Applications of Parity Violation

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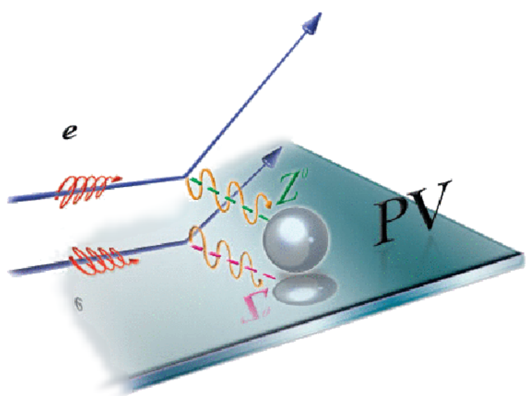


Applications of Parity Violation in the Weak Nuclear Force

Outline

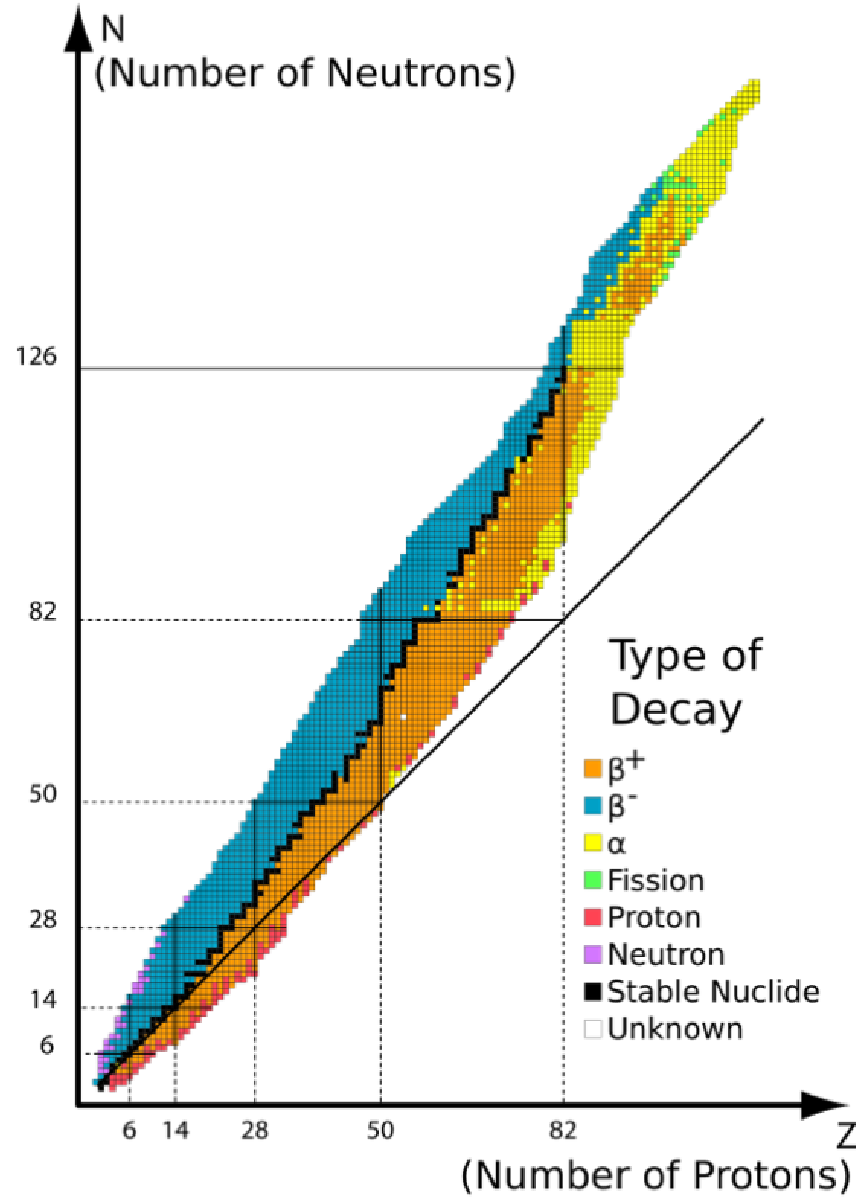
- Beta Decay and Parity Violation
- Standard Model and the Weak Force
- Experiments: PREX/CREX and MOLLER
- Quartz Cerenkov Detector R&D at ISU
- Summary and Outlook

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:

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

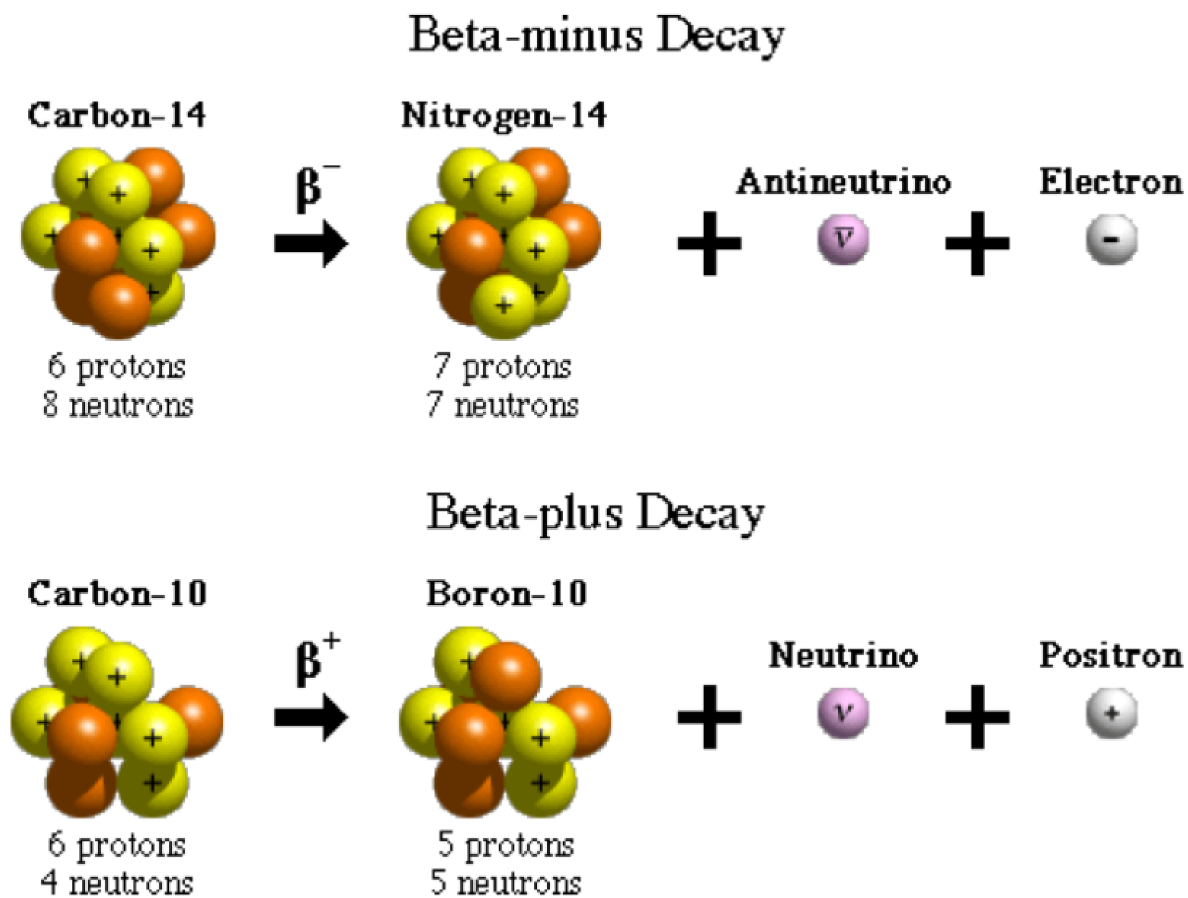
- Thermonuclear fusion--Perhaps the most important reaction for all life on planet Earth is caused by a fundamental force of nature that is rarely discussed in the classroom: Weak Interactions or the weak nuclear force
  - Responsible for nearly all radioactive decay processes
  - Beta decay is most 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: $p \rightarrow n + \nu_e + e^+$

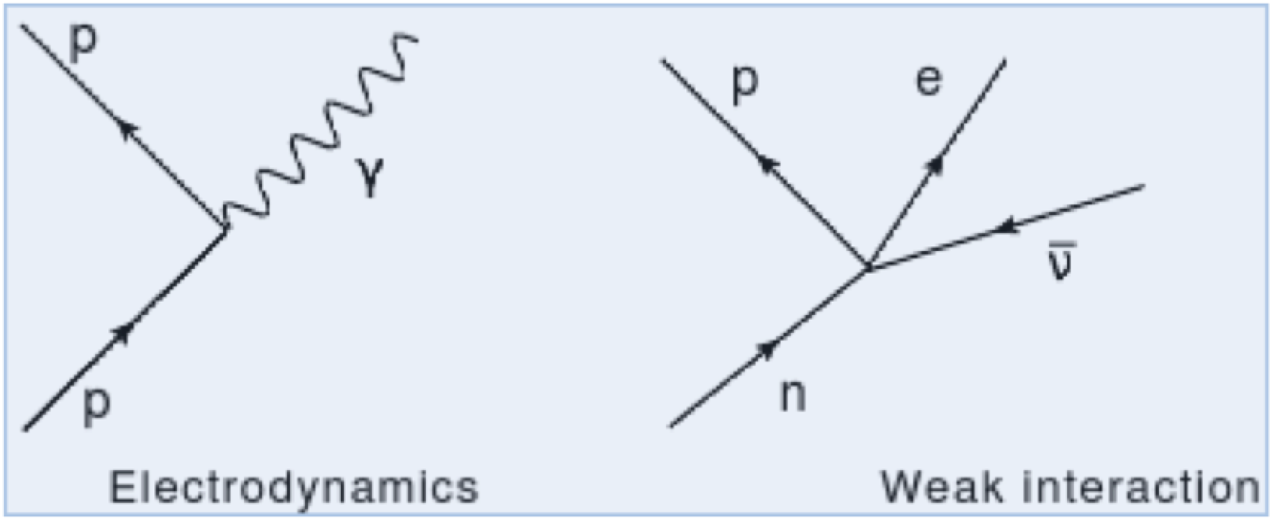
-- Moves nuclei down in the periodic table ($Z \rightarrow Z - 1$)

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.

First Neutrino Observations 1956

- Clyde L. Cowan, Frederick Reines (Awarded 1995 Nobel Prize)
- Experiment conducted near nuclear reactor (~10^{13} ν's /s/cm^2)
- Two water tanks 12m underground and 11m from reactor
- Used inverse beta decay reaction: $\overline{\nu}_e + p \rightarrow n + e^+$
- The e^+ annihilated with an e^- producing two γ rays (detected)

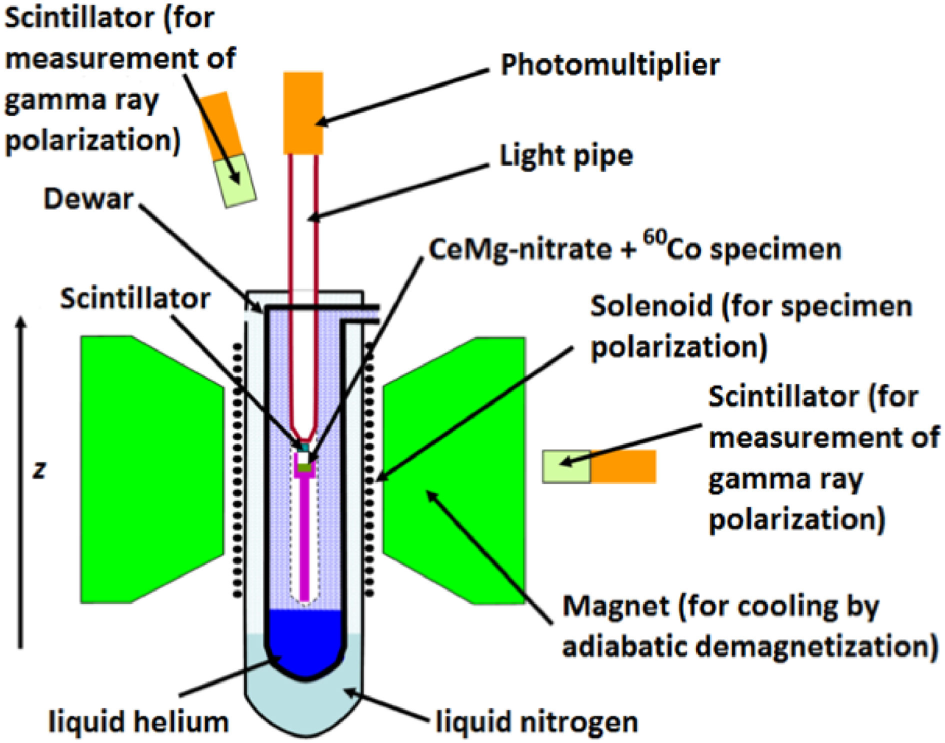
Parity Symmetry

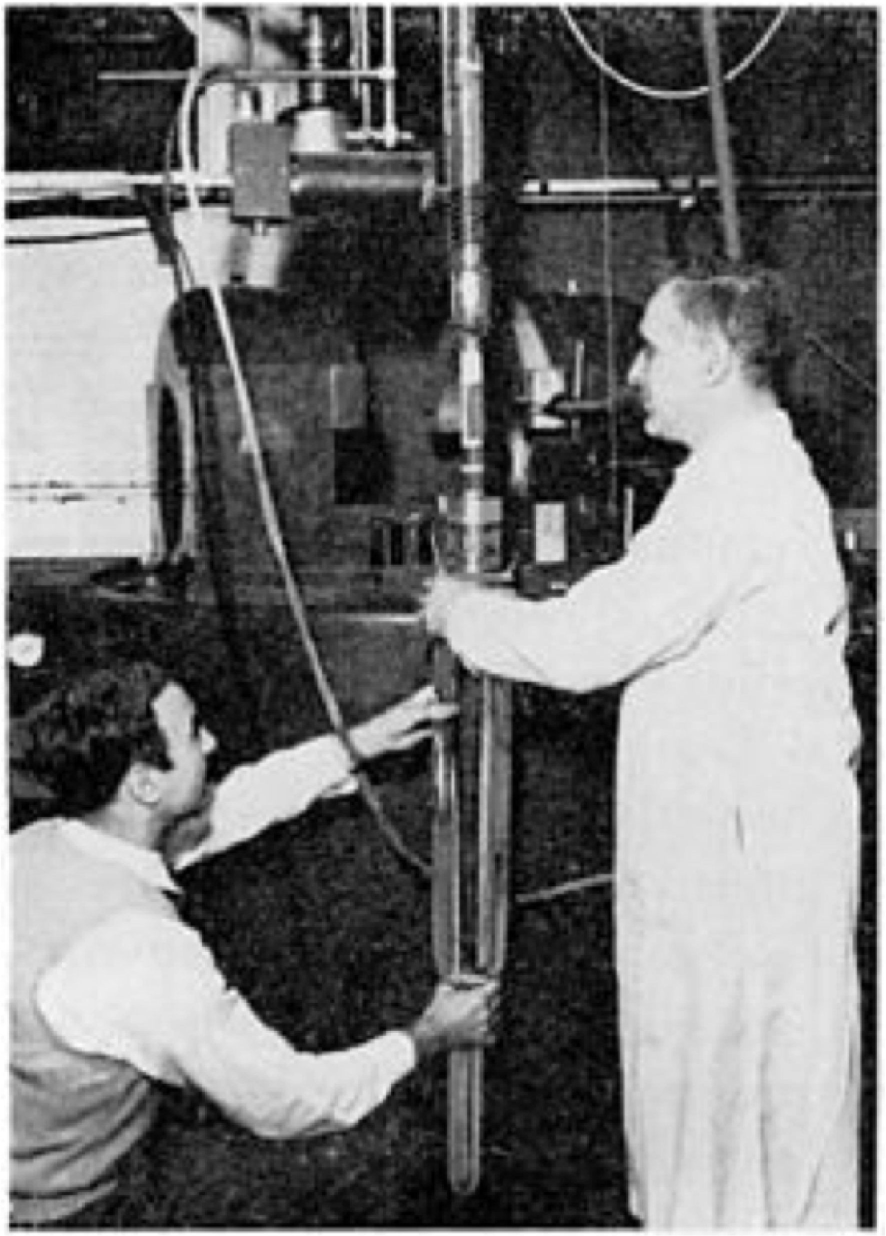
$$\text{P:} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \longrightarrow \begin{bmatrix} -x \\ -y \\ -z \end{bmatrix}$$

- 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

Parity Violation Discovered in β-decay: 1957

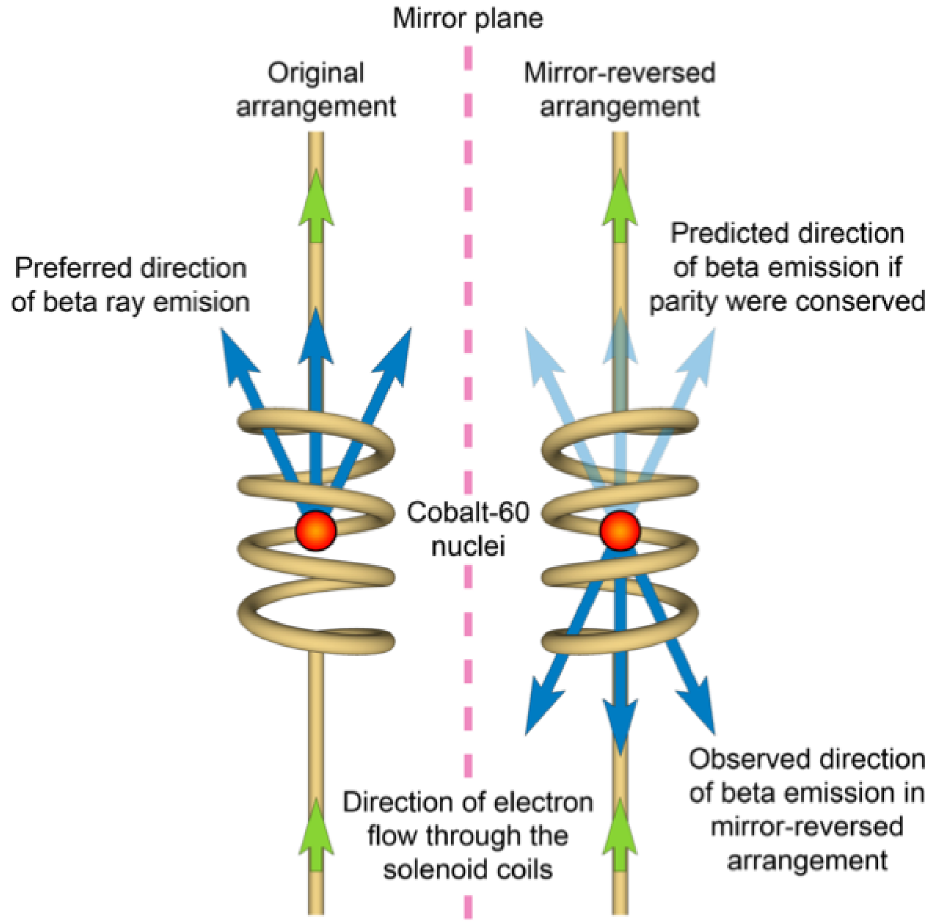
- Chien-Shiung (Madame) Wu Experiment
- Took place at NBS (now NIST)
- Studied β^- decay of super-cooled, spin-aligned ^{60}Co nuclei
- $^{60}_{27}Co \longrightarrow ^{60}_{28}Ni + e^- + \overline{\nu}_e + 2\gamma$
- Achieved 3 mK and 60% polarization

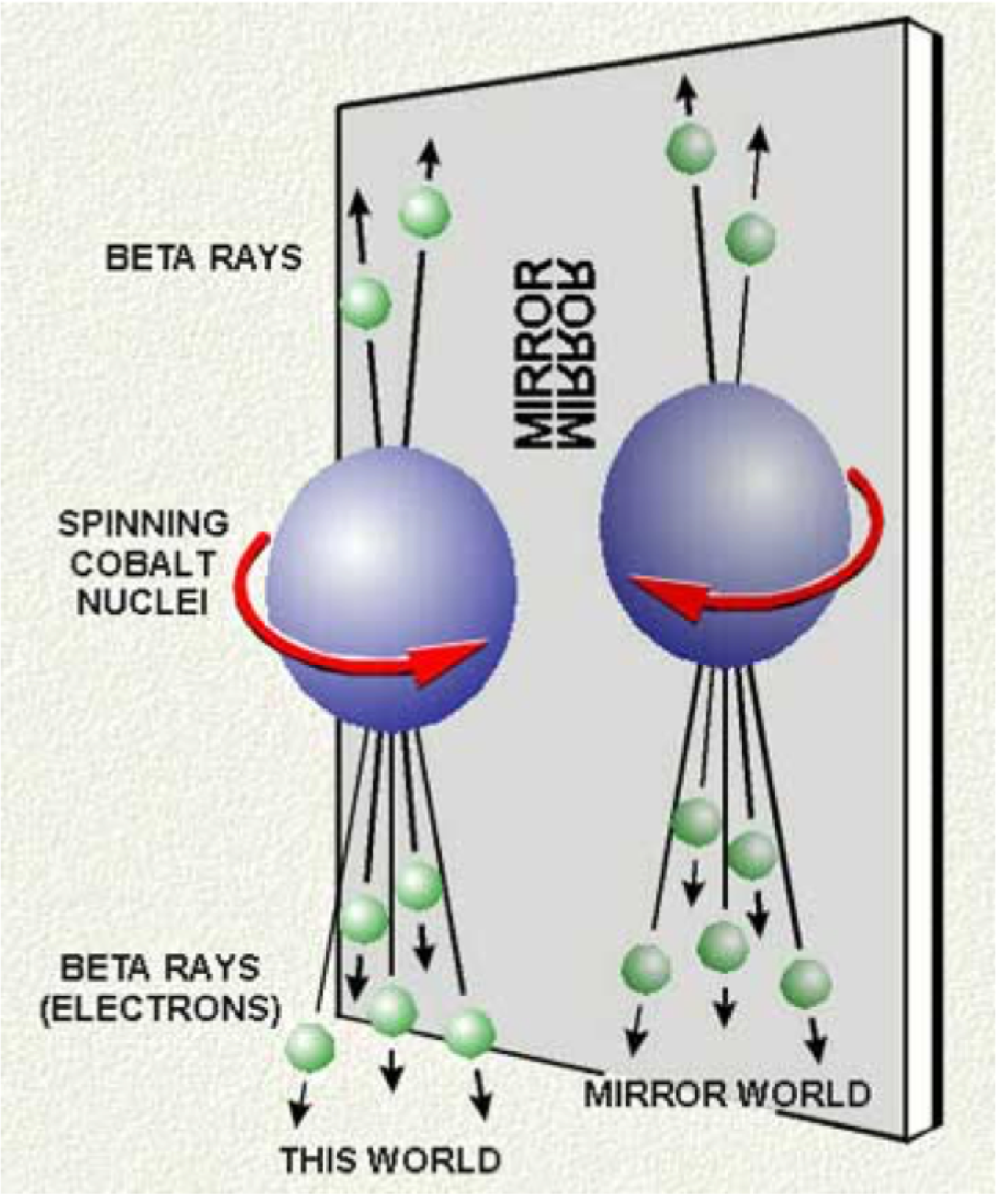




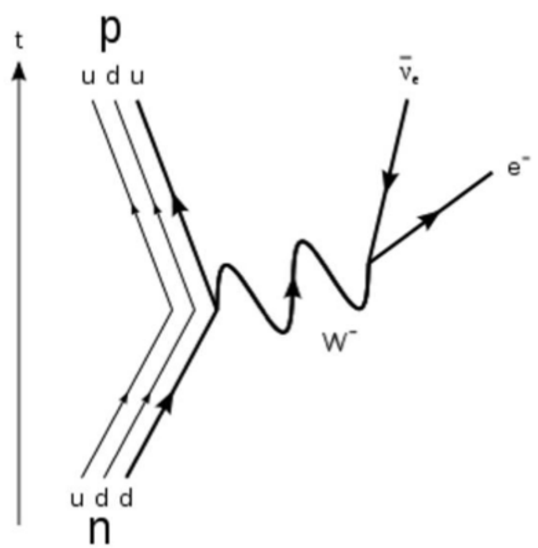
Parity Violation Discovered in β-decay: 1957

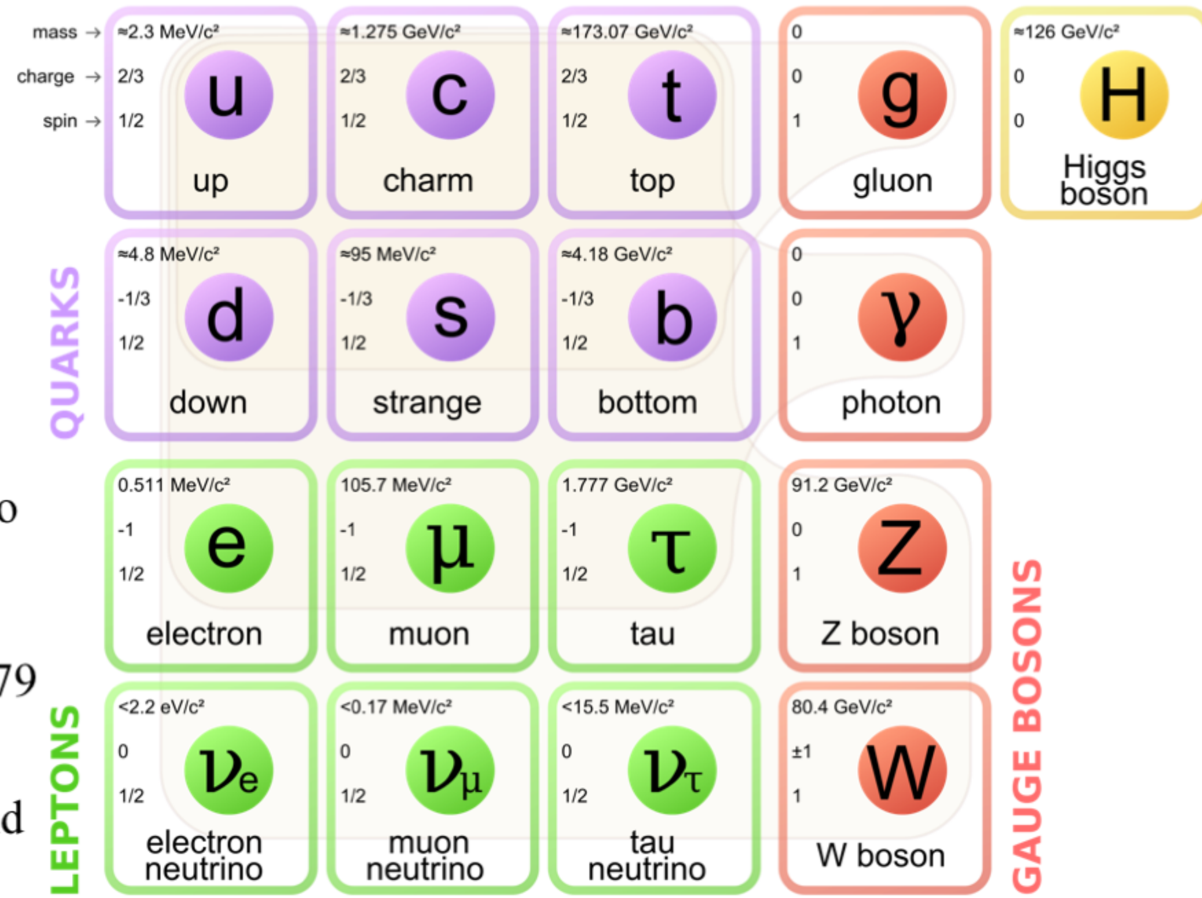
- Parity found to be maximally violated
- T.D. Lee and C.N. Yang awarded 1957 Nobel Prize





