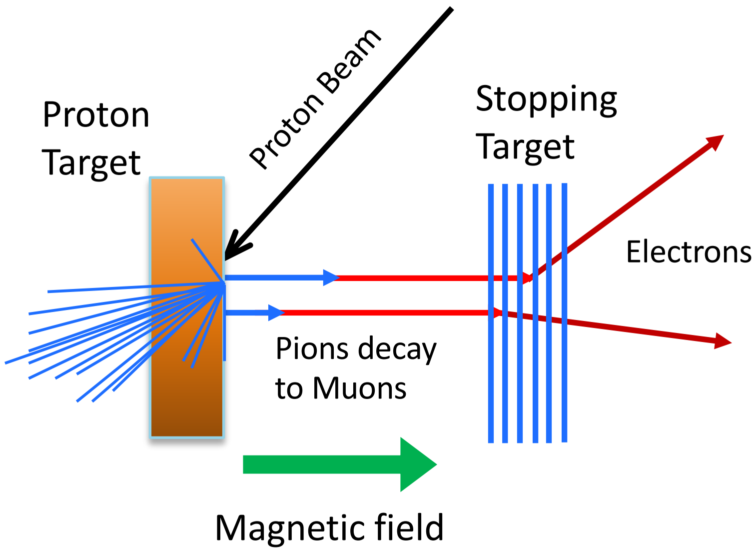
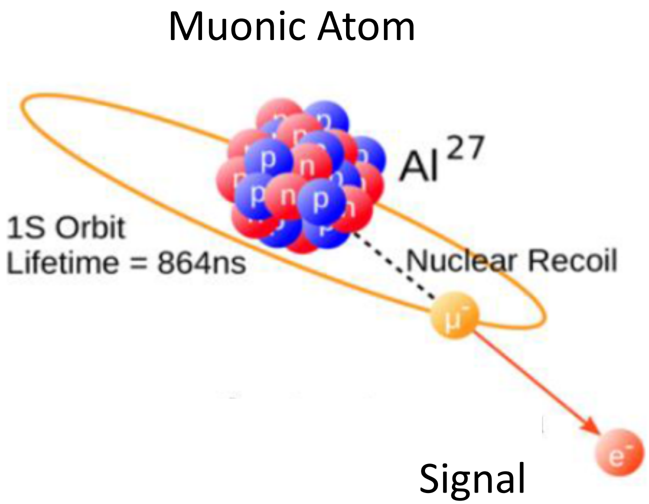
Mu2e at Fermilab

Ron Ray
Fermilab - Mu2e Project Director

Muon to Electron Conversion

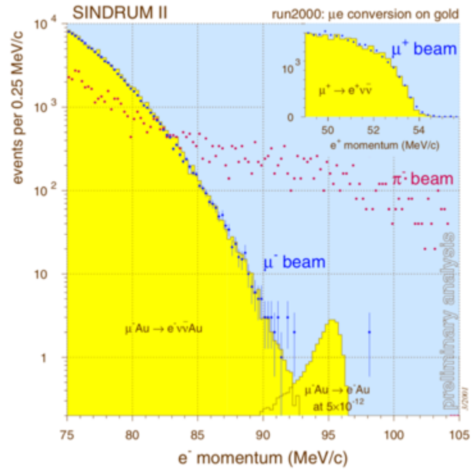




Current state-of-the-art

$$R_{\mu e} = \frac{\Gamma(\mu^- Au \rightarrow e^- Au)}{\Gamma(\mu^- Au\ Capture)} < 7 \times 10^{-13}\ (90\%\ \text{CL})$$

W. Bertl, et al. (SINDRUM-II) Eur. Phys. J. C47 (2006) 337.



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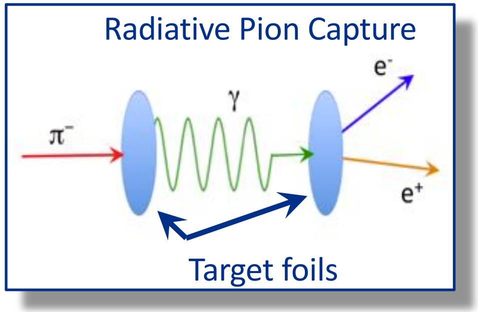
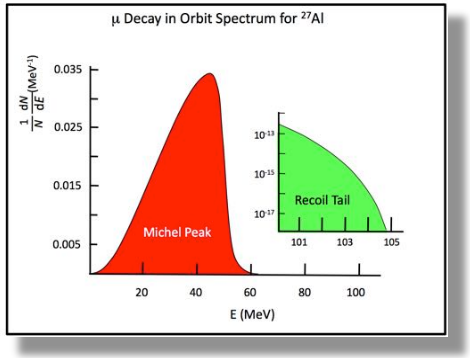
Backgrounds

- Prompt – e⁻ nearly coincident with μ⁻ arrival
  - Radiative Pion Capture (RPC)
  - Muon and pion decay-in-flight



- Intrinsic – scale with the number of stopped muons
  - Decay-in-Orbit (DIO)
    - Recoil tail extends to conversion energy
  - Radiative Muon Capture (RMC)
    - $\mu^{-}Al \rightarrow \gamma\nu Mg$



- Cosmic Rays

- Antiprotons

Backgrounds

- Prompt – e⁻ nearly coincident with μ⁻ arrival
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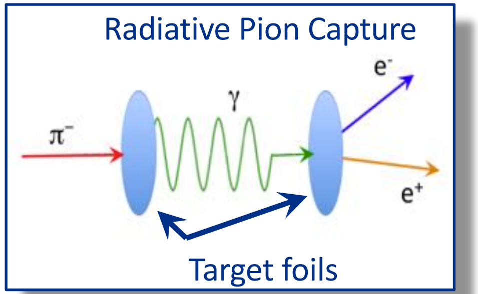
  - Muon and pion decay-n-flight

Pulsed beam + extinction



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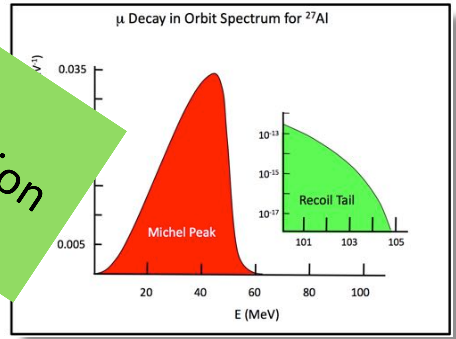
High resolution Tracker



- Cosmic Rays

Active Veto

- Antiprotons

Pbar absorbers

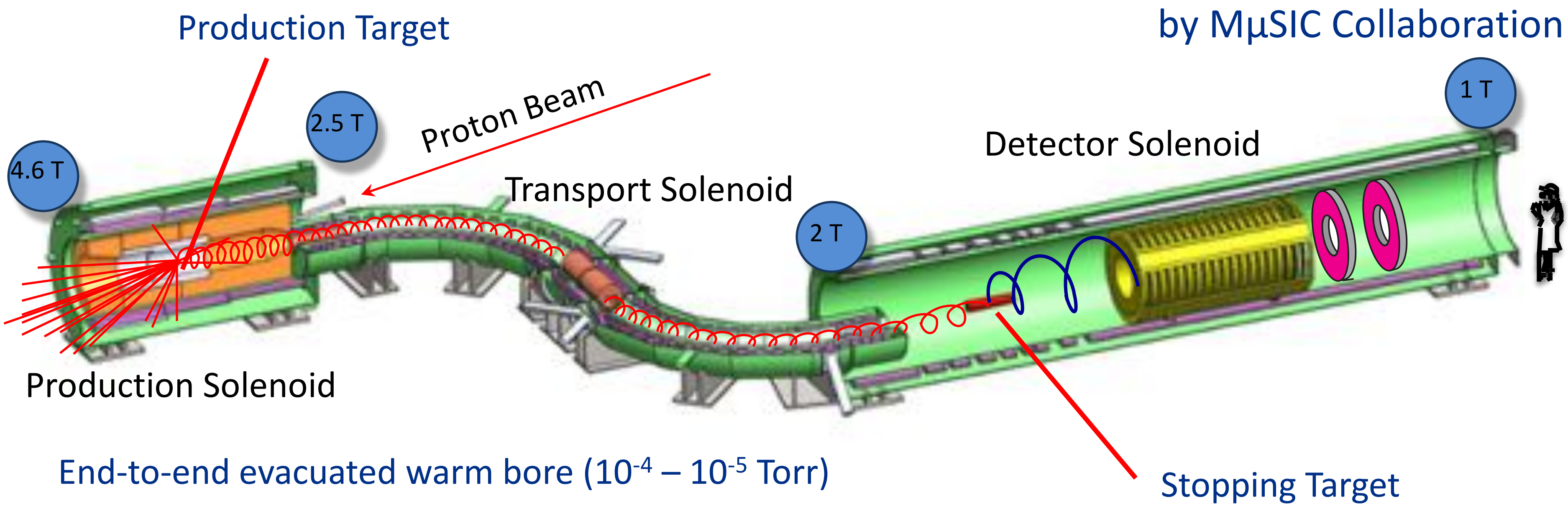
Mu2e

Mu2e Project scope includes

- The Mu2e apparatus
  - Superconducting Solenoids
    - Production Solenoid
    - Transport Solenoid
    - Detector Solenoid

Production and Transport System

- Production target inside superconducting solenoid significantly enhances stopped muon yield
- Collimation system selects muon charge and momentum range
- 10^{10} Hz of stopped muons!
  - Technique demonstrated by MµSIC Collaboration

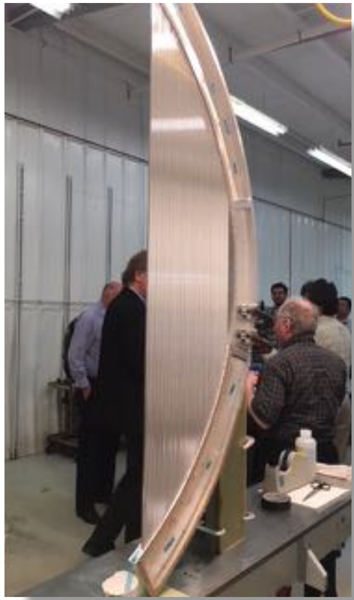


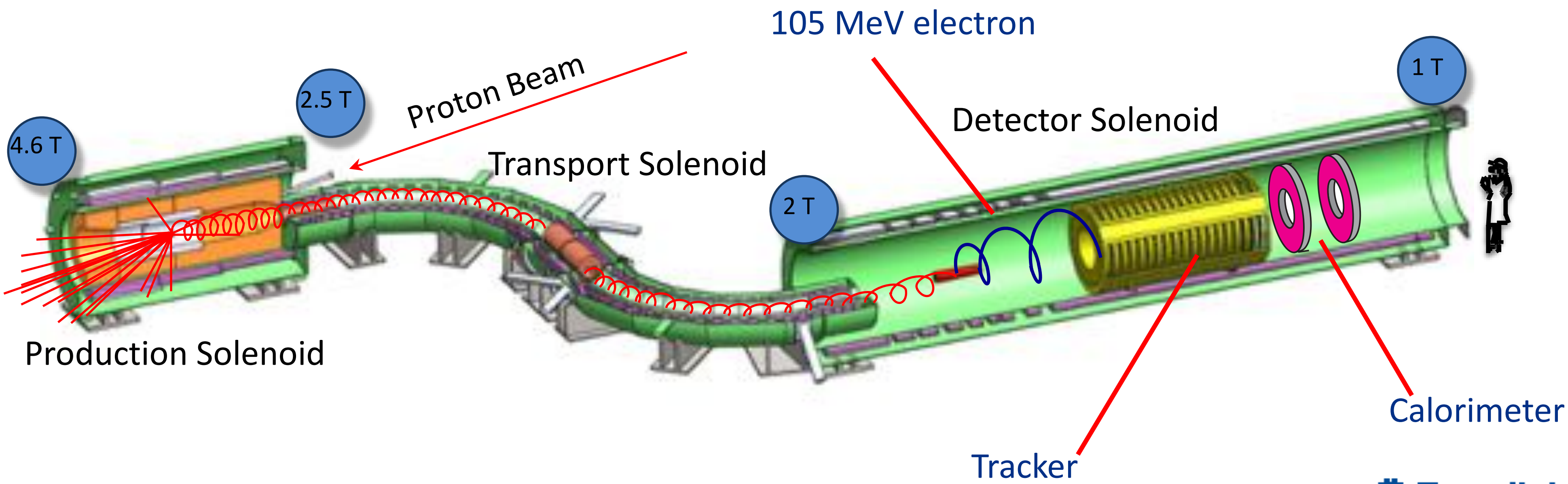
End-to-end evacuated warm bore ($10^{-4} – 10^{-5}$ Torr)

Mu2e Detector

Mu2e Project scope includes

- The Mu2e apparatus
  - Superconducting Solenoids
  - Tracker – Straw drift tubes
  - Calorimeter – Pure CsI crystals

