The Mu2e Experiment at Fermilab

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Introduction

- Mu2e experiment is a search for Charged Lepton Flavor Violation (CLFV) via the coherent conversion of $\mu^- N \rightarrow e^- N$
- In wide array of New Physics models CLFV processes occur at rates we can observe with next generation experiments
- “Phase-I” experiment uses current proton source at Fermilab to achieve world’s best sensitivity
  - Further improvements possible in “Phase-II” using Project-X
- Target sensitivity makes challenging experimental demands
  - Goal: <0.5 events background in 2 years of running
  - Goal: Single-event-sensitivity of 2×10^{-17}

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 $\mu N \rightarrow eN$

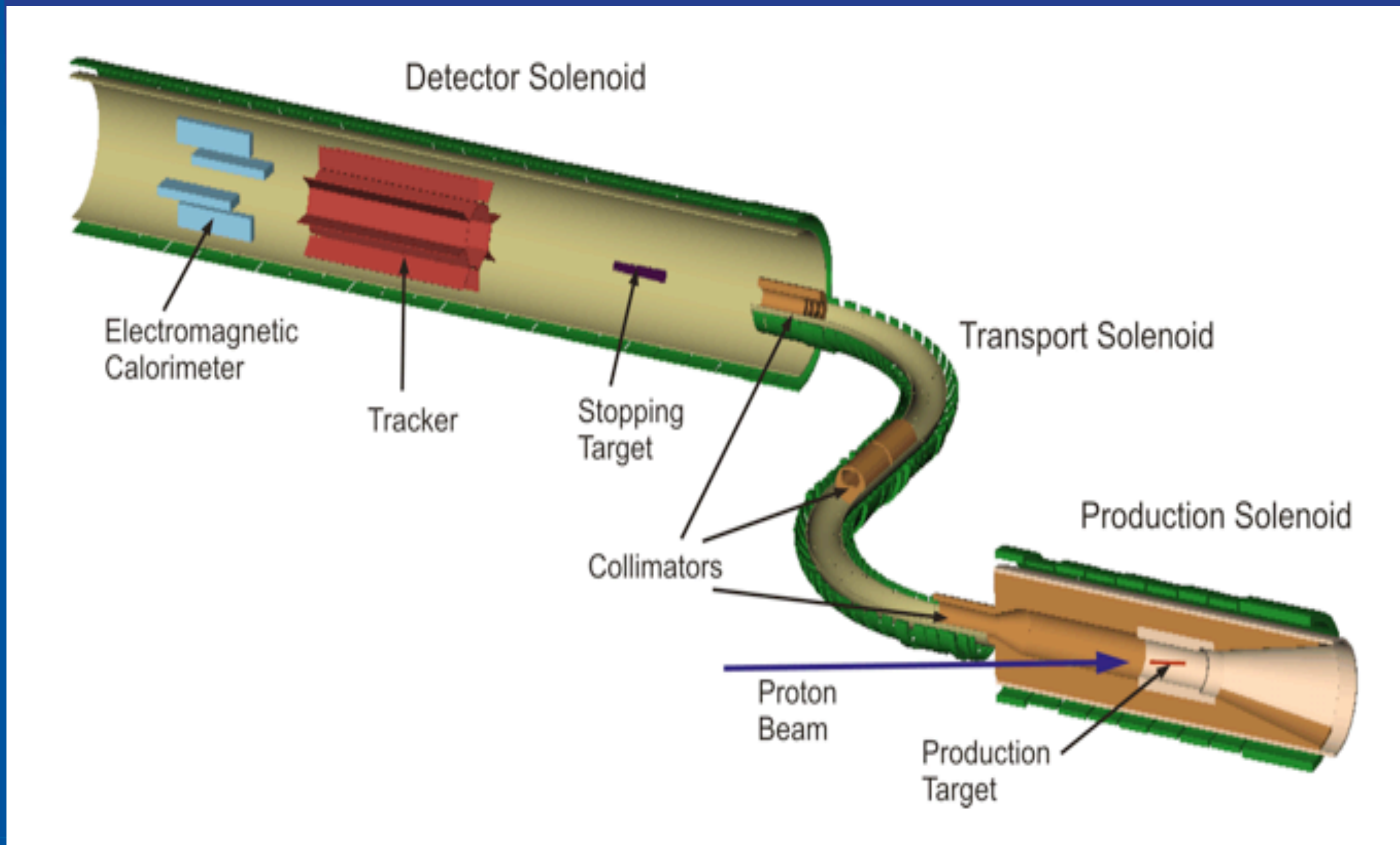
Mu2e Signal

- The process is a coherent decay
  - 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 Apparatus

