A Rare Opportunity, the Mu2e Experiment

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Fermilab

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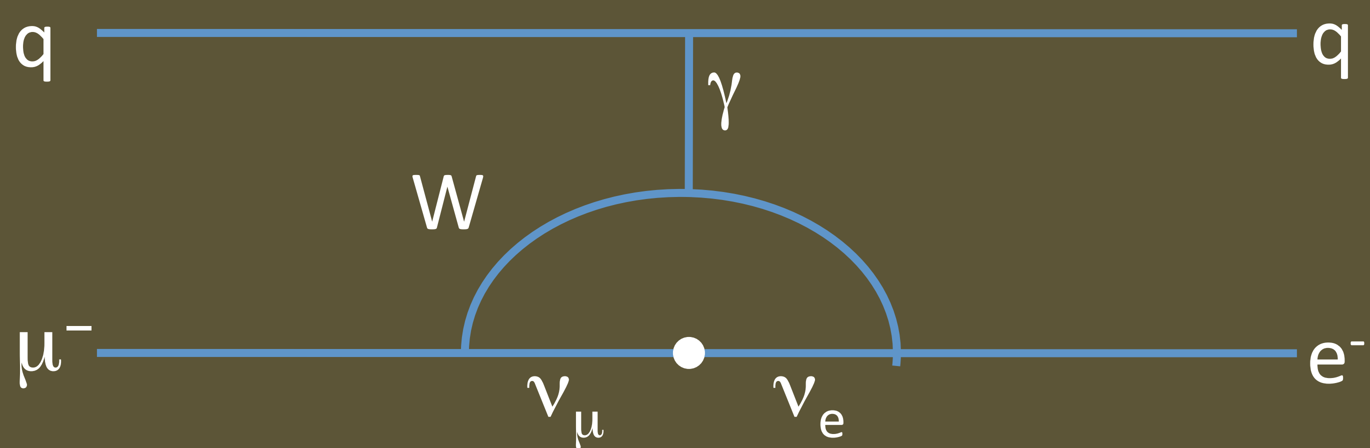
Introduction

- What is Mu2e?
  - A search for Charged-Lepton Flavor Violation via

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

  - Will use *current* Fermilab accelerator complex to reach a sensitivity 10 000 better than current world's best
  - Will have *discovery* sensitivity over broad swath of New Physics parameter space

CLFV in the Standard Model



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

Some CLFV Processes

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8	
$\tau \rightarrow eee$	BR < 3.6 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 7.8 E-8	
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 5.7 E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \rightarrow eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

(current limits from the PDG)

- Most promising CLFV measurements use μ

CLFV Predictions

M.Blanke, A.J.Buras, B.Duling, S.Recksiegel, C.Tarantino

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2.0$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$

Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\mathrm{TeV}$) and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

arXiv:0909.5454v2[hep-ph]

- Relative rates model dependent
- Measure several to pin-down theory details

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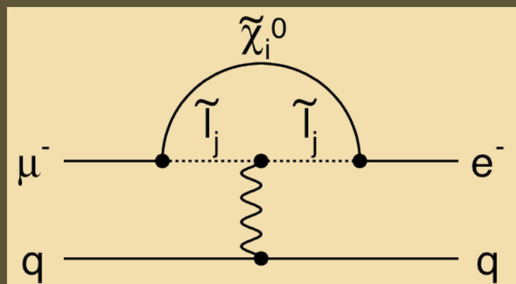
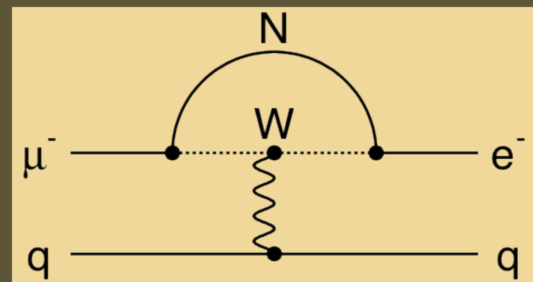
New Physics Contributions to μN→eN

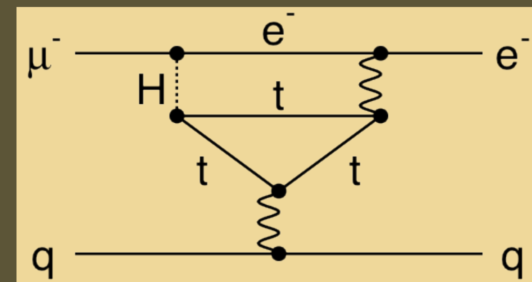
Loops



Supersymmetry

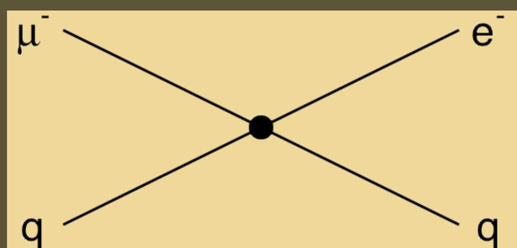


Heavy Neutrinos

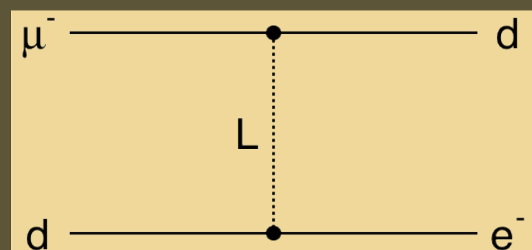


Two Higgs Doublets

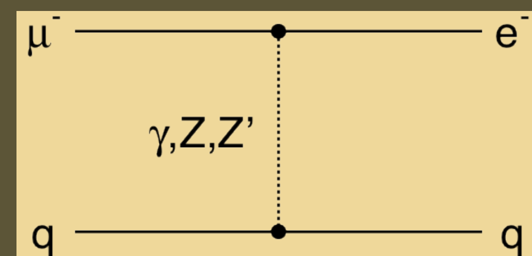
Contact Terms



Compositeness



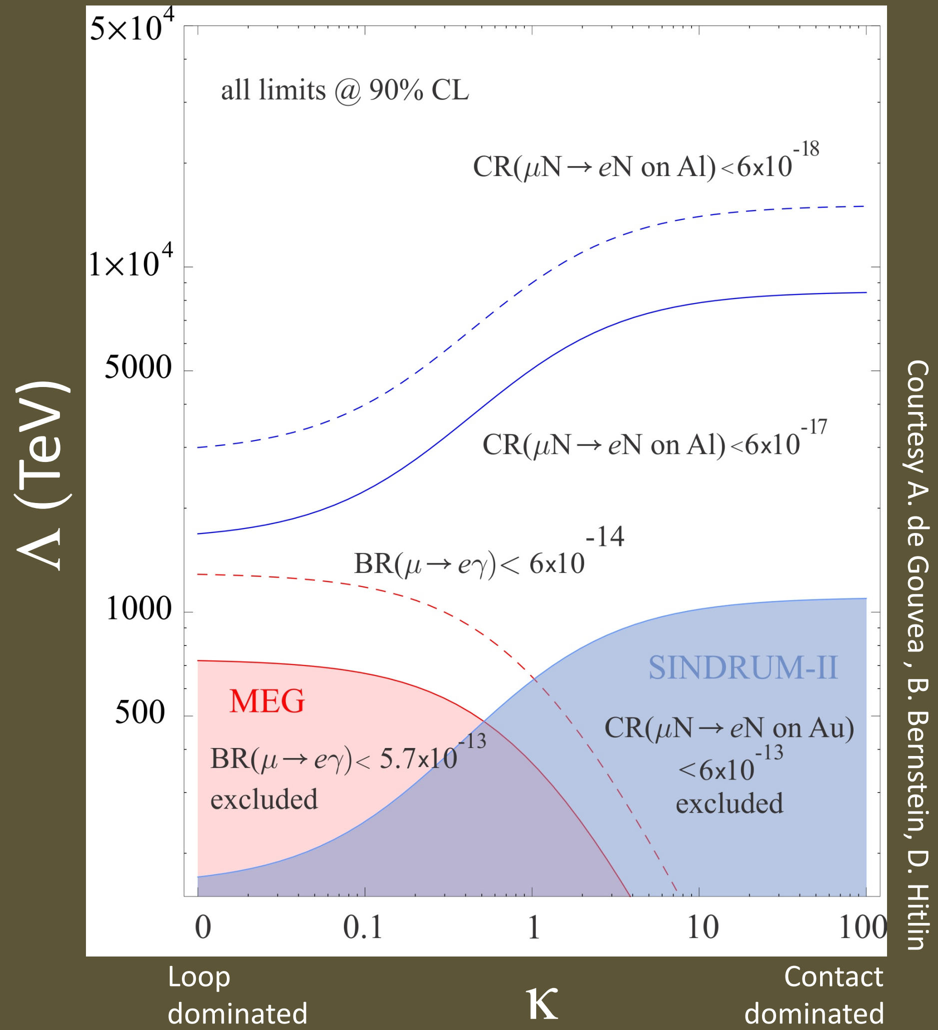
Leptoquarks



New Heavy Bosons /
Anomalous Couplings

μN→eN sensitive to wide array of New Physics models

Mu2e Sensitivty



- Mu2e Sensitivity best in all scenarios

Mu2e Sensitivity

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

★★★ = Discovery Sensitivity

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\mathrm{CP}}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

arXiv:0909.1333[hep-ph]

- Mu2e sensitive across the board

Mu2e Sensitivity

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

★★★ = Discovery Sensitivity

arXiv:0909.1333[hep-ph]

- Mu2e sensitive across the board

Mu2e Sensitivity

CERN-PH-TH-2014-229
LAPTH-227/14

Lepton Flavor Violation in B Decays?

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November 17, 2014

Abstract

The LHCb Collaboration's measurement of $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ $K^+e^+e^-)$ lies 2.6σ below the Standard Model prediction. Several groups su deficit to result from new lepton non-universal interactions of muons. But non leptonic interactions imply lepton flavor violation in B-decays at rates much l are expected in the Standard Model. A simple model shows that these ra lie just below current limits. An interesting consequence of our model, tha $\mu^+\mu^-)_{exp}/\mathcal{B}(B_s \to \mu^+\mu^-)_{SM} \cong R_K \cong 0.75$, is compatible with recent measu these rates. We stress the importance of searches for lepton flavor violations, for $B \to K\mu e$, $K\mu\tau$ and $B_s \to \mu e$, $\mu\tau$.

arXiv:1411.0565

arXiv:1409.5669

MS-TP-14-37

Probing the scotogenic model with lepton flavor violating processes

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Abstract

We study the impact that future lepton flavor violating experiments will have on the viable parameter space of the scotogenic model. Within this model, the dark matter particle is est singlet fermion and two cases are consider relic density is obtained: via self-annihilatio with the scalars. For each case, a scan over

arXiv:1412.2545

PREPARED FOR SUBMISSION TO JHEP

Rare Flavor Processes in Maximally Natural Supersymmetry

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ABSTRACT: We study CP-conserving rare flavor violating processes in the recently proposed theory of Maximally Natural Supersymmetry (MNSUSY). MNSUSY is an unusual supersymmetric (SUSY) extension of the Standard Model (SM) which, remarkably, is un-tuned at present LHC limits. It employs Scherk-Schwarz breaking of SUSY by boundary conditions upon compactifying an underlying 5-dimensional (5D) theory down to 4D, and is not well-described by softly-broken $\mathcal{N} = 1$ SUSY, with much different phenomenology than the Minimal Supersymmetric Standard Model (MSSM) and its variants. The usual CP-conserving SUSY-flavor problem is automatically solved in MNSUSY due to a residual almost exact $U(1)_R$ symmetry, naturally heavy and highly degenerate 1st- and 2nd-generation sfermions, and heavy gauginos and Higgsinos. Depending on the exact implementation of MNSUSY there exist important new sources of flavor violation involving gauge boson Kaluza-Klein

arXiv:1411.6612

Seesaw Models with Minimal Flavor Violation

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[3]*CTS, CASTS, and Department of Physics, National Taiwan University, Taipei 106, Taiwan*

Abstract

We explore realizations of minimal flavor violation (MFV) for leptons in the simplest seesaw models where the neutrino mass generation mechanism is driven by new fermion singlets (type I) or triplets (type III) and by a scalar triplet (type II). We also discuss similarities and differences of the MFV implementation among the three scenarios. To study the phenomenological implications, we consider a number of effective dimension-six operators that are purely leptonic or couple leptons to the standard-model gauge and Higgs bosons and evaluate constraints on the scale of MFV associated with these operators from the latest experimental information. Specifically, we employ the most recent measurements of neutrino mixing parameters as well as the currently available data on flavor-violating radiative and three-body decays of charged leptons, $\mu \to e$ conversion in nuclei, the anomalous magnetic moments of charged leptons, and their electric dipole moments. The most stringent lower-limit on the

- Persistent interest in Lepton Flavor Violation and in muon-to-electron conversion (ie. Mu2e)

Mu2e – High Priority for U.S. HEP

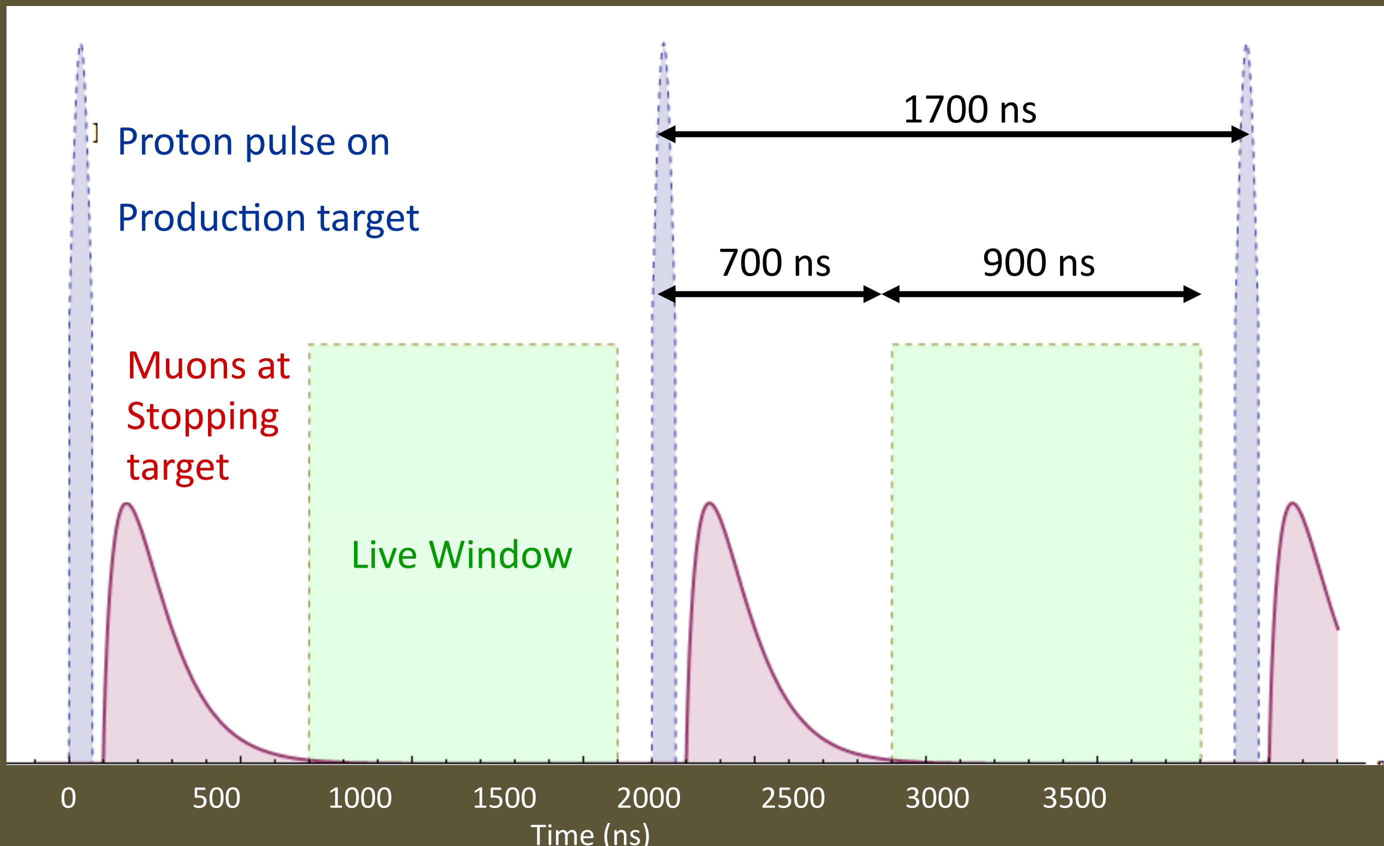
- In the 2008 P5 report Mu2e was strongly supported:
  - "Mu2e should be pursued in all budget scenarios considered by the panel"
- In 2010 P5 reiterated their support of the 2008 plan and the priorities specified therein.
- In 2013 the Facilities Panel gave Mu2e the highest endorsement:
  - "The science of Mu2e is *Critical* to the DOE OHEP mission and is *Ready to Construct*."
- In the 2014 P5 report Mu2e is strongly supported:
  - Recommendation 22, "Complete the Mu2e and Muon (g-2) Projects."

How does Mu2e work?

Mu2e Concept

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

Mu2e Proton Beam



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

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Mu2e Signal

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

Mu2e Sensitivity

- Design goal: single-event-sensitivity 2.4 x 10^{-17}
  - Requires about 10^{18} stopped muons
  - Requires about 10^{20} protons on target
  - Requires extreme suppression of backgrounds
- Expected limit: $R_{\mu e}$ < 6 x 10^{-17} @ 90% CL
  - Factor 10^4 improvement
- Discovery sensitivity: all $R_{\mu e}$ > few x 10^{-16}
  - Covers broad range of new physics theories

Backgrounds

Mu2e Backgrounds

- Intrinsic – scale with no. stopped muons
  - μ Decay-in-Orbit (DIO)
  - Radiative muon capture (RMC)
- Late arriving – scale with no. late protons
  - Radiative pion capture (RPC)
  - μ and π decay-in-flight (DIF)
- Miscellaneous
  - Anti-proton induced
  - Cosmic-ray induced

Mu2e Backgrounds

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.20
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.02
	Beam electrons	<0.01
	μ Decay in Flight	<0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton induced	0.05
	Cosmic Ray induced	0.10
Total Background		0.37

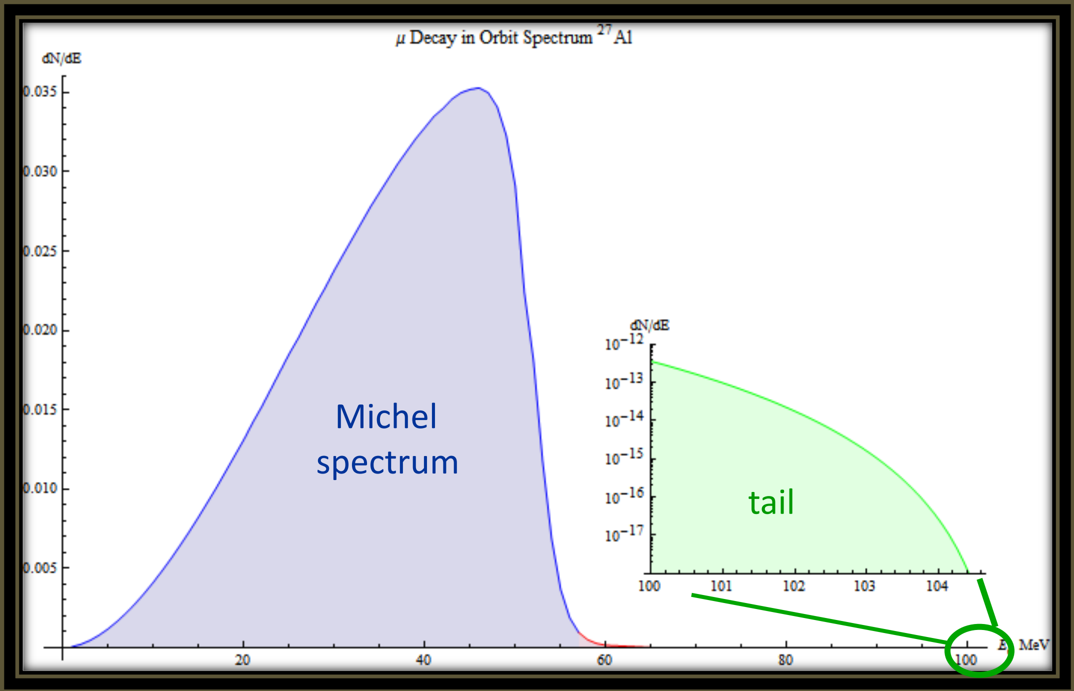
(assuming 6.8E17 stopped muons in 6E7 s of beam time)

- Designed to be nearly background free

Mu2e Intrinsic Backgrounds

Once trapped in orbit, muons will:

1) Decay in orbit (DIO): $\mu^- N \rightarrow e^- \nu_\mu \nu_e N$
   - For Al. DIO fraction is 39%
   - Electron spectrum has tail out to 104.96 MeV
   - Accounts for ~55% of total background



Electron energy in MeV

Mu2e Intrinsic Backgrounds

Once trapped in orbit, muons will:

2) Capture on the nucleus:

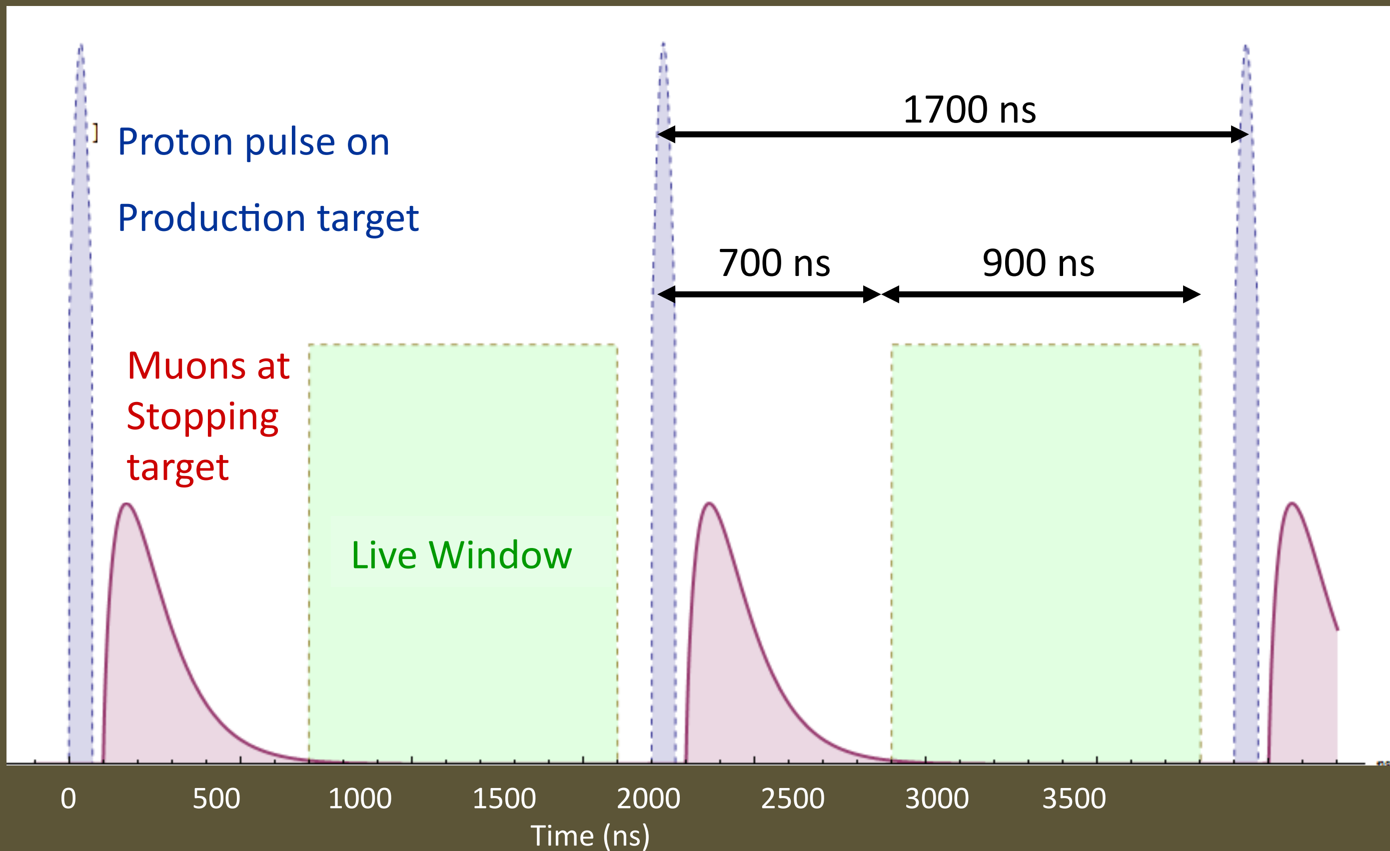
- For Al. capture fraction is 61%
- Ordinary μ Capture
  - $\mu^{-}N_{Z}$ --> νN^{*}_{Z-1}
  - Used for normalization
- Radiative μ capture
  - $\mu^{-}N_{Z}$ --> $\nu N^{*}_{Z-1} + \gamma$
  - (# Radiative / # Ordinary) ~ 1 / 100,000
  - E_{γ} kinematic end-point ~102 MeV
  - Asymmetric γ -->$e^{+}e^{-}$ pair production can yield a background electron

Mu2e Late Arriving Backgrounds

- Backgrounds arising from all the other interactions which occur at the production target
  - Overwhelmingly produce a prompt background when compared to $\tau_{\mu}^{Al} = 864$ ns
  - 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 $< 10^{-10}$

Mu2e Proton Beam



- Protons that arrive late can give rise to prompt backgrounds in the delayed live window.

