The Mu2e
Cosmic Ray Veto System

Ralf Ehrlich
for the Mu2e Collaboration
University of Virginia

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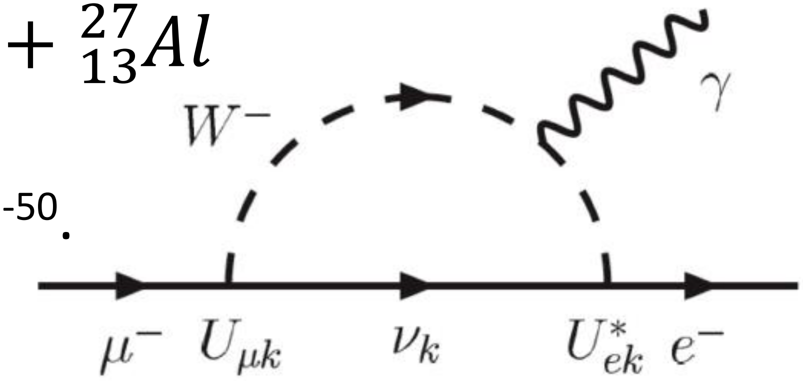
The Mu2e Experiment

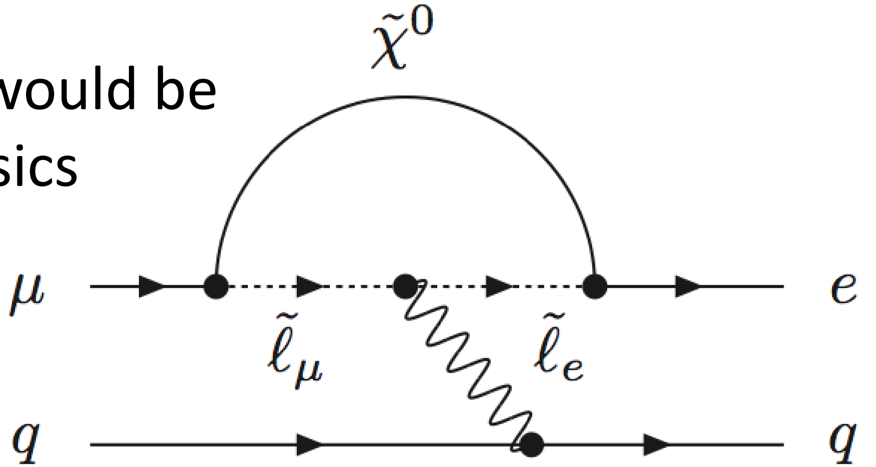
- Mu2e is an experiment under construction at Fermilab to study charged lepton flavor violation and will start taking data in 2023.
- Mu2e will look for neutrinoless muon to electron conversions in the orbit of aluminum atoms.

$$\mu^- + {}^{27}_{13}Al \rightarrow e^- + {}^{27}_{13}Al$$

- Possible with via neutrino oscillation
  - Branching fraction for $\mu \rightarrow e\gamma$ is $\leq 10^{-50}$.
  - Unobservable low probability!



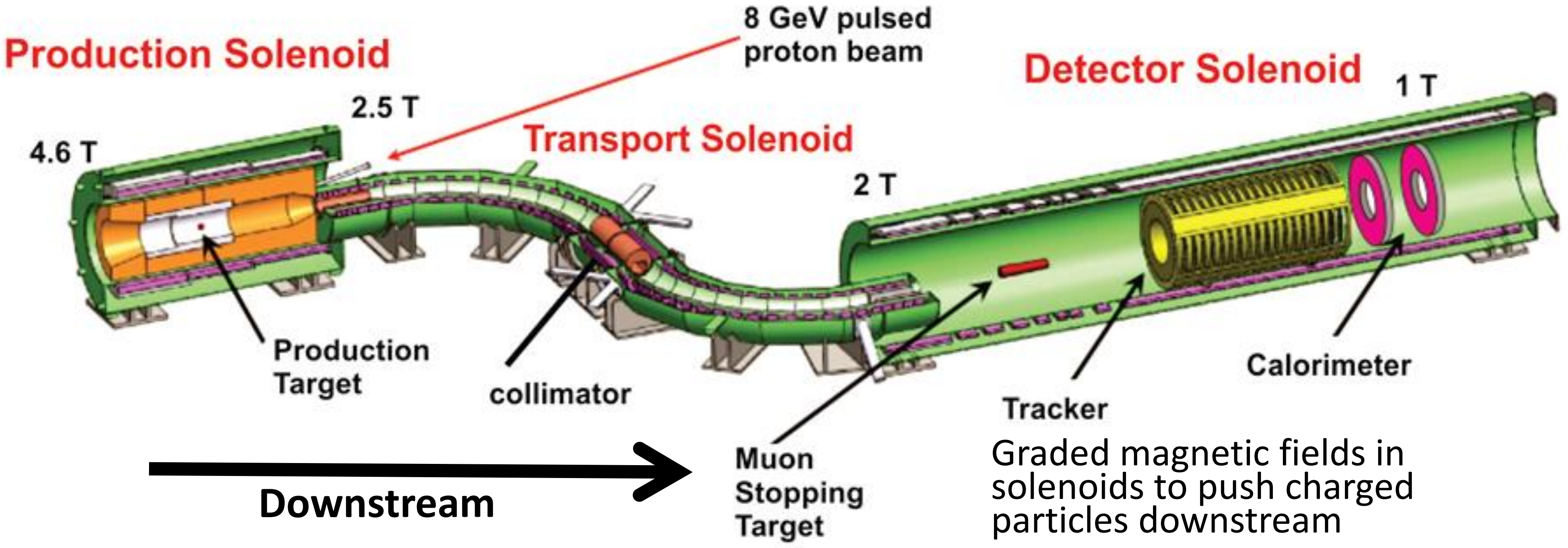
- Any observation of such a process would be unambiguous evidence of new physics beyond the Standard Model.
  - Example: conversion via supersymmetric particles



The Mu2e Experiment

- The current best limit is $7.0 \cdot 10^{-13}$.
- Mu2e intends to reach a single event sensitivity for muon to electron conversions in the field of an atom of $3.0 \cdot 10^{-17}$ assuming we will run
  - for three years,
  - with $3.6 \cdot 10^{20}$ protons,
  - with a run time of $6.0 \cdot 10^{7}$ s,
  - and requires a background under 1 event.
- The signal we are looking for is a delayed monoenergetic electron with an energy of just under 105 MeV (muon mass).

The Mu2e Apparatus

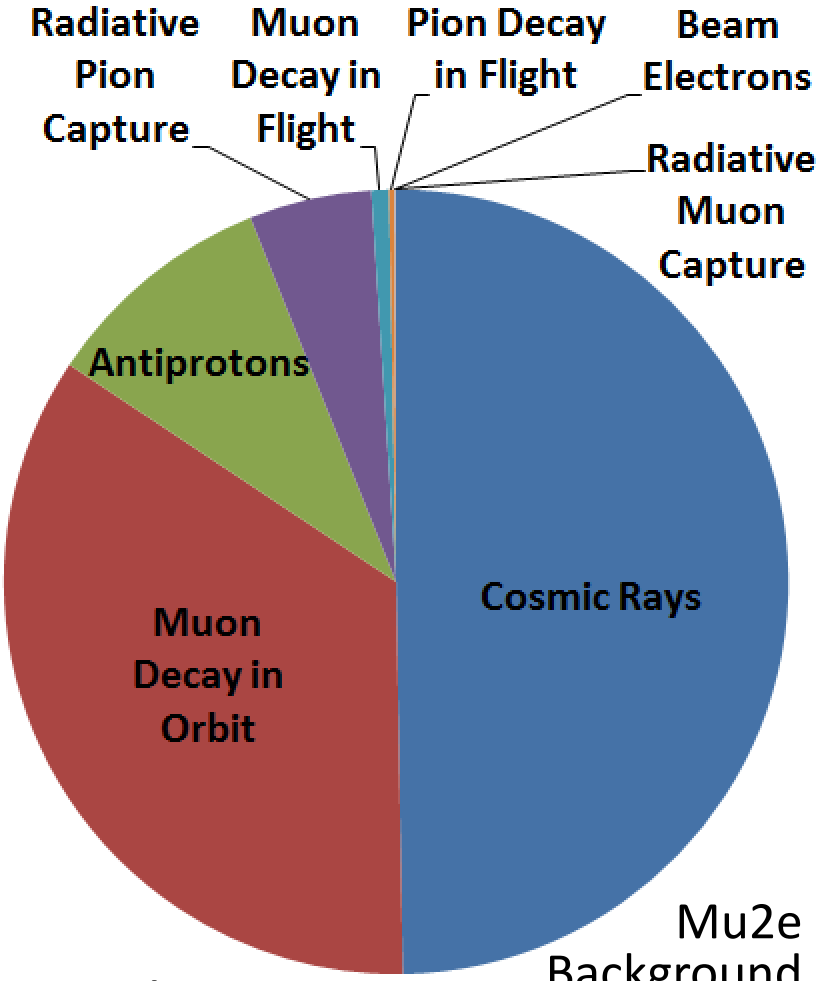


Graded magnetic fields in solenoids to push charged particles downstream

- A pulsed proton beam (from Fermilab’s accelerator complex) hits the production target to produce pions which decay into muons.
- The muons get transported via the transport solenoid to the detector solenoid where they get stopped at the aluminum stopping target.
- If conversion electrons are produced in the stopping target, they will move through the tracker and calorimeter where they can be measured.

