Results from PREX-2

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Talk overview

- Very short introduction (thanks Chuck for doing this elaborately)
- Experimental details
- Results
- Interpretation of the results and its implication to other fields

Introduction

- Neutron star is an important astrophysical object (NS-NS merger is believed to be the source of heavy elements) - its structural information is yet to be explored completely
- The Equation of State (EOS) of neutron-rich matter need to be understood.

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

$$\rho \equiv density$$

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

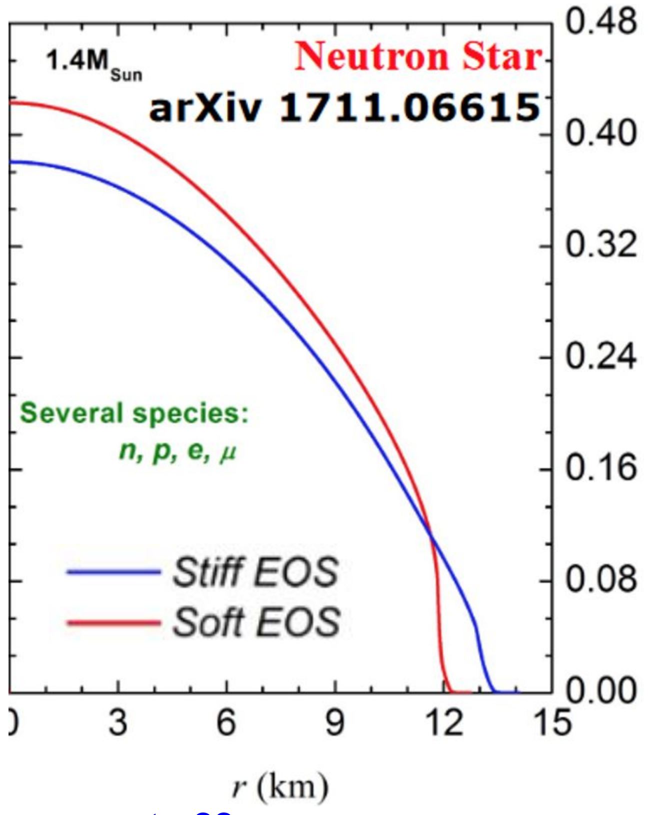
$$S(\rho) \equiv symmetry\ energy - a\ parameter$$

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

$$to\ isospin\ violation$$

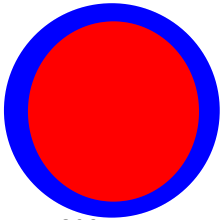
- Slope of Symmetry energy -- $L \propto \frac{\delta S(\rho)}{\delta \rho}\Big|_{\rho_0}$
- Large L - more energy required to add a new neutron - Stiff EOS; Small L - Soft EOS

Jan 24 2018 Jlab Seminar by Farrukh Fattoyev



❖ Can we do a nuclear physics experiment to understand the slope parameter??

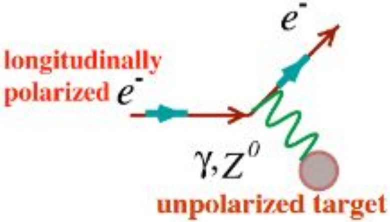
Possibility of performing a nuclear physics experiment

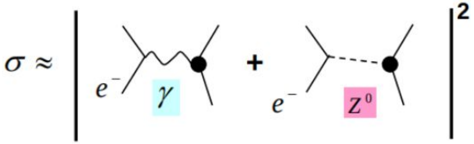


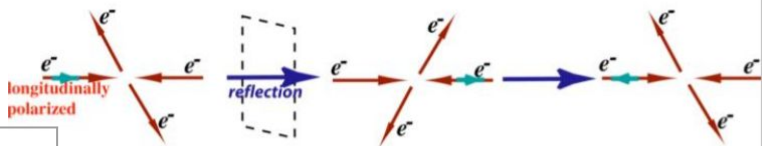
^{208}Pb
(82p+126n)

- Heavy nucleus may have a neutron skin - neutron rich region
- Properties of neutron skin provide information about the slope parameter (L)

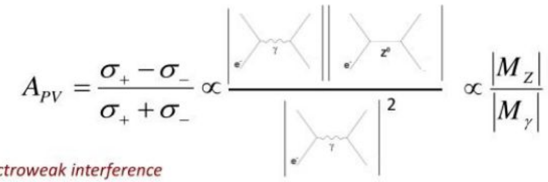
Parity Violating Elastic electron Scattering (PVES):

