A Novel Scintillator Detector for the Mu2e-II Experiment and a Muon Tomography Probe of the Interior of the Great Pyramid

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Frontier Physics Group
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Mu2e Experiment: Muon to Electron Conversion

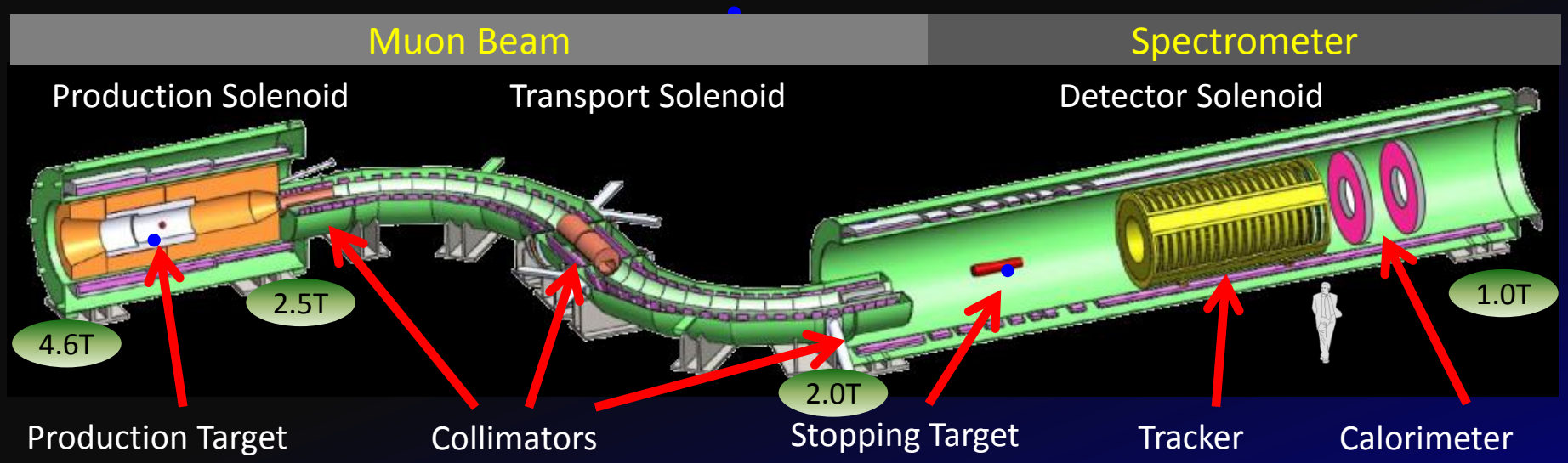
$$\mu^- N \rightarrow e^- N'$$

Probing new physics through lepton flavor violation with a search for muon-to-electron conversion: signal an isolated 105 MeV electron appearing after beam flash

Goal is to improve present limits by a factor of ~1,000-10,000 in two running periods

A high intensity muon beam and novel spectrometer being fabricated

(See Kate Ciampa: DPF #317 for more details on Mu2e)



$$p + tgt \rightarrow \pi's + X$$
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

~30,000 μ^- stop every 1.7 μs

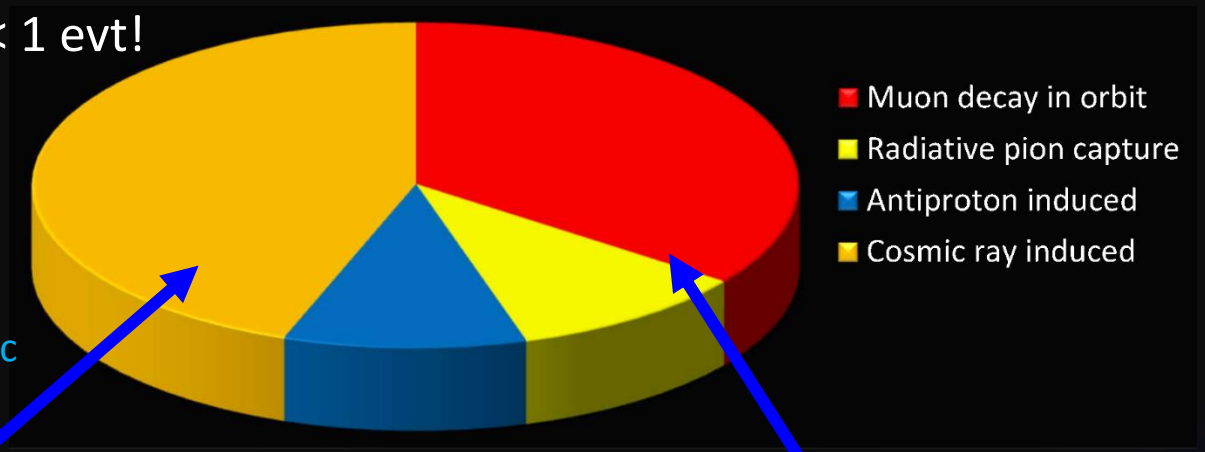
17 billion μ^- stops/spill-second

Keeping Backgrounds in Check is Name of the Game

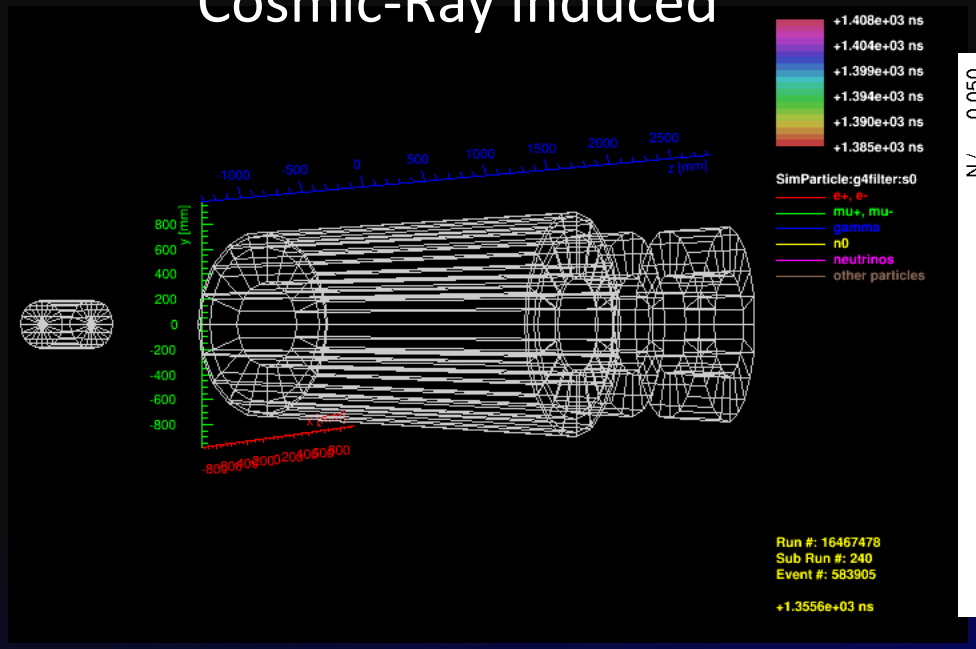
Need to keep backgrounds to < 1 evt!

Two biggest backgrounds are Muon decay-in-orbit and cosmic-ray induced electrons

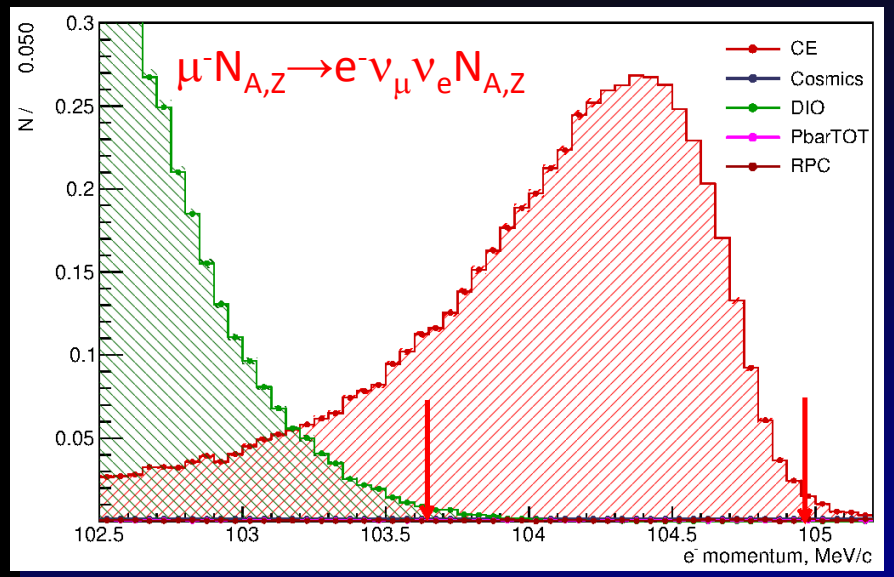
(See Yuri Oksuzian, DPF #354 on cosmic ray backgrounds)



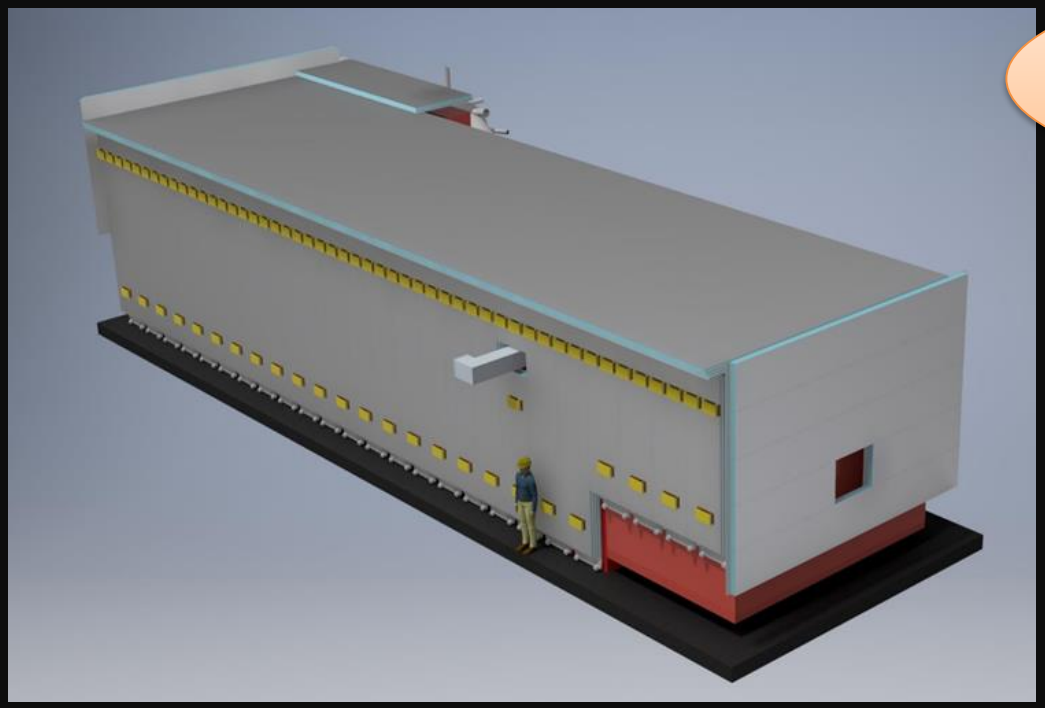
Cosmic-Ray Induced



Muon Decay in Orbit



Cosmic Ray Veto (CRV) Surrounds Spectrometer



1 conversion-like electron per day is produced by cosmic-ray muons

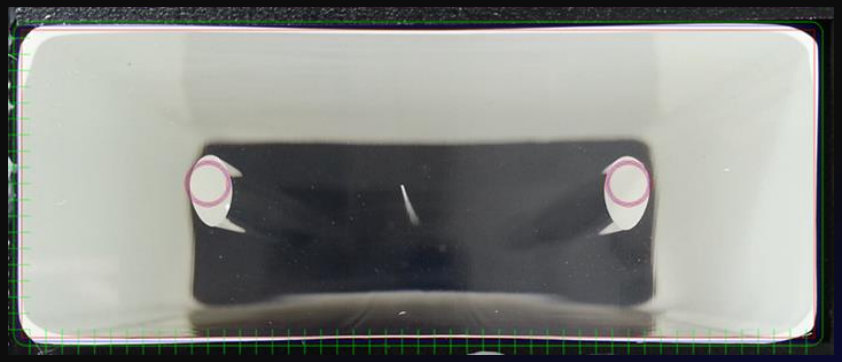
Details:

