# Design and Fabrication of a Large-Area, High-Sensitivity Cosmic Ray Veto Detector for the Mu2e Experiment

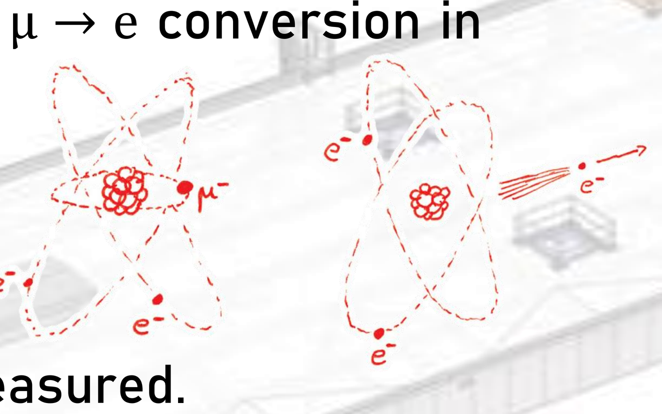
Steven Boi
*On behalf of the Mu2e Collaboration*

## Mu2e at Fermilab

Mu2e will search for coherent, neutrino-less $\mu \rightarrow e$ conversion in the presence of an aluminum nucleus.

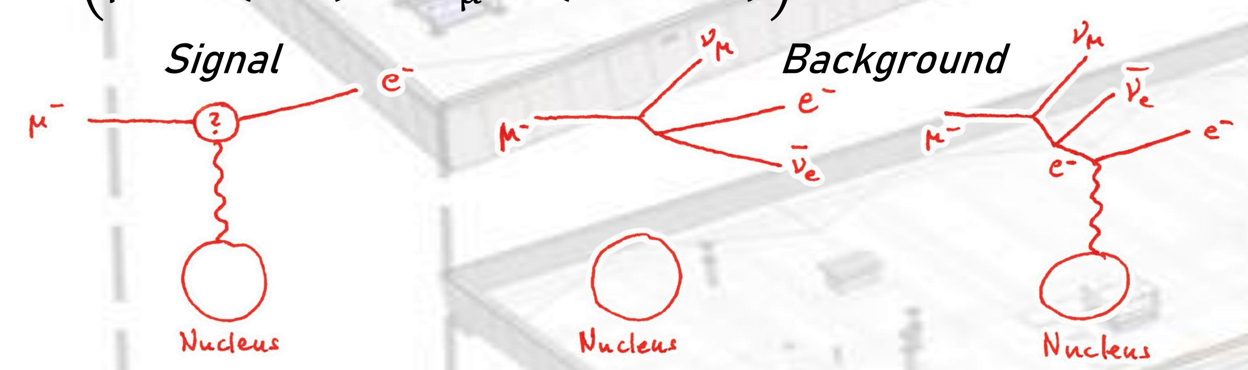
The signal is a monoenergetic electron.

$$E_e \approx m_\mu - E_b - E_{recoil} \approx 104.97\text{MeV}$$



The ratio of $\mu \rightarrow e$ conversions to the number of $\mu$ captures by the aluminum nuclei will be measured.

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma\left(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)\right)}$$




In the search for CLFV, Mu2e will be a 10,000 times improvement over the current best measurement (SINDRUM II).

Mu2e will be indirectly probing mass scales up to 10,000 TeV/$c^2$.

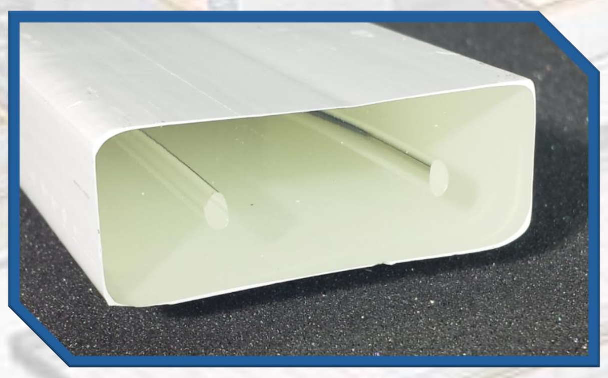
In order to reach this goal, a Cosmic Ray Veto (CRV) is required to veto cosmic ray muons which can create fake $\mu \rightarrow e$ conversion events.