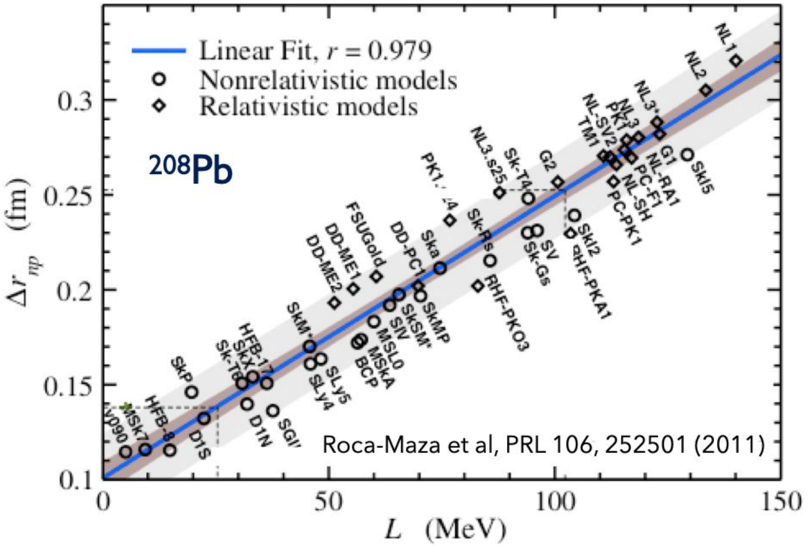






Charge	p	n
Electric	1	0
Weak	0.07	1

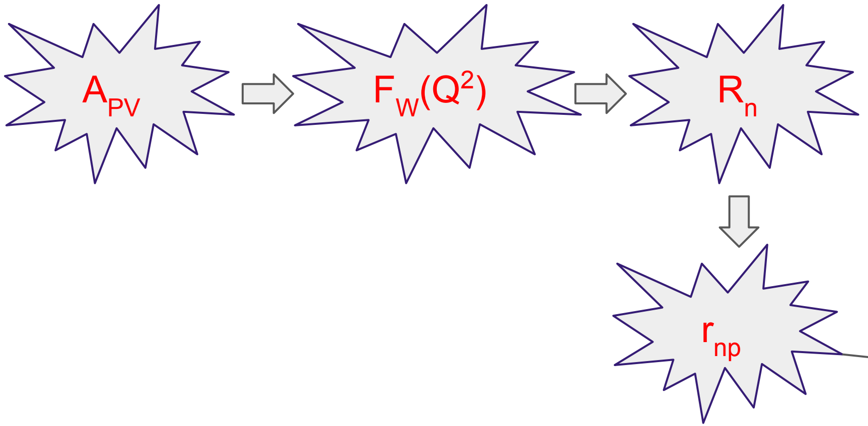




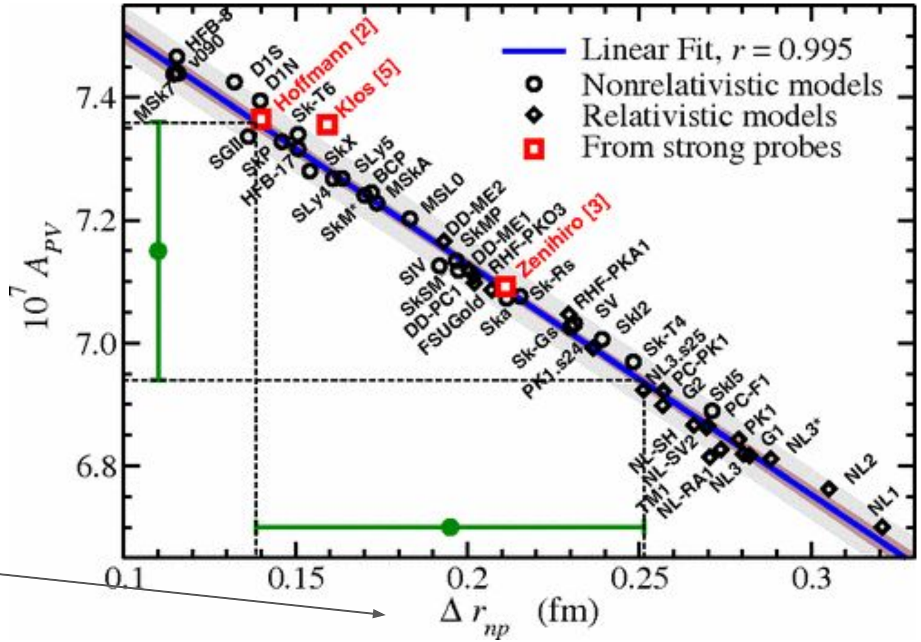
How does A_{pv} correlate with Neutron-skin?

For spin 0 nuclei:

$$A_{PV} \approx -\frac{G_F Q^2 Q_W}{4\pi\alpha\sqrt{2}Z}\frac{F_W(Q^2)}{F_{ch}(Q^2)} \quad \sim 10^{-6}$$



PRL 106, 252501 (2011)



PREX-1 ran in 2010 - statistically limited
PREX-2 ran during the period May to Sept. 2019 in HallA at JLab

PVES is a clean probe to weak charge distributions inside a nucleus

PREX- Choice of target nucleus and target

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

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

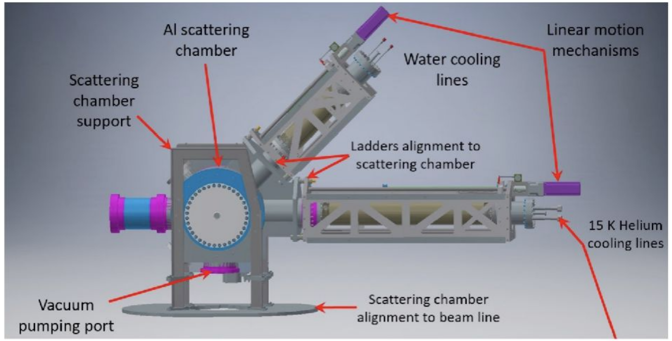
★ First excited state - ^{208}*Pb - 2.6 MeV*; ^{238}U- 44 keV

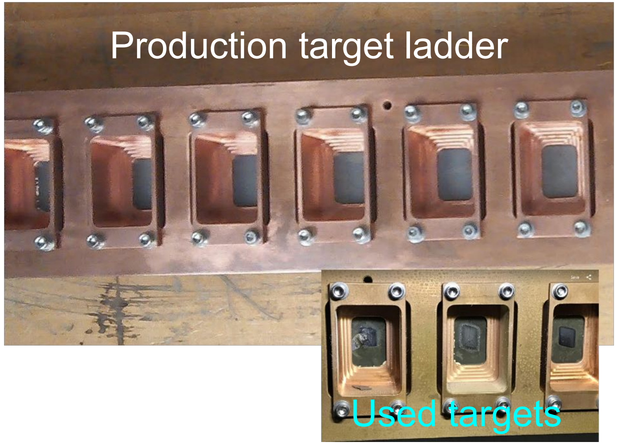
❖ Two target ladders - Production & optics

❖ Diamond-Lead-Diamond sandwich target
  - ➢ Low melting point (327.5^{0}C) & thermal conductivity
  - ➢ Diamond is an excellent heat conductor - iso-spin zero target

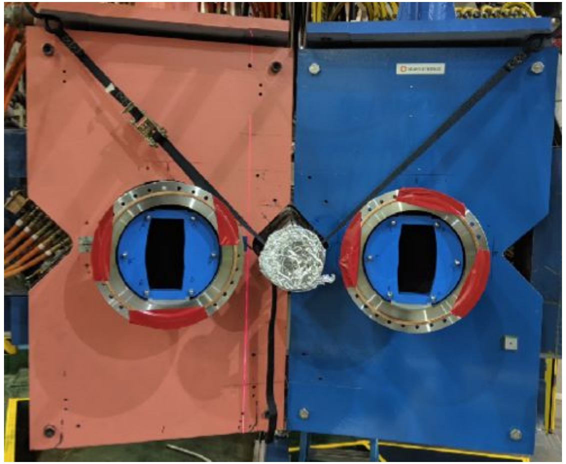
❖ Production ladder is cryo-cooled

❖ Optics (45 deg) normal temperature - Water cell target, C-foil target



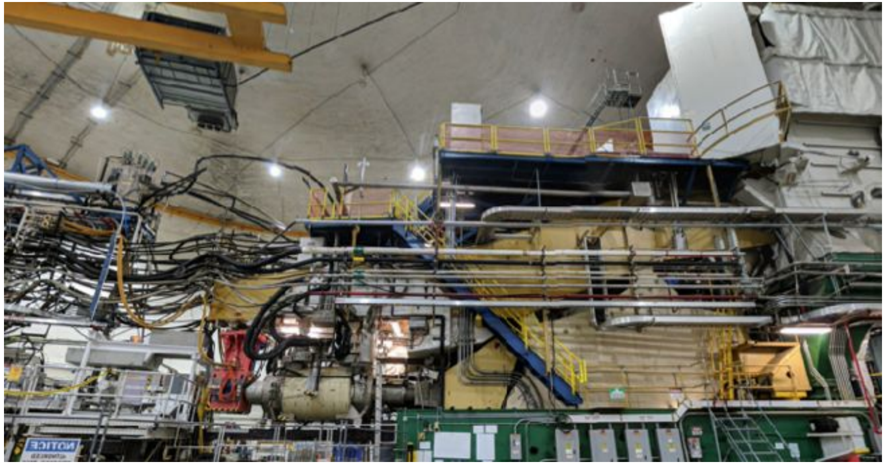


Based on PREX-1 experience, 10 isotopically enriched targets were installed; 6 of them are used

