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

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(for the PREX/CREX and MOLLER Collaborations)

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Detectors for Parity Experiments at JLab

Outline

- 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
  - New Hall A Small Angle Monitors (if time)
  - Shower-max Sampling Calorimeter for MOLLER (if time)
- Summary and Future Plans

Why Parity-Violating Electron Scattering?

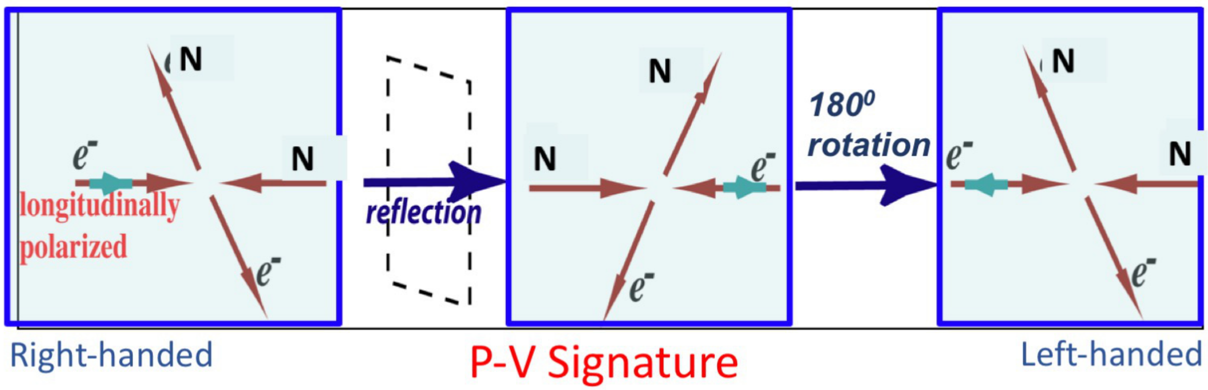
Provides model-independent determinations of nuclear and fundamental-particle weak-charge form factors and couplings with widespread implications for:

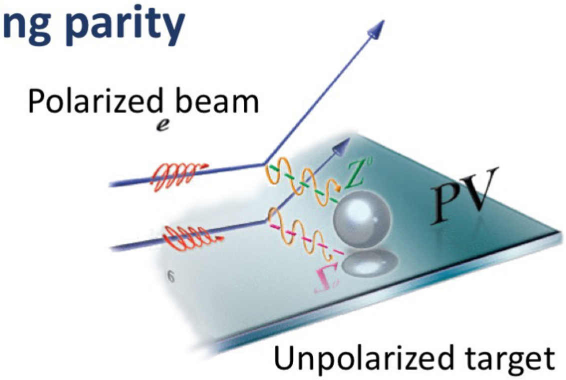
- Understanding nuclear and nucleon structure
  - Strange quark content of nucleon
  - Neutron radii of heavy nuclei $\longrightarrow$ density dependence of Symmetry Energy and EOS of nuclear matter; neutron stars; calibrate hadronic probe reactions on radioactive beams
- Search for physics Beyond the 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

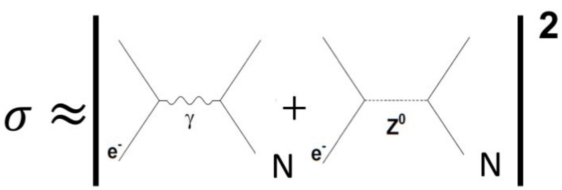
JLab PVES Programs: HAPPEX, G0, PVDIS, PREX, Qweak, CREX MOLLER, SoLID

Parity-Violating Electron Scattering

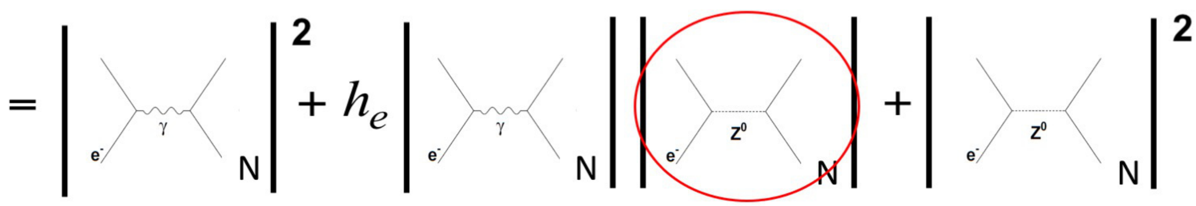
Parity Transformation: Changing beam helicity equivalent to changing parity







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

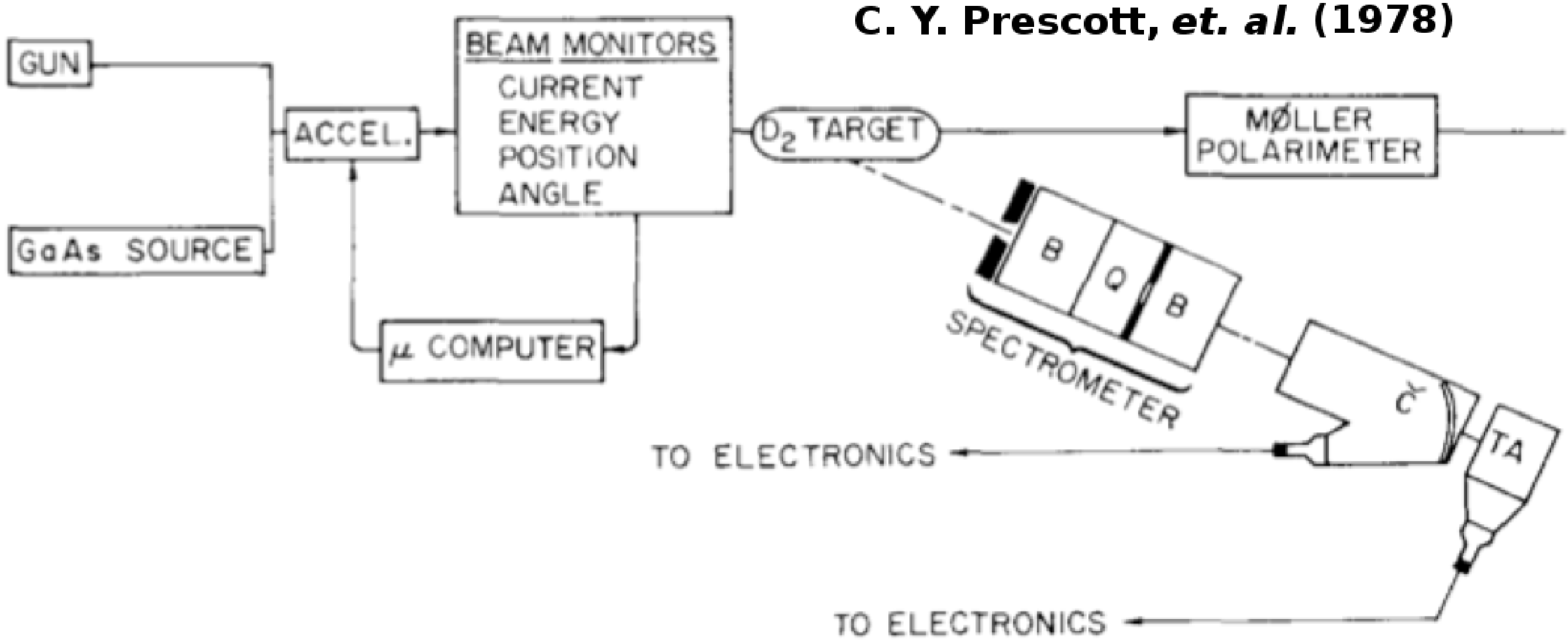


- Flip sign of longitudinal polarization
- Measure fractional rate difference or asymmetry

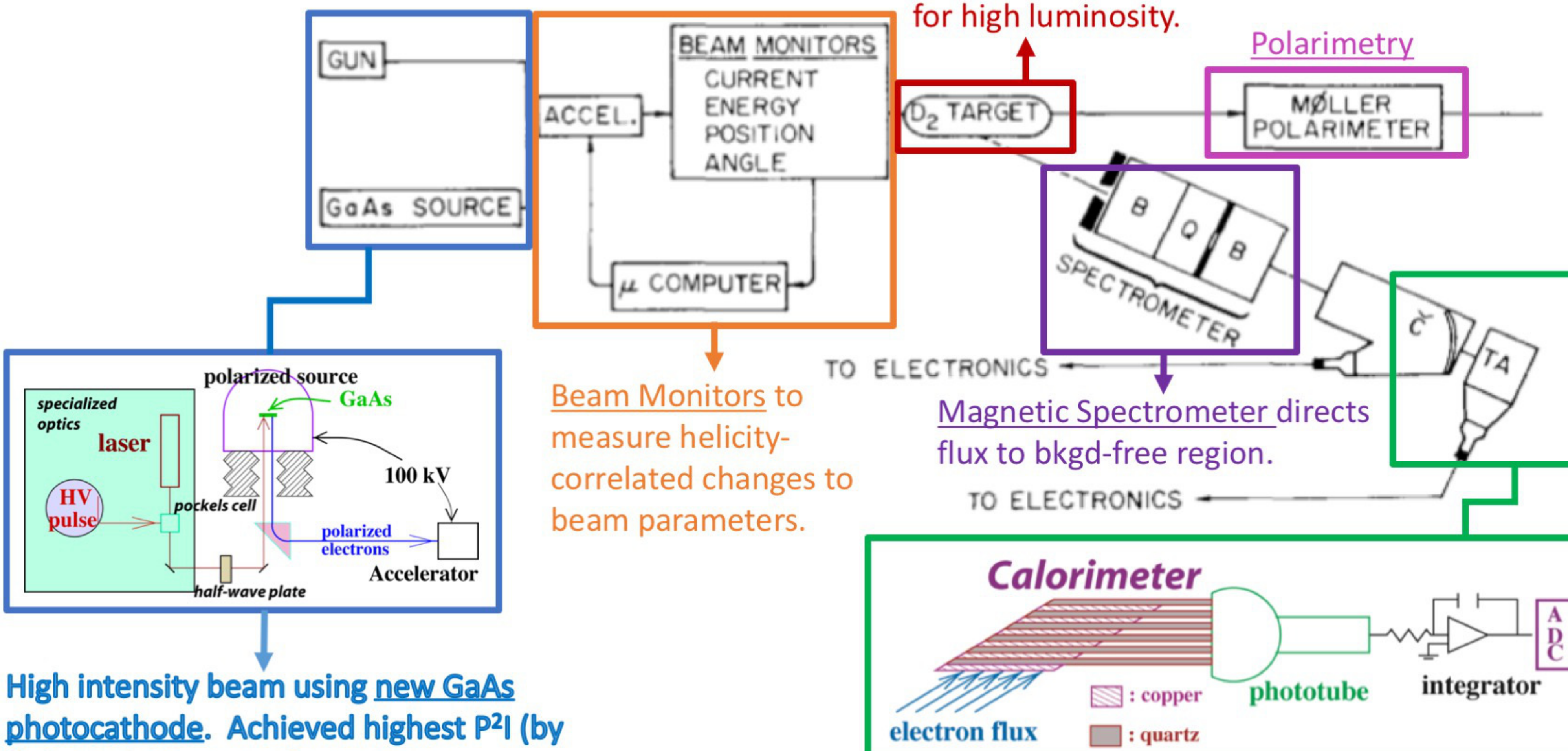
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{M^{NC}_{Weak}}{M_{EM}} \approx \frac{G_F Q^2}{4\pi\alpha} \sim 10^{-4} \cdot Q^2 \, [/\mathrm{GeV}^2]$$

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

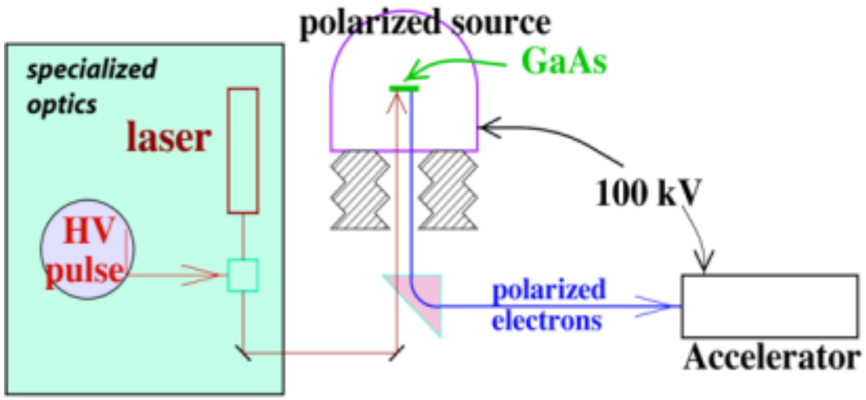
Beam Monitors to measure helicity-correlated changes to beam parameters.

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.

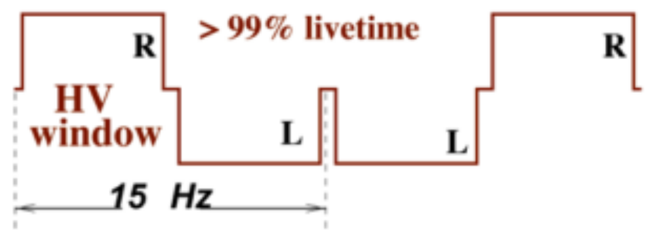
Flux Integration measures high rate without deadtime.

How to do a Parity Experiment



rapid, random, helicity flipping

Rapid, Random Helicity Flips



Measure flux F for each window

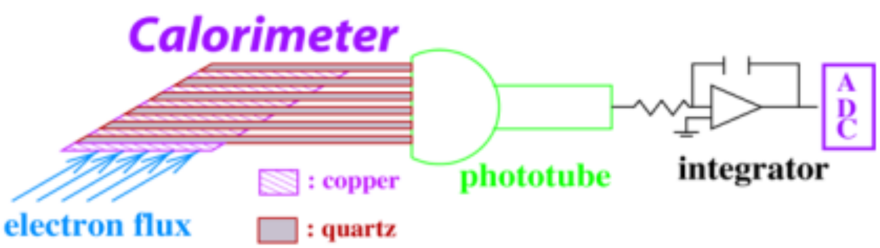
$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

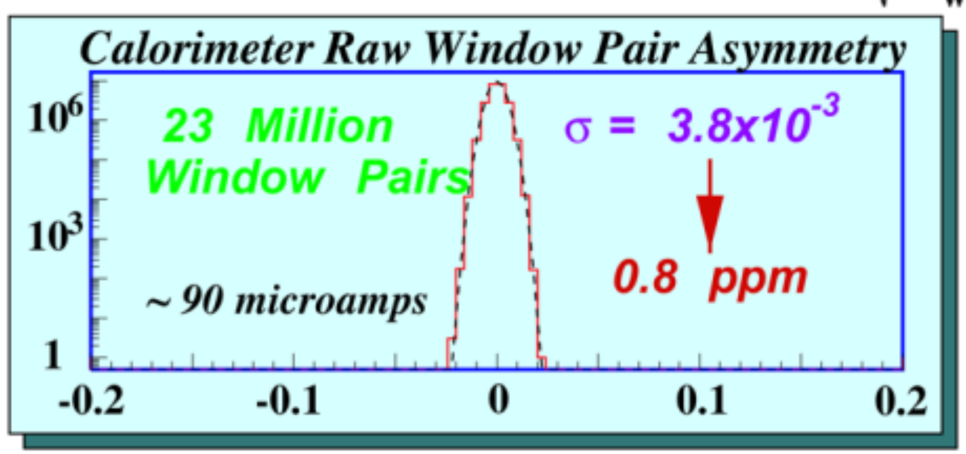
*See Bob Michael's talk on "JLab Parity Review (HAPPEX and PVDIS)" Friday at 9:00 AM

Flux Integration Technique:

HAPPEX: 2 MHz ($A_{PV} \sim 15$ ppm)
HAPPEX-II: 100 MHz ($A_{PV} \sim 1.5$ ppm)
PREX: 1 GHz ($A_{PV} \sim 0.5$ ppm)
PREX-II: 2 GHz ($A_{PV} \sim 0.5$ ppm)
MOLLER: 150 GHz ($A_{PV} \sim 0.035$ ppm)

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





No non-gaussian tails to +/- 5σ

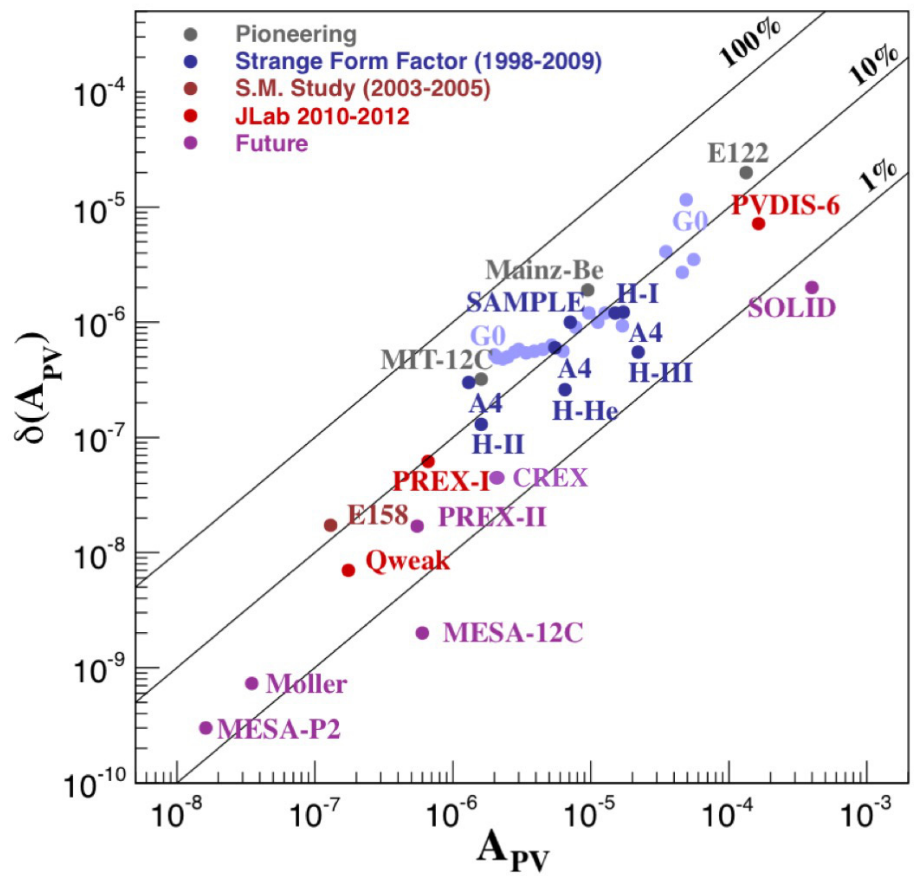
Detector signal noise dominated by electron counting statistics

3 Decades of Technical Progress

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

PVeS Experiment Summary

1st generation
2nd generation
3rd generation
4th generation

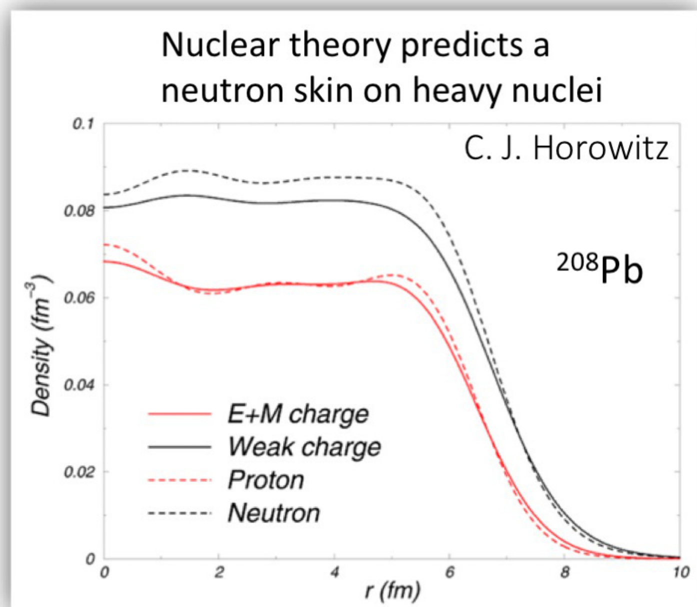


E122 – 1st PVES Expt (late 70's at SLAC)
Mainz & MIT-Bates in mid 80's
JLab program launched in mid 90's
E158 at SLAC meas PV Møller scattering
MOLLER at JLab in mid 2020's

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

PREX/CREX Concept

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



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)

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

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

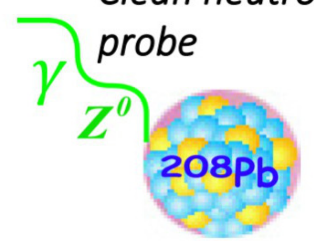
	Proton	Neutron
Electric Charge	1	0
Weak Charge	~0.08	-1

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

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

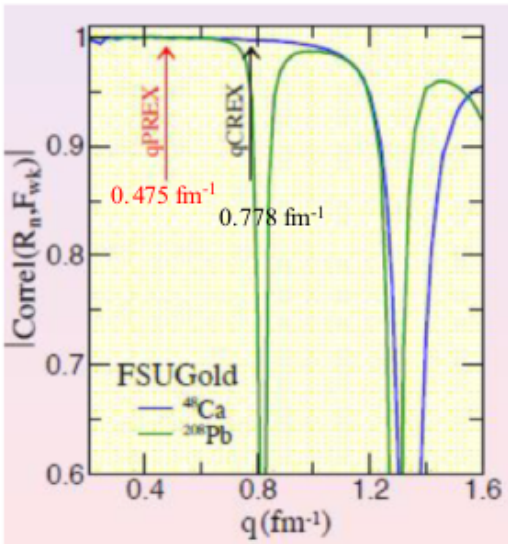
$$F_{n,p}(Q^2) = \frac{1}{4\pi}\int d^3r\ j_0(qr)\ \rho_{n,p}(r)$$

