The Mu2e Experiment

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Outline

- Short Overview of Mu2e
- Charged Lepton Flavor Violation
- The concept behind Mu2e
- Mu2e Design
- Summary

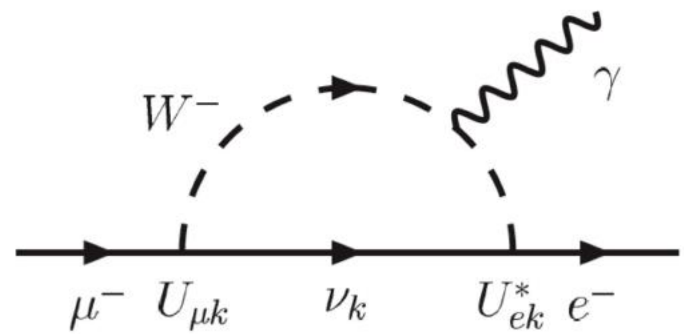
Short Overview of Mu2e

Mu2e is looking for coherent neutrinoless muon to electron conversions in the field of an atomic nucleus.

- A beam of muons is being stopped at a target, where it forms a bound state with this nucleus.
- Coherent neutrinoless muon to electron conversions in the field of a nucleus ($\mu^- N \rightarrow e^- N$) lead to monoenergetic electrons.
- Mu2e searches for these electrons.

Charged Lepton Flavor Violation

- Possible with via neutrino oscillation
  - Branching fraction for $\mu \rightarrow e\gamma$ is ≤10^{-54}
  - Unobservable low probability



- An observation of a CLFV process mean that there is new physics beyond the Standard Model

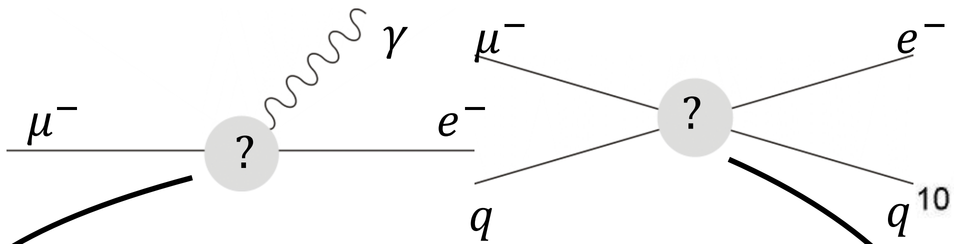
Current Limits on CLFV Processes

- $\mu \rightarrow 3e$: $1.0 \cdot 10^{-12}$ (SINDRUM-I)
- $\mu \rightarrow e\gamma$: $2.4 \cdot 10^{-12}$ (MEG)
- $\mu^{-}N \rightarrow e^{-}N$
  - with titanium $4.3 \cdot 10^{-12}$ (SINDRUM-II)
  - with gold $7.0 \cdot 10^{-13}$ (SINDRUM-II)
  - Mu2e's sensitivity goal (with aluminum) $6.0 \cdot 10^{-17}$

- Mu2e will achieve an improvement of the sensitivity by about 4 orders of magnitude.
- The above channels have different underlying "new physics". So we must study all of them.

Current Limits on CLFV Processes

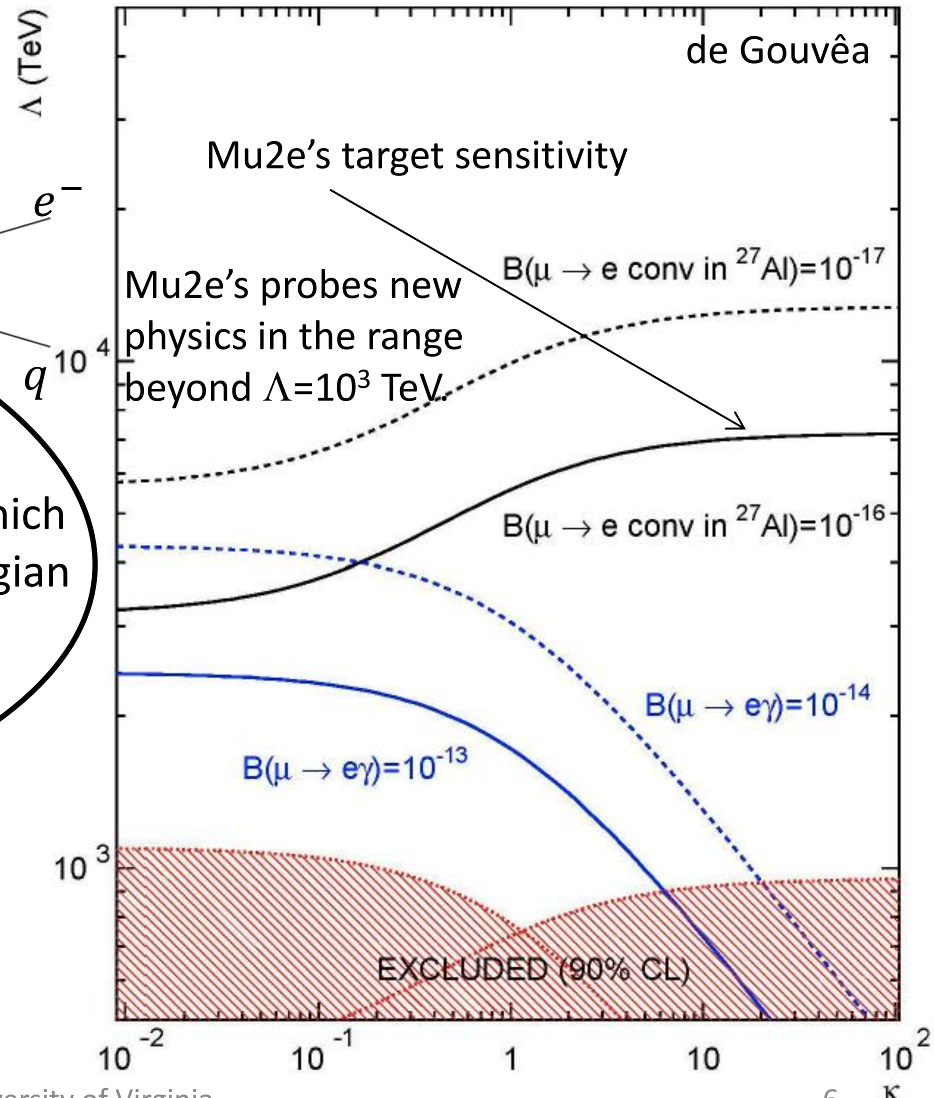
Underlying new physics can be separated into two groups of effective processes



They can be described by the following two model independent effective CLFV terms, which can be added to the Standard Model Lagrangian

$$L_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu}$$
$$+ \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}_L \gamma^\mu q_L\right)$$

where Λ is the mass scale of new physics, and κ weights the relative contributions of both CLFV terms.



