

The Mu2e Experiment at Fermilab

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Flavor Violation

- Quarks mixing → (Quark) Flavor Violation
 - CKM matrix
- Neutrinos mixing → Lepton Flavor Violation (LFV)
 - PMNS matrix
- What about charged leptons?
 - Charged Lepton Flavor Violation (CLFV)

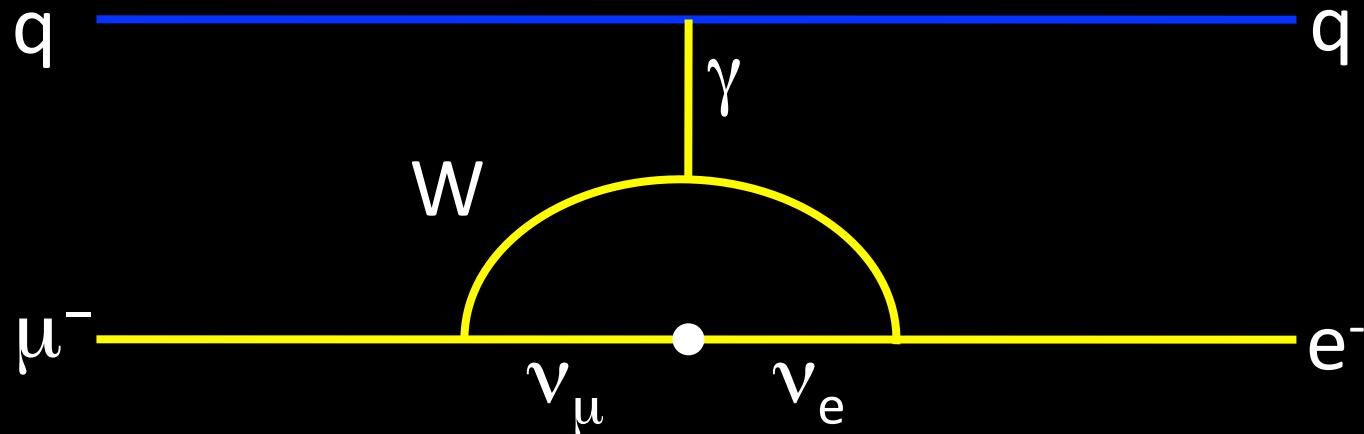
What is Mu2e?

- A search for Charged-Lepton Flavor Violation via



- It will use the new *Fermilab Muon Campus* and modest modifications to the current accelerator complex to reach a sensitivity 10 000 better than world's best
- It will have *discovery* sensitivity over a wide range of New Physics parameter space

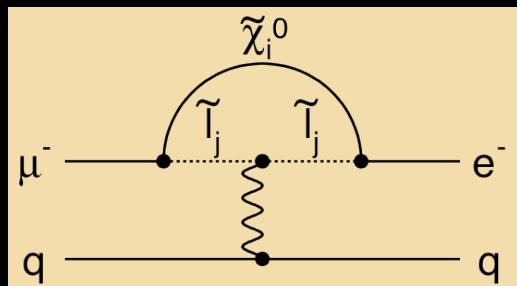
CLFV in the Standard Model



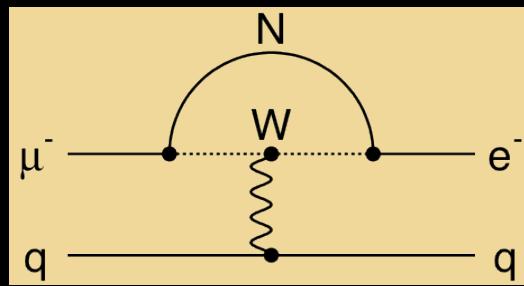
- Strictly speaking, forbidden in the SM
- Even in ν -SM, extremely suppressed
(rate $\sim (\Delta m_\nu^2 / M_w^2)^2 < 10^{-50}$)
- However, most all NP models predict rates observable at next generation CLFV experiments

