The Mu2e experiment at Fermilab

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on behalf of the Mu2e collaboration

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The Mu2e experiment

- **Mu2e searches for charged-lepton flavor violation (CLFV) with muons in the presence of a nucleus:**

$$\mu^- + Al \rightarrow e^- + Al$$

- Measure ratio of $\mu^- \rightarrow e^-$ conversions (CLFV) to the number of μ captures.

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \mathrm{e}^- + \mathrm{N}\right)}{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \text{all captures}\right)}$$

Mu2e goals:

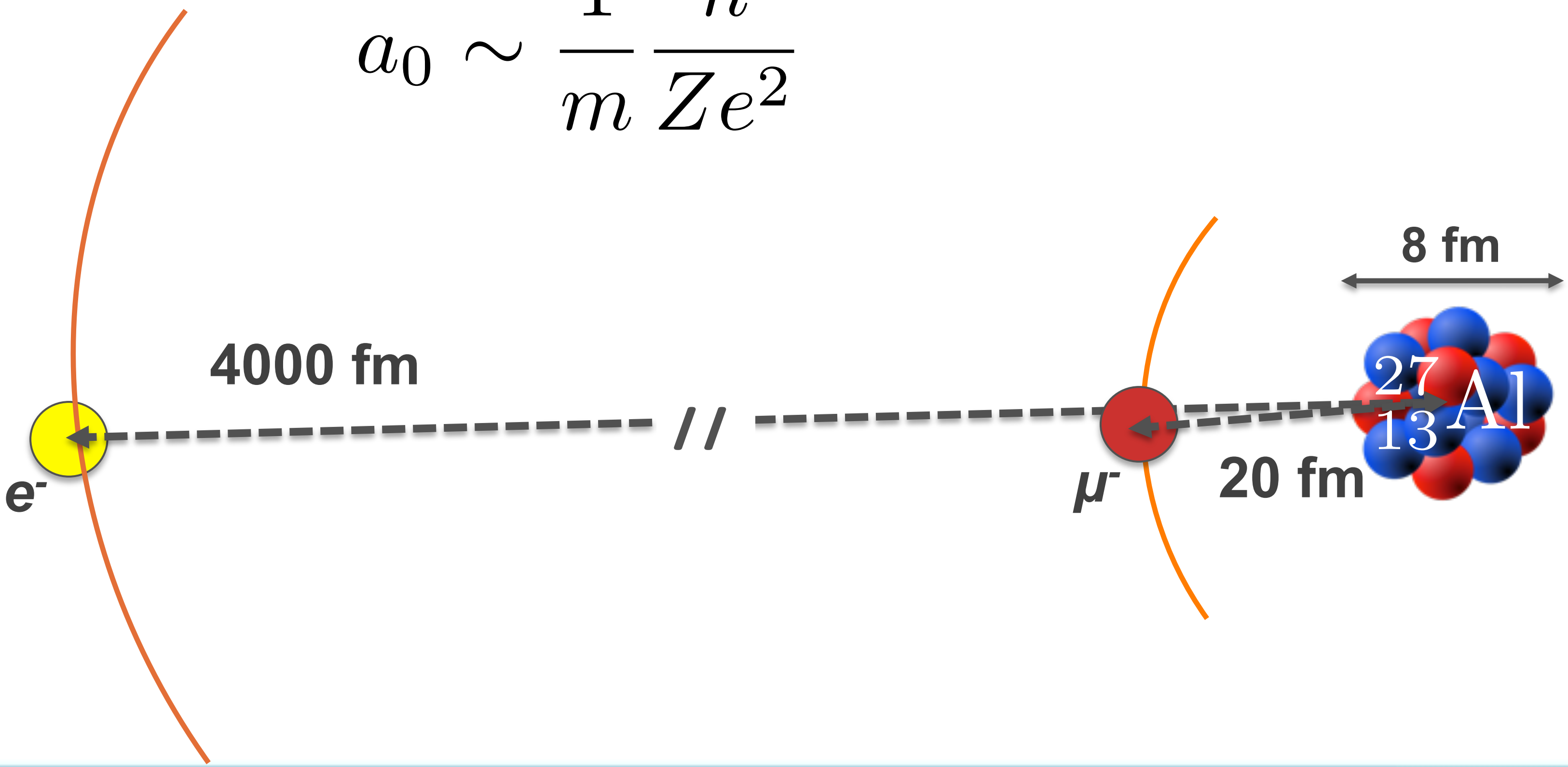
Assuming 3.6 x 10^{20} proton on target collected over 3 years of physics data-taking:

- ❑ Single-event-sensitivity (SES): 2.87×10^{-17} *algorithm under improvement*
- ❑ Upper limit (assuming 0 signal ☹) 7×10^{-17}
- ❑ Provides >5σ discovery sensitivity for all $R_{\mu e}$(Al) > few 10^{-16}

Muonic Atoms – a primer

- Bound muon cascades quickly to the 1*s* ground state (emits *X*-rays)
- Bohr radius of ground state:

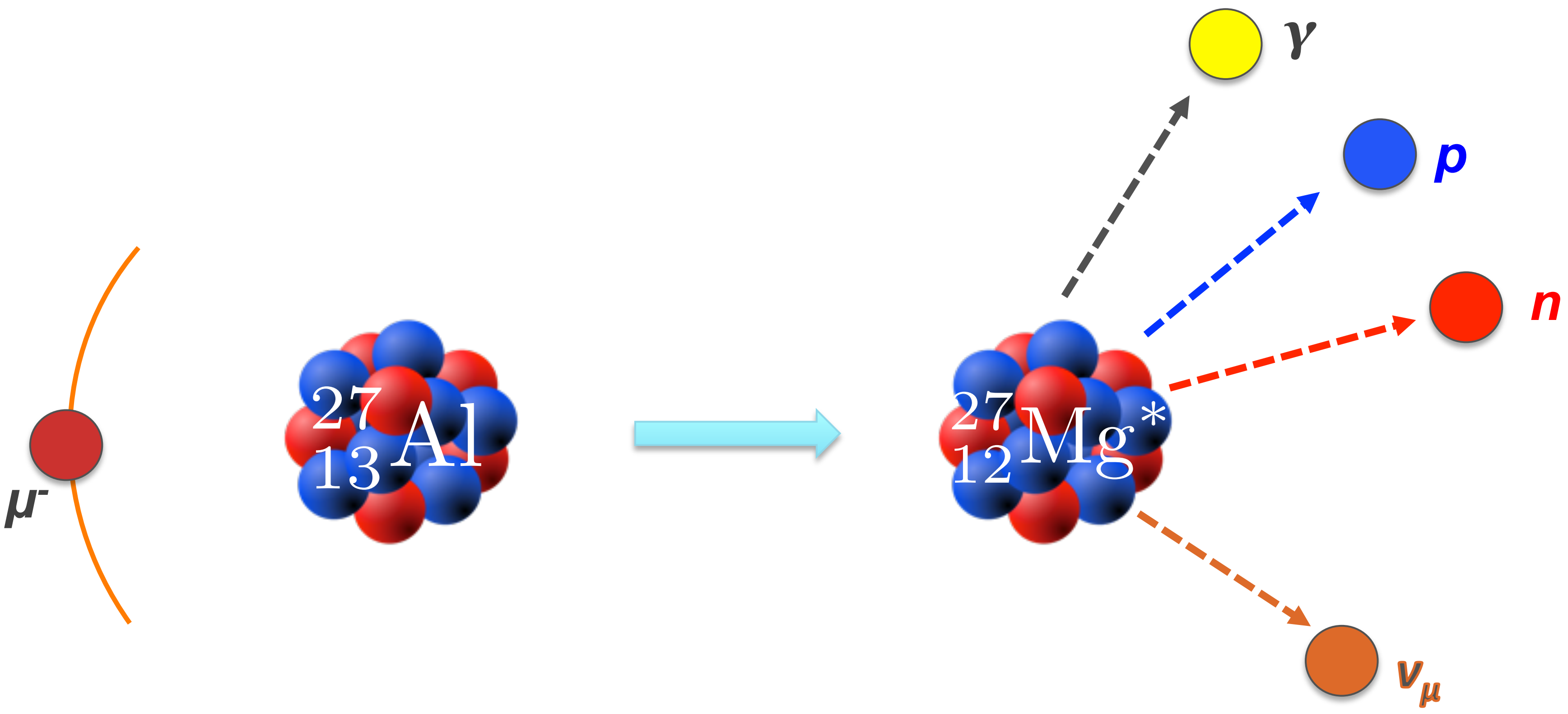
$$a_0 \sim \frac{1}{m}\frac{\hbar}{Ze^2}$$



Muonic Atoms

- **Nuclear capture** (61% of bound muons on Al)