Backgrounds due to Cosmic Rays

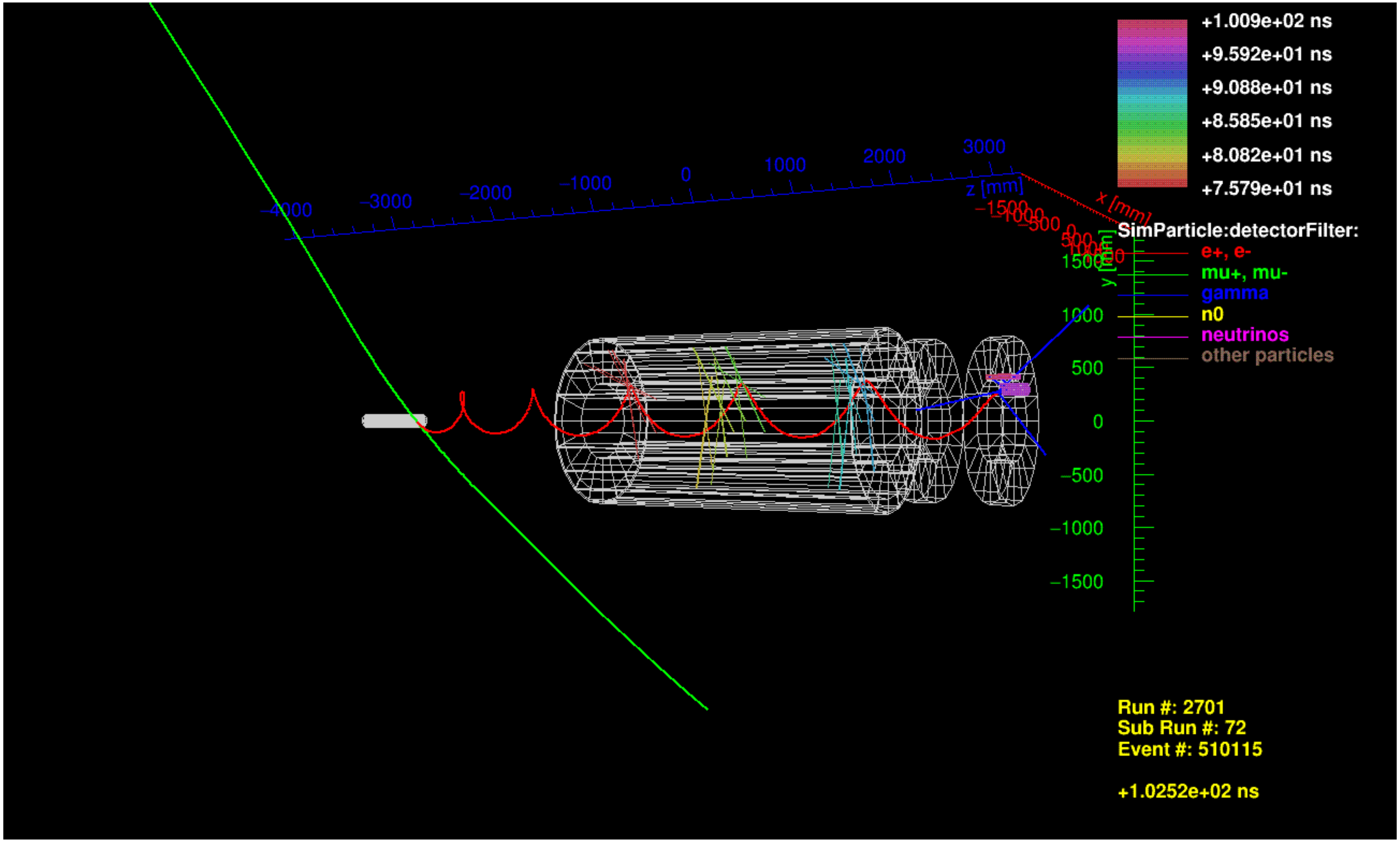
- Cosmic ray muons are the dominant source of background.
  - They can produce electrons that mimic these 105 MeV conversion electrons.
  - About one conversion-like event per day will be produced in the detector.
  - Probability for a cosmic-ray muon hitting the detector to create such an event: $4 \cdot 10^{-9}$
- A cosmic ray veto system (CRV) will be placed around the Mu2e apparatus to detect these cosmic ray muons.
  - All conversion electron-like events coinciding with a cosmic ray muon will be disregarded.
  - The required efficiency for the CRV is ~99.99%.



Mu2e Background Sources

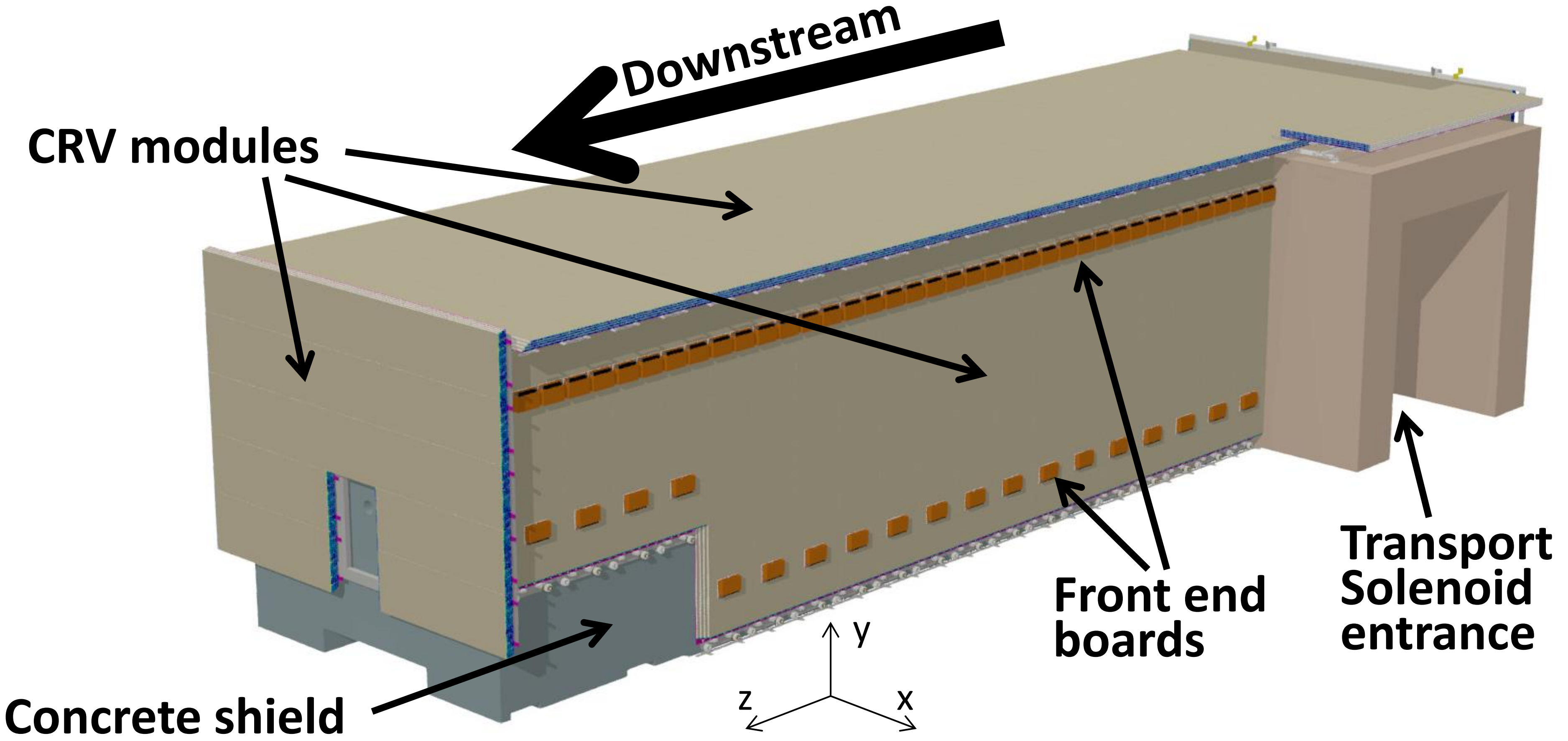
Backgrounds due to Cosmic Rays

- Example of a cosmic ray muon hitting the stopping target, and knocking out an electron which mimics a conversion electron.



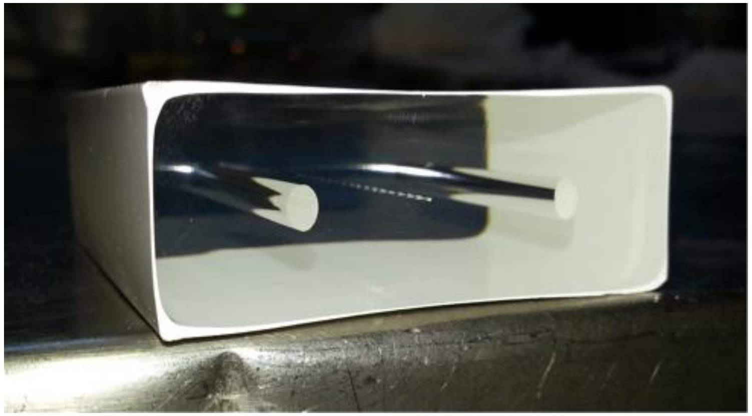
Cosmic Ray Veto

- The CRV system surrounds the Mu2e apparatus.
  - Exists in a high radiation area, which can lead to SiPM damage and create fake hits in the CRV.
  - Concrete shield to reduce the impact of the radiation.



