Stony Brook University

PREX/CREX Experiments at JLab

^{208}Pb and ^{48}Ca Neutron Skin Measurements

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The 11th Workshop on Hadron Physics in China and Opportunities Worldwide

PREX/CREX Collaboration

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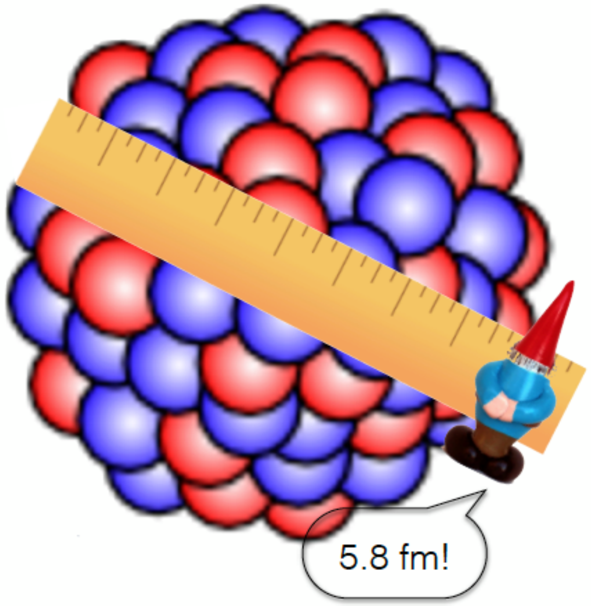
Thanks to PREX/CREX Collaborators,
especially to Ciprian Gal for sharing lots of materials!

What is the size of the atomic nucleus?



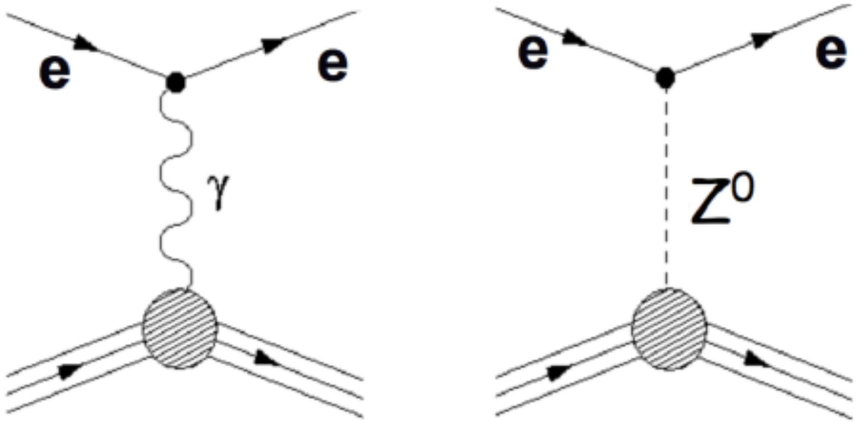
Charge type	Proton	Neutron
Electric	1	0
Weak	~0.08	-1

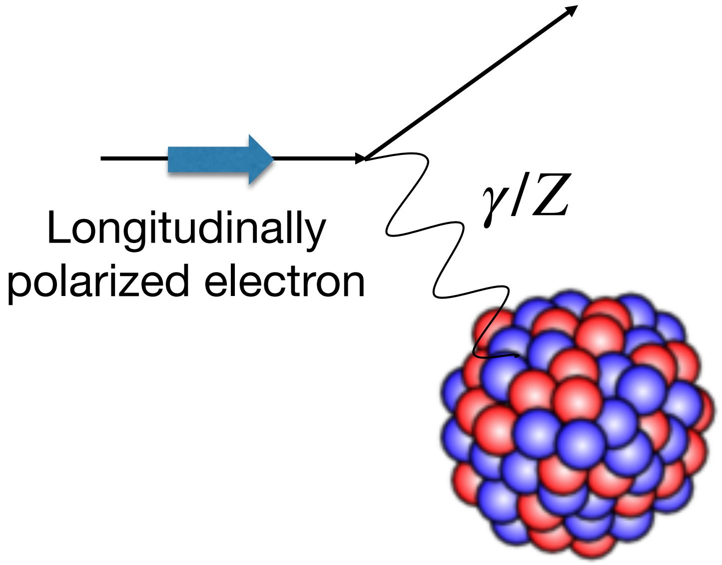
- Proton distribution:
  - Owing to the electric charge, this has been accurately measured for many atomic nuclei
- Neutron distribution:
  - Poorly known
  - Primarily from hadron scattering experiments, highly model dependent
  - Parity-violating electron scattering: via the weak charge

clean and direct

Parity Violating Electron Scattering

Electron elastic scattering:

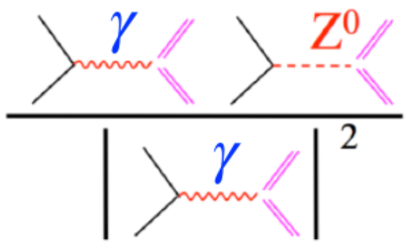




$$\sigma \propto |M_\gamma + M_Z|^2$$

Dominant Parity-violating

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



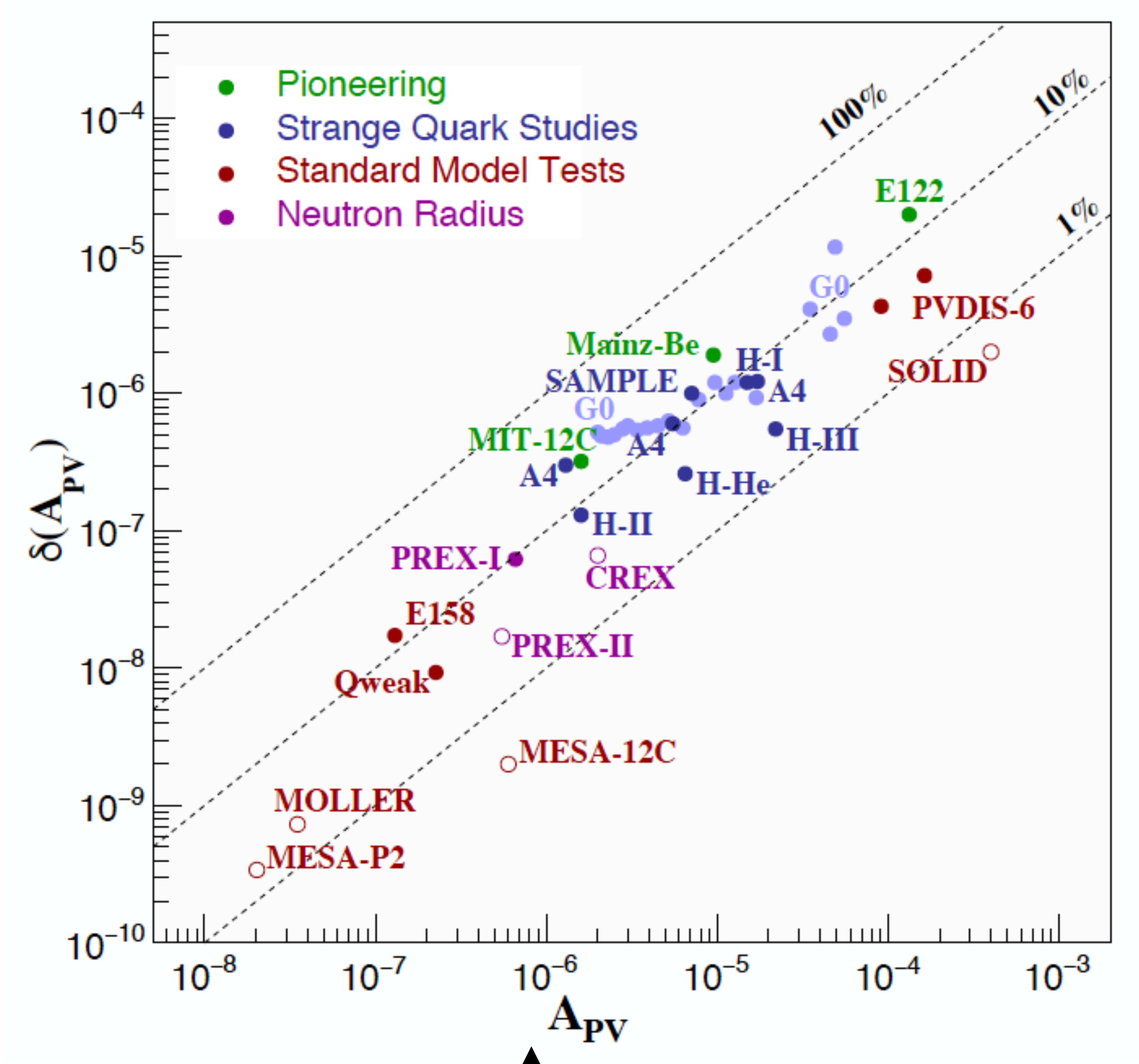
$$\propto \frac{|M_Z|}{|M_\gamma|}$$

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

PVES probes weak form factor;
primarily neutron distributions

Parity Violating Electron Scattering

PVES Landscape



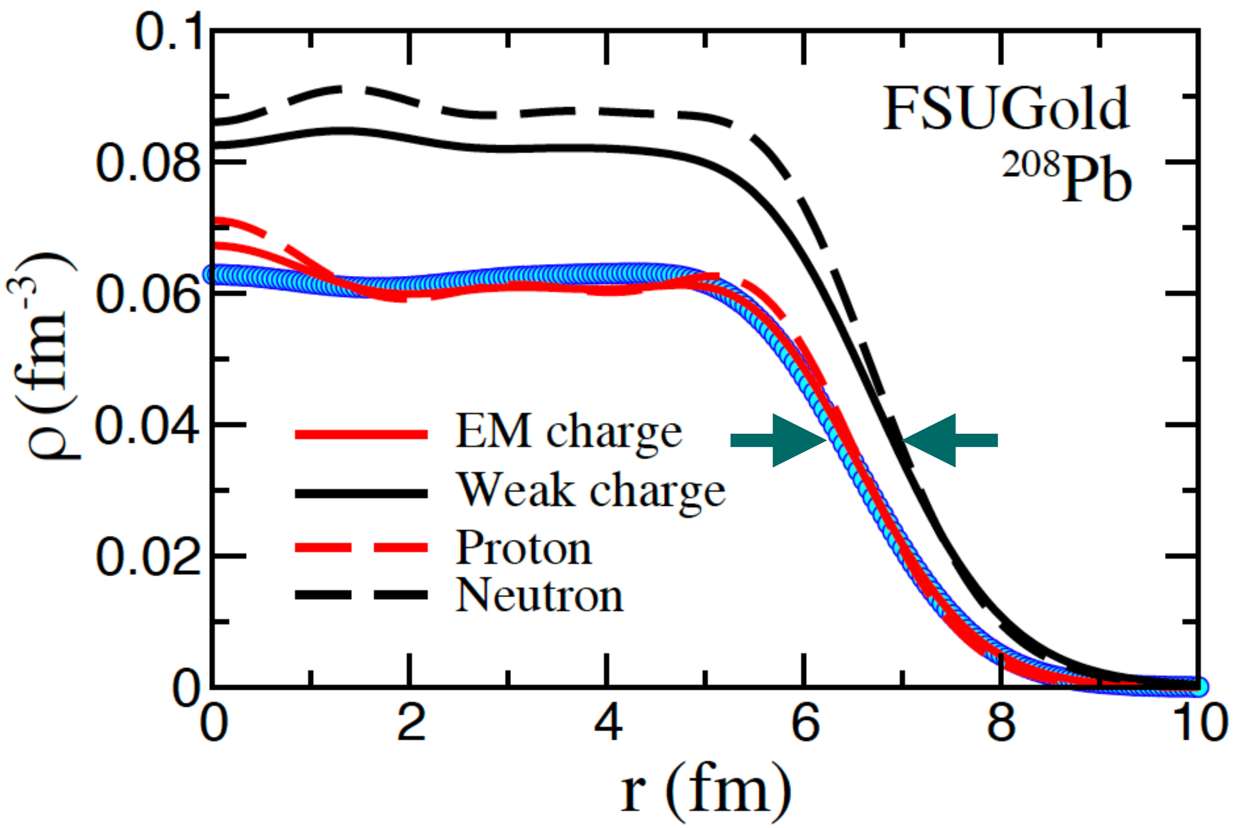
1,000,000 vs. 1,000,001

- PVES has a long history of pushing the limits of precision and discovery
  - E122: (ΔA=10 ppm)
    - pioneering experiment (already had most of the features of modern PVES experiments)
  - Strange form factor
    - G0, HAPPEX
  - Standard Model Tests
    - E158, PVDIS, Qweak
  - **Neutron radius/neutron skin of heavy nucleus**
    - **PREX, PREX-II, CREX**
  - Future:
    - MOLLER, P2, SoLID(see Z.Zhao’s talk)

Neutron Skin

- 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**

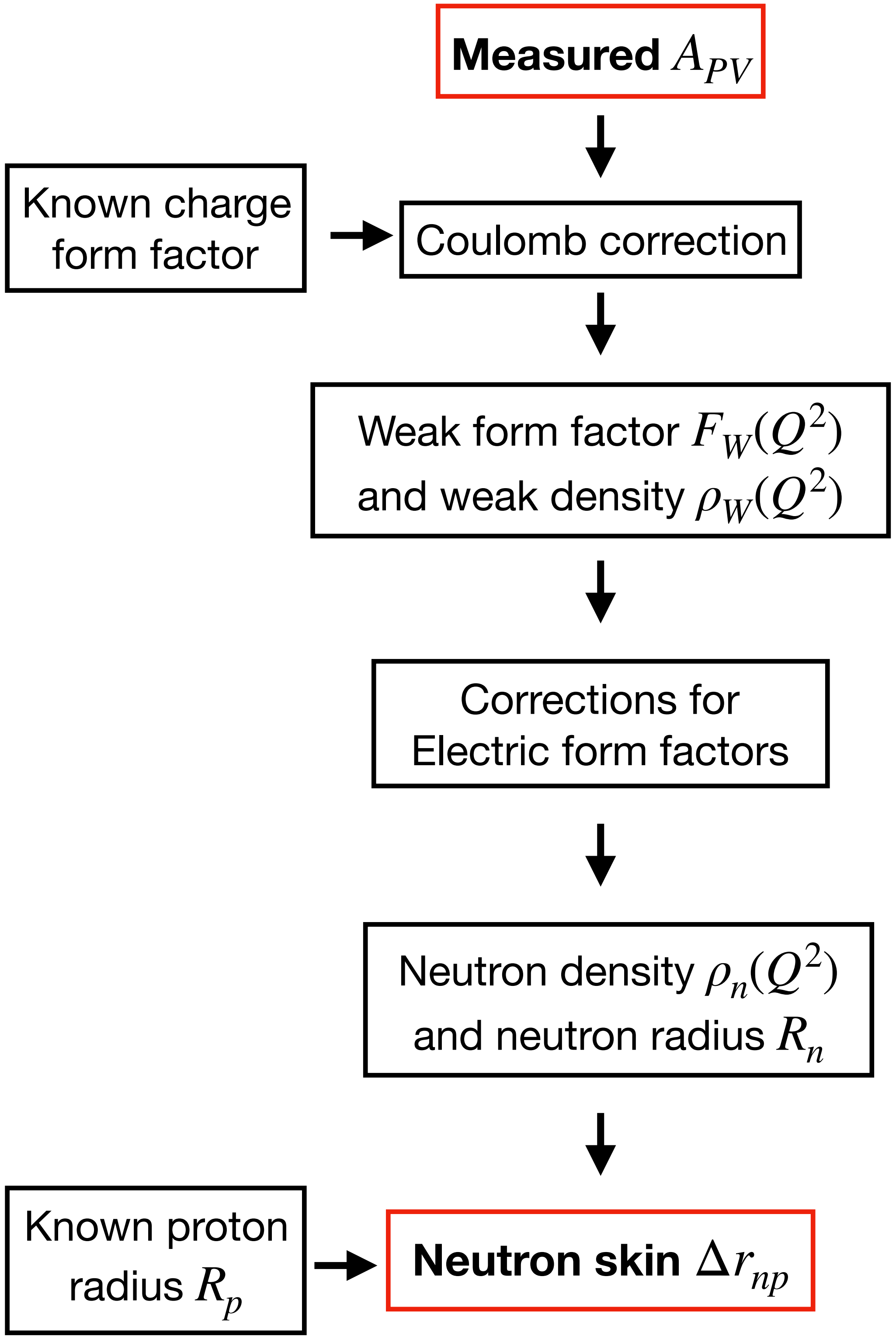
J. Phys. G: Nucl. Part. Phys. 46 (2019) 093003



