From Parity Violating Electron scattering to the EIC

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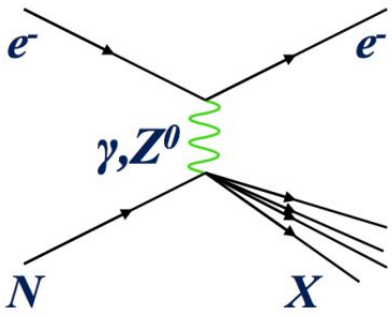
Parity violating electron scattering



- PVES uses longitudinally polarized electron scattering to pick up the weak charge from a target and give us a measurement of the weak form factor
- Most PVES experiments are fixed target because of the need for very high luminosity
- Due to the imbalance between the EM and Weak interactions the asymmetries lead to particular experimental choices

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

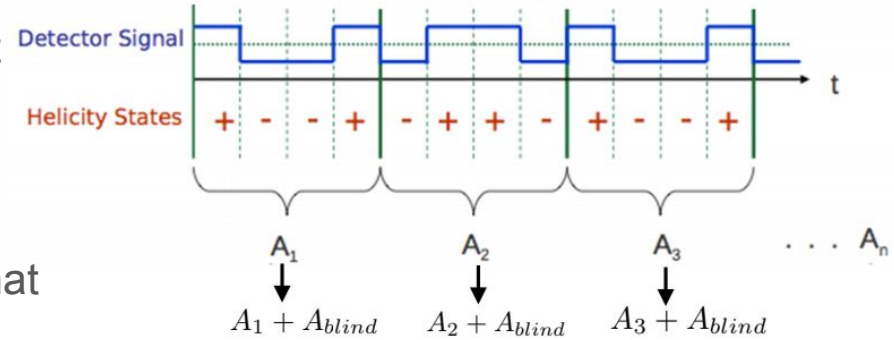
Born approximation

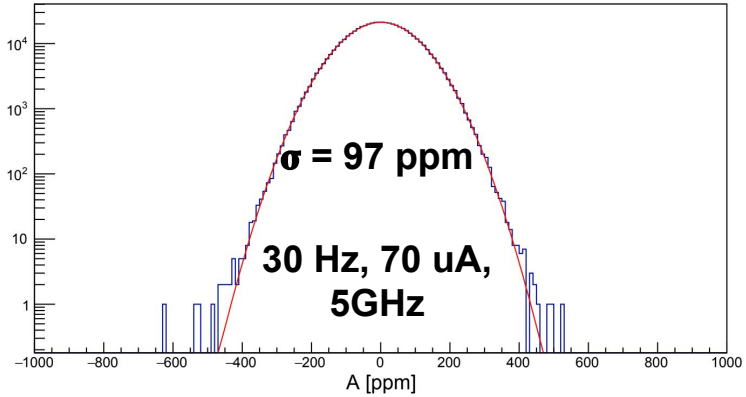
$$A_{PV} \approx \frac{G_{\mathrm{F}} Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W\, F_W(Q^2)}{Z\, F_{\mathrm{ch}}(Q^2)} \sim 10^{-4} \times Q^2$$

PVES in practice

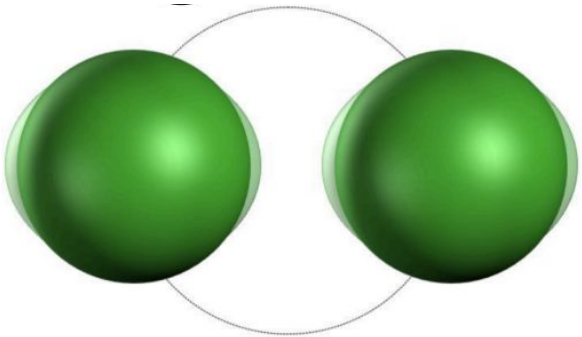
- We look at the integrated photo-electron count from a quartz detector which takes a large flux of electrons
- The helicity of the electron is flipped at different rates allowing for removal of different noise components
  - Asymmetries are formed over a helicity pattern and a blinding factor is added to that result
- We closely monitor beam parameters and remove sources of false asymmetries
  - Beam motion is induced regularly to assess the effect on individual detectors and obtain slopes for corrections

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



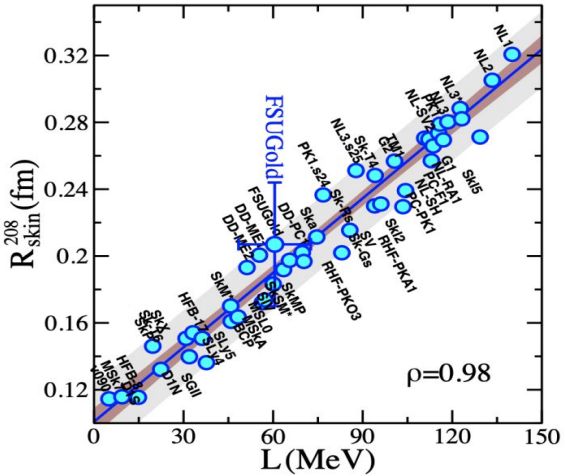


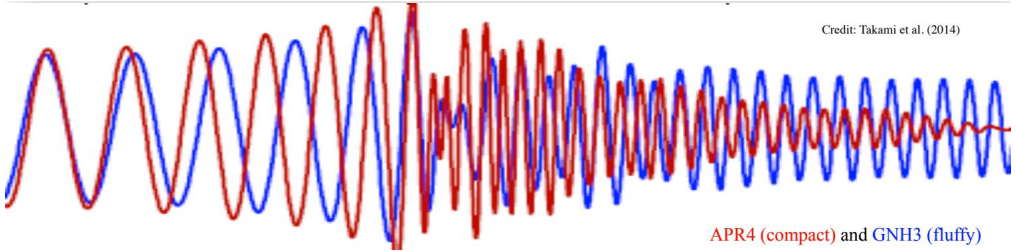
Nuclear equation of state of neutron rich matter



Nuclear EOS

Parameters in the EOS (such as slope of symmetry energy)



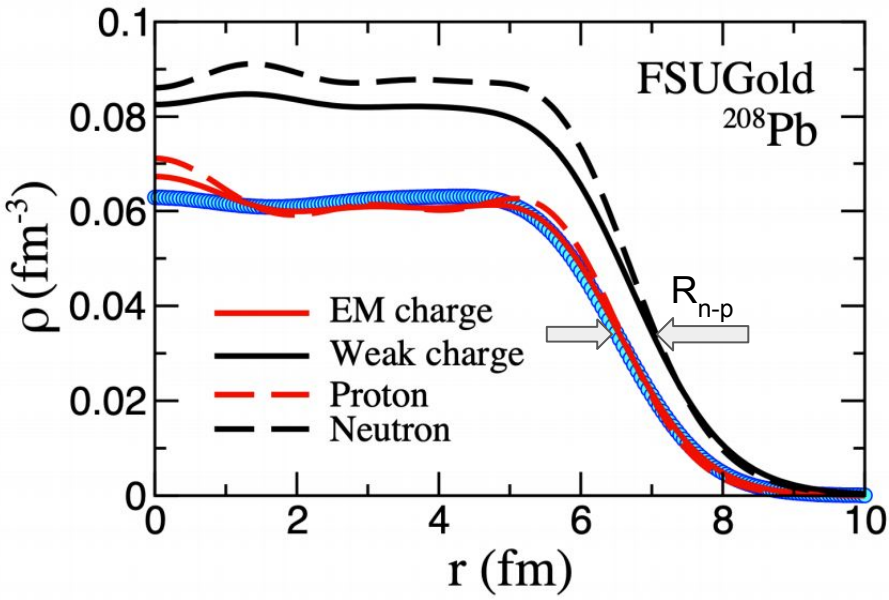


Credit: Takami et al. (2014)

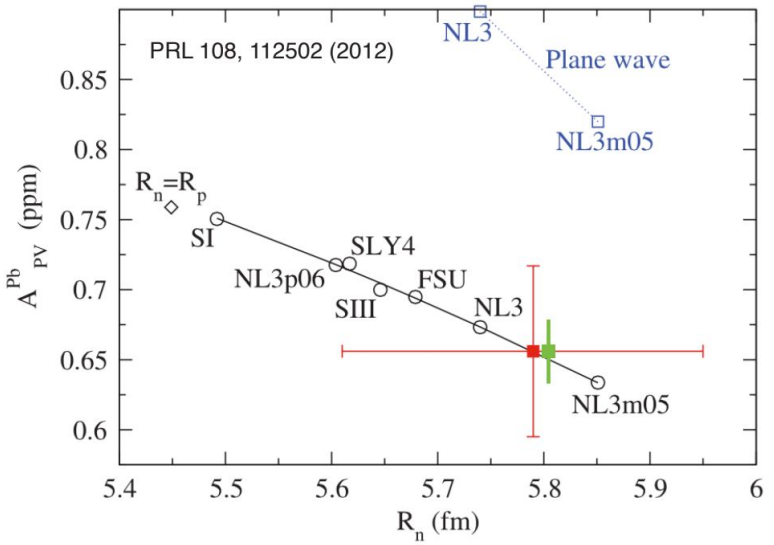
APR4 (compact) and GNH3 (fluffy)

