Detectors for High Flux Parity Experiments at JLab:
PREX-II, CREX and MOLLER

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Detectors for Parity Experiments at JLab

Outline

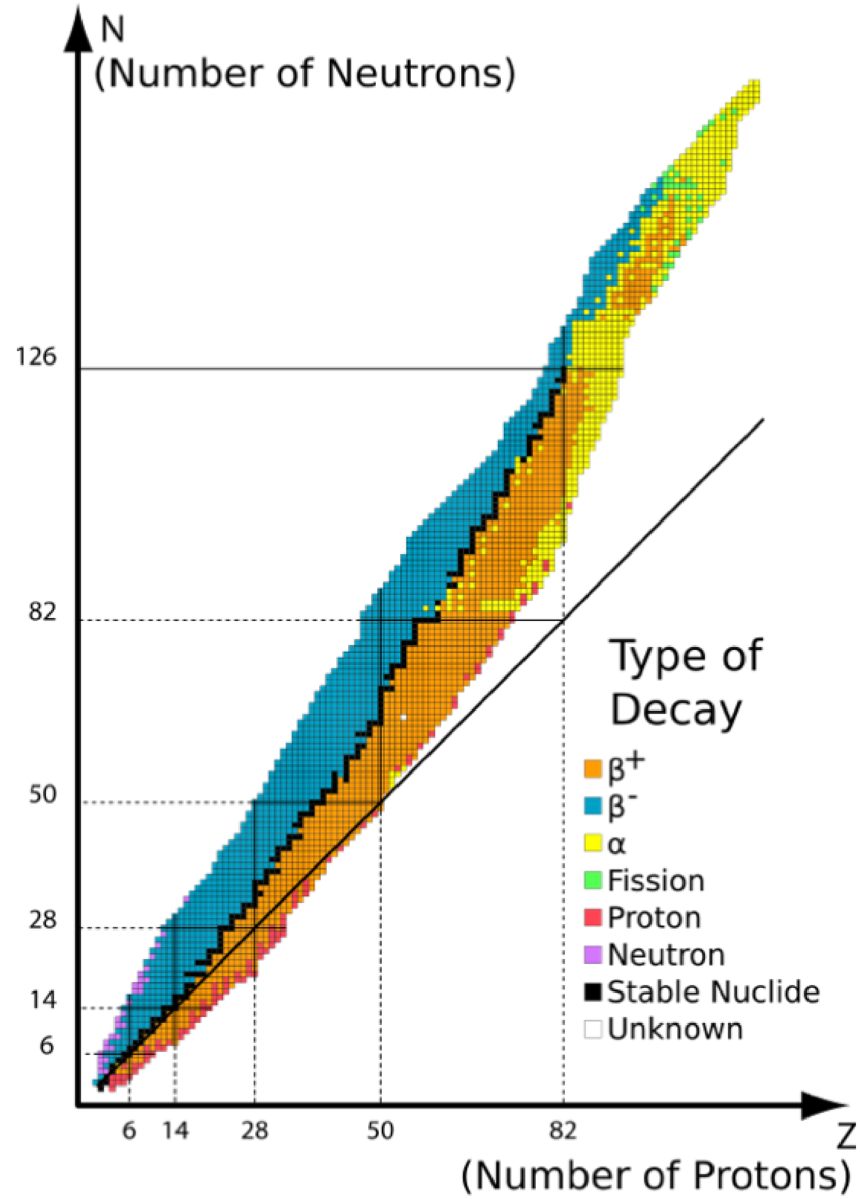
- The Weak force and Parity Symmetry Violation
- Introduction to Parity-Violating Electron Scattering
  - Why PVES?
  - Experiment blueprint, "how-to", and technical progress
- PREX-II/CREX at Jefferson Laboratory
  - Experimental concept, techniques and apparatus
- New Integrating Detectors for PV
  - PREX-I Main and A_T Detectors
  - PREX-II/CREX Main and A_T Detectors
  - Shower-max Sampling Calorimeter for MOLLER (if time)
- Summary and Future Plans

The Weak Force: Oh, I didn't know that?

- Through a series of nuclear reactions, four protons (hydrogen nuclei) in the core of our Sun combine to form a helium nucleus emitting two positrons and two neutrinos and releasing 27 MeV of energy:

$$p + p + p + p \rightarrow He^4 + e^+ + e^+ + \nu_e + \nu_e + 27\text{MeV}$$

- Thermonuclear fusion--Perhaps the most important reaction for all life on planet Earth is caused by a fundamental force of nature that is rarely discussed in the classroom: Weak Interactions or the weak nuclear force
  - Responsible for nearly all radioactive decay processes
  - Beta decay is most common
  - Theoretical understanding is at same level as Quantum Electro Dynamics



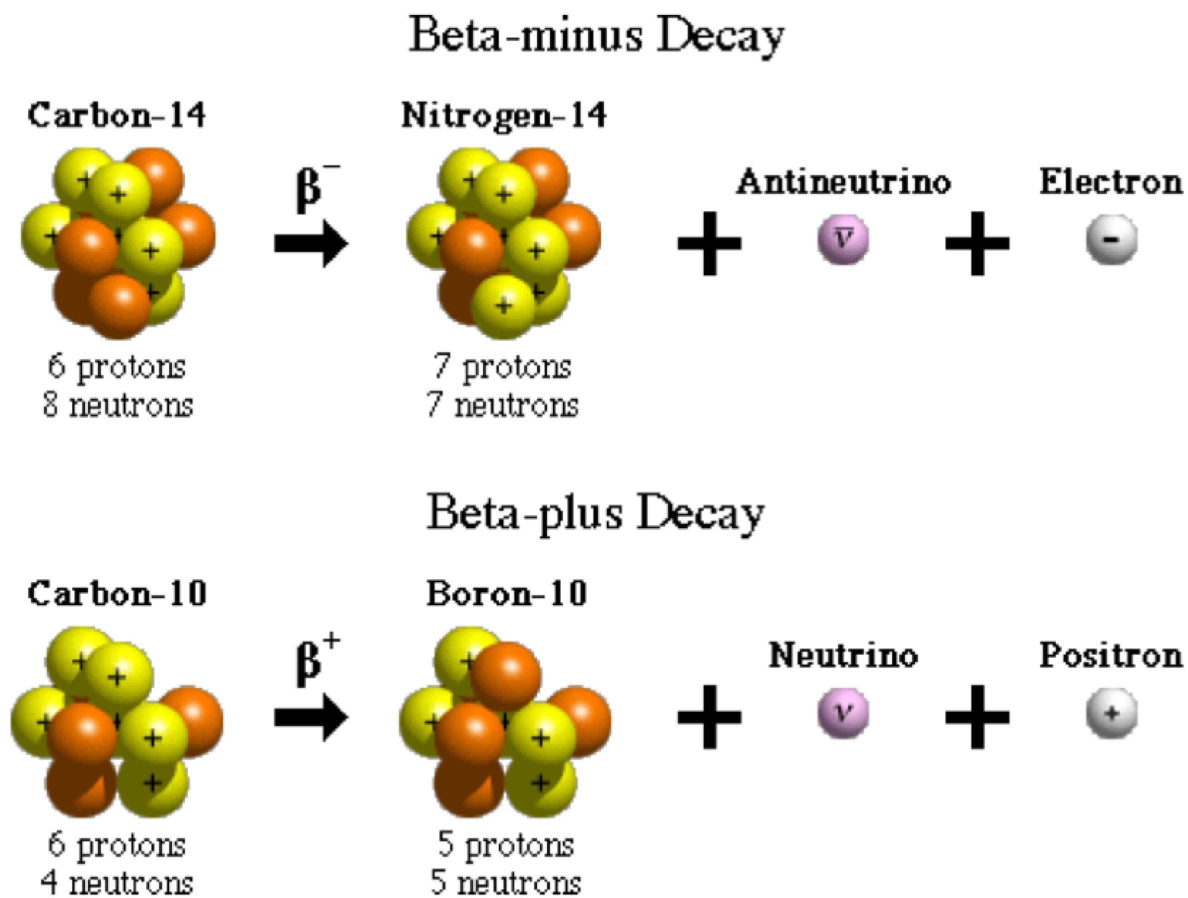
Beta Decay Examples

- β^- decay: $n \rightarrow p + \bar{\nu}_e + e^-$

-- Moves nuclei up the periodic table ($Z \rightarrow Z + 1$)

- β^+ decay: $p \rightarrow n + \nu_e + e^+$

-- Moves nuclei down in the periodic table ($Z \rightarrow Z - 1$)

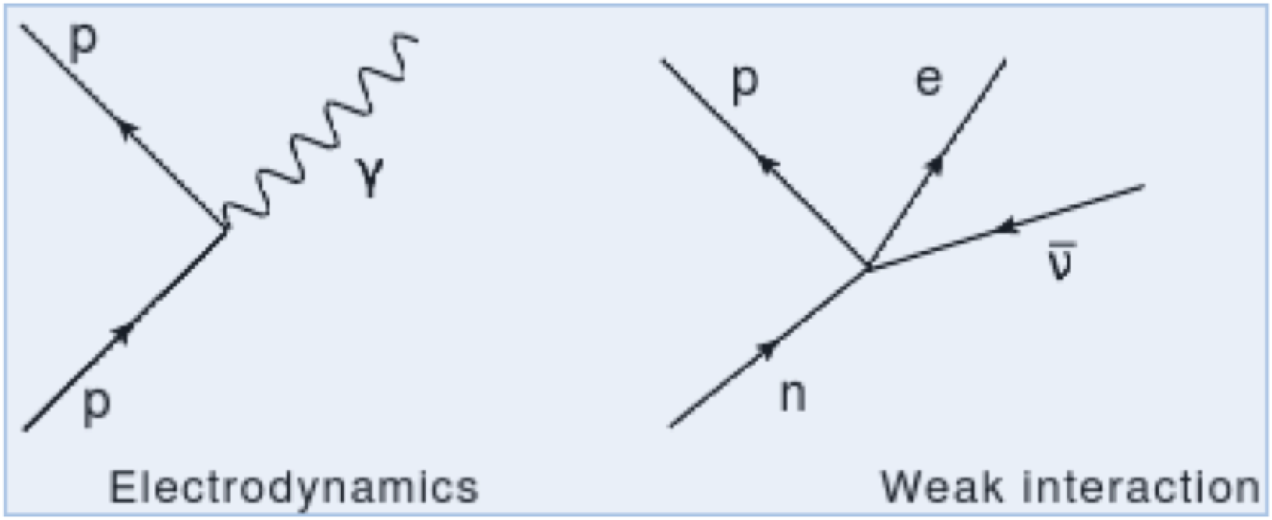


Beta Decay – Nature's Window into the Weak-nuclear Force

A Quick History:

- 1899 Rutherford Rutherford classifies three types of radioactive emissions: alpha, beta, and gamma
- 1931 Pauli postulates existence of neutrino to explain non-discrete energy spectra of β-decay electrons
- 1933 Fermi develops theory to explain β decay -- precursor to theory for weak interaction
- 1956 Neutrino discovered by experiment. $\overline{\nu}_e + p \rightarrow n + e^+$
- 1957 Parity Violation discovered in β decay of ^{60}Co

Fermi's Interaction – Precursor to Weak Theory



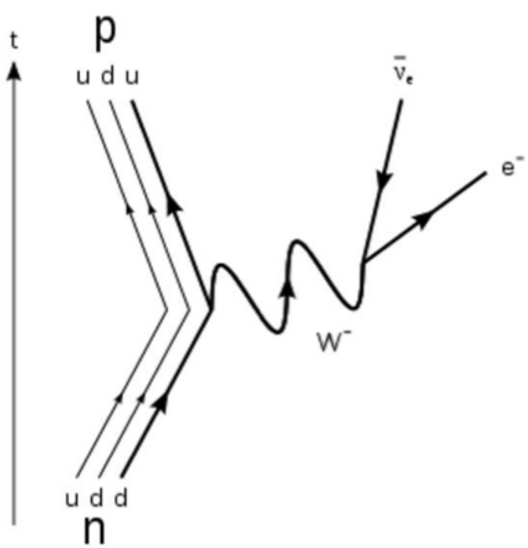
- Fermi's theory invented a physical mechanism for β decay
- 4-fermion contact interaction at single space-time point
- Modeled after electrodynamic field interactions -- where $\vec{J}_E$ of a charged particle interacts with $\vec{A}$ to create a photon
- For Fermi's theory, the ``weak'' current of pn-pair interacts with the ``weak'' current of e$\bar{\nu}$-pair
- Fermi's ``weak'' currents/potentials had vector form just as EM.

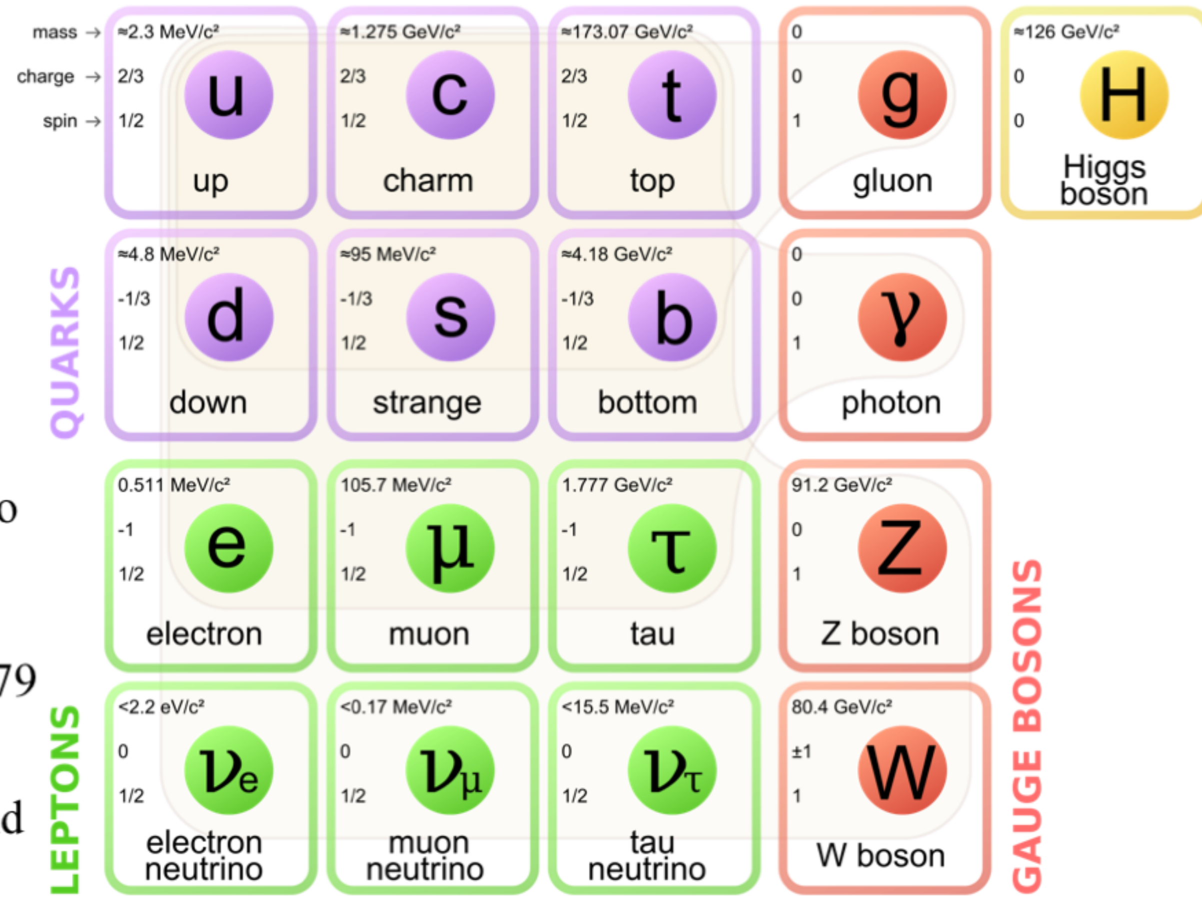
Parity Symmetry

$$P: \begin{bmatrix} x \\ y \\ z \end{bmatrix} \longrightarrow \begin{bmatrix} -x \\ -y \\ -z \end{bmatrix}$$

- Parity operation: Spatial reflection through the origin
- "Even" functions: **P** f(x, y, z) ⟹ +f(x, y, z)
- "Odd" functions: **P** f(x, y ,z) ⟹ -f(x, y, z)
- *Classically*, scalar quantities (m, E, $\boldsymbol{\rho}$, V, M, ...) are mainly "even" while vector quantities ($\vec{x}$, $\vec{a}$, $\vec{F}$, $\vec{E}$, $\vec{A}$, ...) are mainly "odd"
- *Quantum Mechanically*, if **P** commutes with the Hamiltonian, then Parity is conserved (invariant or symmetric)
- Fundamental symmetry of nature known to be conserved in electromagnetism, strong interactions, and gravity

β^- Decay and Standard Model





- Julian Schwinger modifies Fermi's theory to incorporate parity violating potential term (V-A) and idea of intermediate vector bosons; Glashow, Weinberg, and Salam 1979 Nobel Prize
- $W^{\pm}$ only couples to left-handed particles and right-handed anti-particles
- Z^0 couples predominantly to left-handed particles

Why Parity-Violating Electron Scattering?

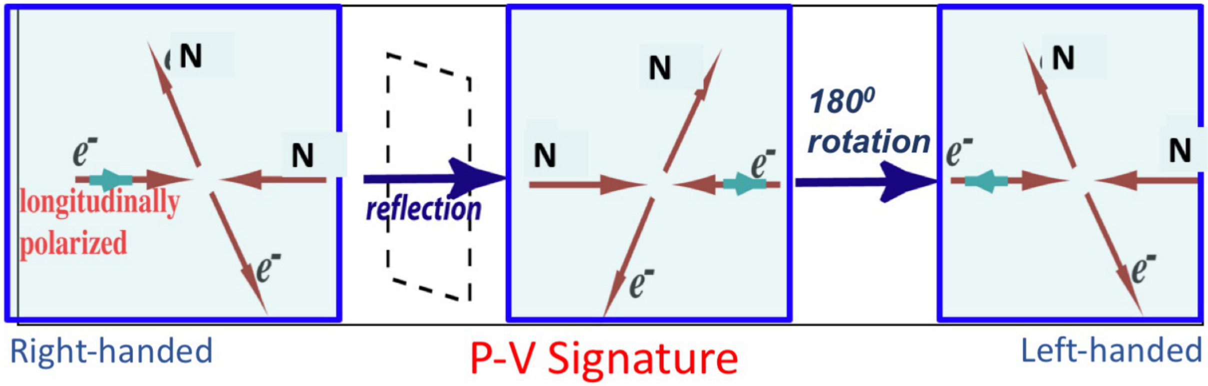
Provides model-independent determinations of nuclear and fundamental-particle weak-charge form factors and couplings with widespread implications for:

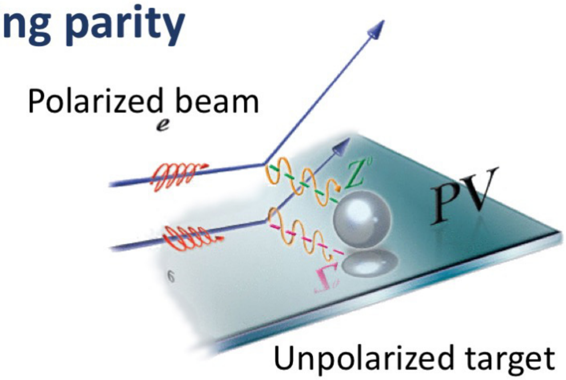
- Understanding nuclear and nucleon structure
  - Strange quark content of nucleon
  - Neutron radii of heavy nuclei $\longrightarrow$ density dependence of Symmetry Energy and EOS of nuclear matter; neutron stars; calibrate hadronic probe reactions on radioactive beams
- Search for physics Beyond the Standard Model (BSM)
  - Indirect searches using low energy ($Q^2 << M_Z^2$) precision electroweak tests at high intensity or precision frontier
  - complements direct searches at high energy frontier

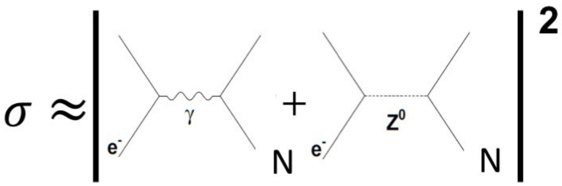
JLab PVES Programs: HAPPEX, G0, PVDIS, PREX, Qweak, CREX MOLLER, SoLID

Parity-Violating Electron Scattering

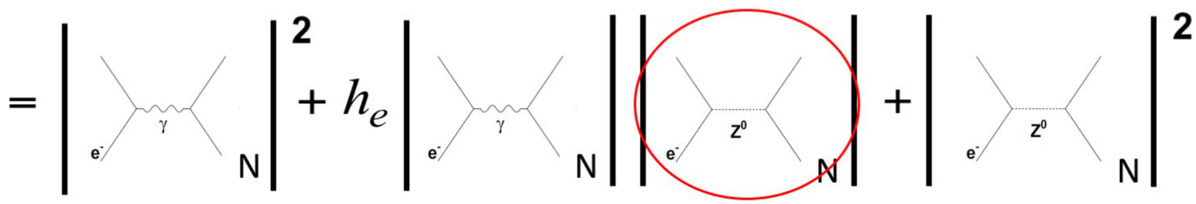
Parity Transformation: Changing beam helicity equivalent to changing parity







- Access NC Weak amplitude via EW interference-dominated asymmetry measurement

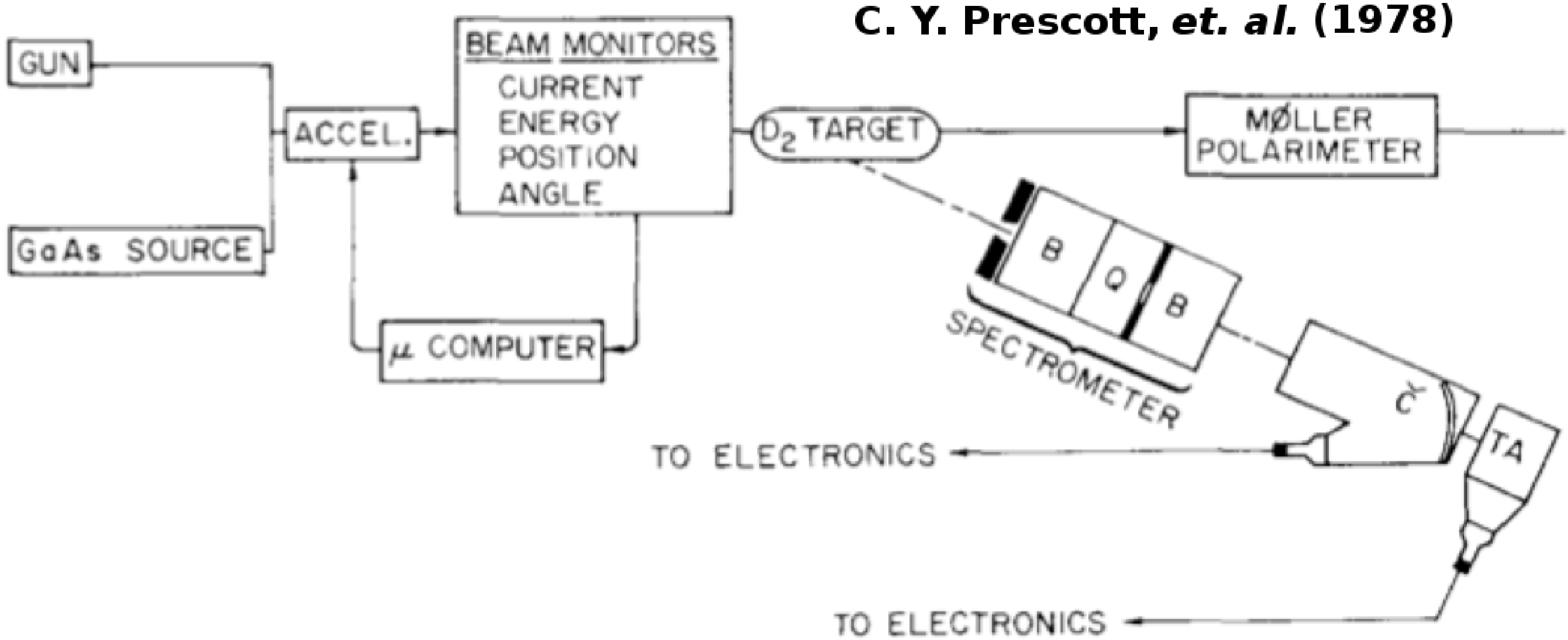


- Flip sign of longitudinal polarization
- Measure fractional rate difference or asymmetry

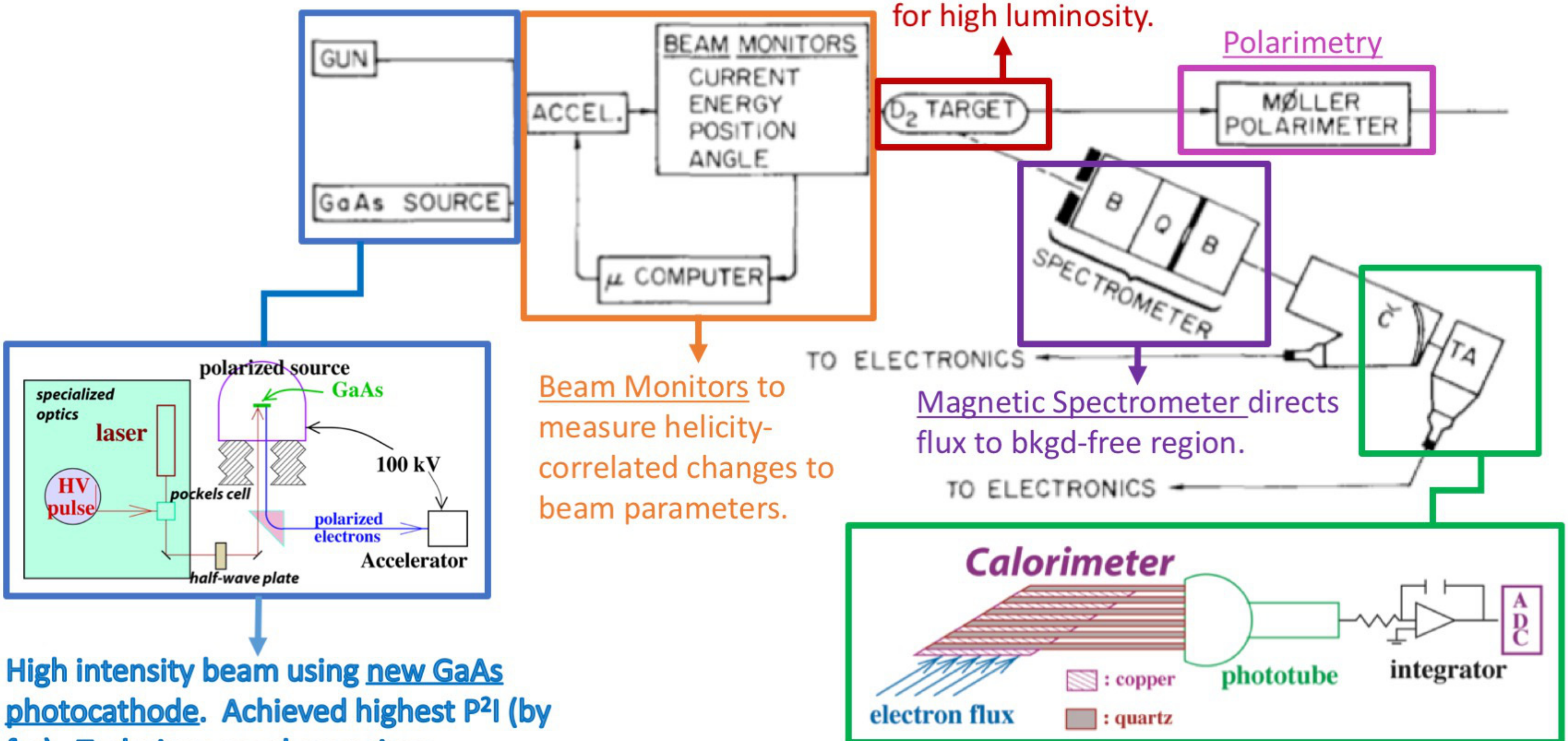
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{M_{Weak}^{NC}}{M_{EM}} \approx \frac{G_F Q^2}{4\pi\alpha} \sim 10^{-4} \cdot Q^2 \text{ [/GeV}^2\text{]}$$

Blueprint of a PVES Experiment (E122 at SLAC)

C. Y. Prescott, *et. al.* (1978)



Anatomy of a PVES Experiment (E122 at SLAC)



High-power cryotarget for high luminosity.