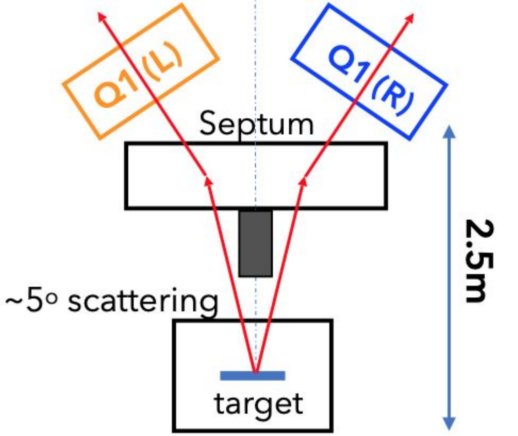


HallA Spectrometers and PREX setup

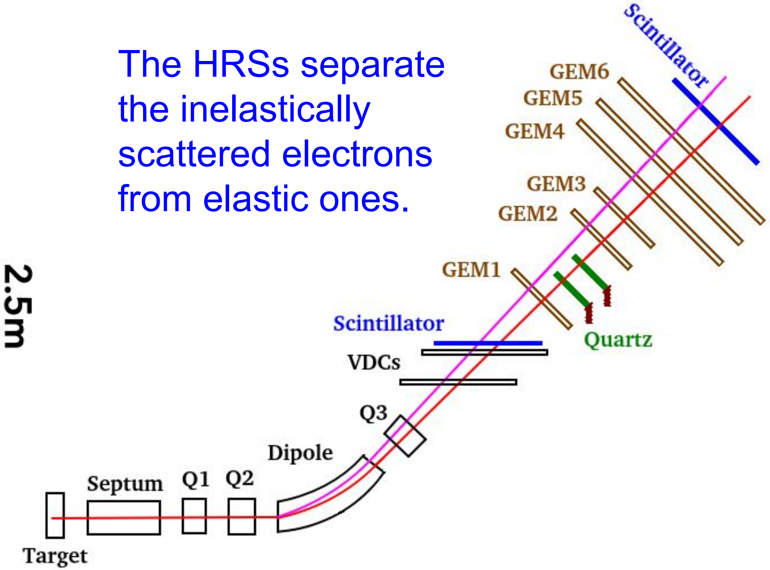
PREX kinematics
E = 950 MeV
I = 70 uA
Scattering angle - 5 deg

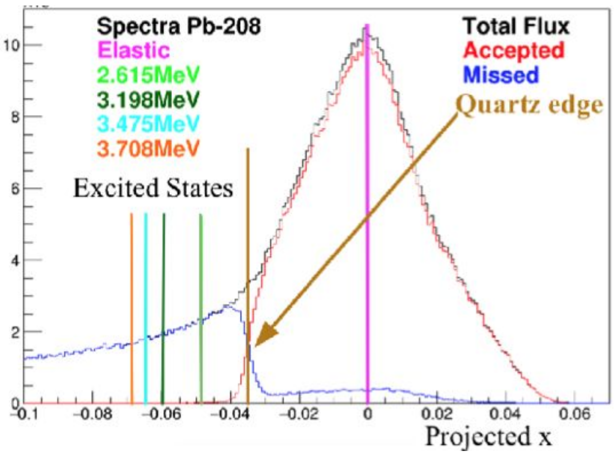


~12.5^0 spectrometers



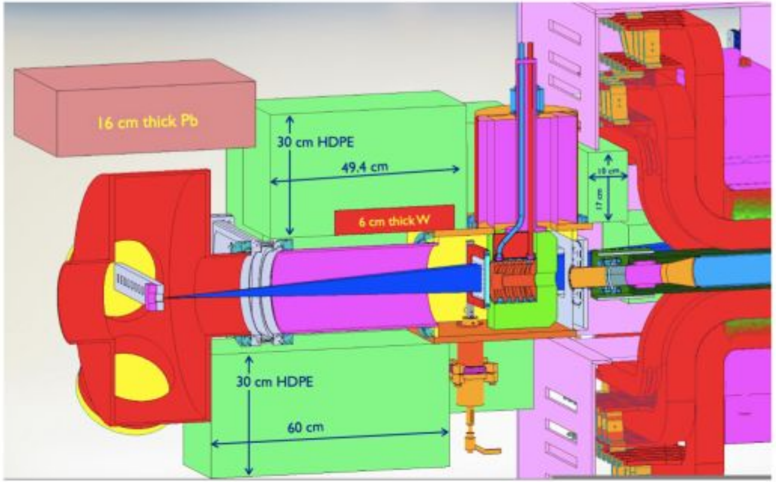
The HRSs separate the inelastically scattered electrons from elastic ones.

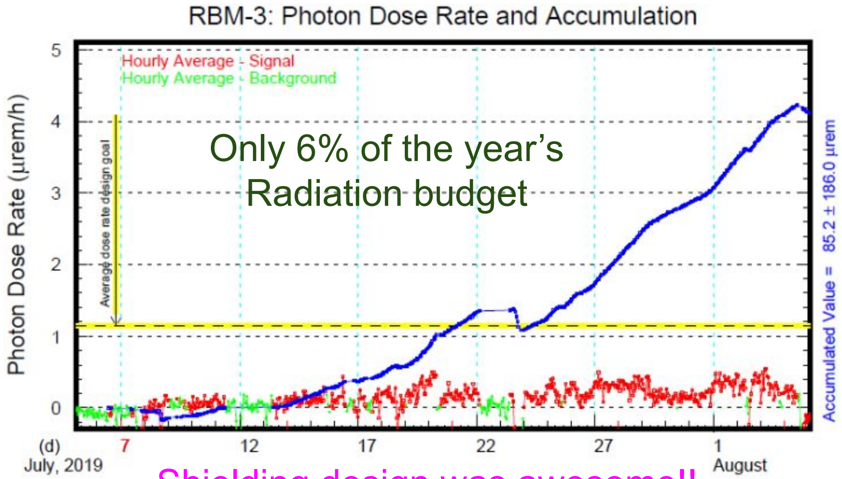




Radiation Shielding

- High target Z, high luminosity produces radiation inside the hall - 2.5 kW power inside the collimator
- Concrete and plastic shielding materials are used to protect electronics inside hall and to lower boundary dose
- Big thanks to HallA designers and staff