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

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

From A_{PV} to Neutron Skin



Measured A_{PV}

Known charge form factor → Coulomb correction

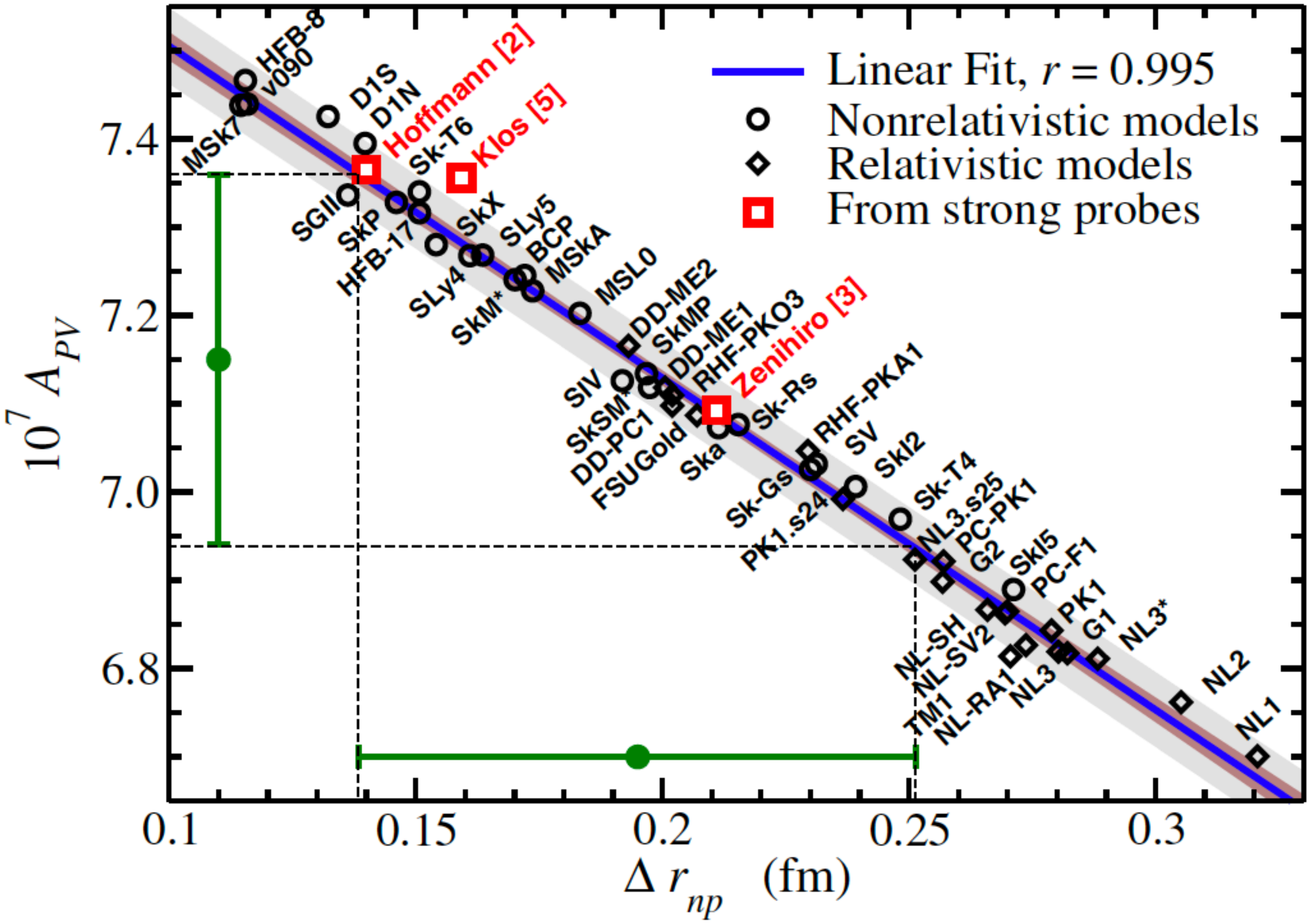
Weak form factor $F_W(Q^2)$ and weak density $\rho_W(Q^2)$

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

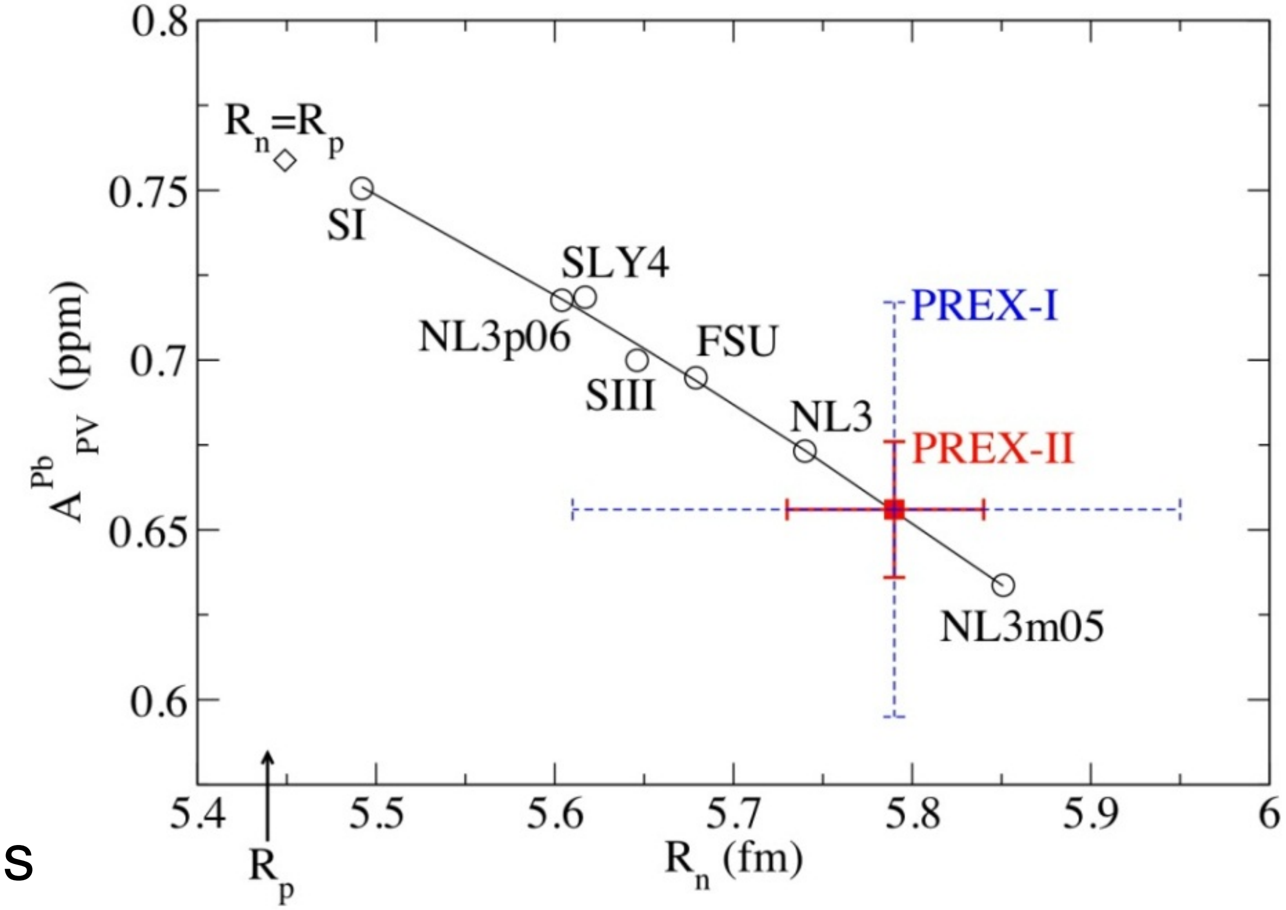


Robust correlation between ^{208}Pb A_{PV} and the neutron skin over existing nuclear structure models

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

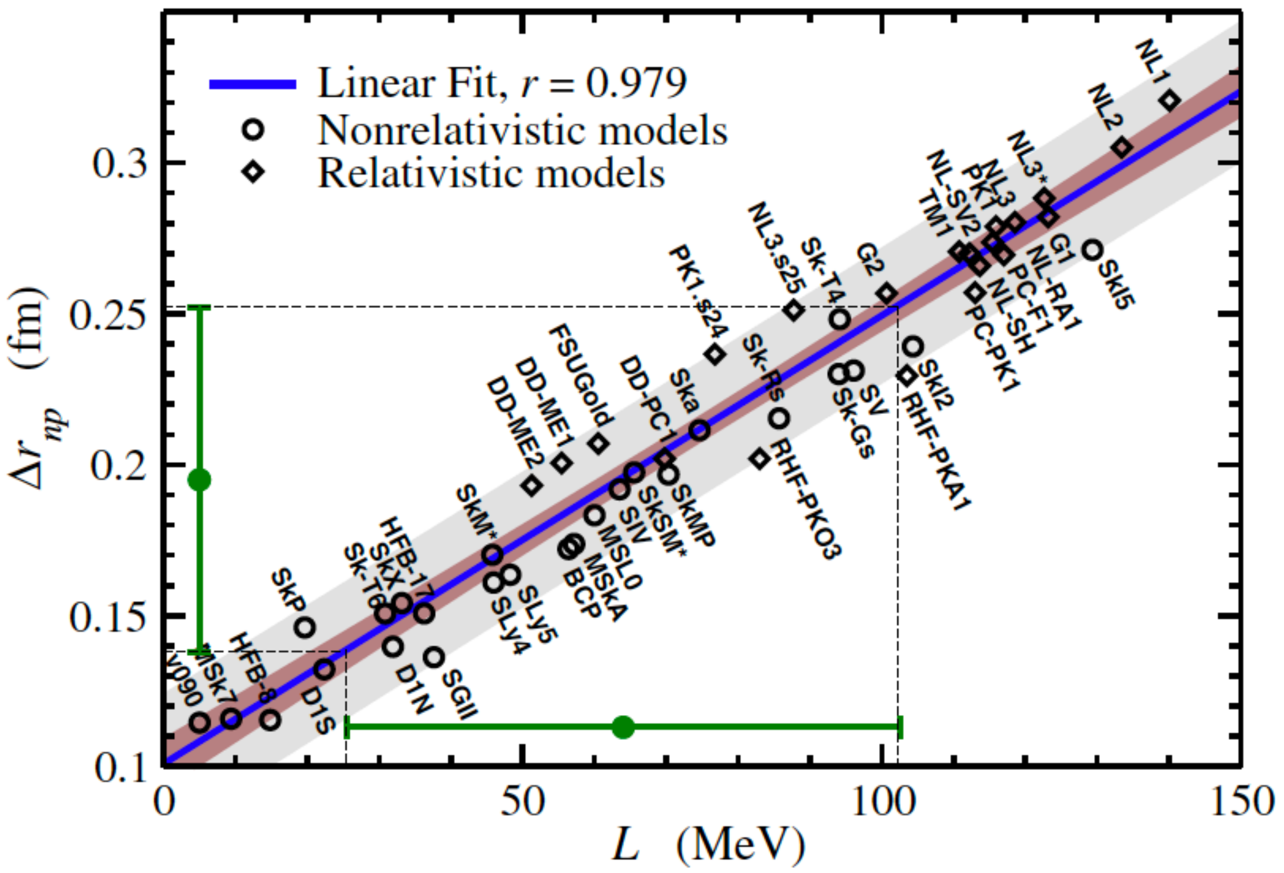
$$R_n - R_p = 0.33^{+0.16}_{-0.18}\ \text{fm}$$

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

Neutron Skin and Symmetry Energy

- Symmetry energy $S(\rho)$: energy penalty for breaking N=Z symmetry

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

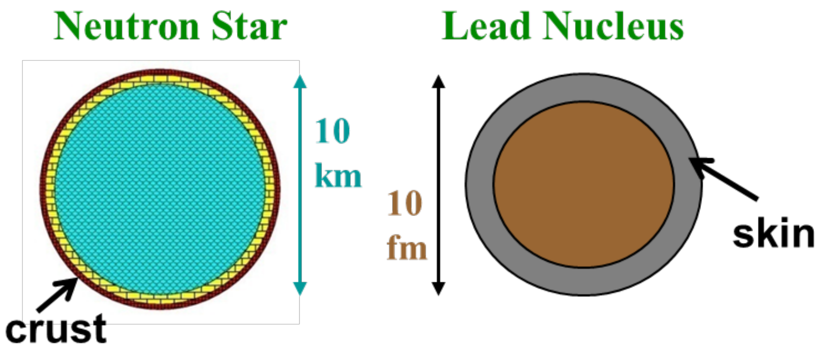


- Mean-Field predictions show a correlation between neutron skin of a heavy nucleus, Δr_{np}, and the density slope of the symmetry energy.

$$L \propto \frac{\partial S(\rho)}{\partial \rho}\Big|_{\rho_0}$$

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

Neutron Skin and Neutron Star



- In spite of the 18 orders of magnitude size difference, heavy nucleus and neutron star are both described with the nuclear Equation of State
  - Both strongly correlated with L
- GW170817 provided up limits for neutron star radius and accordingly for neutron skin as well.
- If results are significantly different it may indicate a phase transition in the interior of neutron-stars