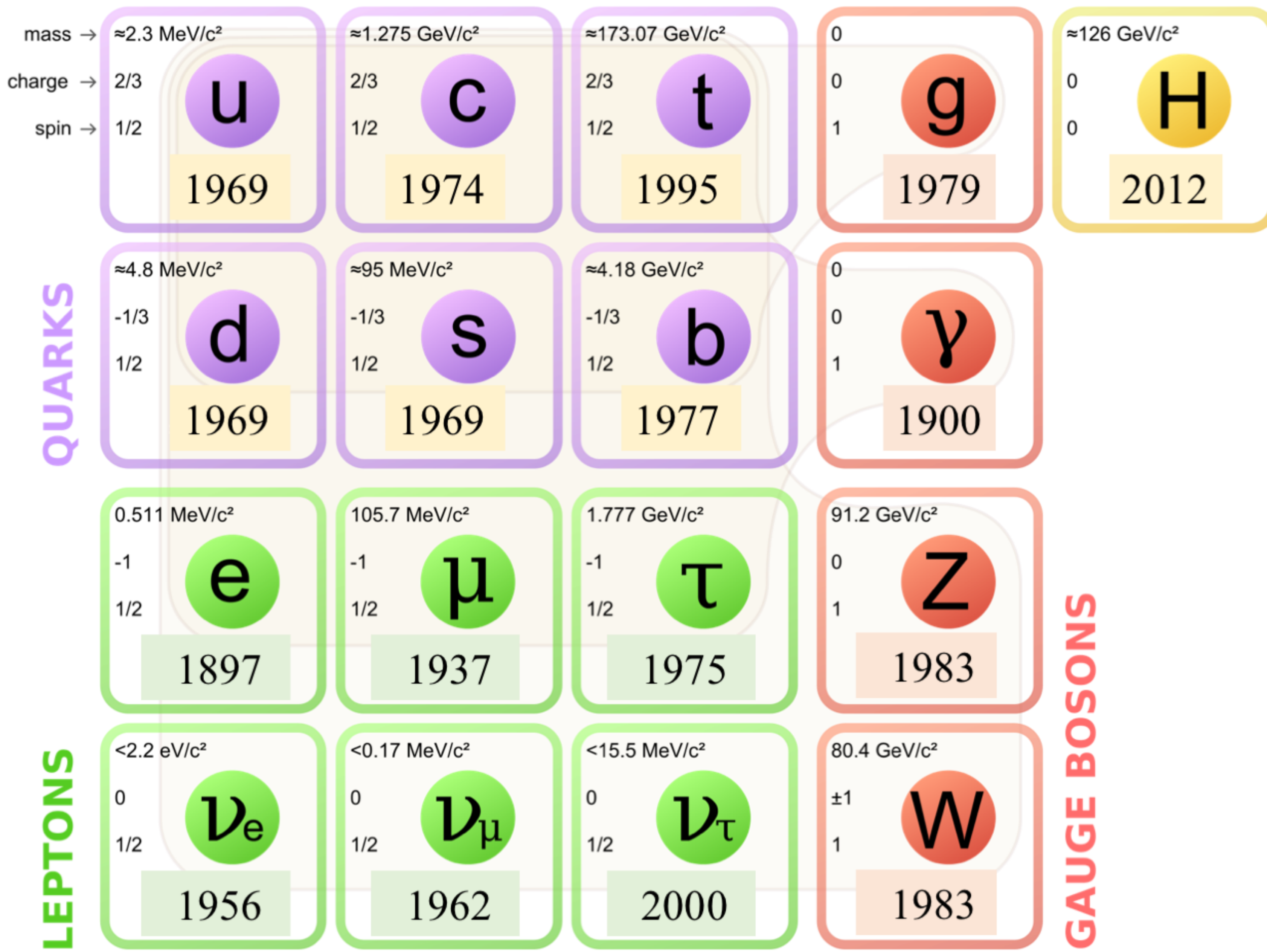
β^- Decay and Standard Model





- 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

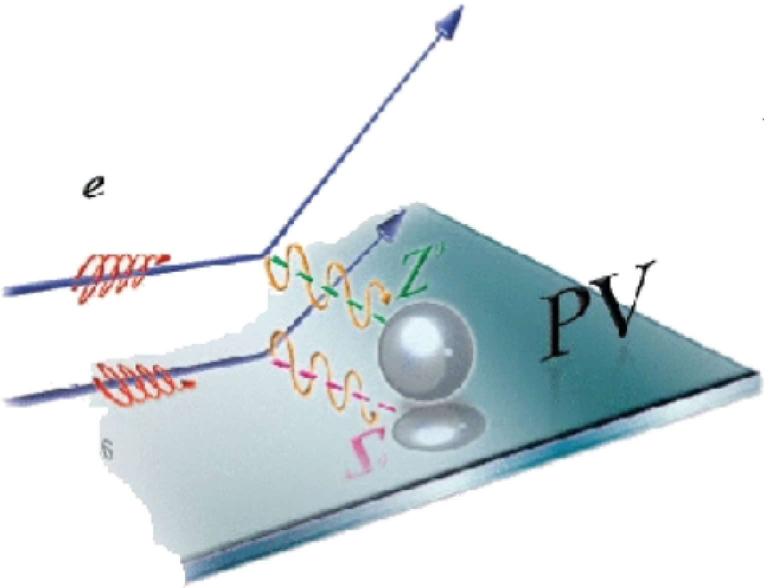
Standard Model of Elementary Particles



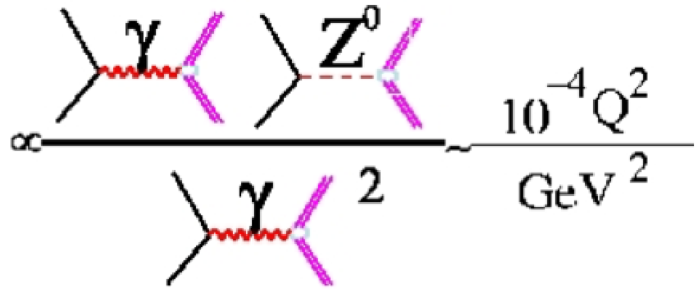
Parity Violation and Electron Scattering

- Electron scattering experiments make first measurement of neutral (Z^0) weak current in late 1970's (at SLAC)
- PVeS experiments scatter longitudinally spin-polarized electron beams (with relatively low energies) off unpolarized, fixed nuclear targets
- Since Z^0 couples to opposite spin (helicity) particles with different strengths, one can measure cross section (σ) differences for opposite helicity beams to access the neutral
- Following technological breakthroughs (at SLAC), high beam polarizations and fast helicity reversals become possible
- PVeS experiments measure an Asymmetry: $A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$
- Since weak scattering process is only tiny fraction of total σ, PV asymmetries are tiny and difficult to measure accurately

A_{PV}: Dominated by Electroweak Interference



$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



- Amplitude for Scattering Process: $S_{tot} \longrightarrow S_{em} + S_w$, but cross section $\sigma \longrightarrow |S_{tot}|^2 = |S_{em}|^2 + |S_w|^2 + 2S_{em}S_w$ (quantum interference term)

- Since $\sigma^{em}{}_R = \sigma^{em}{}_L$ and $|S_w|^2$ is negligible,

$$A_{PV} \longrightarrow \frac{2S_{em}S_w}{2|S_{em}|^2} = \frac{S_w}{S_{em}} \sim 10^{-4} \cdot Q^2$$

where Q^2 is 4-momentum transferred during interaction (GeV)

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

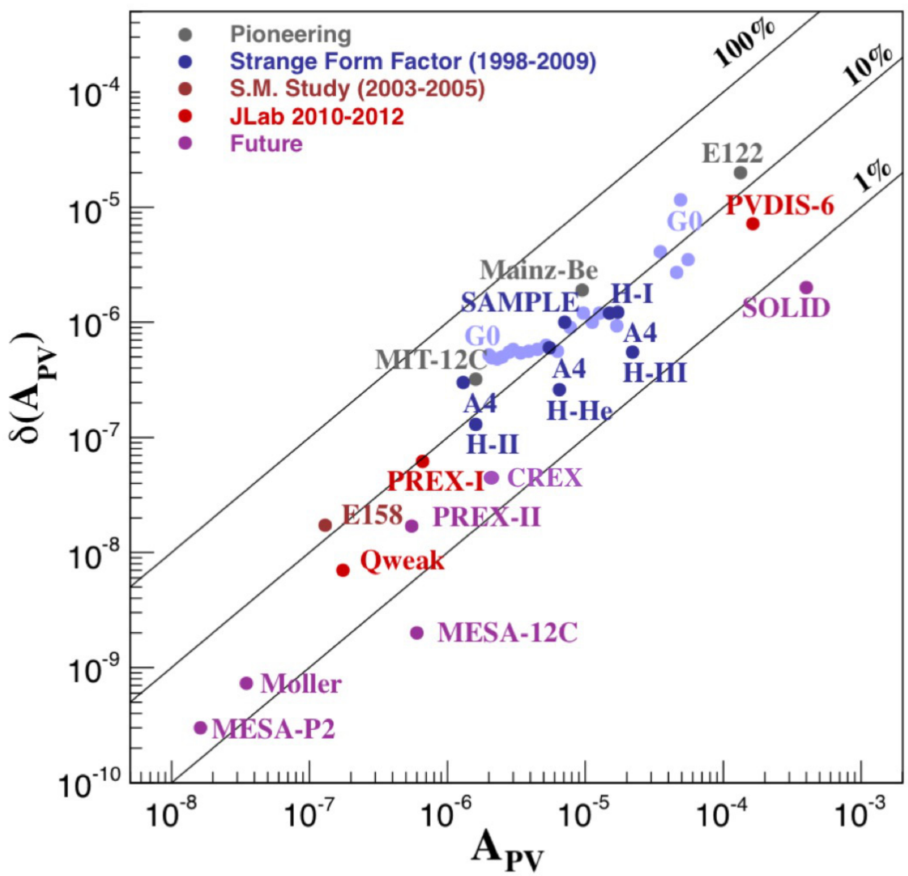
E122 – 1st PVES Expt (late 70's at SLAC)

Mainz & MIT-Bates in mid 80's

JLab program launched in mid 90's

E158 at SLAC meas PV Møller scattering

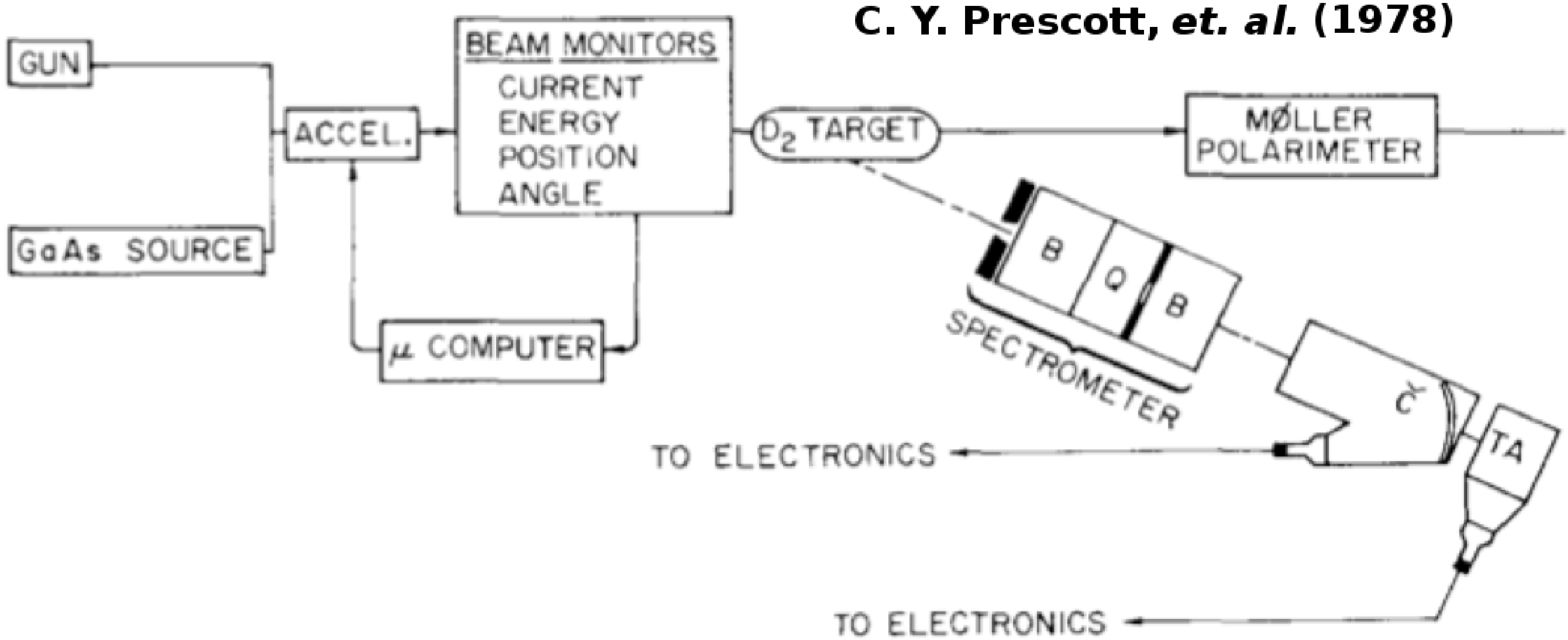
PVeS Experiment Summary



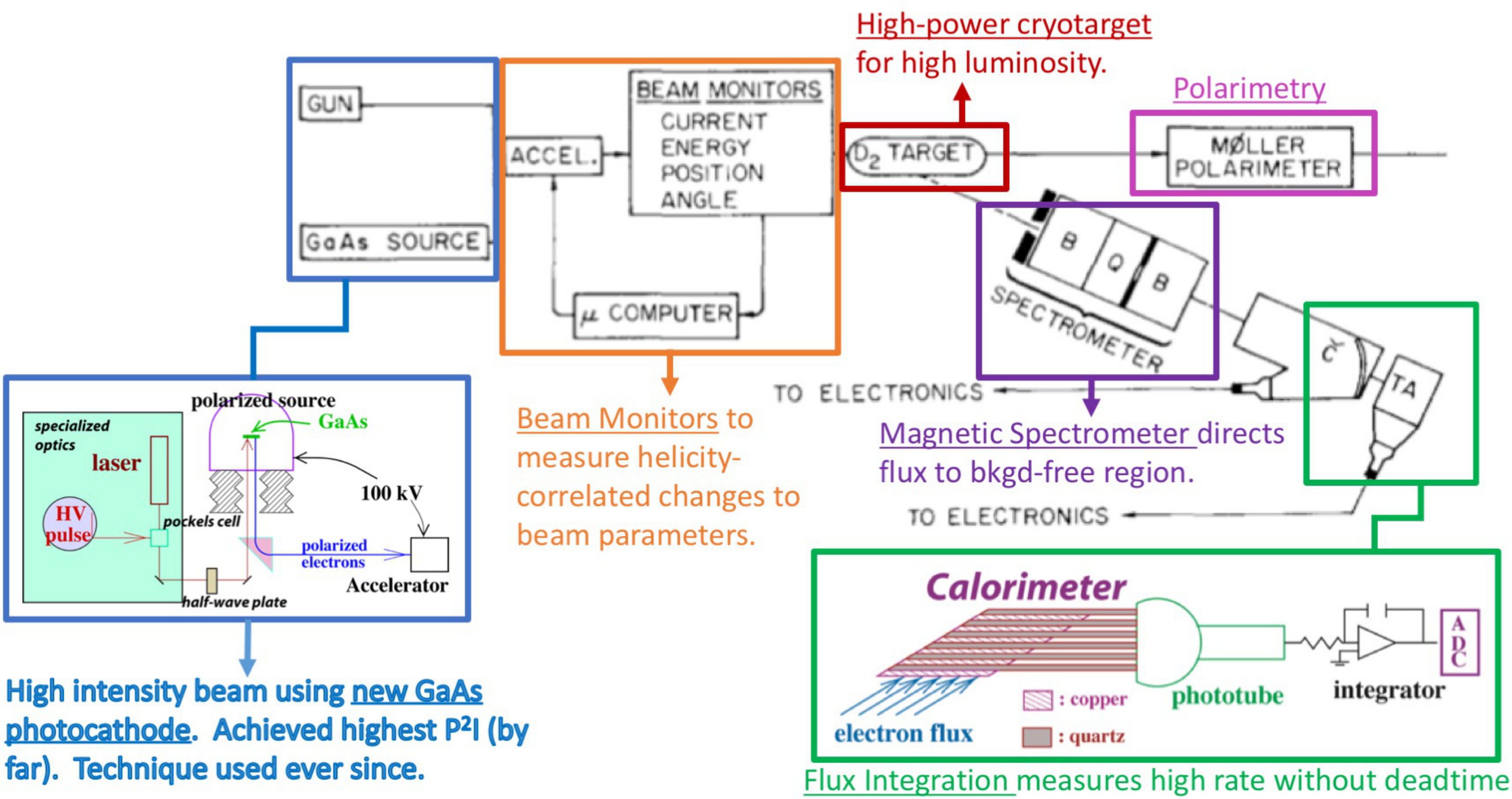
- Parity-violating electron scattering has become a precision tool

Blueprint of a PVES Experiment (E122 at SLAC)

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

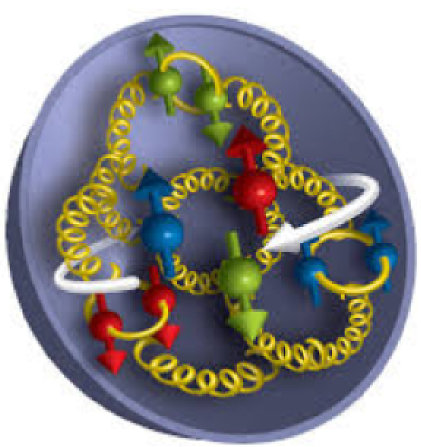


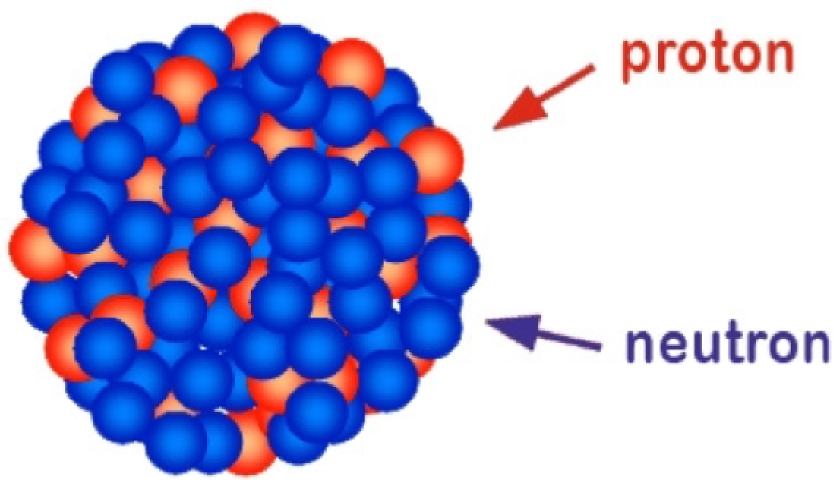
Anatomy of a PVES Experiment (E122 at SLAC)

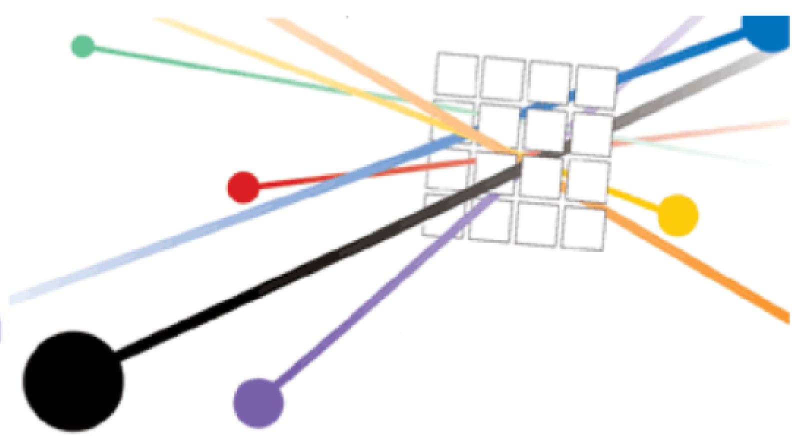


Selected Applications of PVeS

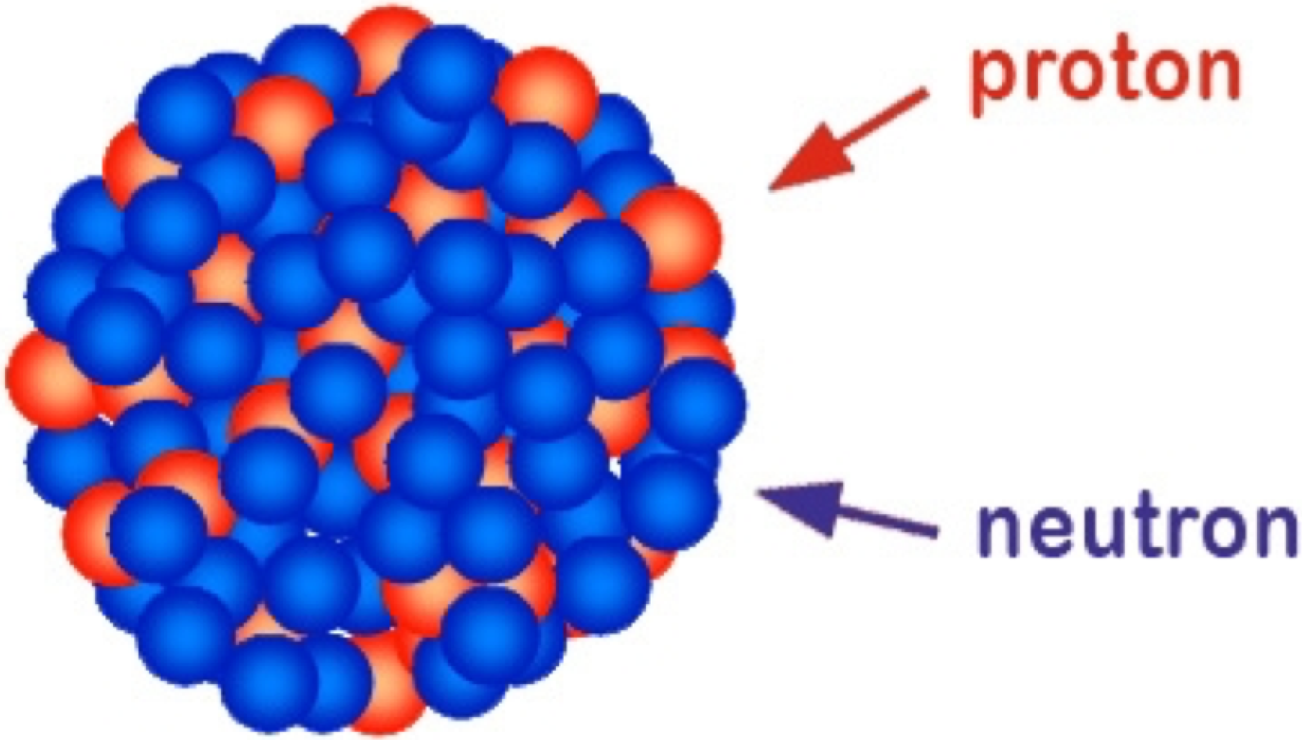
- **Strange Quarks**: What is the role of strange quarks in the electromagnetic structure of the proton or nucleon?
- **Size of Nucleus**: What is the size of a neutron-rich, complex nucleus? What is R_n, n_{skin}? Implications for Neutron Stars? LIGO overlap
- **BSM Searches**: Searching for physics Beyond the Standard Model. Obvious Motivations here: Dark sector matter,...





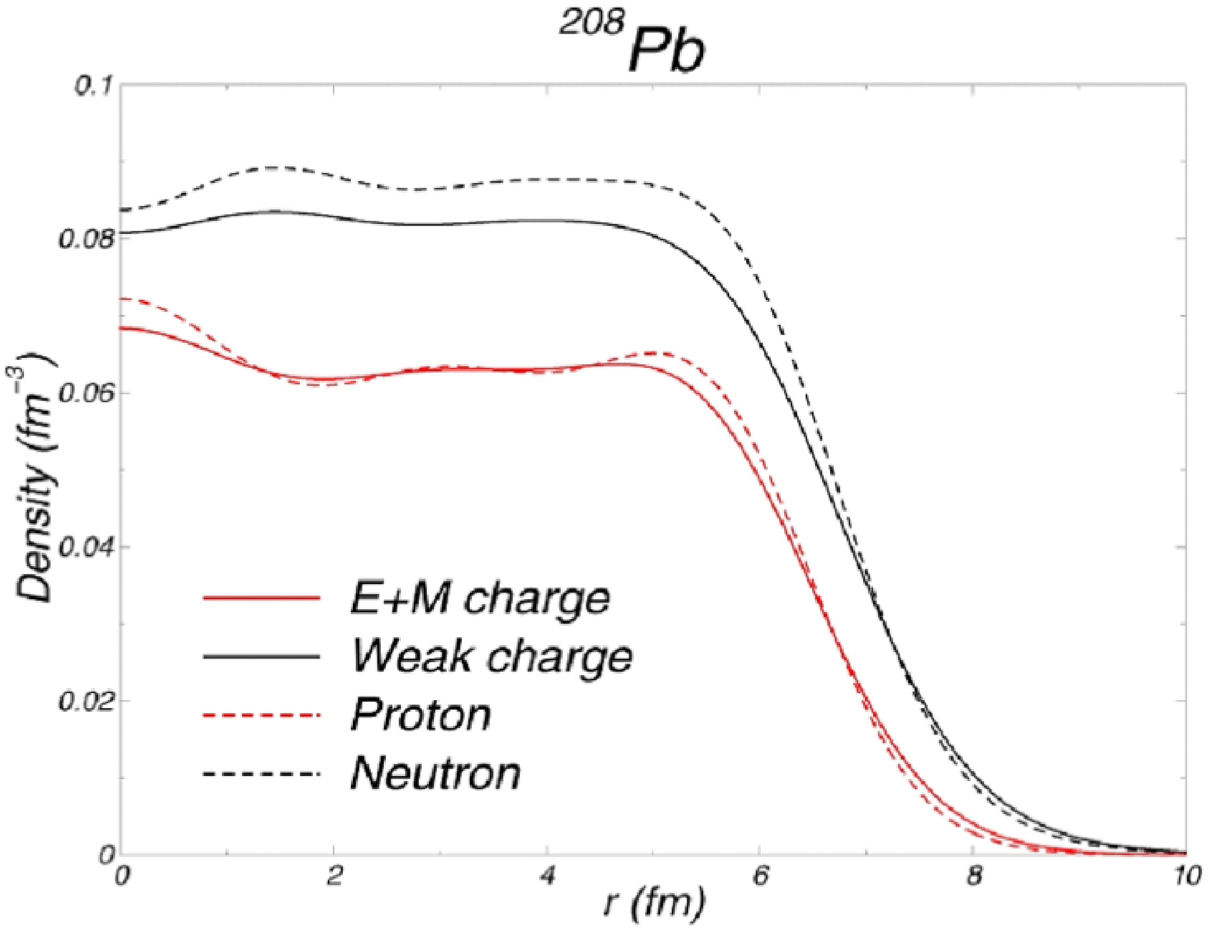


What is the size of a ^{208}Pb nucleus (82p+126n)?