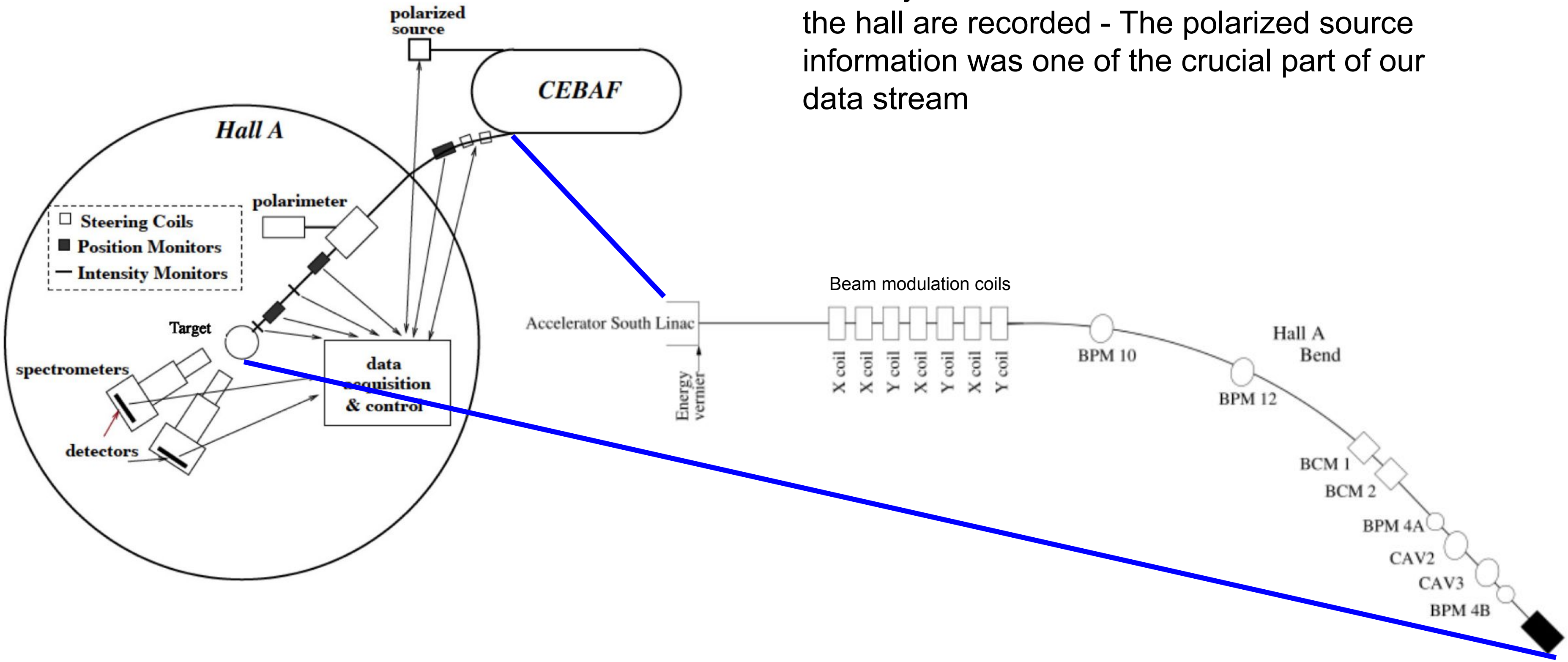




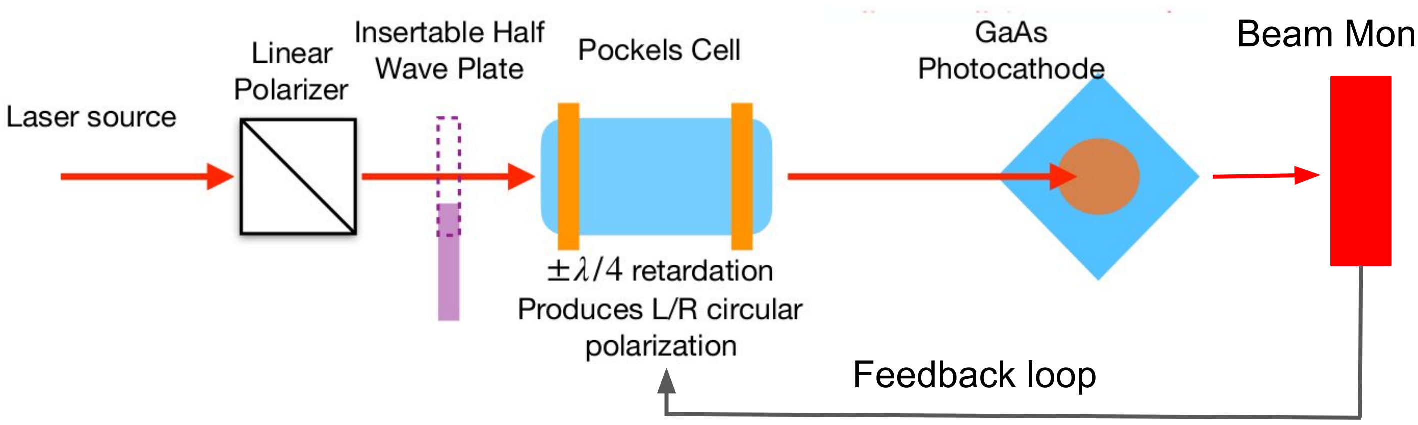
Shielding design was awesome!!

Control of the experiment

Not only detectors and beam instruments in the hall are recorded - The polarized source information was one of the crucial part of our data stream



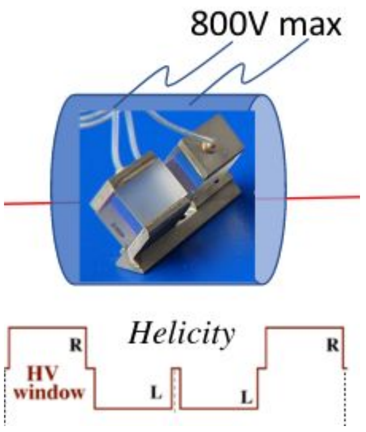
Polarized Source

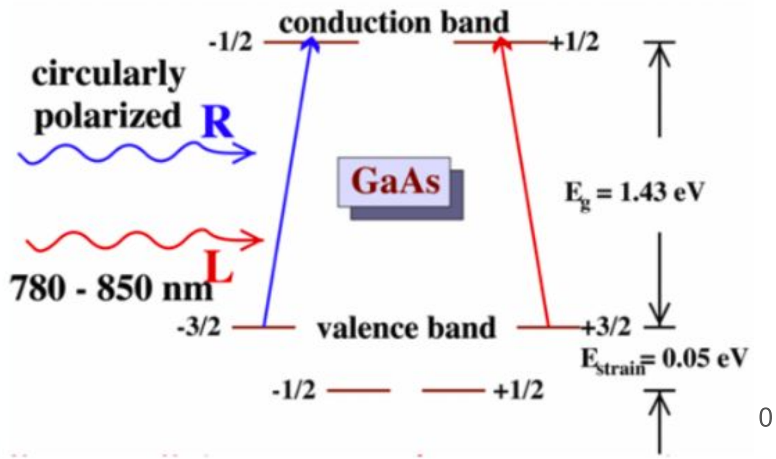


What if this monitor sees some beam asymmetry?? - Helicity correlated asymmetry

To cancel beam asymmetry-

- Need rapid (120 0r 240 Hz) and controlled helicity flip - Pockels Cell
- Slow-helicity reversal (every 6 hours) - Insertable Half wave plate
- Double Wien rotation - Electromagnetically rotate electron's spin -3 Wien flips