## CRV Components

### Plastic Scintillator

At the heart of the CRV is plastic scintillator.

- Polystyrene: DOW STYRON 665 W
- Dopants: 1% PPO + 0.03% POPOP
- 30% $TiO_2$ mixed polystyrene coating (0.25mm thickness)
- Cross-section of 5cm x 2cm with two co-extruded holes for WLS fibers



Scintillator extrusion.

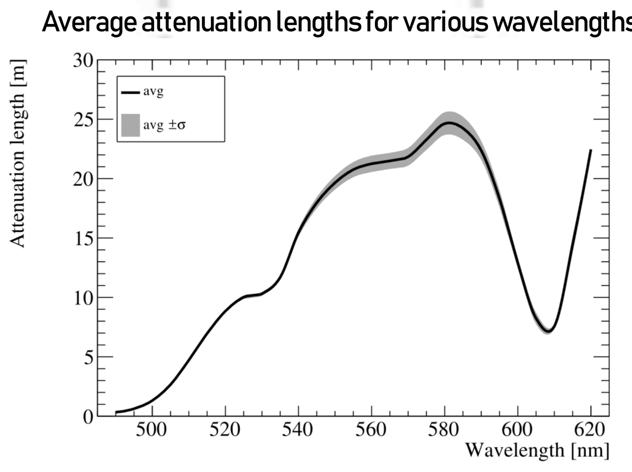
### WLS Fiber

UV light emitted by the scintillator is collected in Kuraray Y11 wavelength shifting (WLS) fibers.

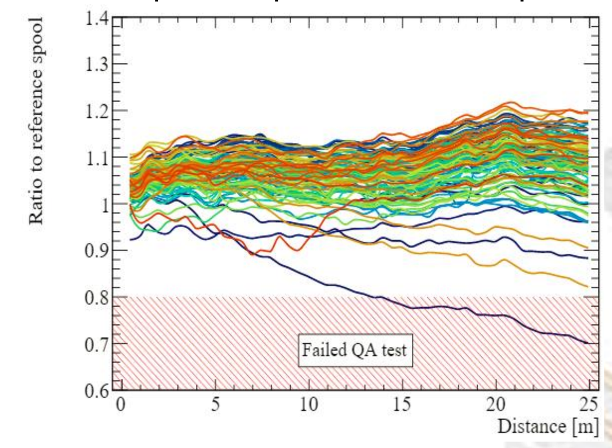
- 1.4mm fiber diameter
- Non-S type
- 175 ppm K27 Dopant
- Double cladding

Every spool of WLS fiber used in the CRV is tested for attenuation length and light output.

Average attenuation lengths for various wavelengths




Light yield at various distances for different spools, compared to a reference spool



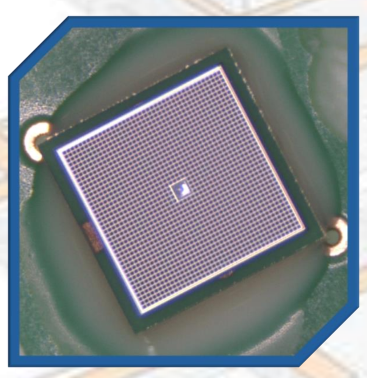

### Silicon Photomultipliers

Light collected by the WLS fibers is read out by Hamamatsu Silicon Photomultipliers (SiPMs).

- 2mm x 2mm, 50 µm pixel size
- Surface-mount, TSV packaging
- PDE >33% (520nm)
- Gain >= $1.25 \times 10^6$
- Rise time <5ns
- Dark count rate <300kHz @ 0.5 PE threshold
- Crosstalk <3.5%

All values @ 25°C, 2.5V overvoltage.