CRV Counters

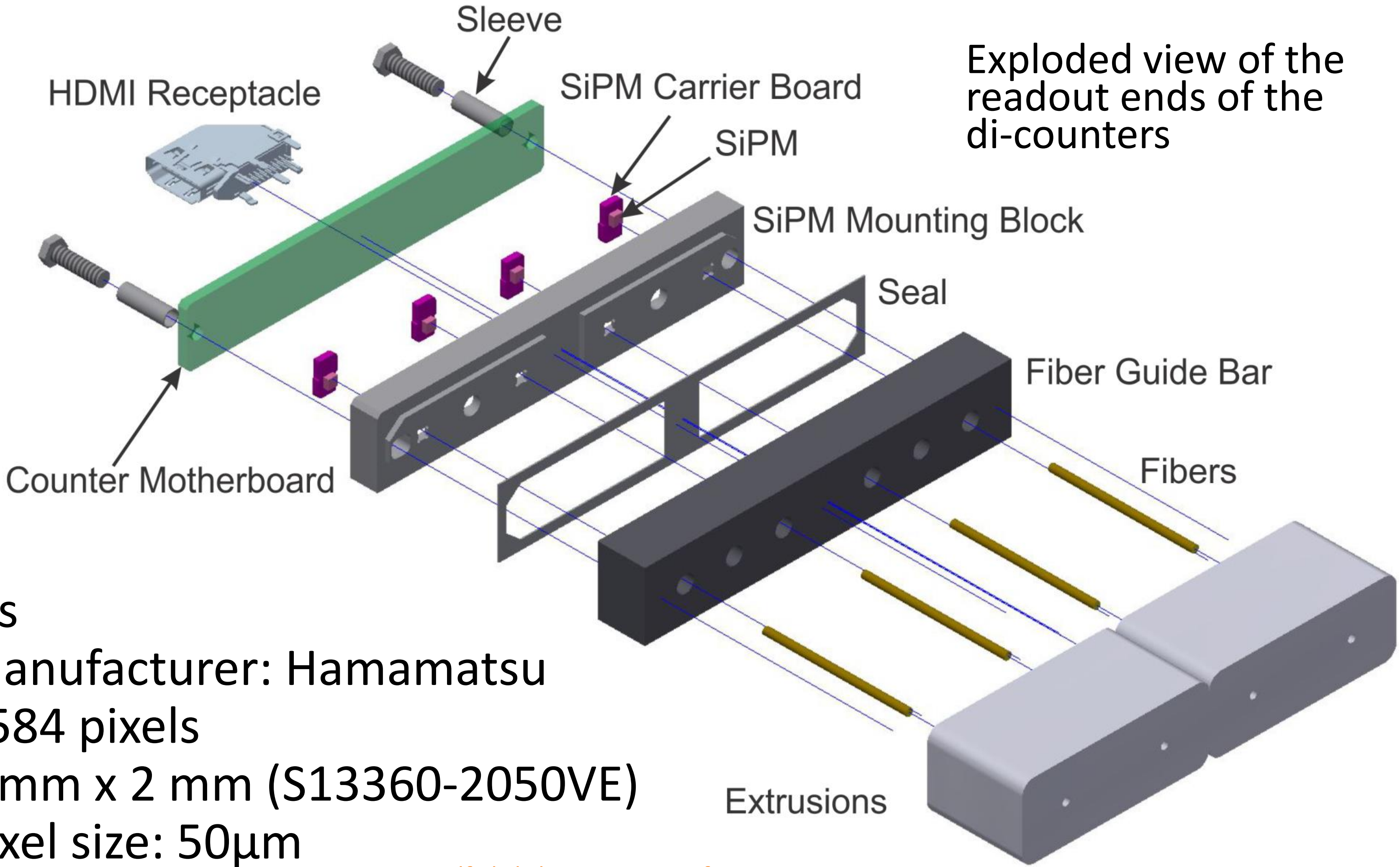
- The CRV is made of 5472 scintillator counters.
- Extrusions
  - 20 mm thick, 51 mm wide, between 0.85 m and 6.9 m long.
  - Made of polystyrene doped with 1% PPO and 0.03% POPOP
  - Coated with a 0.25 mm thick reflective layer of a mixture of 30% TiO_2 and 70% polystyrene
  - Manufactured at the FNAL-NICADD Extrusion Line Facility



- Two embedded wavelength shifting fibers
  - Manufacturer: Kuraray
  - Type: double-clad Y11 doped with 175 ppm K27 dye, non-S-type.
  - Diameters : 1.4 mm
- Each fiber gets readout on both ends by Silicon Photomultipliers (SiPMs) – except in some special cases.

CRV Di-counters

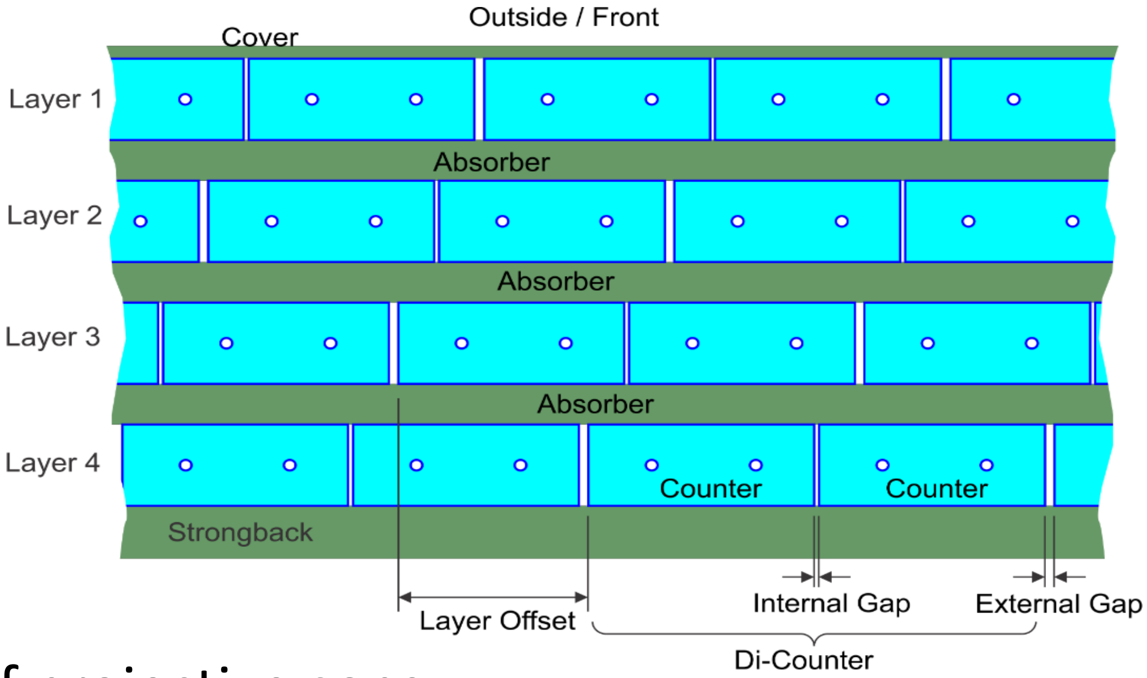
- Two counters are glued together to form a di-counter.
- Assembled at the University of Virginia.



Exploded view of the readout ends of the di-counters

- SiPMs
  - Manufacturer: Hamamatsu
  - 1584 pixels
  - 2 mm x 2 mm (S13360-2050VE)
  - Pixel size: 50µm