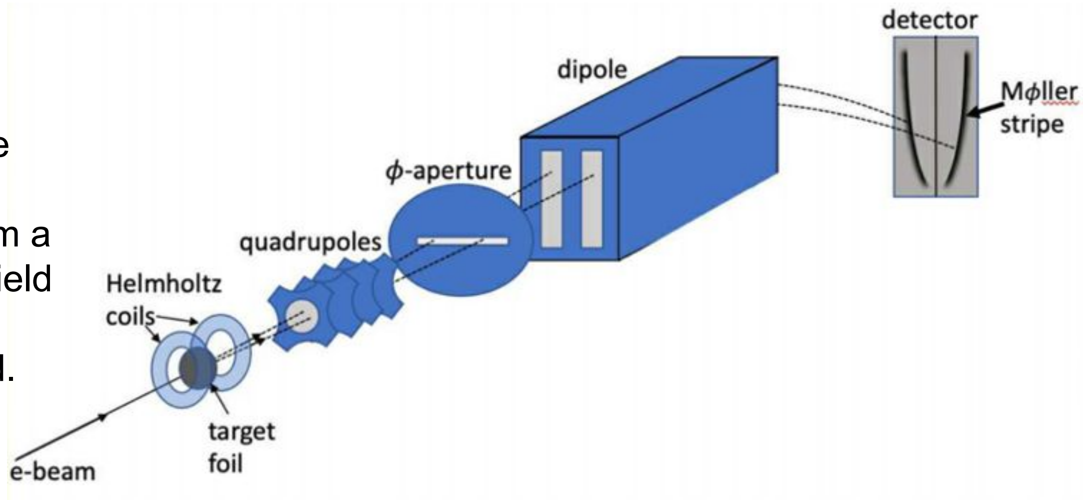




Polarization measurements

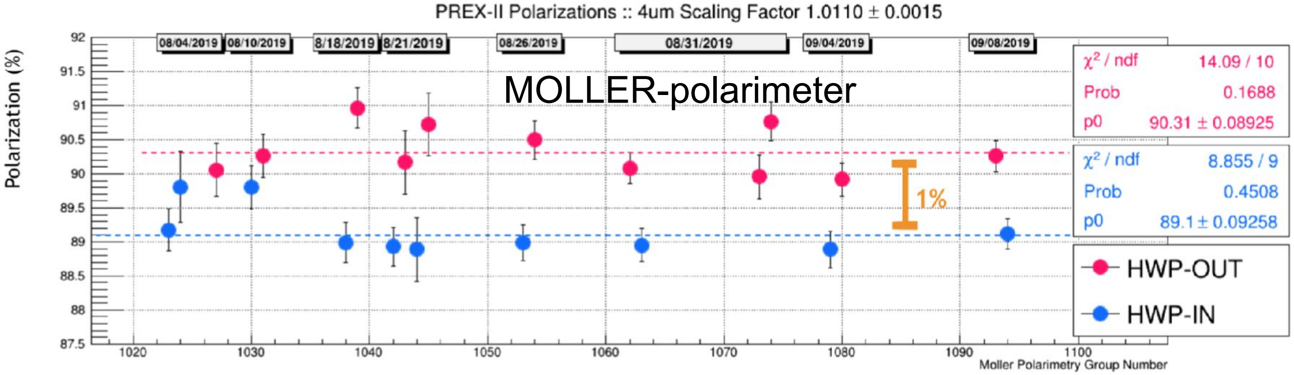
MOLLER Polarimeter

- Low current invasive measurements - Once every week
- 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.



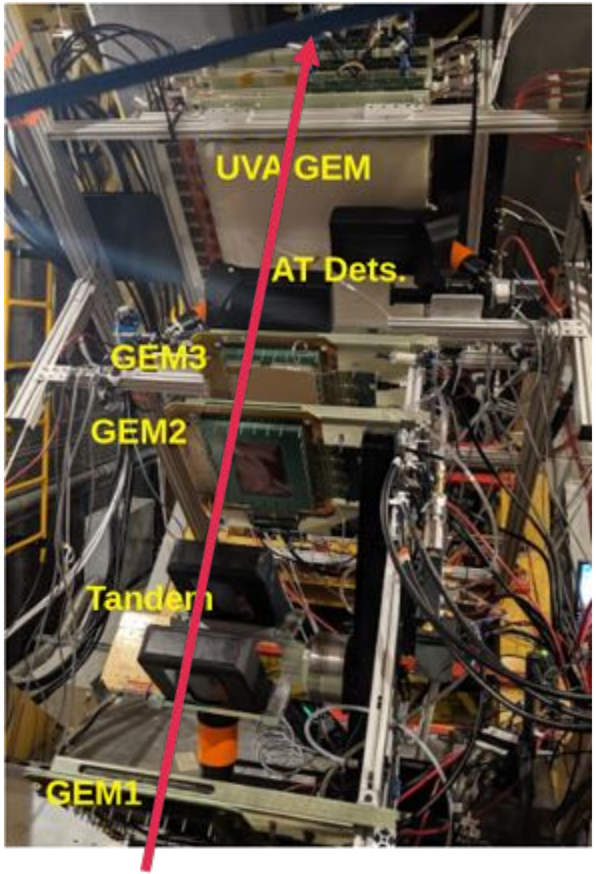
Compton Polarimeter

- Non-invasive measurement
- Challenging at low energy
- Systematic uncertainty is still under review



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

Detector systems

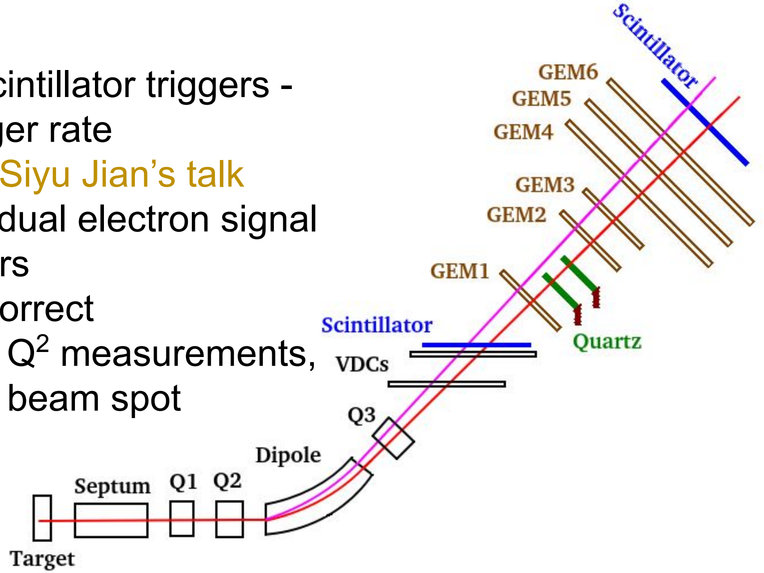


Integrating detectors:

