Applications of Parity Violation

Dustin McNulty
Idaho State University
mcnudust@isu.edu

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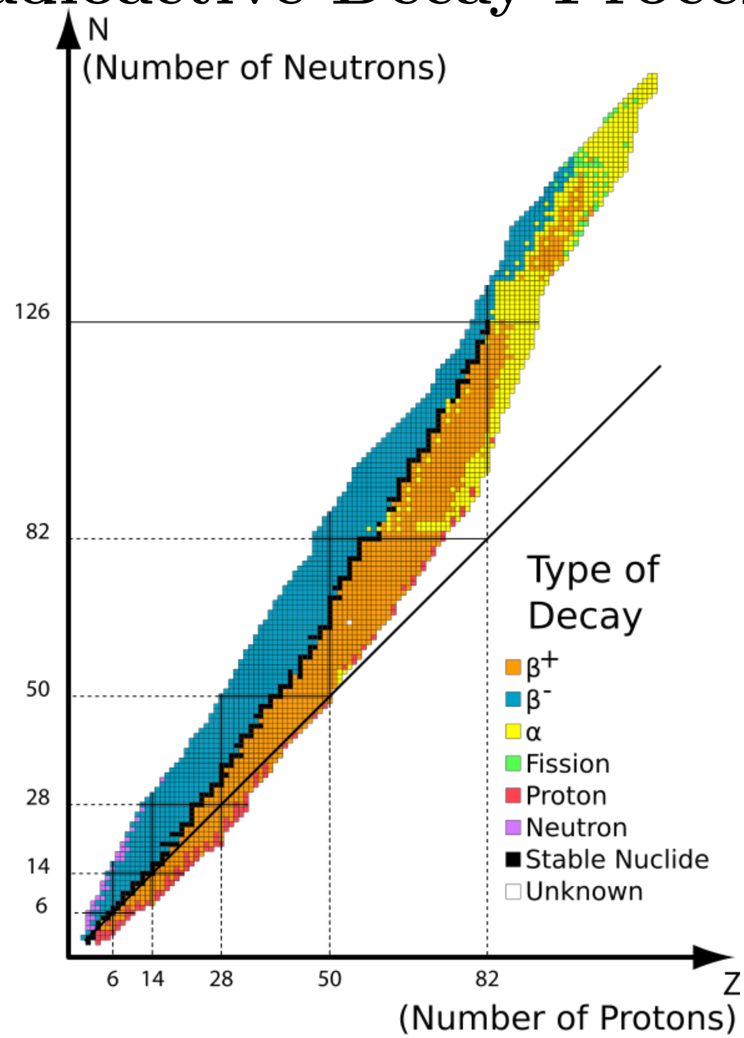
Applications of Parity Violation

Outline

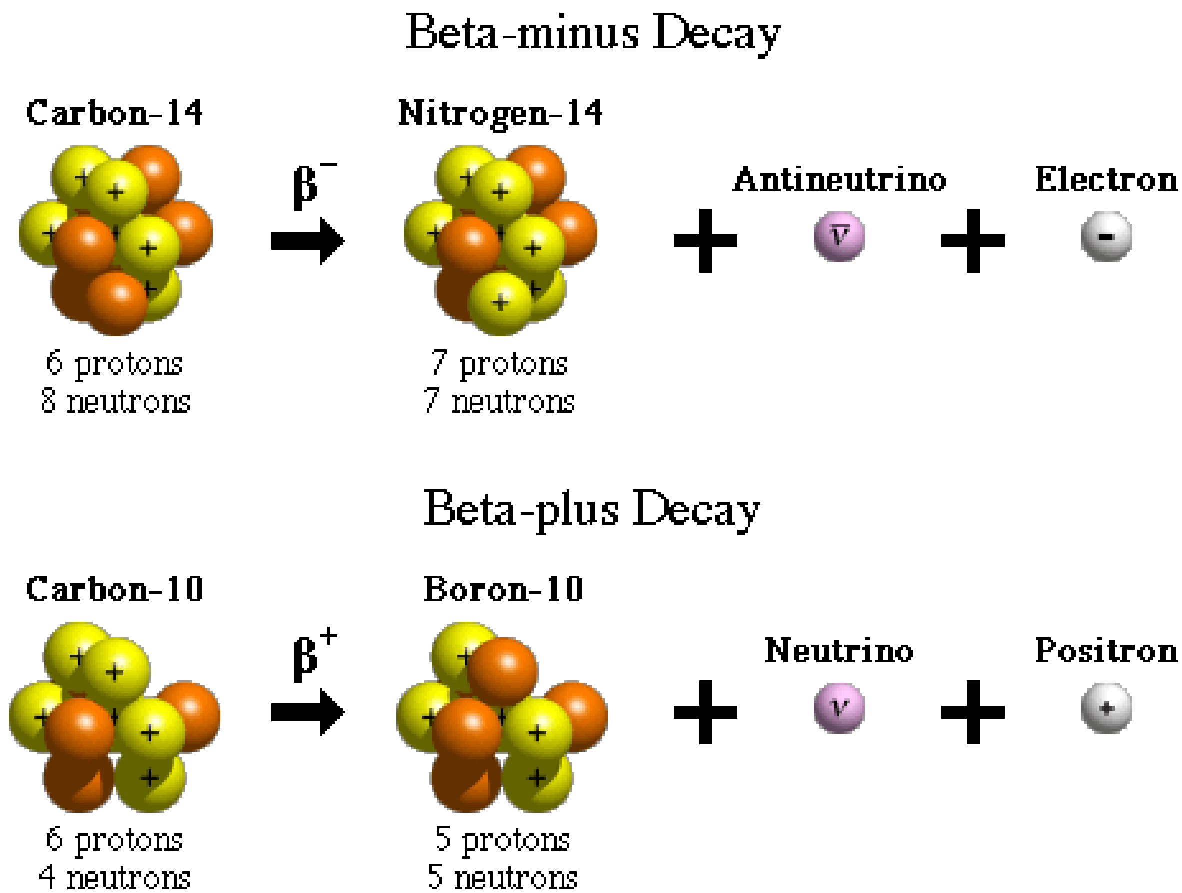
- Beta Decay and Parity Violation
- Standard Model and the Weak Force
- Experiments: PREX/CREX and MOLLER
- Quartz Cerenkov Detector R&D at ISU
- Summary and Outlook

Radioactive Decay Processes



- The Weak-nuclear force is responsible for all radioactive decays
- Beta decay is most common process

Beta Decay Examples



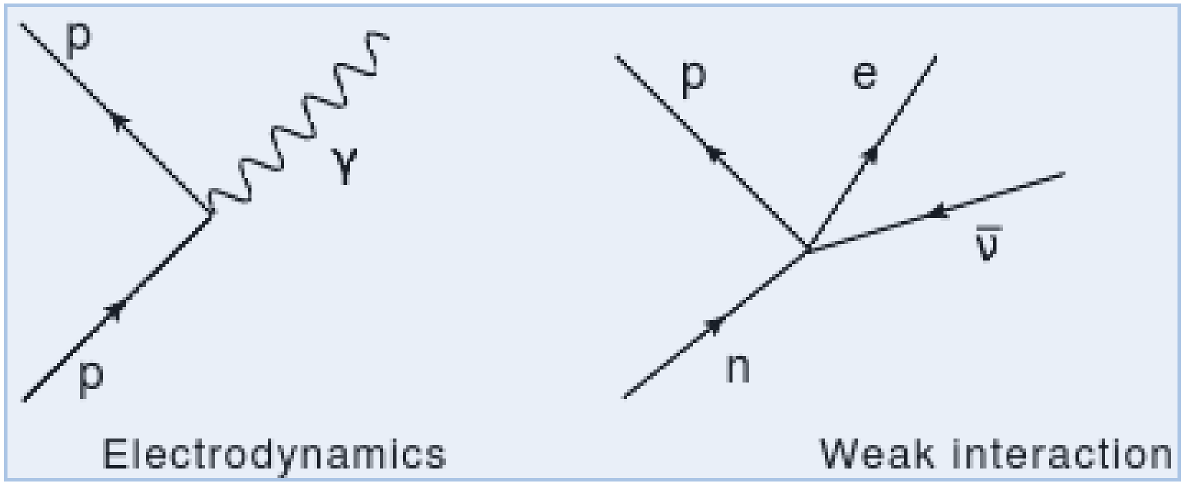
- β^- decay: $n \longrightarrow p + \bar{\nu}_e + e^-$
- β^+ decay: $p \longrightarrow n + \nu_e + e^+$

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

A Quick History

- 1899: 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. $\bar{\nu}_e + p \longrightarrow n + e^+$
- 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 charged particle interacts with $\vec{A}$ to create photon.
- For Fermi's theory, the "weak" current of pn-pair interacts with "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 ($\sim 10^{13}$ ν's /s/cm^2)
- Two water tanks 12m underground and 11m from reactor
- Used inverse beta decay reaction: ($\bar{\nu}_e + p \longrightarrow n + e^+$)
- The e^+ annihilated with an e^- producing two γ rays (detected)

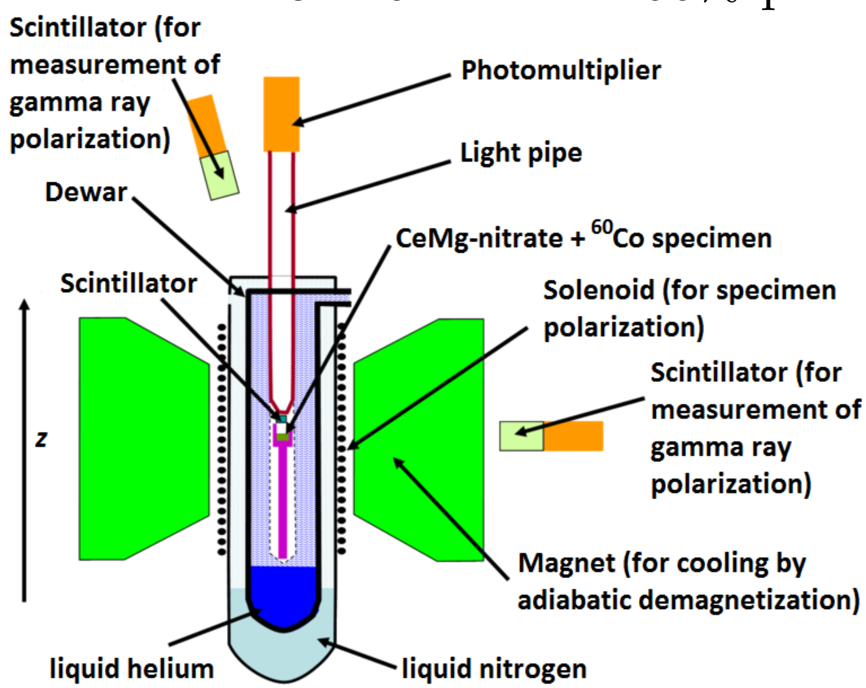
Parity Symmetry

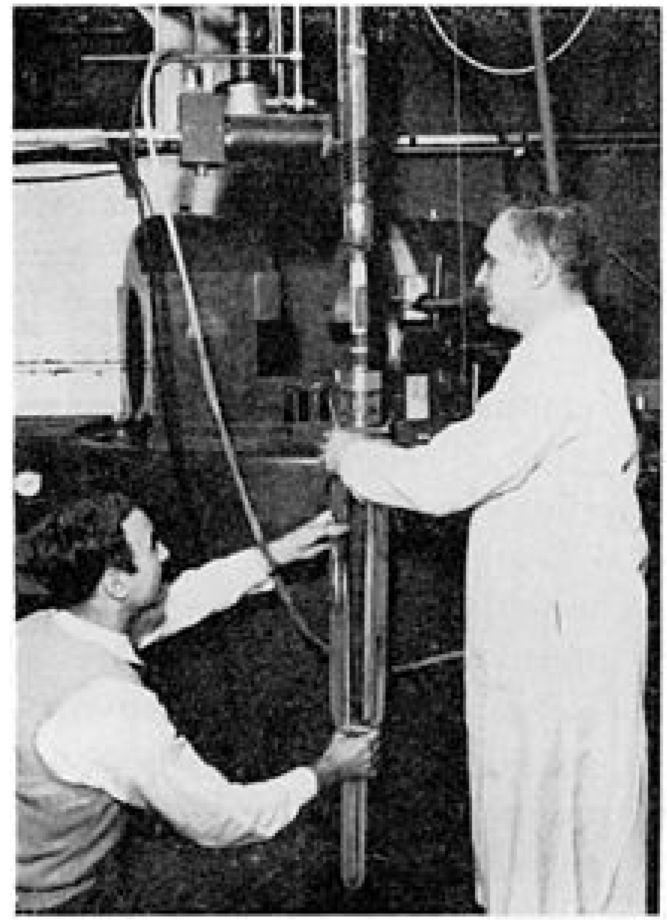
$$\mathbf{P}: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \longrightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

- Parity operation: Spacial reflection through the origin
- "Even" functions: $\mathbf{P} f(x,y,z) \Longrightarrow +f(x,y,z)$
- "Odd" functions: $\mathbf{P} f(x,y,z) \Longrightarrow -f(x,y,z)$
- *Classically*, scalar quantities $(m, E, \rho, V, M, ...)$ 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

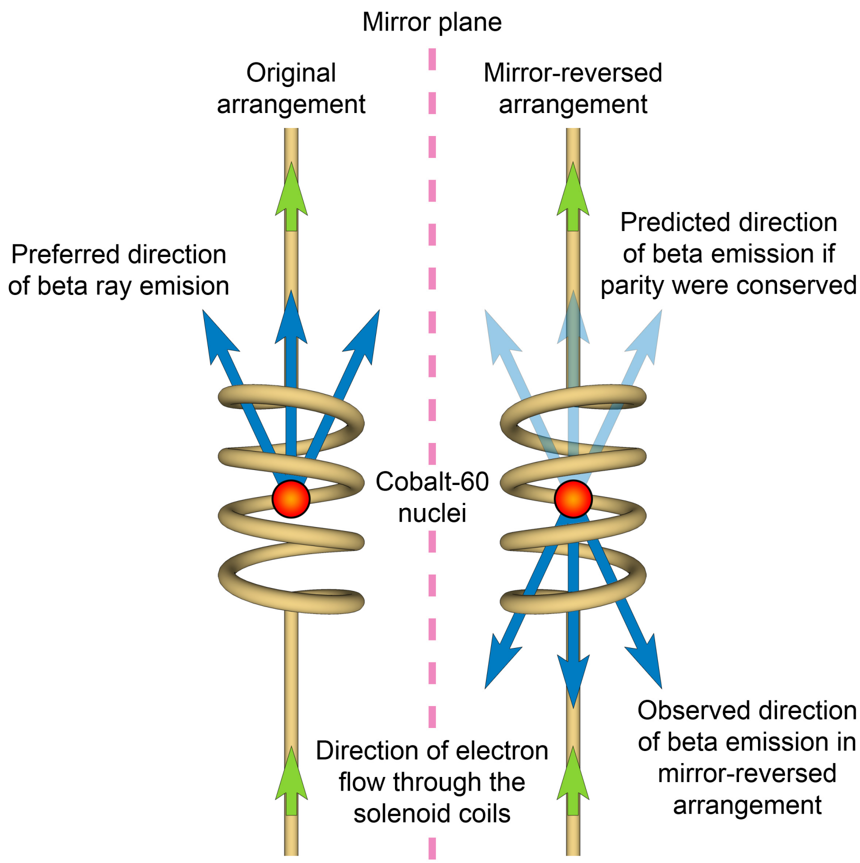
- Chien-Shiung (Madame) Wu Experiment
- Took place at NBS (now NIST)
- Studied β^- decay of super-cooled, spin-aligned ^{60}Co nuclei
- $^{60}_{27}\mathrm{Co} \longrightarrow ^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$
- Achieved 3×10^{-3}K and 60% pol

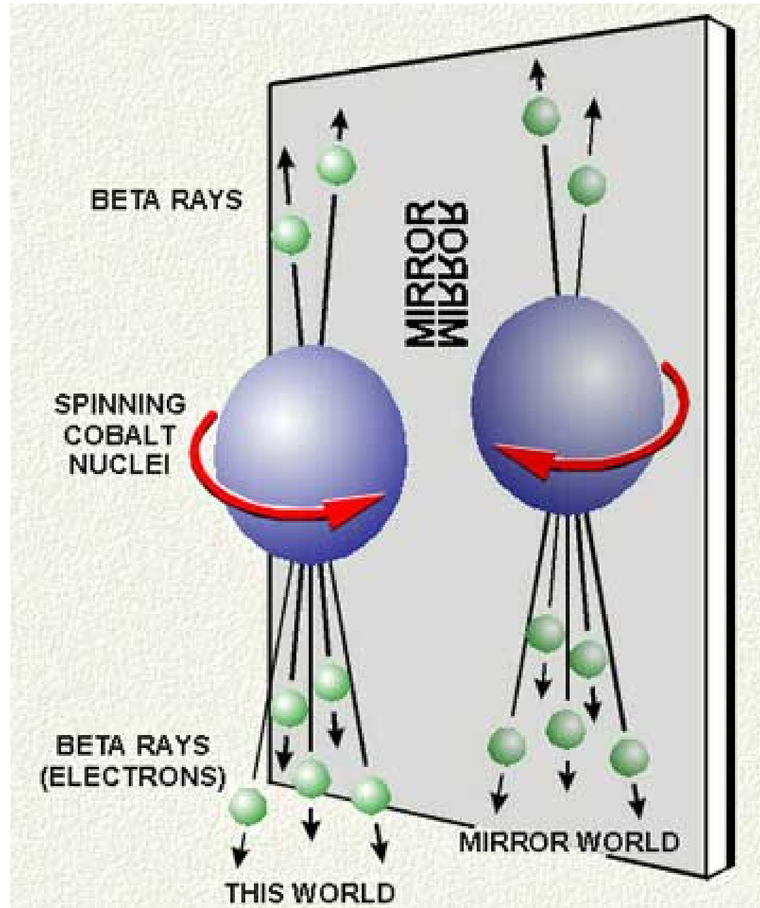




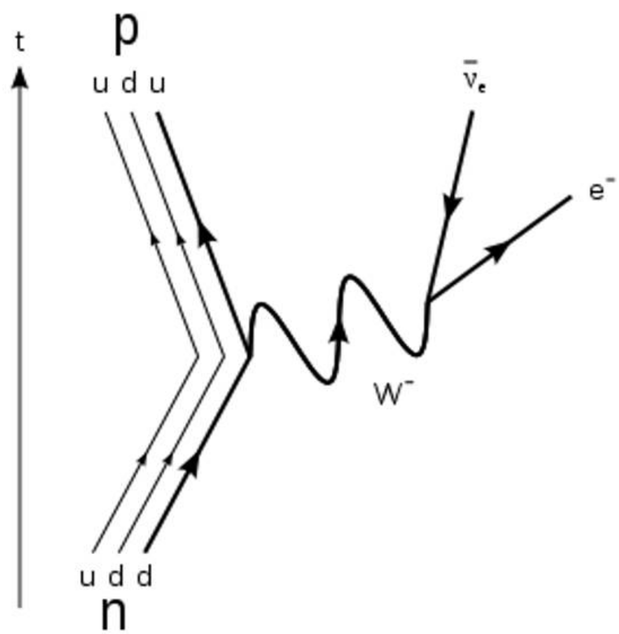
Parity Violation Discovered in β-decay: 1957