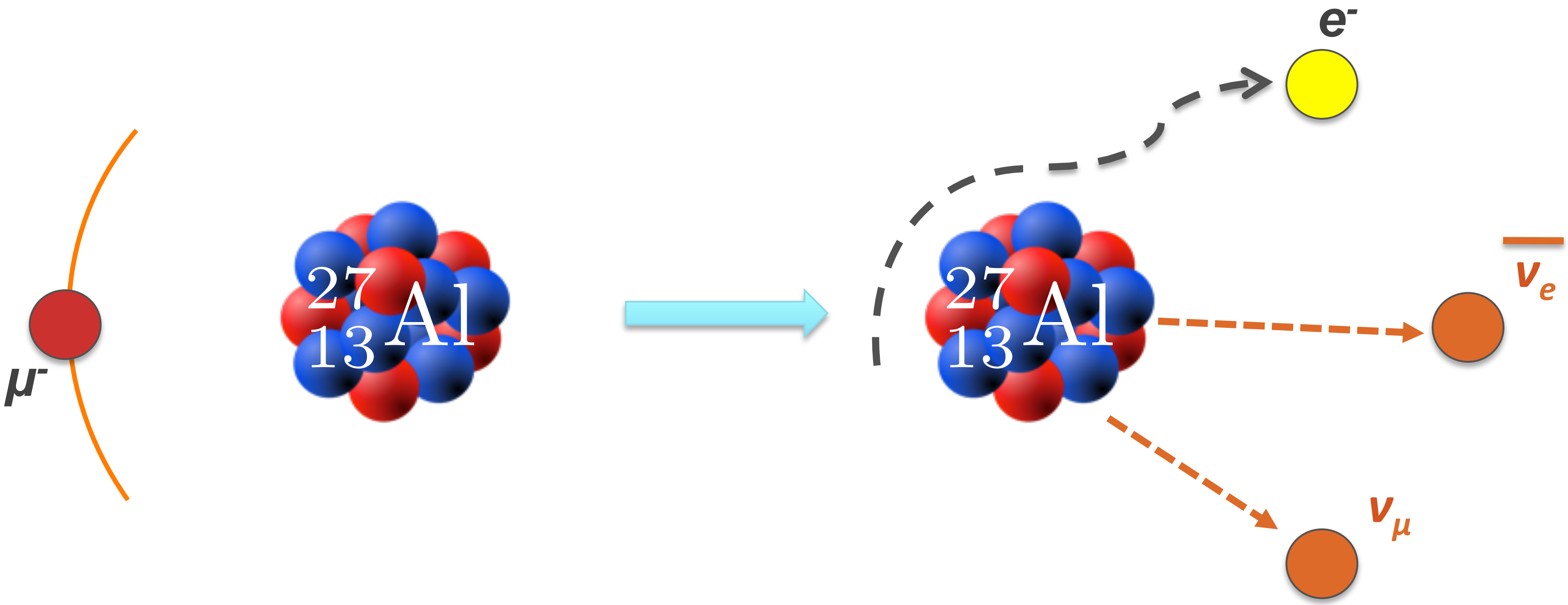
$$\mu^- + N \rightarrow \nu_\mu + N^{'}$$



Muonic Atoms

- **Decay-in-orbit** (39% of bound muons on Al)
  Rest of talk: **DIO**

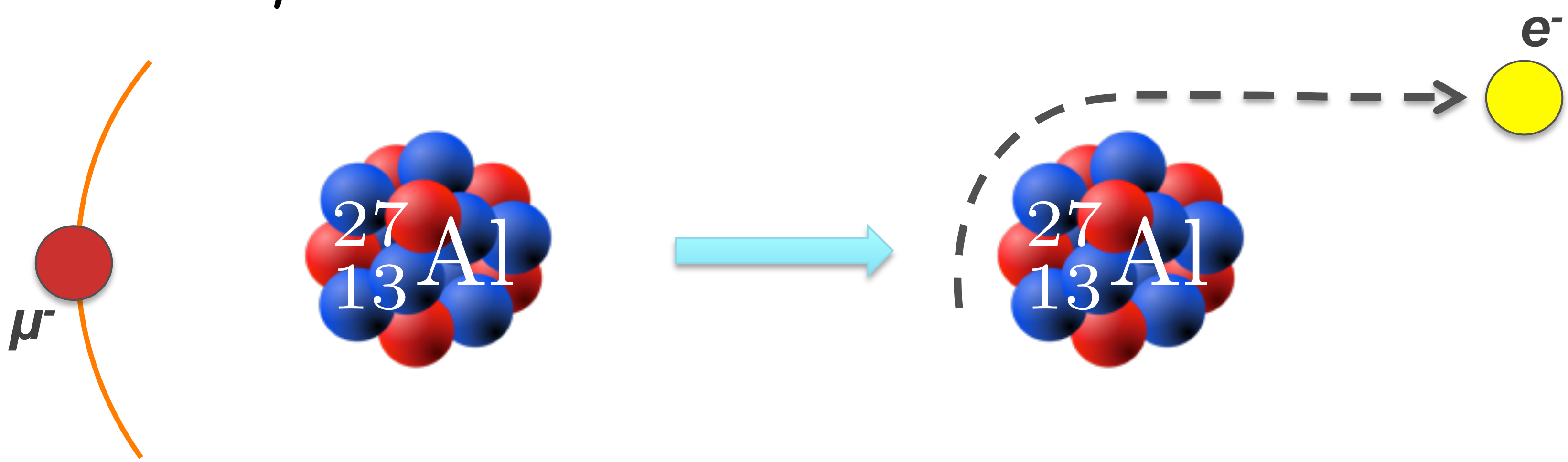
$$\mu^- + N \to e^- \overline{\nu}_e \nu_\mu + N$$



Muonic Atoms

- **Muon to electron conversion**

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



Experimental signature is a mono-energetic electron of energy

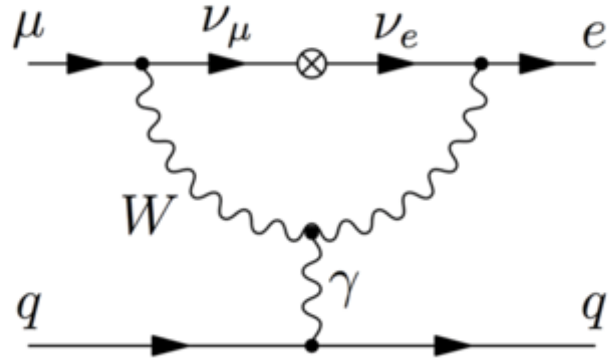
$$\begin{aligned} E_{\mu e} &= m_\mu c^2 - E_b - E_{\mathrm{recoil}} \\ &= 104.973 \text{ MeV} \quad (\text{for Al}) \end{aligned}$$

We know *exactly* where to look.

Charged lepton flavor violation

- **In principle, CLFV is not forbidden by massive-ν SM due to neutrino oscillations**

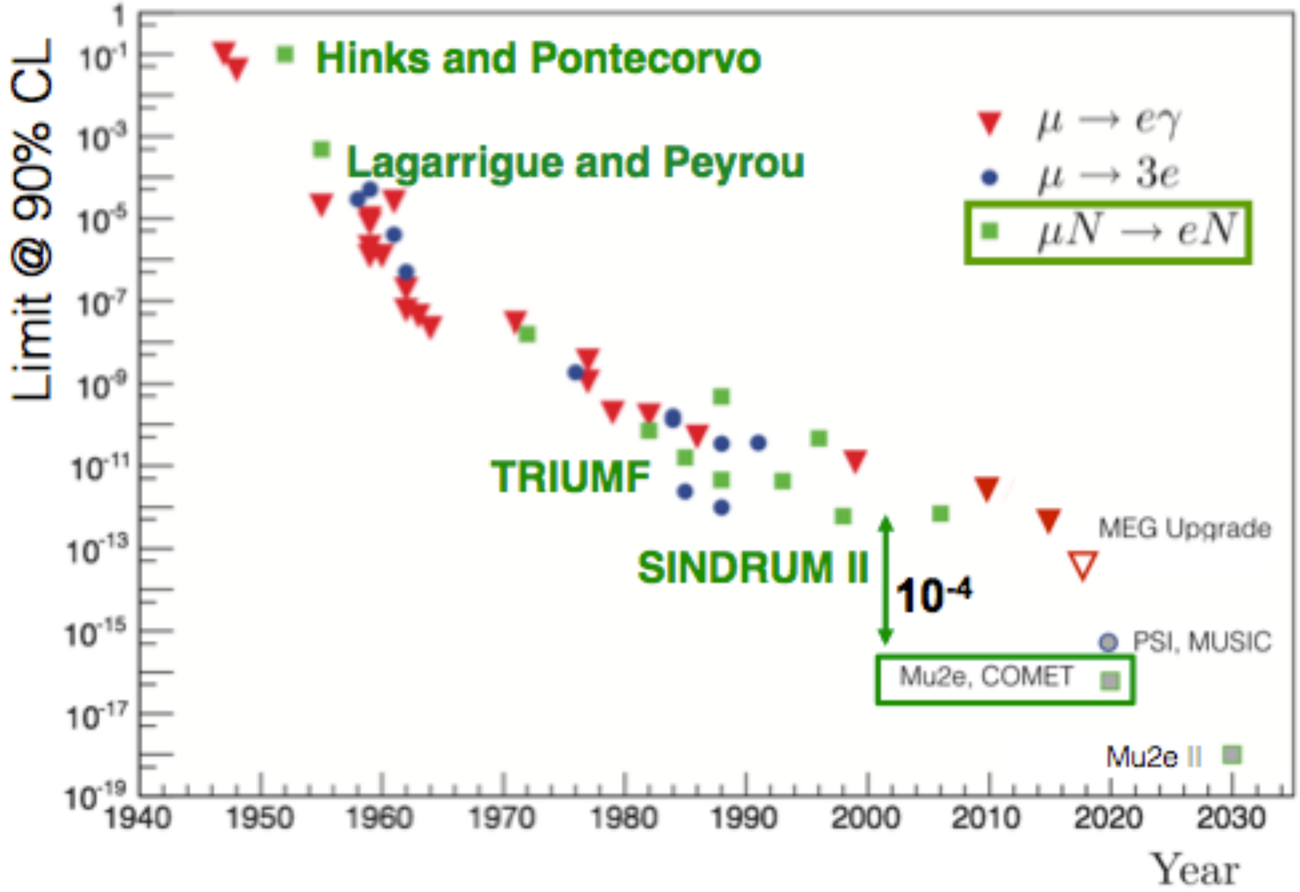
In practice, we will never see the SM process!
Transition rate < 10^{-50}



Various NP models allow CLFV <u>at levels just beyond</u> current CLFV upper limits. Some of these:

- *SO(10) SUSY*
  L. Calibbi *et al.*, Phys. Rev. D **74**, 116002 (2006); L. Calibbi *et al.,* JHEP **1211,** 40 (2012).
- *Scalar leptoquarks*
  J.M. Arnold *et al.*, Phys. Rev D **88**, 035009 (2013).
- *Left-right symmetric model*
  C.-H. Lee *et al.*, Phys. ReV D **88**, 093010 (2013).