- Production Solenoid
  - Slam lots of protons on to target to create lots of π- (plus lots of other stuff)
- Transport Solenoid
  - Collect the π- , momentum and sign select them
  - Transport the μ- from π- → μ-ν decays to the detector
- Detector Solenoid
  - Stop the μ- in a stopping target
  - Measure energy of outgoing electrons very precisely

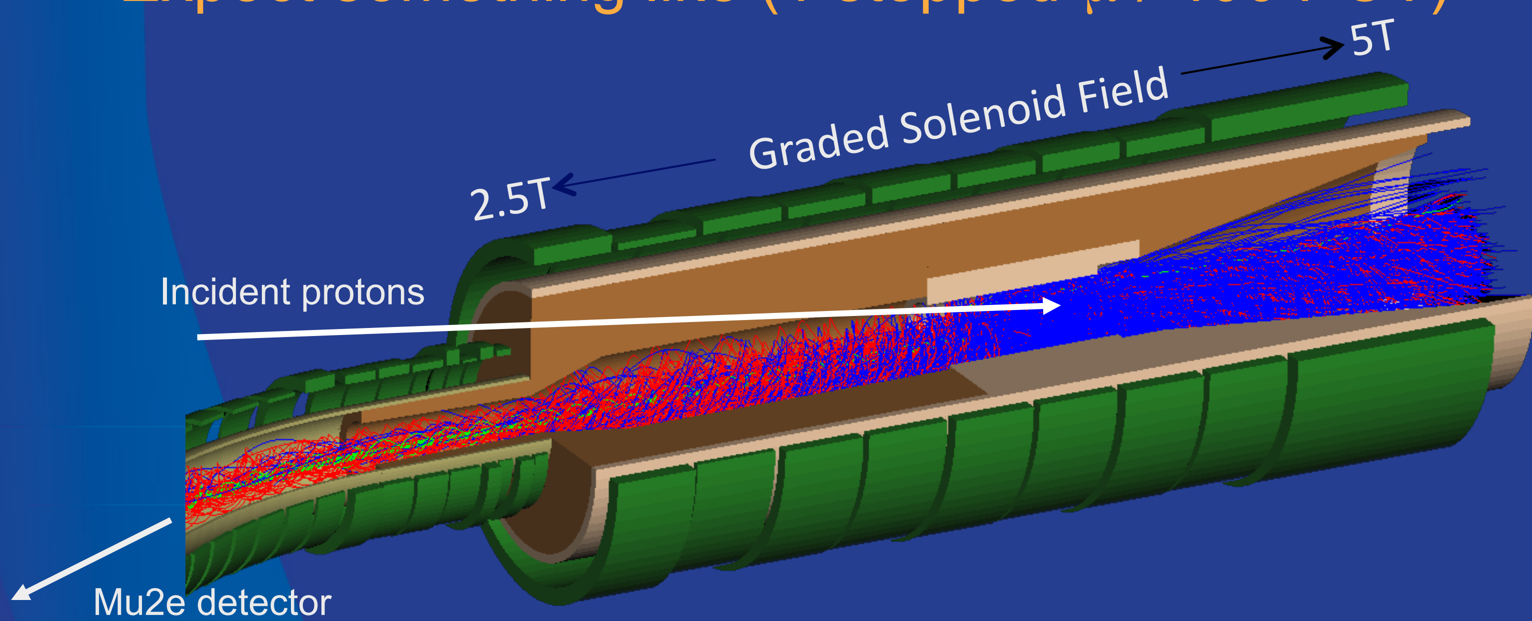
Mu2e Apparatus



- Mu2e experiment consists of 3 solenoid systems

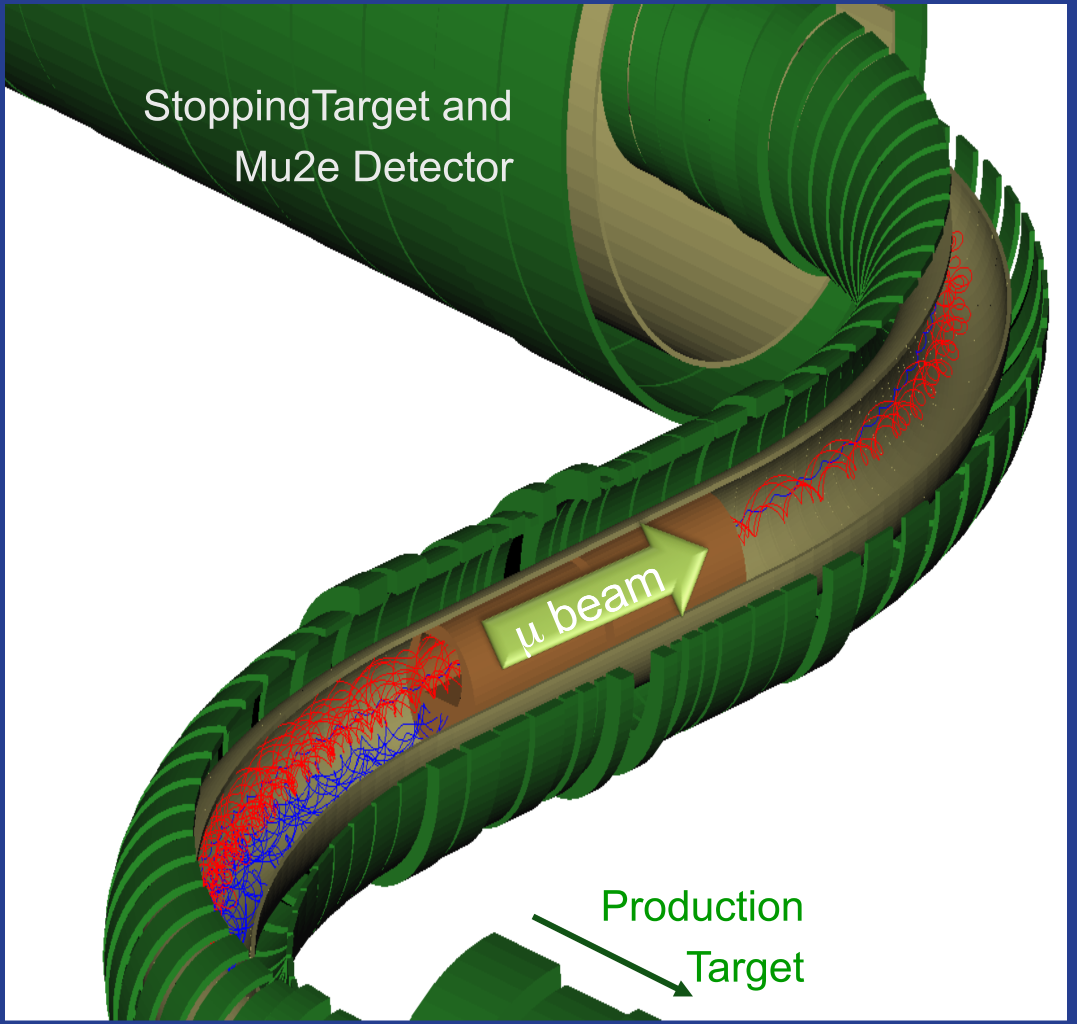
Mu2e Production Target

- Gold or Tungsten target, water cooled
- Capture (mostly) backwards going pions
  - Eliminates backgrounds from the primary beam
  - Expect something like (1 stopped-μ / 400 POT)