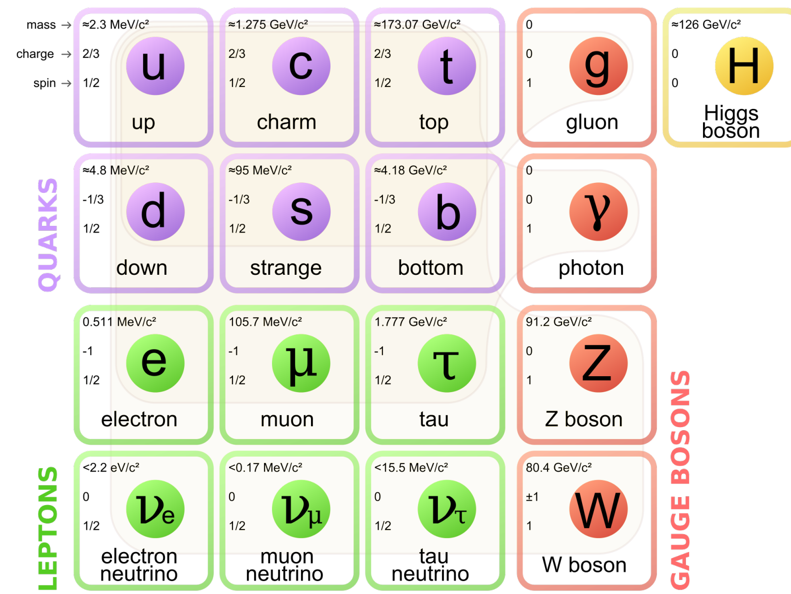
- Parity found to be maximally violated
- T.D. Lee and C.N. Yang awarded 1957 Nobel Prize





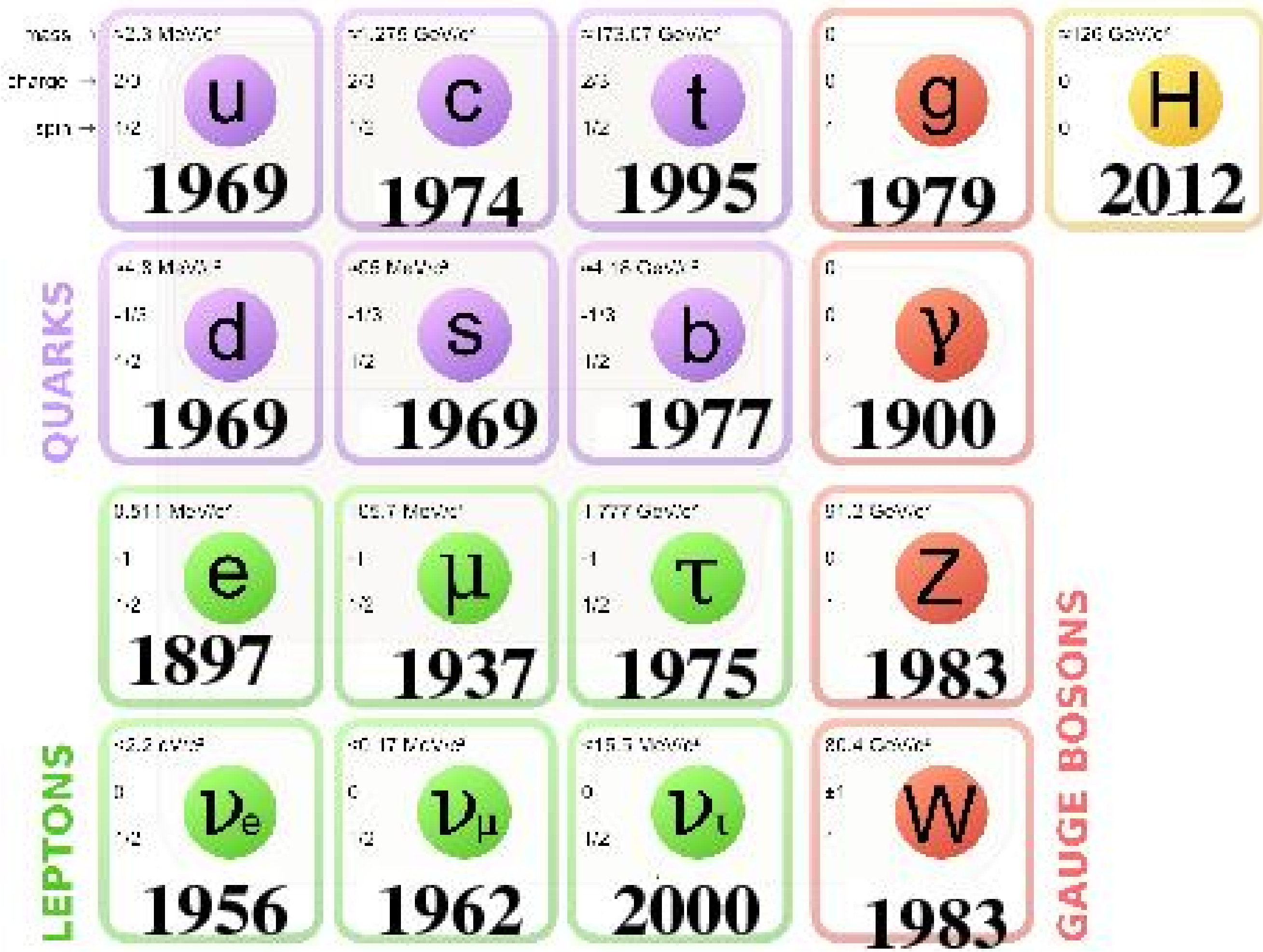
β^- Decay and Standard Model





- 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

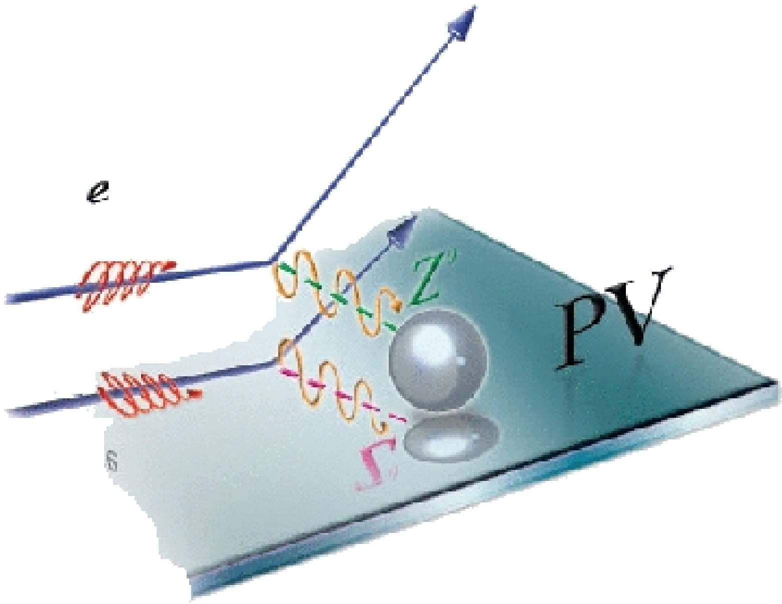
Standard Model of Elementary Particles



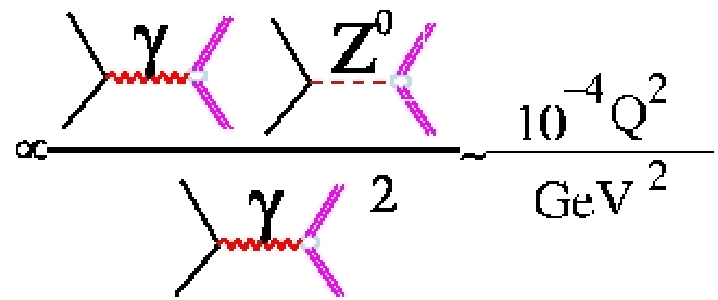
Parity Violation and Electron Scattering

- 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 weak current.
- 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



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



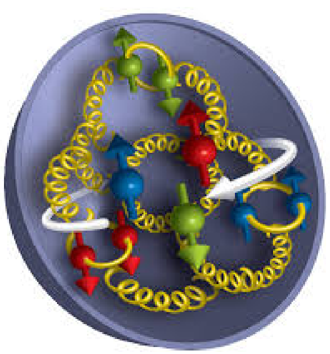
- Amplitude for Scattering Process: $S_{tot} \longrightarrow S_{em} + S_w$, but cross section $\sigma \longrightarrow |S_{tot}|^2 = |S_{em}|^2 + |S_w|^2 + 2S_{em}S_w$
- Since $\sigma_R^{em} = \sigma_L^{em}$ and $|S_w|^2$ is negligible,

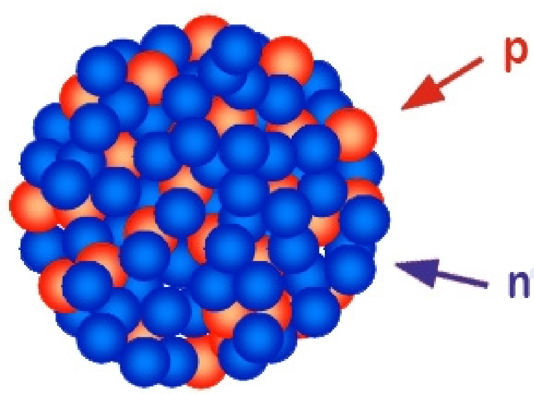
$$A_{PV} \longrightarrow \frac{2S_{em}S_w}{2|S_{em}|^2} = \frac{S_w}{S_{em}} \sim 10^{-4} \cdot Q^2$$

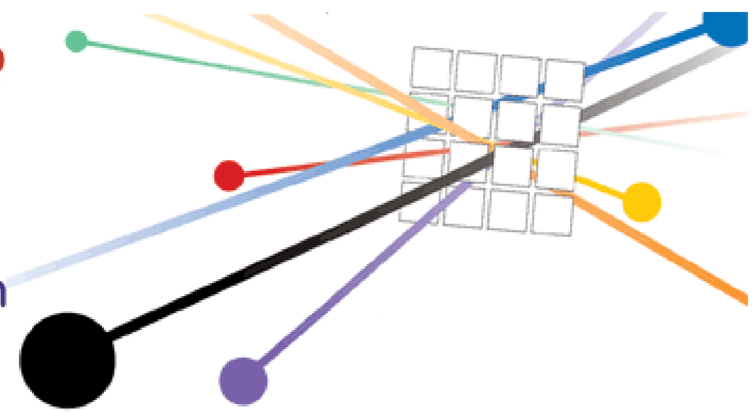
where Q^2 is 4-momentum transferred during interaction (GeV)

Selected Applications of PVeS

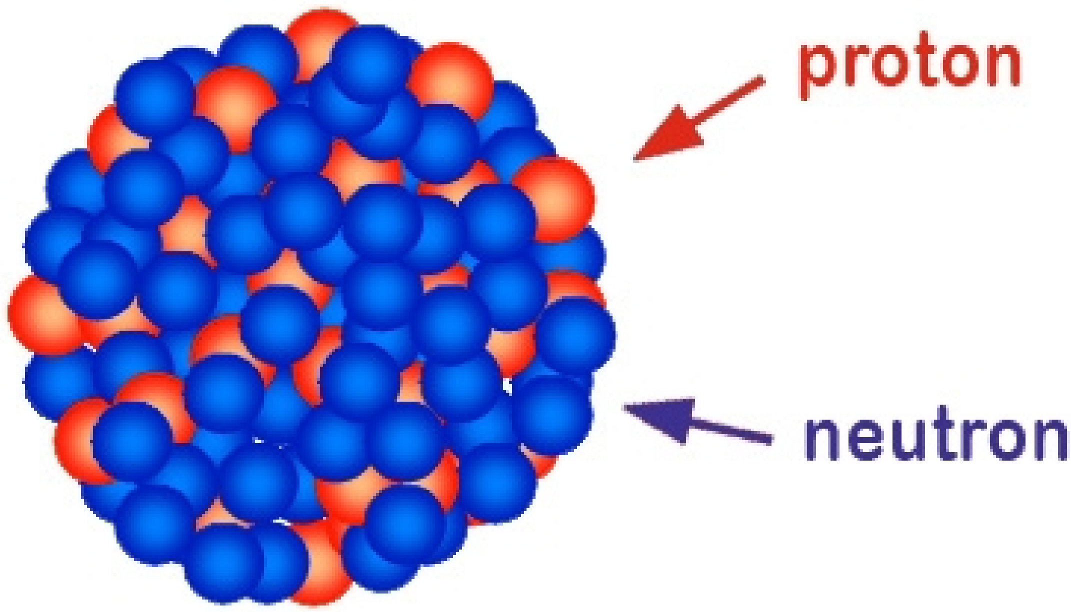
- **Strange Quarks**: What is the role of strange quarks in the electromagnetic structure of the proton or nucleon?
- **Size of Nucleus**: What is the size of a neutron-rich, complex nucleus? What is R_n, n_{skin}? Implications for Neutron Stars ?
- **BSM Searches**: Searching for physics Beyond the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





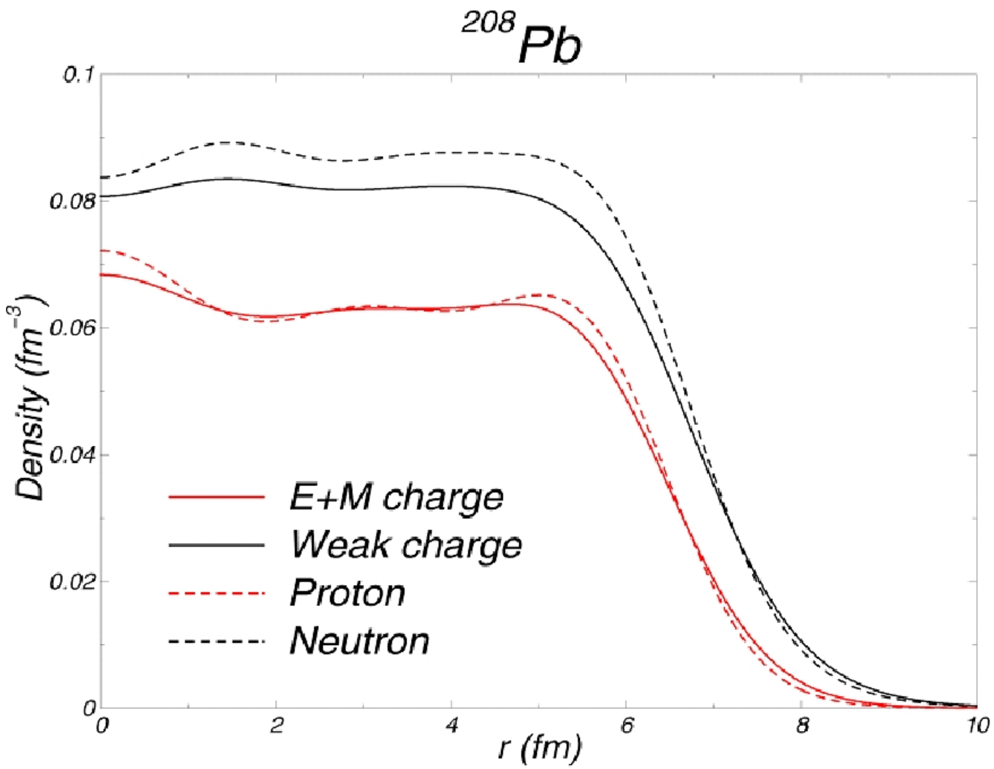


What is the size of a ^{208}Pb nucleus (82p+126n)?



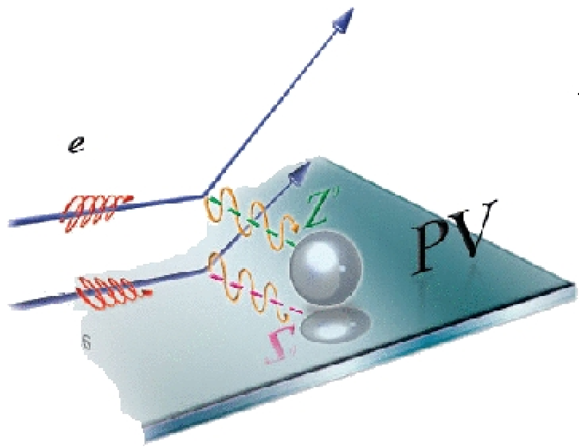
- What do we mean by size? The mass radius, the charge radius?
- PREx (Pb Radius Experiment) addresses this question in a unique way: Uses a "Weak" nuclear force probe to measure how much neutrons stick out past protons (The Neutron "skin")
- CREx (Calcium Radius Experiment) performs same measurement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

Mass versus EM Charge Radii of ^{208}Pb

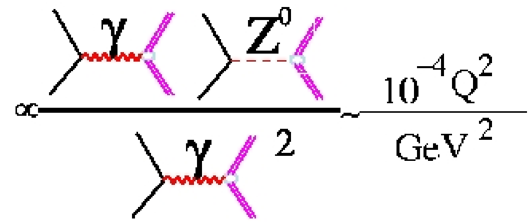


- Electromagnetism: Force mediated by γ exchange; Protons have EM charge "+e" while neutrons have 0...
- Weak Nuclear: Force mediated by Z^0 and $W^\pm$; **Neutrons have 12 times more Weak charge than protons**

PREx Measurement (Pb Radius Ex)



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



- 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

Motivation: Nuclear Radii in Heavy Nuclei

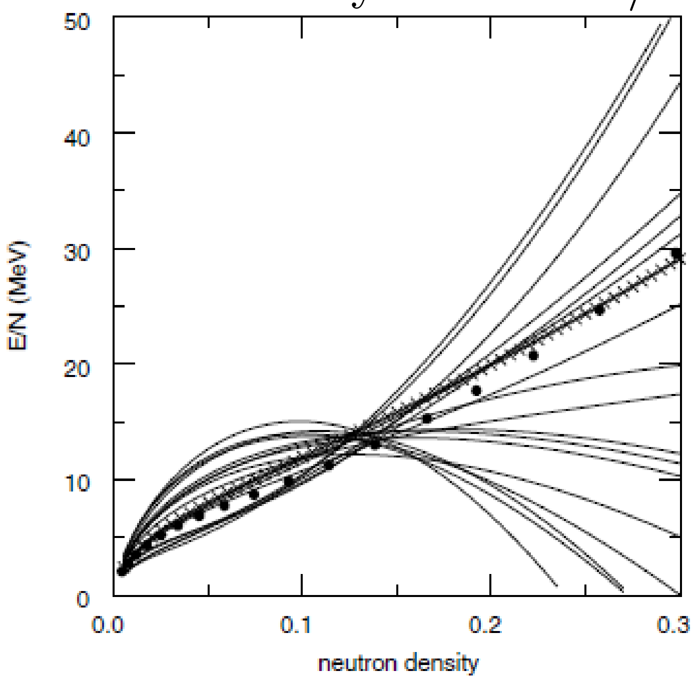
- Measurements are important for understanding the strong nuclear force
- Calculations are difficult due to non-pQCD regime and complicated due to many-body physics
- Interesting for:
  - →Fundamental nuclear structure
  - →Isospin dependence and nuclear symmetry
  - →Dense nuclear matter and neutron 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?