History of CLFV limits with muons



R. Bernstein and P.S. Cooper, Phys Rept C (1307.5787)

- Best limit: $R_{\mu e} < 7\text{x}10^{-13}$ by SINDRUM II at PSI *[Eur.Phys.J C47(2006)]*
- **Mu2e will improve by a factor 10^4**

The Mu2e collaboration

Argonne National Laboratory, Boston University, Brookhaven National Laboratory
University of California, Berkeley, University of California, Irvine, California Institute of Technology, City University of New York, Joint Institute for Nuclear Research, Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, University of Illinois, INFN Genova, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce and Università del Salento, Lewis University, University of Louisville, Laboratori Nazionali di Frascati and Università Marconi Roma, University of Minnesota, Muons Inc., Northern Illinois University, Northwestern University, Novosibirsk State University/Budker Institute of Nuclear Physics, Institute for Nuclear Research, Moscow, INFN Pisa, Purdue University, Rice University, University of South Alabama, Sun Yat Sen University, University of Virginia, University of Washington, Yale University

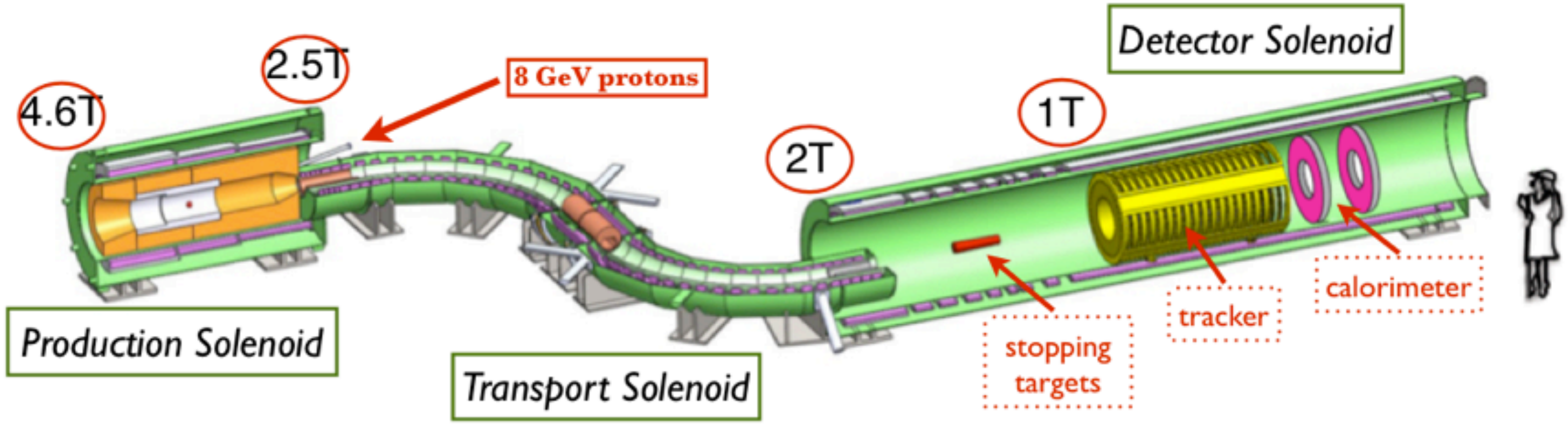
Experimental setup

Production Solenoid:

- Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

Detector Solenoid:

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field “reflects” downstream conversion electrons emitted upstream



Transport Solenoid:

- Select low momentum, negative muons
- Antiproton absorber in the mid-section

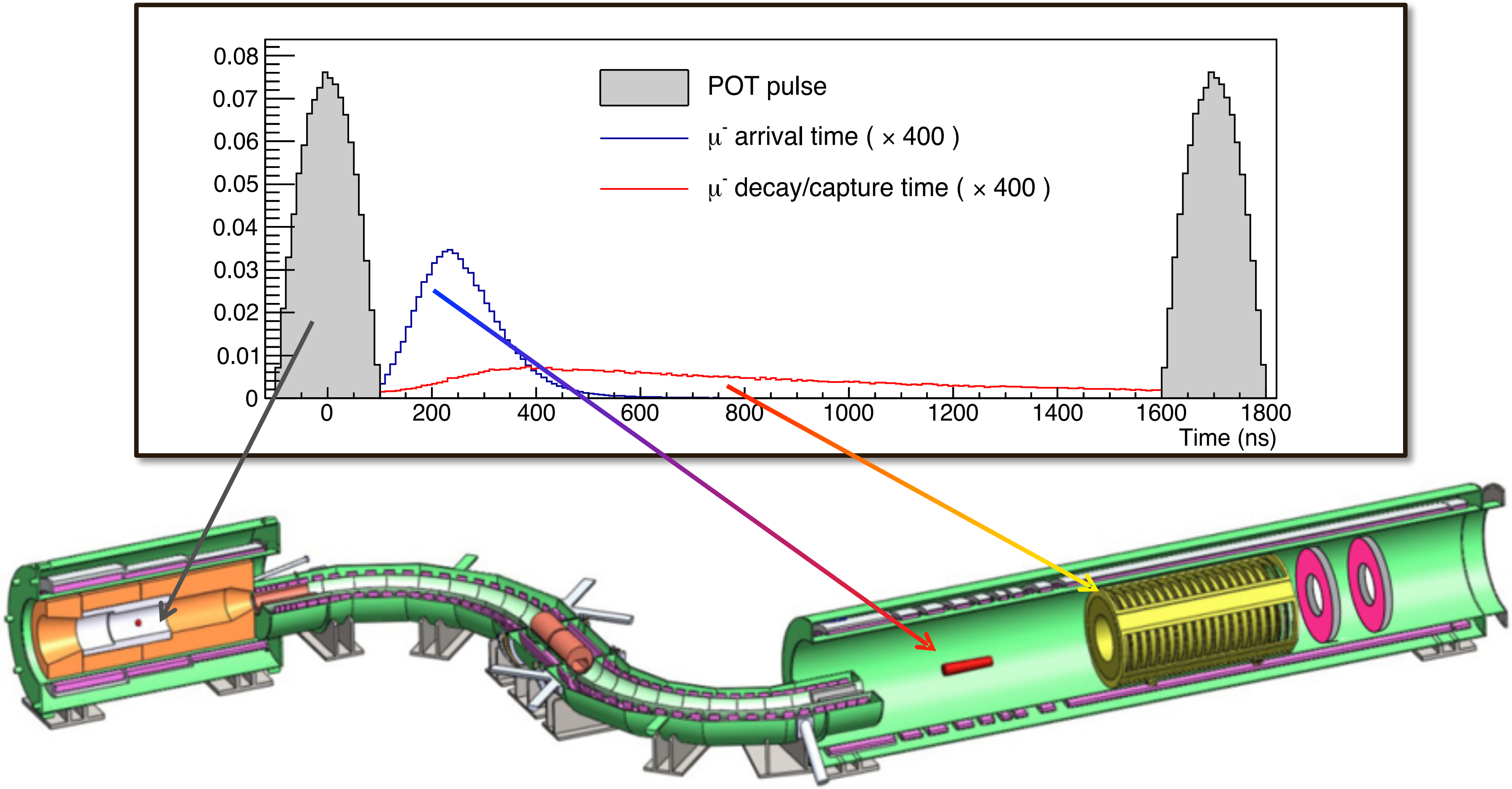
Physics backgrounds

The Mu2e experiment could be affected by many physics backgrounds. Below the most relevant:

- *Radiative π capture;*
- μ decay in orbit;
- Cosmic-induced background.

Radiative π capture -1-

What if a pion doesn't decay but survives and stops in the Al target?
→ A PULSED BEAM



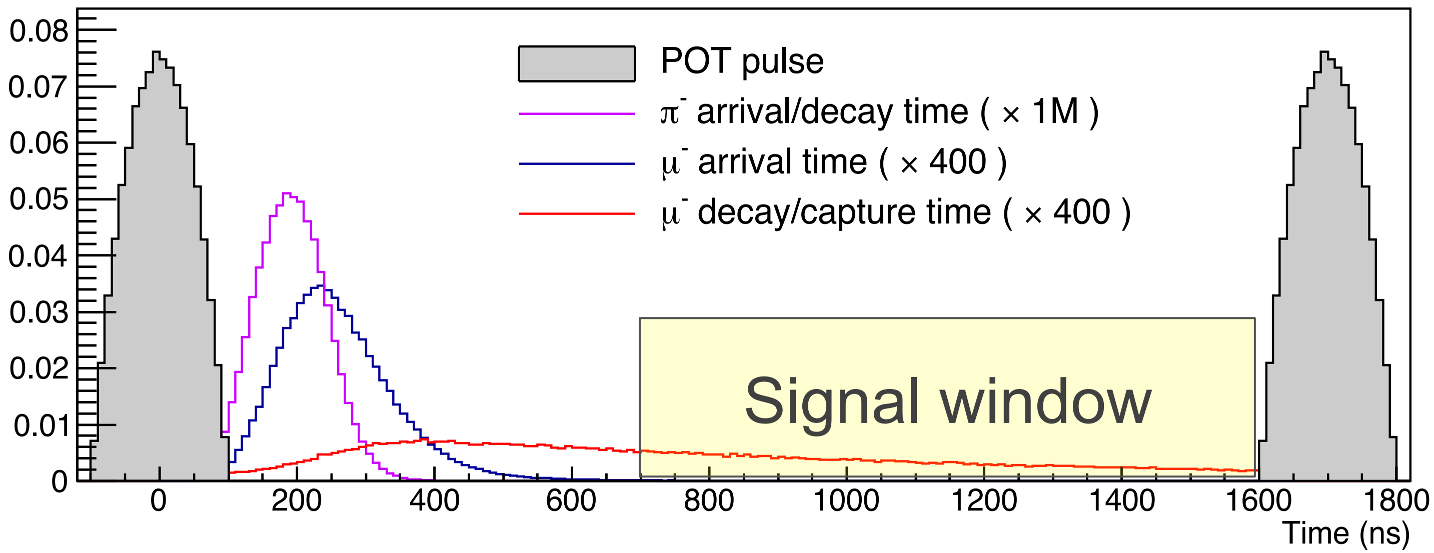
Radiative π capture -2-

- Pion capture can produce a significant background:

$$\pi^- + N \to \gamma_{e^+e^-} + N'$$

- Can produce electron at same energy as the signal electron!
- Trick: Muon decays from Al are slow; pion captures are fast.