New Physics Contributions to $\mu N \rightarrow e N$

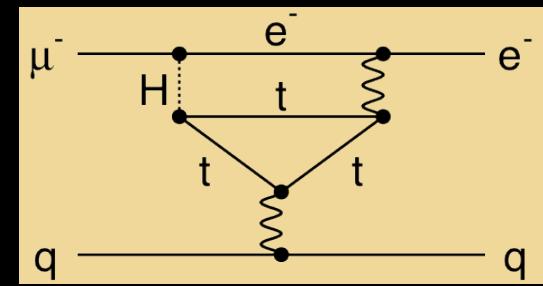
Loops



Supersymmetry

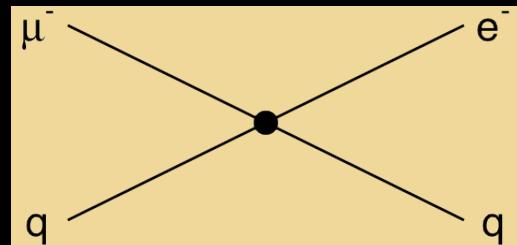


Heavy Neutrinos

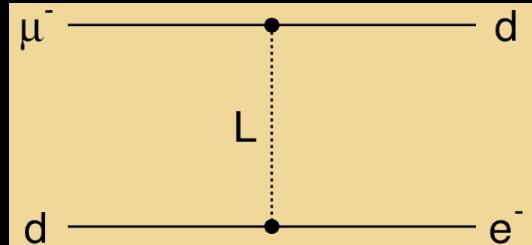


Two Higgs Doublets

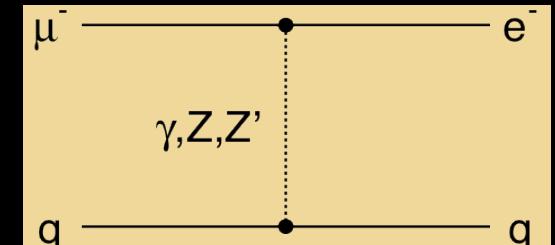
Contact Terms



Compositeness



Leptoquarks

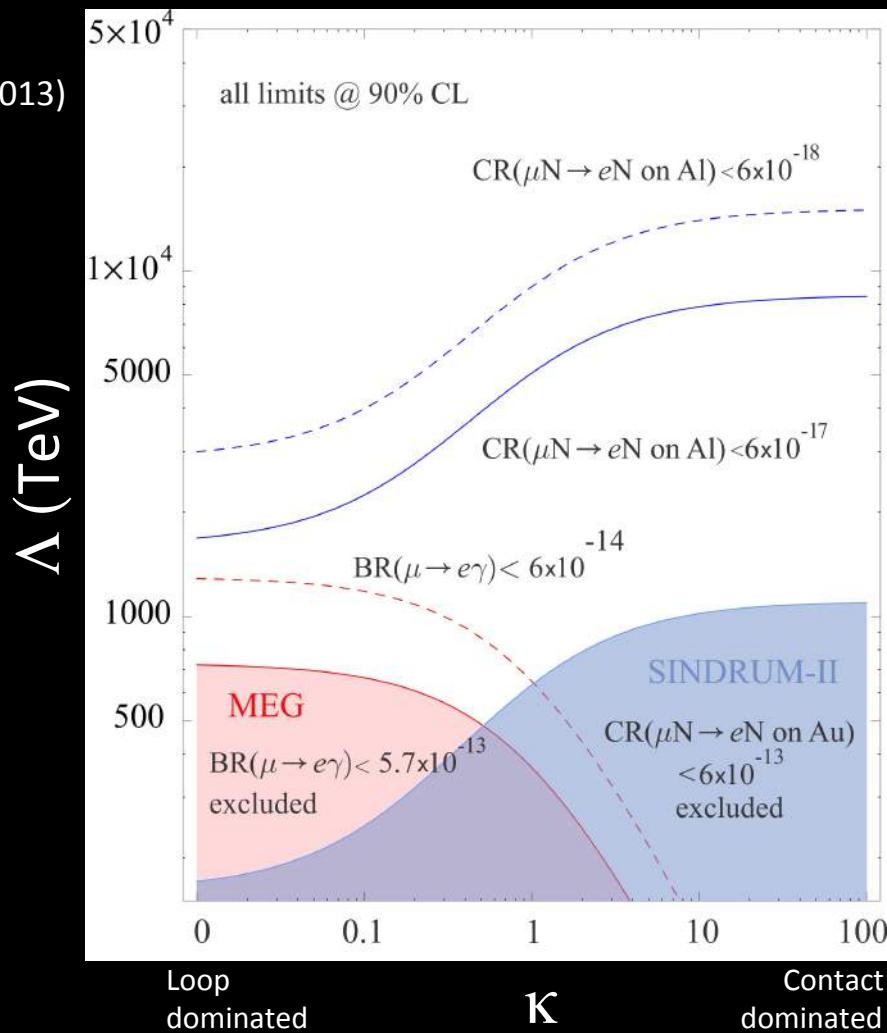


New Heavy Bosons /
Anomalous Couplings

$\mu N \rightarrow e N$ sensitive to wide array of New Physics models

Mu2e Sensitivity

A. de Gouvêa and P. Vogel,
Prog. Part. Nucl. Phys. 71, 75 (2013)



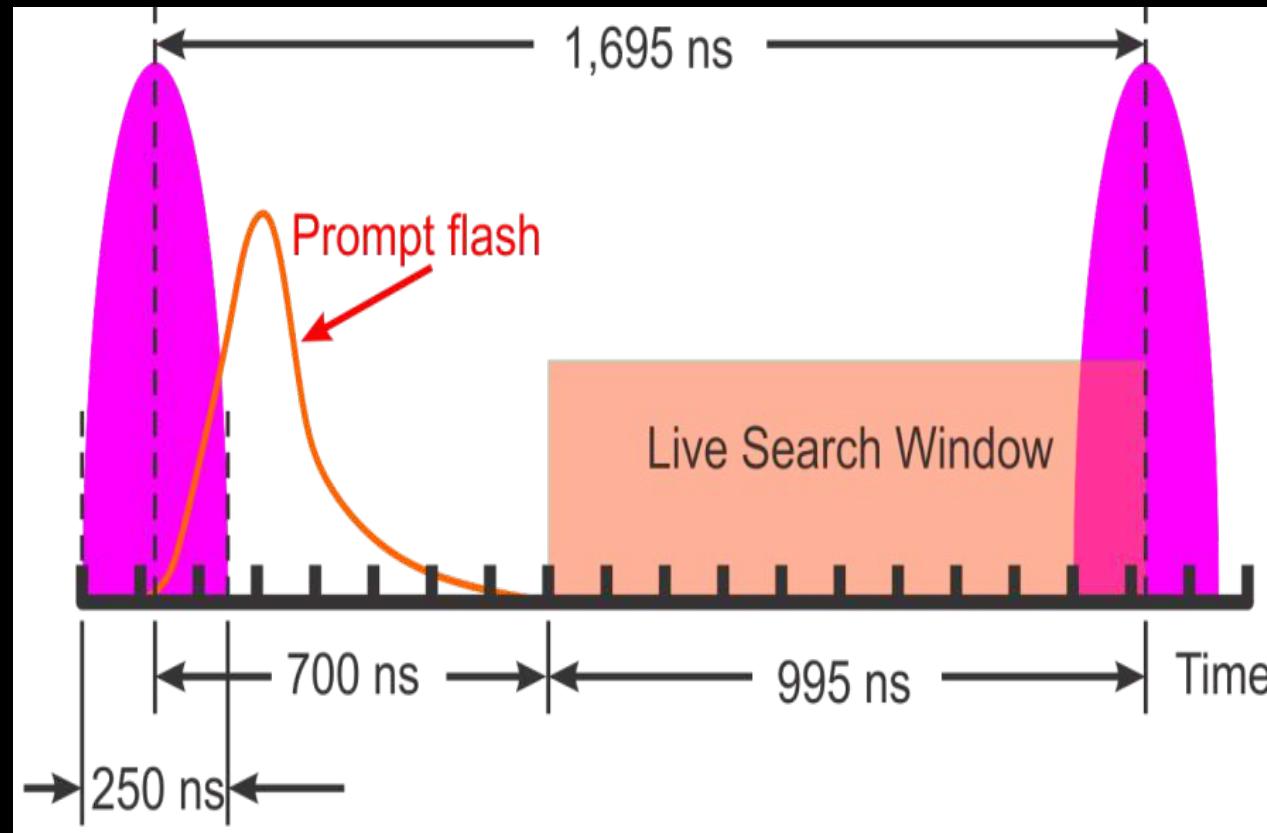
Courtesy A. de Gouvea , B. Bernstein, D. Hitlin

Mu2e Sensitivity best in all scenarios

Mu2e Strategy

- Generate a beam of low momentum muons (μ^-)
- Stop the muons in a target
 - Mu2e plans to use aluminum
 - Sensitivity goal requires $\sim 10^{18}$ stopped muons
- The stopped muons are trapped in orbit around the nucleus
 - In orbit around aluminum: $\tau_\mu^{\text{Al}} = 864 \text{ ns}$
 - Large τ_μ^N important for discriminating background
- Look for events consistent with $\mu N \rightarrow e N$

Mu2e Proton Beam



Mu2e will use a pulsed proton beam and a delayed live gate to suppress prompt backgrounds

Mu2e Signal

- The process is a coherent one
 - The nucleus remains intact
- Very clean signal
- Experimental signature is a monoenergetic electron and nothing else
 - Energy of electron: $E_e = m_\mu - E_{\text{recoil}} - E_{\text{1S-B.E.}}$
 - For aluminum: $E_e = 104.96 \text{ MeV}$
 - Important for discriminating background