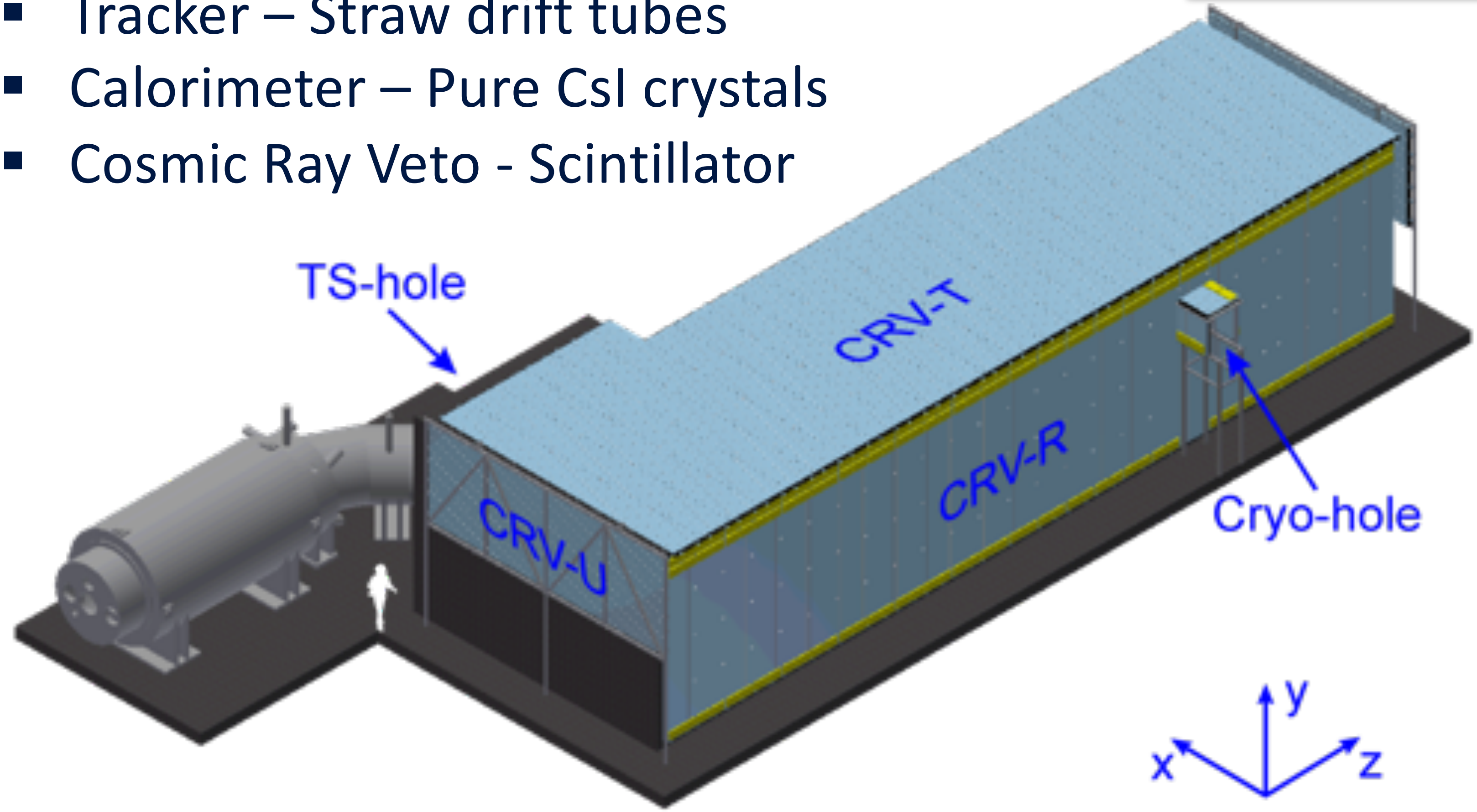




Mu2e Detector

Mu2e Project scope includes

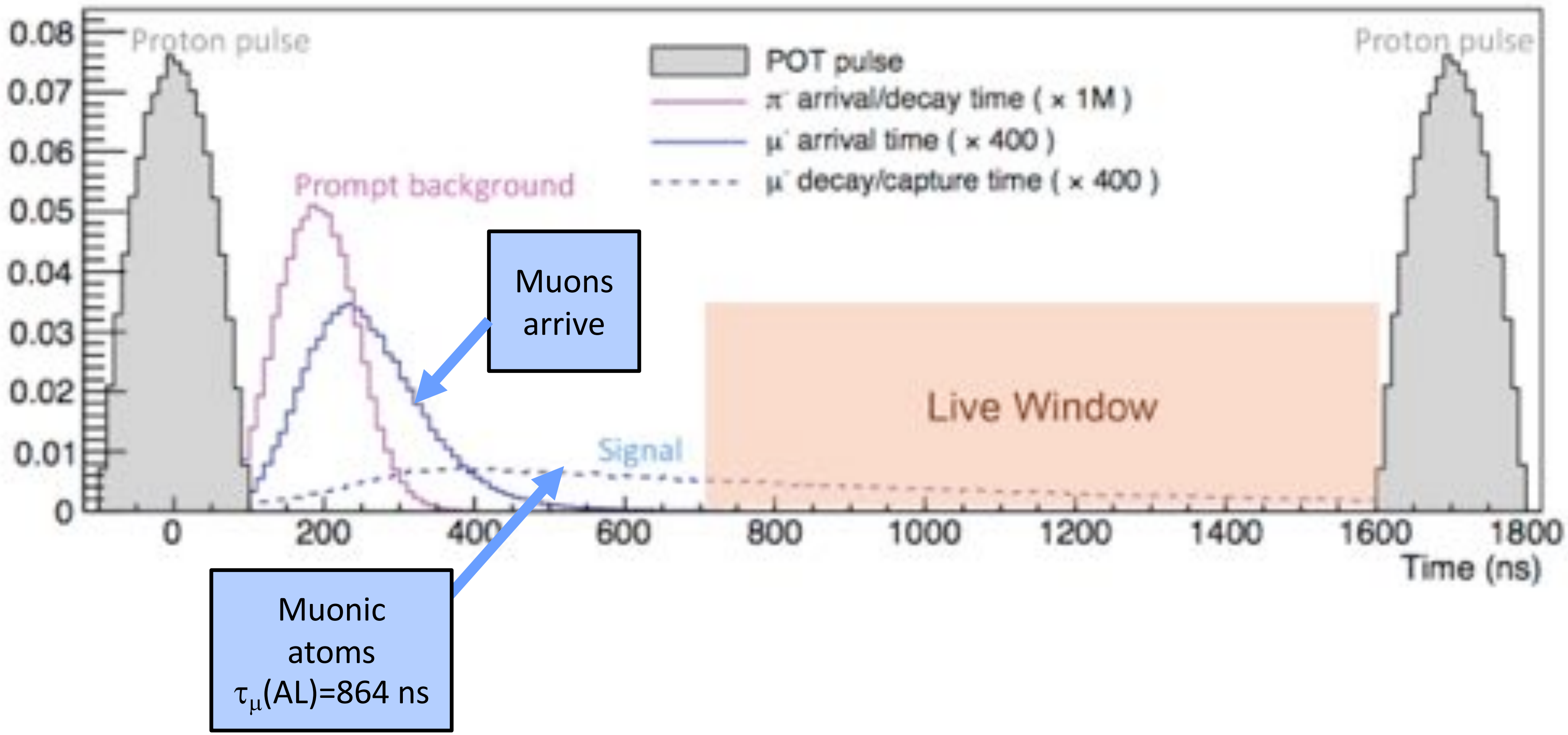
- The Mu2e apparatus
  - Superconducting Solenoids
  - Tracker – Straw drift tubes
  - Calorimeter – Pure CsI crystals
  - Cosmic Ray Veto - Scintillator



Making a Large Flux of Muons for Mu2e

- 8 GeV protons from the Fermilab Booster
  - Booster batch of 4×10^{12} protons at 15 Hz
  - re-bunched in the Recycler Ring to 4 bunches extracted one at a time to Delivery Ring
  - Protons resonantly extracted from the Delivery Ring
  - 1695 ns pulse spacing
  - ~40M protons per pulse
- Mu2e can operate year round, simultaneous with NOvA and short baseline neutrino program
  - Cannot operate at the same time as g-2

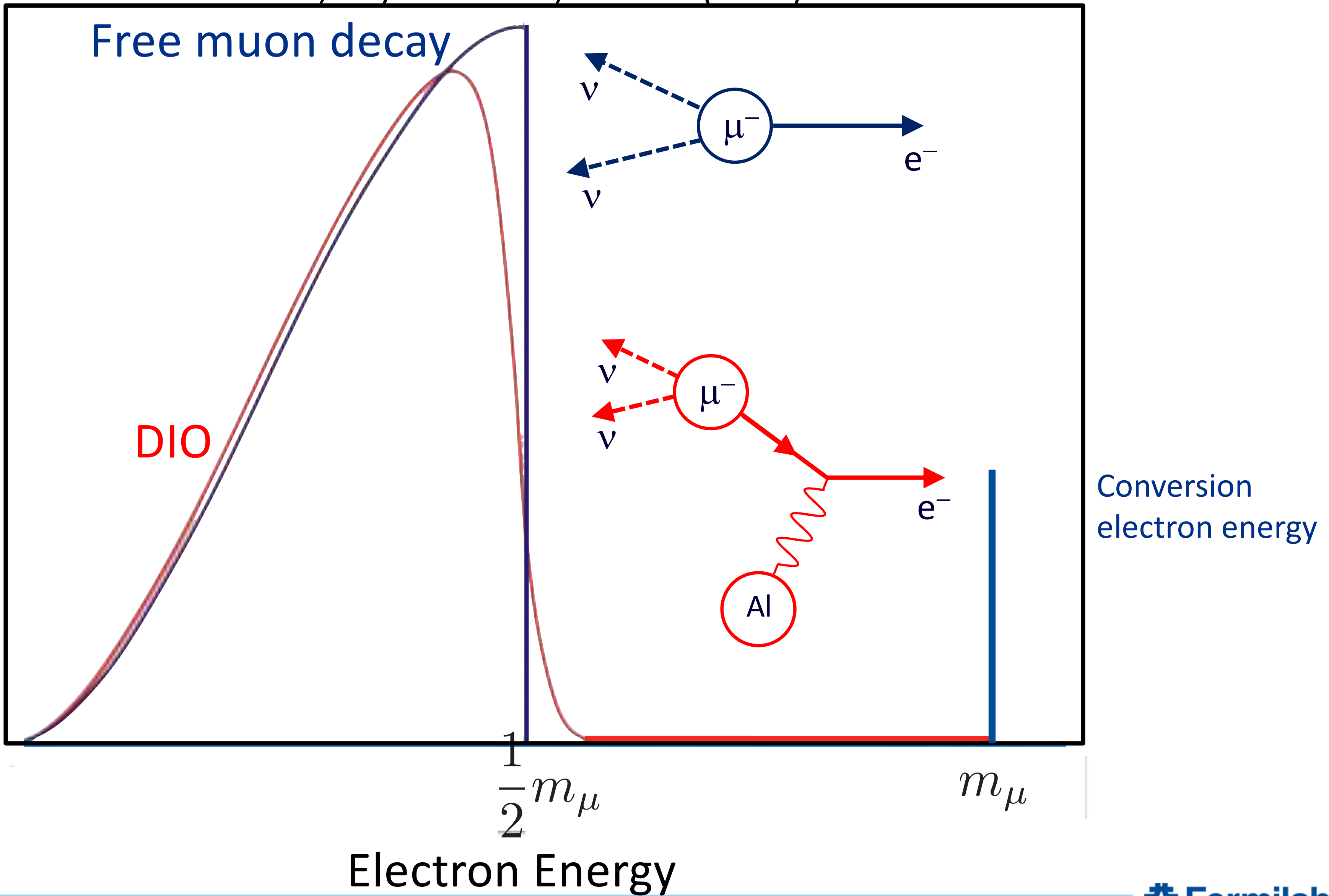
Pulsed Beam Eliminates Prompt Background



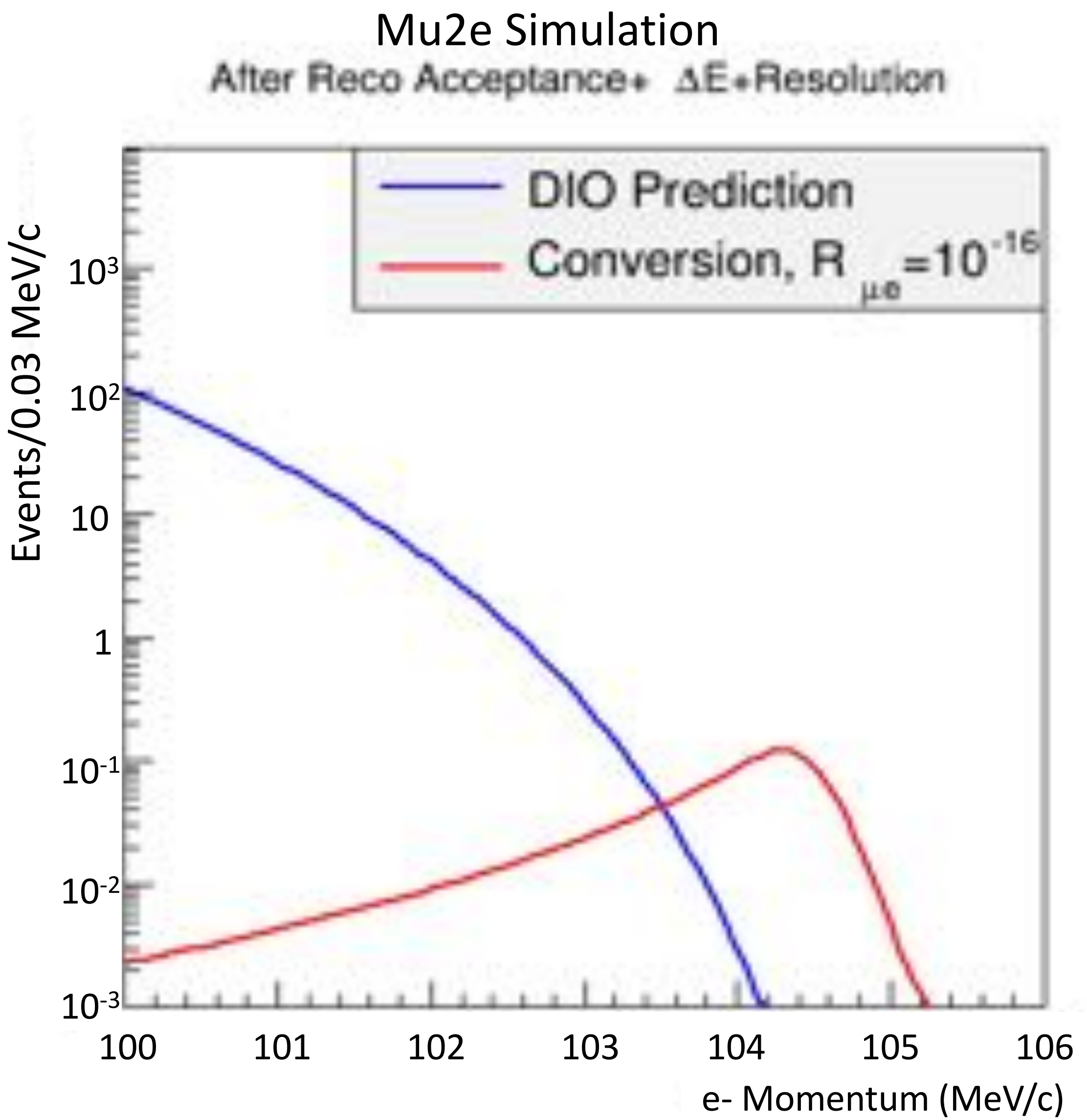
- 1695 ns between proton pulses
- Wait 700 ns before looking for signal while prompt background dies off
- Extinction factor (out-of-time/in-time protons) < 10^{-10} required
  - AC Dipole driven by two harmonics – 300 kHz, 4.5 MHz
  - RF re-bunching in Recycler Ring

Decay-in-Orbit Background

Szafron & Czarnecki, Phys Rev. D94, 051301 (2016)



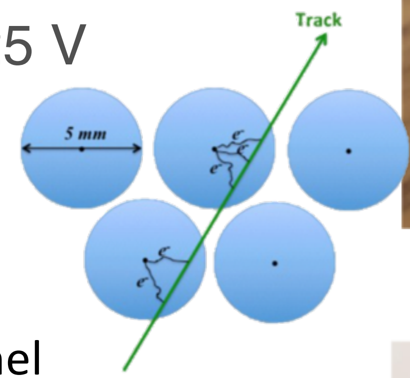
Decay-in-Orbit Background



Requires Tracker core momentum resolution of better than 200 KeV/c and small tails.

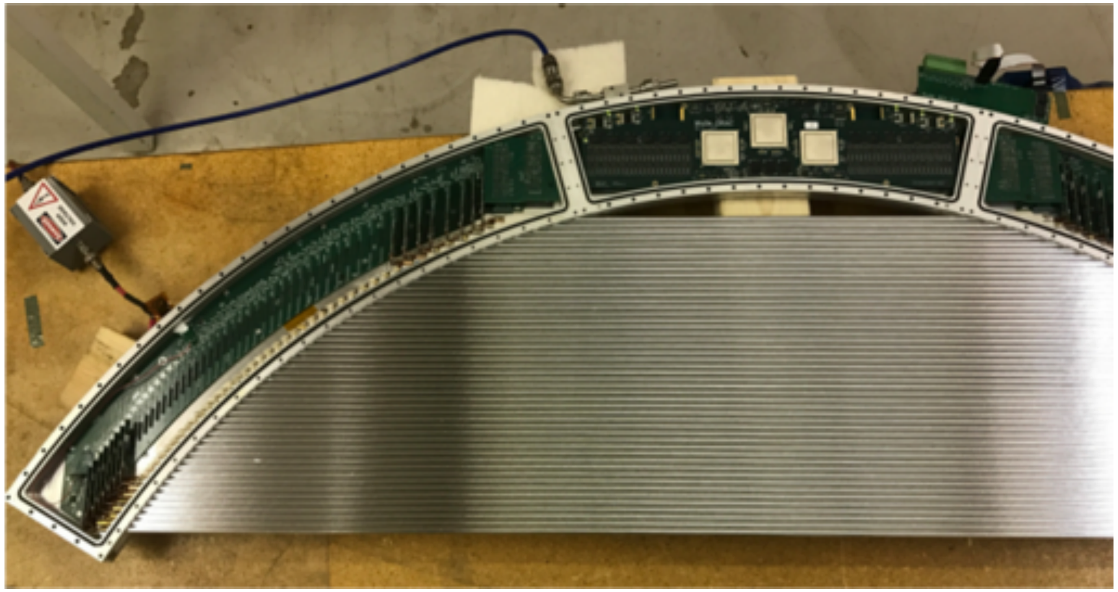
Mu2e Tracker

- 21,000 low mass straw tubes in vacuum
- 5 mm diameter, 15 μm thick metalized mylar walls
- 25 μm tungsten wire at 1425 V
- 80:20 $ArCO_2$