Wait out the pion captures before starting the signal window.



Physics backgrounds

- Radiative π capture:
  → The 1695 ns proton pulse separation allows various backgrounds to significantly dissipate before we start the live gate.
- *μ decay in orbit;*
- Cosmic-induced background.

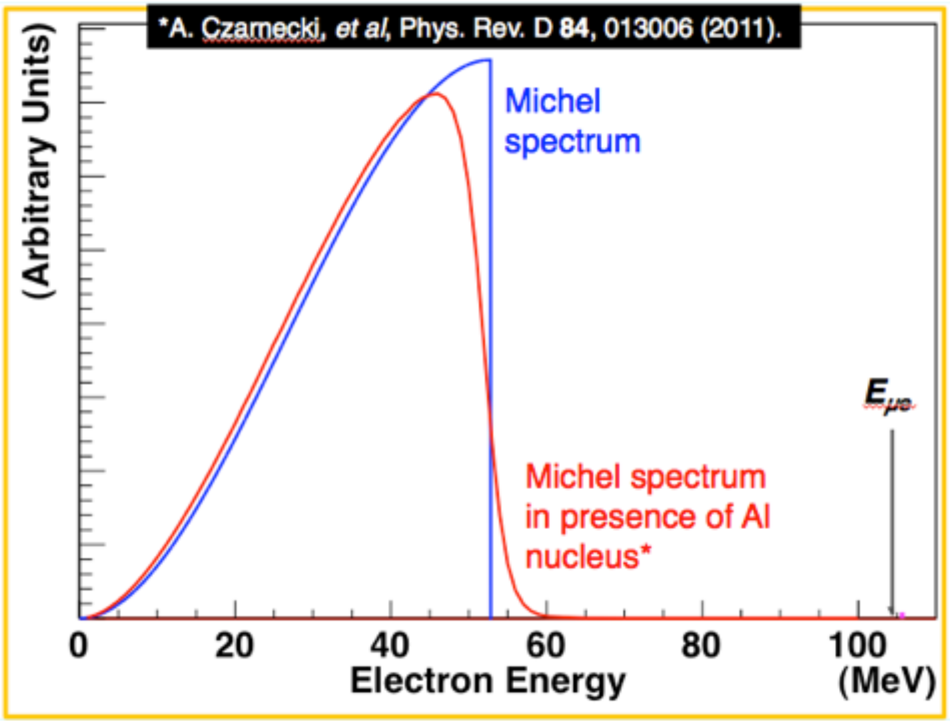
μ decay in orbit

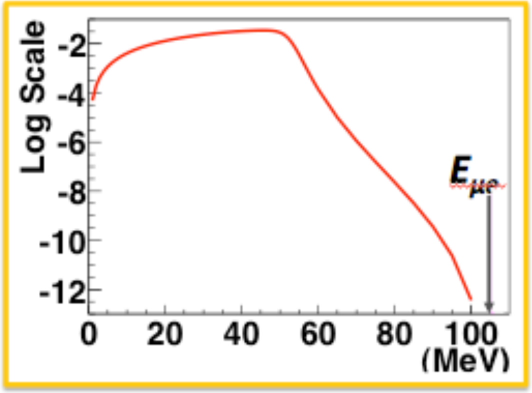
The energy distribution of electrons from muon decay is given by a (modified) Michel spectrum:

→ Michel spectrum endpoint: 52.8 MeV;

→ Presence of atomic nucleus → momentum transfer;

→ DIO electron energies up to signal energy $E_{\mu e}$.





Important design consideration!

Mu2e Detectors

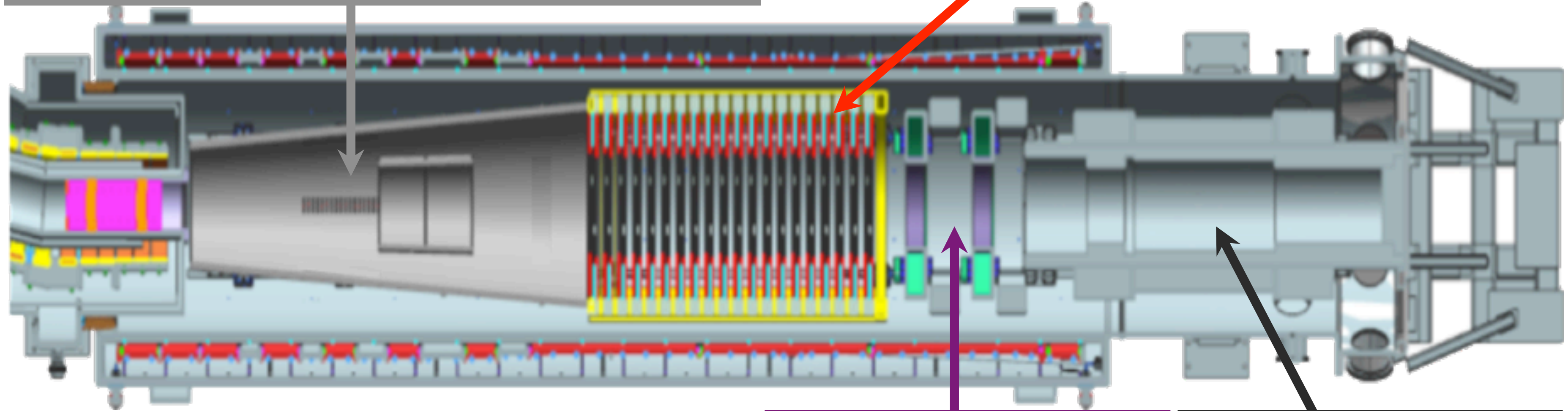
- *Targets:*

❖ 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (864 ns) that matches nicely the need of prompt separation in the Mu2e beam structure.

- *Tracker:*

❖ ~20k straw tubes arranged in planes on stations, the tracker has 18 stations

❖ Expected momentum resolution < 200 keV/c



- *Calorimeter:*

❖ 2 disks composed of undoped CsI crystals

- *Muon beam stop:*

❖ made of several cylinders of different materials: stainless steel, lead and high density polyethylene

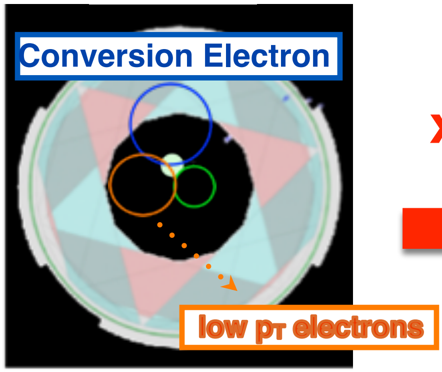
Tracker

- 18 stations with straws transverse to the beam;
- Straw technology employed:
  - ✓ 5 mm diameter, 15 μm Mylar walls
  - ✓ 25 μm Au-plated W sense wire
  - ✓ 80/20 Ar/CO_2 with HV ~ 1500 V
- Inner 38 cm un-instrumented:
  - ✓ blind to beam flash
  - ✓ blind to low pT charged particles coming from the Al target

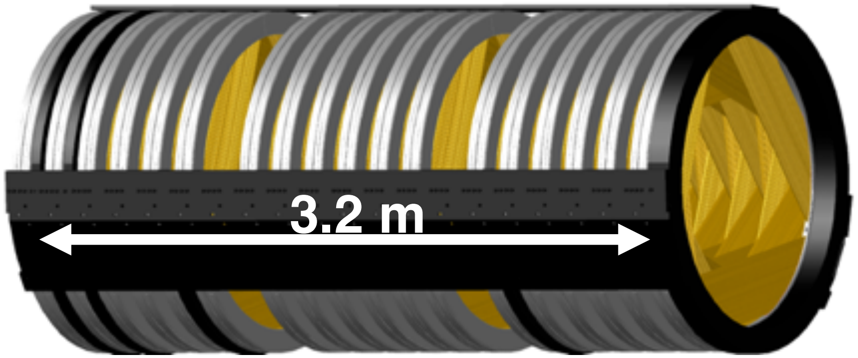
- Expected $\sigma_p < 200$ keV/c.