Polarimetry

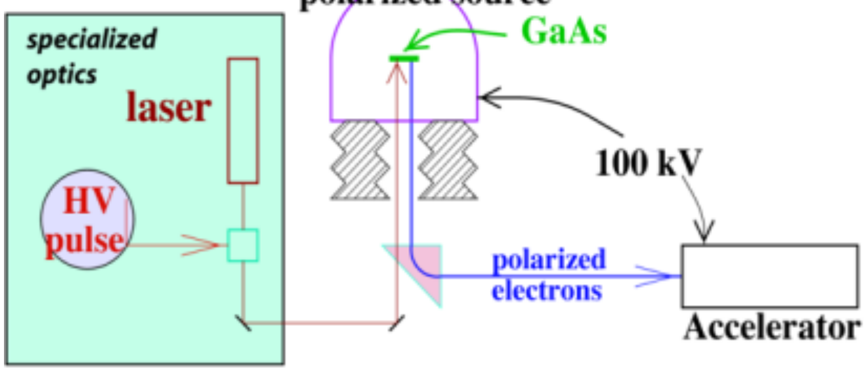
Beam Monitors to measure helicity-correlated changes to beam parameters.

Magnetic Spectrometer directs flux to bkgd-free region.

High intensity beam using new GaAs photocathode. Achieved highest P^2I (by far). Technique used ever since.

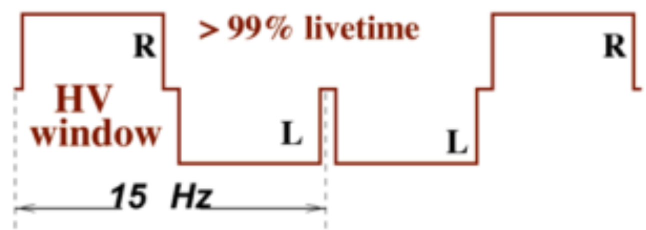
Flux Integration measures high rate without deadtime.

How to do a Parity Experiment



rapid, random, helicity flipping

Rapid, Random Helicity Flips



Measure flux F for each window

$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

Flux Integration Technique:

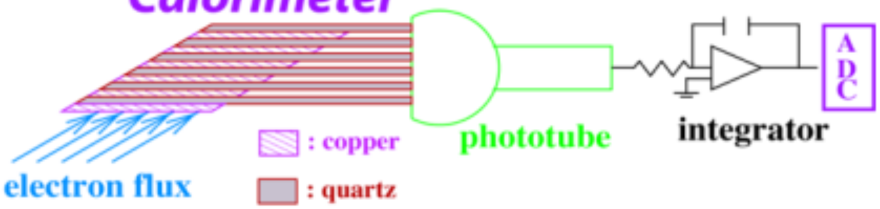
HAPPEX: 2 MHz $(A_{PV} \sim 15ppm)$

HAPPEX-II: 100 MHz $(A_{PV} \sim 1.5ppm)$

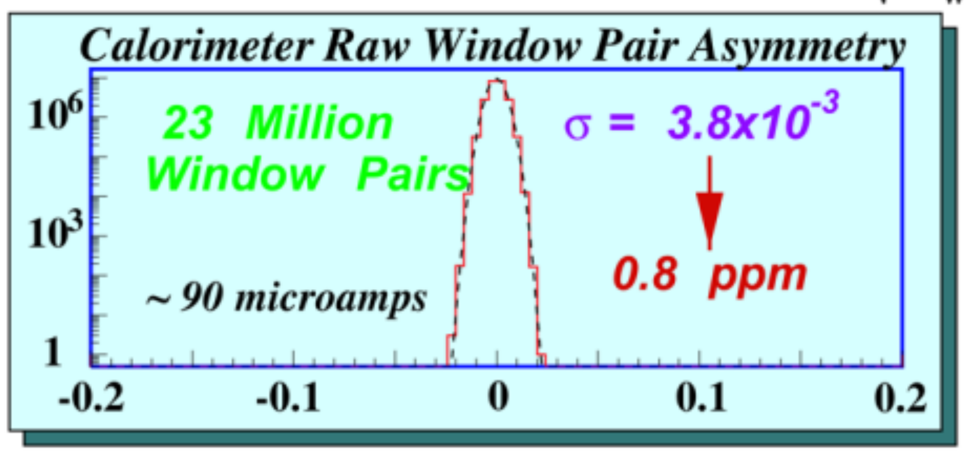
PREX: 1 GHz $(A_{PV} \sim 0.5ppm)$

PREX-II: 2 GHz $(A_{PV} \sim 0.5ppm)$

MOLLER: 150 GHz $(A_{PV} \sim 0.035ppm)$



Signal Average N Windows Pairs: $A \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}$



No non-gaussian tails to +/- 5σ

Detector signal noise dominated by electron counting statistics

3 Decades of Technical Progress

photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, *rad-hard dets*

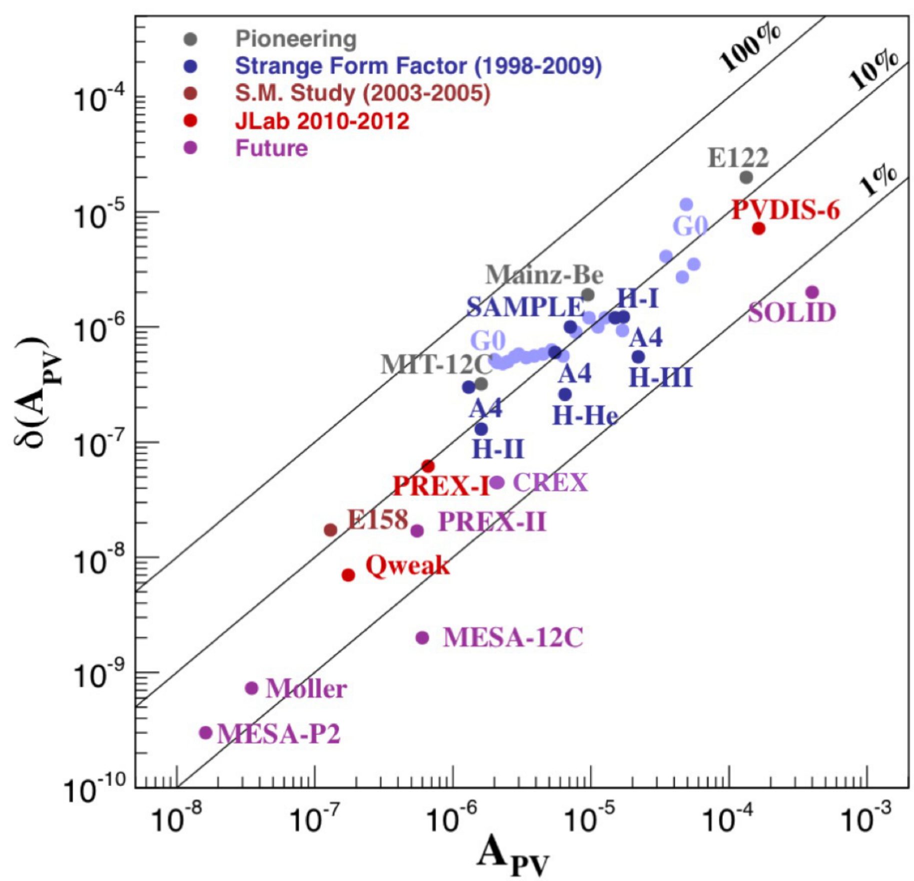
1st generation

2nd generation

3rd generation

4th generation

PVeS Experiment Summary



E122 – 1st PVES Expt (late 70's at SLAC)

Mainz & MIT-Bates in mid 80's

JLab program launched in mid 90's

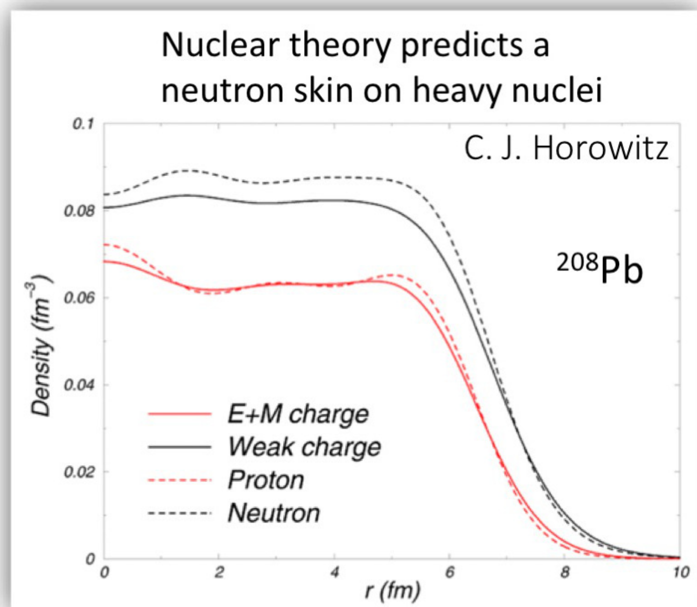
E158 at SLAC meas PV Møller scattering

MOLLER at JLab in mid 2020's

- Parity-violating electron scattering has become a precision tool!

PREX/CREX Concept

(Probing the Weak Charge Distribution of N-rich Nuclei)



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

- Neutron distribution not accessible to the charge-sensitive photon
- Z^0 couples primarily to neutron

Present knowledge of neutron distributions comes primarily from hadron scattering ⟶ model-dependent interpretation, large and uncontrolled uncertainties

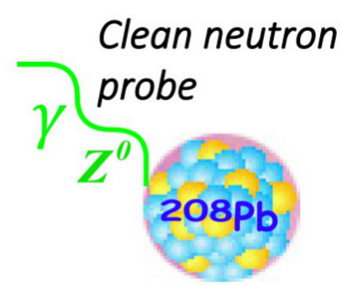
❖ Parity violation can measure neutron and weak-charge form factors *model-independently* with *statistics-dominated uncertainty*

$$M_{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$ (EM amplitude accesses charge or proton form factor)

$$M_{Weak}^{NC} = \frac{G_F}{\sqrt{2}}[(1 - 4\sin^2\theta_W)F_p(Q^2) - F_n(Q^2)]$$

$Q^p{}_W \sim 0$ $Q^n{}_W \simeq -1$

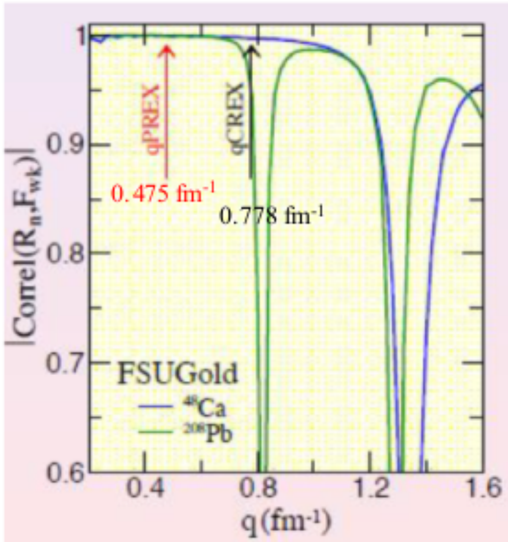
$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$



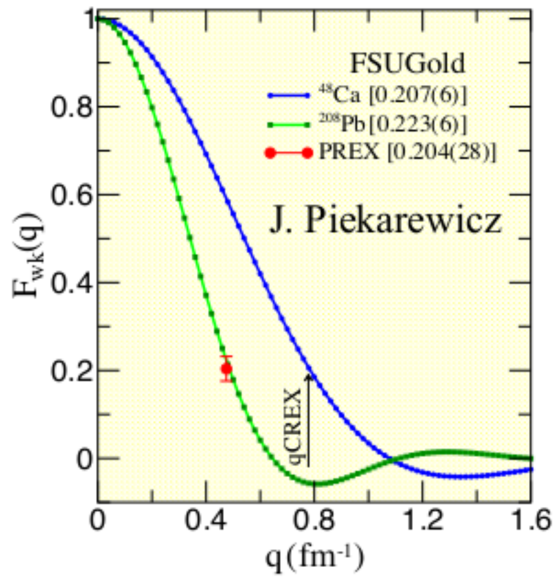
$$F_{n,p}(Q^2) = \frac{1}{4\pi}\int d^3r\; j_0(qr)\;\rho_{n,p}(r)$$

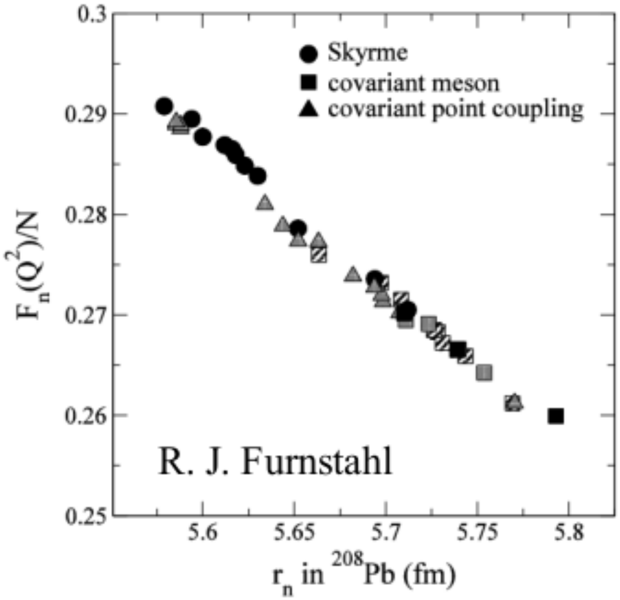
PREX/CREX Concept

At low Q^2 there is a tight correlation between R_n and $F_{wk}(Q^2)$ $\Longrightarrow$ A single measurement of $F_{wk,n}(Q^2)$ translates to a measurement of R_n (via mean-field nuclear models)



Relativistic Mean-field EDF covariant analysis

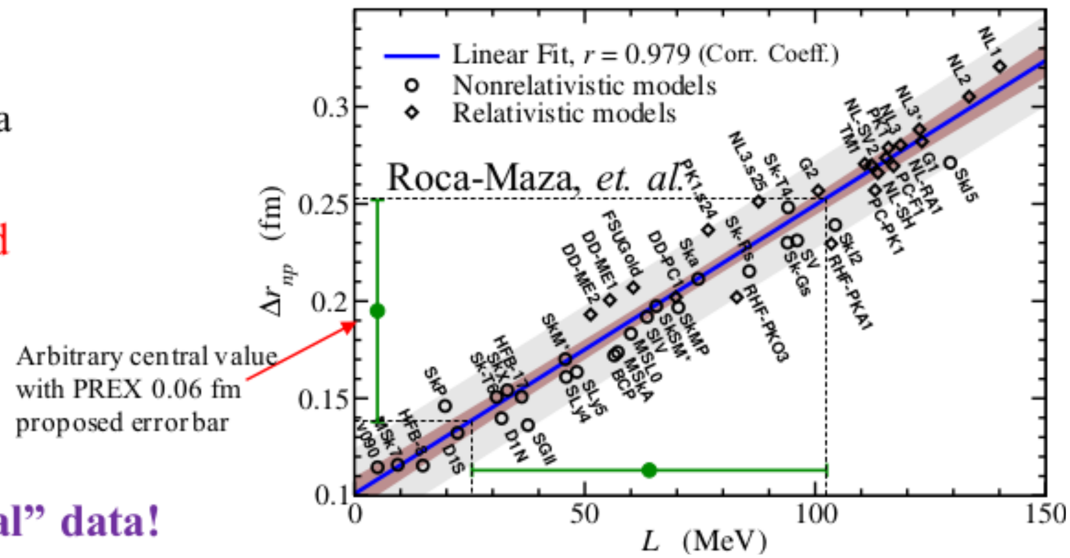




- Energy Density Functions (EDFs) characterized by a dozen free parameters that are calibrated to a host of well known properties of finite nuclei

❖ There is a strong correlation between *Rn* and the density dependence or slope of the symmetry energy,

$$L = 3\rho_0 \left(\frac{\partial S}{\partial \rho}\right)_{\rho_0}$$



At present, L is not well constrained by "Real" data!

PREX/CREX Overview

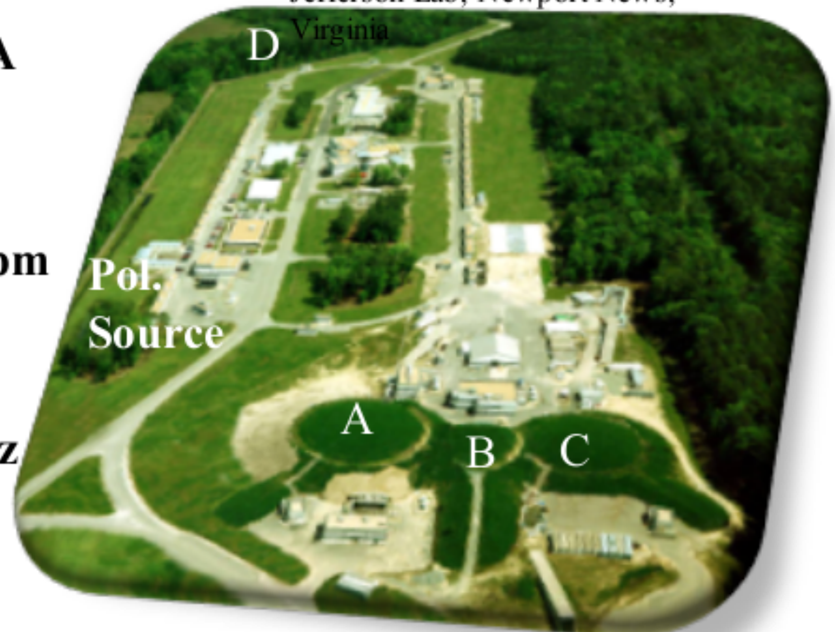
PREX/PREX-II:

- **0.95 GeV e⁻ beam, 50-70 μA**
- **0.5 mm thick ^{208}Pb target**
- **5° scattered electrons**
- **Q^2 =0.0088 GeV², A_{PV}~0.5ppm**
- **680 hours, ~35M pairs**
- **δA_{PV} ~ 15 ppb (3%)**

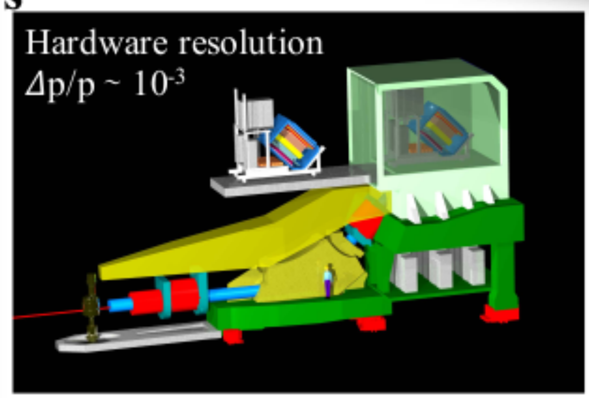
CREX:

- **2.22 GeV e⁻ beam, 150 μA**
- **5 mm thick ^{48}Ca target**
- **5° scattered electrons**
- **Q^2 =0.037 GeV², A_{PV}~2ppm**
- **780 hours, ~40M pairs**
- **δA_{PV} ~ 80 ppb (4%)**

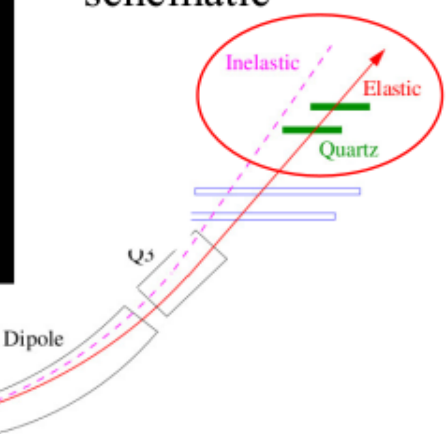
- **high polarization, ~89%**
- **helicity reversal at 240&30 Hz**
- **New thin quartz detectors**

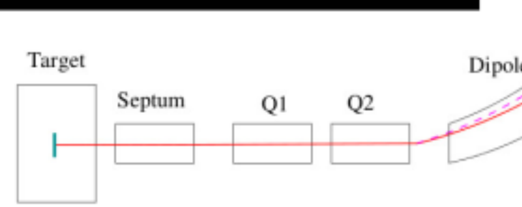


Symmetric High Resolution Spectrometers



HRS and optics schematic

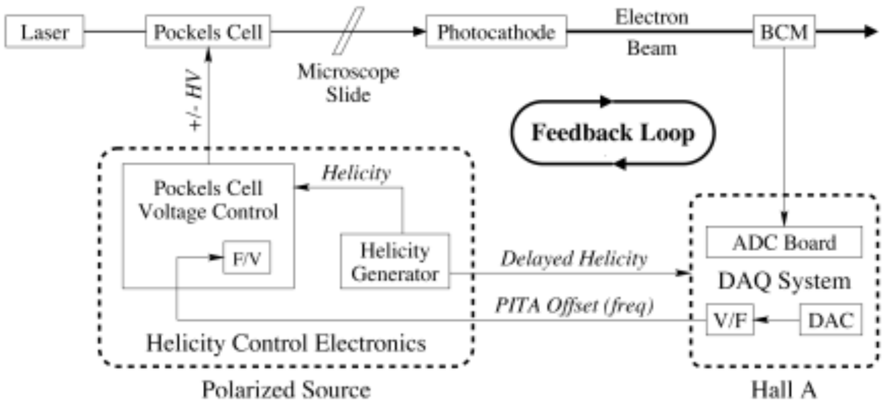




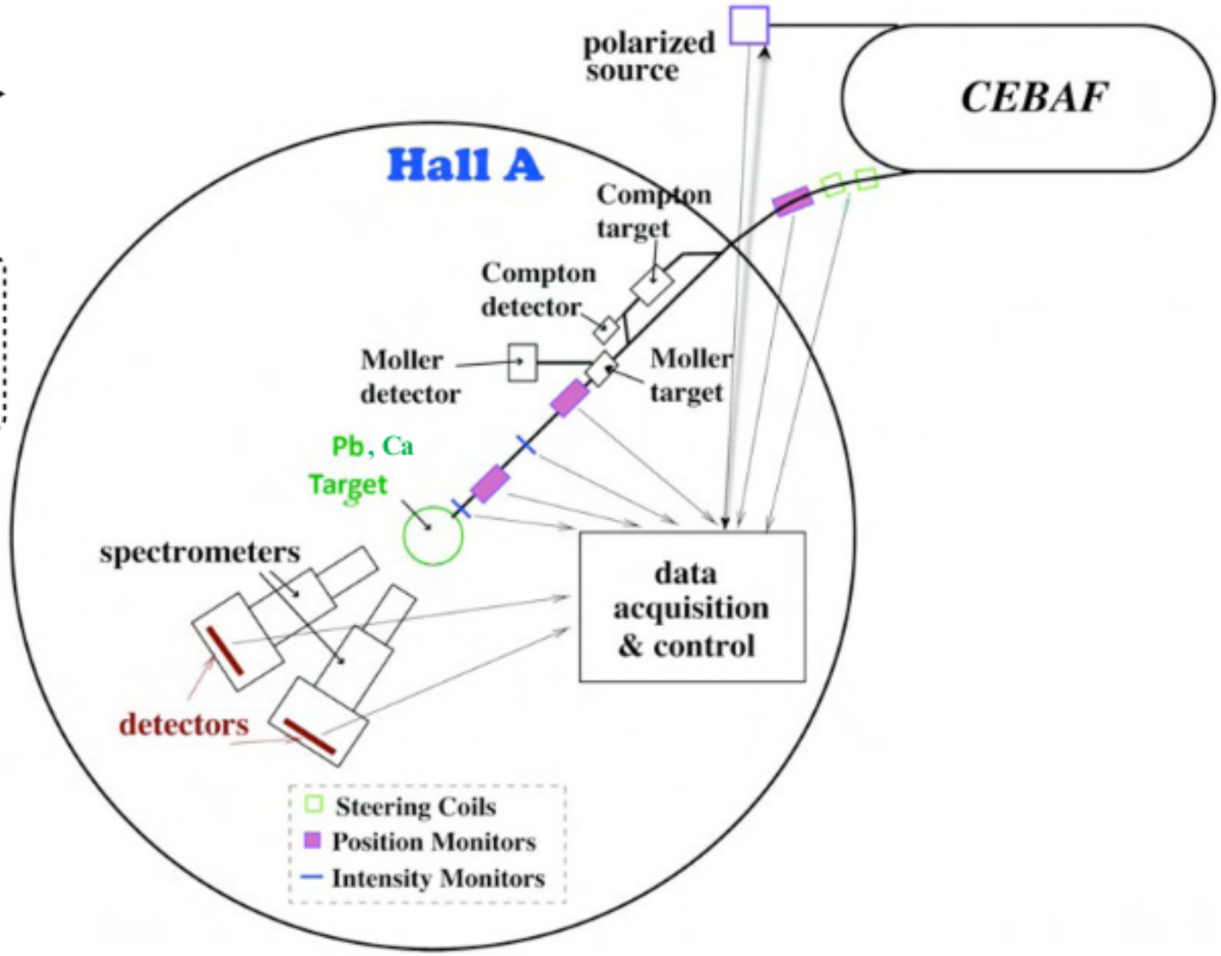
"Parity Quality" Beam Monitoring

(normalization and false-asymmetry systematics control)

- Precision source-laser alignment



- Active feedback on charge asymmetry
- Precision beam position monitoring with active calibration of detector slopes (via beam modulation)
- Two independent methods for "slow" helicty reversals:
  1. Insertable half-wave plate
  2. Double Wien filter
- Continuous beam polarization monitoring with Compton polarimeter



Hall A Parity Quality Beam Monitoring Schematic

PREX-I Systematic Errors

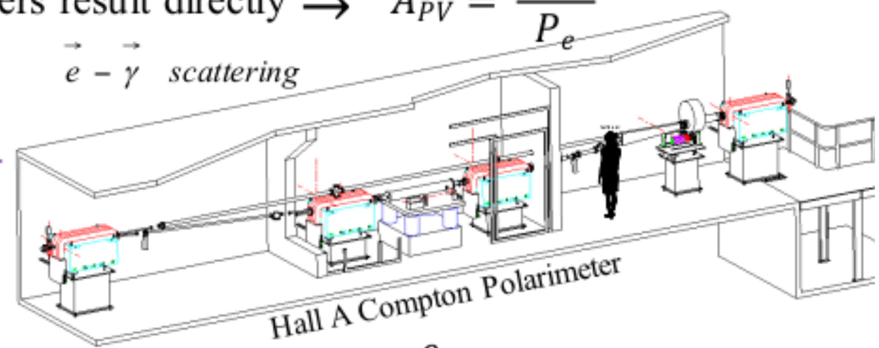
PREX goal for ~ 2% total systematic error achieved!