CRV Modules



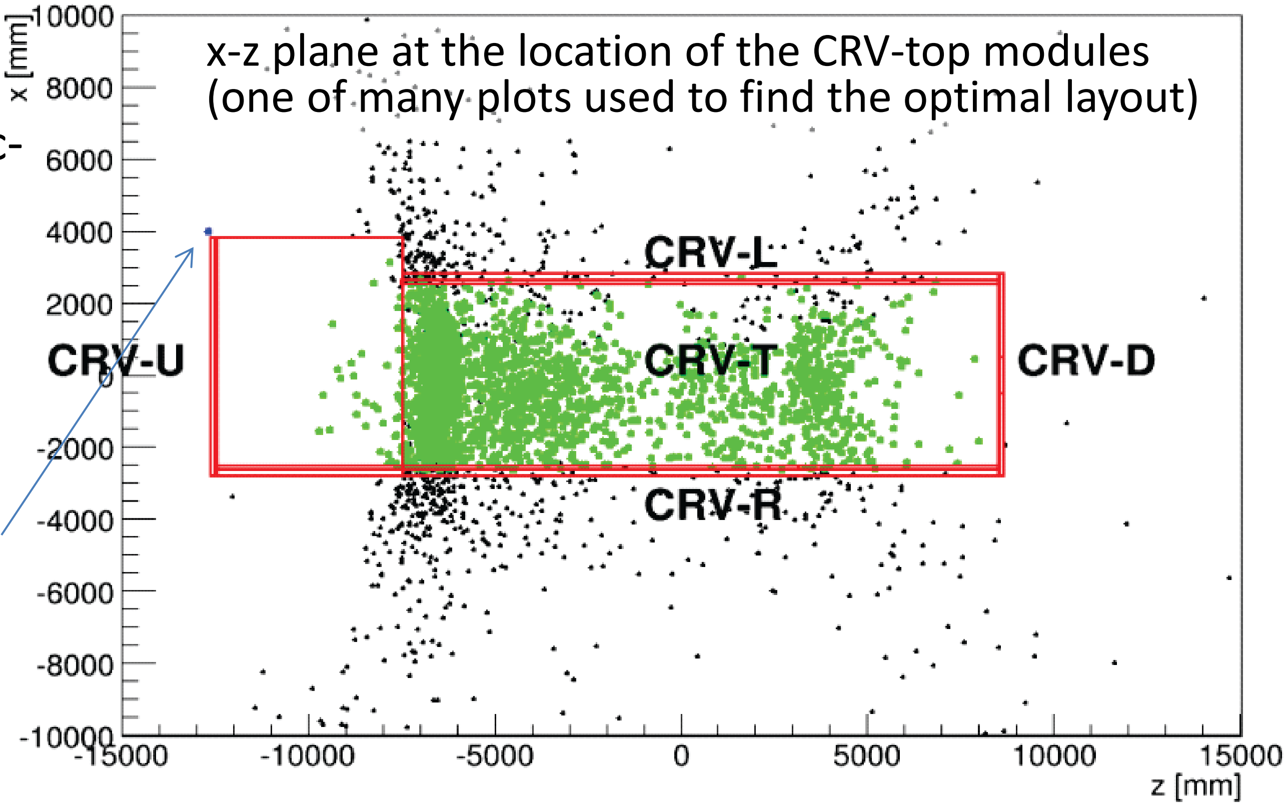
- Made of 4 layers of scintillator counters
- 16 counters per layer
- Aluminum absorbers between each layer
- Relative offset of 42 mm between the layers for most modules
  - Minimizes the effect of projective gaps
  - The optimal value for this offset was determined by simulations.
- Require a 3-out-of-4 layer coincidence to reduce the impact of fake hits
- We will build 86 of these modules at UVA.
  - 5 Modules are already done.

Required CRV Coverage

- Simulated 3.7 trillion cosmic ray muons.
  - Between 5 and 383 live times for different regions of the CRV.
  - Used to find the optimal layout of the CRV

Points of impact at the x-z plane at the location of the CRV-top modules for cosmic-ray muons that produce conversion-like background events.

- Green markers: muons that only hit the CRV-top modules and none other.
- Blue markers: muons that hit no counters.
- Black markers: any other points of impact.

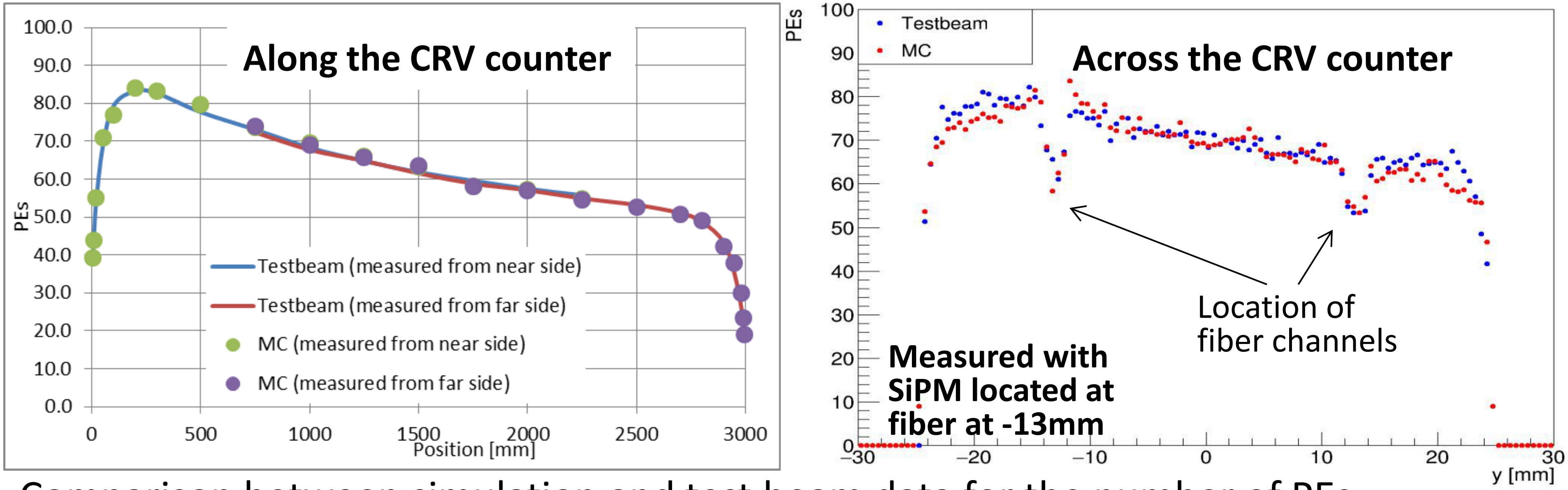


Required CRV Efficiency

- The veto efficiency of a CRV module depends on the PE yield of the CRV counters, the PE hit threshold, and the coincidence time window.
  - A series of simulations were done to find these relationships.
  - A high veto efficiency requires a low PE threshold and a wide coincidence time window.
  - Secondaries from neutrons and gammas cause fake hits, which require a high PE threshold and a small coincidence time window to keep the dead time low.
  - An optimization of the PE thresholds and coincidence time windows was done for all CRV modules depending on their locations.

CRV Counter Simulation

- ➢ The CRV counter simulation include the scintillation and Cerenkov photon production and transport, and the SiPM and electronics responses.
- ➢ The simulation was tuned to match the results of a test beam measurement at Fermilab.
- ➢ Lookup tables were used to increase the speed of the simulations.


Along the CRV counter

Across the CRV counter

Measured with SiPM located at fiber at -13mm

Location of fiber channels

Comparison between simulation and test beam data for the number of PEs for 120 GeV protons normally incident at different locations along/across the counter.

Expected CRV Performance

- CRV gets hit by cosmic ray muons with a rate of 14.5 kHz.
- It is expected that 659 muons will cause conversion electron-like signals during the Mu2e live time.
  - 0.06 muons are not vetoed due to the CRV inefficiency.
  - 0.15 muons enter the detector through a region that cannot be covered by the CRV (the hole at the transport solenoid entrance).
- Total expected background from cosmic ray muons: 0.21 events.

Summary

- Mu2e intends to improve the single event sensitivity for neutrinoless muon-to-electron conversions by 4 orders of magnitude.
- The Cosmic Ray Veto system will be able to reduce the impact of the cosmic ray background by a factor of $3 \cdot 10^{-4}$.
- UVA is in the process of building the CRV modules.
- Construction of the accelerator components, detectors, magnets, and other parts of the experiment are well under way.
- The Mu2e experiment will start taking data in 2023.

- Please see our two posters at the poster session on Thursday about
  - the fabrication of the CRV modules (by Hannah Woodward), and
  - the CRV counter simulation (by Ralf Ehrlich).

Backup Slides

Overview

- Mu2e will measure the ratio of the coherent neutrinoless muon-to-electron conversion rate vs. the ordinary muon capture rate

$$R_{\mu e} = \frac{\mu^- + {}^{27}_{13}Al \rightarrow e^- + {}^{27}_{13}Al}{\mu^- + {}^{27}_{13}Al \rightarrow \nu_\mu + {}^{27}_{12}Mg}$$

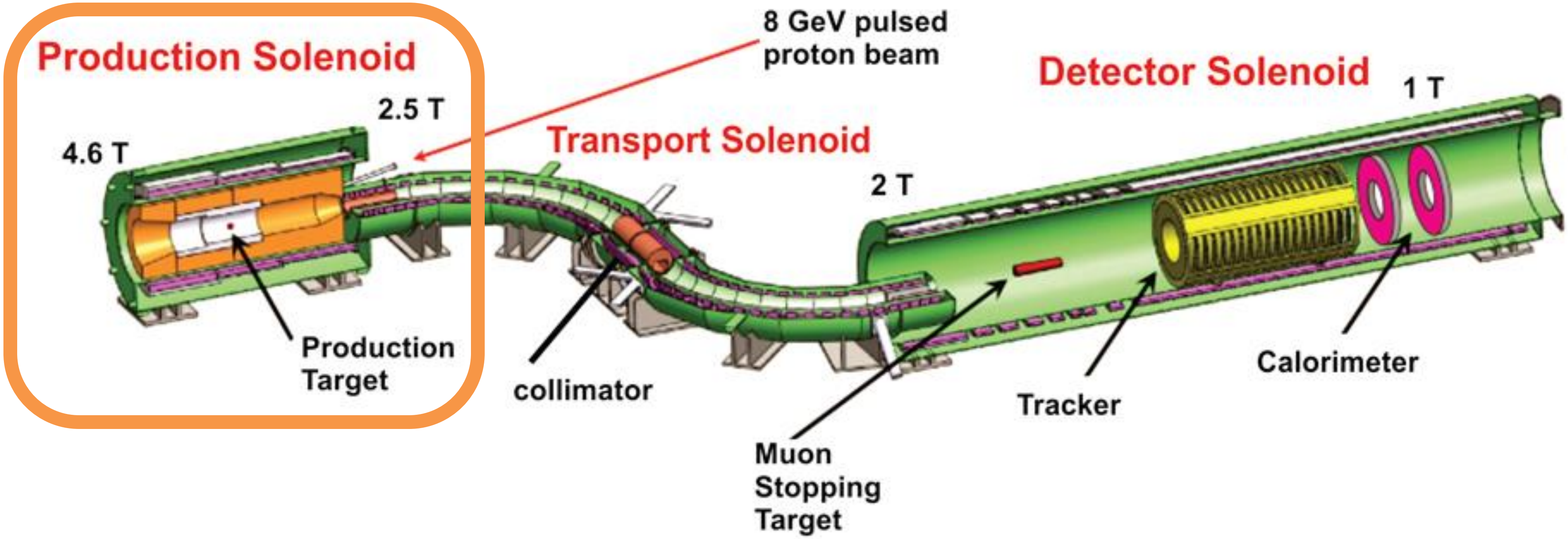
- Mu2e will take data over 3 years, with a total run time of $6.0 \cdot 10^7 s$, and intends to reach a single event sensitivity for $R_{\mu e}$ of $3.0 \cdot 10^{-17}$ (90% CL).