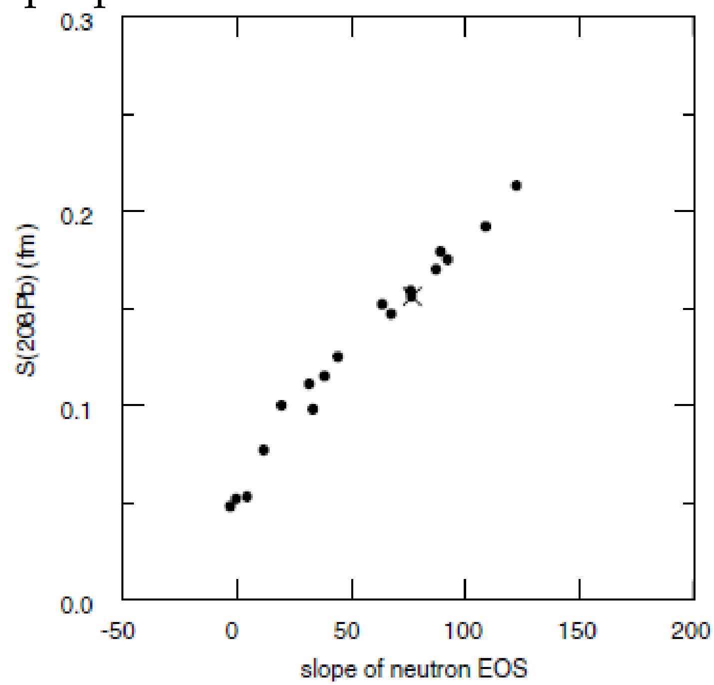
- Constraints on Eqn of State (EOS) and symmetry energy of neutron rich matter – the energy cost for asymmetric matter ($N \neq Z$)
- Slope of EOS can be used to constrain potential models

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

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

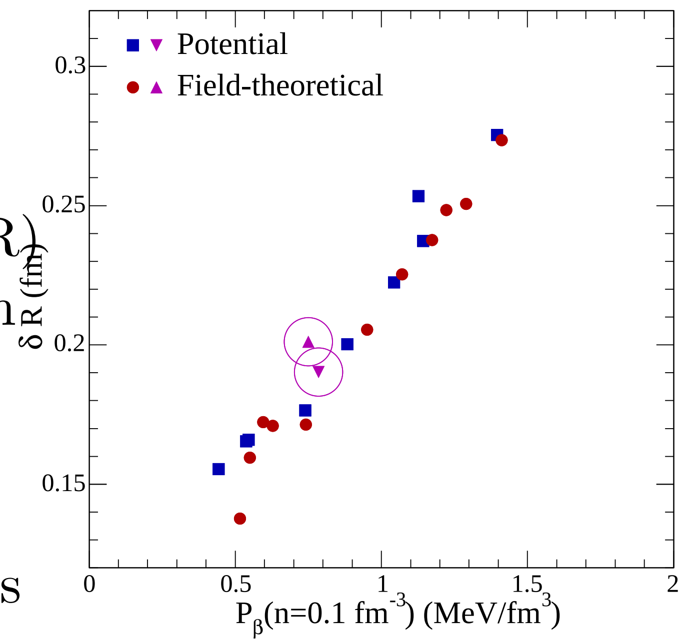


Lead neutron skin vs. corresp. slope parameter of the 18 EOS.



Motivation: Neutron Stars

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



- Neutron star structure is better understood with measurements of R_n
- 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:

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

$$e^- + p \rightarrow n + \nu$$

→Larger symm. energy gives larger proton fraction (need 11%)

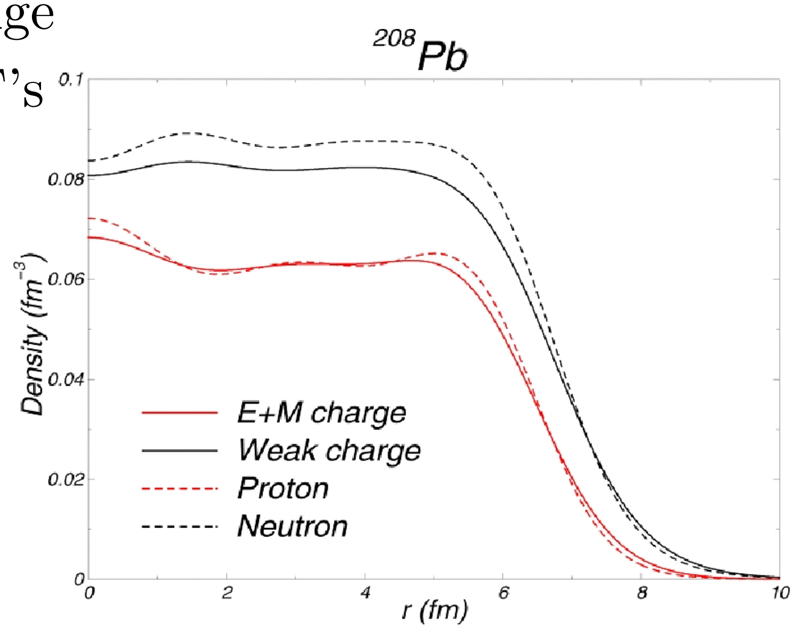
Methods used to Measure R_n

- Hadronic Probes
  - →Elastic pN, $\vec{p}$N, nN, $\pi^{\pm}$N
  - →π^0 photoproduction (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 FF's



$\rightarrow$For spin 0 nucleus:

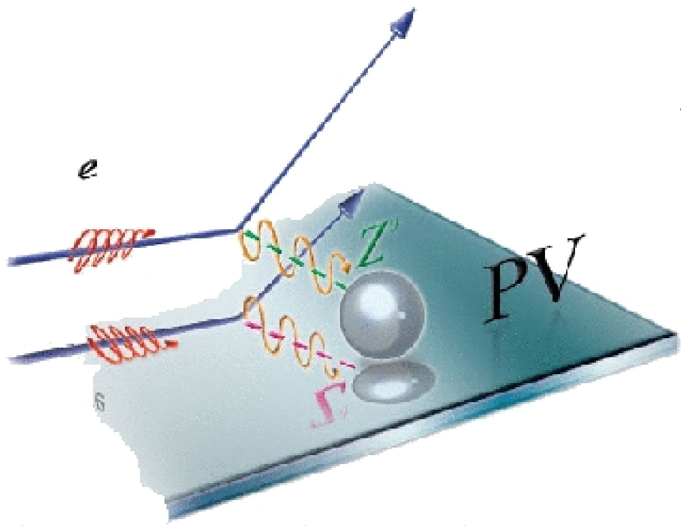
$$\frac{d\Omega}{d\sigma} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} |F(Q^2)|^2$$

$\rightarrow$In limit of small Q^2:

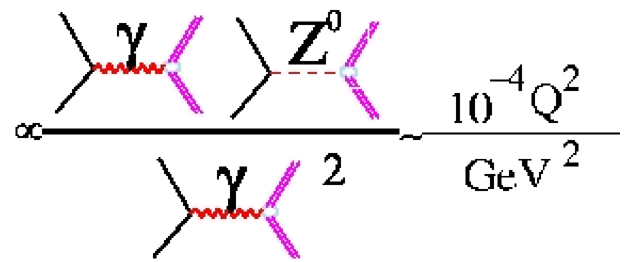
$$F(Q^2) \approx F(0) + \left.\frac{dF}{dQ^2}\right|_{Q^2=0} + \ldots = \int \rho(\vec{x}) d^3x - \frac{1}{6} Q^2 \langle r^2_{\text{charge}} \rangle$$

$\rightarrow$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:

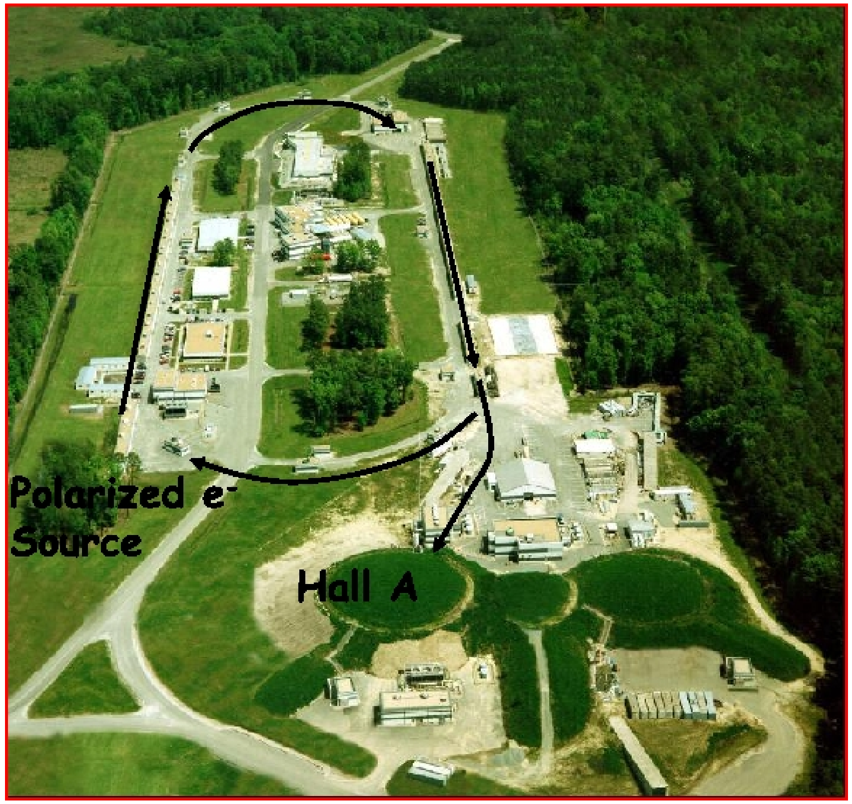
$$Q_{weak}^{proton} \propto 1 - 4\sin^2\theta_W \approx 0.076, \qquad Q_{weak}^{neutron} = -1$$

- 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:

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

PREx Measurement

PREx measures R_n of ^{208}Pb

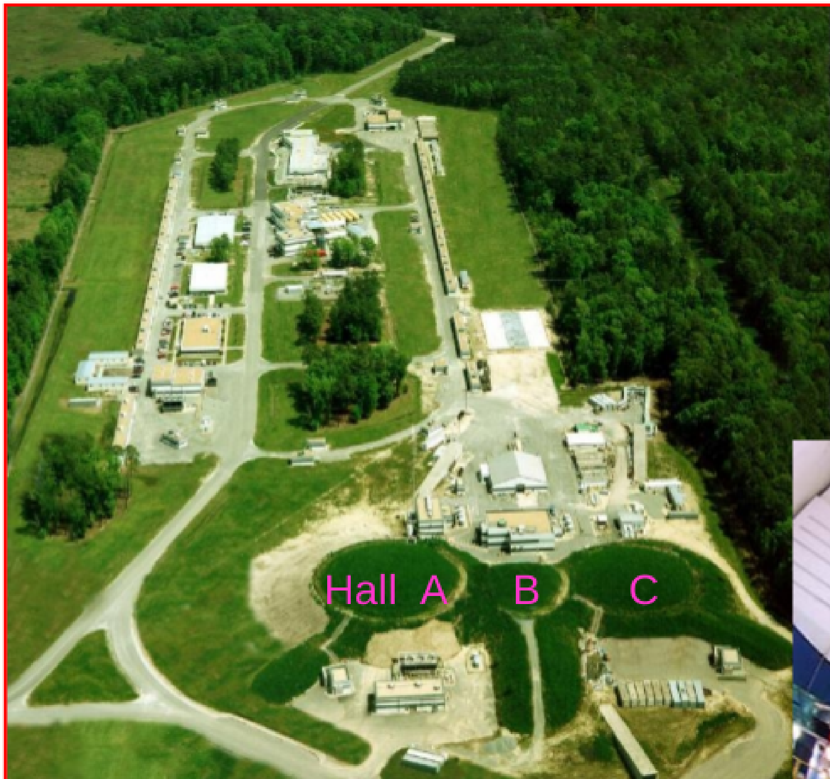
- Lead is nice because:

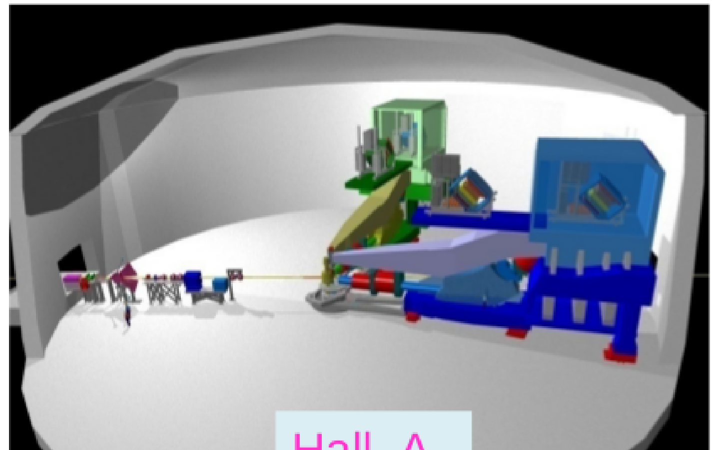
  →Excess of neutrons (44 more–with some expected to form a neutron-rich skin)

  →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

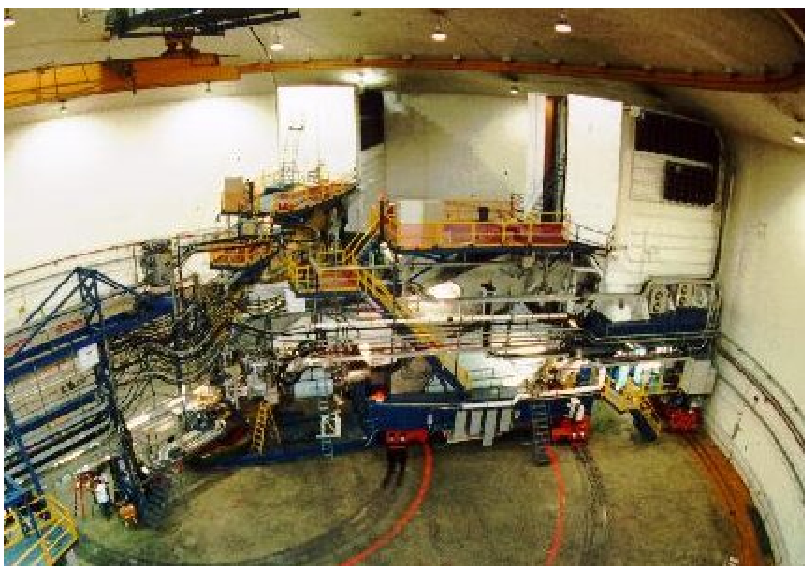
Jefferson Lab Hall A (Newport News, Virginia)

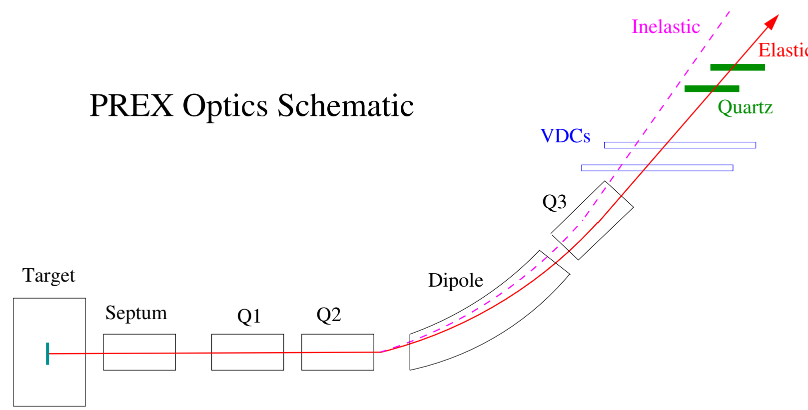




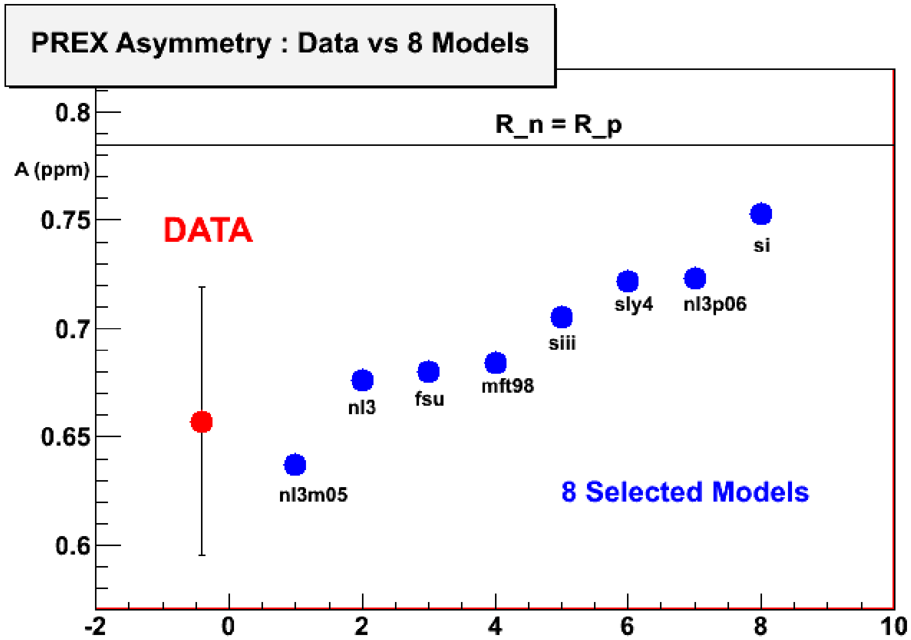
Experimental Setup

- Std. Hall A HRS's with det. huts well shielded against bkgds.
- Run. dual, symm. arms cancels out A_{trans} and other systematics
- Use septum magnet to bend 5^o to 12.5^o
- Upgraded polarimetry (non-inv. Compton$\sim 1\%$, Inv. Moller$\sim 1\%$)
- 0.5mm thick Pb in b/t two 0.15mm Diamond targets ($\sim 1 \times 1\text{in}^2$) with cryogenically cooled frame; used fast rastered beam
- Quartz Cerenkov detectors with 18-bit integrating ADCs





Results



- 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

$\rightarrow$Each model of neutron density is folded into numerical solution of Dirac eqn with Coulomb and weak axial potential