Systematic Error	Absolute (ppm)	Relative (%)
Polarization	0.0083	1.3
Detector Linearity	0.0076	1.2
Beam current normalization	0.0015	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2	0.0028	0.4
Target Backing	0.0026	0.4
Inelastic States	0	0
TOTAL	0.0140	2.1

Crucial normalizations:

- **Polarization**: enters result directly $\longrightarrow$ $A_{PV} = \frac{A_{raw}}{P_e}$

Use Compton Polarimetry for non-invasive, continuous measurement



- **4-momentum transfer**: $Q^2 = 4EE' \sin^2\frac{\theta}{2}$

Calibrations:

E (beam energy): spin precession in the machine

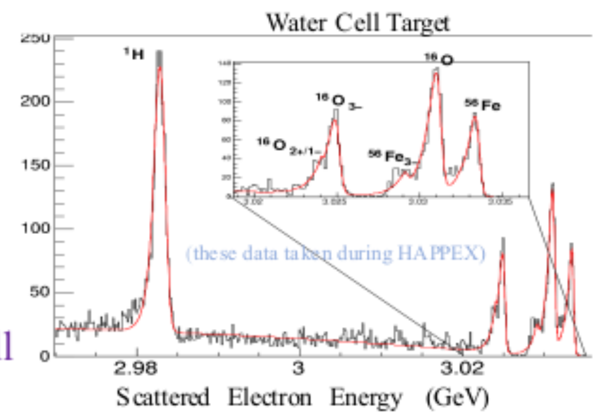
E' (scattered energy): NMR probe in HRS B-field

θ (scattered angle): surveyed to ~1 mrad and measured to 0.2% absolute using water cell target

Absolute angle calibration via nuclear recoil variation

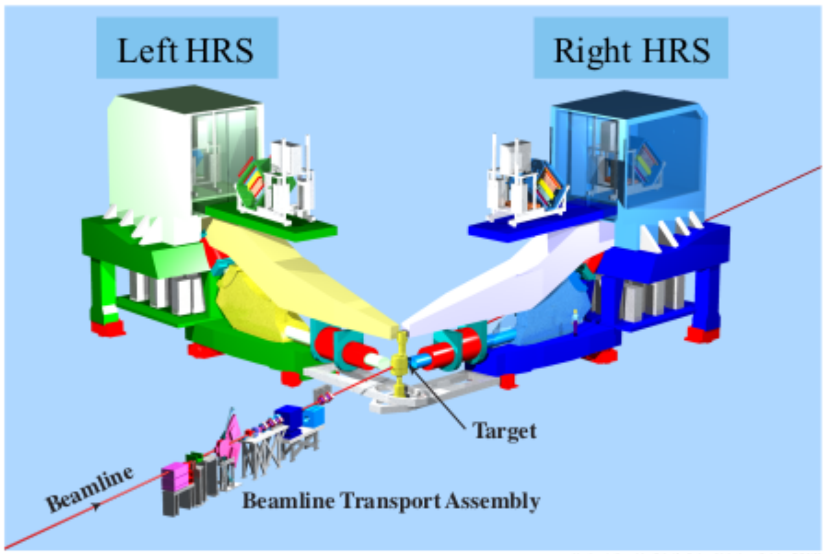
$$\delta E_{\text{loss}} \approx \frac{\theta^2}{2}\frac{E^2}{M_A}$$

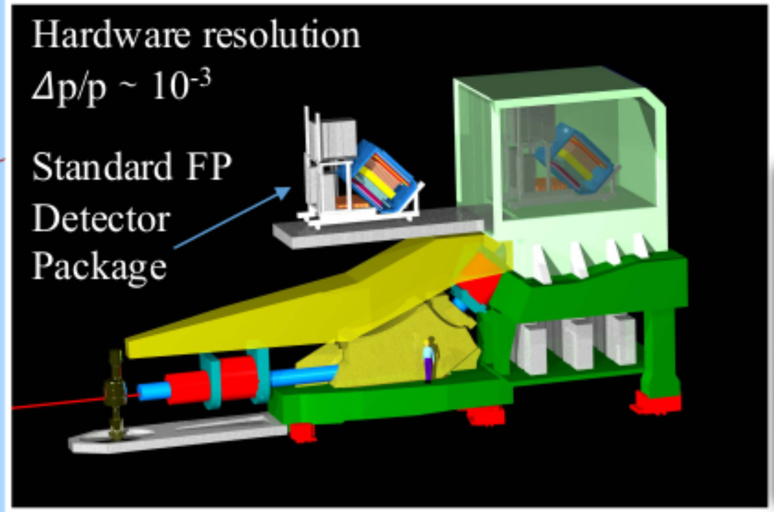
Q^2 distributions obtained by dedicated low-rate runs with tracking detectors triggered on quartz pulse-height (0.4% overall error on Q^2)



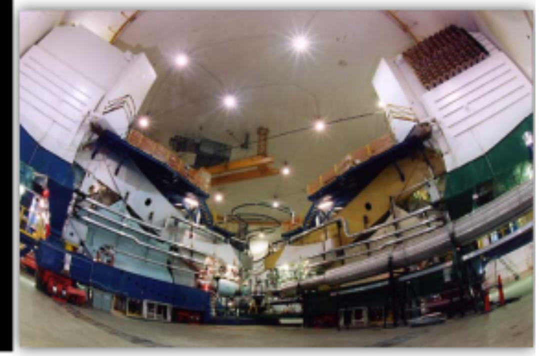
Integrating Detector Focal Plane for PV Experiments: HAPPEX through PREX-II/CREX

Hall A





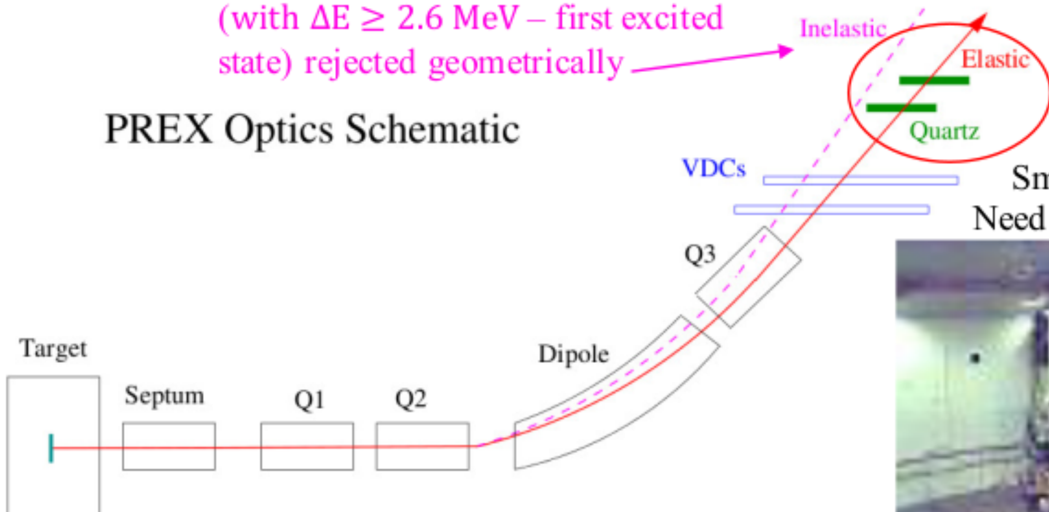
Symmetric High Resolution Spectrometers



- Standard focal plane (FP) detector packages are removed during high flux PV experiments
- Specialized focal plane detectors installed and positioned to **intercept only elastically scattered electrons** – uses precision optics and hardware resolution
- Integrated PE yields from detectors are proportional to electron flux

- For PREX, inelastic events (with $\Delta E \geq 2.6$ MeV – first excited state) rejected geometrically

PREX Optics Schematic



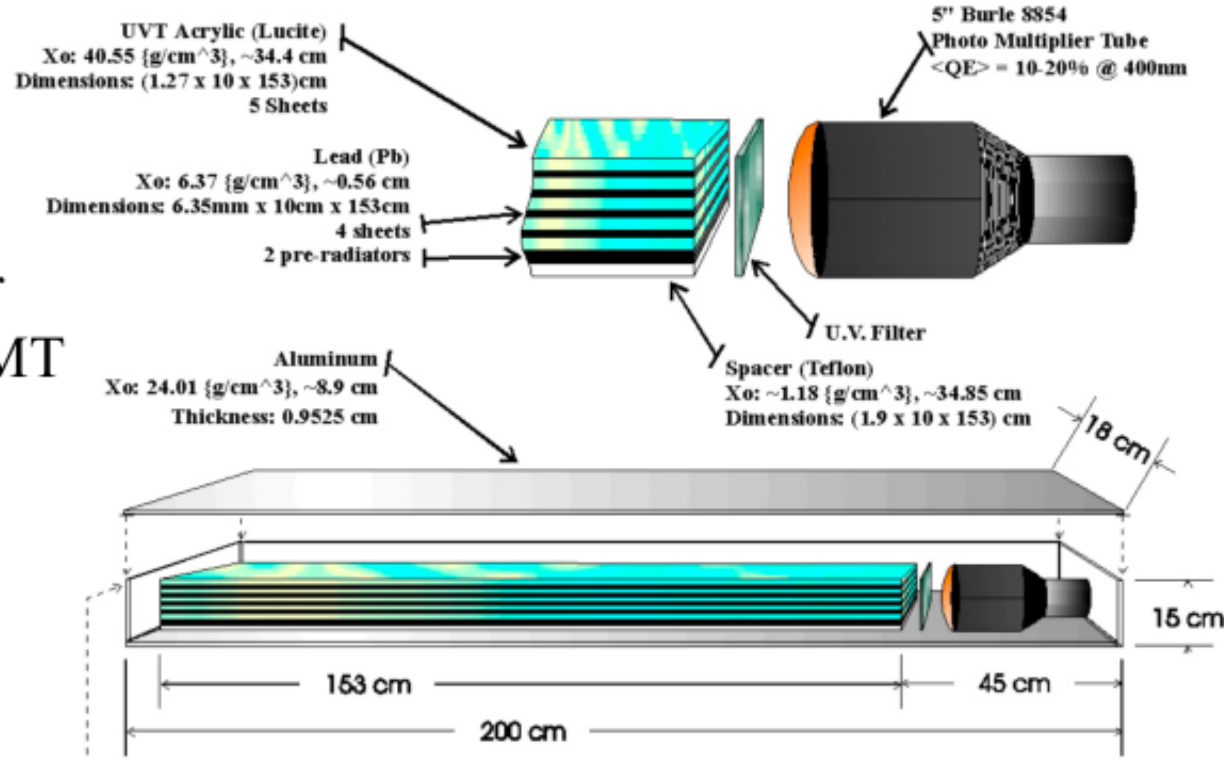
- PV Detectors positioned in FP inside shielded HRS hut

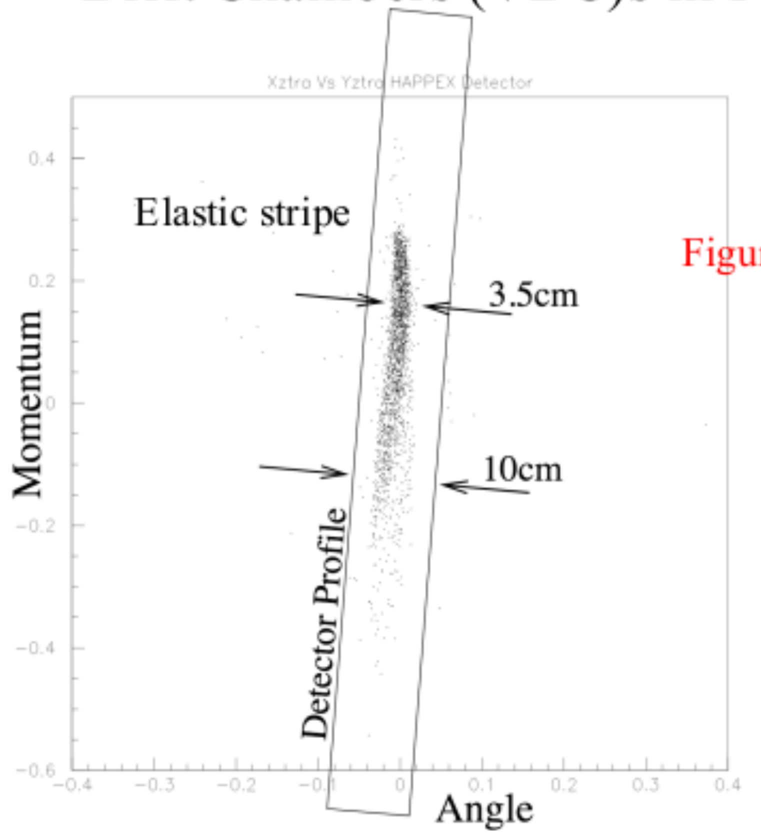
Smallest angle: $\pm 12.5^{\circ}$
Need Septum to get to $\pm 5.0^{\circ}$

Requirements for PVES Integrating Detectors

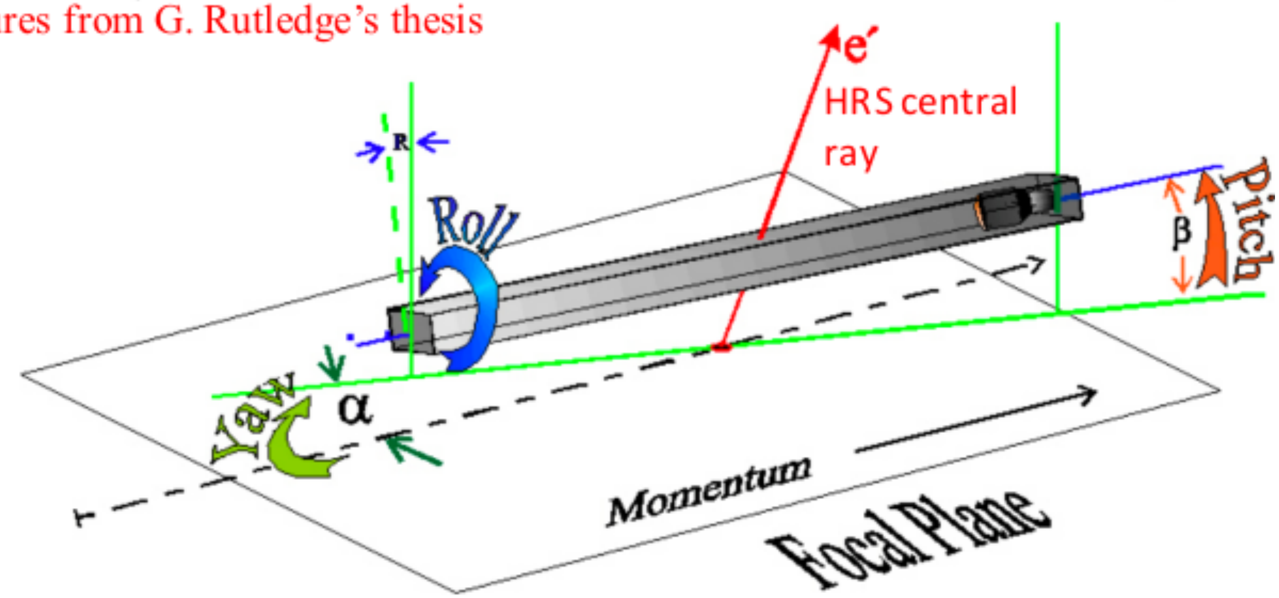
- Radiation hardness – active medium must give consistent response under extreme and prolonged flux exposures
- Should count individual electrons with good ($\sim 20\%$) resolution – to minimize statistical error inflation
- Photo-sensitive device must give highly linear response (at 0.3% level for PREX-II/CREX) – so care must be taken to understand photo-cathode light levels and anode currents during integration mode A_{PV} measurements

- Main integrating detector for HAPPEX, H-II, H-He, H-III
- 5 layer Pb-Acrylic calorimeter 1.5 m long with 5 inch Burl PMT
- Installed just above Vertical Drift Chambers (VDC)s in FP

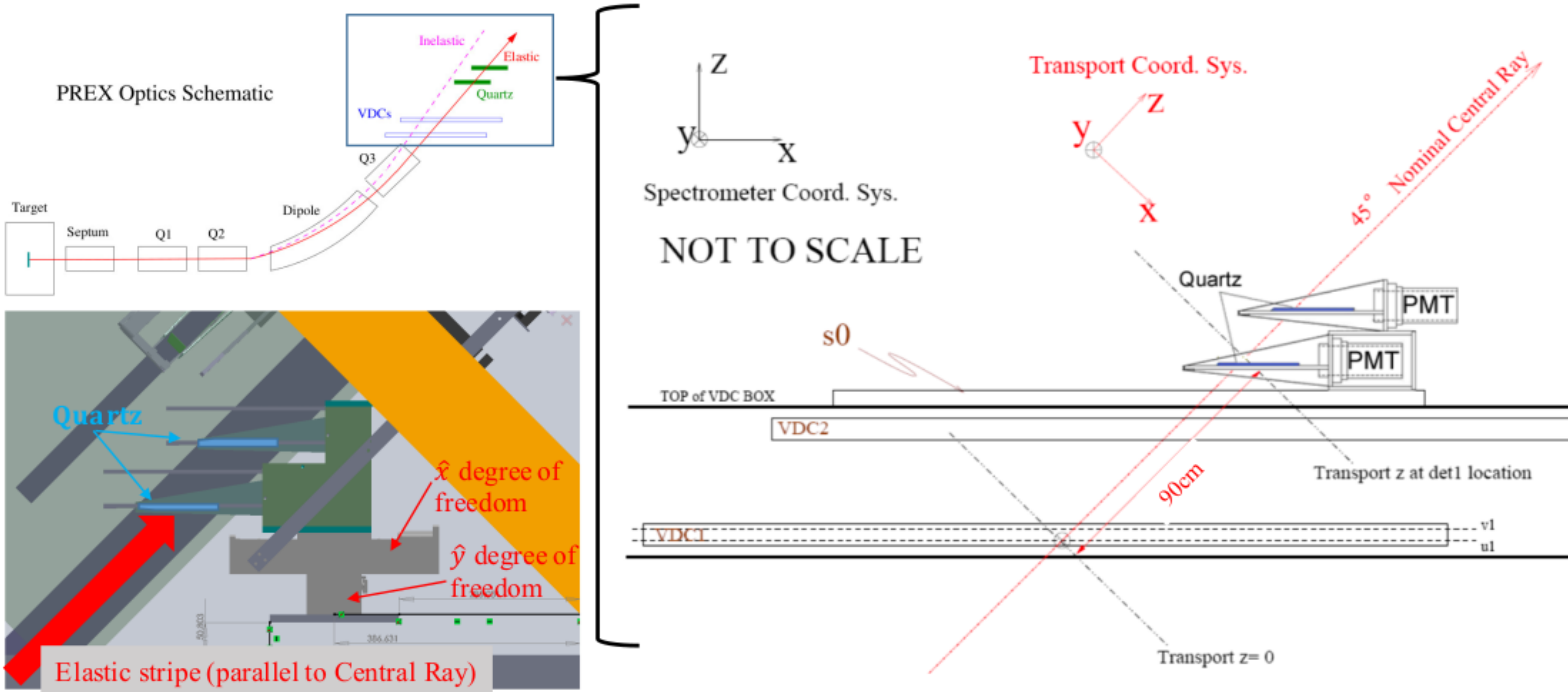




Figures from G. Rutledge's thesis



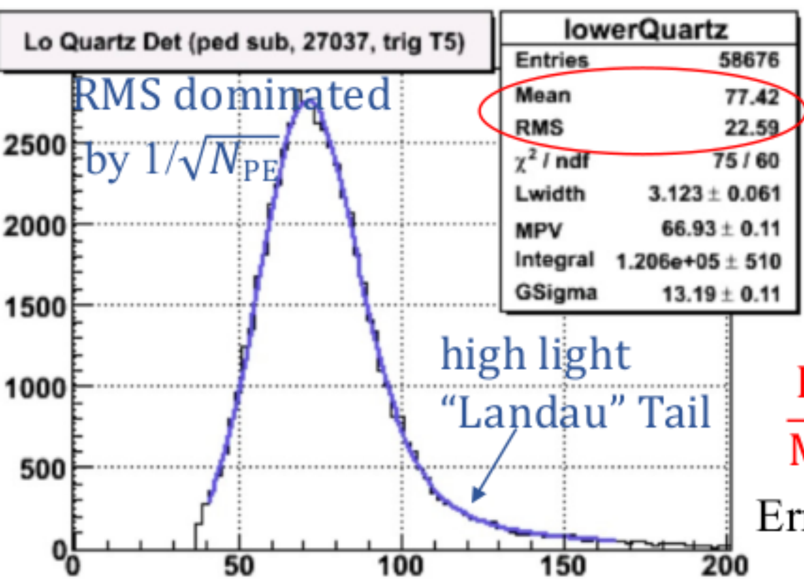
Main Integrating Detector for PREX-I ("thin" quartz Tandem Detector)



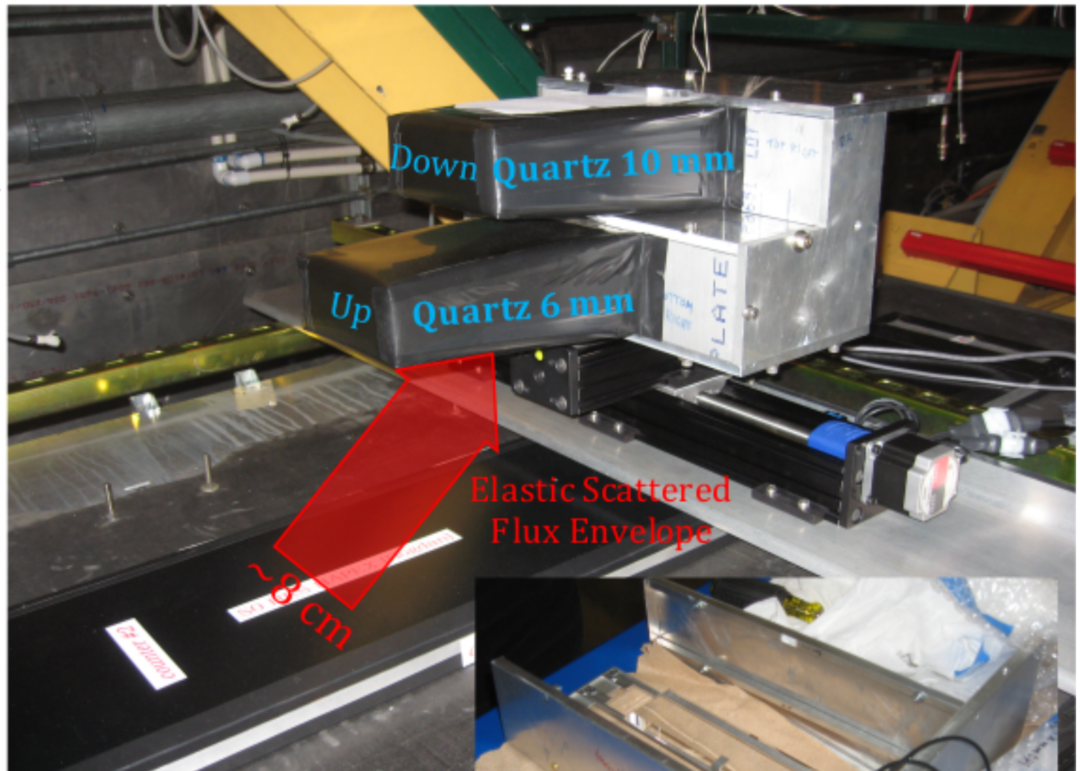
- Uses rad-hard, optically polished fused silica (quartz) tiles for Cherenkov active medium
- Scattered electrons traverse quartz at nominal angle of 45 degrees
- Aluminum air-core (specular reflector) light guide directs Cherenkov light to 2 inch PMT
- Linear translation stages provide precision positioning in "dispersive" $\hat{x}$ and "transverse" $\hat{y}$

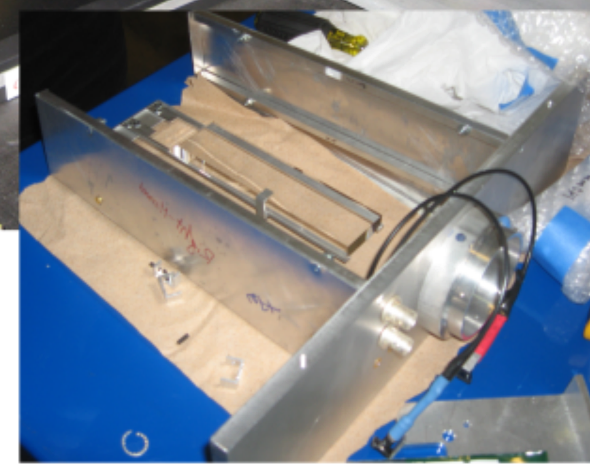
Main Integrating Detector for PREX-I ("thin" quartz Tandem Detector)

- Quartz geometry: 160 mm by 35 mm by 6 mm (upstream) and 10 mm (downstream)
- Conservative Design for PREX-I: orientation between pmt, quartz and central ray gives consistent light yields…but relatively low overall yield and okay resolution…



Detector ADC pulse-height distribution (acquired during "counting-mode" calibration runs)



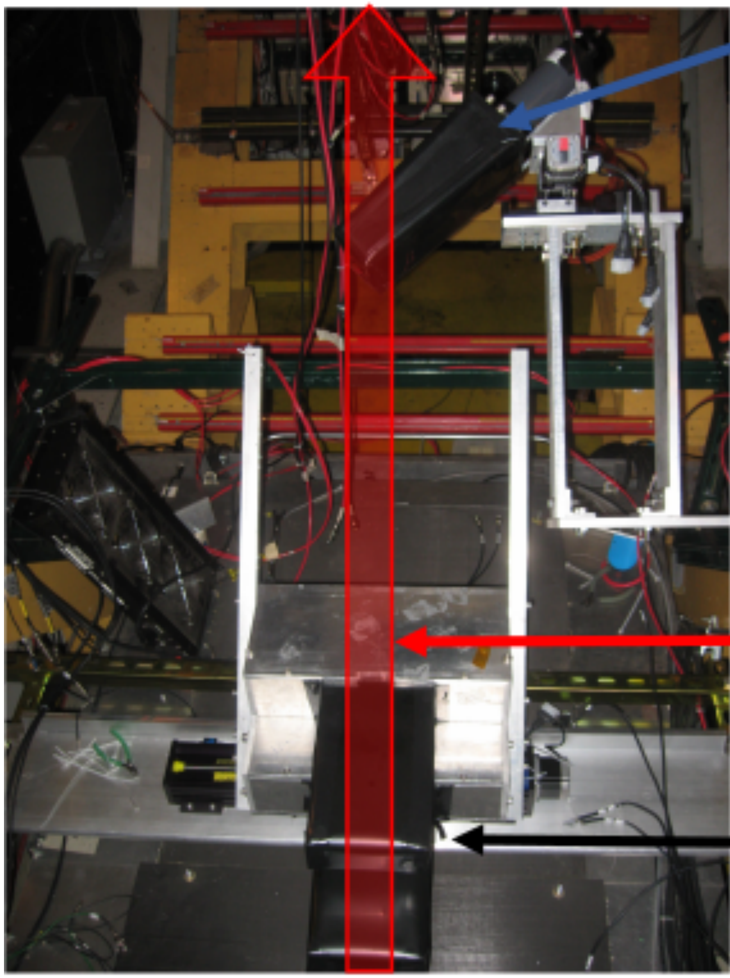


$$\frac{\text{RMS}}{\text{Mean}} = 29\% \text{ resolution}$$

$$\text{Error Inflation} = \sqrt{1 + (\text{RMS/Mean})^2} = 1.04$$

So A_{PV} statistical error increases by ~4%

Integrating Detectors for PREX-I (Tandem and A_T Dets)