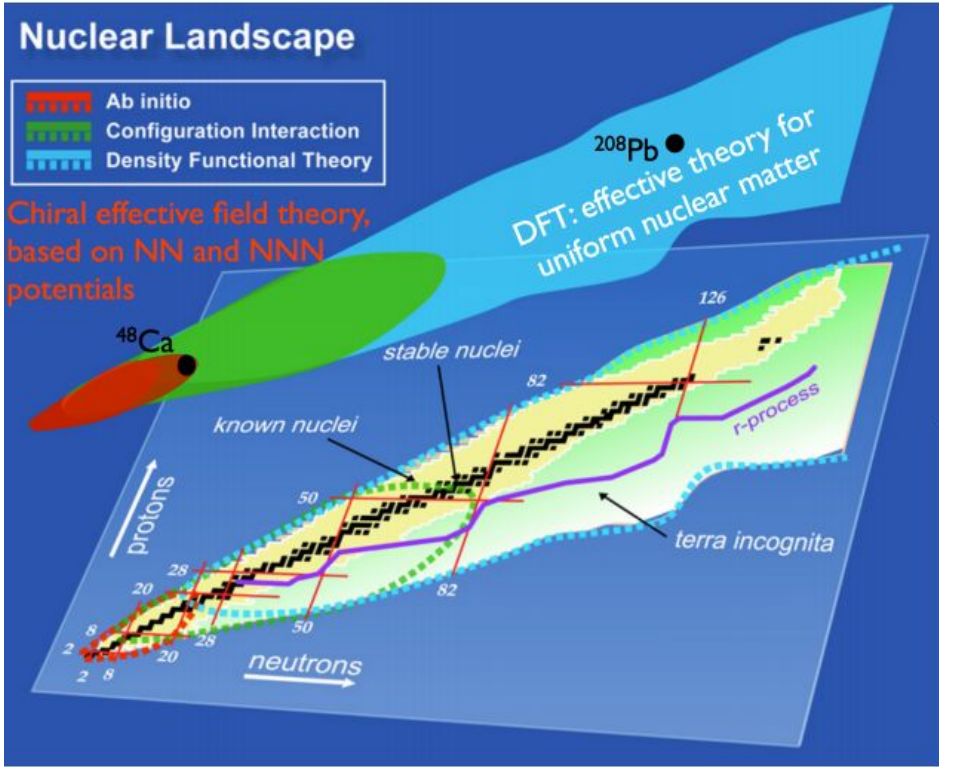
PREX

- PVES is an ideal tool for this problem as it will pick up the weak charge from a target and give us a measurement of the weak form factor
- The weak charge in the nucleus is carried almost exclusively by the neutrons
- Because this is an EW measurement it has a much more easily interpretable result compared to other measurement that use the strong interaction
- The initial measurement in 2010 showed a larger neutron radius at about 2 sigma



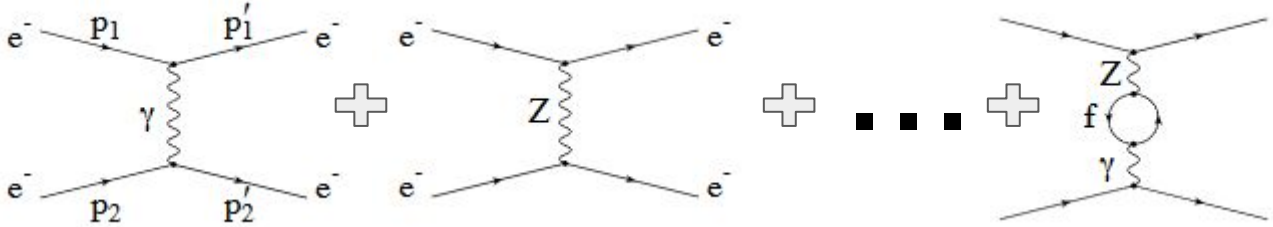
PREX2 and CREX



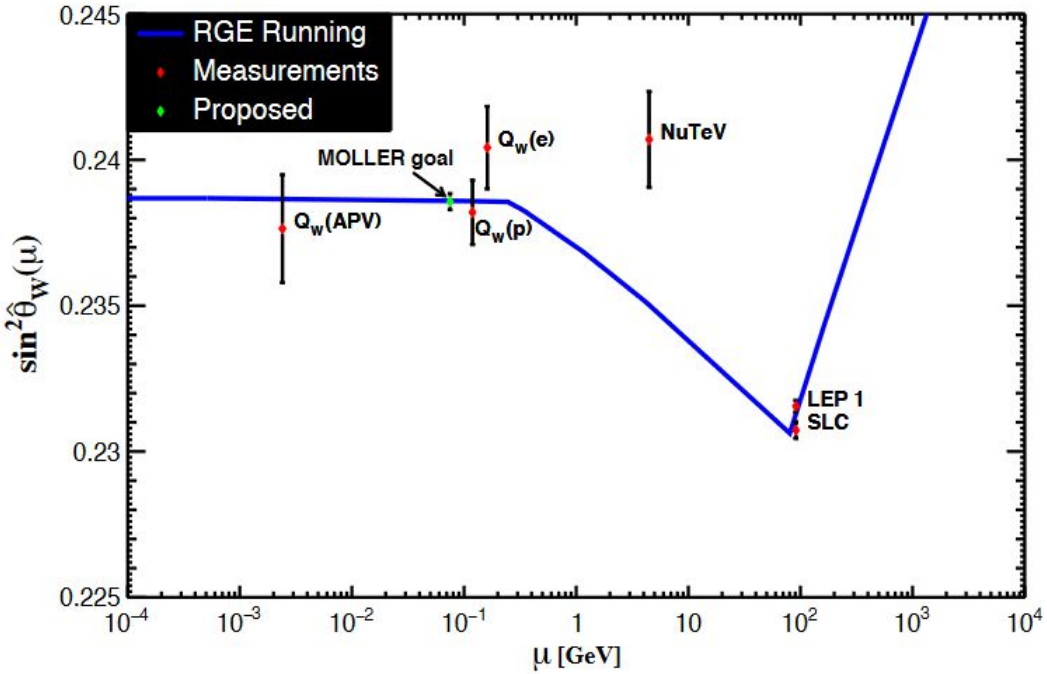


- The PREX2 result is expected in the second half of 2020
- We are now collecting data for the sister experiment CREX to determine the neutron skin thickness in 48Ca

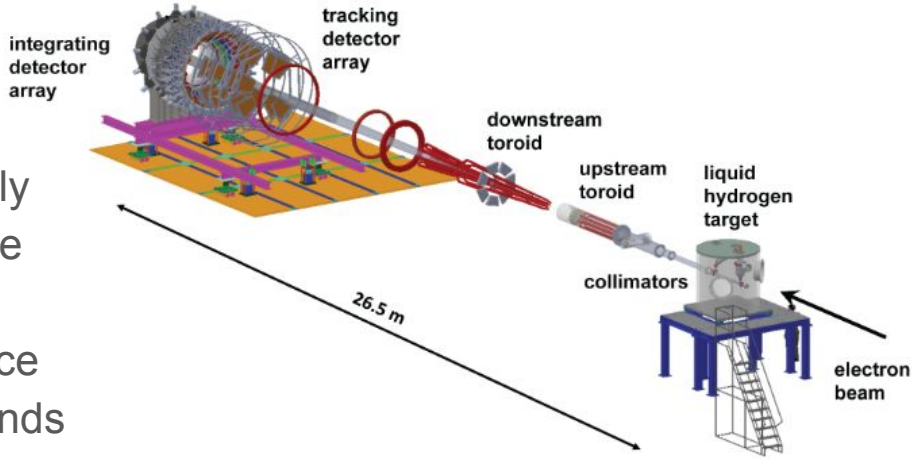
MOLLER



- Using PVES we can test the Standard Model to a precision on the similar level with the Z-pole measurements
- The low Q2 region MOLLER probes still allows a multitude of BSM physics which would introduce a deviation from the SM prediction for the weak mixing angle
- This level of precision will require the lowest systematic of any previous PVES experiment