Mu2e Sensitivity

- Design goal: single-event-sensitivity 2.9×10^{-17}
 - Requires about 10^{18} stopped muons
 - Requires about 10^{20} protons on target
 - Requires extreme suppression of backgrounds
- Expected limit, in absence of a signal:
 $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL
 - Factor 10^4 improvement
- Discovery sensitivity: all $R_{\mu e} > \text{few} \times 10^{-16}$
 - Covers broad range of new physics theories

Mu2e Backgrounds

1. Intrinsic – scale with number of stopped muons
 - μ Decay-in-Orbit (DIO) (55%)
 - Radiative muon capture (RMC) (<3%)
2. Late arriving – scale with number of late protons (10%)
 - Radiative pion capture (RPC)
 - μ and π decay-in-flight (DIF)
3. Miscellaneous (35%)
 - Anti-proton induced
 - Cosmic-ray induced

Designed to be nearly background free

(< 0.4 events for 6.8×10^{17} stopped μ in 6×10^7 s of beam time)

1. Intrinsic Backgrounds

Once trapped in orbit, muons will:

- 1) Decay in orbit (DIO): (39%)
 - $\mu^- N \rightarrow e^- \nu_\mu \nu_e N$
 - e^- spectrum has tail out to 104.96 MeV

- 2) Capture on the nucleus: (61%)

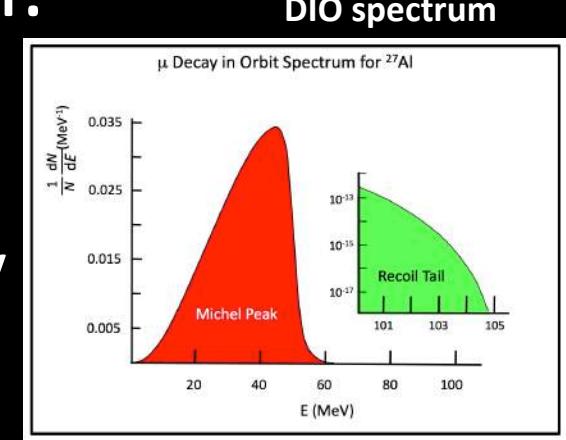
- a) Ordinary μ Capture



- b) Radiative μ capture



(E_γ kinematic end-point ~ 102 MeV: asymmetric $\gamma \rightarrow e^+ e^-$ pair production may yield a background electron)



2. Late Arriving Backgrounds

- Backgrounds arising from interactions at the production target
 - Overwhelming **prompt background** eliminated by defining a signal timing window starting 700 ns after the initial proton pulse
 - Must eliminate **out-of-time** (“late”) protons, which would otherwise generate these backgrounds in time with the signal window
- **out-of-time protons / in-time protons $< 10^{-10}$**
- Radiative π Capture
 - $\pi^- N_z \rightarrow N_{z-1}^* + \gamma$ (for Al, R π C fraction: 2%)
 - E_γ extends out to $\sim m_\pi$
 - Asymmetric $\gamma \rightarrow e^+e^-$ pair production can yield background electron
- Beam electrons
 - Originating from upstream π^- and π^0 decays
 - Electrons scatter in stopping target to get into detector acceptance
- Muon and pion Decay-in-Flight
- They account for $\sim 10\%$ of the total background and scale *linearly* with the number of out-of-time protons

3. Miscellaneous Backgrounds

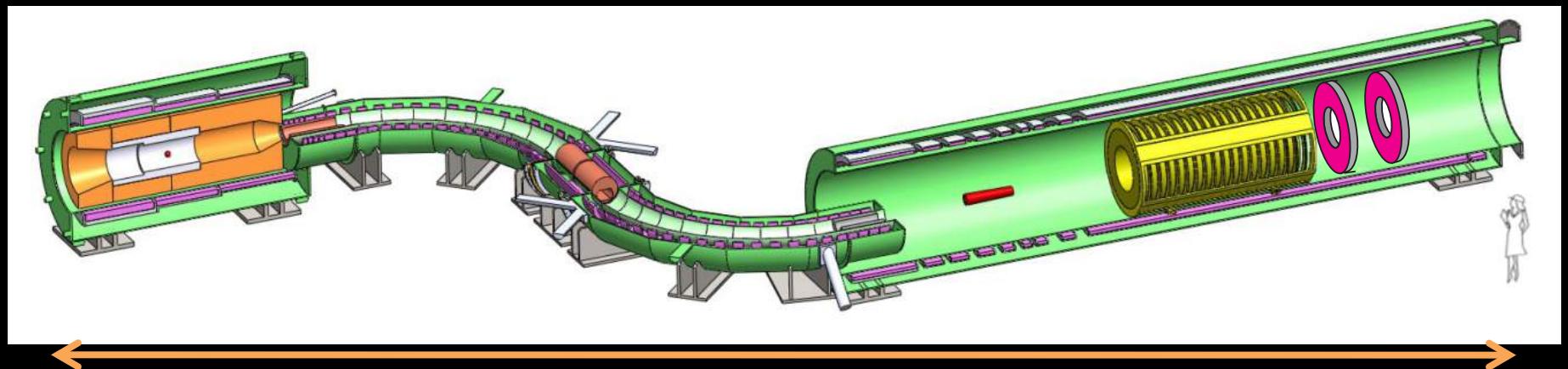
- **Anti-protons**
 - Proton beam is just above pbar production threshold
 - These low momentum pbars wander until they annihilate
 - A thin window in beamline absorbs most of them
 - Annihilations produce high multiplicity final states e.g. π^- can undergo R π C to yield a background electron
- **Cosmic rays**
 - Suppressed by passive and active shielding
 - μ DIF or interactions in the detector material can give an e^- or γ that yield a background electron
 - Background estimates demand veto efficiency of 99.99%