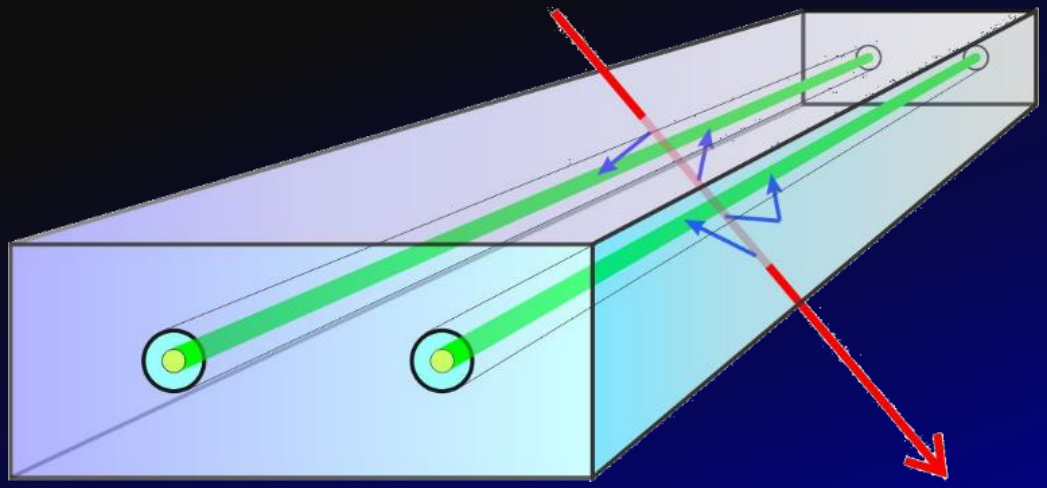
- Area: 335 m^2
- 83 modules 10 types
- 5,344 counters
- 10,688 fibers
- 19,392 SiPMs
- 4,848 Counter Motherboards
- 339 Front-end Boards
- 17 Readout Controllers

- CRV identifies cosmic ray muons that produce conversion-like backgrounds.
- Design driven by need for excellent efficiency, large area, small gaps, high neutron and gamma rates, access to electronics, and constrained space.
- Technology: Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers, read out with SiPM photodetectors.
- Track stub in 3/4 layers, localized in time/space produces a veto in offline analysis.
- **Overall efficiency of 99.99% is needed to keep the background to less than 1 evt**

Mechanical Design: Counter

- Fundamental element of the CRV is the rectangular counter: 51 x 20 mm^2 (5,344 total)
- Counters are extruded at the Fermilab NICADD facility
- Each counter has two 1.4/1.8 mm wavelength-shifting fibers placed in channels in extruded PS doped with 1% PPO + 0.05% POPOP and coated with with TiO_2
- All counters, except a handful where the radiation doses are too high, or if they are too short, are read out on both ends by silicon photomultipliers (SiPMs)
- Counters range from 1045 mm to 6900 mm long

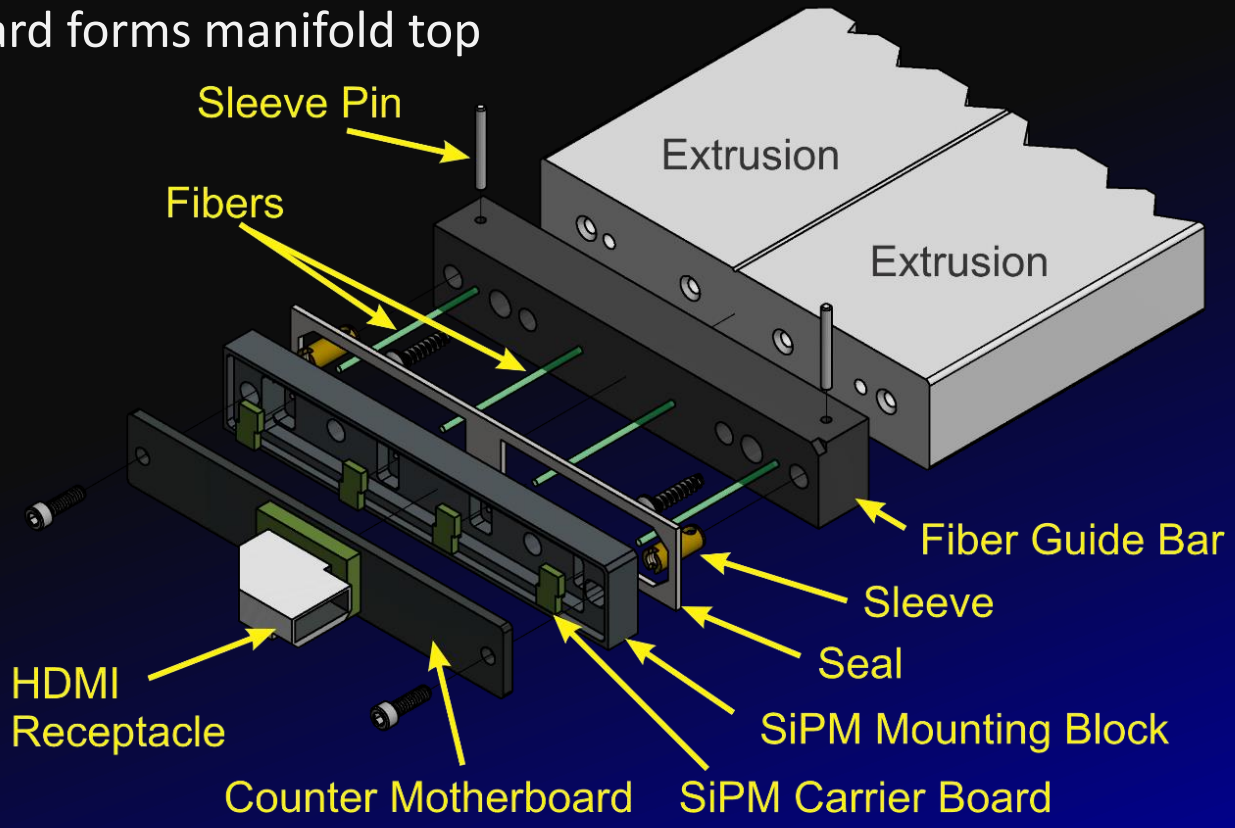




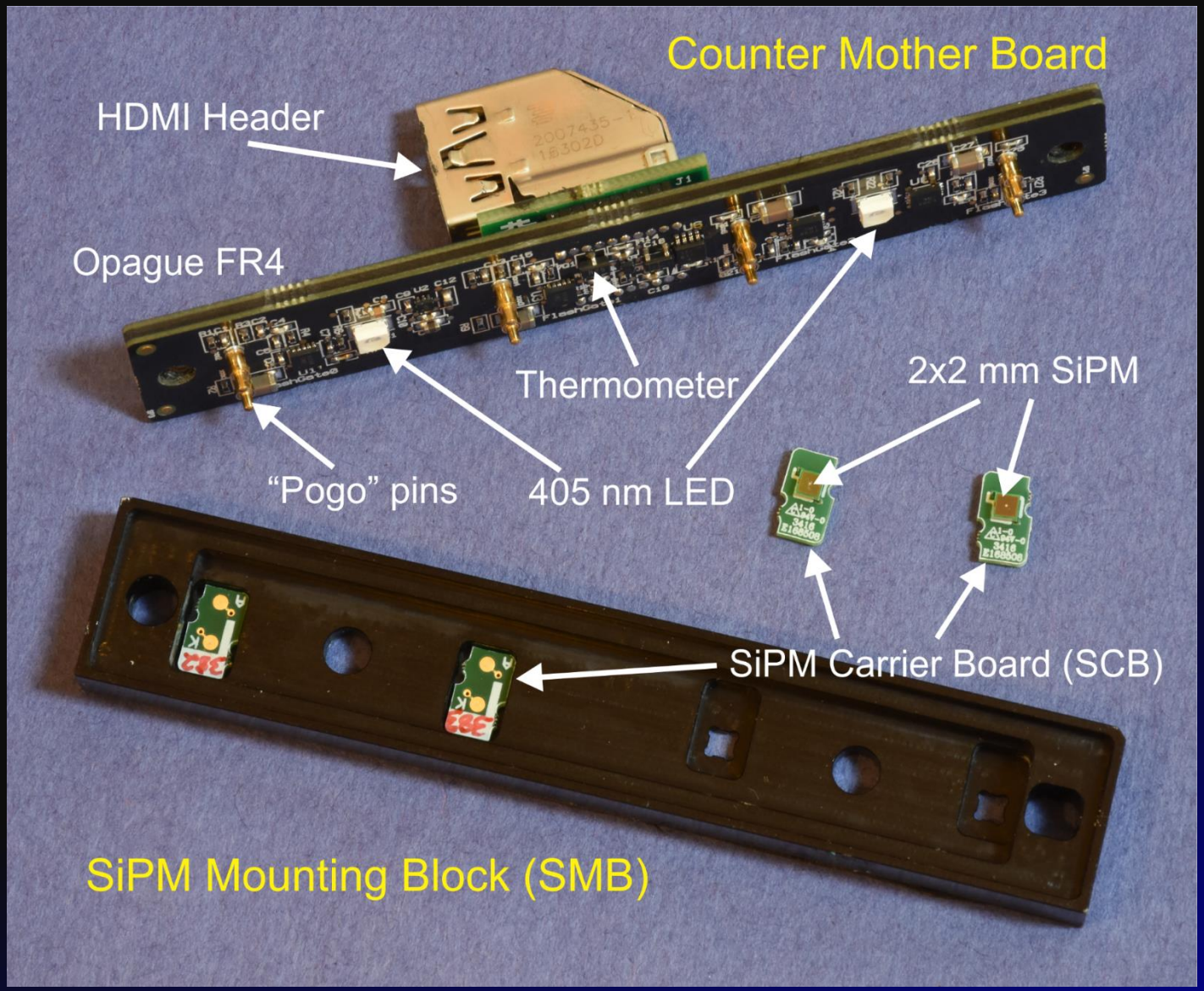
(See Sydney Roberts: DPF #37 on fiber testing)

Mechanical Design: Di-counter Manifold

- Counters grouped in pairs to form a di-counter
- Each di-counter end served by a single counter motherboard with 4 2x2 mm^2 SiPMs, 2 flasher LEDs, 1 thermometer
- Designed to minimize pressure damage to SiPMs, eliminate light leaks, facilitate SiPM-fiber registration, provide easy removal/installation, and have a low profile
- Opaque counter motherboard forms manifold top
- Pogopins connect counter motherboard and SiPM carrier boards
- SiPM temp not controlled, but bias adjusted based on temperature
- HDMI header can have vertical and horizontal orientation