Clean neutron probe

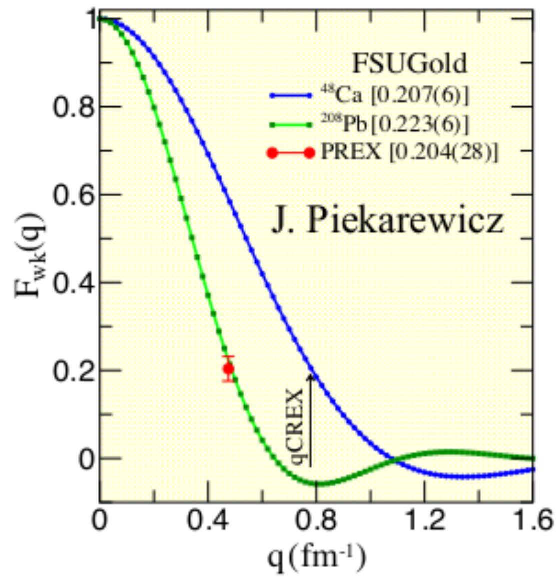


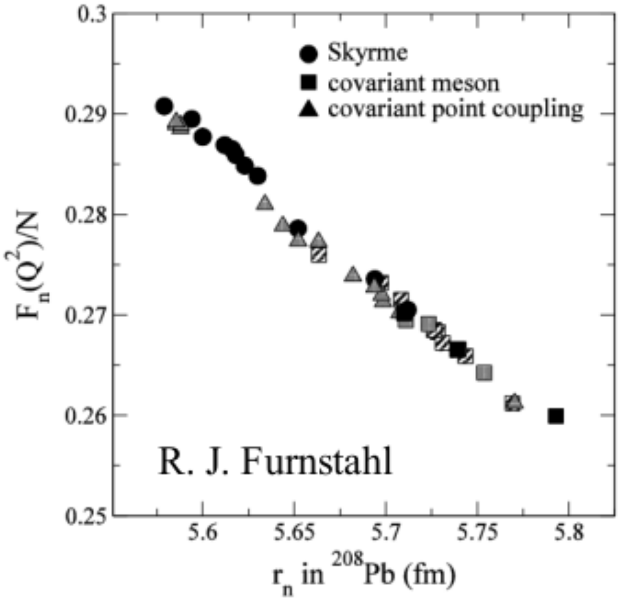
PREX/CREX Concept

At low Q^2 there is a tight correlation between R_n and $F_{wk}(Q^2)$ ⟹ 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





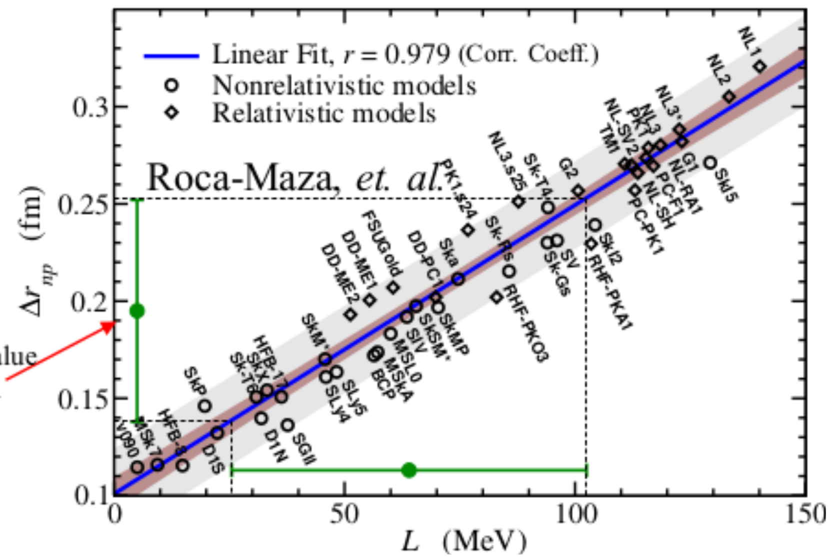
- Energy Density Functions (EDFs) characterized by a dozen free parameters that are calibrated to a host of well known properties of finite nuclei

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

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

* See Javier Roca-Maza's talk about Neutron structure and Symmetry Energy tomorrow at 11:00 AM

Arbitrary central value with PREX 0.06 fm proposed error bar



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

PREX/CREX Overview

PREX/PREX-II:

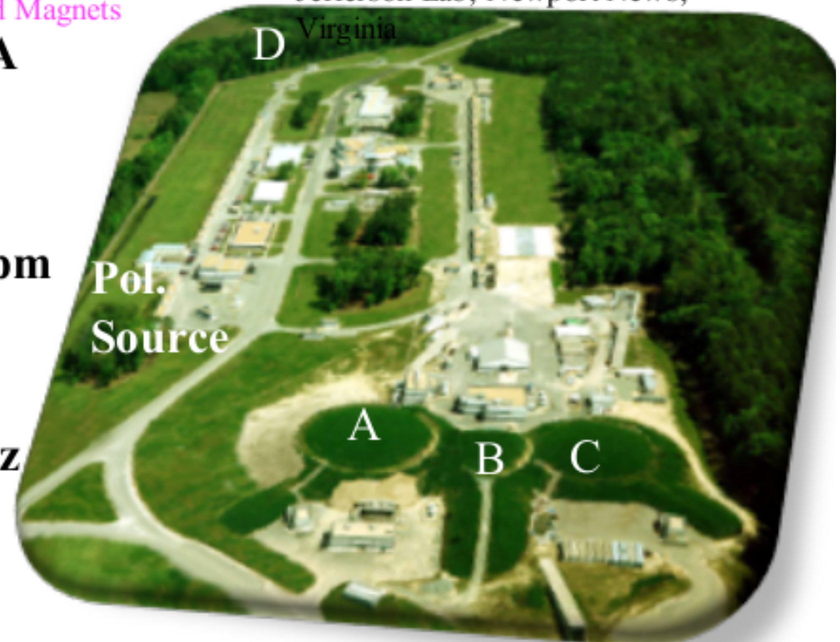
- 0.95 GeV e^- beam, 50-70 μA
- 0.5 mm thick ^{208}Pb target
- 5° scattered electrons
- Q^2 =0.0088 GeV^2, A_{PV}~0.5ppm
- 680 hours, ~35M pairs
- δA_{PV} ~ 15 ppb (3%)

CREX:

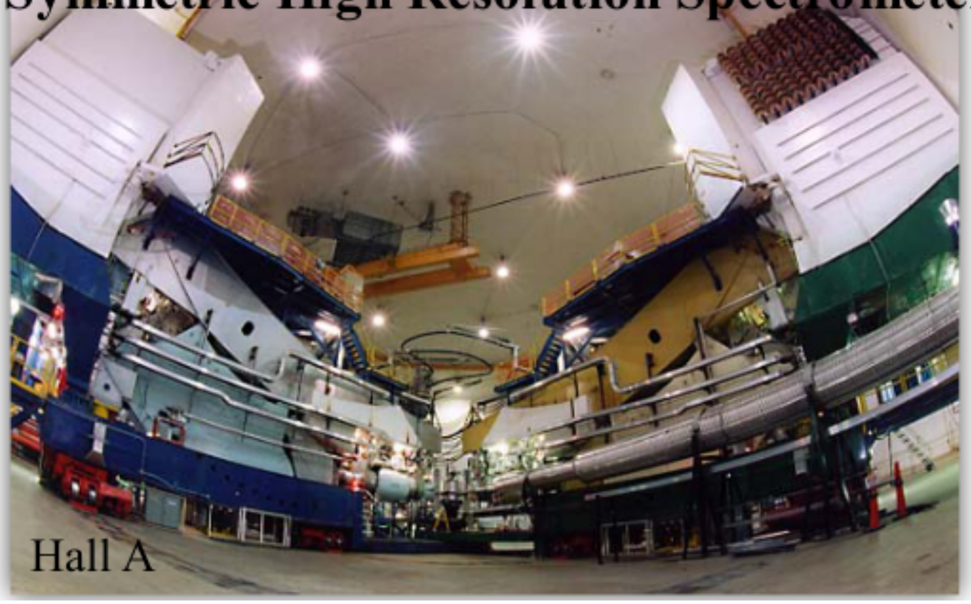
* See next talk by Juliette Mammei about CREX -- Target and Magnets

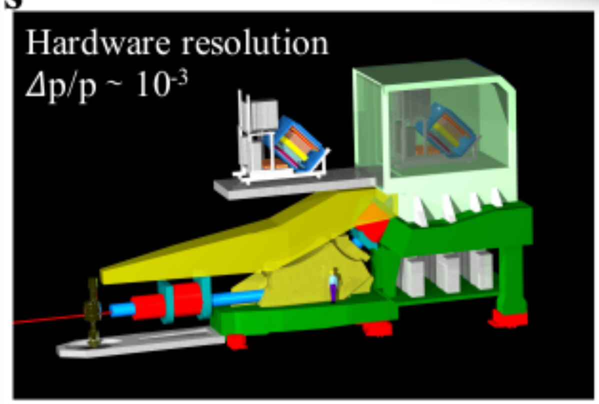
- 2.22 GeV e^- beam, 150 μA
- 5 mm thick ^{48}Ca target
- 5° scattered electrons
- Q^2 =0.037 GeV^2, A_{PV}~2ppm
- 780 hours, ~40M pairs
- δA_{PV} ~ 80 ppb (4%)

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

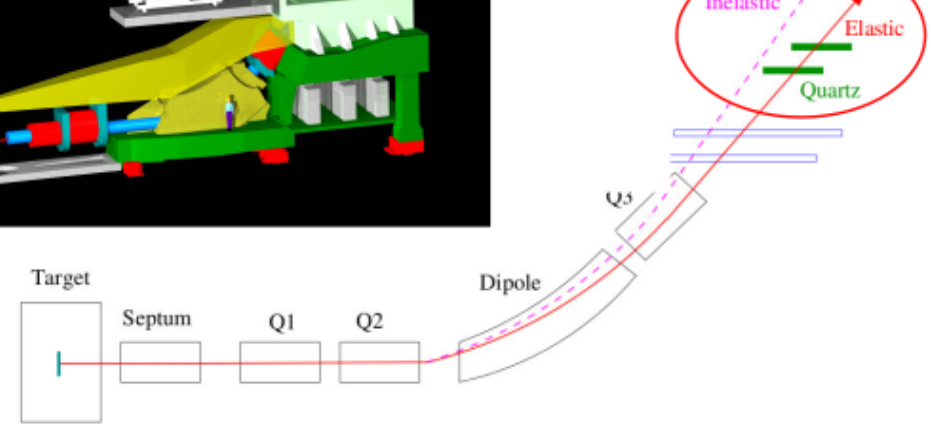


Symmetric High Resolution Spectrometers





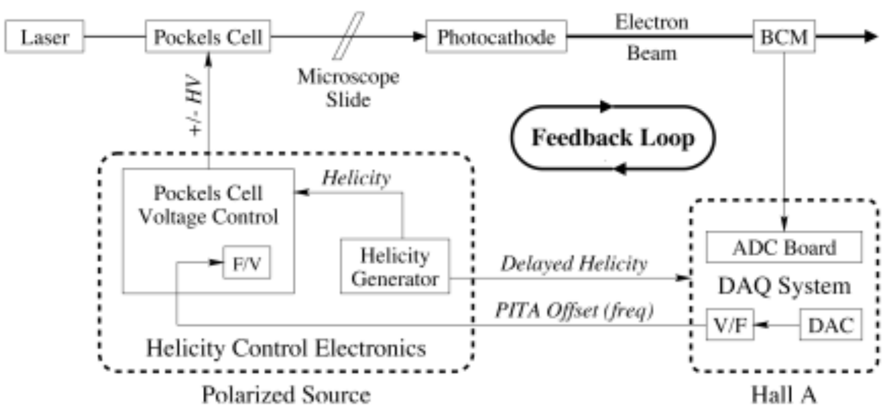
HRS and optics schematic



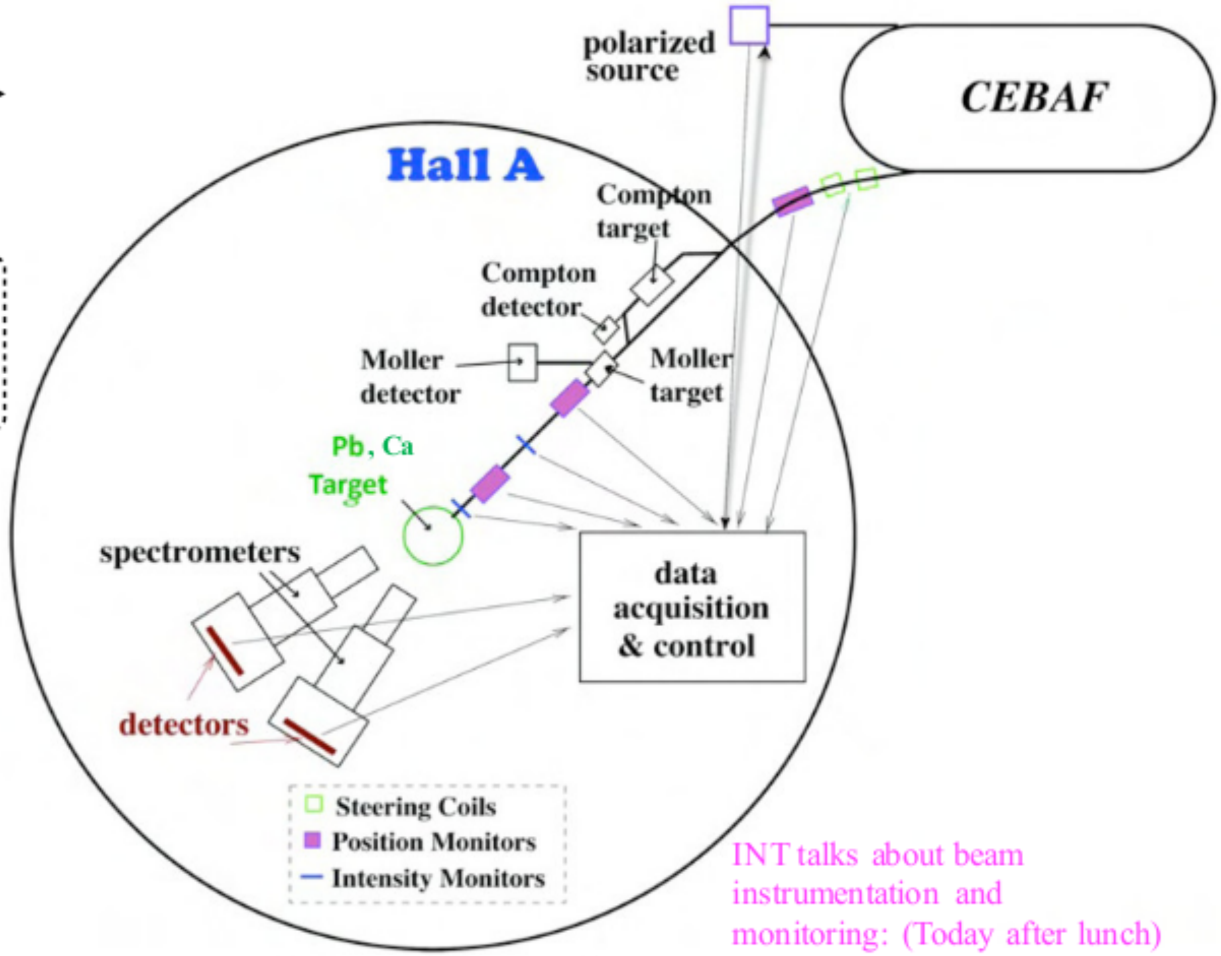
"Parity Quality" Beam Monitoring

(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

INT talks about beam instrumentation and monitoring: (Today after lunch)

Ciprian Gal: 2:00 PM "Source and Polarimetry"

Ye Tian: 2:25 PM "Beam Modulation and Position Monitoring"

PREX-I Systematic Errors

PREX goal for ~ 2% total systematic error achieved!

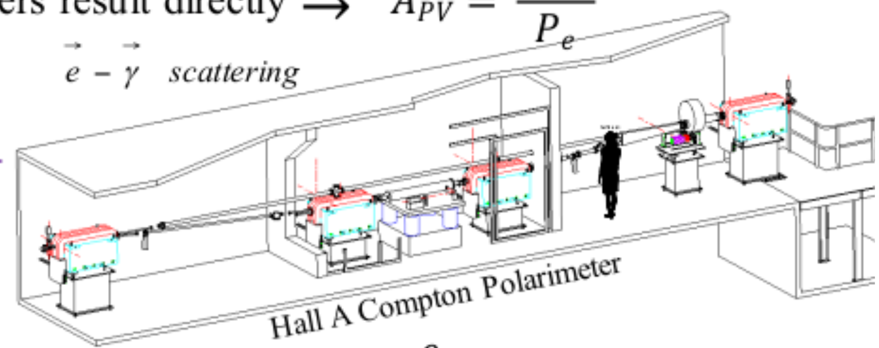
Systematic Error	Absolute (ppm)	Relative (%)
Polarization	0.0083	1.3
Detector Linearity	0.0076	1.2
Beam current normalization	0.0015	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2	0.0028	0.4
Target Backing	0.0026	0.4
Inelastic States	0	0
TOTAL	0.0140	2.1

*See Chandan Ghosh's talk on "Optics and Tracking" today at 2:50 PM

Crucial normalizations:

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

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

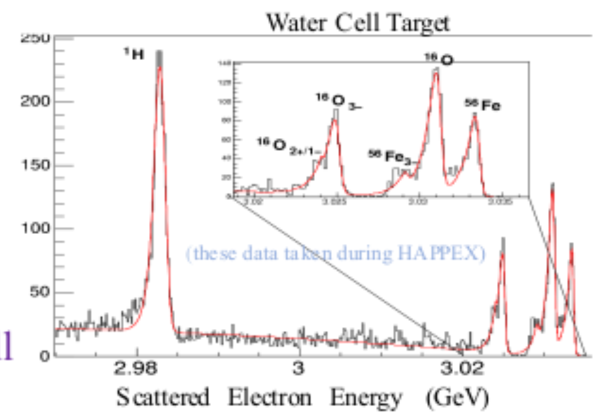
E' (scattered energy): NMR probe in HRS B-field

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

Absolute angle calibration via nuclear recoil variation

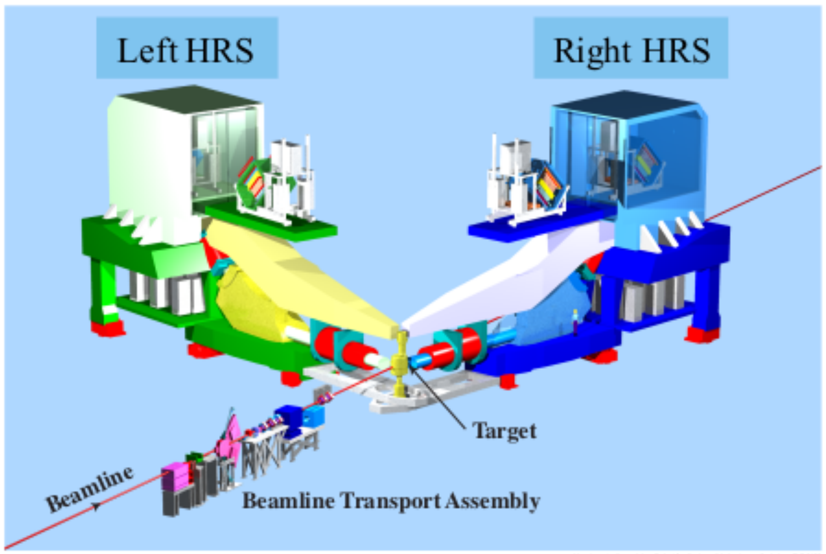
$$\delta E_{\rm loss} \approx \frac{\theta^2}{2}\frac{E^2}{M_A}$$

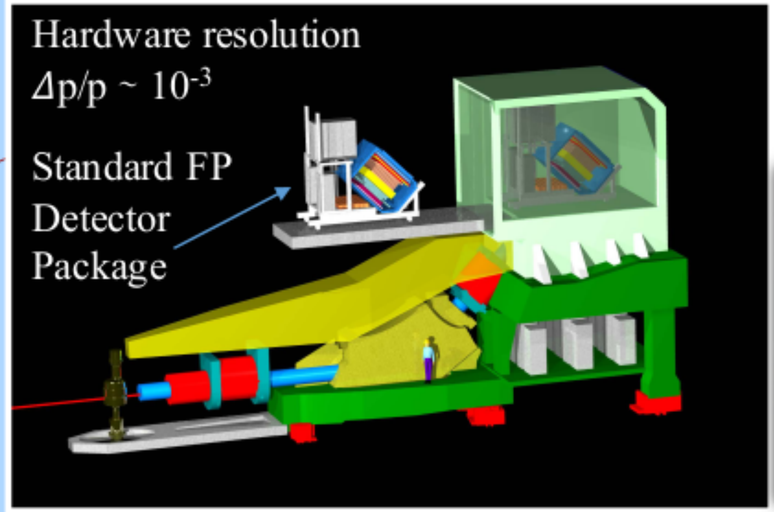
Q^2 distributions obtained by dedicated low-rate runs with tracking detectors triggered on quartz pulse-height (0.4% overall error on Q^2)



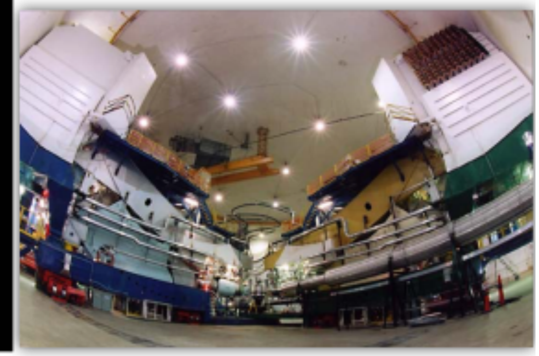
Integrating Detector Focal Plane for PV Experiments: HAPPEX through PREX-II/CREX

Hall A





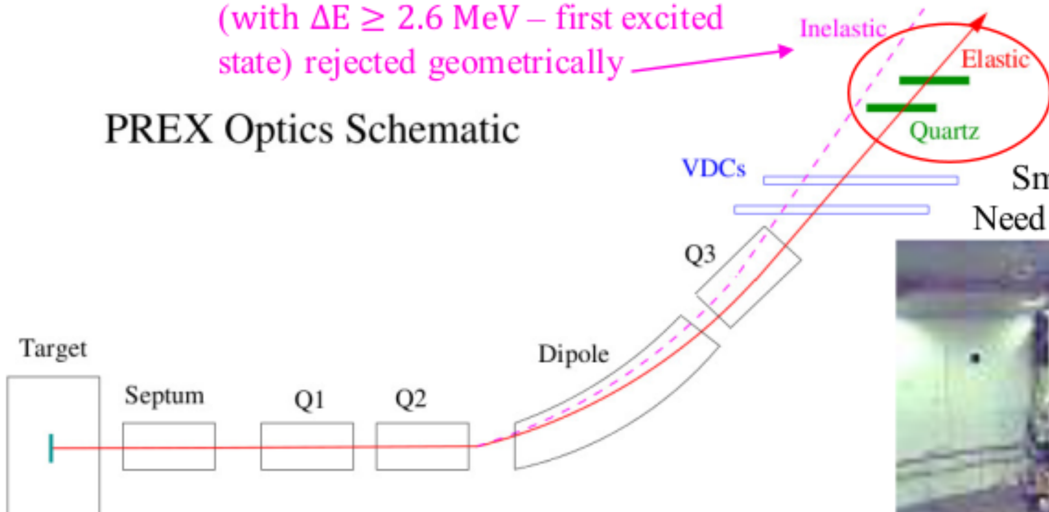
Symmetric High Resolution Spectrometers



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

- PV Detectors positioned in FP inside shielded HRS hut

PREX Optics Schematic



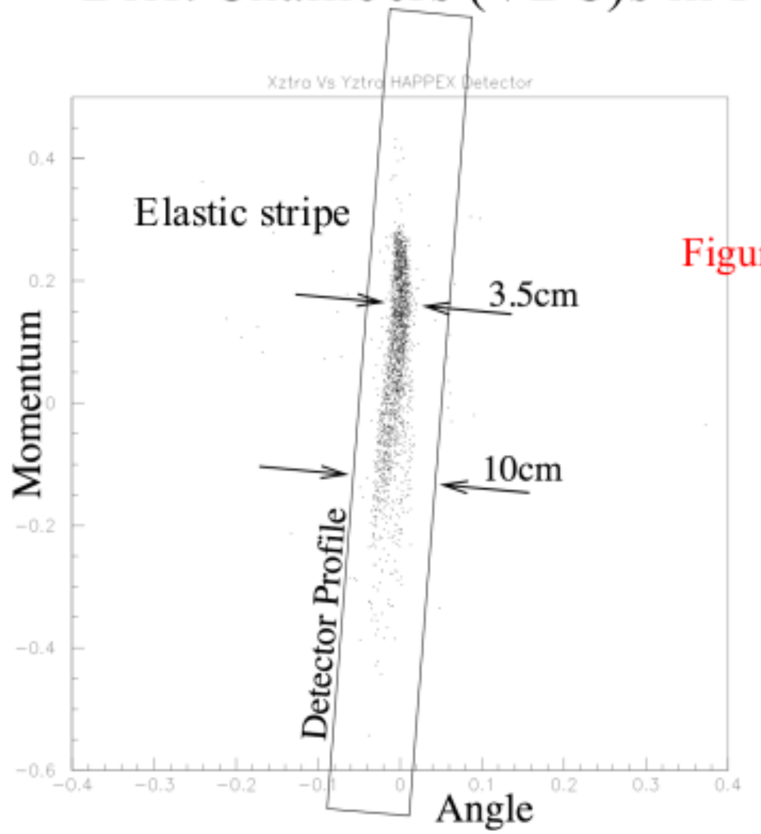
Smallest angle: $\pm 12.5^{o}$
Need Septum to get to $\pm 5.0^{o}$