Mu2e Experimental Apparatus

Production
Solenoid

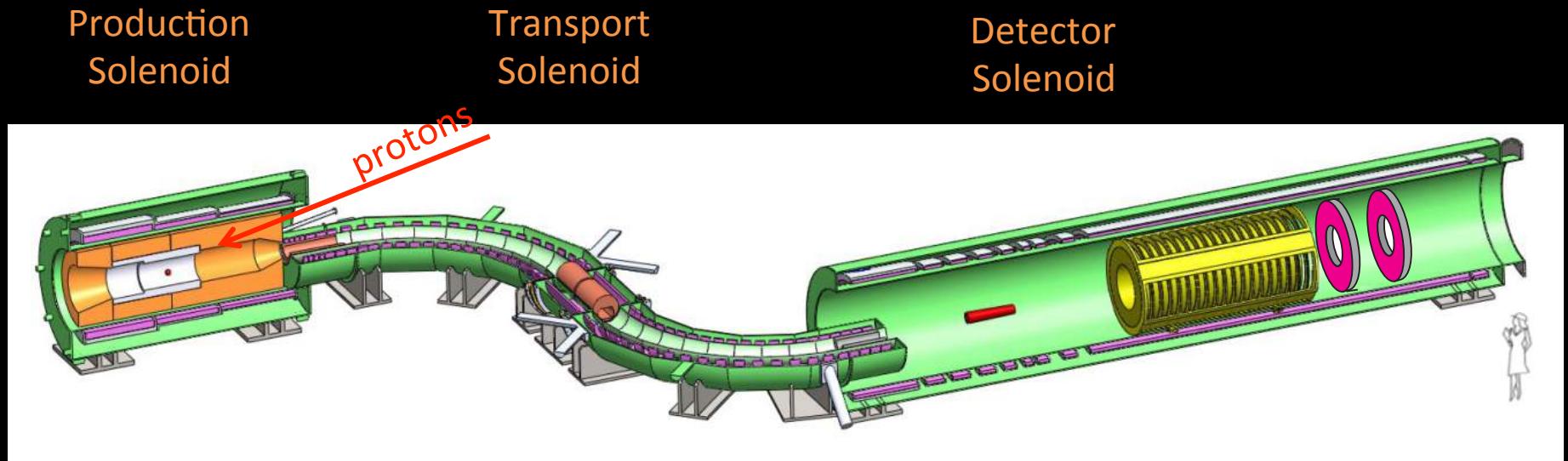
Transport
Solenoid

Detector
Solenoid



(about 25 meters end-to-end)

Mu2e Experimental Apparatus



Production Solenoid:

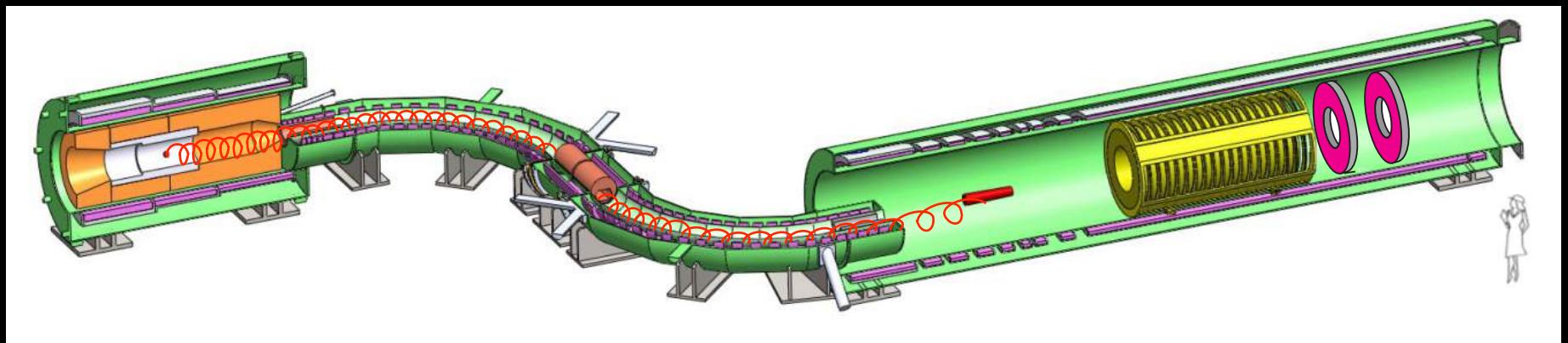
8 GeV protons interact with a tungsten target to produce μ^- (from π^- decay)

Mu2e Experimental Apparatus

Production
Solenoid

Transport
Solenoid

Detector
Solenoid



Transport Solenoid:

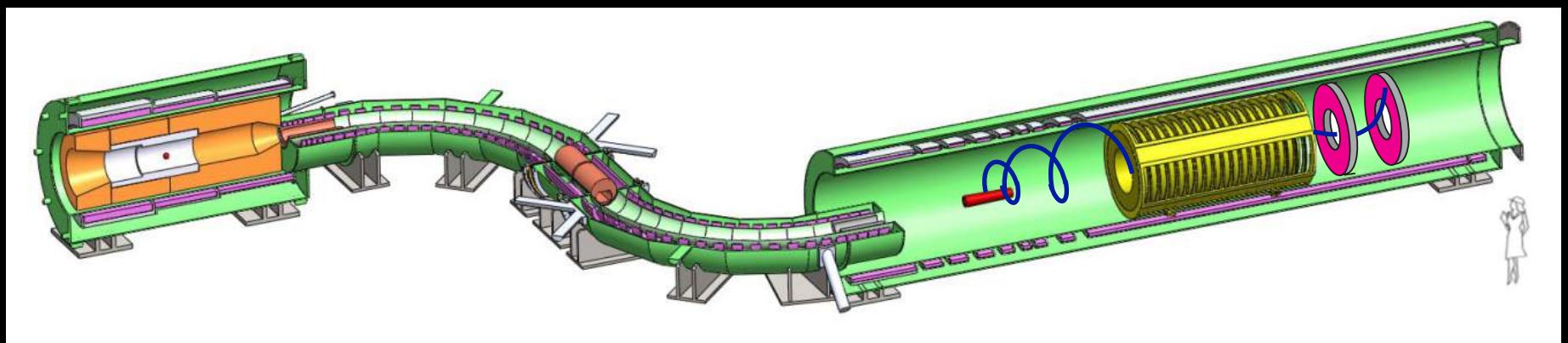
Captures π^- and subsequent μ^- ; momentum- and sign-selects beam

Mu2e Experimental Apparatus

Production
Solenoid

Transport
Solenoid

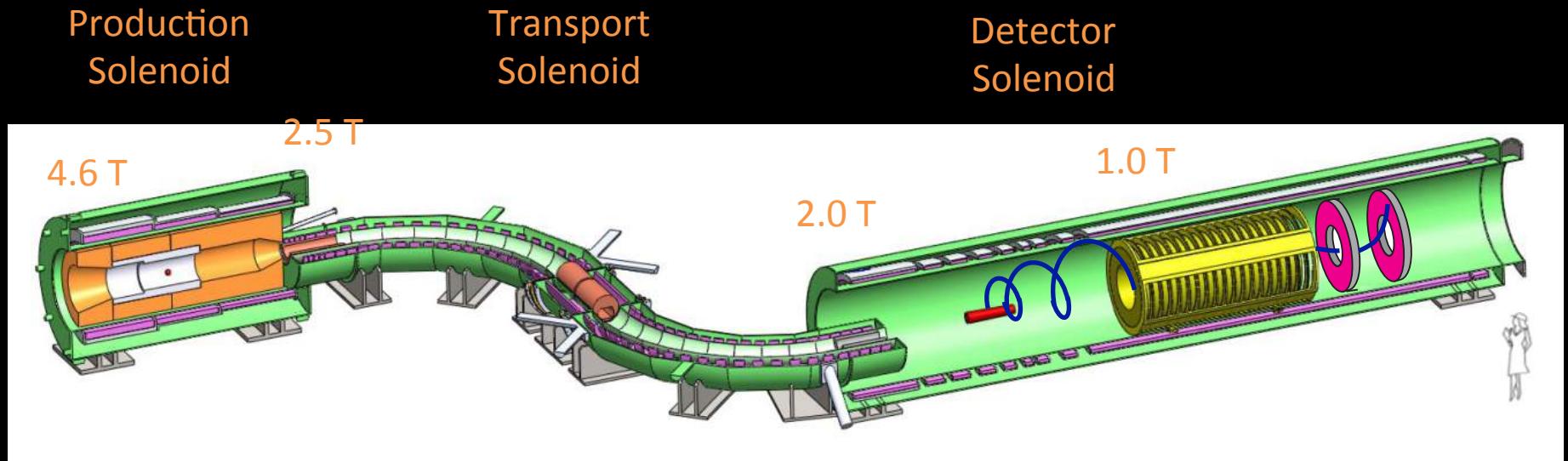
Detector
Solenoid



Detector Solenoid:

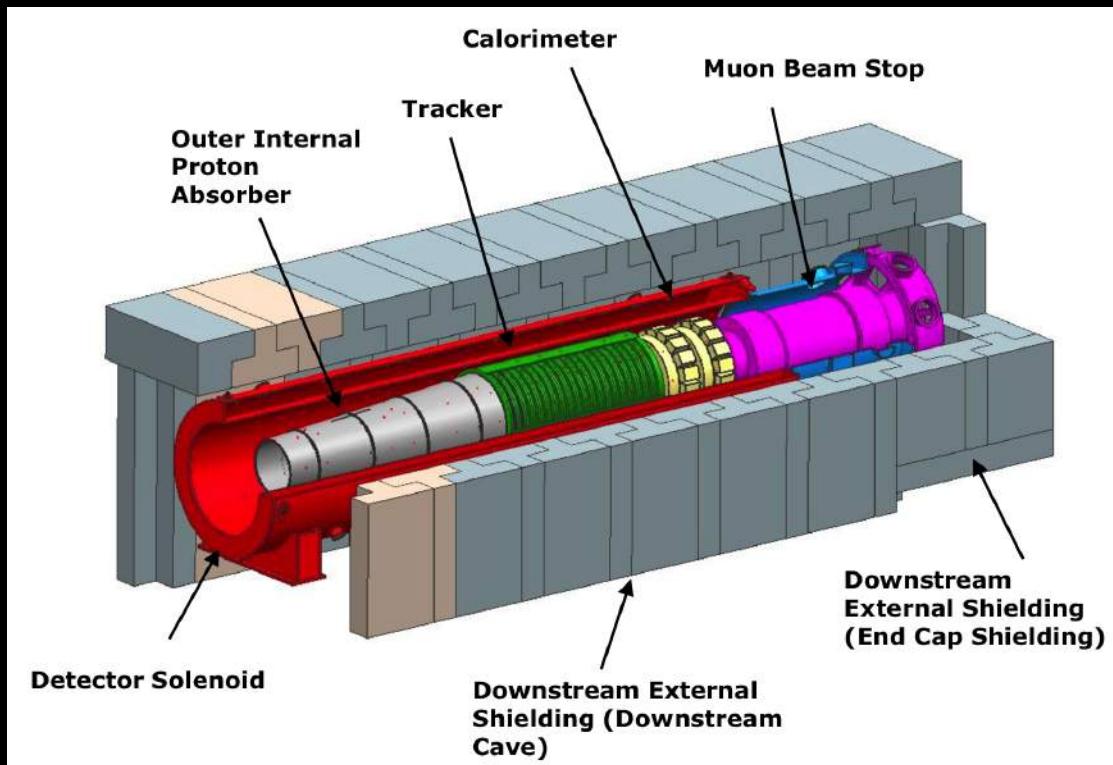
Upstream – Al. stopping target, Downstream – tracker, calorimeter
(not shown – cosmic ray veto system, extinction monitor, target monitor)

Mu2e Experimental Apparatus



Graded fields important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons

The Mu2e Detector



➤ I will cover briefly:

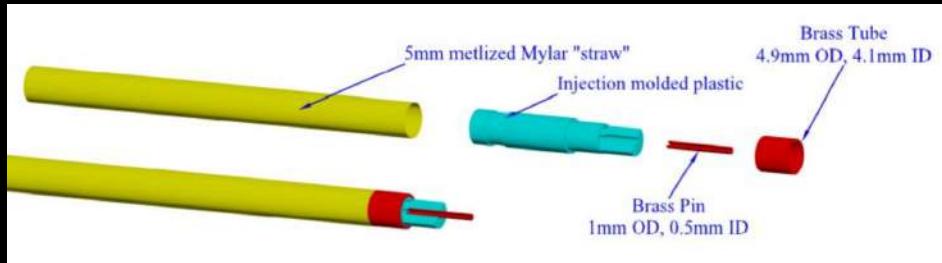
- Tracker
- Calorimeter
- Cosmic-Ray Veto

➤ I will not cover:

- Mu2e beamlines
- Magnets
- Extinction and target monitors
- Shielding and proton absorber

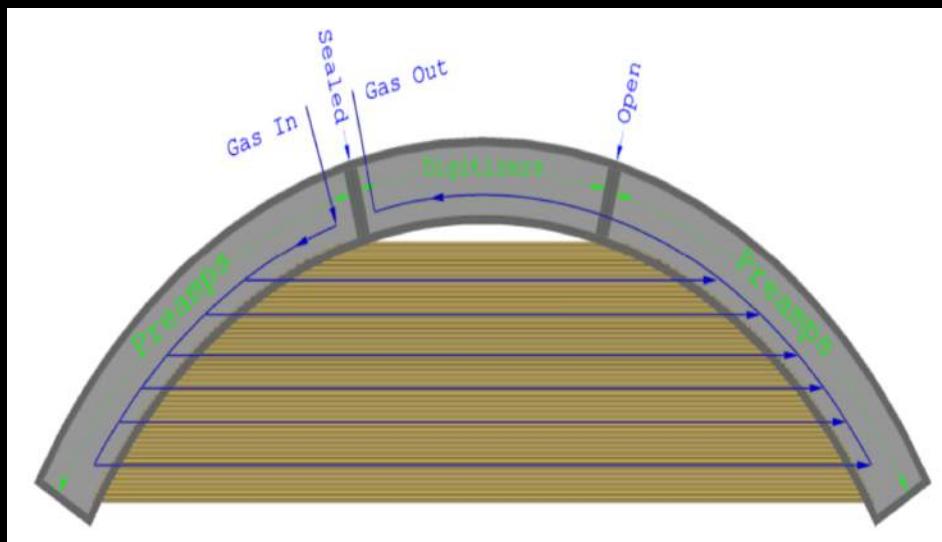
The Mu2e Tracker

straw tube

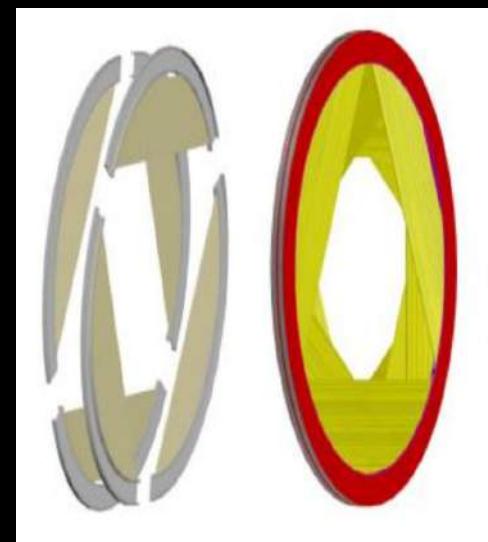


- 5 mm diameter straw, spiral wound
- 12 μm Mylar + 3 μm epoxy
+ (500 Å Al + 200 Å Au) + (500 Å Al)
- 25 μm Au-plated W sense wire
- 334 – 1174 mm active length
- 80/20 Ar/CO₂ with HV < 1500 V