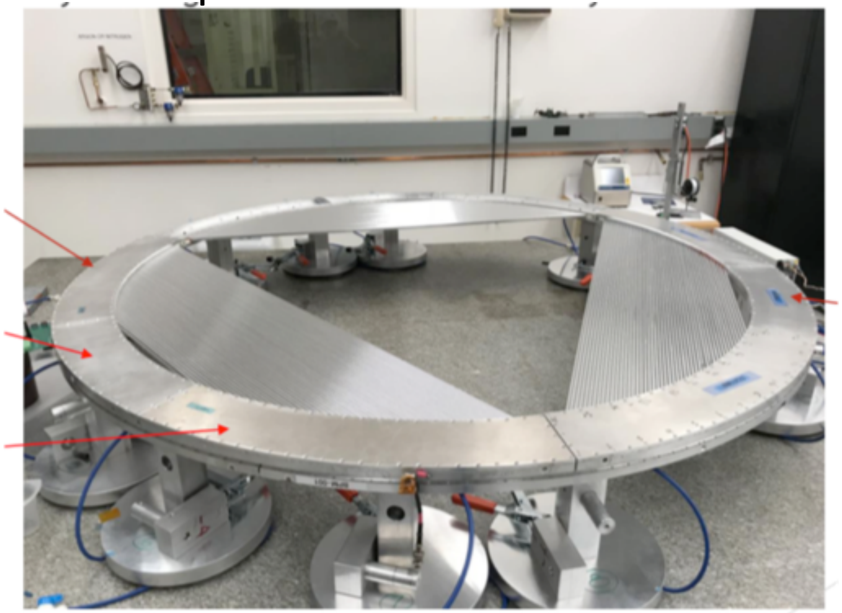


Metalized Straw Tube

Instrumented Tracker Panel

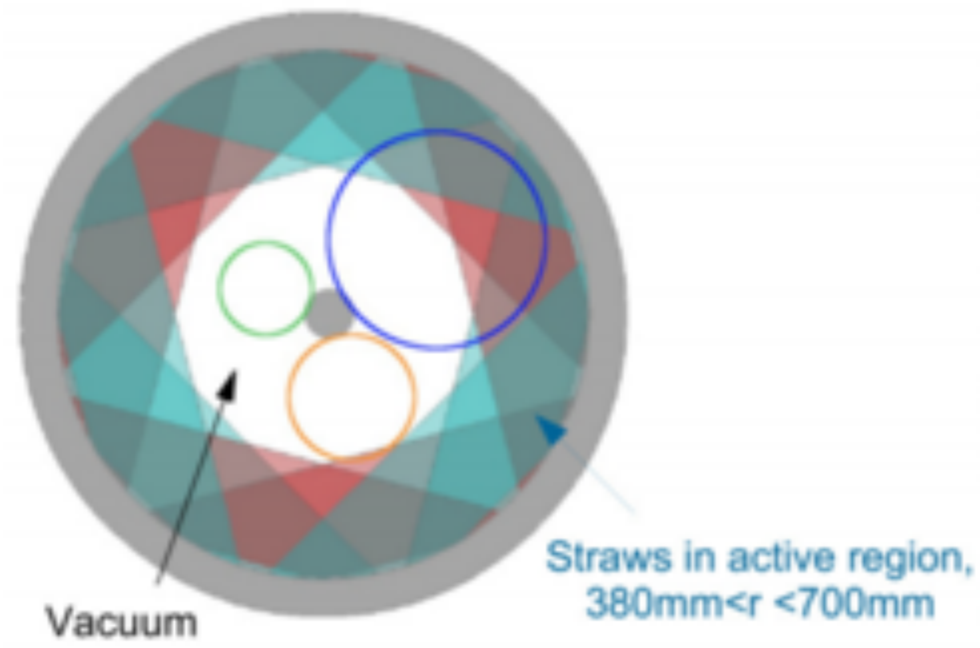


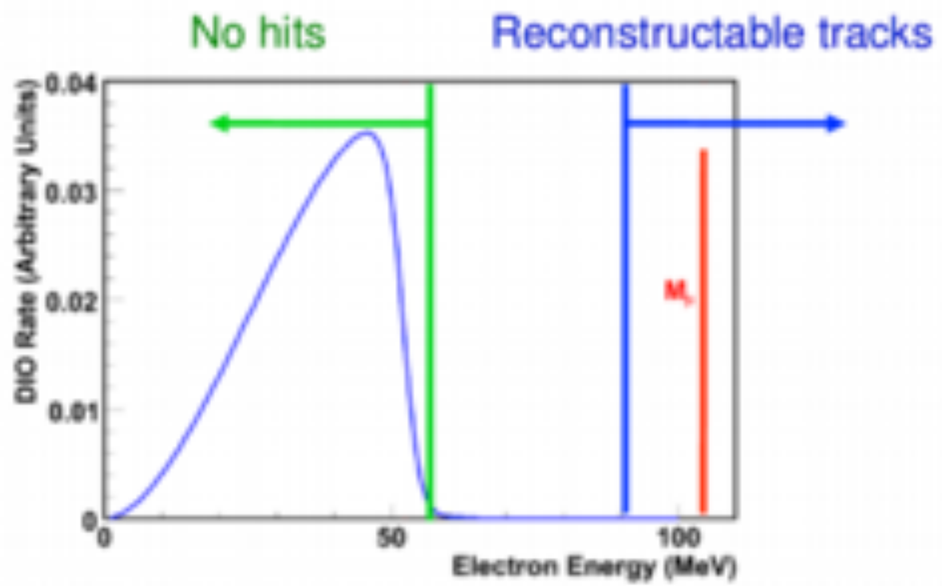
Top half of Tracker Plane



Mu2e Tracker

Blind to peak of DIO spectrum

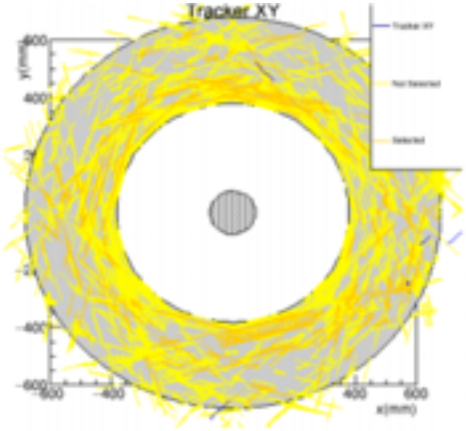




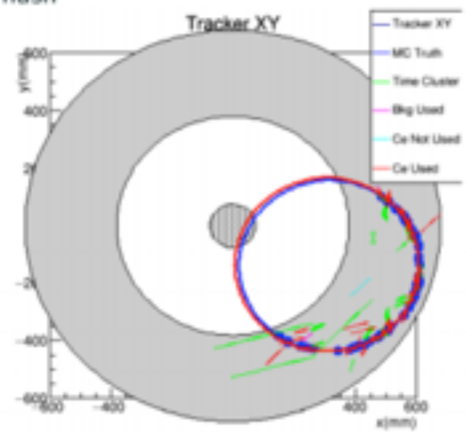
- Blind to beam flash
- Blind to > 99% of DIO spectrum

Tracker Simulation

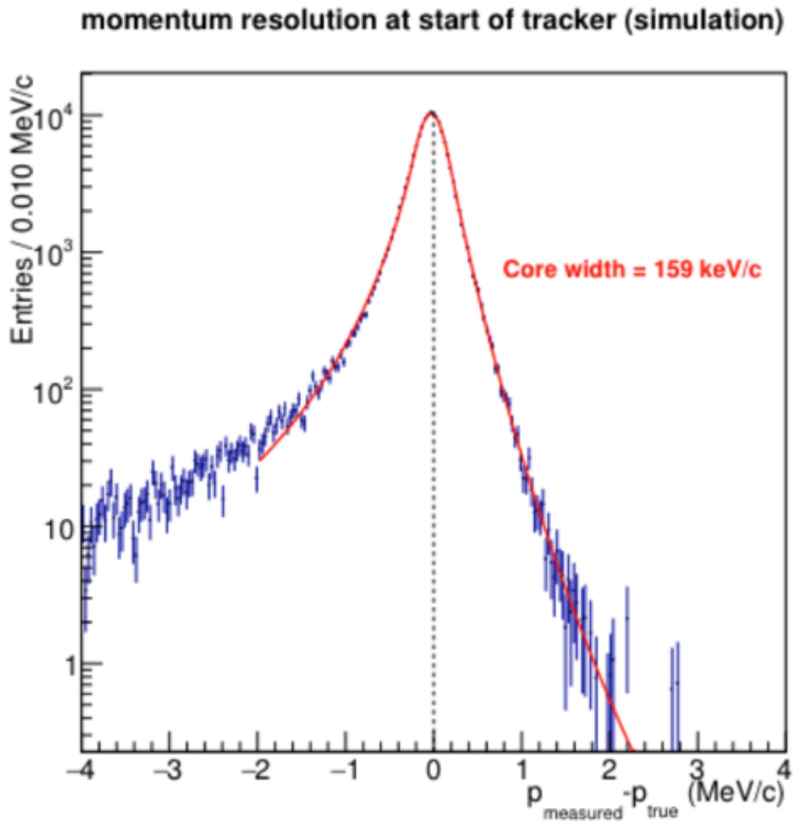
- Simulation tuned to Tracker test beam data.
- Expect to meet requirement.



1 μs selection window after beam flash



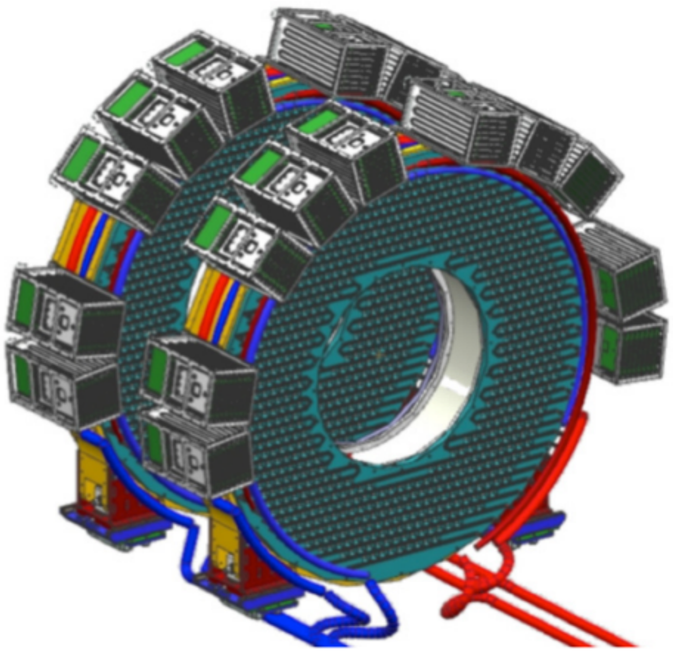
Hits selected by track finder within $\pm$50 ns selection window

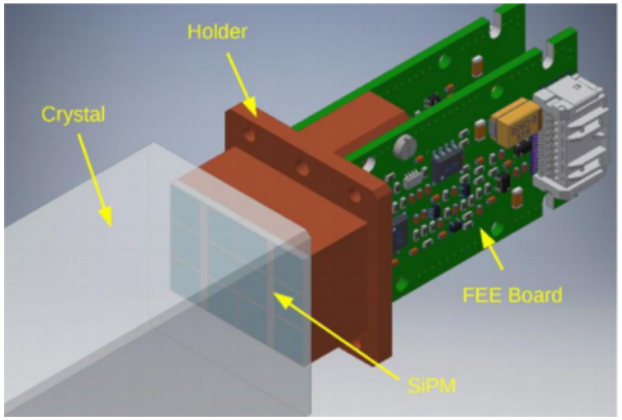


- Core resolution more than adequate.
- Non-Gaussian tails evaluated by signal + DIO simulation with 1000x full run statistics.

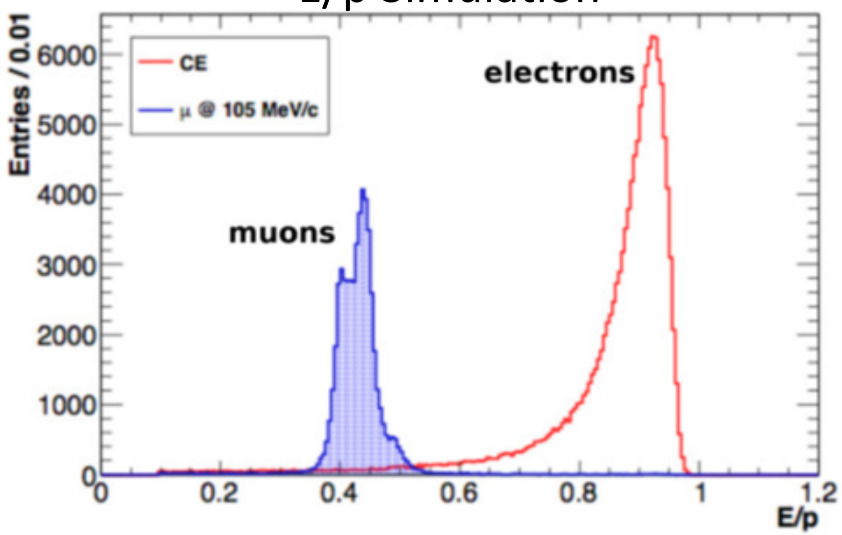
Calorimeter

- Two annular disks separated by "half wavelength"
- Each disk contains 674 pure CsI crystals (34 x 34 x 200 mm^3) read out by SiPMs
  - 75% of crystals, 100% of SiPMs in hand
- Particle ID for cosmic muon rejection
- Seed for tracking algorithm
- Tracker-independent trigger
- Calorimeter effort led by INFN



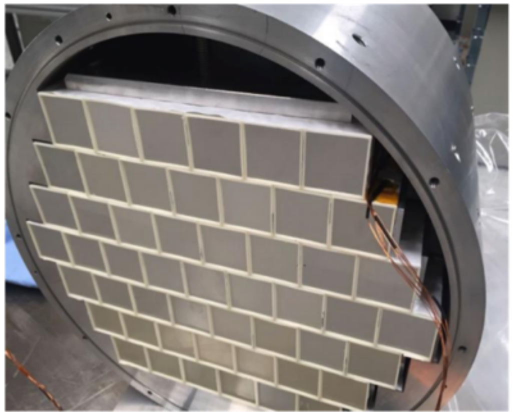


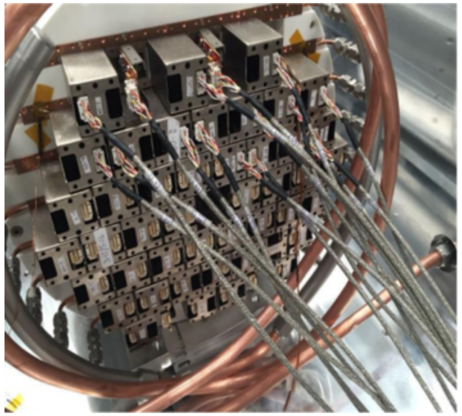
E/p Simulation

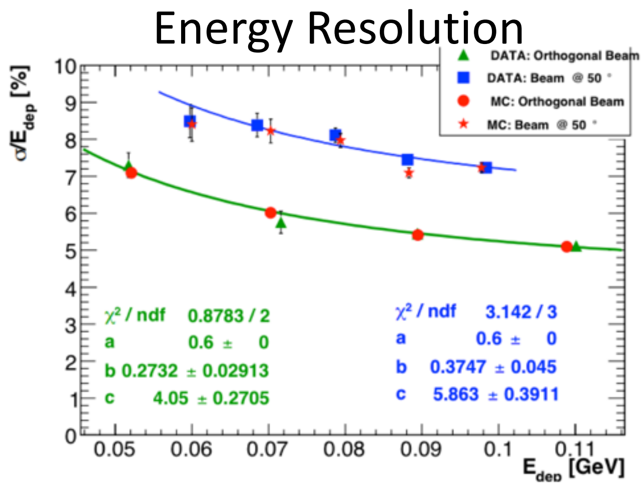


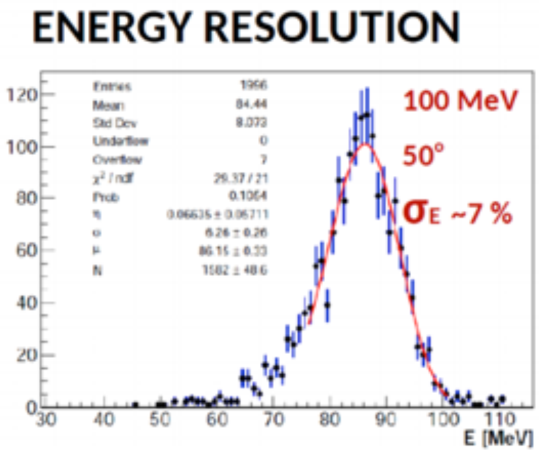
Calorimeter Beam Test

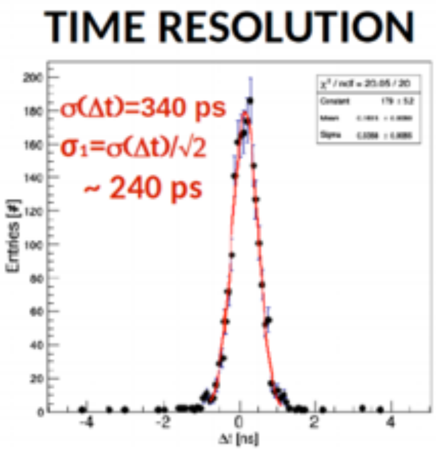
- May 2017 with 50-115 MeV electrons at INFN Frascati
- 51 30 x 30 x 200 mm^3 CsI Crystals, SiPM readout.







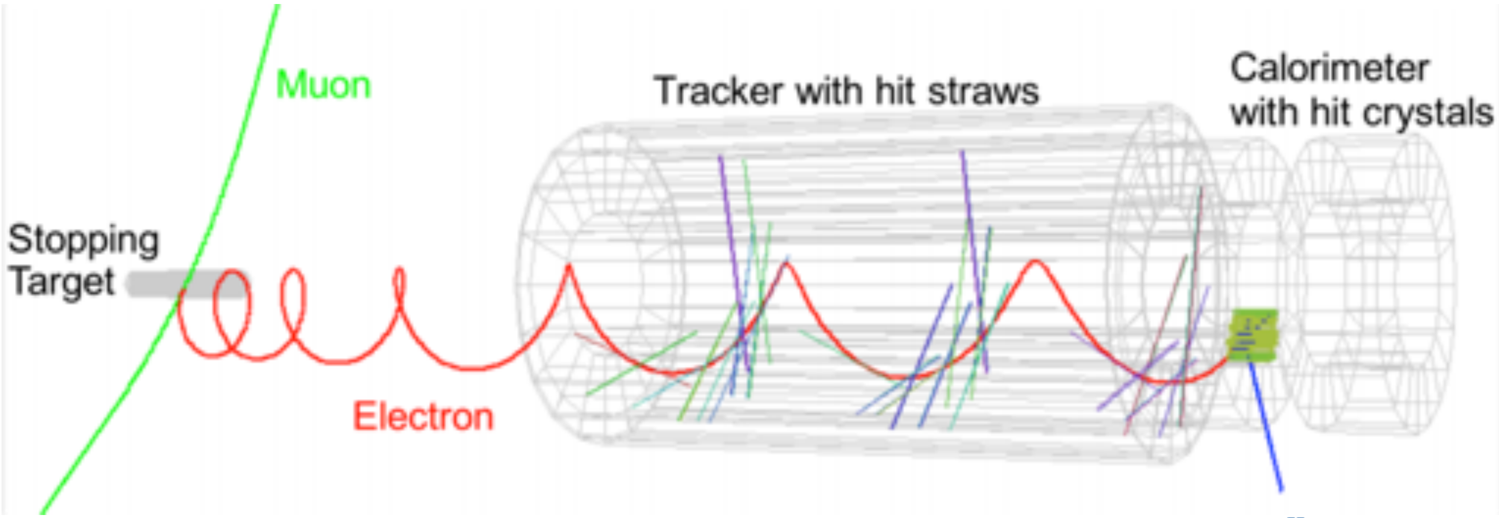




Energy and time resolutions well within requirements

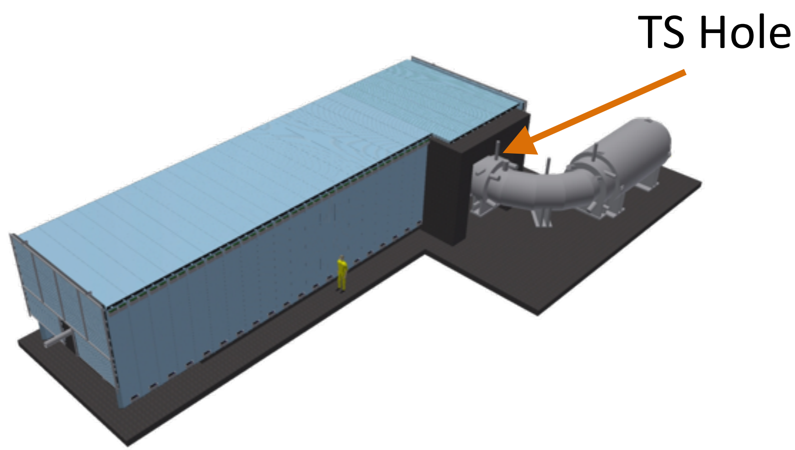
Cosmic Ray Backgrounds

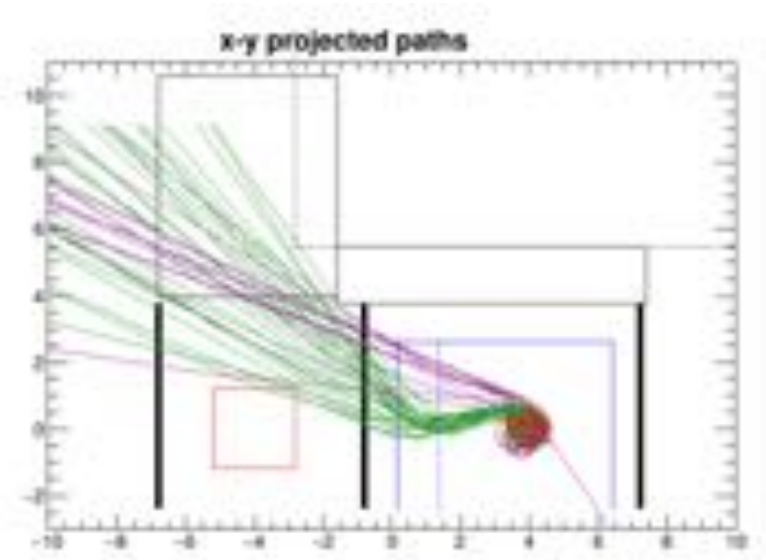
- Cosmic ray muons can generate background events via decay, scattering, or material interactions
- Mu2e expects 1 signal-like event per day from cosmic rays
  - Total expected background from all sources is 0.4 events over entire run
- To achieve design sensitivity, cosmic ray veto detection efficiency required to be > 99.99%.
- Cosmic ray background can be measured between spills and when beam is off.