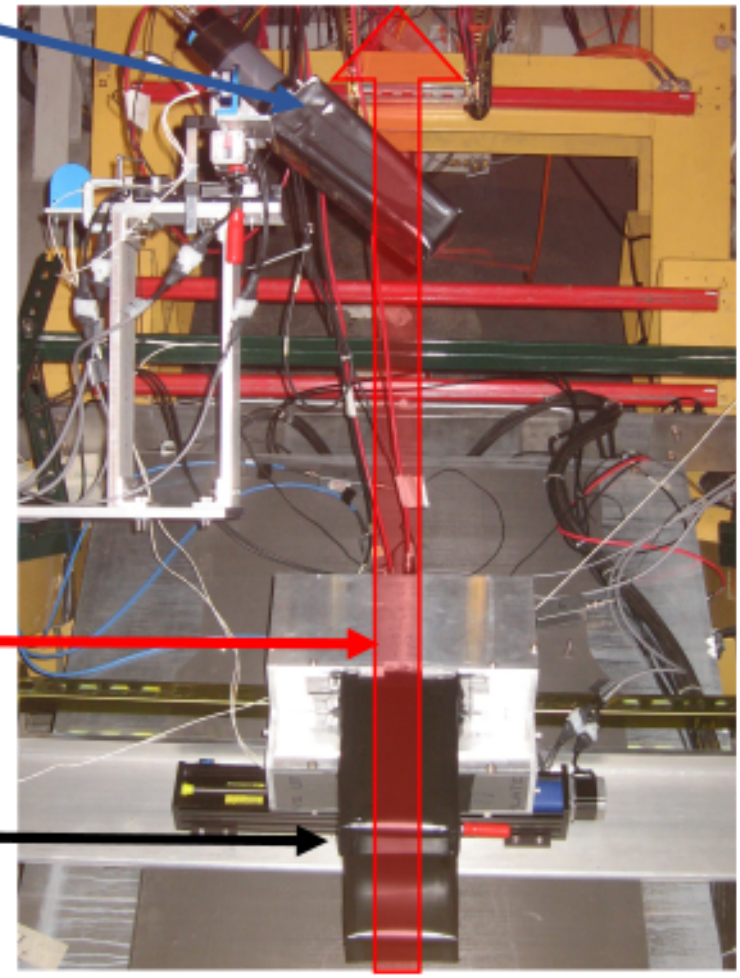


A_T Detectors

- Monitor any residual transverse beam polarization
- Positioned to intercept larger OOP scatters (enhancing analyzing power)

Elastic scattered flux envelopes

Main Tandem Detectors

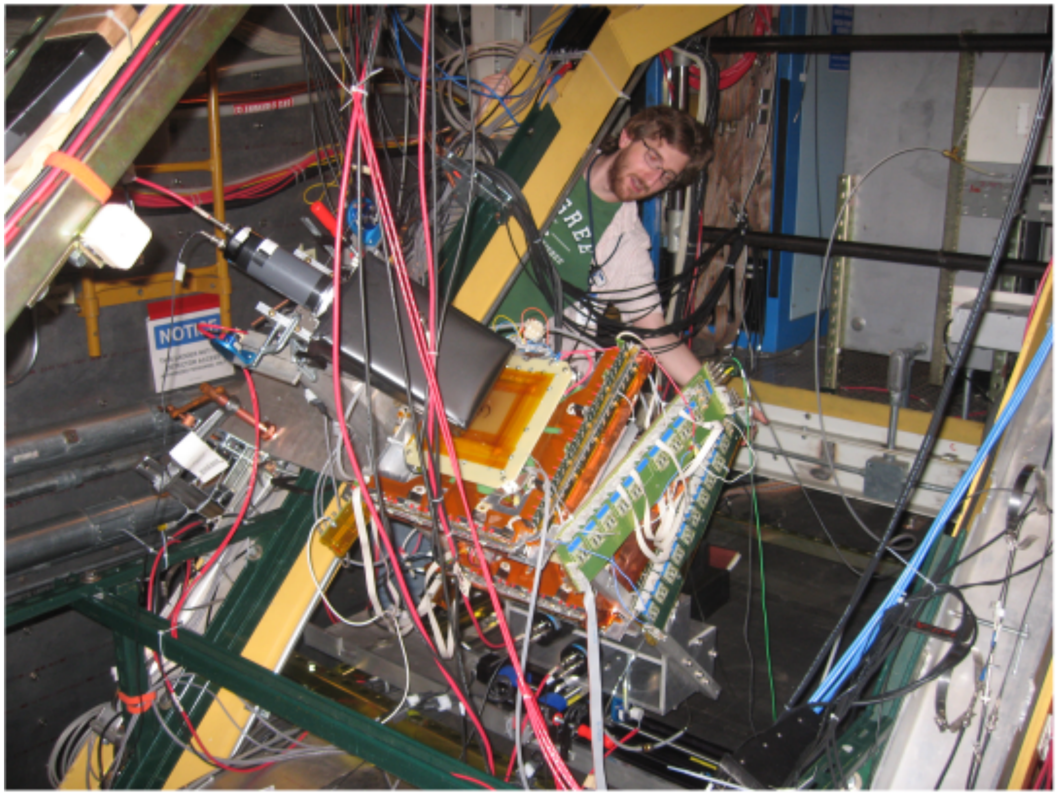


Left HRS

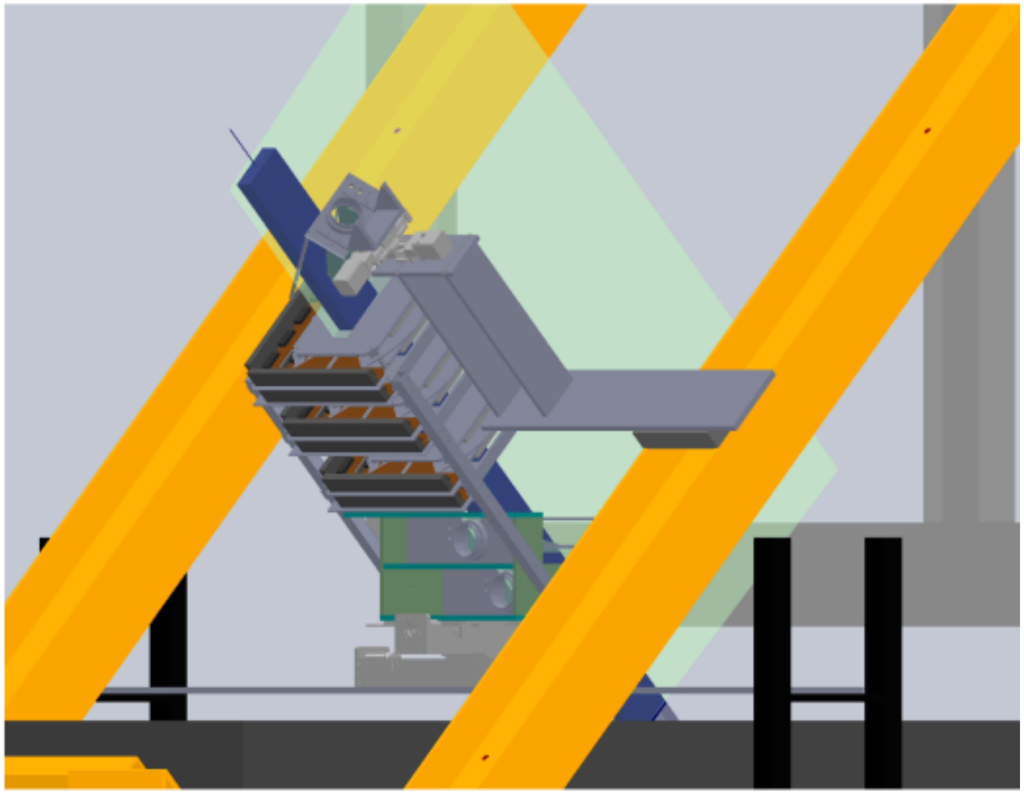
Views along dispersive $\hat{x}$

Right HRS

Integrating Detectors for PREX-I (Tandem Dets, A_T Dets and GEMs)



Left HRS Photo (2010)



Right HRS CAD

- First GEM tracking system to be used at JLab was during PREX-I; system was noisy and cumbersome
- Each HRS used three triple GEM chambers; each 10 by 10 cm^2 active area
- These supplement VDCs during high rate Q^2 and optics calibration runs

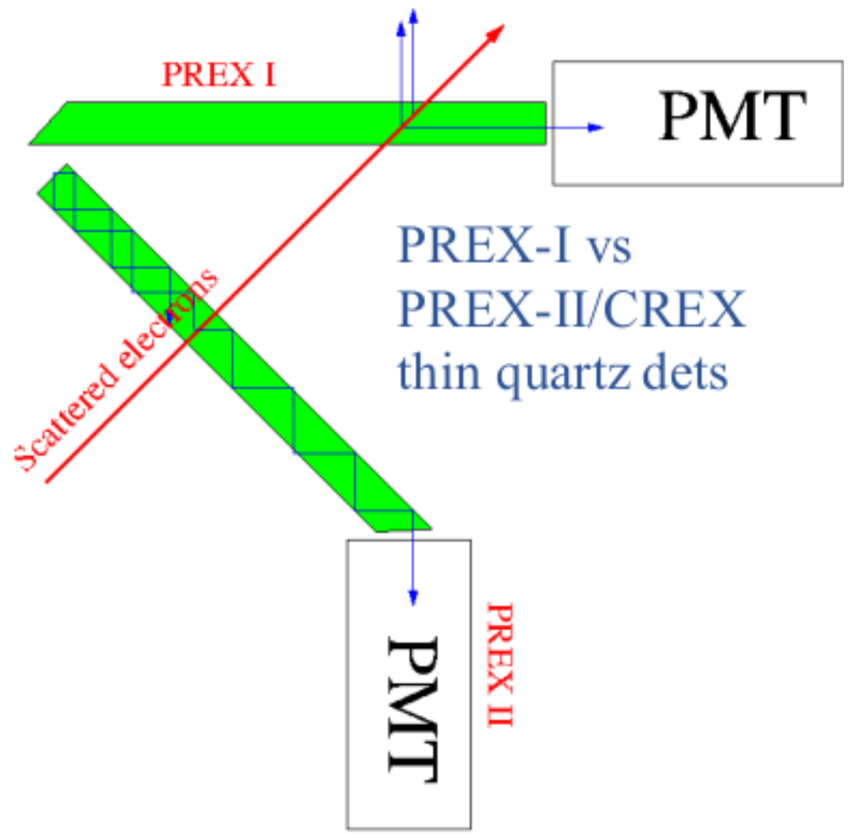
Integrating Detector Design change between PREX-I and PREX-II/CREX

- Orientation between quartz, pmt, and scattered electron changed
  - Allows capture of both sides of Cherenkov cone – instead of losing one side due to critical angle
  - Use TIR inside quartz as light guide – instead of aluminum air-core reflector to direct light to PMT
  - Less sensitivity to extra noise due to delta-ray production

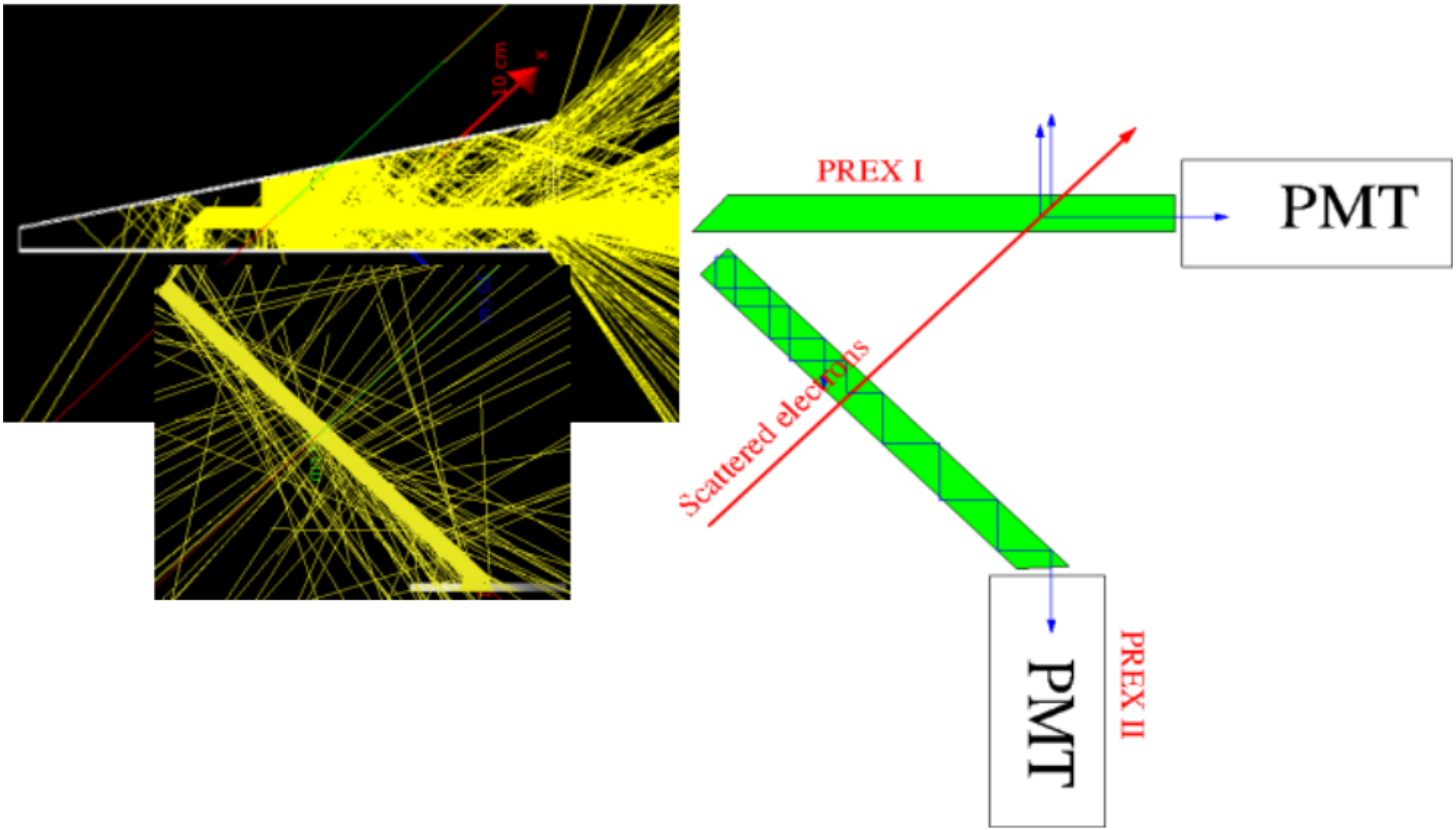
- This change effectively doubles light yield and improves RMS by $\sqrt{2}$

- However, there is more light yield variation for electrons with different incident angles

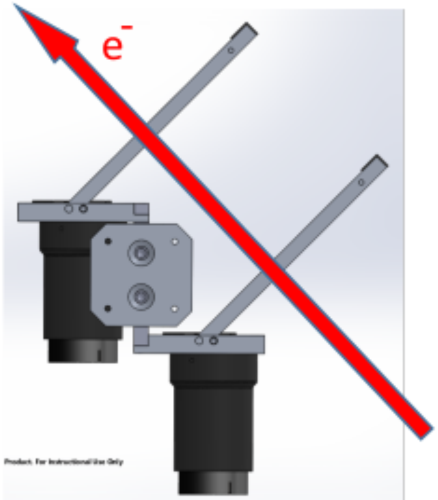
❖ Design validated with G4 optical Monte Carlo benchmarked to “real” Testbeam data

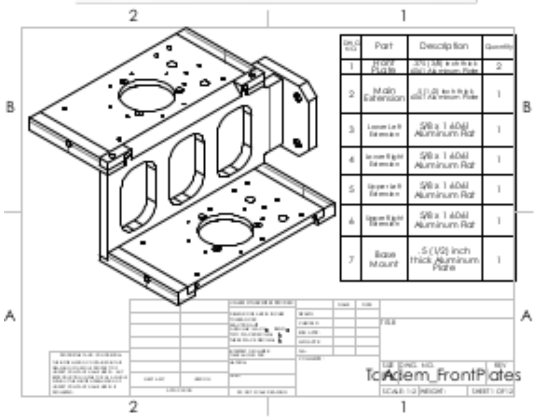


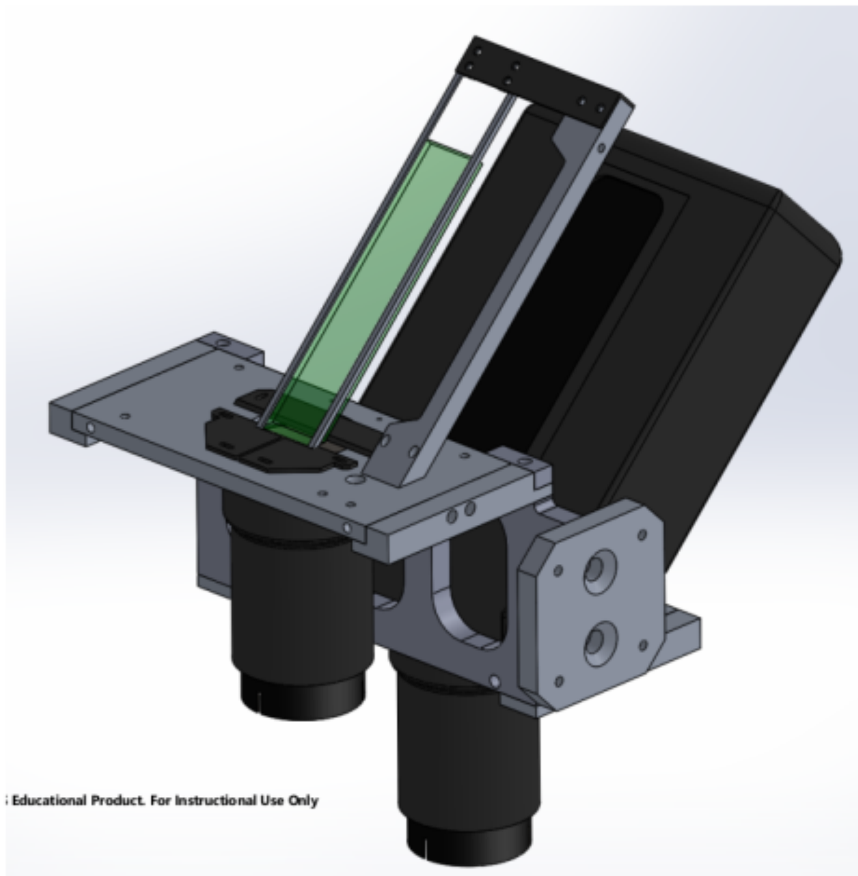
G4 Event Visualizations: PREX-I vs PREX-II/CREX

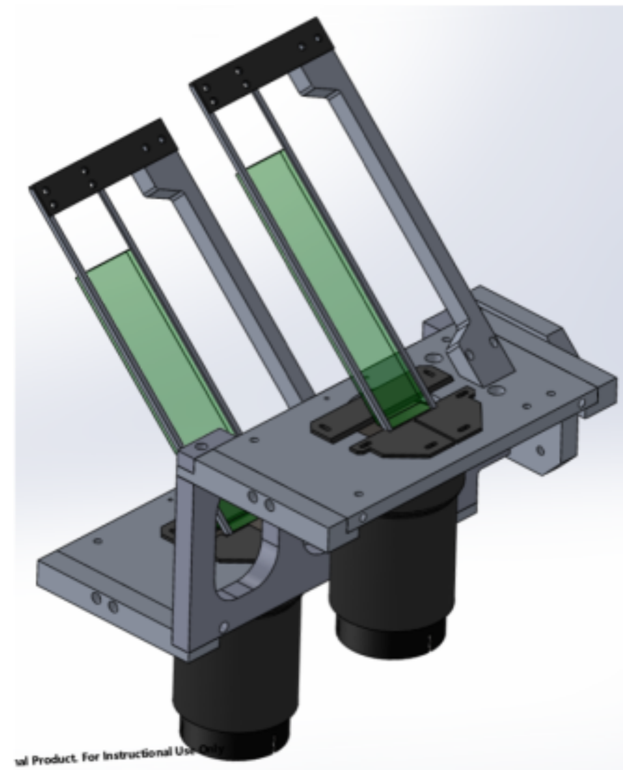


Main Integrating Detectors for PREX-II/CREX





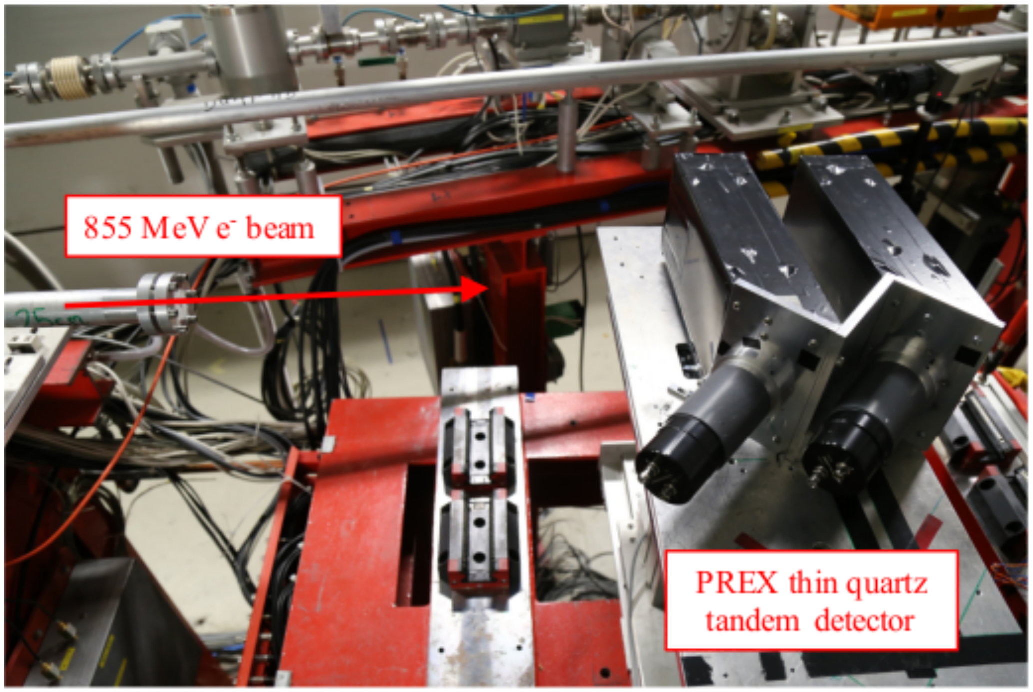


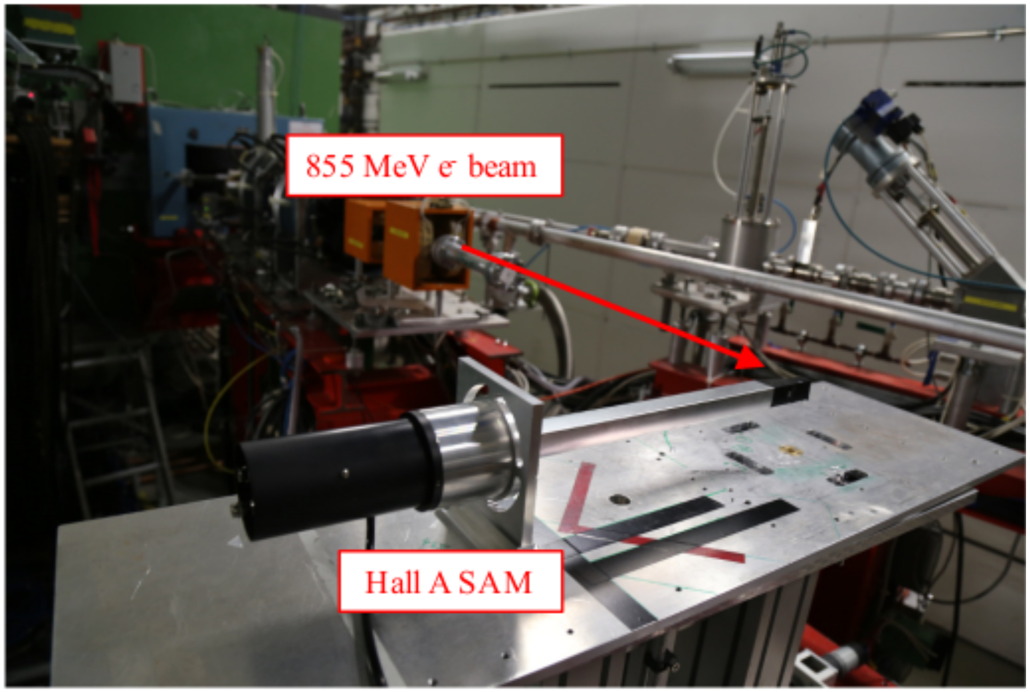


- Both Left and Right HRS main detectors are assembled and ~ready to go
- PREX will use 5 mm thick quartz for all detectors
- CREX will use 6 mm thick quartz upstream and 10 mm downstream