panel = 96 straw tubes



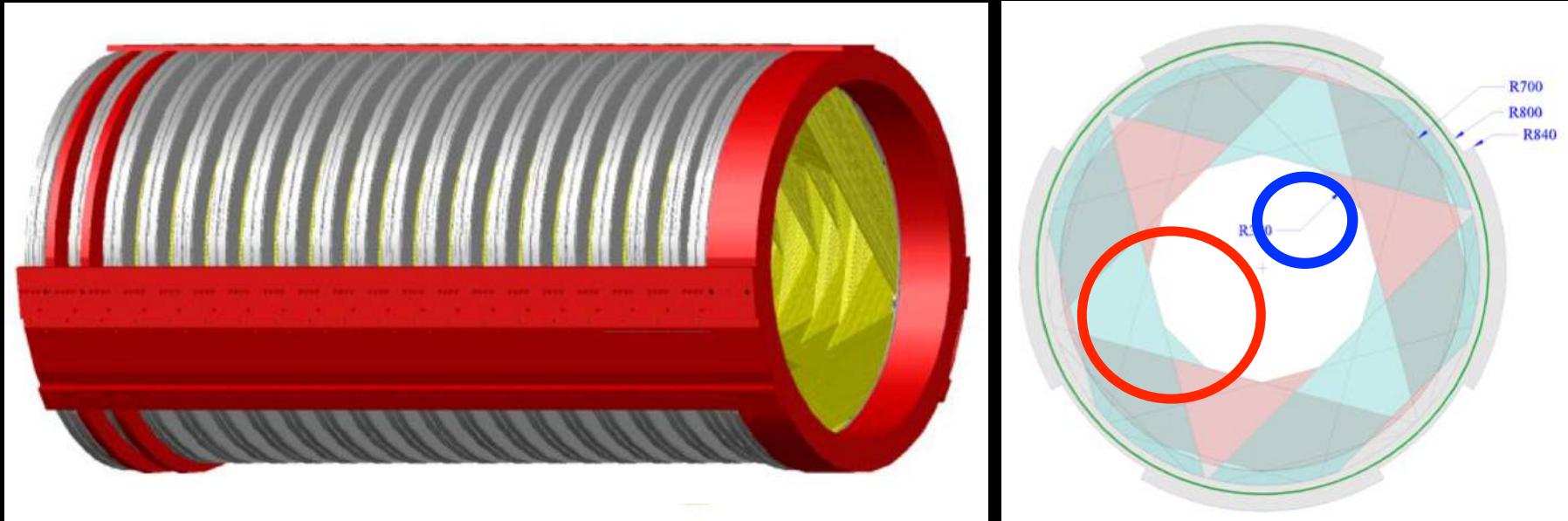
plane = 6 panels



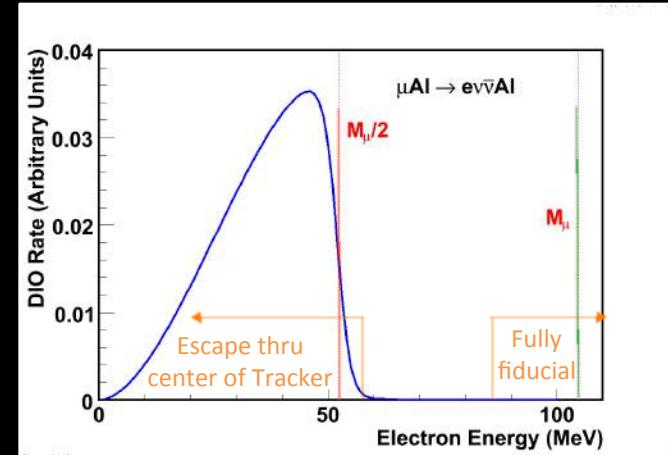
station = 2 planes

The Mu2e Tracker

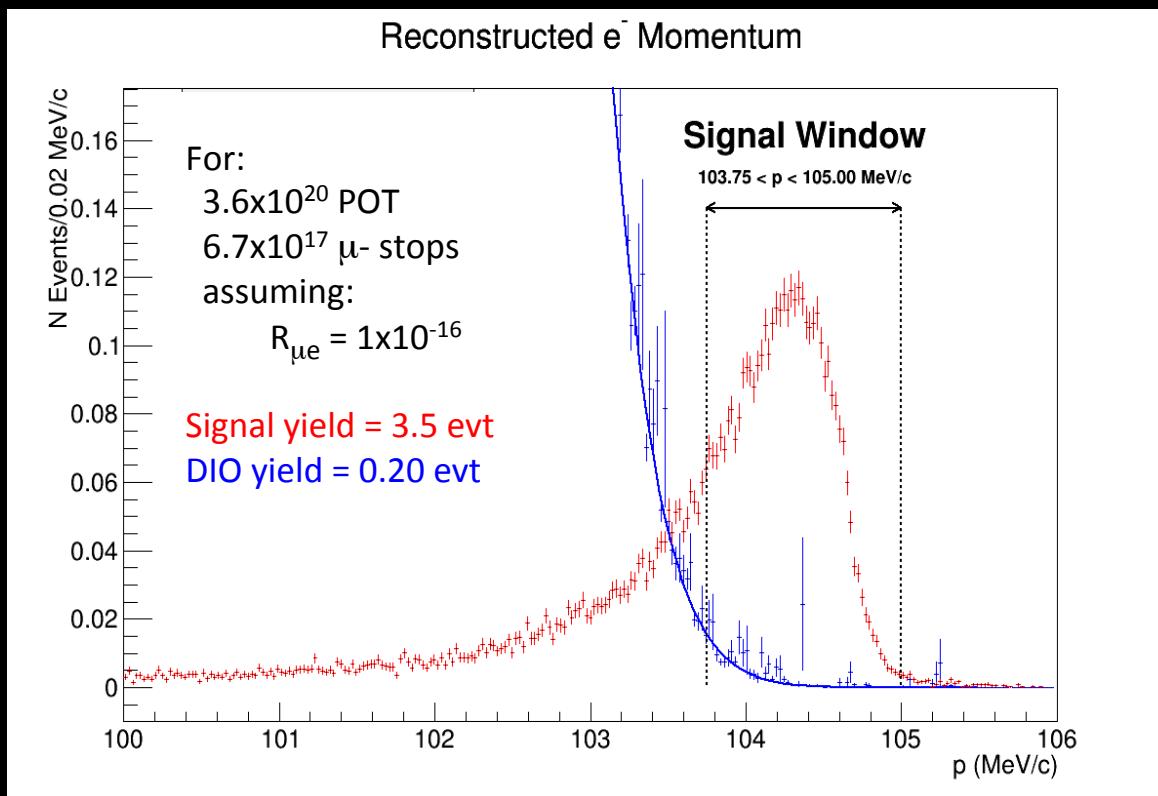
detector= 18 stations



- detector is in vacuum and inner 38 cm is purposefully un-instrumented
 - Blind to beam flash
 - Blind to >99% of DIO spectrum
- Active tracking region from 38 cm to 70 cm
- Services and structure from 70 cm