Mu2e Late Arriving Backgrounds

- Contributions from
  - Radiative π Capture
    - $\pi^- N_Z \rightarrow N^*_{Z-1} + \gamma$
    - For Al. RπC 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
- Taken together these backgrounds account for ~10% of the total background and scale *linearly* with the number of out-of-time protons

Mu2e Miscellaneous Backgrounds

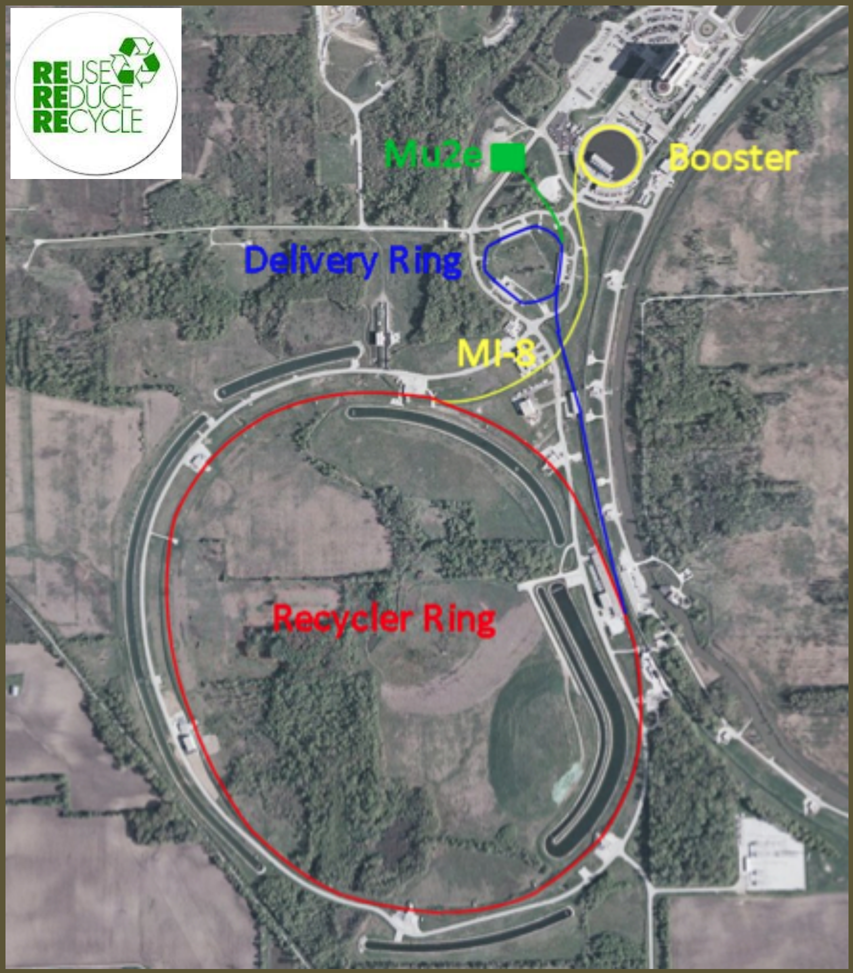
- Several additional miscellaneous sources can contribute background - most importantly:
  - Anti-protons
    - Proton beam is just above pbar production threshold
    - These low momentum pbars wander until they annihilate
    - A thin mylar window in beamline absorbs most if them
    - Annihilations produce high multiplicity final states e.g. π^- can undergo RπC 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 listed assumes veto efficiency of 99.99%

Keys to Mu2e Success

- Pulsed proton beam
  - Narrow proton pulses (< +/- 125 ns)
  - Very few out-of-time protons (< 10^{-10})
- Avoid trapping particles… B-field requirements
  - Further mitigates beam-related backgrounds
- High CR veto efficiency (>99.99%)
- Excellent momentum resolution (<200 keV core)
- Thin anti-proton annihilation window(s)

The Mu2e Beamlines

The Mu2e Proton Beam



- Mu2e begins by using protons to produce pions
- Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons.
- Mu2e can (and will) run simultaneously with NOvA.

The Mu2e Proton Beam

Item	Value	Units
Number of spills per MI cycle	8	
Number of protons per micro-pulse	31	Mp
Maximum Delivery Ring Beam Intensity	1.0	Tp
Instantaneous spill rate	18.5	Tp/sec
Average spill rate	6.0	Tp/sec
Duty Factor	32	%
Duration of spill	54	msec
Spill On Time per MI cycle	497	msec
Spill Off Time per MI cycle	836	msec
Time Gap between 1st set of 4 and 2nd set of 4 spills	36	msec
Time Gap between spills	5	msec
Pulse-to-pulse intensity variation[f]	±50	%

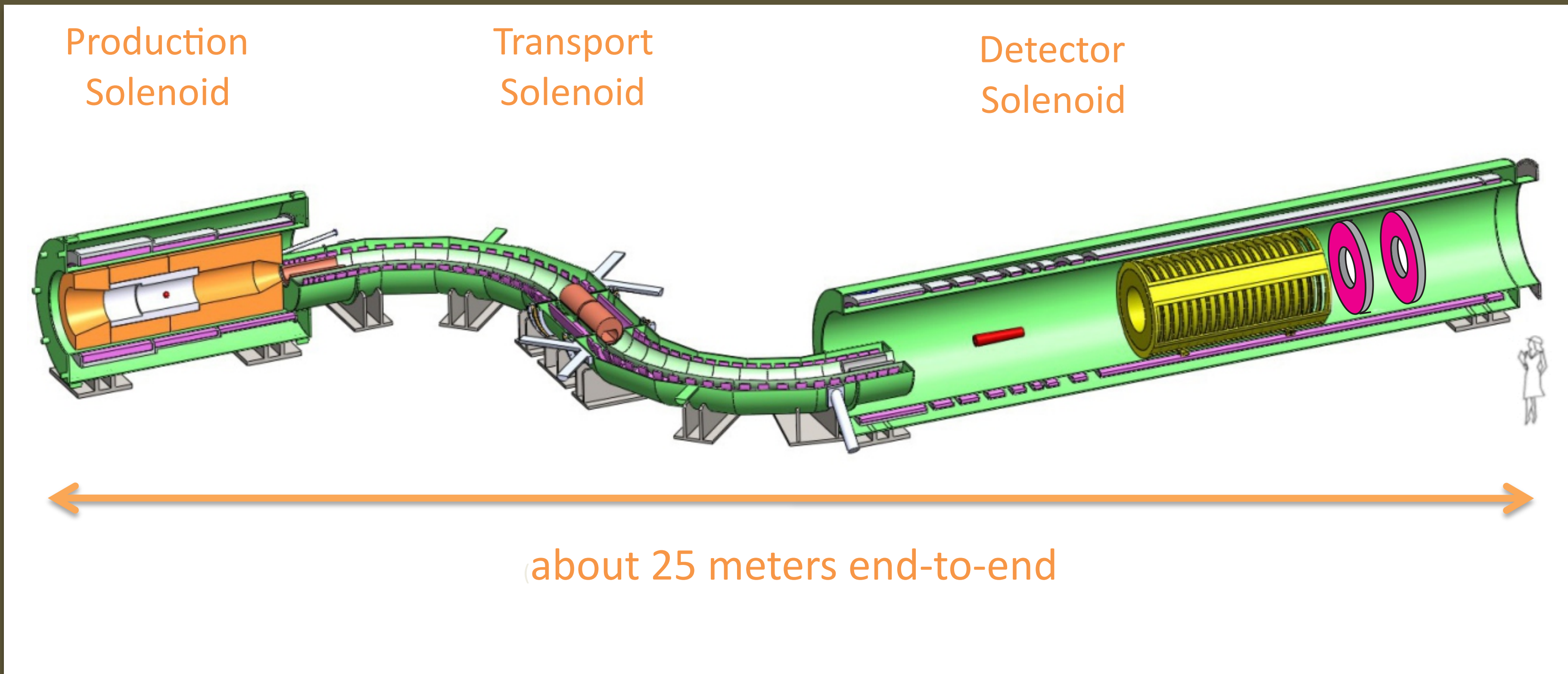
Table 5.2. Delivery Ring Spill Parameters

- Mu2e will use 8kW of 8 GeV proton beam

Mitigating out-of-time protons

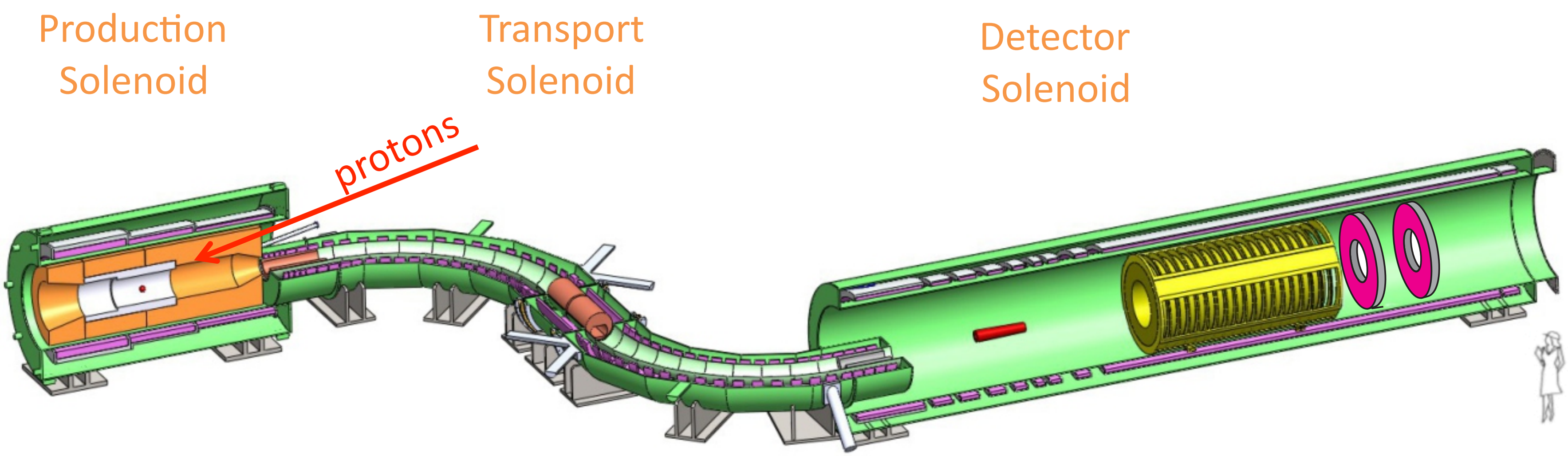
- The RF structure of the Recycler provides some “intrinsic” extinction:
  - Extinction (Intrinsic) = few 10^{-5}
- A custom-made AC dipole placed just upstream of the production target provides additional “external” extinction:
  - Extinction (AC dipole) = 10^{-6} – 10^{-7}
- Together they provide a total extinction:
  - Extinction (Total) = few 10^{-11} – 10^{-12}

Mu2e Experimental Apparatus



- Consists of 3 solenoid systems

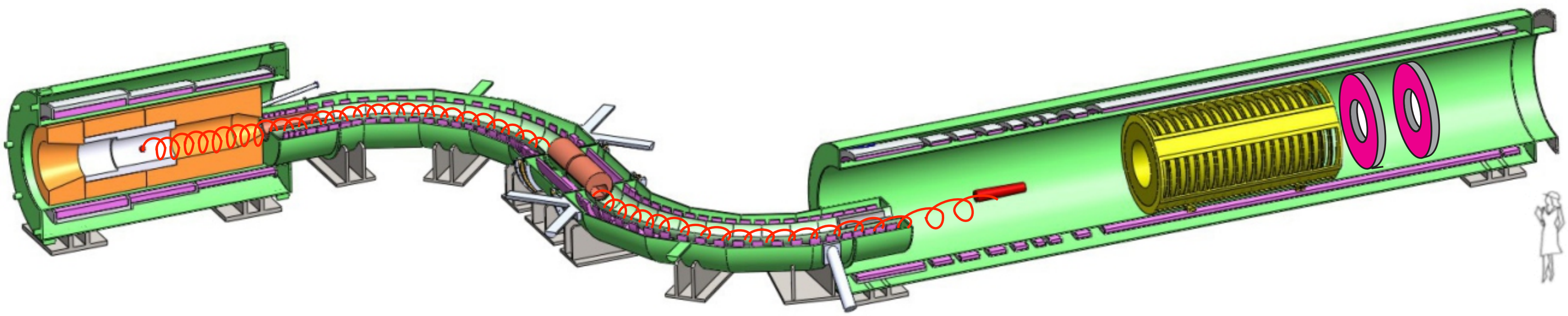
Mu2e Experimental Apparatus



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

- Consists of 3 solenoid systems

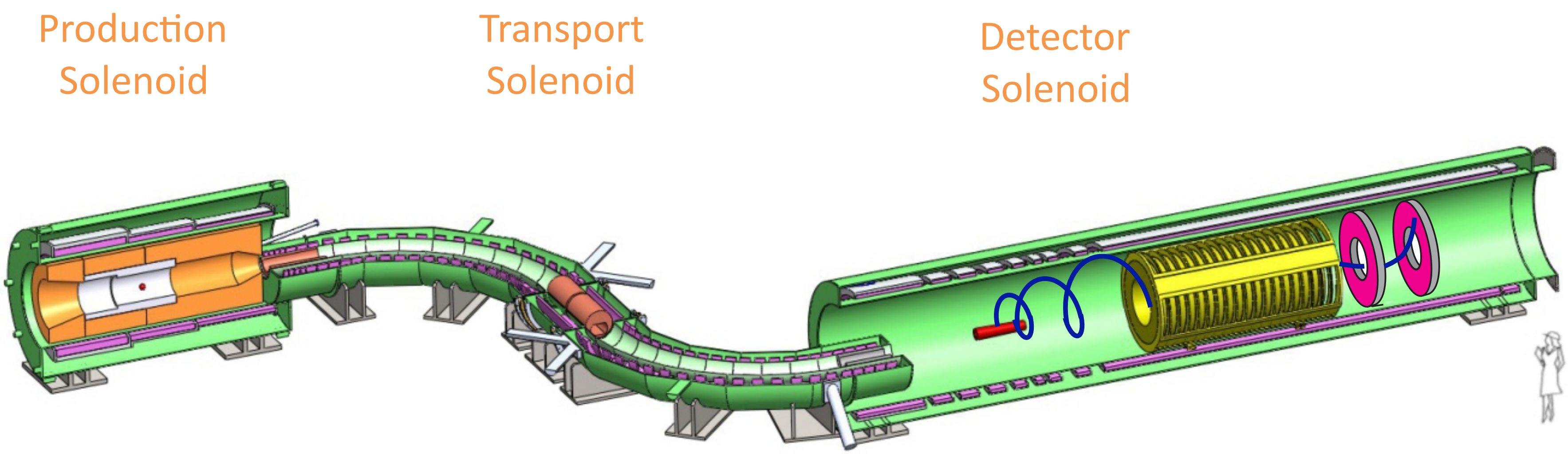
Mu2e Experimental Apparatus



Transport Solenoid:
Captures π- and subsequent μ-; momentum- and sign-selects beam

- Consists of 3 solenoid systems

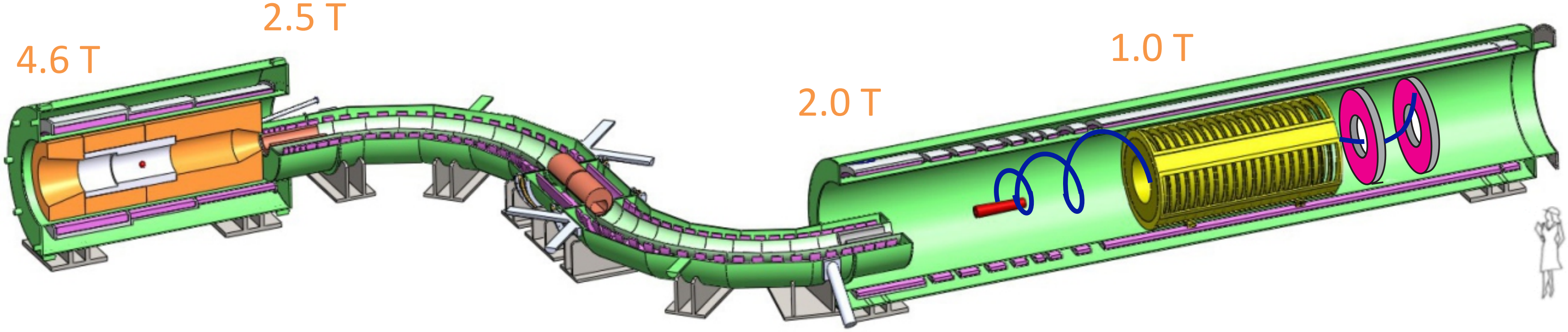
Mu2e Experimental Apparatus



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

- Consists of 3 solenoid systems

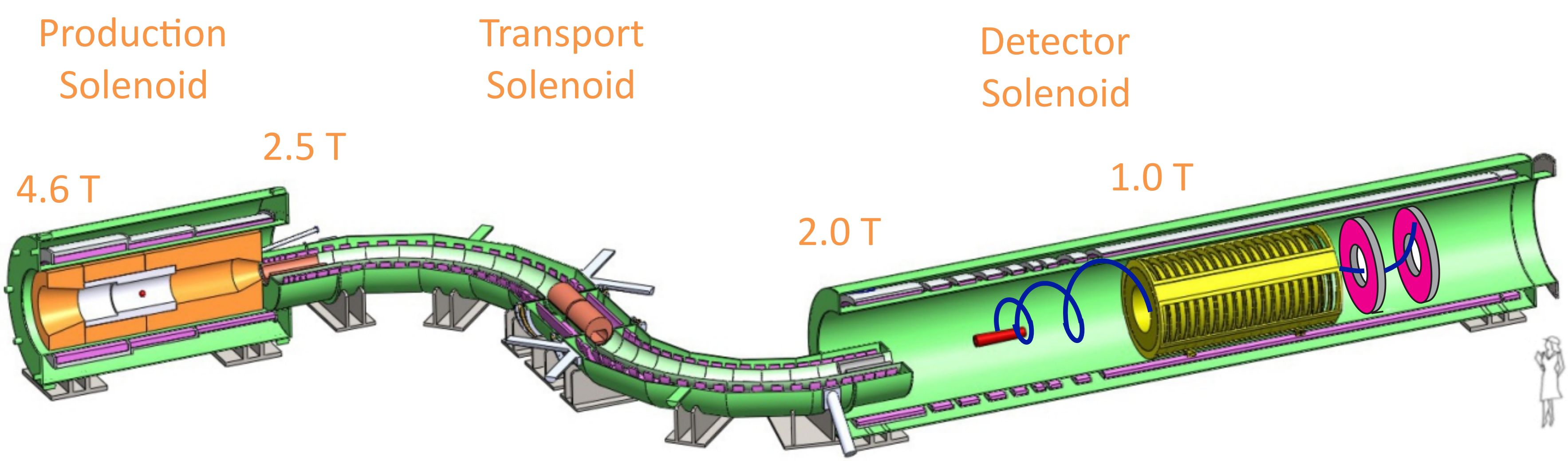
Mu2e Experimental Apparatus



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

- Consists of 3 solenoid systems

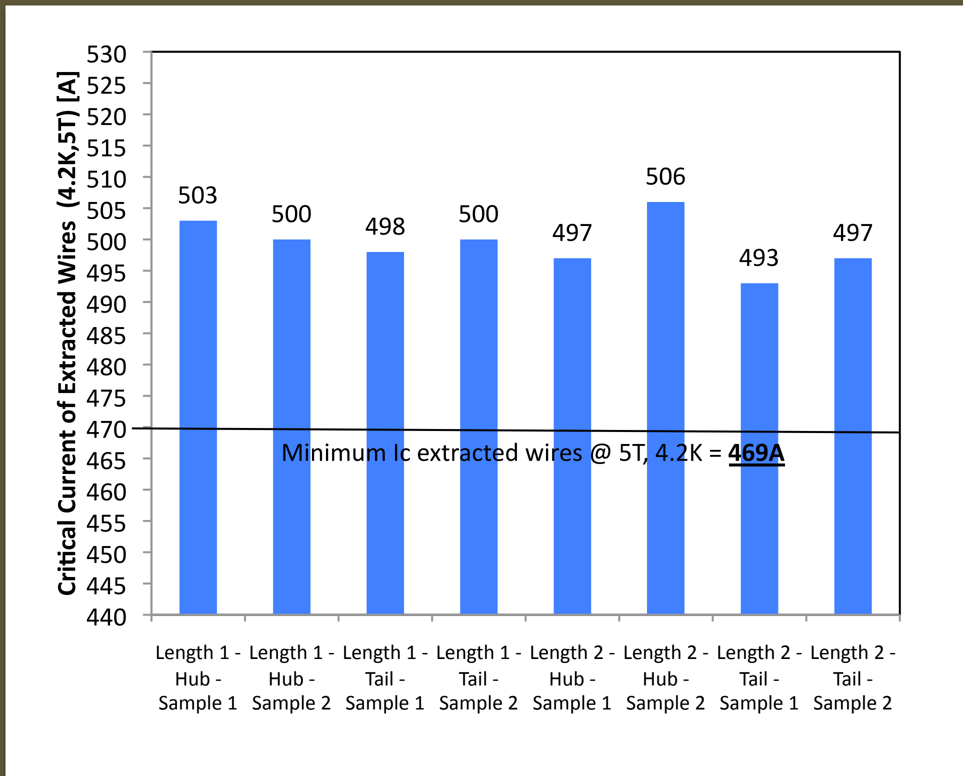
Mu2e Experimental Apparatus

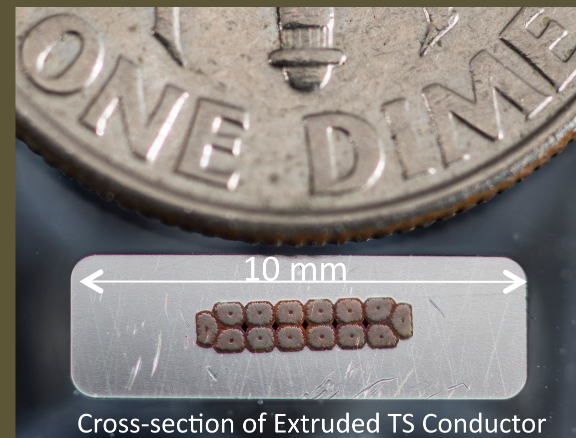


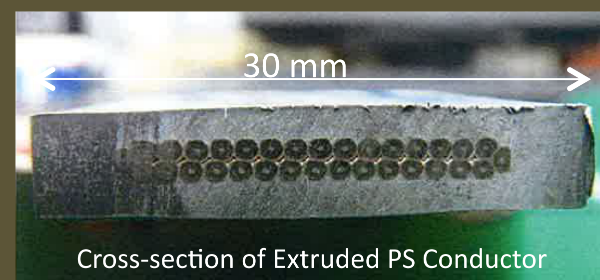
Graded fields important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons

- Derived from MELC concept originated by Lobashev and Djilkibaev in 1989

Mu2e Conductor R&D







- Have completed conductor R&D
  - PS, TS, DS conductor demonstrated
  - Fabrication of production lengths in progress

Mu2e Solenoid Summary

	PS	TS	DS
Length (m)	4	13	11
Diameter (m)	1.7	0.4	1.9
Field @ start (T)	4.6	2.5	2.0
Field @ end (T)	2.5	2.0	1.0
Number of coils	3	50	11
Conductor (km)	10	44	15
Operating current (kA)	10	3	6
Stored energy (MJ)	80	20	30
Cold mass (tons)	11	26	8

- PS, DS will be built in industry
- TS will be assembled at Fermilab

Mu2e Solenoid Summary

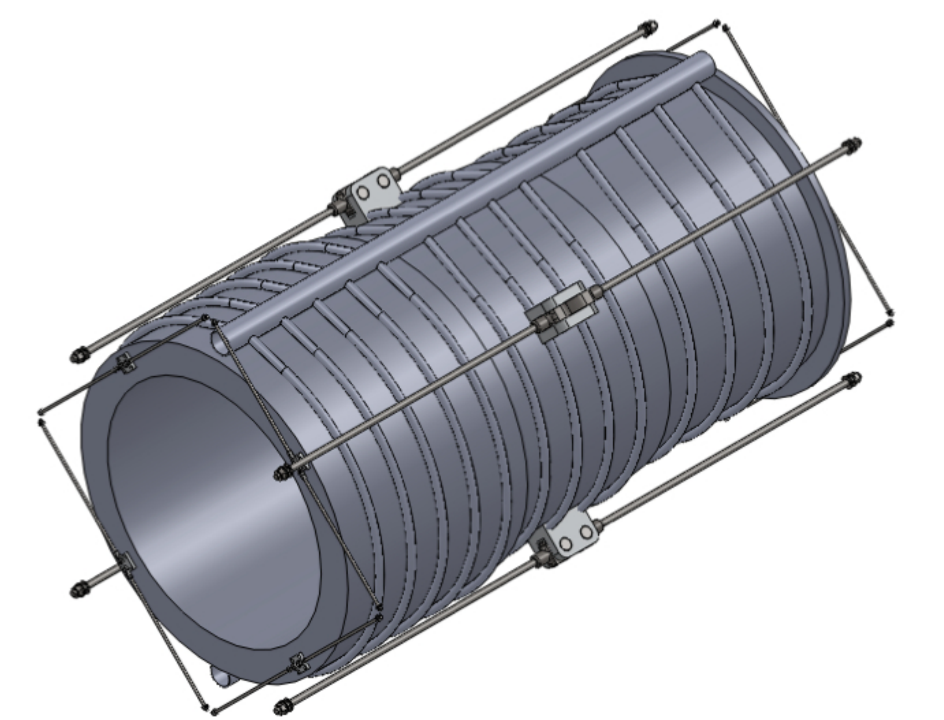


Figure 7.6. Coil cold mass with cooling tubes and support structure.