$\rightarrow$Full acceptance (apertures, septum optics, detectors) applied to A_{PV}

Result and Error Budget

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

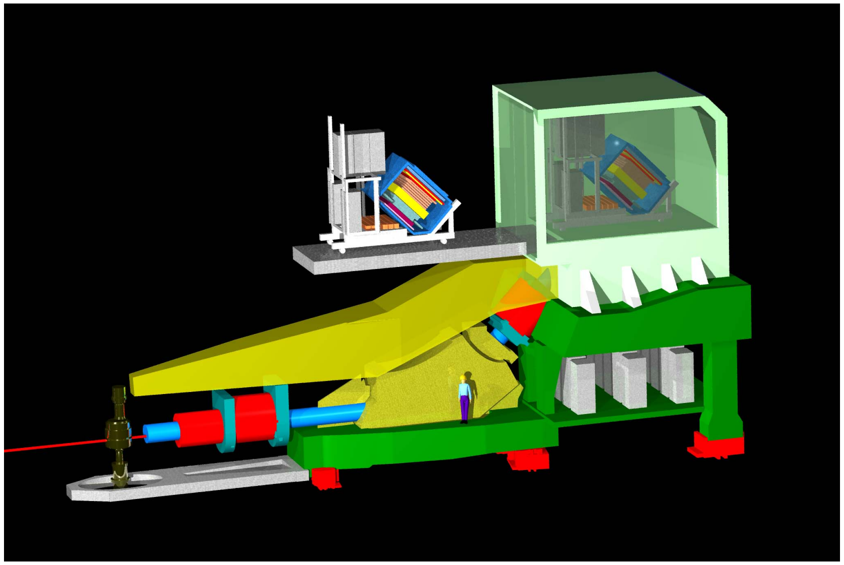
Contributions	abs (ppm)	rel (%)
Polarization	0.0071	1.1%
Detector Lin.	0.0071	1.1%
Beam Corrections	0.0072	1.1%
Q^2	0.0028	0.4%
^{12}C Asymmetry	0.0025	0.4%
Transverse Pol.	0.0012	0.2%
BCM Lin.	0.0010	0.1%
Target Thick	0.0006	0.1%
Rescattering	0.0001	0.0%
Inelastic Cont.	0.0000	0.0%

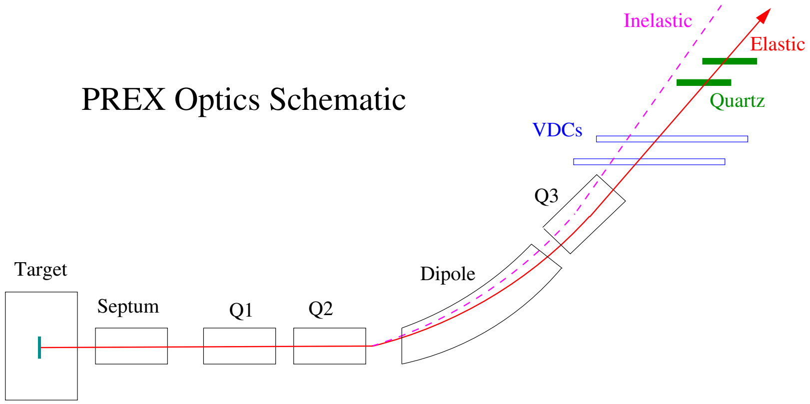
Summary (PREX)

- 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%) ± 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

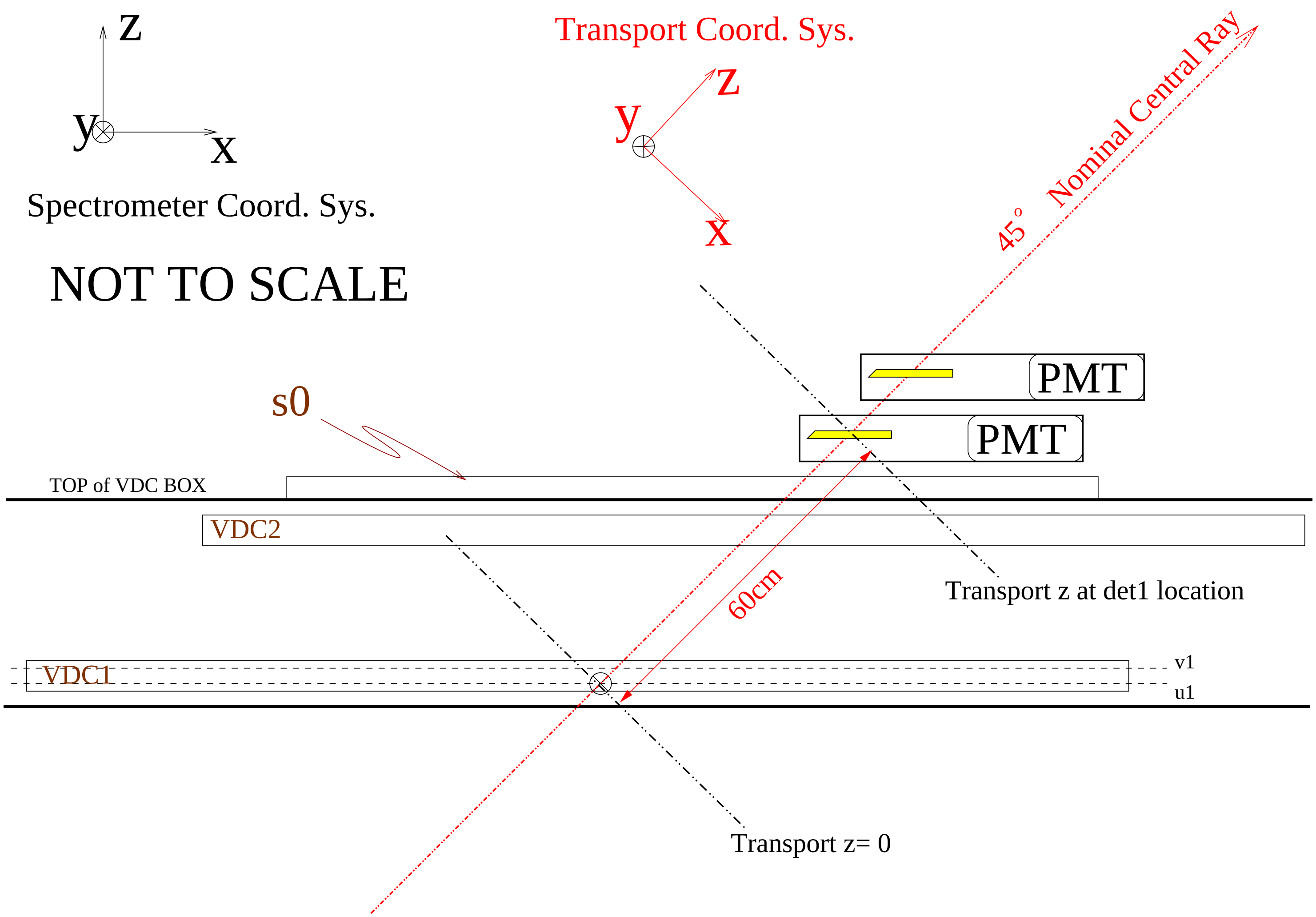
Experimental Setup (Spectrometer & Detectors)

- 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)





Focal Plane Detectors: ISU's Responsibility

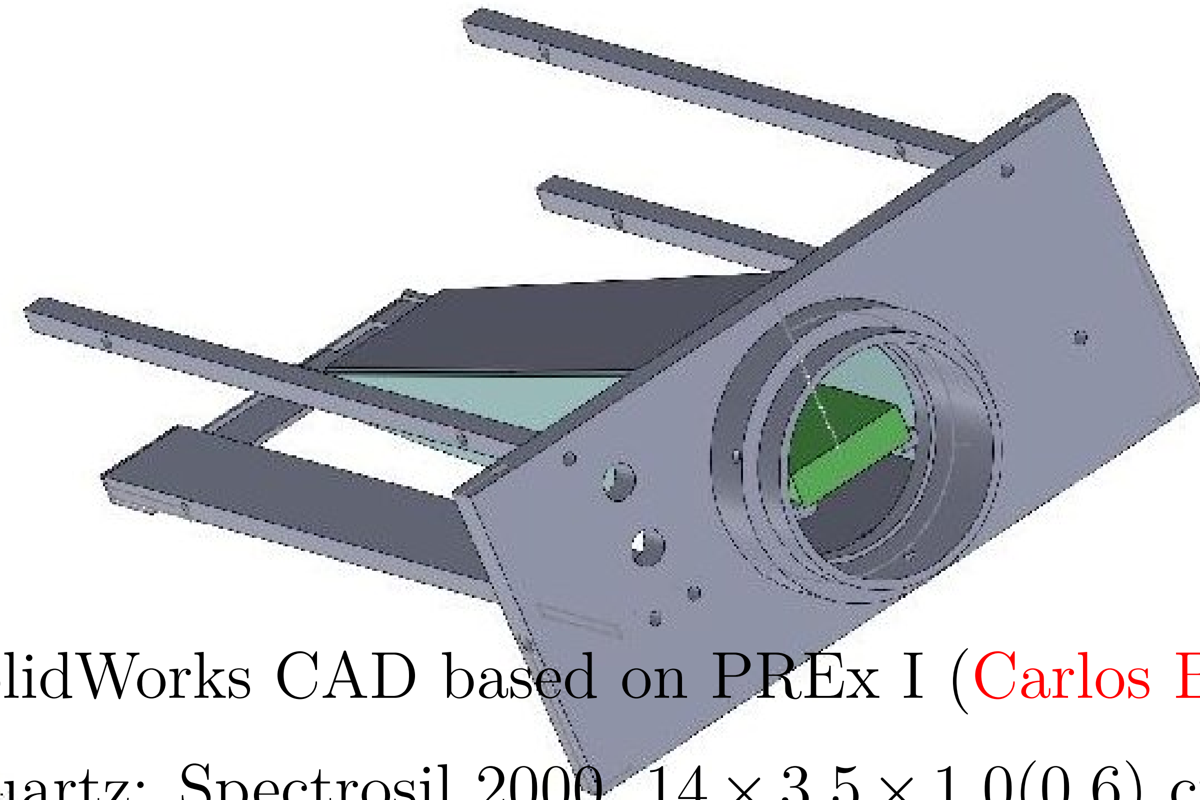


Ongoing Work at ISU for PREx and CREx

Quartz Cerenkov detector development

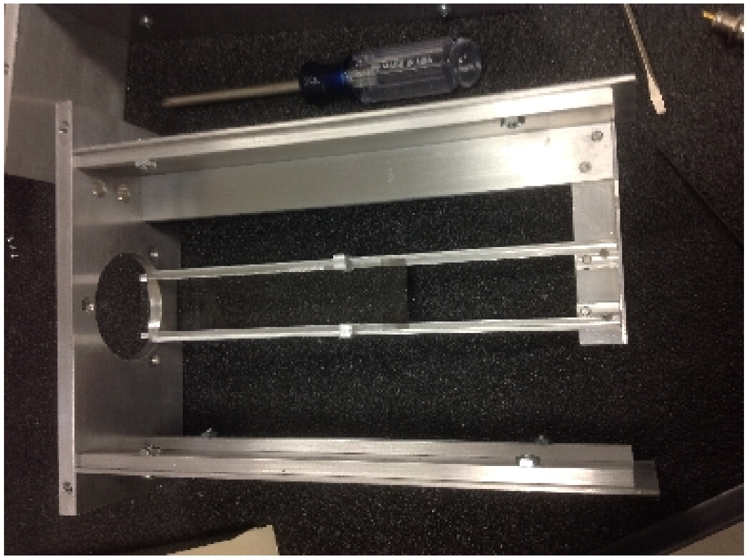
- Cosmic ray tests
  - –Constructed baseline prototype detector
  - –Constructed cosmic/beam test stand
  - –Established counting Data Acquisition System (DAQ)
- Optical Monte Carlo Simulation
  - –Using "qsim" framework: GEANT4, C++ based
  - –Modeled precise geometry of cosmic test setup
  - –Continuing to develop and refine.
  - –Once benchmarked, will use to optimize detector design

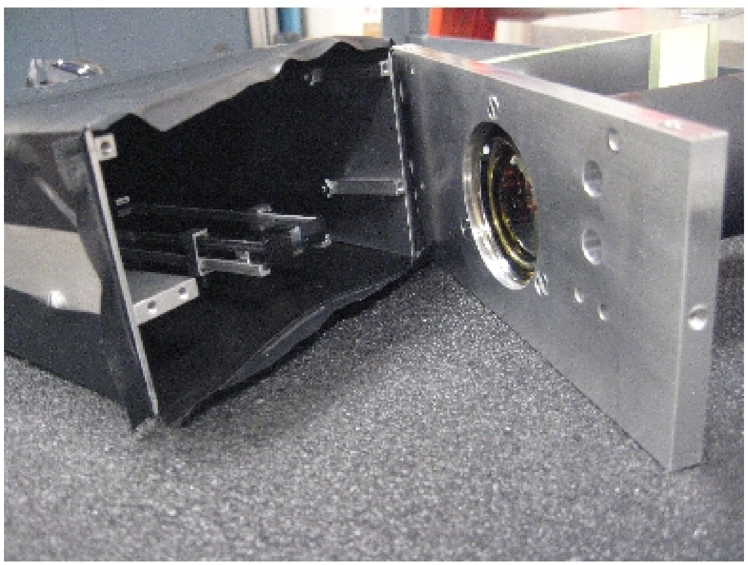
Baseline prototype Quartz Detector

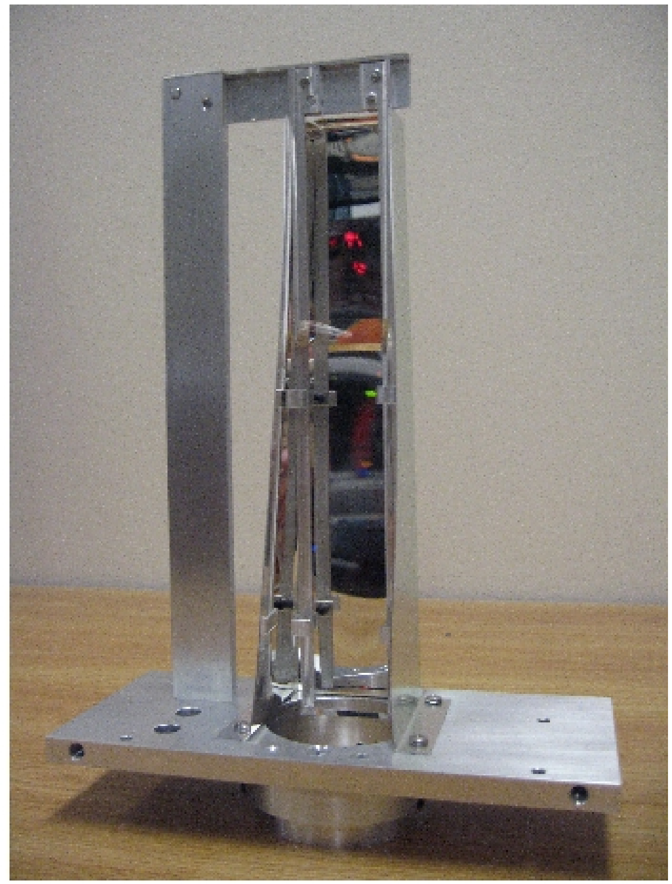


- SolidWorks CAD based on PREx I (Carlos Bula)
- Quartz: Spectrosil 2000, $14 \times 3.5 \times 1.0(0.6)$ cm^3, 45^o bevel on one end, optical polish all sides
- Light guide: Anolux Miro-silver 4270AG, ...