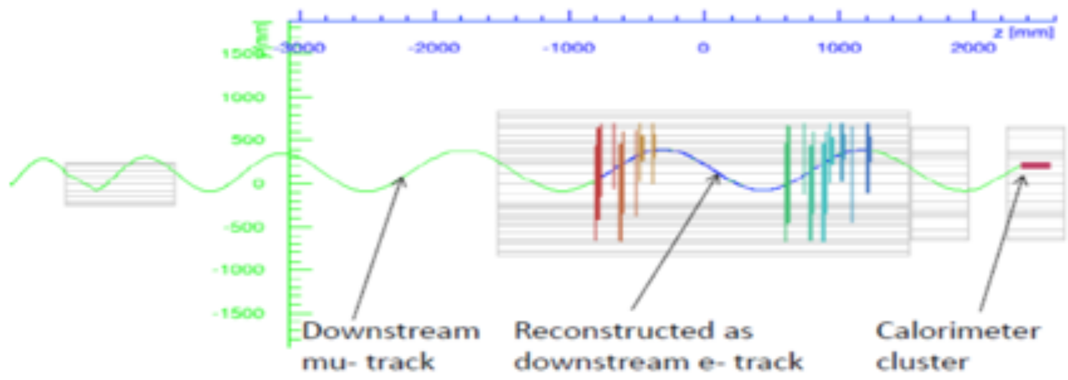


Cosmic Ray Muon Background

- Muons can elude Cosmic Ray Veto and enter through the hole at the TS entrance
- 10 times more than cosmic-induced electron background.
- Suppressed by particle ID

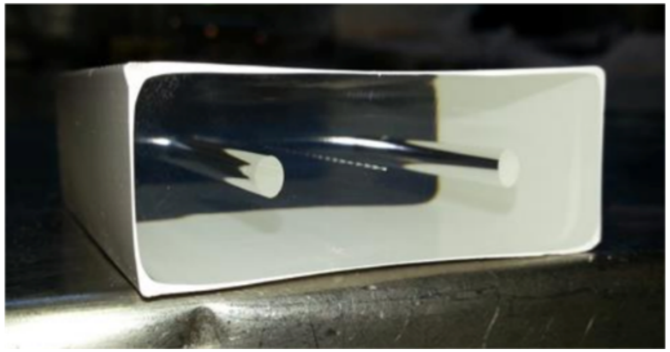


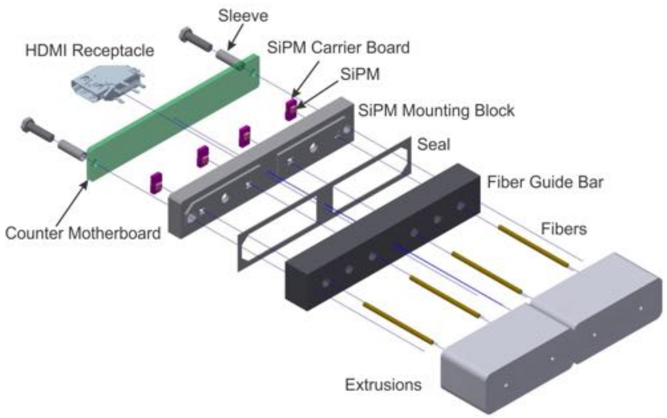


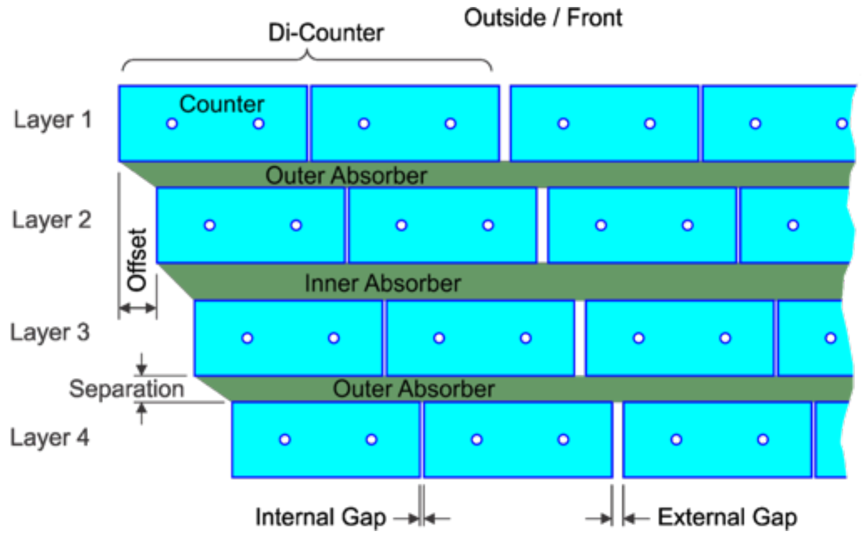


Mu2e Cosmic Ray Veto

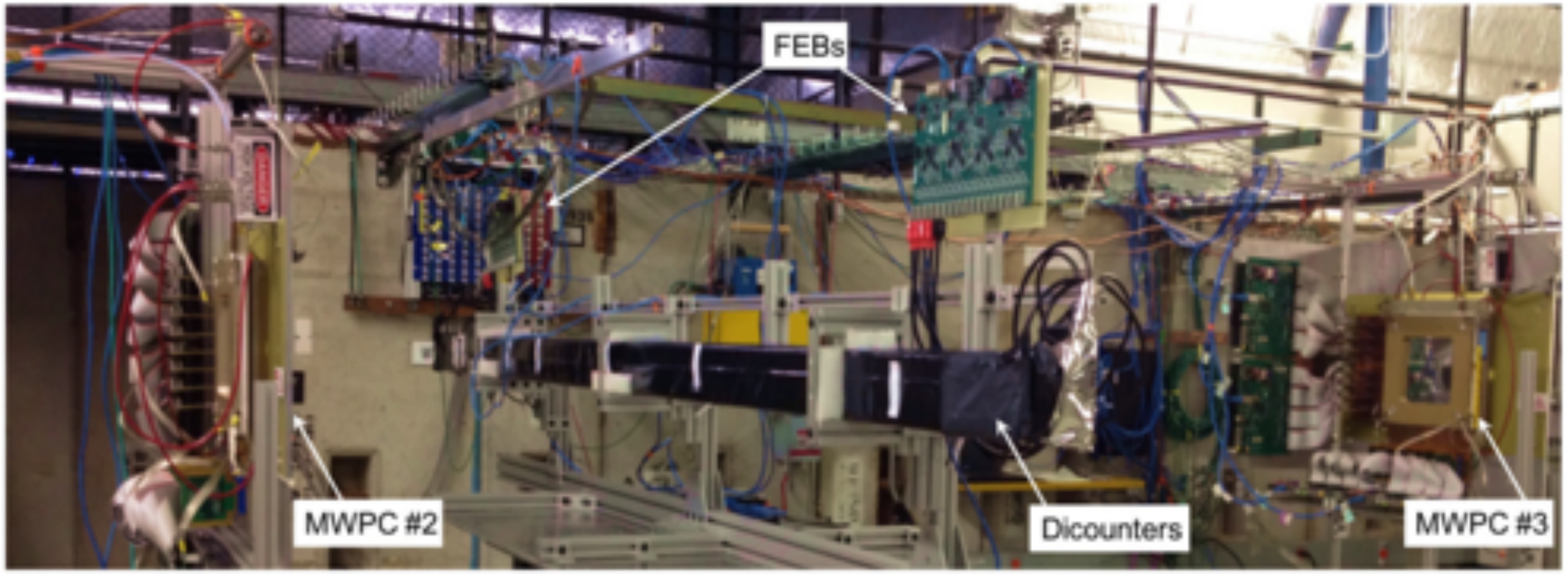
- 4-layers of extruded scintillator bars, wavelength shifting fibers, read out at both ends with SiPMs.
  – Scintillator and SiPMs all in hand.
- Covers all of DS, half of TS, better than 10^{-4} inefficiency

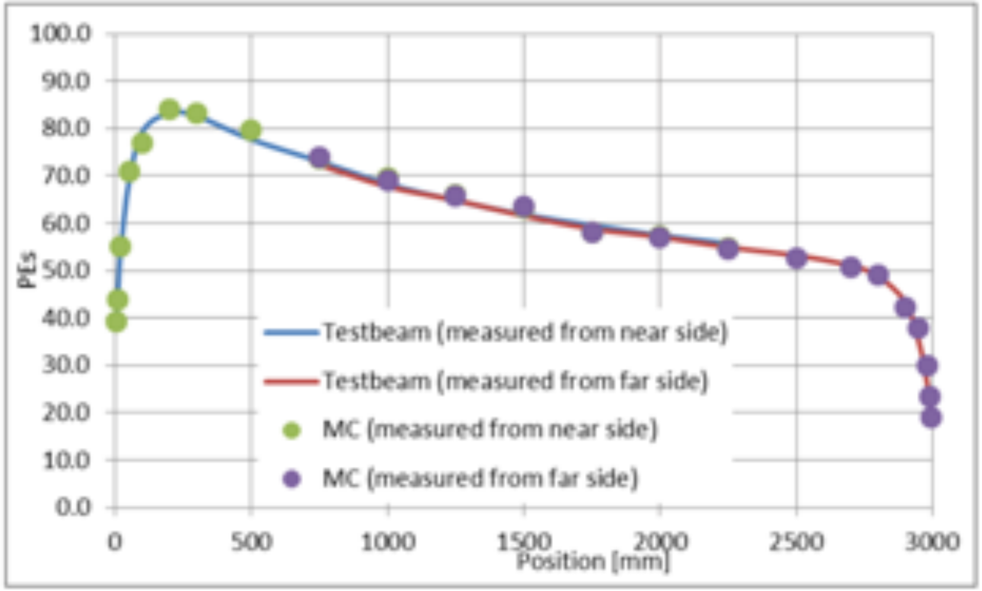






CRV Beam Test





CRV beam test with 120 GeV protons at Fermilab Test Beam.

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Sum of Backgrounds

Estimated background for 3.6 x 10^{20} protons on target

Process	Expected event yield
Cosmic ray muons	$\mathbf{0.21} \pm \mathbf{0.02}(\text{stat}) \pm \mathbf{0.06}(\text{syst})$
Muon decay in orbit	$\mathbf{0.14} \pm \mathbf{0.03}(\text{stat}) \pm \mathbf{0.11}(\text{syst})$
Antiprotons	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
Pion capture	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
Muon decay in flight	< 0.003
Pion decay in flight	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Radiative muon capture	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13(\text{stat+syst})$

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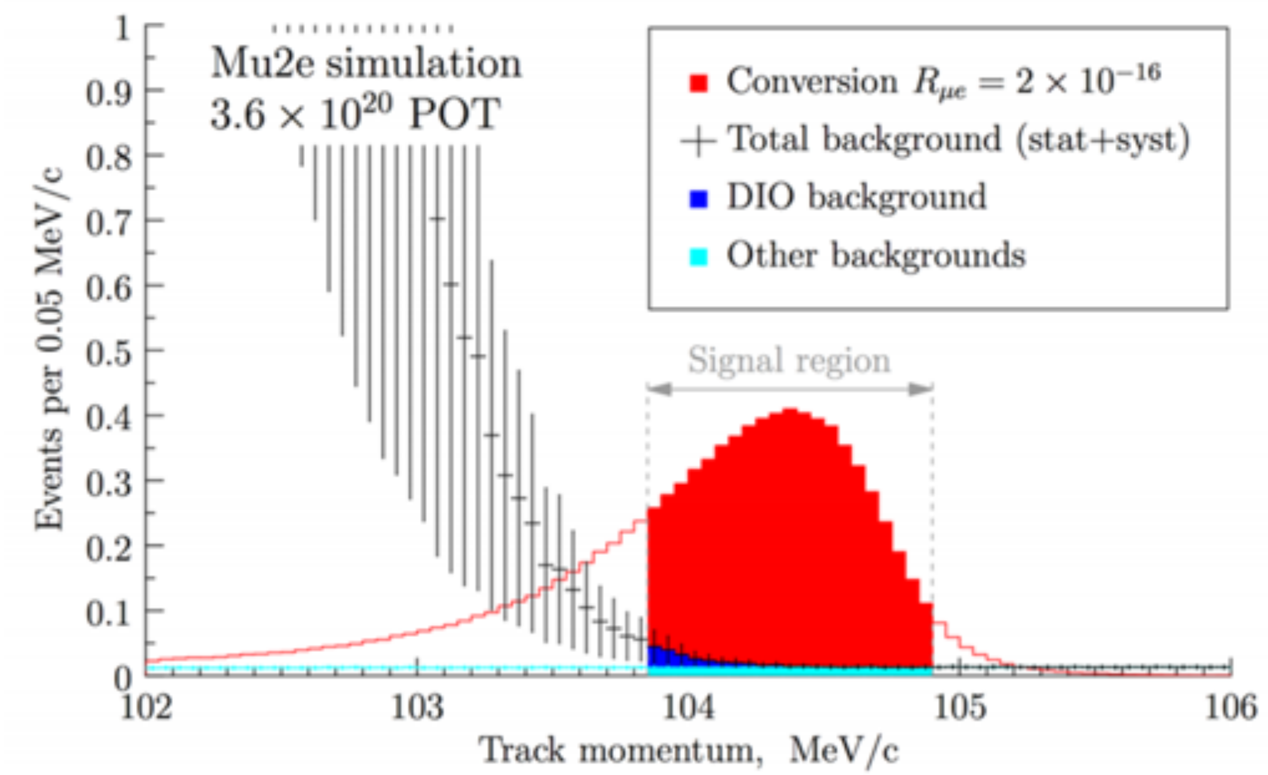
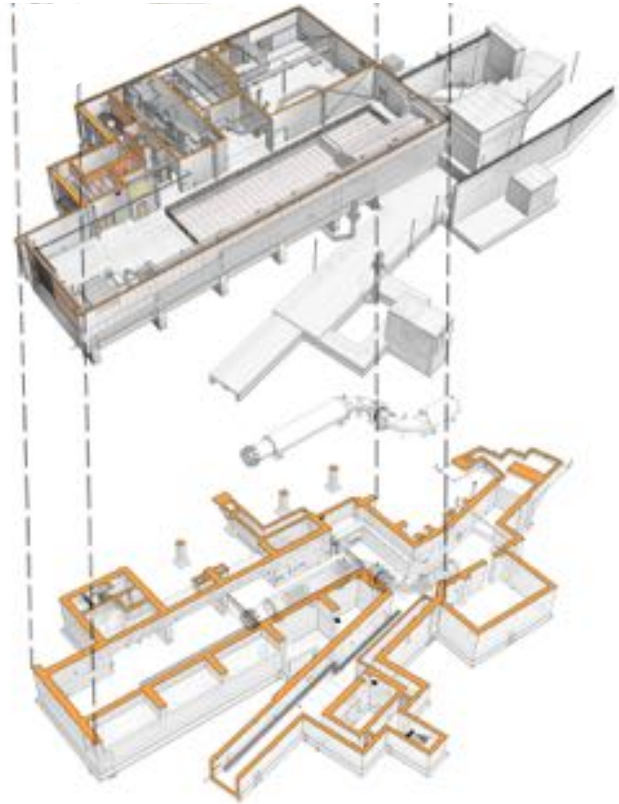
Sensitivity