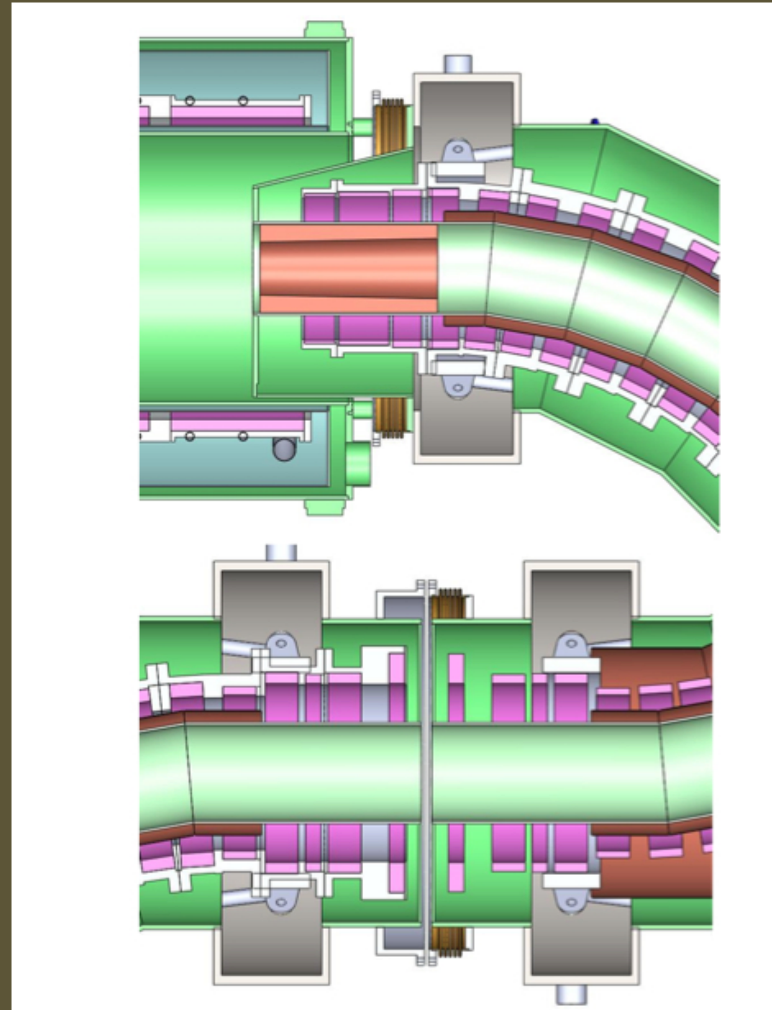


Figure 7.25. TSu Cryostat Interfaces. Top: TSu-PS interface; Bottom; TSu-TSd interface.

- Designs are well advanced.

Mu2e Solenoid Summary

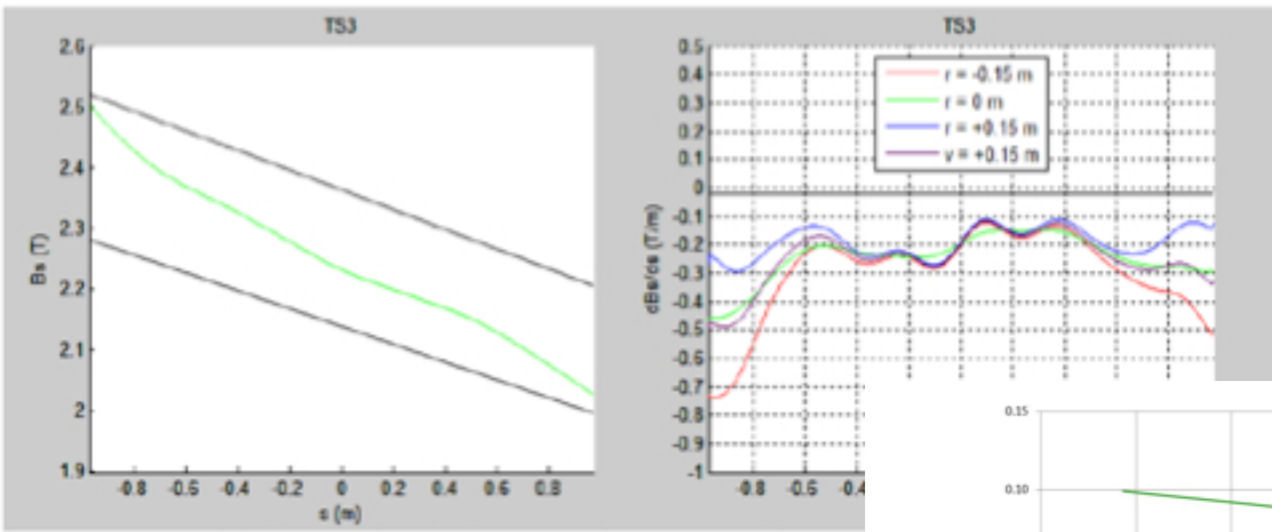


Figure 7.28. Axial field distribution at the center of TS3 (le
(right).

- Designs meet field specs (including fabrication and design tolerances).

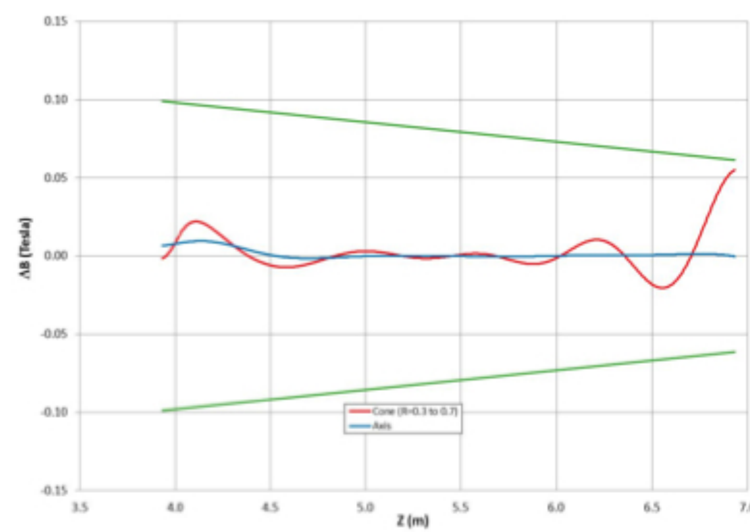
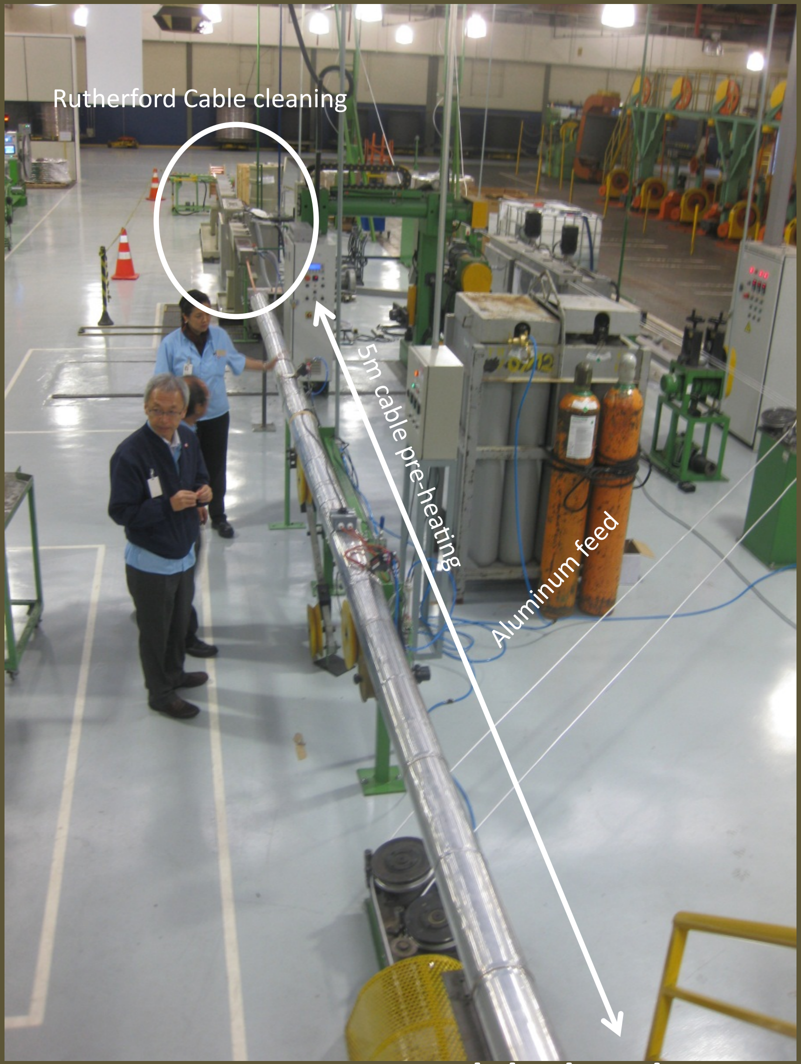
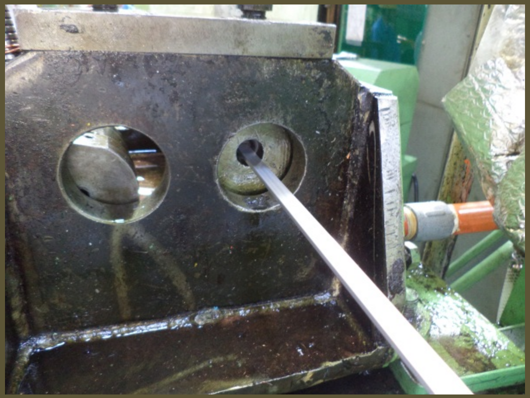
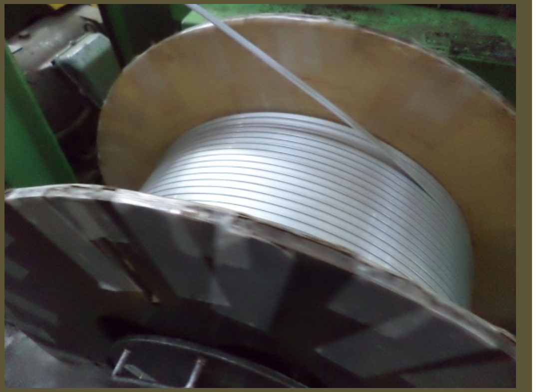


Figure 7.39. Comparison of the magnetic field with the field requirements in the DS gradient section (DS1 Gradient). Field requirements from Table 7.2 are shown in green. ΔB is relative to uniform gradient of -0.25 T/m and a field value of 1. 5 T at the stopping target on axis (blue); on a radial cone from 0.3m to 0.7 m starting at the upstream end of DS1 section (red).

Mu2e Conductor R&D







- Have established a good relationship with the vendors

Some Mu2e numbers

- Every 1 second Mu2e will
  - Send 7,000,000,000,000 protons to the Production Solenoid
  - Send 26,000,000,000 μs through the Transport Solenoid
  - Stop 13,000,000,000, μs in the Detector Solenoid
- By the time Mu2e is done…

Total number of stopped muons

1,000,000,000,000,000,000

Some Perspective

1,000,000,000,000,000,000

= number of stopped Mu2e muons

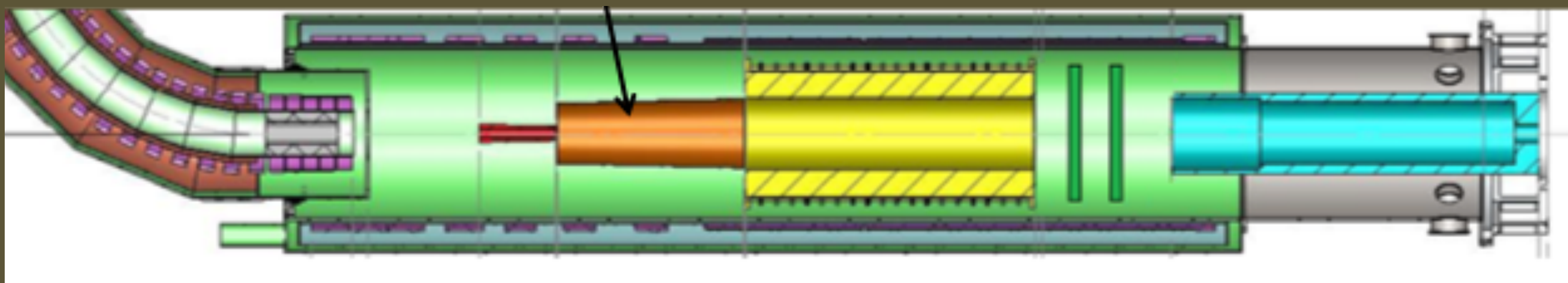
= number of grains of sand on earth's beaches

The Mu2e Detectors

The Mu2e Detector

Transport
Solenoid

Detector Solenoid



Stopping
Target

Tracker

Calorimeter

Muon-beam
Stop

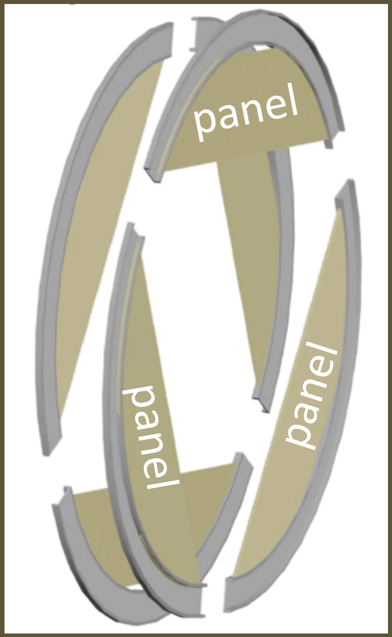
- I am going to focus on the principle elements:
  - Tracker, Calorimeter, Cosmic-Ray Veto

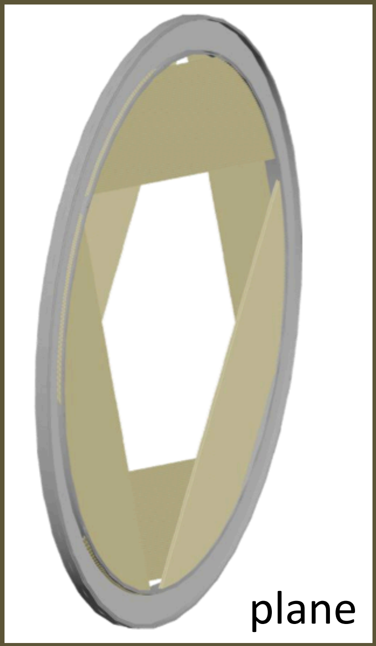
The Mu2e Tracker

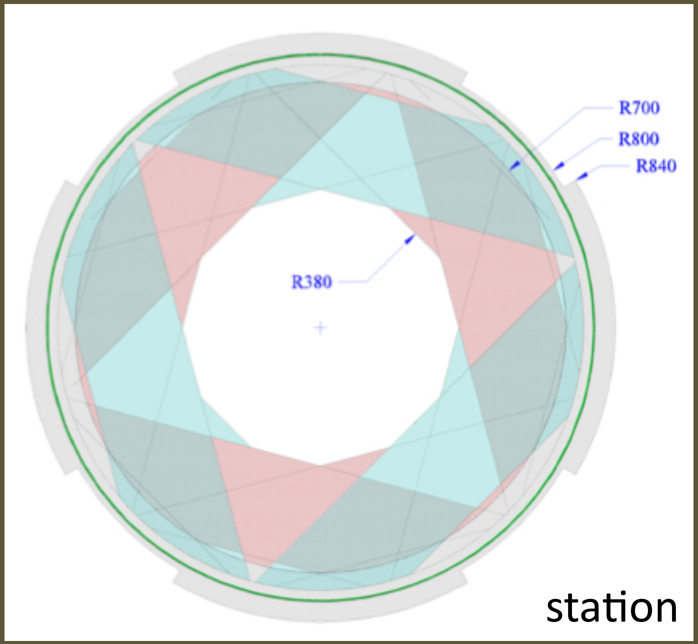
- Will employ straw technology
  - Low mass
  - Can reliably operate in vacuum
  - Robust against single-wire failures

- 5 mm diameter straw
- Spiral wound
- Walls: 12 μm Mylar + 3 μm epoxy + 200 Å Au + 500 Å Al
- 25 μm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO_2 with HV < 1500 V

The Mu2e Tracker

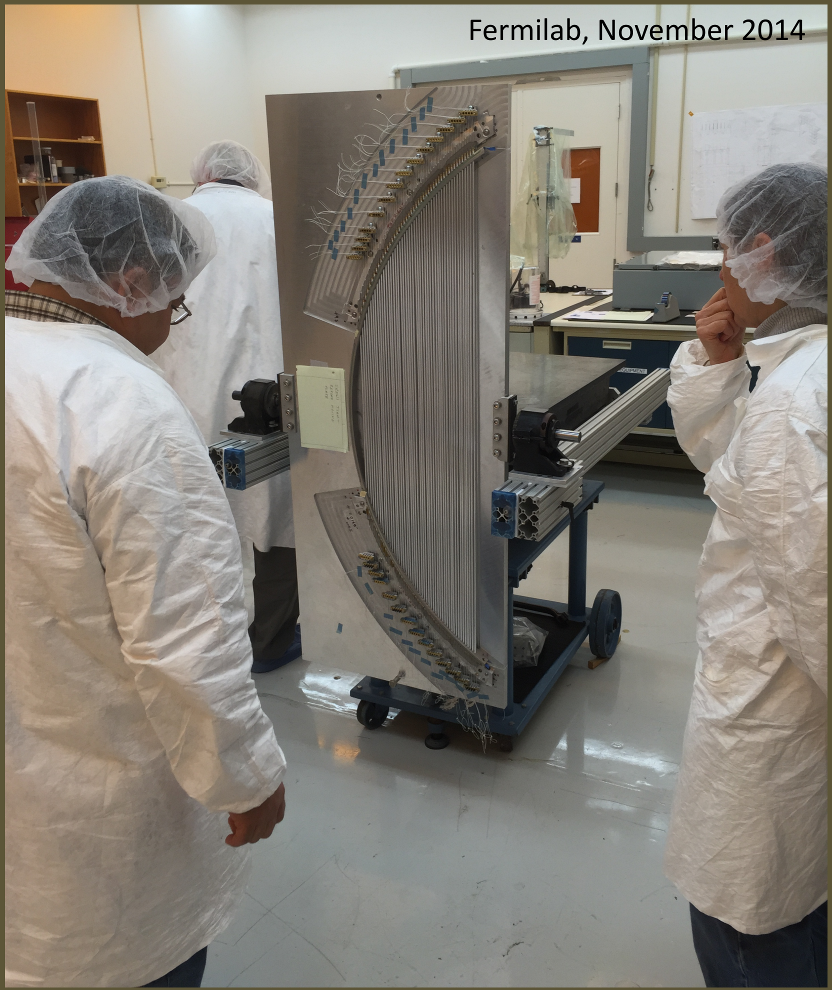






- Self-supporting “panel” consists of 100 straws
- 6 panels assembled to make a “plane”
- 2 planes assembled to make a “station”
- Rotation of panels and planes improves stereo information
- >20k straws total

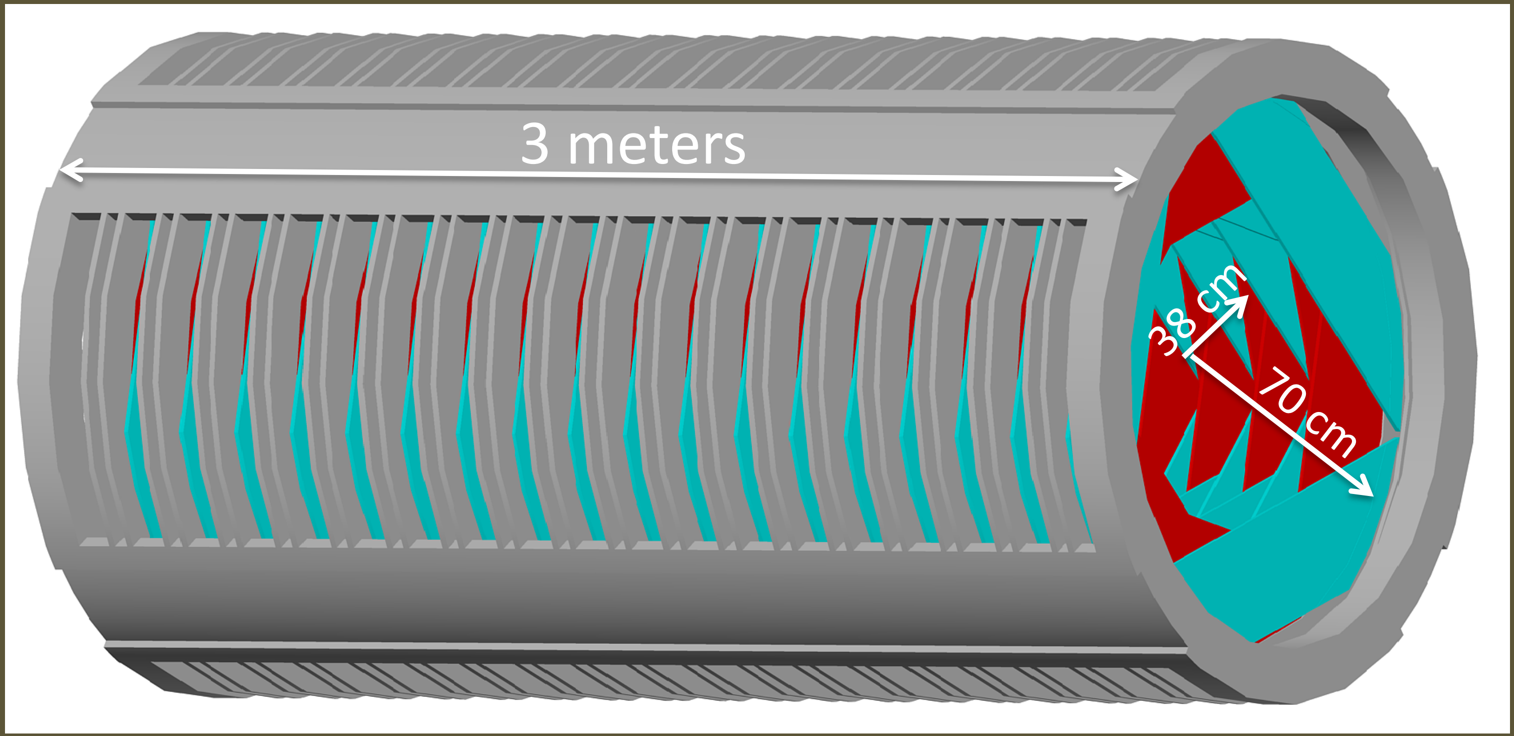
First Prototype Panel



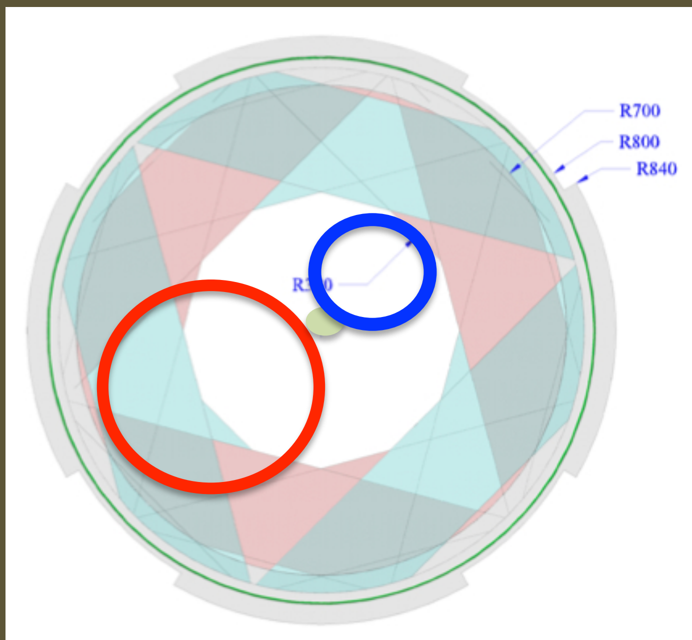
- Will be tested in vacuum early 2015

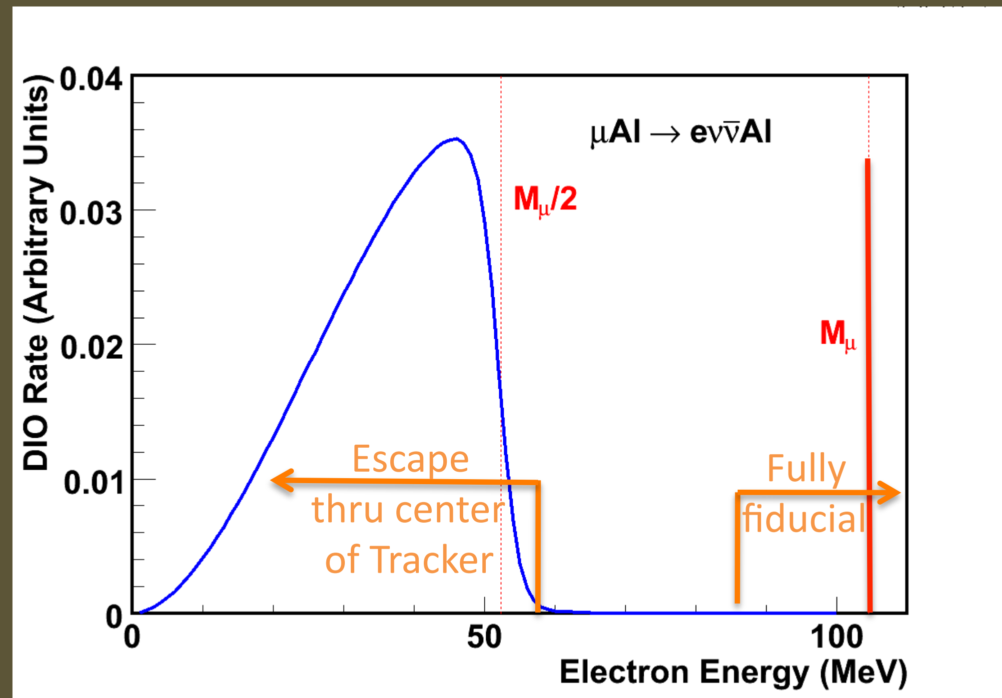
The Mu2e Tracker

- 18-20 “stations” with straws transverse to beam
- Naturally moves readout and support to large radii, out of active volume