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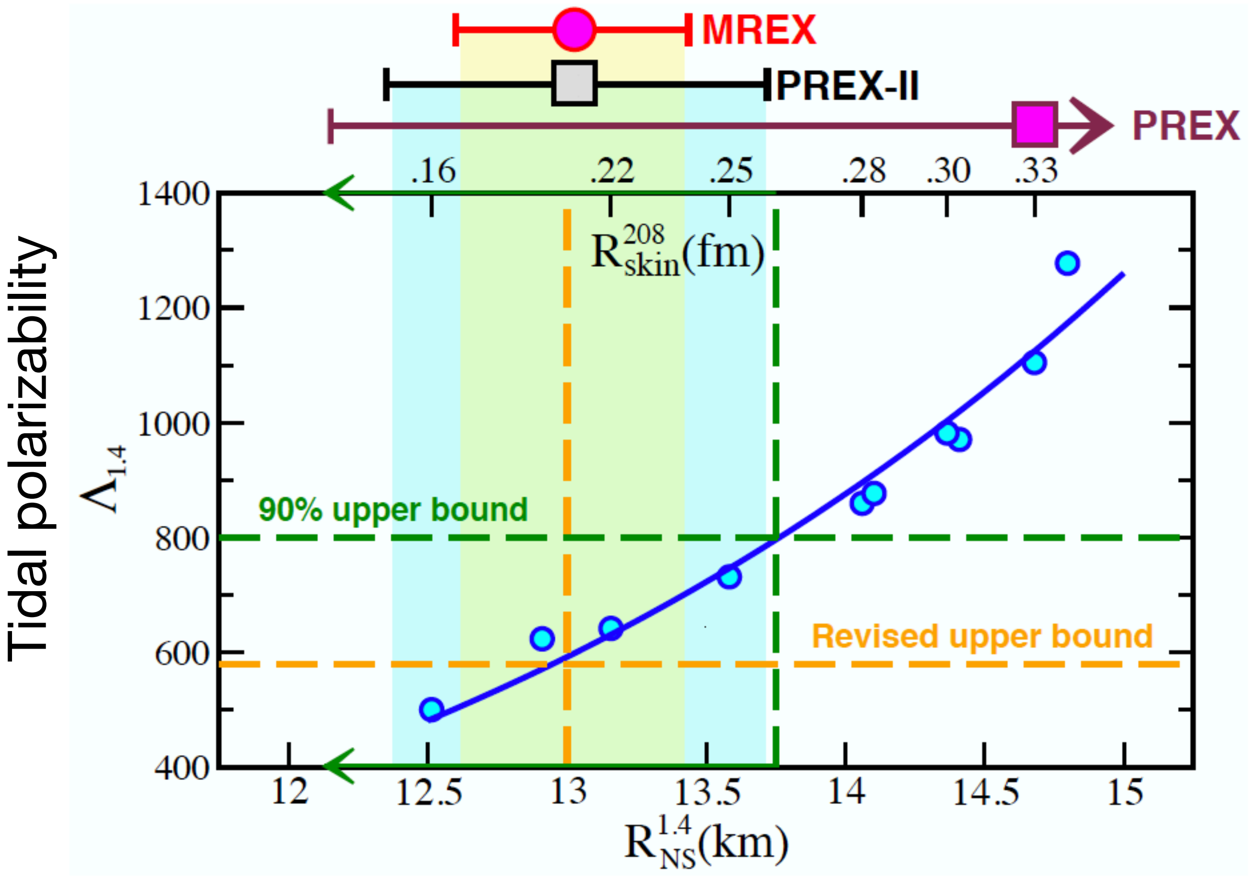
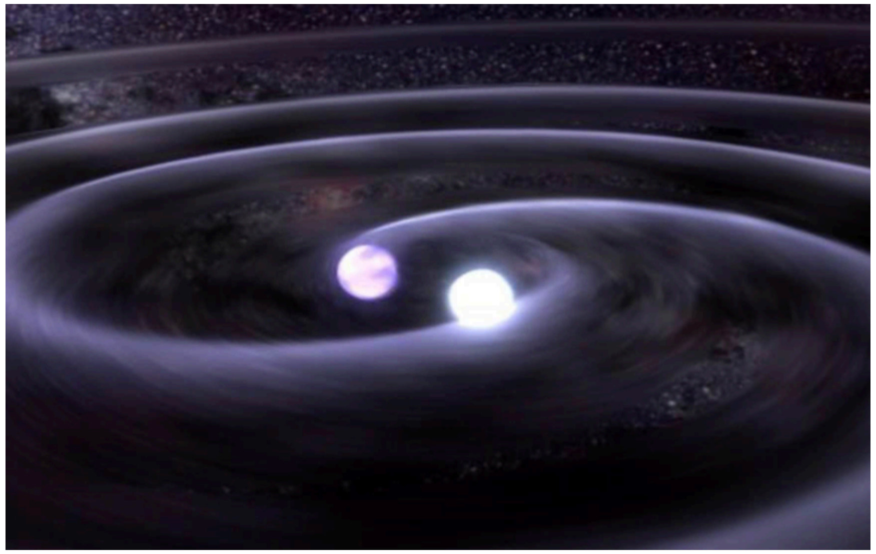


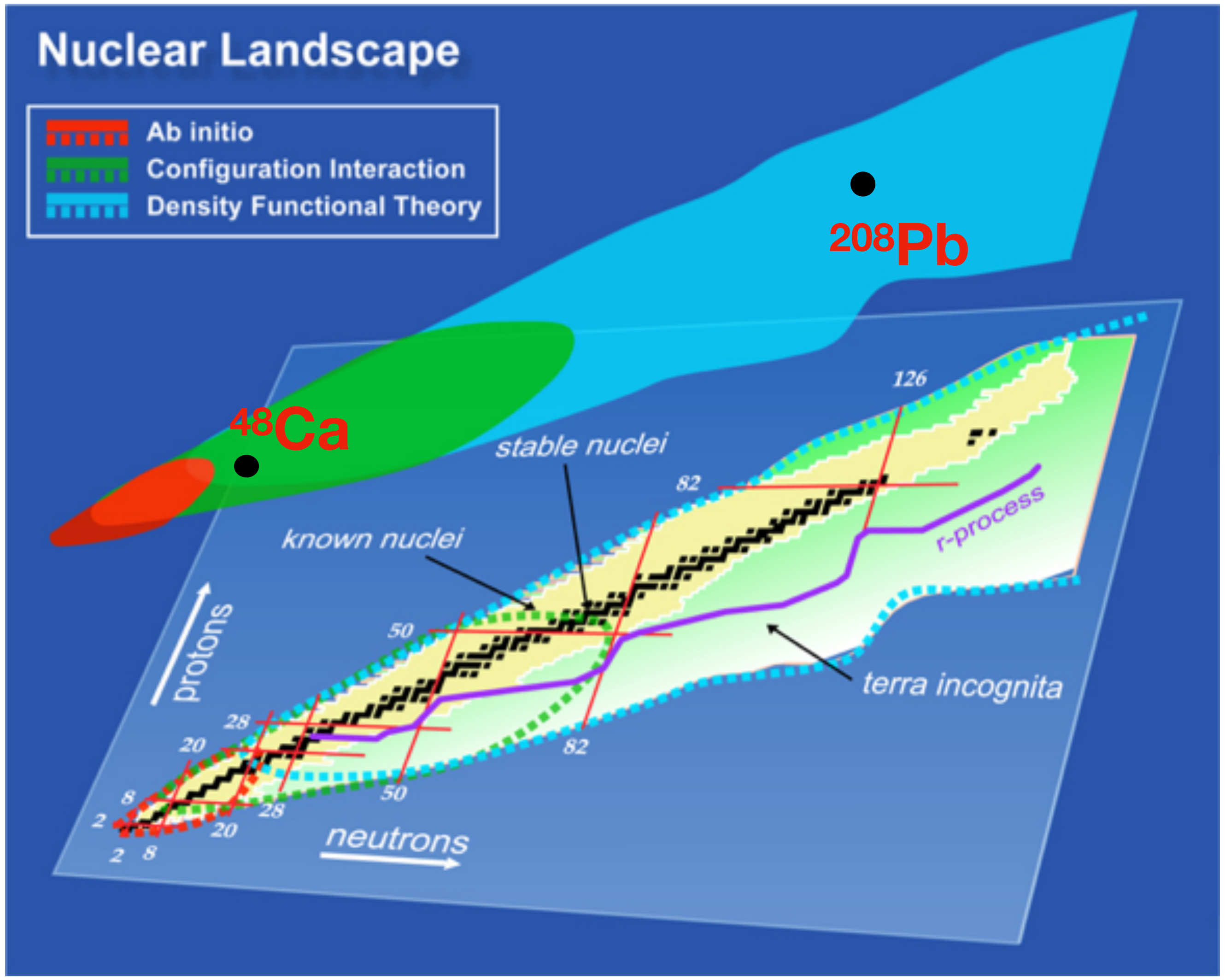
Constraints deduced from GW170817



Choice of Nuclei Target

Least theoretical uncertainties

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



^{208}Pb:

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

^{48}Ca:

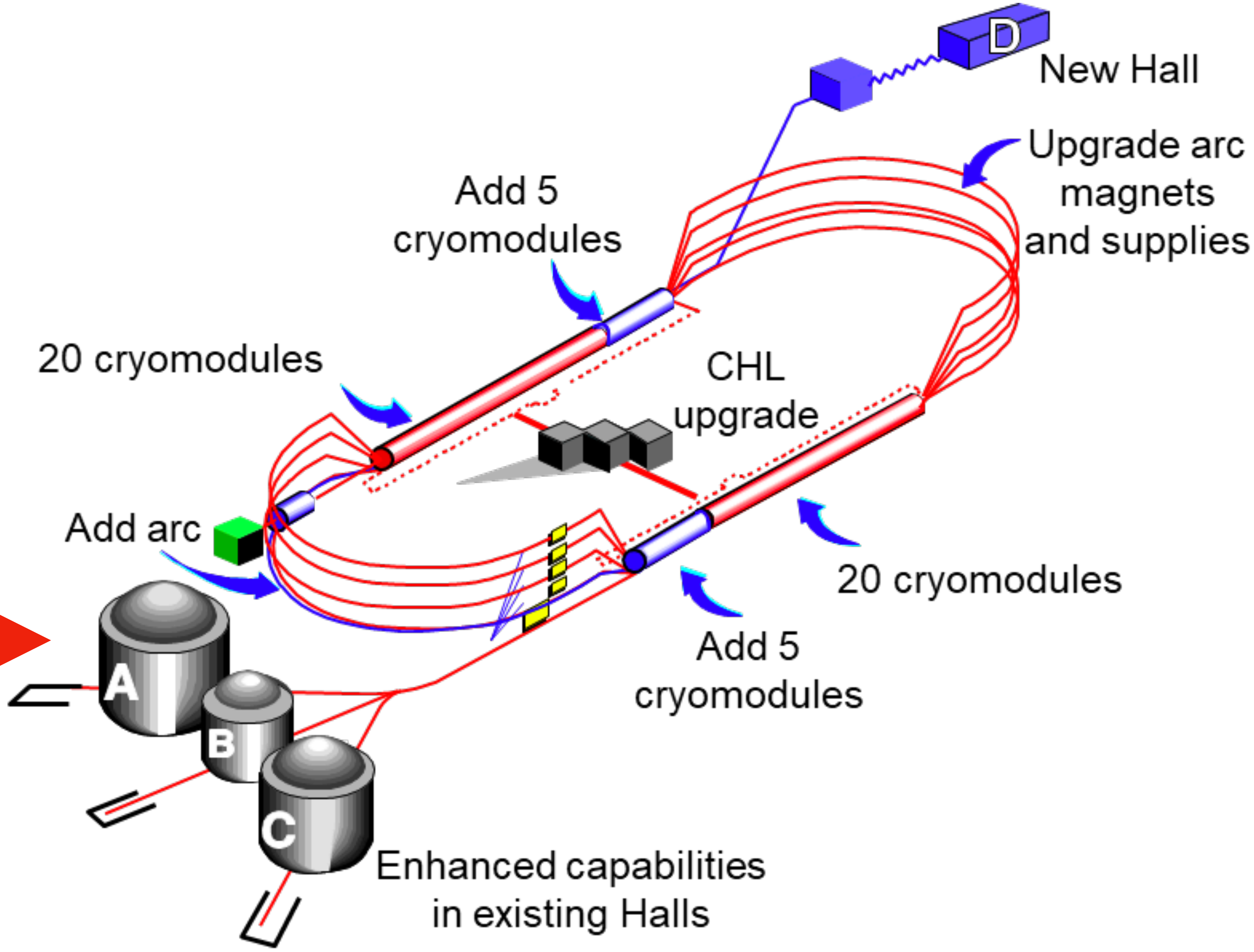
- "Ab Initio" (exact microscopic) calculations of R_{skin} for ^{48}Ca have recently been published. G. Hagen et al., Nature Physics 12, 186(2016).
- bridge between *ab initio* models and effective theory (DFT)

Systematic Budget

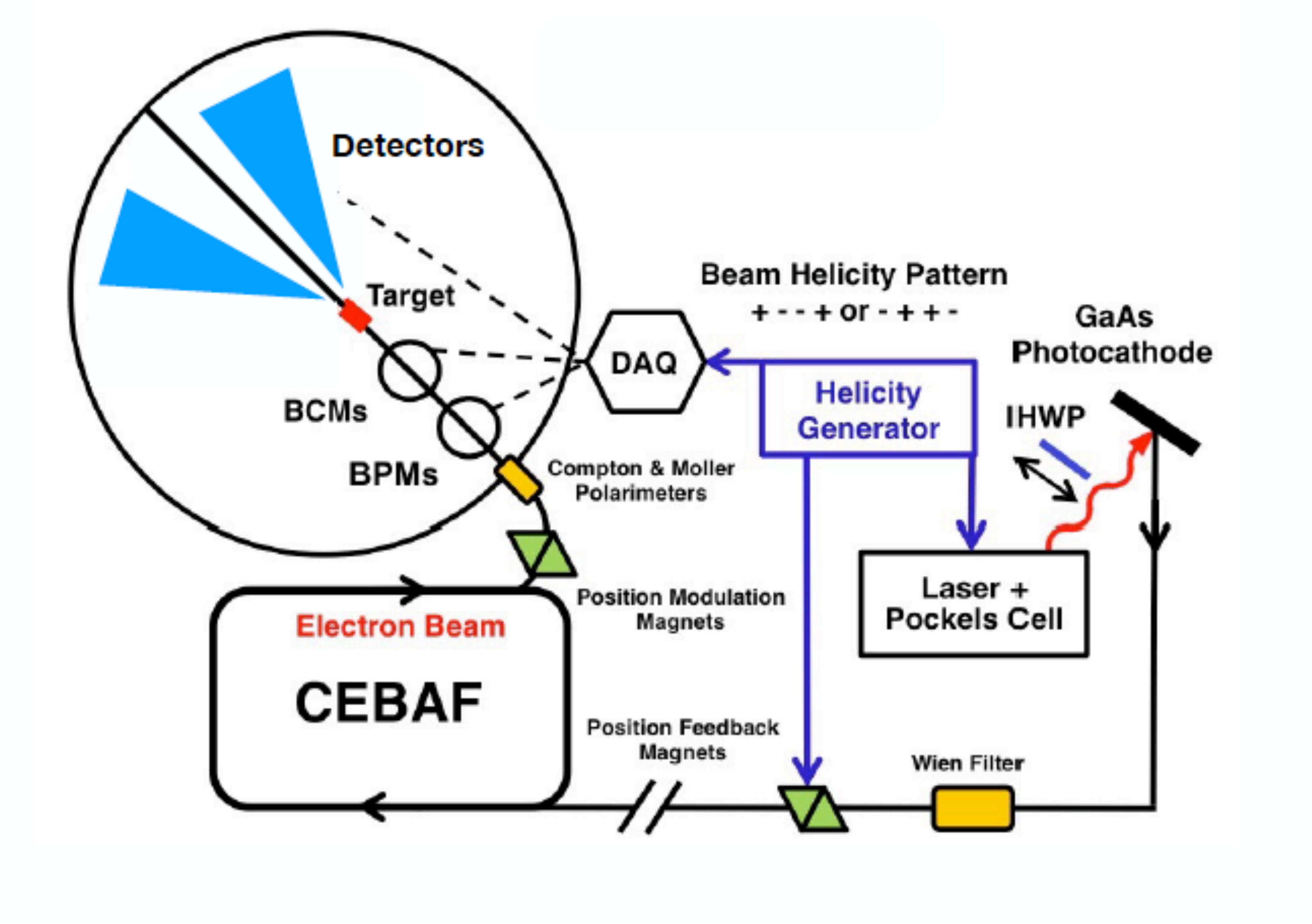
	PREX-I 1.1GeV, 5^o, A~0.6ppm	PREX-II 0.95 GeV, 70 uA, 5^o, A~0.6ppm	CREX 2.2 GeV, 150 uA, 5^o, A~2.28ppm
Charge normalization	0.2%	0.1%	0.1%
Beam asymmetry	1.1%	1.1%	0.3%
Detector Non-linearity	1.2%	1.0%	0.3%
Transverse asymmetry	0.2%	0.2%	0.1%
Beam polarization	1.3%	1.1%	0.8%
Target backing/contamination	0.4%	0.4%	0.2%
Inelastic contribution	<0.1%	<0.1%	0.2%
Effective Q^2	0.5%	0.4%	0.8%
Total Systematic	2.1%	2%	1.2%
Statistical	9%	3%	2%
	Achieved	Leading syst. could be improved beyond proposal	More sensitive to Q2 uncertainty than PREX