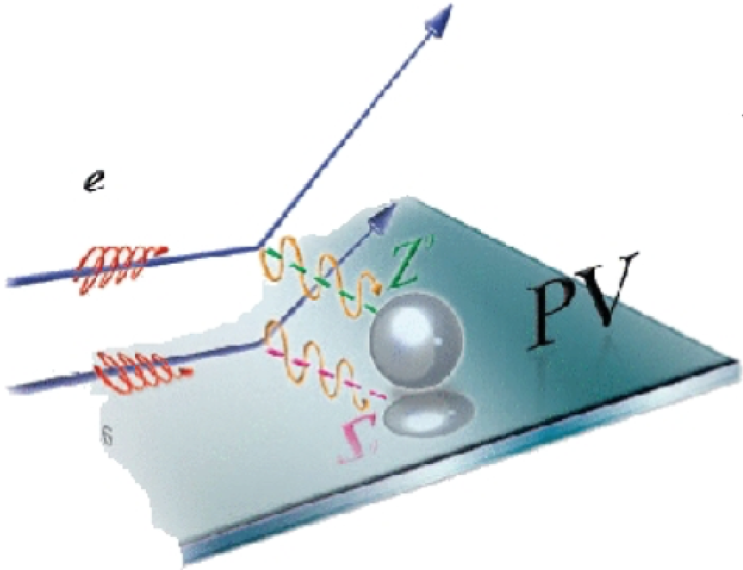
- What do we mean by size? The mass radius, the charge radius?
- PREX (Pb Radius EXperiment) addresses this question in a unique way: Uses a "Weak" nuclear force probe to measure how much neutrons stick out past protons in ^{208}Pb nucleus (called the Neutron "skin")
- CREX (Calcium Radius EXperiment) performs same measurement but on ^{48}Ca

Mass versus EM Charge Radii of ^{208}Pb

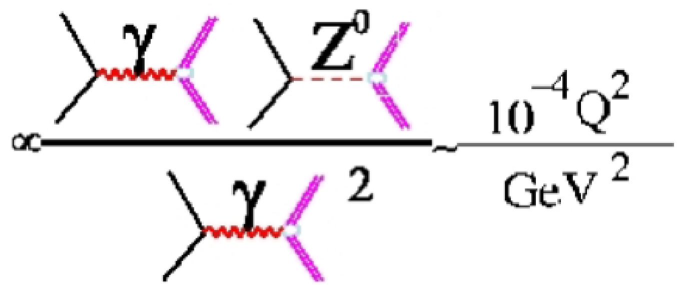


- Electromagnetism: Force mediated by γ exchange; protons have EM charge "+e" while neutrons have 0...
- Weak Nuclear: Force mediated by Z^0 and $W^{\pm}$; **neutrons have ~12 times more Weak charge than protons**

PREX Measurement (Pb Radius EXp)



$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



- Uses ~1 GeV elastically scattered electrons (at ±5 deg) off 0.5 mm thick isotopically pure ^{208}Pb target
- e^- beam is longitudinally spin-polarized, target is unpolarized
- Measurement relies on the maximal parity-symmetry violating nature of the Weak force
- e^-'s dominant interaction is EM, but it can also interact via the Weak force; but it does so predominately for only one of the polarization states and not the other -- thus the Asymmetry (A_{PV}) measurement

Motivation: Nuclear Radii in Heavy Nuclei

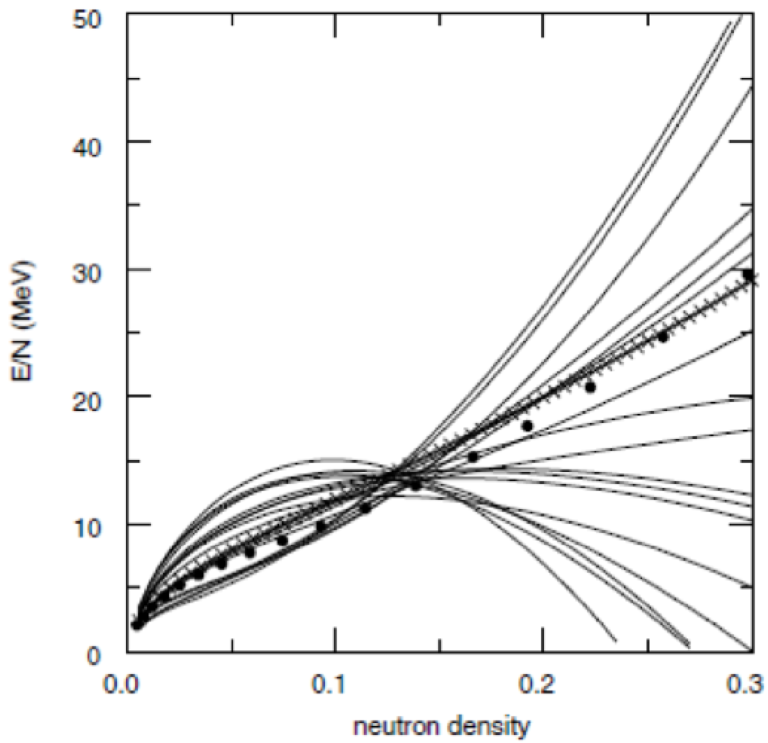
- Measurements are important for understanding the strong nuclear force
- Calculations are difficult due to non-pQCD regime and complicated due to many-body physics
- Interesting for:
  - ➢ Fundamental nuclear structure
  - ➢ Isospin dependence and nuclear symmetry
  - ➢ Dense nuclear matter and neutron stars
- Proton radius is relatively easy - electromagnetic probes
- Neutron radius is difficult:
  - ➢ Weakly couples to electroweak probes
  - ➢ Hadronic probes have considerable uncertainty
  - ➢ Theory has range of $R_n - R_p$ for Pb of 0 - 0.4 fm

Motivation: What do we learn from R_n?

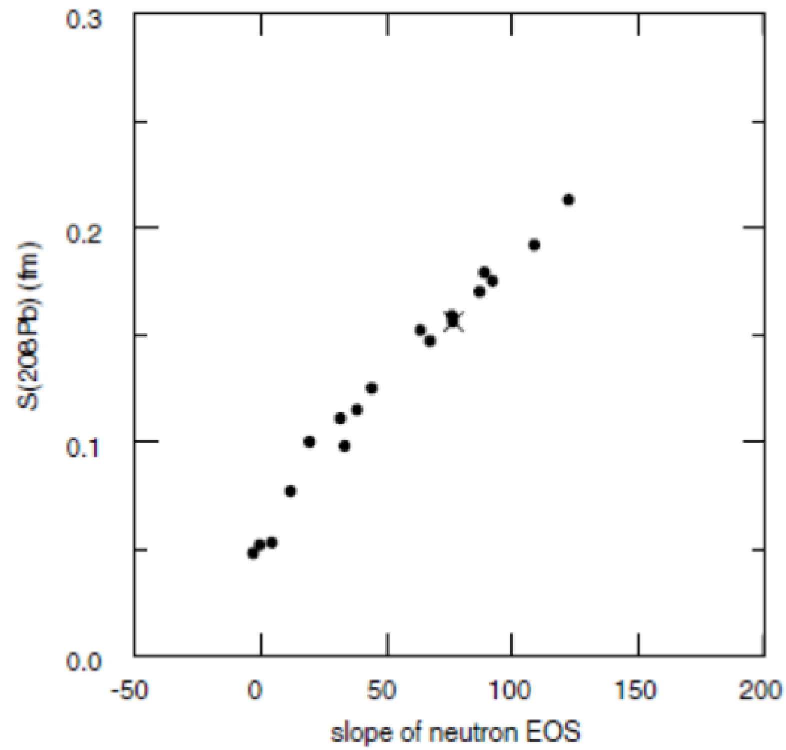
- Constraints on Equation of State (EOS) and symmetry energy of neutron rich matter -- the energy cost for asymmetric matter (N ≠ Z)
- Slope of EOS can be used to constrain potential models

B.A. Brown, PRL 85, 5296 (2000)

Neutron EOS for 18 Skyrme model sets; dots are FP calcs; crosses are SkX; neutron density in neutron/fm^3



Lead neutron skin vs. corresponding slope parameter of the 18 EOS sets



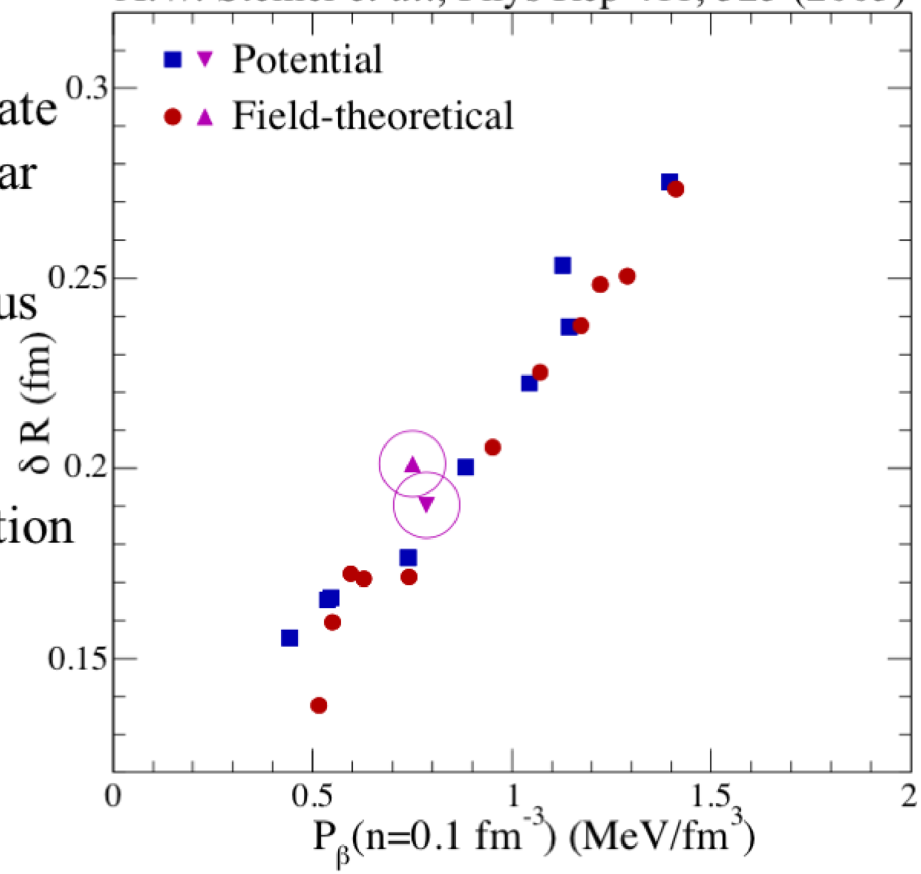
Motivation: Neutron Stars

- Neutron star structure is better understood with measurements of R_n
- Larger R_n (and thus ΔR--the skin) correlates with larger pressure P
- Larger P pushes neutrons out against surface tension increasing R_n:
  - Thus measurement of R_n (and ΔR) could calibrate the pressure of neutron star matter at sub-nuclear densities
  - Combining ΔR with observed neutron star radius could allow access to pres.-dens. rel't inside neutron stars
- Additionally, symmetry energy governs proton fraction
  - Direct URCA cooling depends on processes:

$$n \longrightarrow p + e^- + \bar{\nu}$$
$$e^- + p \longrightarrow n + \nu$$

  - Larger symmetry energy gives larger proton fraction (need 11\%)

A.W. Steiner *et al.*, Phys Rep 411, 325 (2005)



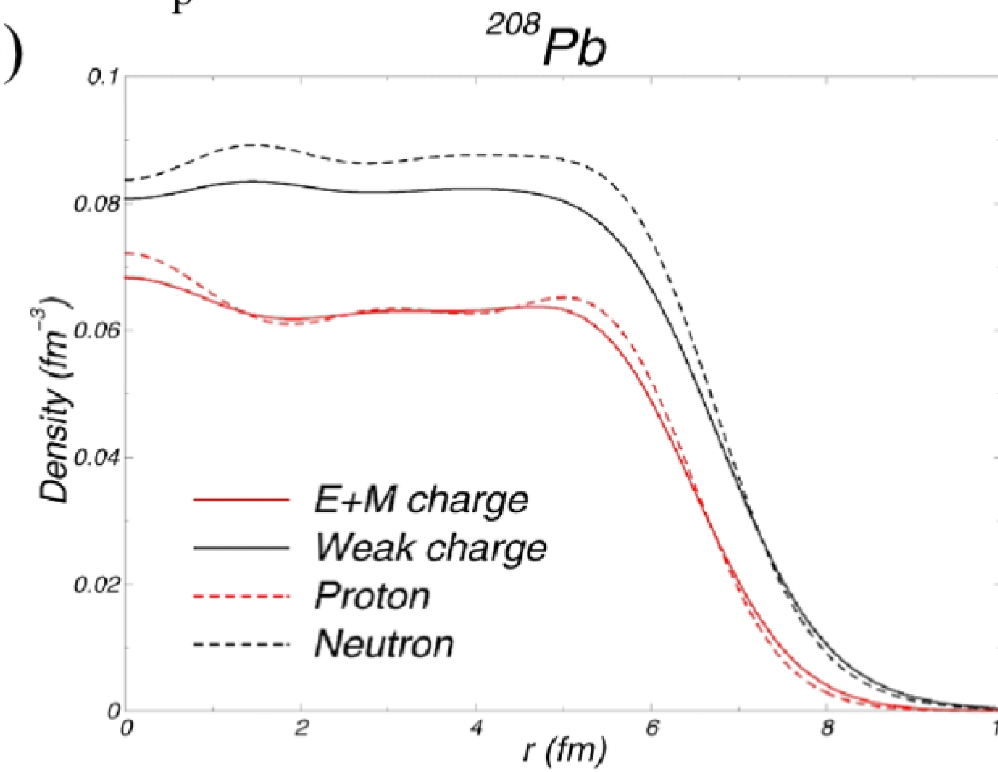
Methods used to Measure R_n

- Hadronic Probes
  - Elastic pN, $\vec{p}$N, nN, $\pi^{\pm}$N
  - π^0 photo-production (Kruche, et al.)
  - GDR
  - Antiproton scattering
  - Have theoretical uncertainty

- Electroweak Probes
  - Parity violating electron scattering
  - Atomic parity violation
  - "Clean" measurements, fewer systematics
  - Technically challenging

Non-Parity Violating Electron Scattering

- Electron scattering γ exchange provides R_p through nucleus form factors ($F(Q^2)$)



  - For spin 0 nucleus:

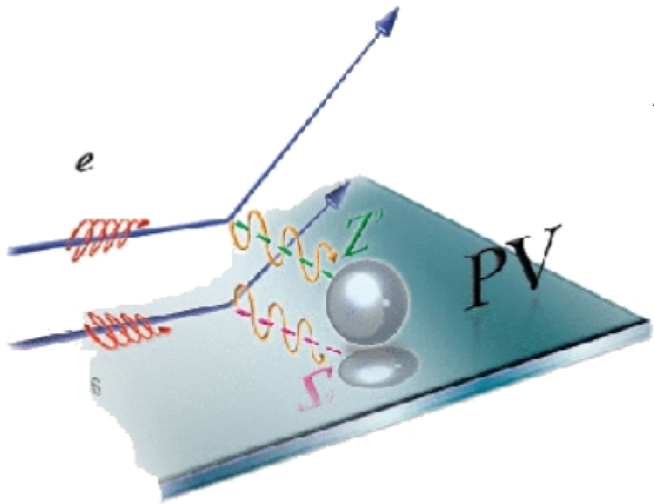
$$\frac{d\Omega}{d\sigma} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} |F(Q^2)|^2$$

  - In limit of small Q^2:

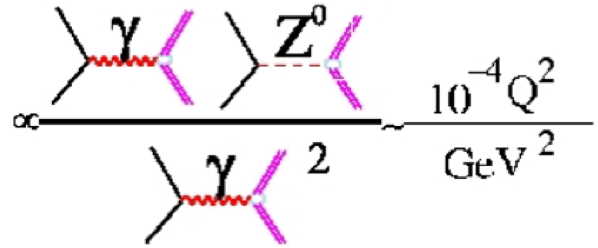
$$F(Q^2) \approx F(0) + \left.\frac{dF}{dQ^2}\right|_{Q^2=0} + \ldots = \int \rho(\vec{x})d^3x - \frac{1}{6}Q^2 \langle r^2_{\text{charge}} \rangle$$

  - So small Q^2 measurements give density and RMS electromagnetic radius (dominated by R_p)

Parity Violating Electron Scattering



$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



- The e^- can also exchange a Z^0 which is parity violating (PV)
- Z^0 primarily couples to the neutron, since:

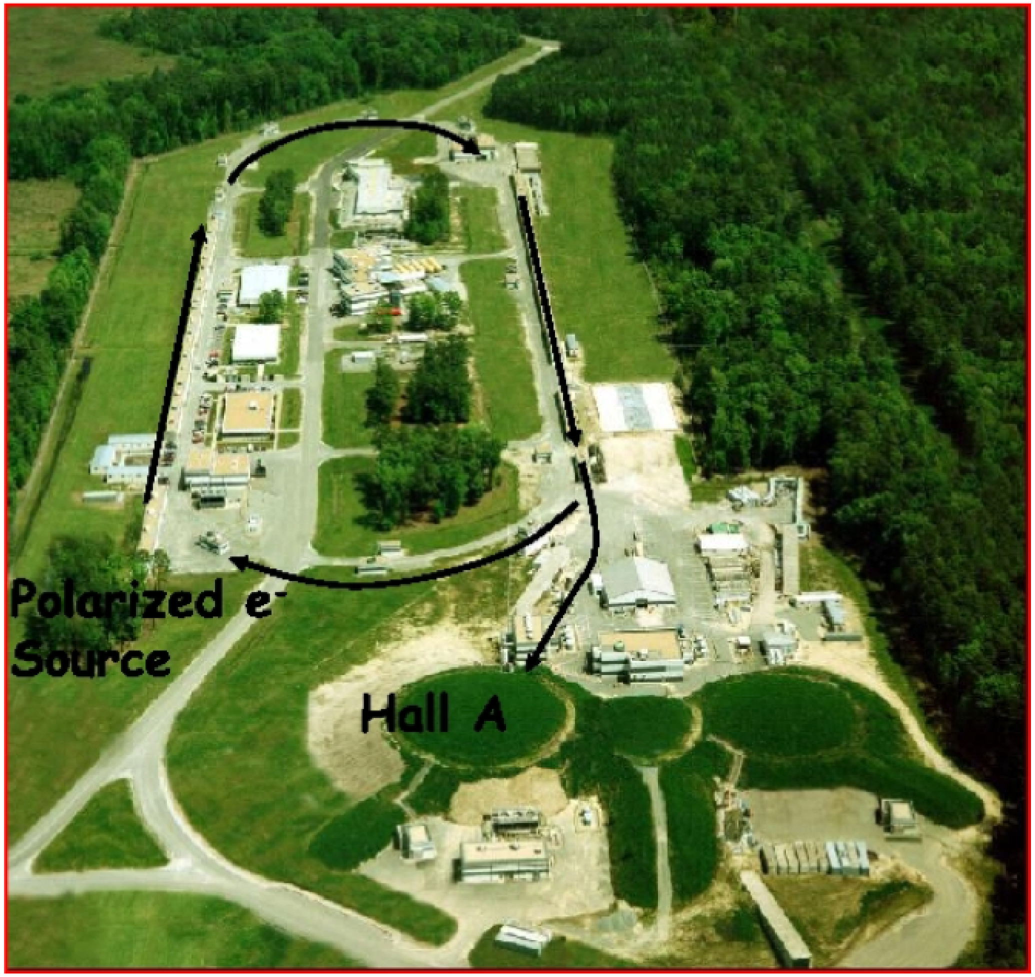
$$Q_{\rm weak}^{\rm proton} \propto 1 - 4\sin^2\theta_W \approx 0.076, \qquad Q_{\rm weak}^{\rm neutron} = -1$$

- Detectable in PV asymmetries of e^- with opposite helicities
- In Born approximation, $Q^2 \ll M_Z$, from γ - Z interference:

$$A_{PV} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[4\sin^2\theta_W - 1 + \frac{F_n(Q^2)}{F_p(Q^2)}\right], \quad F_n(Q^2) = \frac{1}{4}\int d^3r' j_0(qr)\rho_n(r)$$

- For fixed target experiment, typical $A_{PV} \sim 10^{-8}$ - 10^{-4}

JLab's CEBAF is Excellent Facility for PV Measurements



- High quality polarized beam, $P_e \sim 85 - 90\%$
- PV expt's need quiet beam parms over helicity windows:

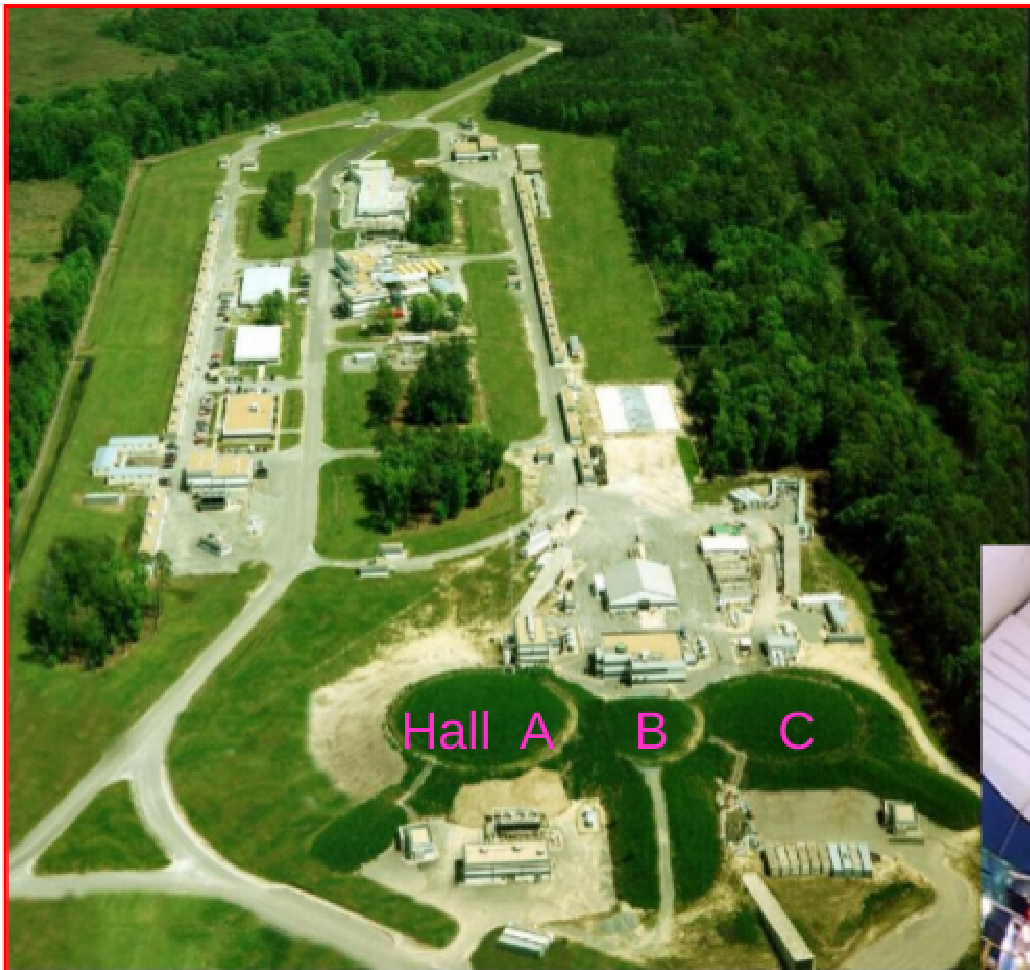
$\Delta x < 10\ \mu m$ $\Delta x' < 2\ \mu rad$ $\Delta E/E < 10^{-3}$

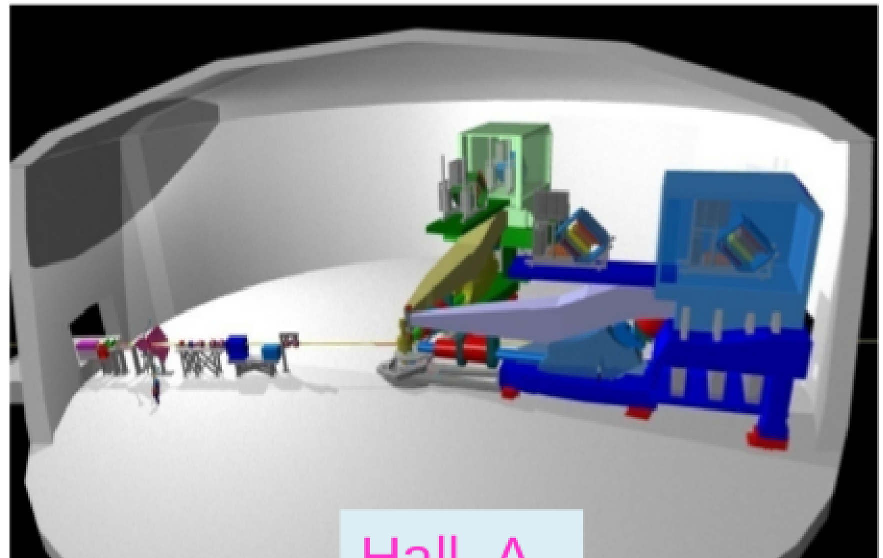
PREx Measurement

PREX measures R_n of ^{208}Pb

- Lead is nice because:
  - Excess of neutrons (44 more--with some expected to form a neutron-rich skin)
  - Doubly magic nucleus (82 protons, 126 neutrons)
  - Nearest excited state is 2.6 MeV from elastic peak (possible to exclude inelastics using HRS)
- Ran in Spring 2010 (approved 30 PAC days)
- $E_e = 1.063$ GeV, $\theta_e \approx 5^o$, $Q^2 \approx 0.009$ GeV^2
- $I_e \sim 50 - 75\ \mu A$
- Proposed uncertainty on A_{PV} of 3%, $R_n \sim 1\%$
- Uncertainty dominated by statistical error

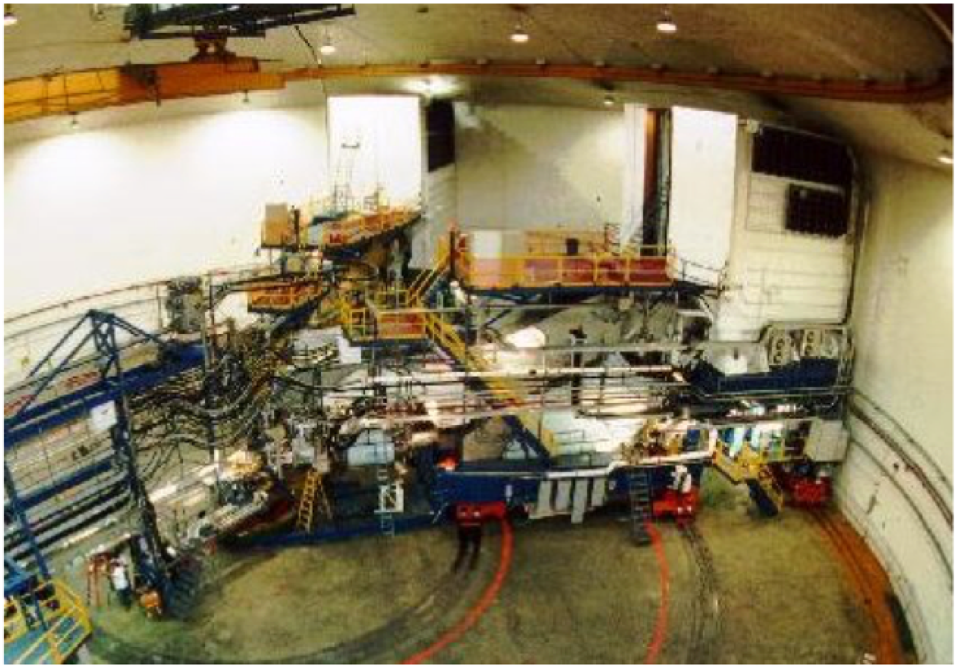
Jefferson Lab Hall A (Newport News, Virginia)