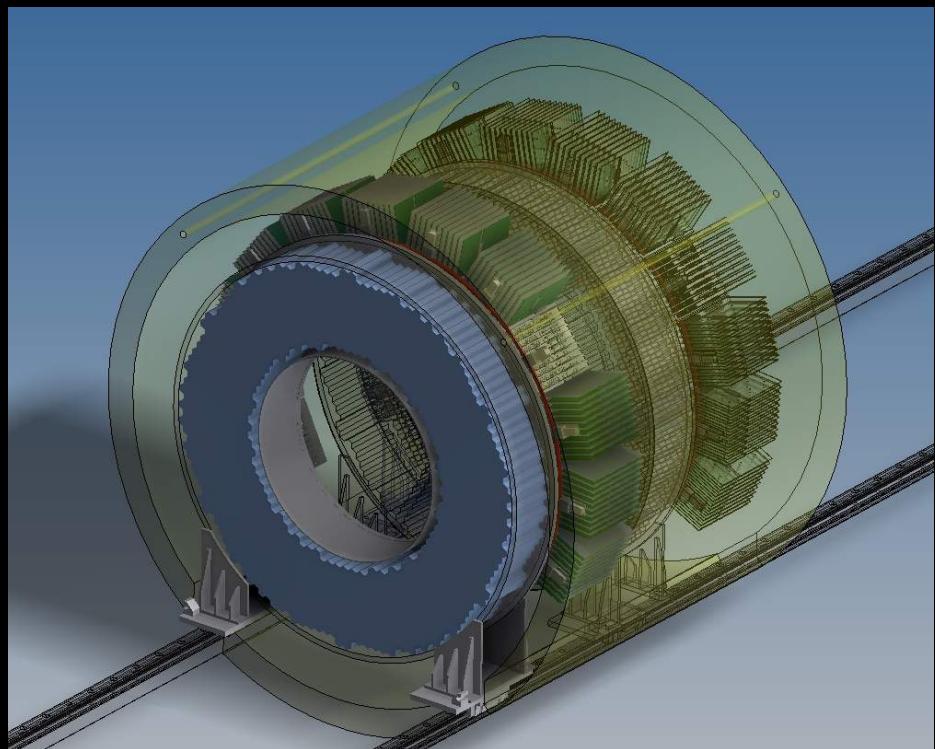
Expected Result



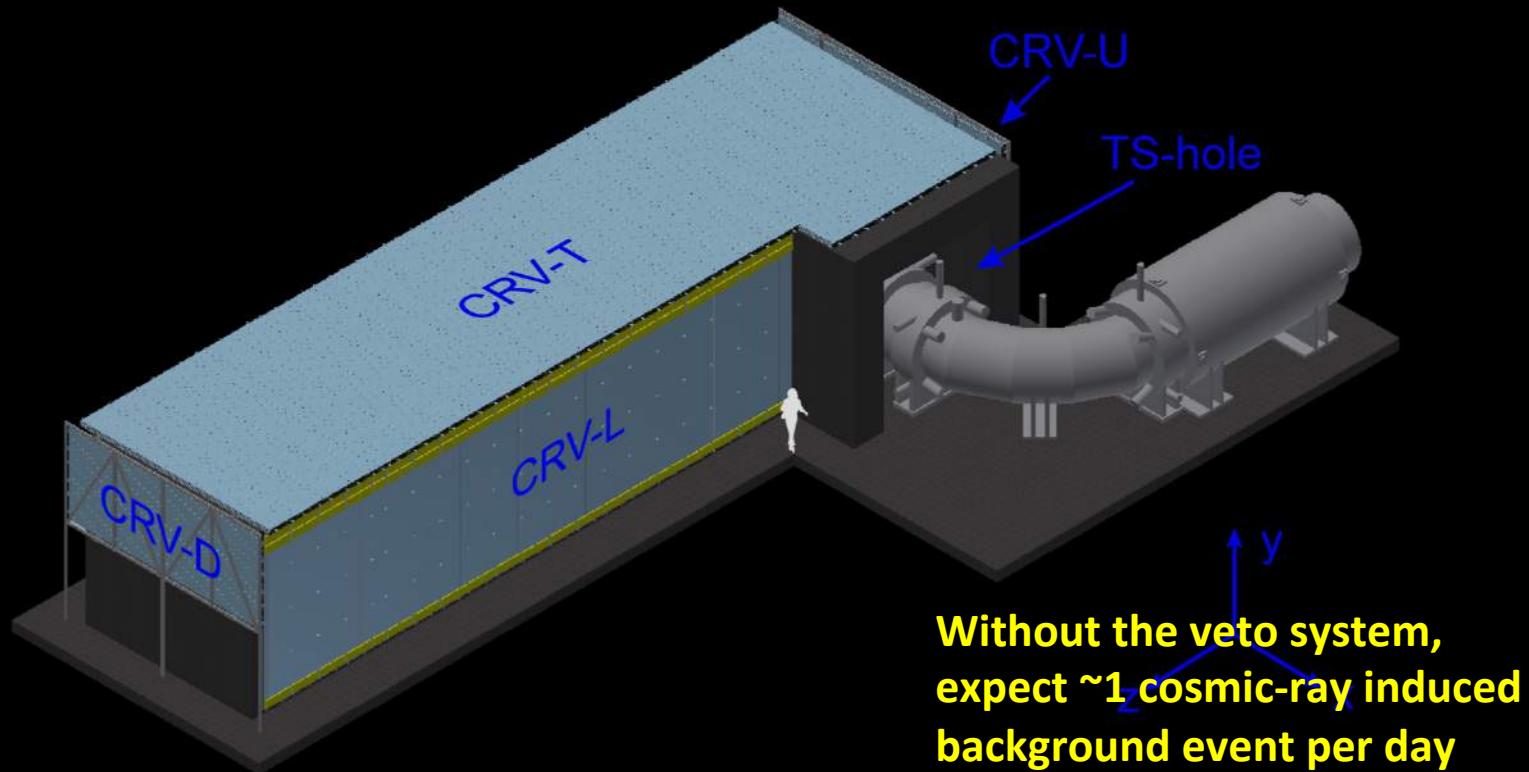
Single-event-sensitivity = 2.9×10^{-17}
Total background < 0.5 events