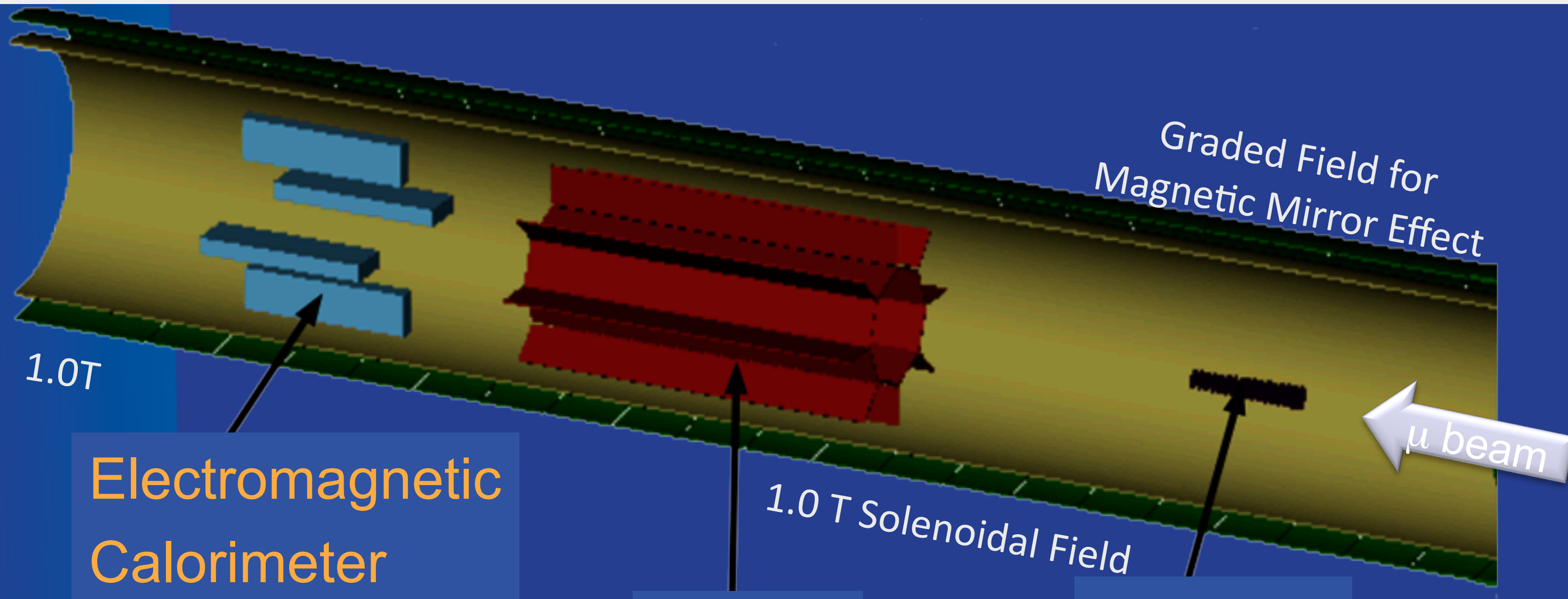


Mu2e Transport Solenoid

- Designed to sign select the muon beam
  - Collimator blocks positives after first bend
  - Negatives brought back on axis by the second bend
  - No line of sight between primary target and detector



Mu2e Detector



Electromagnetic Calorimeter

- 1.2k $PbWO_4$ crystals
- σ_E / E = 5% at 100 MeV
- confirmation of track
- can provide a trigger

Tracker

- 2.8k 3m long straws
- 17k cathode pads
- intrinsic resolution at 105 MeV/c: 190 keV/c