MAMI testbeam May 24-27, 2016

- ¾ shift total for PREX-II/CREX and SAM

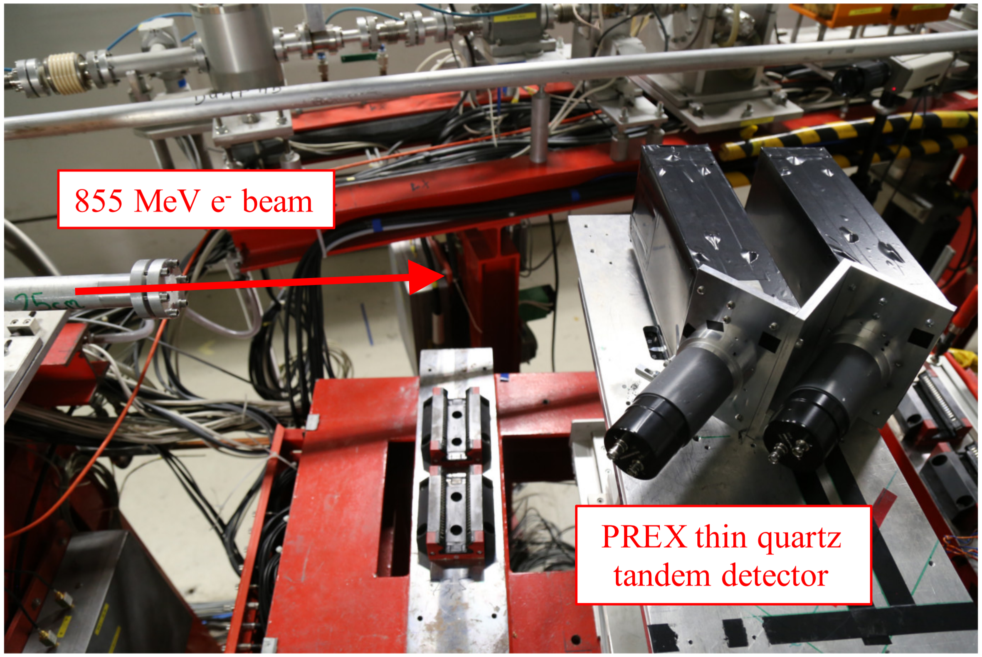


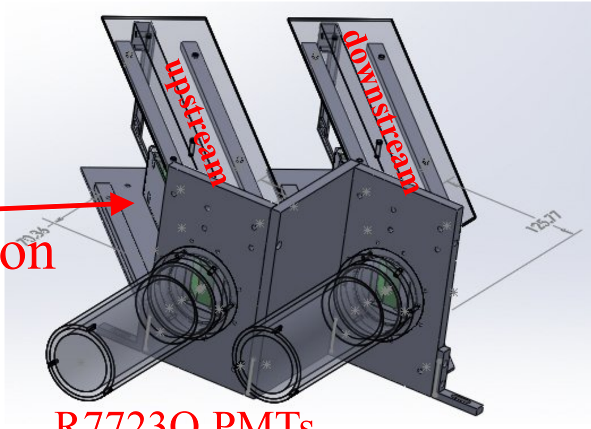


- 6mm and 10mm Tandem mount
- Near normal e^- incidence

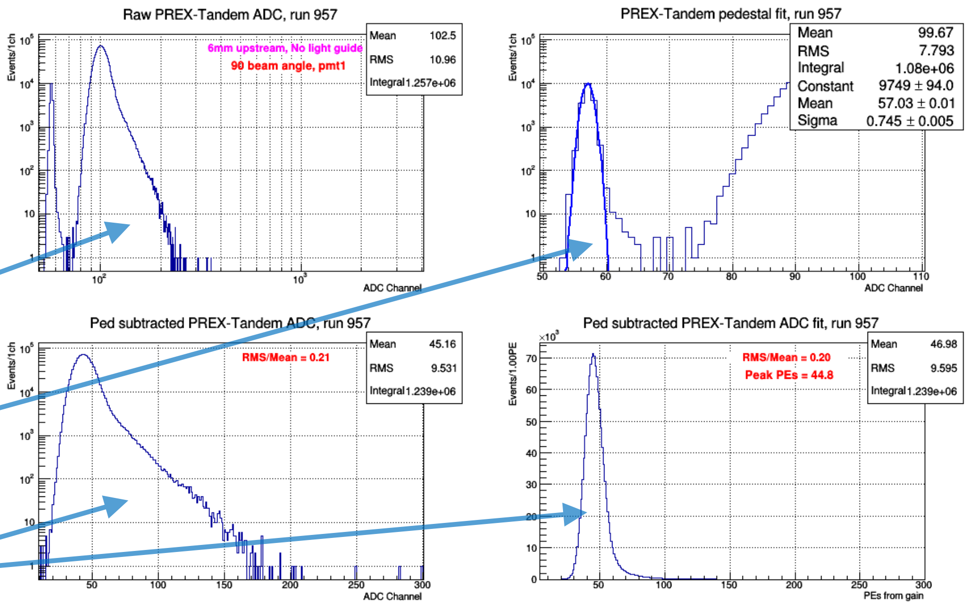
- v3 (2015) SAM detector PE yield studies:
  - Miro27 and UVS light-guides
  - With and without 1cm tungsten pre-radiator

PREX-II/CREX Tandem Detector Tests

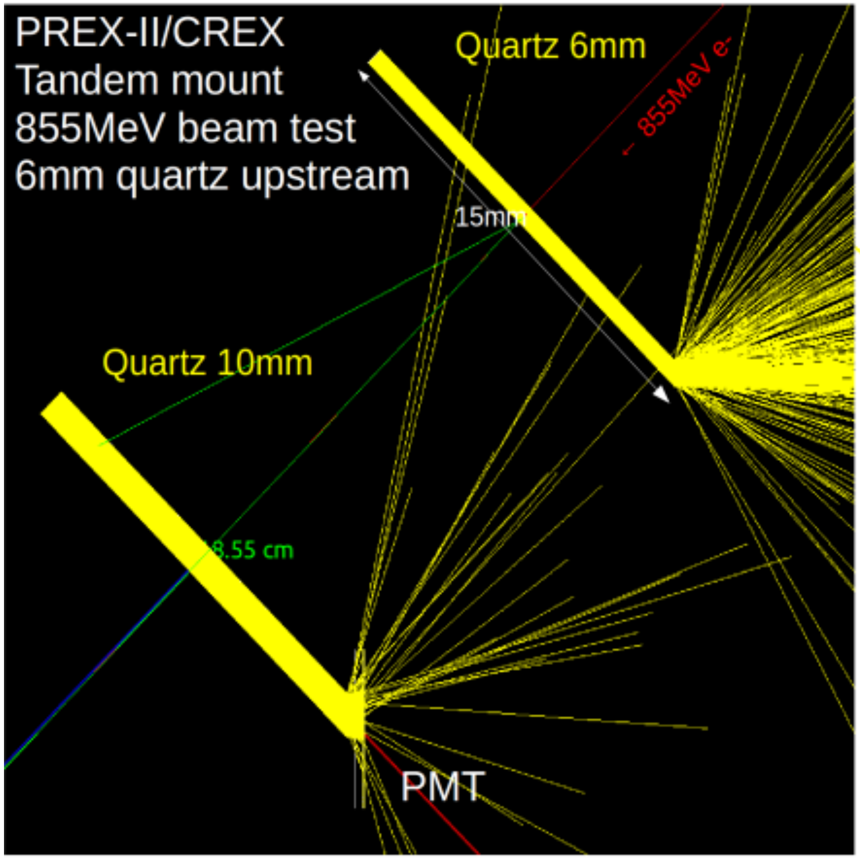


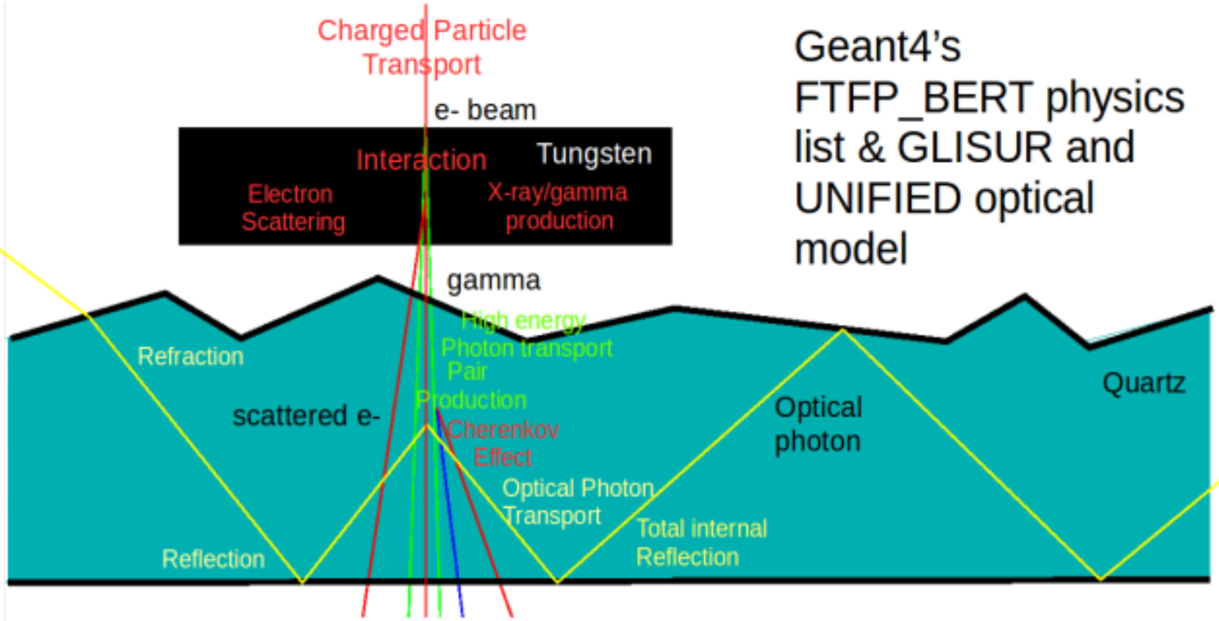


- Quartz spacing same as for rotary tandem mount (~16 cm)
- Used two Hamamatsu R7723Q pmts
- Quartz is wrapped with 1 mil Al. Mylar
- Took runs for each quartz thickness upstream and downstream
- Example raw data, pedestal fit, and ped-corrected ADC and PE dists



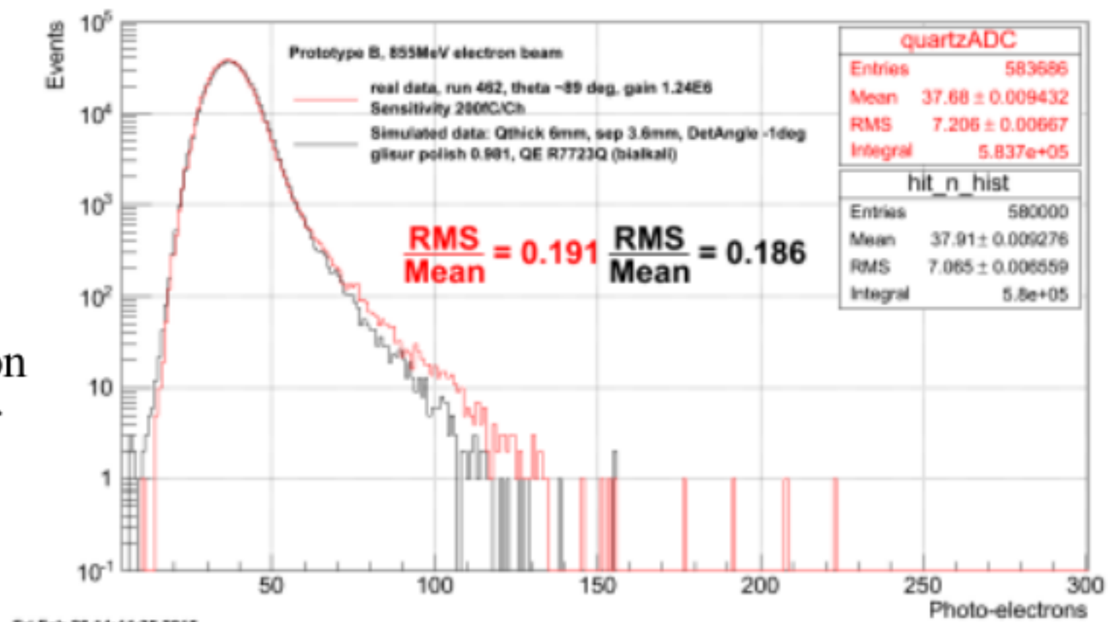
Optical Monte Carlo (qsim) Benchmarking





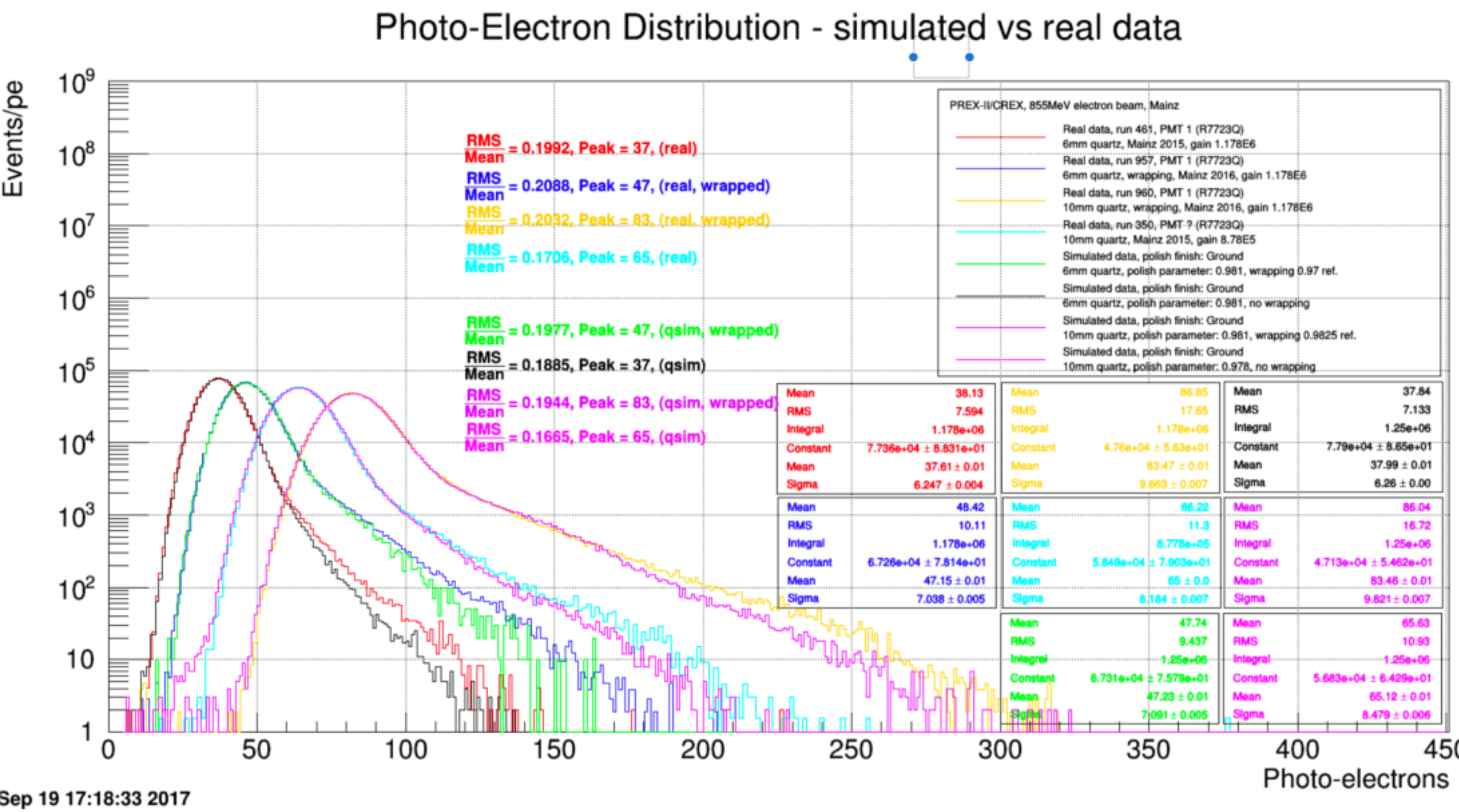
Geant4's FTFP_BERT physics list & GLISUR and UNIFIED optical model

Photo-Electron Distribution - Prototype B Detector

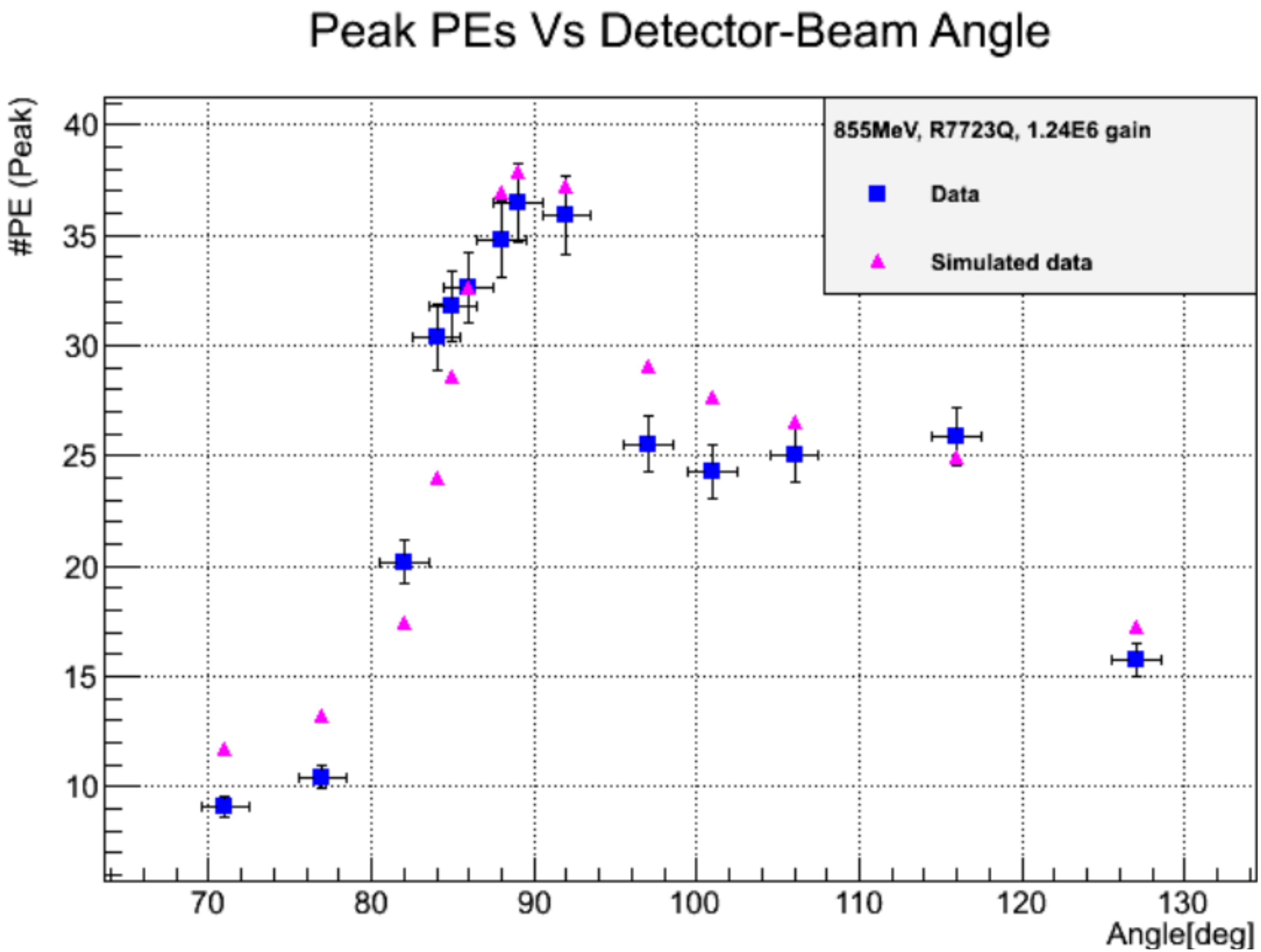


- Detailed geometry; pmt quantum efficiency sampling; refractive index dispersion; light attenuation in quartz; photo-cathode attenuation and reflection; quartz ground polish parameter
- Glisure ground polish parameter is tuned to make agreement between simulation and data

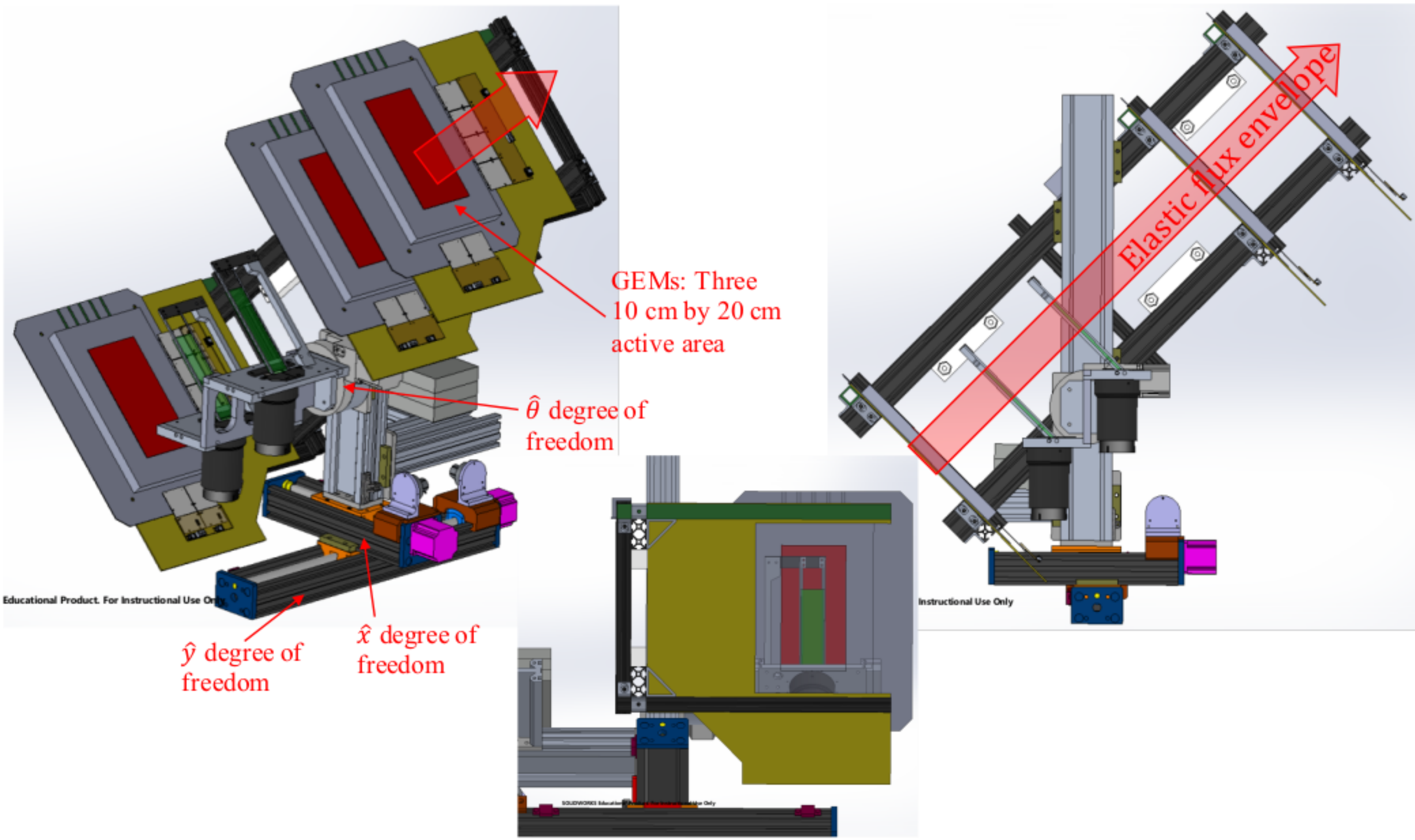
Optical Monte Carlo (qsim) Benchmarking



Optical Monte Carlo (qsim) Benchmarking

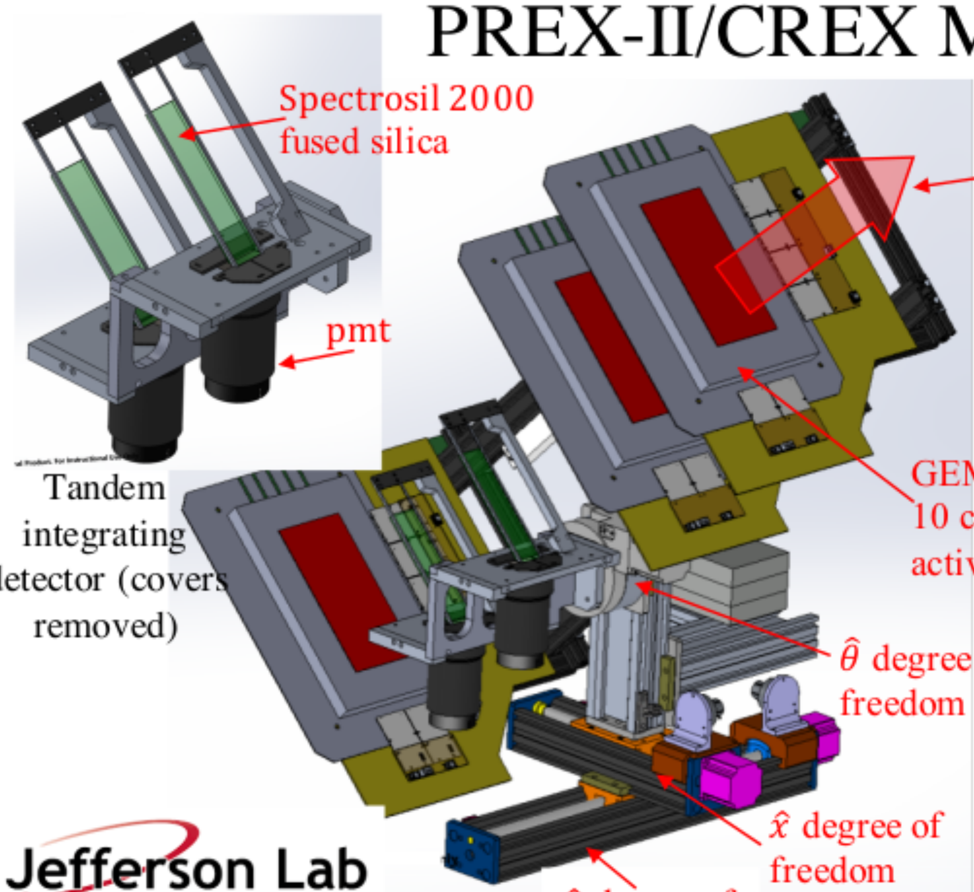


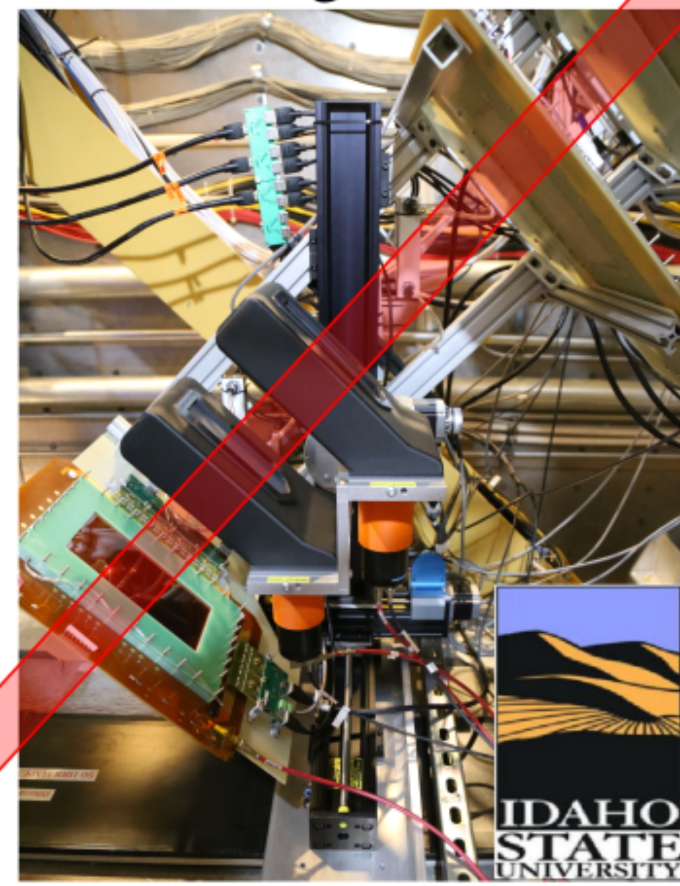
RHRS Tandem PREX-II/CREX Dets with GEMs



Electron's view (from below)