Mechanical Design: Di-counter Manifold



Mechanical Design: Modules

- Fundamental mechanical element of the CRV
- 4 layers of counters with 3 layers of Al absorbers sandwiched between them: 16 counters (8 di-counters) /layer
- Layers are offset to avoid projective gaps between counters
- Total: 83; of 10 different types
- Mechanical tolerances very tight and critical as large gaps cannot be tolerated
- Weight: 179 kg - 1165 kg.
- Lengths ramge from
  1.0 m – 6.9 m

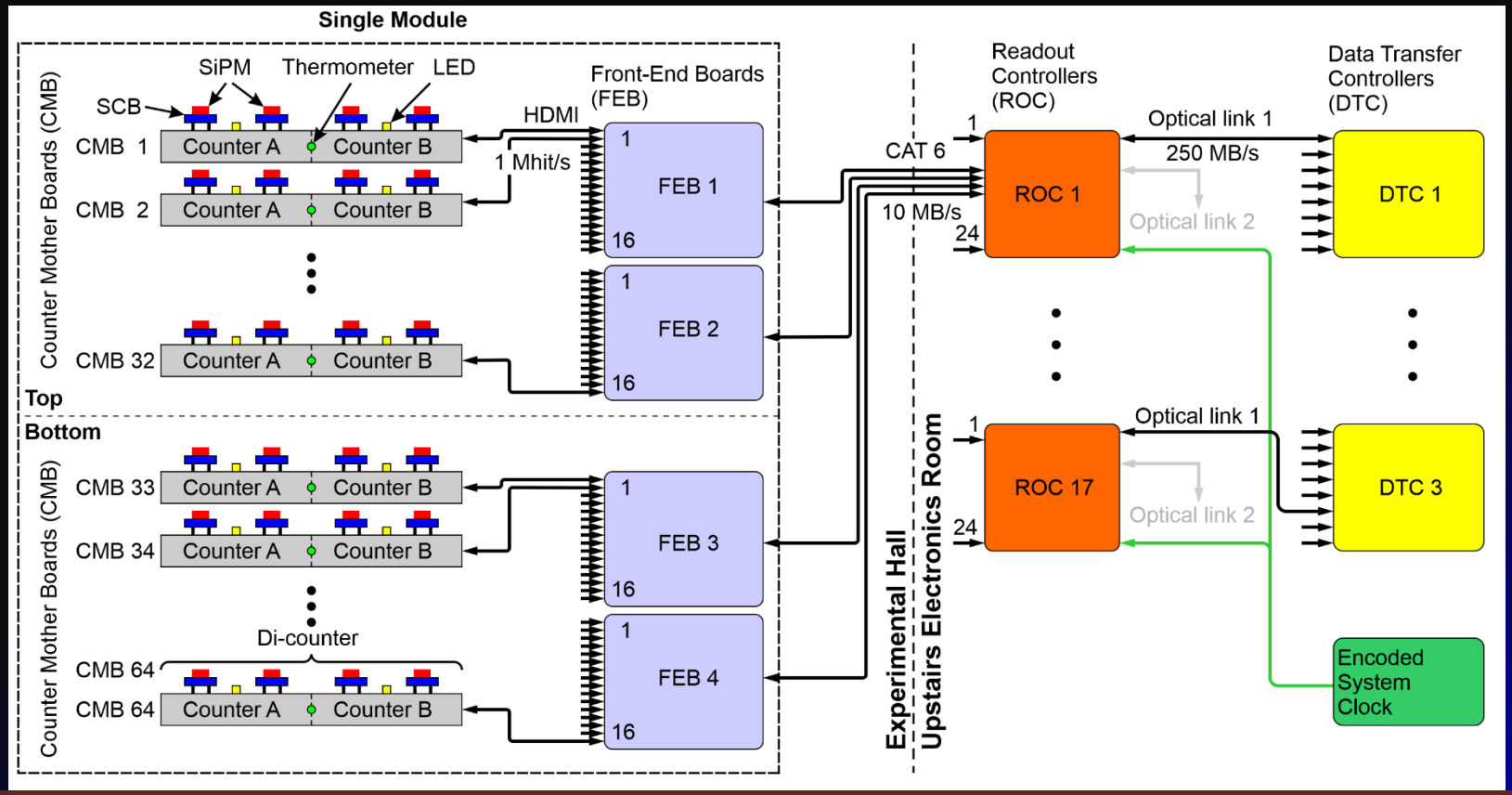
(See Craig Group, DPF #38 on CRV fabrication)

Electronics: Block Diagram

Four components: (1) Mounted SiPMs (SCB w SiPM: 19,392, $9.56 ea), (2) Counter Motherboards (CMB: 4848, $32.71 ea), (3) Front-end Boards (FEB: 339, $1750 ea), (4) Readout Controllers (ROC: 17, $2000 ea)

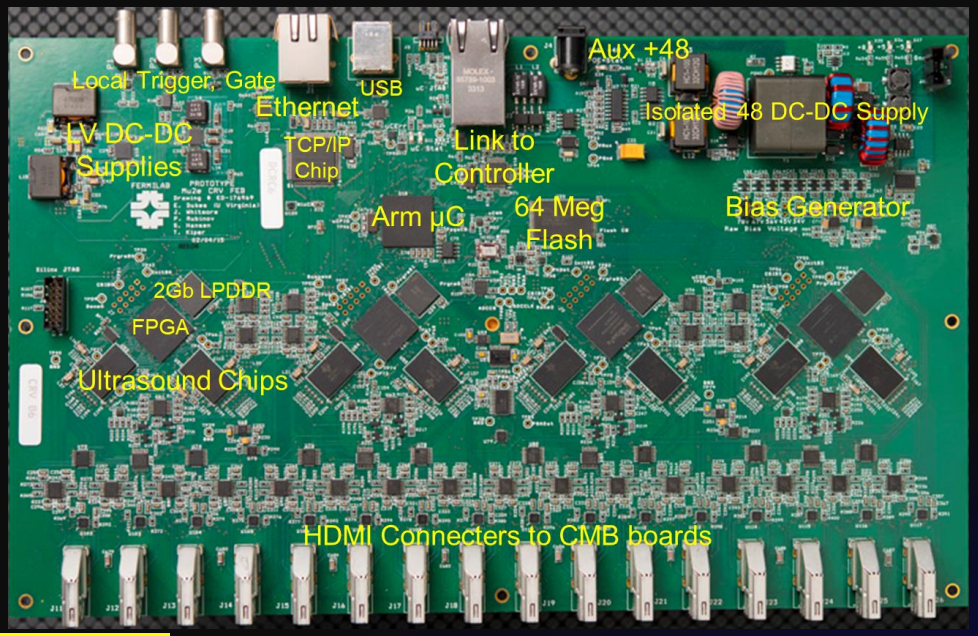
All commercial-off-the-shelf parts (80 MHz ultrasound octal amp/ADC)

Dynamic range:	2000
Max rate/SiPM:	1 MHz
Max rate FEB-ROC:	10 MB/s
Max rate ROC-DTC:	250 MB/s
Time resolution:	~ 2 ns
Magnetic field:	~ 0.1 T
Max dose:	10^{10} n/cm^2

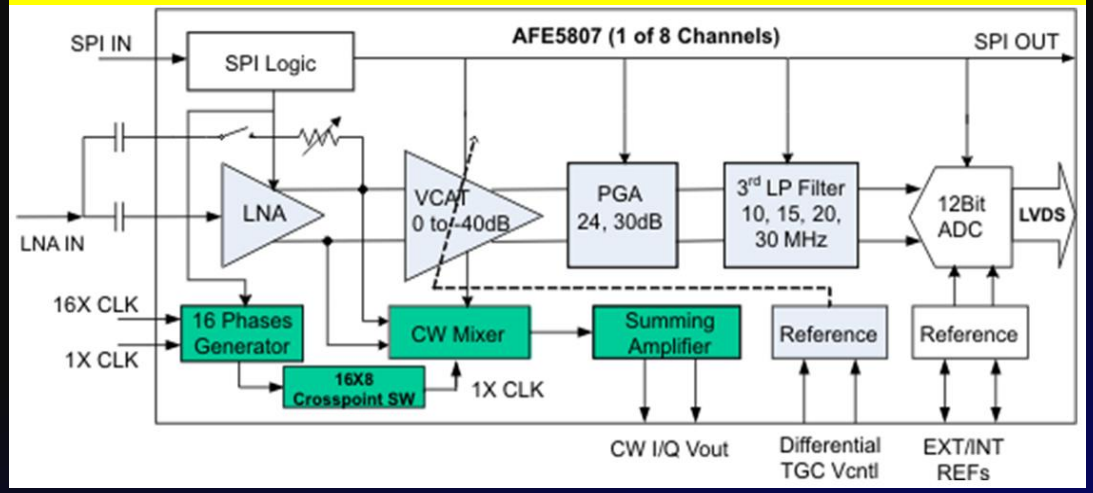


Front End Board: Amplifier, Digitizer, Shaper

- Amplifies, shapes, digitizes in amplitude and time, zero-suppresses, and buffers signals
- Serves 64 SiPMs
- Takes SiPM signals from 16 CMBs over HDMI cables
- Individual bias for all 64 SiPMs
- Read out (& powered) locally or through a readout controller



The core of the readout is a commercial ultrasound chip

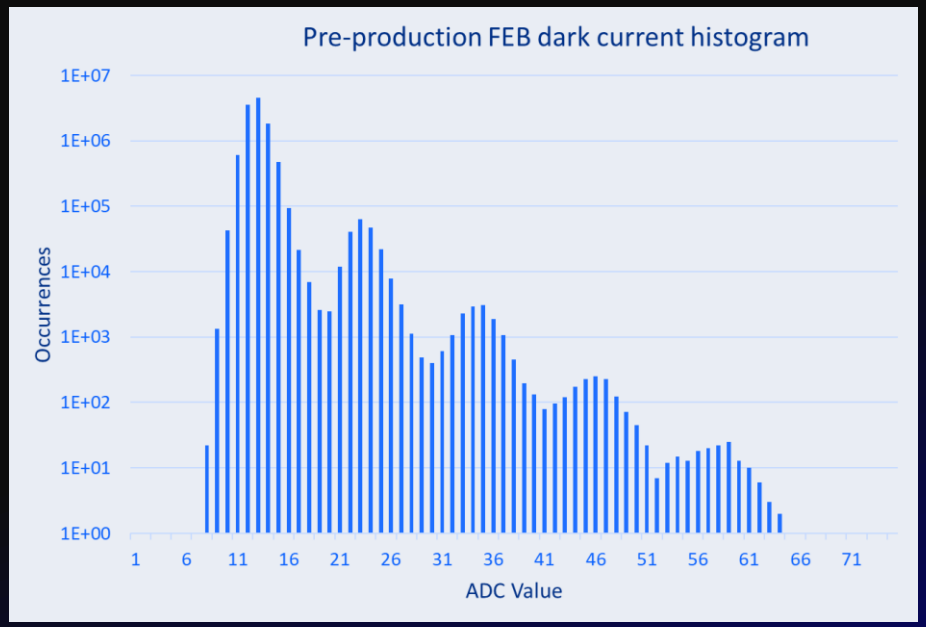


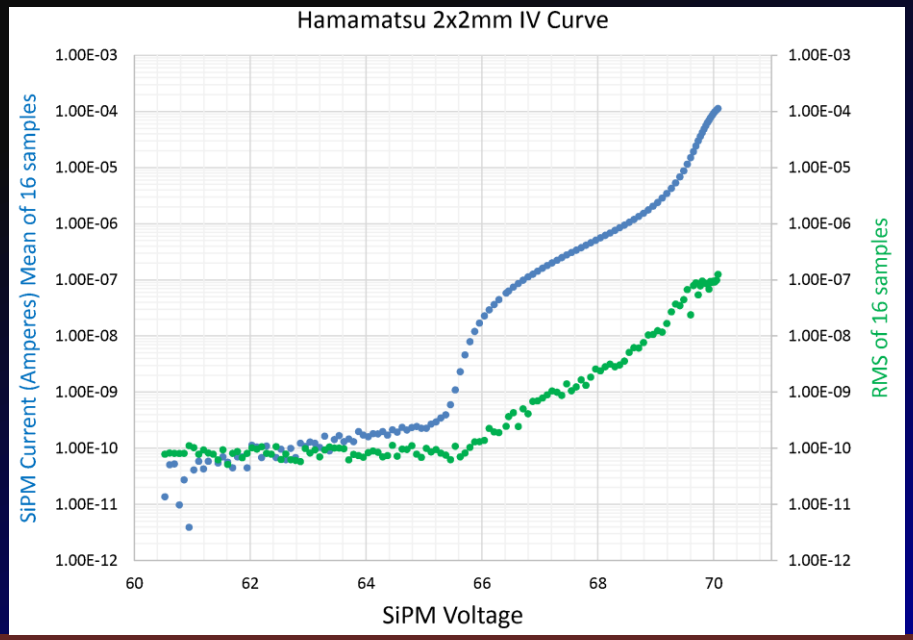
TI Ultrasound chip (AFE5807):

- 8 channels low noise preamp, programmable gain amp
- 80msps 12 bit ADC
- $7 per channel
- 120mW per channel.