The concept behind Mu2e

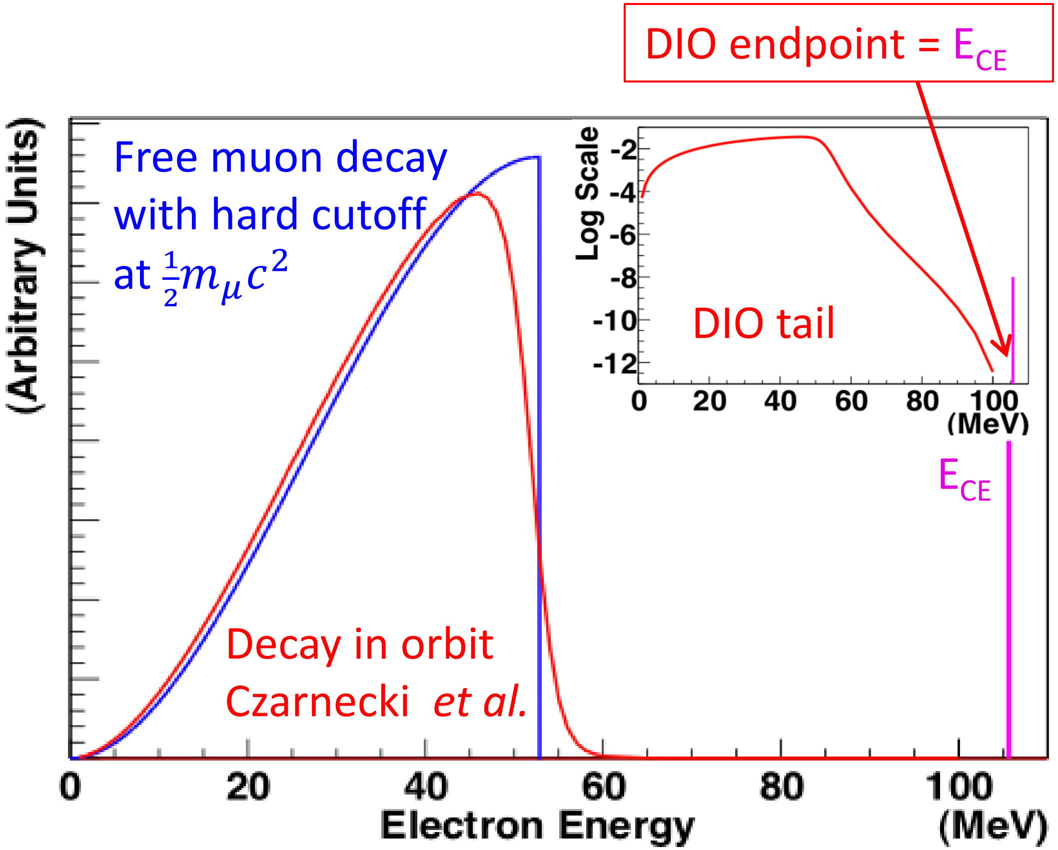
- μ^- gets stopped in an aluminum atom to form a 1S bound state.
- One of the following three things may happen:
  - The muon decays in orbit: $\mu^- + Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu + Al$
    (40 % probability)
  - Since the wave functions of muon and nucleus overlap significantly, the nucleus can easily capture the muon: $\mu^- + Al \rightarrow \nu_\mu + Mg$
    (60 % probability)
  - Coherent neutrinoless muon to electron conversion $\mu^- + Al \rightarrow e^- + Al$

The concept behind Mu2e

- Coherent neutrinoless muon to electron conversion in the orbit of an Al atom
  - results in an electron with an energy of 104.97 MeV
  - $E_{CE} = m_\mu c^2 - B_\mu(Z = 13) - C_\mu(A = 27)$
    - m_μ muon mass 105.66 MeV/c^2
    - B_μ atomic binding energy of the muon in the 1S state in the orbit of ${}^{27}_{13}Al$ 0.48 MeV
    - C_μ nuclear recoil energy of ${}^{27}_{13}Al$ 0.21 MeV

The concept behind Mu2e

- Muon decay in orbit (DIO)
  - Signal energy interval around the conversion electron energy is far away from the majority of the electrons coming from muon decays in orbit.
  - A small fraction of only 10^{-17} DIO electrons are in the signal region (1.2 MeV around E_{CE}).



The concept behind Mu2e

- Mu2e will measure the ratio of the coherent neutrinoless muon-to-electron conversion rate vs. the muon capture rate $R_{\mu e} = \frac{N_{\mu e}}{N_C}$

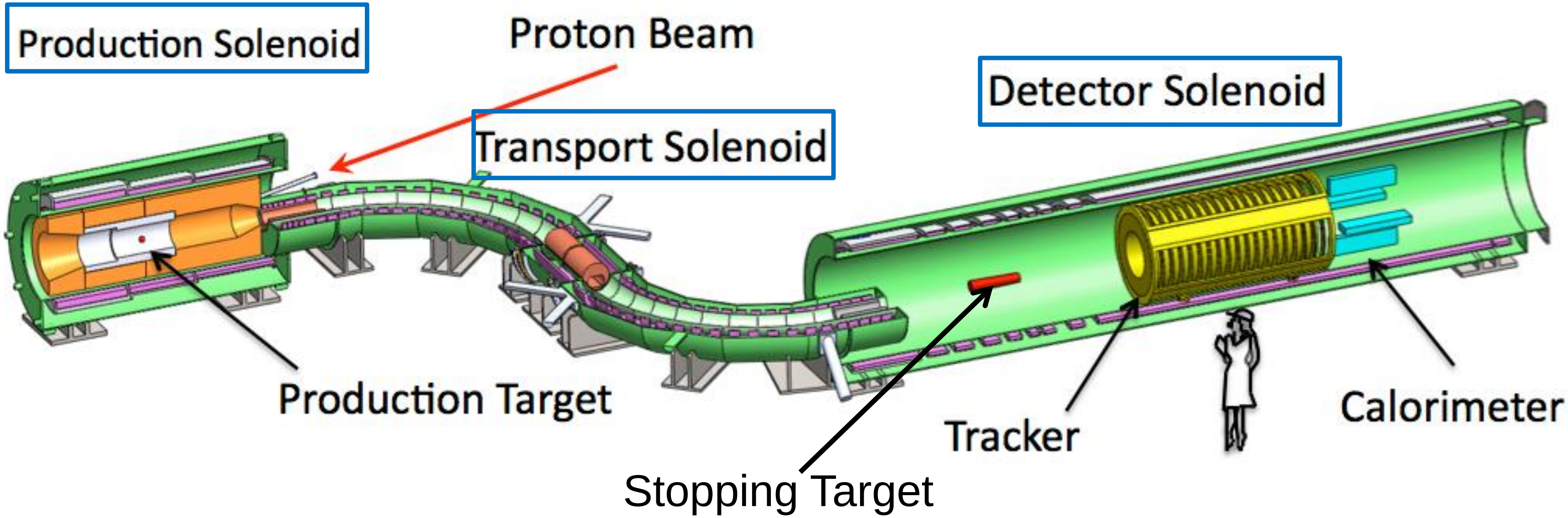
- Mu2e will take date over three years, with a run time of $2.0 \cdot 10^7 s$ per year to reach a single event sensitivity of $6.0 \cdot 10^{-17}$ (90% CL).