Straw Tube

Station



x18



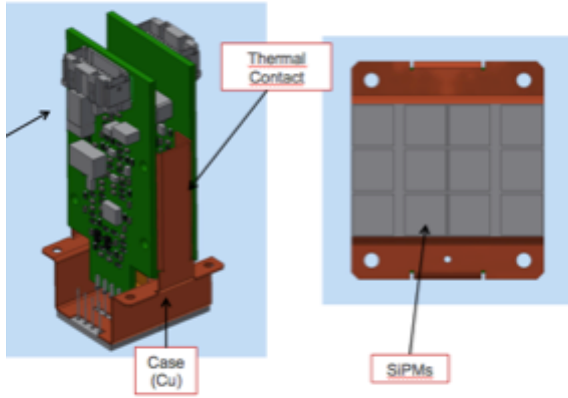
FEE

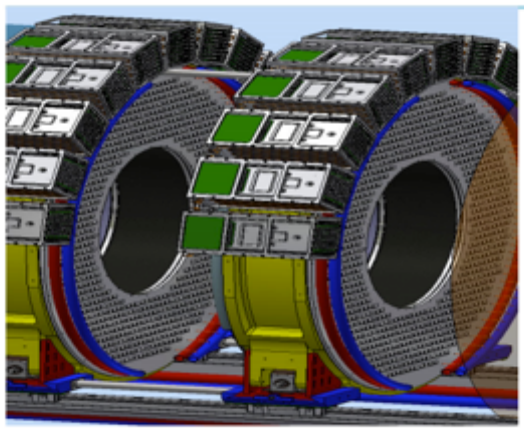
Calorimeter

- 2 disks; each disk contains 674 undoped CsI crystals 20 x 3.4 x 3.4 cm^3;
- Readout by 2 large area MPPC each + waveform digitizer boards @ 250 MHz;

Allows to measure:

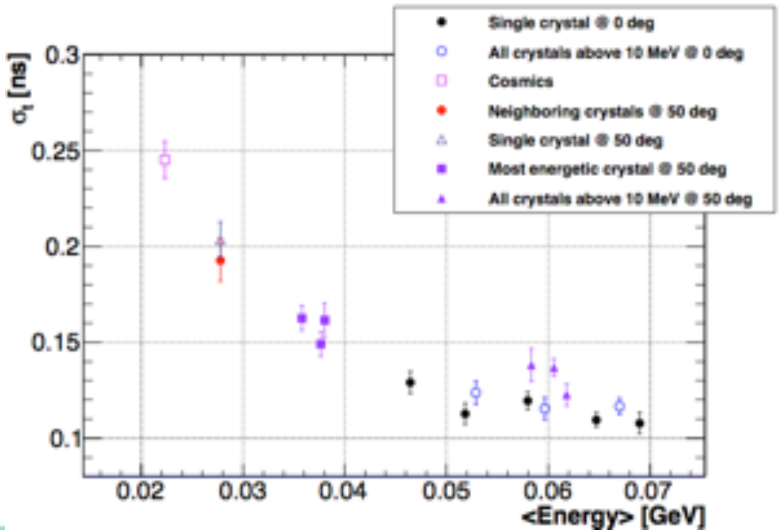
- ✓ Electron/muon discrimination from cosmic rays;
- ✓ **Improve track search via a calorimeter-seed pattern recognition;**
- **Time resolution $\sigma_t < 200$ ps @ 100 MeV measured @ BTF in Frascati.**





Undoped CsI

Beam test @ BTF in Frascati



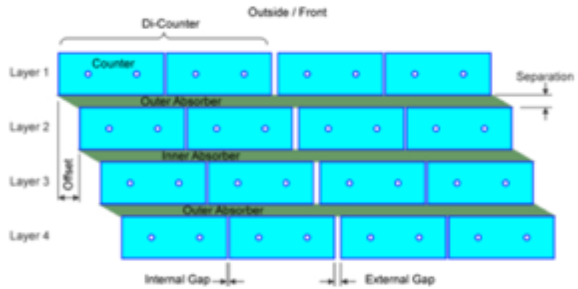
Physics backgrounds

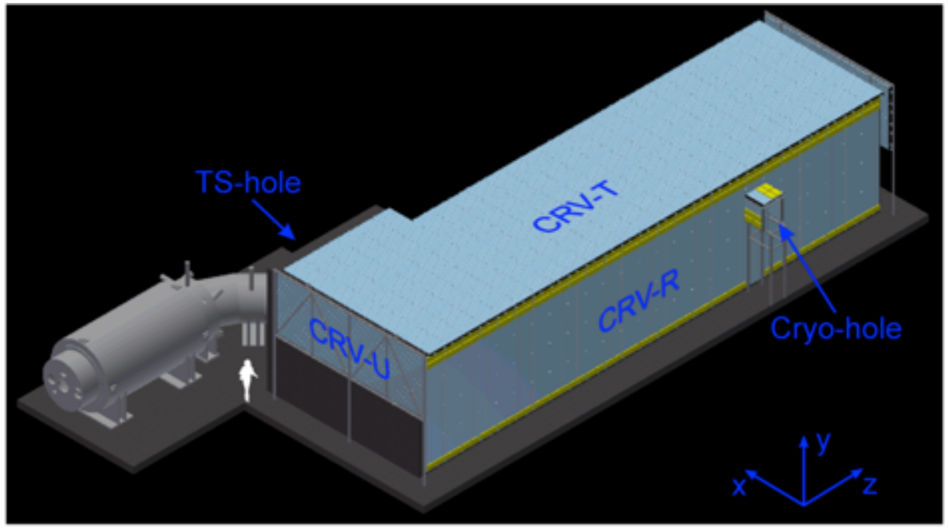
- Radiative π capture;
- μ decay in orbit:
  → low-mass tracker with high performance and fast calorimeter with timing information for background reduction.
- *Cosmic-induced background.*

Cosmic Ray Veto

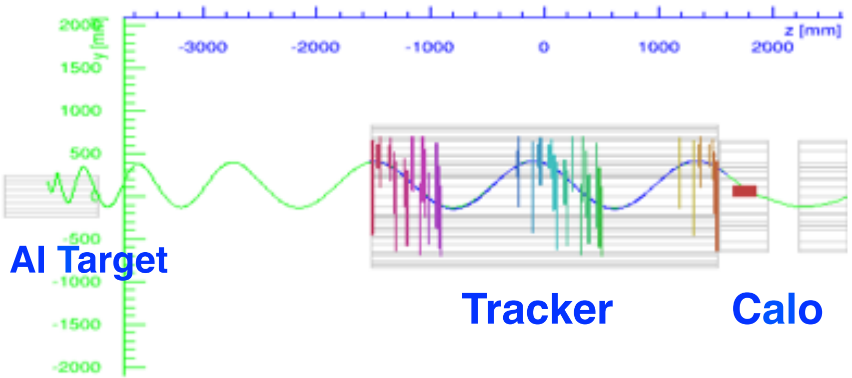
- Veto system covers entire DS and half TS;
- 4 layers of scintillator:
  - ❖ each bar is 5x2x(~450) cm^3
  - ❖ 2 WLS fibers/bar
  - ❖ read out with SiPM

- Inefficiency < 10^{-4}





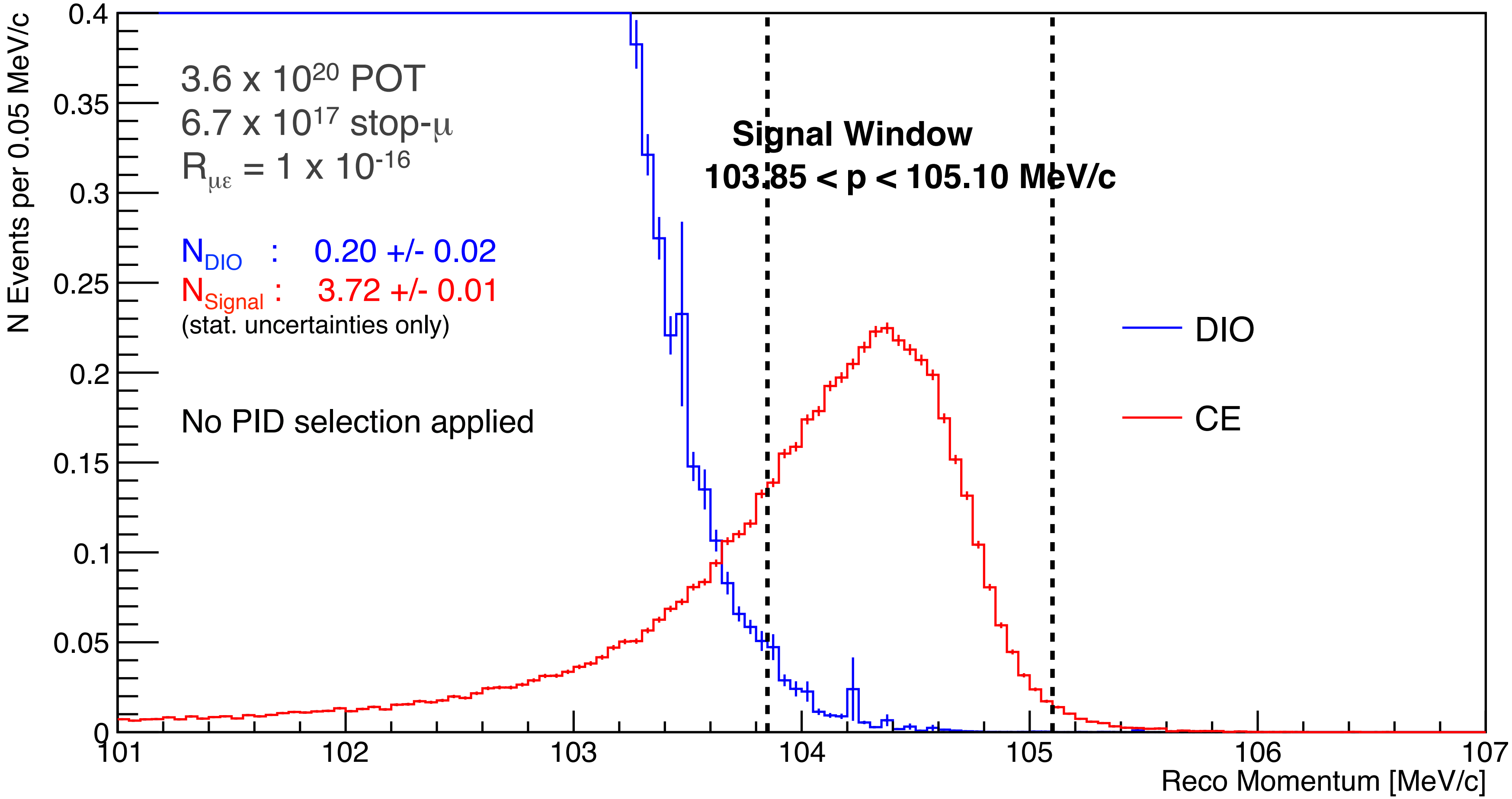
***μ* mimicking the signal**



Physics backgrounds

- Radiative π capture;
- μ decay in orbit;
- Cosmic-induced background:
  → cosmic ray veto and PID with the Calorimeter