MOLLER

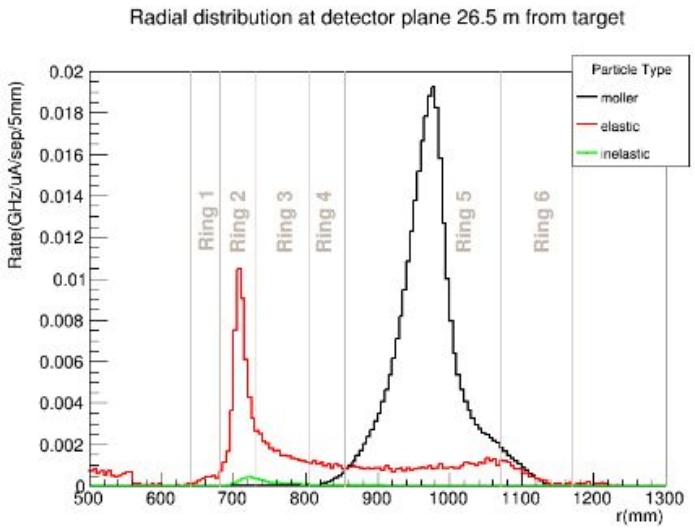


- The novel spectrometer design allows to cleanly separate the elastic e-e events (signal) from the elastic and inelastic e-p events (background)
- The full azimuth and extended radial acceptance allows for the measurements of both backgrounds and signal asymmetries
- The 2% fractional uncertainty on the weak charge of the electron translates into a 0.1% uncertainty on the weak mixing angle due to the near perfect cancellation in the weak charge

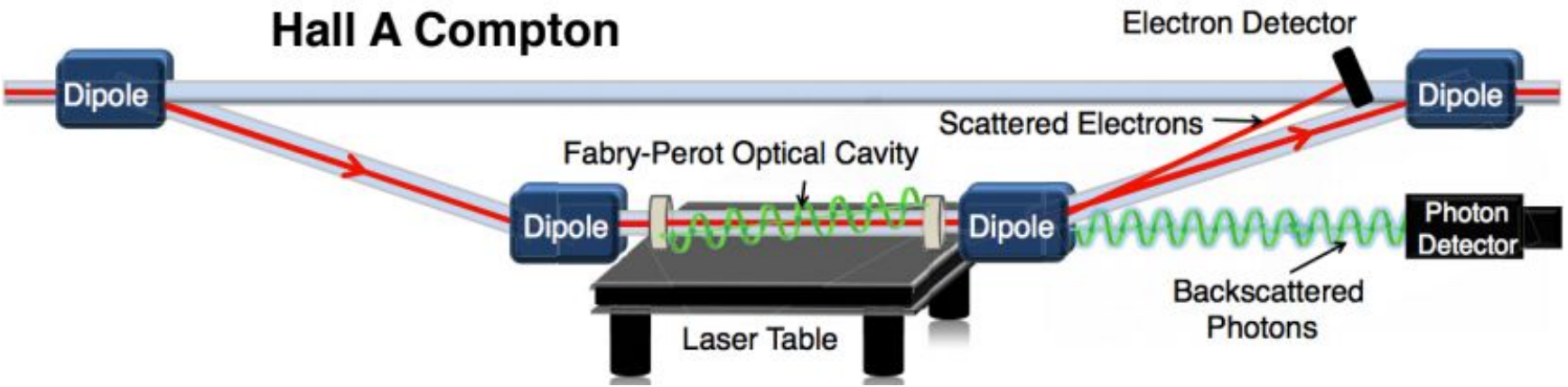
$$A_{PV} = 35.60 \pm 0.73 \text{ ppb}$$

$$\delta(Q_W^e) = 2.1 \text{ (stat)} \pm 1.0 \text{ (syst) } \%$$

$$\delta(\sin^2\theta_W) = 0.00024 \text{ (stat)} \pm 0.00013 \text{ (syst)} \sim 0.1\,\%$$

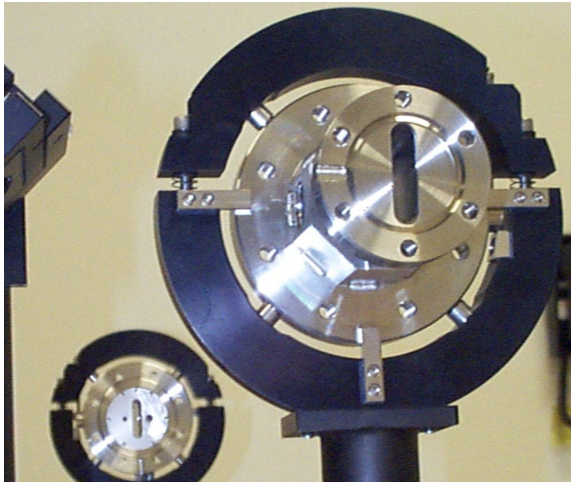


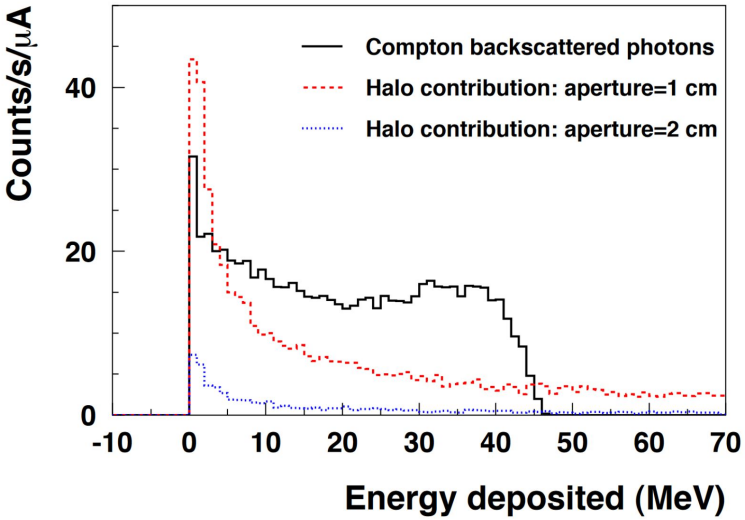
Basics of Compton polarimetry at JLab



- The high statistical precision for PVES experiments requires a small systematic uncertainty
- One of the leading systematics is the determination of the electron beam polarization
- The Hall A Compton polarimeter can measure both the scattered photon and electron to make a redundant measurement concurrent with production data taking
    - The High Finesse FP Continuous Wave cavity allows for enough luminosity to be able to monitor polarization over the run (power stored on the level of 4kW)
- It has reached ~1% relative uncertainty and will need to reach 0.4% for future experiments