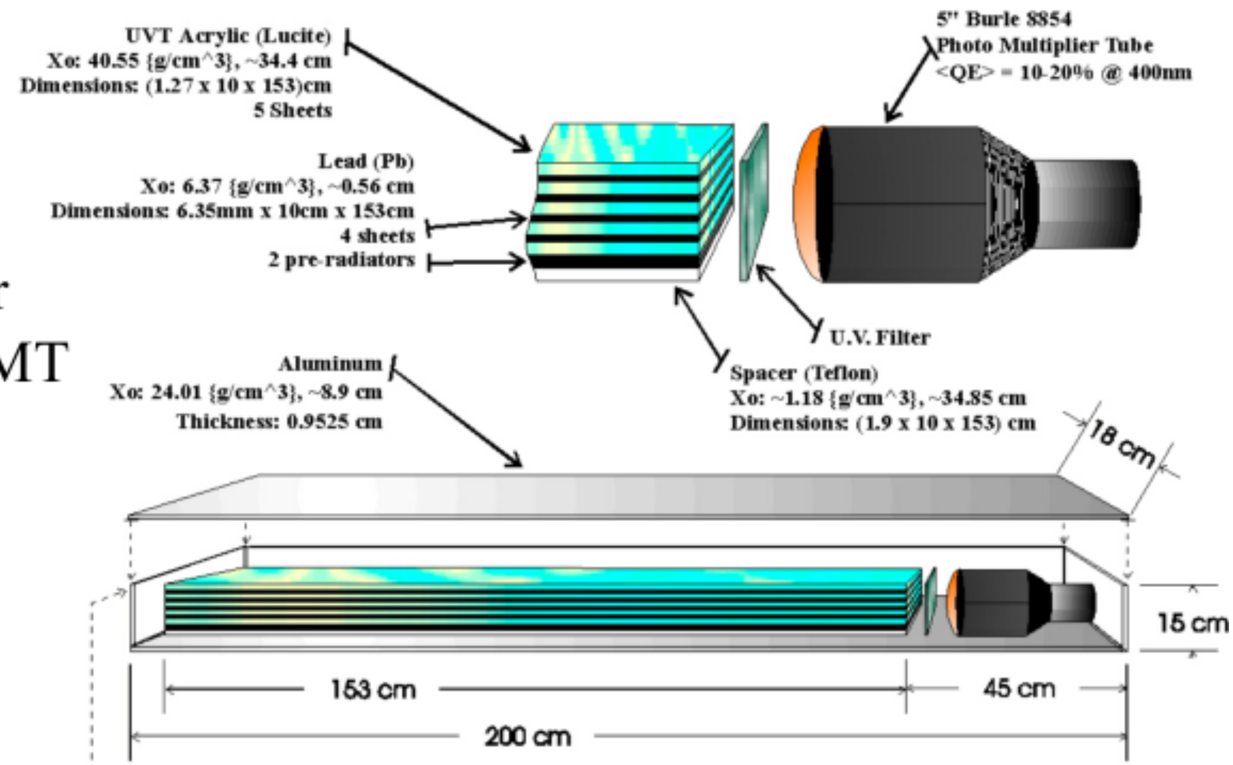
- Standard focal plane (FP) detector packages are removed during high flux PV experiments
- Specialized focal plane detectors installed and positioned to **intercept only elastically scattered electrons** – uses precision optics and hardware resolution
- Integrated PE yields from detectors are proportional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

Requirements for PVES Integrating Detectors

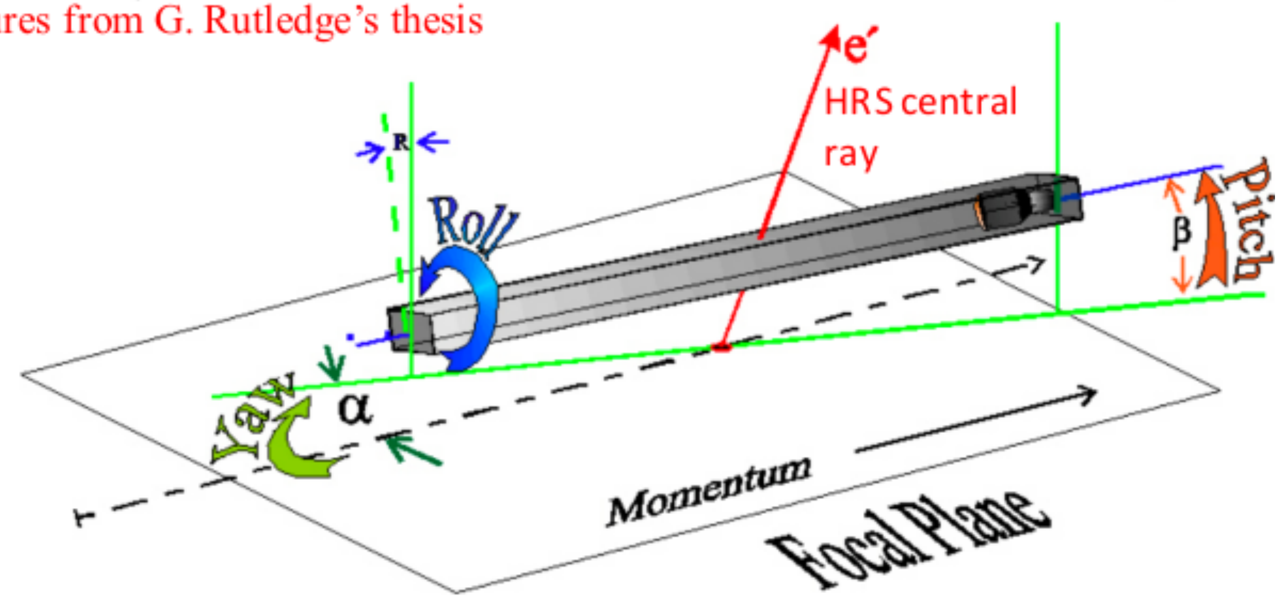
- Radiation hardness – active medium must give consistent response under extreme and prolonged flux exposures
- Should count individual electrons with good ($\sim$ 20%) resolution – to minimize statistical error inflation
- Photo-sensitive device must give highly linear response (at 0.3% level for PREX-II/CREX) – 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

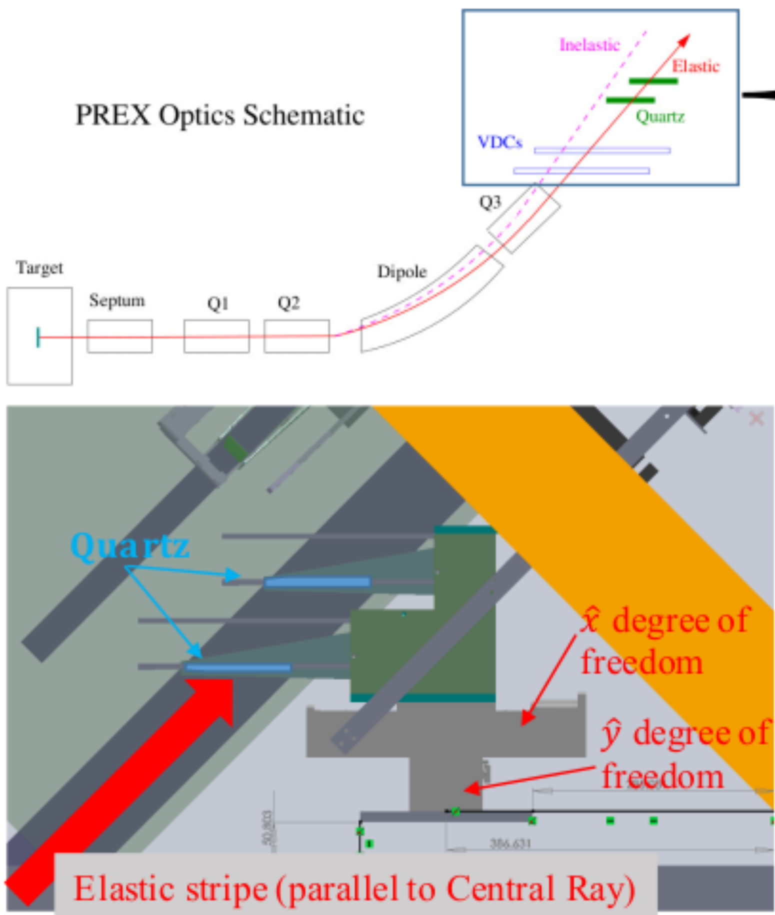


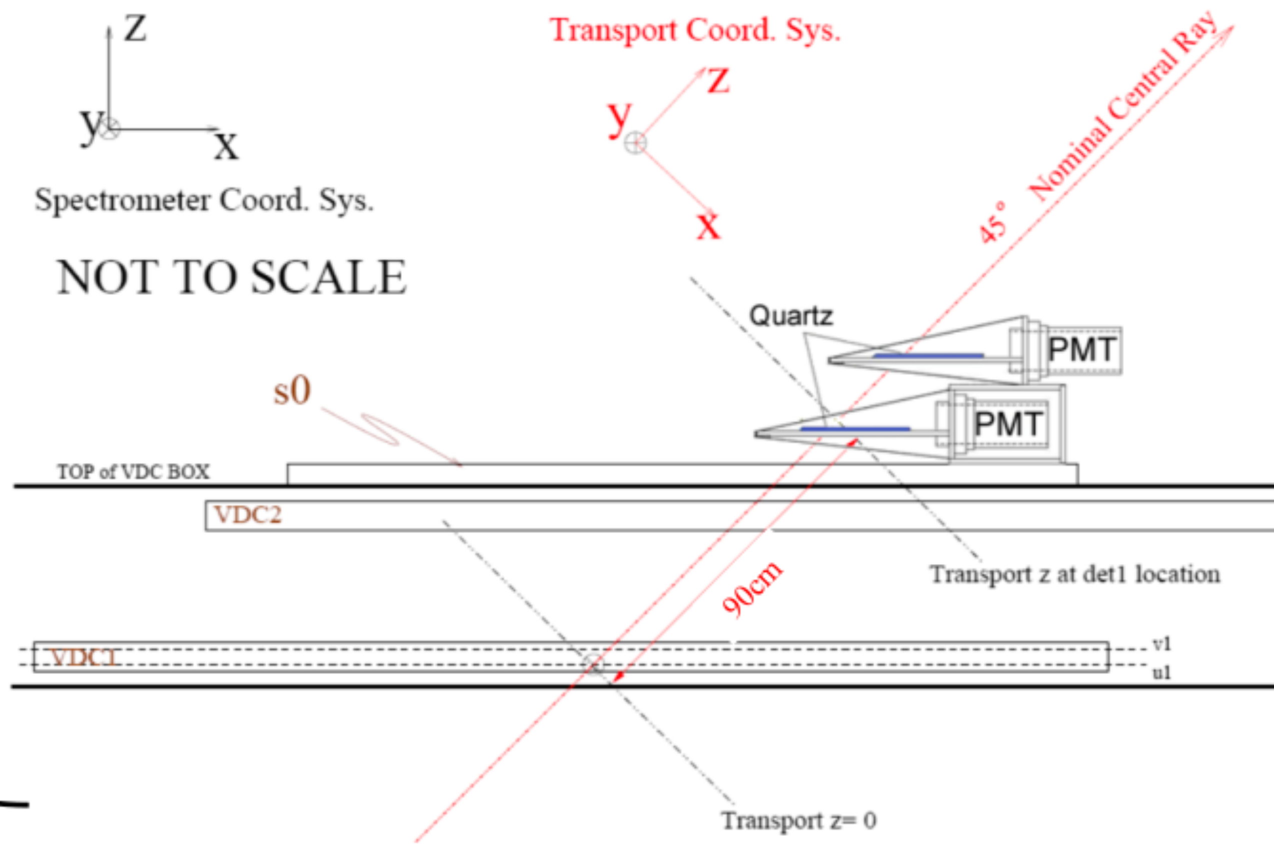


Figures from G. Rutledge's thesis



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

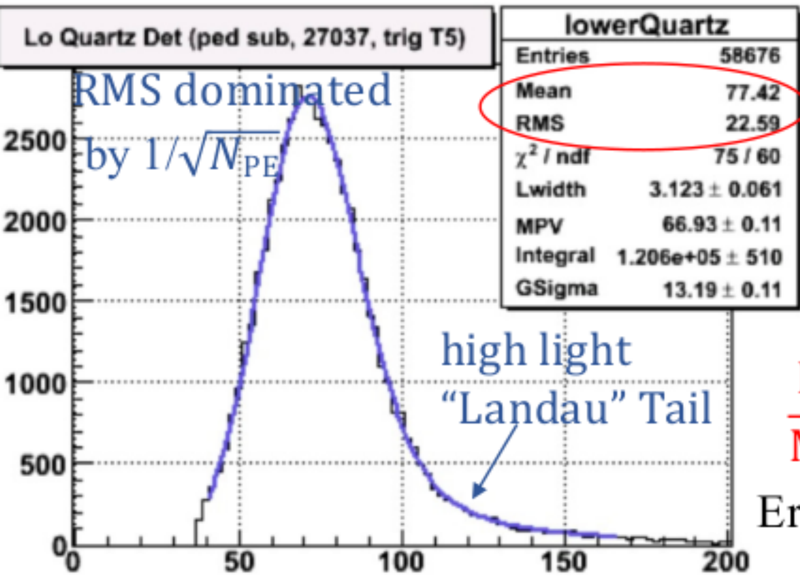




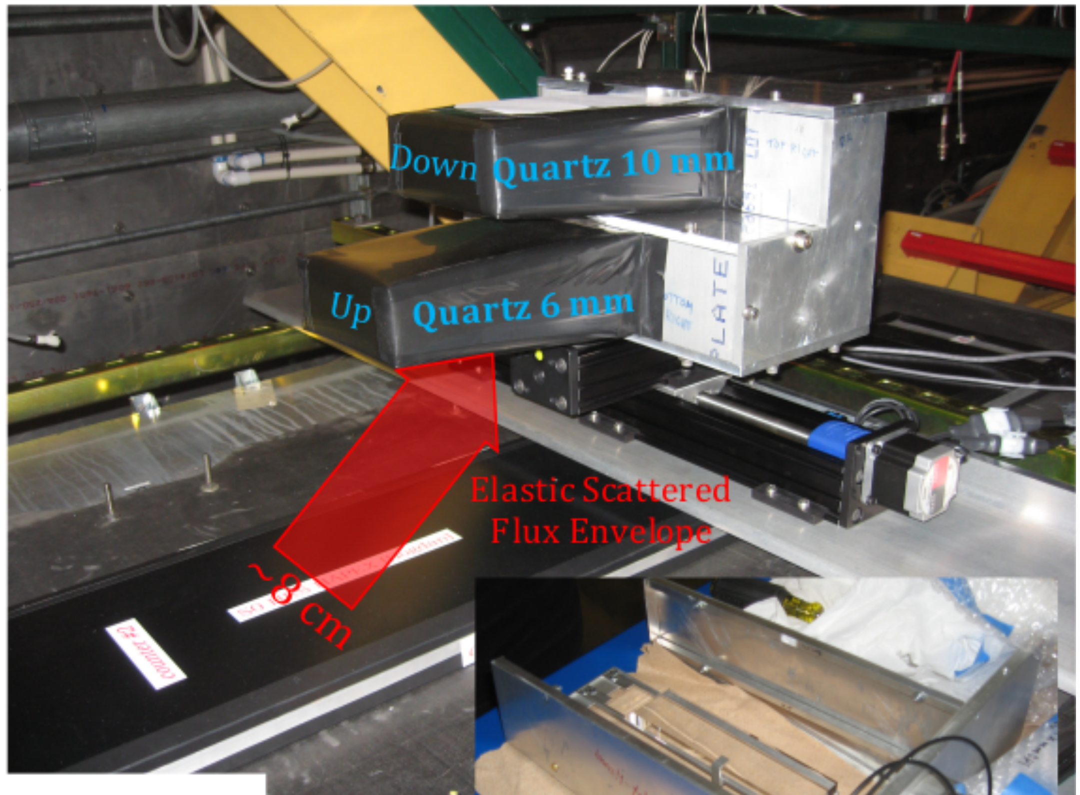
- Uses rad-hard, optically polished fused silica (quartz) tiles for Cherenkov active medium
- Scattered electrons traverse quartz at nominal angle of 45 degrees
- Aluminum air-core (specular reflector) light guide directs Cherenkov light to 2 inch PMT
- Linear translation stages provide precision positioning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

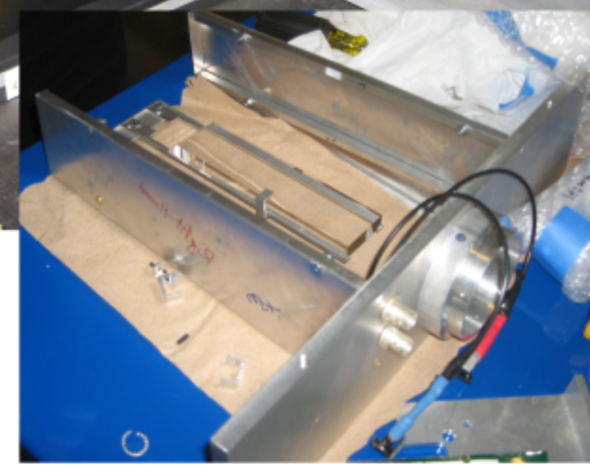
Main Integrating Detector for PREX-I ("thin" quartz Tandem Detector)

- 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)