Stopping Target

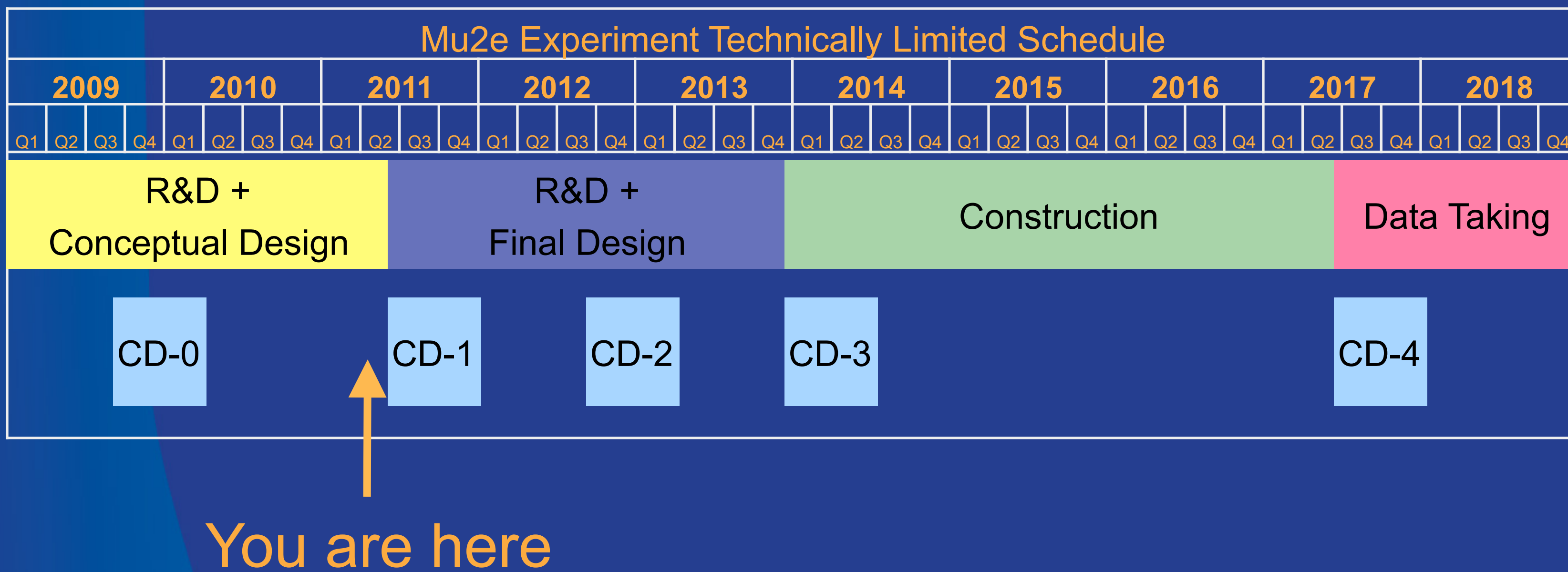
- 17 Al. foils each 200 μm thick
- spaced 5 cm apart
- radius tapers 10.0 to 6.5 cm
- <4% radiation length

- Designed to detect 105 MeV signal and suppress DIO

Mu2e Sensitivity

- Single Event Sensitivity = 2 x 10^{-17}
  - For 10^{18} stopped muons
  - If $R_{\mu e} = 10^{-15}$ will observe ~50 events
  - If $R_{\mu e} = 10^{-16}$ will observe ~ 5 events
- Expected background < 0.5 event
  - Assuming 2 x 10^{7} seconds of run time
- Expected limit < 6 x 10^{-17} @ 90% CL
- >5σ sensitivity for all rates > few E-16 (my estimate)
  - LHC accessible SuSy gives rates as large as 10^{-15}

Status and Schedule



- Cost estimated at $200M (fully loaded, escalated, and including contingency)

Why did I join the Mu2e experiment?