Background Estimate

Muon decay in Al orbit	53 %
Antiprotons	24 %
Cosmic Rays	12 %
Radiative pion capture in Al	7 %
Muon decay-in-flight	3 %
Pion decay-in-flight	1 %
Beam electrons	$1 \cdot 10^{-3}$ %
Radiative muon capture in Al	$5 \cdot 10^{-6}$ %

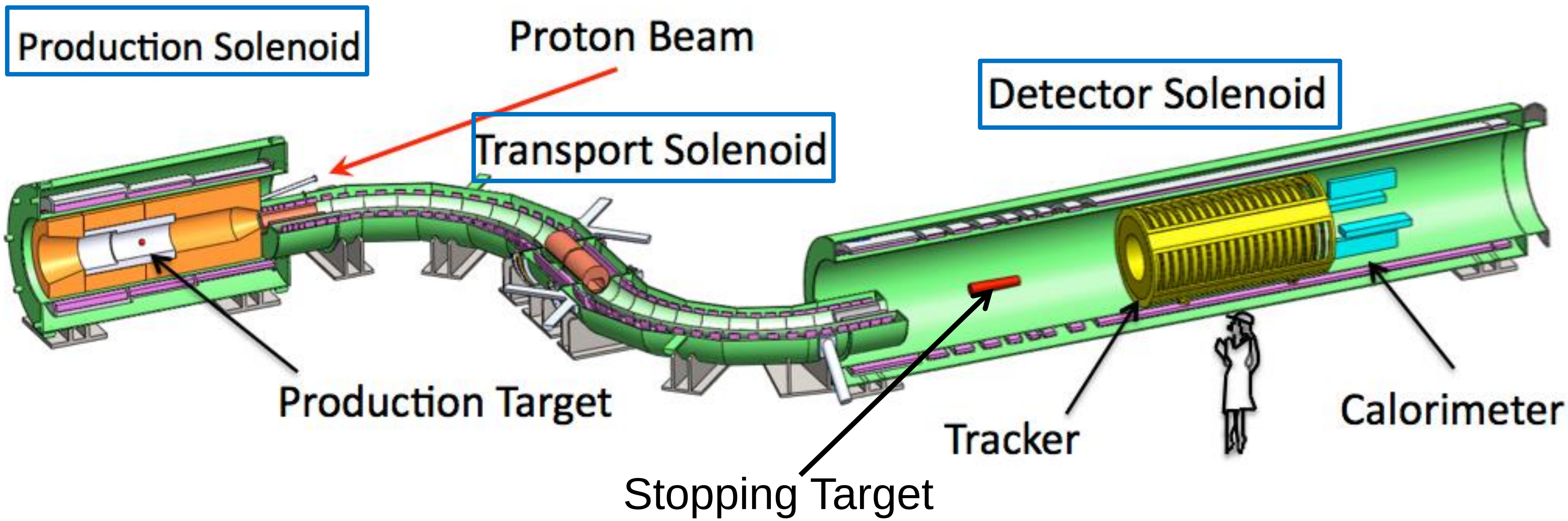
Total background for the three year run is estimated to be 0.41 events.

The Mu2e Design – Overview



- Three Superconducting Solenoids
  - Production Solenoid
  - Transport Solenoid
  - Detector Solenoid
- Inner bore evacuated to
  - 10^{-1} Torr (Production Solenoid, and upstream half of Transport solenoid)
  - 10^{-4} Torr (Detector Solenoid, and downstream half of Transport solenoid)