- This is an improvement of 4 orders of magnitude relative to the SINDRUM-II result, which currently provides the best limit of $7.0 \cdot 10^{-13}$.

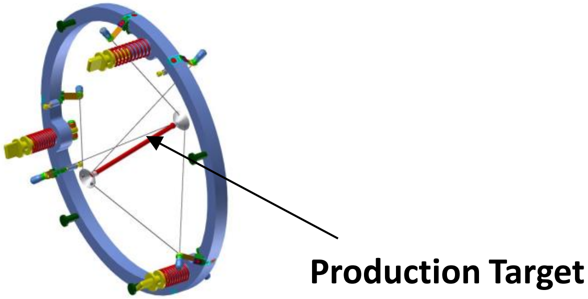
Overview

- This conversion process $\mu^- + {}^{27}_{13}Al \rightarrow e^- + {}^{27}_{13}Al$ of stopped muons in the field of aluminum nuclei produces monoenergetic electrons with energies of about 105 MeV.
  - m_μ (muon mass): $105.66\ \mathrm{MeV}/c^2$
  - B_μ (atomic binding energy of the muon in the 1S state in the orbit of ${}^{27}_{13}Al$): $0.48\ \mathrm{MeV}$
  - C_μ (nuclear recoil energy of ${}^{27}_{13}Al$): $0.21\ \mathrm{MeV}$
  - $E_{CE} = m_\mu c^2 - B_\mu - C_\mu = 104.97\ \mathrm{MeV}$

The Apparatus

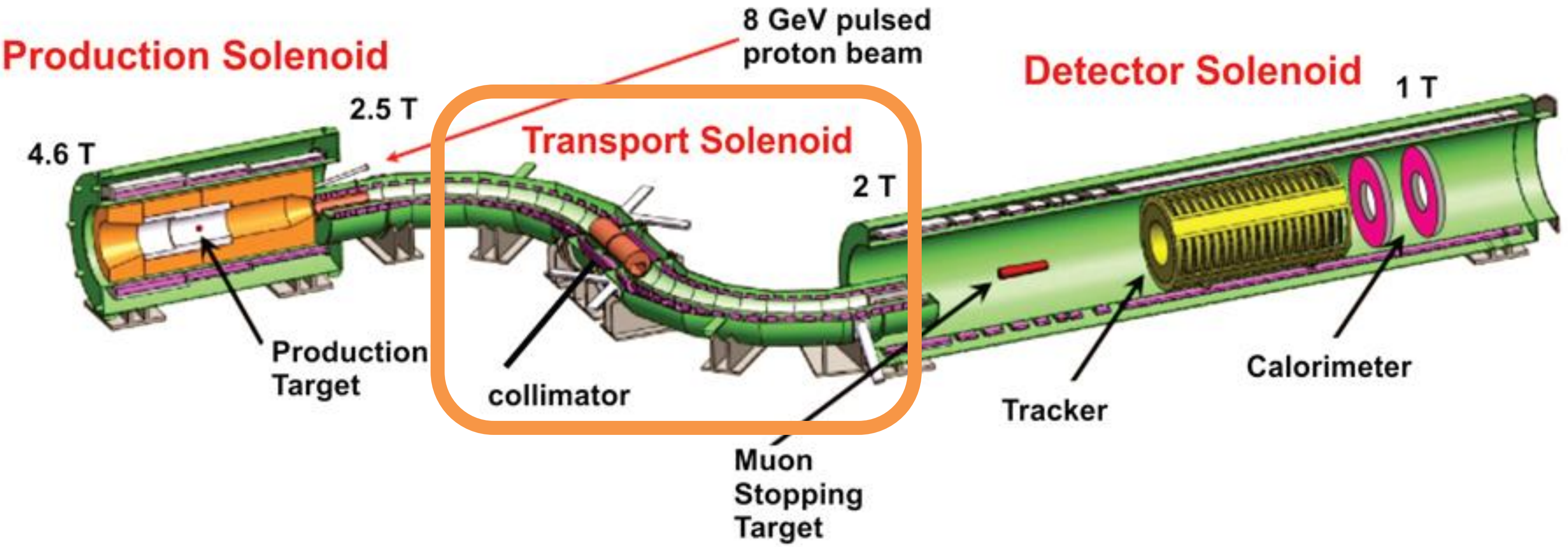


- Pulsed 8 GeV proton beam coming from Fermilab's accelerator complex
  - Every 1695 ns / 200 ns width
- Production target
  - Tungsten rod
  - Produces pions, which decay into muons



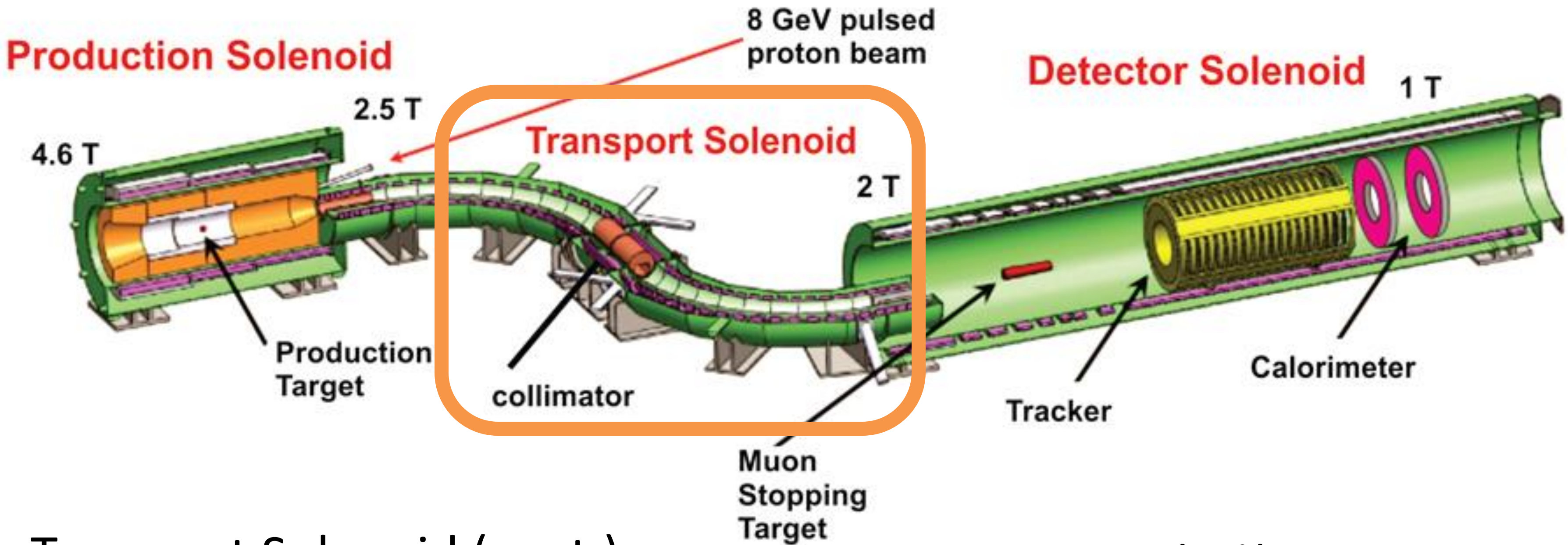
- Production Solenoid
  - Produces a graded magnetic field between 4.6 T and 2.5 T
  - Traps the charged particles and accelerates them toward the transport solenoid

The Apparatus

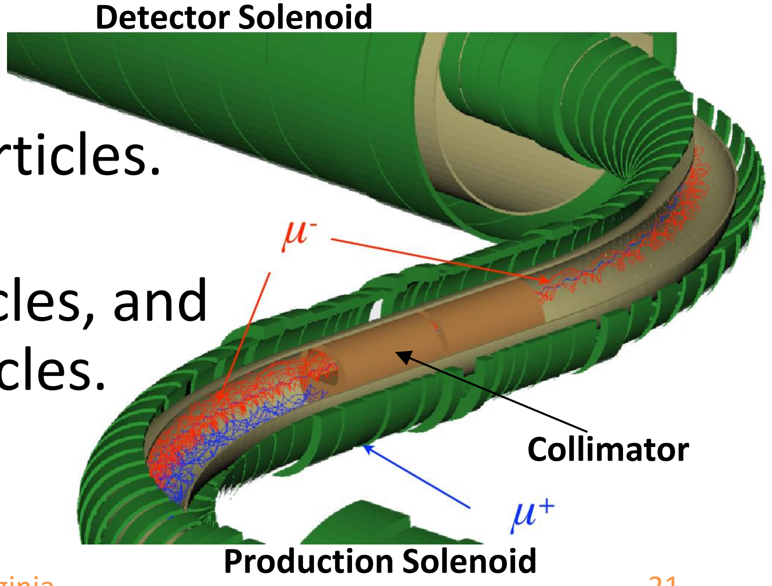


- Transport Solenoid
  - Produces a graded magnetic field between 2.5 T and 2.0 T
  - Muons travel on a helical path from the production solenoid to the detector solenoid.
  - The S-shape moves the detector solenoid out of the line of sight of the production solenoid to prevent neutral particles produced at the production solenoid to enter the detector solenoid.