The full simulation



- **Total background < 0.5 events**

Summary

❑ Mu2e is an experiment to search for CLFV in μ coherent conversion

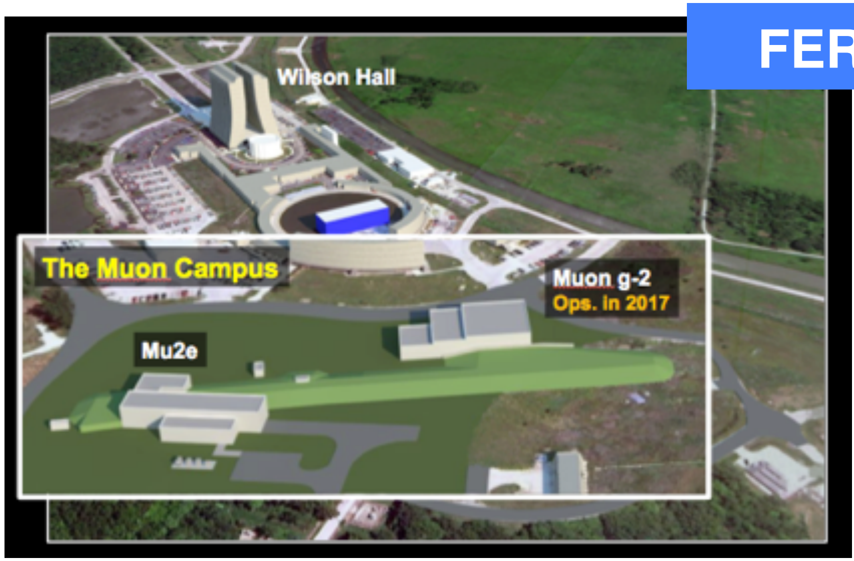
✓ aims 4 orders of magnitude improvement

➢ Civil construction and magnets procurement already started

➢ R&D mature with data taking scheduled on 2021

- More info: http://mu2e.fnal.gov

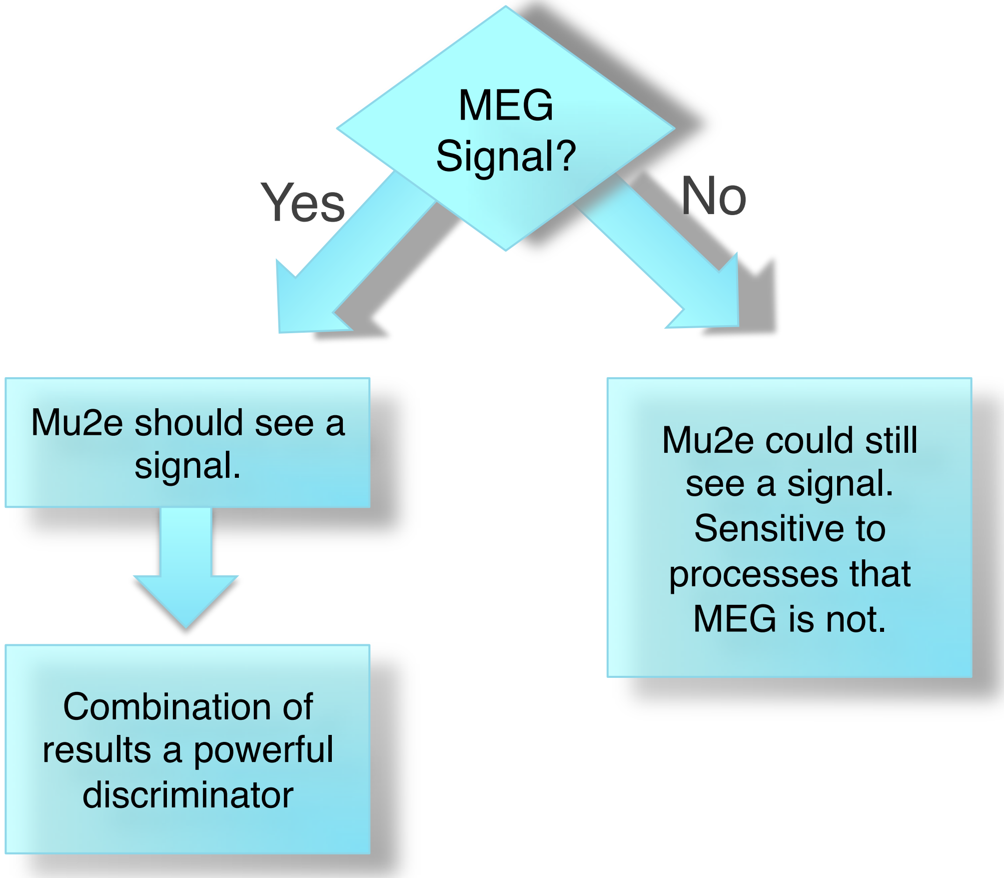
FERMILAB

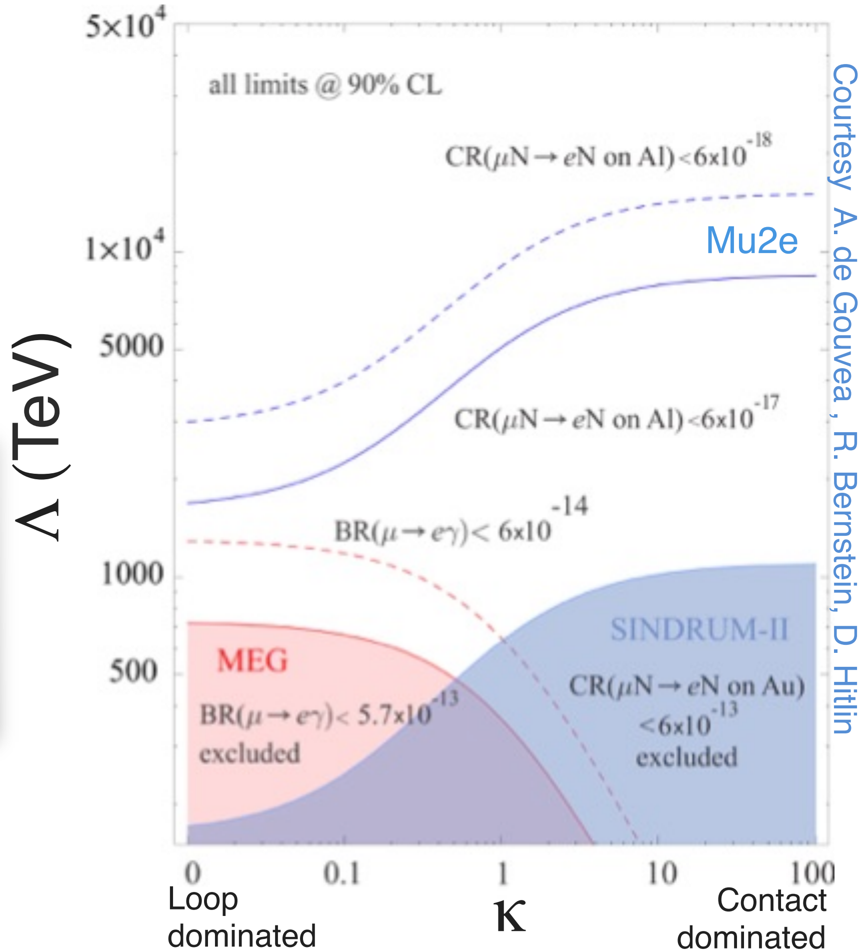


SPARES

Mu2e and MEG

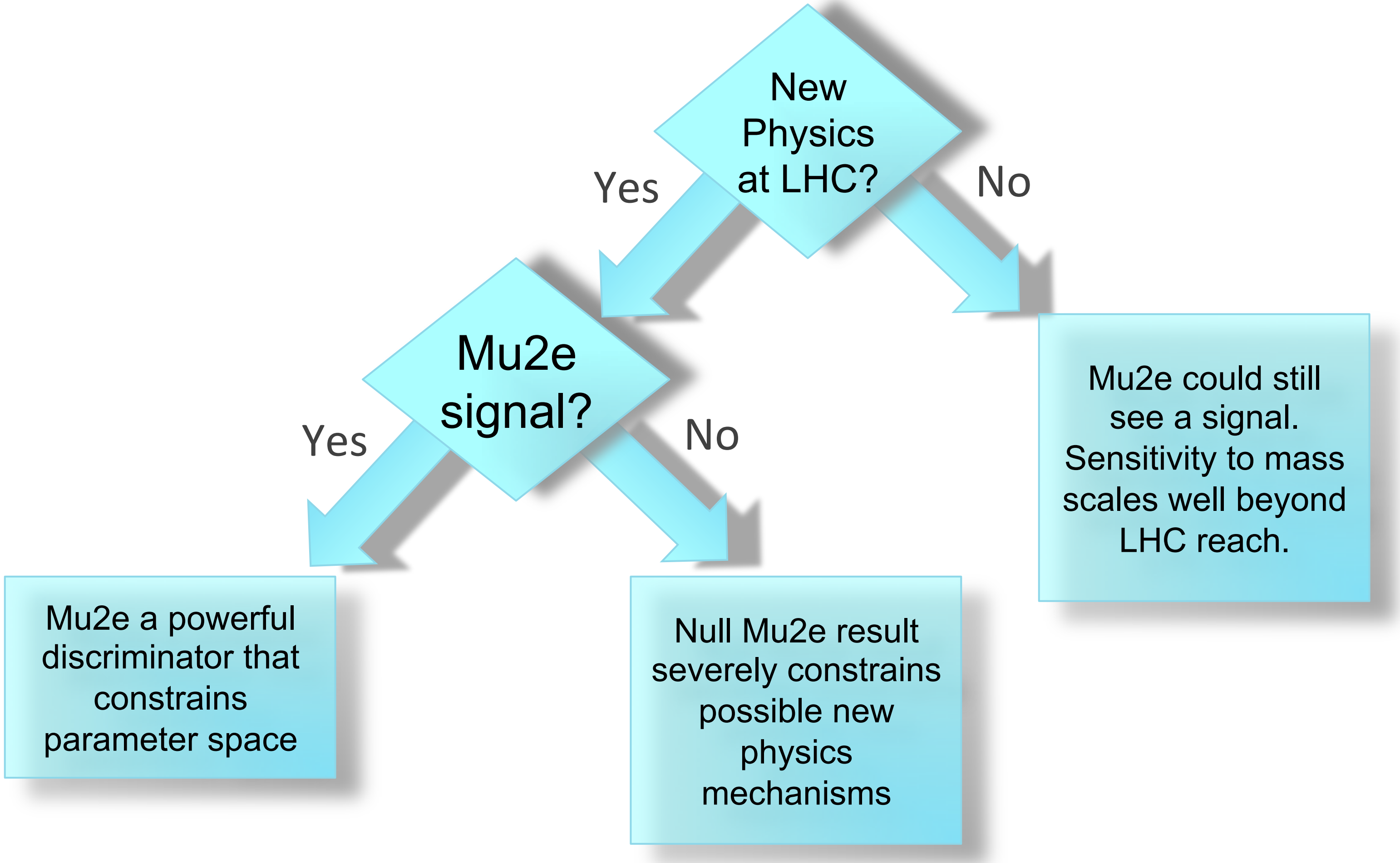
- **Mu2e is a potential discovery experiment that is relevant in all possible scenarios**