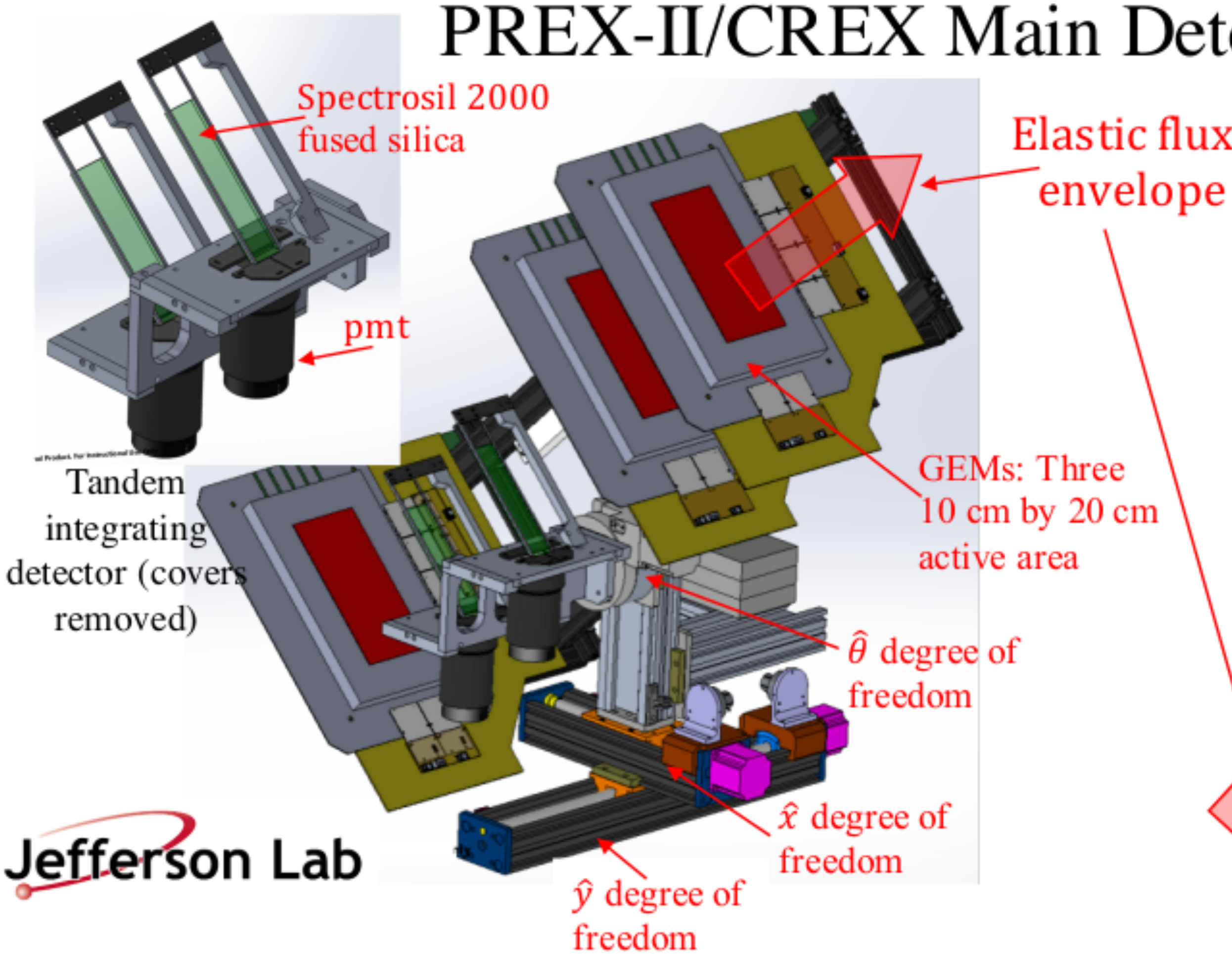
PREX-II/CREX Main Detector Package

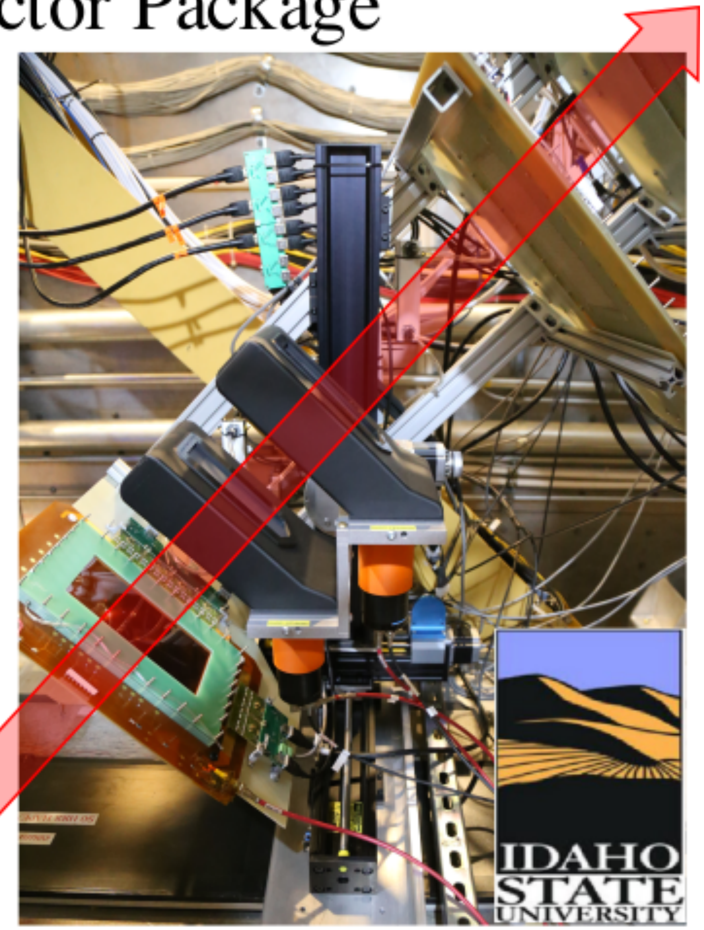




- PREX-II took place over summer 2019 and completed successfully in early September
  - Measured ~0.5 ppm A_{PV} from ^{208}Pb with ~1 GeV beam at 5° θ_{lab} to ~3% stat. precision
  - Integrated flux rates were >2 GHz per arm (Left and Right HRS); 26% detector resolution
  - Achieved 14 ppb statistical precision with a few nanometer control on beam positions
  - GEMs operated at 95% efficiency; provided precision Q^2 avg and systematic checks
  - Overall systematic error well below 14 ppb; will extract neutron skin to ±0.07 fm precision

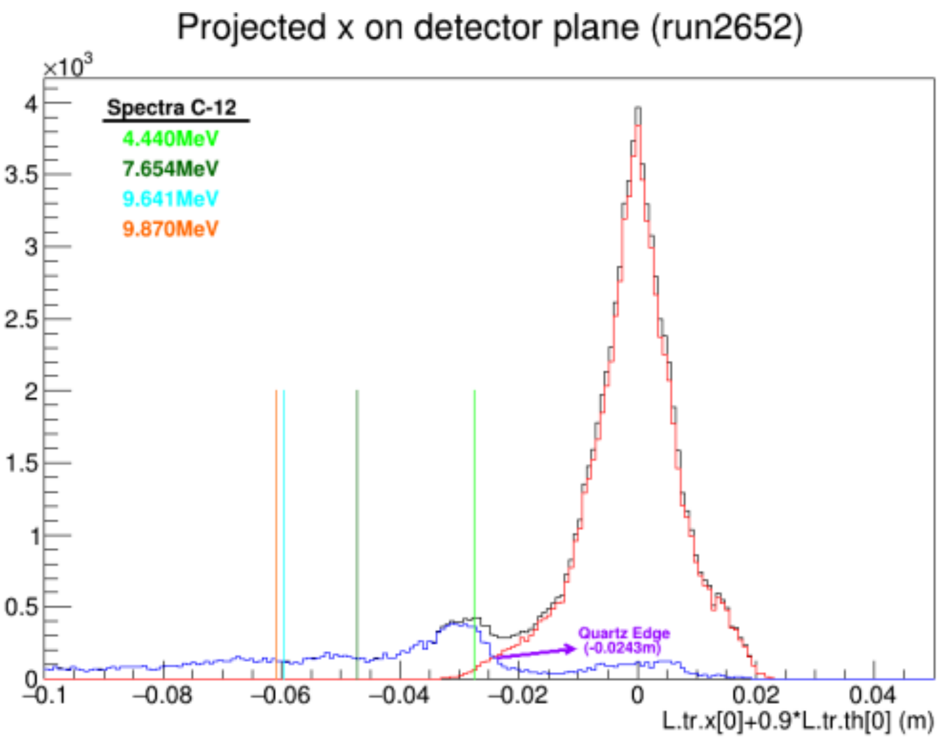
PREX-II/CREX Main Detector Package



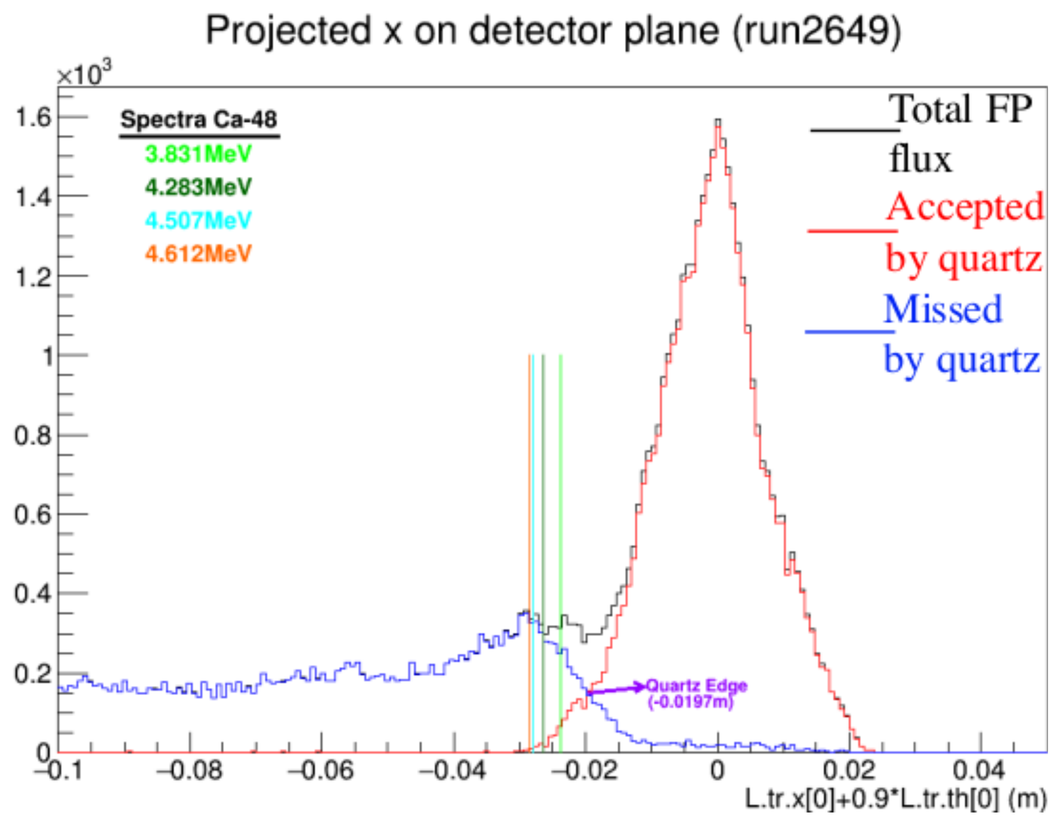


- CREX (Calcium Radius Experiment) will run from this Dec to April 2020 in Hall A, JLab
  - ➢ Measure ~2 ppm A_{PV} from ^{48}Ca with ~2 GeV beam at 5° θ_{lab} to ~2% stat. precision
  - ➢ Integrated flux rates are ~30 MHz per arm (Left and Right HRS); 26% detector resolution
  - ➢ 45 ppb (proposed) statistical precision with a few nanometer control on beam positions
  - ➢ Overall systematic error contribution 26 ppb (proposed); will measure neutron radius and skin with ±0.02 fm precision

Examples of Focal Plane, Elastic Peak Spectra

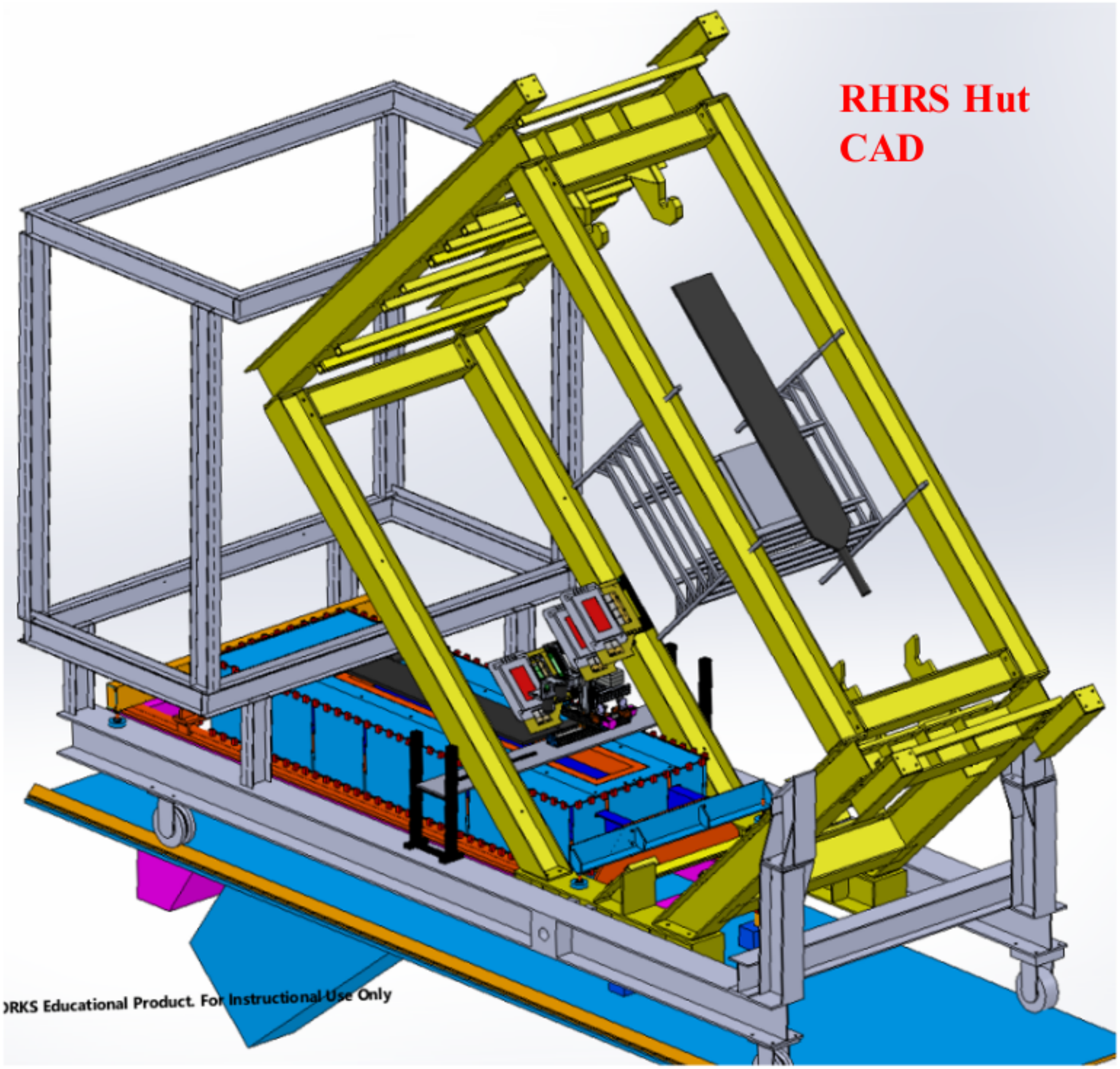


- CREX has established its HRS tune giving expected rates and Q^2 (FOM)

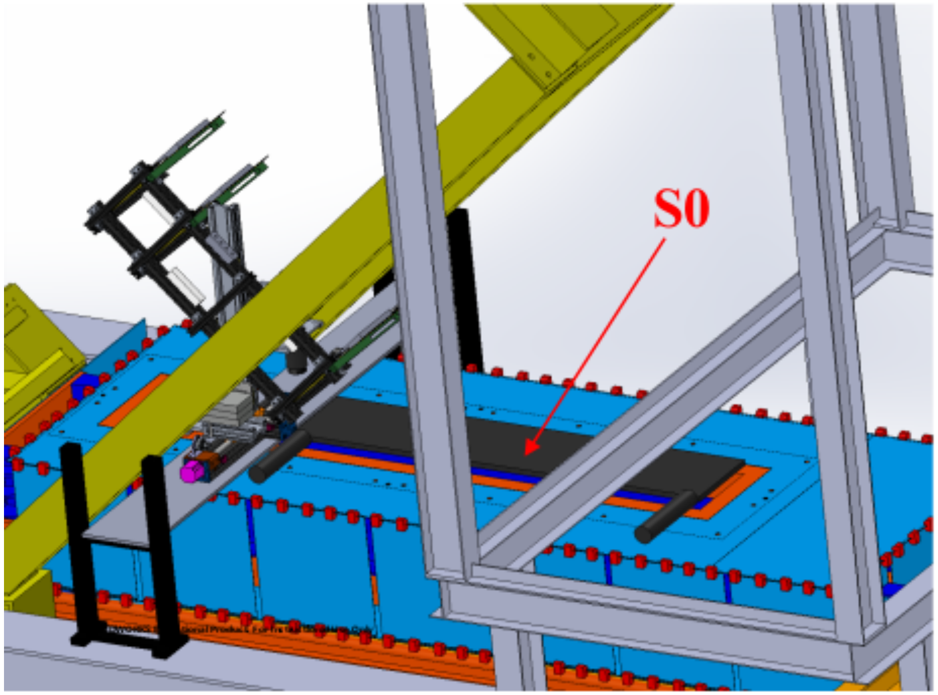


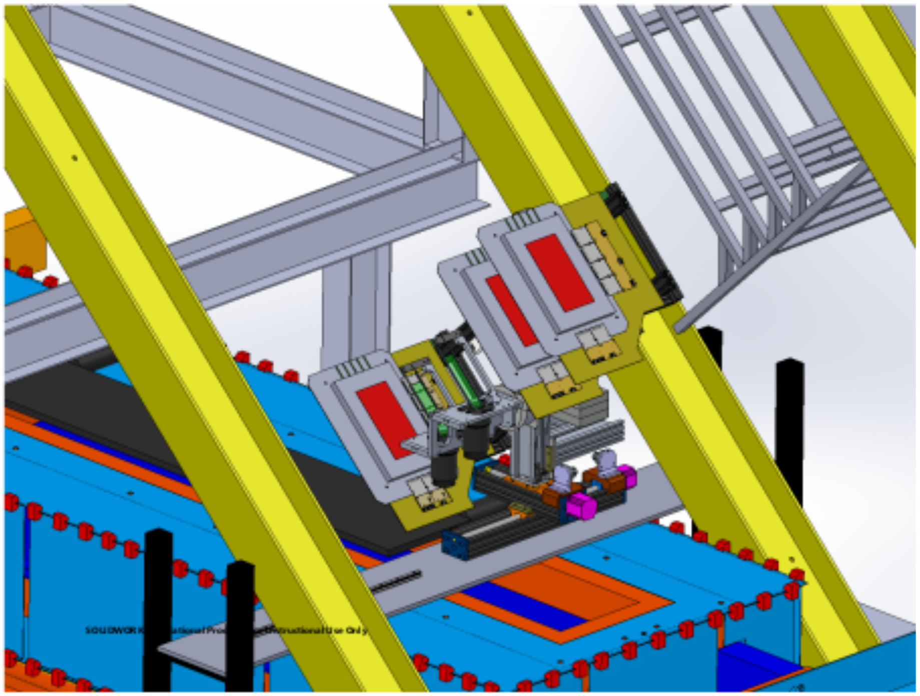
- HRS dispersion: 14.3 cm / *%dp/p* at det. plane
- At 1-pass (2.183 GeV), this corresponds to ~6.57 mm elastic-peak shift per MeV change
- **Energy lock** with full-scale slow drift stability of 0.4 MeV ($1.8*10^{-4}$) provides $\pm$ 1.3 mm stability in peak position