Continuous Electron Beam Accelerator Facility at Jefferson Lab

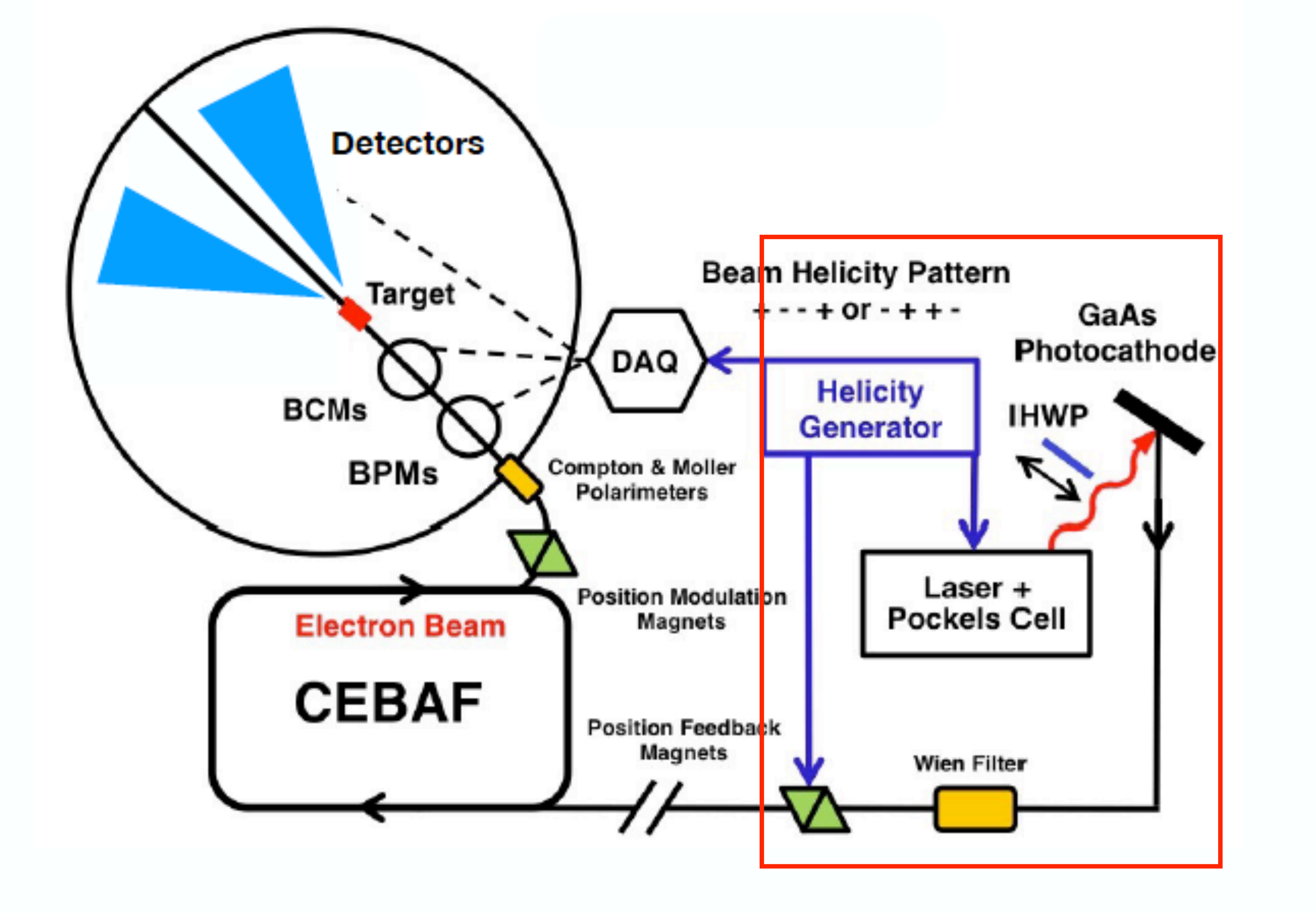
PREX/CREX



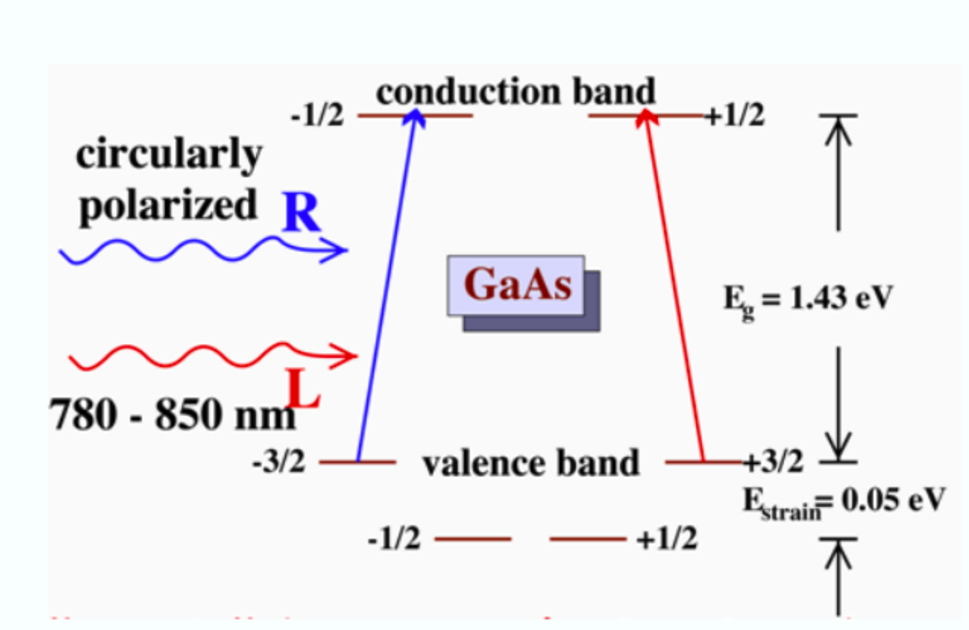
PVES at JLab

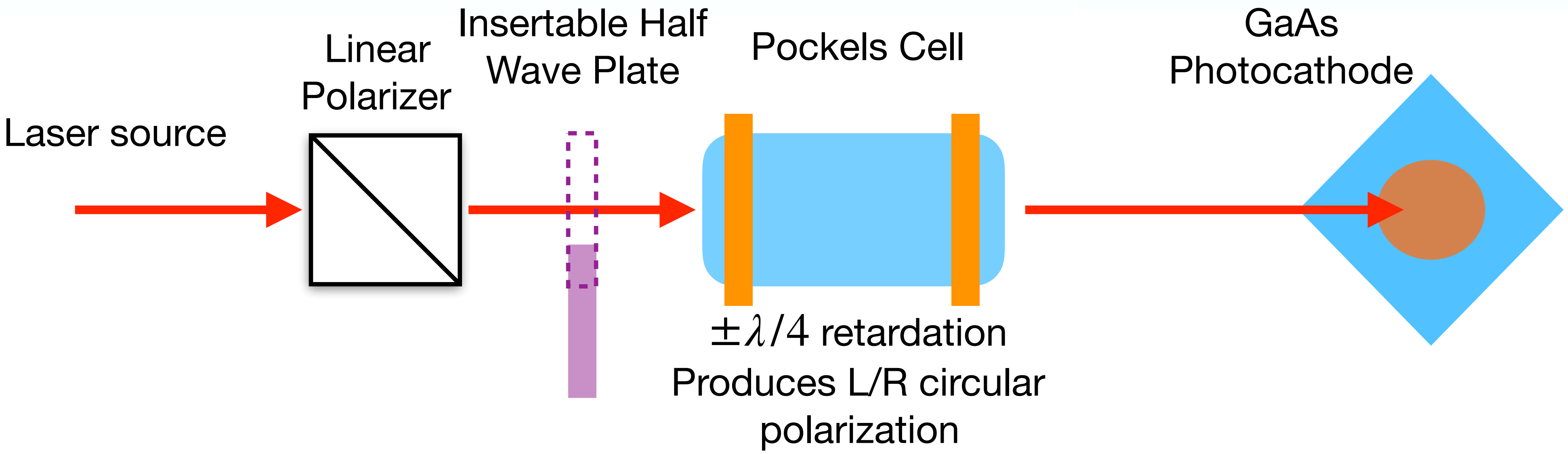

Detectors
Target
BCMs
BPMs
Compton & Moller Polarimeters
DAQ
Beam Helicity Pattern
+ - - + or - + + -
Helicity Generator
GaAs Photocathode
IHWP
Laser + Pockels Cell
Position Modulation Magnets
Electron Beam
CEBAF
Position Feedback Magnets
Wien Filter