Mu2e expects a 10^4 x increase in sensitivity over SINDRUM II

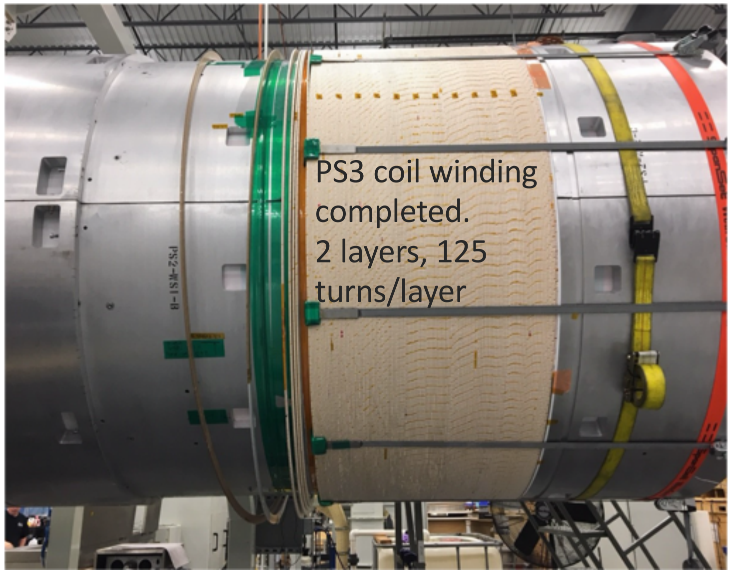


- Discovery Reach (5σ): $R_{\mu e} > 2 \times 10^{-16}$
- Exclusion power (90% C.L.): $R_{\mu e} > 8 \times 10^{-17}$

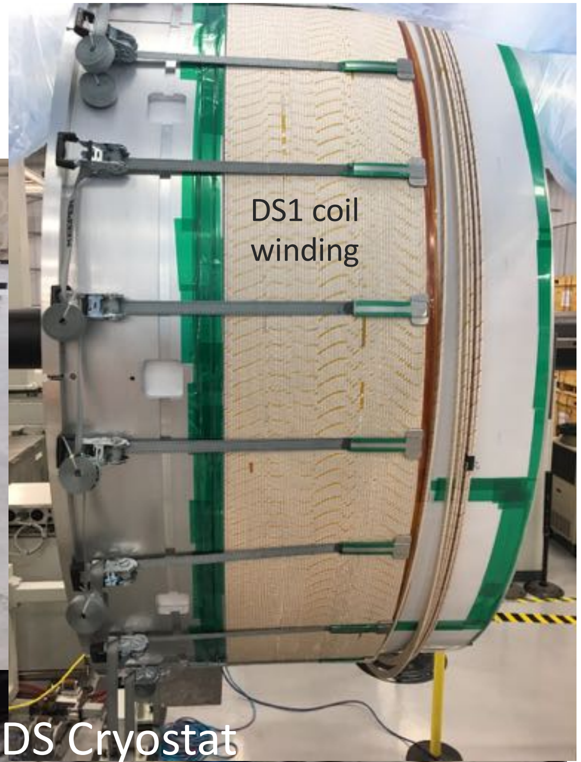
Detector Hall - Completed

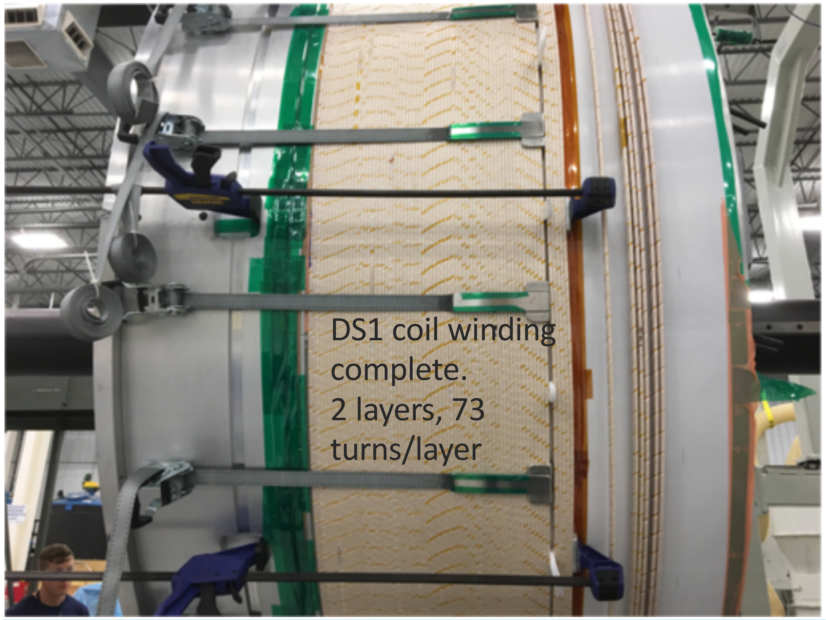


Mu2e Status - PS/DS



DS Stand



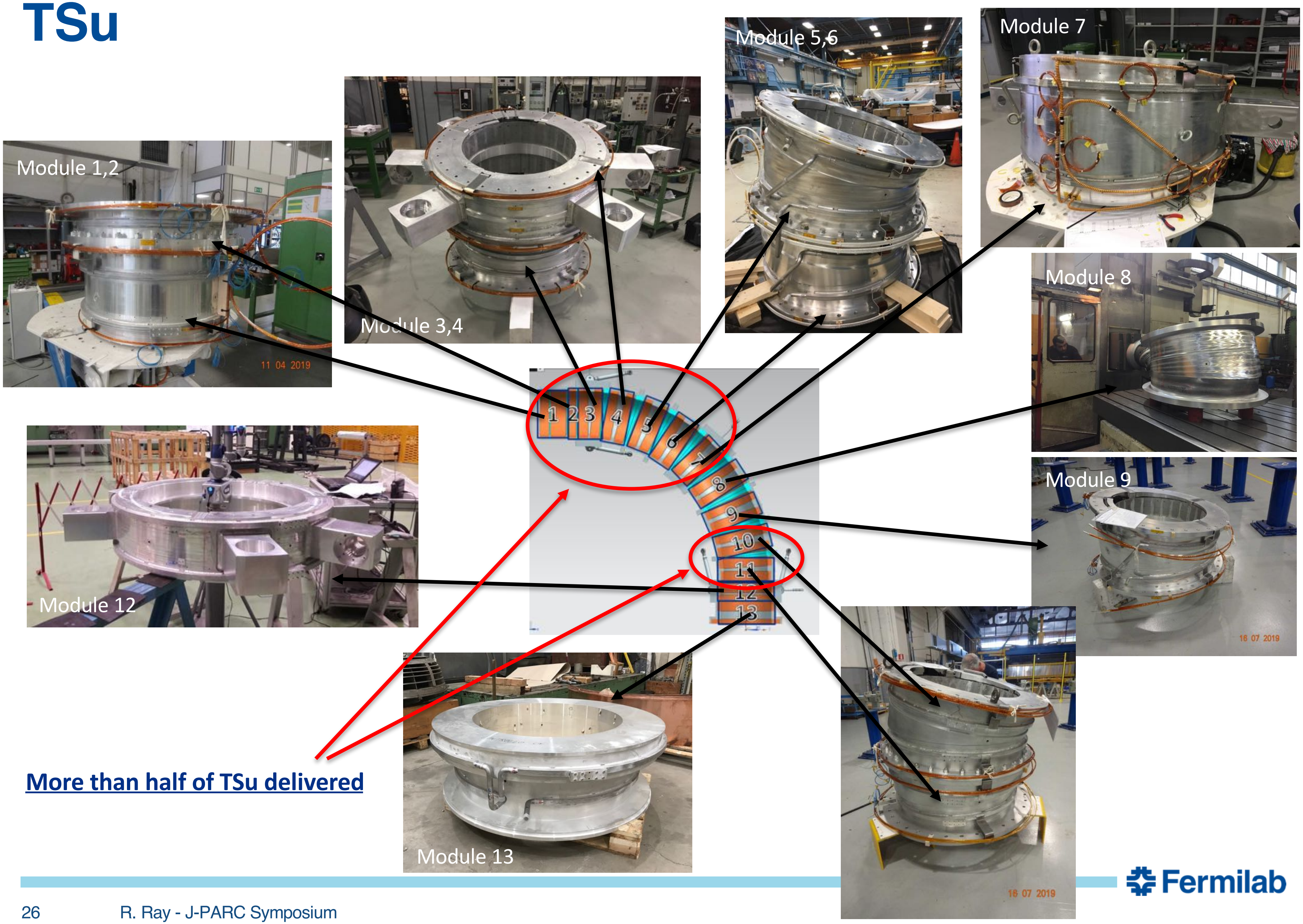


DS Cryostat

Mu2e Status - TS

- S-shaped magnet constructed from series of wedge-shaped modules
- Divided into upstream (TSu) and downstream (TSd) sections
- Superconducting Modules fabricated in Italian industry
- Delivered modules cooled to Liquid Helium and powered at Fermilab
- Magnets assembled at Fermilab

TSu

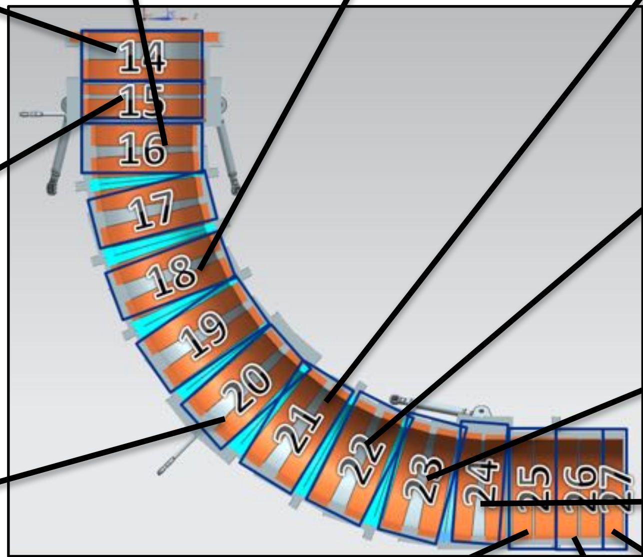


More than half of TSu delivered

TSd

Module 16
- Rough machining completed

Module 18
- Rough machining completed



Module 24
- Rough machining completed
- Welding completed

Module 25
- Rough machining completed

Module 27
- Rough machining ongoing

Module 26
- Rough machining completed
- Welding completed

TSd modules in various stages of fabrication

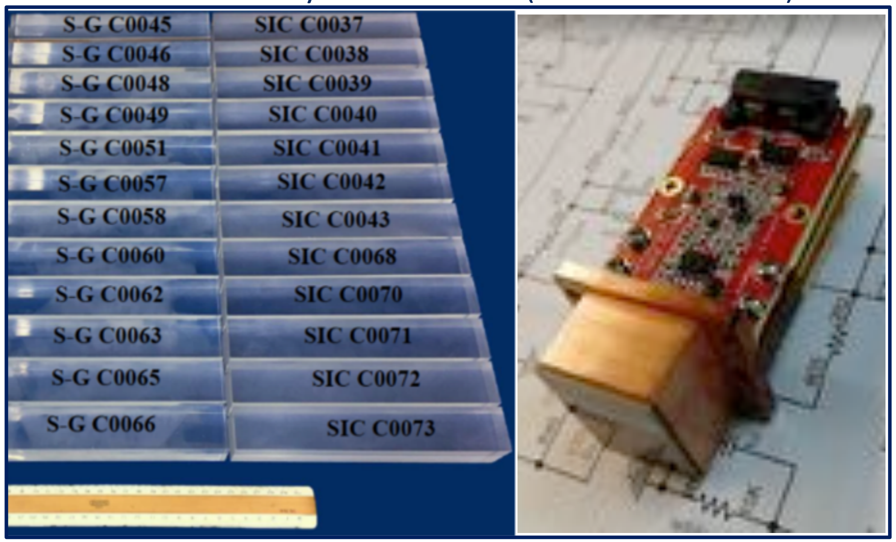
Mu2e Beamline Installation Making Significant Progress

- Most beamline elements installed or being fabricated
- Prototype AC Dipole fabricated and tested
- Extinction collimators fabricated
- Resonant extraction sextupoles fabricated
- Begin running beam to dump next summer

Detector Progress

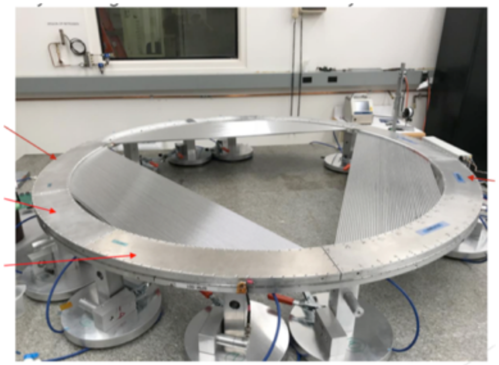
Cosmic Ray Veto Module Construction at University of Virginia

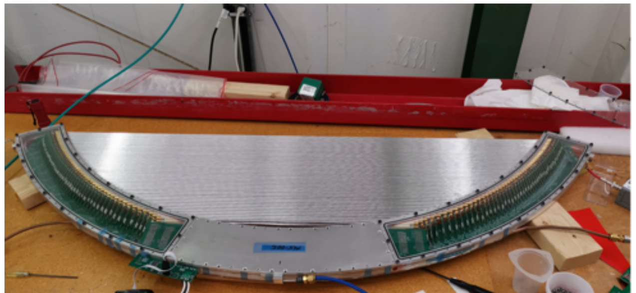
TDAQ Test Stand



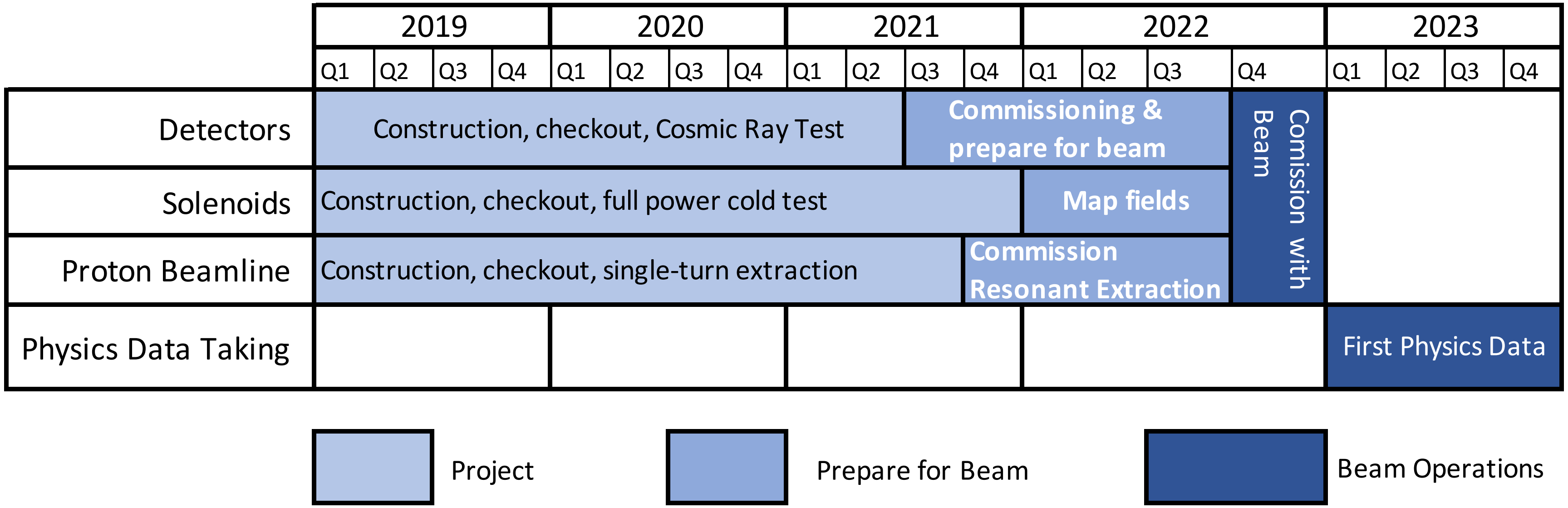
Calorimeter crystals and SiPM (INFN Contribution)

Tracker panel production is behind schedule. Expect to ramp up production rate this Fall at University of Minnesota


Half Tracker Plane comprised of 3 panels


Instrumented Tracker Panel

Schedule



- Schedule is driven by delivery, installation and commissioning of the Solenoids.
- First beam to diagnostic dump – Fall 2020. Ahead of schedule.
- Begin commissioning resonant extraction – late 2021
- Begin commissioning detectors with beam– Early 2022
- First physics data taking – Early 2023
- Anticipate 4-5 years of running to reach target sensitivity.