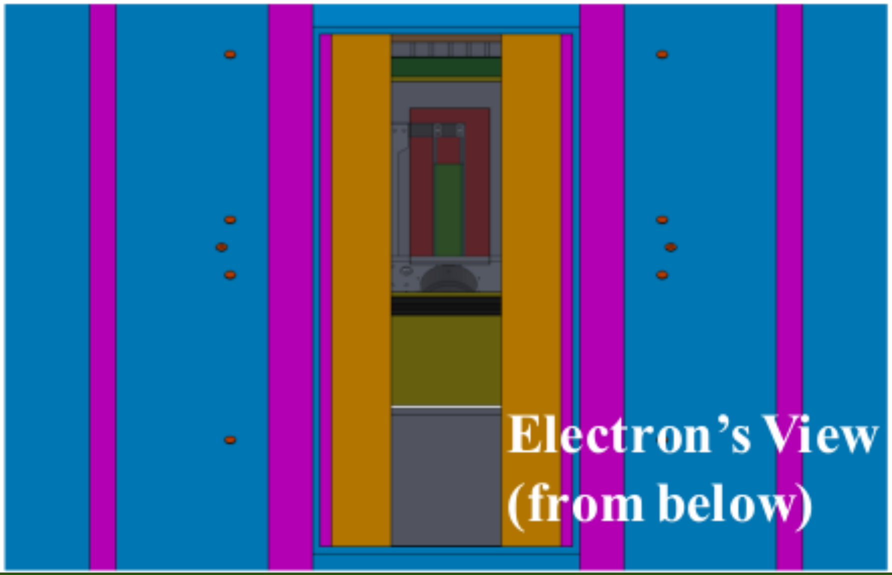
PREX-II/CREX Detector Package

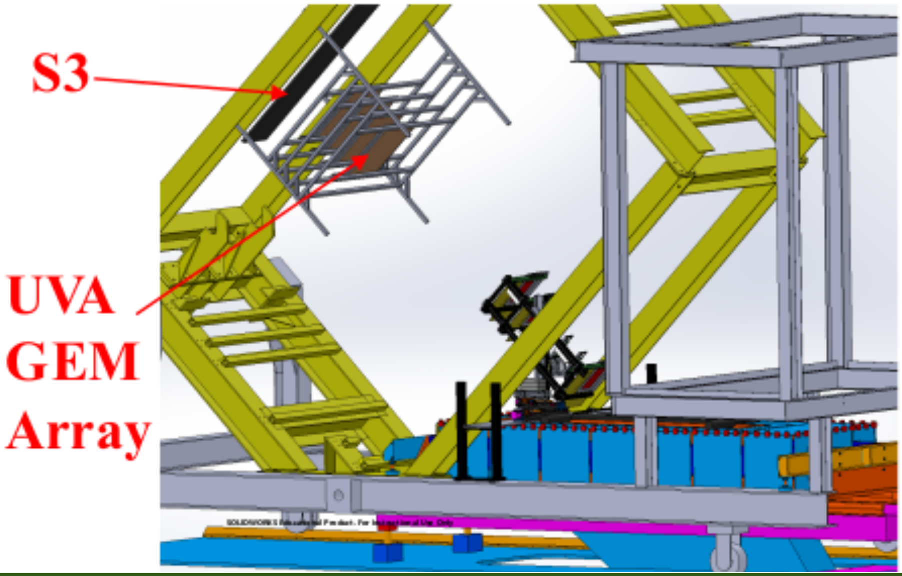


PREX-II/CREX Detector Package

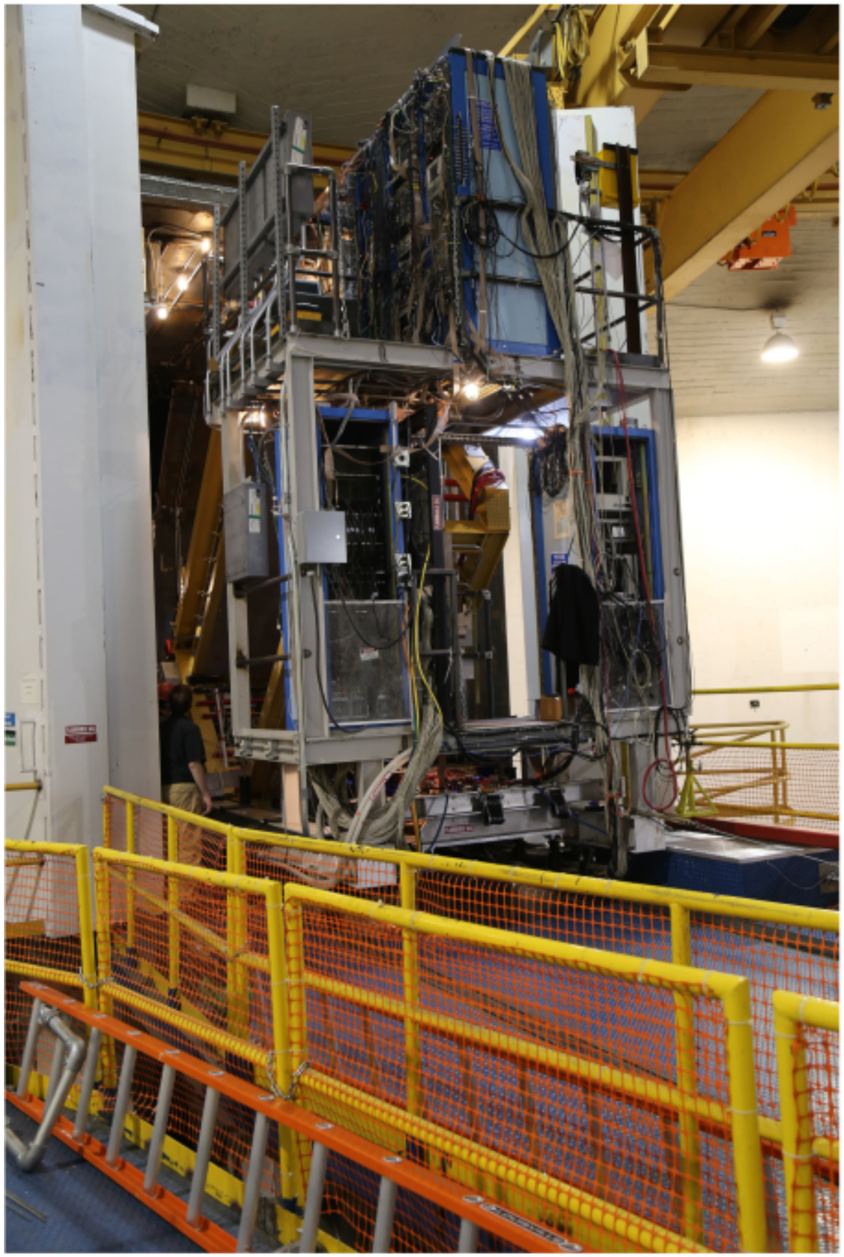


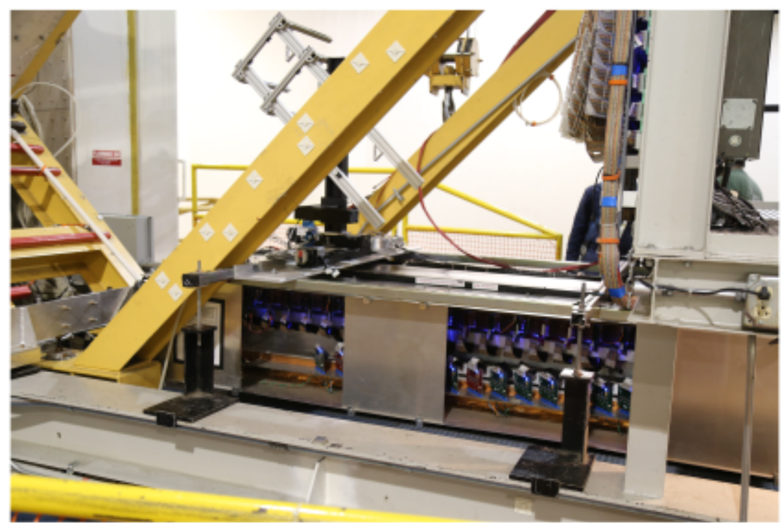




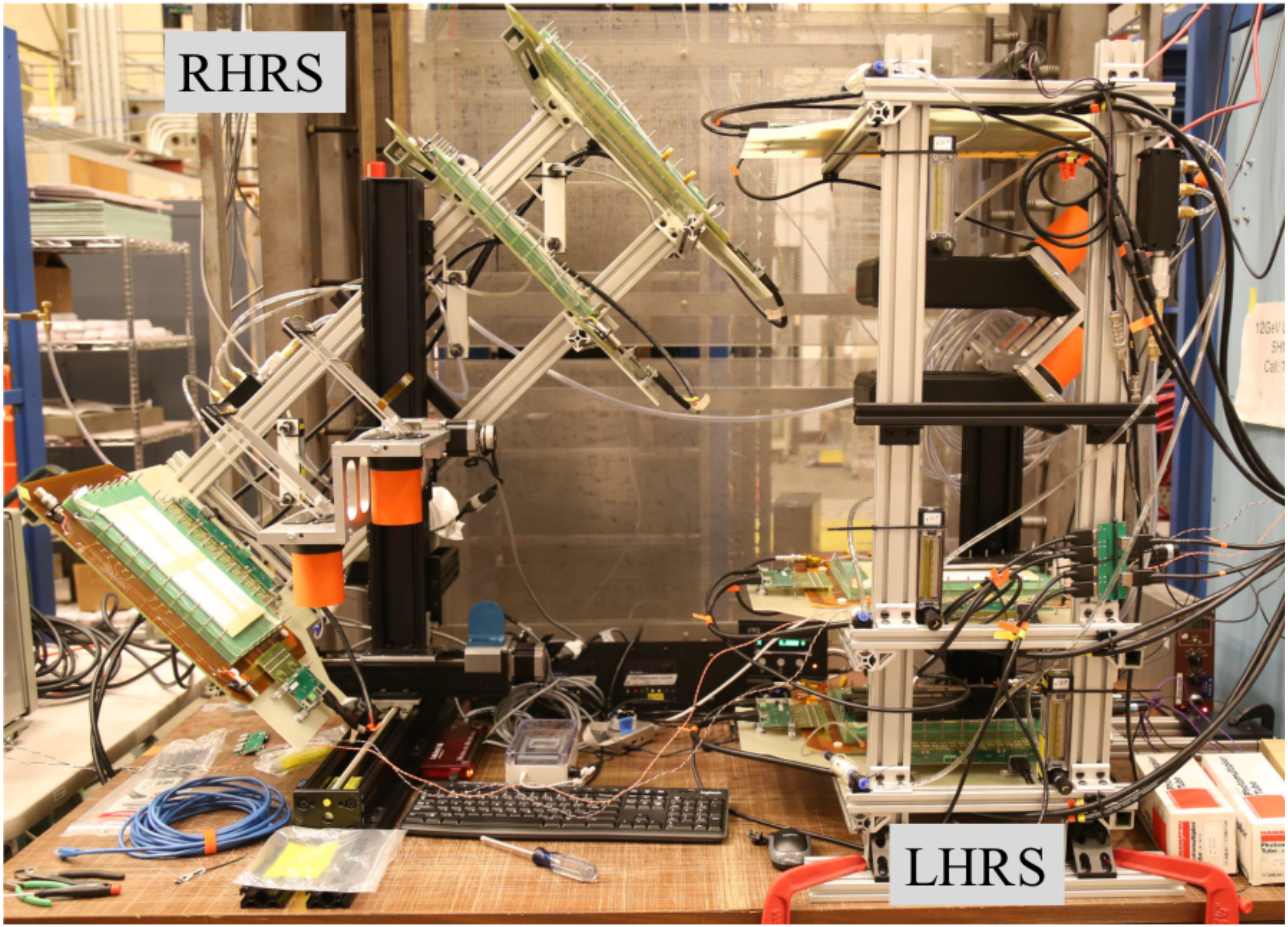


Right HRS Detector Package Installation June 2019

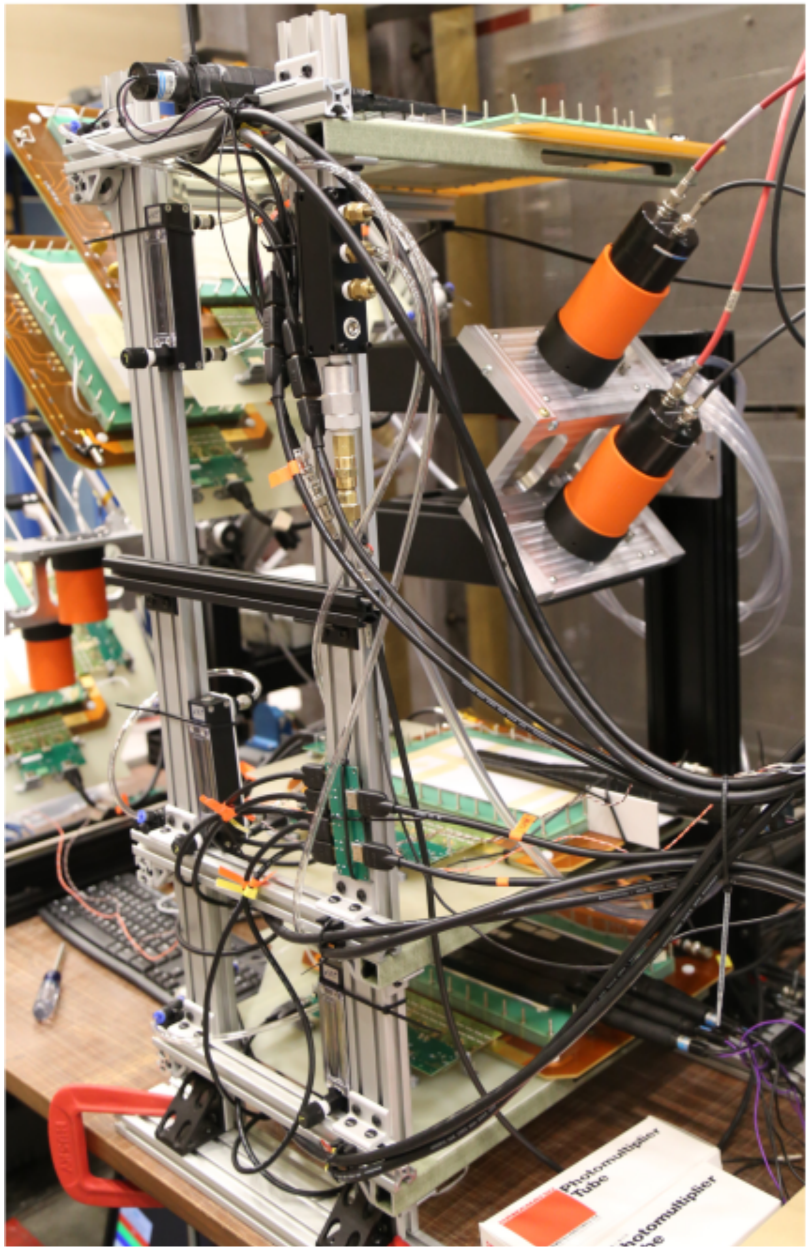


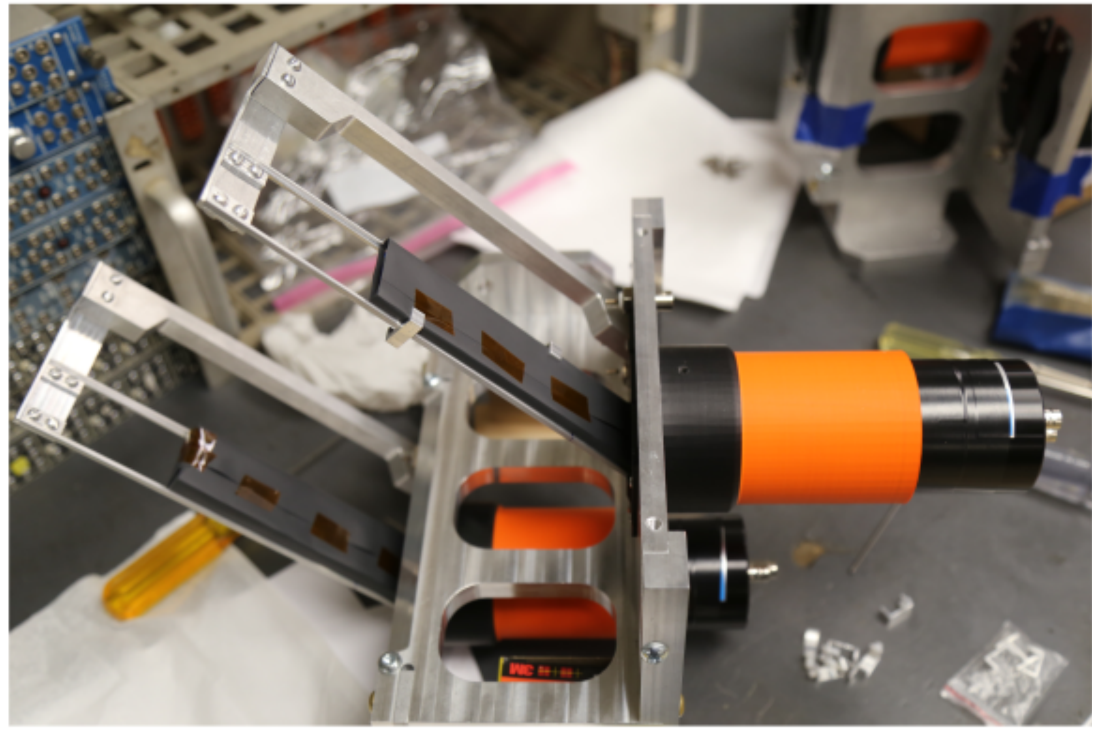


PREX-II/CREX Main Detector Assemblies



LHRS GEM stand in Cosmic-ray mode



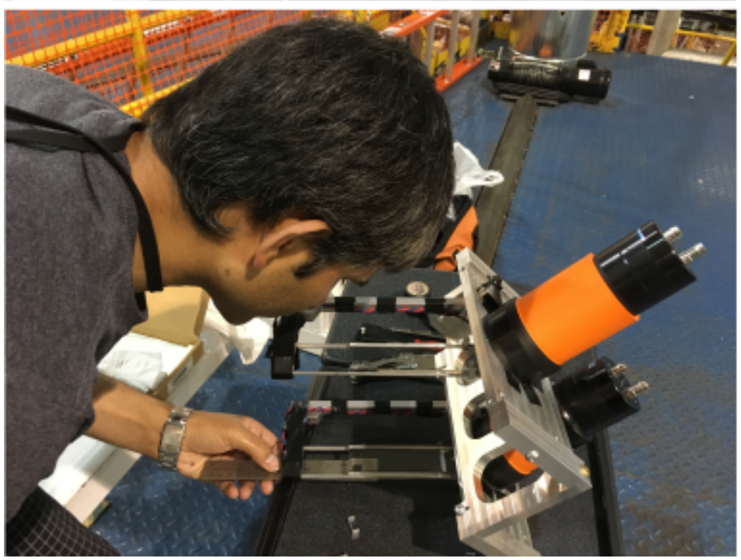


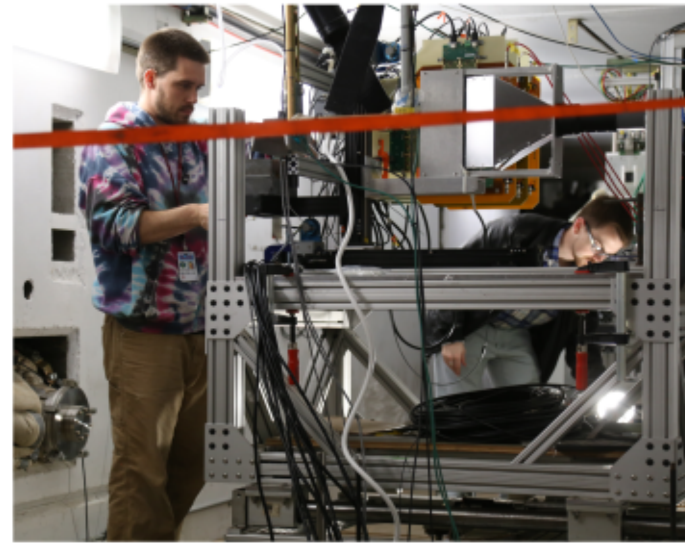
- PREX-II will use 5mm thick quartz.
- Main and A_T detectors will use R7723Q pmts

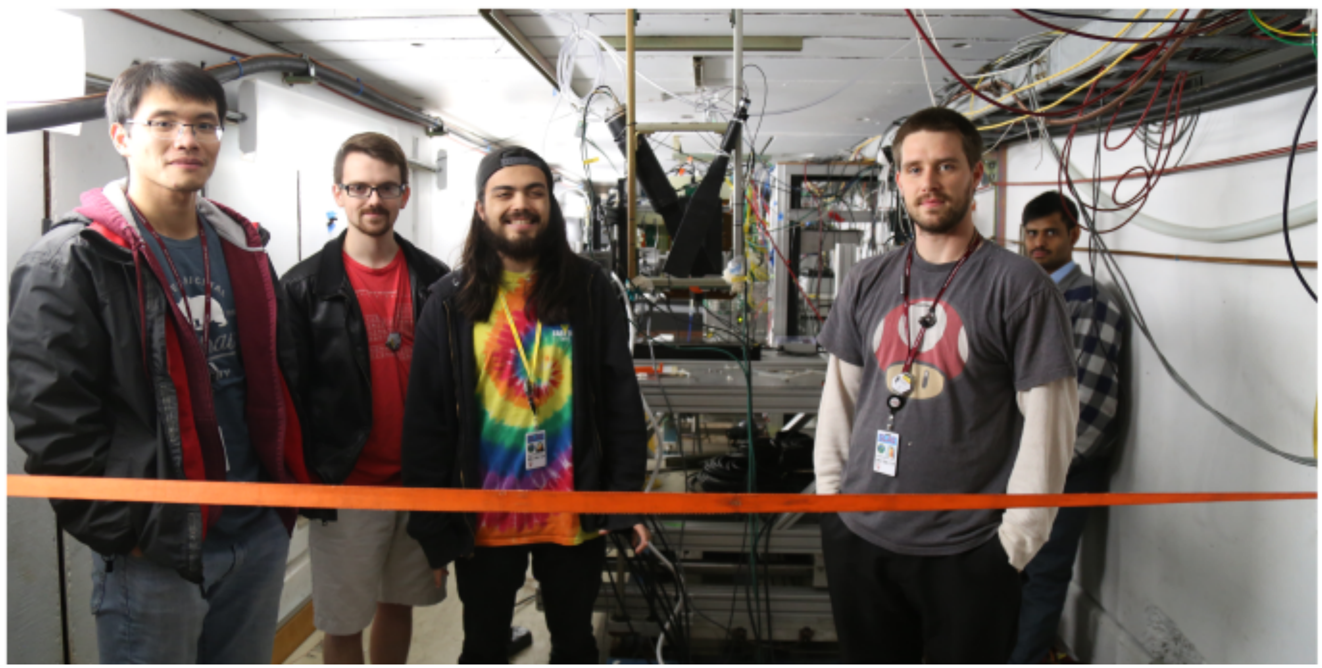
List of past and present undergraduate research assistants within past 6 years

Student	Contribution	Current Status
Kevin Rhine	LG Designs: SAMs and Shwr-max	Grad. 2015
Brady Lowe	DAQ setup, PMT gains, CREX det.	Grad. 2015; MS 2019
Blake French	CODA event-viewer, Cosmic-stand	Grad. 2015; job at Micron
Dayah Chrisman	PMT gain analysis macro	Grad. 2015; Grad.Stud. MSU
Will Gorman	Cosmic-ray data analysis	Grad. 2014;Grad.Stud. U of Roch.
Max Sturgeon	Bending Al. Light Guides for SAMs	Grad. 2017
Chase Juneau	CAD; reflectivity meas.	Grad. 2017; job at INL
Daniel Sluder	Shower-max support frame CAD, ...	Grad. 2016; MS 2018
Joey McCullough	GEM readout backplanes;SLAC tests	Grad. 2017; MS expected 2019
C. Royal Cole	SLAC testbeam stand	Grad. Dec 2018; Medical School
Eighdi Aung	GEM CAD	Grad. 2019; Grad. Stud. Va Tech
Rajul Chauhan	PREX-II/CREX det. motion control	Grad. 2019
Justin Gahley	SLAC testbeam stand motion control	Expected Grad. 2020
Alec Lepisto	3D printing parts; SLAC analysis	Expected Grad. 2021
Brandon Pearson	Designing and 3D printing parts	Expected Grad. 2021

Students at Work at Jefferson Lab and SLAC







Summary and Future Plans

- PVES is a precision tool for measuring weak-charge distributions with implications for nuclear structure and BSM discovery

PREX/CREX:

- PREX-II collected 80% of proposed data and together with PREX-I will reach full precision: ± 0.07 fm resolution on the neutron radius and skin of ^{208}Pb with implications for neutron stars, ...
- CREX currently running and on target to reach proposed measurement goal: ± 0.02 fm resolution on the neutron radius and skin of ^{48}Ca with implications for nuclear structure and forces

Integrating Detectors

- Much progress over past 5 years – new robust design
- "thin" quartz detectors becoming well understood
- Future detector work for MOLLER will quantify rad-hardness of detector materials, including quartz and aluminum reflectors

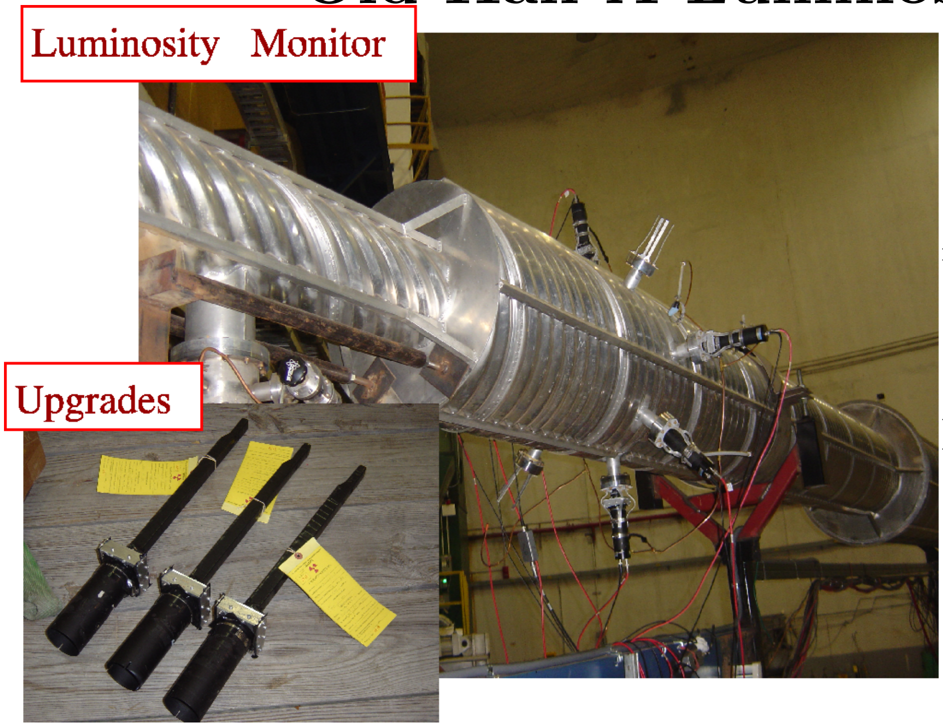
Extra Slides

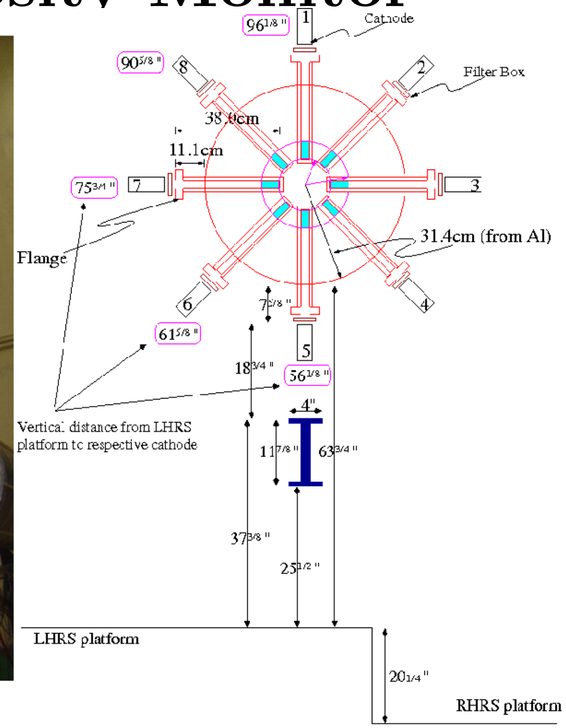
Motivations for Downstream Lumi's or SAM's

- Need them for their high sensitivity to helicity-correlated beam parameters
  - Detect charged particle flux at extreme forward angles
  - Very high rates and thus narrow pulse-pair widths – powerful diagnostic tool

- Provides measure of overall electronic noise floor in the hall
- In theory, should have very low/no PV asymmetry and can serve as null asymmetry monitor
- Symmetric 8 piece design helps disentangle beam position and angle HCBP's while 8 SAM sum is insensitive
- Could provide important tests of regression procedures

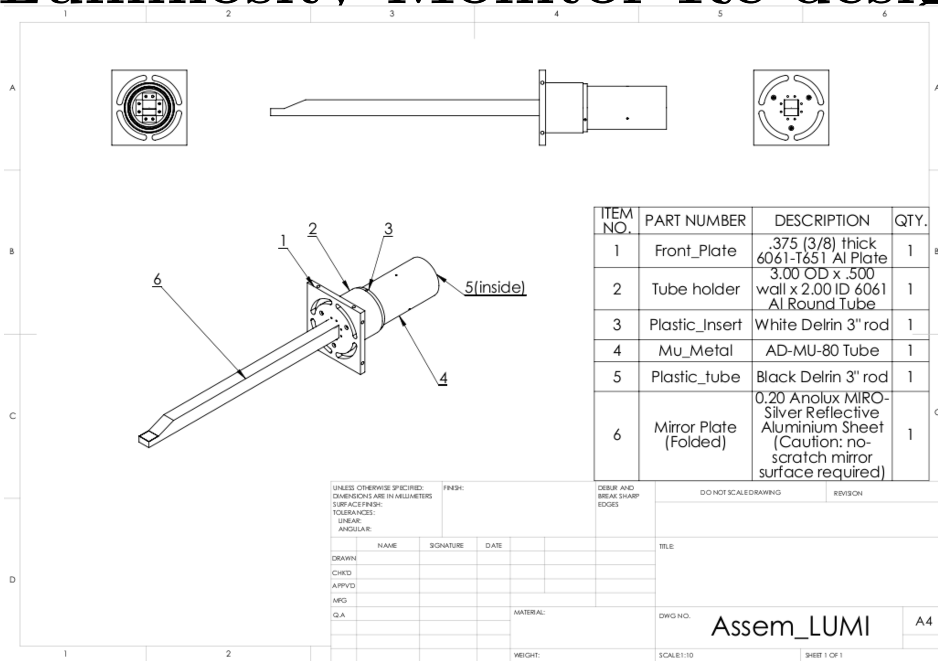
Old Hall A Luminosity Monitor

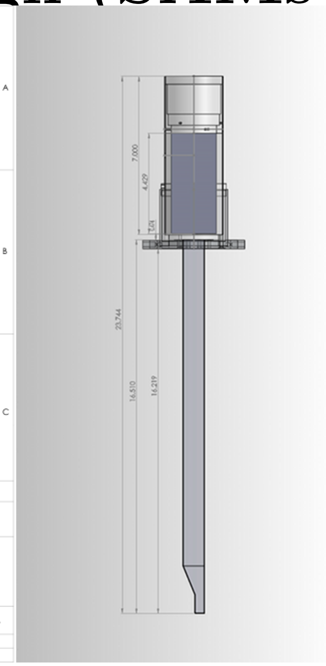




- Conceptual Design 2002–Riad Suleiman; refurbished in 2008
- 8 quartz Cherenkov detectors with air-core light guides placed symmetrically around beam line 7m downstream of pivot
- Used $6.0 \times 2.0 \times 1.0$ cm^3 quartz placed 4.5 cm from beam center $\Rightarrow$ 0.3 - 0.8 deg polar angle acceptance

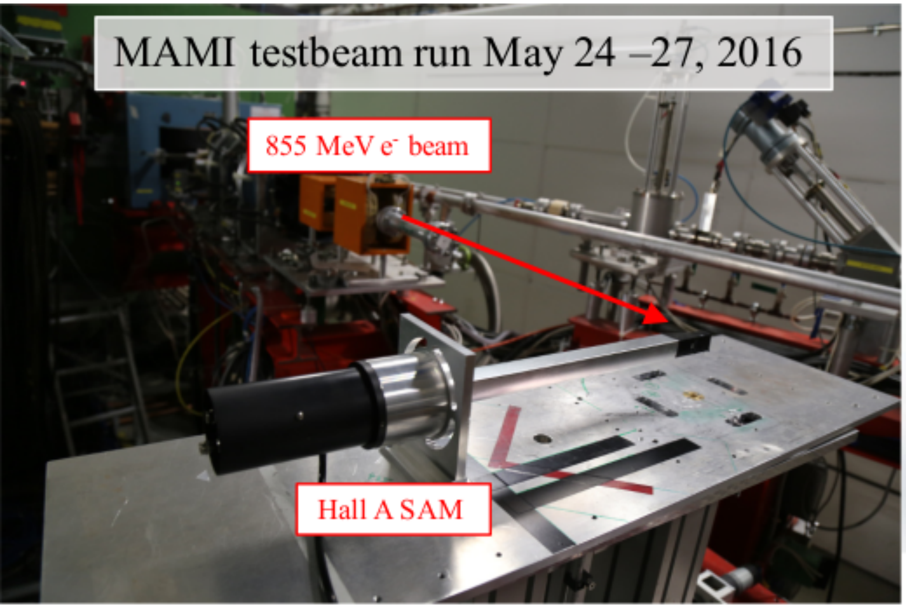
Luminosity Monitor Re-design (SAMs)





- Incorporate Qweak's downstream Lumi experience:
  - –Use pre-radiator and "unity gain" PMT
  - –Use radially smaller, but thicker quartz
  - –May achieve desired linearity at anticipated photocathode currents, but running unity gain mode guarantees it
  - –Use TRIUMF preAmps at SAM for signal cond. and gain
- *Work within constraints of existing beampipe insertion tubes*

Final SAM Design and 2016 Testbeam



- Final (v3) SAM detector PE yield studies:
  - MiroSilver27 and UVS light-guides
  - With and without 1cm tungsten pre-radiator