PVES at JLab



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




Laser source

Linear Polarizer

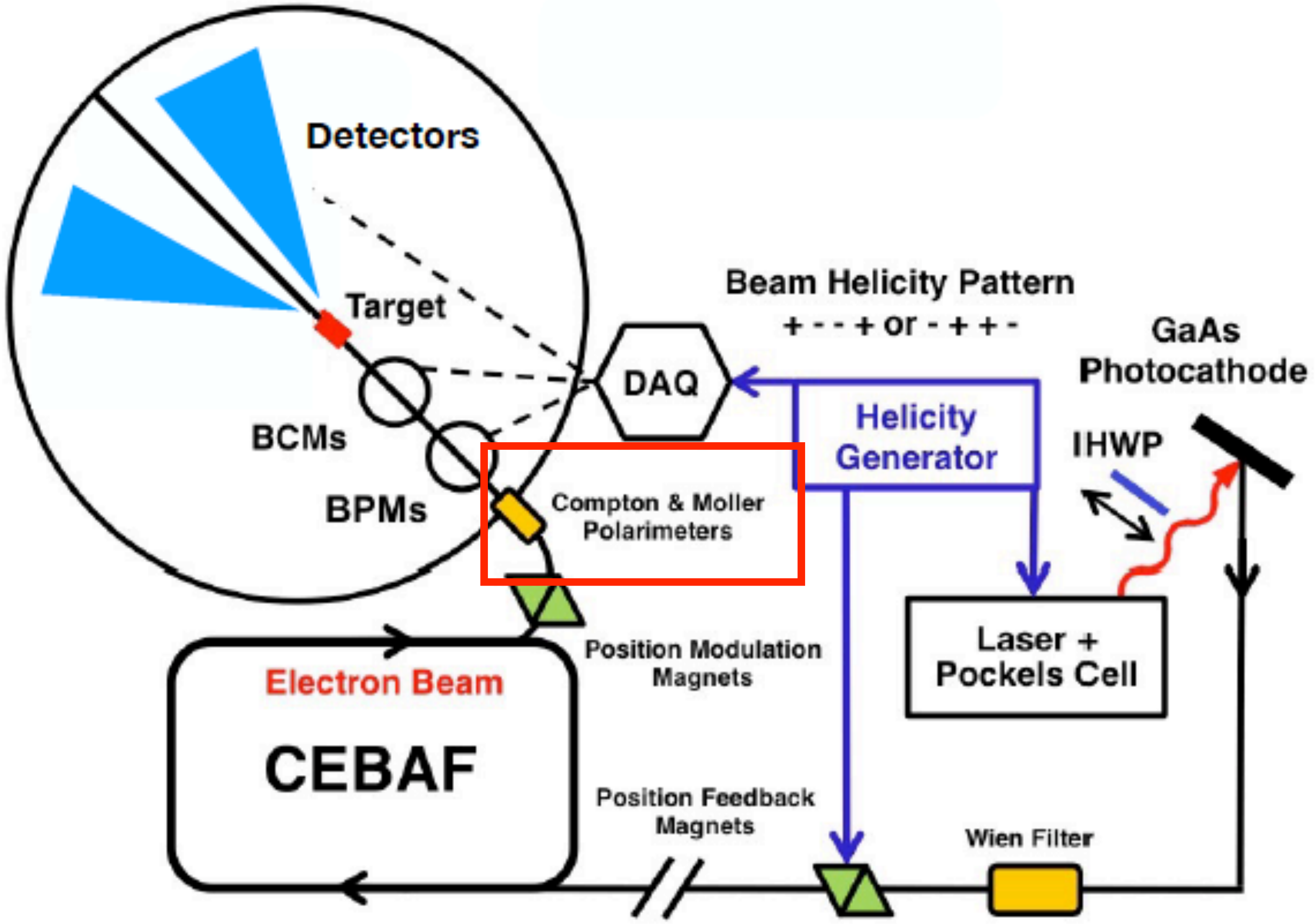
Insertable Half Wave Plate

Pockels Cell

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

GaAs Photocathode

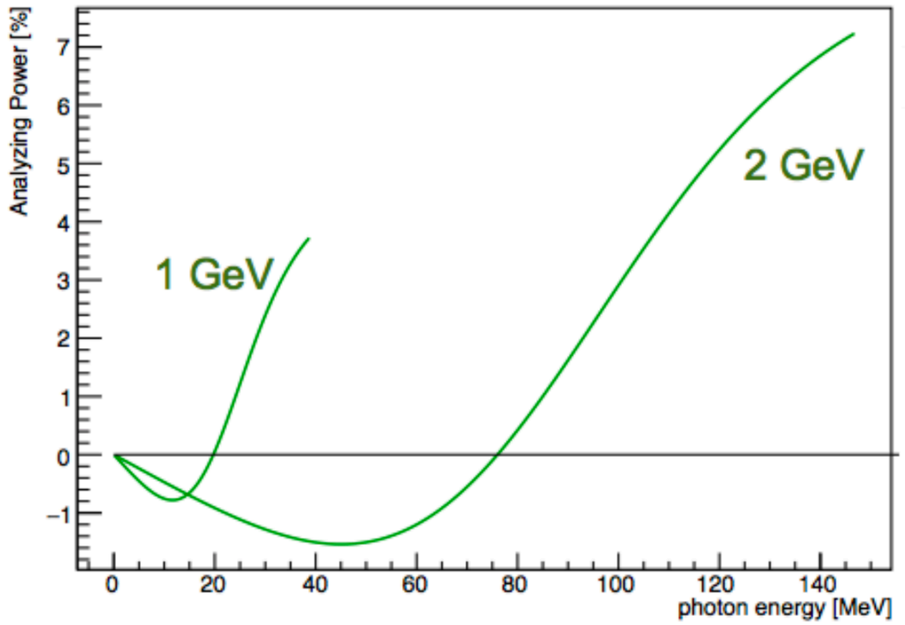
PVES at JLab

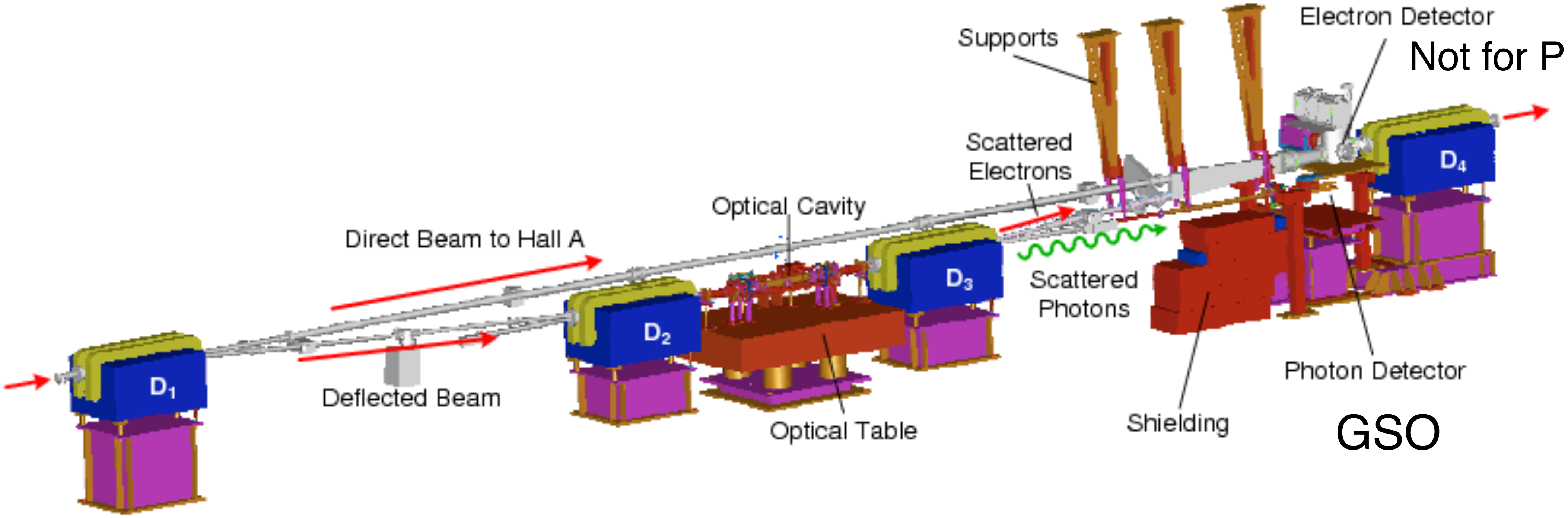


Polarimeters:
- Mott at Injector
- Compton and Moller at Hall
- ~1% level systematic uncertainty

Compton Polarimeter

- Polarized cross section of Compton scattering
- **Non-destructive** measurement: continuous monitoring of beam polarization
- PREX2 will need 1% at 950 MeV and CREX will need 0.8% at 2.22GeV
- Integrating DAQ; GSO photon detector





Not for PREX

GSO

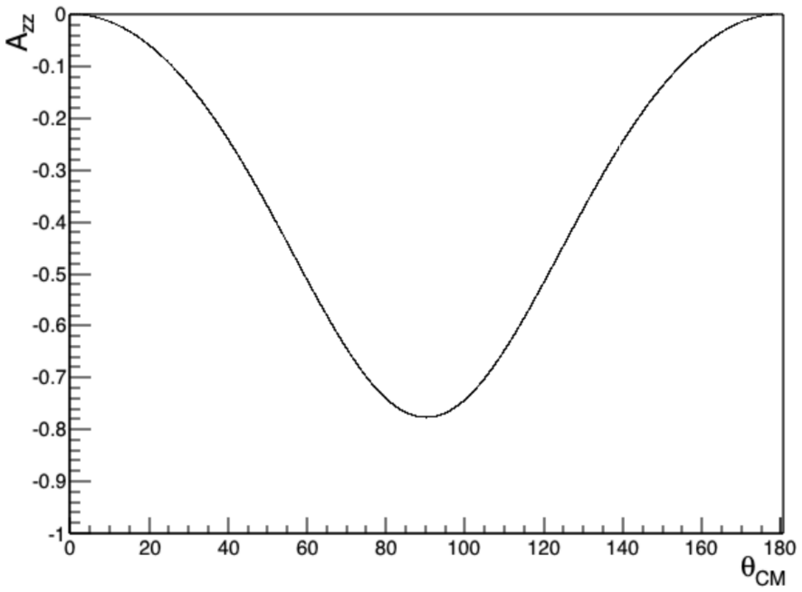
Moller Polarimetry

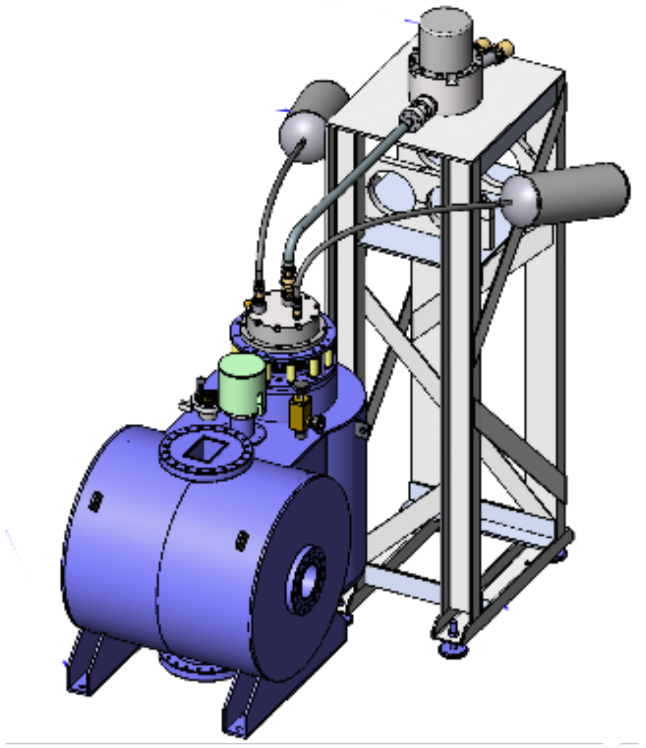
- Polarized cross section of Moller scattering (elastic electron-electron scattering)
- Rapid, high precision measurement; **Destructive** only low beam current

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

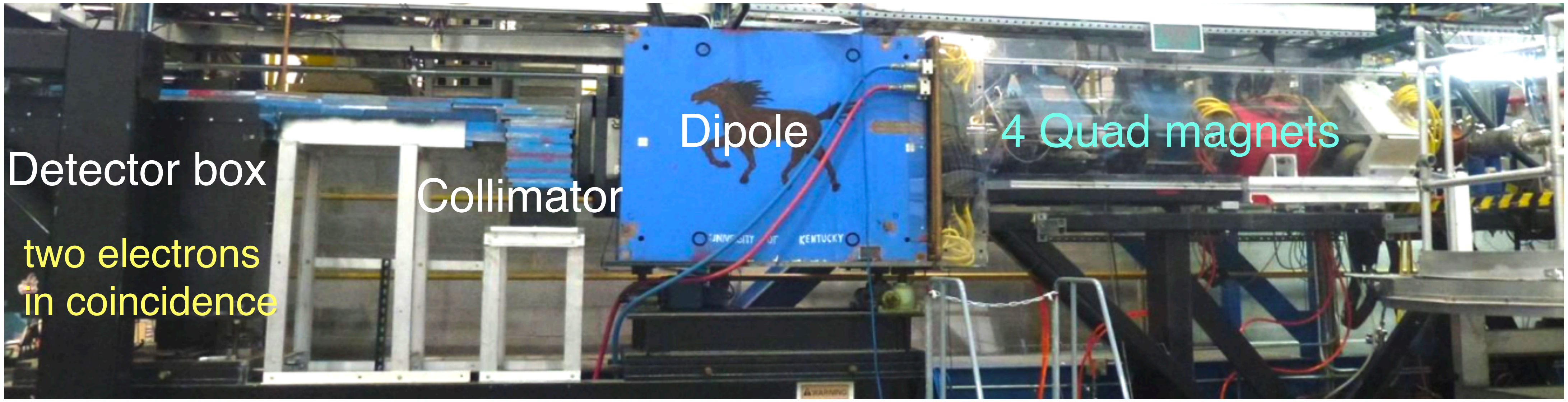
$$A_{ZZ} \;=\; -\frac{\sin^2\theta_{CM} \cdot (7 + \cos^2\theta_{CM})}{(3 + \cos^2\theta_{CM})^2}$$

Energy independent

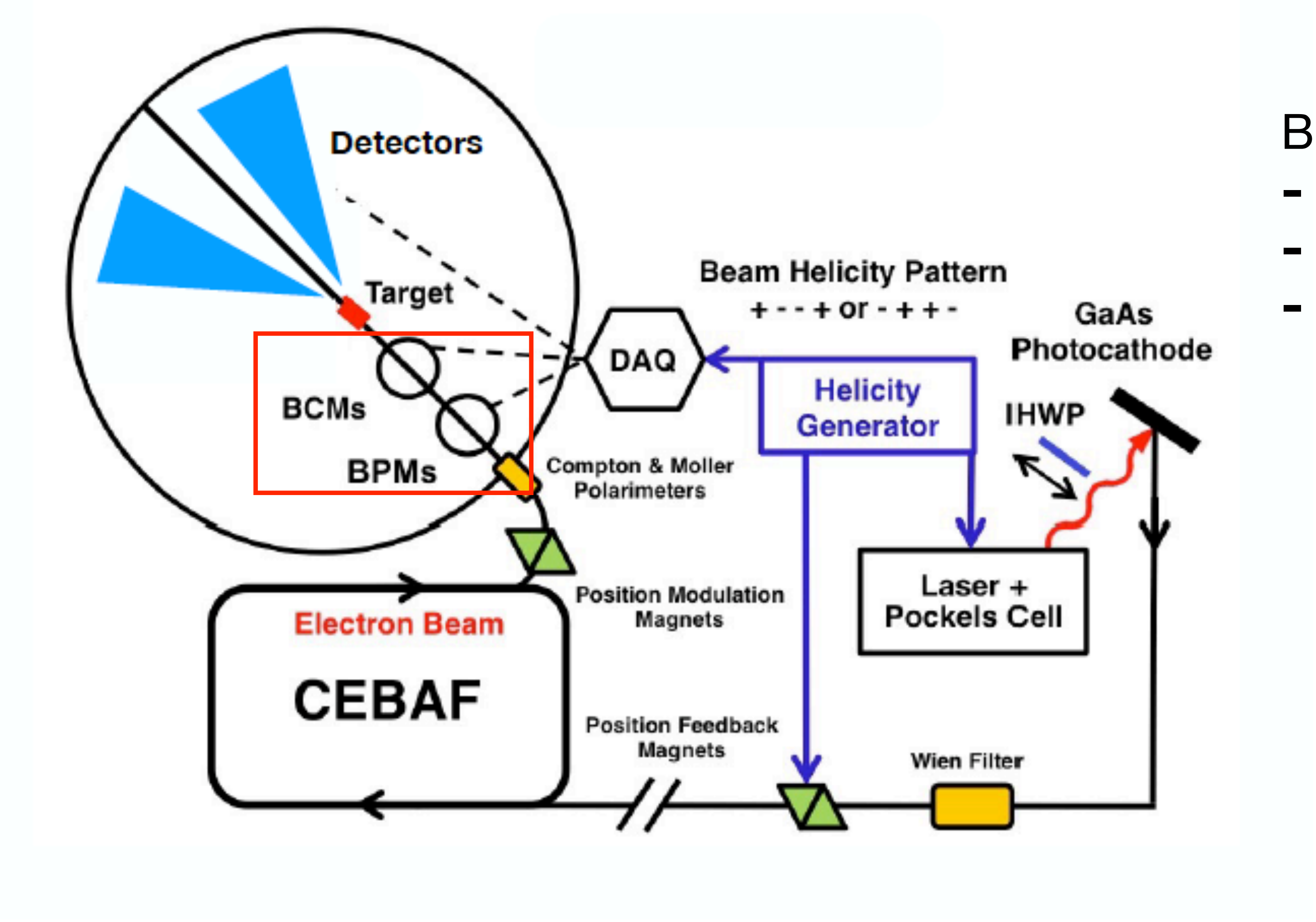




Iron Foil Target in high-field superconductor magnet.



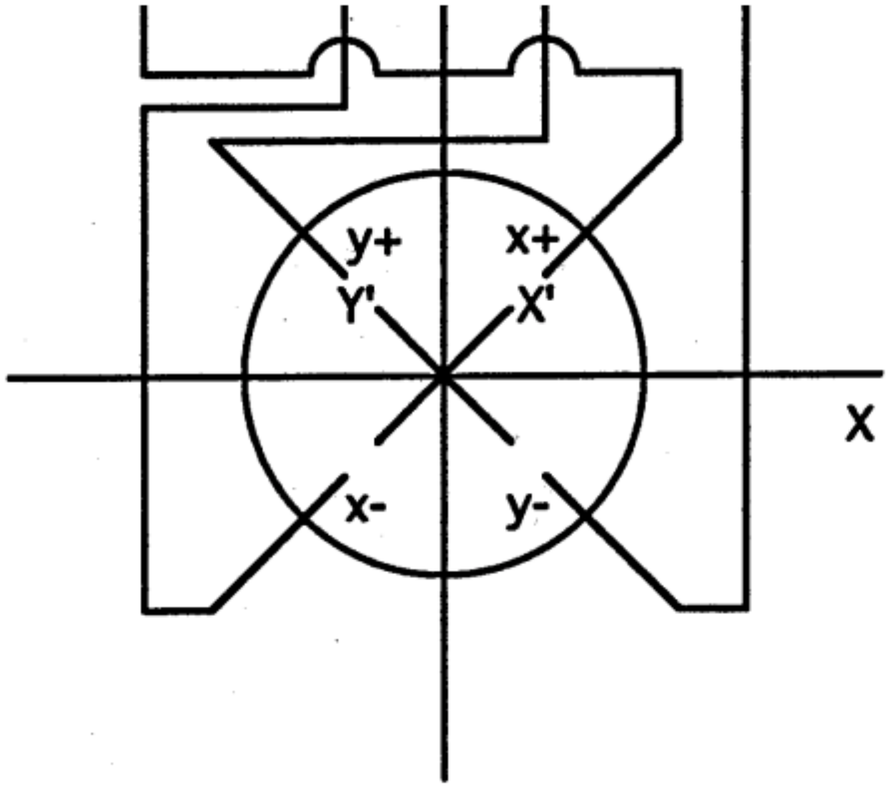
PVES at JLab

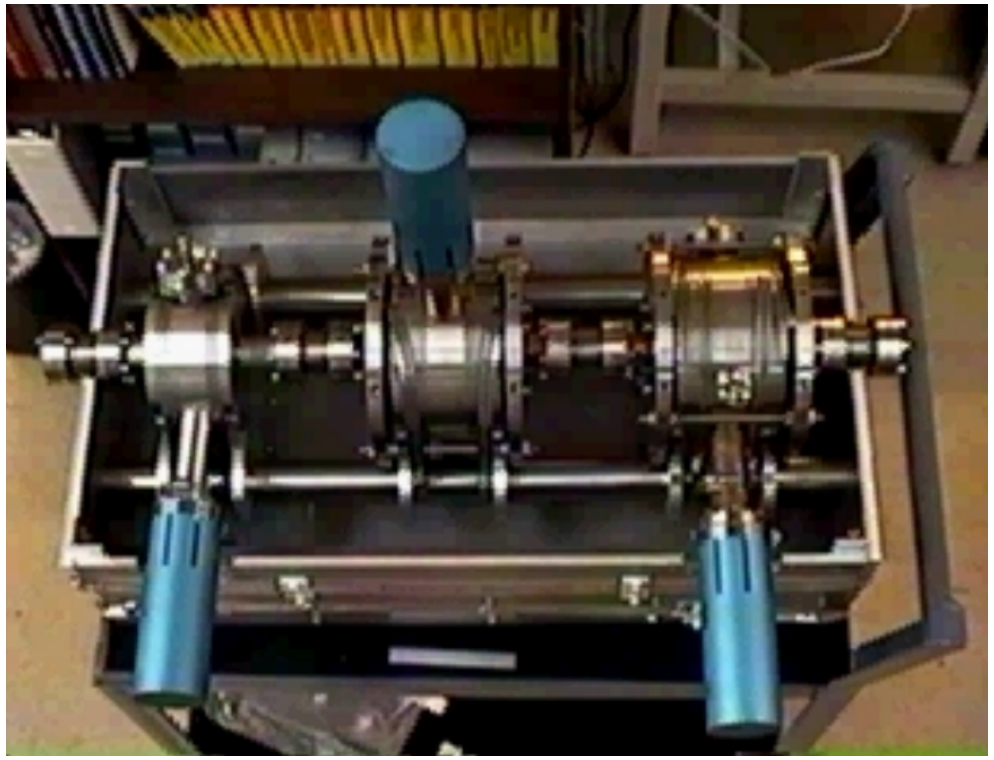


Beam monitoring:

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

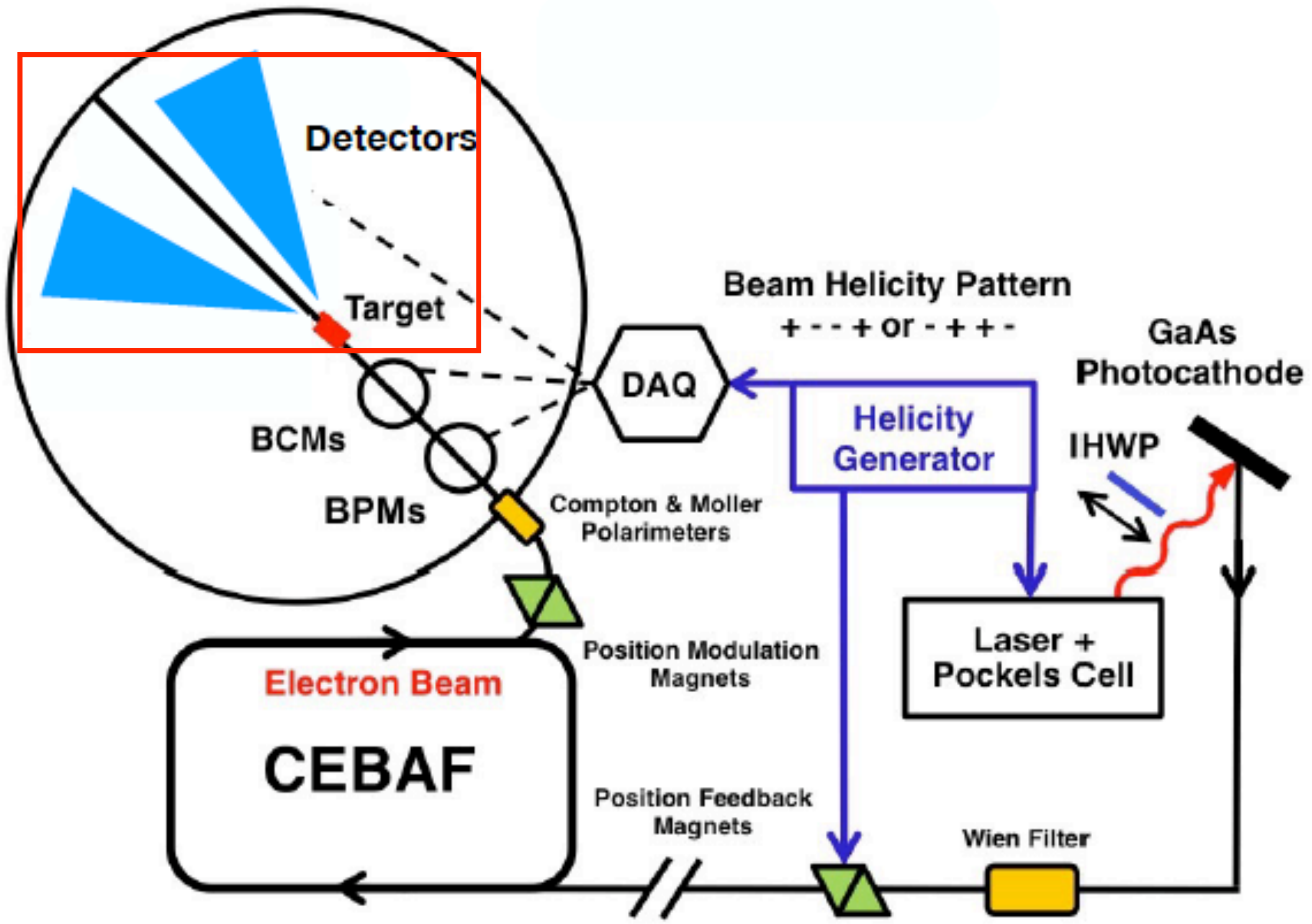
Beam Monitoring





- Mostly use RF antennas or RF resonating cavities
  - They can measure beam charge to about 30 ppm and positions to about 1 micron
- Electronics are used to **feedback** and reduce large helicity correlated beam asymmetries

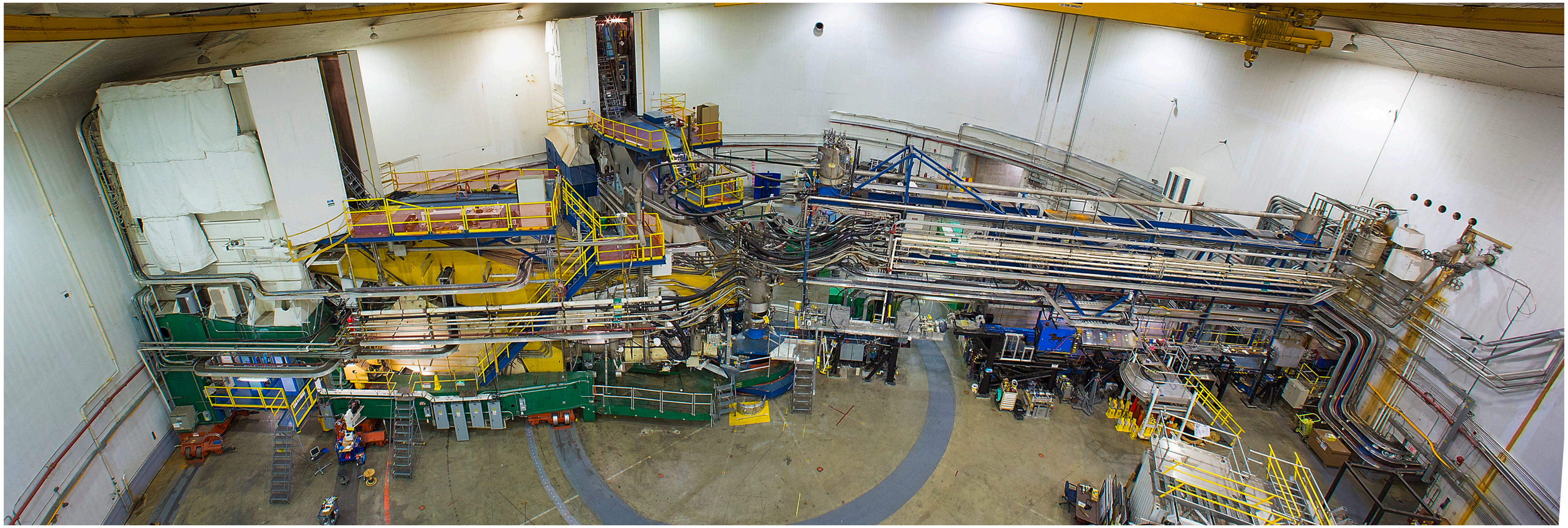
PVES at JLab

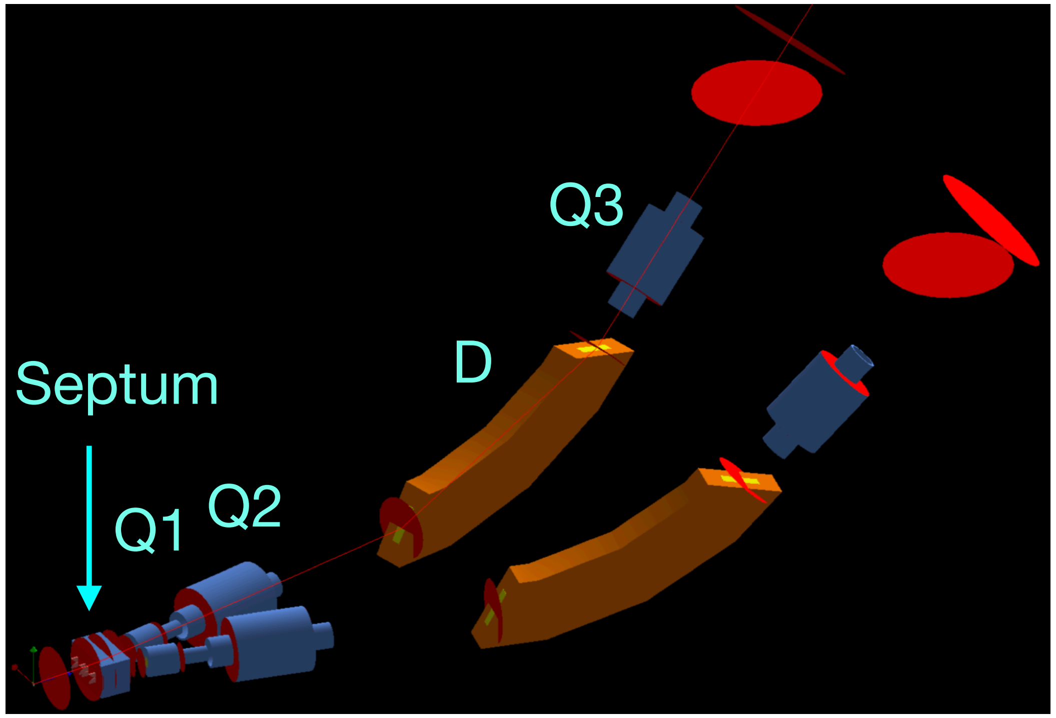


Spectometers:

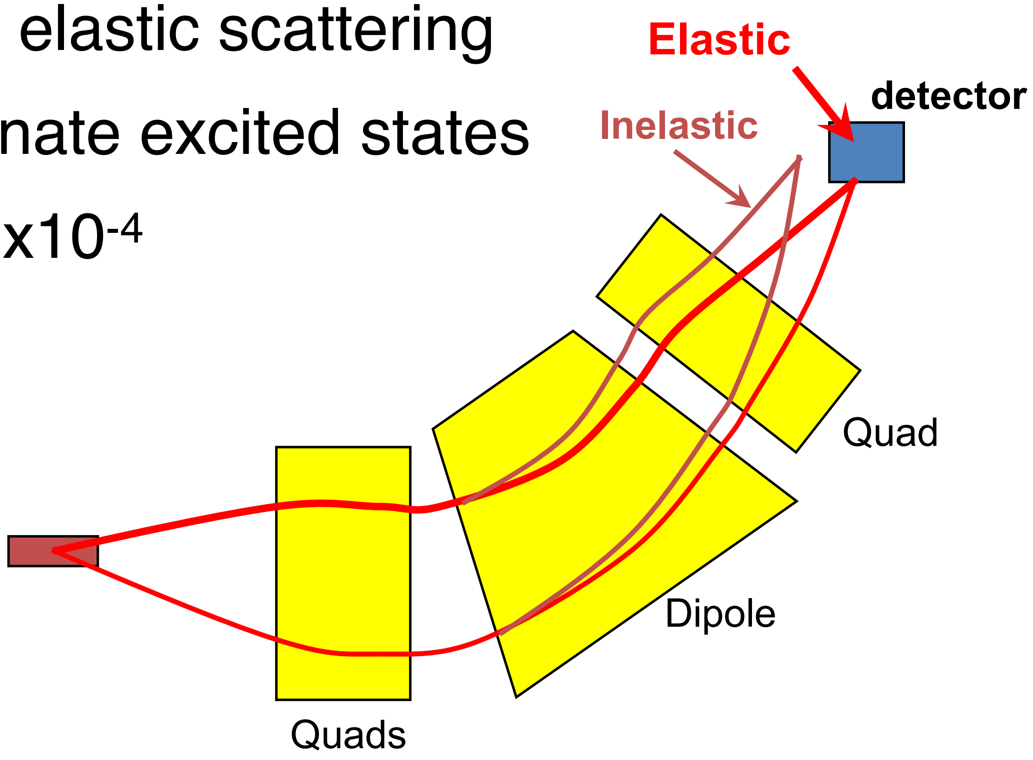
- HRS - High Resolution Spectrometers
- dp/p ~ 2×10^{-4}