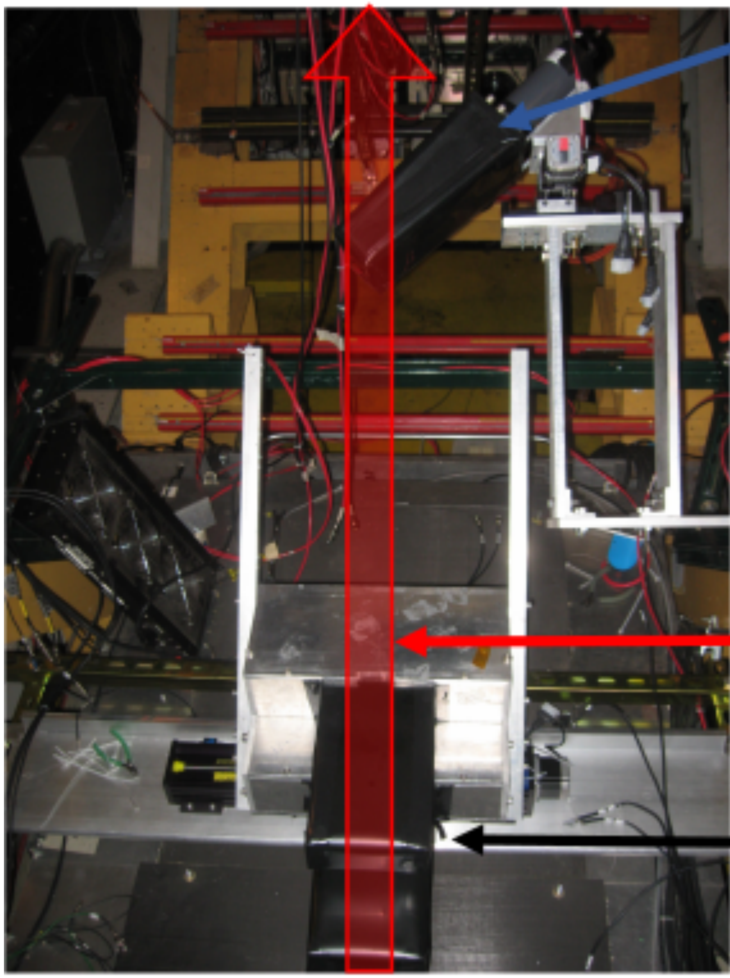


$$\frac{\text{RMS}}{\text{Mean}} = 29\% \text{ resolution}$$

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

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

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

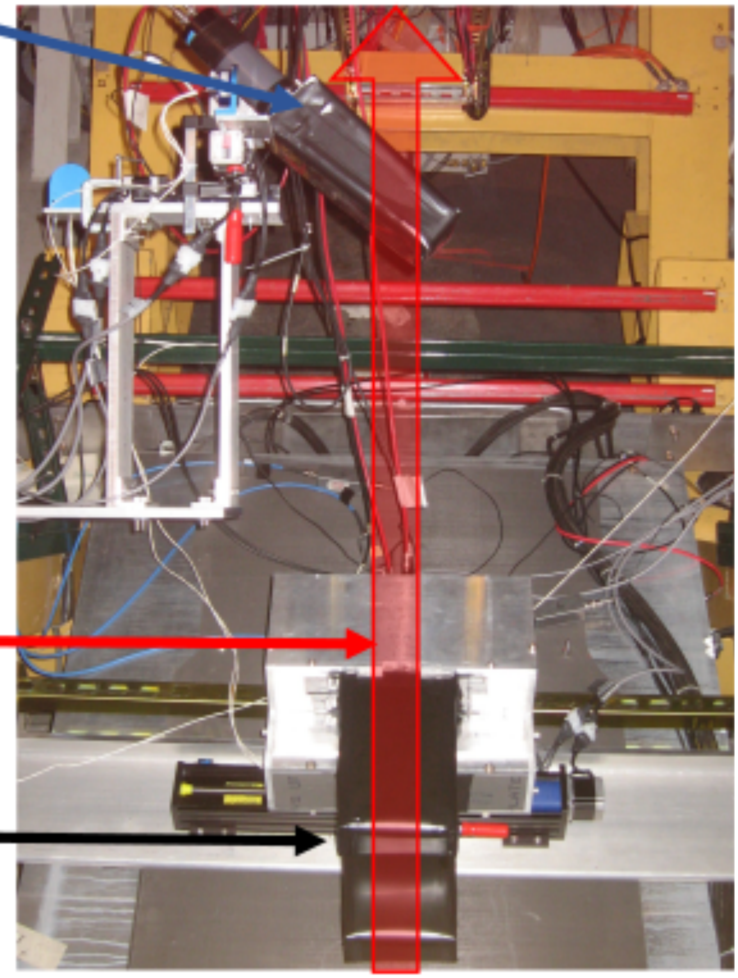


A_T Detectors

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

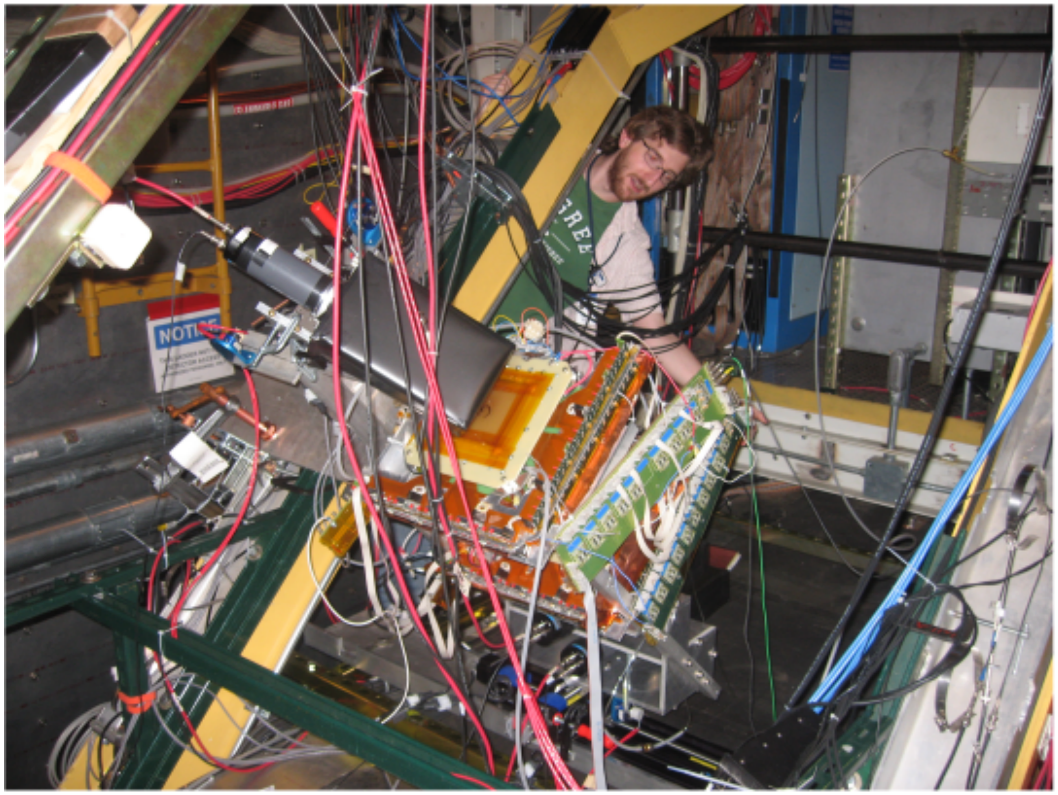
Elastic scattered flux envelopes

Main Tandem Detectors

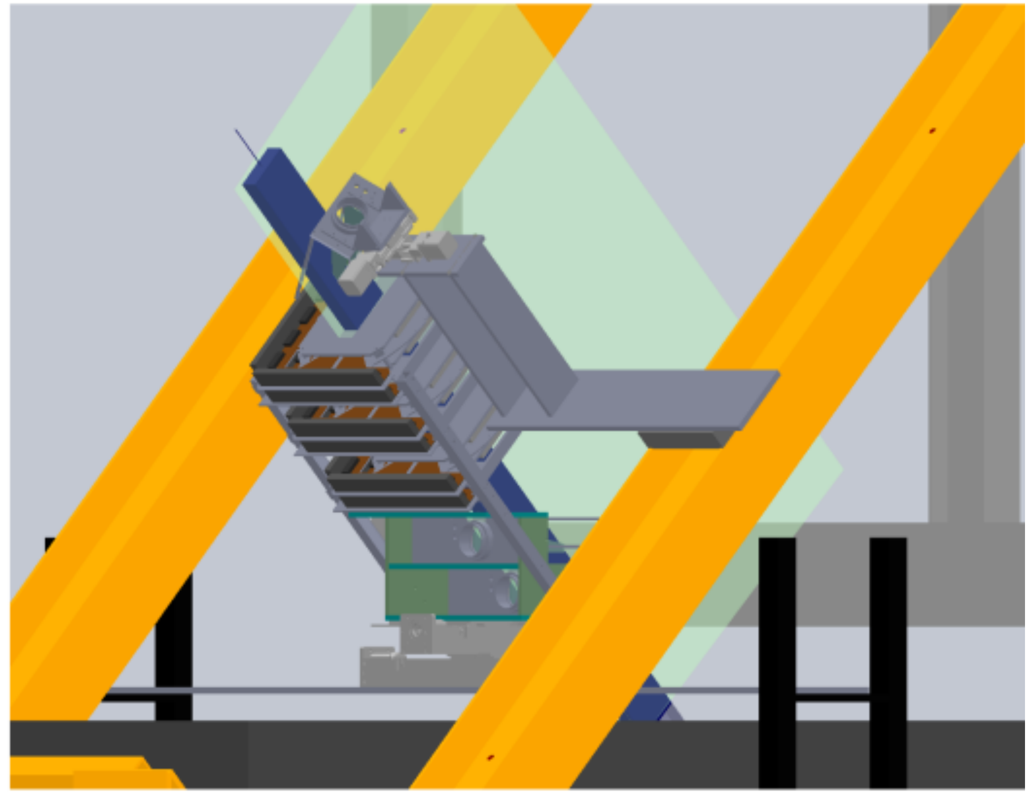


Left HRS — Views along dispersive $\hat{x}$ — Right HRS

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

Beam Normal Single Spin Asymmetry

Introduction

- Electron beam polarized transverse to beam direction
- Induces azimuthal parity-conserving asymmetry (A_n)

  $\longrightarrow A_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$, with $\uparrow$ ($\downarrow$) parallel (anti-parallel) to normal pol. vector $\hat{n} = \frac{(\vec{k} \times \vec{k\prime})}{|\vec{k} \times \vec{k\prime}|}$; $\vec{k}$ ($\vec{k\prime}$) initial (final) electron mom.

  $\longrightarrow A_{meas}(\phi) = A_n \vec{P}_e \cdot \hat{n}$ where ϕ is angle between $\vec{P}_e$ and $\hat{n}$
- A_n vanishes in the Born approximation, thus can provide sensitive probe of two (or multi) photon exchange effects
- Order of magnitude: $A_n \sim \alpha_{em} \cdot \frac{m_e}{E_e} \sim 10^{-6} - 10^{-5}$

  $\longrightarrow$Historically, very challenging measurement

  $\longrightarrow$Precision measurements feasible with PV expt. setup

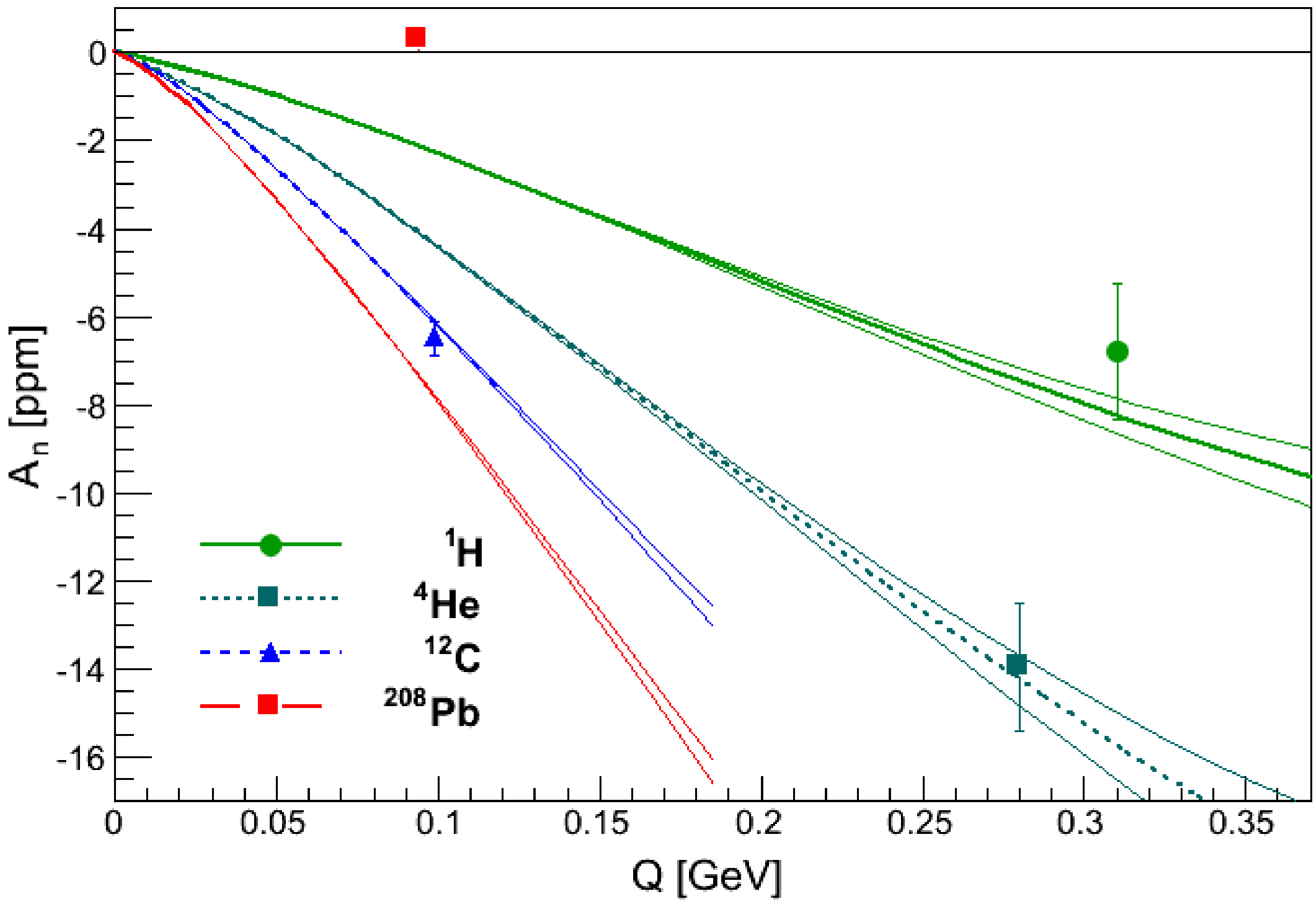
Beam Normal Single Spin Asymmetry

Measurement Motivations

- One of the largest potential false asymmetries in precision PVeS experiments
- As PVeS experiments push to higher precision, corrections for BNSSA leakage become increasingly important
  - ⟶Leakage suppressed by axially symmetric detectors and minimizing transverse polarization component
  - ⟶But still has potential for large systematic contribution
  - ⟶PVeS experiments perform dedicated measurements of A_n to quantify leakage correction
- Test theoretical framework of calculations, and specifically the 2γ exchange contribution, to further push precision frontier

Data and Calculations: HAPPEX/PREX

- S. Abrahamyan, *et. al.*[Jlab HAPPEX and PREX Collab.] PRL **109**, 192501 (2012)
- M. Gorchtein, C. J. Horowitz, PRC **77**, 044606 (2008)
- Surprising result: Wild disagreement for Pb measurement!



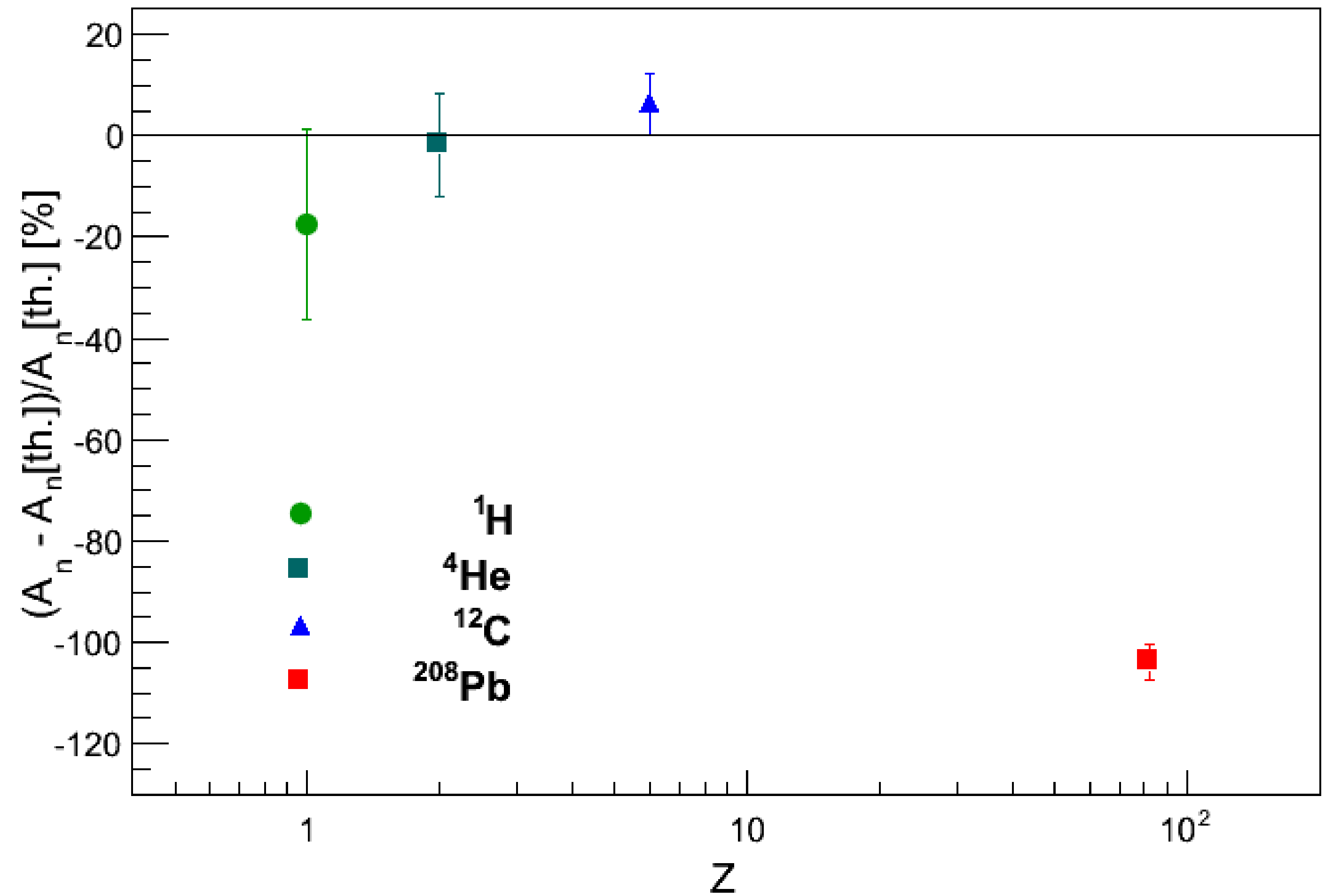
PREX Pb Discrepancy/CREX Ca Measurements

- What is the reason for wild disagreement?

Coulomb Distortions? Something else? Need new calculation

- Will measure intermediate Z nuclei ^{40}Ca and ^{48}Ca:

Can give understanding of dispersion versus Coulomb corrs



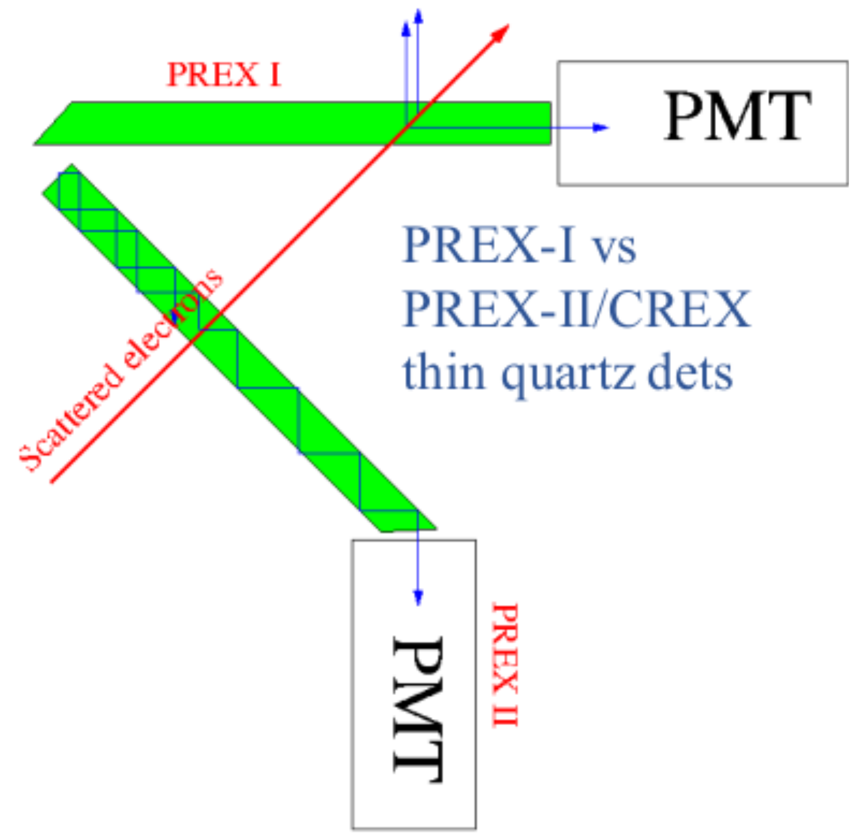
Integrating Detector Design change between PREX-I and PREX-II/CREX

- 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 $\sqrt{2}$

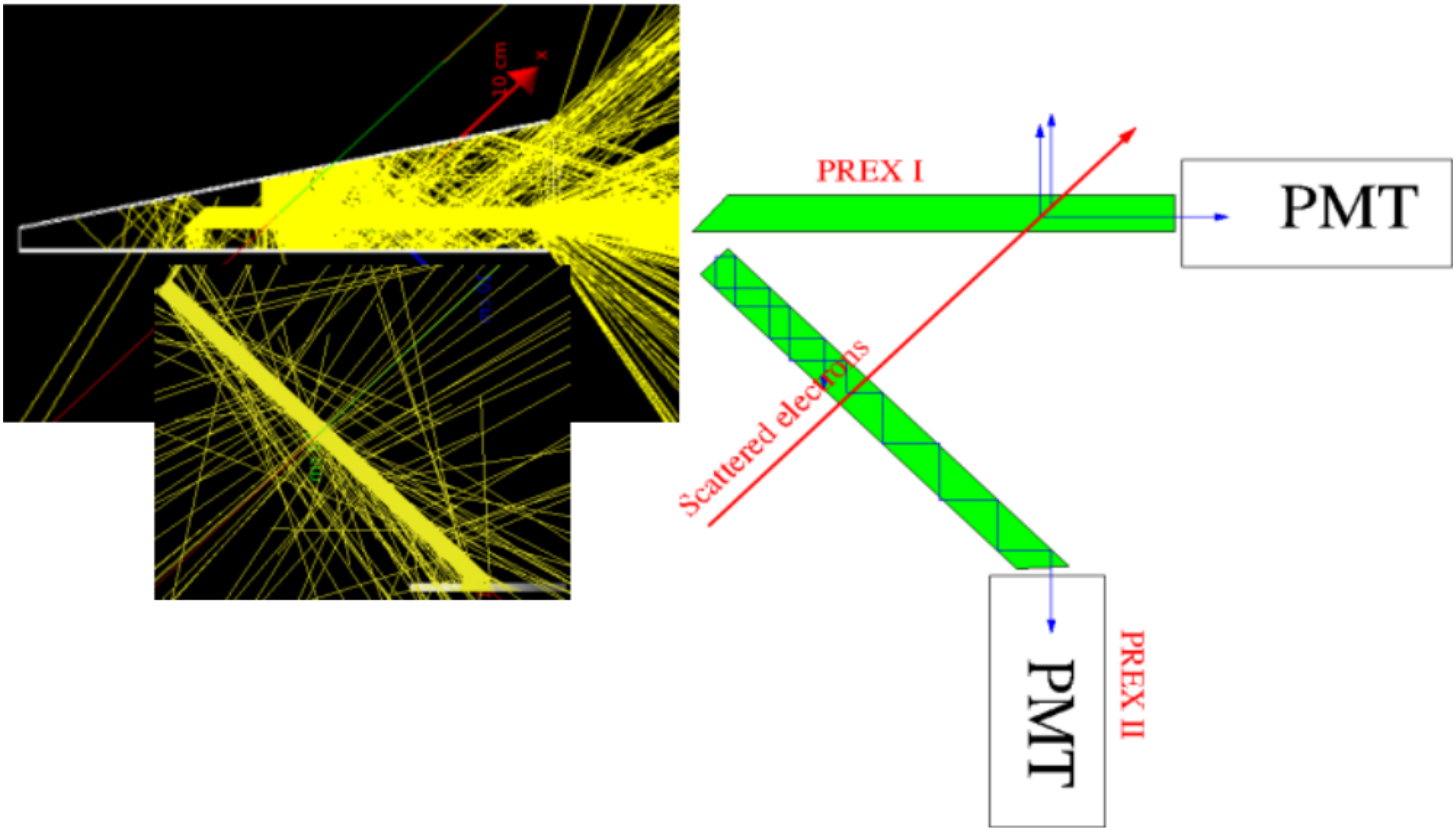
- However, there is more light yield variation for electrons with different incident angles