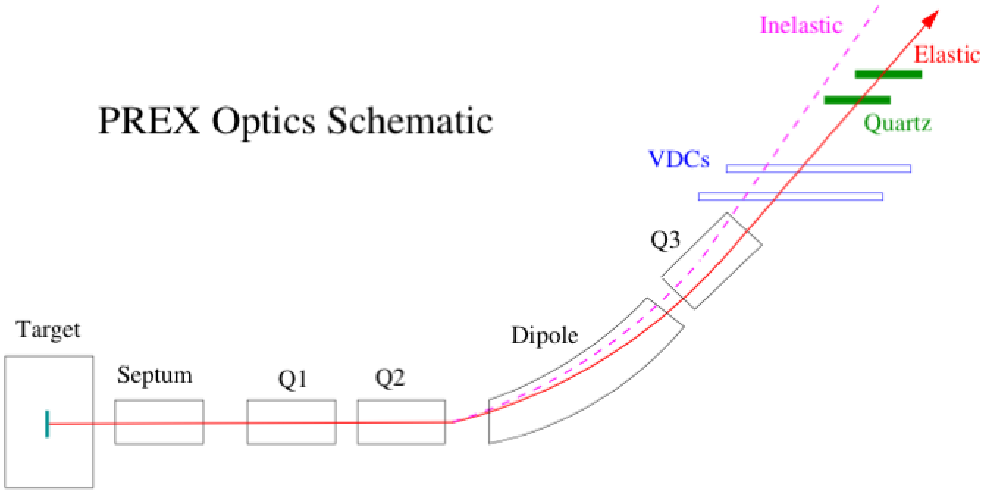




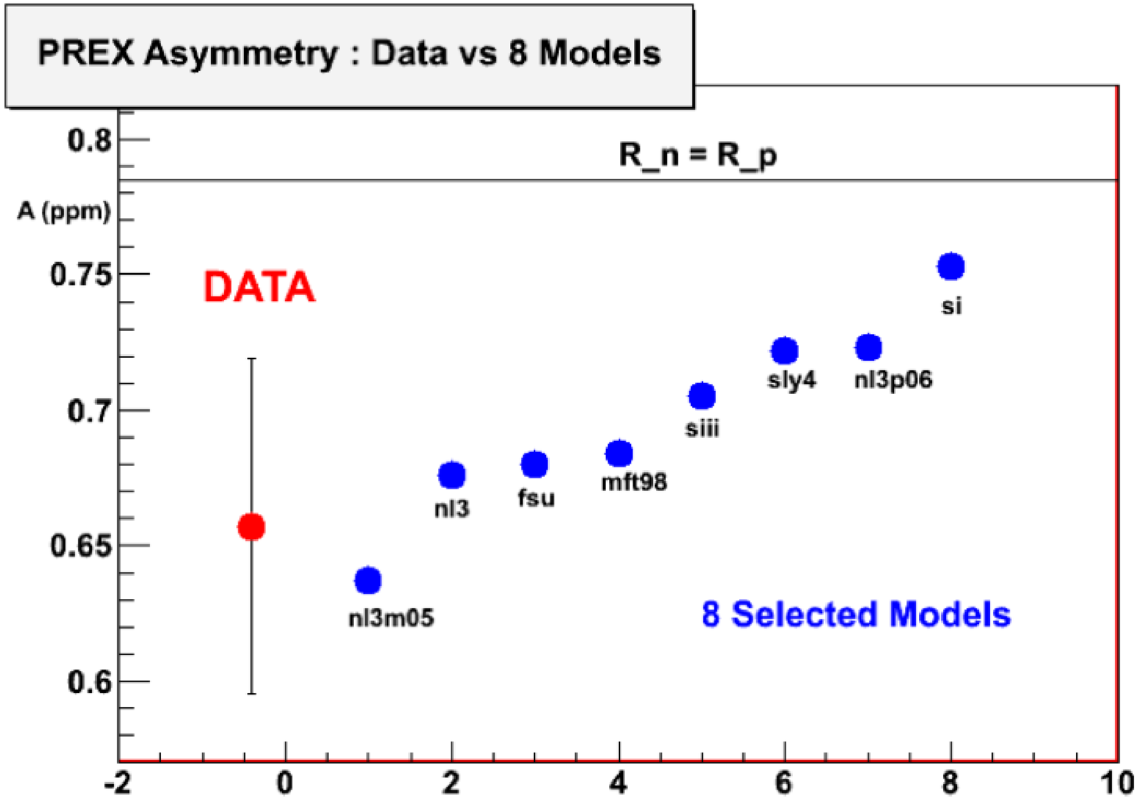
Experimental Setup

- Std. Hall A HRS's with detector huts well shielded against bkgds
- Run dual, symmetric arms-- cancels out A_{trans} and other systematics
- Use septum magnet to bend 5^o to 12.5^o
- Upgraded polarimetry (non-inv. Compton ~1%, Inv. Moller ~1%)
- 0.5mm thick Pb foil in between two 0.15mm Diamond targets (~1 in^2) with cryogenically cooled frame; used fast rastered beam
- Quartz Cerenkov detectors with 18-bit integrating ADCs





PREX Result



- Set 95\% CL on existence of neutron skin
- $R_n = 5.78^{+0.15}_{-0.17}$ fm, $\Delta R = R_n - R_p = 0.34^{+0.15}_{-0.17}$ fm
  - ➢ Each model of neutron density is folded into numerical solution of Dirac eqn with Coulomb and weak axial potential
  - ➢ Full acceptance (apertures, septum optics, detectors) applied to A_{PV}

Result and Error Budget

$$A_{\mathrm{PV}} = 0.658 \pm 0.0604 \pm 0.0130 \text{ ppm}$$
$$\pm 9.2\%(\text{stat}) \pm 2.0\%(\text{syst})$$

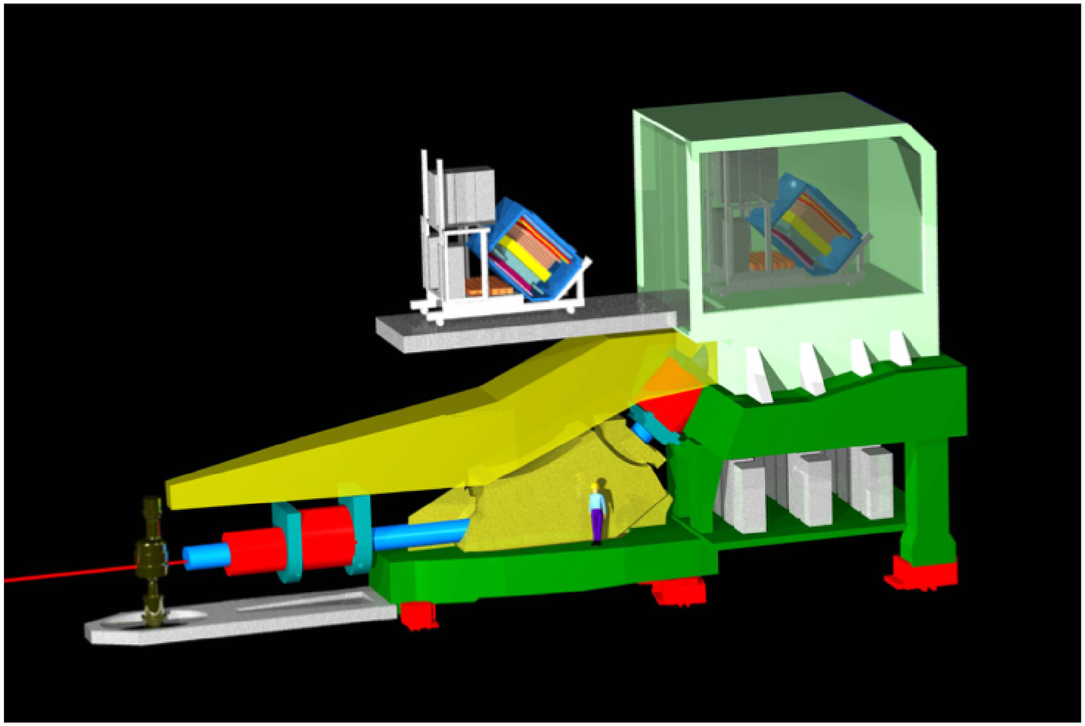
Contributions	abs (ppm)	rel (%)
Polarization	0.0071	1.1%
Detector Lin.	0.0071	1.1%
Beam Corrections	0.0072	1.1%
Q^2	0.0028	0.4%
^{12}C Asymmetry	0.0025	0.4%
Transverse Pol.	0.0012	0.2%
BCM Lin.	0.0010	0.1%
Target Thick	0.0006	0.1%
Rescattering	0.0001	0.0%
Inelastic Cont.	0.0000	0.0%

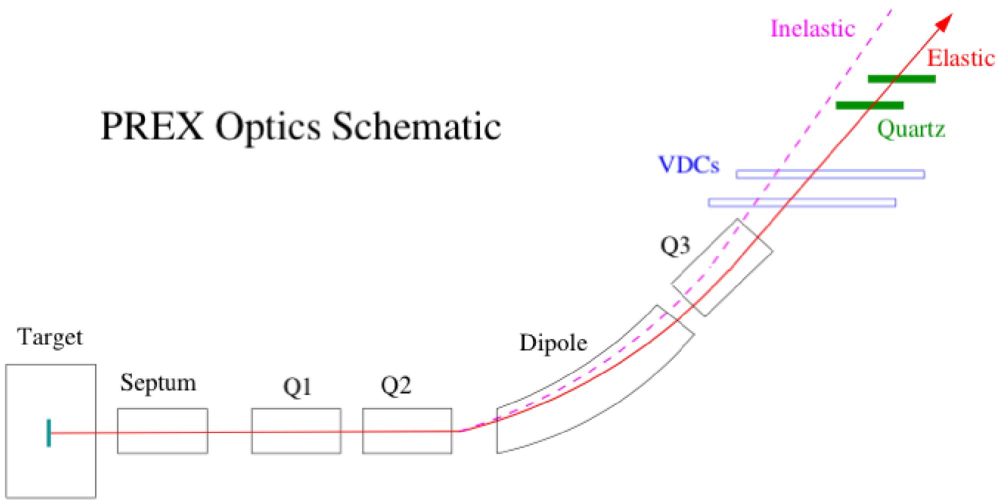
Summary (PREX)

- PREx exp. ran March - June 2010 to measure R_n on ^{208}Pb; Published in Phys. Rev. Lett. 108, 112502 (2012)
- After all corrections: $A_{PV}^{Pb} = 0.658 \pm 0.0604$ (9.2%) $\pm$ 0.0130 (2.0%) ppm (statistics dominated uncertainty)
- From simple fit over calcs: $R_n = 5.78^{+0.15}_{-0.17}$ fm
- Neutron skin: R_n - R_p = $0.34^{+0.15}_{-0.17}$ fm
- Established existence of neutron skin with 95% CL
- PREx-II experiment set to run in late 2016 – will improve stat. err of PREx-I by factor of 3
- PREx-II precision will better discriminate between models allowing predictions relevant for the description of neutron stars

Experimental Setup (Spectrometer & Detectors)

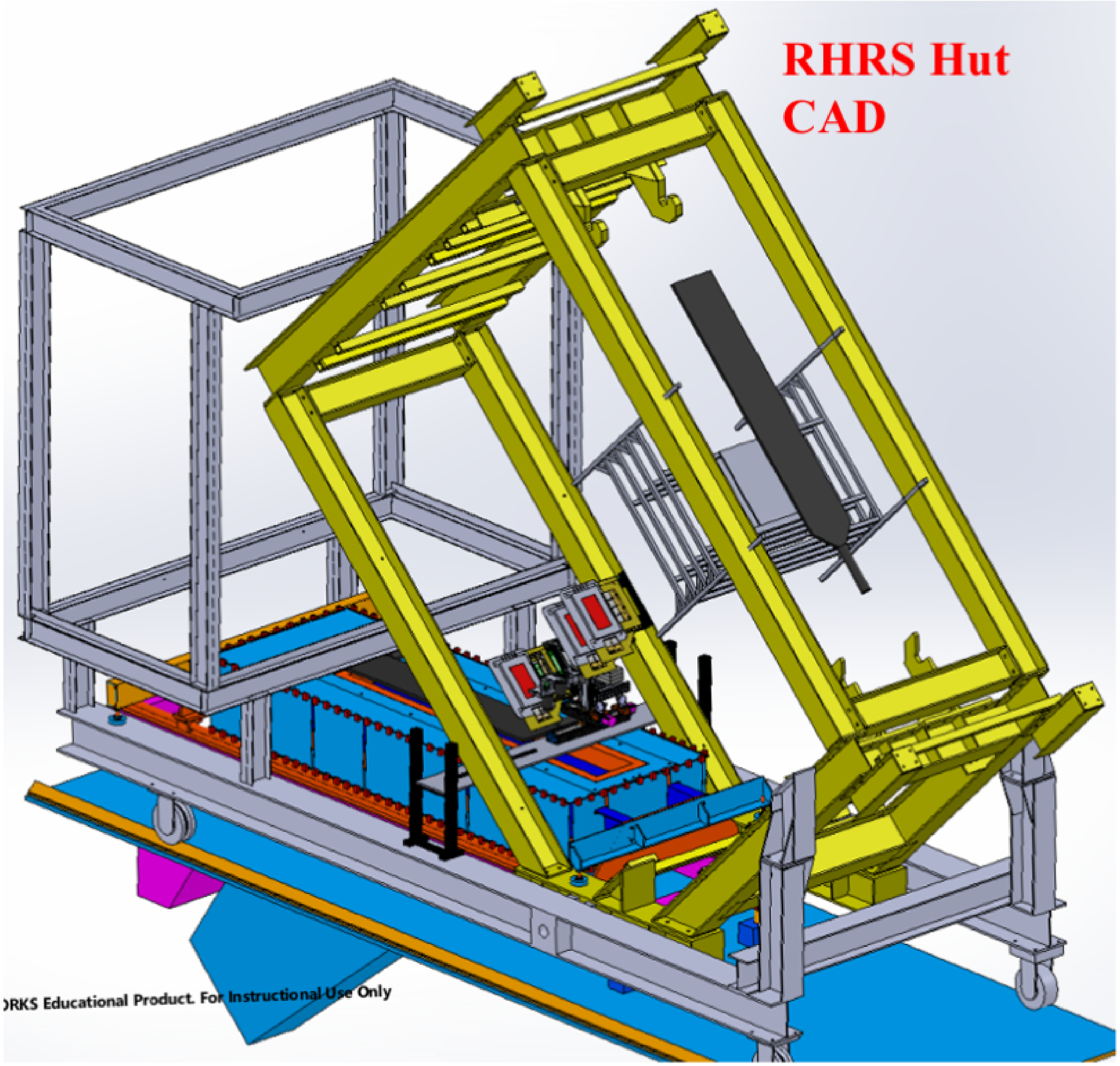
- Thin quartz Cerenkov detectors with PMTs used to measure scattered electron flux
- Highly relativistic electrons travel faster than light travels through the quartz, thus creating Cerenkov radiation (UV light)
- High purity quartz necessary due to its extreme radiation hardness (maintains transparency during high doses (Grad) of radiation)



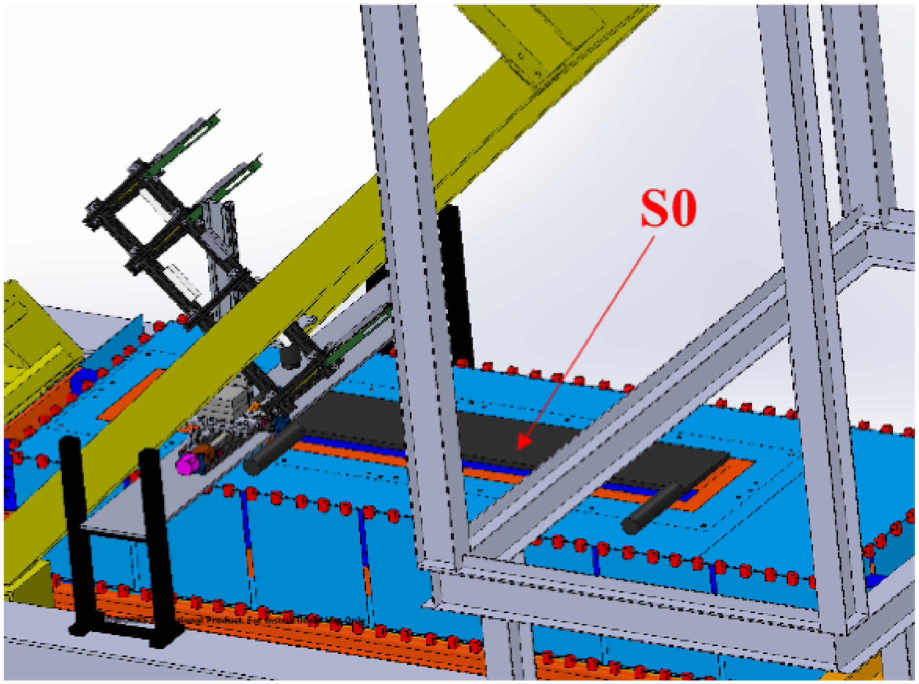


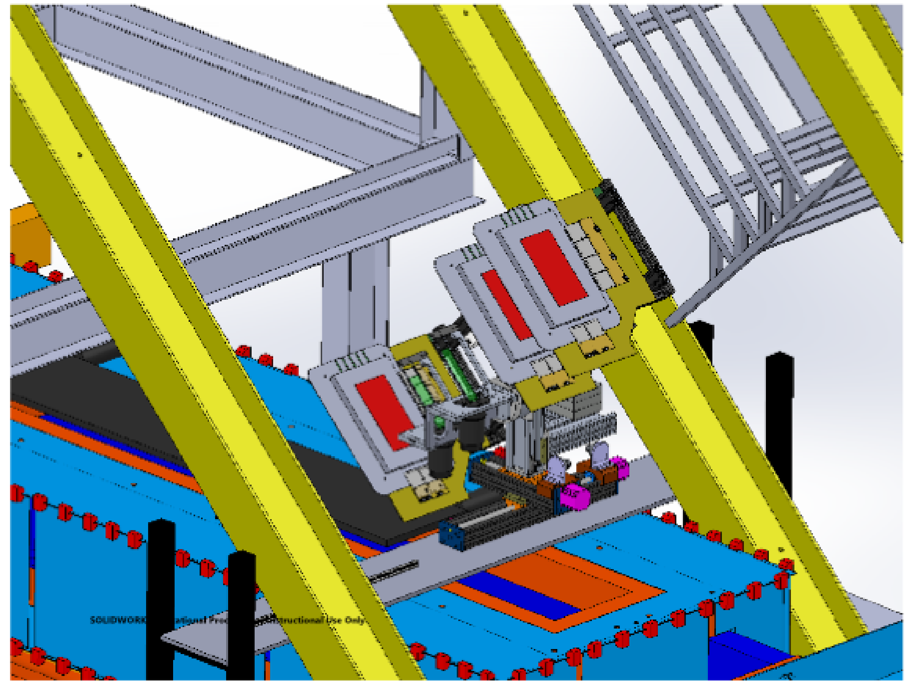
HRS Detector Package for PREX-II/CREX

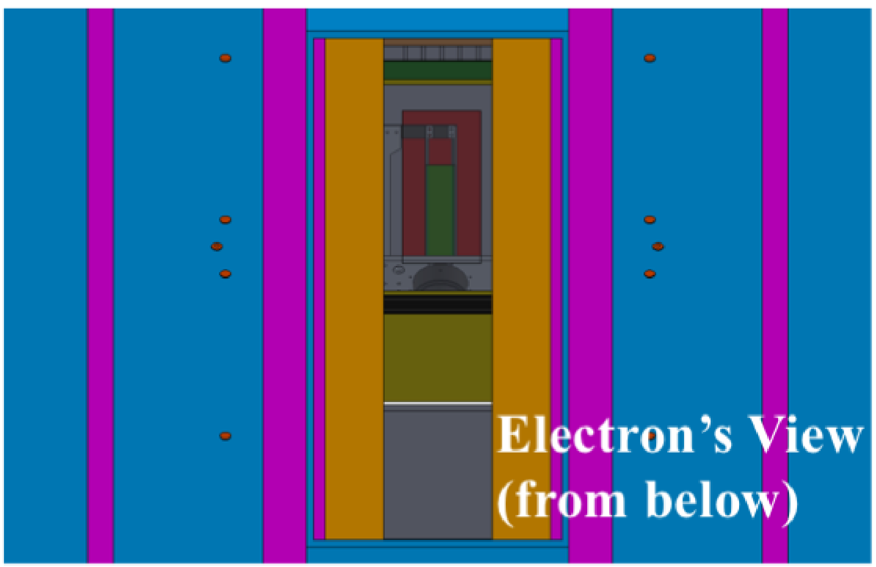
- All HRS standard detector packages removed except for VDCs: No S1, S2, Cerenkov, or Calorimeter
- For counting-mode operation: Use S0 + S3 for triggering
- Additional array of large GEMs from UVA group installed above PREX detector package
- A_T detector not shown: will mount just above small GEMs
- Plan to reuse same hardware and mounting/installation concept developed for PREX-I