2x2mm SiPM with TSV in center



## Acknowledgements

We are grateful for the vital contributions of the Fermilab staff and the technical staff of the participating institutions. This work was supported by the US Department of Energy; the Italian Istituto Nazionale di Fisica Nucleare; the Science and Technology Facilities Council, UK; the Ministry of Education and Science of the Russian Federation; the US National Science Foundation; the Thousand Talents Plan of China; the Helmholtz Association of Germany; and the Eu Horison 2020 Research and Innovation Program under the Marie Sklodowska-Curie Grant Agreement No.690385. Fermilab is operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the US Department of Energy.

## Cosmic Ray Veto

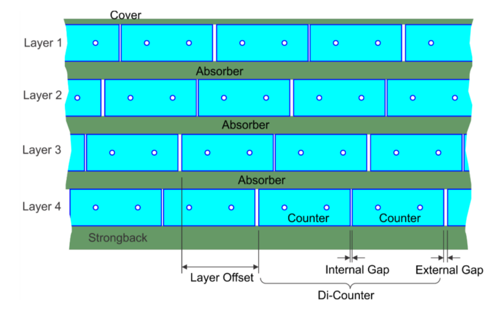
Because cosmic ray $\mu$ can fake $\mu \rightarrow e$ conversion, a veto detector that surrounds the detector apparatus is required. Because one conversion-like $e^-$ is expected to be produced per day, the CRV requires an overall efficiency of 99.99%.

The CRV is made up of four layers of scintillator extrusions, read out through wavelength shifting fiber (WLS) and silicon photomultipliers (SiPMs).

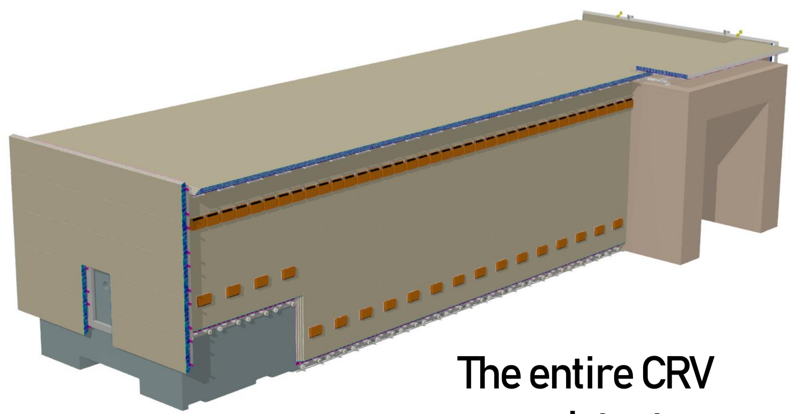
Between the layers of scintillator are aluminum absorbers, which help reduce punch-through from electrons.

The entire assembly is epoxied together, with an offset between layers to eliminate projective gaps.

- 391$m^2$ of coverage
- 75.5 tons of aluminum and plastic
- 19.8k SiPMs
- 5.5k scintillator extrusions
- 52.7km of WLS fiber
- 320 Front-end Boards



The layered structure of the CRV.



The entire CRV detector.

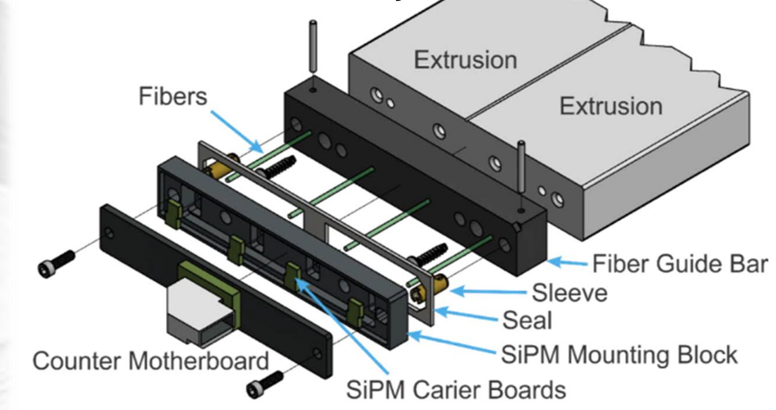
## CRV Fabrication

### Dicounter Construction

Scintillator extrusions are joined together to form dicounters.