1) Excellent Physics Motivation

2) Fermilab / Mu2e are a good fit

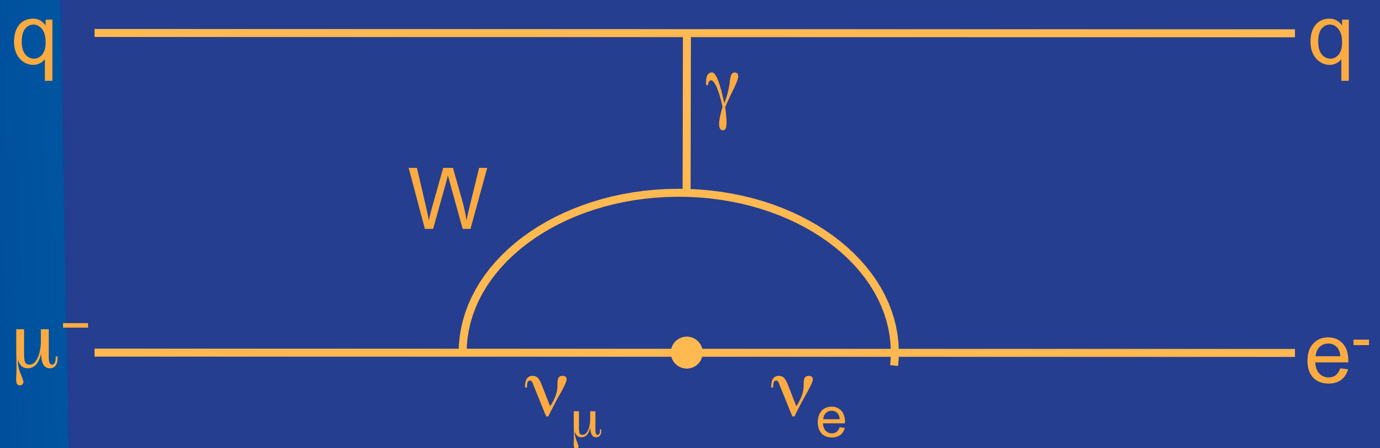
3) It’s hard

Physics Motivation

Mu2e Physics Motivation

- Factor of 10^4 improvement over world's previous best results
  - W.Bertl et al. (Sindrum II), Eur Phys J C47 (2006) 337
  - C. Dohmen et al. (Sindrum II), Phys Lett B317 (1993) 631
- Discovery sensitivity over a very broad range of New Physics Models
  - SuperSymmetry, Little Higgs, Leptoquarks, Extended Technicolor, Extra Dimensions
- Complementary sensitivity to rest of the world HEP program
  - LHC, ν mixing, B-factory

Mu2e in the Standard Model

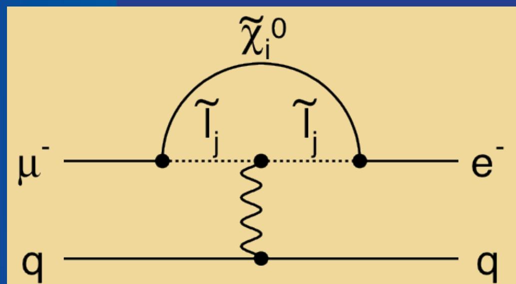


- Strictly speaking, forbidden in the SM
- Even in ν-SM, extremely suppressed

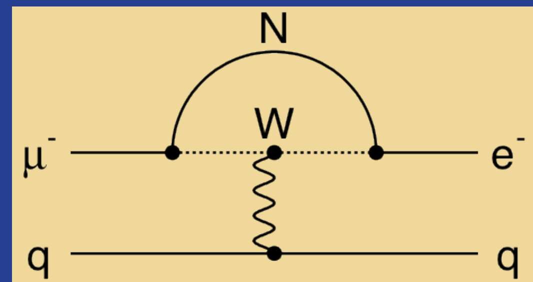
  (rate ~ $\Delta m_\nu^2 / M_W^2 < 10^{-50}$)
- However, most all NP models predict rates observable at next generation CLFV experiments