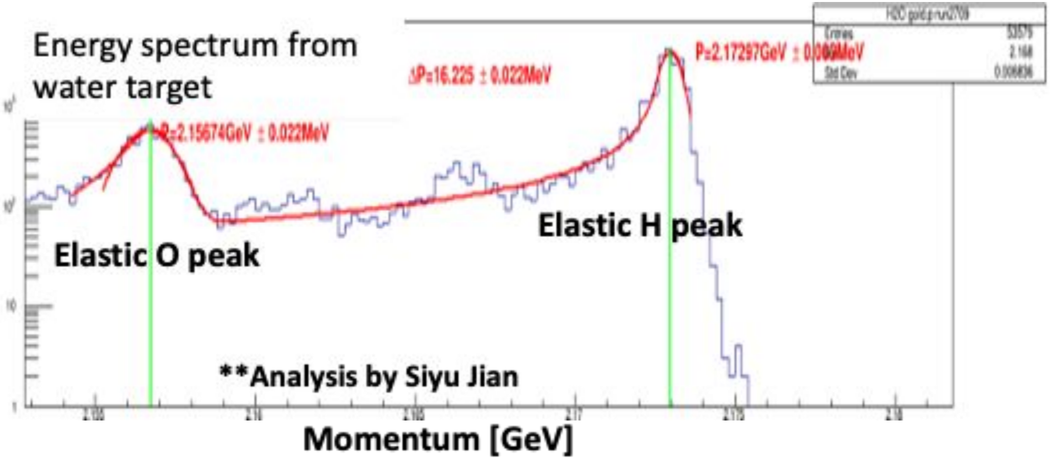
- Charge integration method to reach statistical goal - 70 uA beam with helicity trigger - 2 GHz electrons ~ 3x3 cm^2 area
-**Radiation hard** fused silica (Two in each HRS arm) - Cherenkov detectors
- PMT non-linearity is tested on bench and with beam during the experiment
-Total 6x10^{15} electrons (~9mC) detected.

Counting detectors:

- 30 nA beam with scintillator triggers - few hundred Hz trigger rate
- VDCs, GEMs (see Siyu Jian's talk tomorrow) and individual electron signal in the quartz detectors
- Used to establish correct spectrometer optics, Q^2 measurements, detector alignments, beam spot checking etc.

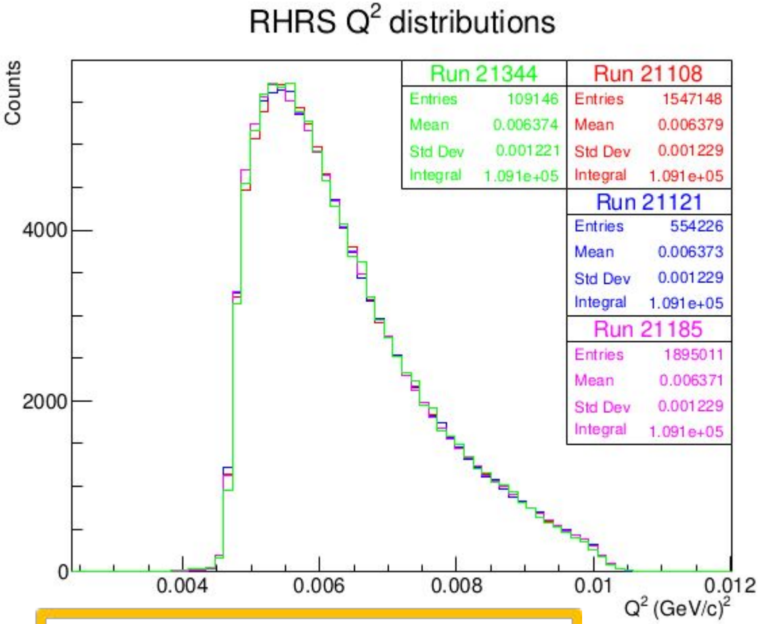


Absolute angle determination and Q^2 measurement



Absolute angles of the spectrometers are determined by measuring the recoil H and O nuclei using a watercell target.

L-HRS angle:	R-HRS angle:
(4.765 ± 0.016)°	**(4.747 ± 0.018)°**



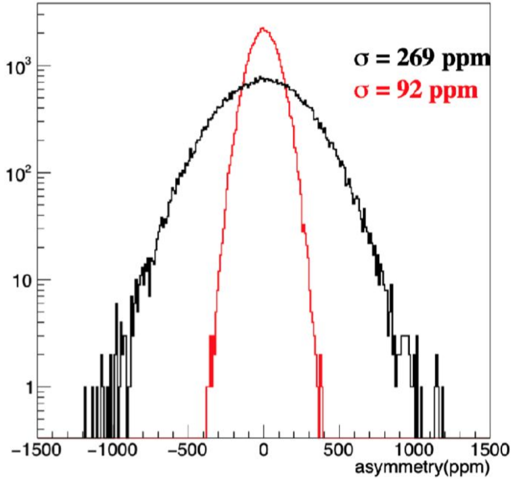
Q^2 average:
(0.00616 ± 0.00004) GeV²

Q^2 are measured periodically and no significant variation is observed

Beam Corrections

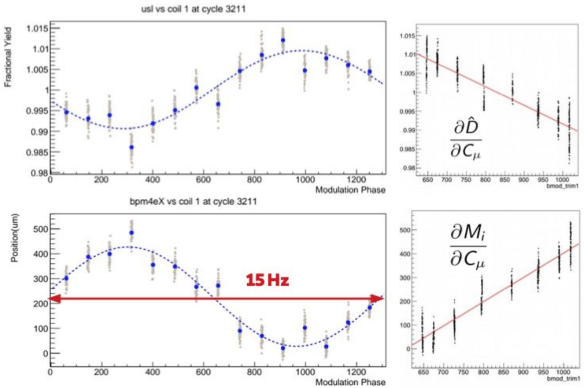
- Steep Pb form-factor and very forward angle scattering make the observed yield difference very sensitive to beam corrections
- Beam jitter noise is several times greater than counting statistics
- A potential source of large systematic error!!