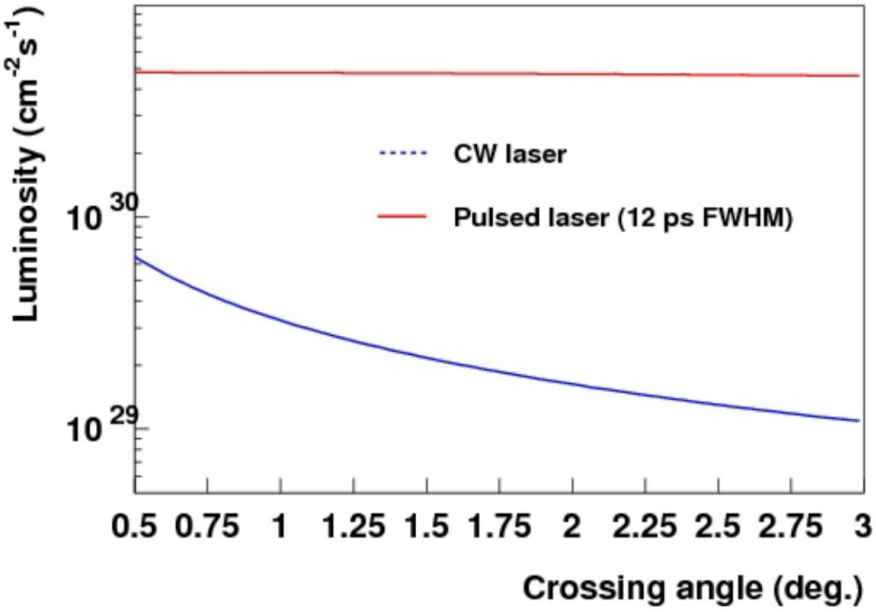
Beamline in cavity

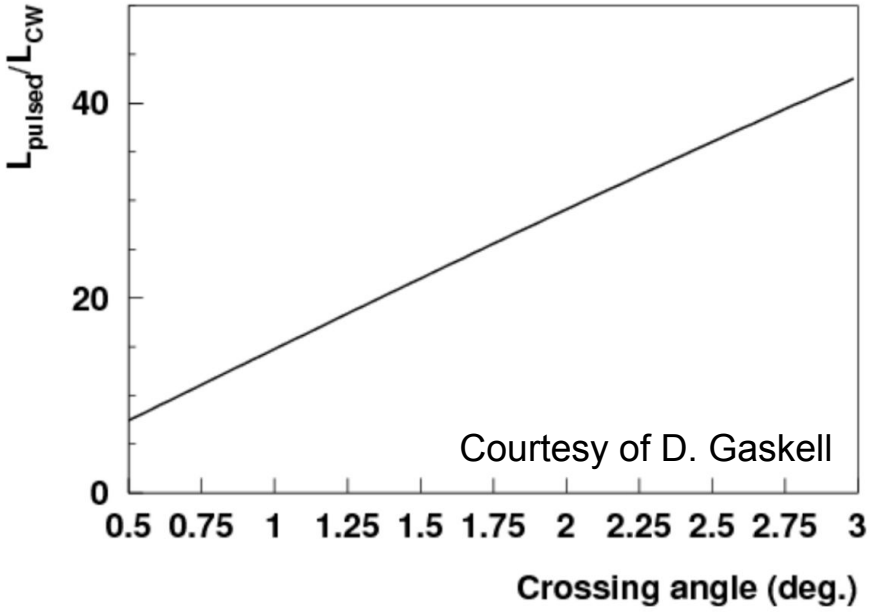




- Currently a 1 cm aperture allows the electron beam to pass through the chicane (typical beam pipe in CEBAF is at least 1 in)
- The contribution from a possible halo could be significant and reduce the precision of the measurement
- To maximize luminosity the mirrors need to be very close to the beamline

Luminosity considerations for CW and Pulsed laser



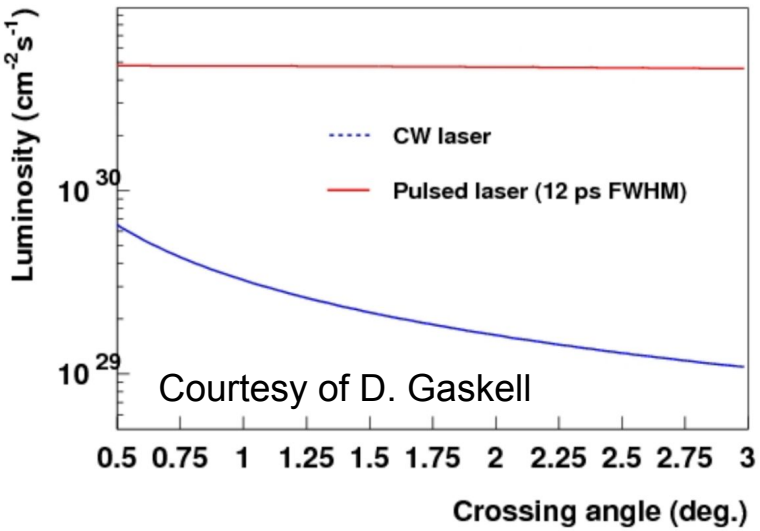


- A CW system will see a significant drop in luminosity with increased scattering angle
- A pulsed system will maintain a high luminosity even at a lower level of stored power inside the cavity

EIC Polarimetry requirements

- Challenges:
  - Making measurements during the machine ramp from 400 MeV to 18 GeV (10 nC in bunch)
  - Measure both longitudinal and transverse components (transverse measurement were performed at HERA)
  - Measure polarization for each individual bunch

- Most of these challenges will be met with a pulsed laser system
  - Luminosity increases (by having a large power cavity) will allow for measurements of low charges
  - Locking the pulses to a specific electron bunche will allow for a measurement on each one

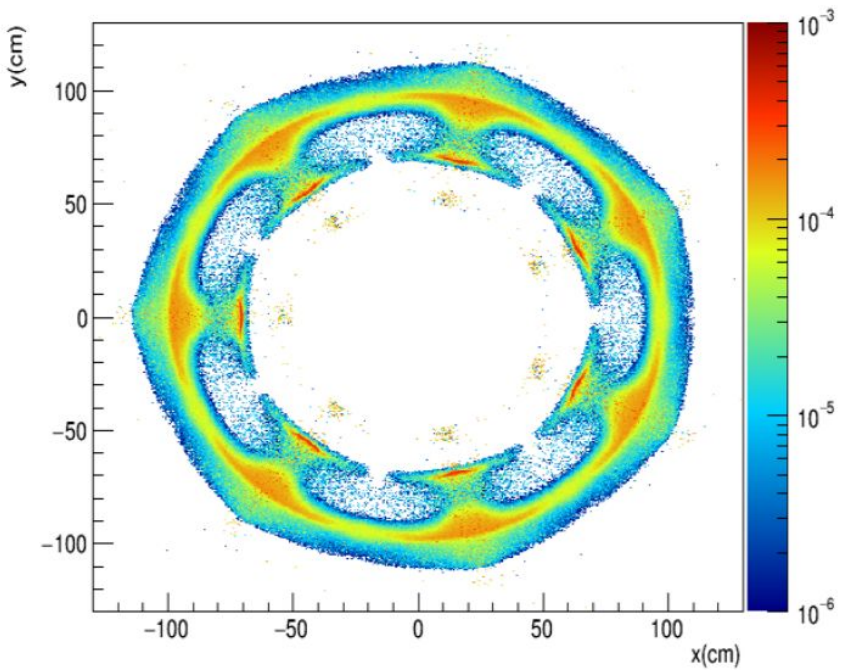


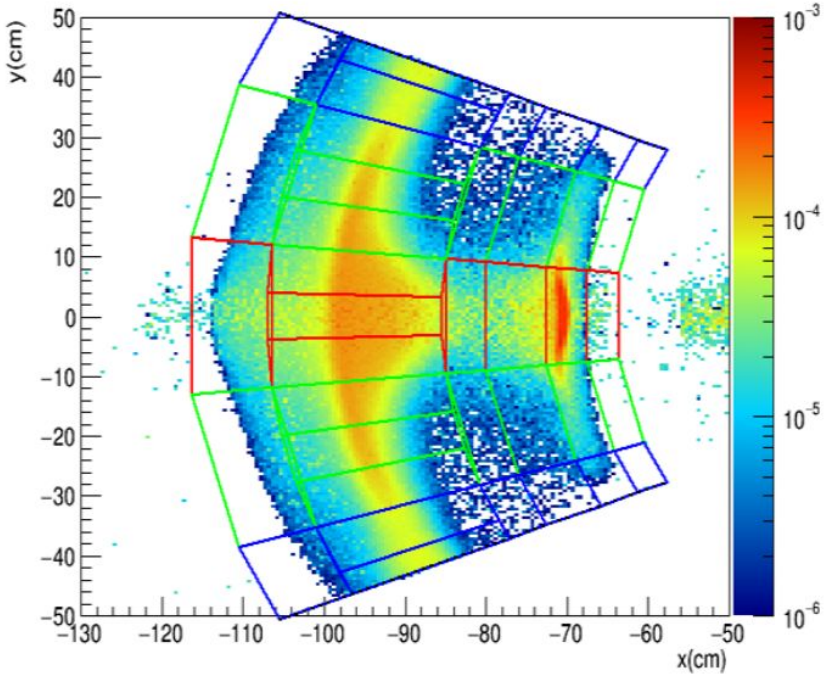
Summary

- The high precision PVES experiments at JLab will provide theoretically clean and important results for nuclear and high energy physics communities
  - These experiments will require very high precision polarimetry measurements
- The knowledge acquired through these experiments will be vital for the EIC where some challenges still remain
- Developing a pulsed laser system for the Compton polarimeter in time for MOLLER will give us the opportunity to test it and deploy it well in advance of the EIC