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

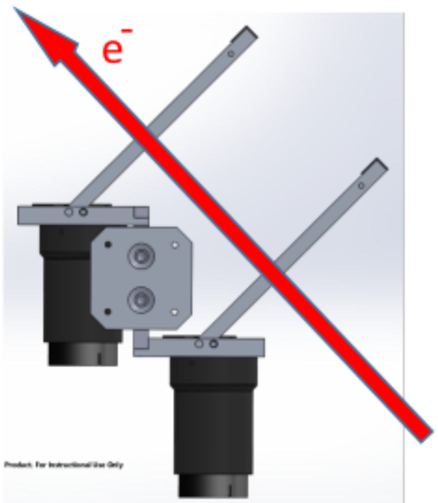


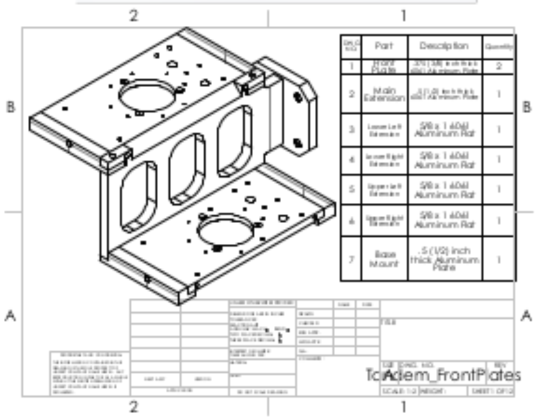
PREX-I vs PREX-II/CREX thin quartz dets

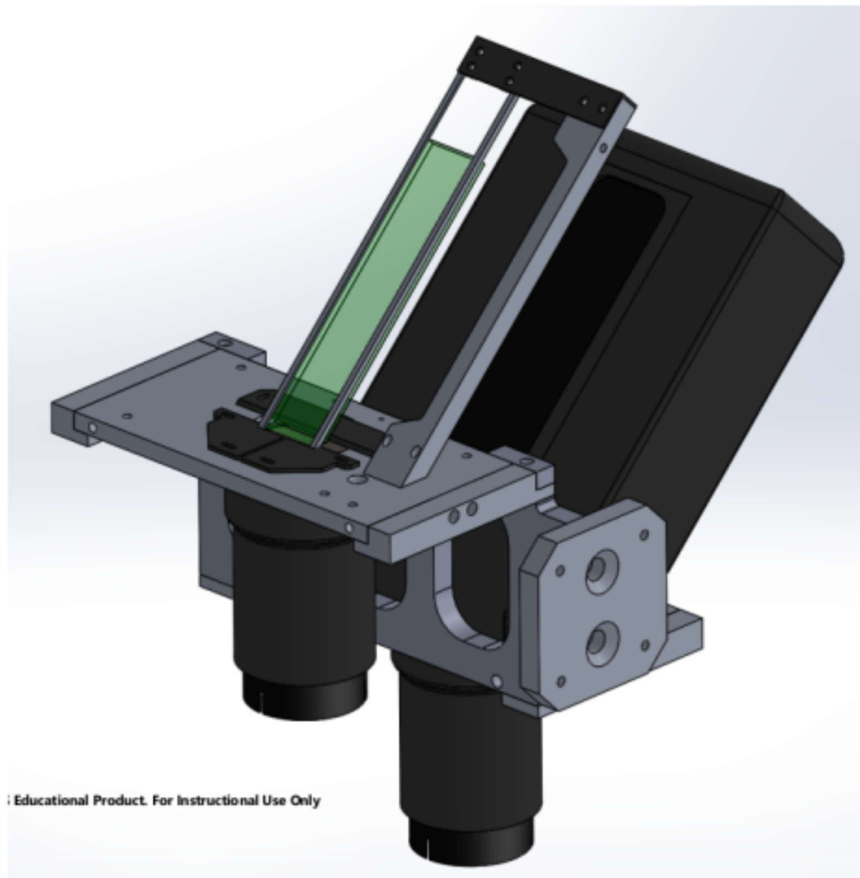
G4 Event Visualizations: PREX-I vs PREX-II/CREX

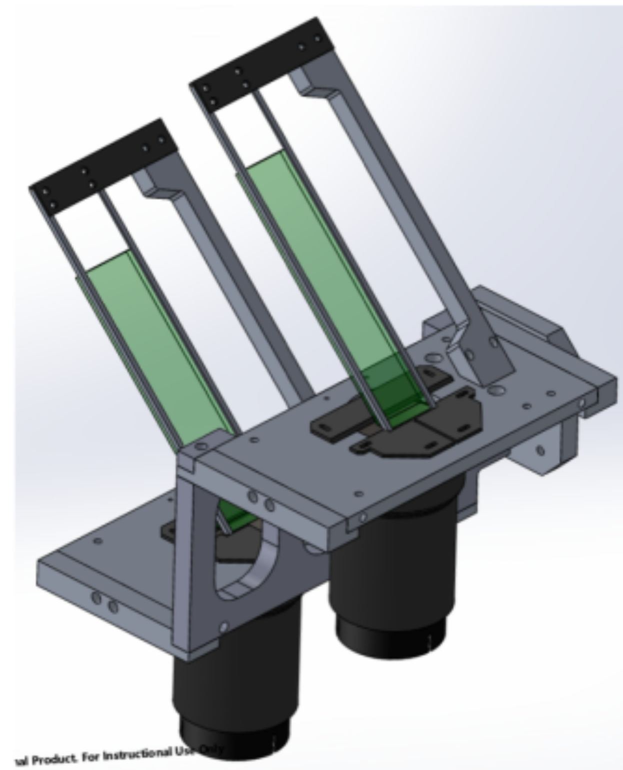


Main Integrating Detectors for PREX-II/CREX





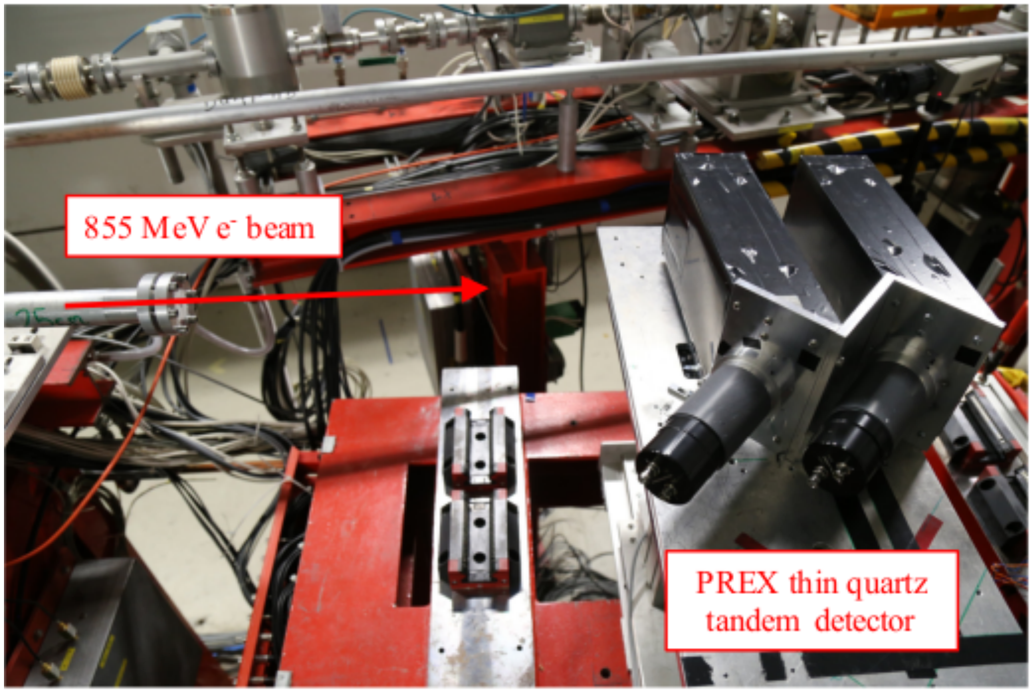


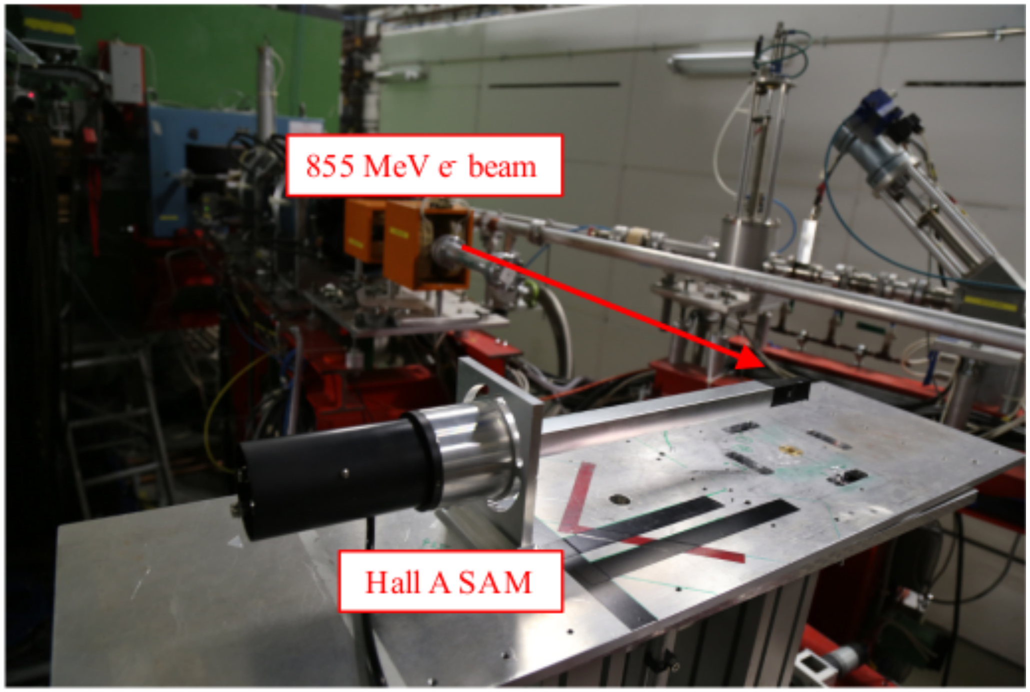


- Both Left and Right HRS main detectors are assembled and ~ready to go
- PREX will use 5 mm thick quartz for all detectors
- CREX will use 6 mm thick quartz upstream and 10 mm downstream

MAMI testbeam May 24-27, 2016

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

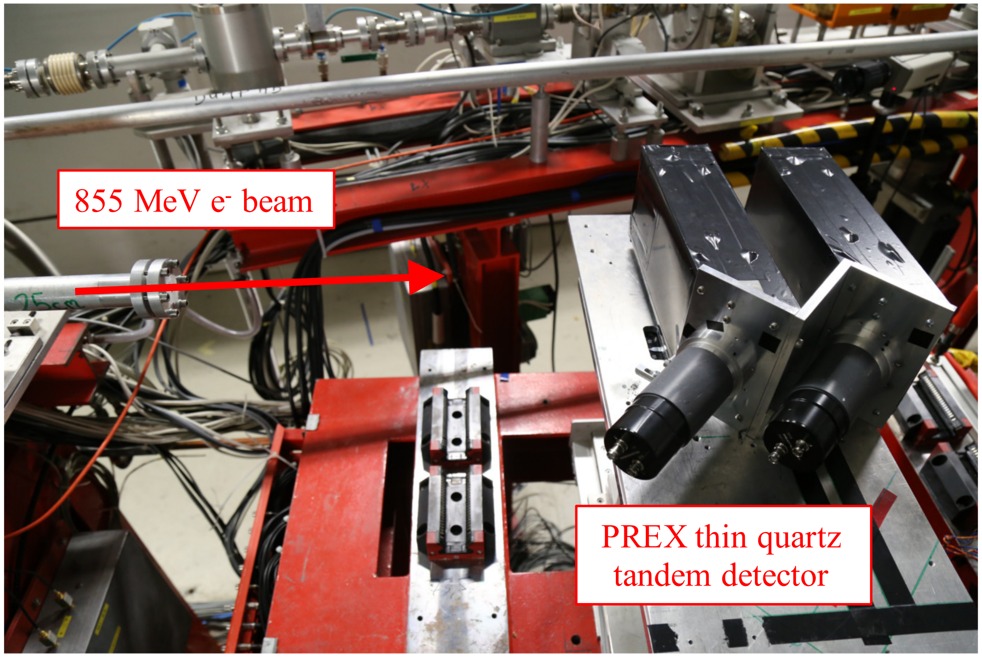




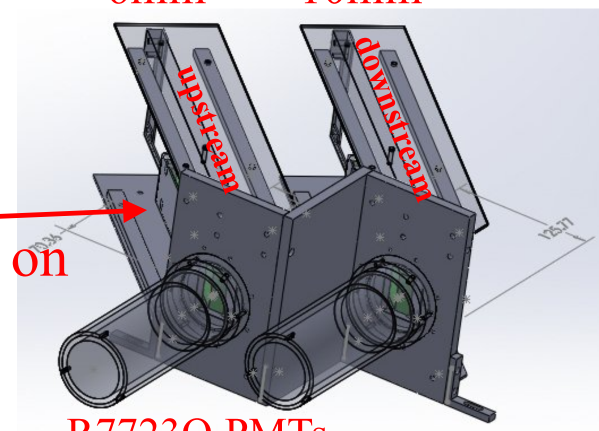
- 6mm and 10mm Tandem mount
- Near normal e^- incidence

- 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



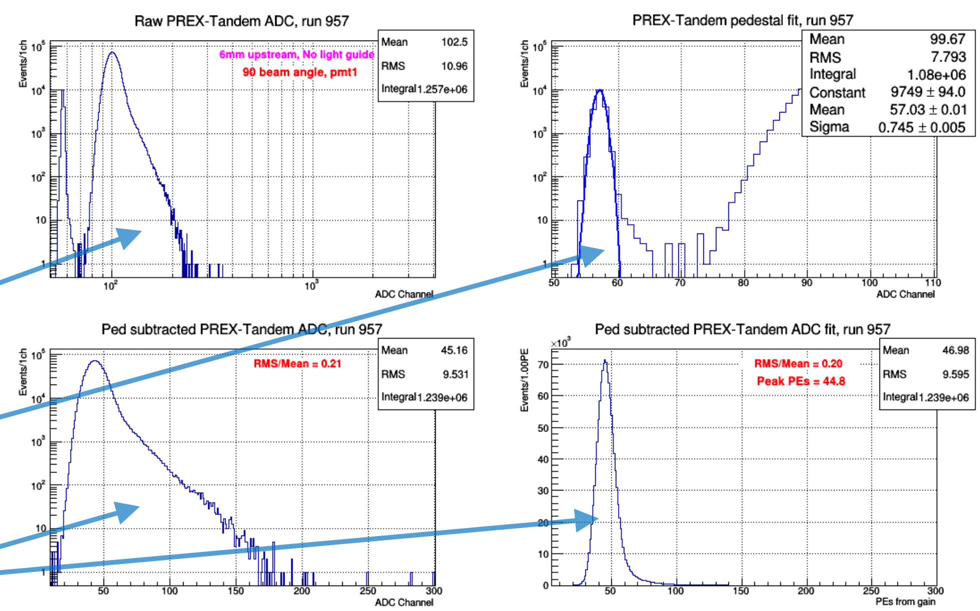
Spectrosil2000 thicknesses: 10mm 6mm and 6mm 10mm