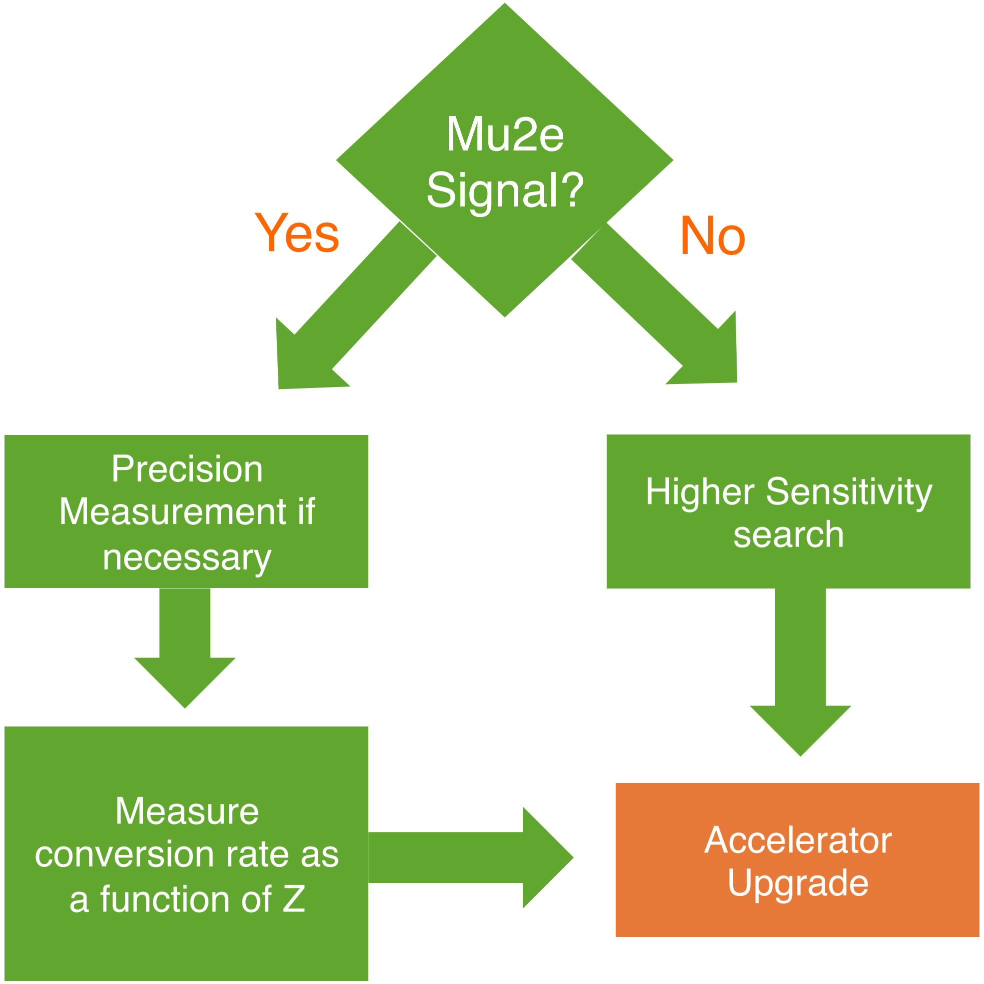


Mu2e and the LHC

- **Mu2e is a potential discovery experiment that is relevant in all possible scenarios**

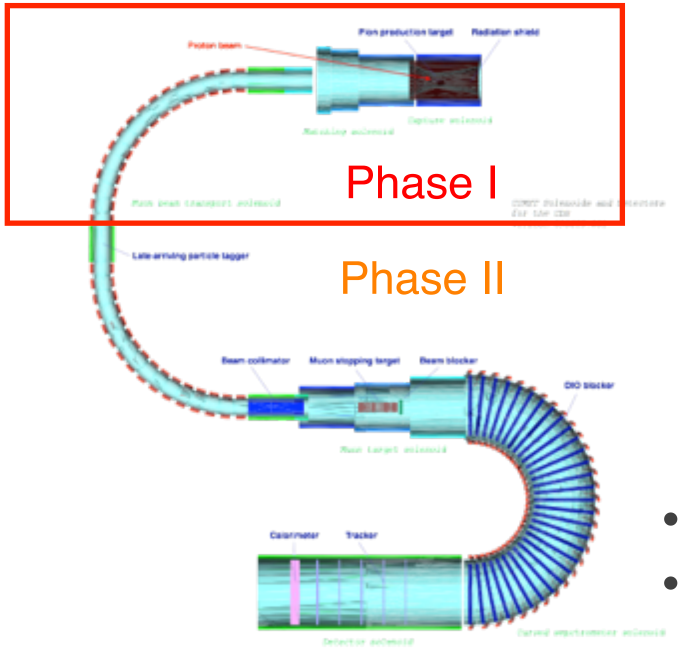


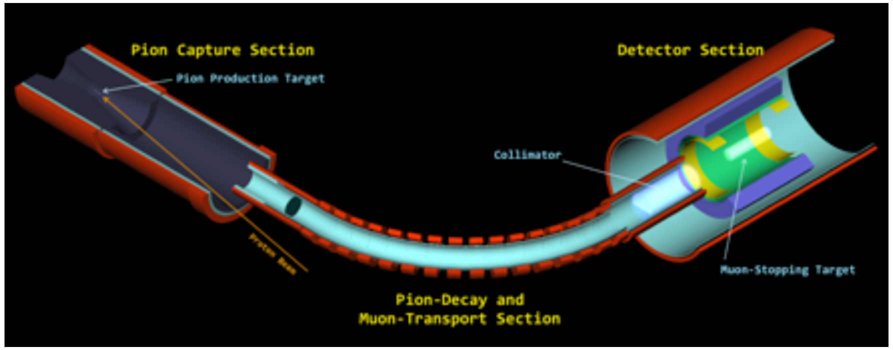
Next Generation Mu2e



- A next-generation Mu2e experiment makes sense in all scenarios
  - Push sensitivity or
  - Study underlying new physics
  - Will need more protons → upgrade accelerator
  - Snowmass white paper, arXiv:1307.1168
  - X10 improvement in sensitivity plausible with modest upgrades of current design

COMET





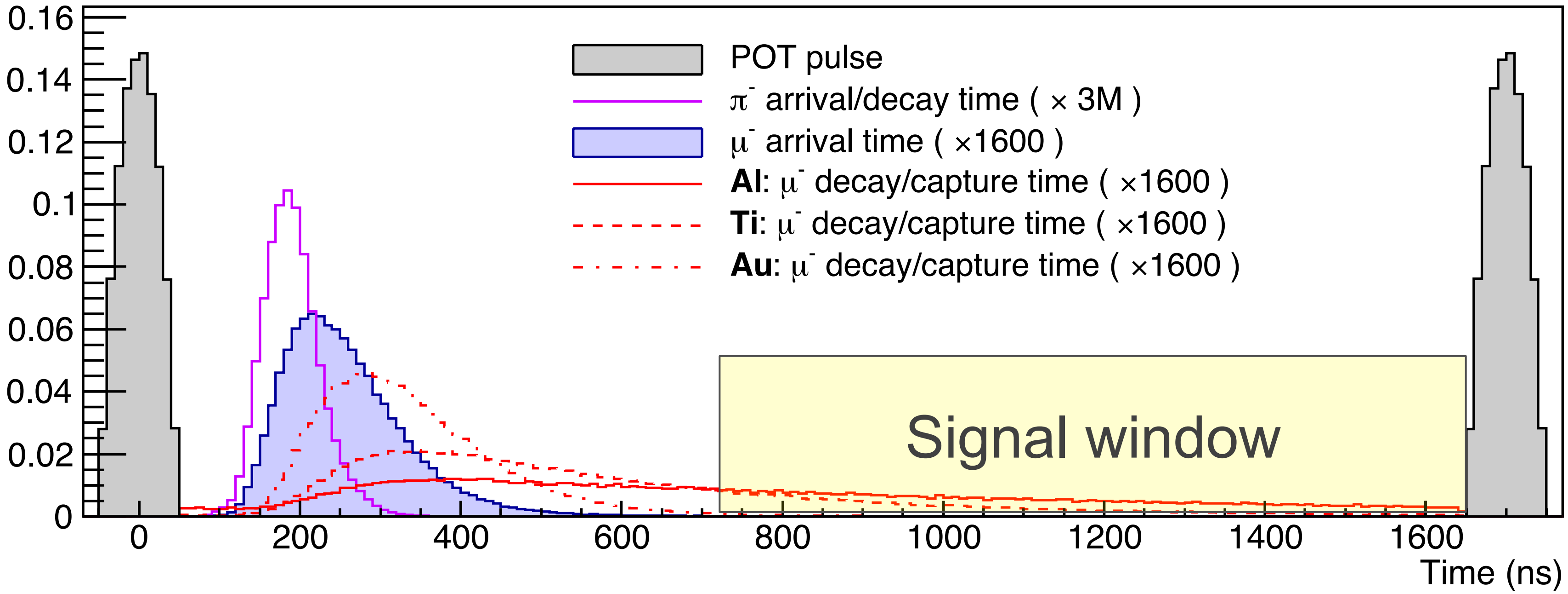
- Design beam power: 56 kW (8kW for Mu2e)
- Path length of solenoids: ~38m (28m for Mu2e)

- Phase 1: scheduled to begin 2019, x100 improvement
- Phase 2: aim to begin so that they’re competitive with Mu2e, another x100 improvement

Why aluminum?

