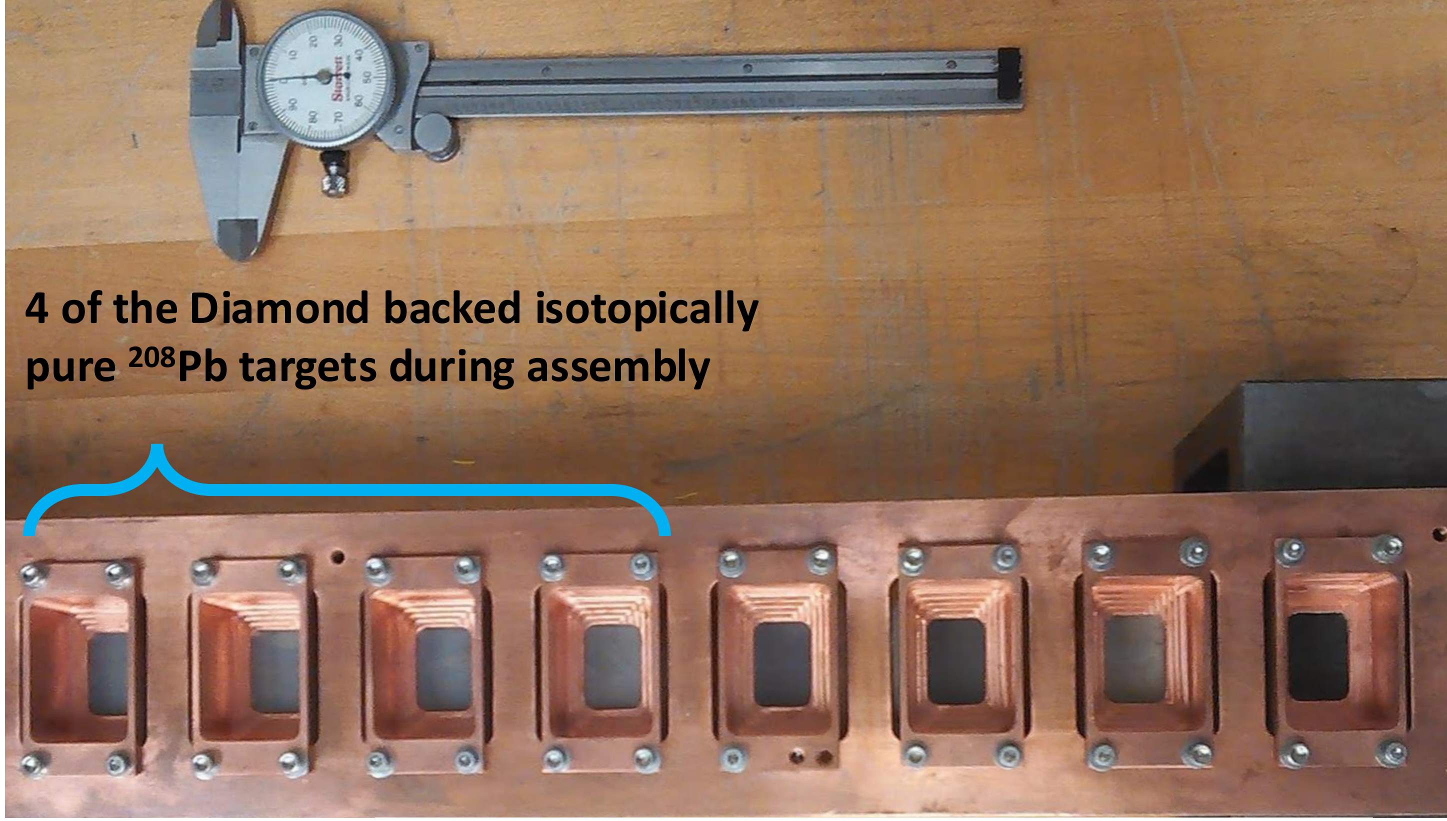

Beam view



Design turned into reality

^{208}Pb Target





- PREX-1 confirmed that the poor thermal conductivity of Pb will eventually lead to the breakdown of the target
  - Even though we provide Carbon (Diamond) backing to increase heat flow
- For PREX-2 we prepared a complement of 10 isotopically pure targets in the expectation that we will use approximately 6
  - Simulations predicted approximately 72 W of power deposition from the 70 μA rastered beam