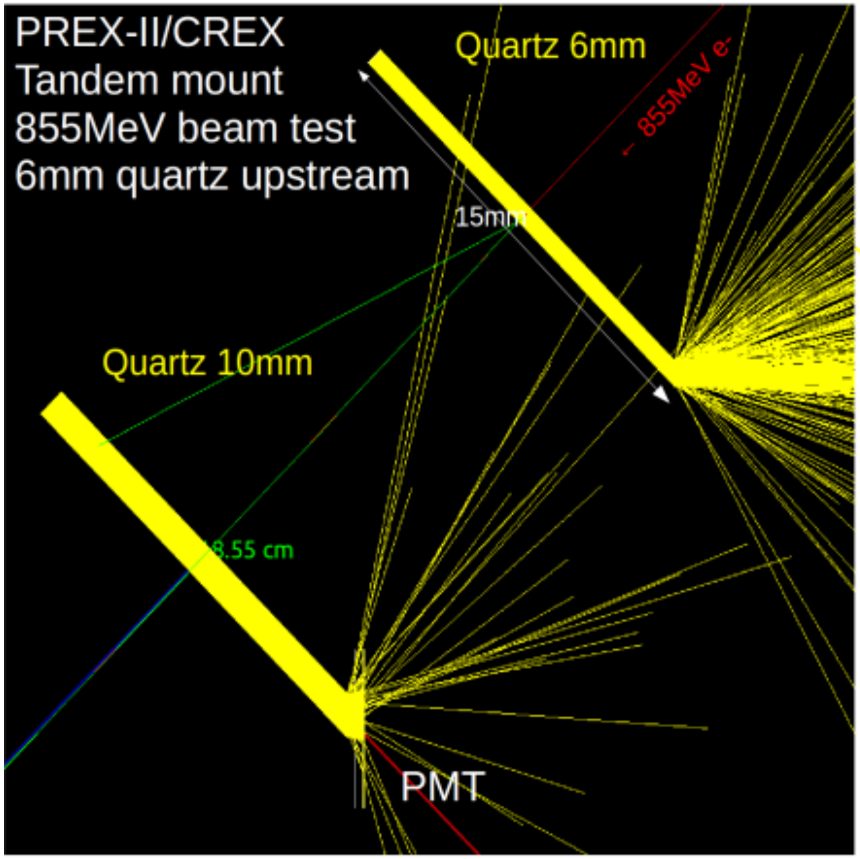
e- beam Centered on quartz at ~90°

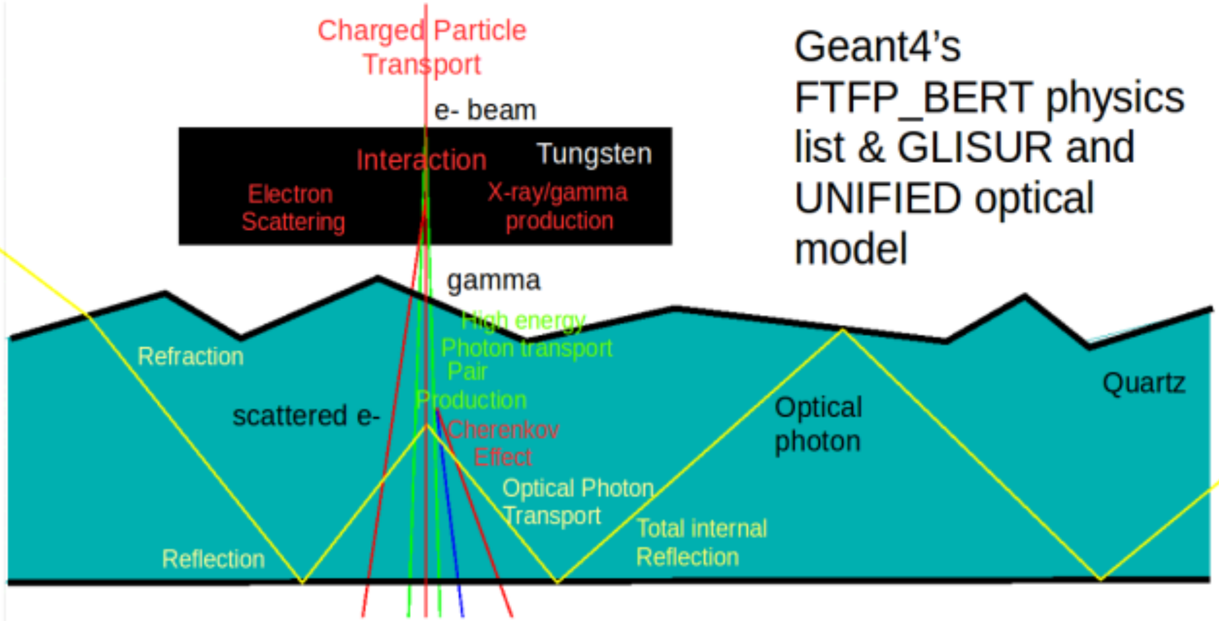
R7723Q PMTs

- 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

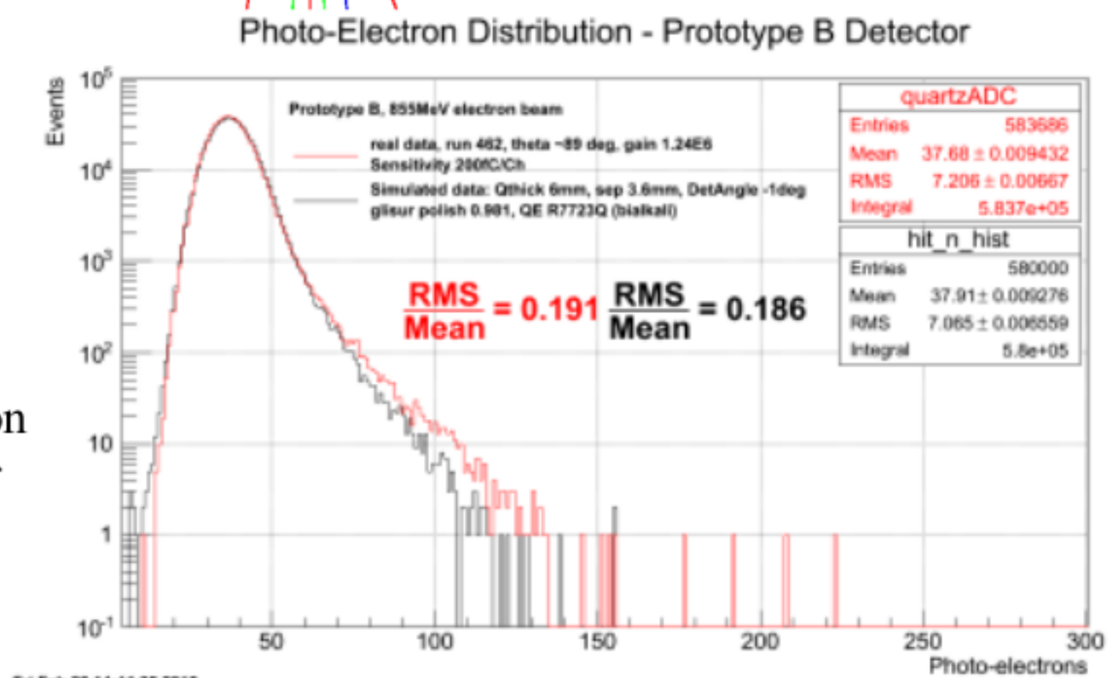


Optical Monte Carlo (qsim) Benchmarking



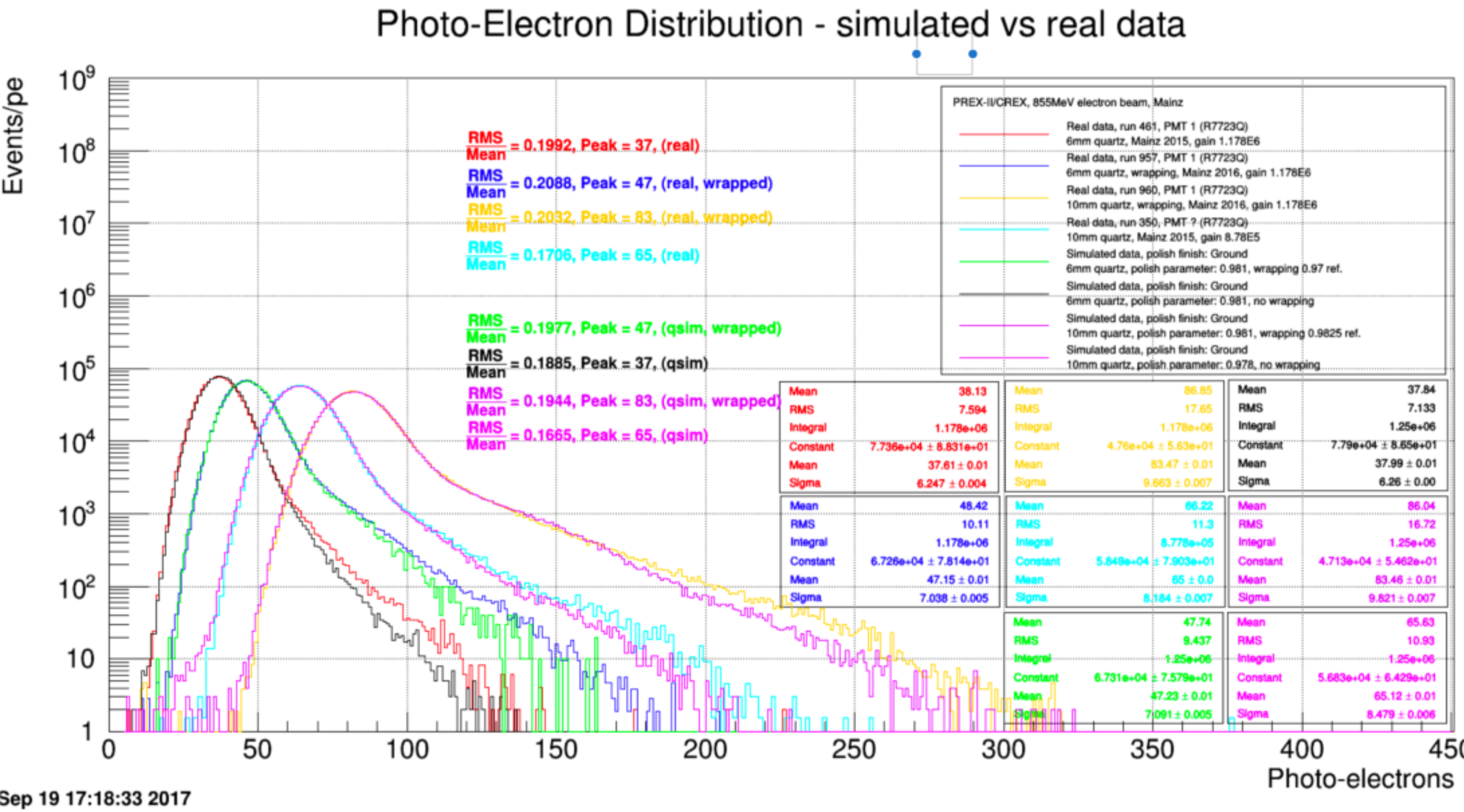


Geant4's FTFP_BERT physics list & GLISUR and UNIFIED optical model

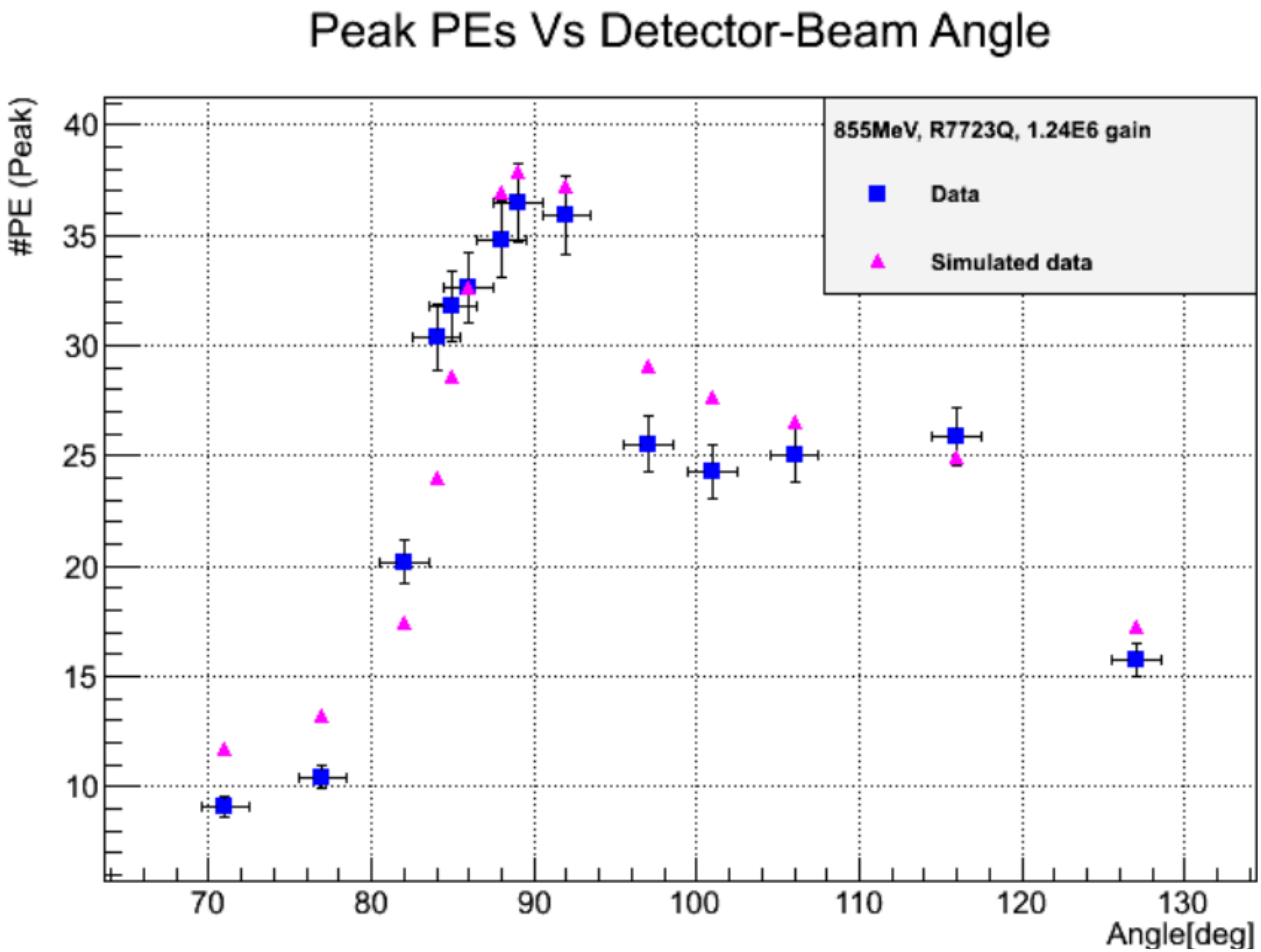


- Detailed geometry; pmt quantum efficiency sampling; refractive index dispersion; light attenuation in quartz; photo-cathode attenuation and reflection; quartz ground polish parameter
- Glisure ground polish parameter is tuned to make agreement between simulation and data

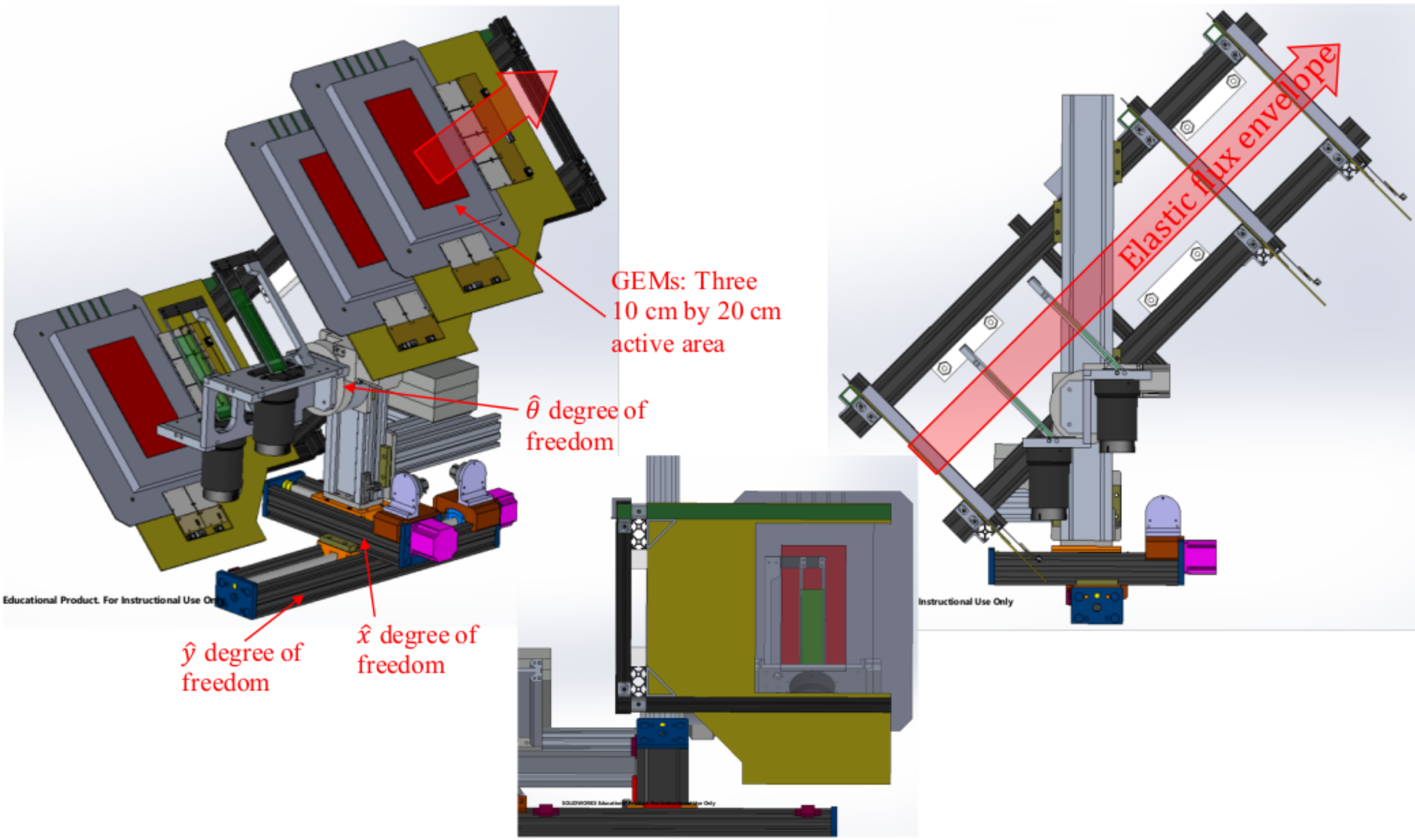
Optical Monte Carlo (qsim) Benchmarking



Optical Monte Carlo (qsim) Benchmarking

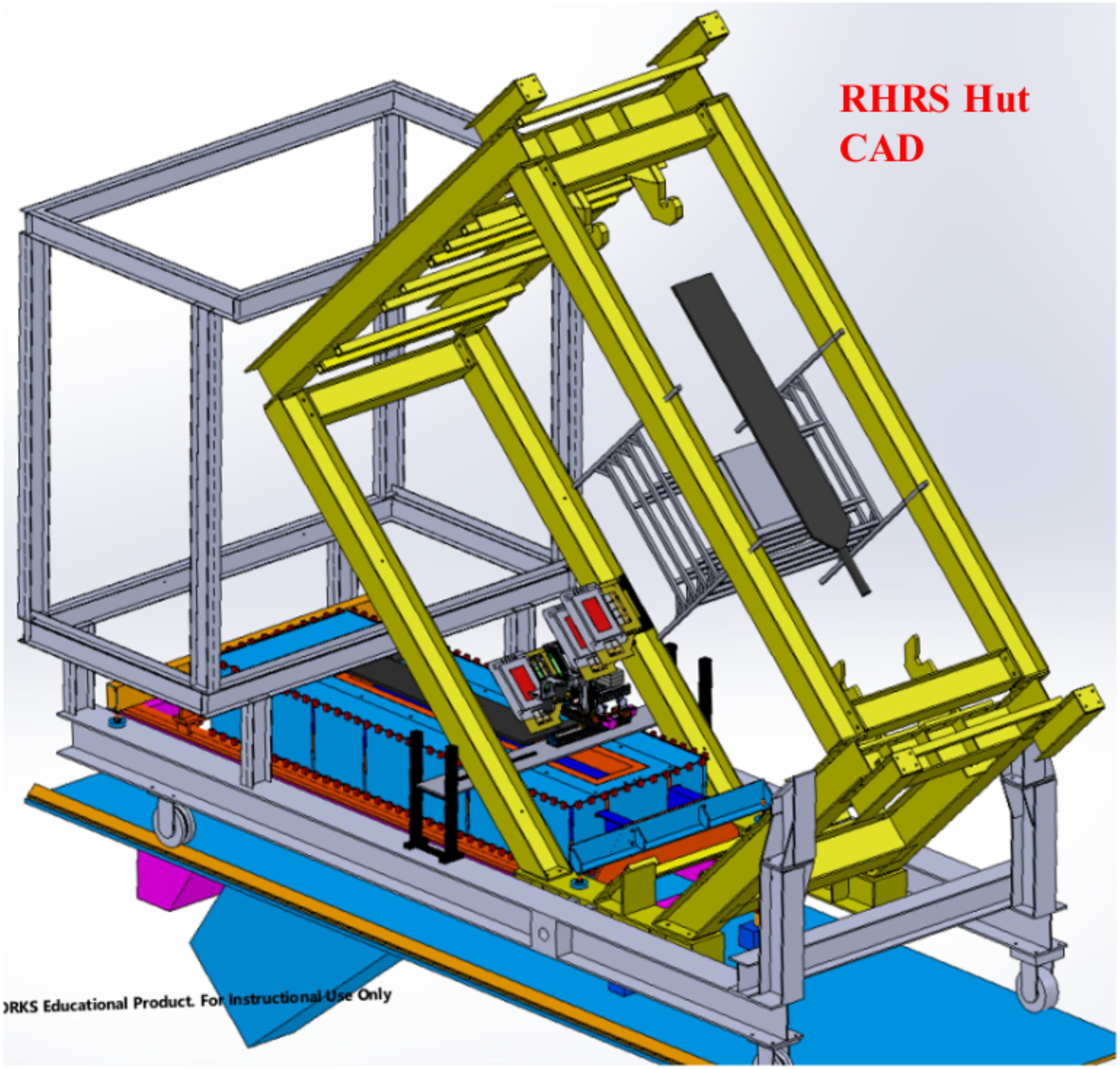


RHRS Tandem PREX-II/CREX Dets with GEMs

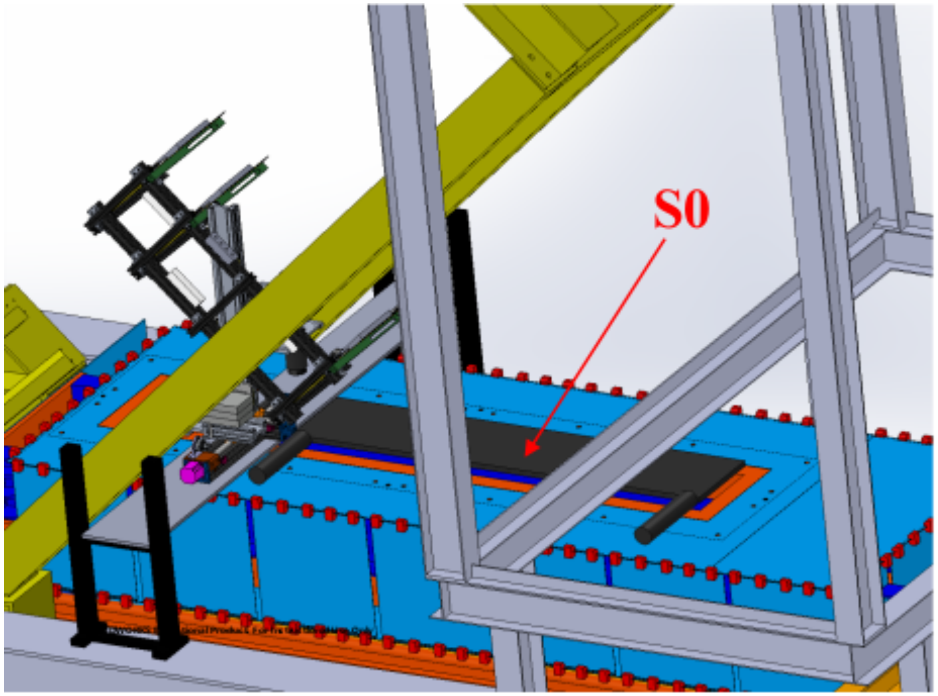


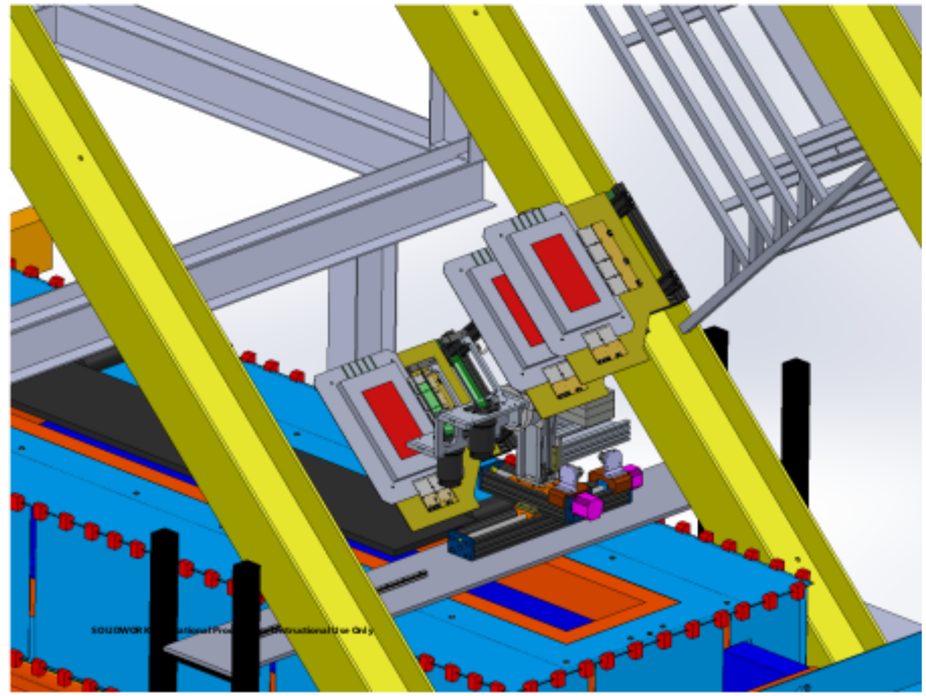
Electron's view (from below)

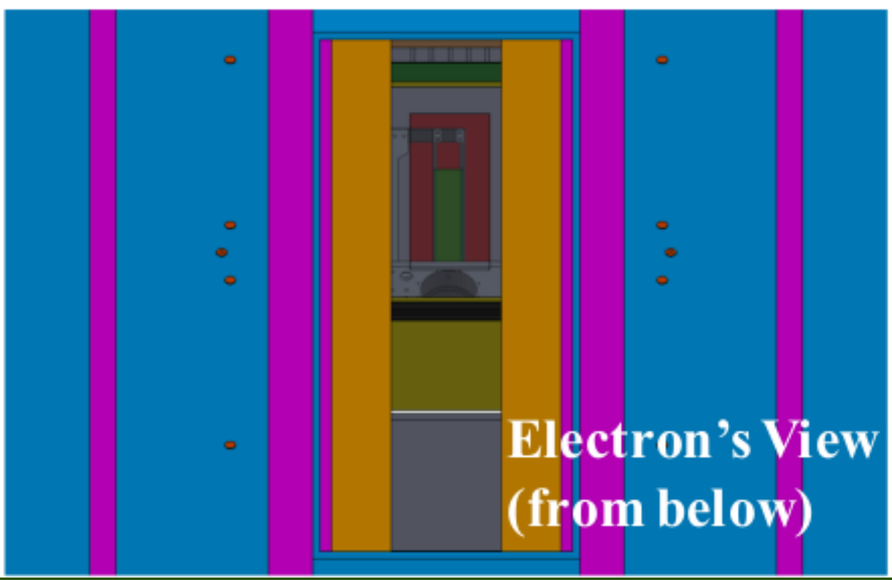
PREX-II/CREX Det Package (no A_T's shown)

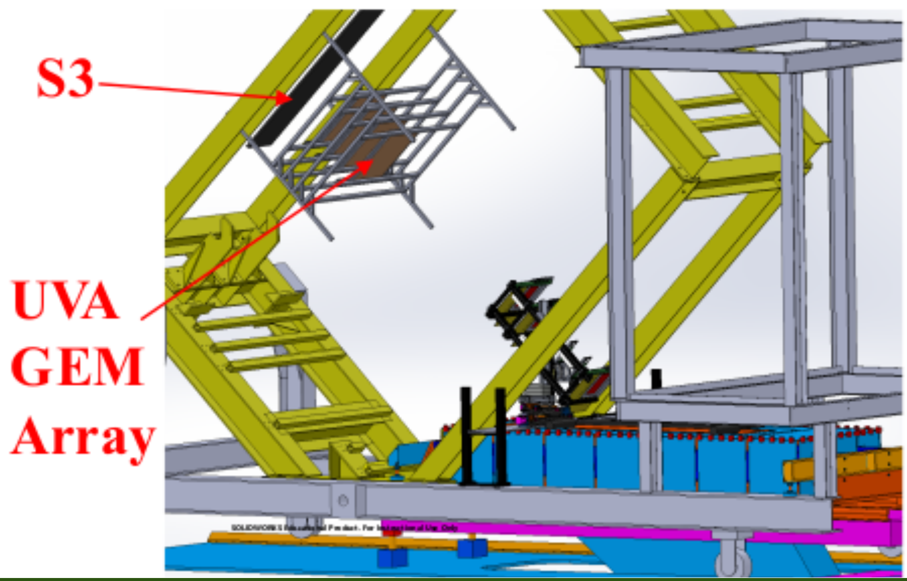


PREX-II/CREX Det Package (no A_T's shown)