- Since pion capture process happens very quickly, need a target where the muon decay/capture happens slowly, so we can collect as many muon decays as possible

	Al	Ti	Au
Stopped muons that decay	39%	15%	3%
Stopped muon decays in sig. window	50%	30%	1%
Time constant for muon decay	**864 ns**	**329 ns**	**75 ns**



Updated Background Estimate

Process	TDR (stat+syst)
Decay in Orbit:	0.199 +/- 0.092
Radiative μ Capture:	$0.000^{+0.004}_{-0.000}$
π Capture:	0.023 +/- 0.006
μ DIF:	< 0.003
π DIF:	0.001 +/- <0.001
Beam electrons:	0.003 +/- 0.001
Anti-protons:	0.047 +/- 0.024
Cosmic ray induced:	0.082 +/- 0.018
Total Background:	0.36 +/- 0.10
SES for signal (10^{-17}):	(2.87 +/-0.32)

- For 3.6 x 10^{20} POT, extinction of 10^{-10}, and a CRV inefficiency of 10^{-4}
- Momentum window tuned to give ~0.20 DIO events.
- After all selection requirements.

Why Particle Identification is needed

- Cosmic ray and antiproton induced background can be divided into 2 main categories:
    1. e^- generated via interactions producing a track mimicking the CE
    2. non-electron particles (μ and π) that are reconstructed as an "electron-like" track mimicking the CE
- (1) represents the irreducible background, while (2) can be suppressed using a PID method

Mu2e PID method:

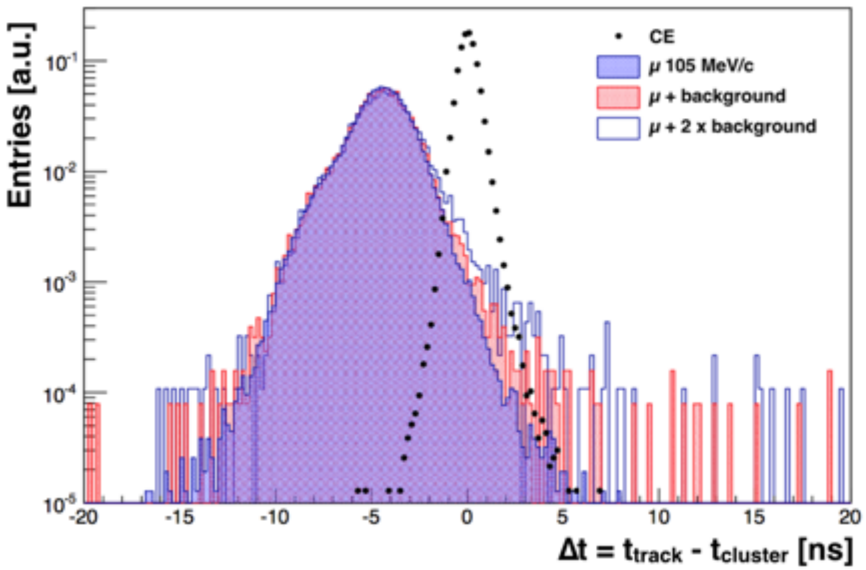
✓ Information from reconstructed tracks and calorimeter clusters are combined for identifying group (2)

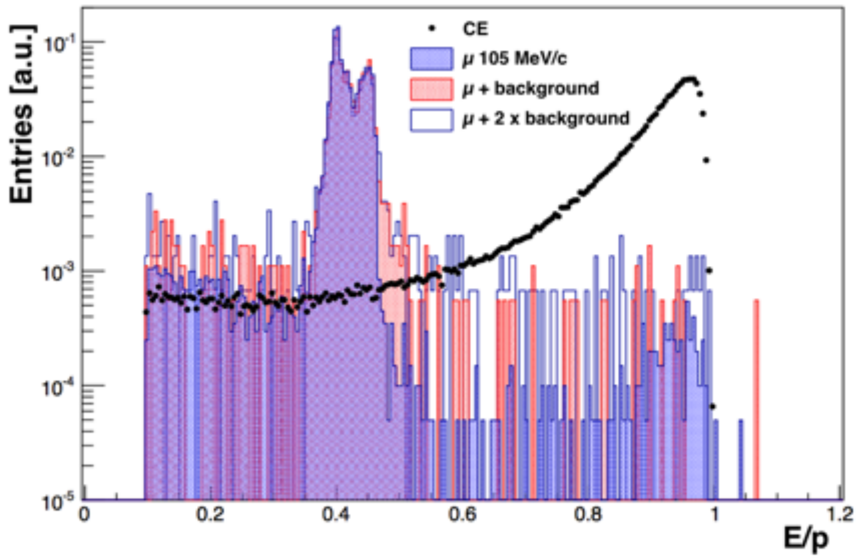
✓ Stringent requirement from Cosmic: μ-rejection factor ≥ 200

Cosmic μ rejection

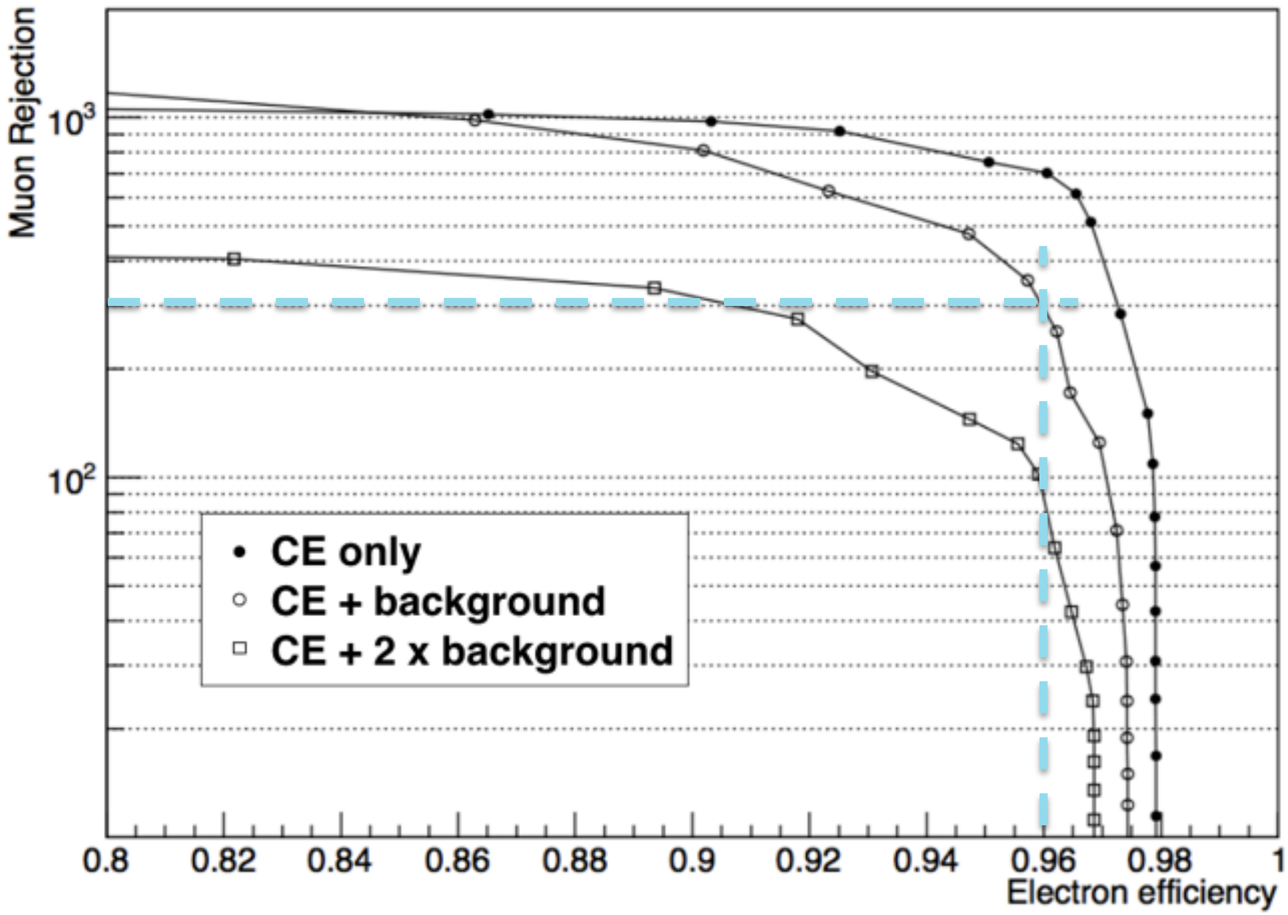
- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have $\beta \sim 0.7$ and a kinetic energy of ~ 40 MeV;
- Likelihood rejection combines $\Delta t = t_{track} - t_{cluster}$ and E/p:

$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta t) + \ln P_{e,\mu}(E/p)$$





PID performance



- A muon-rejection of 200 corresponds to a cut at ln $L_{e/\mu} > 1.5$ and an e^- efficiency of ~ 96%

Mu2e Schedule