Hall A High Resolution Spectrometers

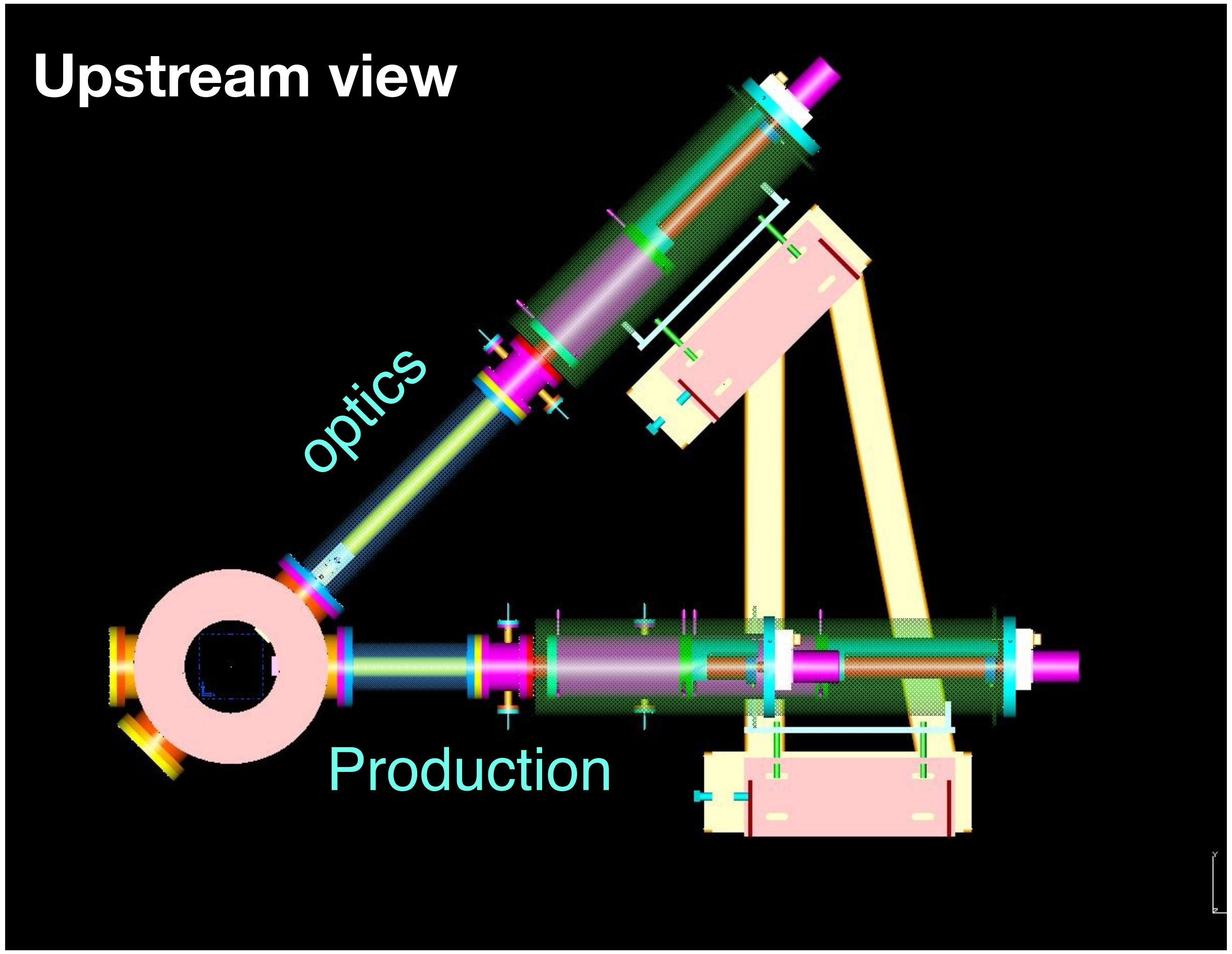


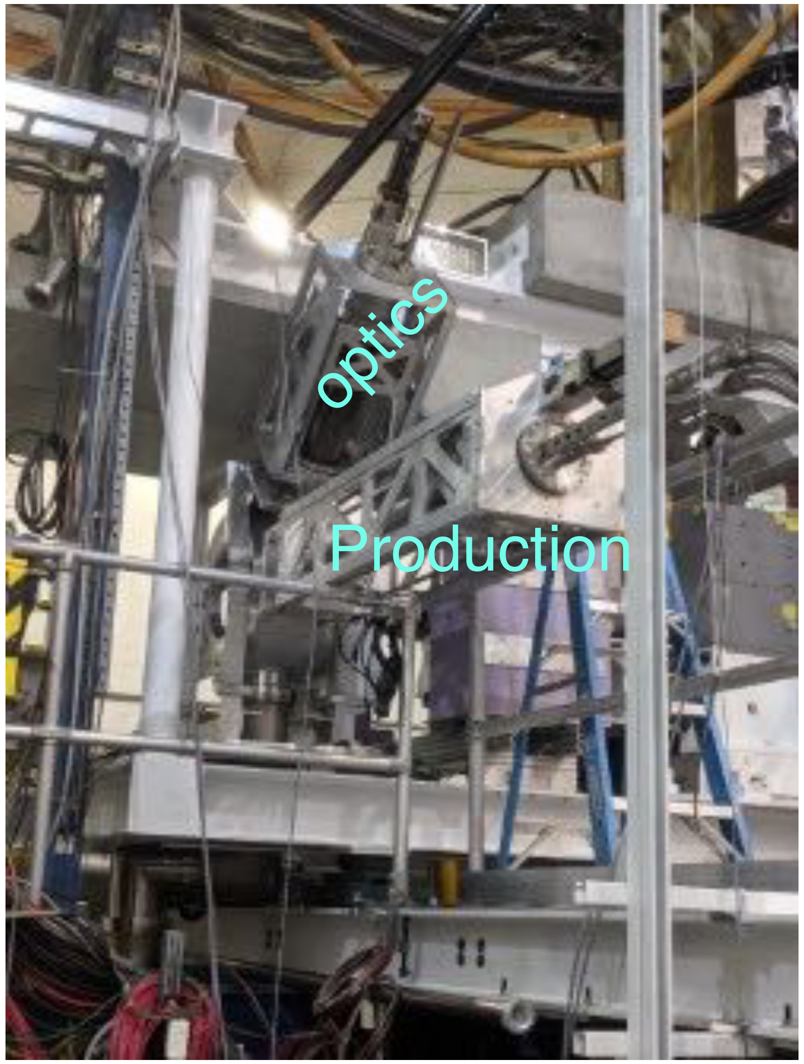


- Resolve elastic scattering
- Discriminate excited states
- dp/p ~ 2x10^{-4}



Scattering Chamber

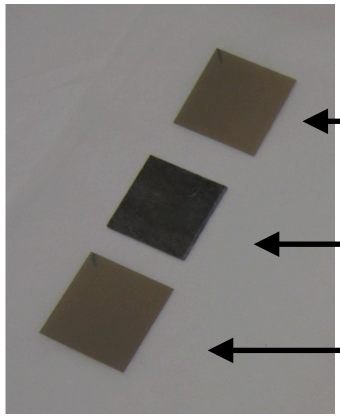




- One cryogenic production target ladder and one optics ladder at single target location
- Improved based on lessons learned during PREX-I
- Solves vacuum and mechanical assembly considerations

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



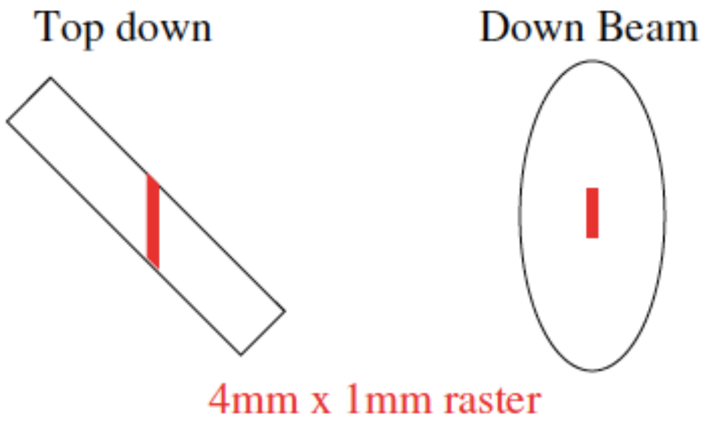
Diamond

Lead

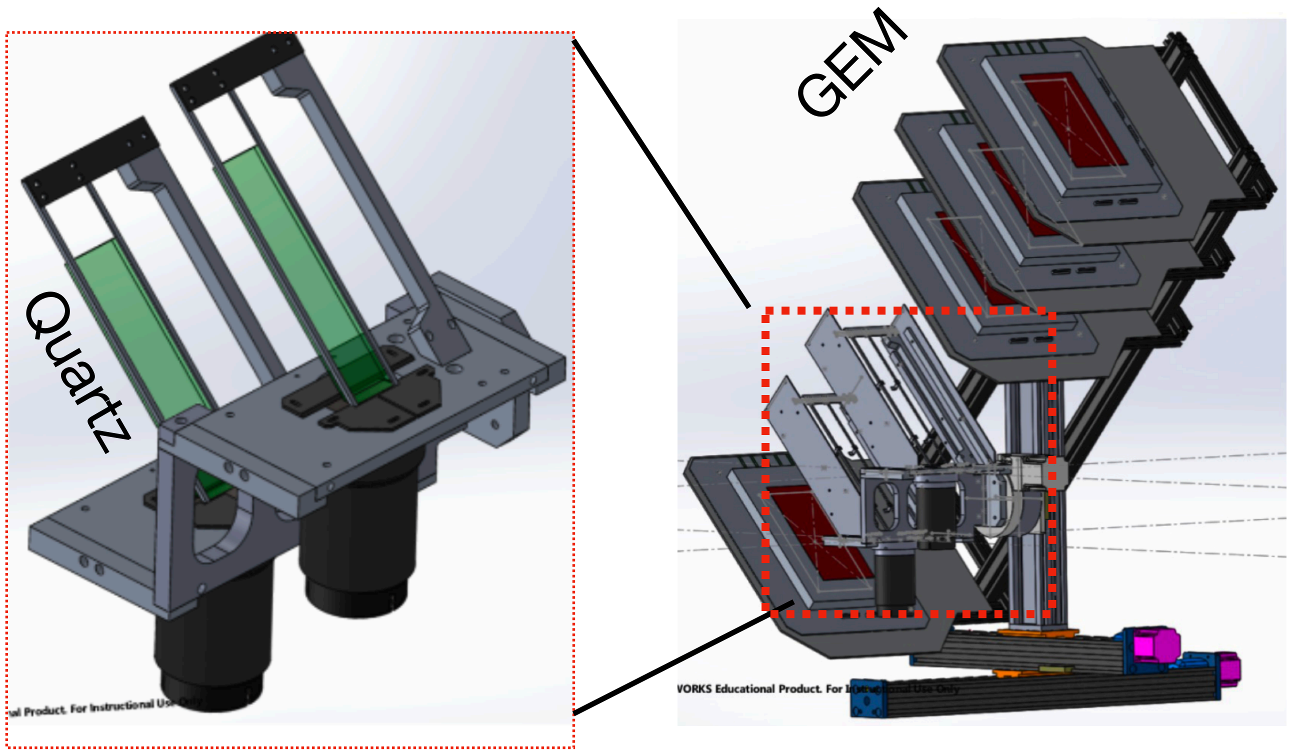
Diamond

Cryogenic production target ladder

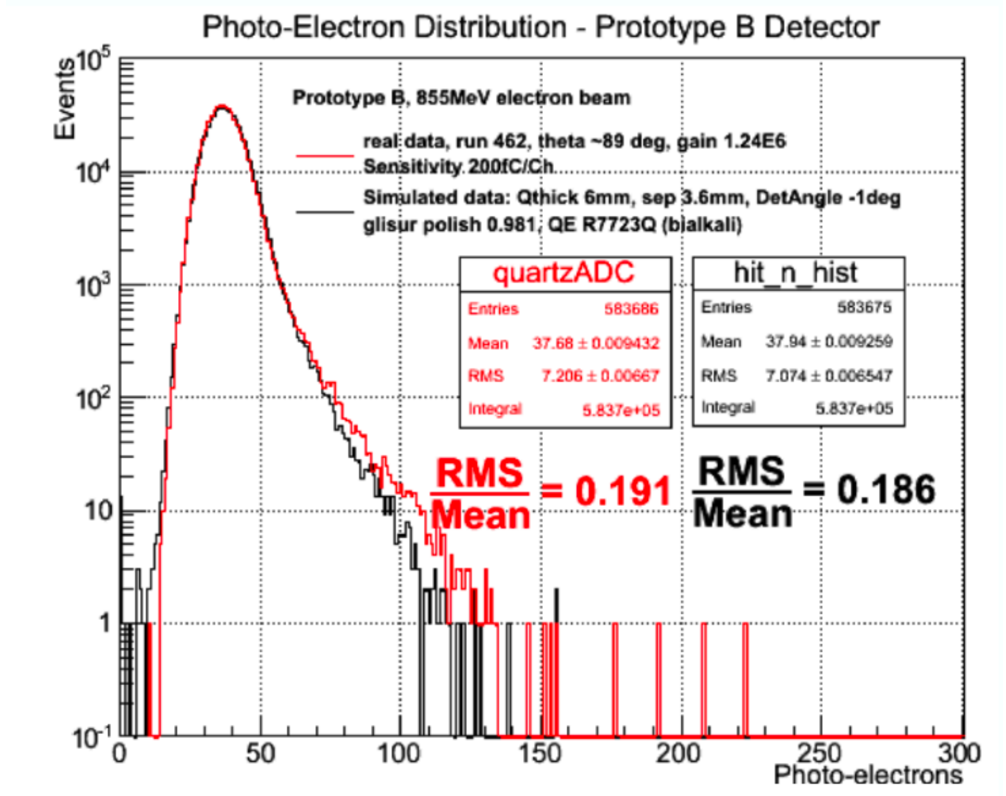
- ^{48}Ca target deployed in previous Hall A experiment in 2011
- Run “tilted" at 45^{o} to compensate for thinner target - 1.1g/cm2



Main Detectors



D. McNulty



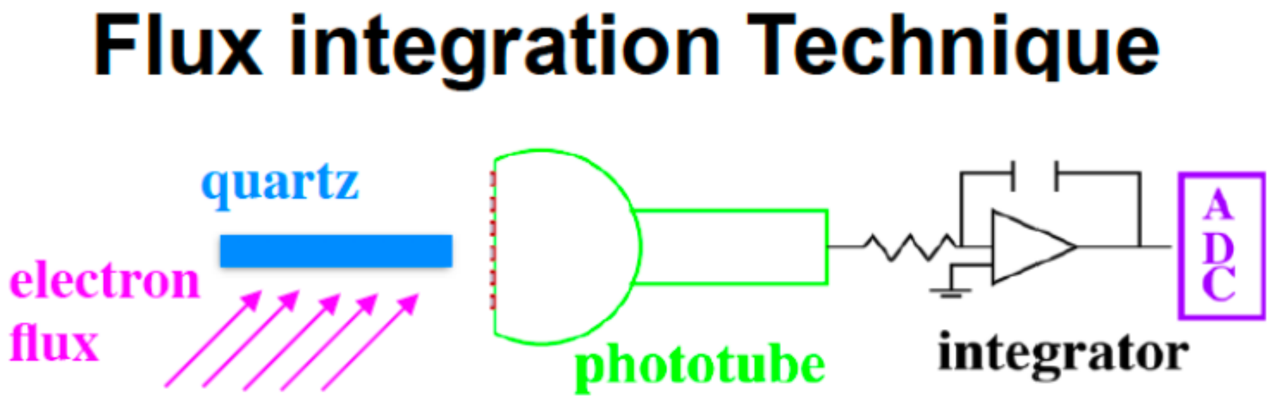
Beam test

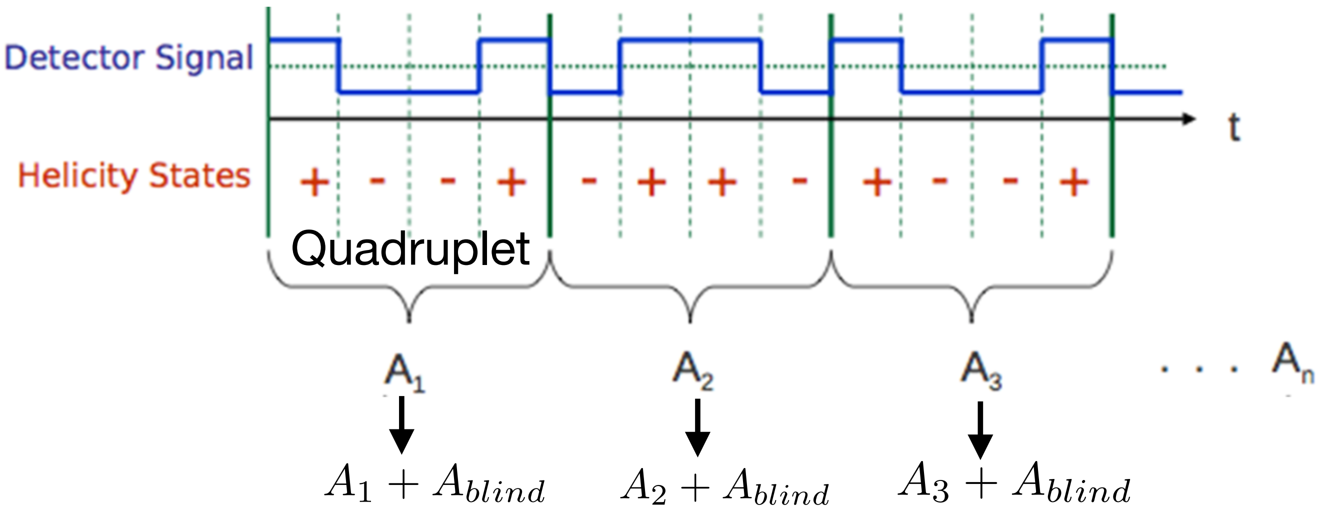
New quartz detector design for PREX-II/CREX