Electronics: Features

- All COTs parts: system can be reproduced inexpensively by others
- PoE from ROC to FEB eliminates need for any power supplies (other than 110V wall power)
- Histogramming firmware in FPGA allows fast dark-noise spectra to be obtained within seconds to calibrate the PE spectrum
- In-situ IV curves can be taken (100 pA precision, 1 mA max) that rivals commercial test equipment

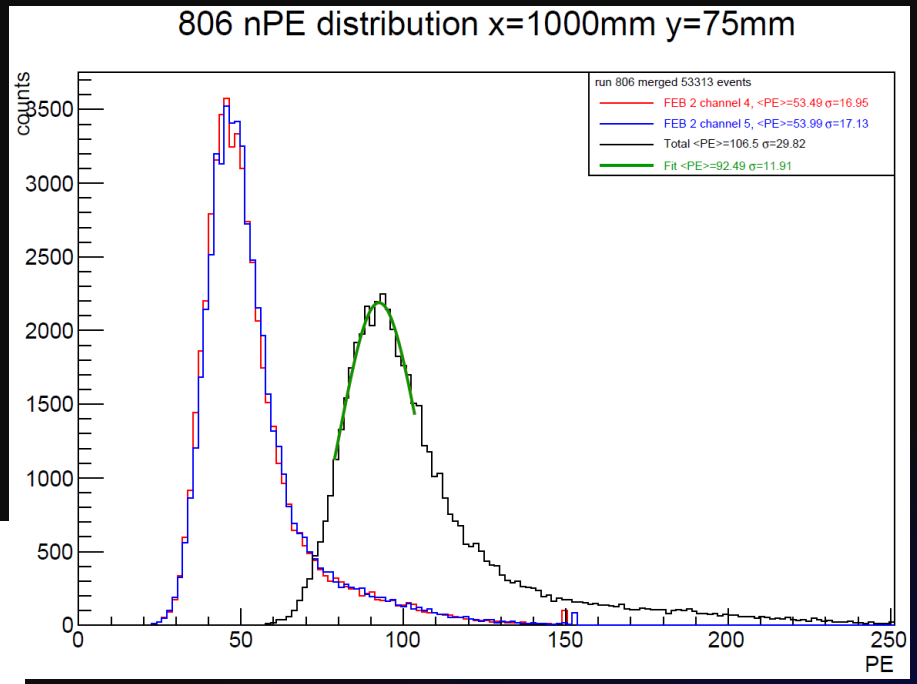


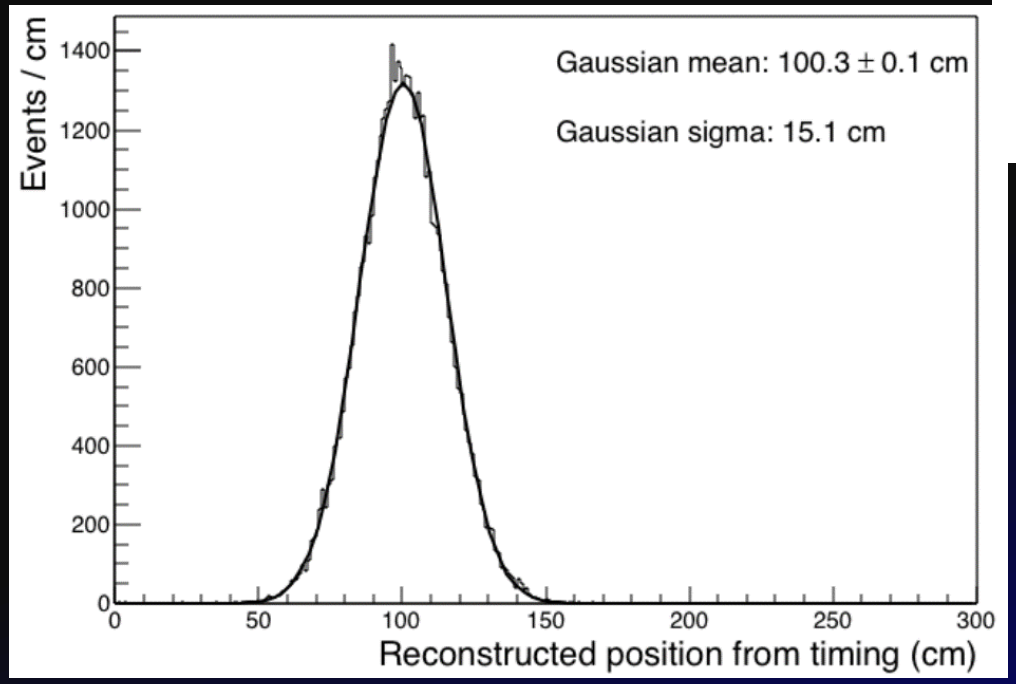


Performance

Light yield from 120 GeV protons normally incident 1 m from readout end

- ~53 PE/SiPM
- 1.4 mm fibers





Reconstructed position along counter using TOF from readout on both ends of a counter

- σ = 15 cm
- 1.4 mm fibers

Mu2e-II: Mu2e in the PIP-II Era

We wish to seize the opportunity provided by upgrades of the Fermilab accelerator complex being built for DUNE to increase the Mu2e sensitivity:

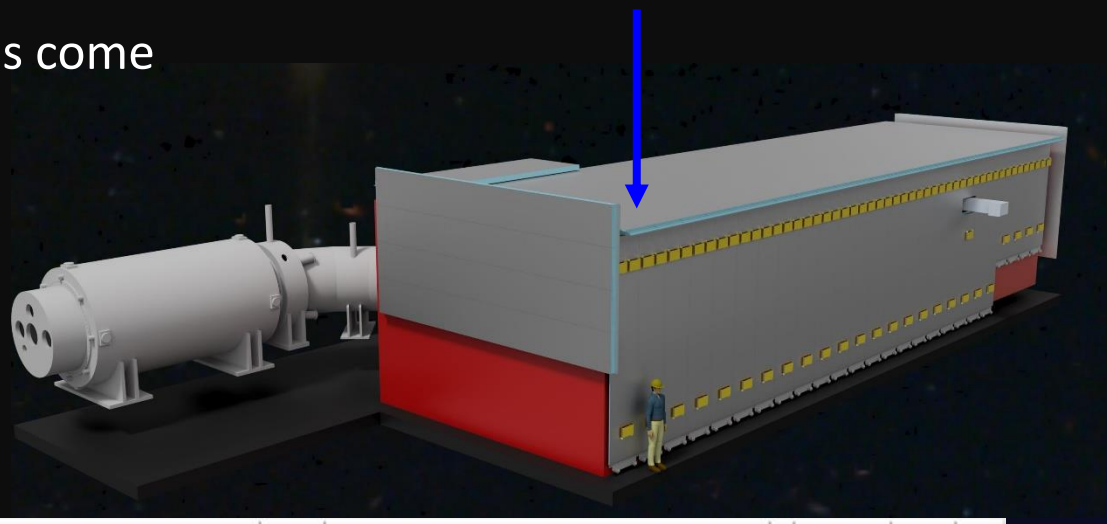
- Proton Improvement Plan II (PIP-II): Present Booster proton beam replaced by Superconducting Linac
- Allows an order of magnitude increase in sensitivity over Mu2e
  - ~3X in muon beam stops
  - ~3X in running time (through a better duty factor): Note cosmic-ray background scales with time!

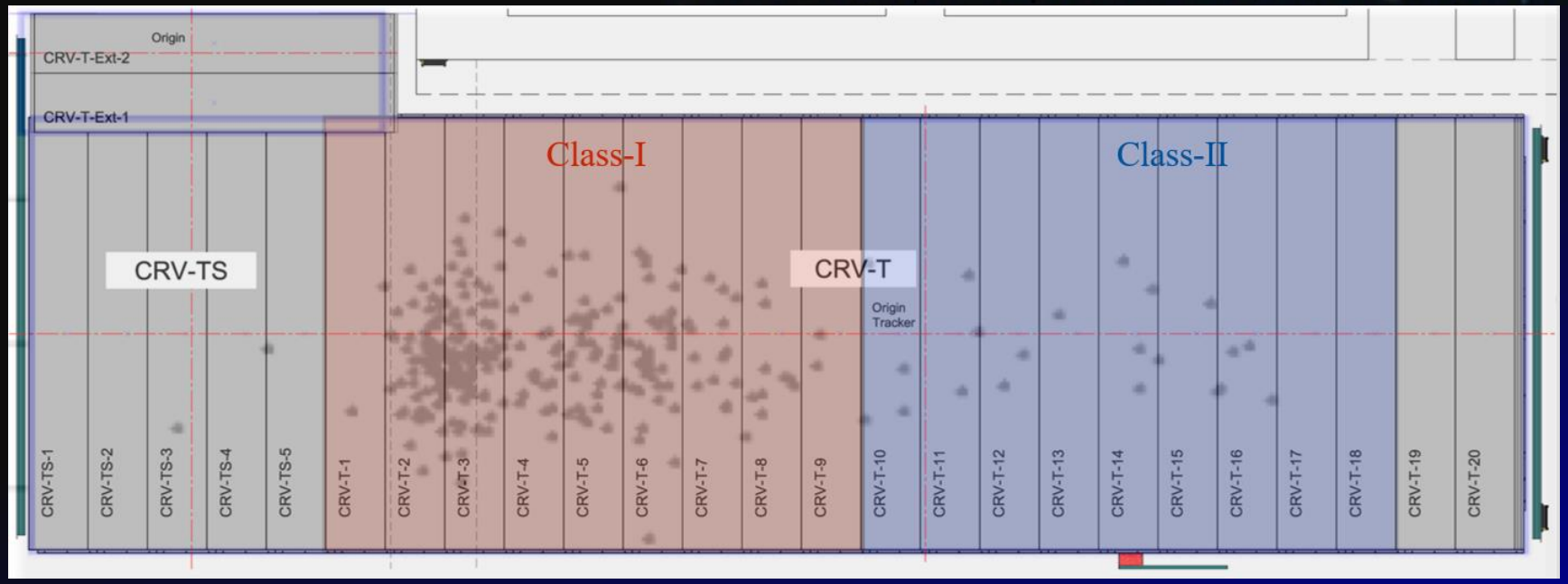
Need to improve the CRV efficiency: cosmic-ray induced background 3X larger