The Mu2e Tracker



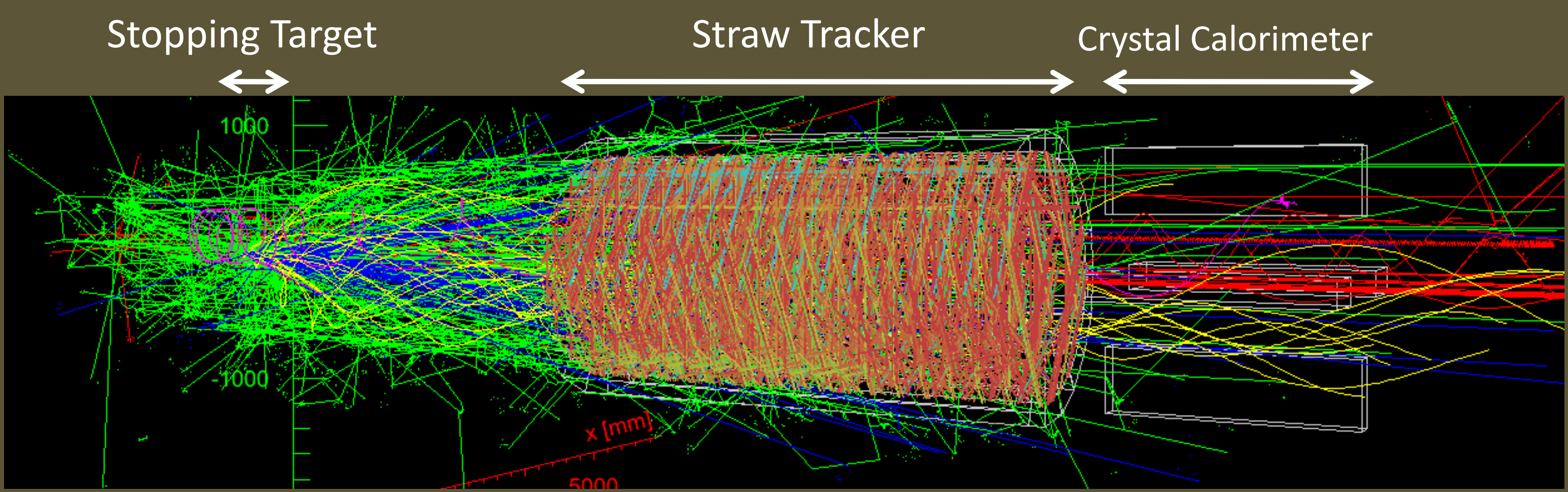


- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum

Mu2e Track Reconstruction

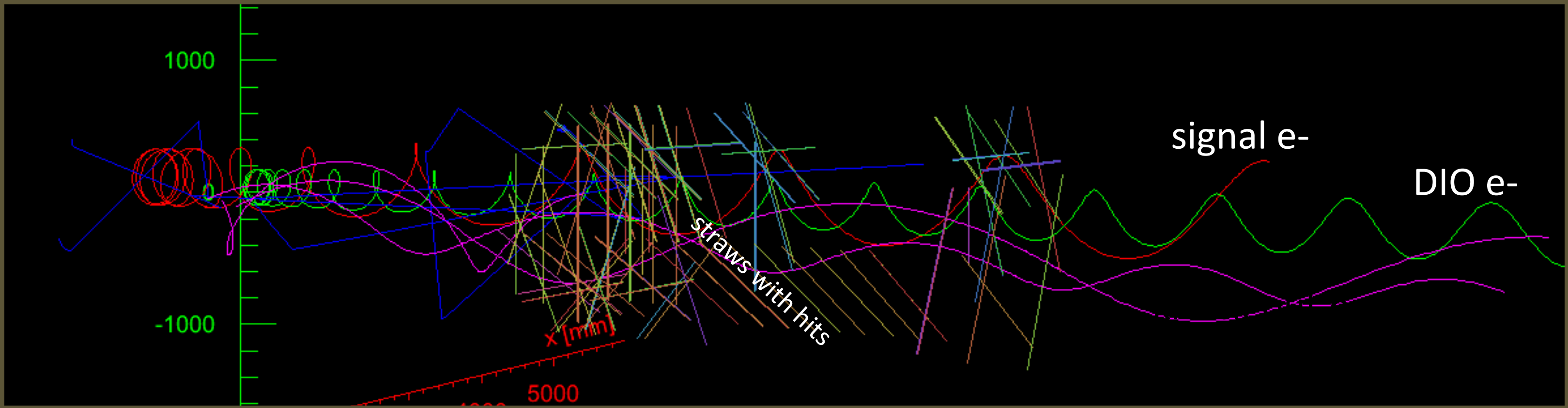
- Straw-hit rates
  - From beam flash (0-300 ns): ~1000 kHz/cm^2
    - Need to survive this, but won't collect data
  - Later, near live window (>500 ns)
    - Peak ~ 20 kHz/cm^2 (inner straws)
    - Average ~ 10 kHz/cm^2 (over all straws)

Mu2e Pattern Recognition



- A signal electron, together with all the other "stuff" occurring simultaneously, integrated over 500-1695 ns window

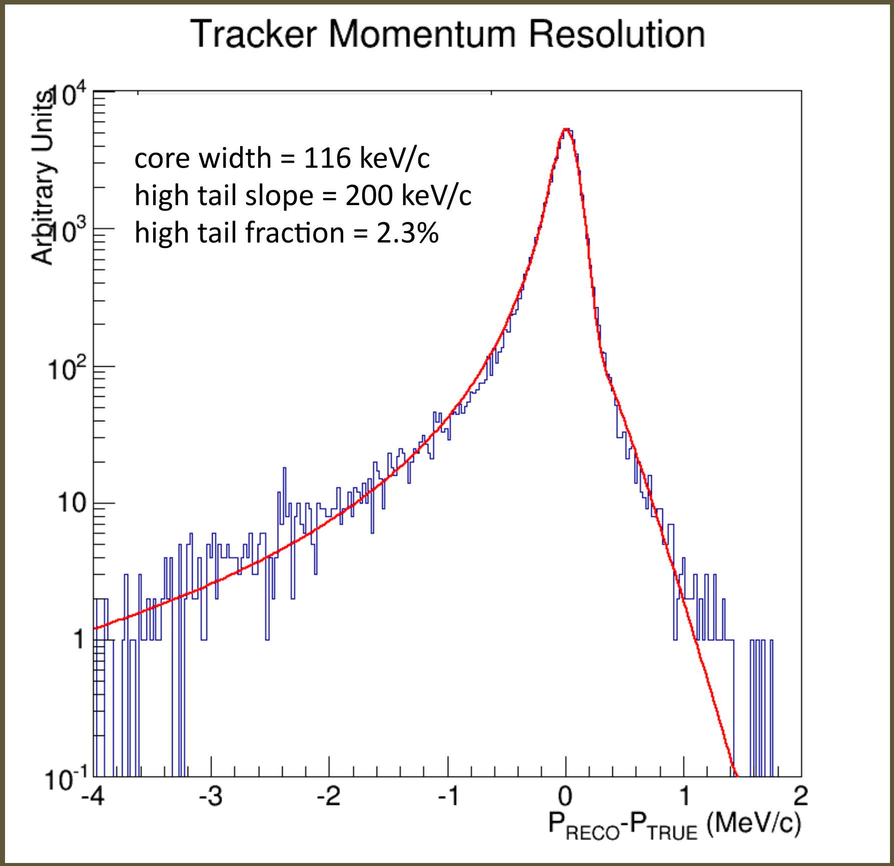
Mu2e Pattern Recognition



(particles with hits within +/-50 ns of signal electron t_{mean})

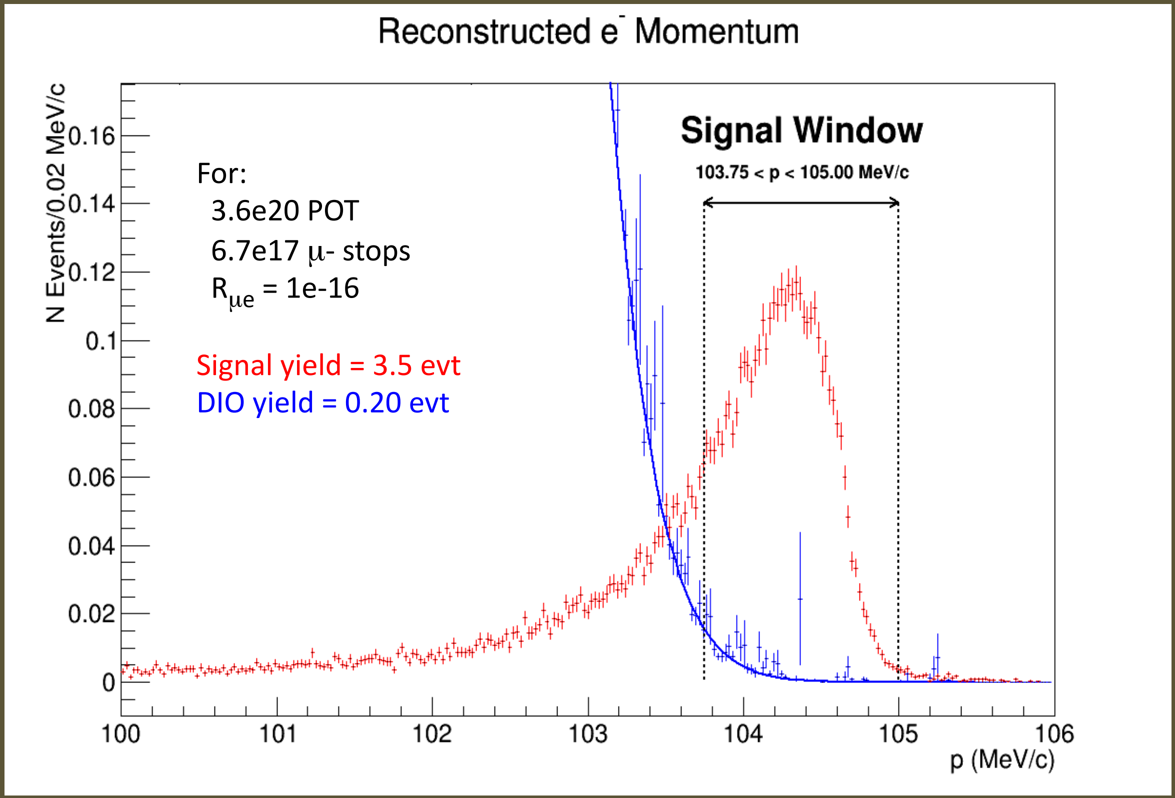
- We use timing information to look in +/- 50 ns windows – significant reduction in occupancy and significant simplification for Patt. Rec.

Mu2e Spectrometer Performance



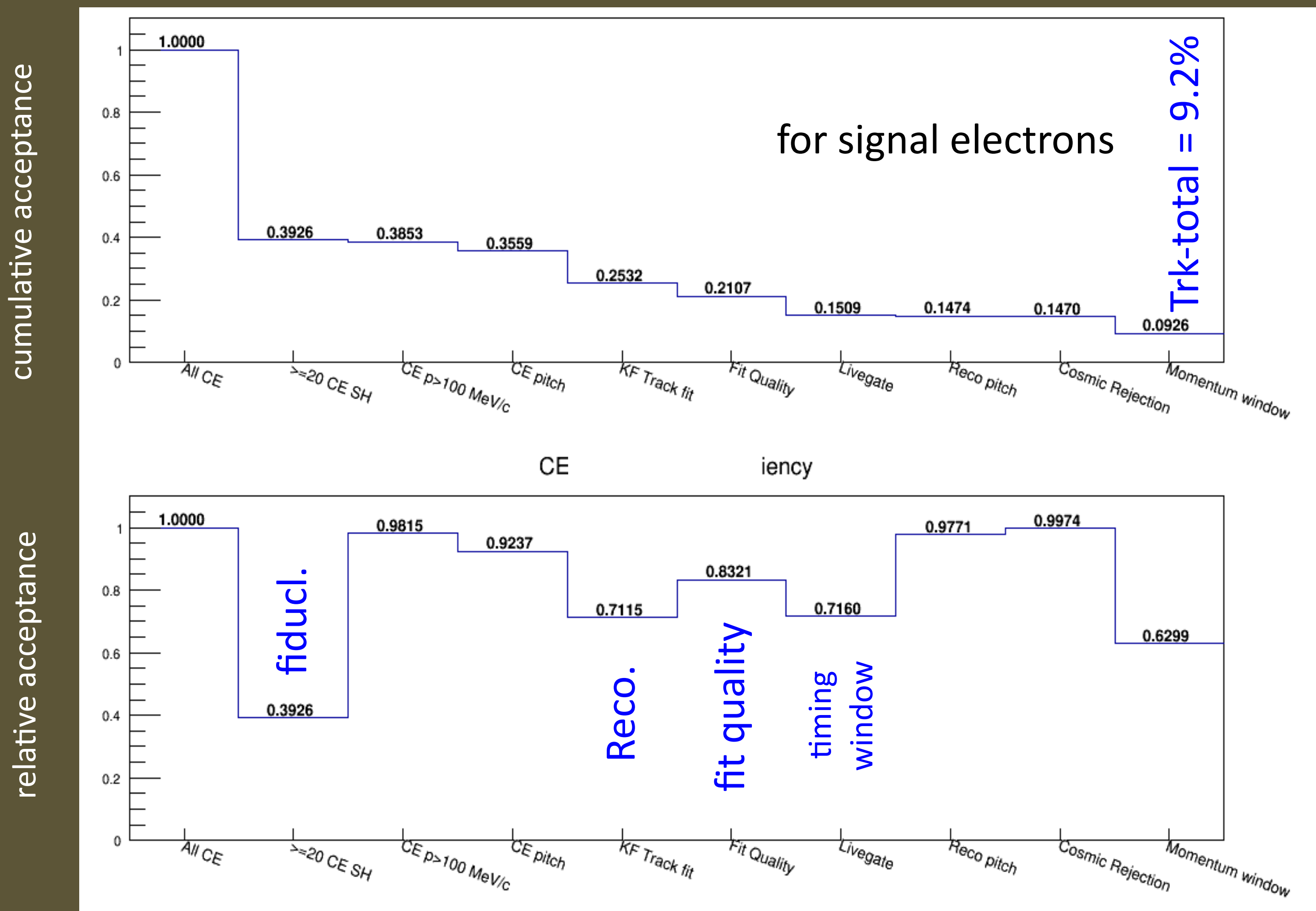
- Performance well within physics requirements

After all analysis requirements



- Single-event-sensitivity = 2.9 x 10^{-17}
  (SES goal 2.4 x 10^{-17})
- Total background < 0.5 events

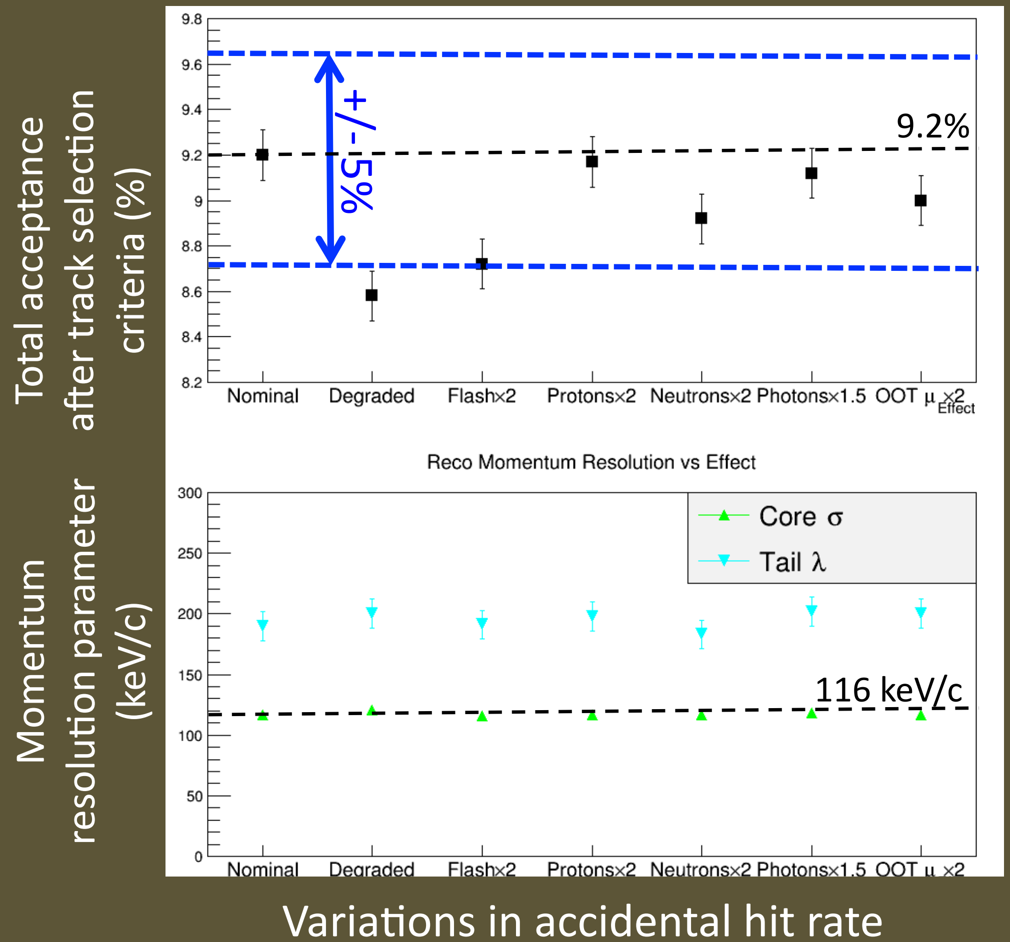
Track Reconstruction and Selection



Inefficiency dominated by geometric acceptance

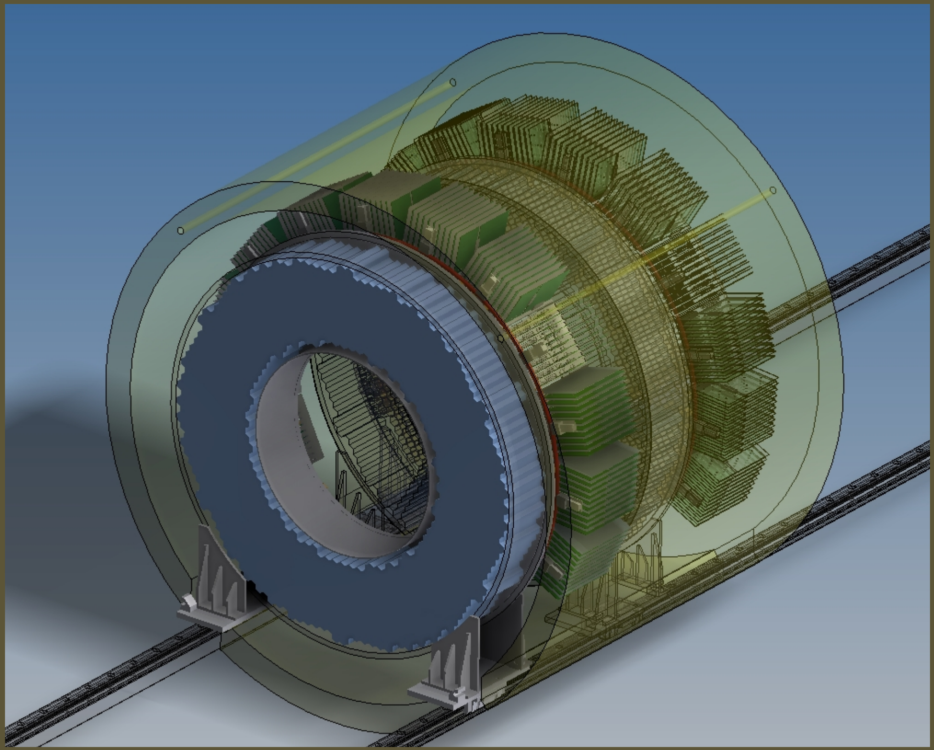
After calorimeter PID and CRV deadtime, Total = 8.5%

Mu2e Performance



- Robust against increases in rate

Mu2e Calorimeter



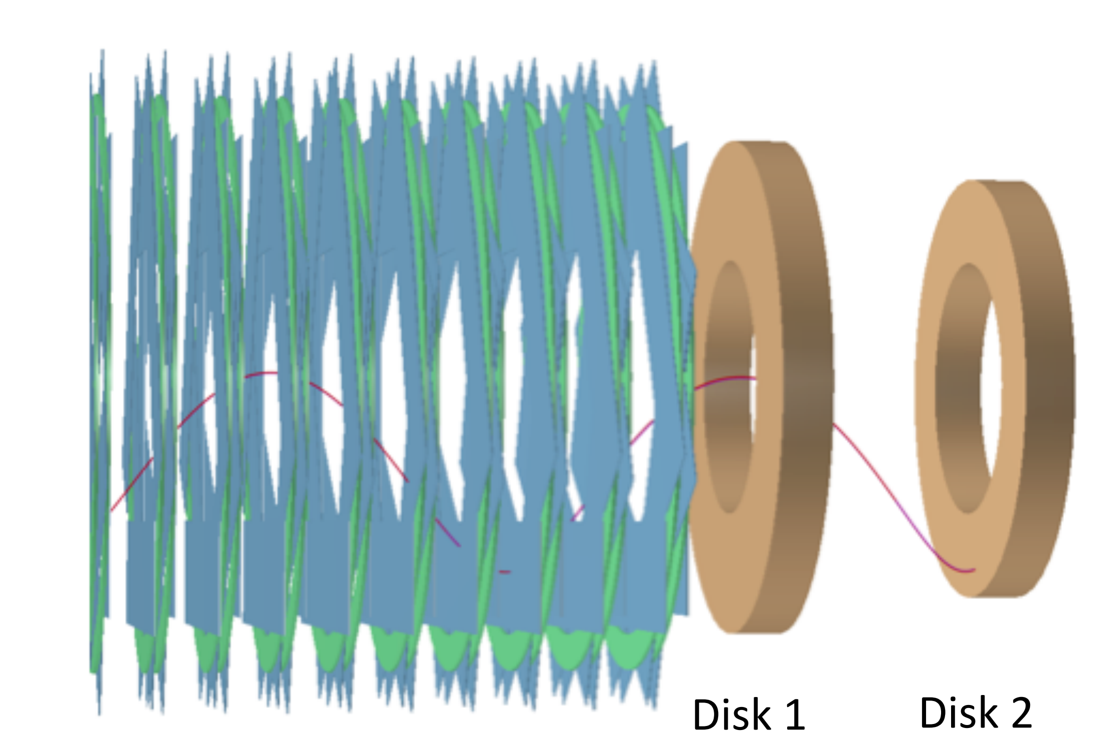
- Crystal calorimeter
  - Compact
  - Radiation hard
  - Good timing and energy resolution

Mu2e Calorimeter

- Baseline design : Barrium Flouride (BaF_2)
  - Radiation hard, very fast, non-hygroscopic

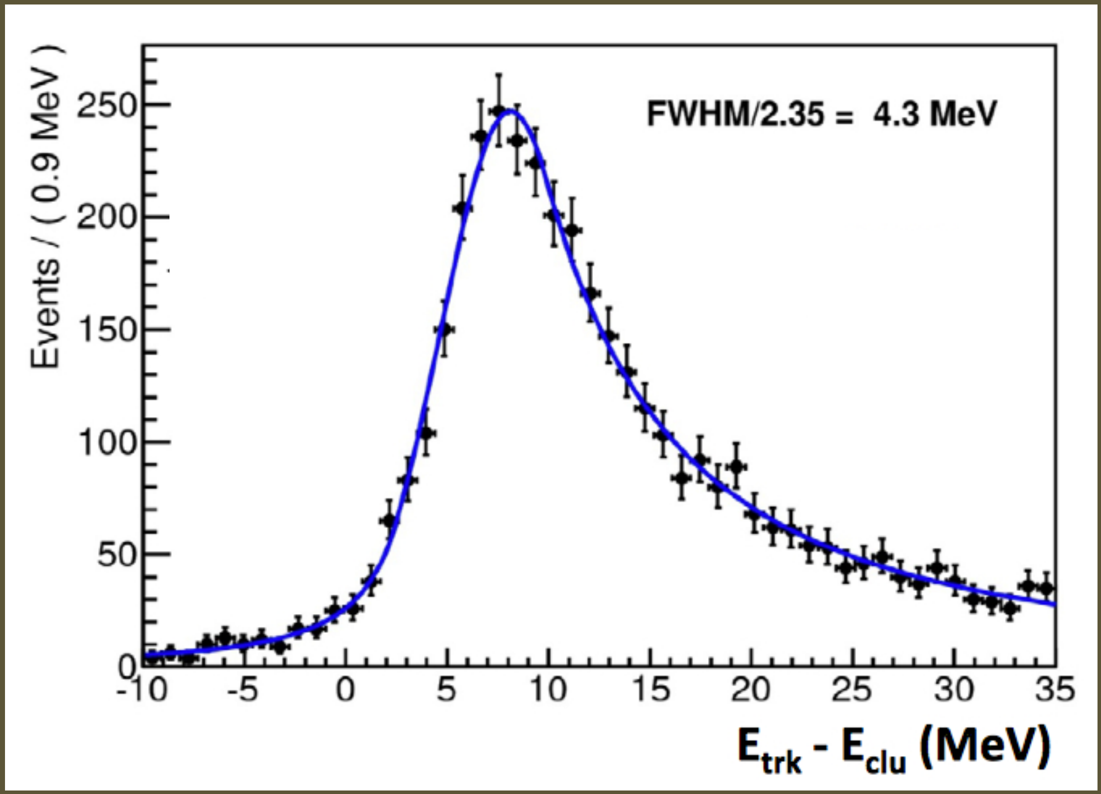
	BaF_2
Density (g/cm3)	4.89
Radiation length (cm)	2.03
Moliere Radius (cm)	3.10
Interaction length (cm)	30.7
dE/dX (MeV/cm)	6.52
Refractive index	1.50
Peak luminescence (nm)	220 (300)
Decay time (ns)	1 (650)
Light yield (rel. to NaI)	5% (42%)
Variation with temperature	0.1% (-1.9)% / deg-C