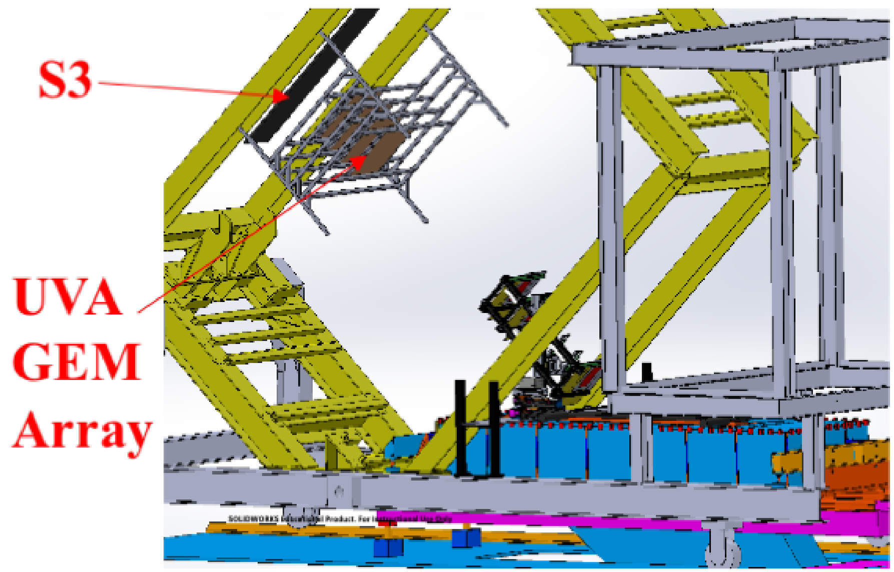


HRS Detector Package for PREX-II/CREX

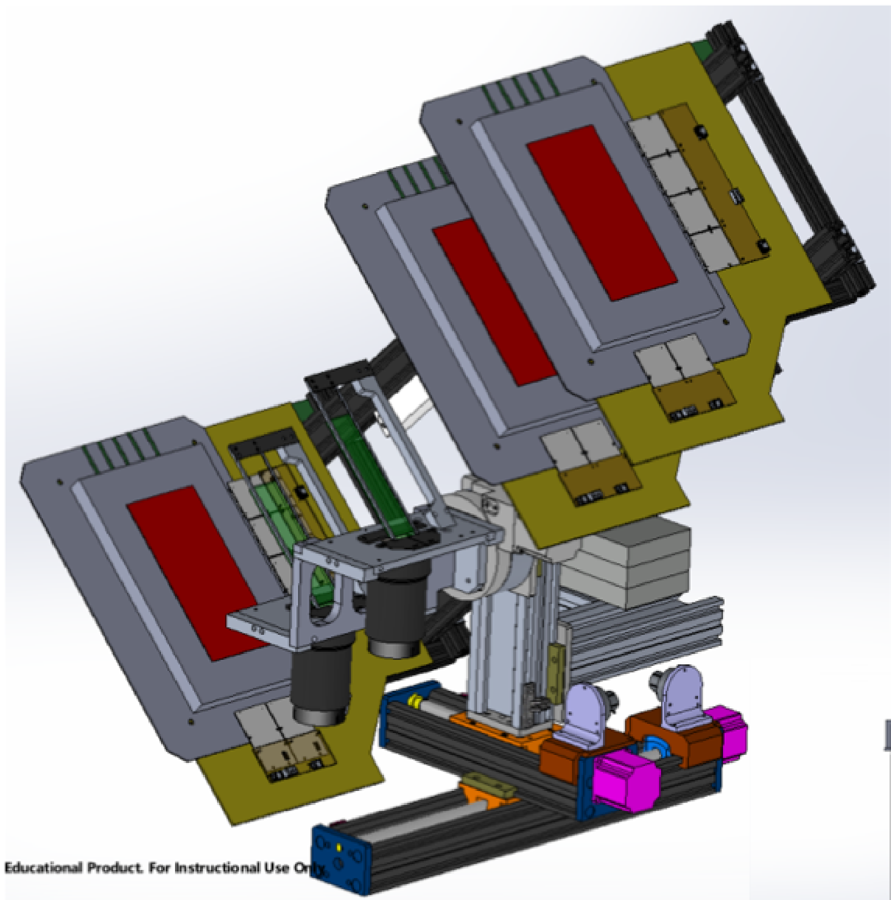


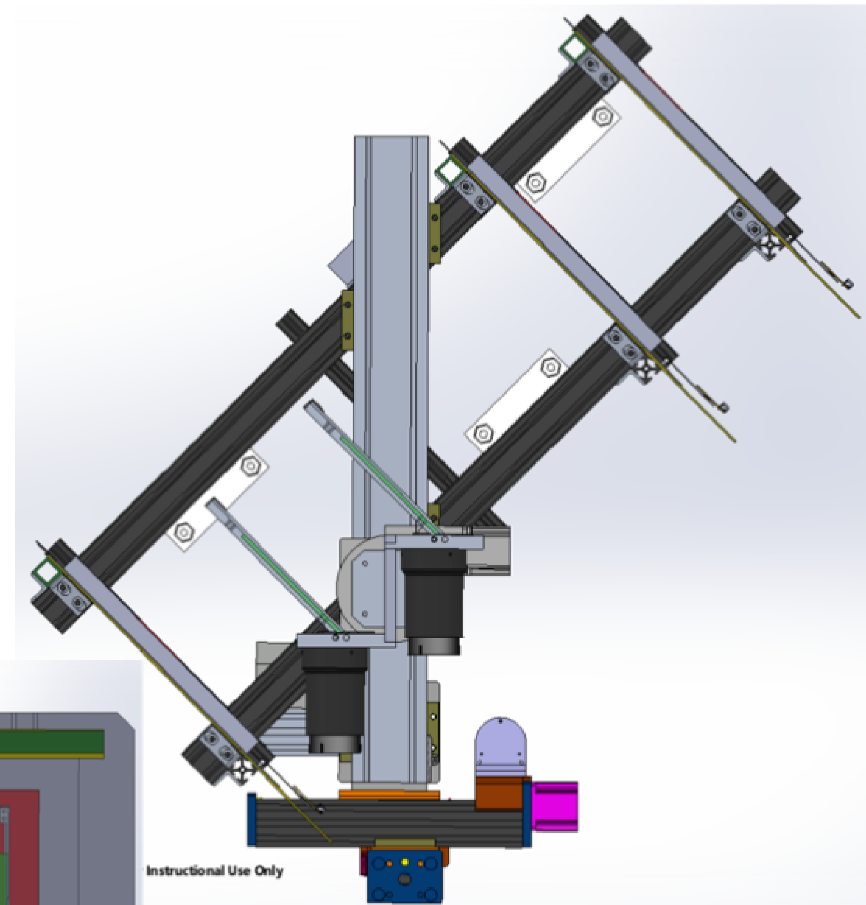


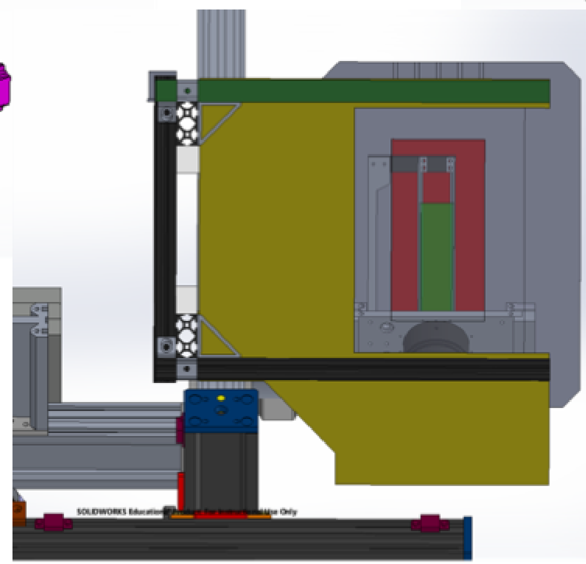




RHRS Tandem Quartz Mount with GEMs

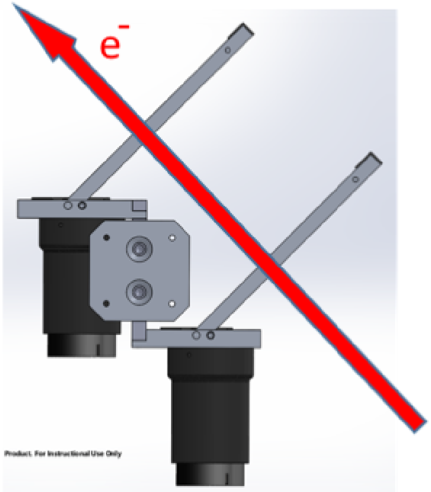


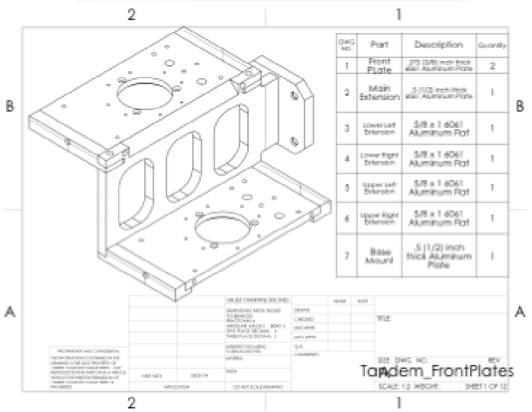


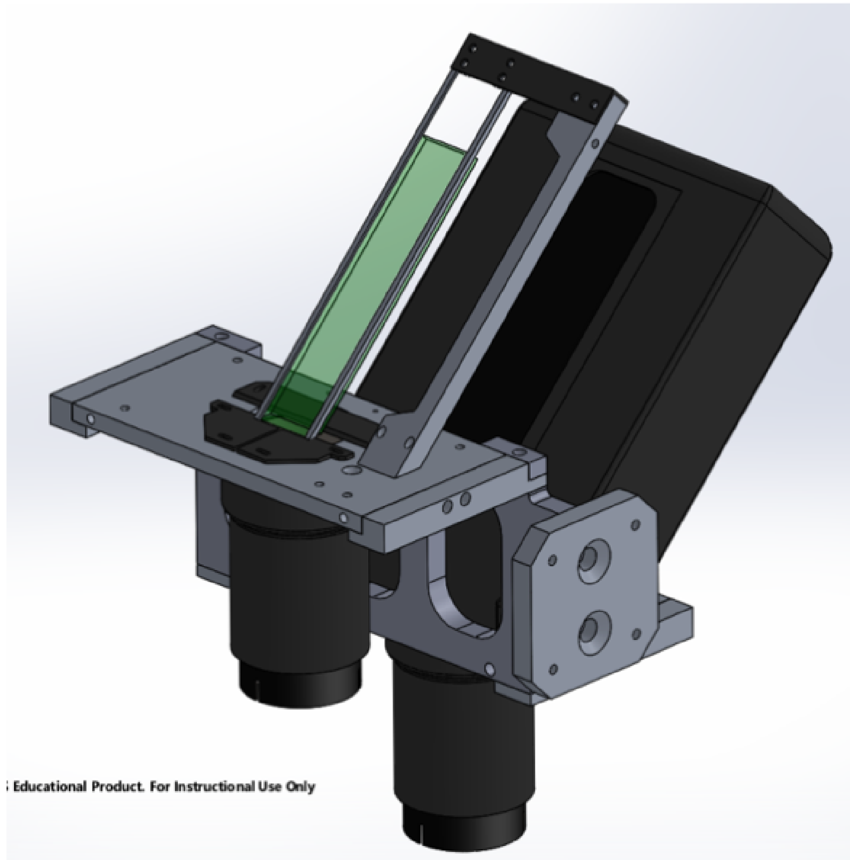


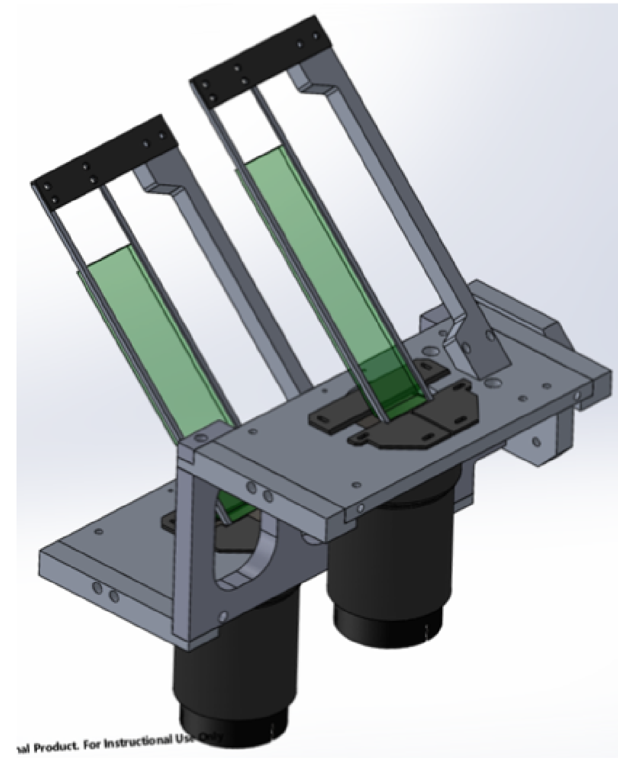
Electron's view (from below)

Main Integrating Tandem Detector Design





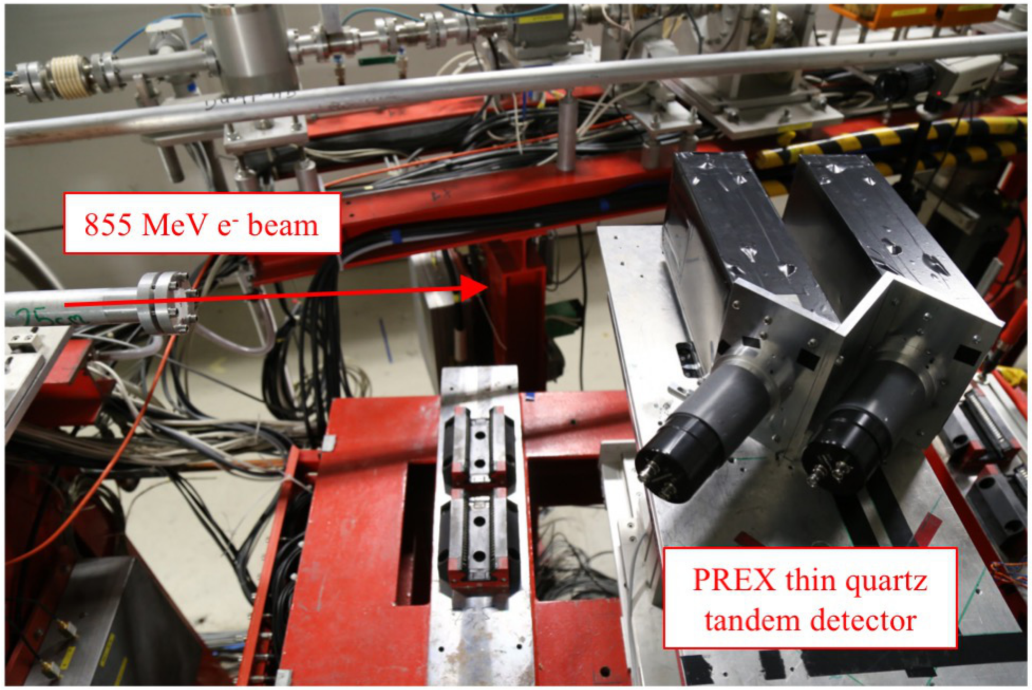


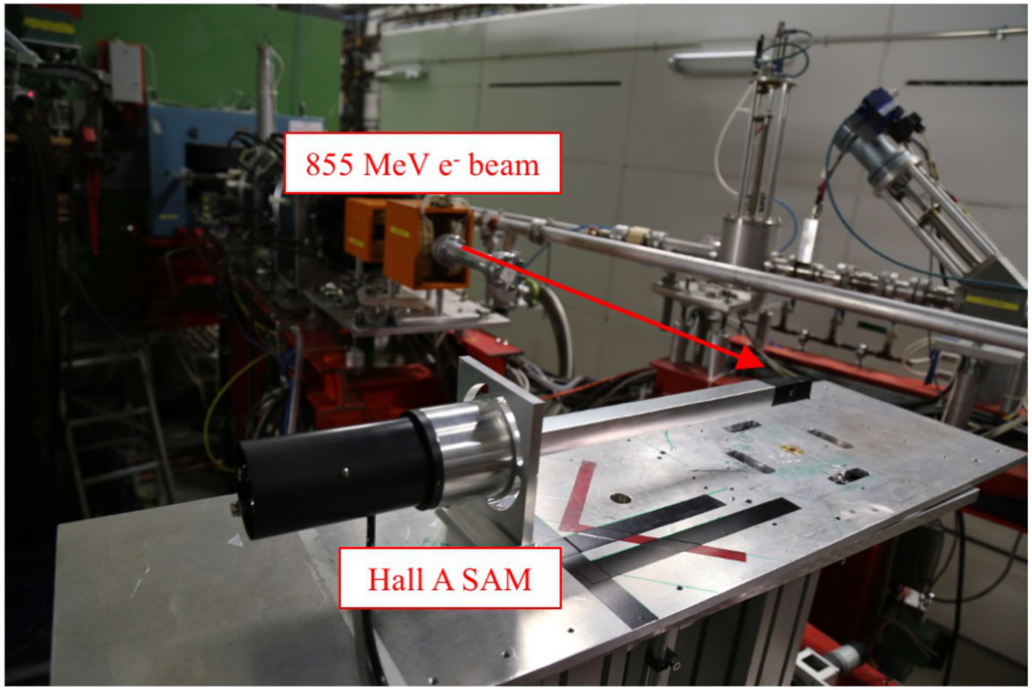


- PREX-II/CREX main detector design based on UMass Design-3.
- Rotatable tandem mount designed and prototype constructed
- New design has shorter quartz rails and incorporates mu-metal shields and 3D printed Nylon enclosure with Kapton windows

MAMI testbeam May 24-27, 2016

- ¾ shift total for PREX/CREX and SAM tests

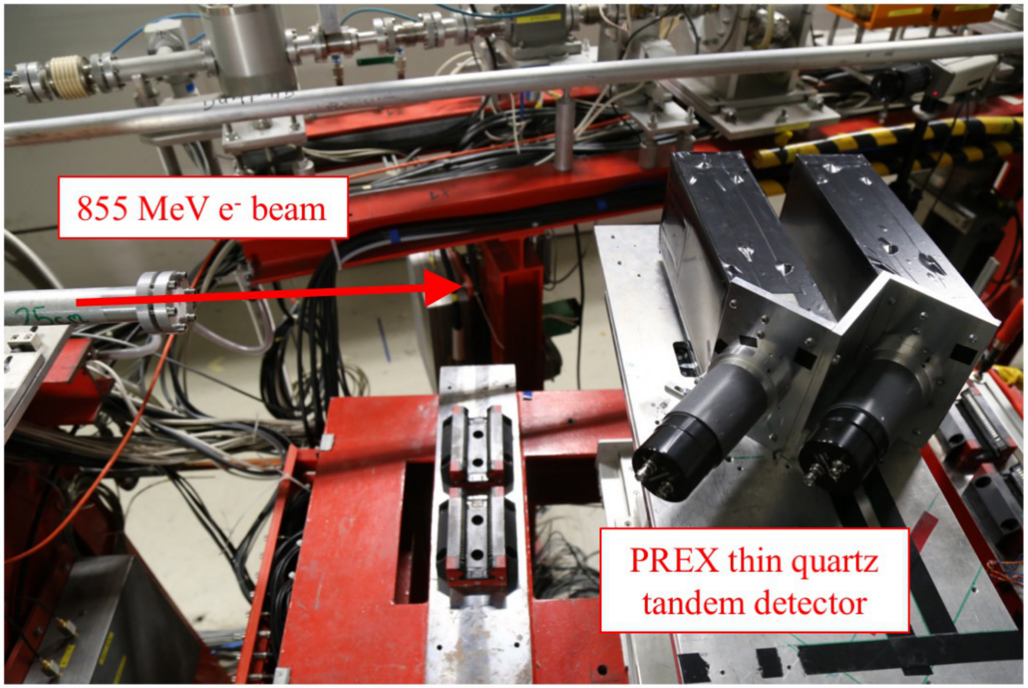




- 6mm and 10mm Tandem mount
- Near normal e^- incidence

- Final SAM detector PE yield studies:
  - Miro27 and UVS light-guides
  - With and without 1cm tungsten pre-radiator

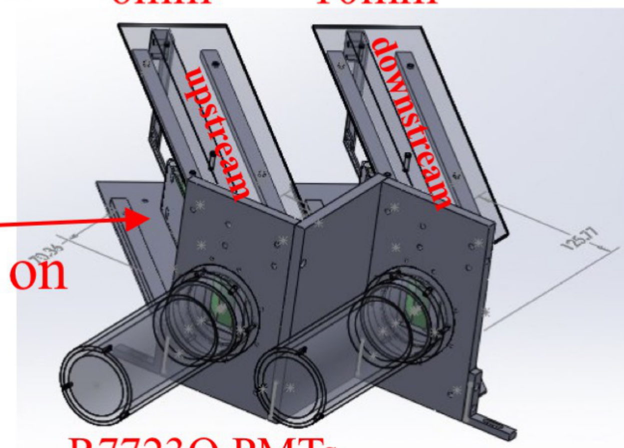
PREX/CREX Tandem mount Tests



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

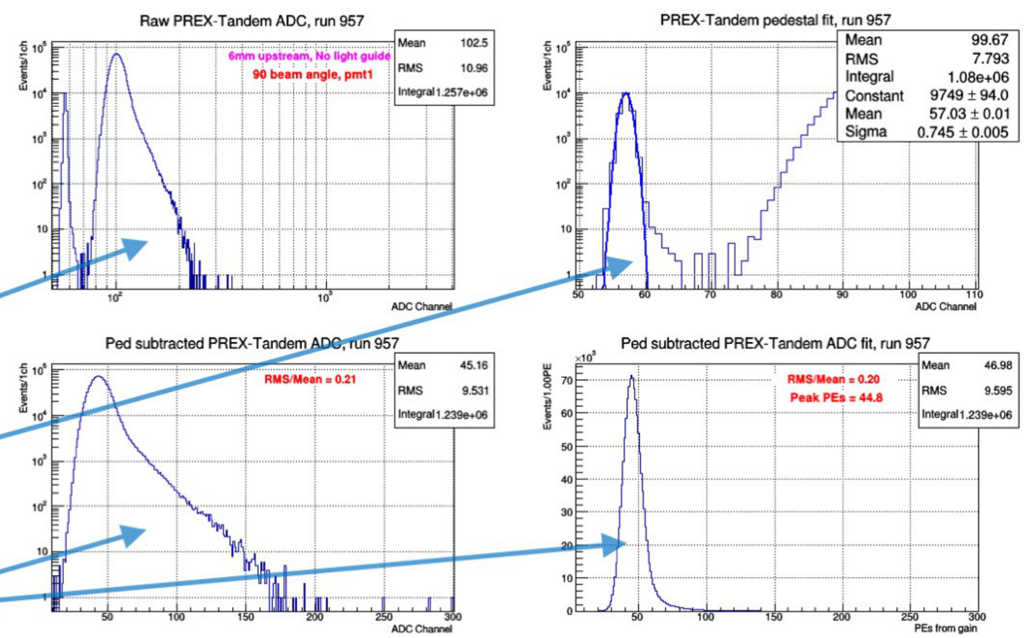
e^- beam

Centered on quartz at ~90°

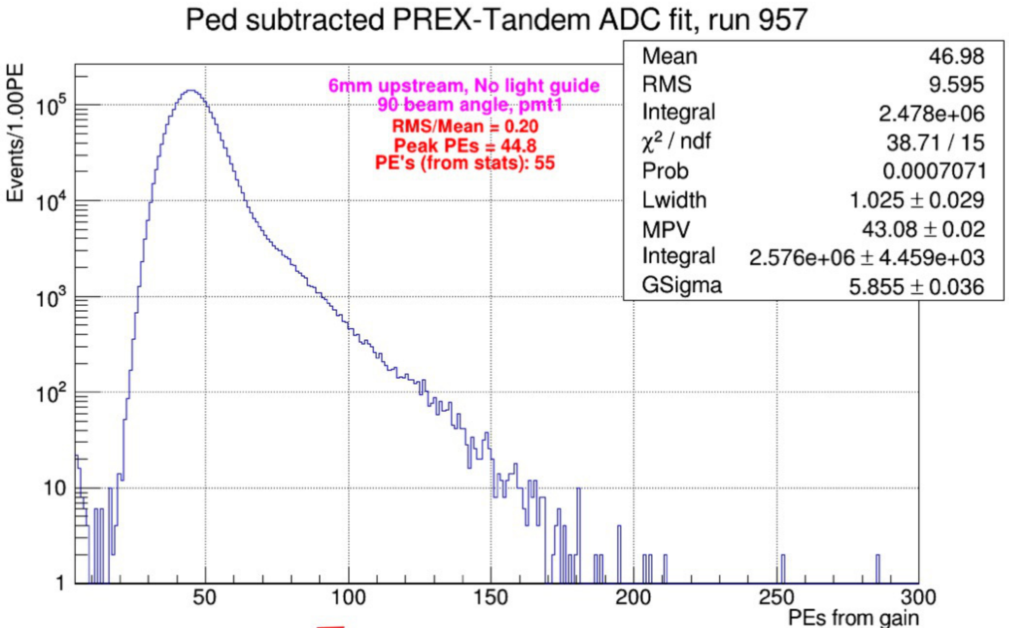


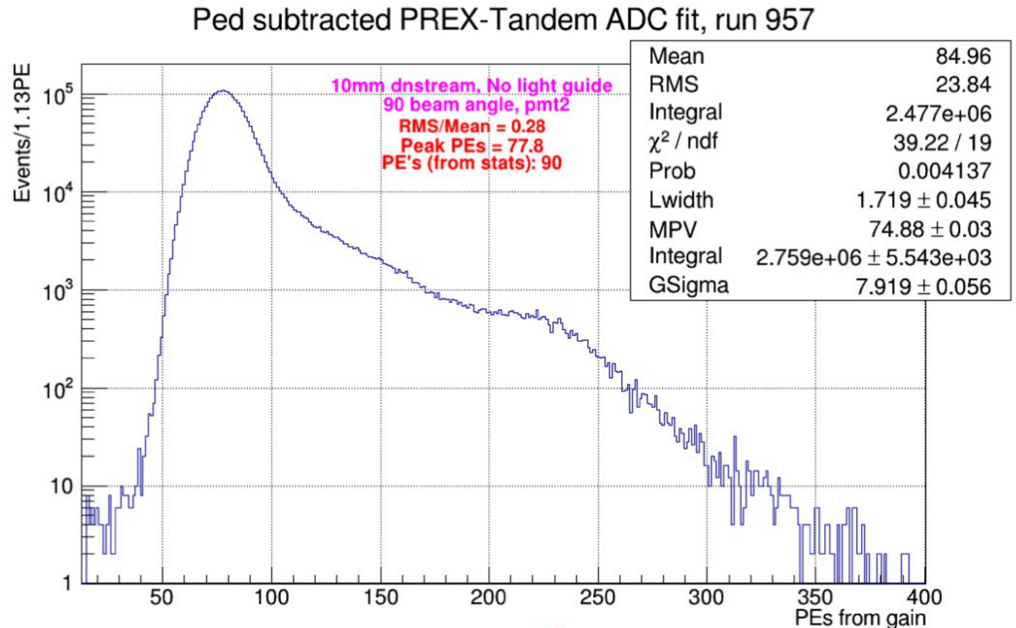
R7723Q PMTs

- 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



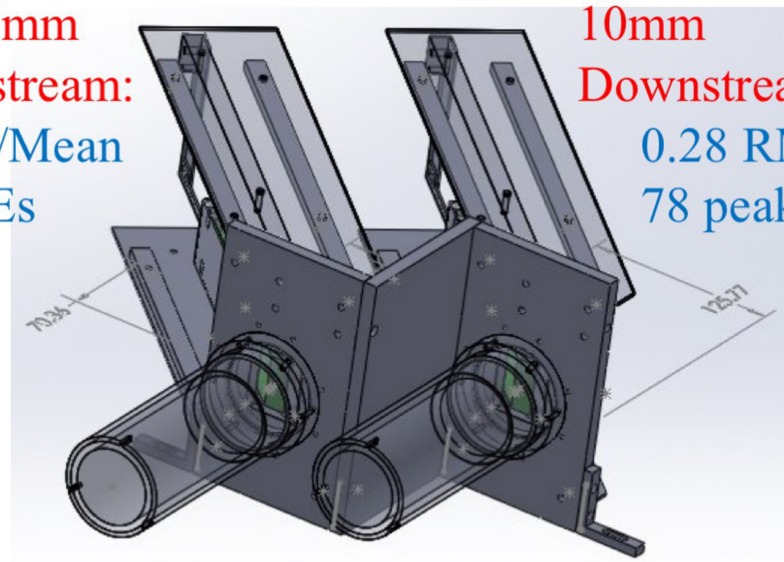
6 mm/10 mm Tandem Testbeam Results





- PEs converted from ADC units using PMT gains
- Peak PE's from Langau fit parameters did not agree with PE's from gain; fits were poor and very sensitive to fit domain around peak

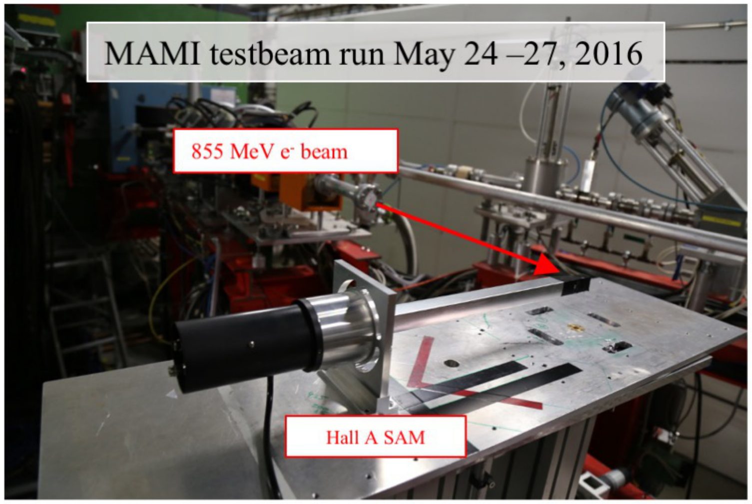
6mm Upstream:
0.20 RMS/Mean
45 peak PEs



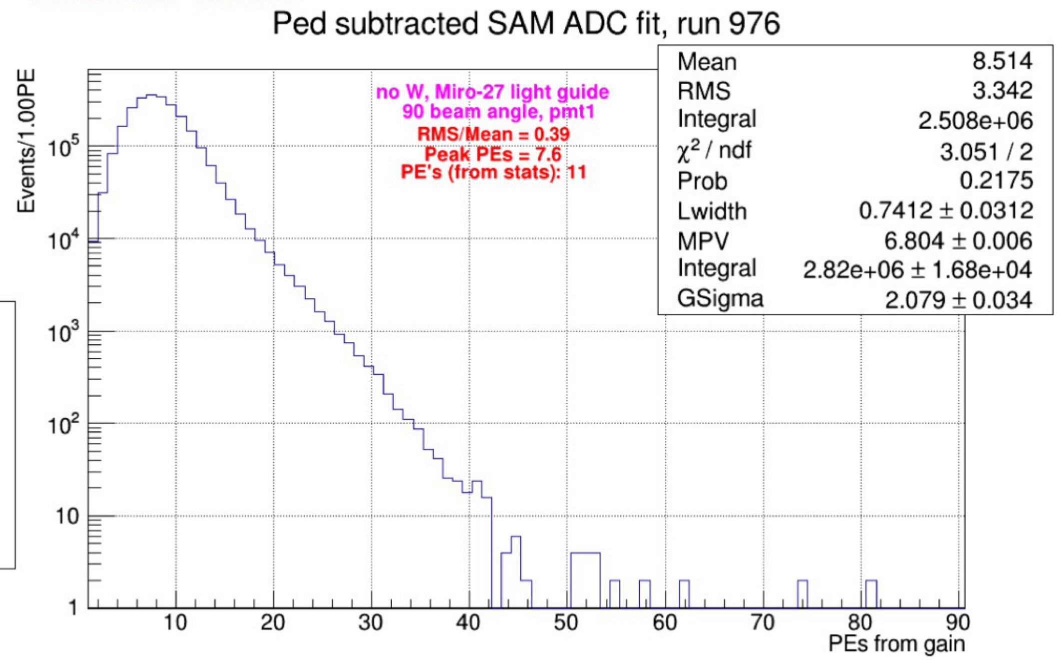
10mm Downstream:
0.28 RMS/Mean
78 peak PEs

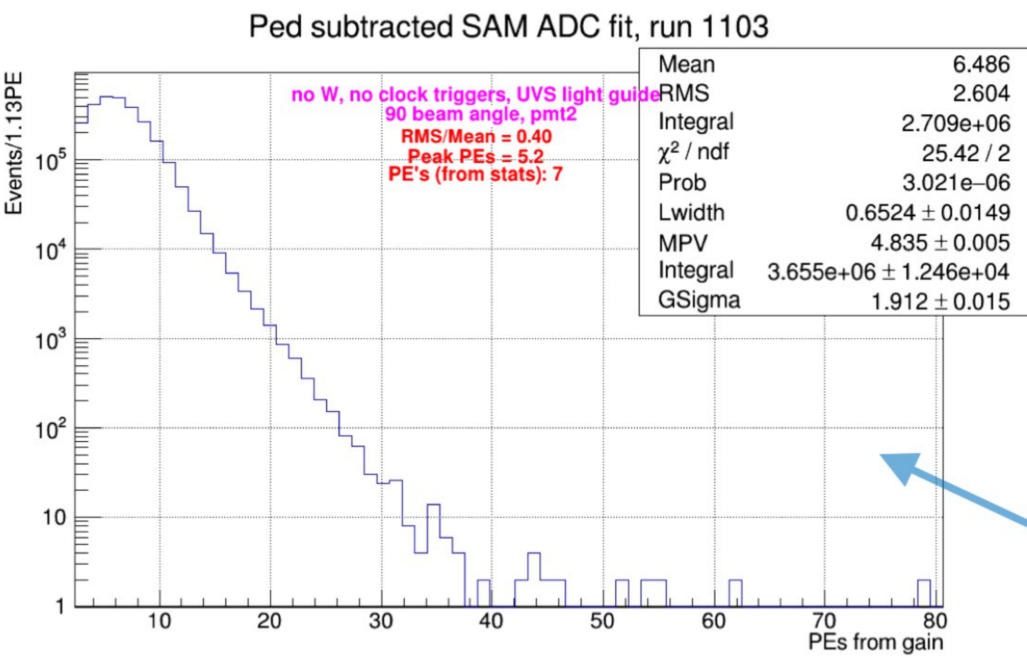
- Uncertainty in PMT gains between 5 – 10%

SAM PE Yield & LG Testbeam Study: Miro-silver27 vs Anolux UVS (no tungsten)



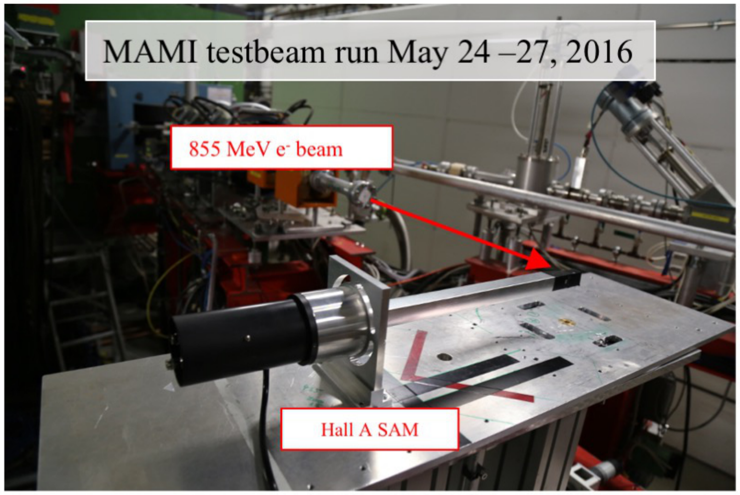
- Miro-silver27, no tungsten, N_2 gas flowing: ~7 - 8 peak PEs (using PMT gain) with 39% relative width