- Significant improvement of the resolution
  - PREX-I ~50% -> Beam Test ~19%

GEMs for tracking runs (Q^2 measurement)

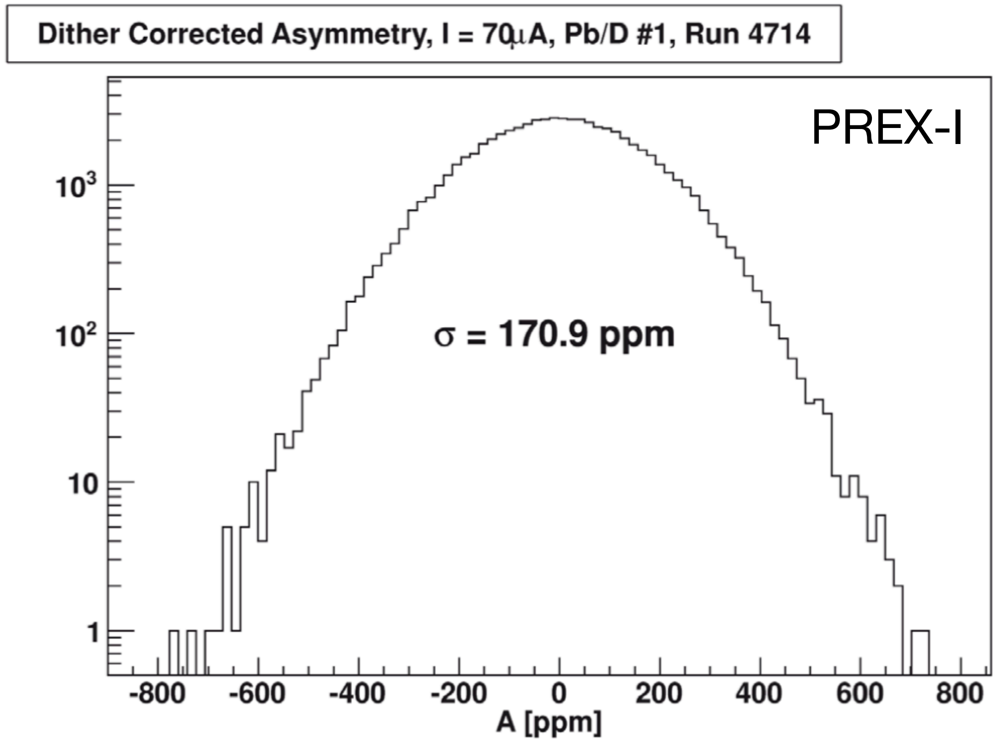
Integrating DAQ





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

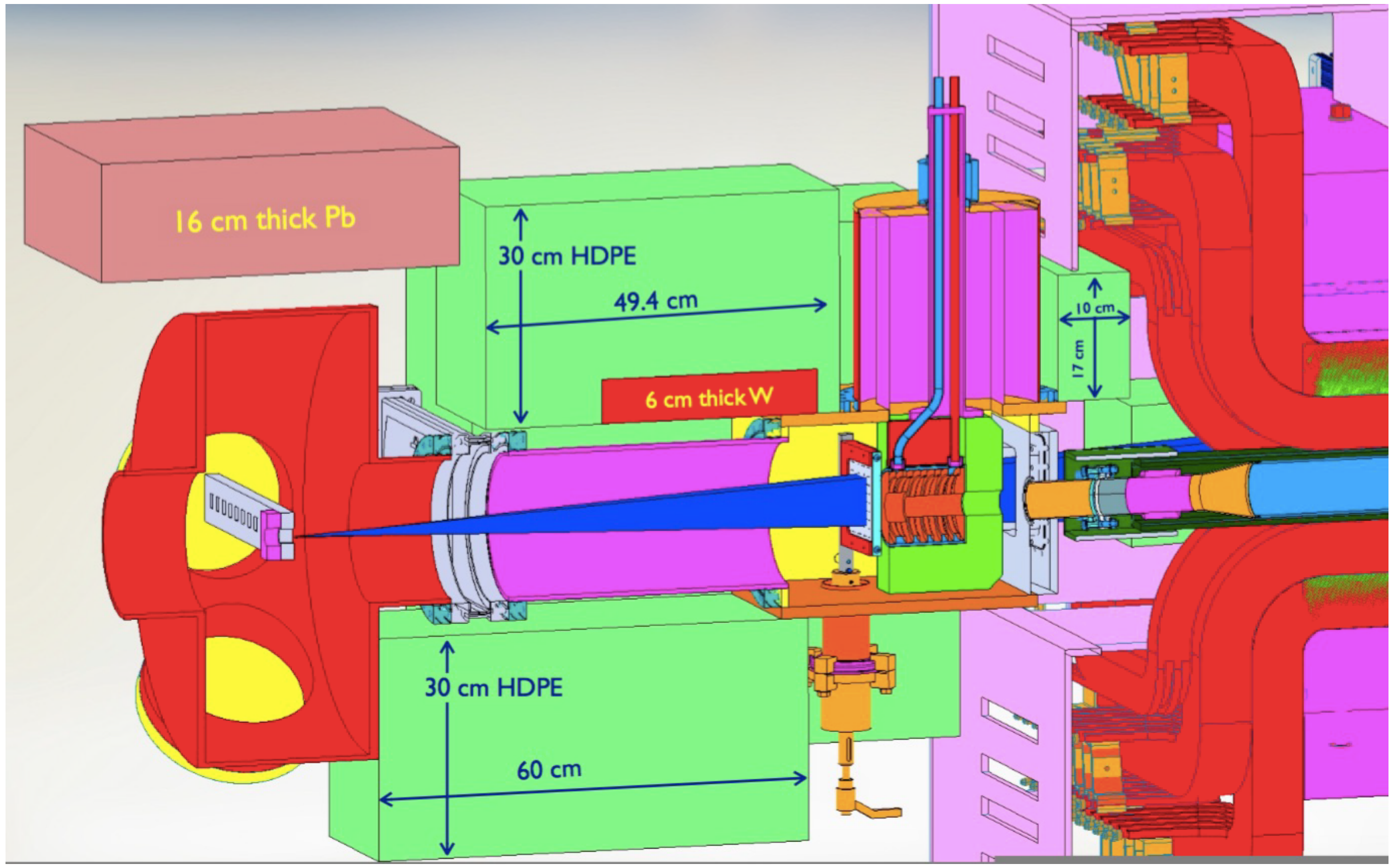
D: detector signal, I: beam current



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

Radiation Shielding

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

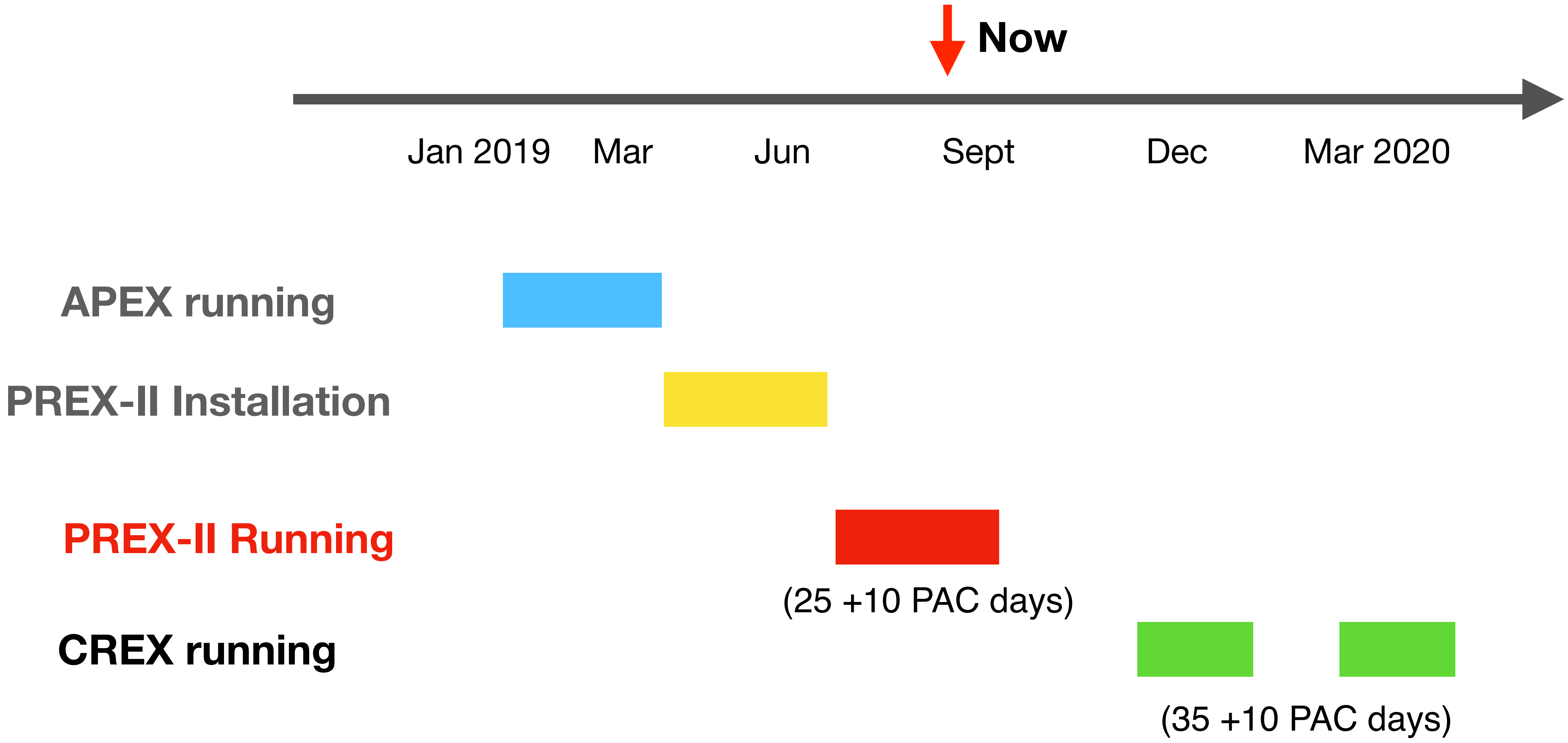


	PREX-I	PREX-II	CREX
Power in collimator (W/μA)	9.7	**28.8**	6.8
Power in hall (W/μA)	18.0	**3.0**	~1.5

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

Time Line



Now

Jan 2019 Mar Jun Sept Dec Mar 2020

APEX running

PREX-II Installation

PREX-II Running

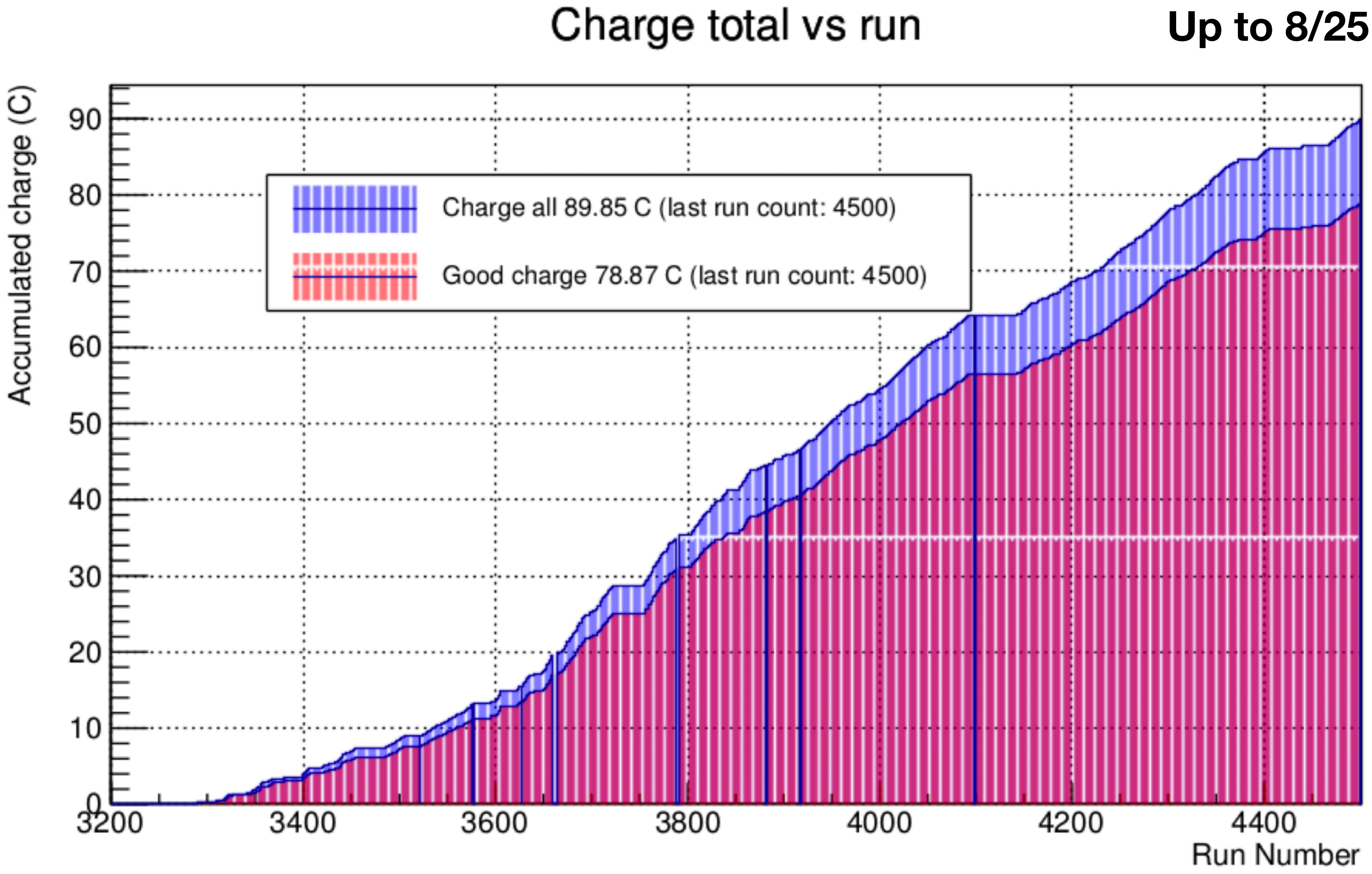
(25 +10 PAC days)

CREX running

(35 +10 PAC days)

PREX-II Status

Up to 8/25



Quality of data we are taking is far better than PREX-I

Summary

- PREX/CREX: Neutron skin of ^{208}Pb and ^{48}Ca, will provide a crucial benchmark for the understanding of nuclear structure

- PREX-II: running until early Sept; a factor of 3 improved precision from PREX-I;   tightly linked to neutron stars

- CREX: will run 2019 Fall and 2020 spring; extend studies over long lever arm of size and atomic number; bridge *ab initio* calculation to DFT

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Thank you for your attention!