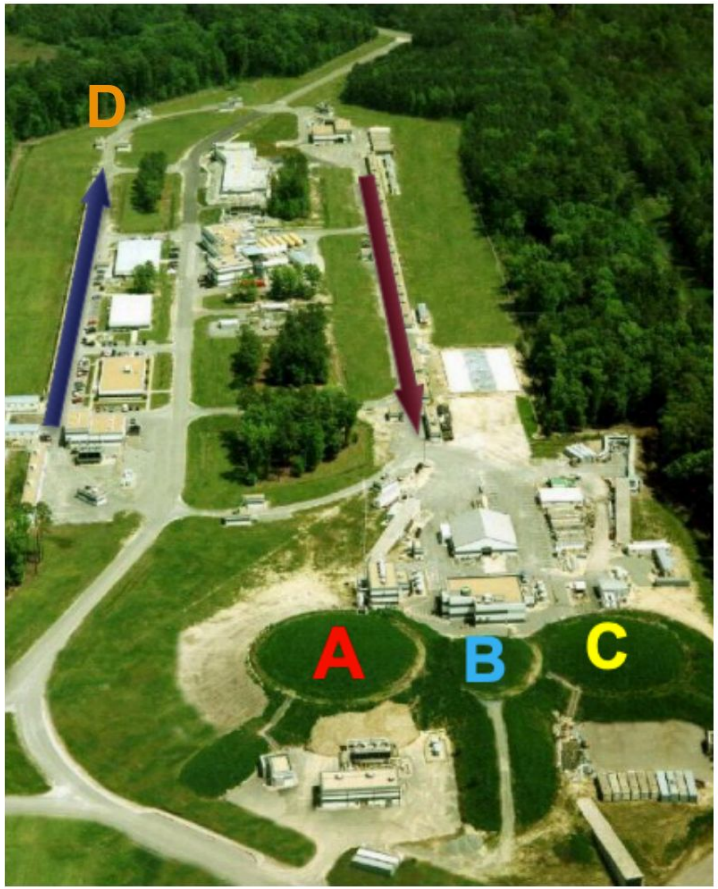
Backup

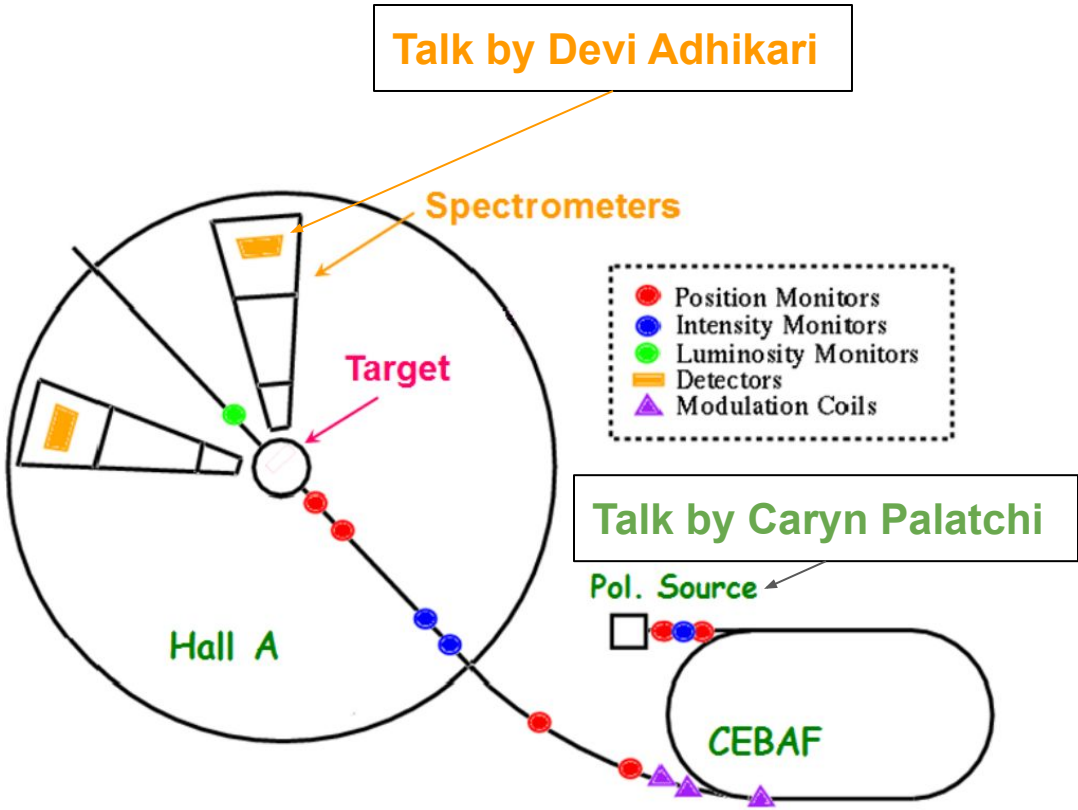
Moller simulated events at detector plane





Experimental setup





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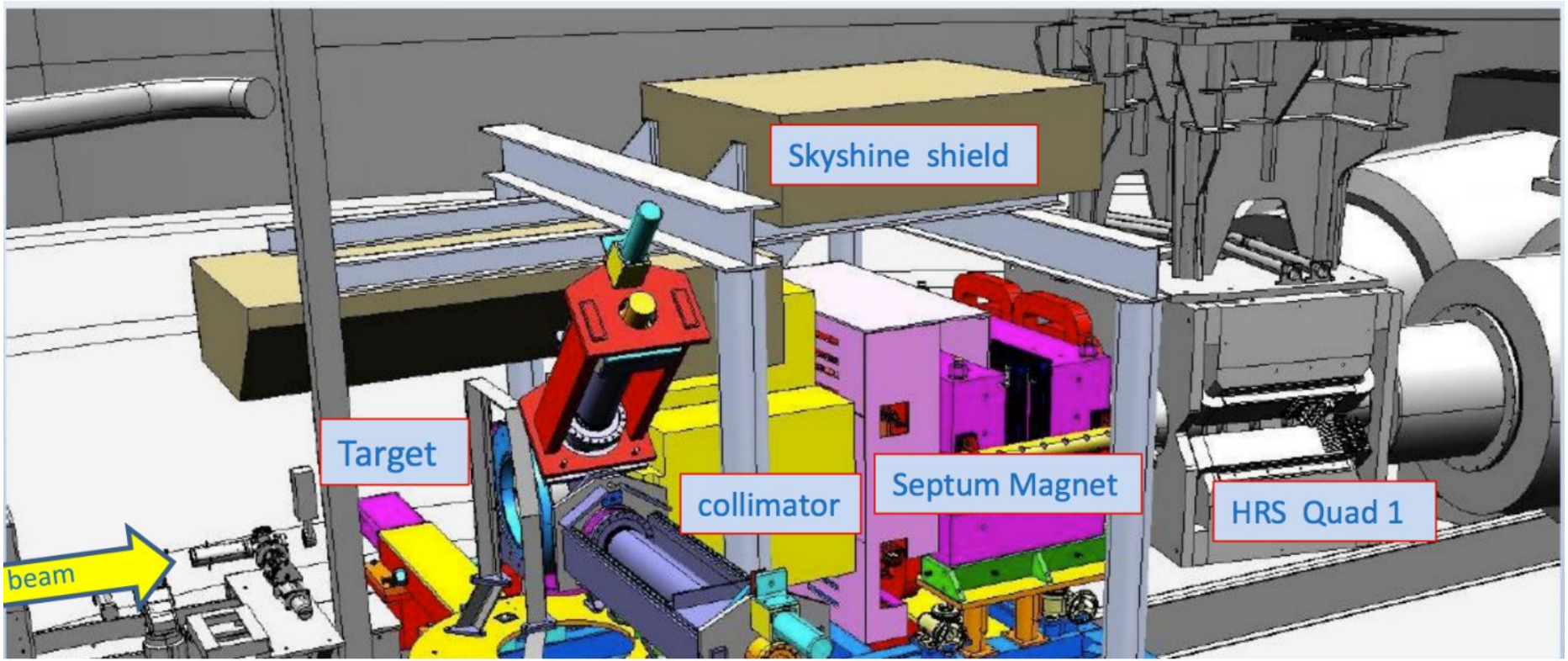
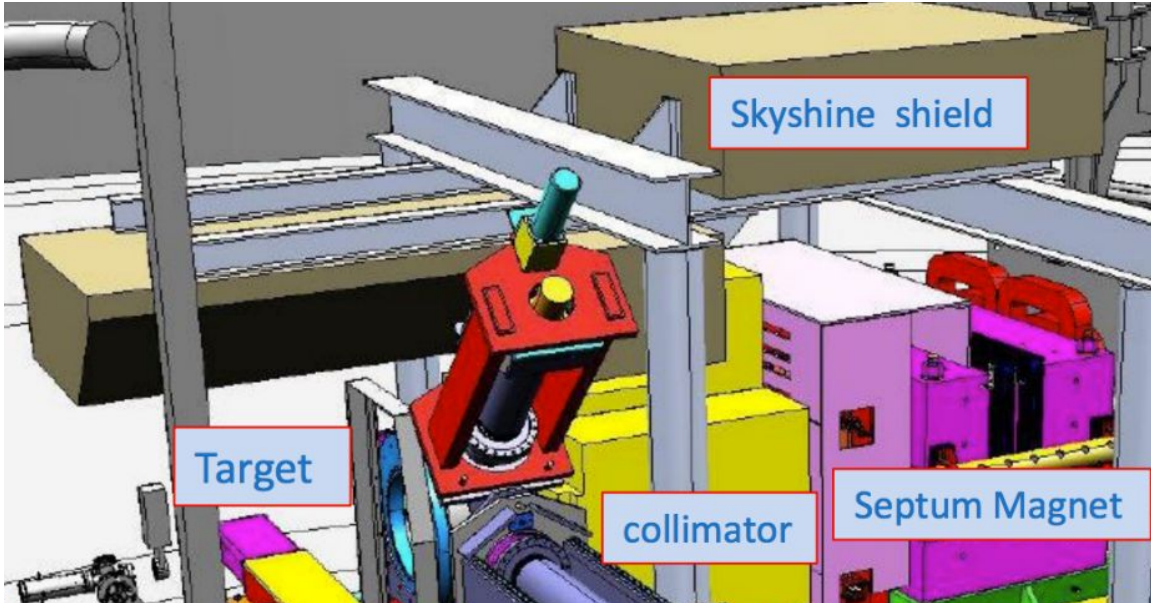