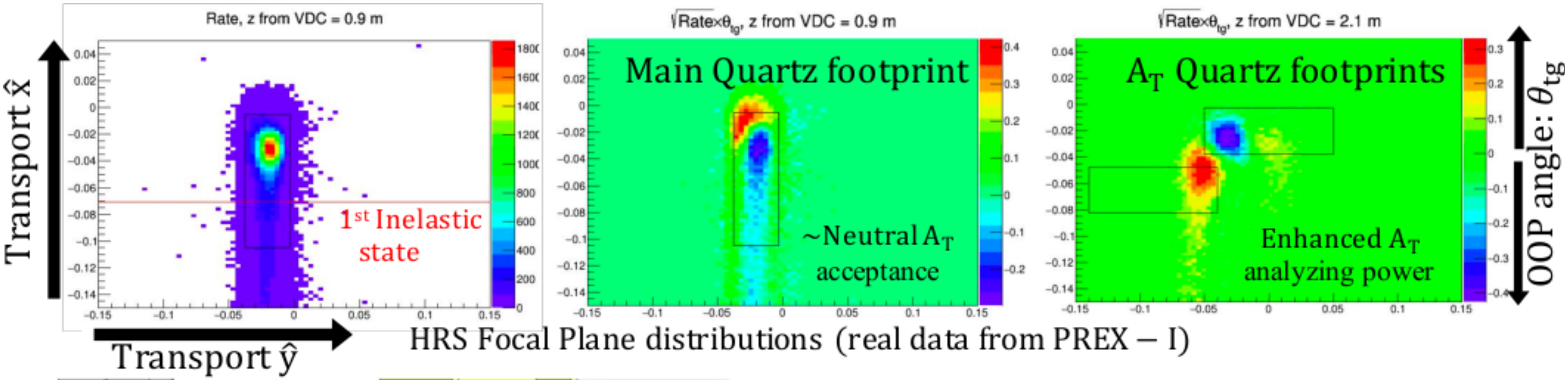




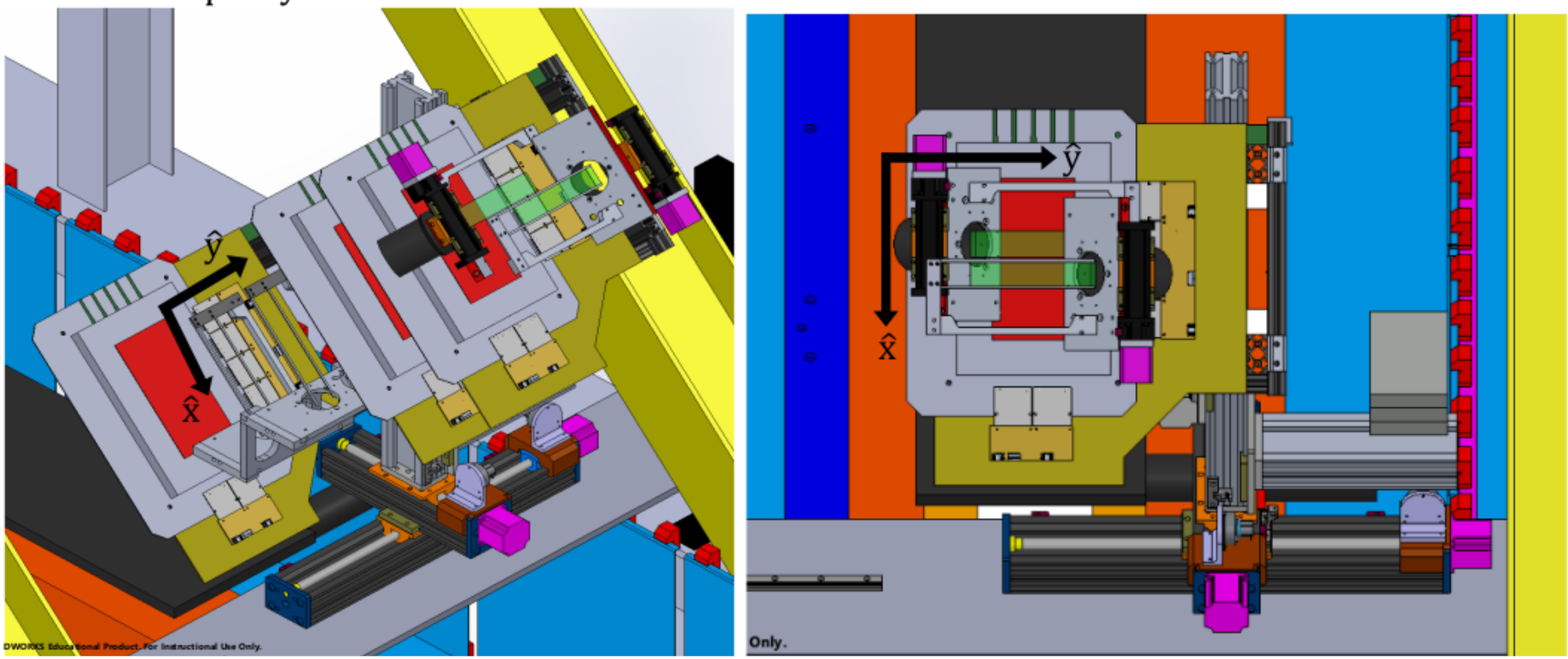




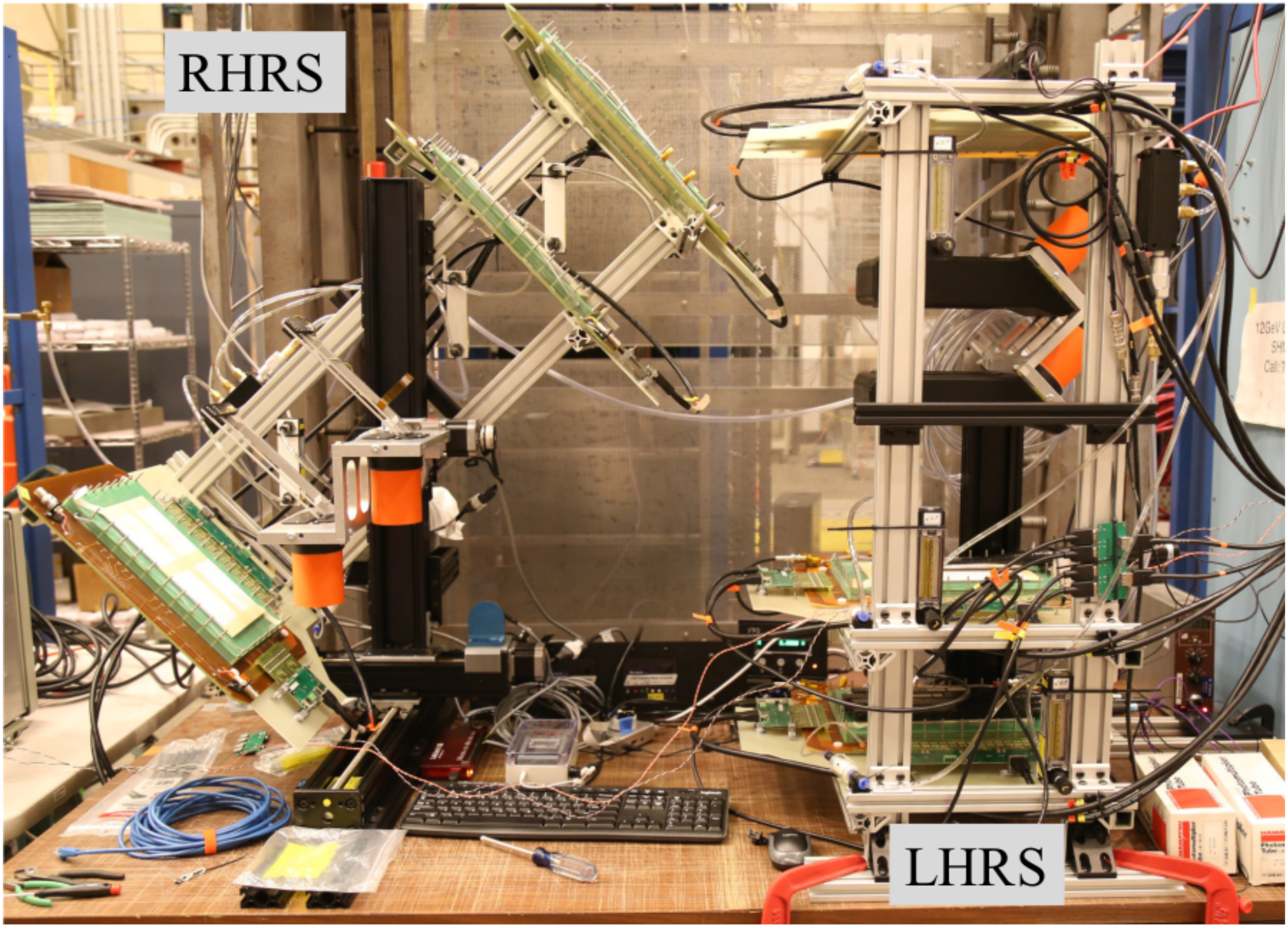
Prel. New HRS CAD with rough A_T positioning



HRS Focal Plane distributions (real data from PREX – I)



PREX-II/CREX Main Detector Assemblies



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 achieved systematic error goal and PREX-II poised to reach full precision
- Schedule update: PREX-II and CREX to run concurrently starting in June this year

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

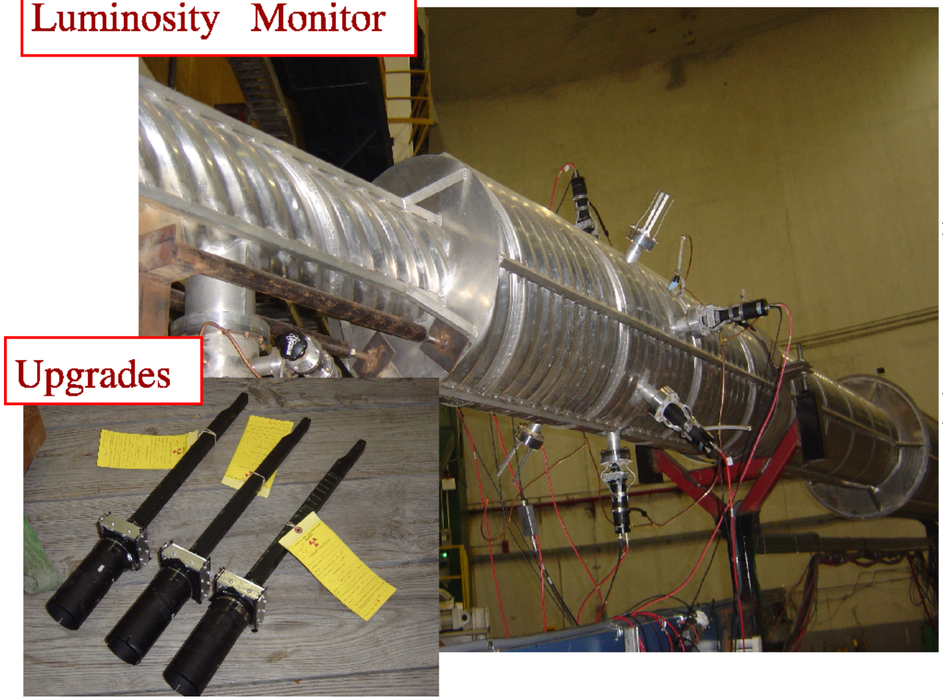
Extra Slides

Motivations for Downstream Lumi's or SAM's

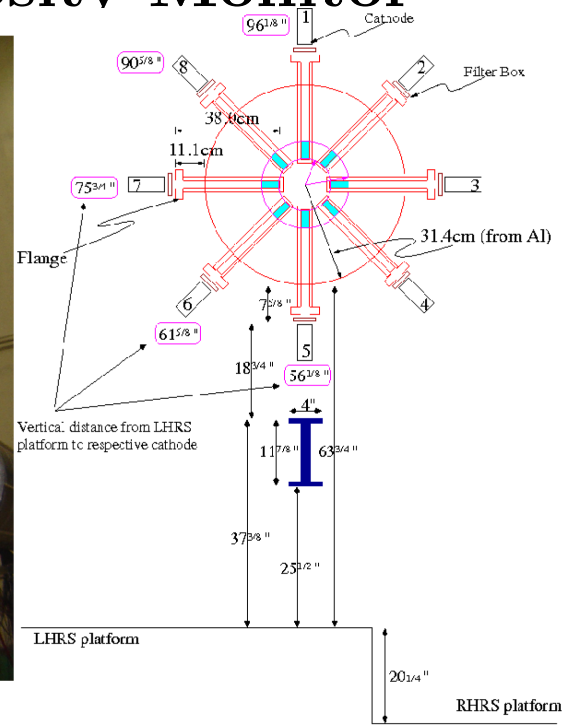
- Need them for their high sensitivity to helicity-correlated beam parameters
  - Detect charged particle flux at extreme forward angles
  - Very high rates and thus narrow pulse-pair widths – powerful diagnostic tool
- Provides measure of overall electronic noise floor in the hall
- In theory, should 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

Luminosity Monitor

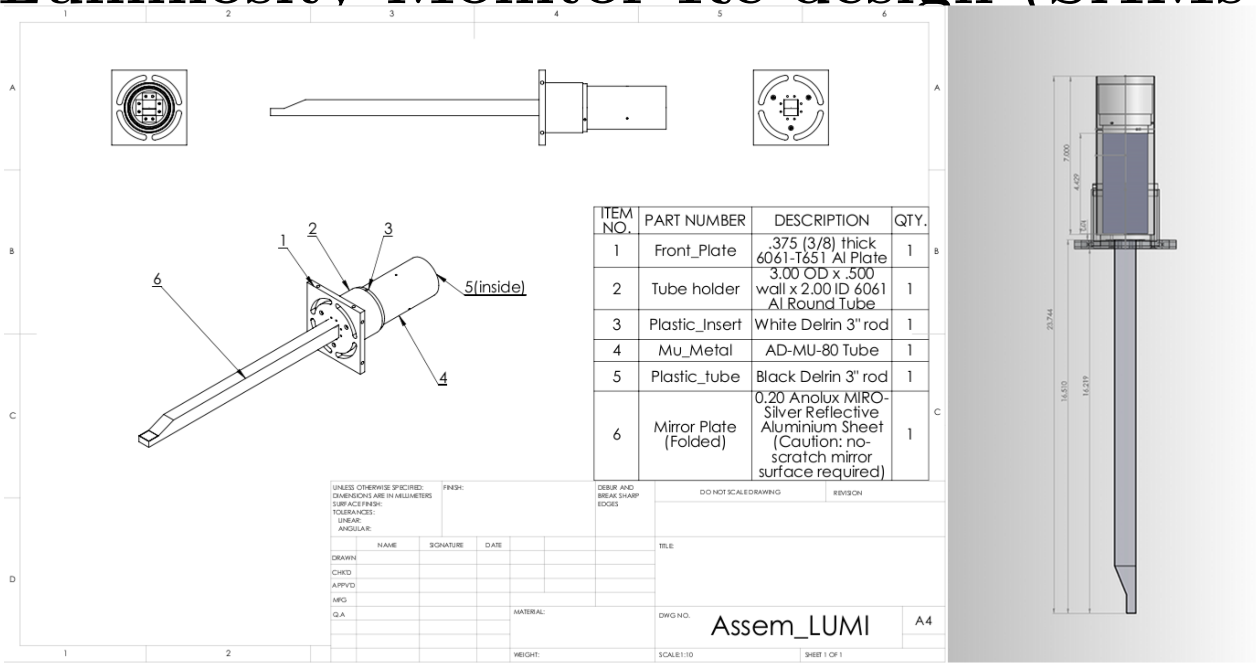


Upgrades



- 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

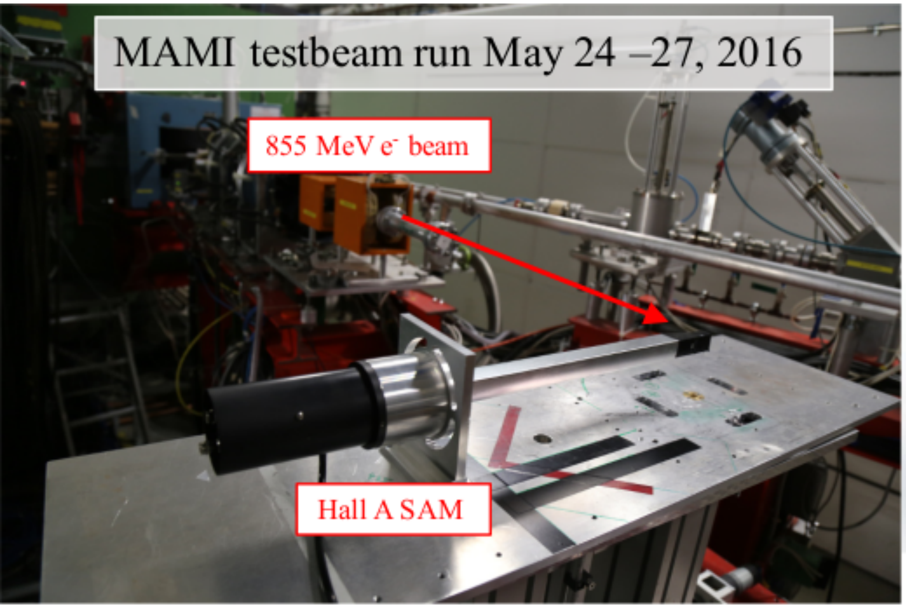
Luminosity Monitor Re-design (SAMs)



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Front_Plate	.375 (3/8) thick 6061-T651 Al Plate	1
2	Tube holder	3.00 OD x .500 wall x 2.00 ID 6061 Al Round Tube	1
3	Plastic_Insert	White Delrin 3" rod	1
4	Mu_Metal	AD-MU-80 Tube	1
5	Plastic_tube	Black Delrin 3" rod	1
6	Mirror Plate (Folded)	0.20 Anolux MIRO-Silver Reflective Aluminium Sheet (Caution: no-scratch mirror surface required)	1

- 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



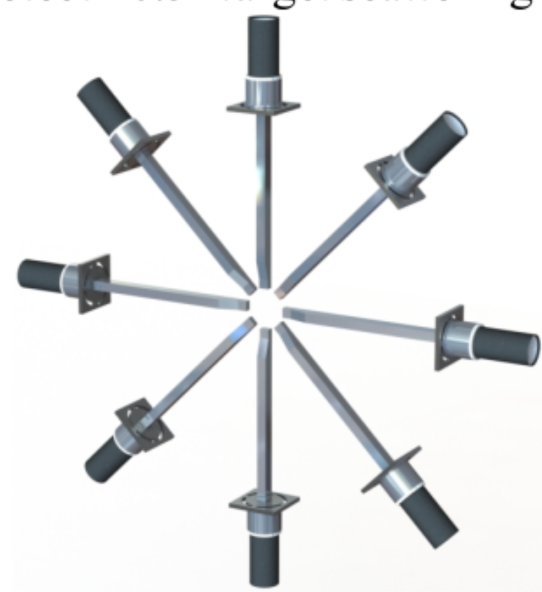
- Final (v3) SAM detector PE yield studies:
  - MiroSilver27 and UVS light-guides
  - With and without 1cm tungsten pre-radiator

Assembled & Installed in Hall A Fall 2015

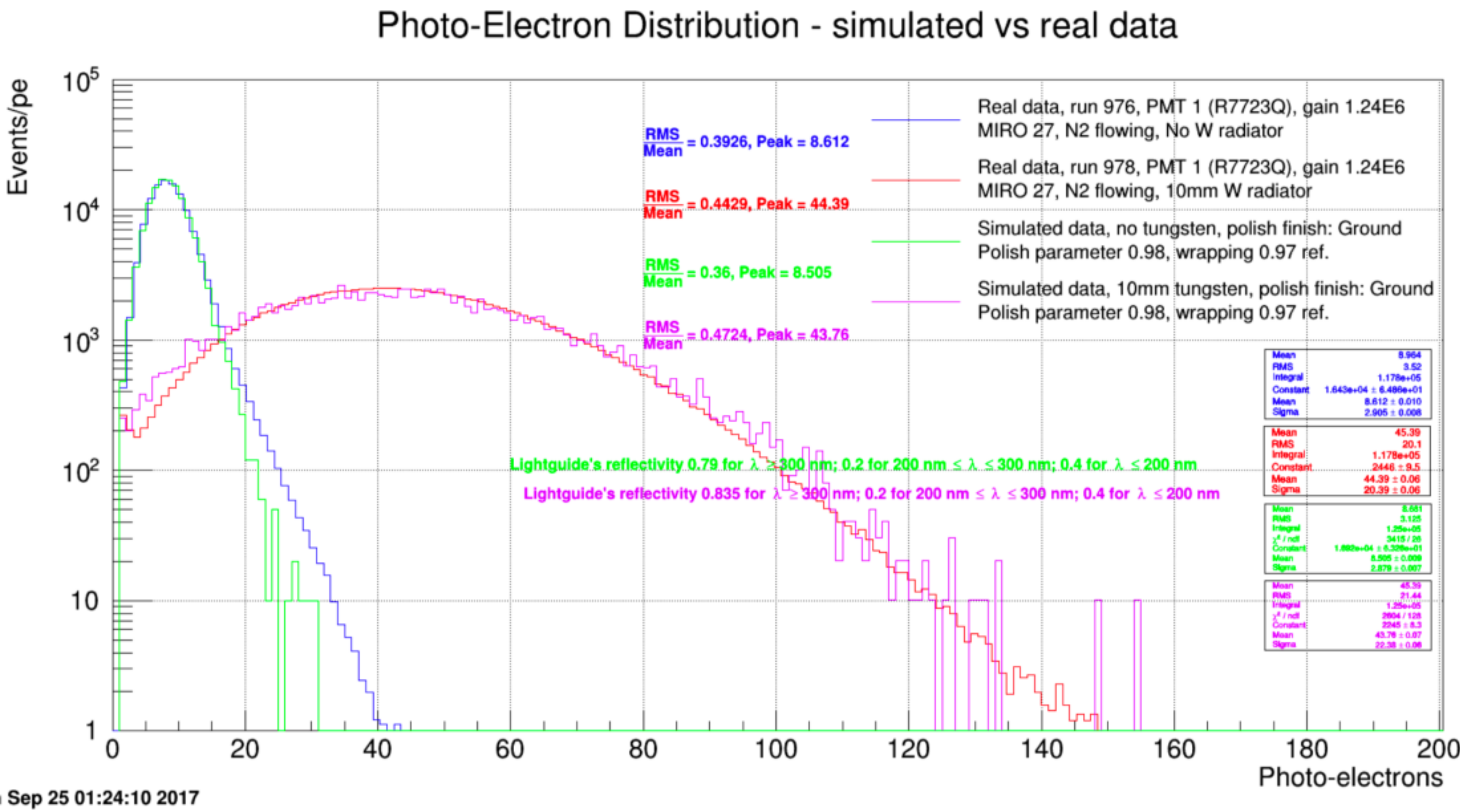
v3 SAM detector

- 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)