The Apparatus



- Transport Solenoid (cont.)
  - S-shape separates the helix paths of positively and negatively charged particles.
- Central Collimator
  - Absorbs the positively charged particles, and high energy negatively charged particles.
  - Includes an anti-proton absorber to remove anti-protons.



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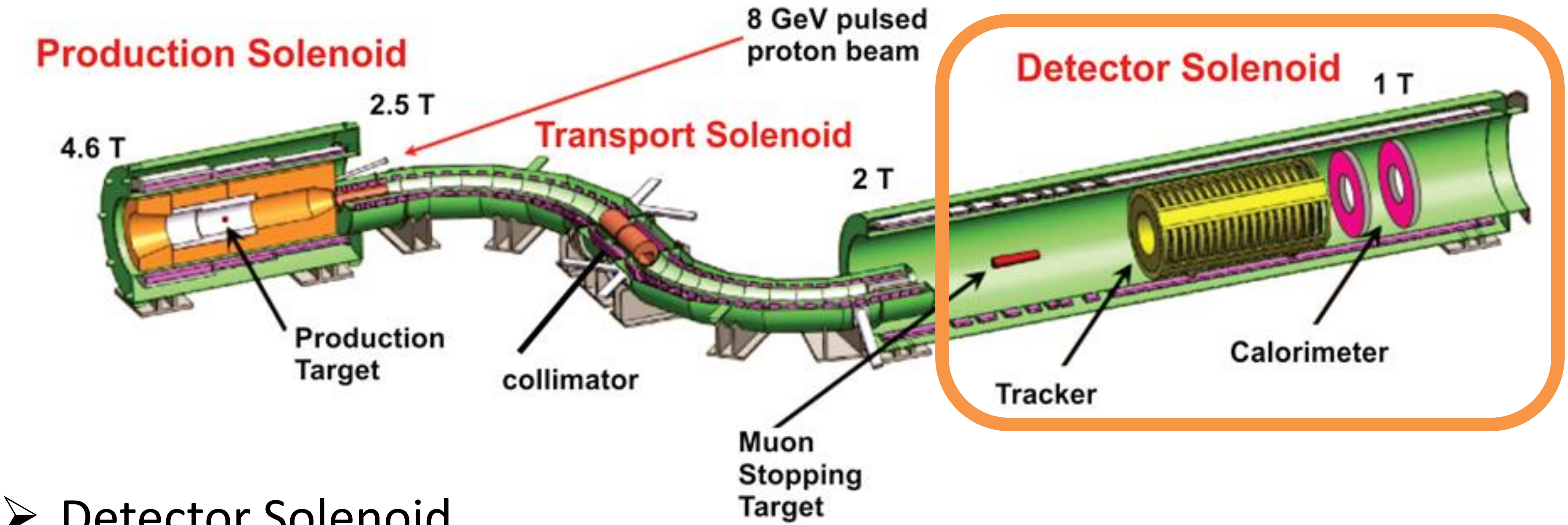
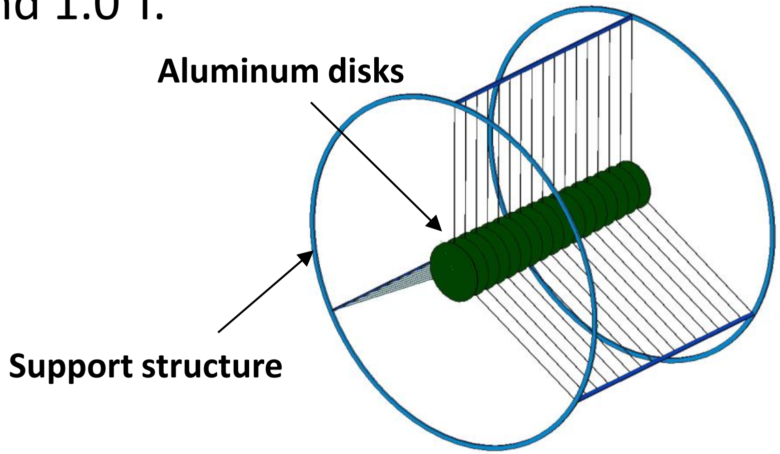


- **Detector Solenoid**
  - Produces a magnetic field between 2.0 T and 1.0 T.
- **Muon Stopping Target**
  - 37 aluminum disks, 0.1 mm thick
  - Stops muons
    - 39% of the muons decay in orbit.
    - 61% of the muons get captured by the aluminum nucleus.



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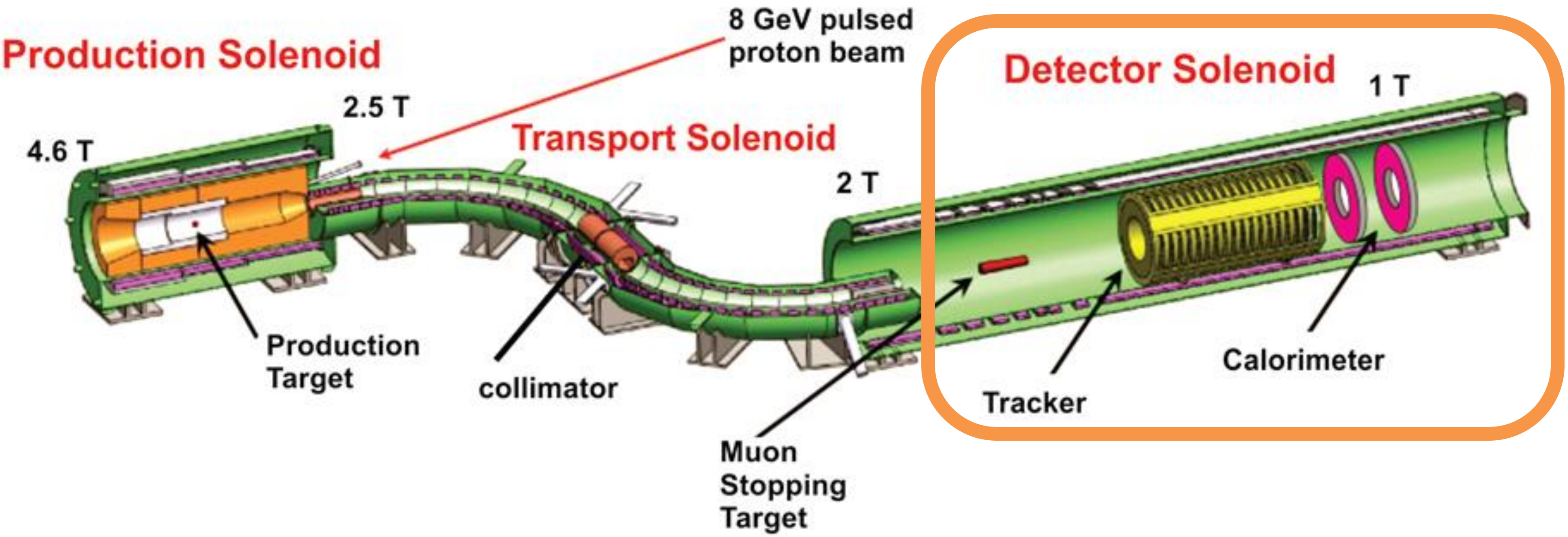
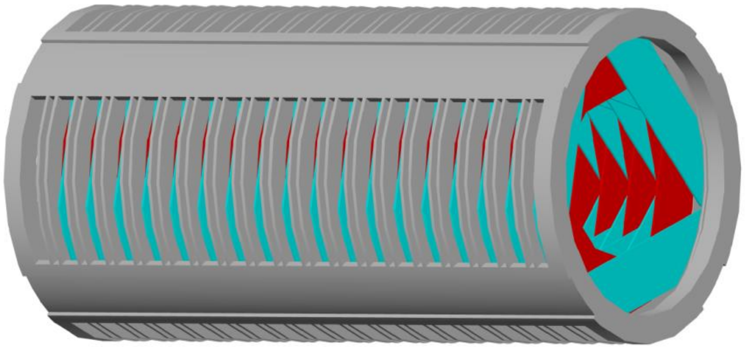
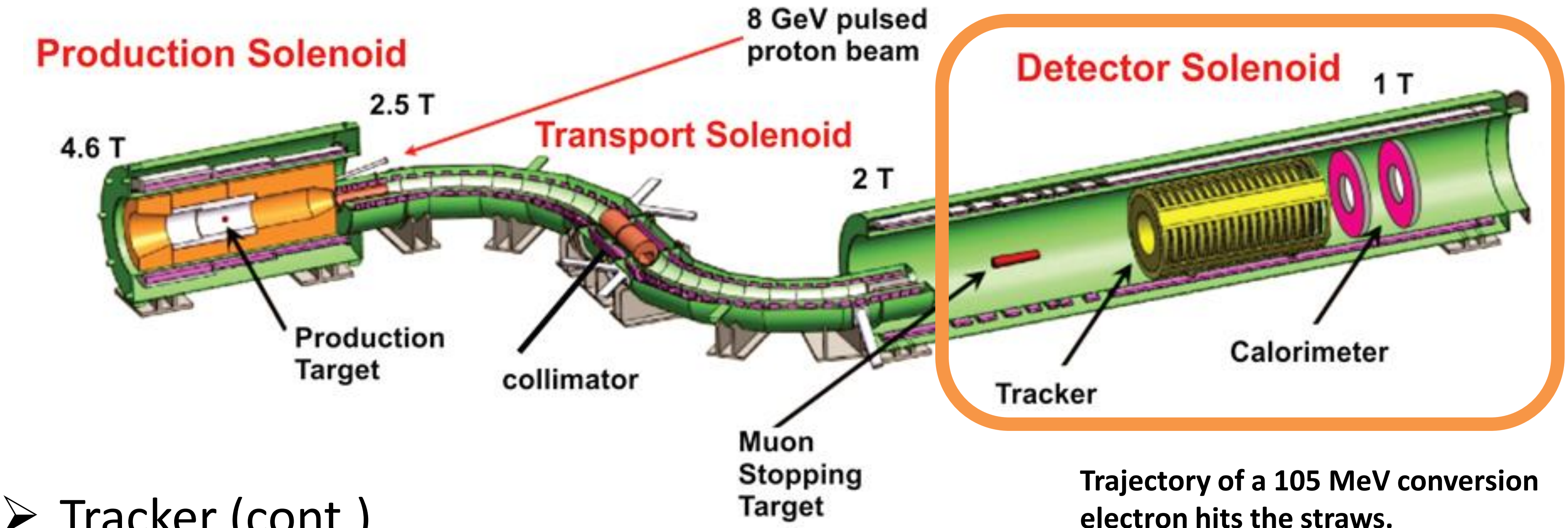