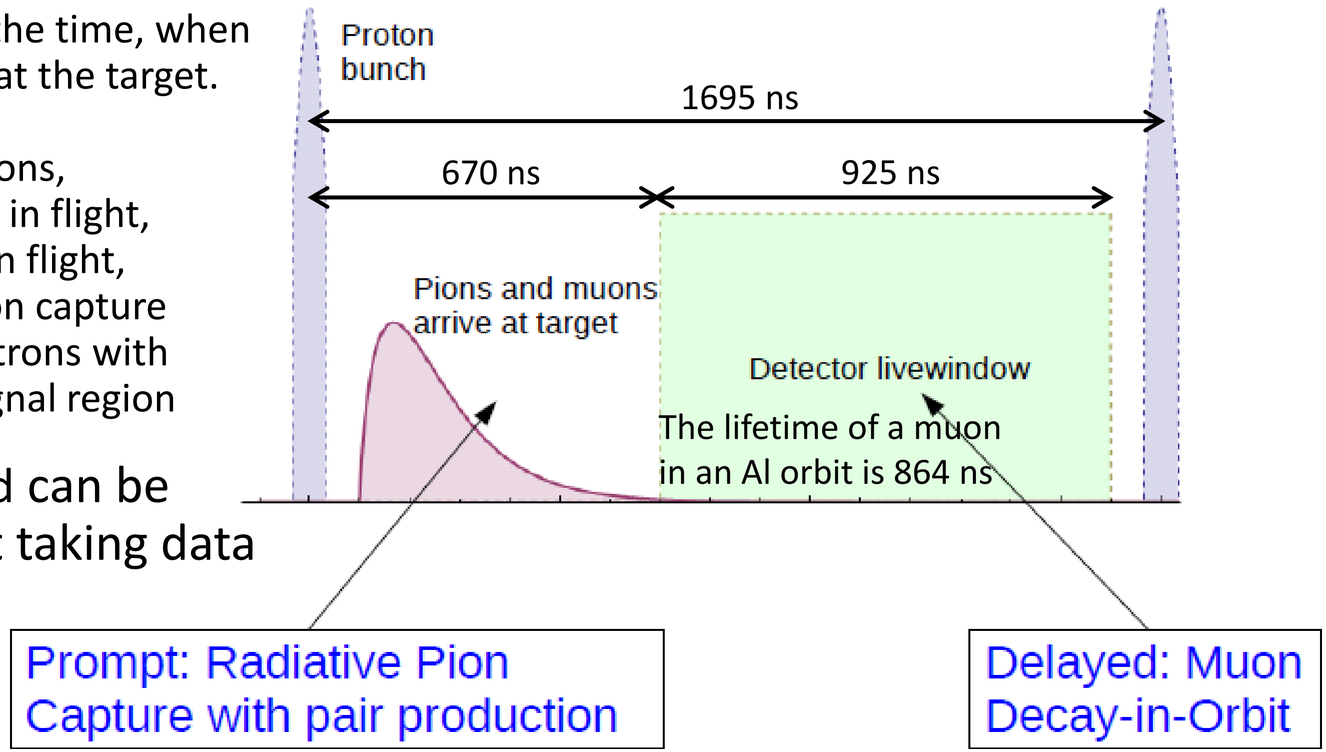
The Mu2e Design – Overview



- A pulsed proton beam 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 hit the aluminum stopping target.
- If conversion electrons are produced in the stopping target, they will move through the tracker to the calorimeter.

Prompt Background Suppression

- Prompt background
  - Happens around the time, when the beam arrives at the target.
  - Sources
    - beam electrons,
    - muon decay in flight,
    - pion decay in flight,
    - radiative pion capture
  - May creaste electrons with energies in the signal region

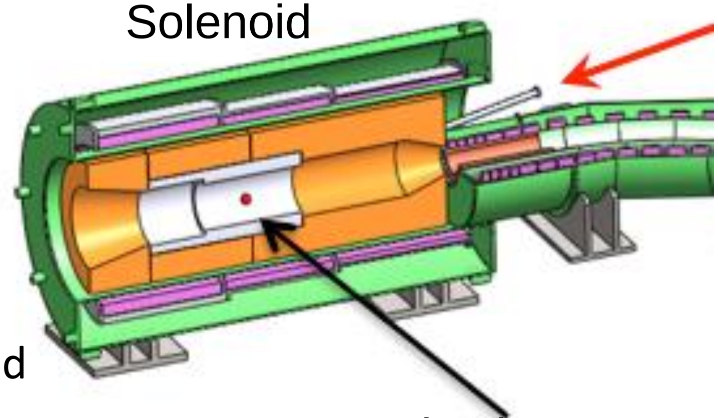


- Prompt background can be suppressed by not taking data during the first 670 ns after the peak of the proton pulse.

- However, this prompt background cannot be eliminated entirely, since some of the protons arrive "out of time".
  - A ratio of 10^{-10} is required for the beam between pulses vs. the beam contained in a pulse.

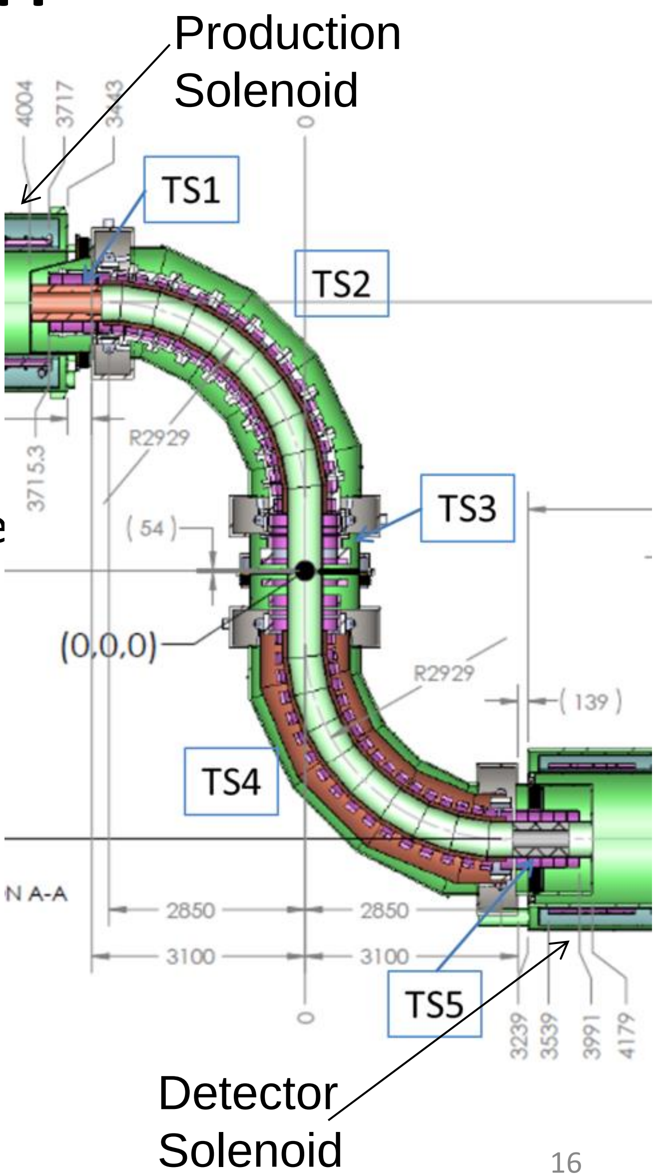
Mu2e Design

- Production Solenoid
  - Pulsed proton beam coming from Fermilab's Booster
    - 8 GeV protons
    - every 1695 ns / 200 ns width
  - Production target
    - tungsten rod
    - 16 cm long with a 3 mm radius
    - produces pions, which decay into muons
  - Production Solenoid
    - produces a graded magnetic field between 4.6 T (at end) and 2.5 T (towards the transport solenoid) traps the charged particles and accelerates them toward the transport solenoid