Mu2e Calorimeter



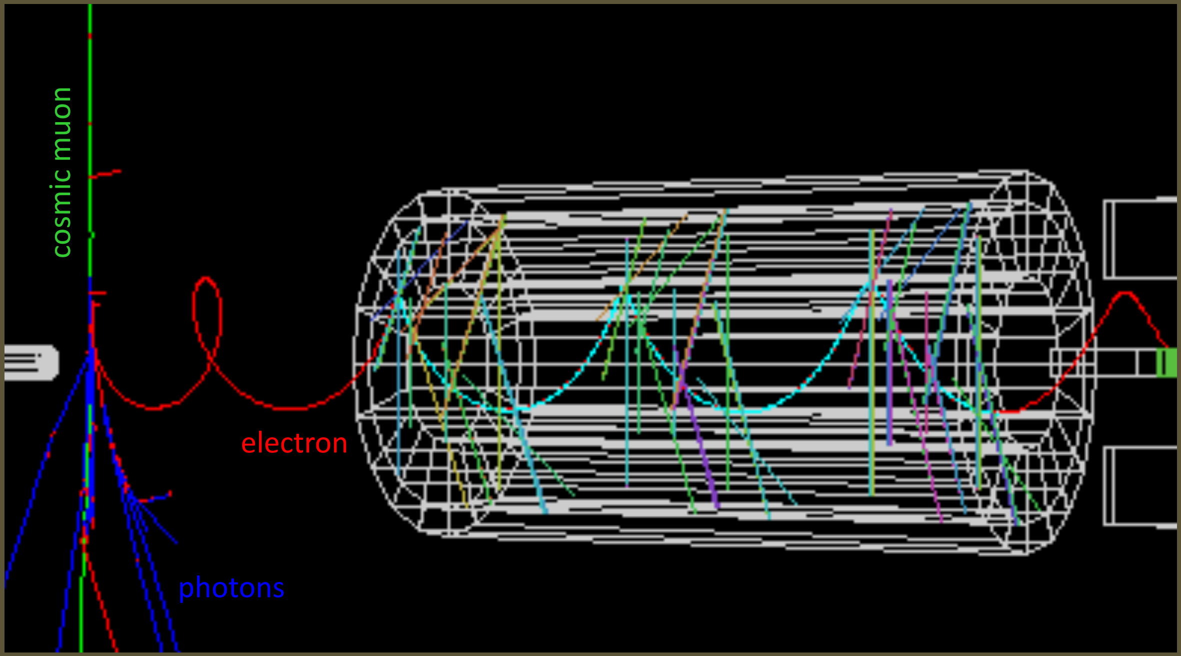
- Will employ 2 disks (radius = 36-70 cm)
- ~2000 crystals with hexagonal cross-section
  - ~3 cm diameter, ~20 cm long (10 X_0)
- Two photo-sensors/crystal on back (APDs or SiPMs)

Mu2e Calorimeter



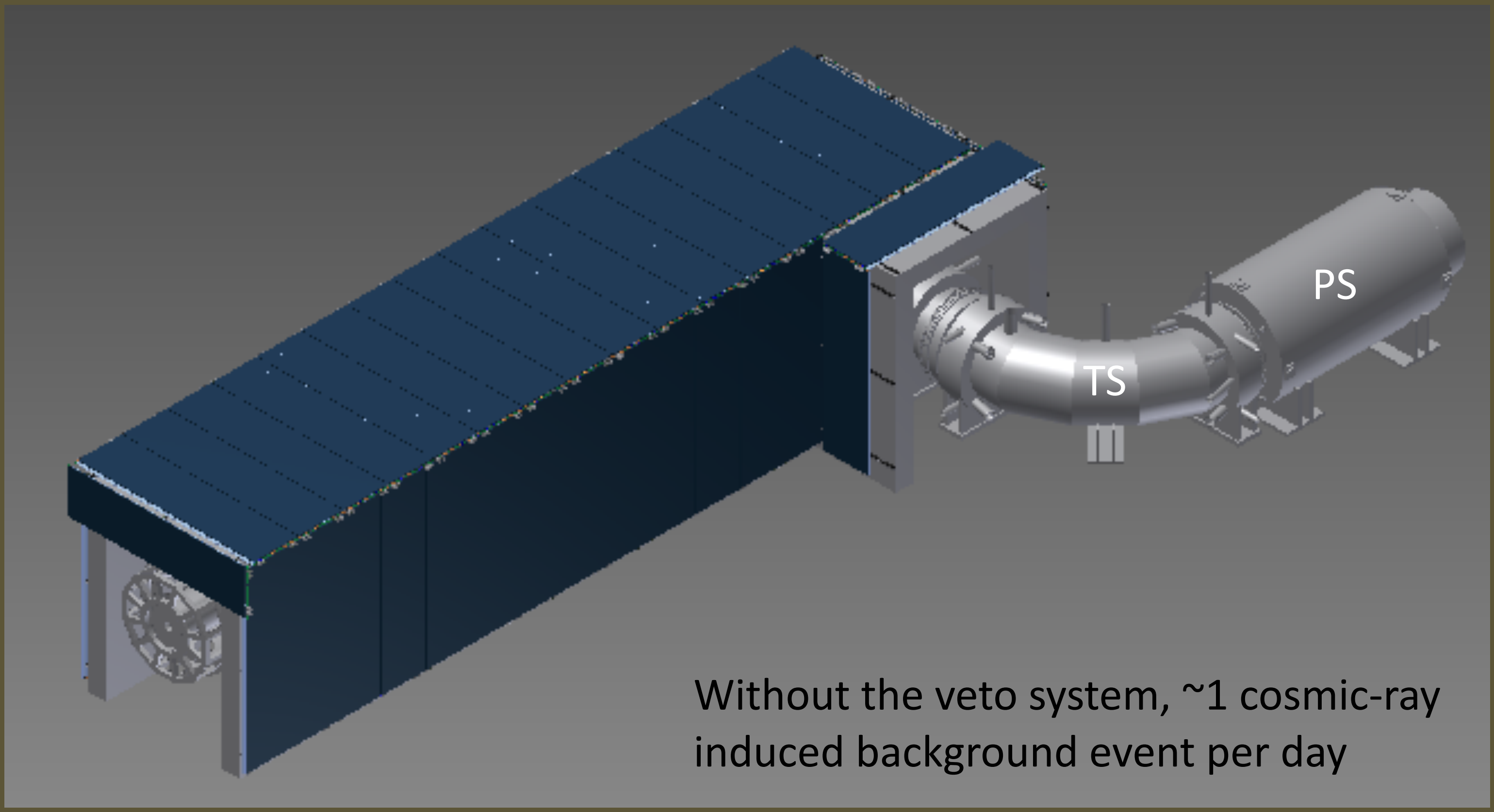
- With 40 ns hit separation, expect to achieve an energy resolution <5% for 105 MeV electrons
  - Performance a weak function of rate in relevant range

Mu2e Cosmic-Ray Veto



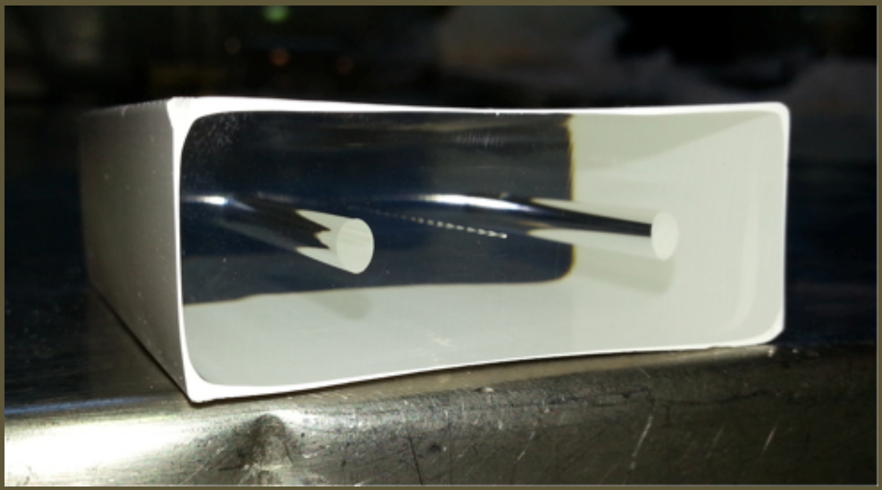
- Cosmic μ can generate background events via decay, scattering, or material interactions

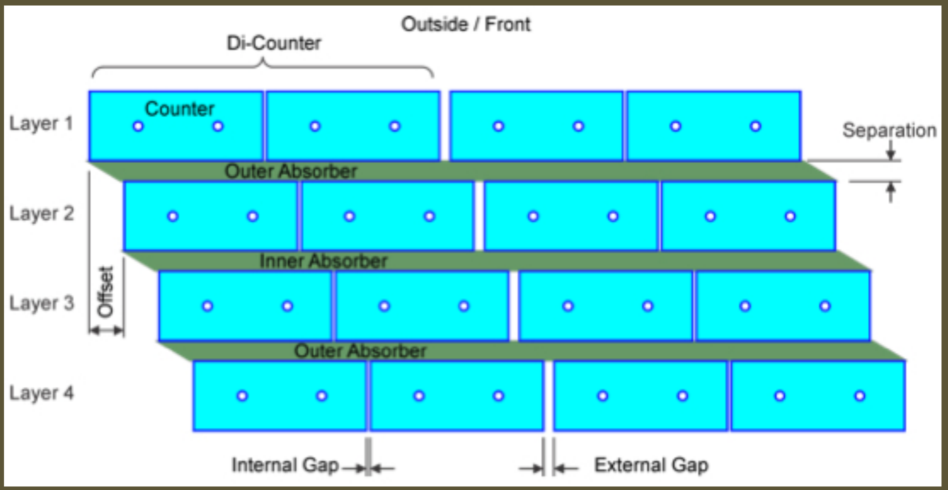
Mu2e Cosmic-Ray Veto



- Veto system covers entire DS and half TS

Mu2e Cosmic-Ray Veto



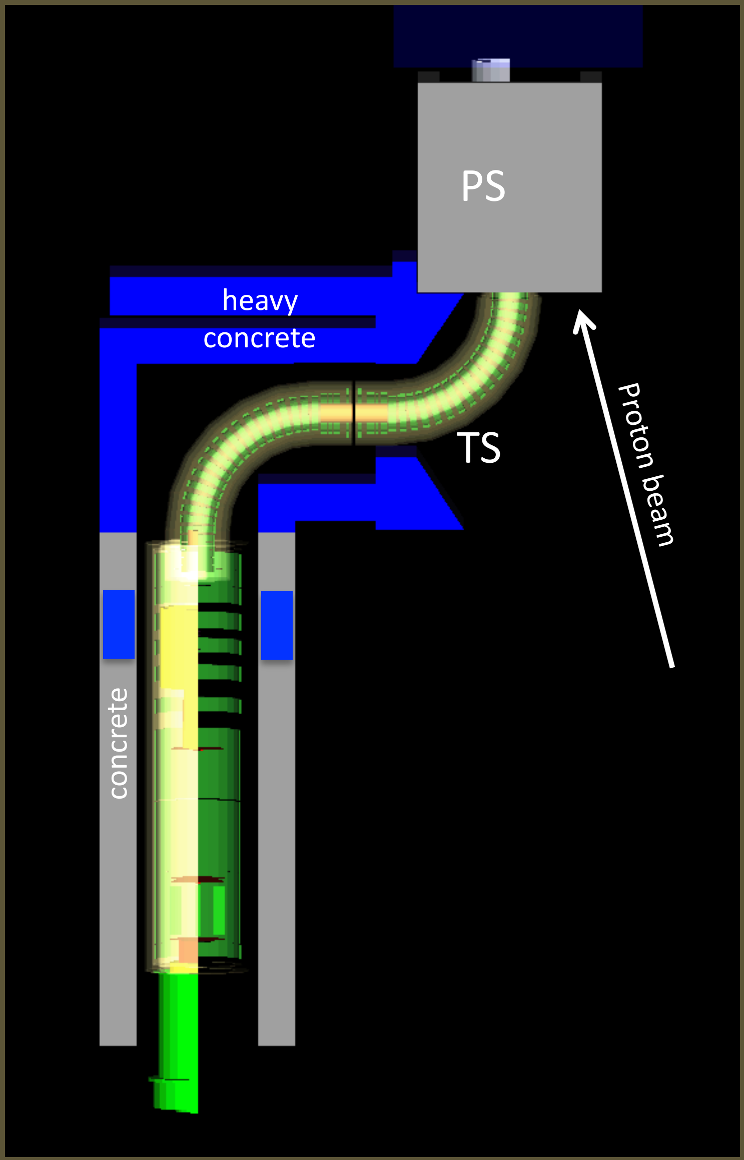


- Will use 4 overlapping layers of scintillator
  - Each bar is 5 x 2 x ~450 cm^3
  - 2 WLS fibers / bar
  - Read-out both ends of each fiber with SiPM
  - Have achieved $\varepsilon > 99.4\%$ (per layer) in test beam

Mu2e Neutron Shielding

- Several copious sources of neutrons
  - Production target, stopping target, collimators
- Lots of neutrons and subsequent photons (from n- capture and activation processes)
  - Generate false vetos in CRV… if rate high enough becomes a source of significant dead-time
  - Cause radiation damage to the read-out electronics (esp. SiPMs)

Mu2e Neutron Shielding



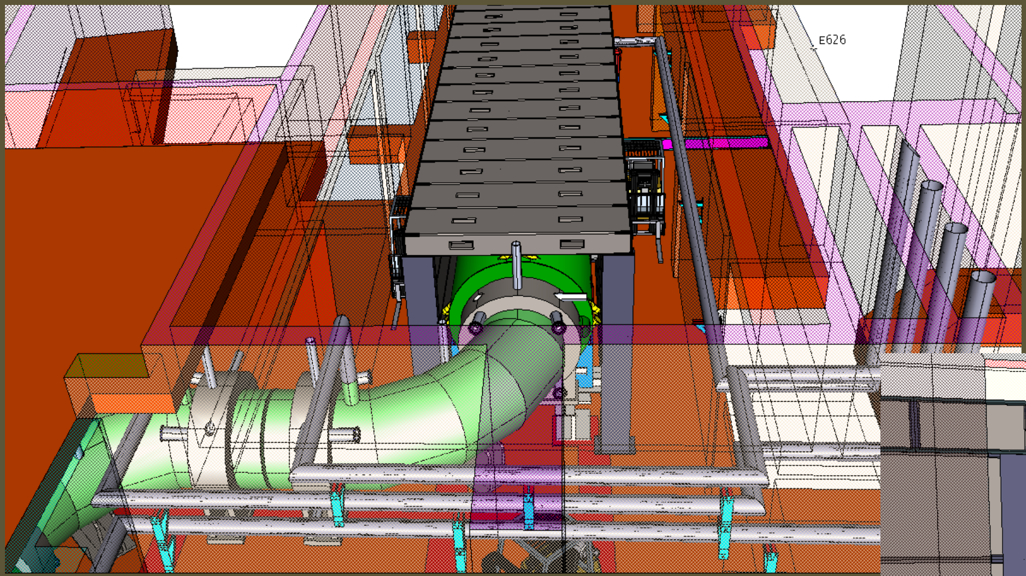
- Have identified a cost effective shielding solution
- Non-trivial optimization required
- Reduces rates of neutrons and photons at CRV to acceptable level

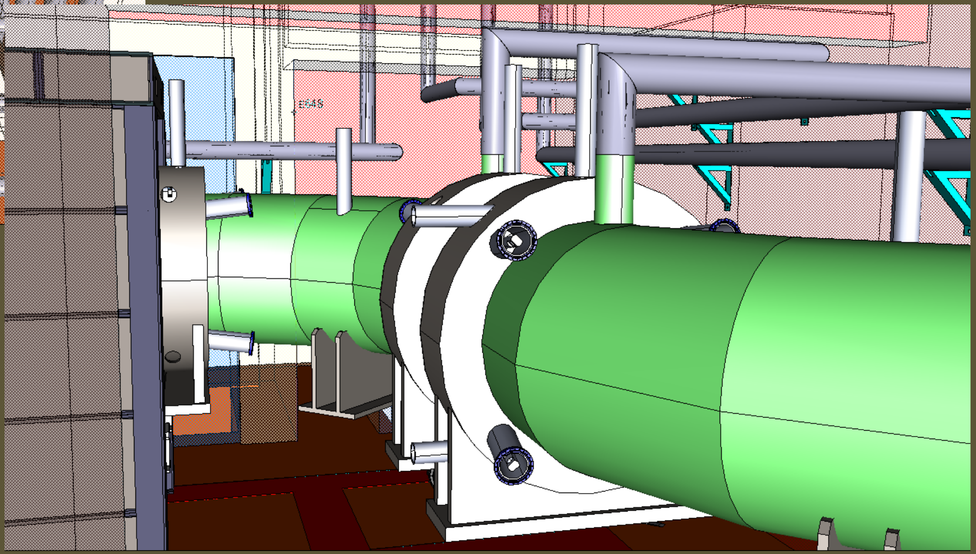
Mu2e Detector Hall

Graphic of proposed Mu2e Detector Hall

- Final Designs completed
  - Have broke ground on Mu2e beamline
  - Will break ground on Detector Hall in early 2015

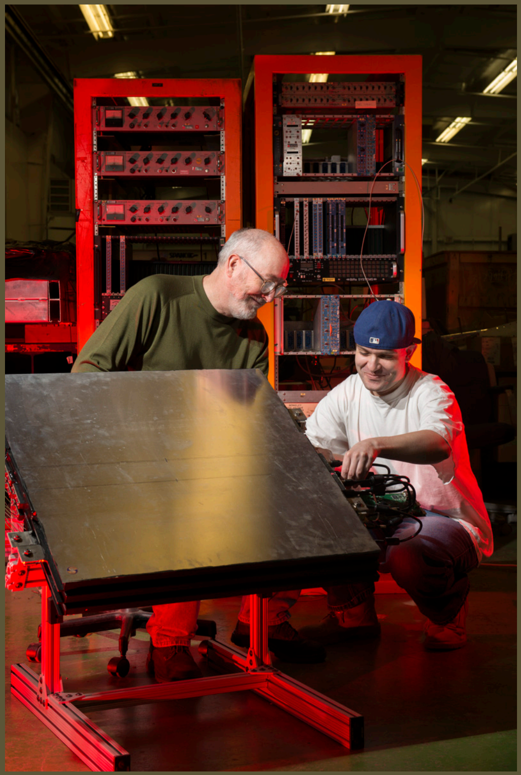
Details, details, details

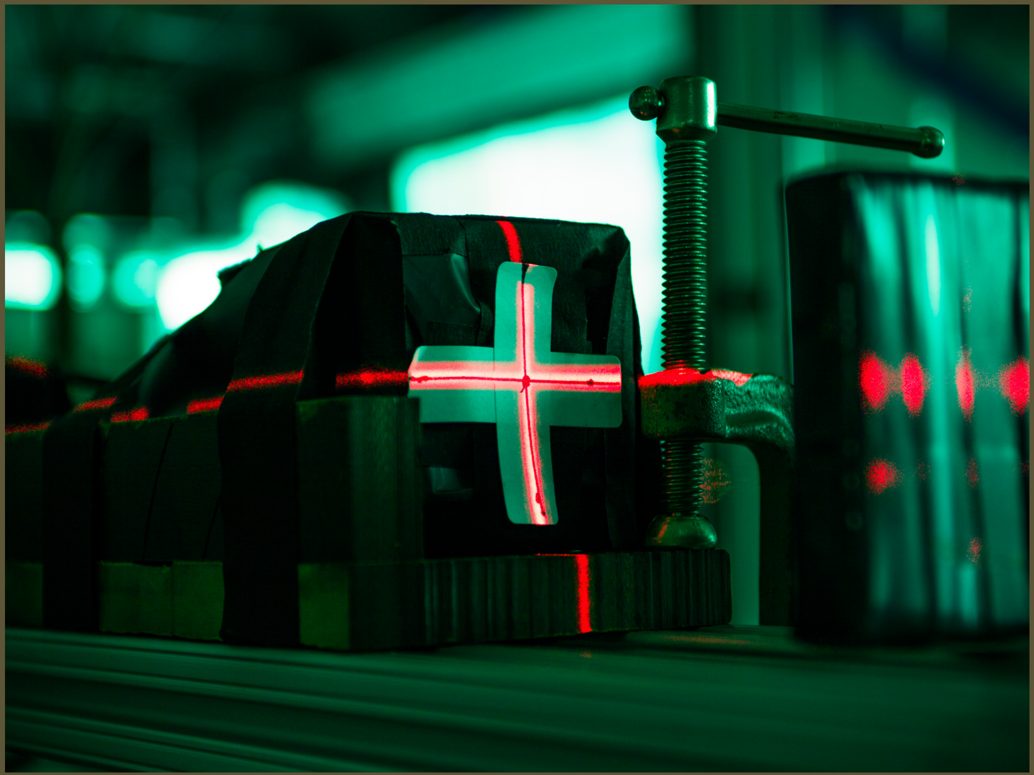




- Working to identify and resolve interface issues

Test Beam Efforts

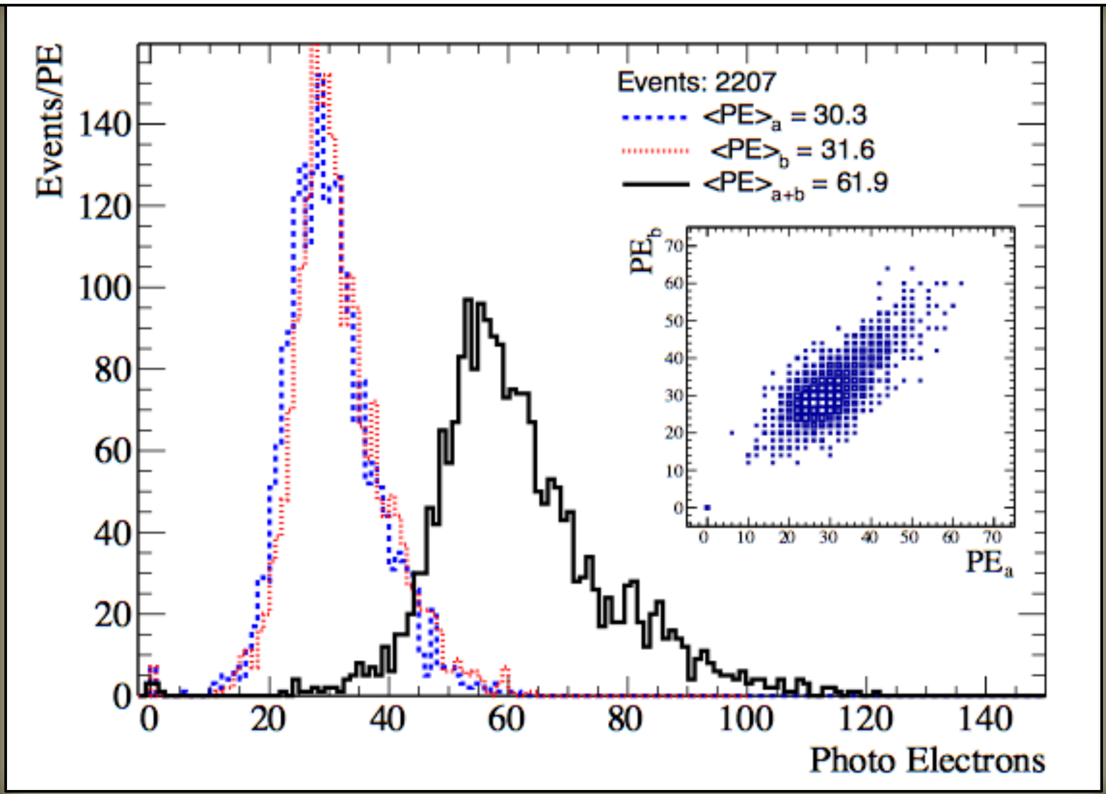




- Cosmic Ray Veto – SiPM, WLS, and component prototype tests
- Upstream Extinction Monitor – conceptual demonstration

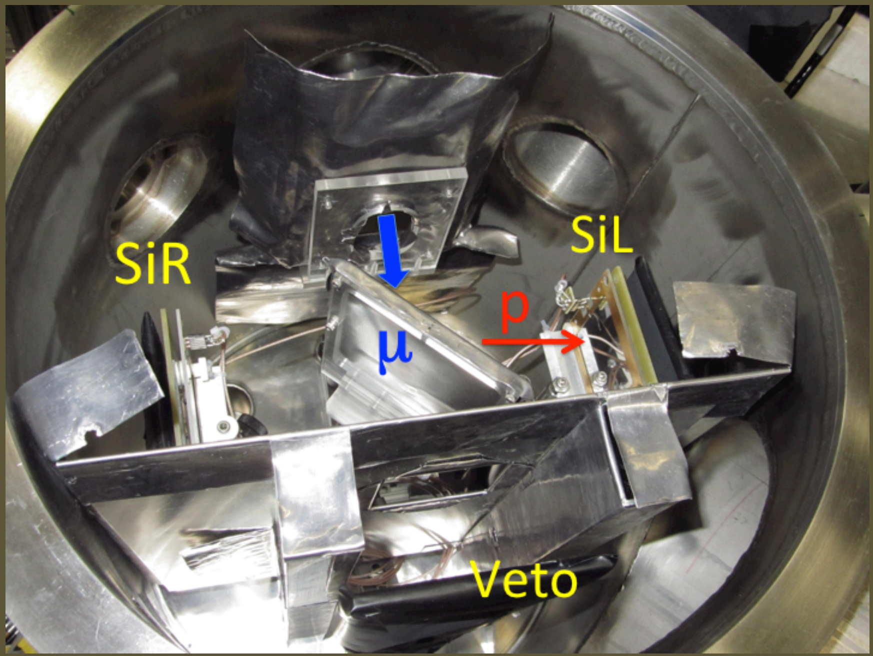
Test Beam – CRV results

Typical light yield from CRV counter prototype – 20 cm from RO end



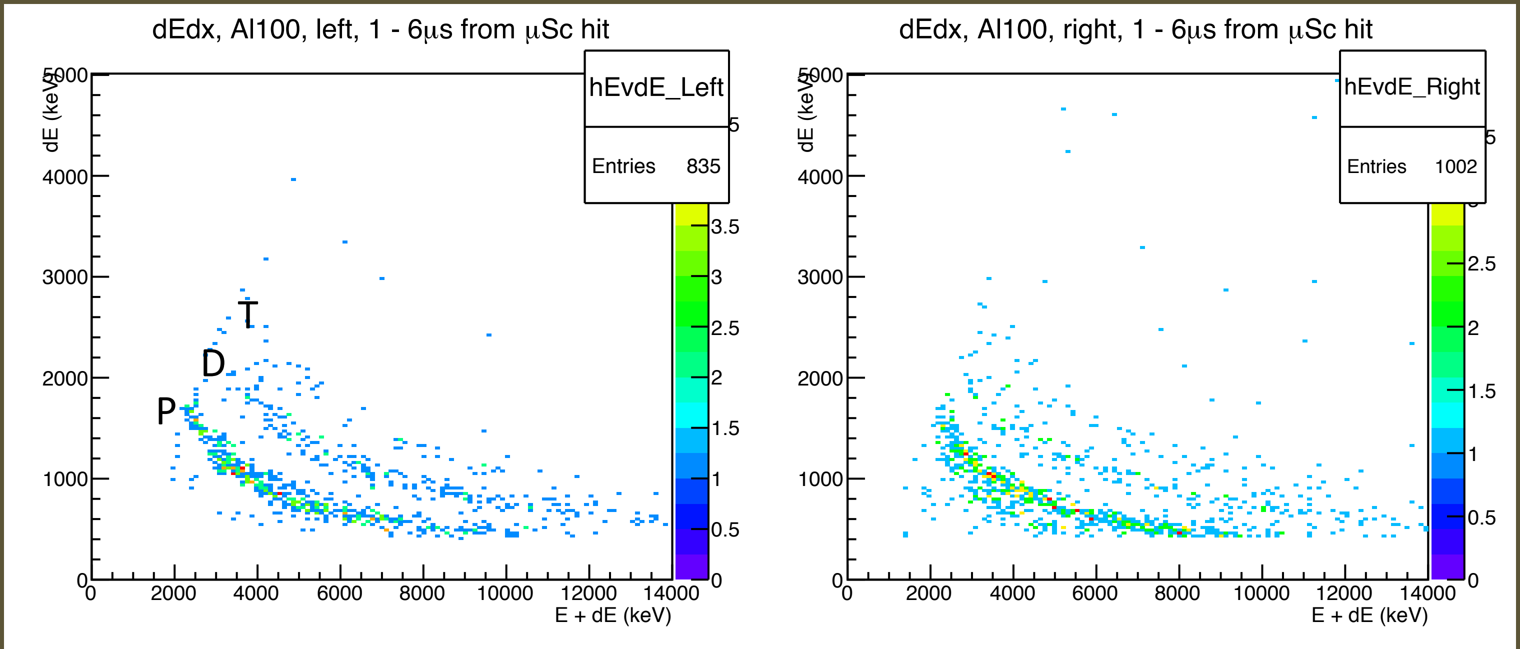
- Achieves veto efficiency >99% at 2.5m from RO
  - want more light to allow for SiPM failure, 10y lifetime
  - will move from 1mm WLS fiber to 1.4 mm