New Physics Contributions to Mu2e

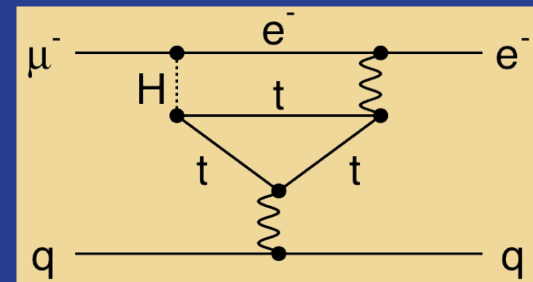
Loops



Supersymmetry

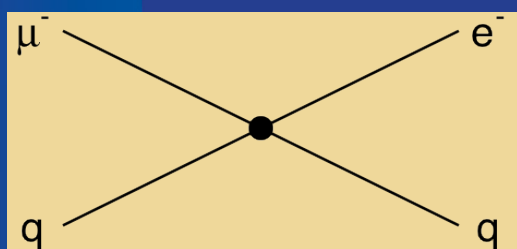


Heavy Neutrinos

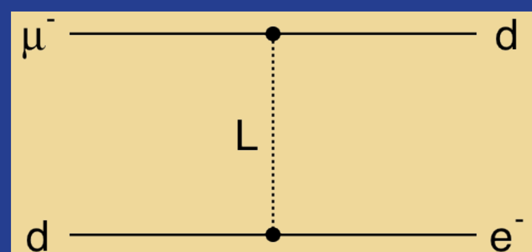


Two Higgs Doublets

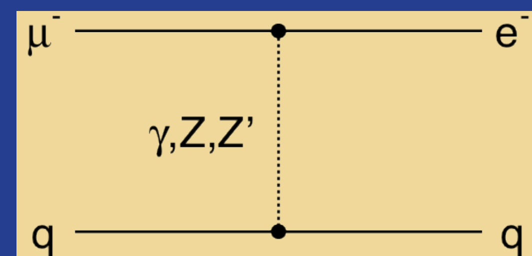
Contact Terms



Compositeness



Leptoquarks



New Heavy Bosons /
Anomalous Couplings

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

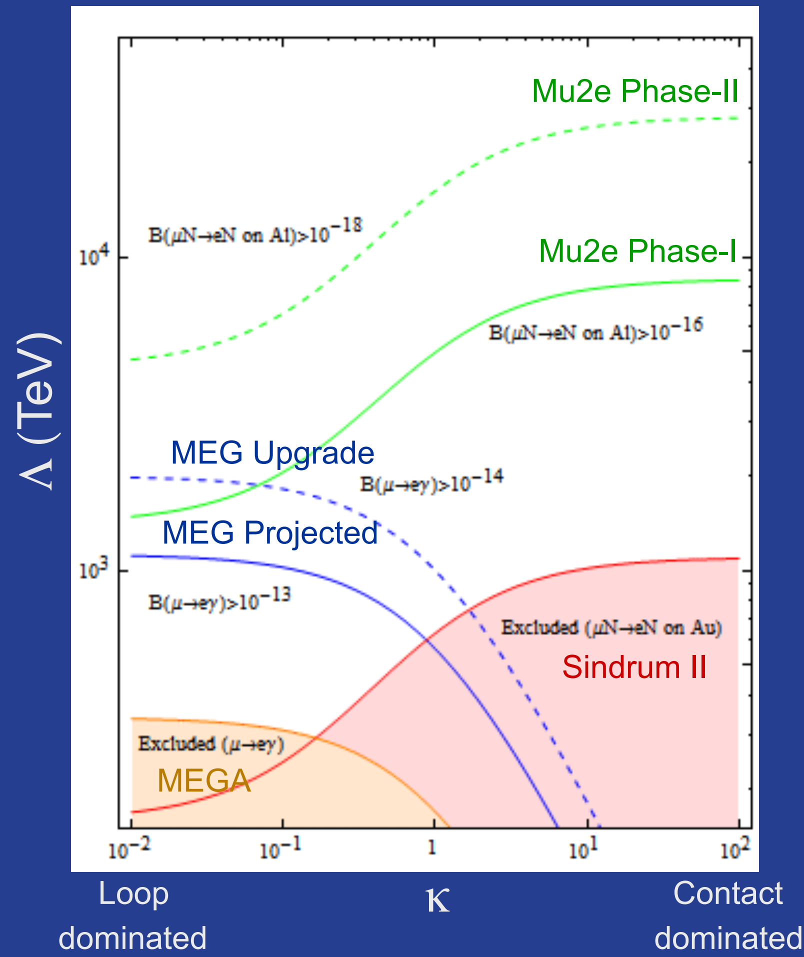
Some CLFV Processes

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} (SuperB)
$\tau \rightarrow \mu\mu\mu$	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 < 1.2 E-11	10^{-13} - 10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	
$\mu N \rightarrow eN$	$R_{\mu e}$ < 4.3 E-12	10^{-16} (Mu2e, COMET)