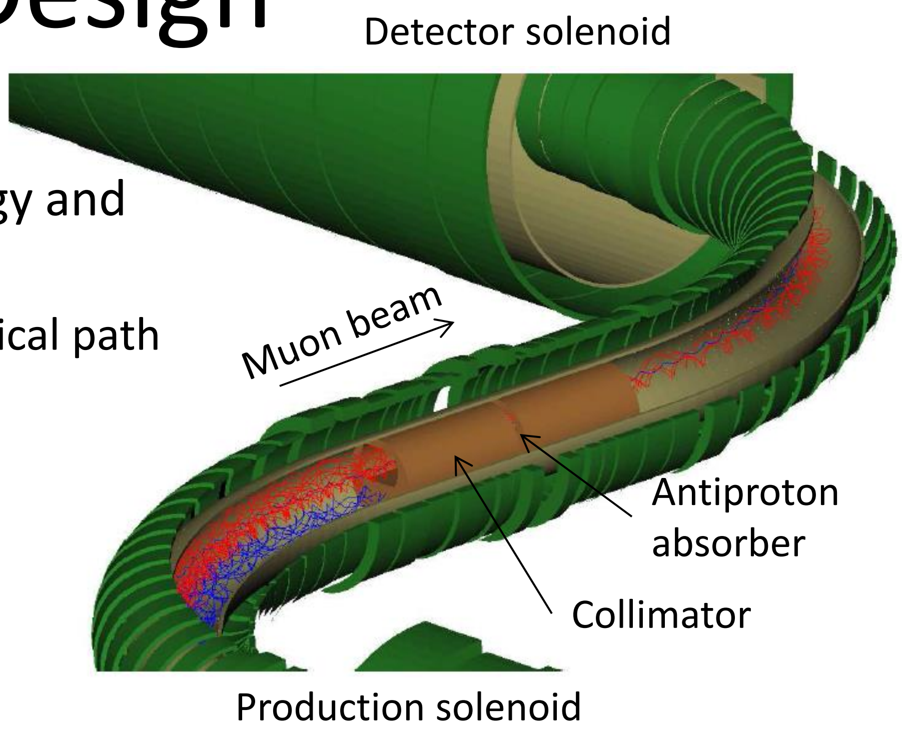
Mu2e Design

- Transport Solenoid
  - Graded magnetic from 2.5 T (at the production solenoid entrance) to 2.0 T (at the detector solenoid entrance)
  - Muons to travel on a helical path from the production solenoid to the detector sole
  - S-shaped to remove the detector solenoid out of the line of sight from the production solenoid
    - Prevents neutrons and gammas produced at the production target to enter the detector solenoid.



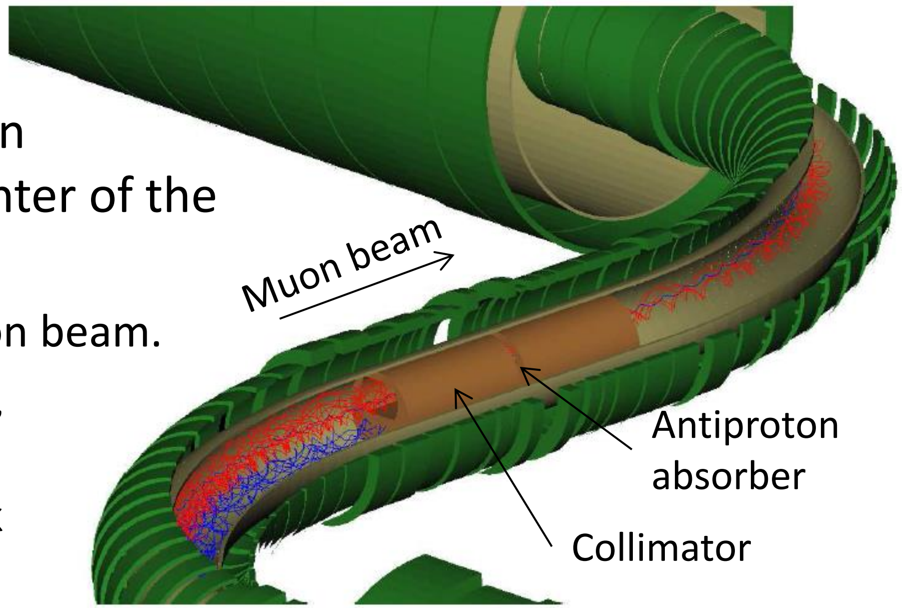
Mu2e Design

- Transport Solenoid (cont.)
  - Negative particles with high energy and positive particles get removed
    - In the first toroid section, the helical path of the negative (positive) particles are bent up (down) due to the magnetic field.
    - The deflection depends on their momentum.
    - An asymmetric collimators in the straight section allows only low energy negative particles through.
    - In the second toroid section, the helical path of the remaining particles are bent back to the center axis.



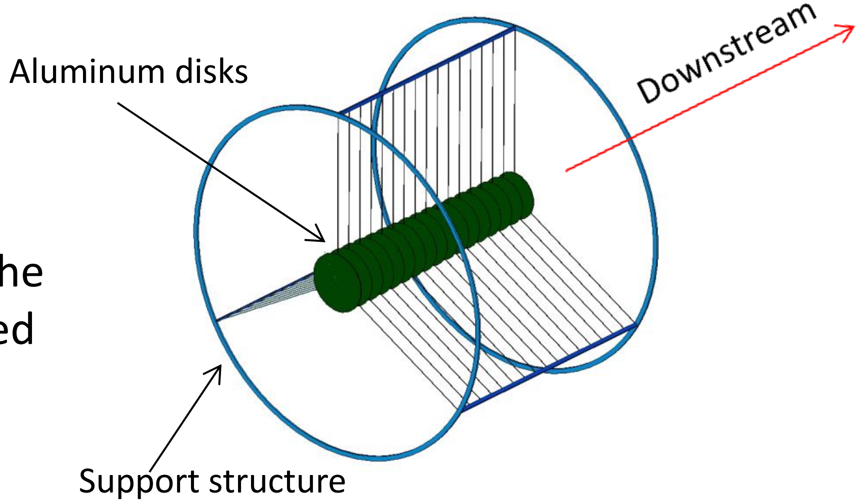
Mu2e Design

- Transport Solenoid (cont.)
  - Antiprotons are absorbed by a thin low Z absorber material at the center of the transport solenoid.
    - Has only little impact on the muon beam.
    - Antiprotons need to be removed, since their annihilation products may include electrons which look like conversion electrons.



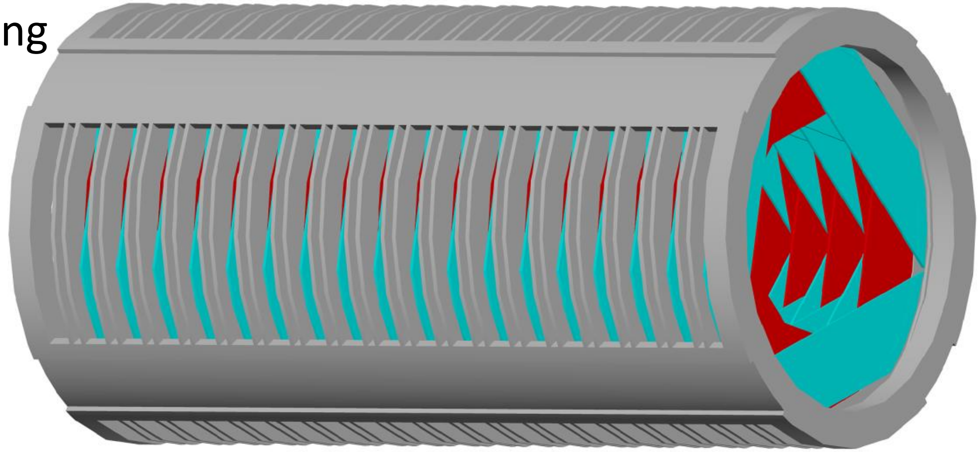
Mu2e Design

- Detector Solenoid
  - Stopping Target
    - 17 Aluminum disks
      - 0.2 mm thick
      - radius between 8.3 mm (upstream) and 6.53 mm (downstream)
    - Is surrounded by graded magnetic field from 2.0 T (upstream) to 1.0 T (downstream)
      - Conversion electrons will travel on a helical path toward the tracker.
      - Electrons ejected away from the tracker experience an increased magnetic field which reflects them back toward the tracker.