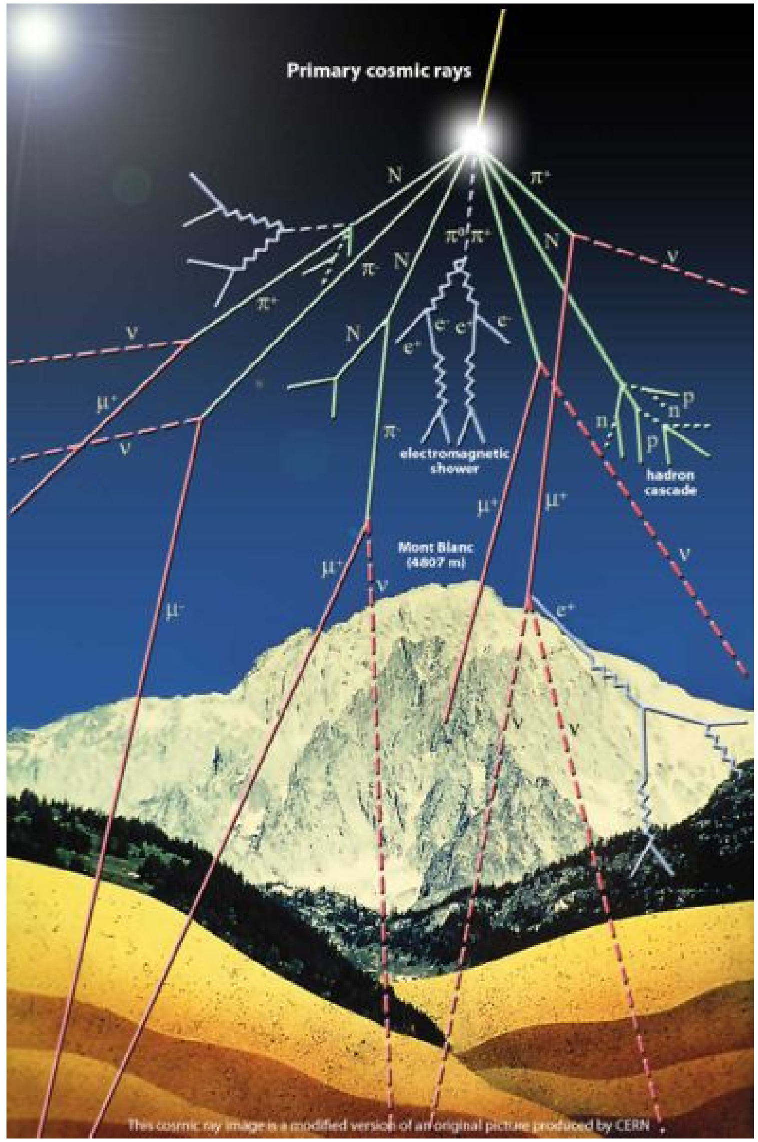
Baseline prototype Quartz Detector



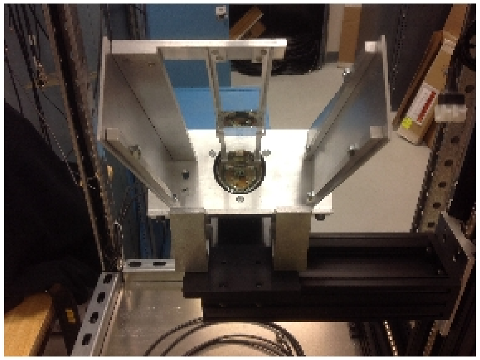


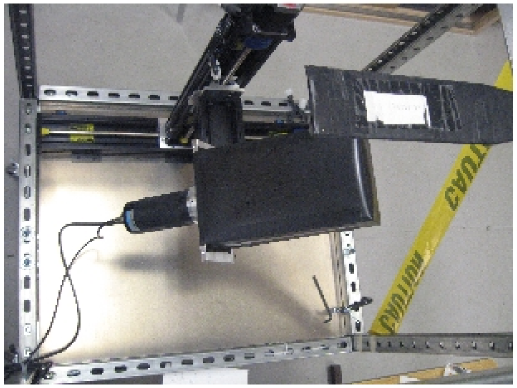


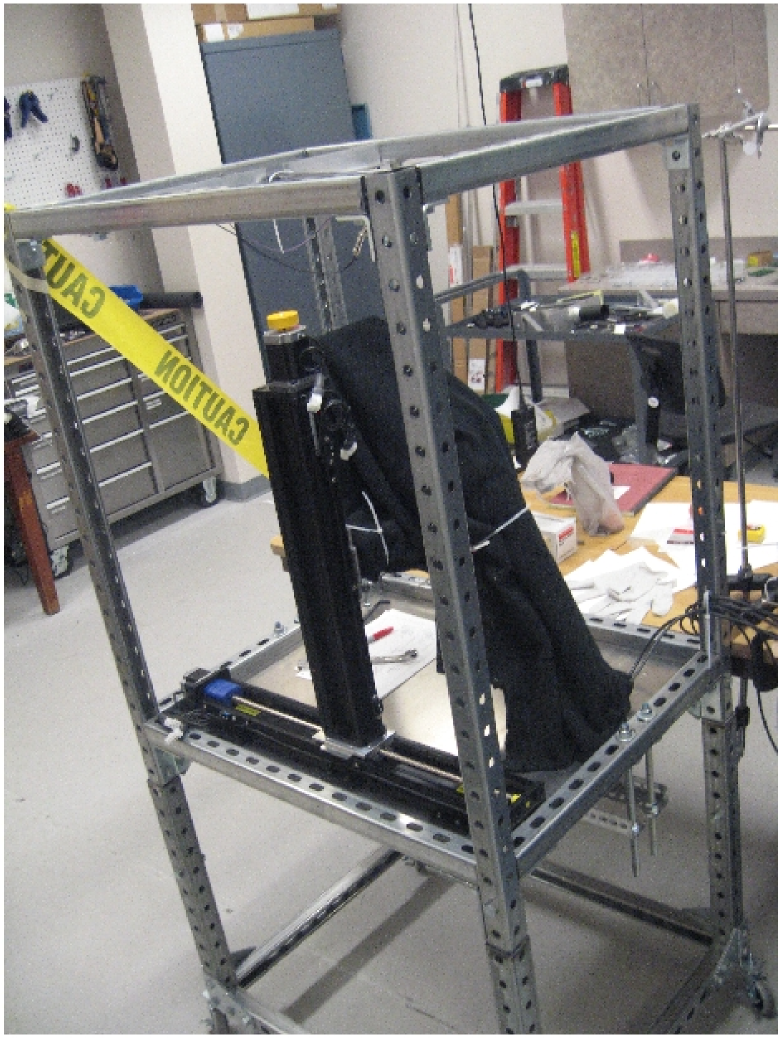
Cosmic Rays


Primary cosmic rays
electromagnetic shower
hadron cascade
Mont Blanc (4807 m)
This cosmic ray image is a modified version of an original picture produced by CERN

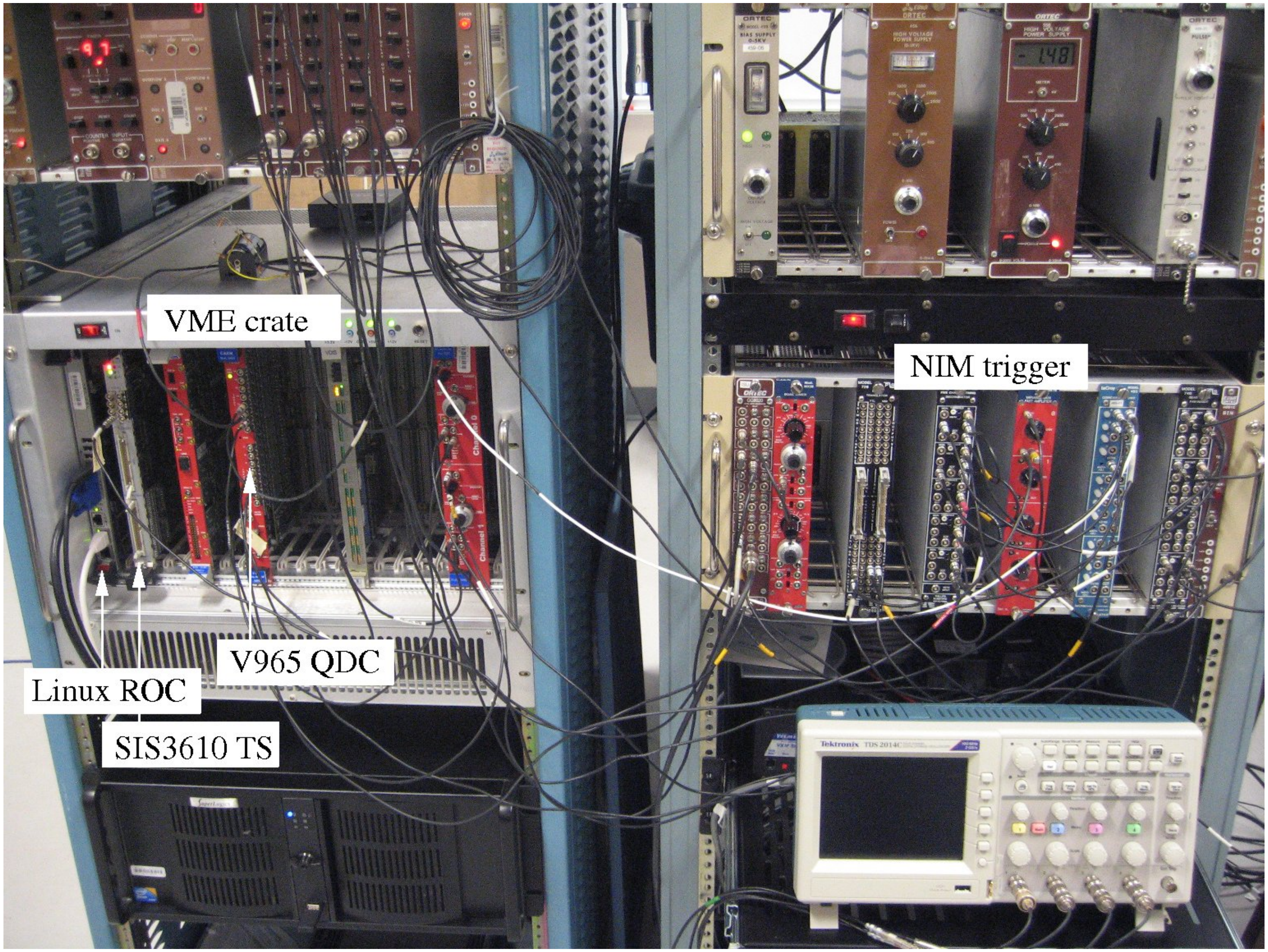
Cosmic/Beam Test Stand



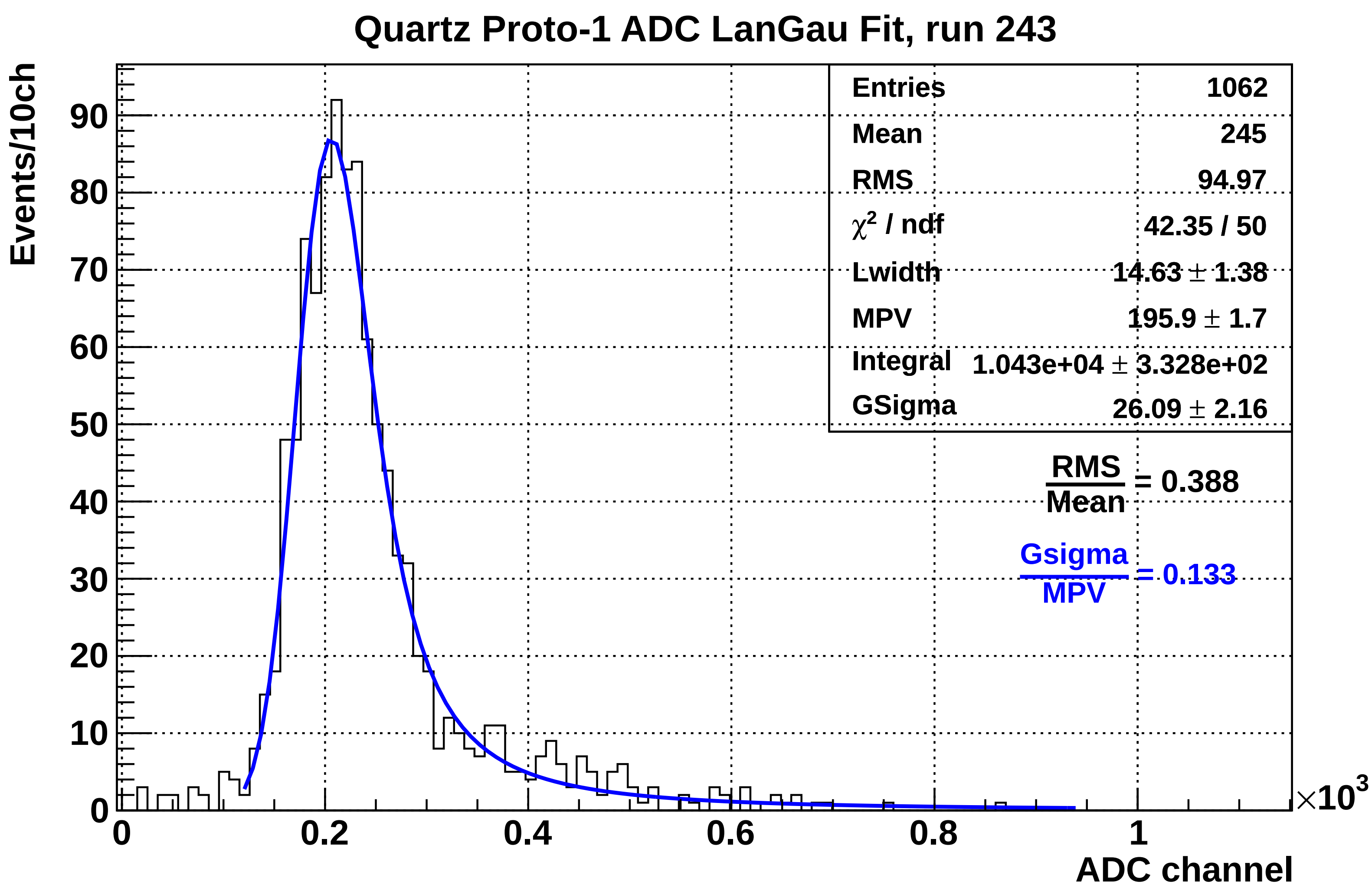




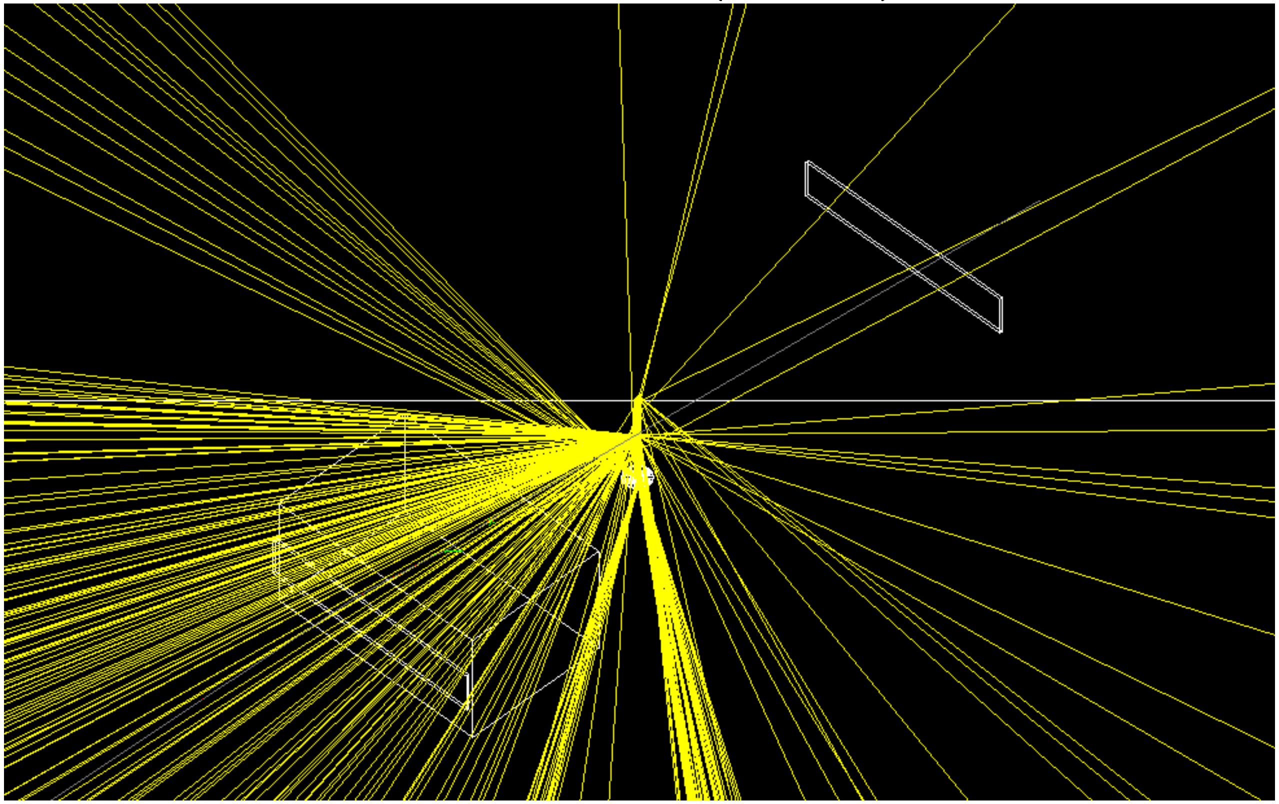
Counting DAQ



Initial Cosmic Test Results (Real Data)

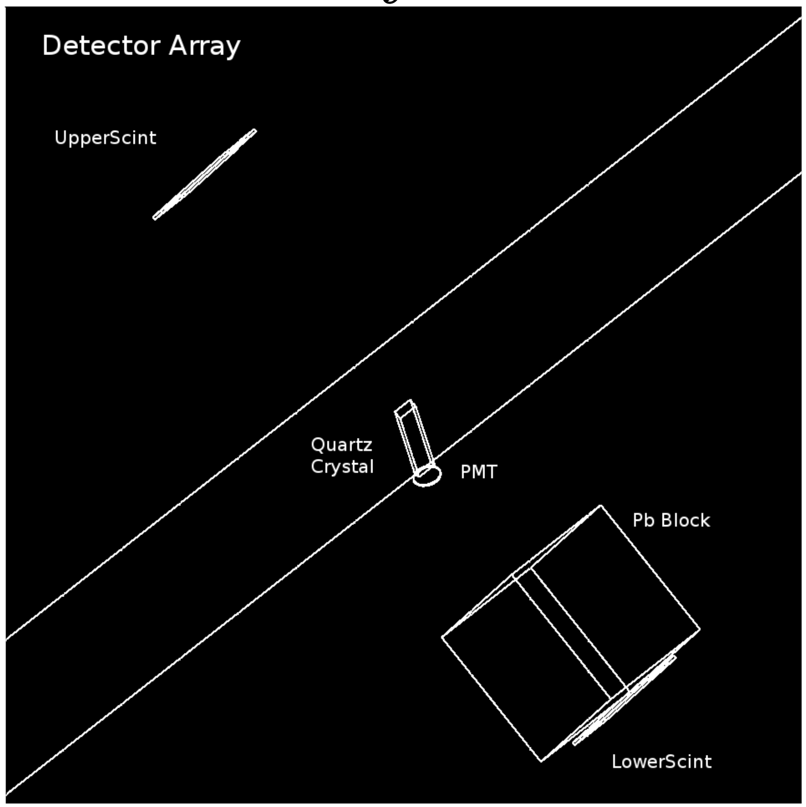


G4 Optical Simulations (qsim): Carlos Bula



- "qsim" framework developed by Seamus Riordan
- Geometry adapted to ISU cosmic test setup
- Additional realistic features implemented: muon angle smearing, PMT QE, scintillator coinc. trigger

qsim Geometry: Cosmic Tests



- Two scintillators: each 20 cm $\times$ 7 cm, separated by 110 cm
- bare PREX detector: quartz bar, 5 mm from 2in PMT, angled at 45° wrt scintillators
- 8 inches of Pb installed just above lower scintillator

qsim Beam Source: Cosmic Tests

- μ^- beam Energy: realistic sample
- Angles:

  $\theta : \{34.7^{o}, 55.3^{o}\}$

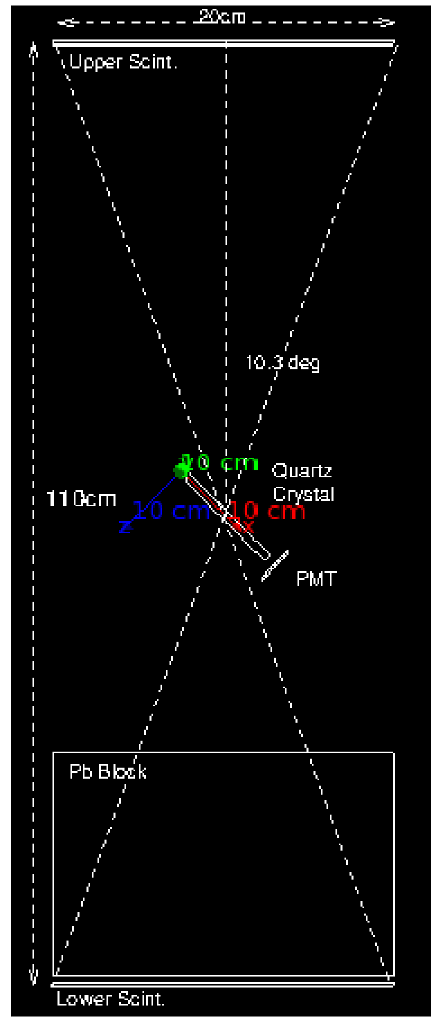
  $\phi : \{-3.6^{o}, 3.6^{o}\}$

  Uniformly sampled
- Positions:

  Uniformly sampled

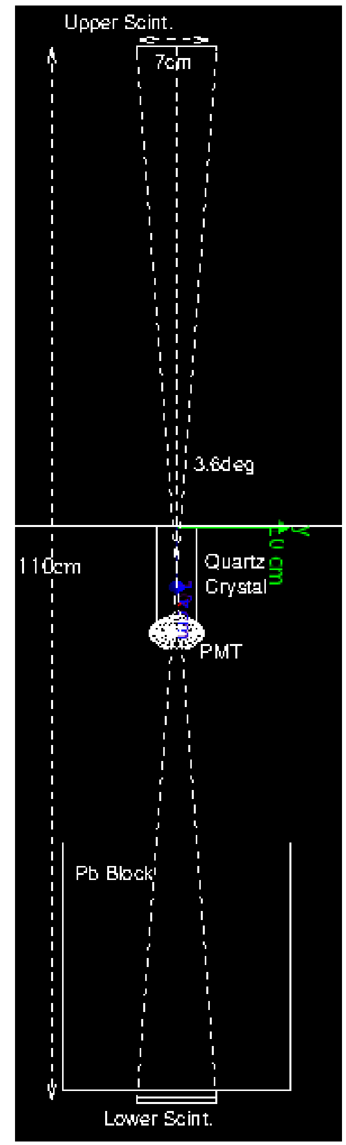
  over scintillator area

θ acceptance: +–10.3°

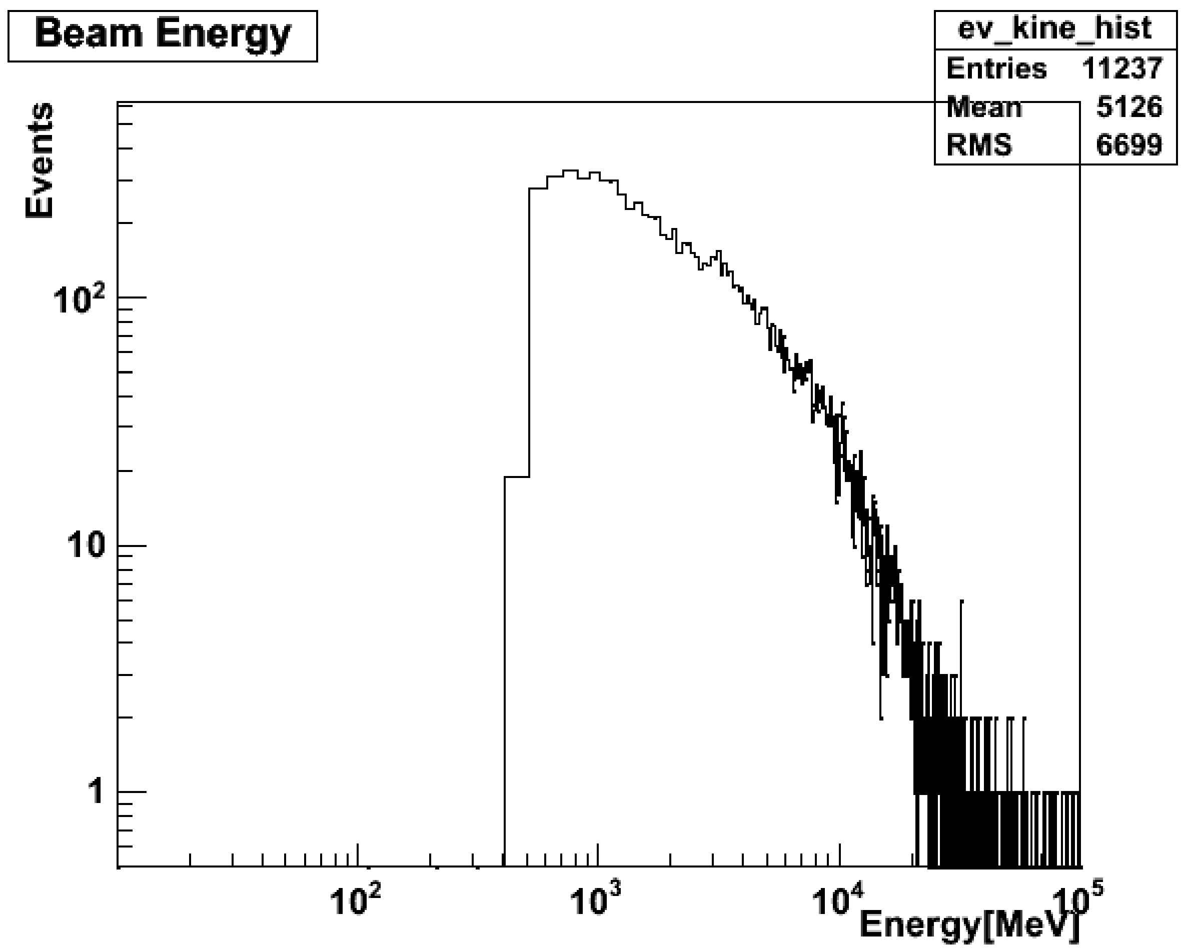


NOT TO SCALE

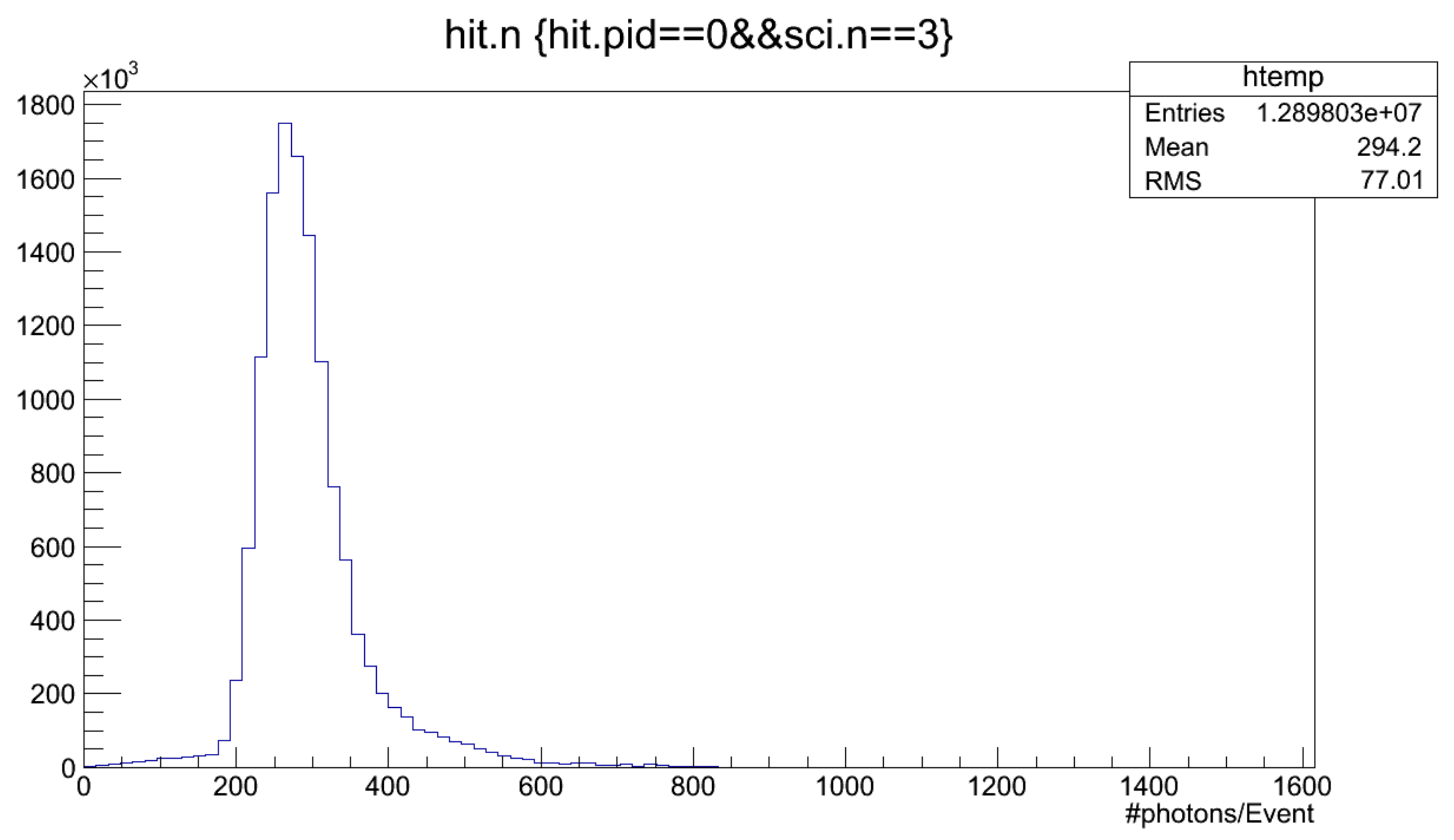
ϕ acceptance: +–3.6°



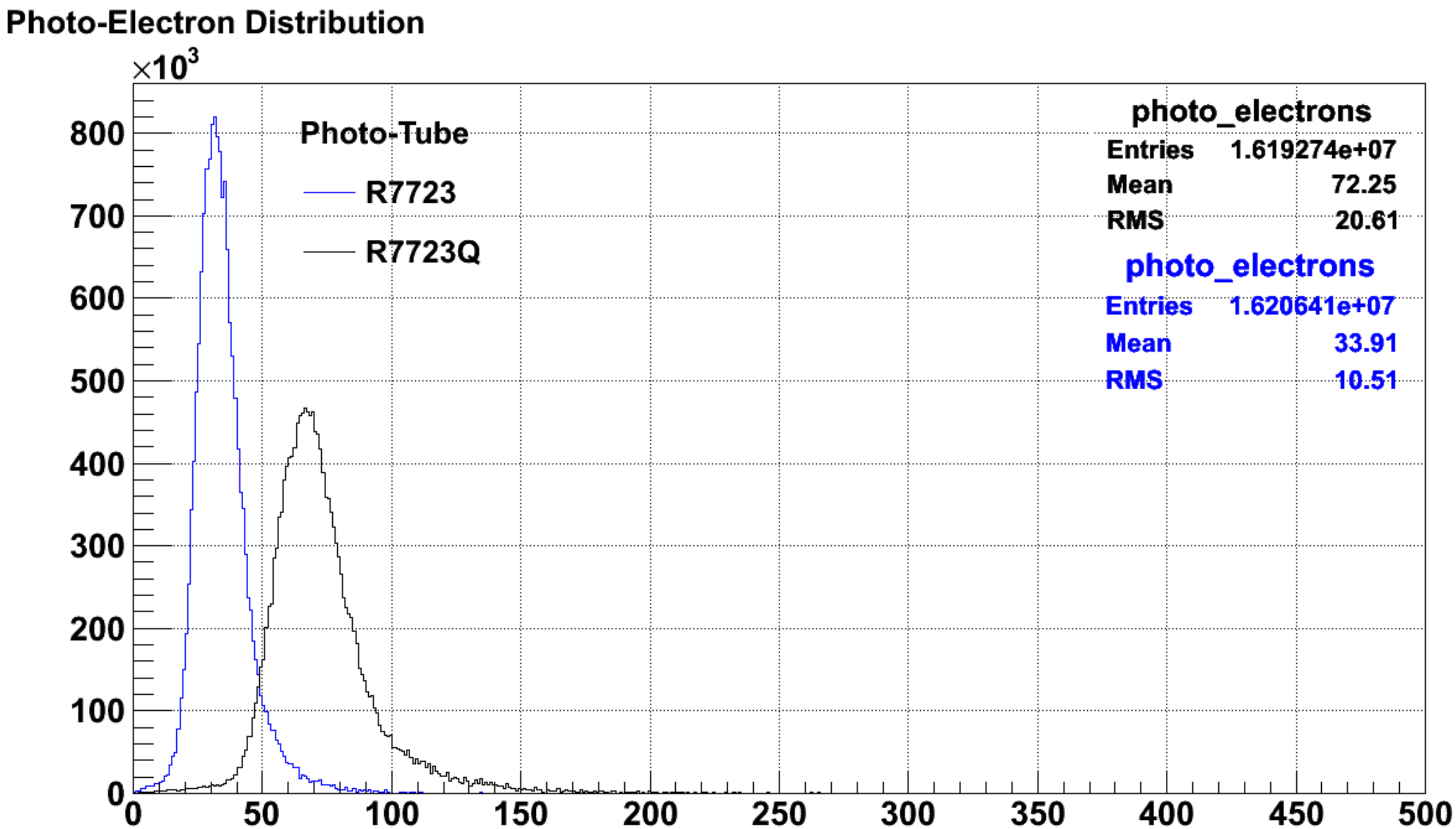
Realistic Muon Beam Energy



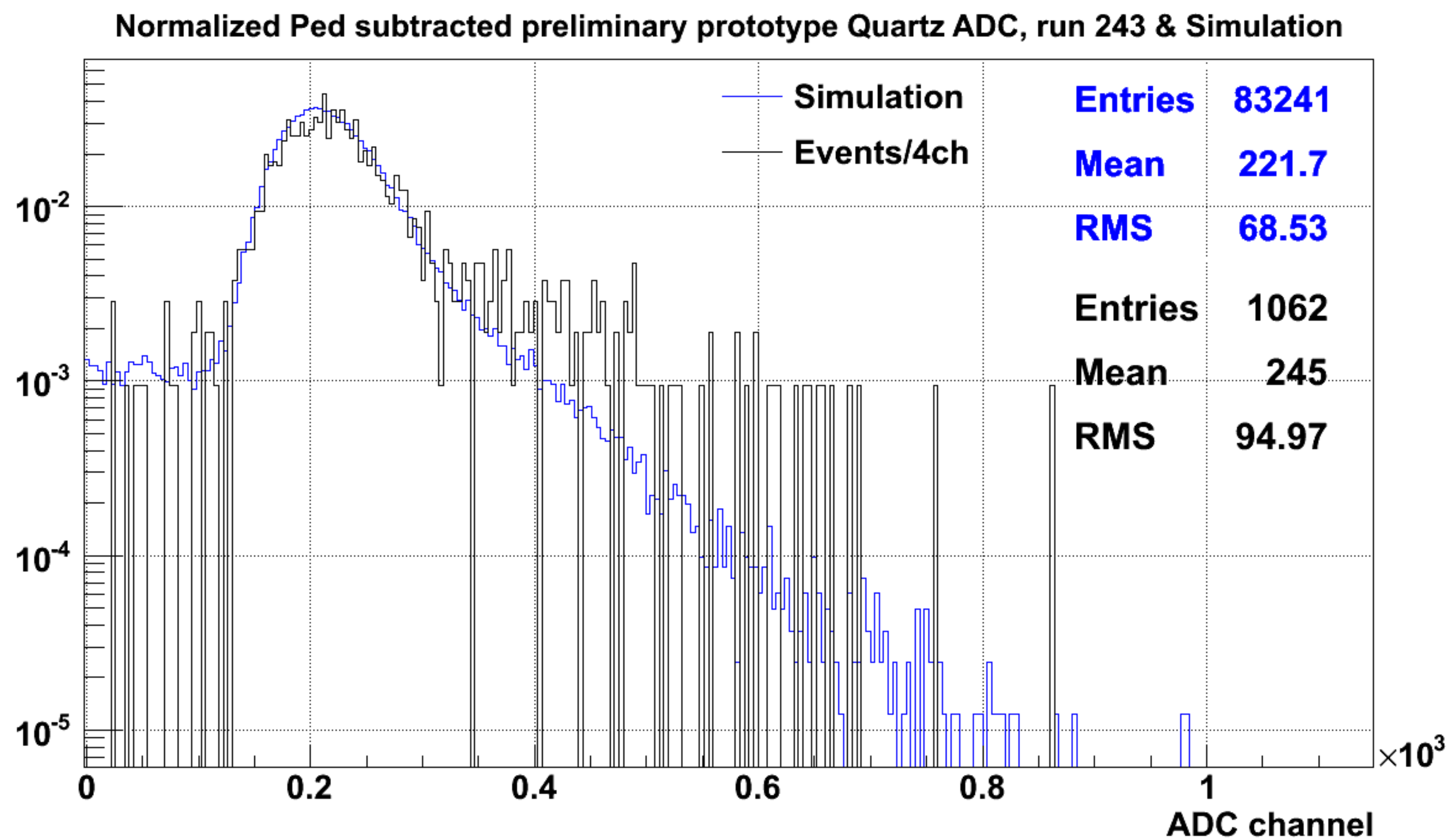
Distribution of Photons/Muon Hitting PMT



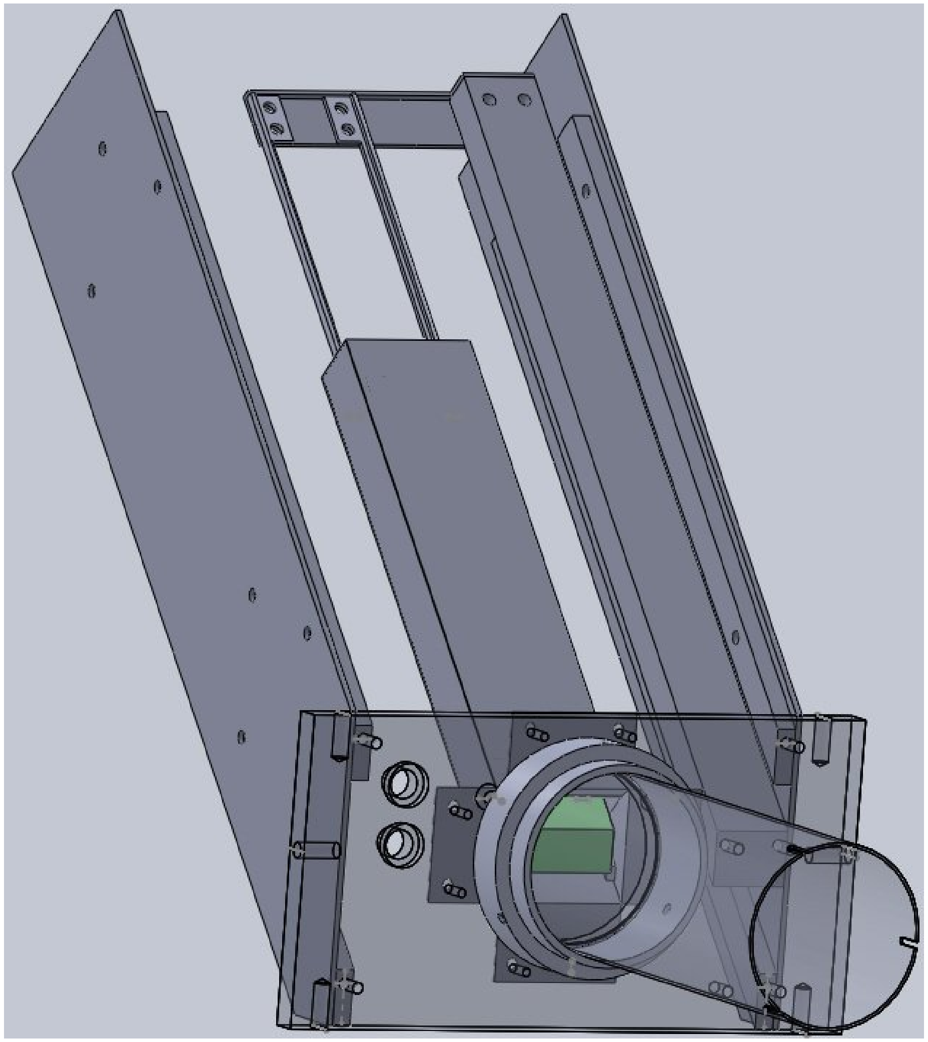
Distribution of Photo-electrons (PE's) per Muon