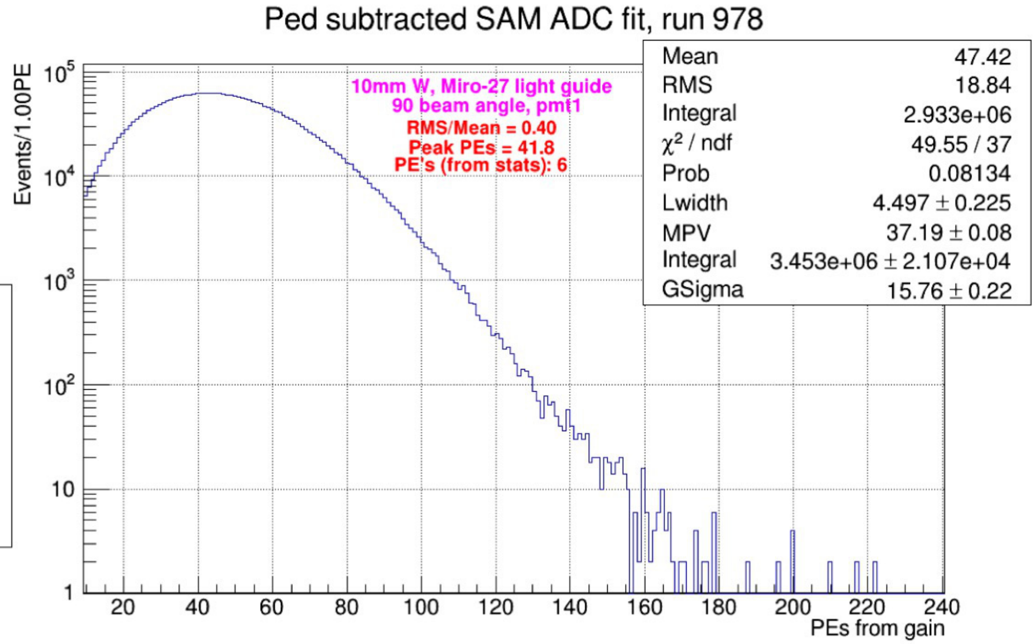


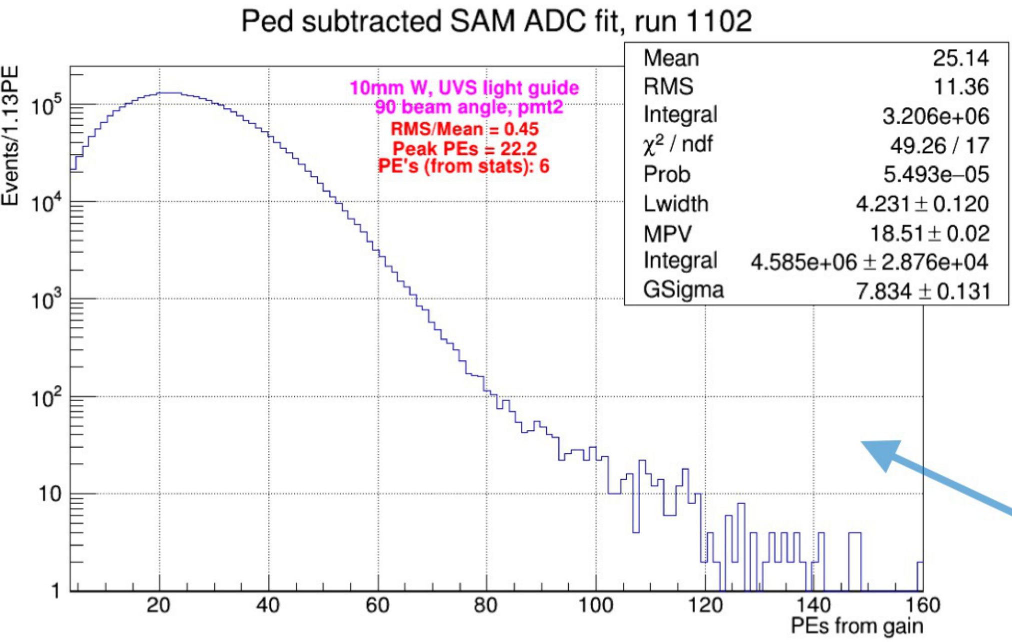
- Anolux UVS, no tungsten, N_2 gas flowing, and no clock-triggers: ~5 peak PEs (using PMT gain) with 40% relative width

SAM PE Yield & LG Testbeam Study: Miro-silver27 vs Anolux UVS (w/ tungsten)



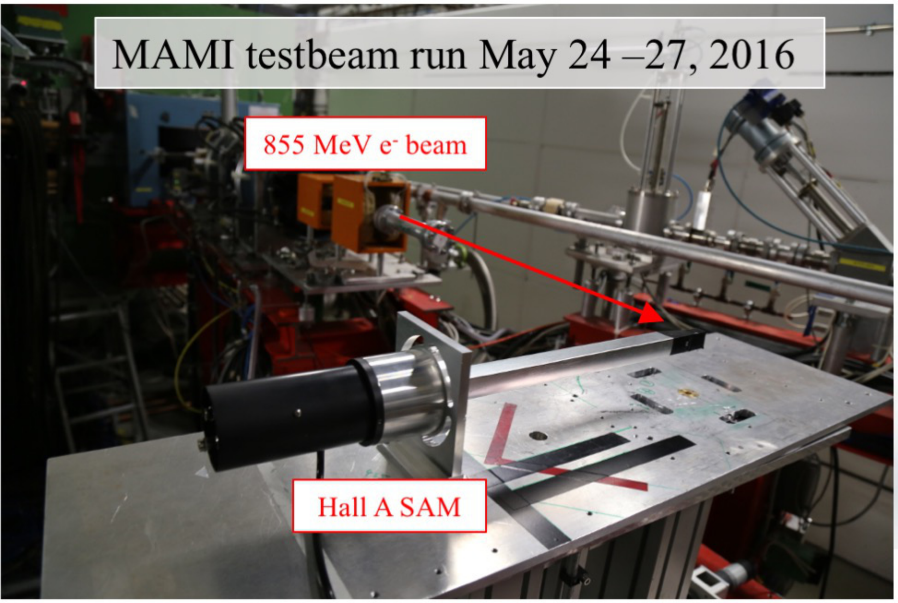
- Miro-silver27, w/ 10mm tungsten, N_2 gas flowing: ~42 peak PEs (using PMT gain) with 40% relative width





- Anolux UVS, w/ tungsten, N_2 gas flowing: ~22 peak PEs (using PMT gain) with 45% relative width

Final SAM Design and 2016 Testbeam



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

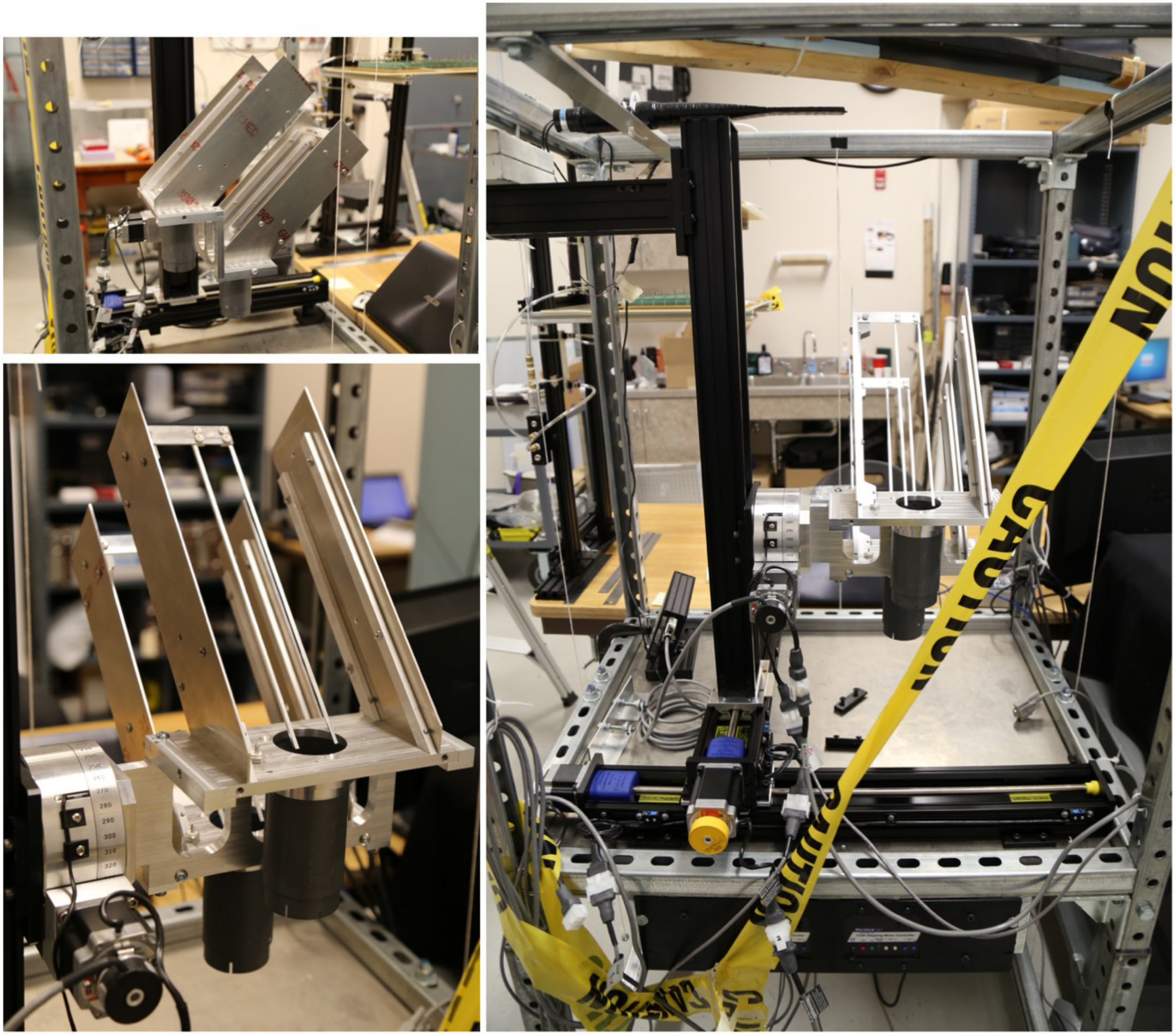
Assembled & Installed in Hall A Fall 2015

Final SAM detector

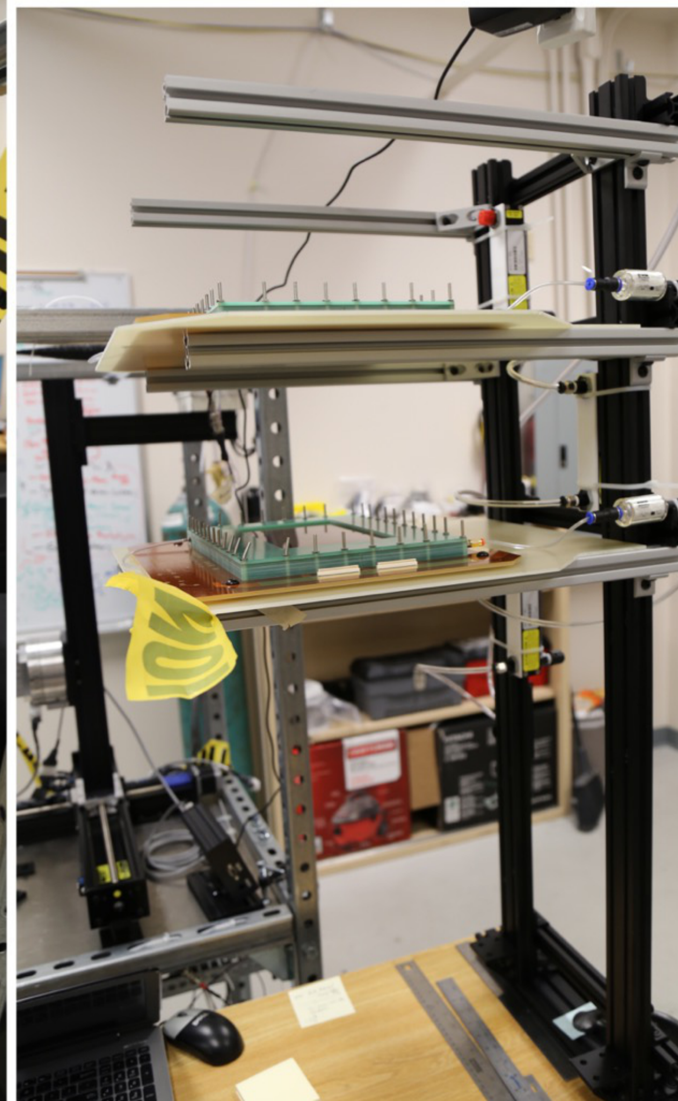
- Quartz: 33 x 20 x 13 mm^3
- Miro27 LG: 36 x 2.6 x 2.1 cm^3
- Optimized 1-bounce funnel mirror
- Unity or high-gain R375 2” PMTs
- Use of pre-radiator not decided
- Dry-air inlet and outlet ports
- Custom flange adapter for easy de-install/re-install (radcon permitting)

Small Angle Monitors:
Detect ~0.5° target scattering

Prototype Development at ISU



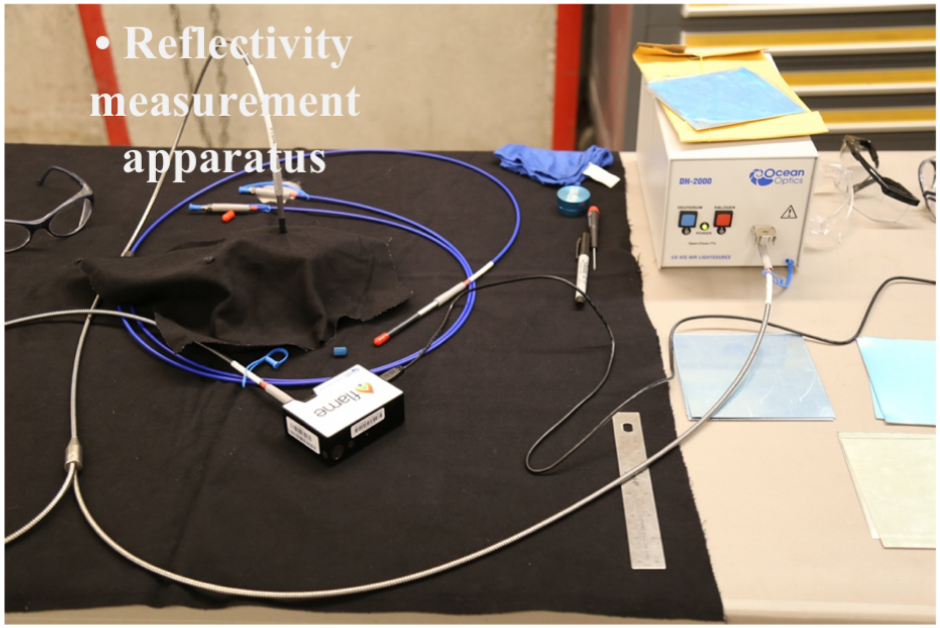
Prototype LHRS Tandem mount



Prototype GEM stand
(under construction)

Light guide reflectivity measurements

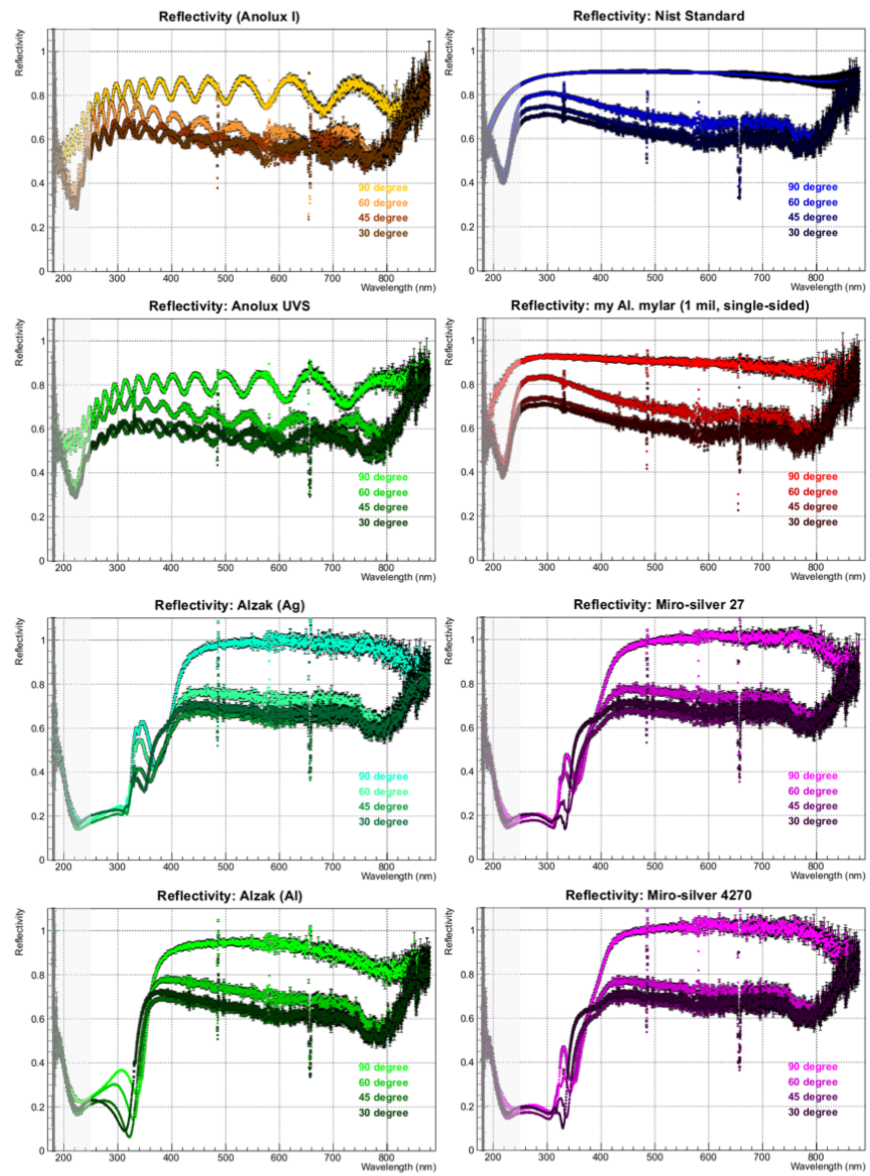
- Measuring light guide (LG) reflectivity as function of angle (10 – 90°) and λ (200 – 800nm); ongoing



- Light source: Ocean Optics DH2000: 200 - 800nm, 25W Deuterium bulb
- Spectrometer: Ocean Optics USB Flame, enhanced sensitivity, UV-VIS grating
- NIST specular calibration standard

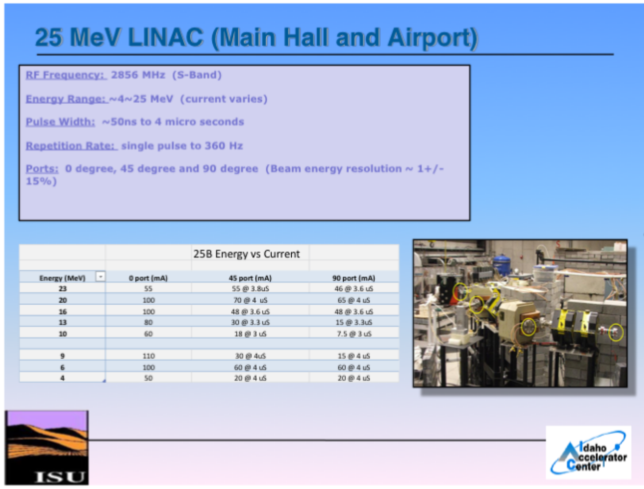
Light guide materials tested:

Miro-silver 4270	Miro-silver 27
Anolux I and UVS	Alzak-Al and Alzak-Ag
Miro 2000Ag (diffuse)	1 mil, single-sided aluminized mylar



Reflectivity vs. λ for various materials at diff. angles

LG reflectivity radiation hardness study

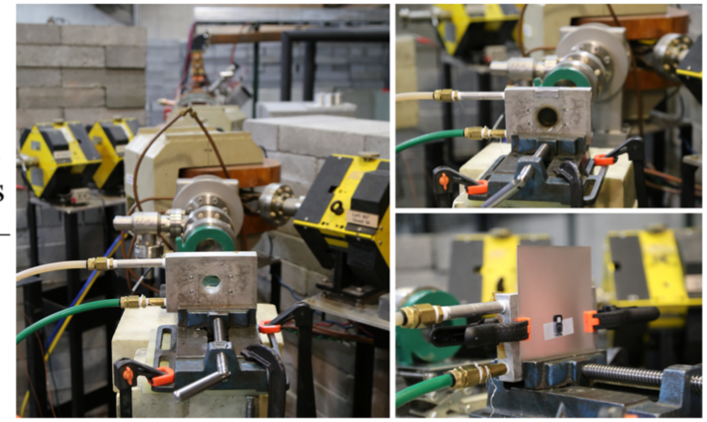


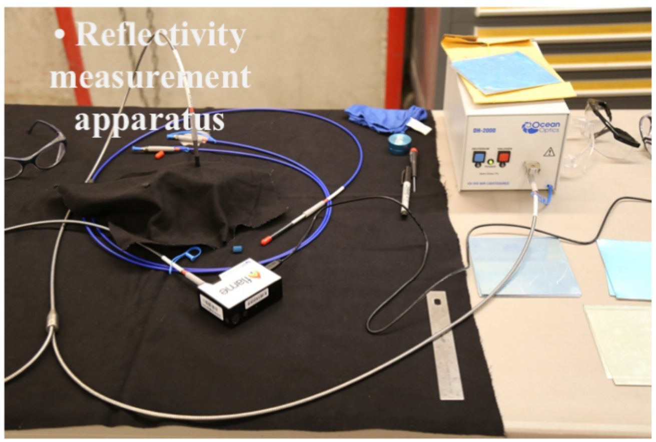
25B Energy vs Current

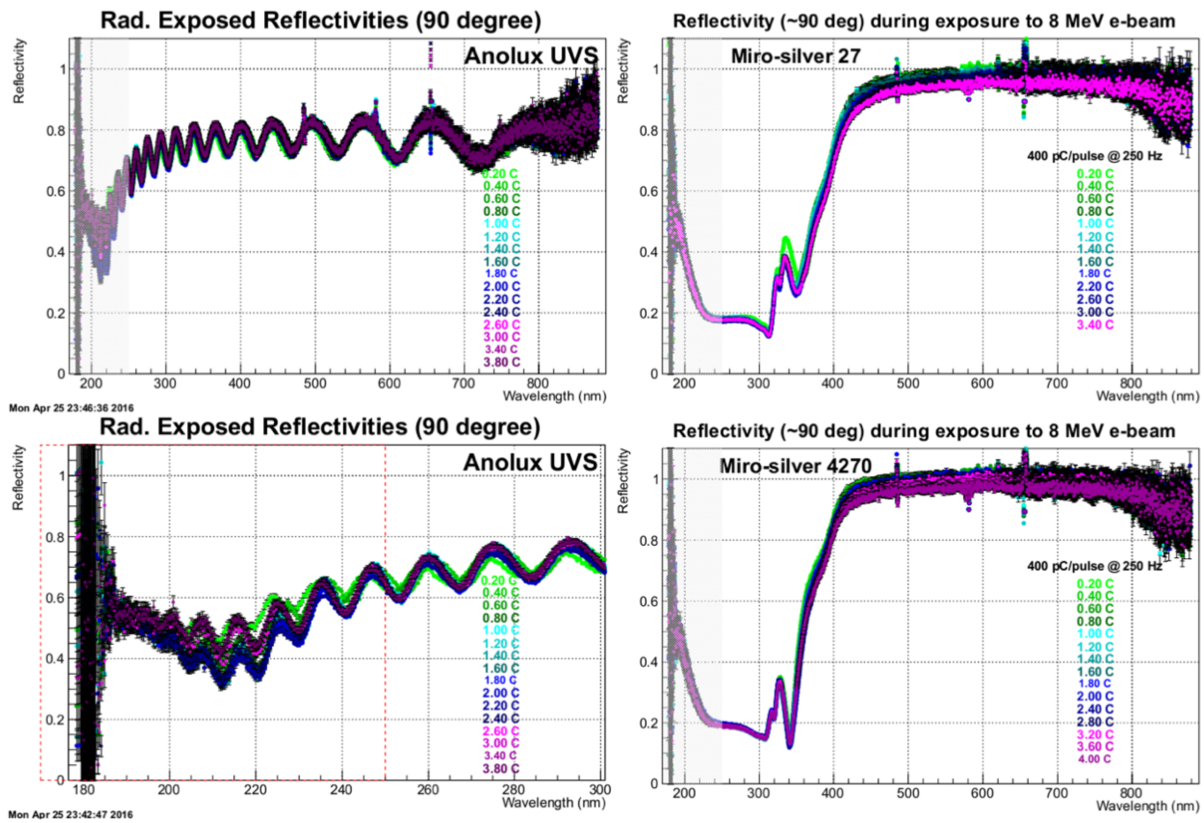
Energy (MeV)	0 port (mA)	45 port (mA)	90 port (mA)
23	55	55 @ 3.8uS	46 @ 3.6 uS
20	100	70 @ 4 uS	65 @ 4 uS
16	100	48 @ 3.6 uS	48 @ 3.6 uS
13	80	30 @ 3.3 uS	15 @ 3.3uS
10	60	18 @ 3 uS	7.5 @ 3 uS
9	110	30 @ 4uS	15 @ 4 uS
6	100	60 @ 4 uS	60 @ 4 uS
4	50	20 @ 4 uS	20 @ 4 uS

- Used 8 MeV e^- beam, 65 - 110mA I_{peak}, 4μs pulse width at 250 Hz, 310 – 880 W

- Water-cooled (15^o C) aluminum brick w/ 1.5 cm radius hole (for beam) – more than adequate cooling.