Understanding muon capture



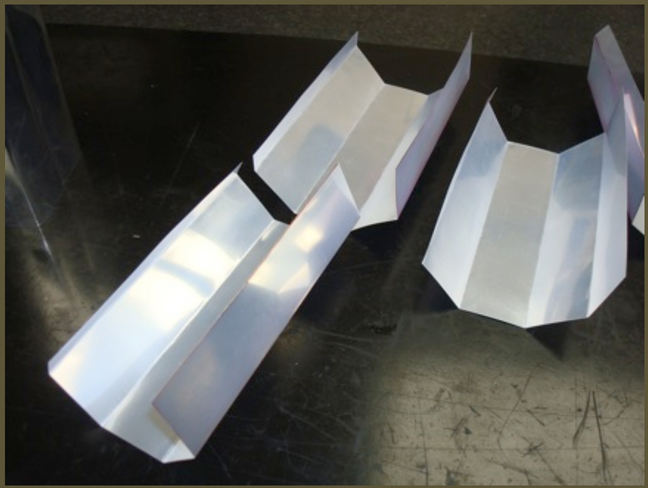
- AlCap – measurement of products of muon captures on aluminum
  - Joint Mu2e/COMET effort
  - Took data Dec 2013, 2nd run in spring 2015

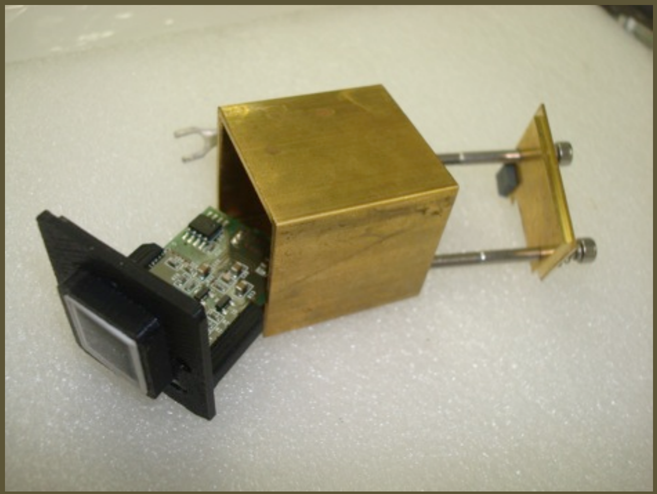
Test Beam – December 2013

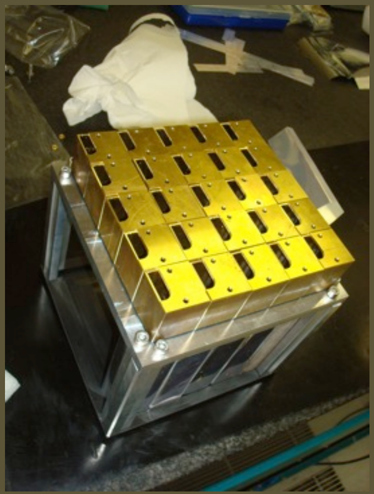


- Preliminary AlCap results
  - Analysis ongoing, but proton, deuteron lines clear

Test Beam Efforts - Calorimeter

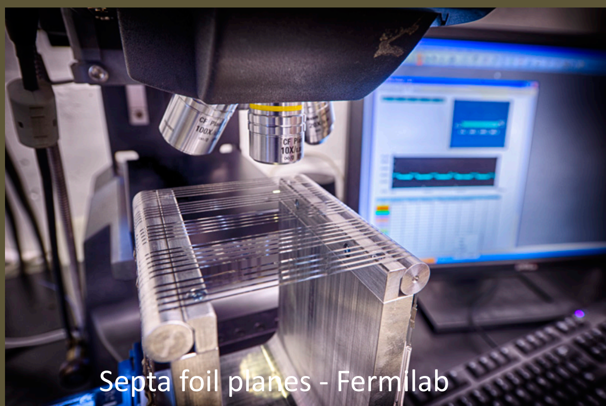




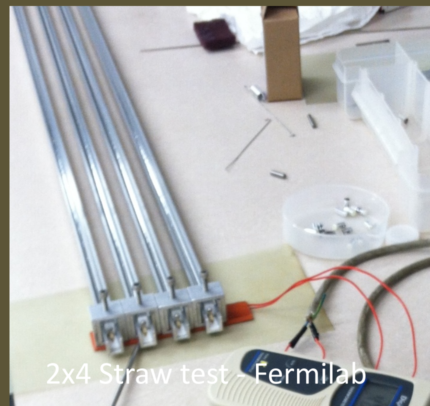


- Test beam (5 -500 MeV e-) in Frascati

Other Mu2e R&D



Septa foil planes - Fermilab



2x4 Straw test - Fermilab

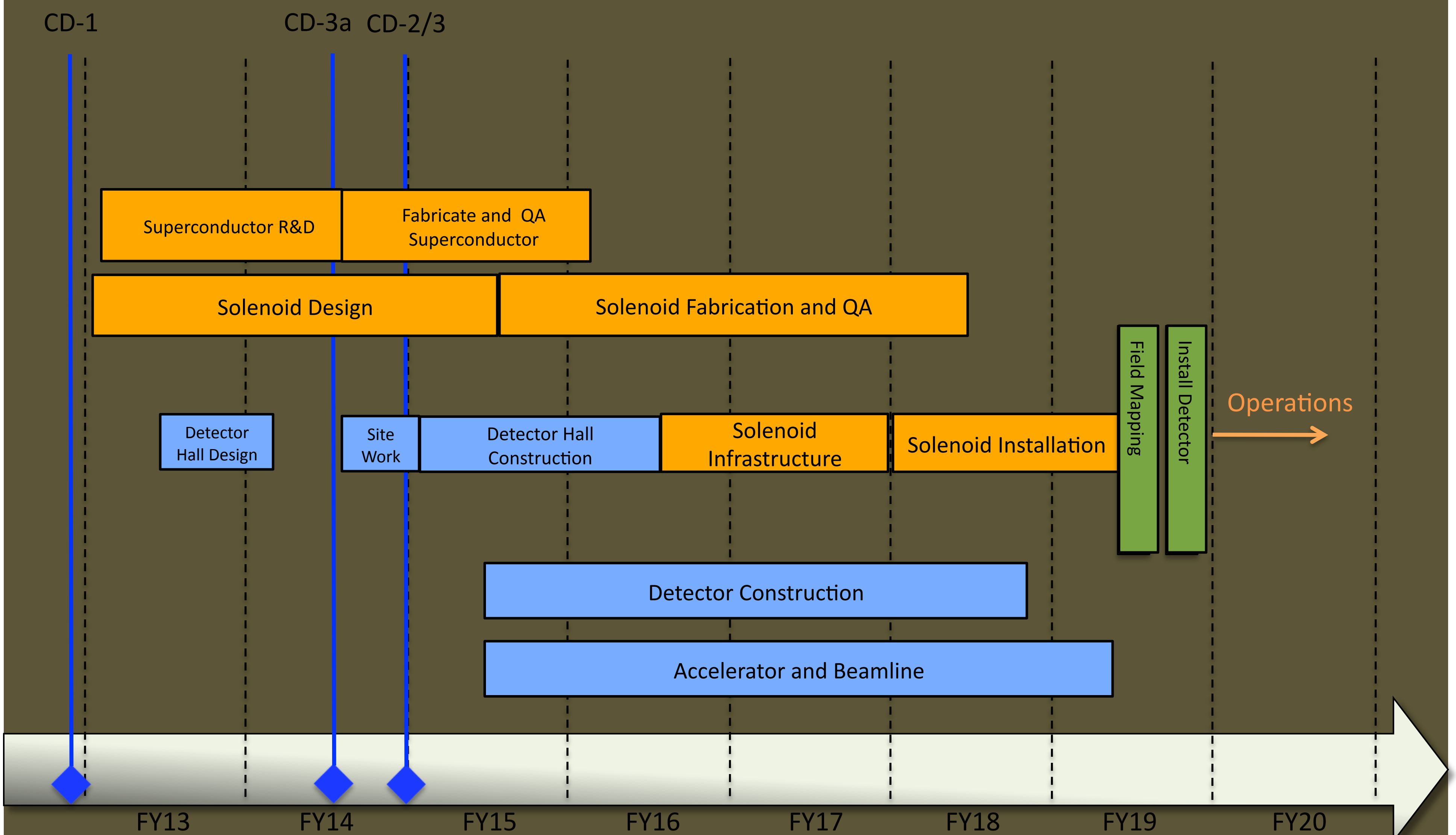
Custom pulsed power supply for fatigue tests on prototype production target - RAL

CRV Manifolds – U.Virginia

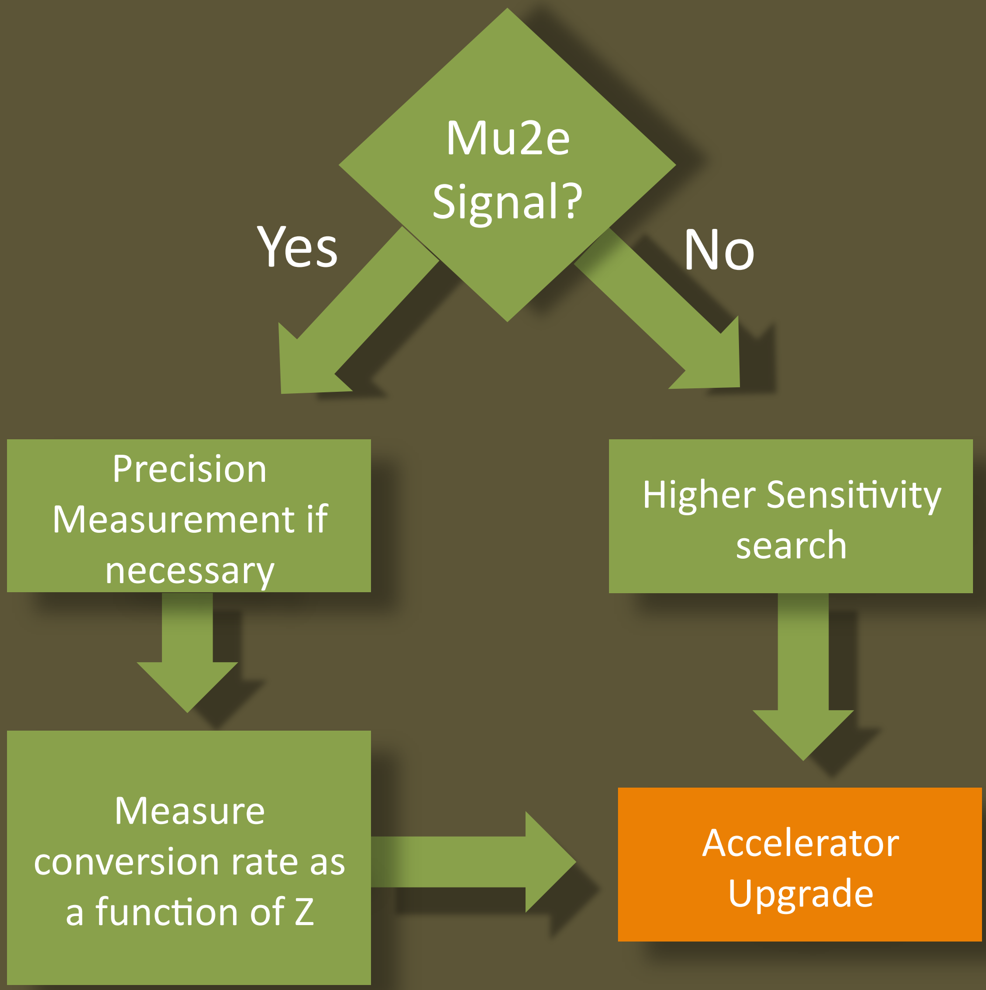
Straw leak test - CUNY

- Active R&D campaign across project

Mu2e Technical Schedule



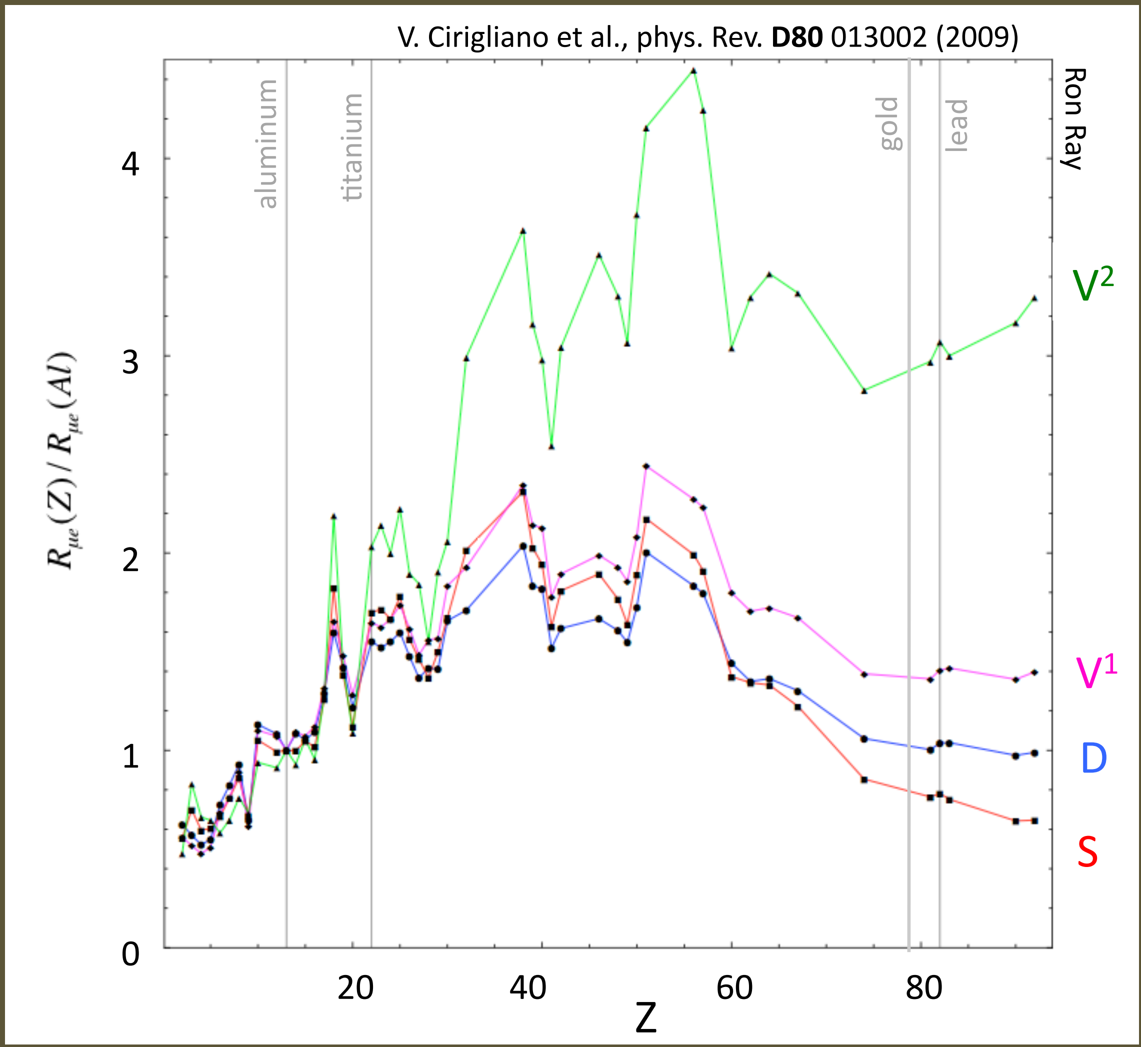
What next?



- 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

$\mu N \rightarrow eN$ vs stopping-target Z

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



Concluding remarks

Summary

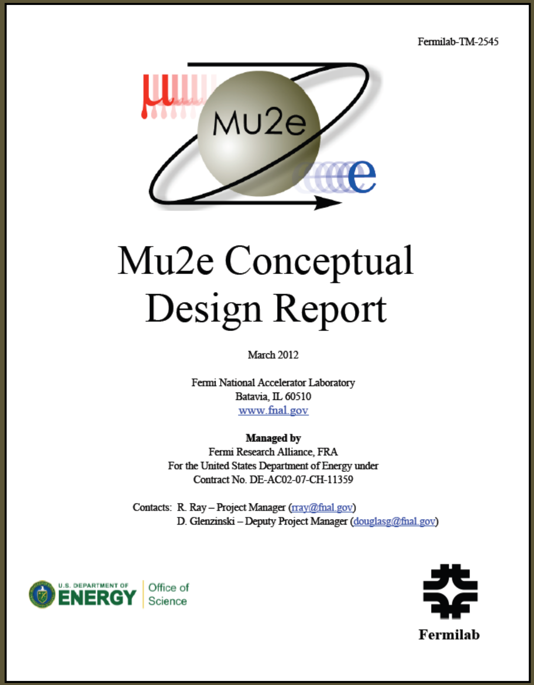
The Mu2e experiment:

- 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
- Has broken ground

Interested in learning more?

- Conceptual Design Report
  - http://arXiv.org/abs/1211.7019

- Experiment web site
  - http://mu2e.fnal.gov



Fermilab-TM-2545

Mu2e

Mu2e Conceptual Design Report

March 2012

Fermi National Accelerator Laboratory
Batavia, IL 60510
www.fnal.gov

Managed by
Fermi Research Alliance, FRA
For the United States Department of Energy under
Contract No. DE-AC02-07-CH-11359

Contacts: R. Ray – Project Manager (rray@fnal.gov)
D. Glenzinski – Deputy Project Manager (douglasg@fnal.gov)

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The Mu2e Collaboration

Mu2e Collaboration, November 2013

- ~150 People, 32 Institutions, 3 Countries

Thank You!

- Mu2e Conceptual Design Report
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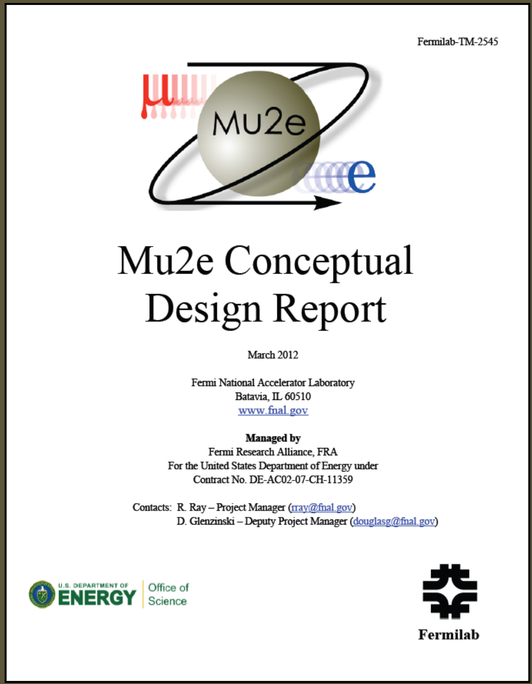

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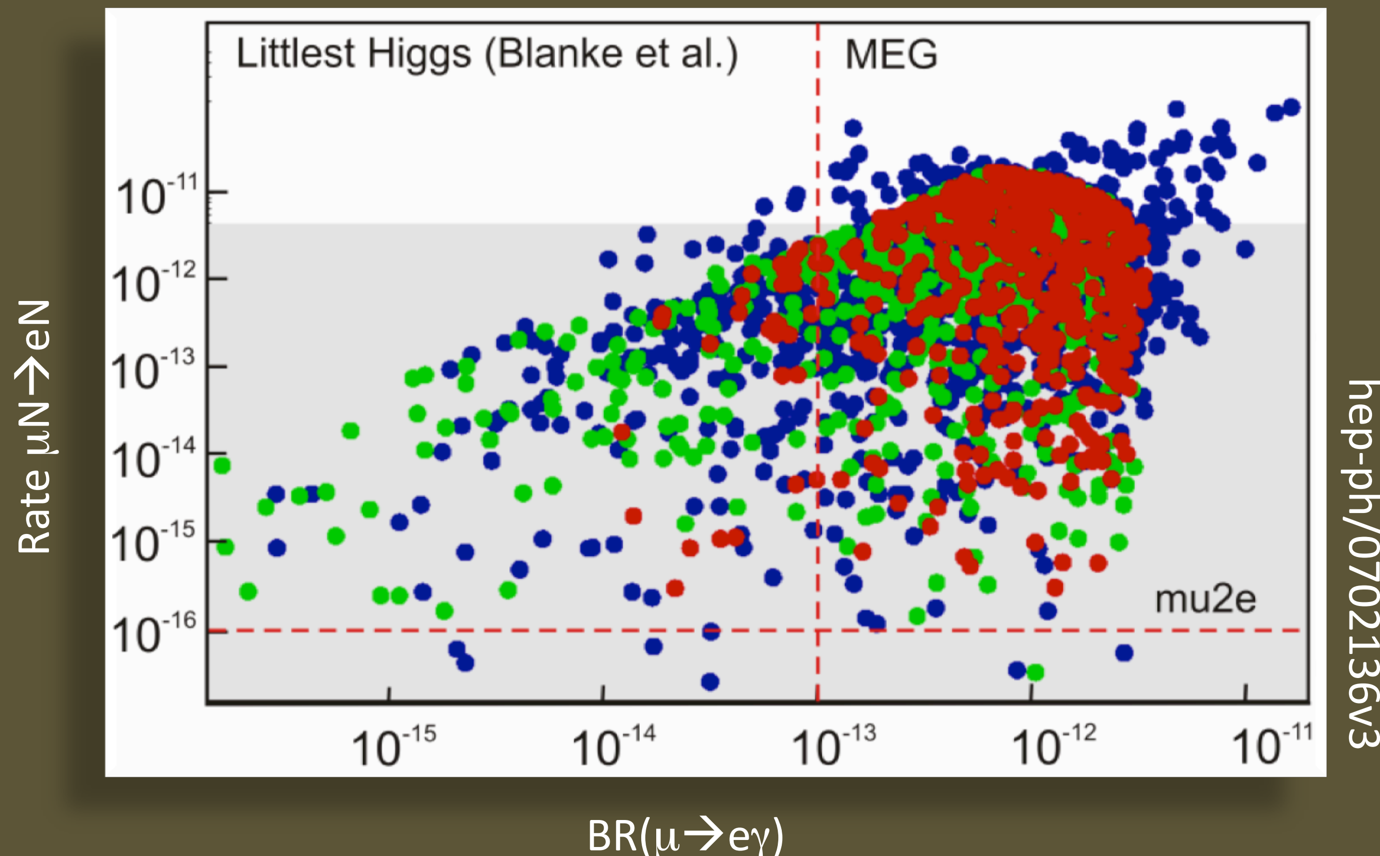
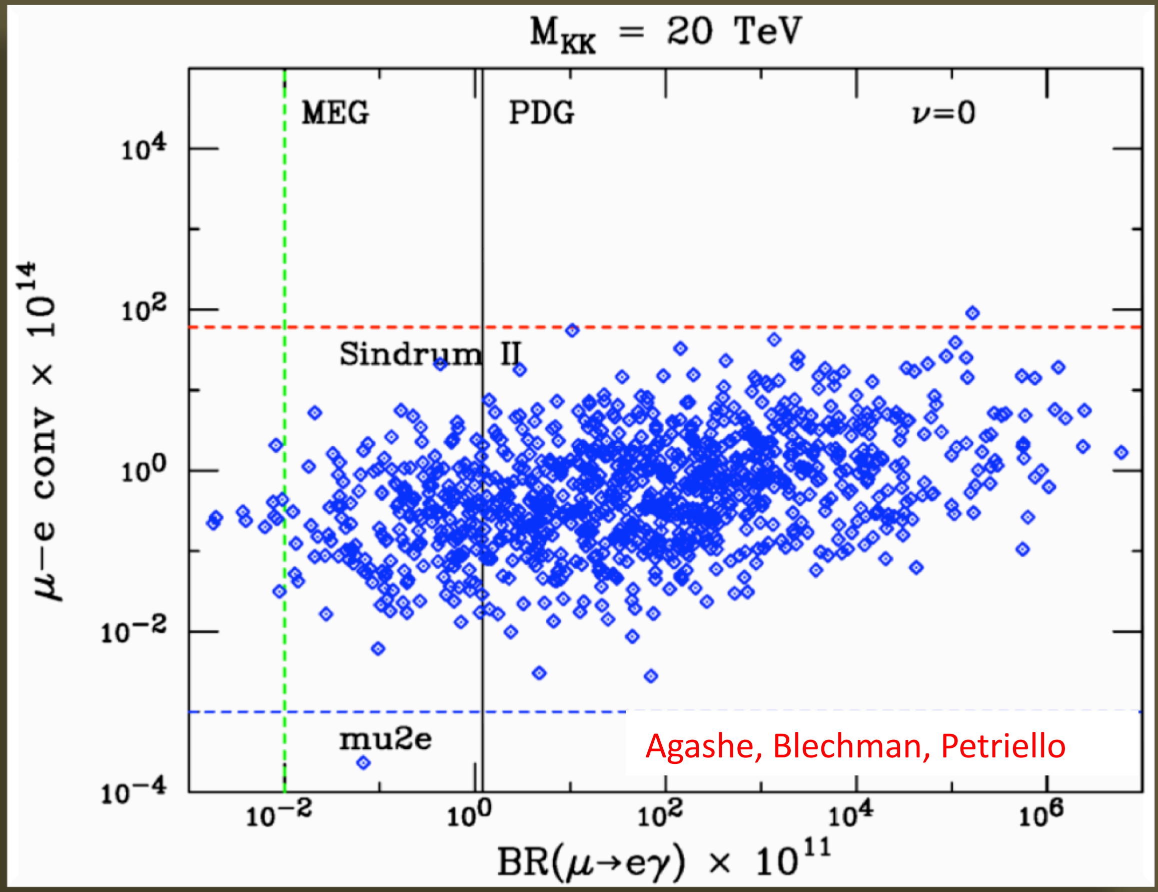
Additional Slides