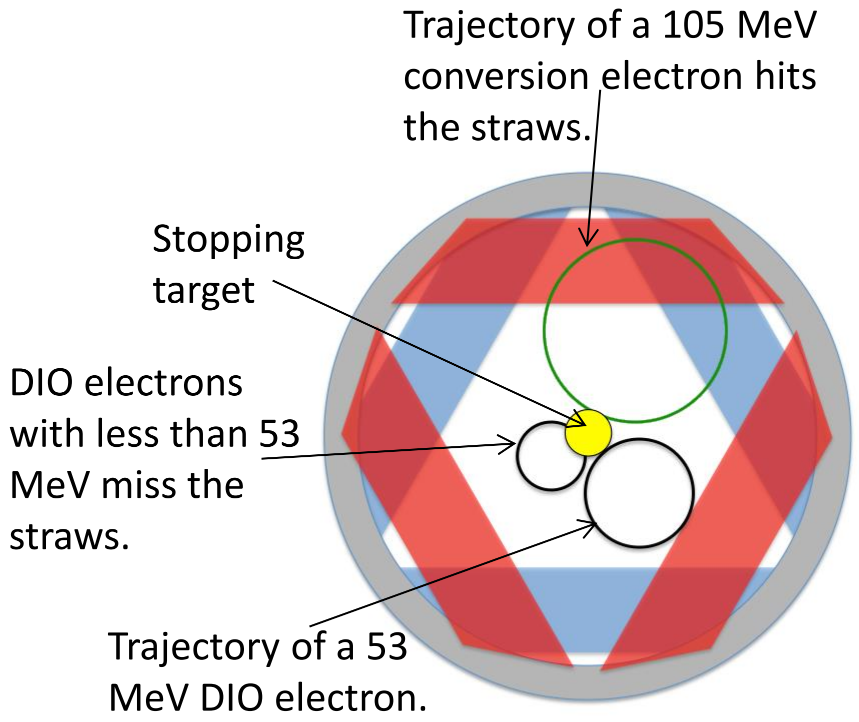
Mu2e Design

- Detector Solenoid (cont.)
  - Tracker
    - Surrounded by a uniform 1 T magnetic field
    - Conversion electrons will travel on a helical path through the tracker
    - Measures the trajectories of conversion electrons
    - Most decay-in-orbit electrons have radii which are so small so that they don't intercept the tracker straws (due their low energies)
    - 3 m long
    - Made of 21,600 straw drift tubes
      - 5 mm diameter tube, 15 µm thick walls
      - 334 mm to 1174 mm long
      - 25 µm diameter sense wire in the center



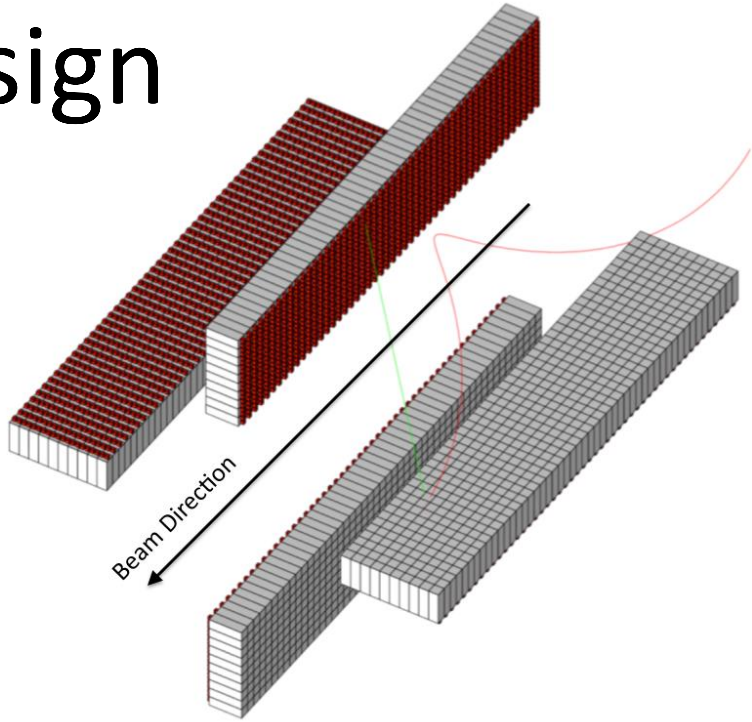
Mu2e Design

- Detector Solenoid (cont.)
  - Tracker

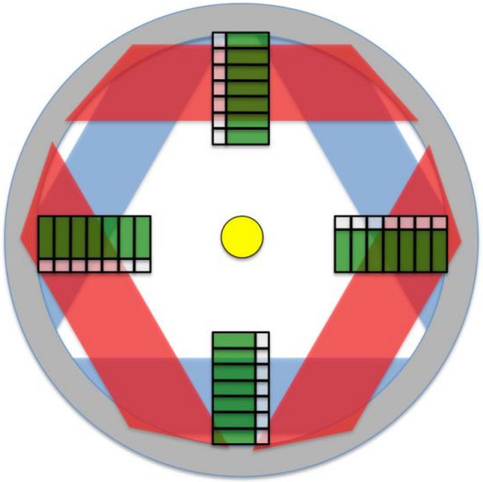


Cross sectional view of the Mu2e tracker

Mu2e Design



- Detector Solenoid (cont.)
  - Calorimeter
    - Provides a secondary and independent tool to measure the energy and trajectory of the electrons.
    - Useful to reduce the background
    - 4 vanes of LYSO crystals
      - Each vane is made of 11 by 44 crystals
      - Crystal dimensions: $3 \times 3 \times 11$ cm^3
      - Read out by avalanche photo diodes