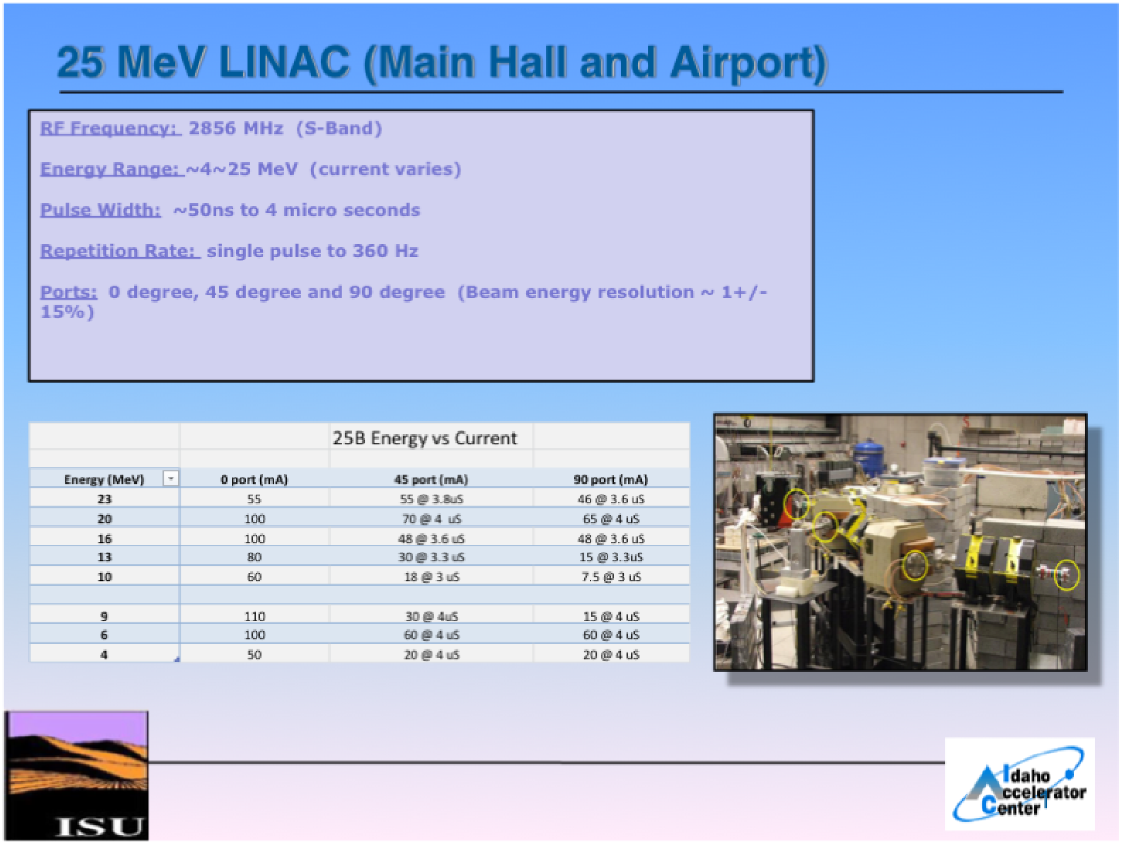




Irradiated several light guide material samples over a 3 day period from Mar 22 - 24, 2016:

Miro-silver 4270
Anolux UVS
Miro 2000Ag (diffuse)
Miro-silver 27 (from Michael)
Alzak-Al and Alzak-Ag (from KK)
1 mil, single-sided aluminized mylar

Radiation Hardness QC for quartz and other components



25 MeV LINAC (Main Hall and Airport)

RF Frequency: 2856 MHz (S-Band)

Energy Range: ~4~25 MeV (current varies)

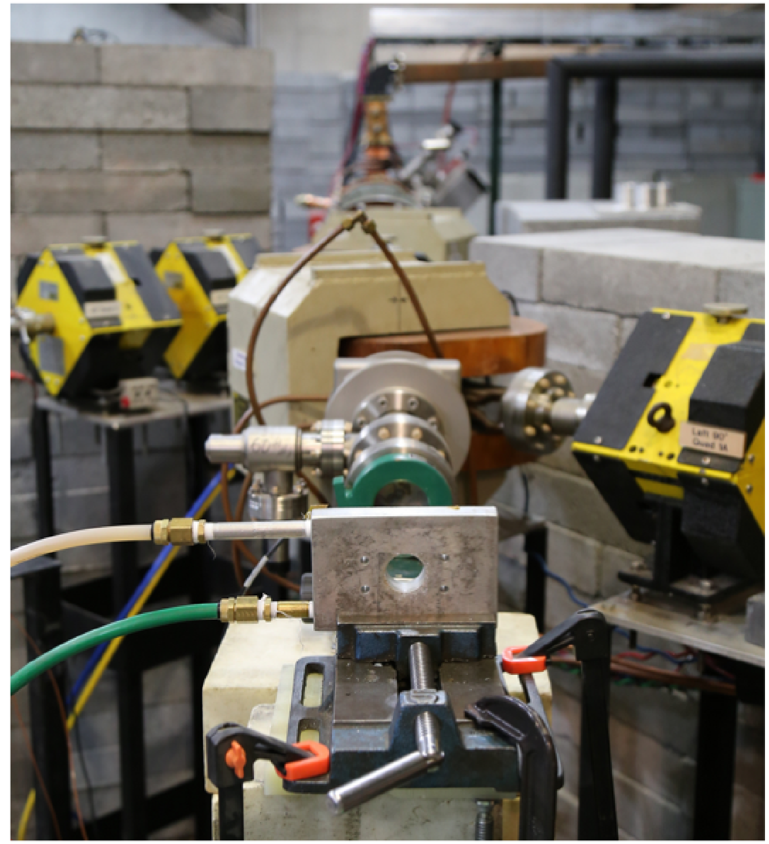
Pulse Width: ~50ns to 4 micro seconds

Repetition Rate: single pulse to 360 Hz

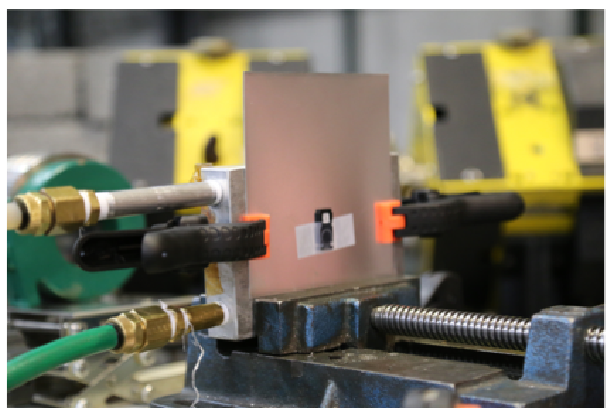
Ports: 0 degree, 45 degree and 90 degree (Beam energy resolution ~ 1+/-15%)

25B Energy vs Current

Energy (MeV)	0 port (mA)	45 port (mA)	90 port (mA)
23	55	55 @ 3.8uS	46 @ 3.6 uS
20	100	70 @ 4 uS	65 @ 4 uS
16	100	48 @ 3.6 uS	48 @ 3.6 uS
13	80	30 @ 3.3 uS	15 @ 3.3uS
10	60	18 @ 3 uS	7.5 @ 3 uS
9	110	30 @ 4uS	15 @ 4 uS
6	100	60 @ 4 uS	60 @ 4 uS
4	50	20 @ 4 uS	20 @ 4 uS



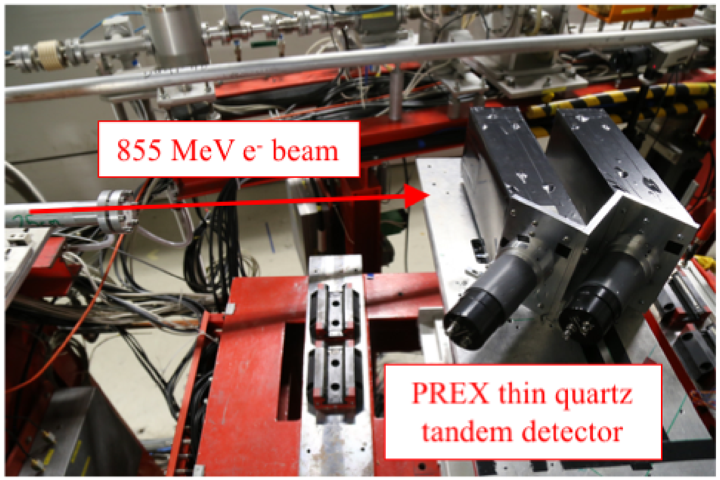
- A key issue is how well can we calibrate dose exposure?
- Another issue is how low can we go in beam current (while still monitoring it)



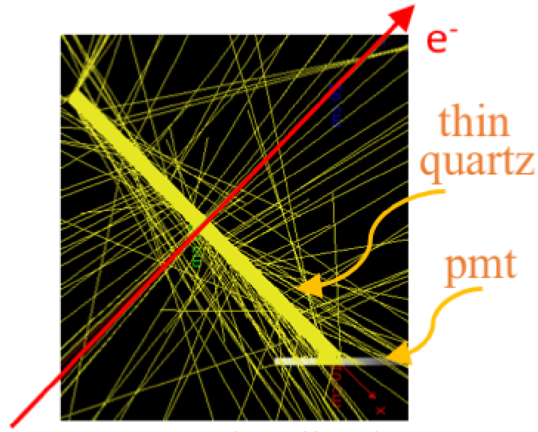
- Planning for a 1 - 2 day engineering run late spring or early summer to address these questions.

Monte Carlo tuning and Shower-max Simulations

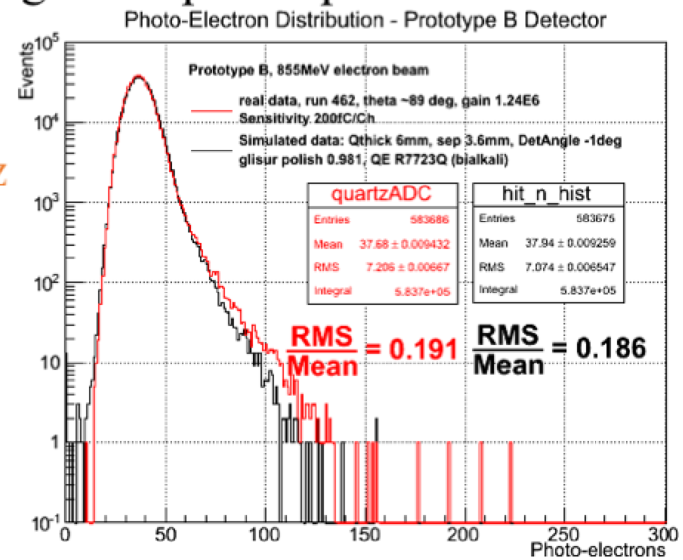
- Quartz optical G4 properties benchmarked at MAMI: Glisur ground polish parameter ~0.981



MAMI testbeam with PREX detector



G4 event visualization for PREX detector

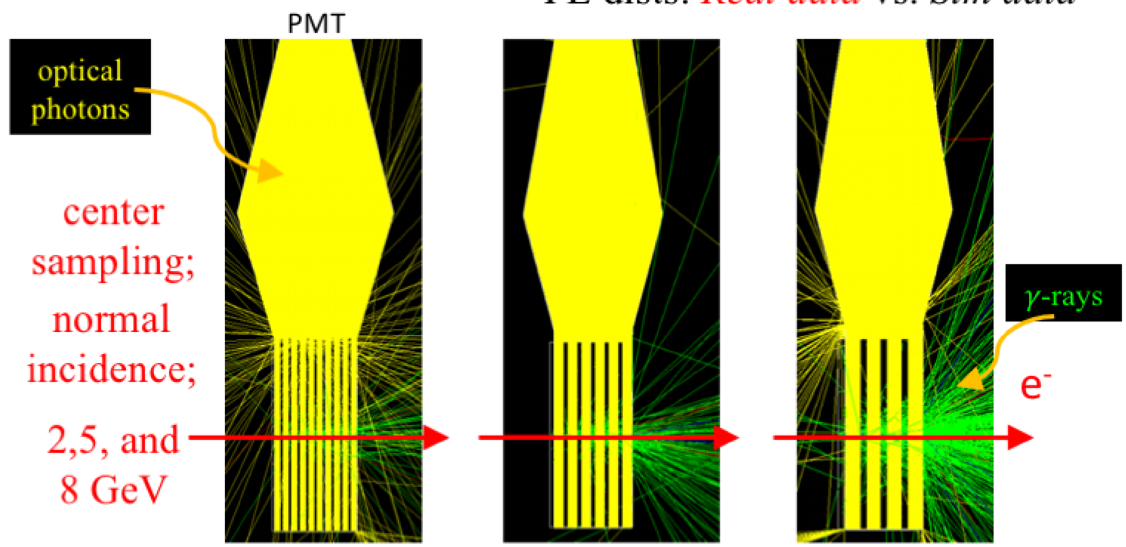


PE dists: *Real data* vs. *Sim data*

- Stack configuration MC study:
  - Stack thicknesses all same (7.2 X_0)
  - 2, 5, and 8 GeV incident electrons
  - PE dists generated using tuned polish parameter and 60% LG reflectivity

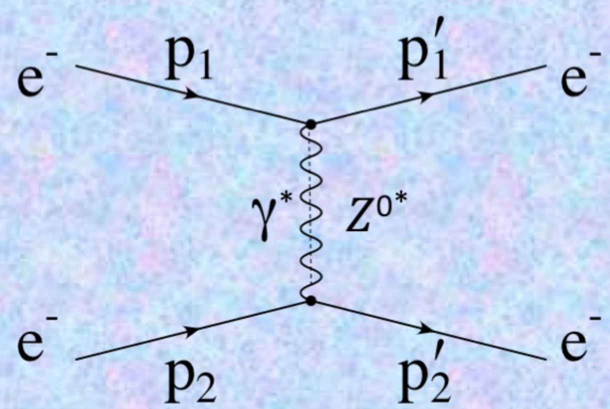
Conclusion:

4-layer gives comparable performance to 10-layer (and is easier and cheaper to build)

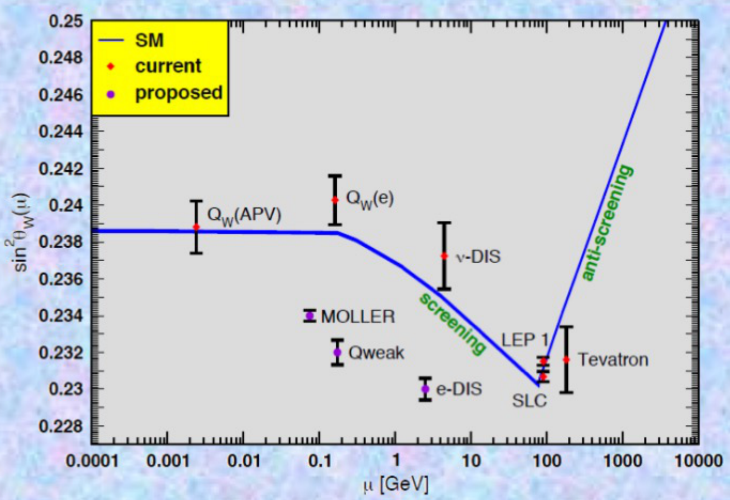


Shower-max event visualizations

The *MOLLER* Project at Jefferson Lab:

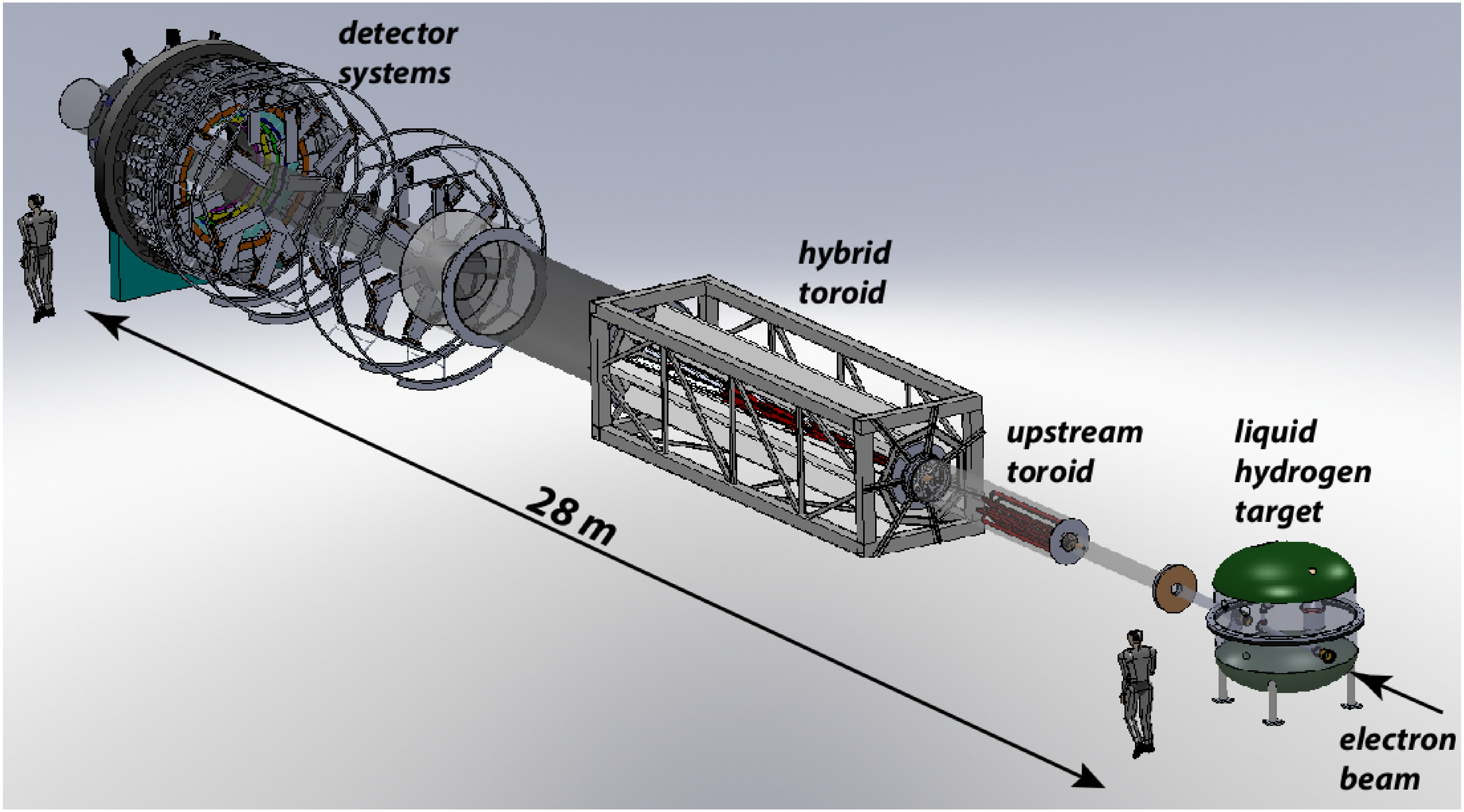


***M**easurement*
***o**f*
***L**epton*
***L**epton*
***E**lectroweak*
***R**eaction*

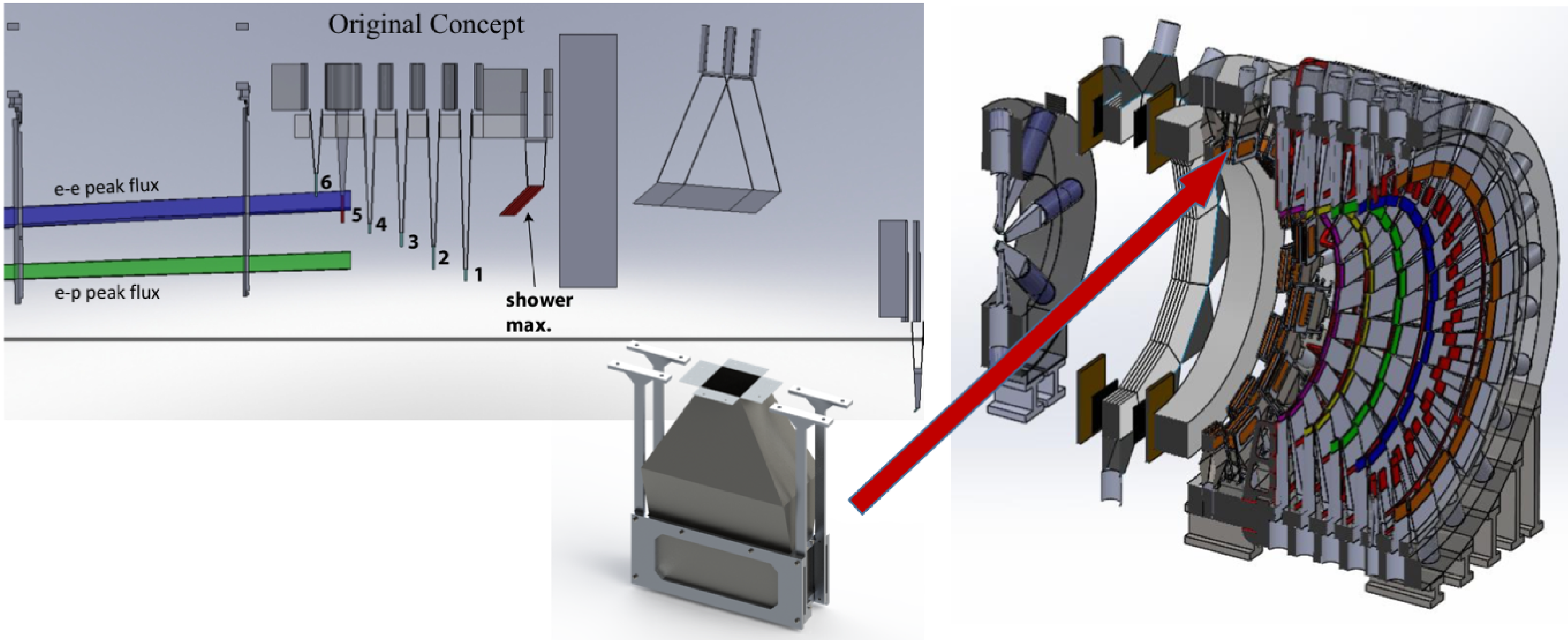


MOLLER Apparatus

(major new installation experiment for Hall A)

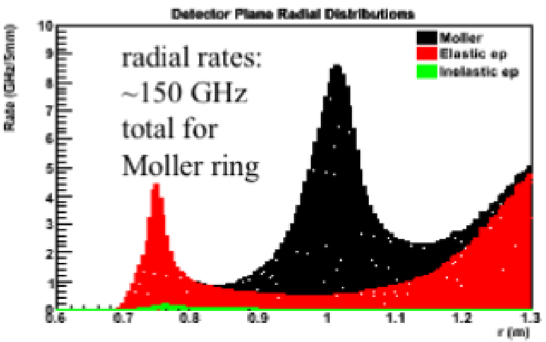


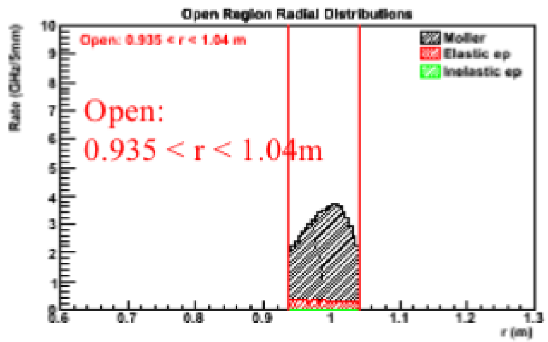
ShowerMax Motivation & Requirements

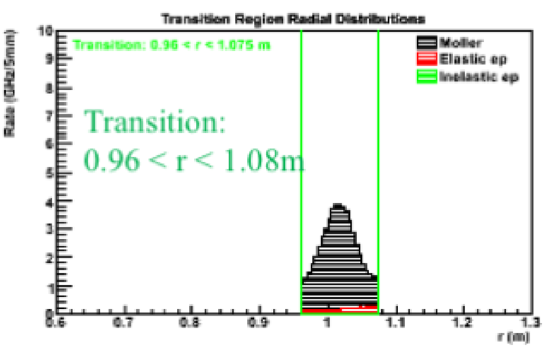


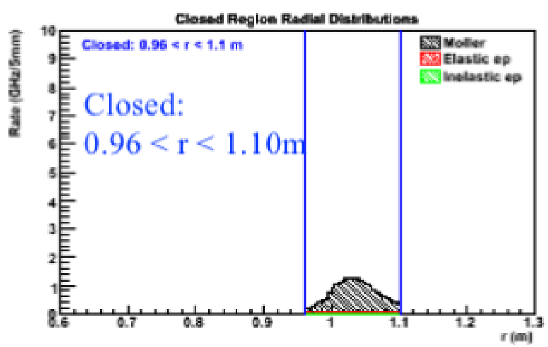
- Provides additional measurement of e-e ring integrated flux
- Weights flux by energy $\Longrightarrow$ less sensitive to low energy and hadronic backgrounds
- Will also operate in tracking mode to give additional handle on background (pion) identification – gives MIP-like signal
- Should have good resolution over full energy range ($\frac{\sigma}{\langle n \rangle} \lesssim 25\%$), long term stability and be radiation hard

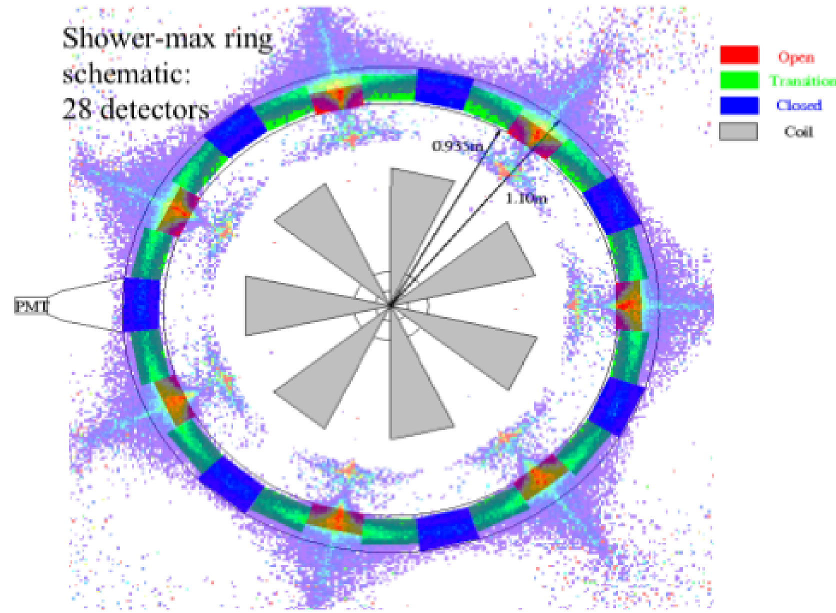
Shower-max phi-segmentation, rates and energies



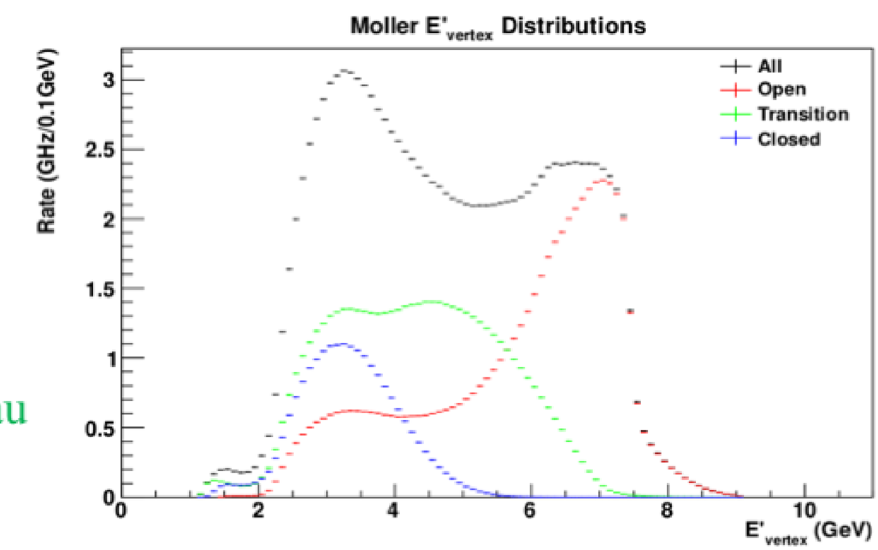








- Large range of rates and energies for different phi-region detectors:
  - Open ~9 GHz/det; 2 - 9 GeV, peak at 7 GeV…
  - Closed ~3.5 GHz/det; 2 - 5 GeV, peak at ~3 GeV
  - Transition ~4.5 GHz/det; 2 - 7 GeV, 3 – 5 GeV plateau



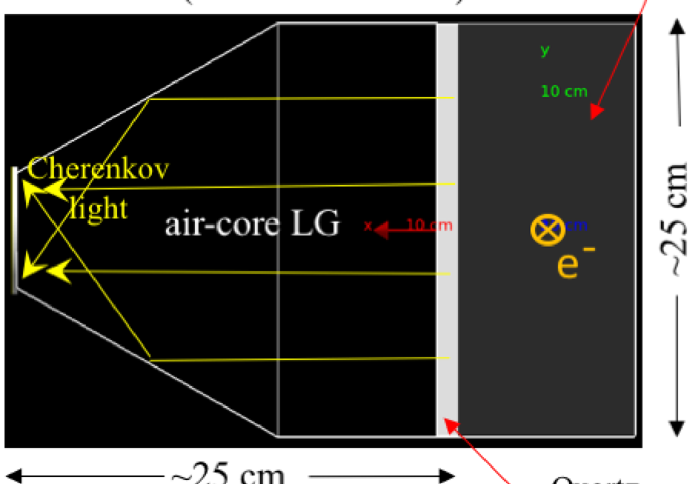
Baseline Design Stack and Light Guide Concepts

- Detector concept uses a layered "stack" of tungsten and fused silica (quartz) to induce EM showering and produce Cherenkov light
- "Baseline" design developed using GEANT4 optical MC simulation:
  - Current design uses a **4-layer stack** with **8mm tungsten** and **12.5mm quartz** pieces
  - Cherenkov light directed to **3inch PMT** using **air-core, aluminum light guide**

"Baseline" LG Design
(front face view)

tungsten: 1st upstream piece (dark grey)