Mu2e Sensitivity



- Mu2e will cover the entire space

Mu2e Sensitivity

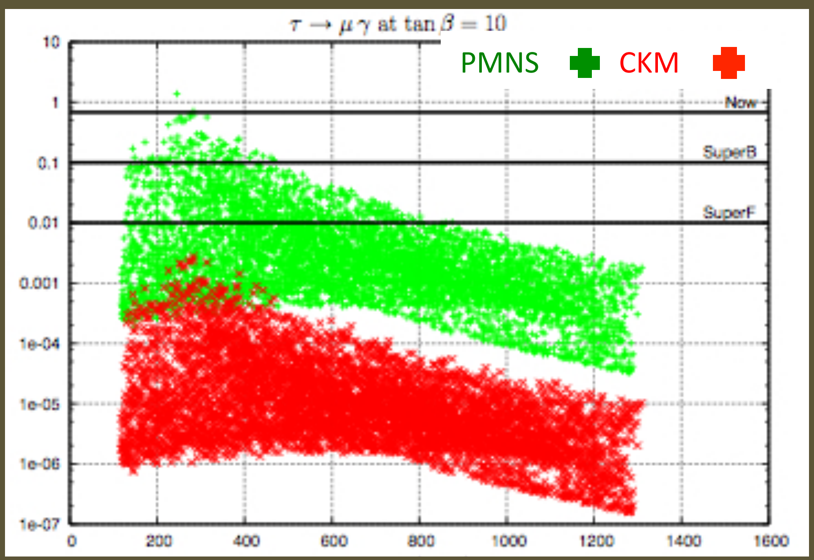


hep-ph/0606021v2

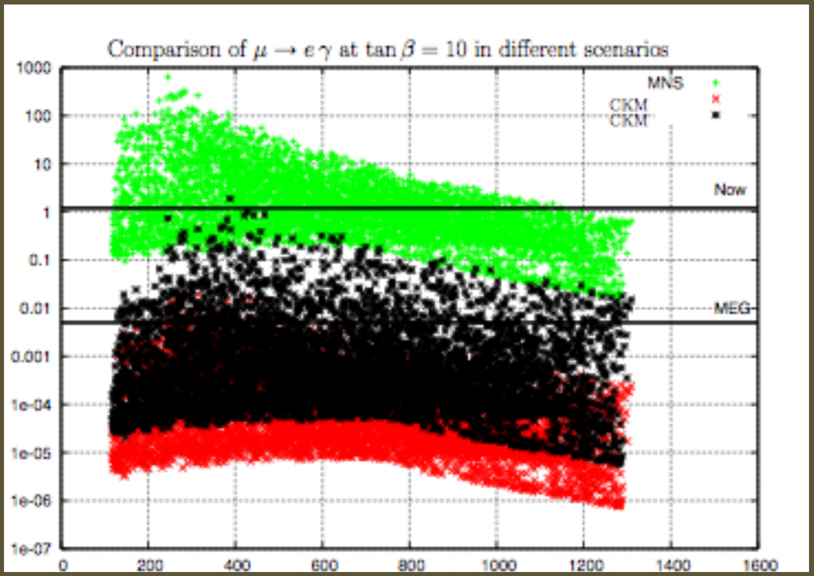
- Mu2e, MEG will each cover entire space

Mu2e Sensitivity

BR(τ→μγ) / 10^{-7}



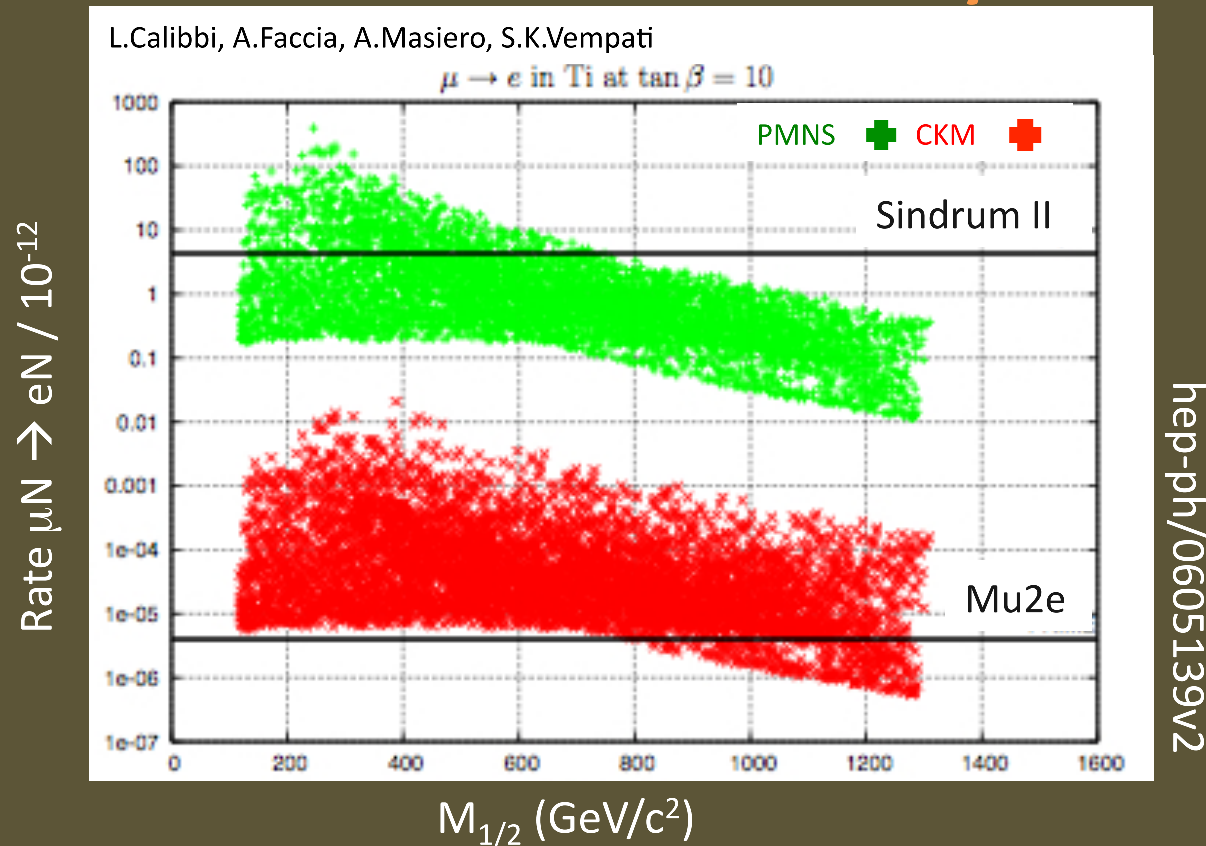
BR(μ→eγ) / 10^{-11}



$M_{1/2}$ (GeV/c^2)

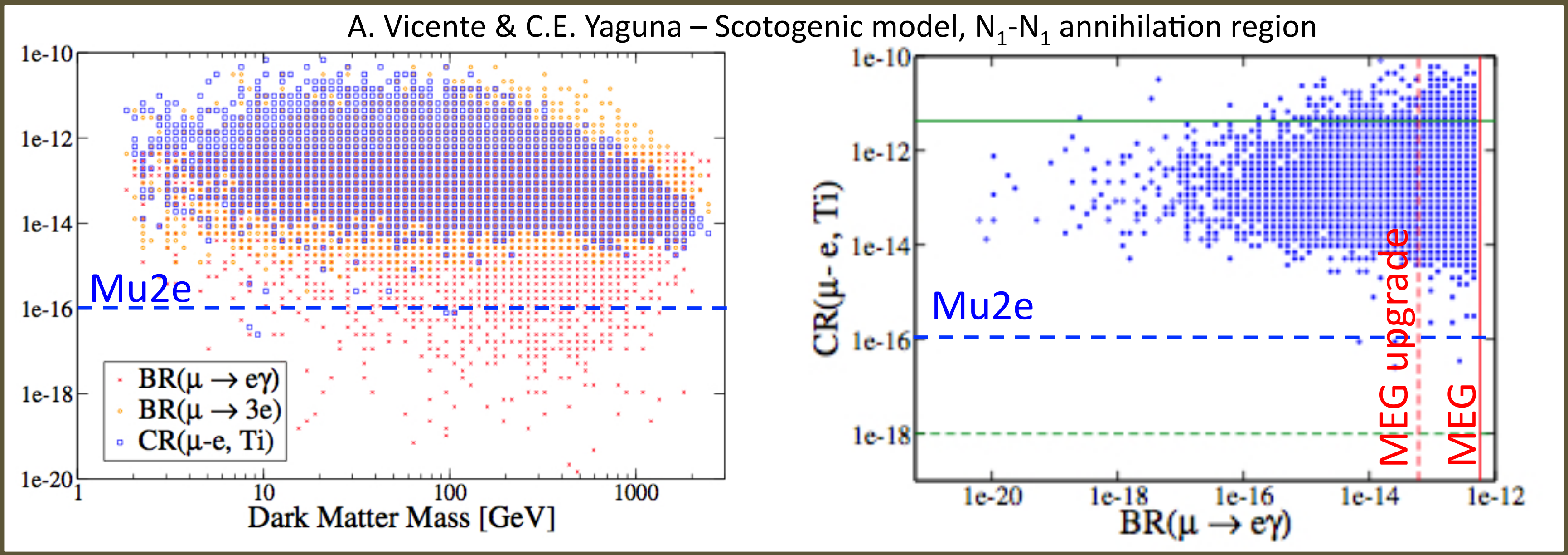
- μ→eγ, τ→μγ will begin to probe this space

Mu2e Sensitivity



- Mu2e will cover (almost) entire space

Mu2e Sensitivity



arXiv: 1412.2545 [hep-ph]

- Mu2e will explore a significant fraction of the parameter space

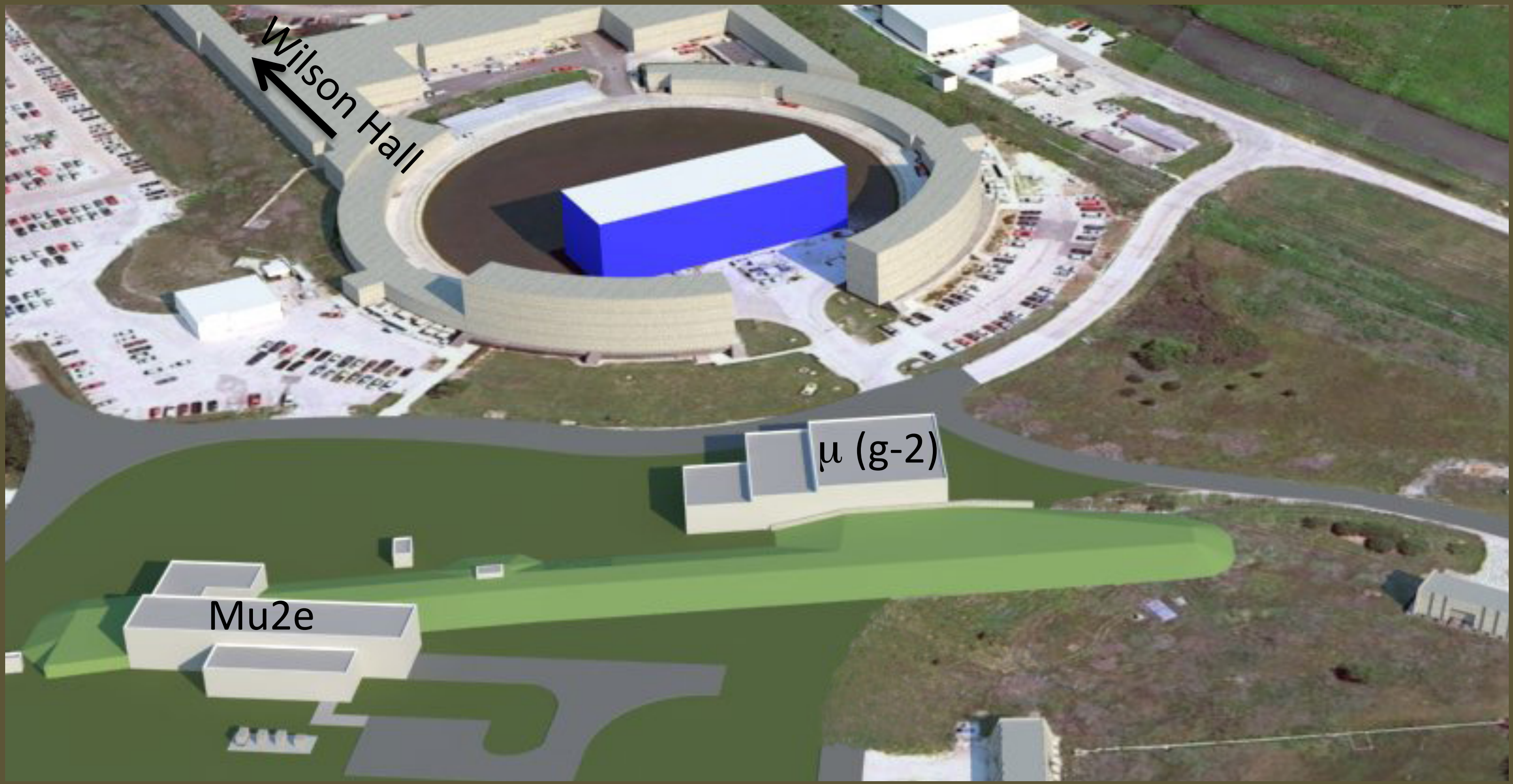
Mu2e Sensitivity

TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME, Super Flavour factory) highlighted in italics.

	SPS 1a		SPS 1b		SPS 2		SPS 3		Future
Process	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	Sensitivity
$\mathrm{BR}(\mu \to e\,\gamma)$	$\mathbf{3.2 \cdot 10^{-14}}$	$\mathbf{3.8 \cdot 10^{-13}}$	$\mathbf{4.0 \cdot 10^{-13}}$	$\mathbf{1.2 \cdot 10^{-12}}$	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
$\mathrm{BR}(\mu \to e\,e\,e\,)$	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
$\mathrm{CR}(\mu \to e \text{ in Ti})$	$\mathit{2.0 \cdot 10^{-15}}$	$\mathit{2.4 \cdot 10^{-14}}$	$\mathit{2.6 \cdot 10^{-15}}$	$\mathit{7.6 \cdot 10^{-14}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{6.7 \cdot 10^{-16}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{8.4 \cdot 10^{-16}}$	$\mathcal{O}(10^{-18})$
$\mathrm{BR}(\tau \to e\,\gamma)$	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to e\,e\,e)$	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to \mu\,\gamma)$	$5.0 \cdot 10^{-11}$	$\mathbf{1.1 \cdot 10^{-8}}$	$7.3 \cdot 10^{-11}$	$\mathbf{1.3 \cdot 10^{-8}}$	$2.9 \cdot 10^{-12}$	$\mathit{7.8 \cdot 10^{-10}}$	$2.7 \cdot 10^{-12}$	$\mathit{6.0 \cdot 10^{-10}}$	$\mathcal{O}(10^{-9})$
$\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

- These are SuSy benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/SuprB
- All of these will be observable by Mu2e

Mu2e at Fermilab



- Mu2e will be located together with Muon (g-2) just west of Wilson Hall.

Selection Requirements

Parameter	Requirement
Track quality and background rejection criteria	
Kalman Fit Status	Successful Fit
Number of active hits	$N_{active} \geq 25$
Fit consistency	$\chi 2$ consistency > $2x10^{-3}$
Estimated reconstructed momentum uncertainty	$\sigma_p < 250$ keV/c
Estimated track t_0 uncertainty	$\sigma_t < 0.9$ nsec
Track t_0 (livegate)	700 ns < t_0 < 1695 ns
Polar angle range (pitch)	$45° < \theta < 60°$
Minimum track transverse radius	-80 mm < d_0 < 105 mm
Maximum track transverse radius	450 mm < d_0+2/ω < 680 mm
Track momentum	103.75 < p < 105.0 MeV/c
Calorimeter matching and particle identification criteria	
Track match to a calorimeter cluster	$E_{cluster}$ > 10 MeV $\chi 2$ (track-calo match) < 100
Ratio of cluster energy to track momentum	E/P < 1.15
Difference in track t_0 to calorimeter t_0	$\Delta t = \|t_{track} - t_{calo}\| < 3$ ns from peak
Particle identification	$\log(L(e)/L(\mu)) < 1.5$

- Full set of selection criteria employed to estimate backgrounds and sensitivity reported in TDR (Summer 2014)

Estimated background yields

Table 3.4 A summary of the estimated background yields using the selection criteria of Section 3.5.3. The total run time and corresponding number of protons on target are provided in Table 3.1. An extinction of 10^{-10}, a cosmic ray inefficiency of 10^{-4}, and particle-identification with a muon-rejection of 200 is used. 'Intrinsic' backgrounds are those that scale with the number of stopped muons, 'Late Arriving' backgrounds are those with a strong dependemce on the extinction, and 'Miscellaneous' backgrounds are those that don't fall into the previous two categories.

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.20 ± 0.09
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	< 0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm < 0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.096 ± 0.020
	Total	0.37 ± 0.10

Single event sensitivity = (2.87+0.35-0.29) x 10^{-17}

(goal = 2.4 x 10^{-17})

Systematic Uncertainties

Effect	Uncertainty in DIO background yield	Uncertainty in CE single-event-sensitivity ($\times 10^{-17}$)
MC Statistics	±0.02	±0.07
Theoretical Uncertainty	±0.04	-
Tracker Acceptance	±0.002	±0.03
Reconstruction Efficiency	±0.01	±0.15
Momentum Scale	+0.09, -0.06	±0.07
μ-bunch Intensity Variation	±0.007	±0.1
Beam Flash Uncertainty	±0.011	±0.17
μ-capture Proton Uncertainty	±0.01	±0.016
μ-capture Neutron Uncertainty	±0.006	±0.093
μ-capture Photon Uncertainty	±0.002	±0.028
Out-Of-Target μ Stops	±0.004	±0.055
Degraded Tracker	-0.013	+0.191
Total (in quadrature)	+0.10, -0.08	+0.35, -0.29

- Evaluated for all background sources

Mu2e Proton Timing

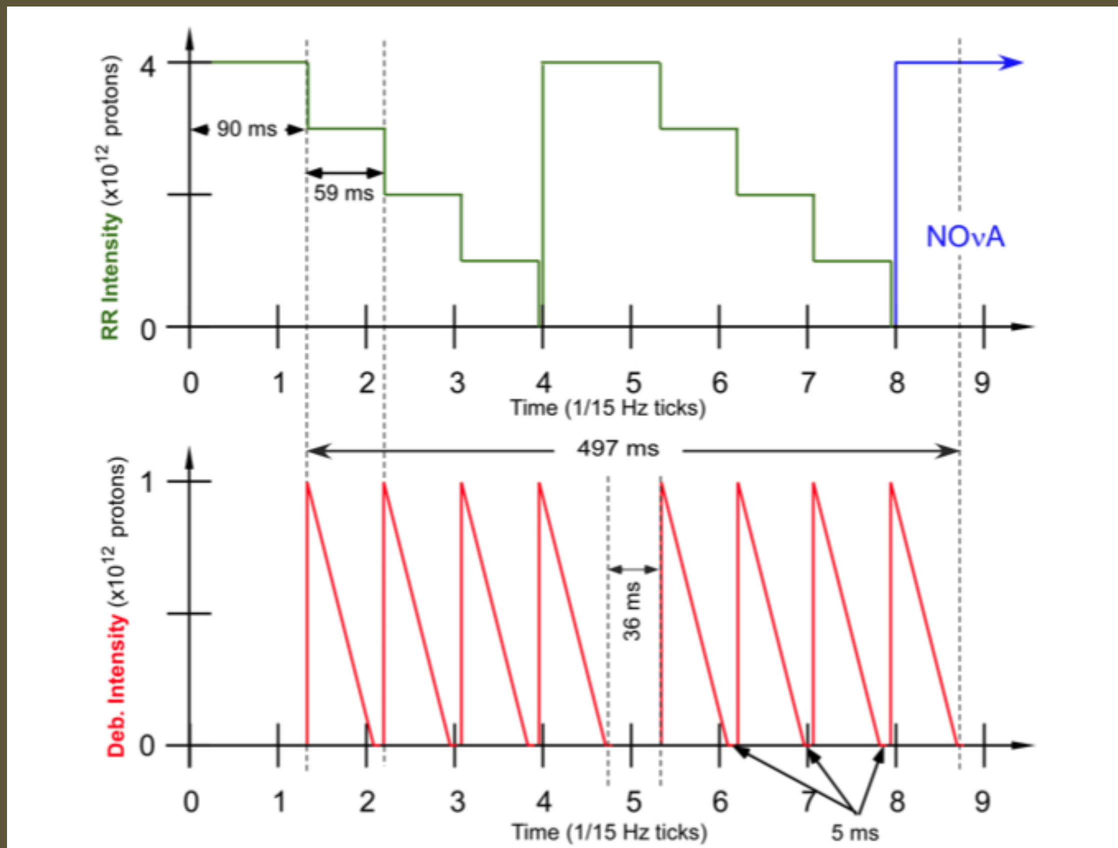
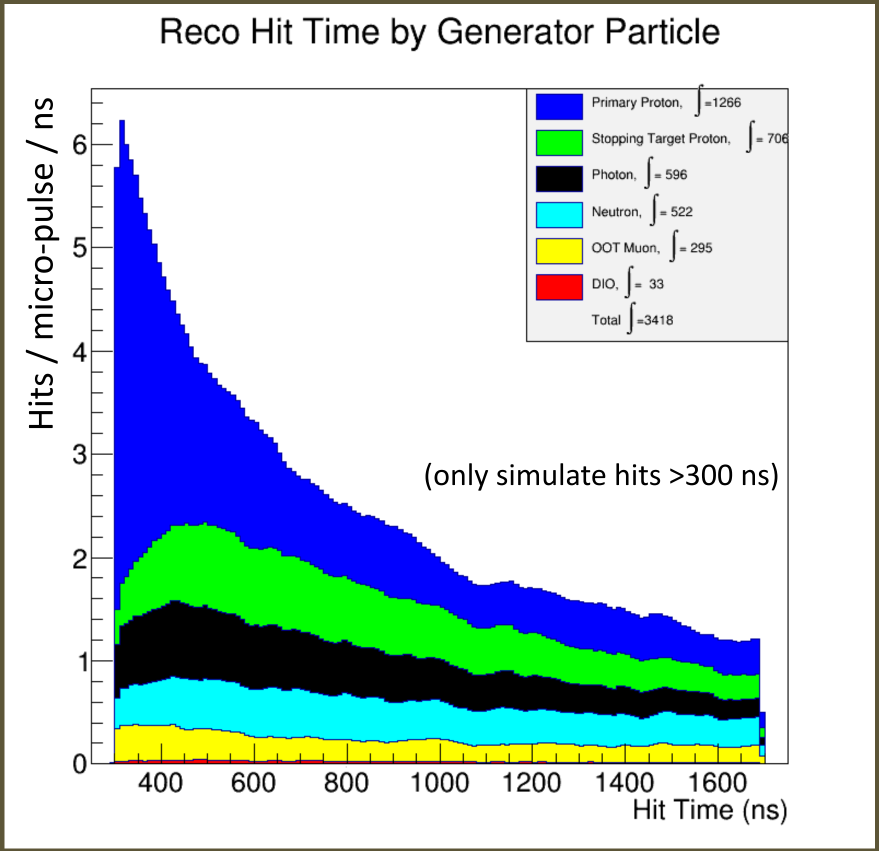


Figure 5.4. This figure shows the first eight Booster ticks of a Main Injector cycle. Proton batches are injected into the Recycler at the beginning of the cycle and again at the fourth tick. After each injection, the beam is bunched with 2.5 MHz RF and extracted one bunch at a time.