CRV needs to handle 3X higher instantaneous rates

Sources of non-Vetoed Cosmic Ray Muons

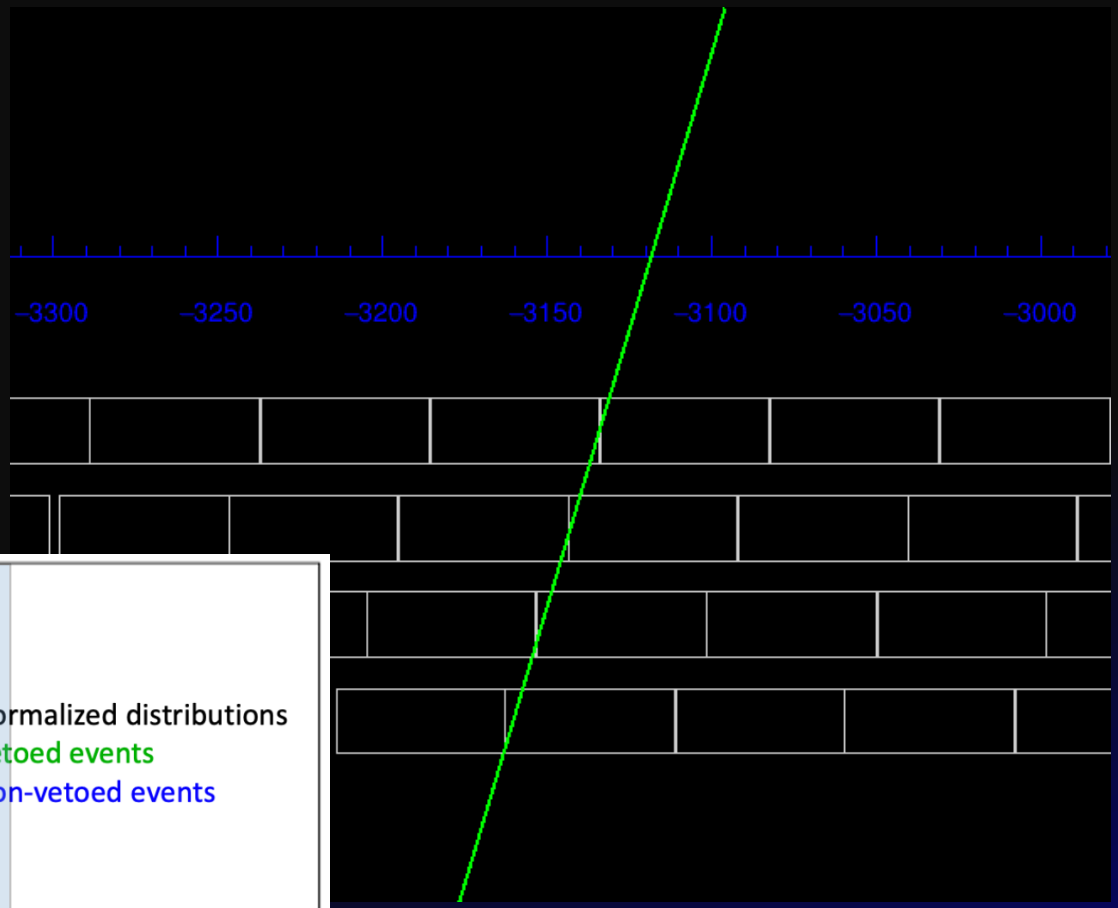
Most background producing muons come through top of CRV

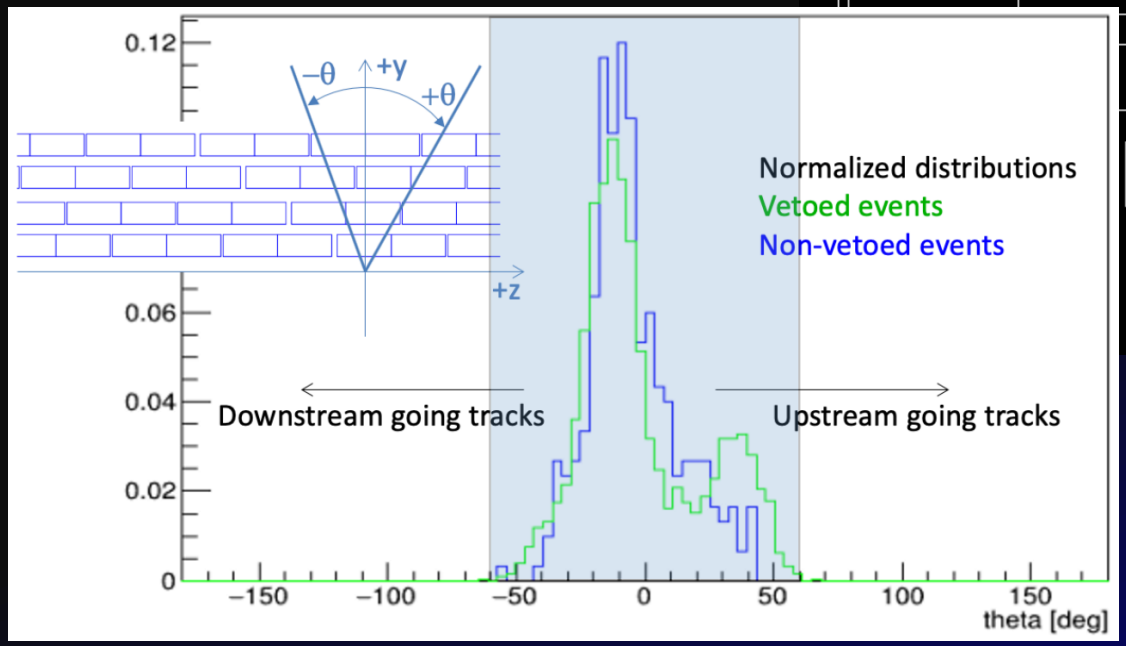




Sources of non-Vetoed Cosmic Ray Muons

Most come at nearly vertical angles, and can traverse gaps between counters and not be vetoed



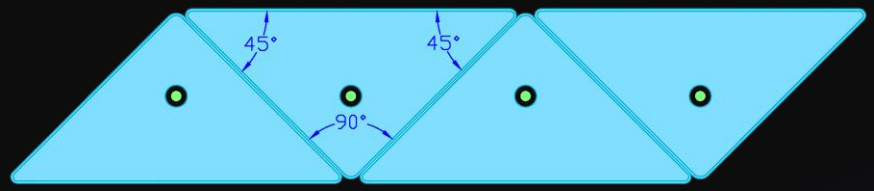


Continues on hitting material in the spectrometer, producing a 105 MeV electron

Improving the Cosmic Ray Veto Design

Replace the critical top modules with modules using triangular-based extrusions

Mu2e “di-counter”



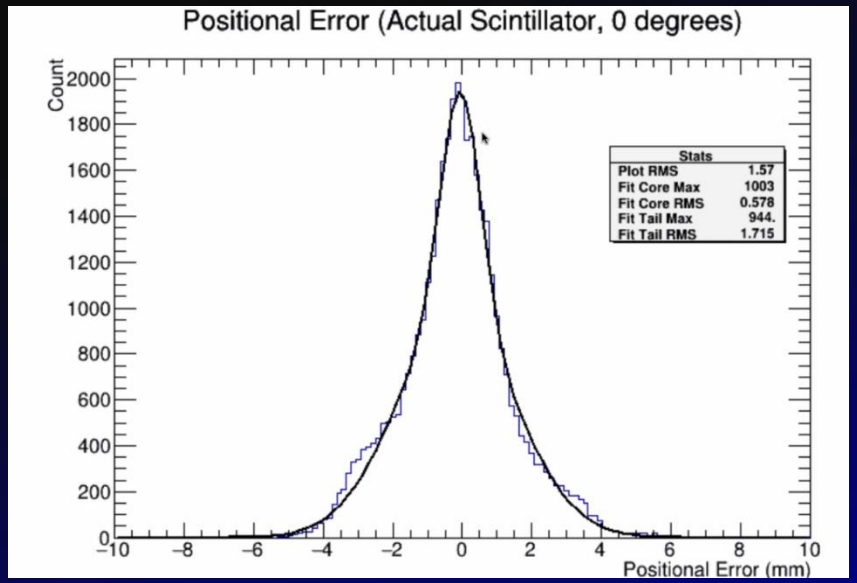
Mu2e-II “quad-counter”

(See Mohit Srivastav: DPF #322 on track-stub finding using machine learning)

Minimize gap problem by using triangular extrusions

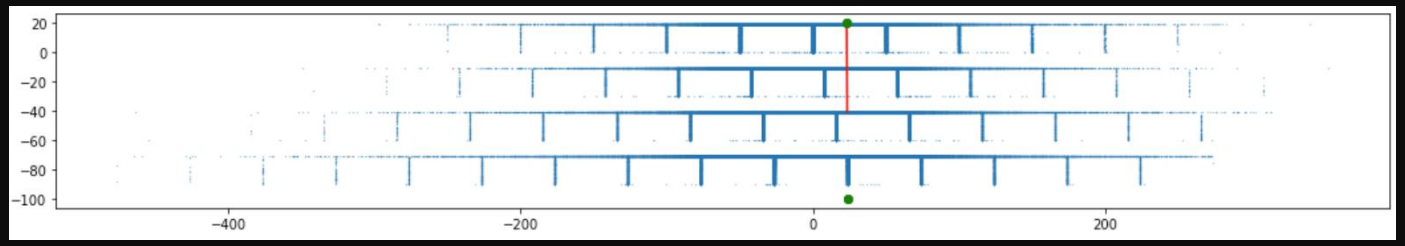
Smaller size reduces singles rates, which are extremely high

Better resolution (σ~1.5 mm) reduces fake track-stub coincidences, and hence deadtime