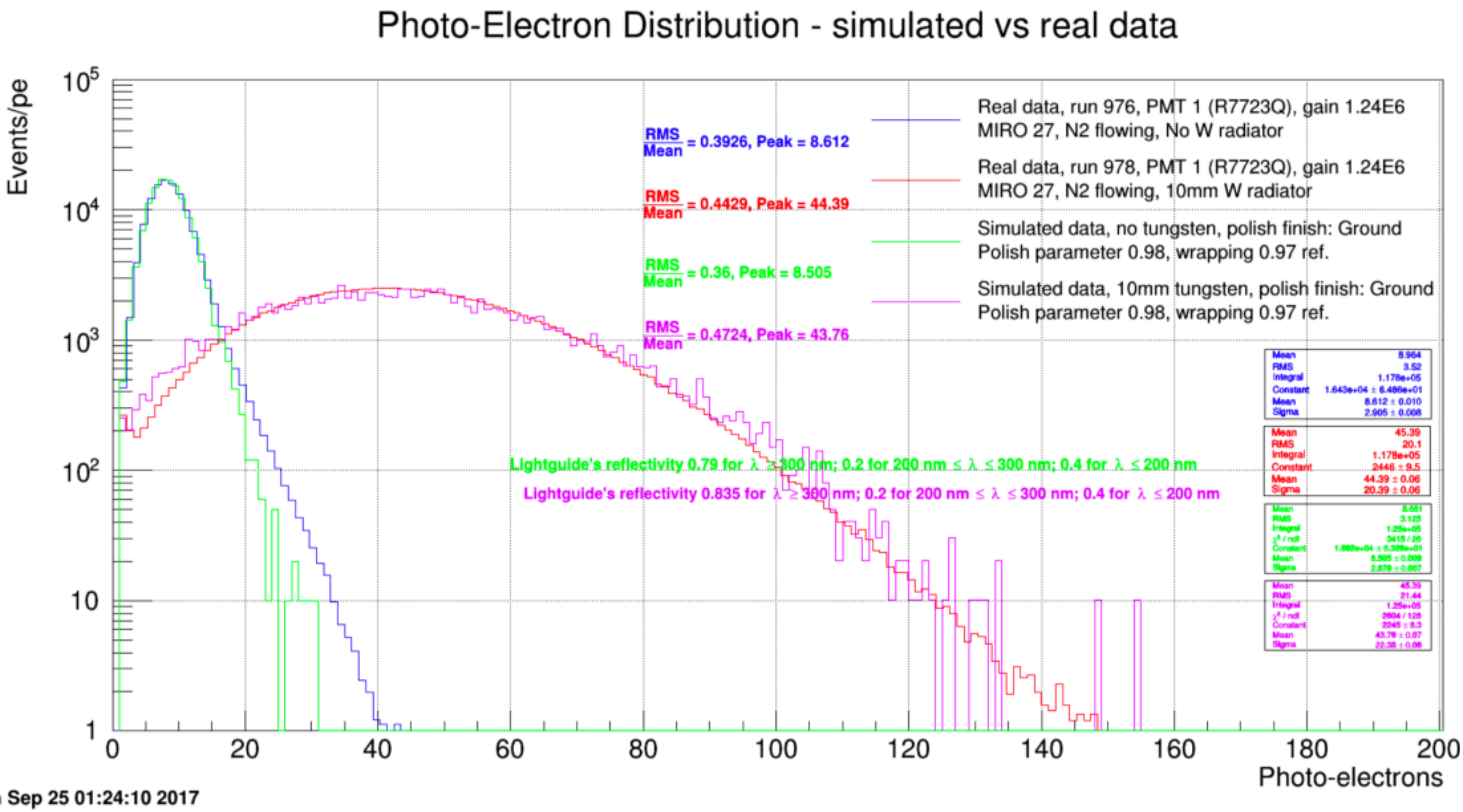
Small Angle Monitors:
Detect ~0.5° target scattering

Assembled & Installed in Hall A Fall 2015

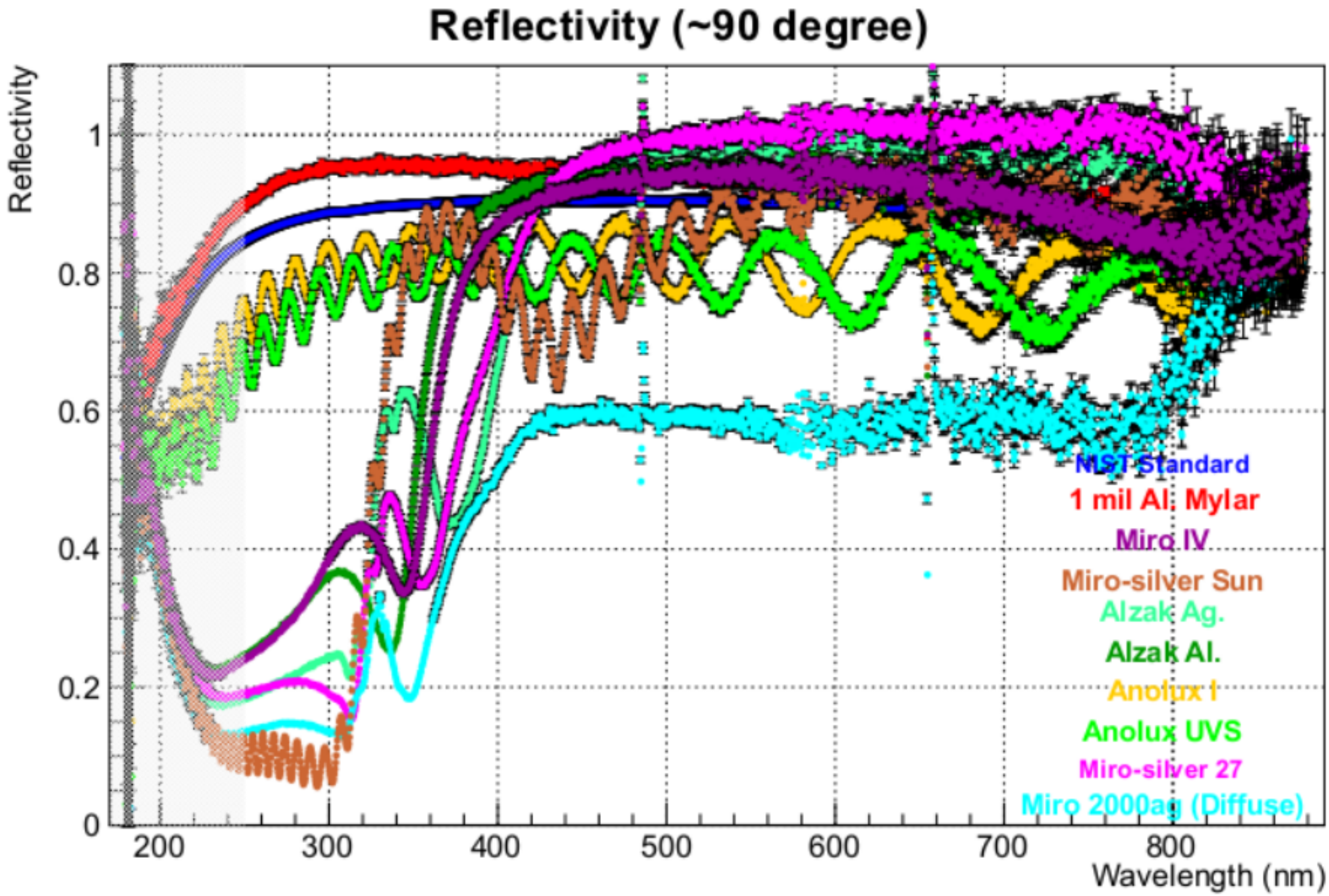
v3 SAM detector

- Quartz: 33 x 20 x 13 mm^3
- Miro27 LG: 36 x 2.6 x 2.1 cm^3
- Optimized 1-bounce funnel mirror
- Unity or high-gain R375 2" PMTs
- Use of pre-radiator not decided
- Dry-air inlet and outlet ports
- Custom flange adapter for easy de-install/re-install (radcon permitting)

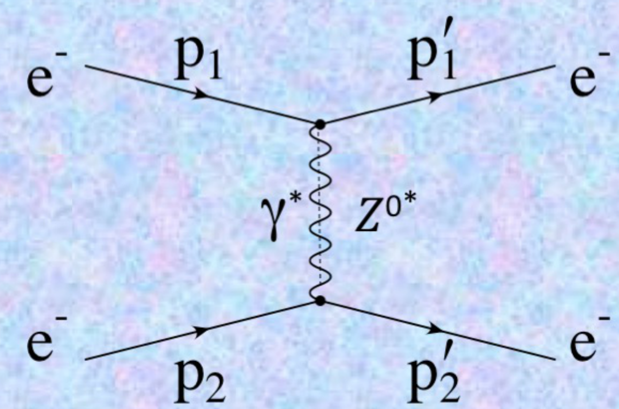
Optical Monte Carlo (qsim) Benchmarking: SAMs



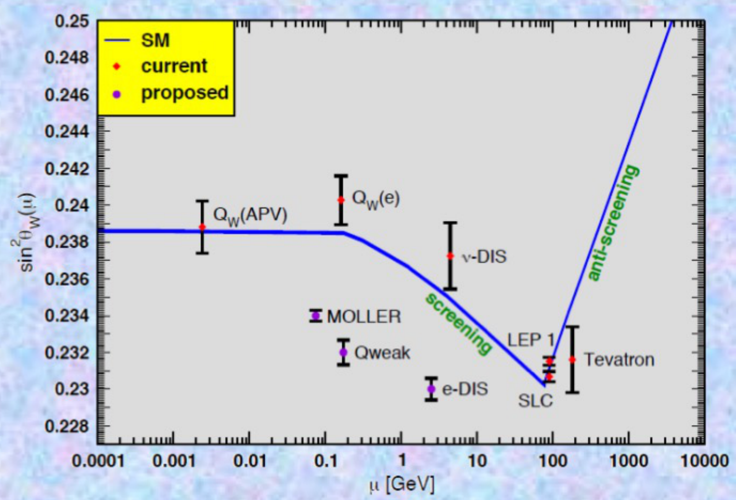
SAM light guide reflectivity: explored many options



The MOLLER Project at Jefferson Lab:



Measurement
of
Lepton
Lepton
Electroweak
Reaction

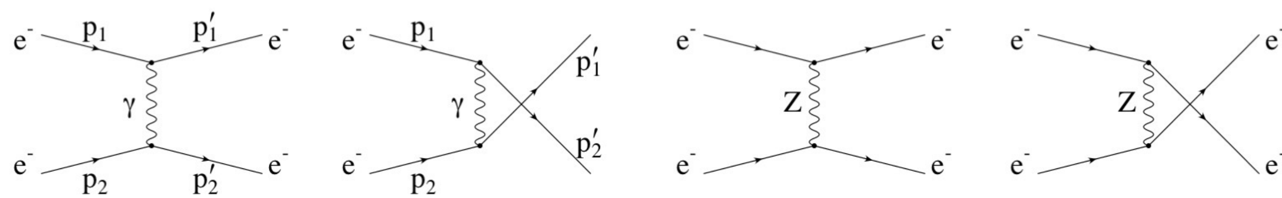


Møller Scattering A_{PV} Measurement

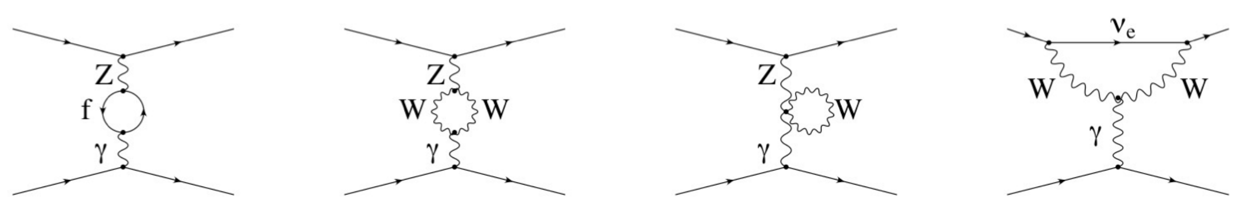
- MOLLER aimed at precision measurement of parity-violating asymmetry A_{PV} in polarized electron-electron scattering.
- Standard Model gives precise prediction for Møller A_{PV} –which can be measured as a test.

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{M_\gamma M_Z}{M_\gamma^2} = m_e E_{lab} \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4 sin^2\theta_{lab}}{(3 + cos^2\theta_{lab})^2} Q_W^e,$$

$$Q_W^e \equiv 4 \cdot g_V^e \cdot g_A^e = -(1 - 4 sin^2\theta_W) \quad (1)$$



Feynman diagrams for Moller Scattering at tree level



γ - Z mixing diagrams and W loops. “Hard” radiative corrections involving the massive vector bosons—modify the tree level prediction significantly.

The MOLLER A_{PV} Measurement

- At proposed kinematics: 11GeV $e^-_{\rm beam}$(75μA, 80% P_e), and 5mrad $< \theta_{lab} <$ 20mrad:
  $\rightarrow$ Predicted $\langle A_{PV} \rangle$=36ppb at $\langle Q^2 \rangle$=0.0056 (GeV/c)^2
- For 49 (PAC) week run: δA_{PV}= 0.74ppb:
  $\rightarrow \delta Q^e_W / Q^e_W = \pm 2.1\%$(stat) $\pm$ 1.0%(syst)
  $\rightarrow \delta\theta_{\rm W} = \pm 0.00026$(stat) $\pm$ 0.00012(syst) $\sim$0.1% precision!

Challenging 4th generation measurement requiring:

- Unprecedented precision matching of electron beam characteristics for Left versus Right helicity states
- Precision non-invasive, redundant continuous beam polarimetry
- Precision knowledge of luminosity, spectrometer acceptance (Q^2) and backgrounds

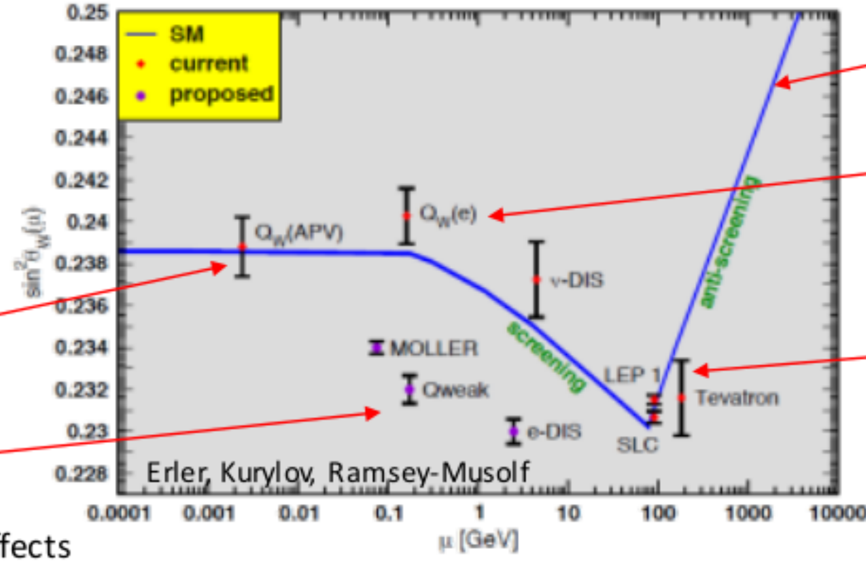
MOLLER Motivations

Ultra-precise (~0.1%) measurement of weak mixing angle will test SM

Running of $\sin^2\theta_W$: complicated and scheme-dependent – many orders in loops of all particles

6s ⟶ 7s ^{133}Cs atomic transition

Major improvements for near future



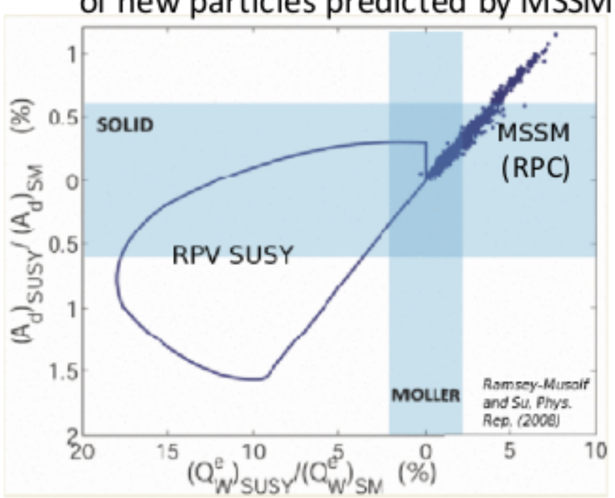
Electroweak fit with uncertainty

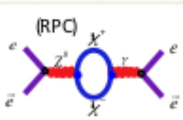
Parity violating Moller scattering (E158)

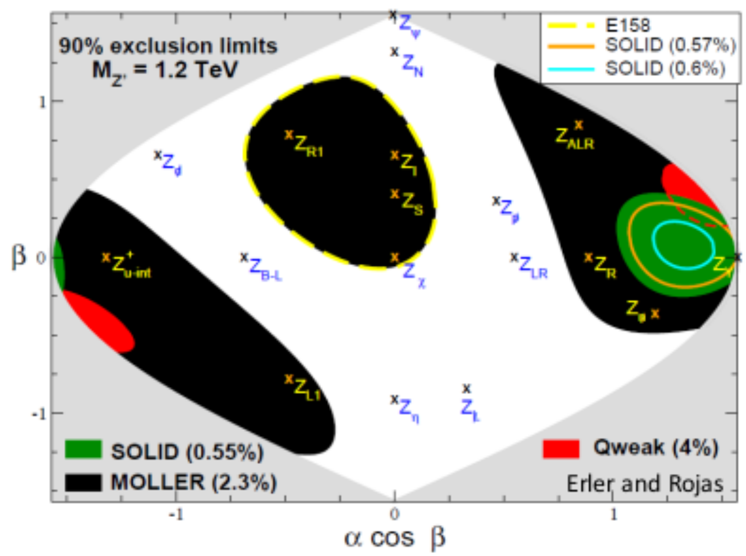
Collider experiments near Z-pole (most precise 0.1%)

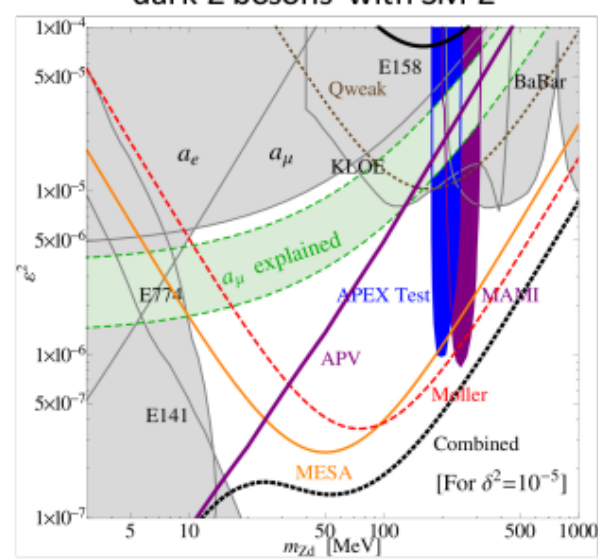
- Probe potential kinetic-mixing of super-light (10 to 500 MeV) dark Z bosons with SM Z

- Sensitivity to radiative loop effects of new particles predicted by MSSM





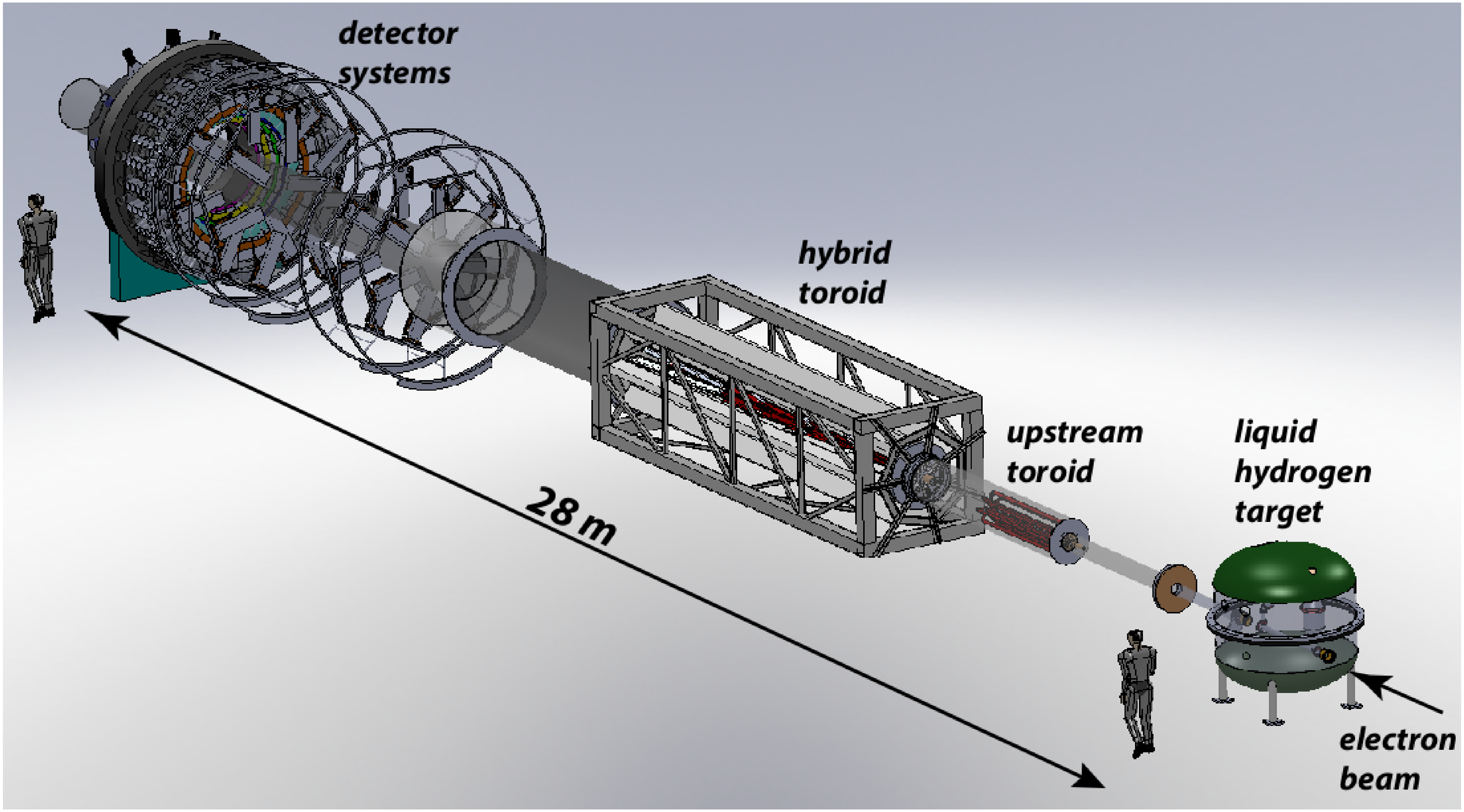




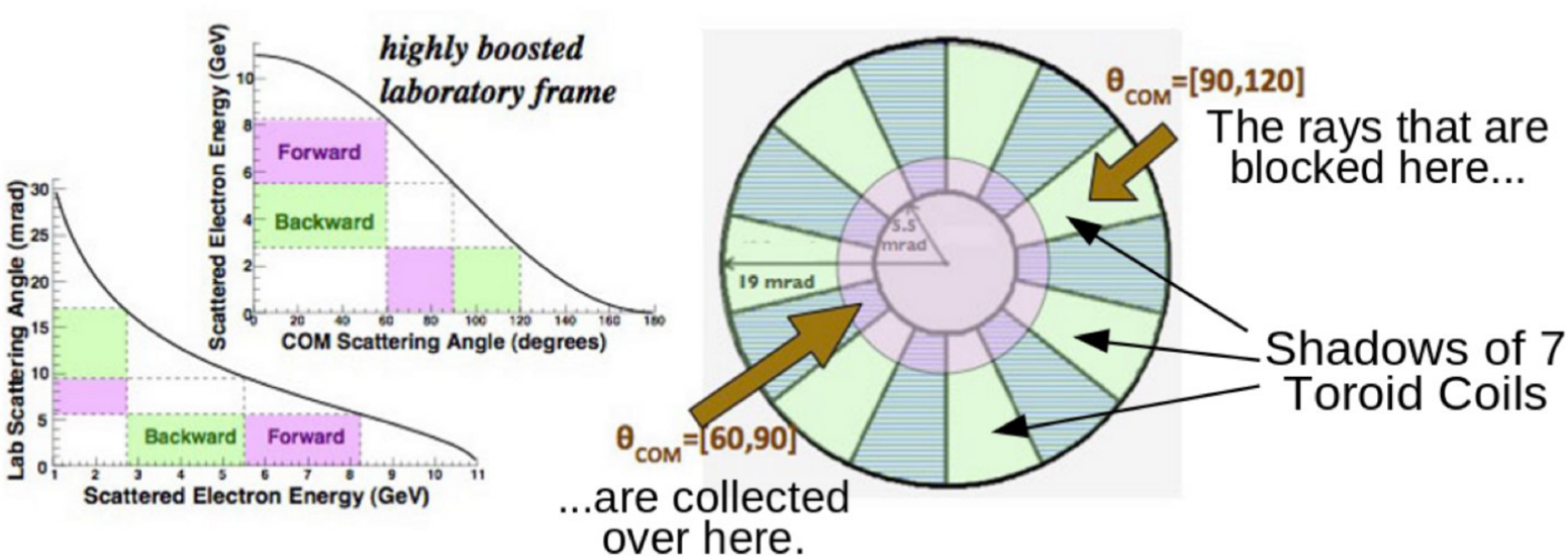
- MOLLER can help discriminate between competing GUT models which predict new 1 – 2 TeV Z's

MOLLER Apparatus

(major new installation experiment for Hall A)

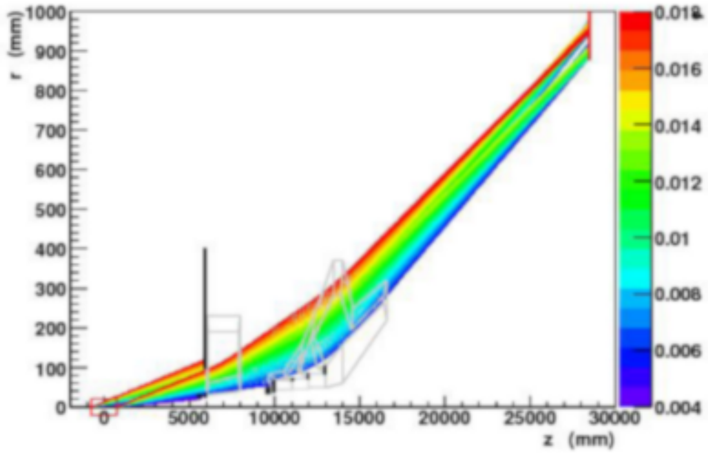


Optimized Spectrometer (∼ 100% Acceptance)

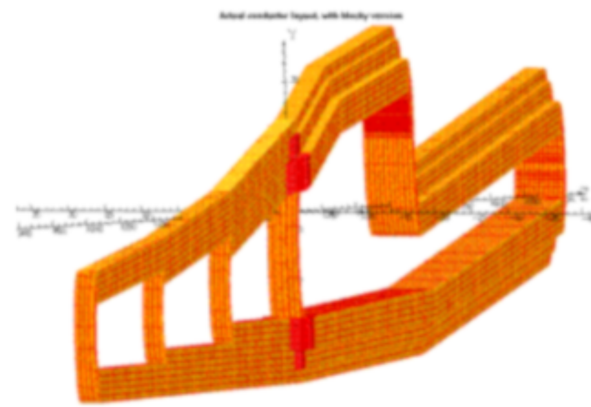


- The combination of a toroidal magnetic system with an odd number of coils together with the symmetric, identical particle scattering nature of the Møller process allows for ∼ 100% azimuthal acceptance

Toroid Design Concept



Projected radial coordinate of scattered Møller electron trajectories. Colors represent θ_{lab} (rad). Magnet coils (grey) and collimators (black) are overlaid.



Single Hybrid coil shown with 1/10 scale in z direction. Note the 4 current returns give successively higher downstream fields.

- Spectrometer employs two back-to-back toroid magnets and precision collimation:
  - Upstream toroid has conventional geometry
  - Downstream "hybrid" toroid novel design inspired by the need to focus Møller electrons with a wide momentum range while separating them from e-p (Mott) scattering background

MOLLER Integrating Detector Layout and Rates

- Spectrometer separates signal from bkgd and radially focuses at detector plane
- Rates for 11 GeV/75 μA (80% pol.) beam, 1.5m liquid hydrogen target. See fig. $\longrightarrow$
- Six radial rings, 28 phi segments per ring*
- Ring 5 intercepts Moller peak (~150 GHz), Ring 2 intercepts bkgd "ep" peaks
- 250 quartz tiles: allow full characterization and deconvolution of bkgd and signal processes