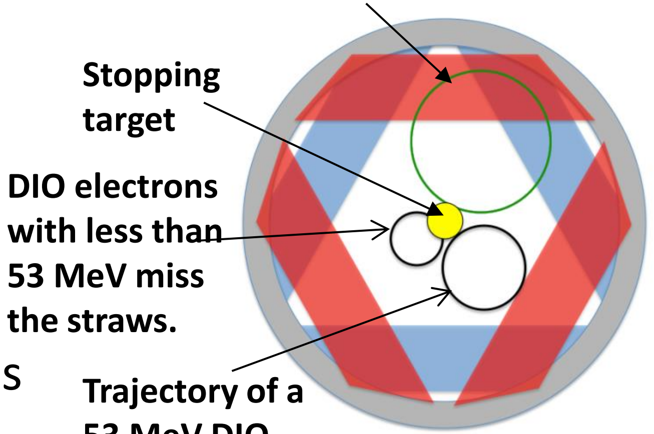
- Tracker
  - 3 m long, made of 21,600 straw drift tubes
  - Straw drift tubes: 5 mm diameter, 334 mm to 1174 mm long, 15 µm thick walls, 25 µm diameter sense wire in the center
  - Surrounded by a uniform 1 T magnetic field
  - Conversion electrons will travel on a helical path through the tracker.



The Apparatus



- Tracker (cont.)
  - Tracker measures the trajectories of the conversion electrons.
  - Radii of most decay-in-orbit electrons are too small to hit the straws (due their low energies).
- Calorimeter
  - Independently verifies the tracker measurements
  - Used for particle identification
  - Used as trigger



Trajectory of a 105 MeV conversion electron hits the straws.

Stopping target

DIO electrons with less than 53 MeV miss the straws.

Trajectory of a 53 MeV DIO electron.

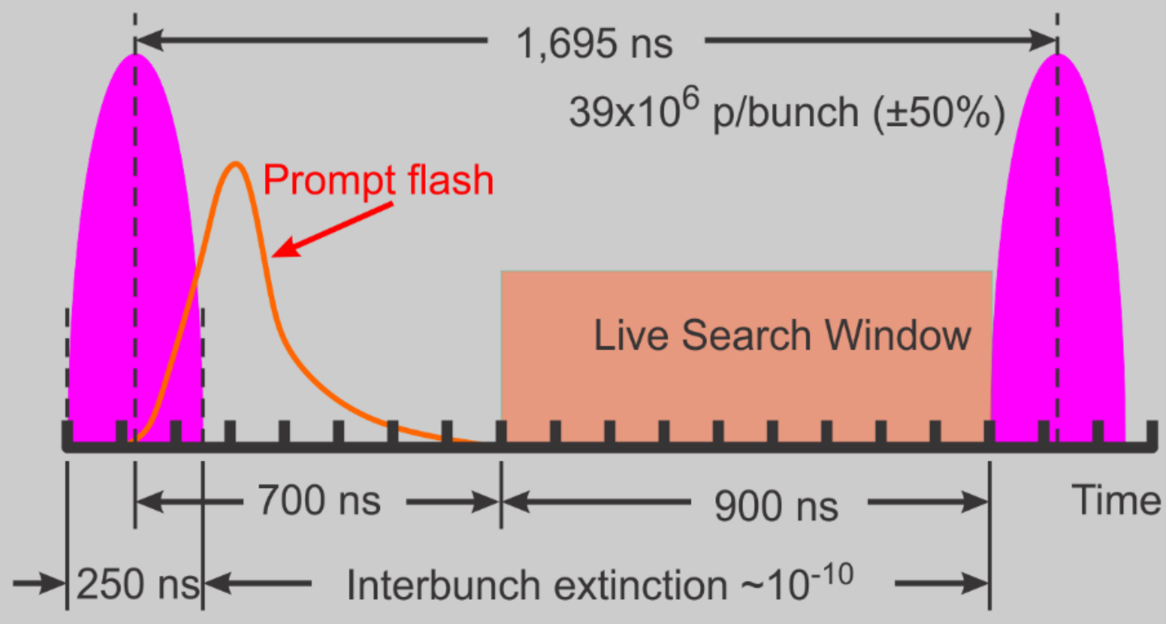
Cross sectional view of the Mu2e tracker

The Apparatus

- Muon Stopping Target Monitor
  - Located downstream of the detector solenoid
  - Germanium detector
  - Used to determine the ordinary muon capture rate for the process $\mu^- + {}^{27}_{13}Al \rightarrow \nu_\mu + {}^{27}_{12}Mg$
    - This process happens in 13% of all muon captures in Al.
    - This rate is the rate in the denominator of the conversion rate $R_{\mu e}$ (the number which we are interested in).
  - Measured indirectly via
    - X-ray (347 keV, 80% of all muon stops in Al) when muons transition from the 2p to 1s state in the aluminum.
    - Prompt γ (1809 keV, 51% of all muon captures in Al): $\mu^- + {}^{27}_{13}Al \rightarrow \nu_\mu + {}^{26}_{12}Mg^* + n$ → ${}^{26}_{12}Mg^* \rightarrow {}^{26}_{12}Mg + \gamma$
    - Delayed γ (844 keV, 9% of all muon captures in Al): ${}^{27}_{12}Mg \rightarrow {}^{27}_{13}Al^* + e^- + \bar{\nu}_e$ → ${}^{27}_{13}Al^* \rightarrow {}^{27}_{13}Al + \gamma$