The Mu2e Calorimeter

- Role of calorimeter
 - particle id.
 - CR rejection
- Crystal calorimeter
 - Compact
 - Radiation hard
 - Good timing (1 ns) and energy resolution (5%)
- Will employ 2 disks
(radius = 36-70 cm)
~2000 BaF₂ crystals with
hexagonal cross-section ~3 cm diameter, ~20 cm long ($10X_0$)
Two photo-sensors/crystal on back (APDs or SiPMs)



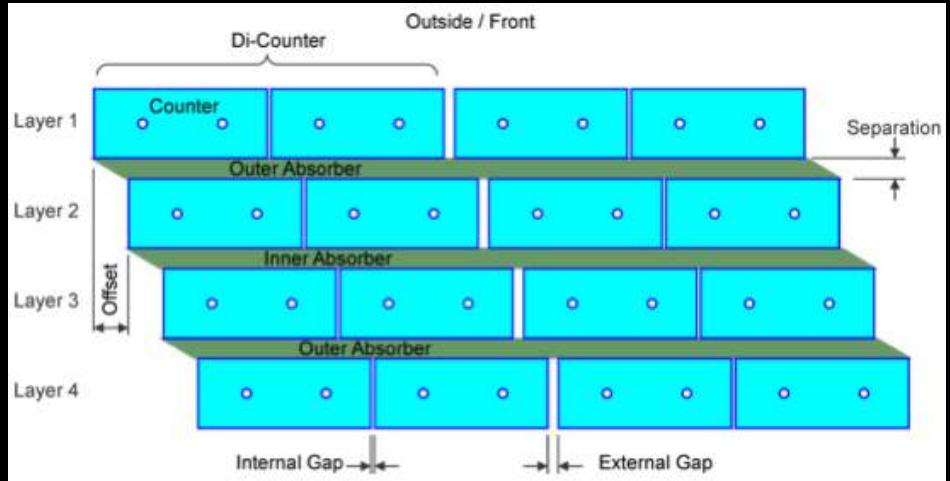
The Mu2e Cosmic-Ray Veto



Cosmic μ can generate background events via decay, scattering, or material interactions

Veto system covers entire DS and half TS

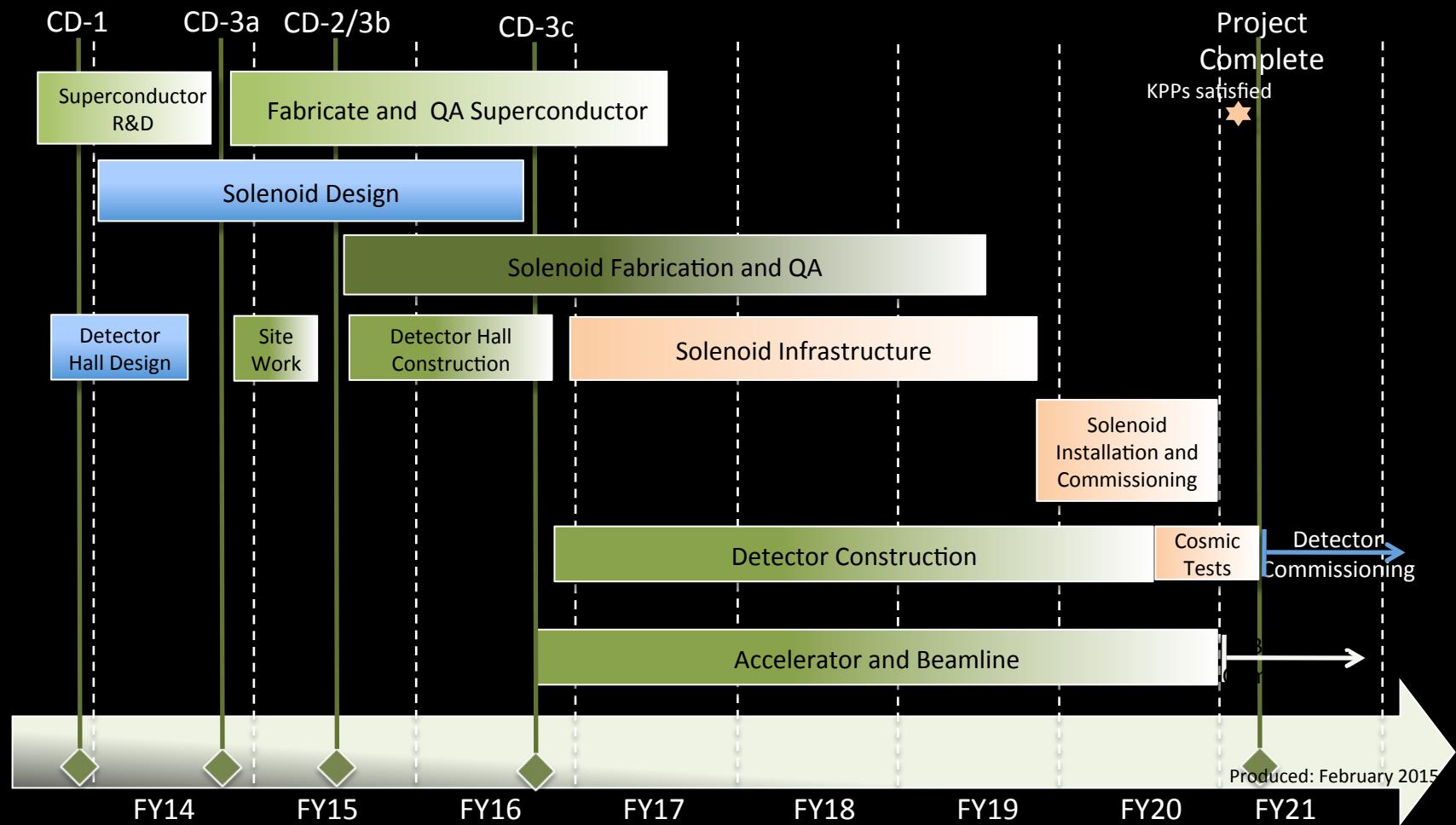
The Mu2e Cosmic-Ray Veto



Will use 4 overlapping layers of scintillator bars separated by ~ 10 mm absorber

- Each bar is $5 \times 2 \times (300 \div 660) \text{ cm}^3$
- 2 WLS fibers / bar
- Read-out both ends of each fiber with SiPM
- Have achieved $\varepsilon > 99.4\%$ (per layer) in test beam

Mu2e Schedule



Summary

The Mu2e experiment:

- Improves sensitivity by a factor of 10^4
- Provides *discovery capability* over wide range of New Physics models
- Is complementary to LHC, heavy-flavor, and neutrino experiments

The Mu2e Collaboration



- ~160 People, 32 Institutions, 3 Countries

Additional information

- Technical Design Report

[arXiv.org > physics > arXiv:1501.05241](https://arxiv.org/abs/1501.05241)

- Experiment web site

[**http://mu2e.fnal.gov**](http://mu2e.fnal.gov)