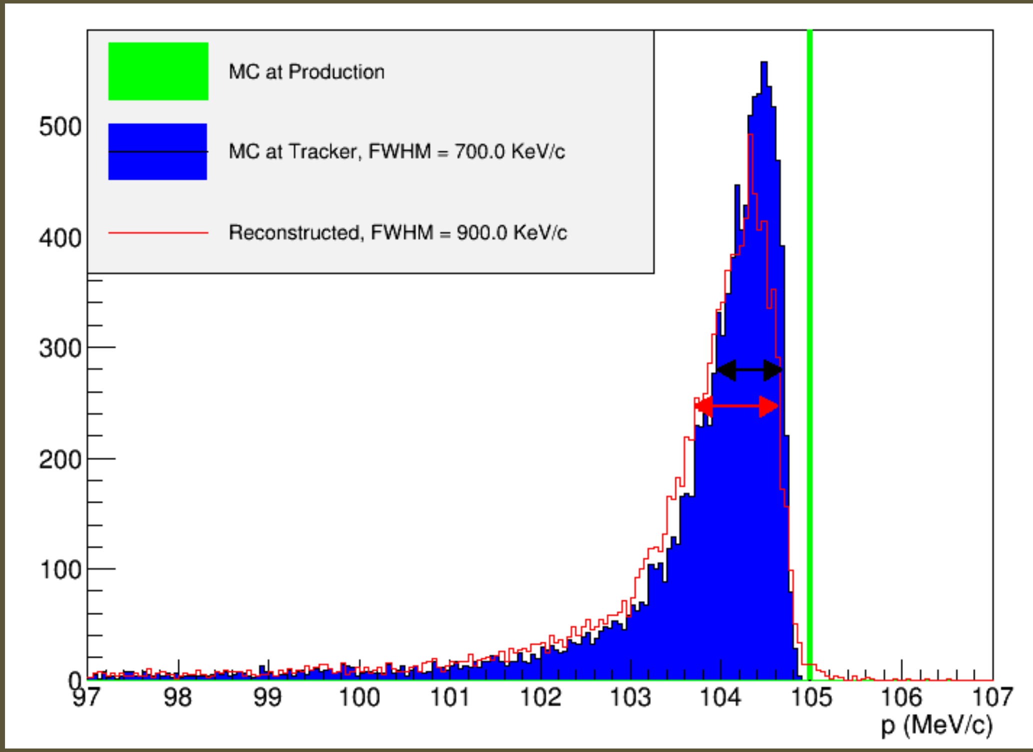
- Mu2e will run simultaneously with NOvA

Tracker Occupancy



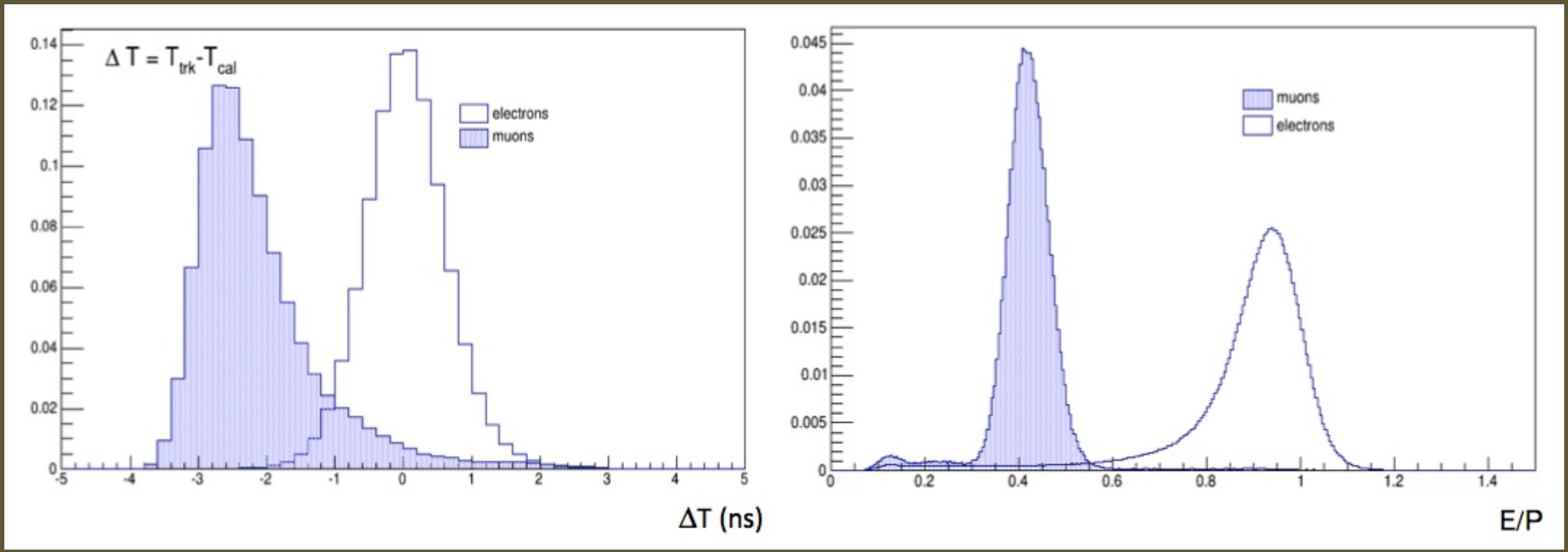
- Accidental occupancy from beam flash, μ capture products, out-of-target μ stops, etc.

Signal Momentum Spectrum



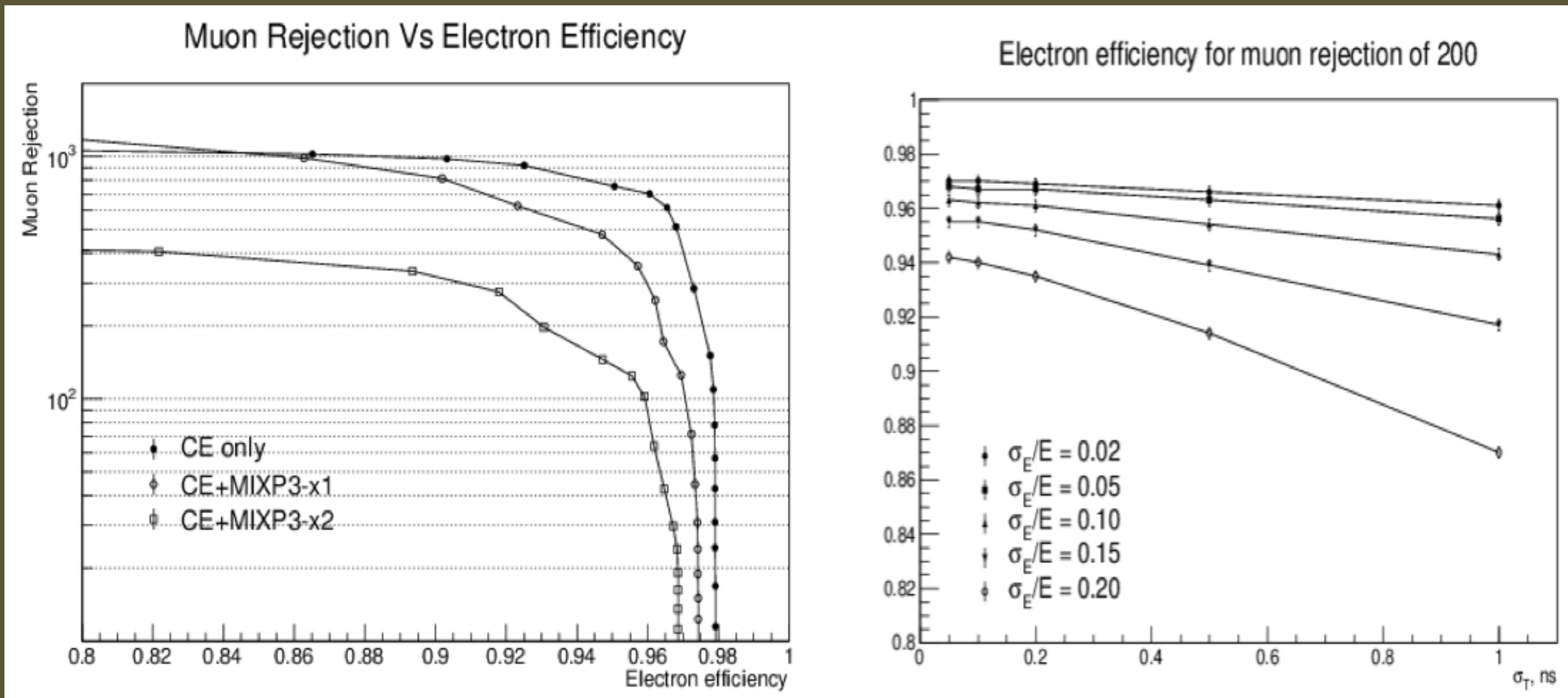
- Smearing dominated by interactions in (neutron/ proton) absorbers upstream of tracker

Calorimeter Particle ID



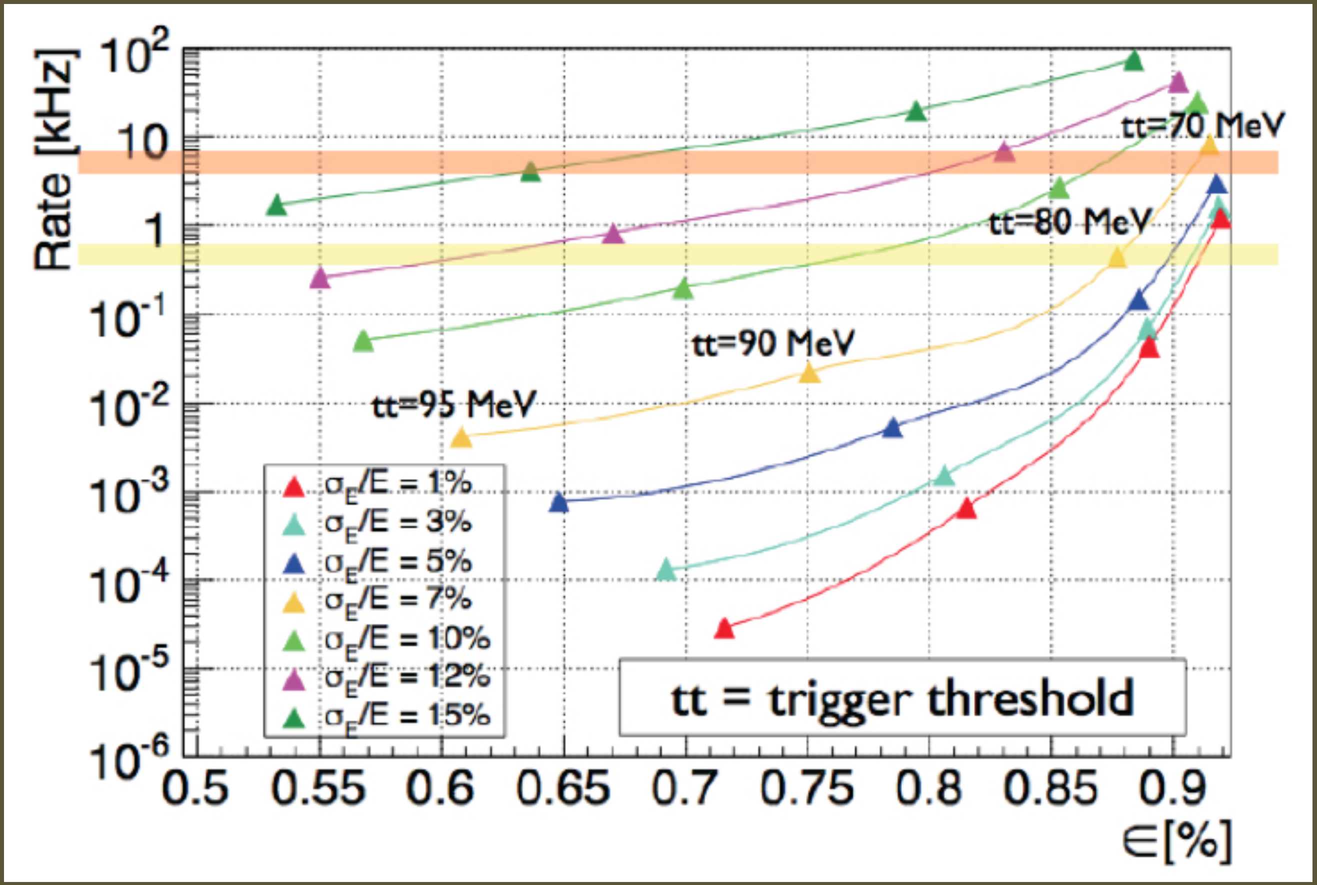
- Electrons and muons well separated

Calorimeter Particle ID



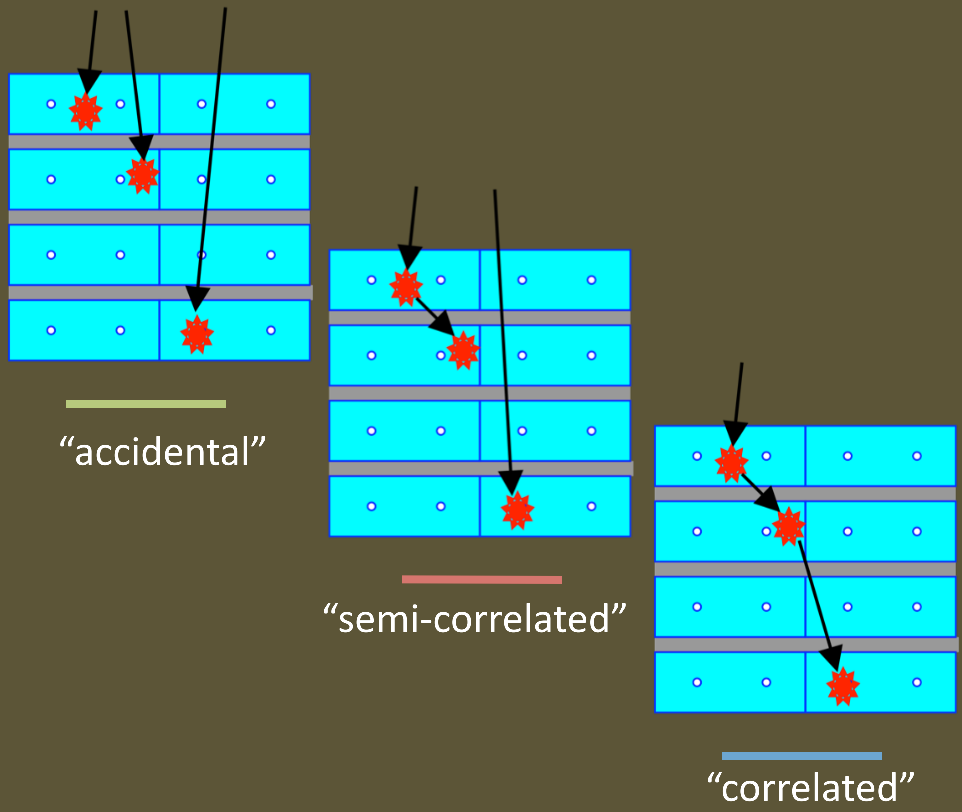
- Combine TOF and E/P information in LLR
  - 96% electron efficiency for muon rejection x200

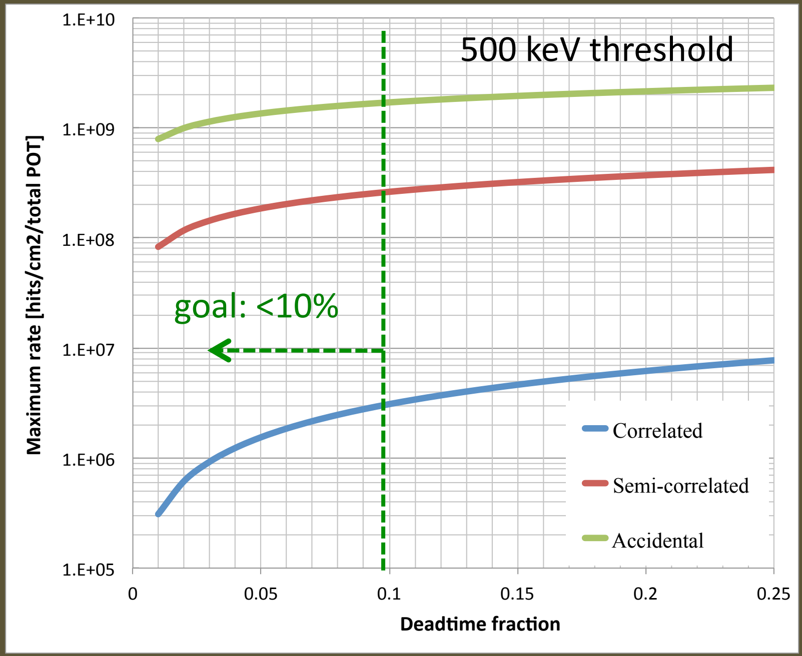
Calorimeter as fast trigger



- To achieve required reduction with high efficiency requires σ_E/E ~ 10% or better

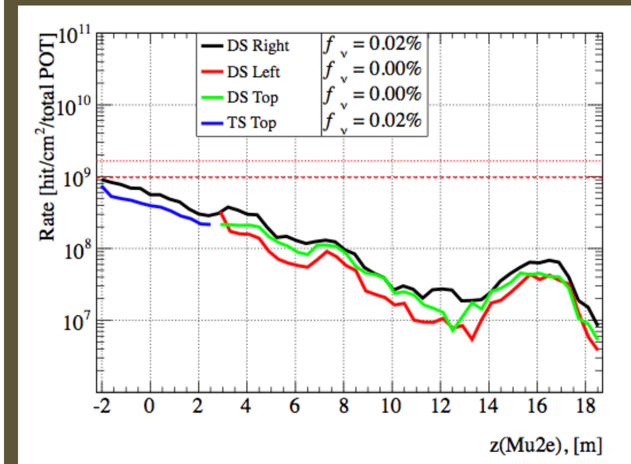
False vetoes in CRV



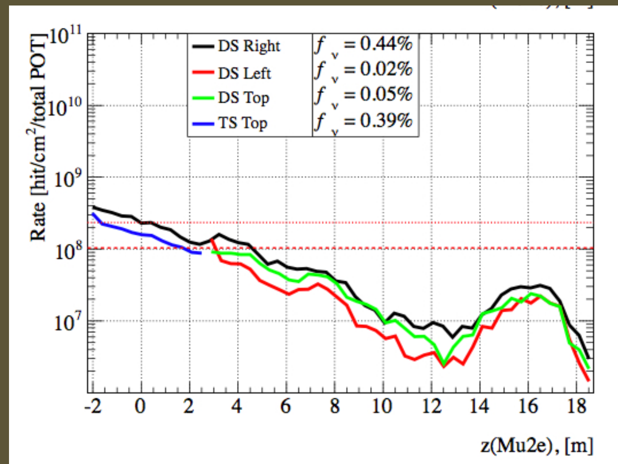


- We need to understand contributions from accidentals and correlated-accidentals
  - For neutrons and photons as a function of time, energy, timing resolution, and read-out threshold

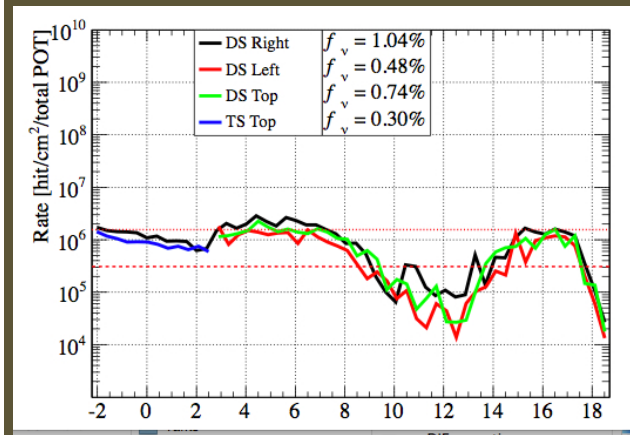
Estimated dead time from CRV vetos – dominated by n/γ background



accidental



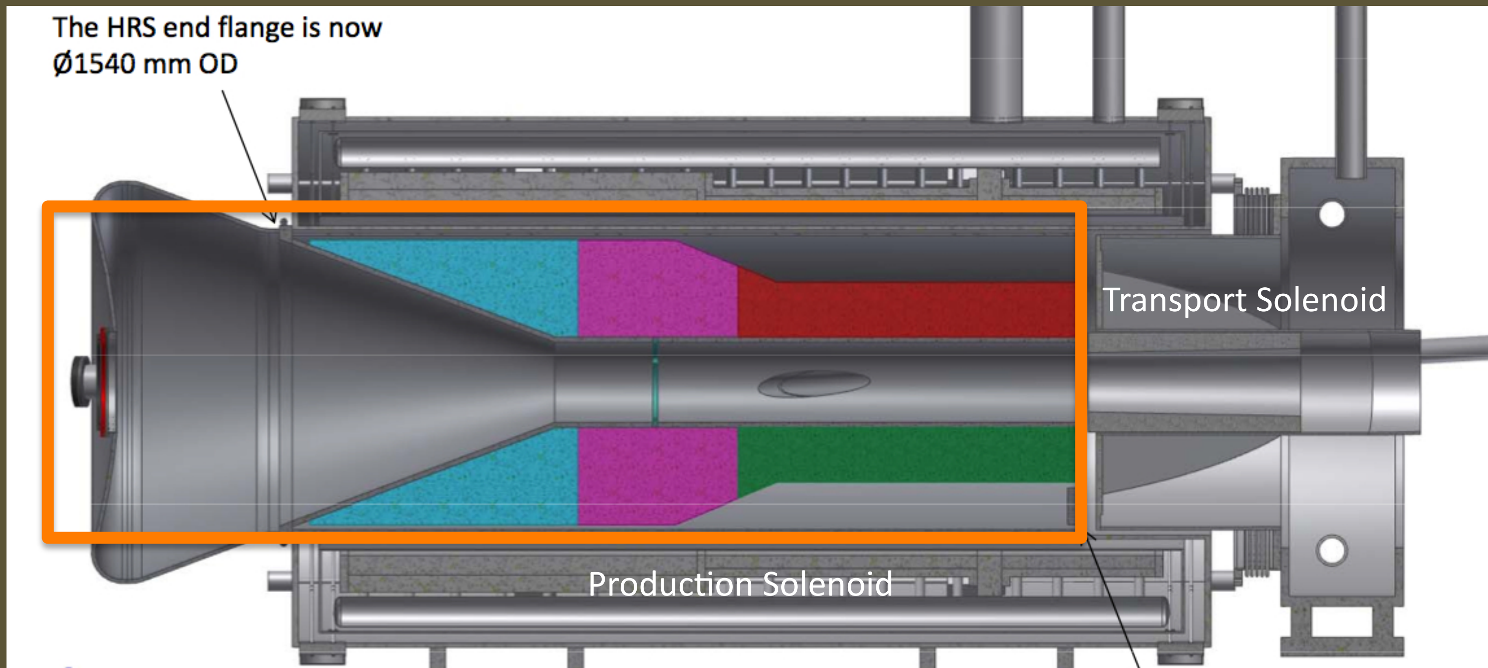
semi-correlated



correlated

- Total dead time from neutron/photon "noise" = 5%
  - For 500 keV readout threshold
  - Increasing to 1 MeV reduces to 2%
  - Cross-check with a separate physics generator (MARS) yields dead time within 50%

PS Heat and Radiation Shield



- Must protect production solenoid from heat and radiation deposits from proton beam

Epilogue

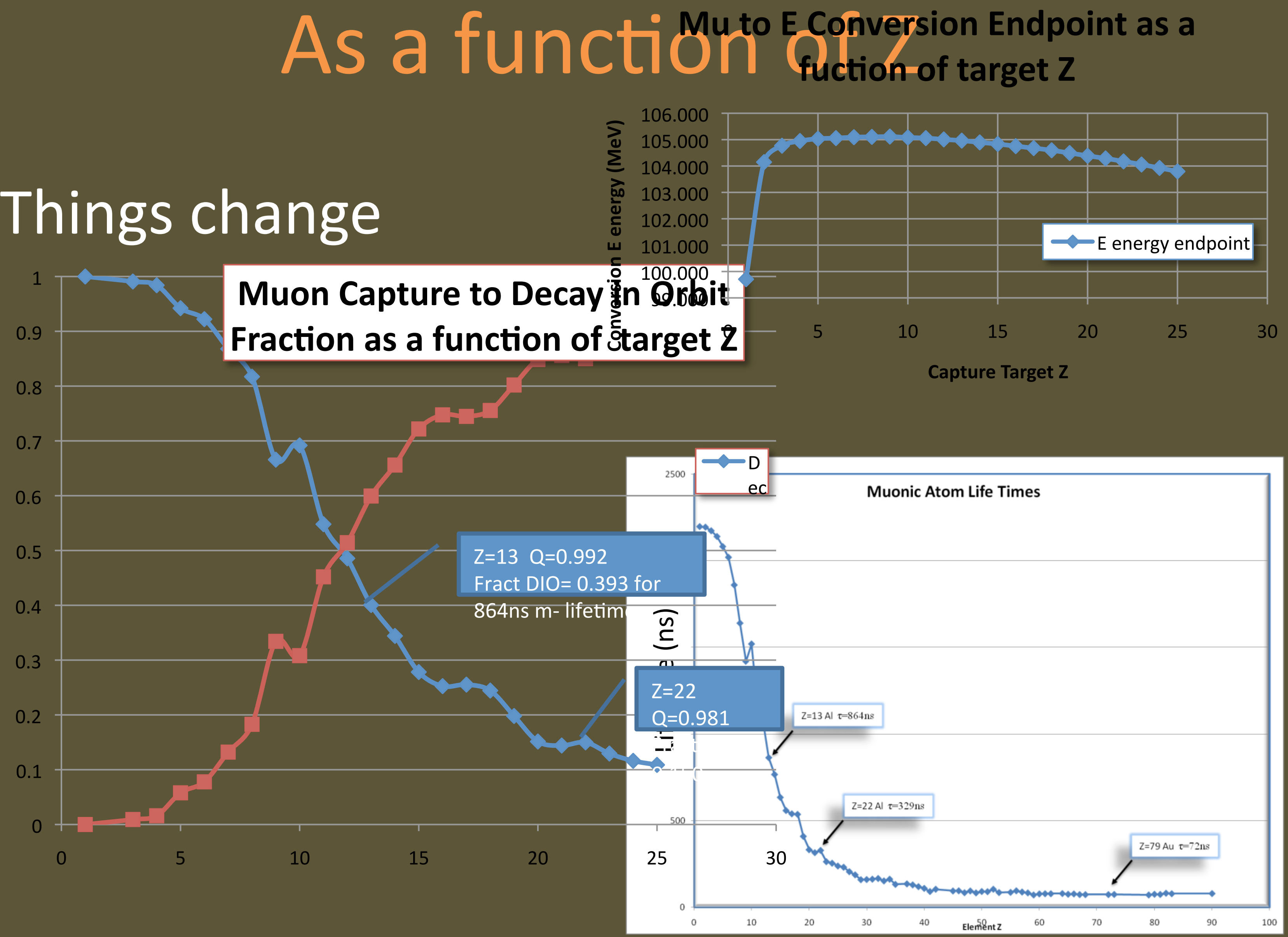
- High Energy Physics is at a crossroads
  - We know that the Standard Model is incomplete
  - We have lots of ideas about what a more complete model might look like
  - … but we have no idea which is the right one

Epilogue

Fermilab's Mu2e experiment is important because it is designed to discover which direction is the right one

As a function of Z

- Things change



Flavor Violation

- We've known for a long time that quarks mix → (Quark) Flavor Violation
  - Mixing strengths parameterized by CKM matrix
- In last 15 years we've come to know that neutrinos mix → Lepton Flavor Violation (LFV)
  - Mixing strengths parameterized by PMNS matrix
- Why not charged leptons?
  - Charged Lepton Flavor Violation (CLFV)