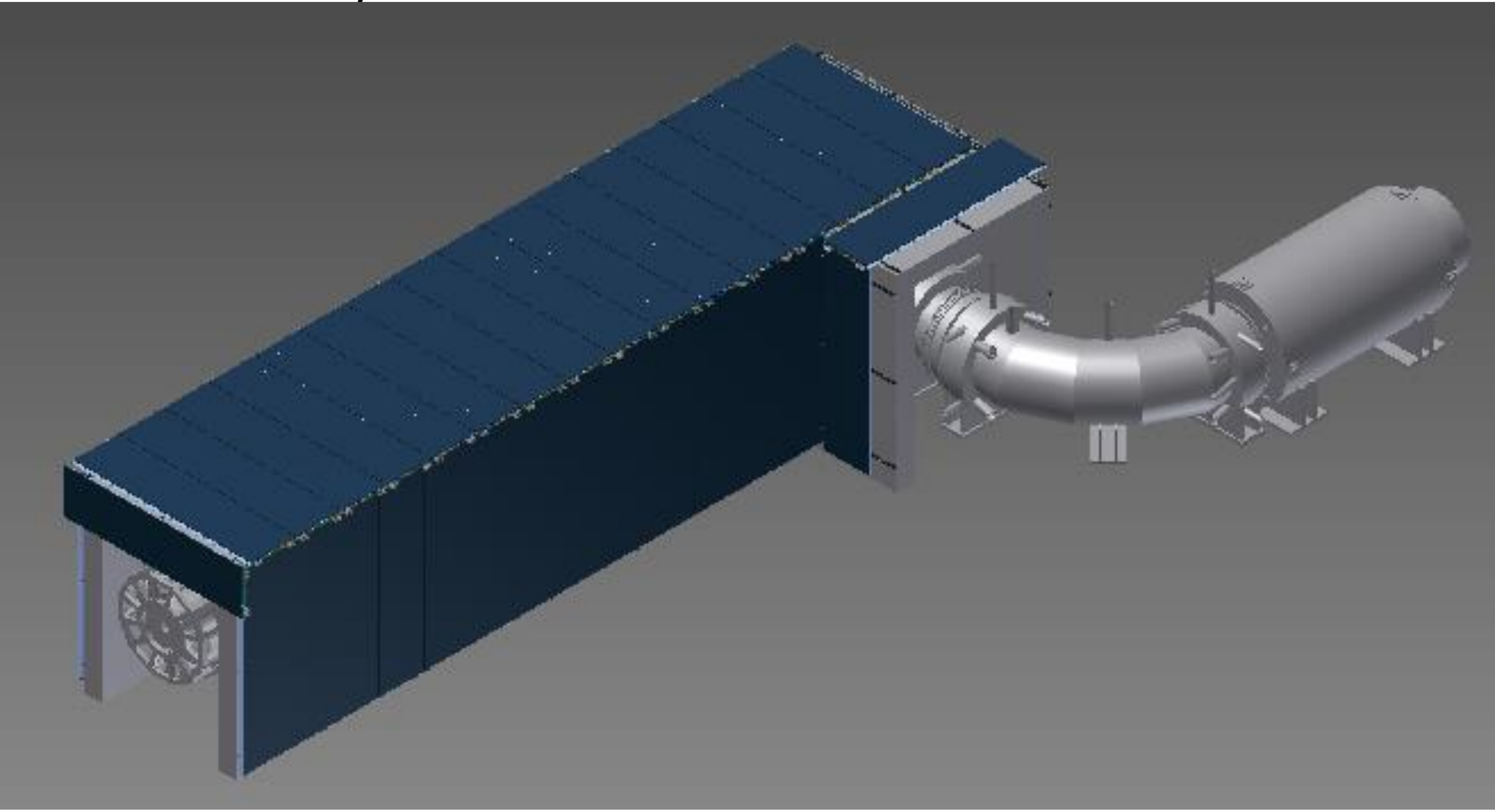
Endview of tracker and calorimeter vanes

Mu2e Design

- Cosmic Ray Veto
  - Cosmic rays have the potential to create electrons which look like conversion electrons.
  - Cosmic rays will get vetoed by active shielding (veto counters) around the detector solenoid and a portion of the transport solenoid.
  - Needs to have an efficiency of more than 0.9999 to achieve the proposed background rate
  - Consists of 3 layers of scintillator counters with embedded wave shifting fibers
    - read out by SiPMs
    - Counter dimensions $4{,}700 \times 100 \times 10\ mm^3$
    - Total of 2088 counters

Mu2e Design

- Cosmic Ray Veto



Status

- Currently in the prototype stage
- Data taking expected to begin in 2019

The Mu2e collaboration

- Boston University
- Brookhaven National Laboratory
- California Institute of Technology
- City University of New York
- Duke University
- Fermi National Accelerator Laboratory
- Institute for Nuclear Research, Moscow, Russia
- Instituto Nazionale di Fisica Nucleare Lecce and Università del Salento
- Instituto Nazionale di Fisica Nucleare Lecce and Università Marconi Roma
- Instituto Nazionale di Fisica Nucleare Pisa
- Joint Institute for Nuclear Research, Dubna
- Laboratori Nazionali di Frascati
- Lewis University
- Muons, Inc.
- Northern Illinois University
- Northwestern University
- Pacific Northwestern National Laboratory
- Rice University
- Universita di Udine and INFN Trieste/Udine
- University of California, Berkeley
- University of California, Irvine
- University of Houston
- University of Illinois, Urbana-Champaign
- University of Massachusetts, Amherst
- University of Virginia
- University of Washington

Summary

- Mu2e's goal is to improve the sensitivity on charged lepton flavor violation by four orders of magnitude to $6.0 \cdot 10^{-17}$ (90 % CL).
- An observation of coherent neutrinoless muon to electron conversions means that there is new physics beyond the Standard Model.
- If we don't see coherent neutrinoless muon to electron conversion, we will put huge constraints on many models of new physics.