Comparison between Simulation and Experiment

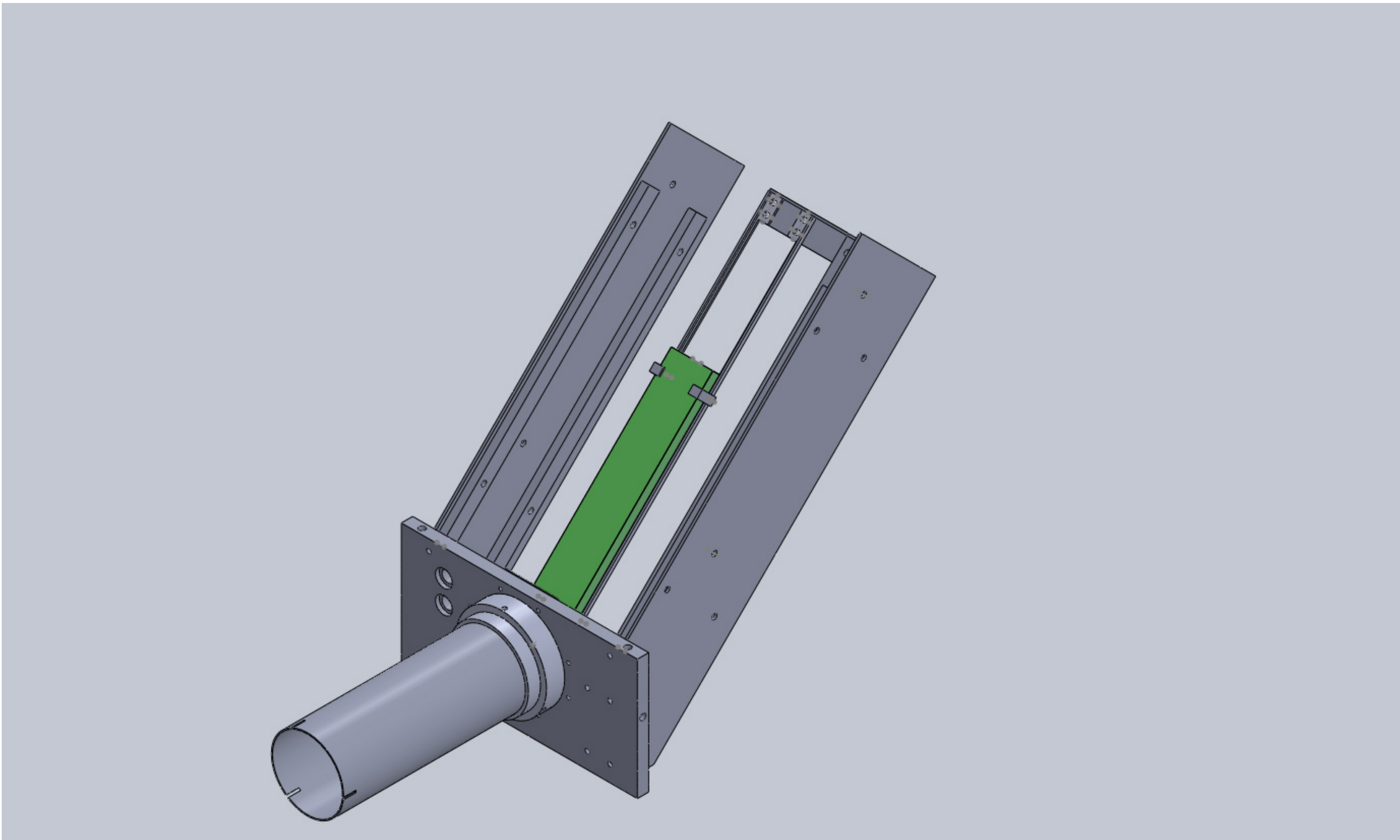


New Detector Prototype (B)

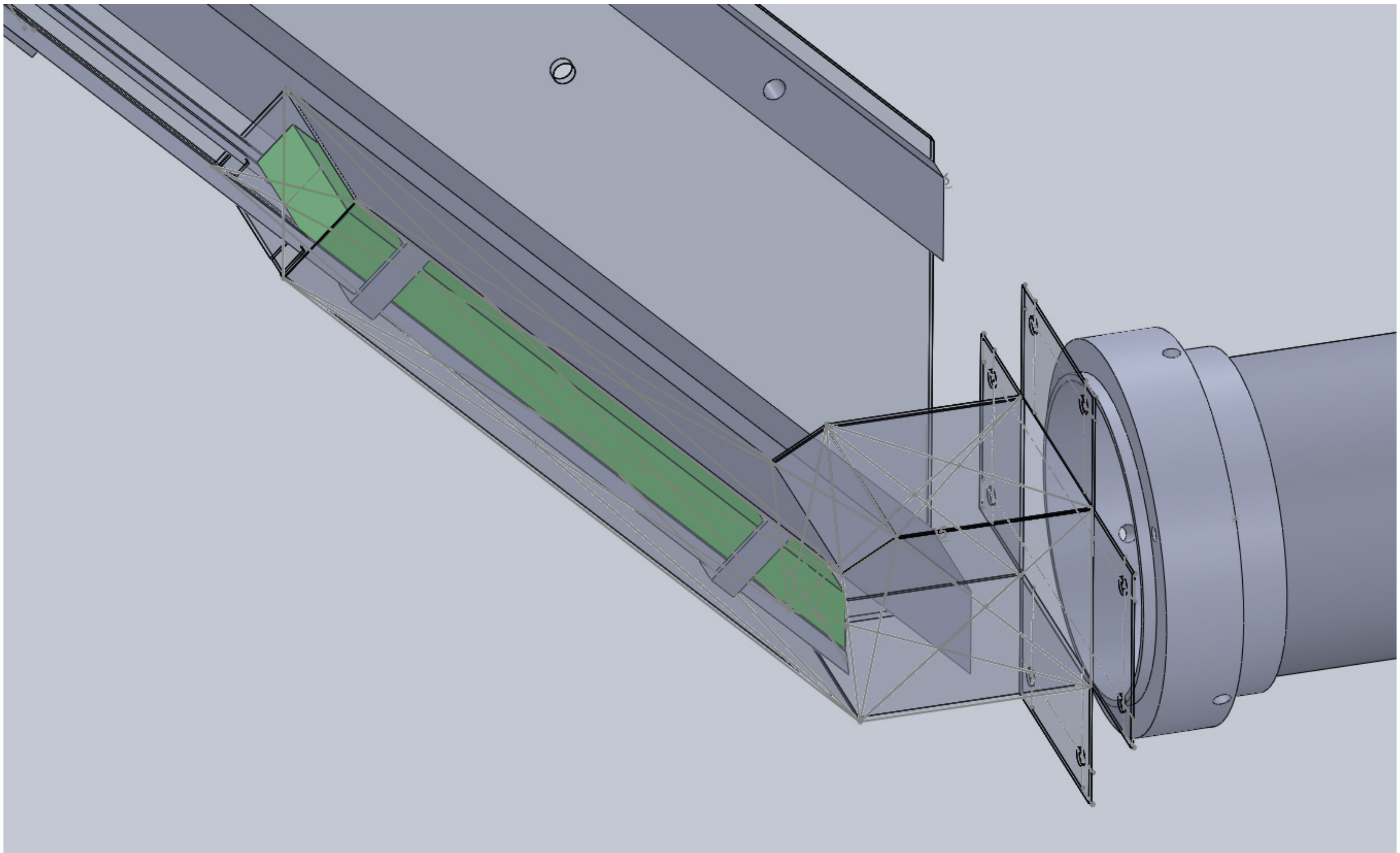


- Designed by Brady Lowe using SolidWorks

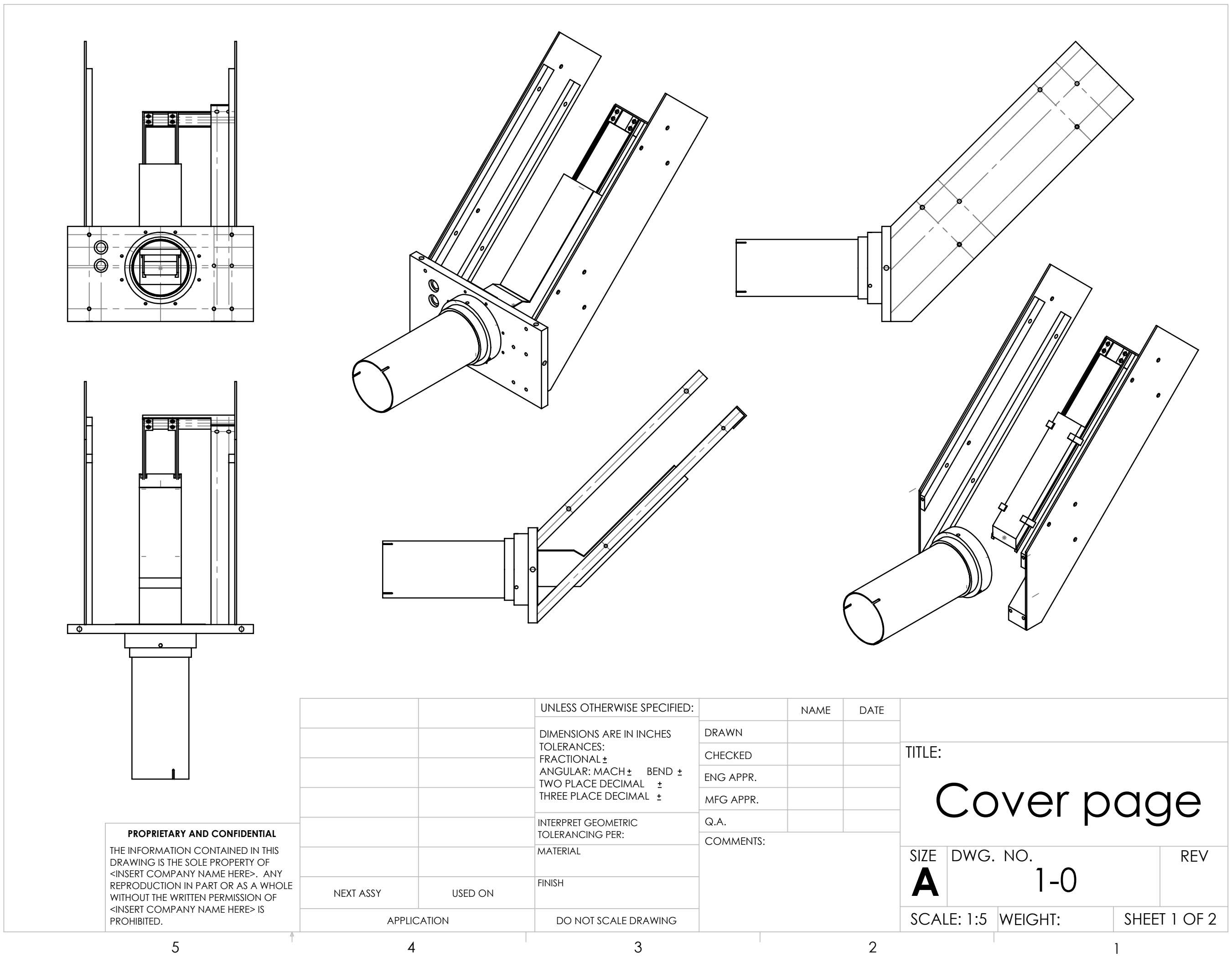
New Detector Prototype B (Alternate Views)



New Detector Prototype B (Alternate Views)

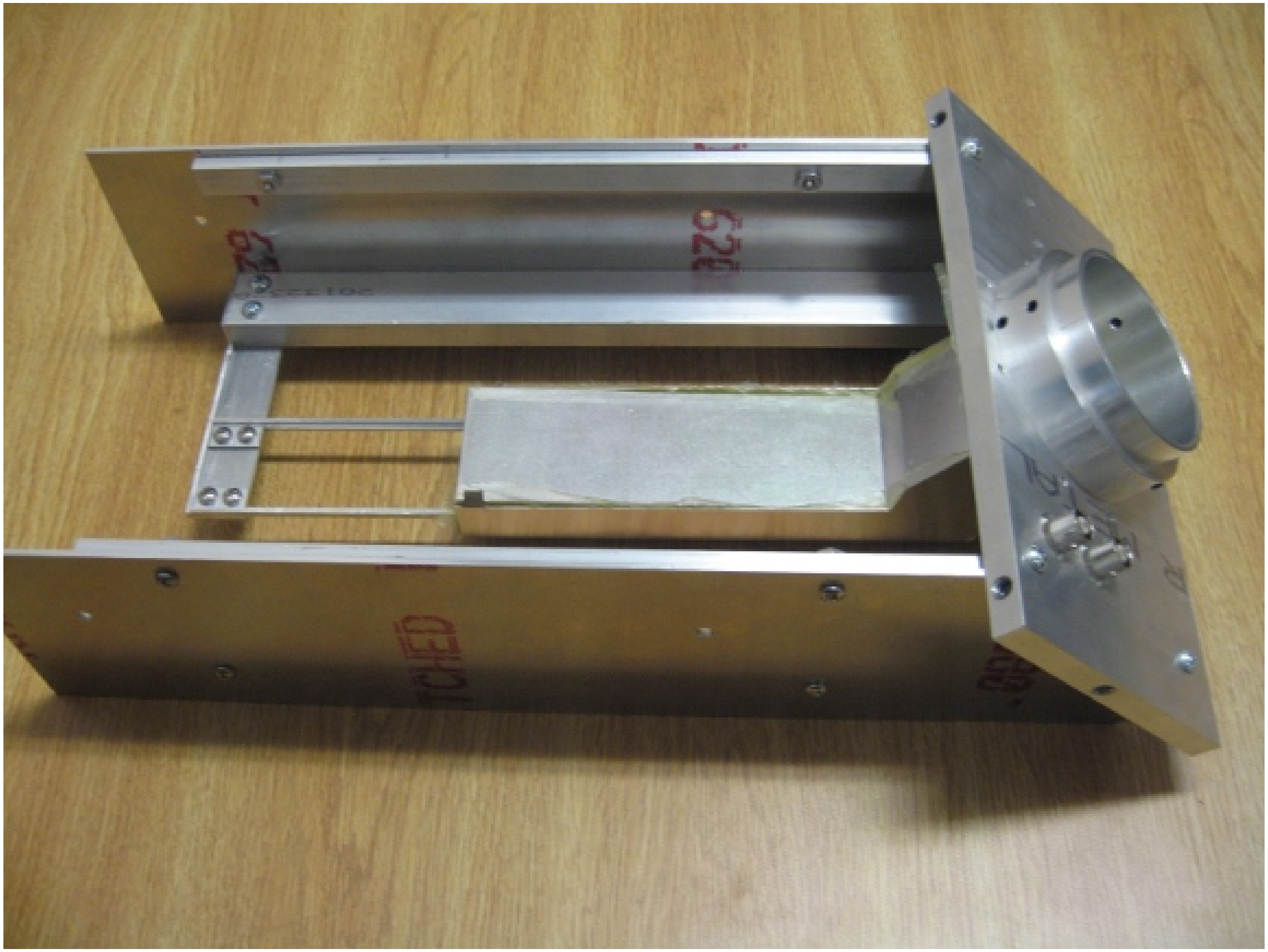


New Detector Prototype B (Mech. Drawings)