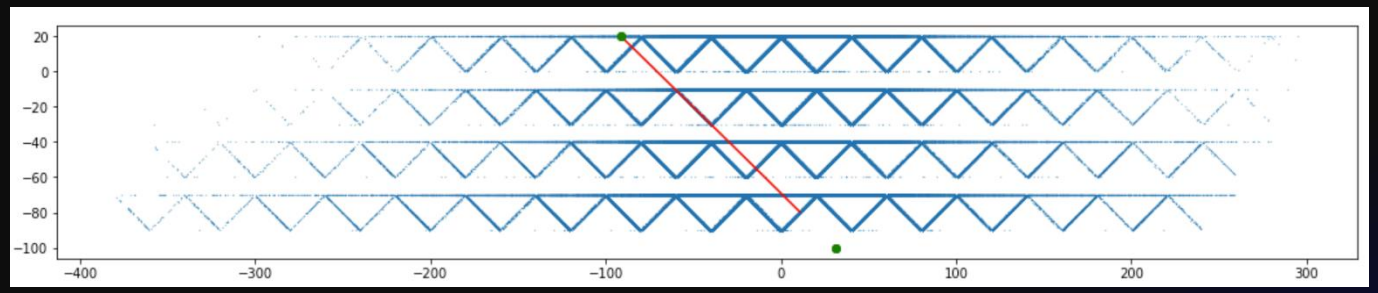
Simulated position resolution

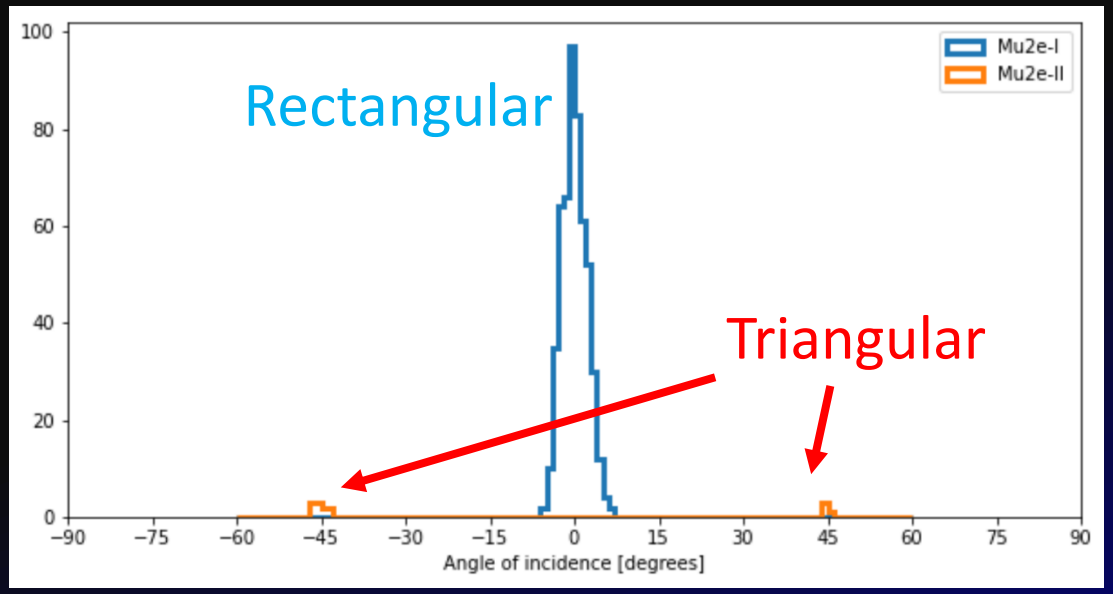
Simulated Response to Cosmic Ray Muons



Mu2e rectangular

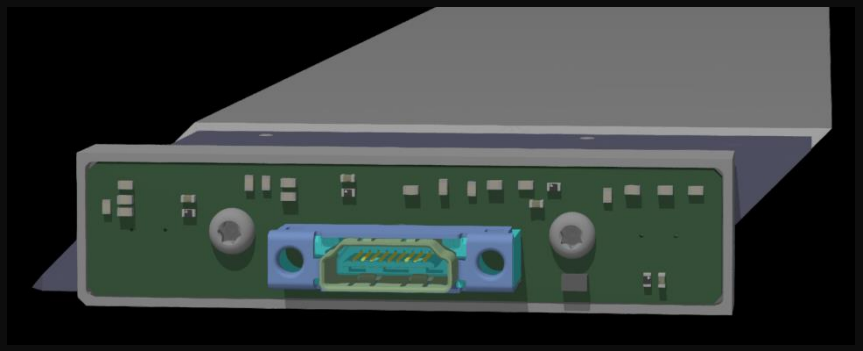
Mu2e-II triangular





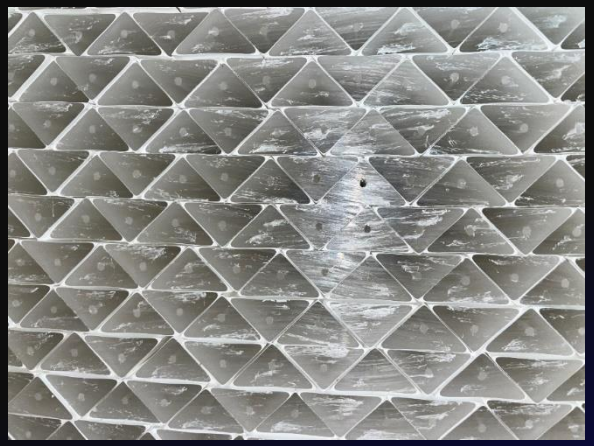
Rectangular counters have highest inefficiency at 0°
Triangular counters at $\pm 45^o$

Prototype Detector Fabrication Underway

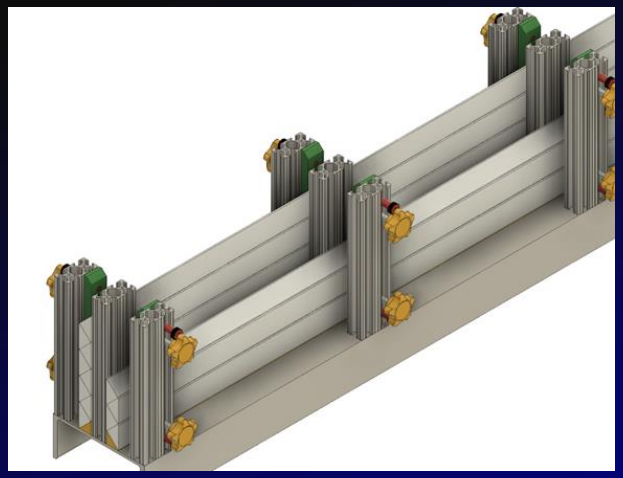


Quad-counter manifold end showing counter motherboard

- Quad-counter design completed
- Extrusions fabricated
- Manifold parts ordered
- Counter motherboard design completed; prototypes in hand
- Fabrication jig design completed
- Prototype detector to be fabricated and tested in fall



Triangular extrusions fabricated at Fermilab NICADD facility

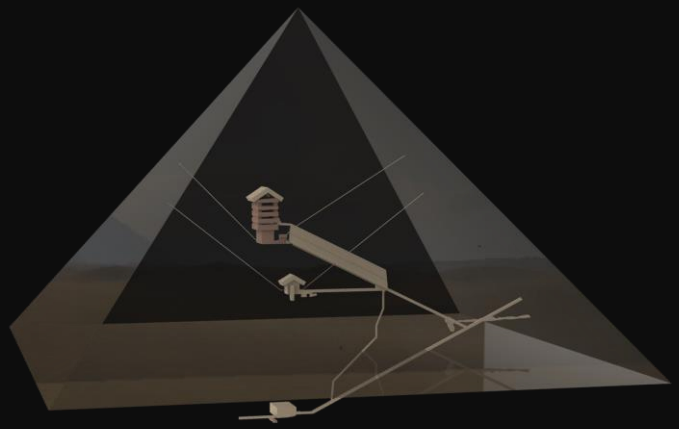


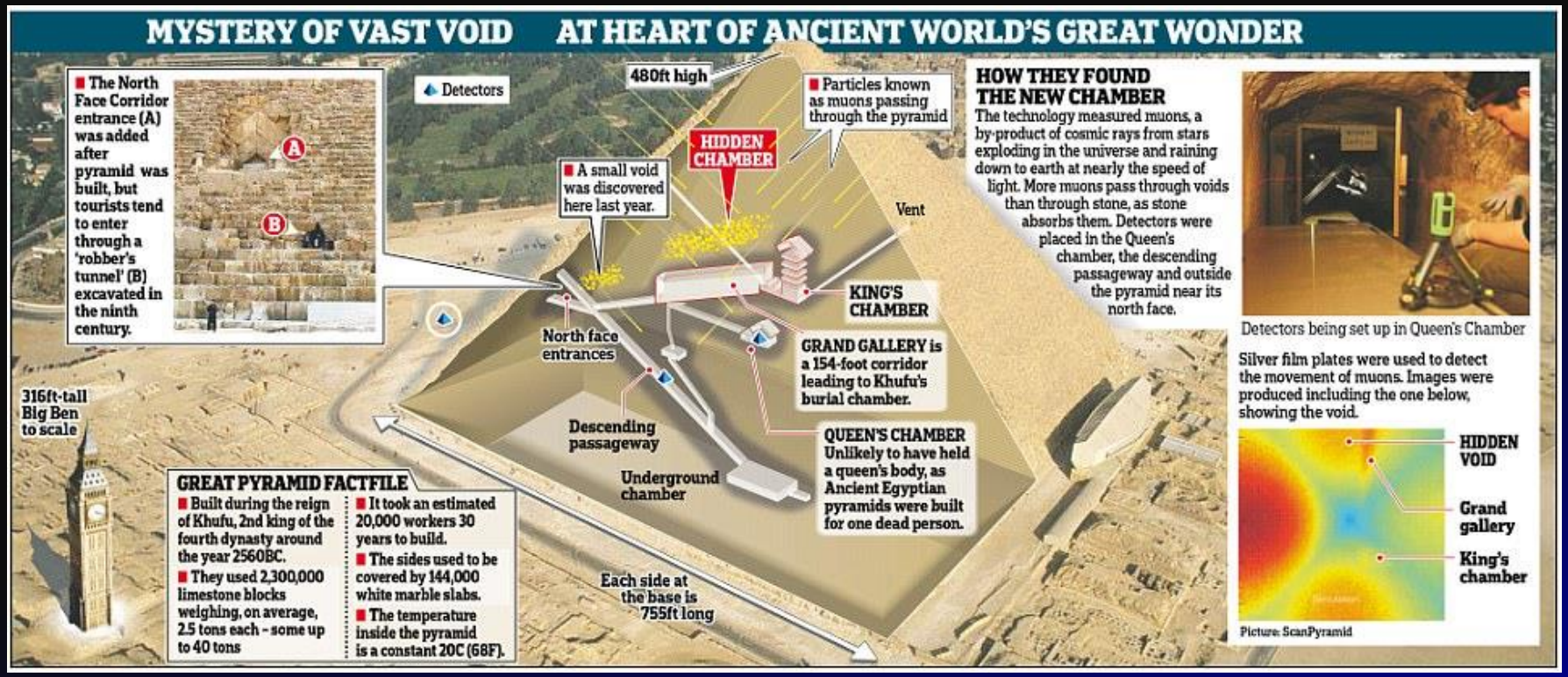
Vertical assembly jig design

Exploring the Great Pyramid (EGP)

2017
"Scientists Discover a Void Inside Giza's Great Pyramid"

The New York Times





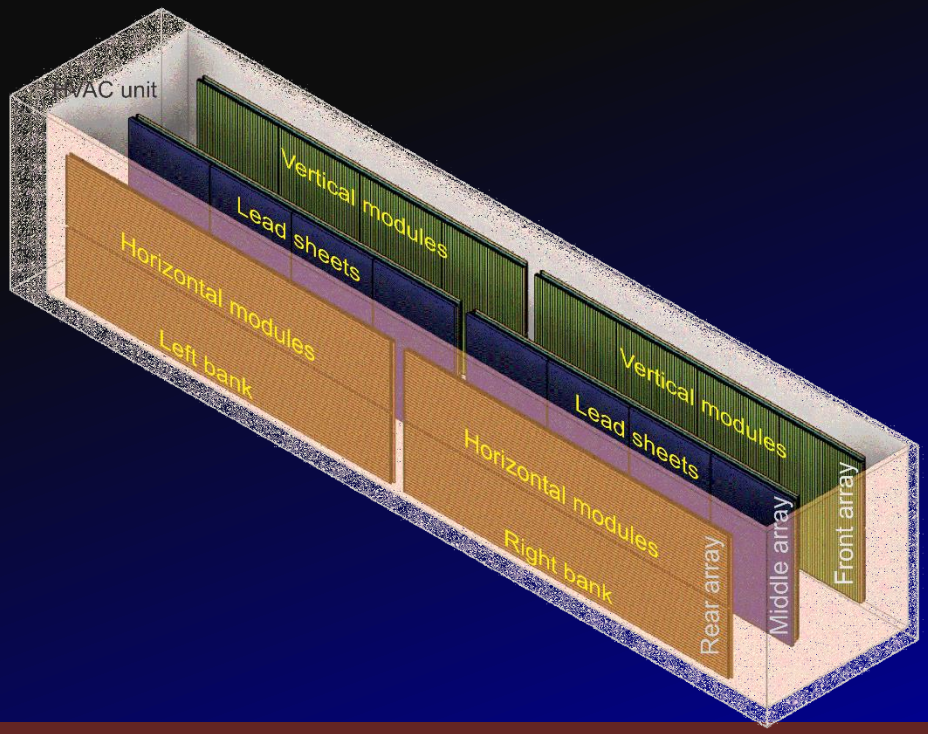
Exploring the Great Pyramid

Use the Mu2e-II CRV quad-counter design to fabricate an inexpensive detector to detect cosmic-ray muons coming through the pyramid