References

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- A. Czarnecki *et al.*, Muon decay in orbit: spectrum of high-energy electrons, arXiv [hep-ph] 1106.4756v1, 2011
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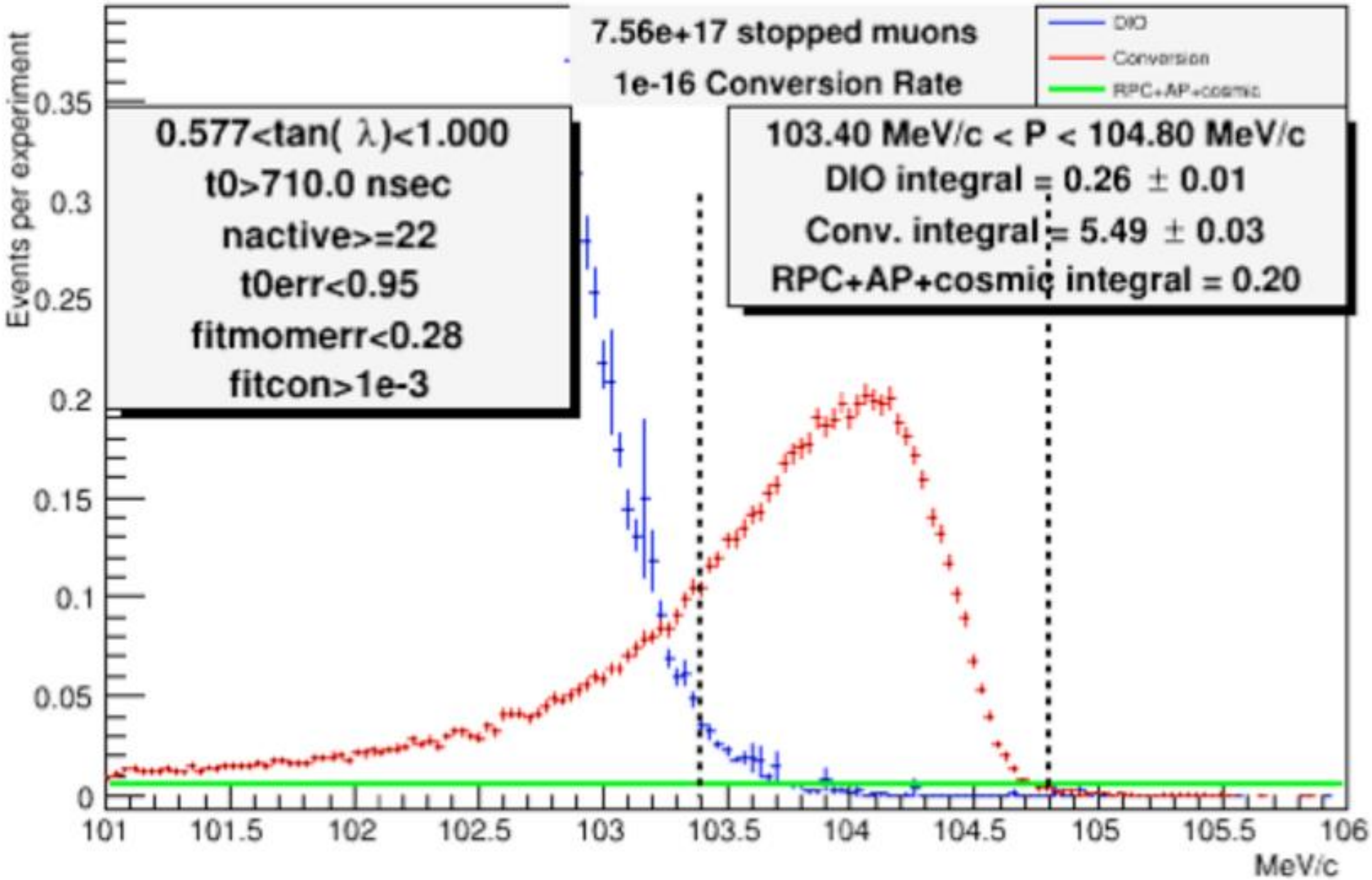
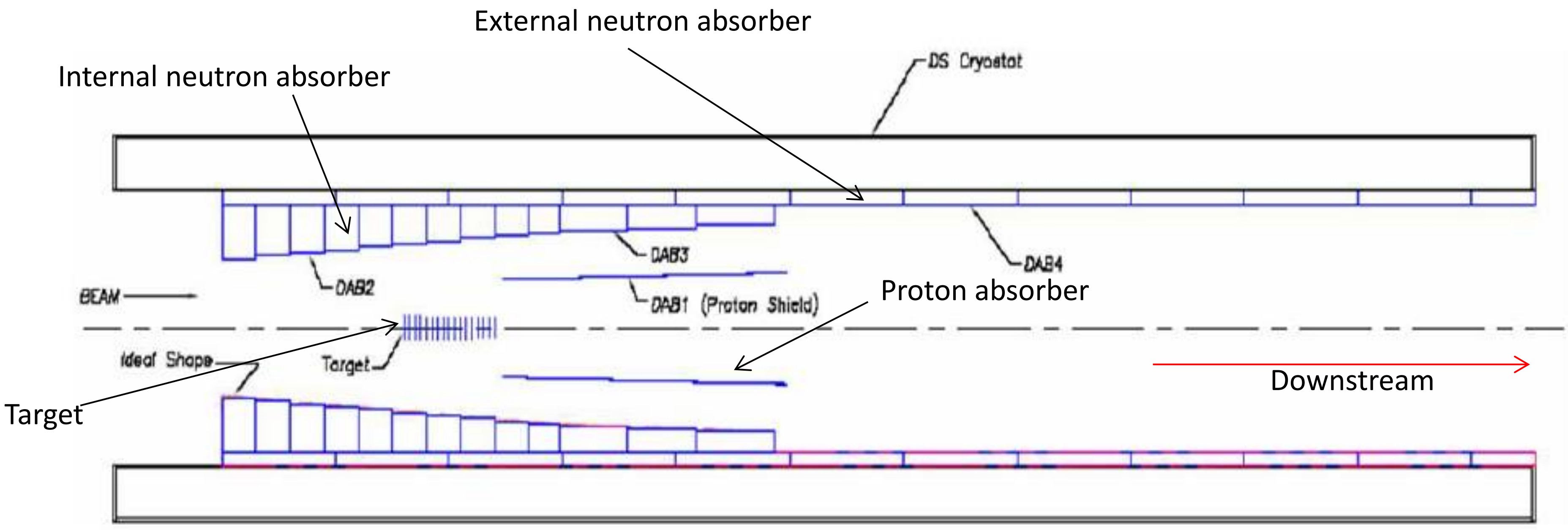
Backup Slide

- Reconstructed Momentum



Backup Slide

- Proton absorber
  - needs to reduces the proton rate from the target (due to muon capture at Al) with only little impact on the conversion electrons.
    - protons may cause misreconstructions in the tracker.
  - thin polyethylene absorber between stopping target and tracker
  - tapered cylindrical shell 0.5 mm



Backup Slide

- Neutron absorber
  - needs to reduces the neutron rate of neutrons coming from the target (due to muon capture on Al)
    - neutrons may cause misreconstructions in the tracker, and also increase the trigger rate in the cosmic ray veto counters
  - External neutron absorber: made of concrete blocks
  - Internal neutron absorber: PE (perhaps loaded with boron or lithium), if it must be used.