Fibers are fed through the co-extruded holes and glued into fiber guide bars (FGB), which are attached to the scintillator ends.

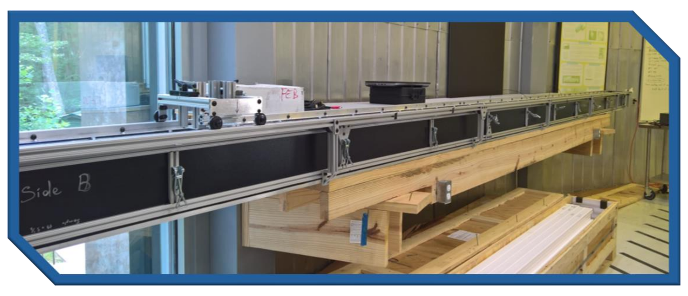
Dicounter assembly.




The fibers are then fly-cut to produce a polished, optically-clear surface.

Polished fiber face.

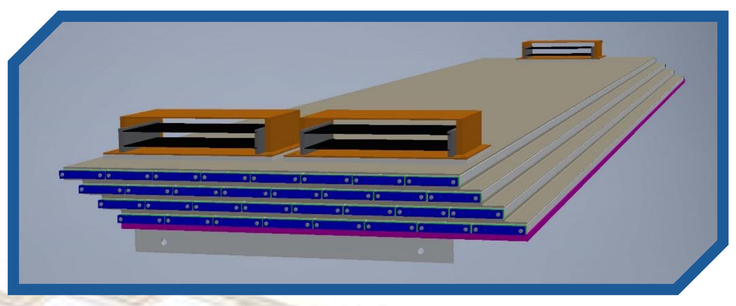
Every dicounter goes through QC checks, which includes imaging of the fibers, roughness testing of the fly-cutting, fiber transmission testing, and finally testing with a Cs-137 source.



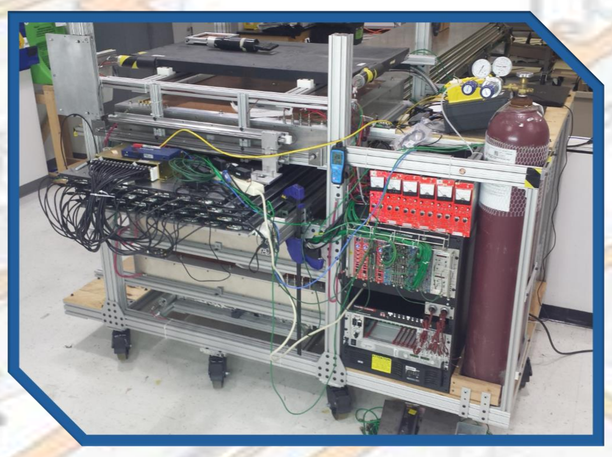
Dicounter dark box with the Cs-137 source on a moveable cart.

### Module Assembly

A total of 32 completed dicounters are used to assembly a four-layer module, with eight dicounters per layer. Between the layers are aluminum absorbers, with the entire assembly epoxied together to an aluminum strong-back.



Module assembly with front-end board enclosures on top.



Cosmic ray test stand with module end visible.

Completed modules are tested using a cosmic ray test stand, where dicounter light yield and layer efficiencies are evaluated.

### Production Status

The completed CRV will consist of 2736 dicounters, which form 85 modules.

As of June 5th, 2019, dicounter production is nearly 40% complete, with a total of five modules produce