Detectors placed in shipping containers around the Great Pyramid

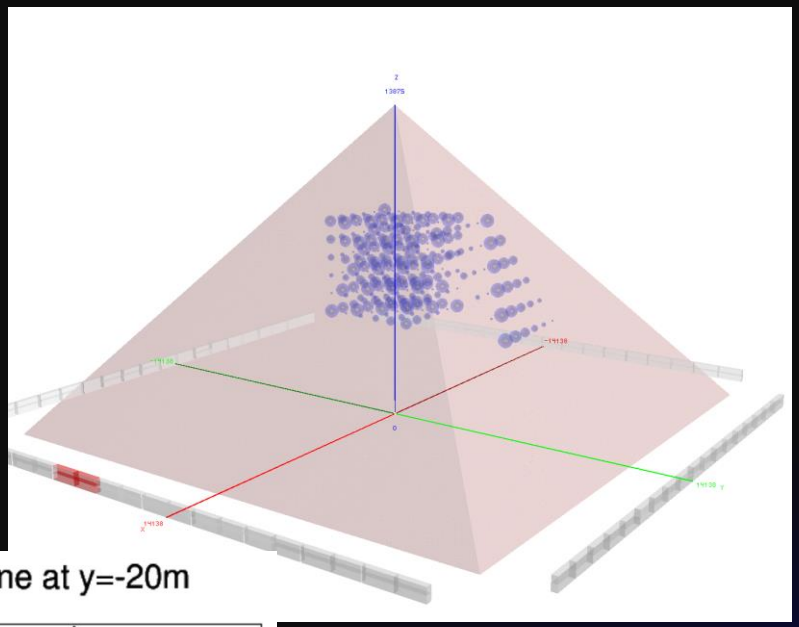
Large detector area → better images

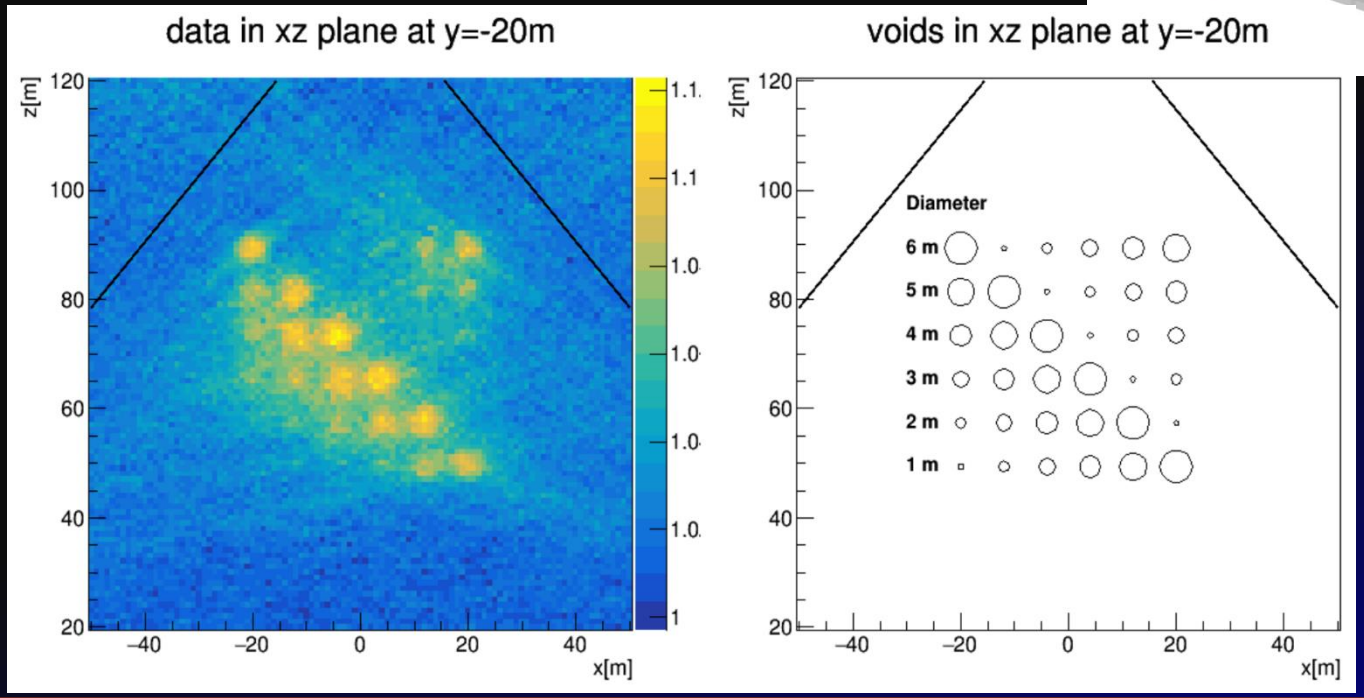
Refrigerated shipping container



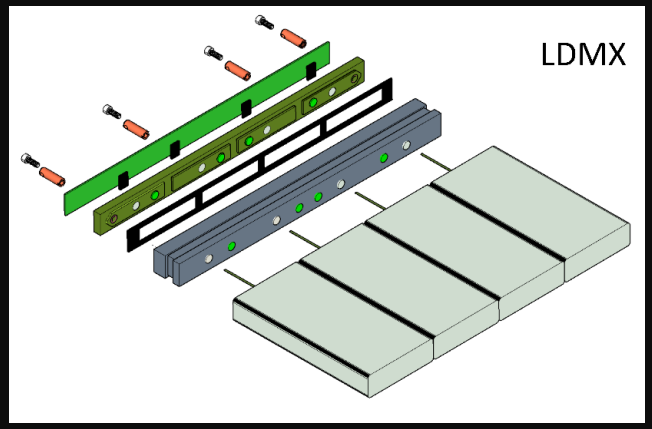
Exploring the Great Pyramid: Results at xz Planes

- With simple reconstruction code can image voids ~3 m size
- Work in progress: better tomography algorithms being developed





Other Experiments using Mu2e Design



Light Dark Matter eXperiment (LDMX) hadronic calorimeter

- Rectangular quad-counter with 1 fiber/50-mm wide extrusion rather than di-counter

Exploring the Temple of Kukulcan at Chichen Itza

- Same design as EGP, but smaller arrays
- Funded by NSF

DUNE

- Exploring similar design for Near Detector

Summary

- We have developed a high-efficiency detector system based on scintillator counters with embedded wavelength-shifting fibers read out by SiPMs
- The detector is simple to fabricate using modest resources and is inexpensive
- A fast, inexpensive readout system using all COTS parts has been designed: it can be reproduced with ease
- The design is flexible and is being used or considered for multiple experiments

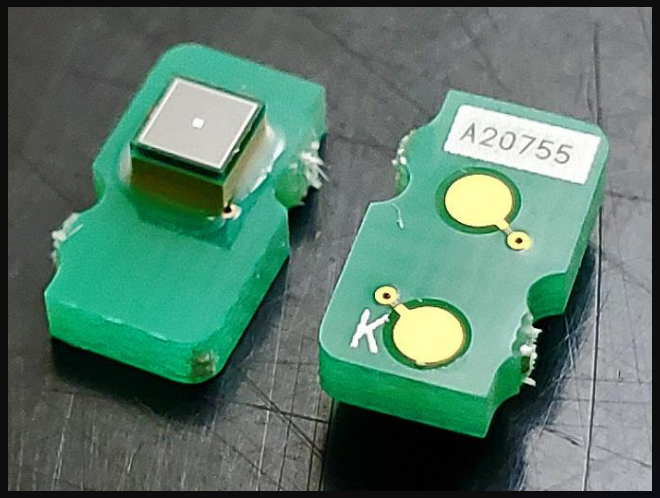
Many thanks to my colleagues on Mu2e, EGP, and LDMX

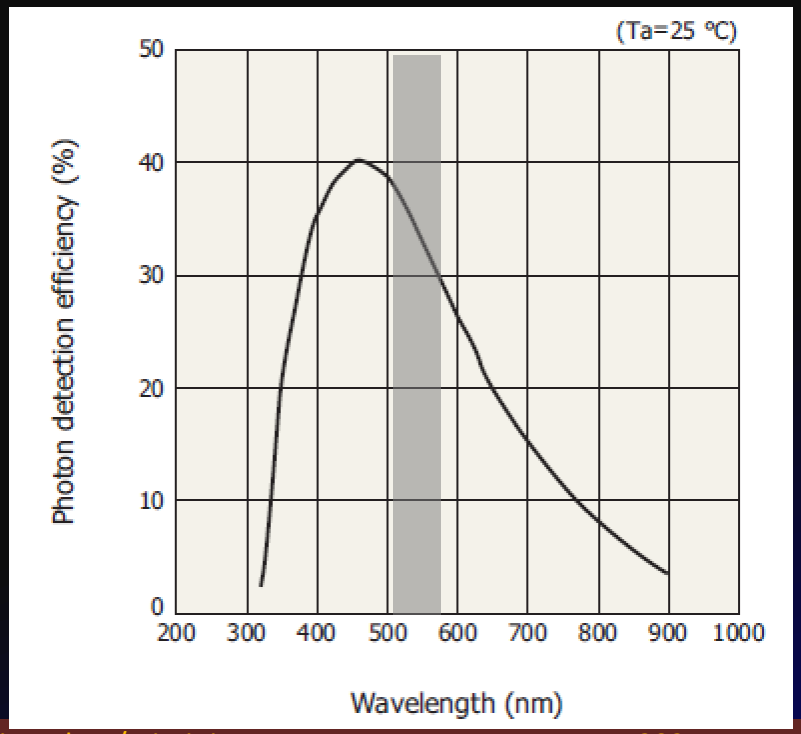
Backup Slides

Silicon Photomultipliers (SiPMs)

We chose this photodetector type because:

- Good effective quantum efficiency
- Ability to measure absolute light yield
- Small size: facilitates on detector mounting
- Works in high magnetic fields
- Low cost: $9.56/ch mounted on carrier board





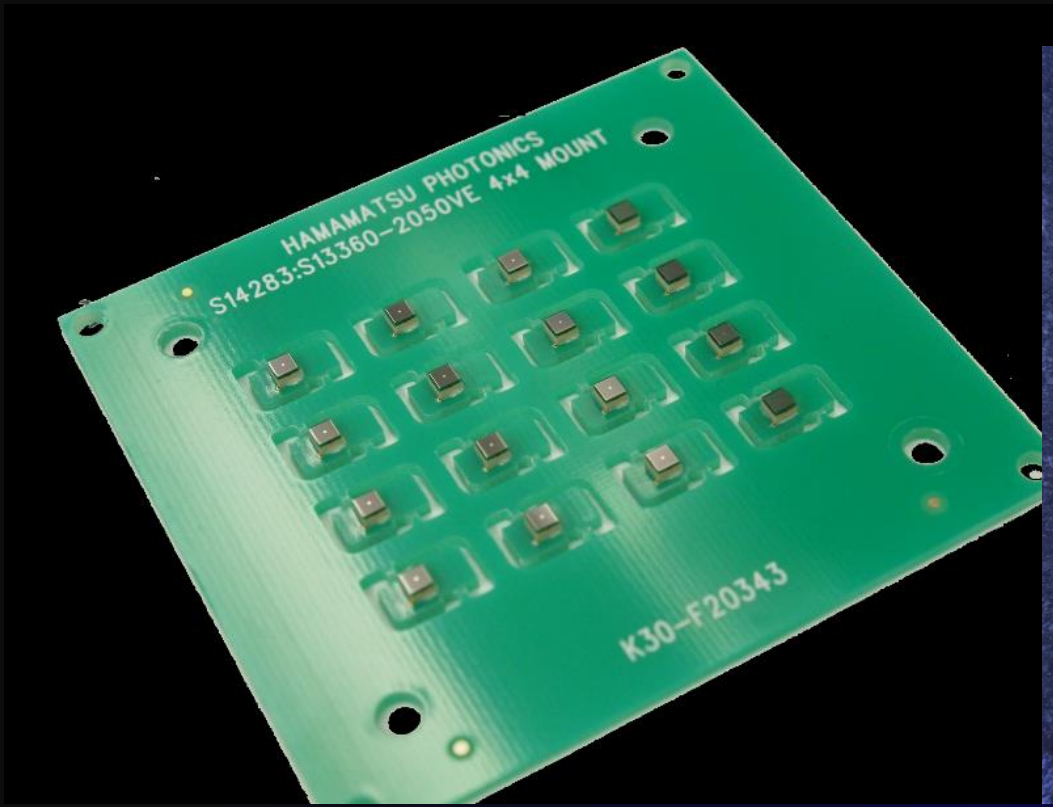
Hamamatsu MPPC S13360-2050VE

All values at 25° C at overvoltage of 2.5V:

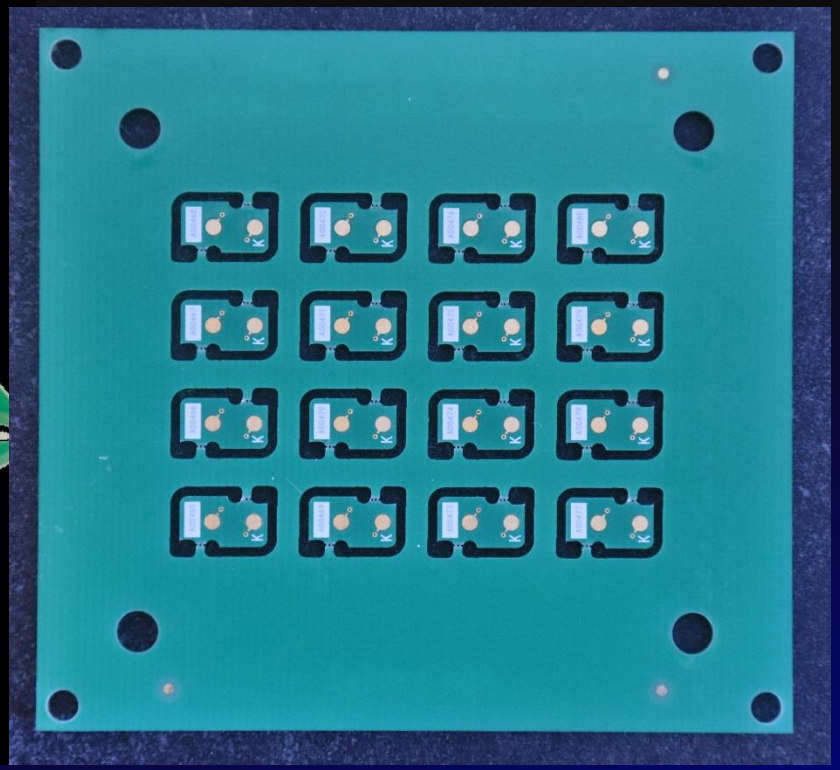
1) 2mm x 2mm, 50 µm pixel
2) Surface-mount, TSV packaging
3) PDE > 35% (530 nm)
4) Gain ≥ 1.0×10^6
5) Pulse rise time < 5 nsec
6) Dark rate < 250 kHz @ 0.5 PE threshold
7) X-talk (inter-pixel) < 2%
8) Bias spread: ±0.5V (within batch); ±1.5V (all)
9) Temperature dependence ≤ 50 mV/°C

SiPM Delivery and Testing

SiPMs are mounted on small 8.4 x 4.9 mm^2 "SIPM carrier boards" (SCBs)
They are delivered and tested on "waffle" pack boards, each with 4 x 4 = 16 SCBs
Punched out of the waffle pack when needed



SiPM side of "waffle pack"



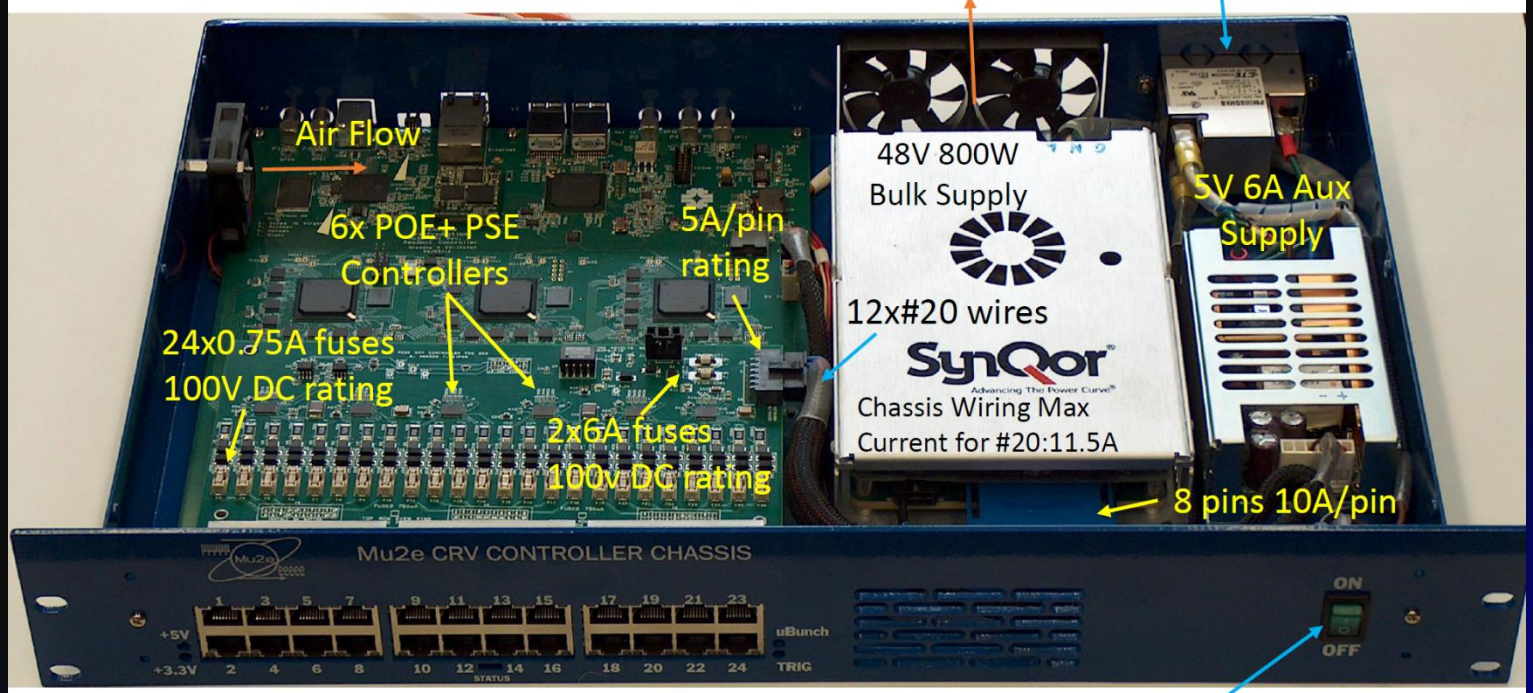
Pogopin pad side of "waffle pack"

Readout Controller

- Powers entire system
- Serves up to 24 FEBs (PoE)
- Interface to the DAQ computer

Controller Power Distribution details:

Controller Photo:



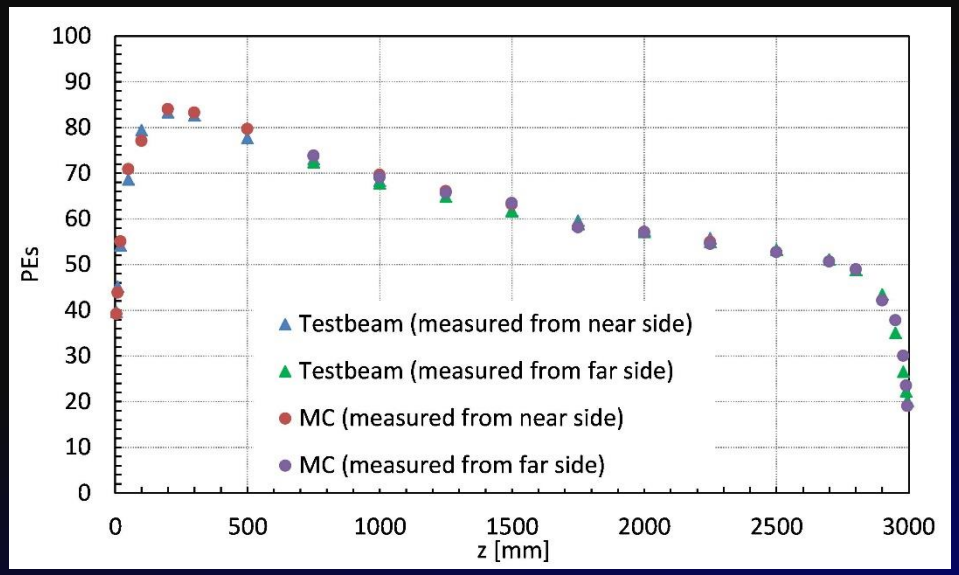
Harmonica Jacks POE+ 720mA/port

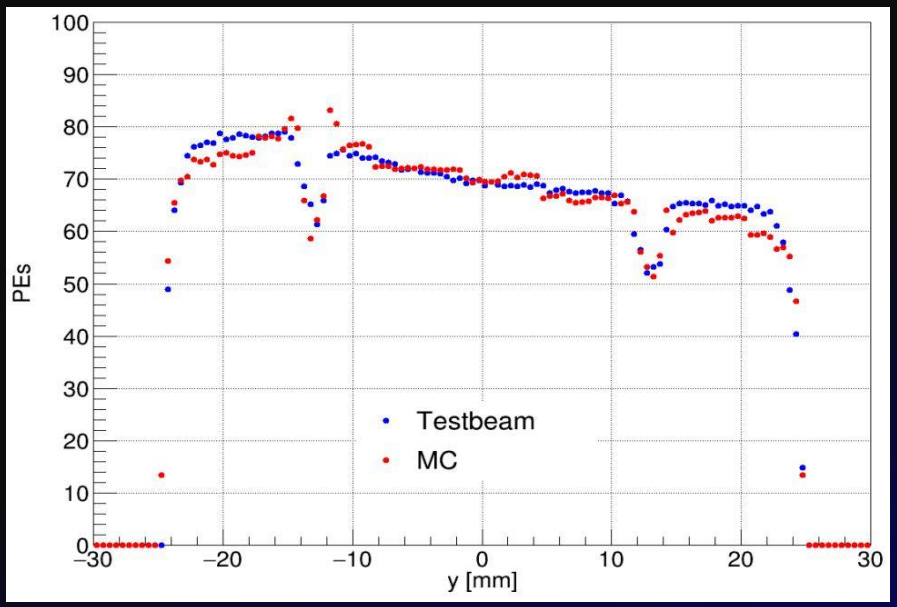
Power Switch
10A 208V

Simulation Code

- A huge effort has gone into developing a detailed, fast, soup-to-nuts MC with a complete simulation of the counter response to incident particles.
- MC includes timing jitter, SiPM crosstalk, and afterpulsing, Front-end Board digitization, etc.
- MC has been extensively tuned to agree with test-beam data.

Response to 120 GeV protons along a 3-m long counter





Transverse response to 120 GeV protons for a 3-mm wide counter. Only data from left fiber used.