Radiation shielding

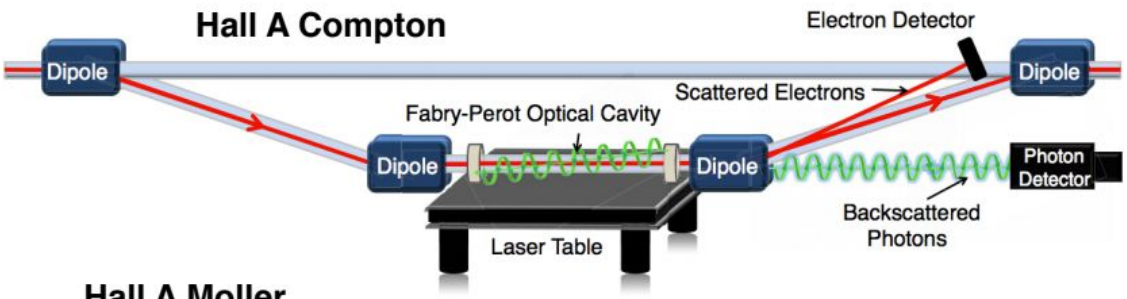
- Local shielding protected both the electronics needed to run the experiment and produced very little radiation on the site boundary of the lab



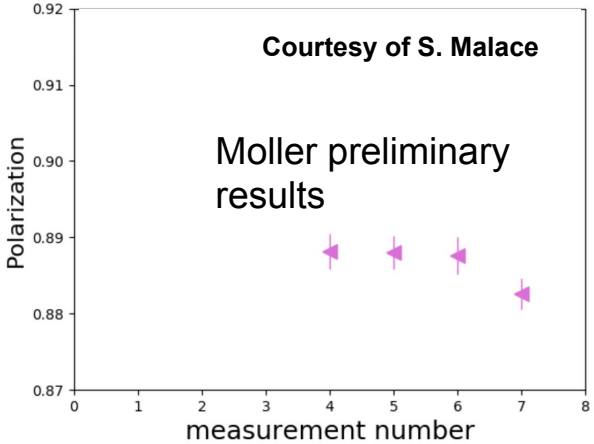
- Studies showed that the most important sources of rad damage were neutrons
  - High energy neutrons for personnel protection and thermal neutrons for electronics damage
- The spectrometer and different electronics functioned well and we had no major interruptions related to radiation

Electron polarimetry

- The two independent systems performed well and provided crucial cross checks through the run
- We expect both will be able to reach the systematic goal of 1%



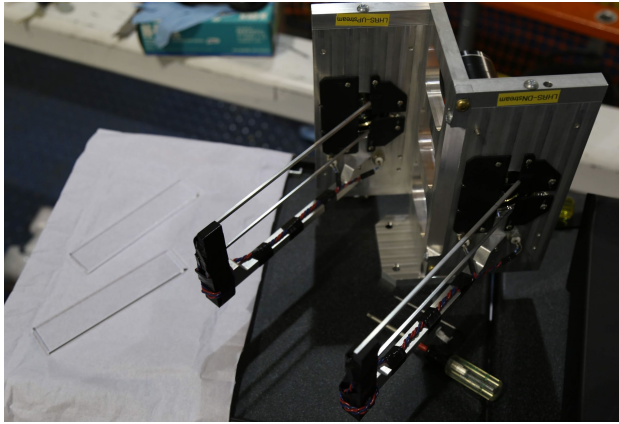
Hall A Moller



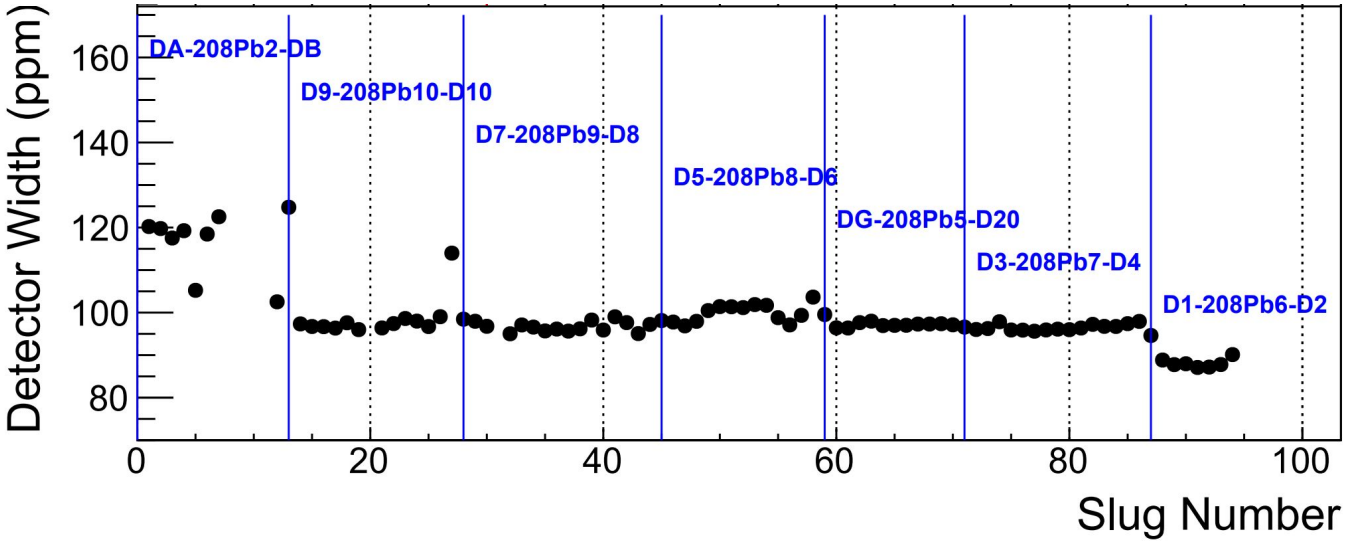
- Polarization was ~88% on average in good agreement between polarimeters