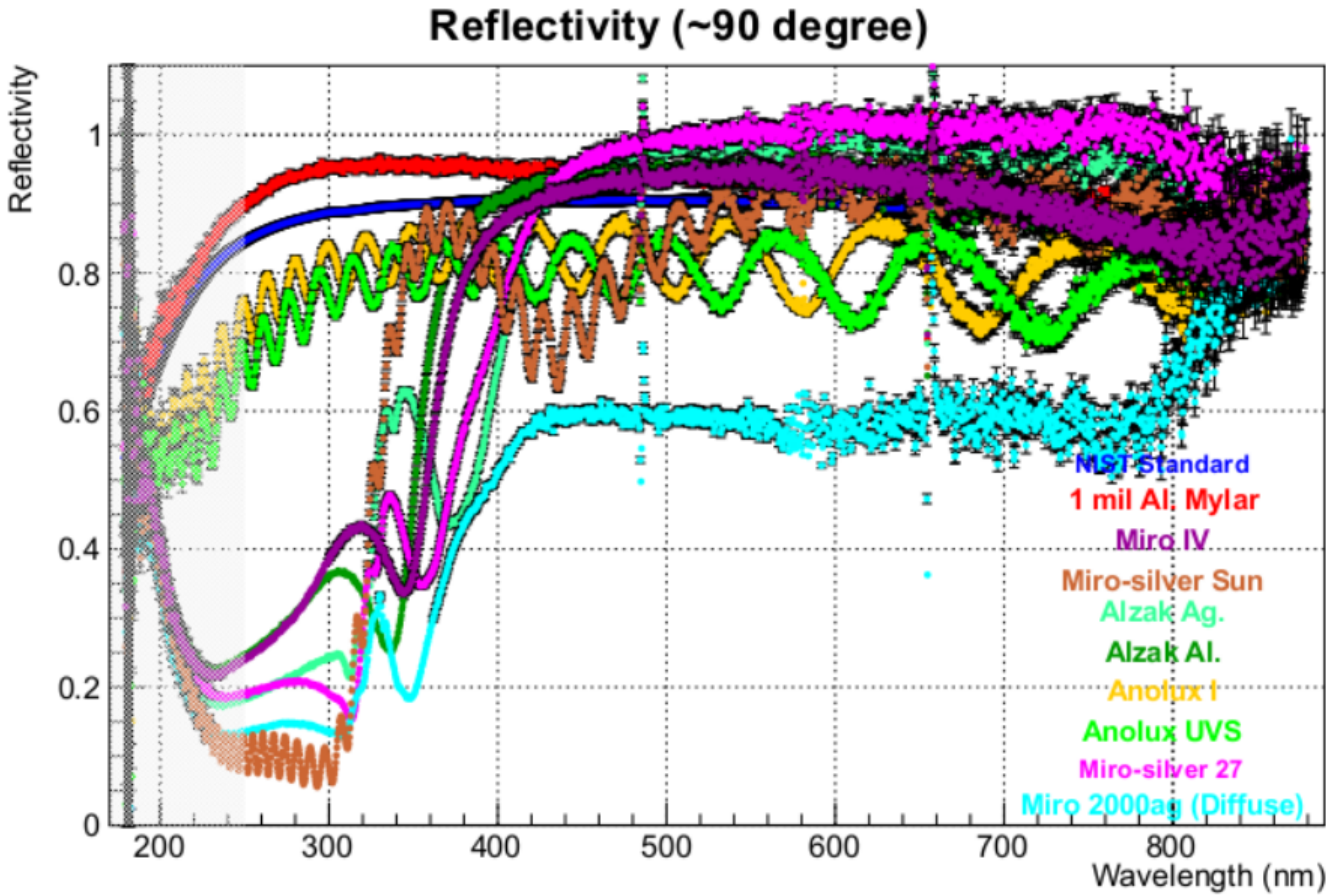
Small Angle Monitors:
Detect ~0.5° target scattering



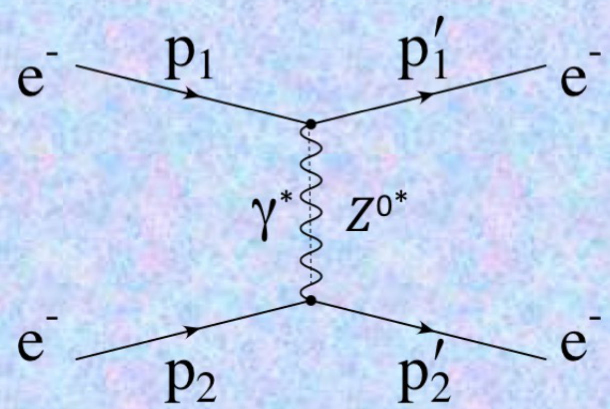
Optical Monte Carlo (qsim) Benchmarking: SAMs



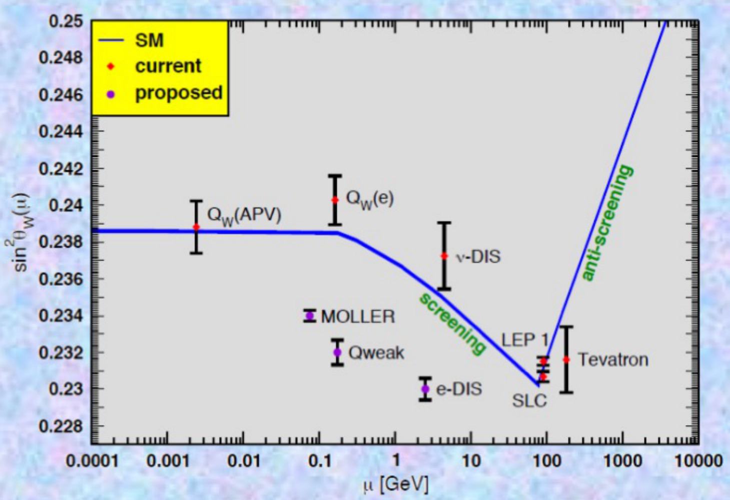
SAM light guide reflectivity: explored many options



The MOLLER Project at Jefferson Lab:



Measurement **o**f **L**epton **L**epton **E**lectroweak **R**eaction

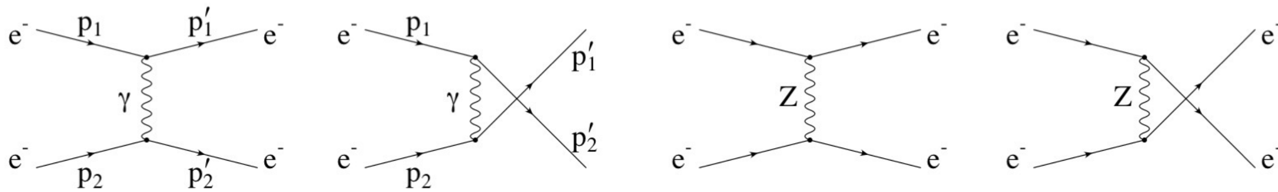


Møller Scattering A_{PV} Measurement

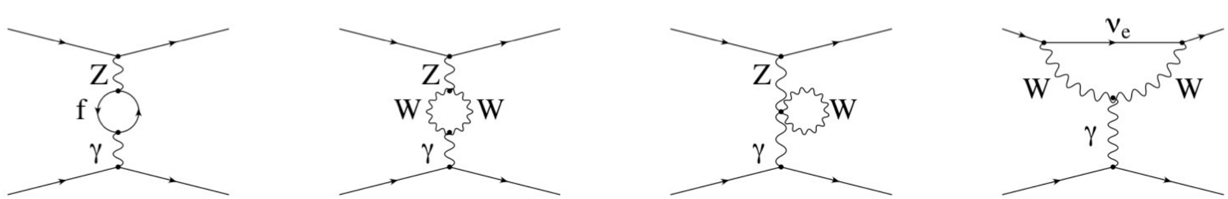
- MOLLER aimed at precision measurement of parity-violating asymmetry A_{PV} in polarized electron-electron scattering.
- Standard Model gives precise prediction for Møller A_{PV} –which can be measured as a test.

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

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



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^-_{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:
  $\rightarrow \delta Q^e_W / Q^e_W = \pm 2.1\%(\text{stat}) \pm 1.0\%(\text{syst})$
  $\rightarrow \delta\theta_{\text{W}} = \pm 0.00026(\text{stat}) \pm 0.00012(\text{syst})$ ~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

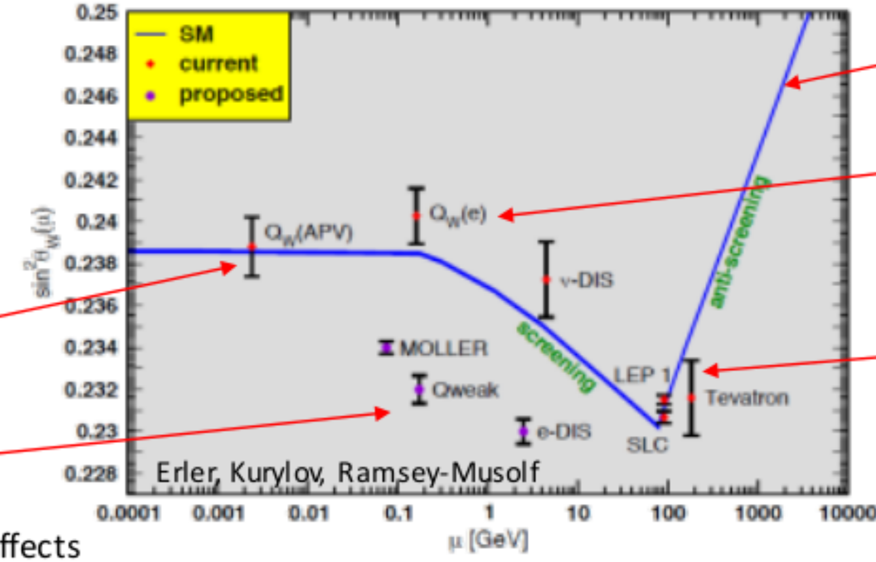
MOLLER Motivations

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

$6s \longrightarrow 7s$ ^{133}Cs atomic transition

Major improvements for near future

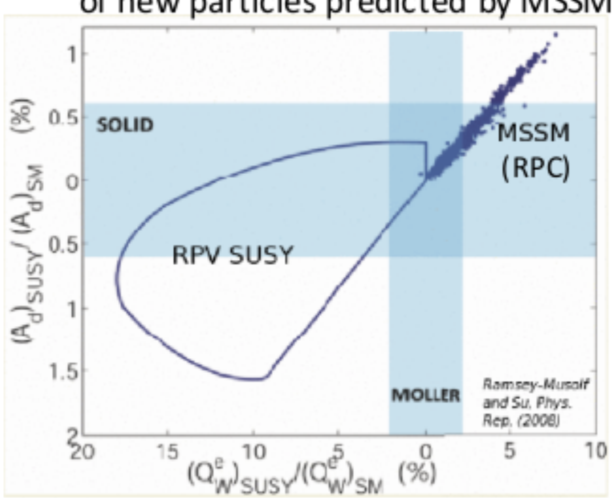


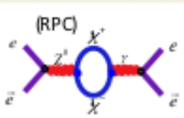
Electroweak fit with uncertainty

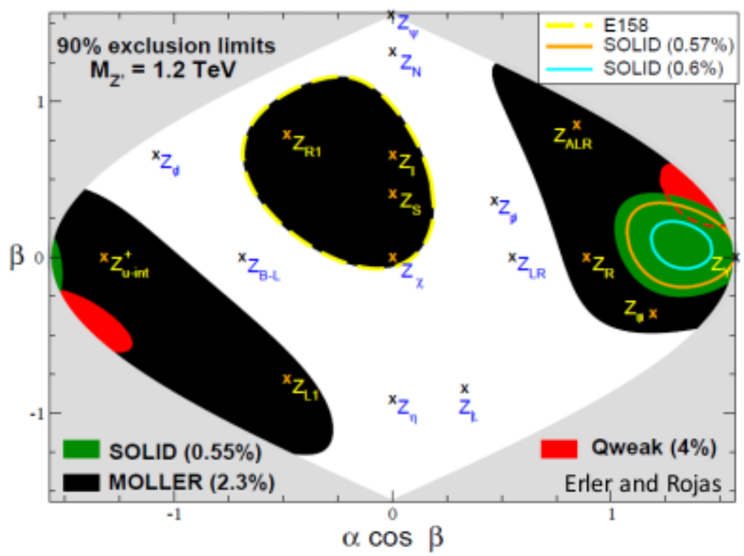
Parity violating Moller scattering (E158)

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

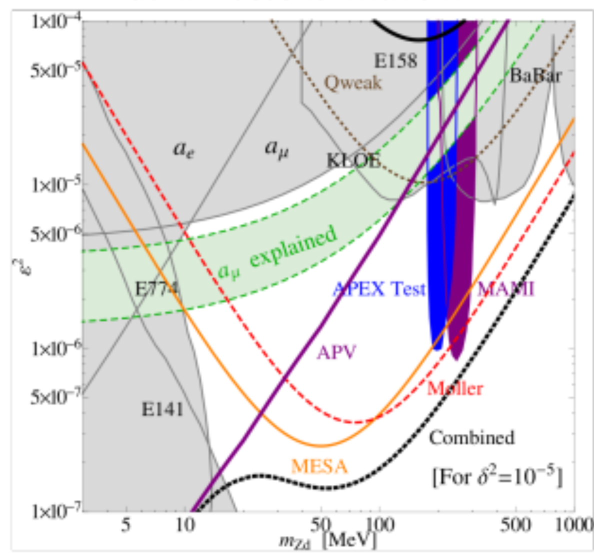
❖ Sensitivity to radiative loop effects of new particles predicted by MSSM







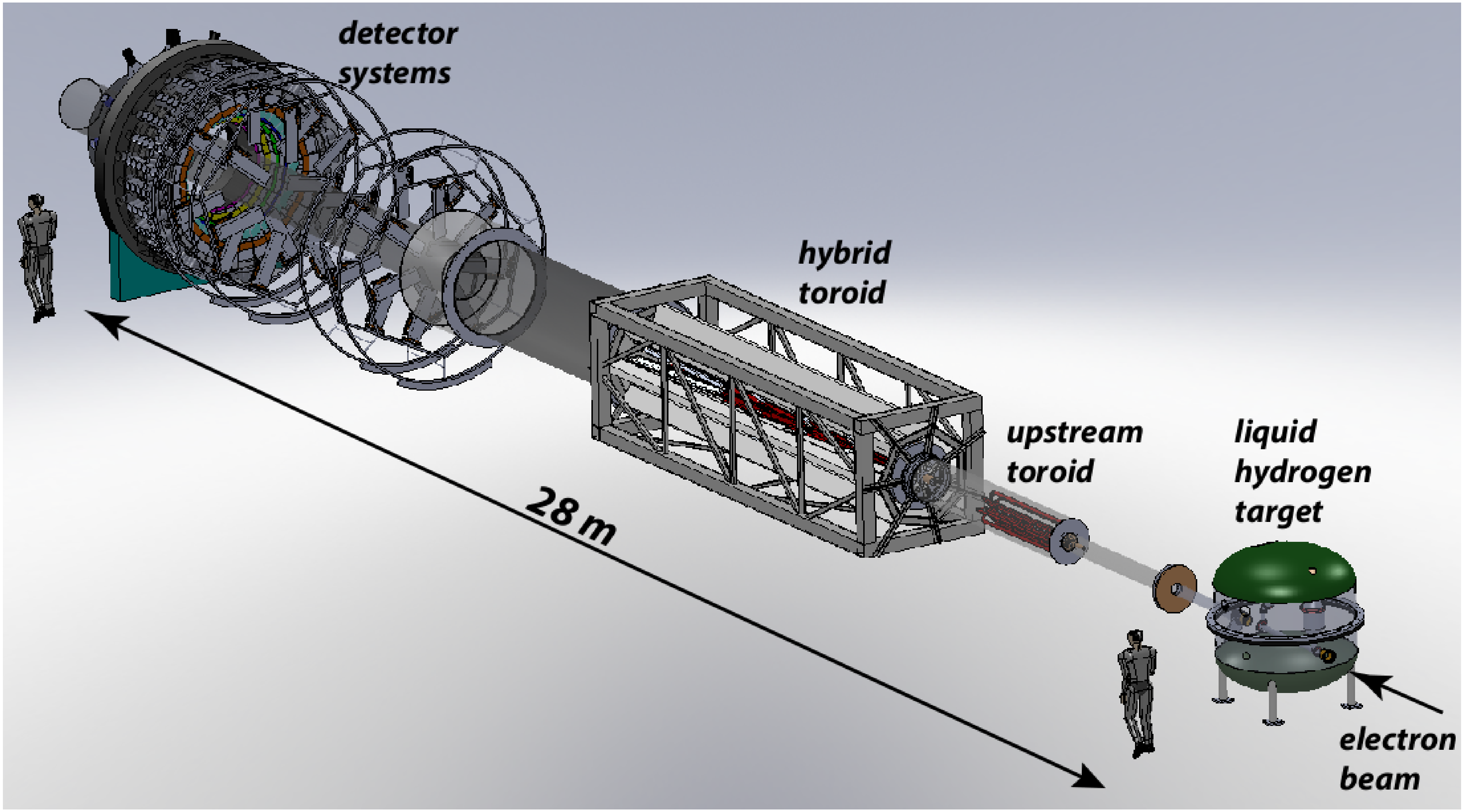
❖ Probe potential kinetic-mixing of super-light (10 to 500 MeV) dark Z bosons with SM Z



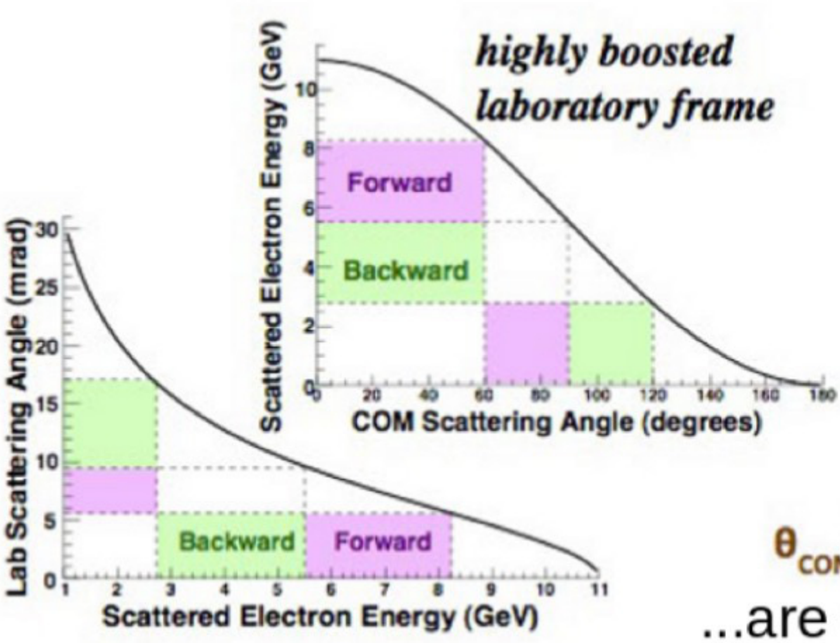
❖ MOLLER can help discriminate between competing GUT models which predict new 1 – 2 TeV Z's

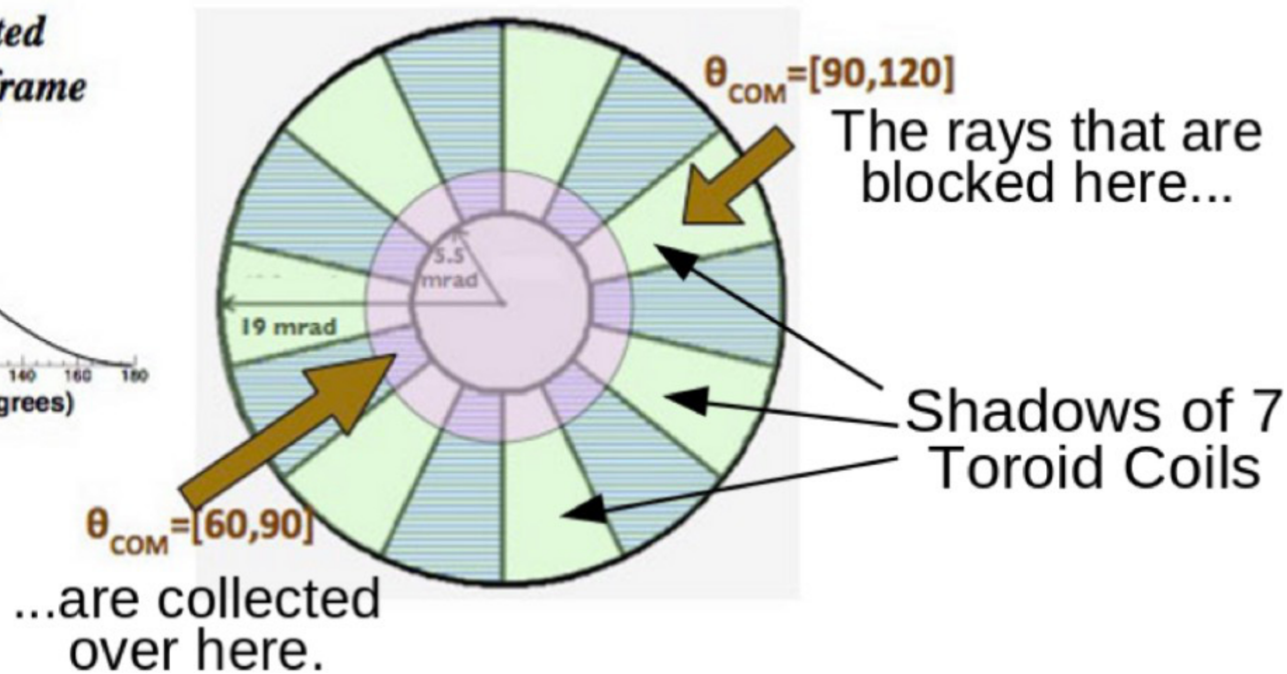
MOLLER Apparatus

(major new installation experiment for Hall A)



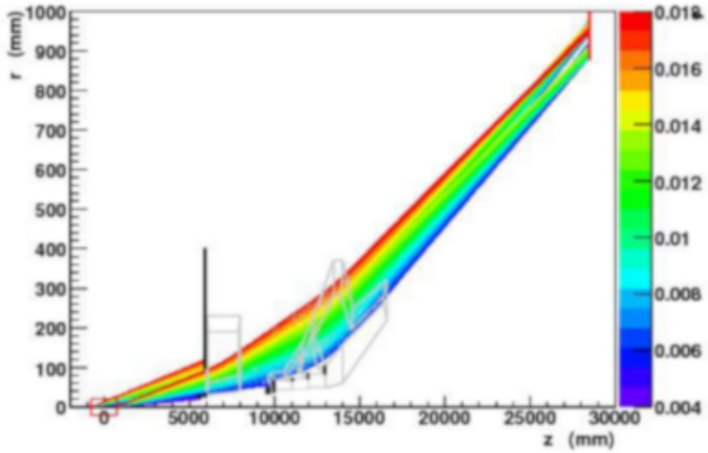
Optimized Spectrometer (∼ 100% Acceptance)



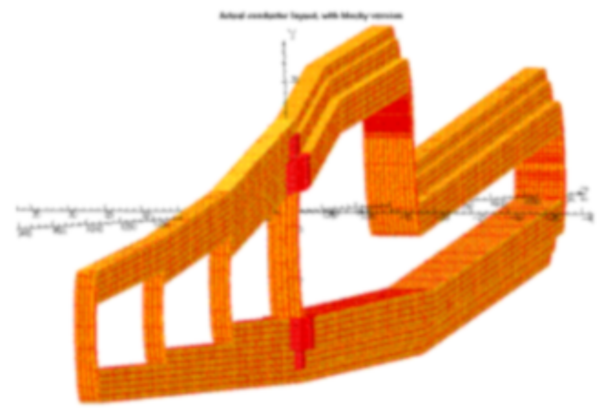


- The combination of a toroidal magnetic system with an odd number of coils together with the symmetric, identical particle scattering nature of the Møller process allows for ∼ 100% azimuthal acceptance

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 ($\sim$150 GHz), Ring 2 intercepts bkgd "ep" peaks
- 250 quartz tiles: allow full characterization and deconvolution of bkgd and signal processes