Summary

- Mu2e will search for muon-to-electron conversion with a sensitivity of 8×10^{-17} (90% C.L.)
- Construction well underway on all fronts
- Performance demonstrated with prototypes and simulations
- Expect to begin physics data taking in 2023

Backup Slides

Mu2e Collaboration

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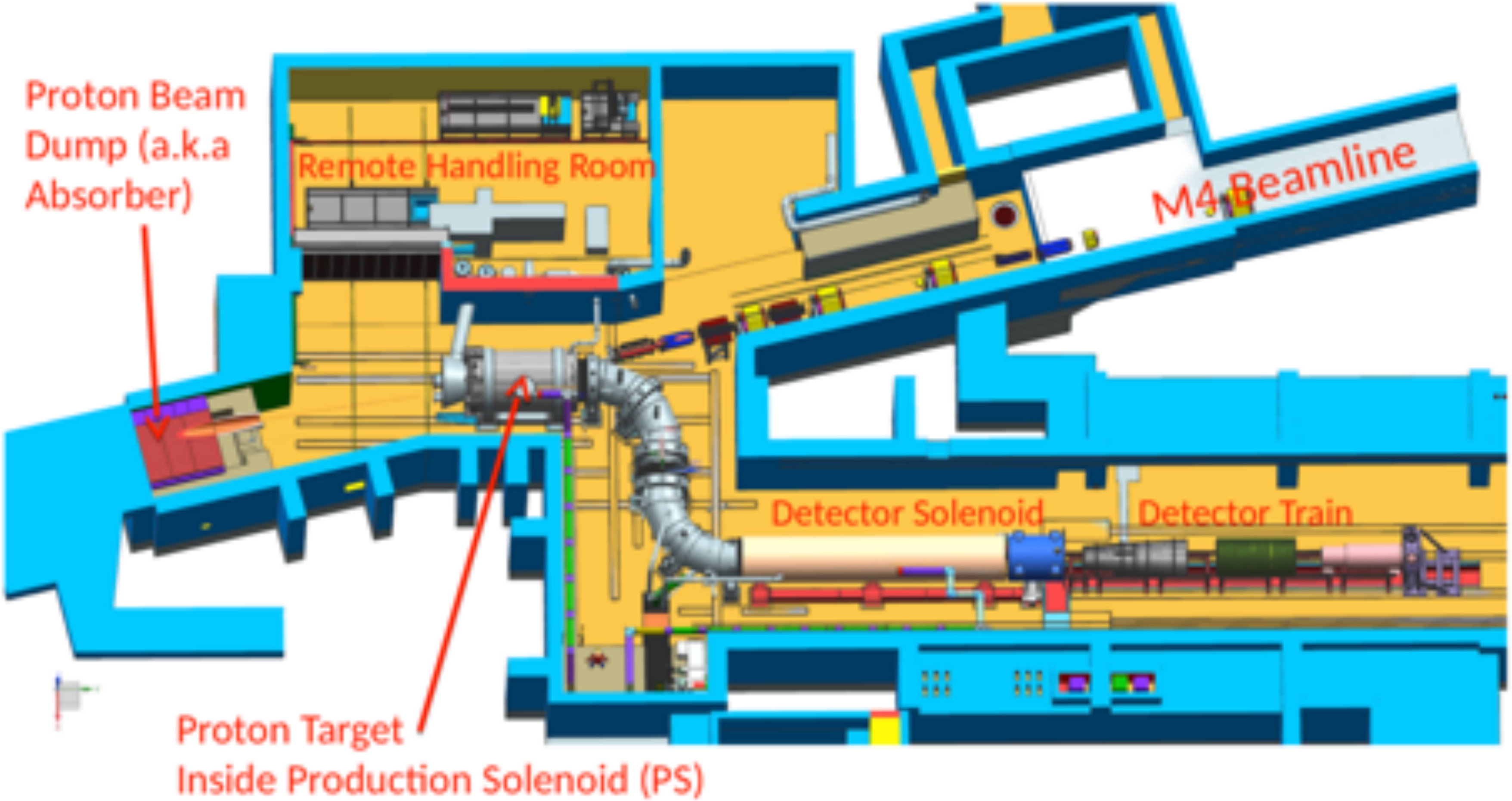
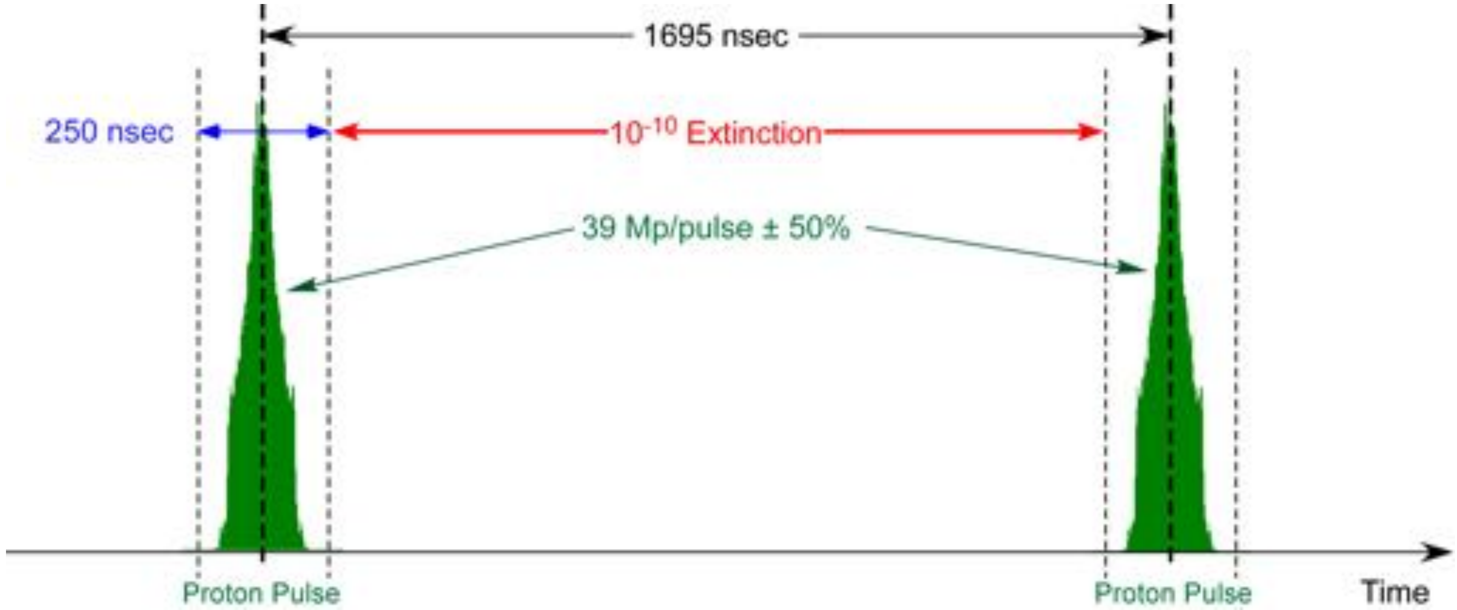
Experimental Layout



Beam Extinction

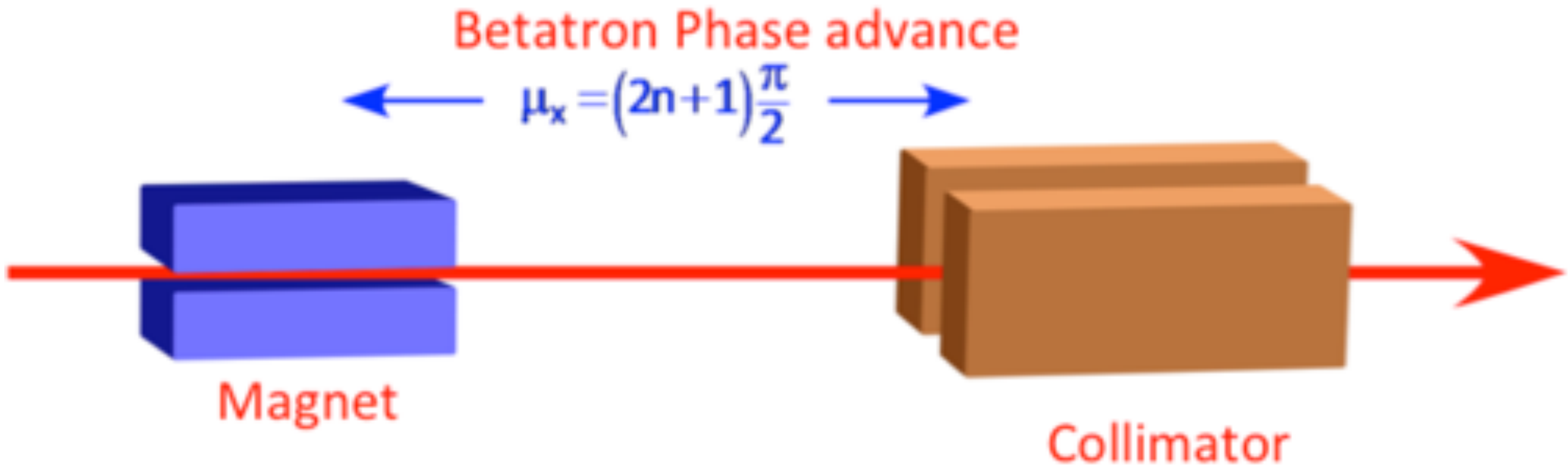
- Mu2e has very stringent limits on the amount of beam that appears between pulses. Require extinction factor of 10^{-10}.
- Required to eliminate prompt backgrounds



- Re-bunching in the Recycler Ring provides an extinction factor of about 10^{-4}.
- Remainder must be provided by the Mu2e beamline.

Beam Extinction

- A magnet is used to deflect out-of-time beam into a downstream collimator



- Ideally, we would use a square pulse to kick out-of-time beam out of (or in-time beam into) the transmission channel, but the 600 kHz bunch rate makes this impossible with present technology.
- We will therefore focus on a system of resonant magnets or “AC Dipoles”.

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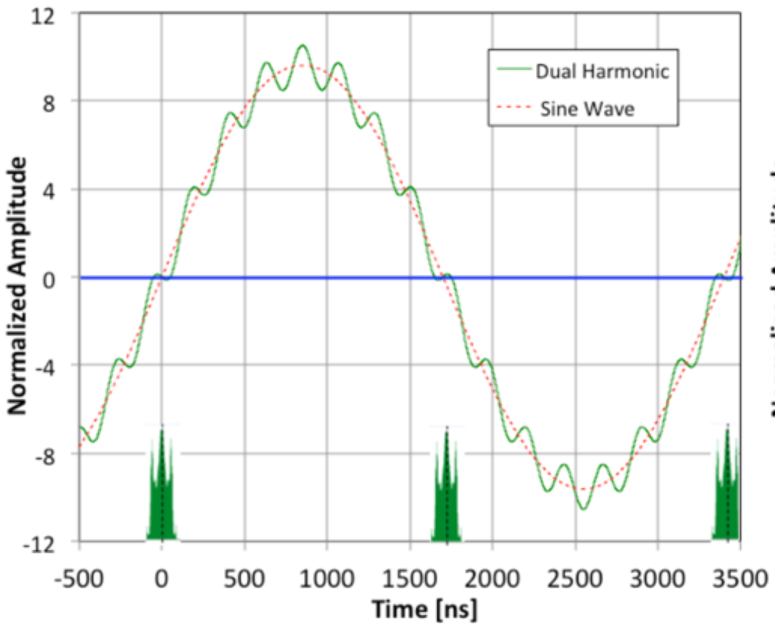
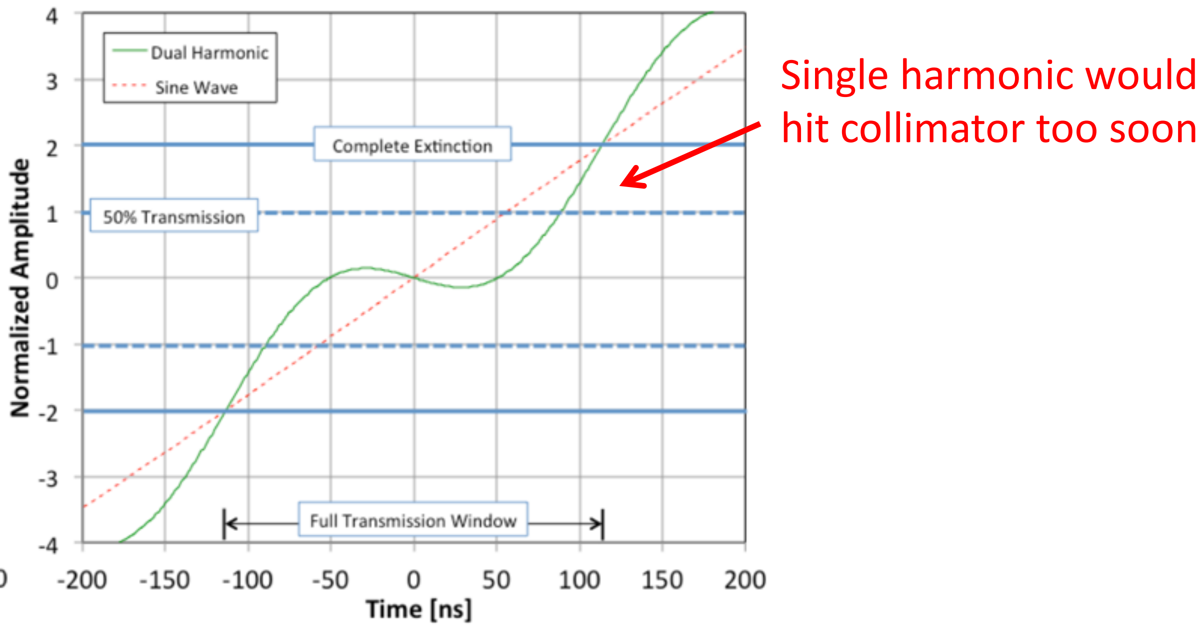
Extinction – Dual Harmonic Waveform

- AC Dipole driven by two harmonics
  - 300 kHz (half bunch frequency) to sweep out of time beam into collimators
  - 4.5 MHz (15th harmonic) to maximize transmission of in-time beam
  - Beam transmitted at nodes!

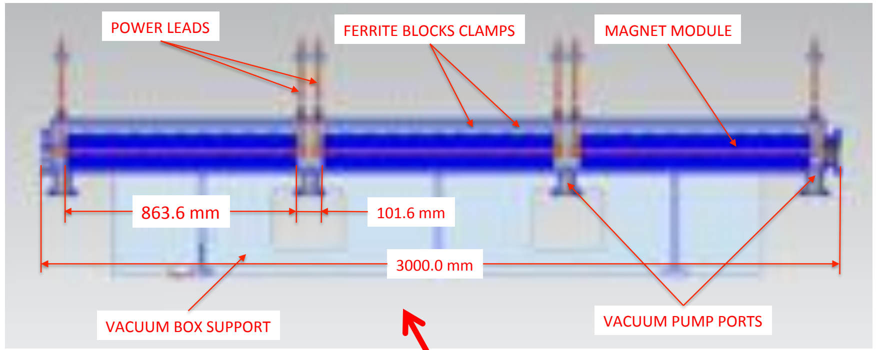




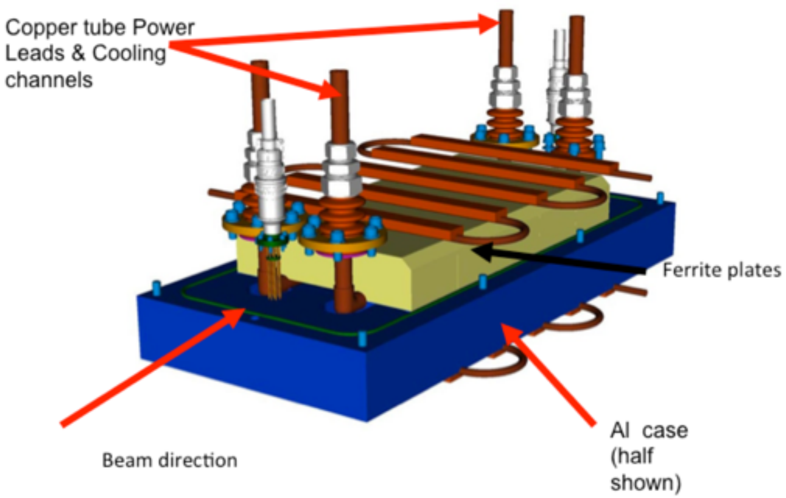
- Higher harmonic optimized for maximum transmission: 99.5%

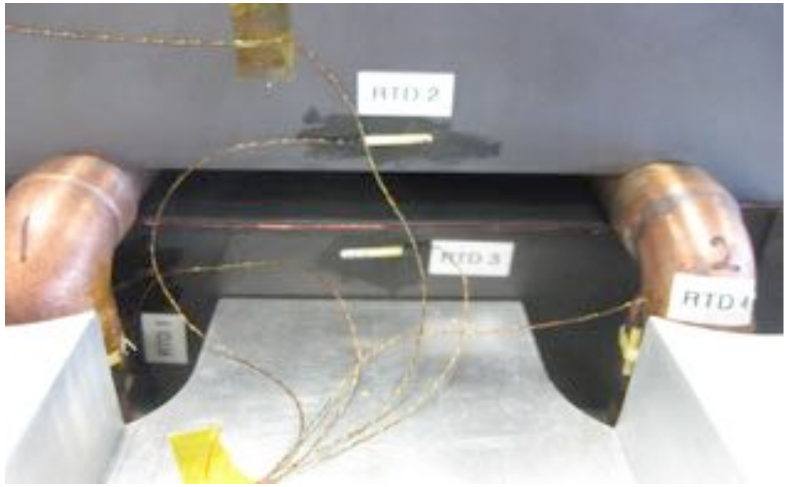
AC Dipole Design and Prototype

- AC dipole system consists of 6 identical one meter elements, arranged in two 3-meter vacuum vessels.
- Extensive tests done with half-meter prototype
  - meets all specifications