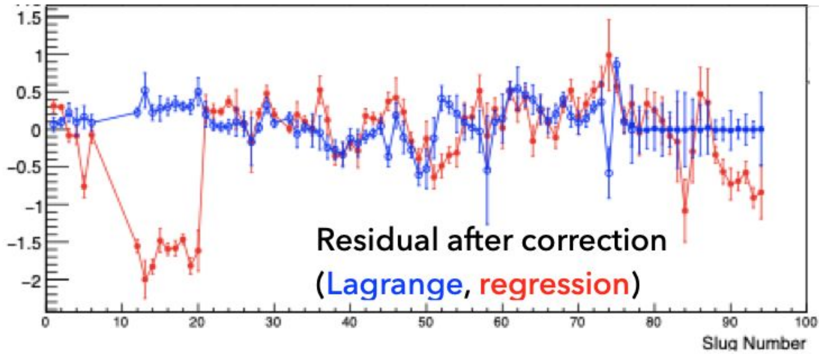
$$A = A_{raw} - A_Q - \sum_i \alpha_i \Delta x_i - \alpha_E A_E$$



❖ 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

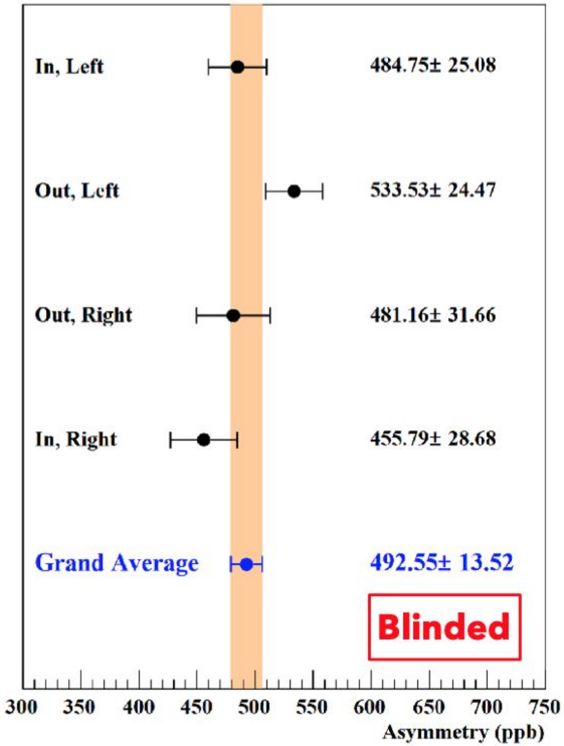




Total beam corrections:
(60.4 ± 2.5) ppb

Extracting A_{PV} from Clean data

Corrected asymmetries

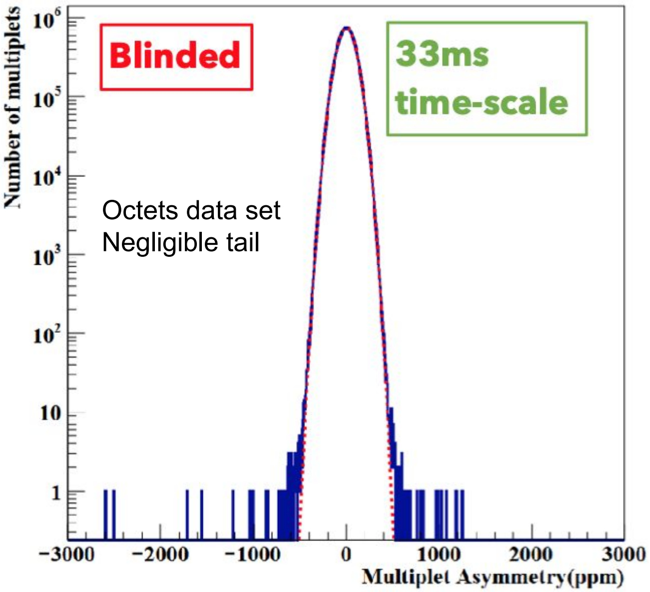


$$A_{PV} = R_{acceptNorm}\frac{A_{corr}/P_e - \sum_i A_i f_i}{1-\sum_i f_i}$$

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

- $R_{acceptNorm}$: Acceptance normalization
- A_{corr}: Corrected asymmetry
- P_e: Polarization
- A_i: Background asymmetry
- f_i: Background fraction

*Dedicated runs for background estimates



Blinded A_{PV}:
(549.4 ± 16.1)ppb

Systematics

PREX-2: 3% stat, 0.06 fm
CREX: 4% stat, 0.02fm

Improved on proposed systematic uncertainty

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

PREX-2 Results	Apv uncertainty contribution (ppb)	Apv 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**

Blinded A_{PV}:
(549.4 ± 16.1)ppb

Unblinded

PREX-2 $Q^2 = 0.0062\ \mathrm{GeV}^2$

$$A_{pv} = 550 \pm 16\ (stat) \pm 8\ (syst)\ \mathrm{ppb}$$

The final error is statistics dominant

Weak Radius of Neutron skin from PREX-2

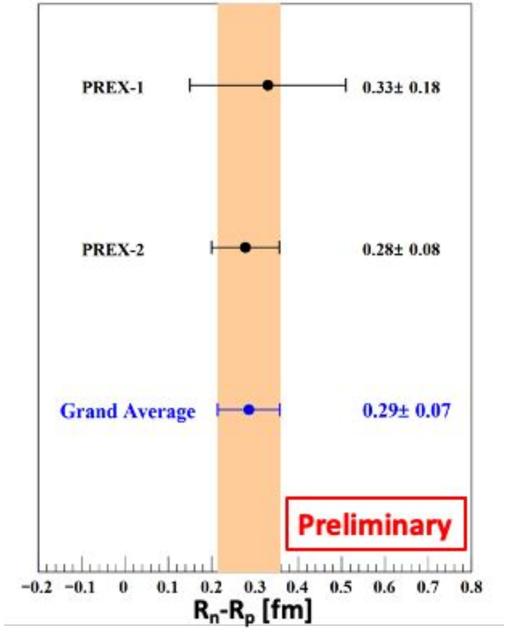
Calculation from Chuck Horowitz

$$Weak\ Charge\ radius \equiv R_w = 5.795 \pm 0.082\ fm\ (1.4\%)$$

$$R_w - R_{ch} = 0.292 \pm 0.082\ fm$$

$$R_n - R_p = 0.278 \pm 0.078\ fm$$

The centroid of the neutron skin thickness from the present measurement is almost one sigma away from the grand central value of (R_n-R_p) measured using other techniques - posed questions about their methods of extracting neutron skin thickness



Combined PREX-1 & -2 results

Future:: MREX at Mainz, Germany proposed to measure Pb neutron skin with 0.03 fm precision… We are looking for that...