Backgrounds

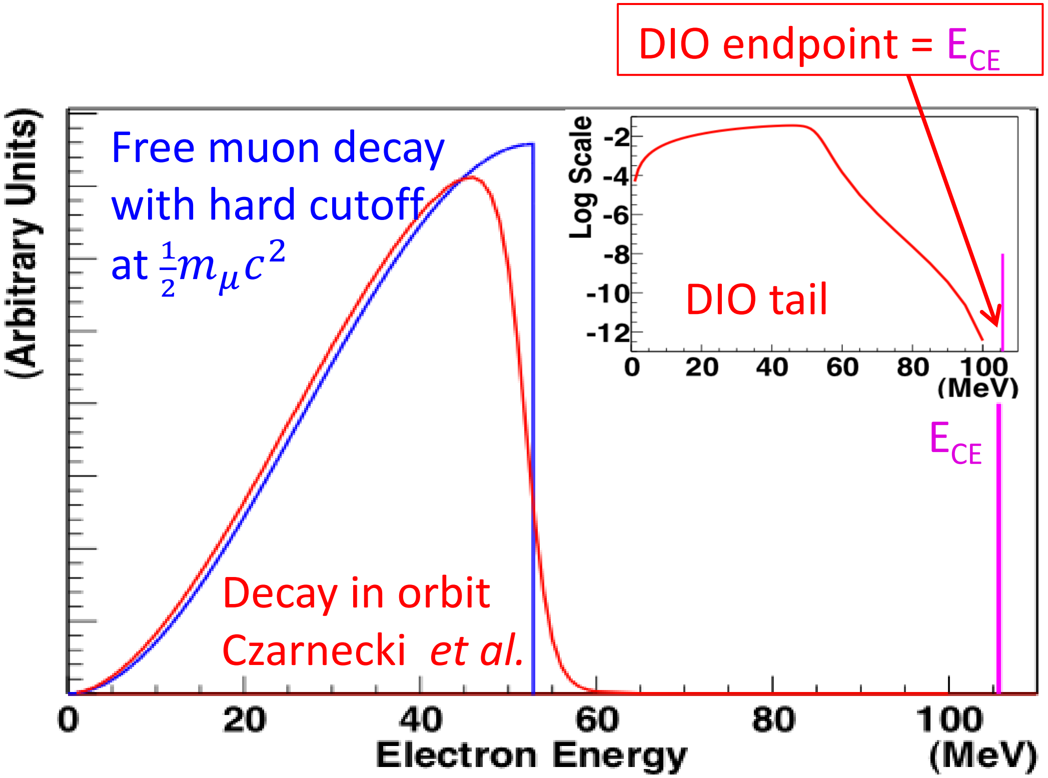
- Prompt background around the time when the beam arrives at the stopping target
  - Sources
    - Beam electrons
    - Muon decay in flight
    - Pion decay in flight
    - Radiative pion capture



- May create electrons with energies close to 105 MeV (energy of the conversion electrons).
- Can be suppressed by not taking data during the first 700 ns after the peak of the proton pulse.
  - However, this prompt background cannot be eliminated entirely, since some of the protons arrive "out of time".

Backgrounds

- Electrons from muon decay in orbit (DIO) of the aluminum
  - Only a small fraction of these electrons are in the signal interval of 1.25 MeV around the conversion electron energy E_{CE} of 105 MeV.



DIO endpoint = E_{CE}

Free muon decay with hard cutoff at $\frac{1}{2}m_\mu c^2$

DIO tail

E_{CE}

Decay in orbit Czarnecki *et al.*

- Anti-protons
  - Annihilation products may mimic conversion electrons.

- Cosmic ray muons
  - Main topic of this talk

CRV Electronics

- The readout ends of the counters are connected to front end board (FEBs) via HDMI cables.
- FEBs
  - 64 channels
  - Provides bias voltage to the SiPMs
  - Responsible to signal pre-amplification and shaping, analog to digital conversion
  - Digitization happens in 12.55 ns intervals.
- High-speed serial links via Ethernet between FEBs and a readout controller
- CRV data processing is done offline.

Event Reconstruction: Pulse Fit

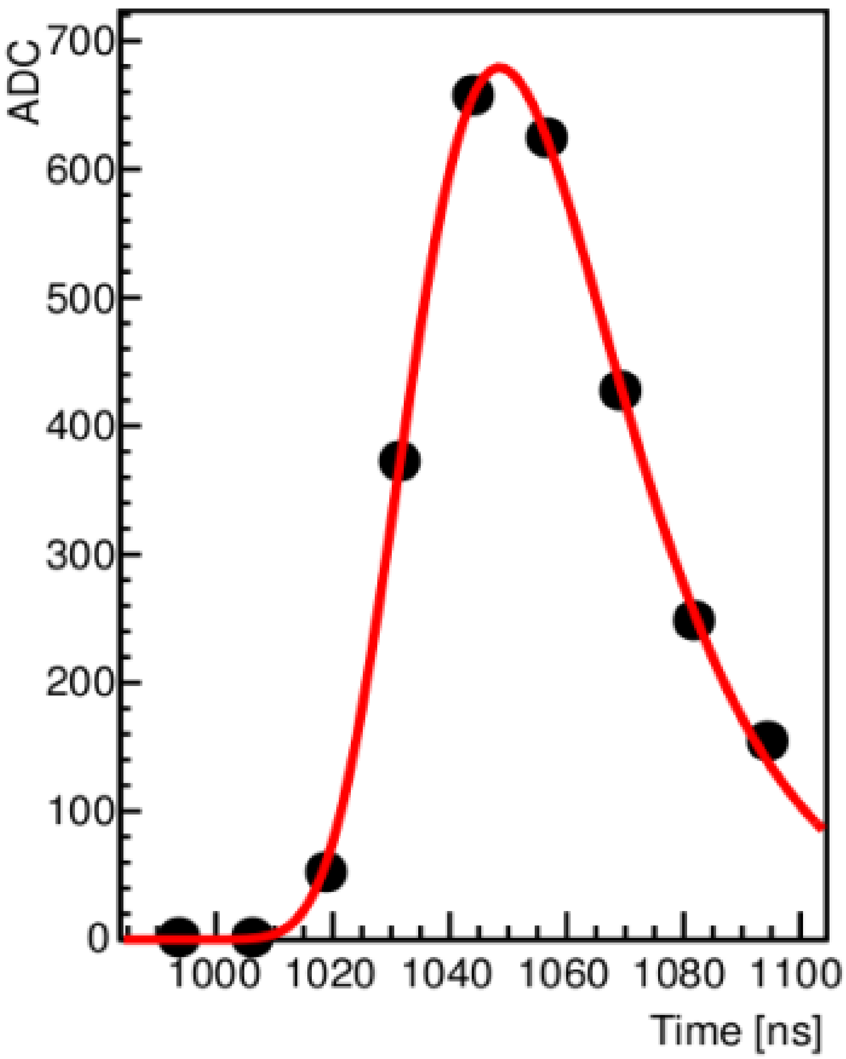
- Pulses are fitted with a modified form of the Gumbel distribution

$$f(t) = A \cdot e^{-\frac{t-\mu}{\beta} - e^{-\frac{t-\mu}{\beta}}}$$

  - Pulse height: A/e
  - Peak time: μ
  - Pulse area: $A \cdot \beta$

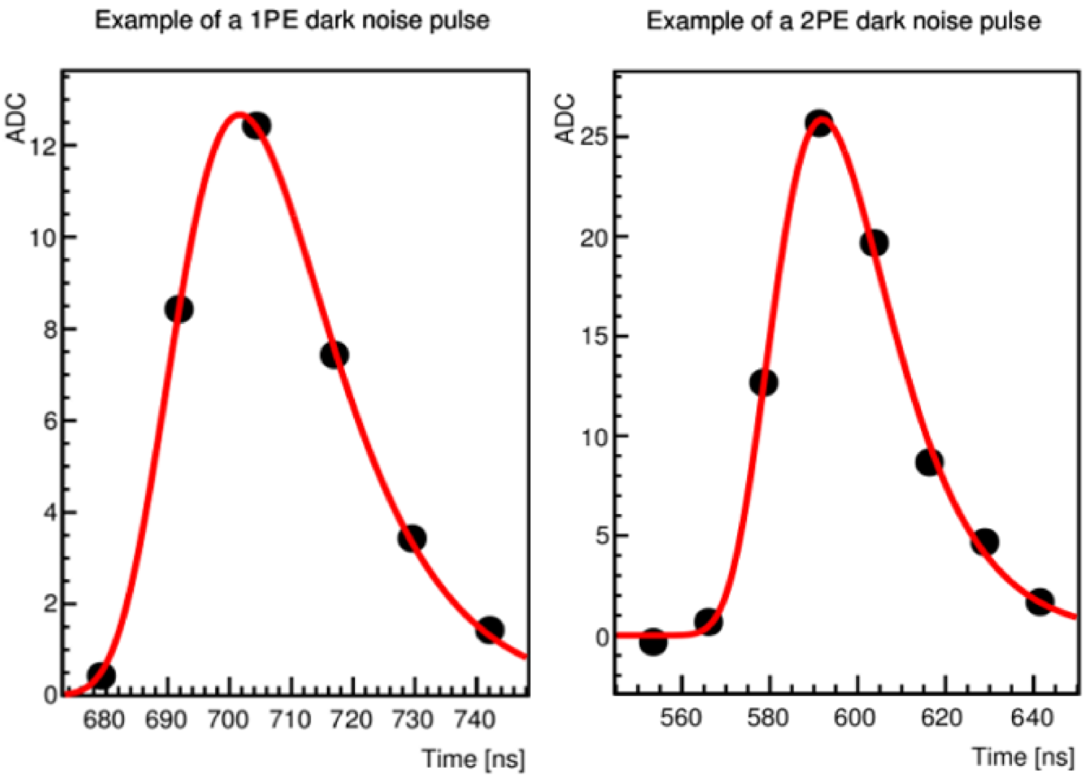
- Pulse area is proportional to the number of PEs.
  - A calibration is required to translate the pulse area into PEs.

Example of a 78PE pulse



Event Reconstruction: Calibration

- Calibration to find a translation between pulse area and number of PEs.
- Search for dark noise pulses in the pre-signal region of the waveform. The area under these pulses corresponds to 1 PE.



- Occasionally, optical cross talk may create simultaneous pulses in more than one pixel. In these cases, the measured pulse areas will correspond to 2 PEs, 3 PEs, or even more PEs.
- These pulse areas are put into a histogram (see next slide).

Event Reconstruction: Calibration

- Find the 1PE and 2PE peaks in the pulse area histogram.
- Make a linear fit to find the calibration factor.