Elements individually powered

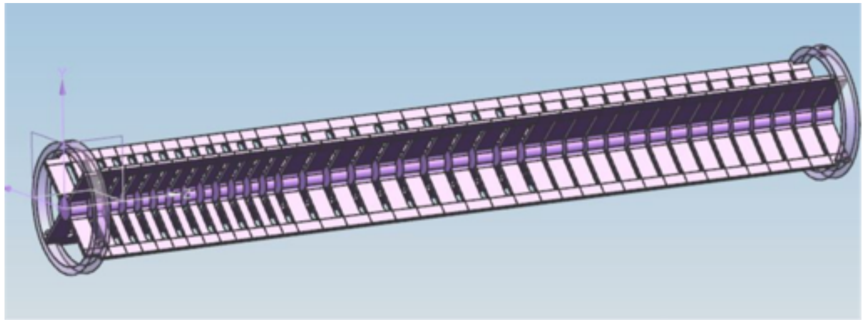




Fermilab

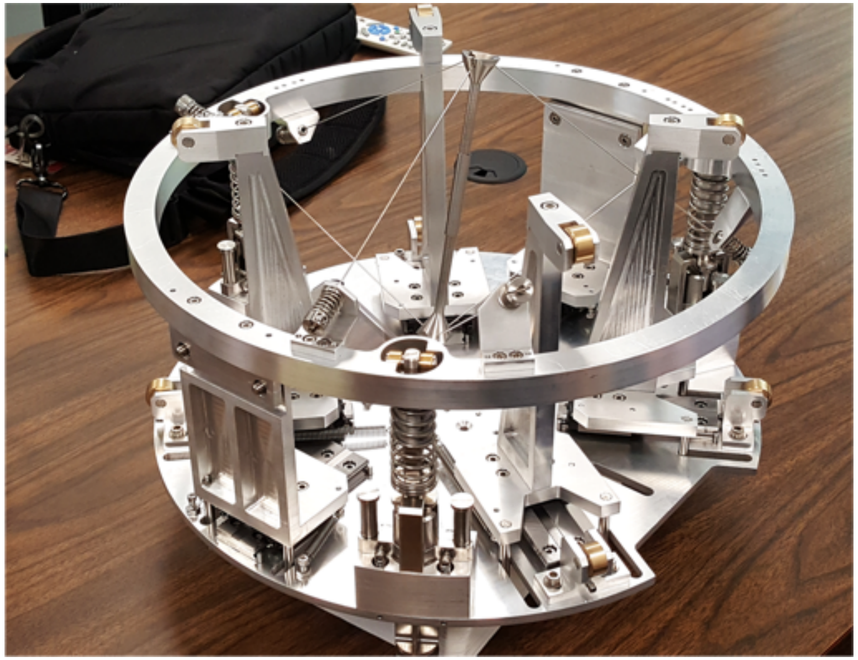
Production Target

- Intersects 8 kW beam of 8 GeV protons
- Radiatively cooled, distributed target
- Fins radiate heat and provide stiffness
- Operates in 10^{-5} T vacuum



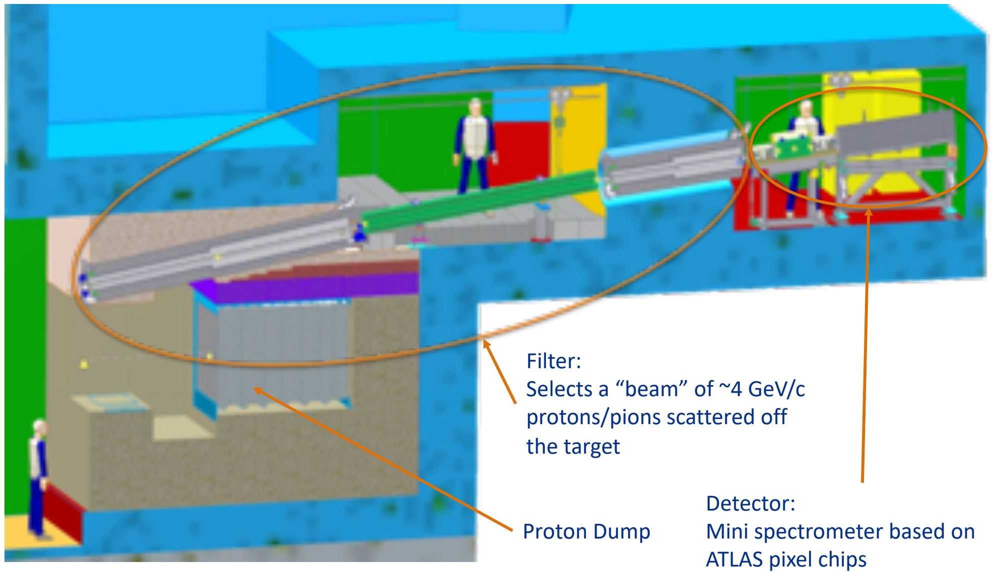
Testing@ Rutherford-Appleton Lab (England)

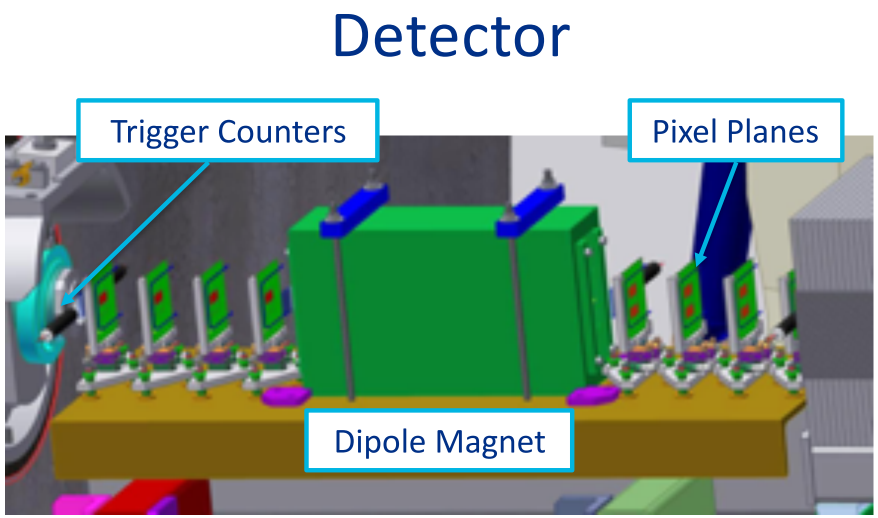
Target End-of-Arm Tooling@ Fermilab



Extinction Monitor

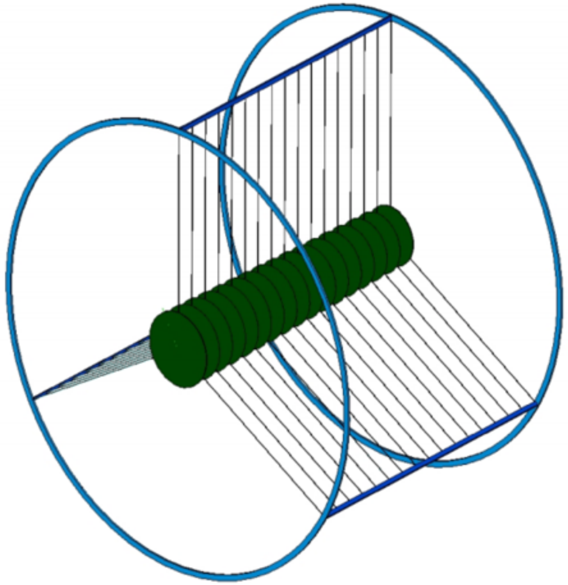
- Detect a small fraction of scattered particles from production target to monitor beam extinction
- Detector located above and behind primary proton dump.
- Statistically build up precision profile for in-time and out-of-time beam.
- Measure extinction at 10^{-10} to 10% in ~ 4h

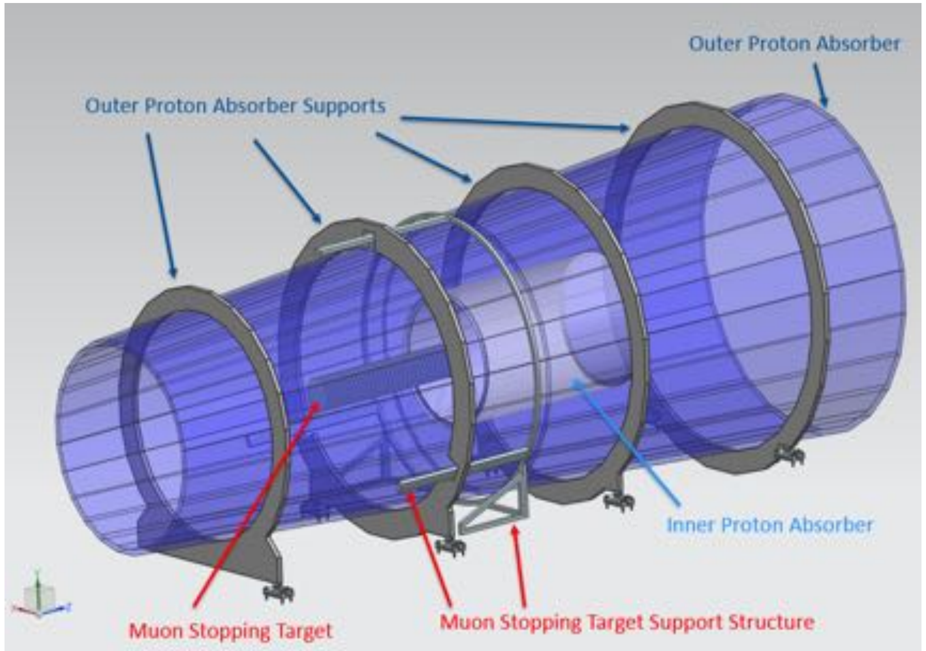




Stopping Target

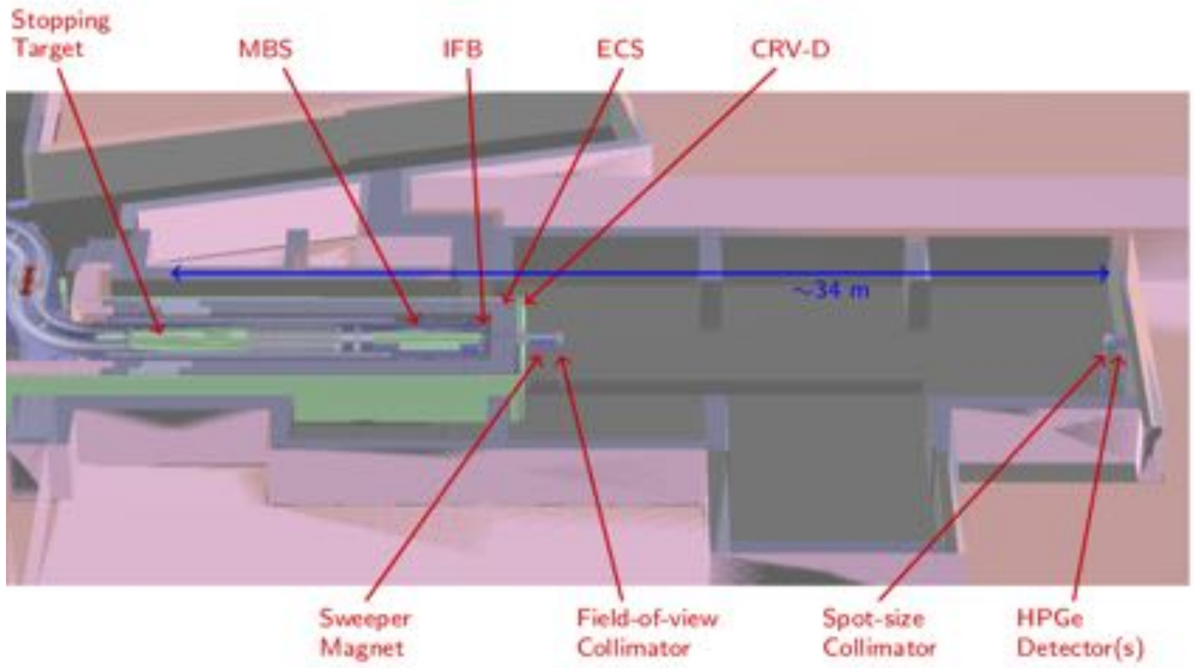
- 34 isotopically pure aluminum foils, 100 micron thick, 15 cm diameter
- Surrounded by plastic absorbers to reduce tracker rates.



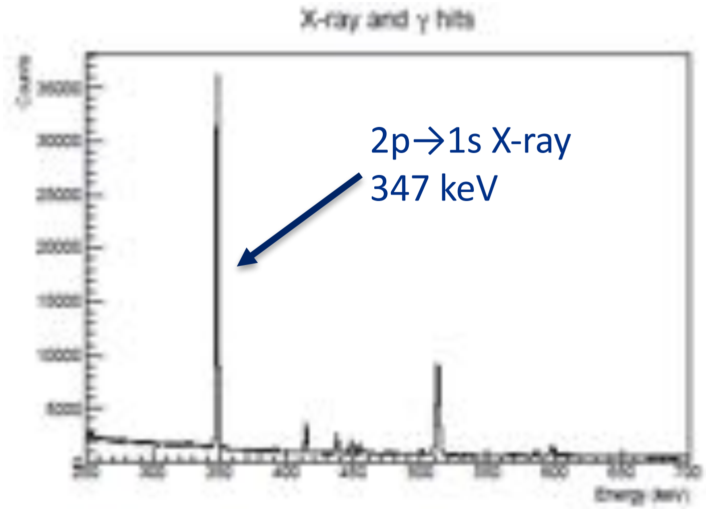


Stopping Target Monitor

- HPGe detector located far downstream to limit rates and radiation damage
- Gives ~ 2 keV FWHM resolution in energy range of interest



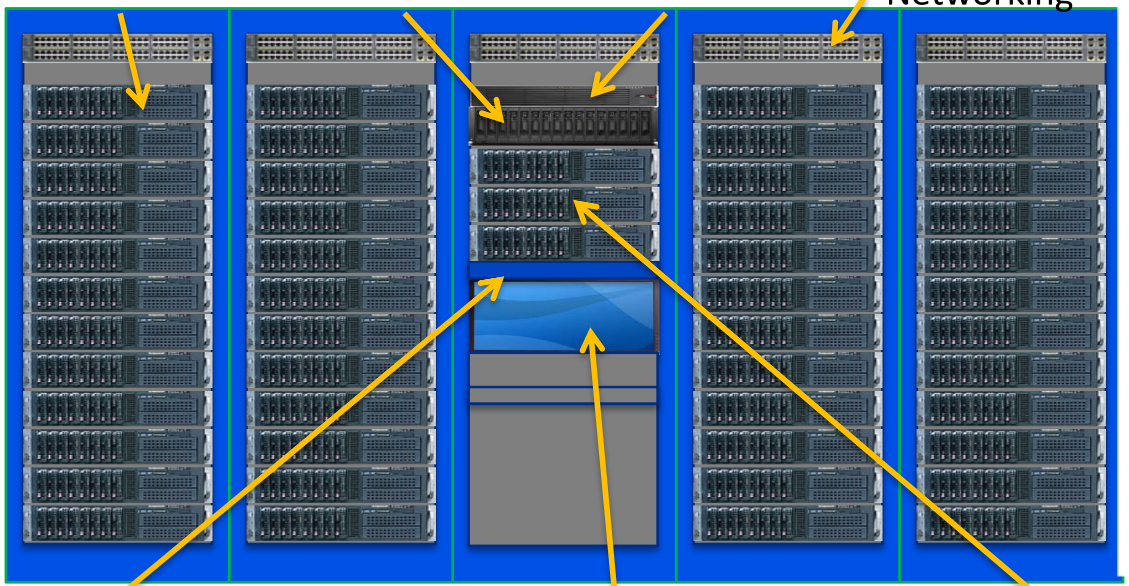
AlCap Data



347 keV 2p→1s muonic X-ray, no time cut

- Stopped muons in Al
- Ge self-triggered
- Energy resolution ~ 2 keV

Trigger and DAQ System



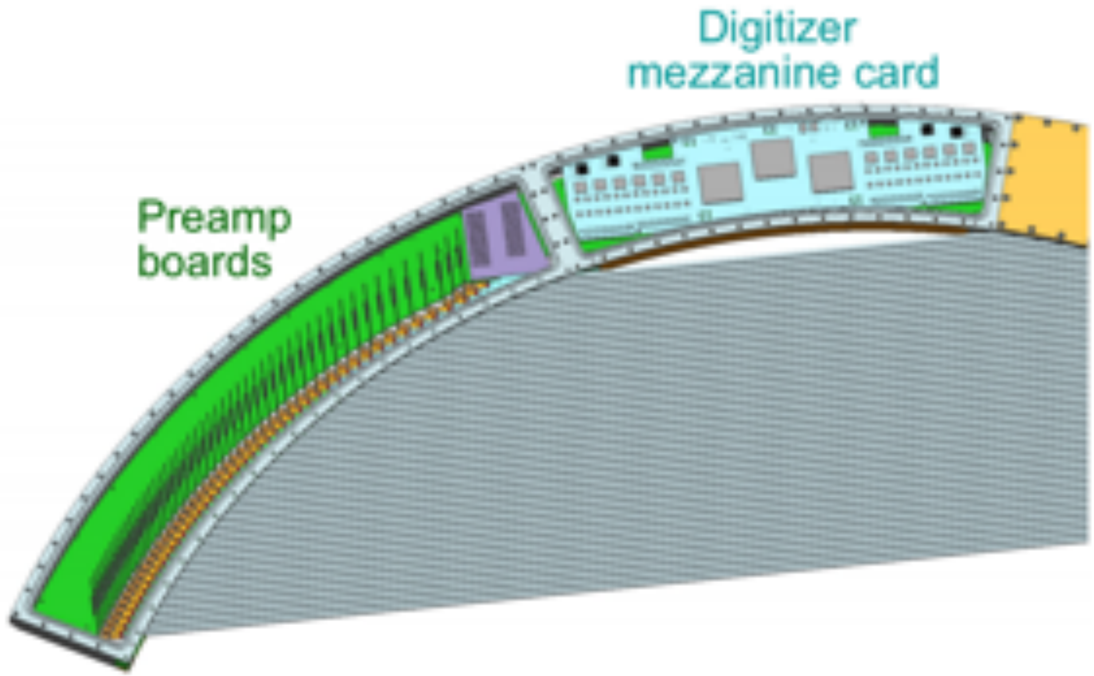
Parameter	Value
DAQ Servers	36
Detector Optical Links	216
System Bandwidth	40 GBytes/sec
Online Processing	40 TFLOPS
Input Event Size (average)	120 KBytes
Input Event Rate	192 KHz
Input Data Rate	35 GBytes/sec
Rejection Factor	≥ 100
Output Event Size (average)	130 KBytes
Output Event Rate	≤ 2000 Hz
Output Data Rate	≤ 260 MBytes/sec
Offline Storage	~7 PByte/year

Stream data in time slices to CPU farm. Employ software trigger filters to identify good events.