Summary

- PREX-2 run was a grand success
- Completed **blinded analysis** and already published our results in the last DNP meeting.
- Extracted neutron skin thickness is 0.28(0.08) fm.
- We improved on proposed systematics error
- Result is not systematic dominant, rather statistics
- PRL paper is under preparation
- Looking for MREX for new results with better precision

Please don't worry... This is from pre-covid era

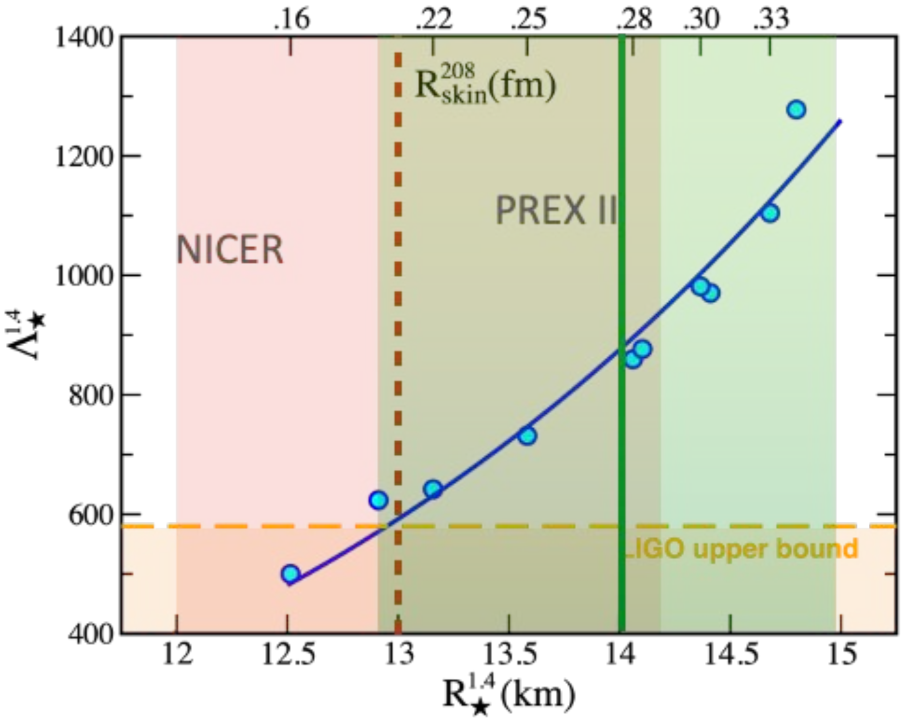
Thanks to HallA staffs, MCC crews, all shift-takers, and all of you..

Supporting slides

Broader Implications: Example 1

Preliminary

- We can make use of the existing models to relate the deformability of neutron stars to both neutron skin of Pb and to the neutron star radius
- The PREX-2 result is in good agreement with the NICER result and in slight tension with the tidal polarizability result obtained from GW170817 neutron star merge event observed by LIGO

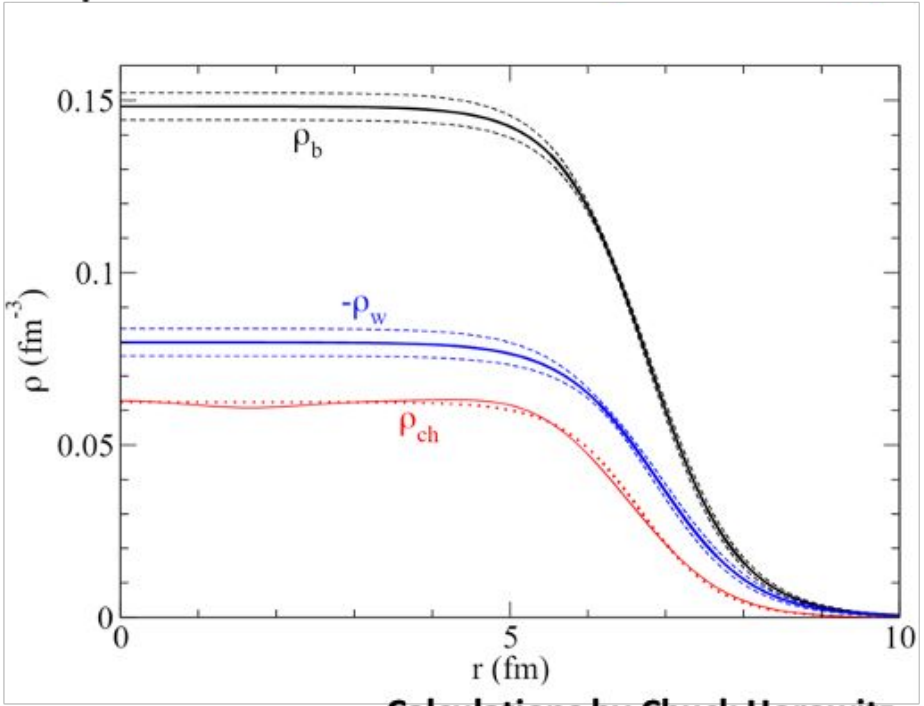


We are proud to see our results with two other important experiments

Broader Implications: Example 2

Preliminary

- The weak radius can be combined with the well known charge density to obtain the baryon density of ^{208}Pb
- This is the first clean determination of the central baryon density of a heavy nucleus and is accurate to 2%
- Provides an important benchmark to chiral EFT calculations that is closely related to nuclear saturation density



Calculations by Chuck Horowitz following PRC 102(2020) 044321

Isovector constraints

“Blinding box”: an additive term on every octet asymmetry, randomly selected (flat) at the start of the run,
from ± 160 ppb

Blinding term turned out to be 0.5313 ppb

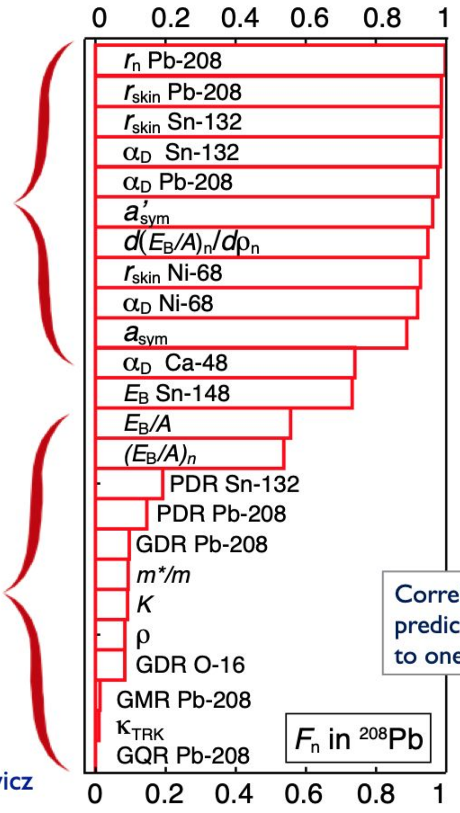
This is entirely just luck-of-the-draw 🙄

	Blindedasym - rawasym (ppb)	
ops	0.5313	Roadkill stew sounds mighty good right NOW. --- Unspecified collaborator
test1	6.0223	Roadlife stew sounds mighty good right NOW. --- Unspecified collaborator
test2	-96.6812	Porkbean stew sounds mighty good right NOW. --- Unspecified collaborator
test3	53.2091	Suspicious stew sounds mighty good right NOW. --- Unspecified collaborator
test4	-121.4924	Road-kill stew sounds mighty good right NOW. --- Unspecified collaborator

Good Isovector Indicators

Poor Isovector Indicators

(collective excitations, binding energies, etc.)
Relatively well measured



Correlation of prediction vs. changes to one empirical input

Jorge Piekarewicz