3inch PMT

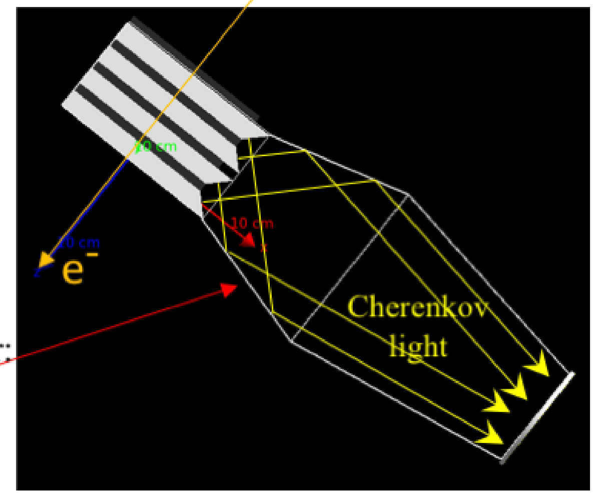


Quartz bevel

4-layer Stack: 8mm thick tungsten (dark grey), interleaved with 12.5mm thick quartz (white)

alternating quartz bevel design

single-bounce mirror: "funnel" angle and length optimized

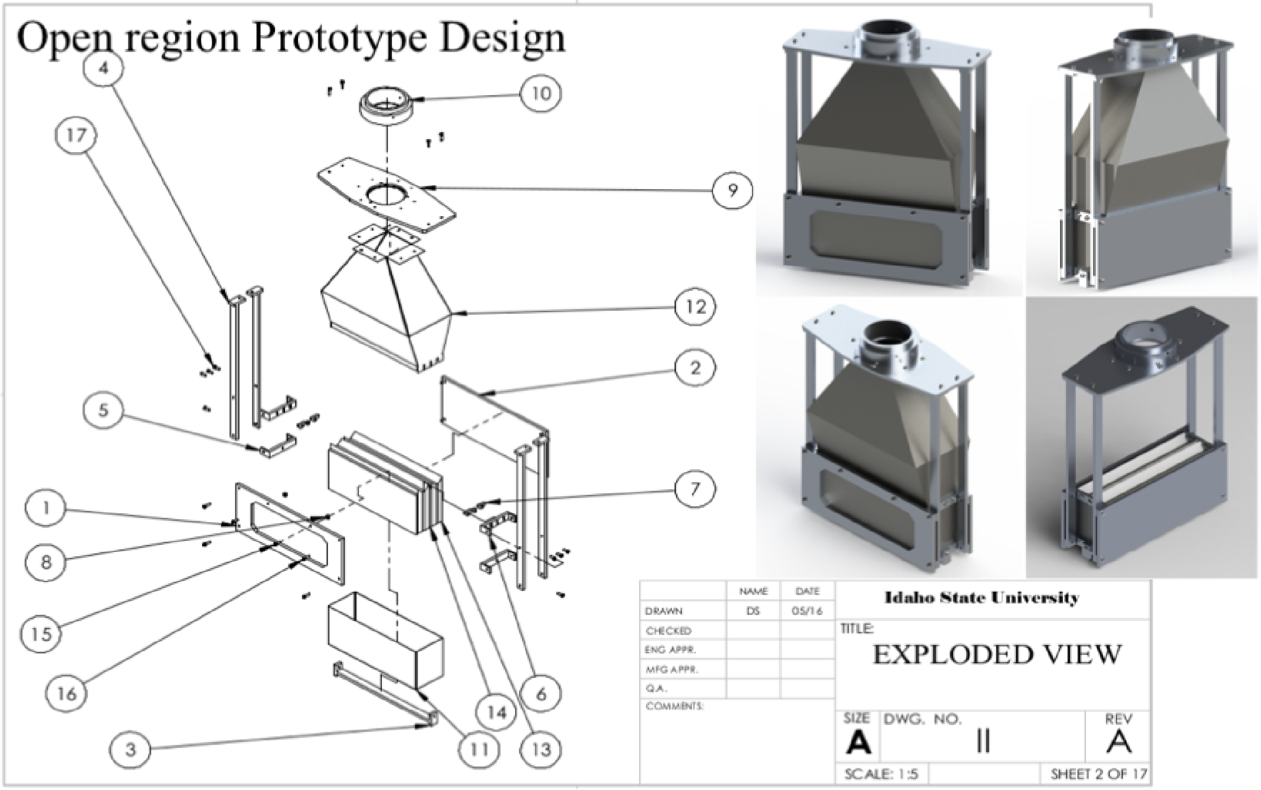


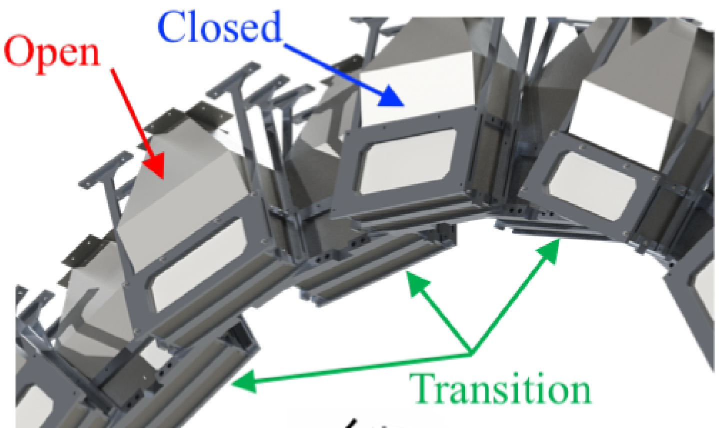
"Baseline" Design
(side view)

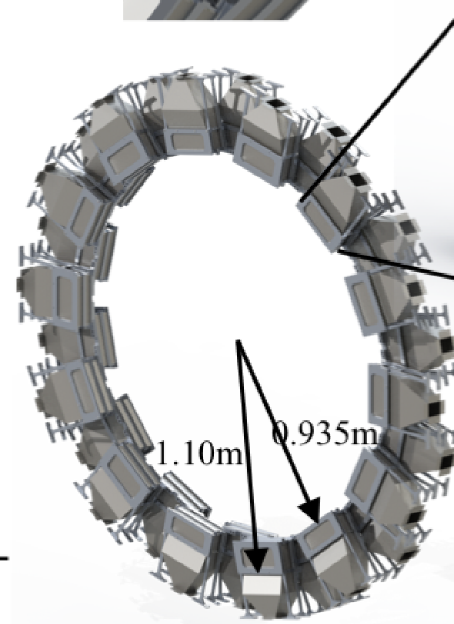
Materials (all rad-hard):

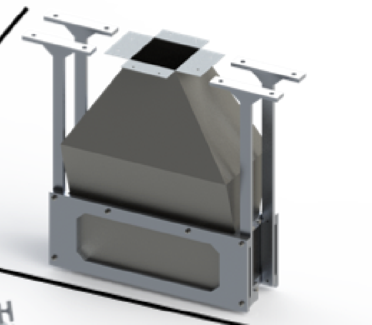
- Tungsten is high purity (99.95%) and quartz is optically polished Spectrosil 2000
- Light guides are aluminum specular reflectors (Miro-silver 27, Anolux, or al. mylar, …)
- Total radiation length: 9.1 X_0 tungsten + 0.4 X_0 quartz = 9.5 X_0

Prototype Baseline Design and ring concept









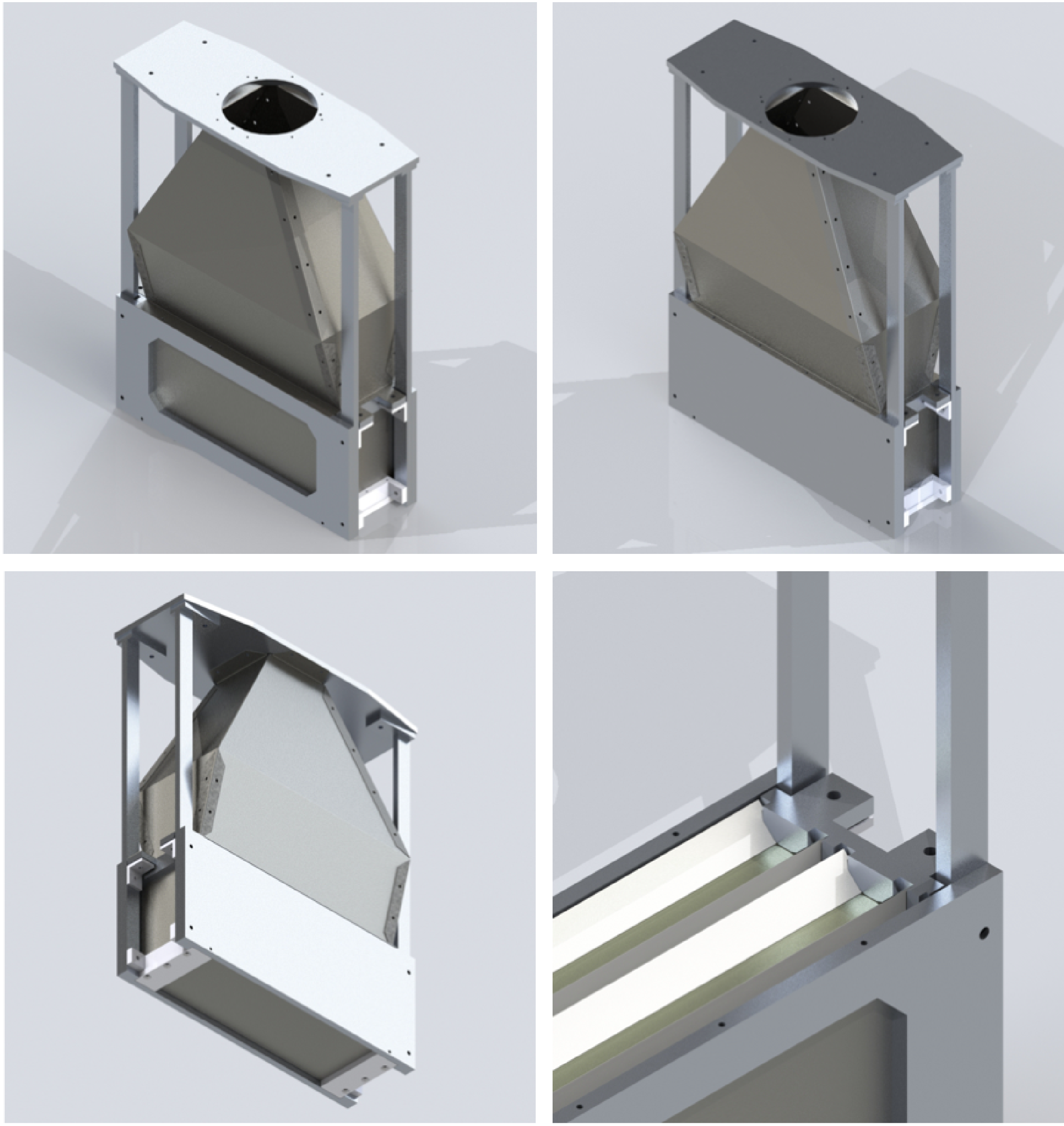
"Baseline"

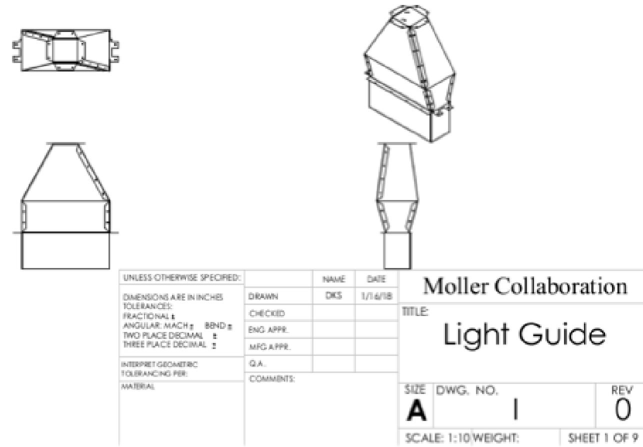
Costs: Total w/ spares
quartz: $150k (Heraeus)
tungsten: $60k
alum.: $10k (machined)
grand total: $220k

Weights of each assembly:
Open: 39.7 lbs.
Transition: 42.5 lbs.
Closed: 50.8 lbs.
ring weight: 1230 lbs.

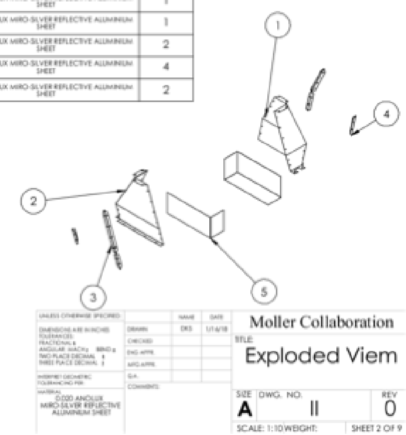
- Engineered shop drawings and Prototype CADs in hand
- ***PLANS***: Finalize prototype Stack designs this summer, order quartz by fall, construct in winter 2018 and test in spring using 5 - 8 GeV electron testbeam at SLAC
- Shower-max ring design concept: staggered in $\hat{z}$ with reinforced struts and brackets. 28 detectors in ring: 7 Open, 7 Closed, and 14 Transition

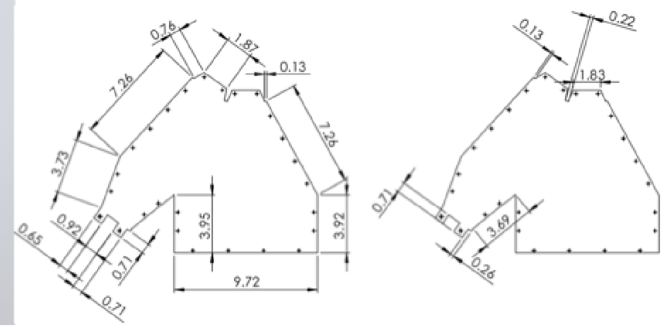
Updated Full-Scale Prototype (1A) for Beamtest





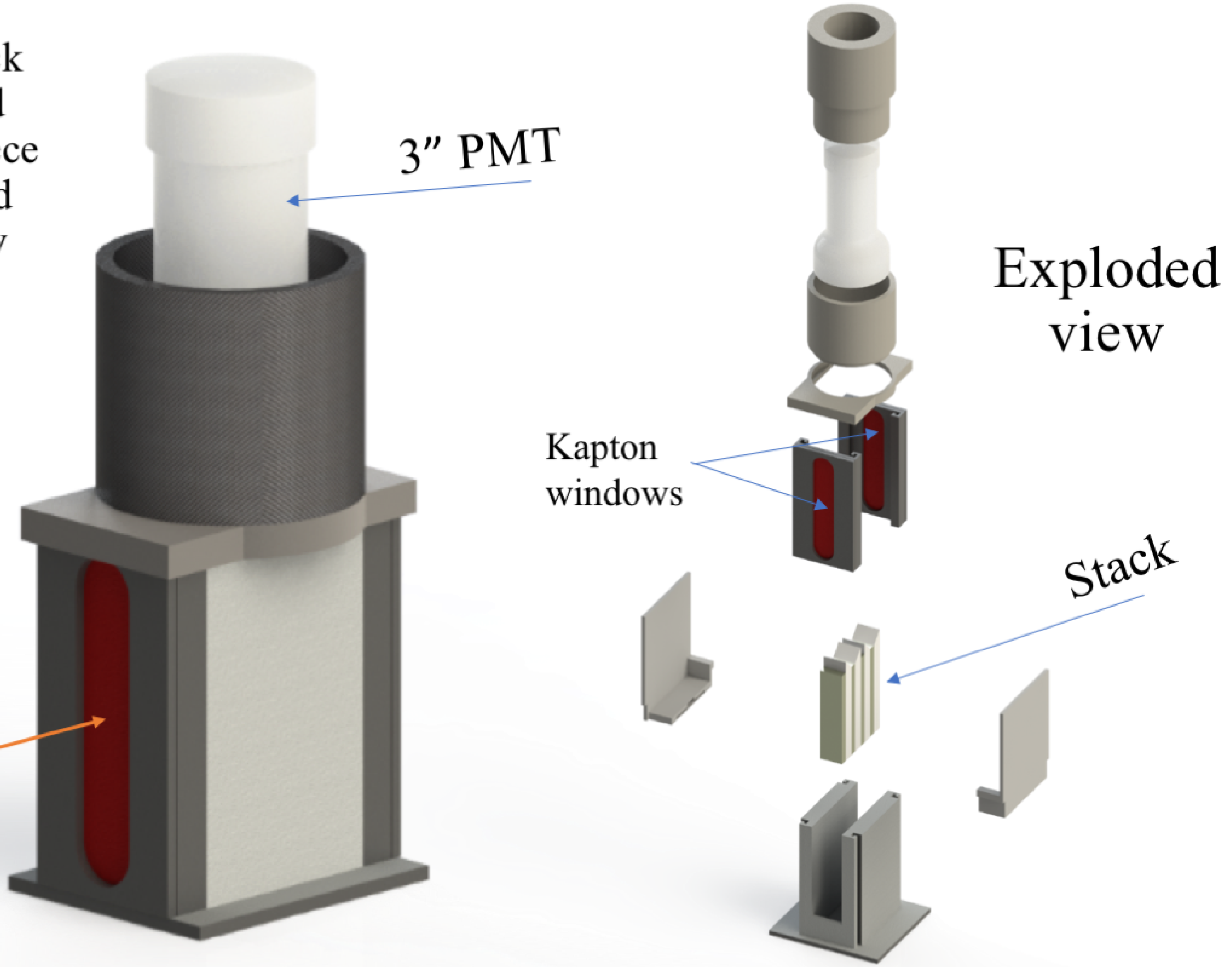
ITEM NO.	PART	MATERIAL	QTY.
1	Light Guide - Back	0.020 ANOLUX MIRO-SILVER REFLECTIVE ALUMINIUM SHEET	1
2	Light Guide - Front	0.020 ANOLUX MIRO-SILVER REFLECTIVE ALUMINIUM SHEET	1
3	Long Flap	0.020 ANOLUX MIRO-SILVER REFLECTIVE ALUMINIUM SHEET	2
4	Short Flap	0.020 ANOLUX MIRO-SILVER REFLECTIVE ALUMINIUM SHEET	4
5	Suitcase	0.020 ANOLUX MIRO-SILVER REFLECTIVE ALUMINIUM SHEET	2





Shower-max Benchmarking Prototype concept

- Concept allows stack to be assembled and beam-tested one piece at a time for detailed benchmarking study
- Fabricated with Nylon and ABS plastic using 3D printer



Config #1 (original baseline) benchmarking Prototype

Quartz and Tungsten Ordered in Nov 2017

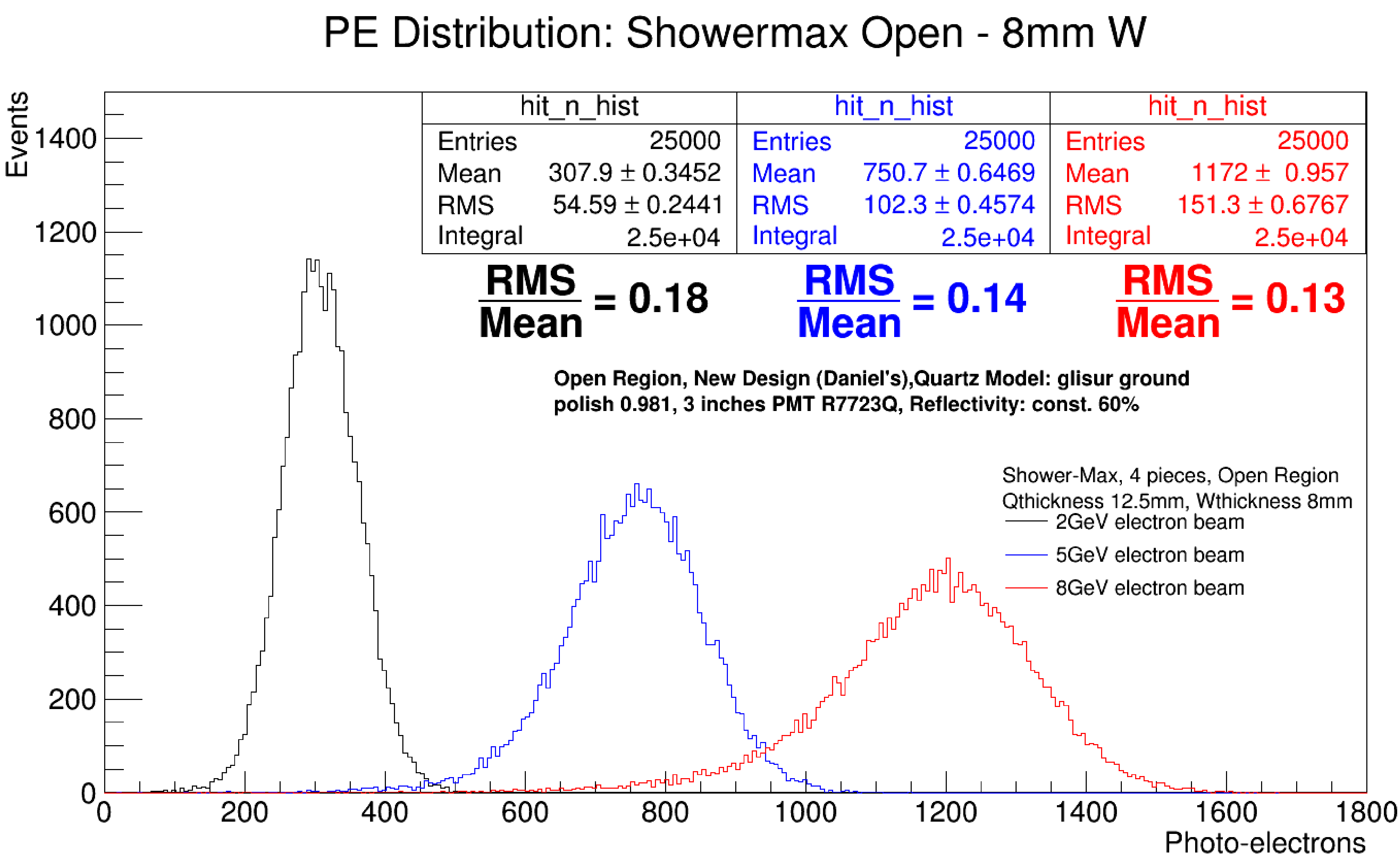
- For "benchmarking" prototype stack:
  - Quartz: 6 mm (thick) by 86 mm (tall) by 40 mm (wide) --4 pieces ($975/piece = $3.9k)
  - Quartz: 10 mm (thick) by 90 mm (tall) by 40 mm (wide) --4 pieces ($1005/piece = $4.0k)
  - Tungsten: 6 mm (thick) by 80 mm (tall) by 40 mm (wide) – 4 pieces ($85/piece = $340)
  - Tungsten: 8 mm (thick) by 80 mm (tall) by 40 mm (wide) – 4 pieces ($110/piece = $440)
  - Tungsten: 2 mm (thick) by 80 mm (tall) by 40 mm (wide) – 4 pieces ($25/piece = $100)
- For "full-scale" prototype stack:
  - Quartz: 6 mm (thick) by 111 mm (tall) by 246 mm (wide) -- 4 pieces (~$1750/piece = $7.0k)
  - Quartz: 10 mm (thick) by 115 mm (tall) by 246 mm (wide) -- 4 pieces (~$1940/piece = $7.8k)
  - Tungsten: 6 mm (thick) by 105 mm (tall) by 246 mm (wide) – 4 pieces ($600/piece = $2.5k)
  - Tungsten: 8 mm (thick) by 105 mm (tall) by 246 mm (wide) – 4 pieces ($820/piece = $3.2k)
  - Tungsten: 2 mm (thick) by 105 mm (tall) by 246 mm (wide) – 4 pieces ($200/piece = $0.8k)

Purchasing these pieces allows for Configs 1, 3, and 4 (A and B) to be tested

Total quartz: $25k, total tungsten: $7.5k: Total = $32.5k

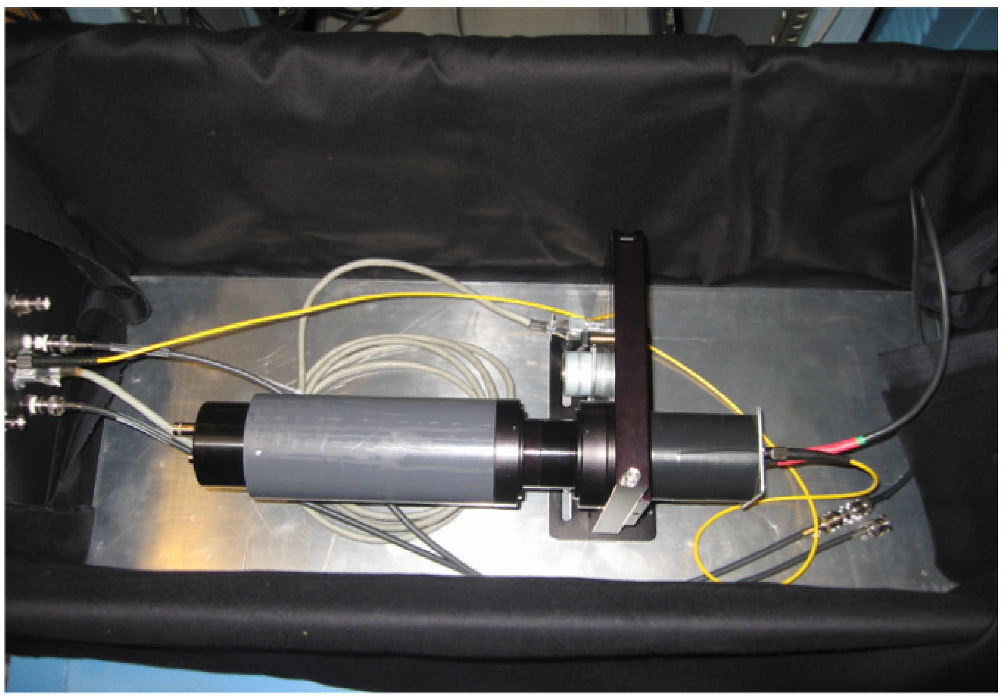
- Going with 6mm tiles allows construction of two benchmarking and two full-scale prototype sets
- Building two sets of prototypes will allow for more efficient testing during both SLAC testbeam and cosmic tests at SBU and ISU. We can each build a different configuration to test

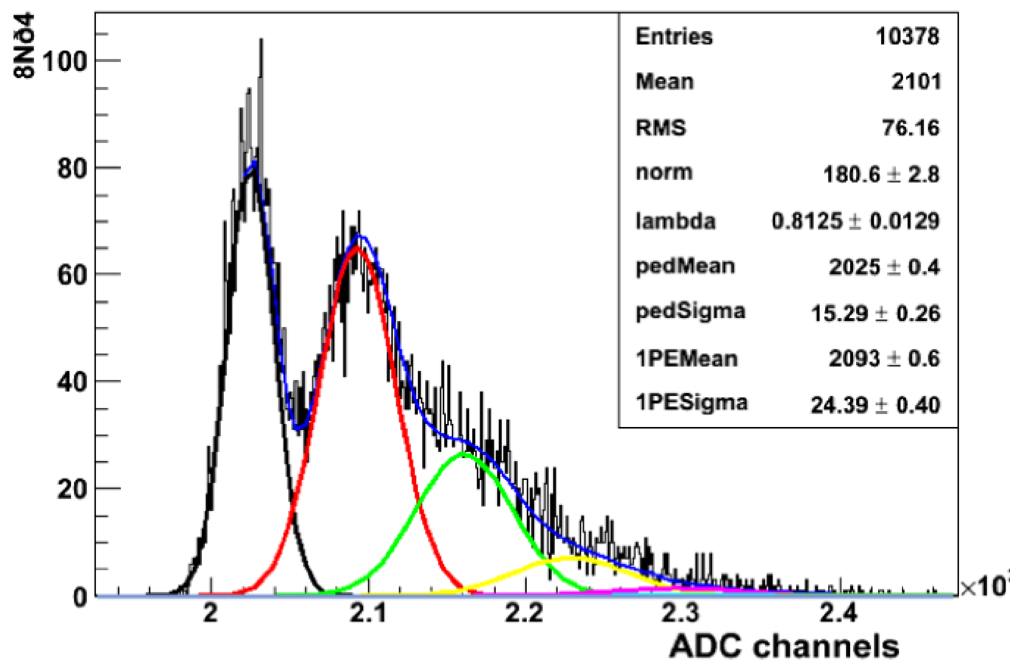
4-layer baseline PE Dists for 2, 5, and 8 GeV



Precision PMT Gain Measurements Planned

- ADC charge sensitivity calibrated
- PE peaks extracted using multi-Poisson fit algorithm
- Gains measured using linearity apparatus with CAEN LED driver, ND filter wheel, and CAEN fast amplifier
- Purchased 4 new R7723Q pmts (with Mod. base); purchasing two 3" ET9305QKB PMTs this spring





Thank you