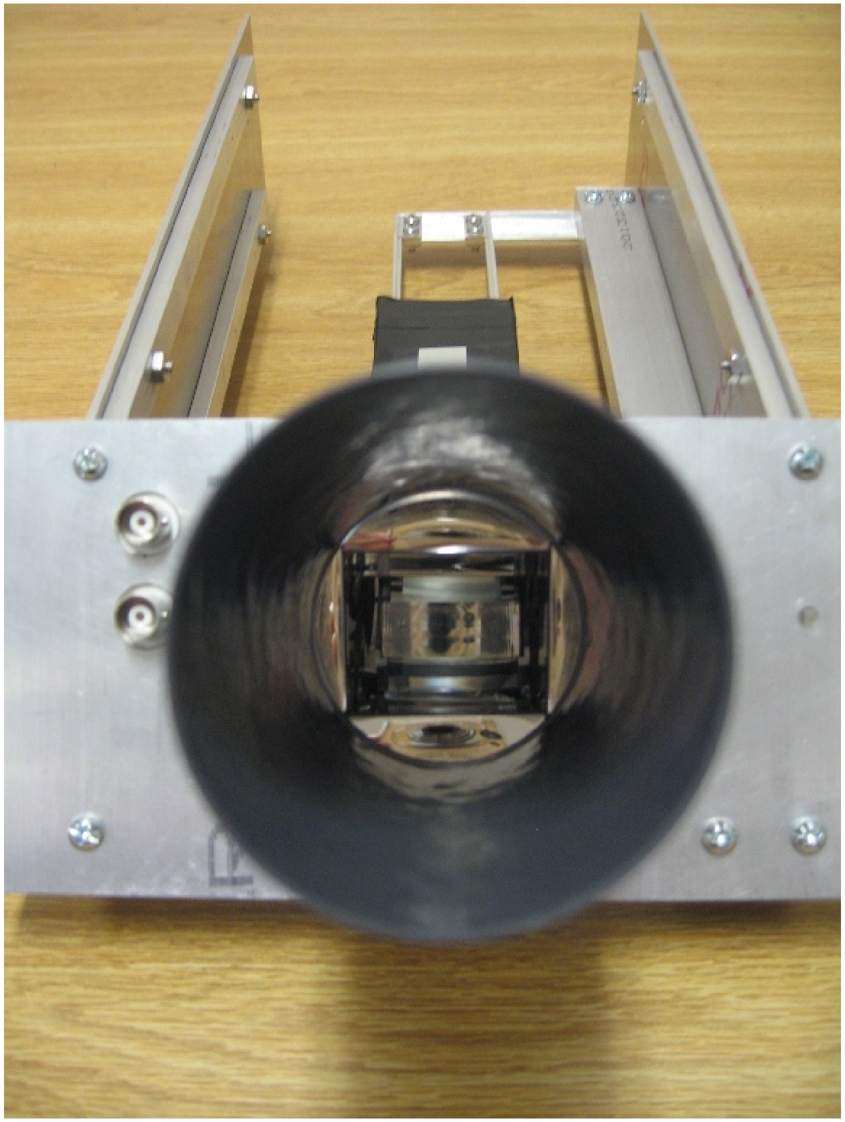


New Detector Prototype B: Parts Machined

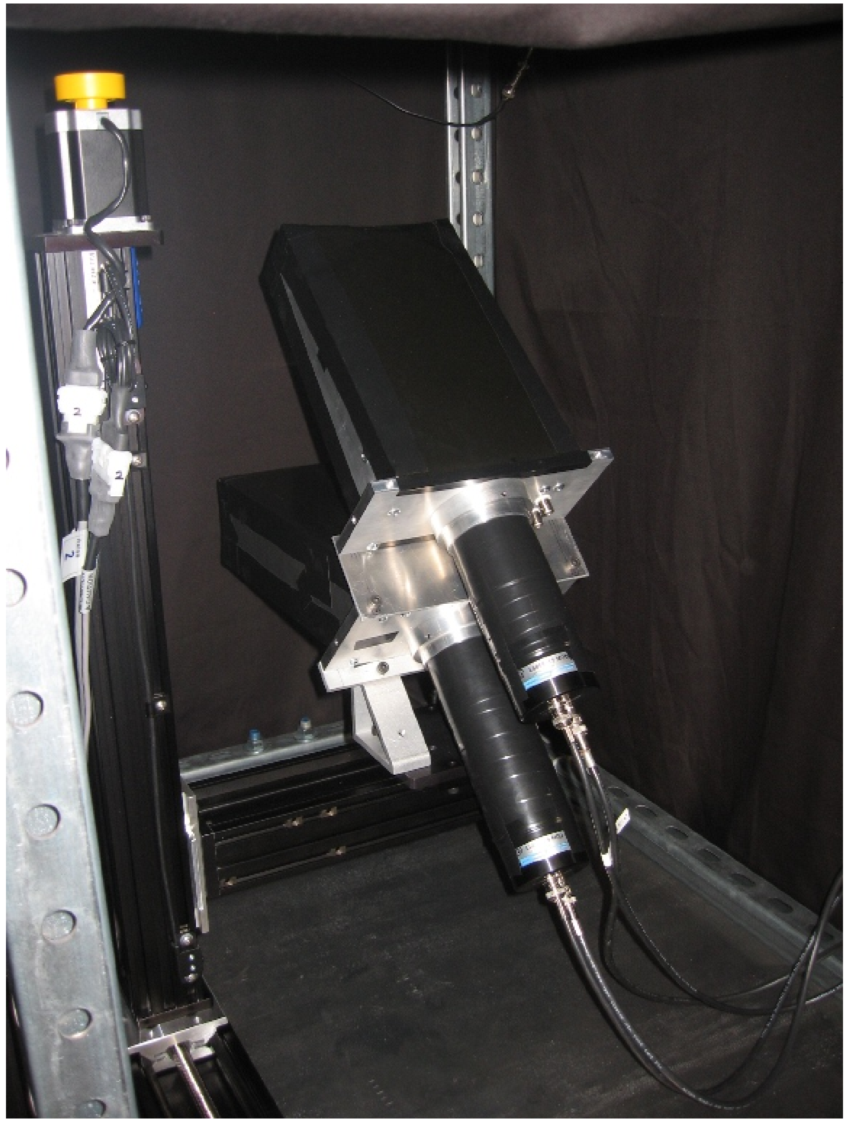
New Detector Prototype B: Constructed



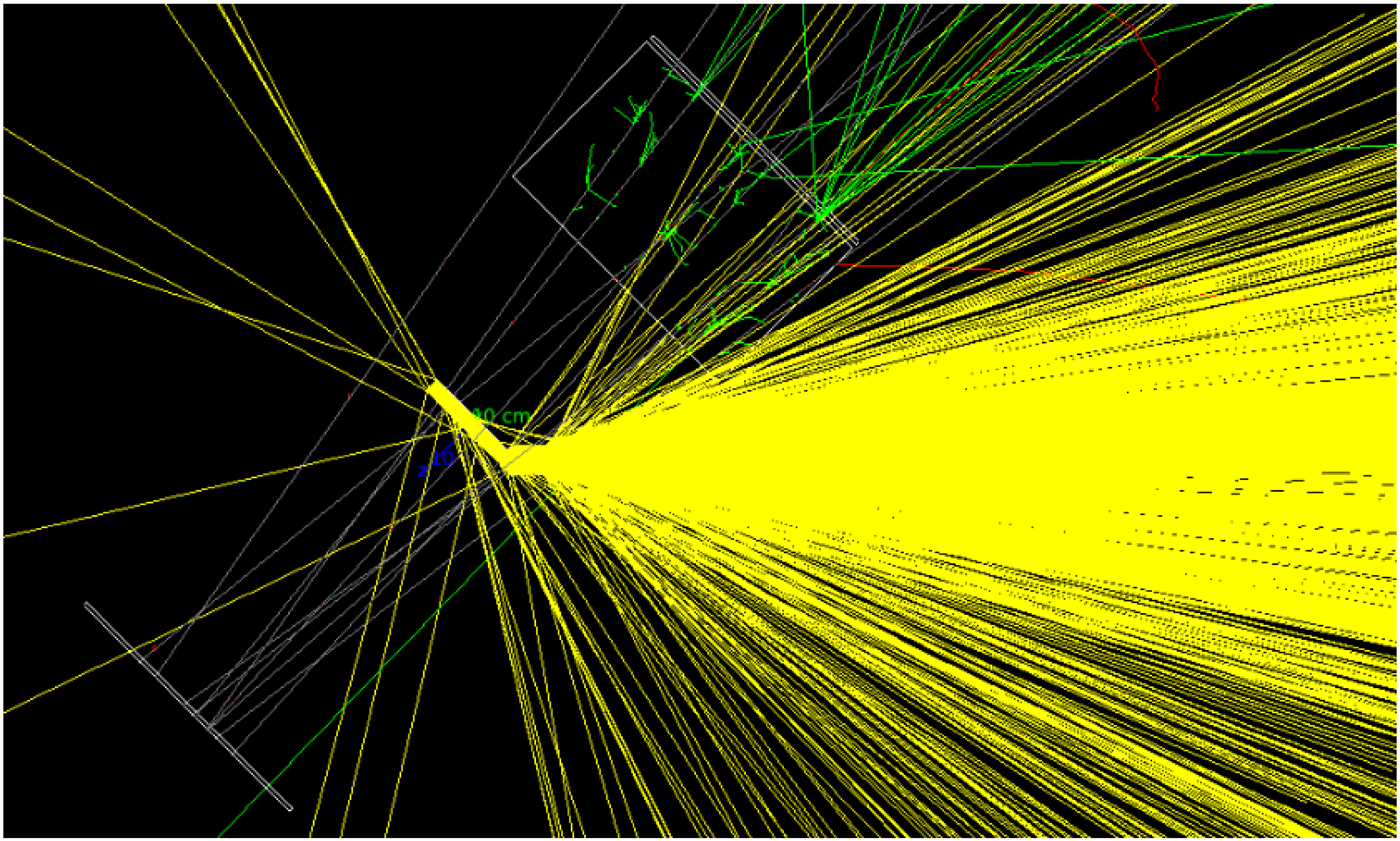
New Detector Prototype B: Constructed



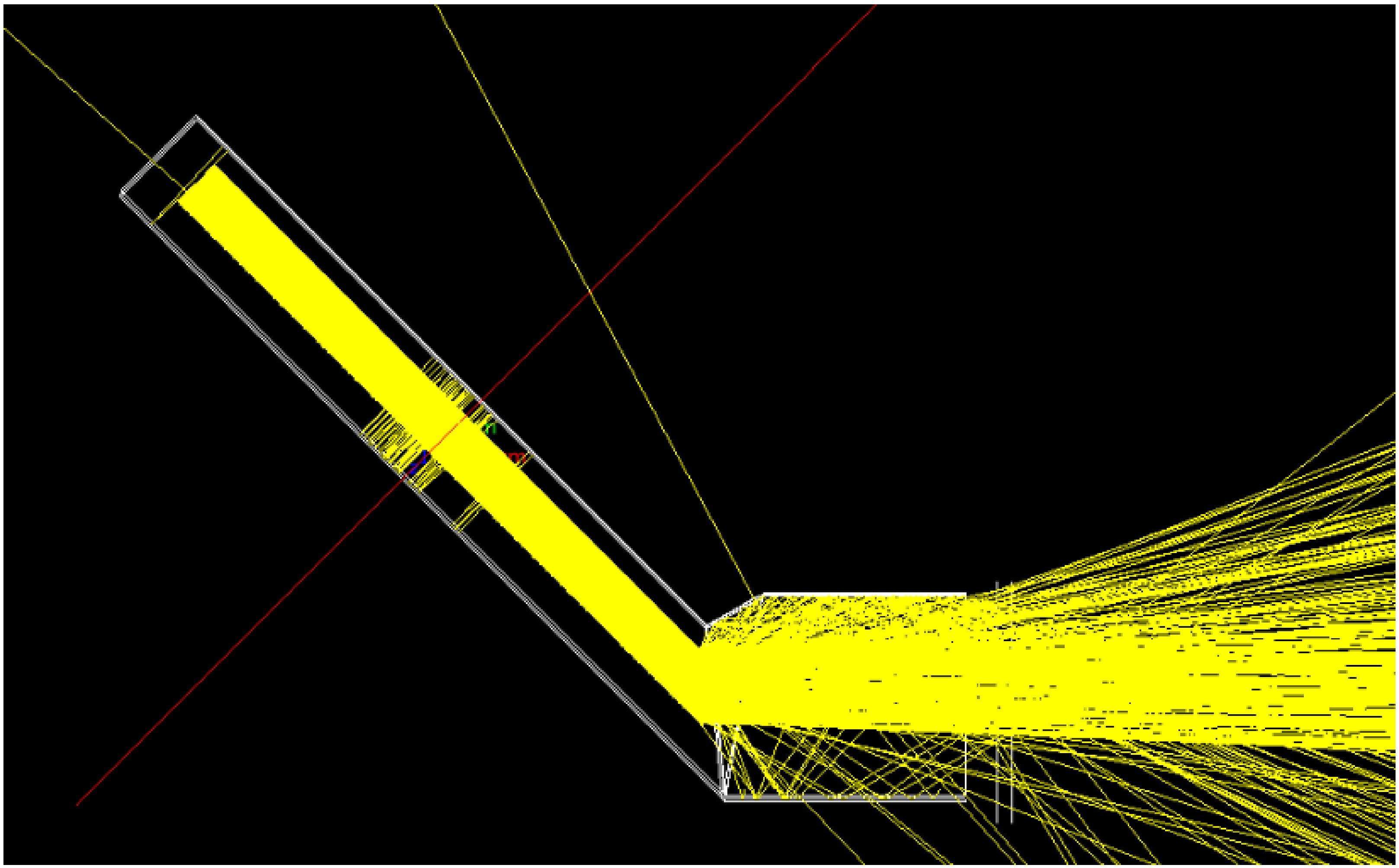
New Detector Prototype B: Cosmic Tests



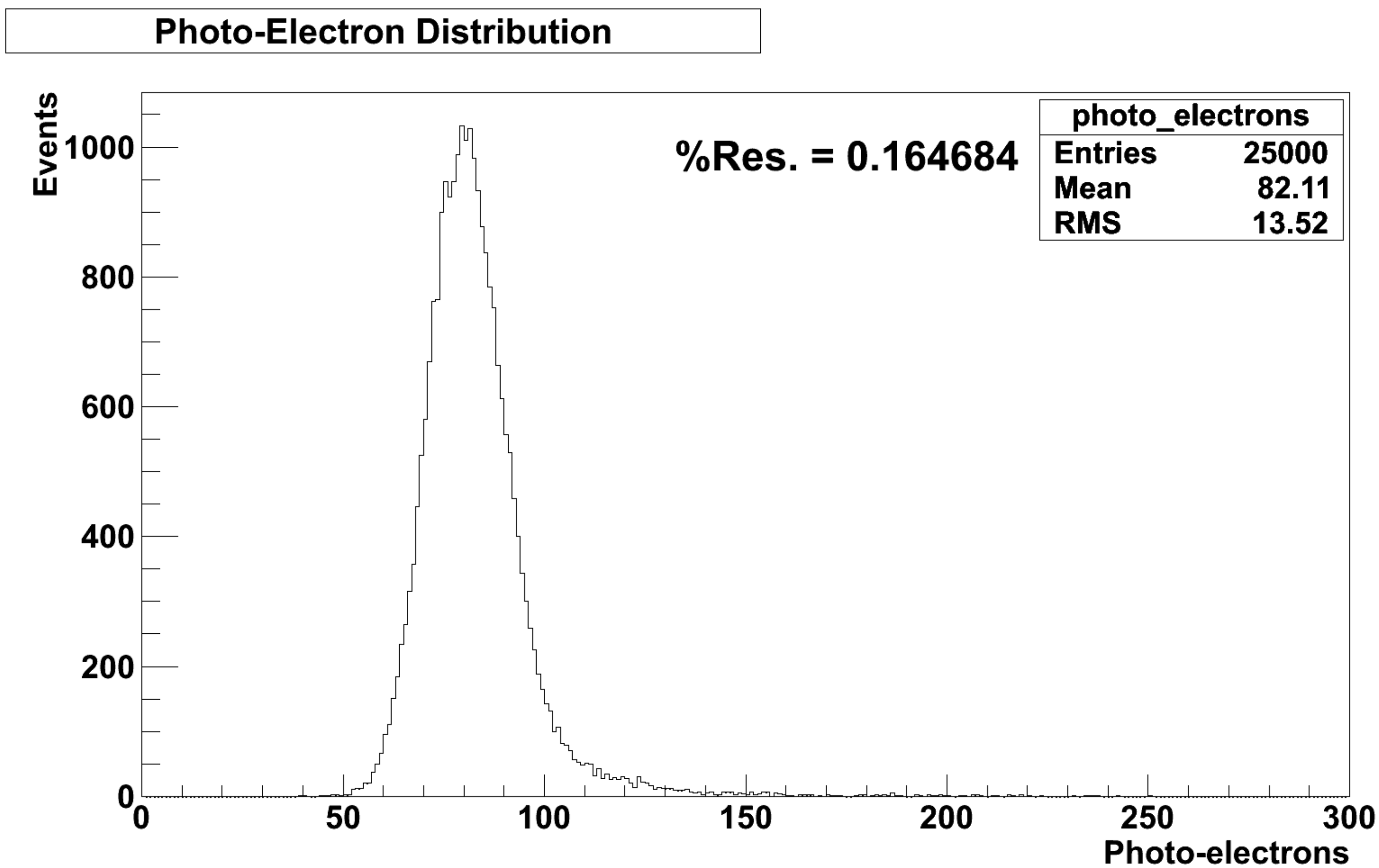
Prototype B: Cosmic simulations



Prototype B: e$^-$ Beam simulations



Prototype B: e^- Beam simulations



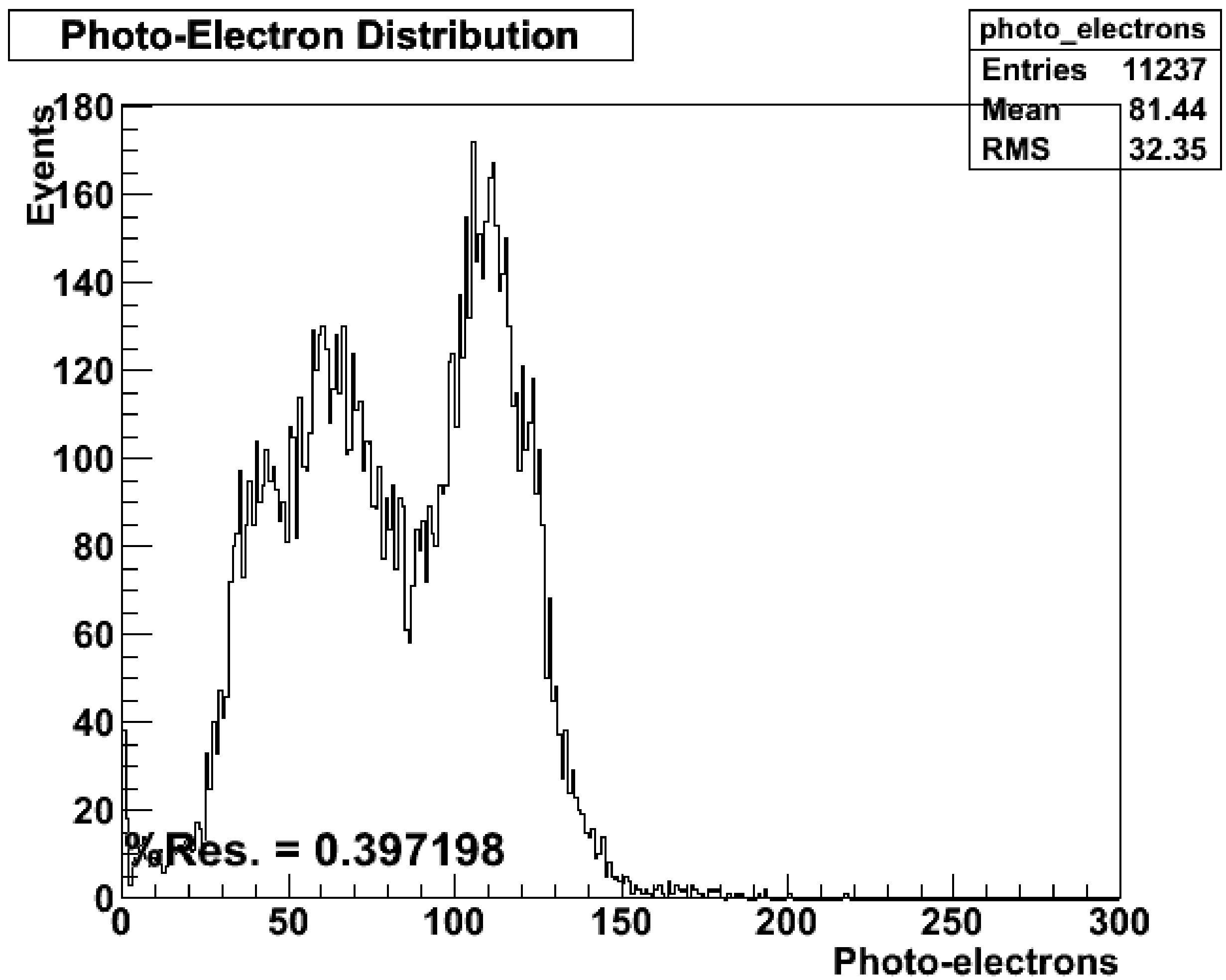
R&D Summary and Plans

- Continued cosmic ray testing of baseline prototype
- Continued refinement and studies of GEANT simulations by Carlos Bula
- New prototype design completed by Brady Lowe
- New prototype constructed and ready for cosmic testing
- Work started on shower-max quartz detector for MOLLER: Carlos – simulation, Kevin Rhine – light guide and support structure designs
- Plans to test Prototype B using 850MeV e^- beam at MAMI May/June 2015

More info can be found at http://www.isu.edu/~mcnudust

Extra Slides

Prototype B: Cosmic PE Distribution



Prototype B: Cosmic simulations PE vs. θ