Detector widths

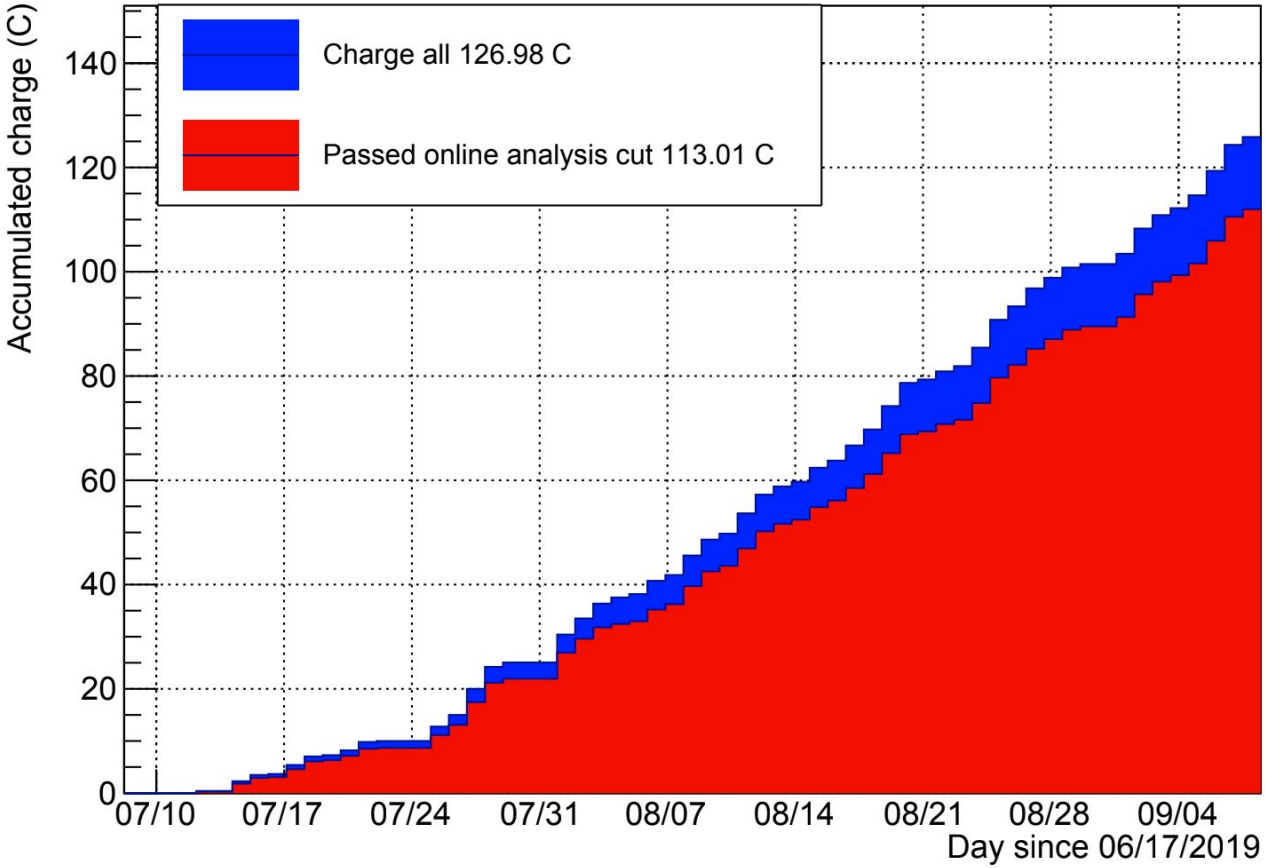
- The detector system performed really well being able to take ~2.5GHz on a 10 x 3.5 cm piece of quartz in each arm
    - Qweak had a total rate of 8GHz
- Before beam corrections our combined detector widths were on the level of 200-300 ppm



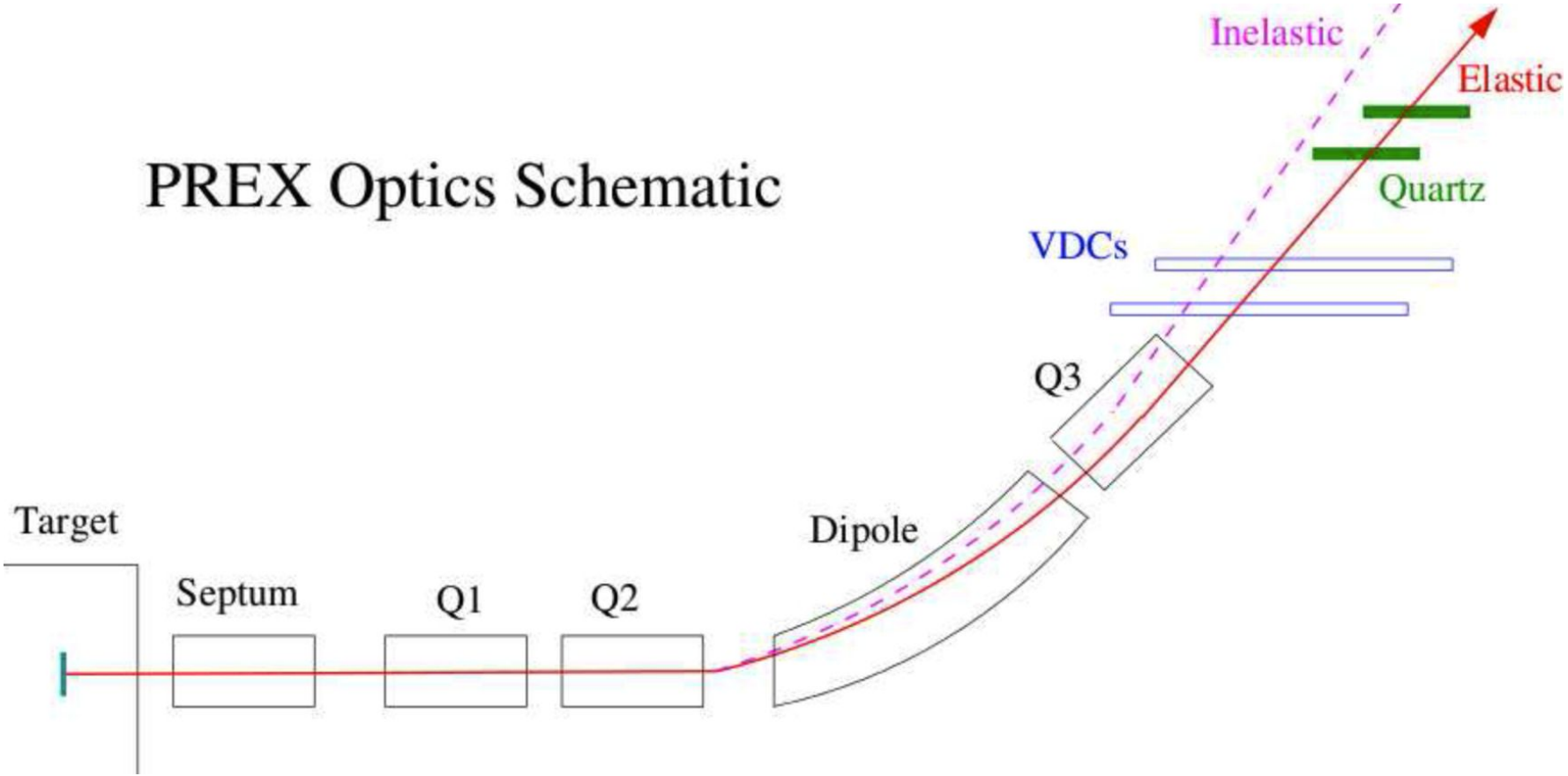
- Regression allowed us to remove the added noise and gave us rock solid ~100 ppm widths throughout the run



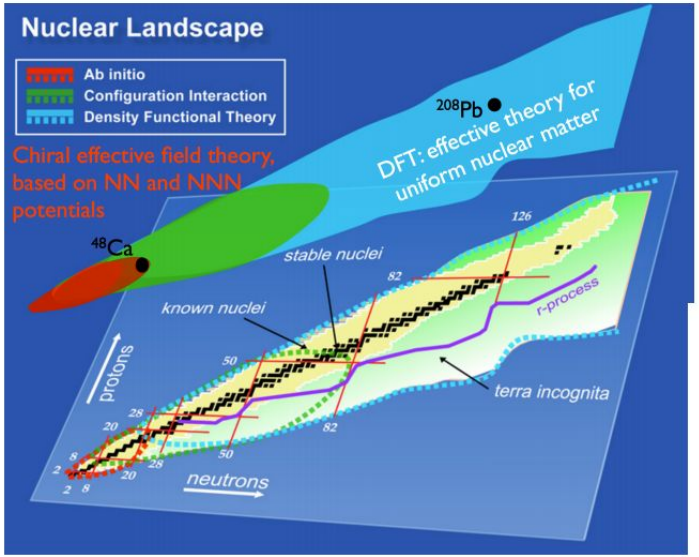
Accumulated charge on target



Backup


PREX Optics Schematic
Inelastic
Elastic
Quartz
VDCs
Q3
Dipole
Target
Septum
Q1
Q2