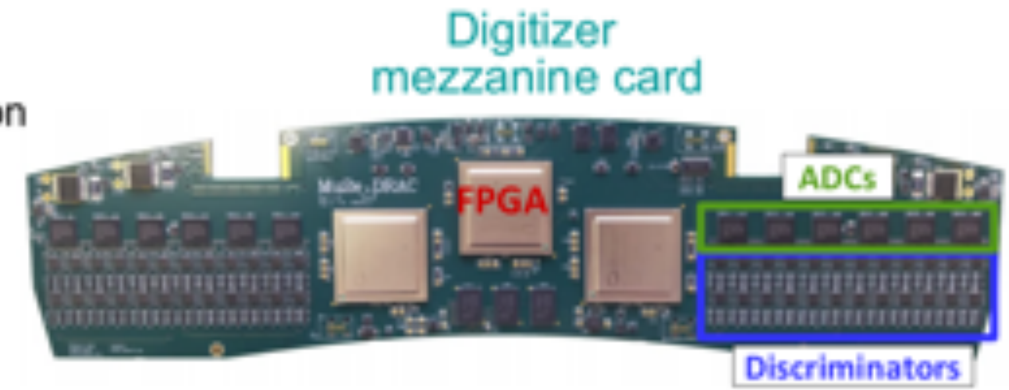
Tracker Front-End Electronics

Electronics volume $71<r<80$ cm
- on every panel inside cryostat

Readout at both ends of straw, preamp and digitization
- Drift time resolution: 2ns (100μm drift radius)
- Time difference resolution: 4cm along straw axis
- ADC for dE/dx measurement to identify highly-ionizing proton hits



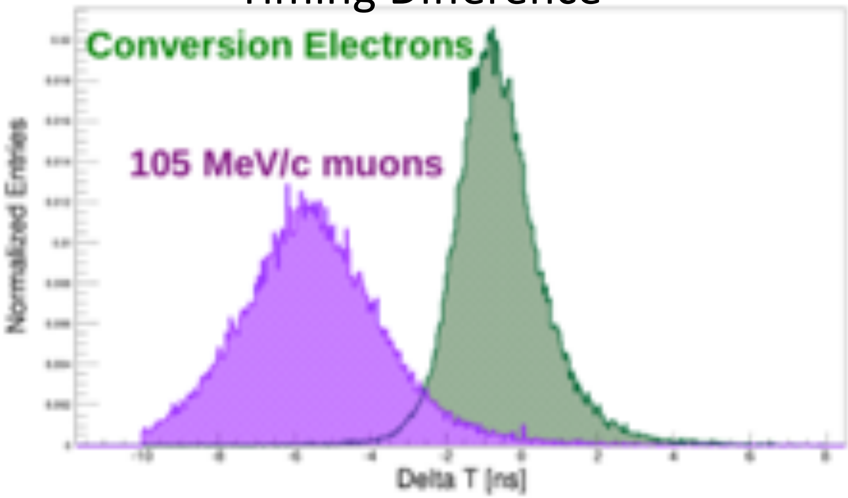
Requirements:
- Supply HV to straws (and remote disconnect)
- B-field perturbation <1G in active detector region
- Low power <10kW within cooling capabilities
- Sustain radiation damage from target
- $<12 \times 96$ dead channels in 5 yrs at 90% CL



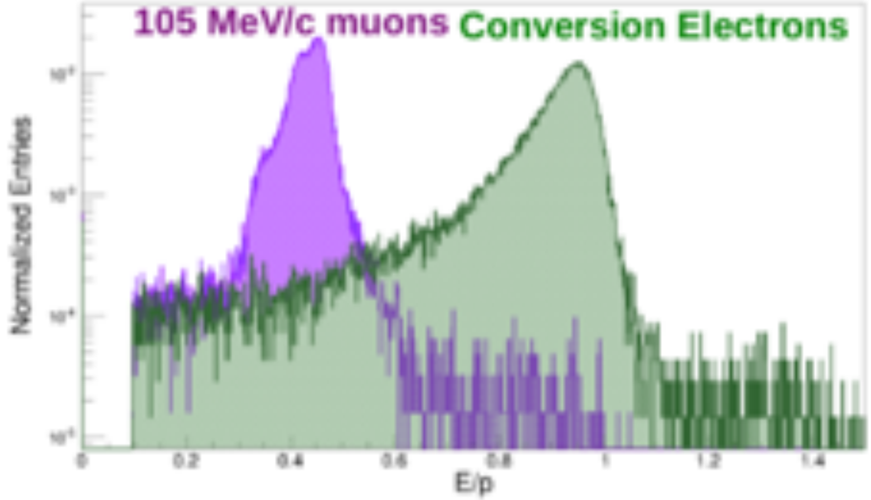
Mu2e Particle ID

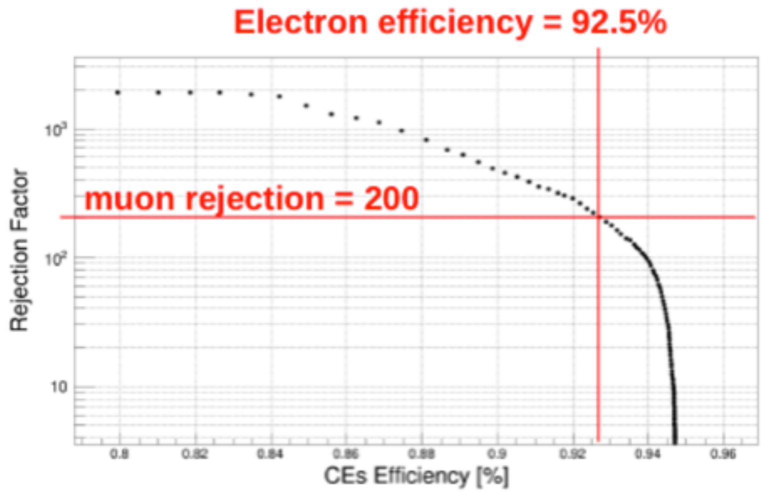
Tracker – Calorimeter track matching + likelihood analysis

Timing Difference



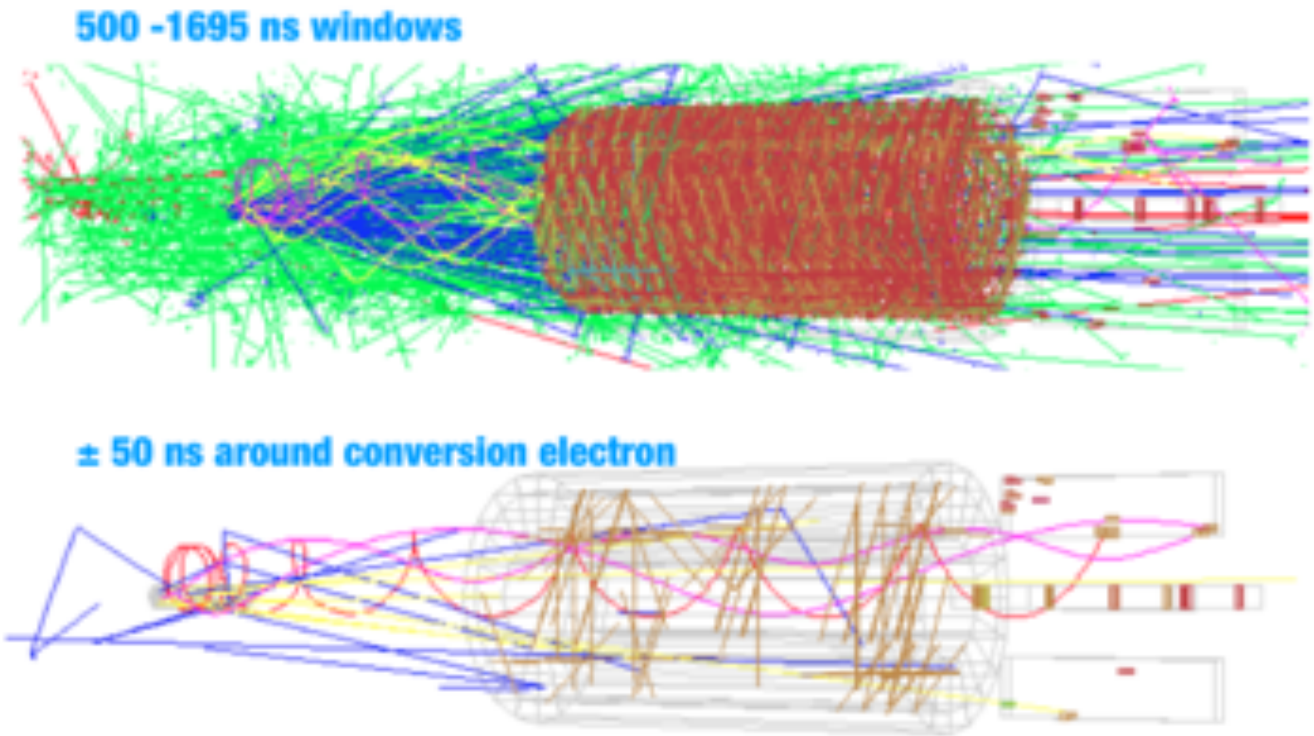
Energy/Momentum





Rejection factor of 200 eliminates this background

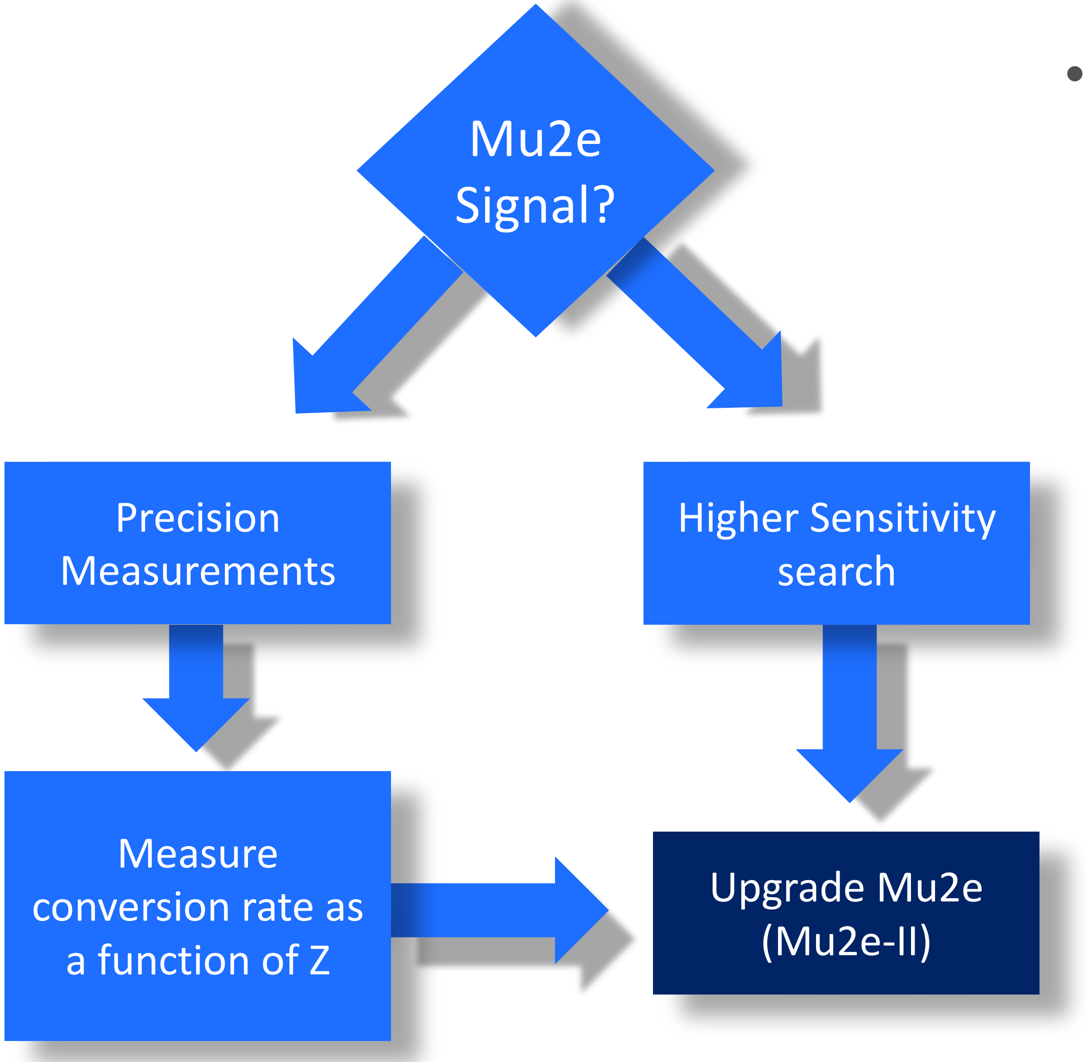
A Typical Event



Search for tracker hits with time and azimuthal angle that are compatible with calorimeter cluster ($\Delta T < 50$ ns).

- ➢ Significantly simplifies pattern recognition.

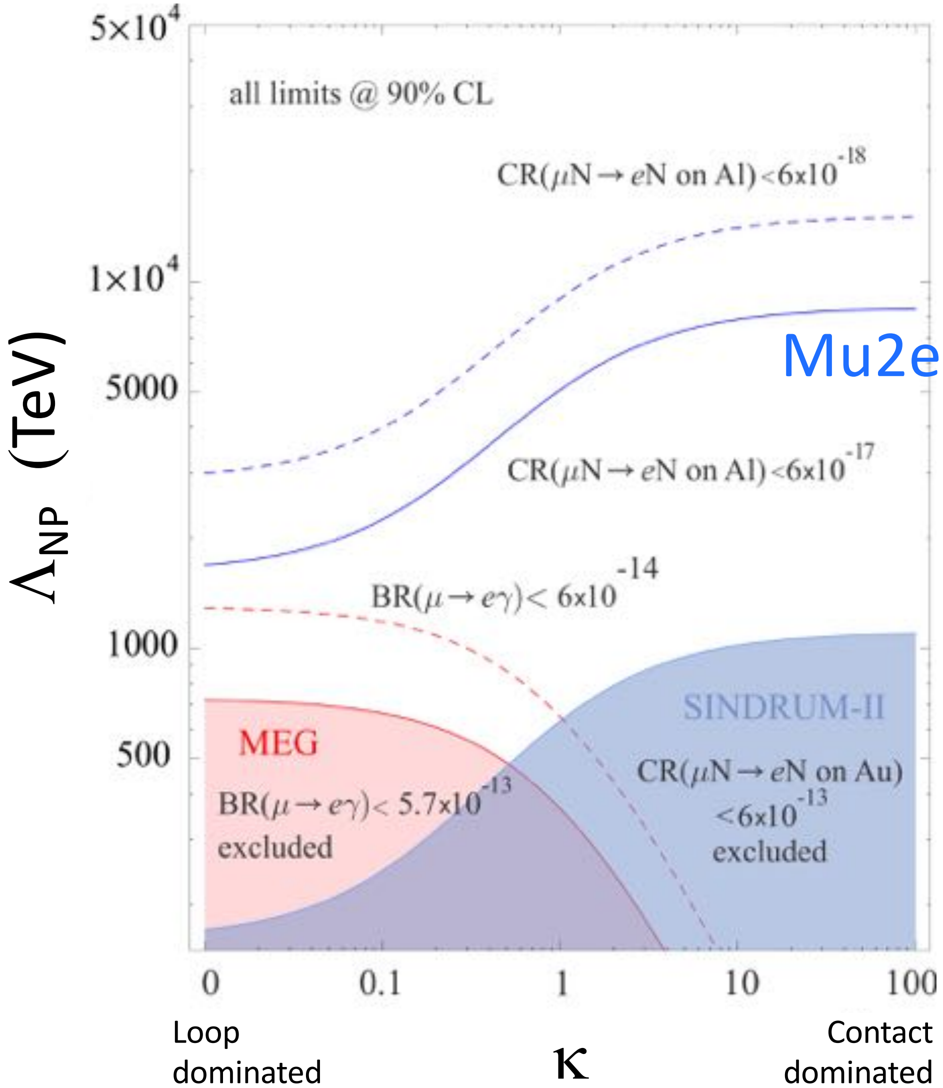
What Next?



- A next-generation Mu2e experiment makes sense in all scenarios
  - Push sensitivity or
  - Achieve precision to study underlying new physics
  - white paper, arXiv:1307.1168
  - EOI to FNAL PAC arXiv:1802.02599

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Λ: effective mass scale of New Physics κ: relative contribution of the contact term



Derived from A. de Gouvea , P. Vogel arXiv:1303.4097

Fermilab

μN→eN vs stopping-target Z

By measuring the ratio of rates using different stopping targets Mu2e-II can unveil underlying new-physics mechanism

V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)