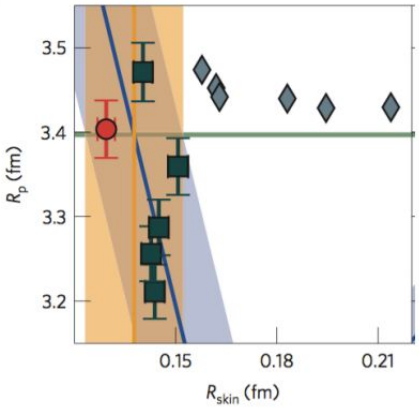
Near future: CREX



^{48}Ca neutron radius with a precision of 0.02 fm

Within reach of microscopic calculations
Recent coupled cluster calculations predict

$$0.12 \leqq R_{skin} \leqq 0.15 \text{ fm}$$



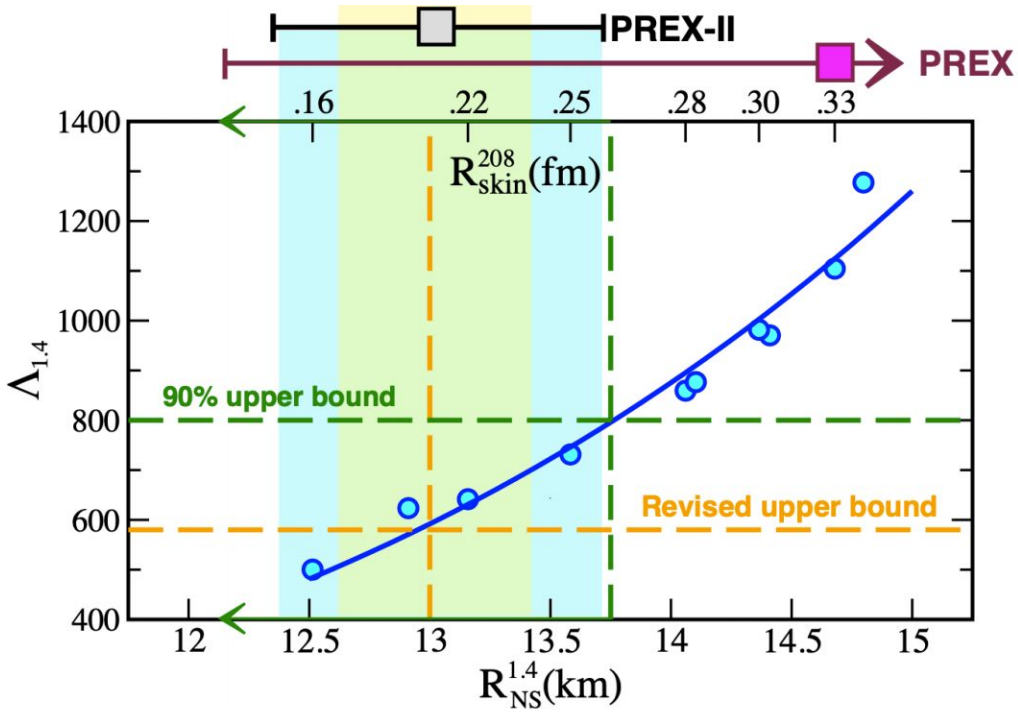
Coupled cluster calculation for ^{48}Ca

- NNNLO chiral interactions tuned to light nuclei
- range of chiral interactions
- DFT calculations
- Emperical R_p

G. Hagen et al,
Nature Physics 12, 186-190 (2016)

PREX and CREX: two measurements at different nuclear densities

GW and PREX



$$R_\star^{1.4} < 13.76\,\mathrm{km}$$

$$R^{208}_{skin} = 0.25\,\mathrm{fm}$$

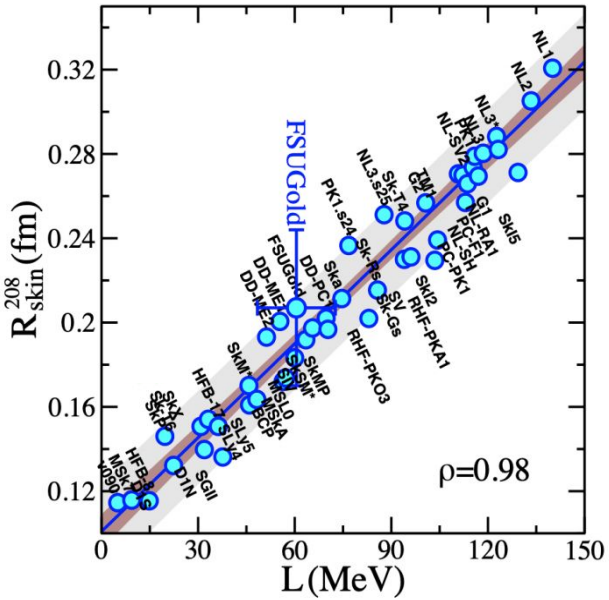
•

Nuclear equation of state and Symmetry energy

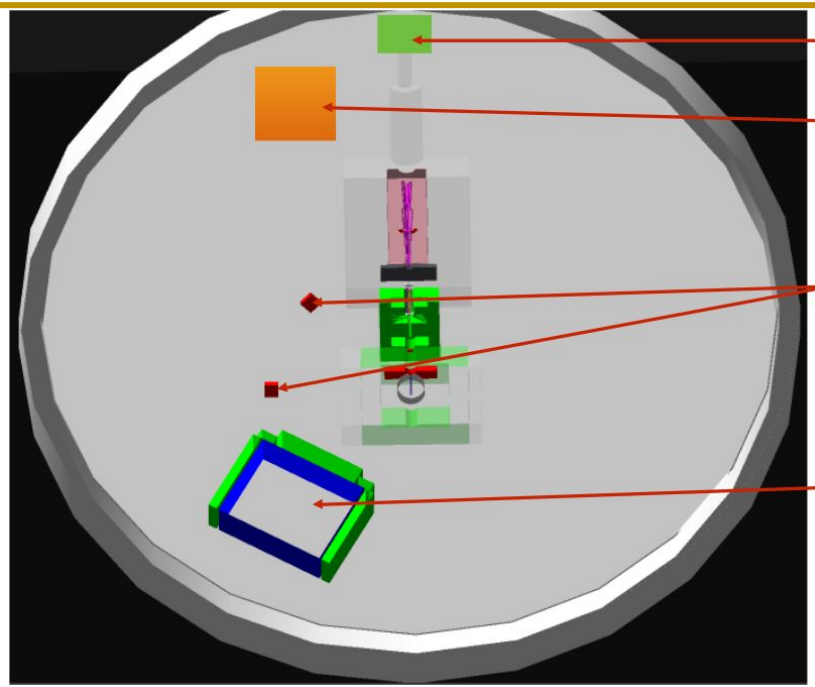
$$\mathcal{E}_{\mathrm{SNM}}(\rho) = \varepsilon_0 + \frac{1}{2}K_0 x^2 + \ldots,$$

$$\mathcal{S}(\rho) = J + Lx + \frac{1}{2}K_{\mathrm{sym}} x^2 + \ldots,$$

- While L is an important parameter it is not a physical observable
- It however has a clear connection with other measurable quantities such as the neutron skin of neutron rich nuclei
- Similarly it can be deduced from other observations such as Gravitational Wave measurements of neutron star mergers



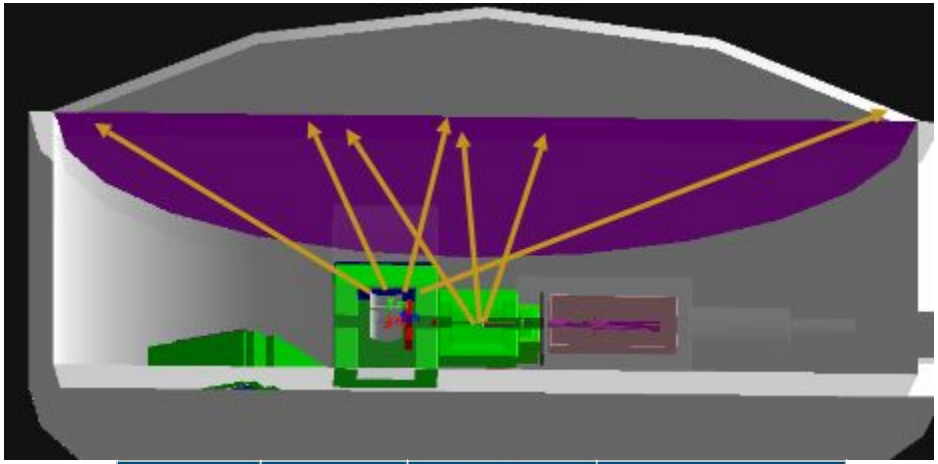
Status at Director's Review



- Included all sources of possible damage all the way to the dump
- The hall itself and the air atmosphere inside the hall also included

- We have reduced the cost of the shielding significantly through optimization
- We did a preliminary run-through with the new experimental configuration with a smaller target
- We estimate that the boundary dose is not going to be a major issue with this configuration
- The major items for the electronics damage inside the hall have been checked and there are no major causes for concern

Boundary dose estimates



	current	Running time	charge on target
MOLLER	60uA	30 wks	585 C
PREX1	>50 uA	~8 wks	82 C

	mW/uA	boundry/yr
MOLLER	0.6	**2.4 mrem**
PREX1	2.4	**1.34 mrem**

- We evaluate the dose on the boundary by looking at high energy (E>30 MeV) neutrons reaching the roof of the hall
- This has been shown by RadCon to be a good proxy
- We benchmark this proxy by simulating experimental configurations that produced significant (measureable) boundary dose
- We compare the HE neutron integrated power of previous experiment to different MOLLER configurations
- The current shielding will allow MOLLER to remain under the JLab limit