(current limits from the PDG)

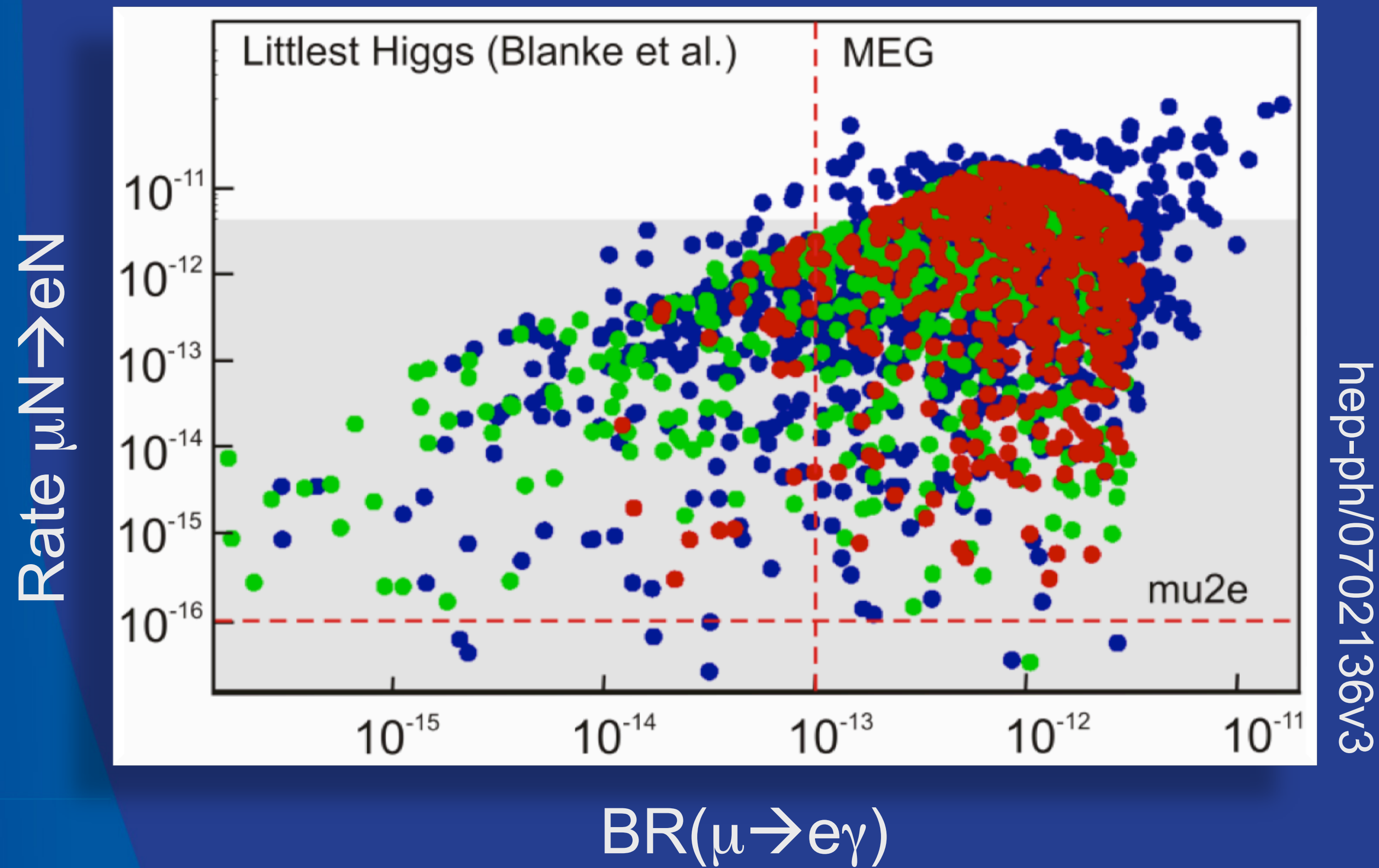
- Relative sensitivities model dependent
- Measure several to pin-down NP details

Mu2e Sensitivty



- Target Mu2e Sensitivity best in all scenarios

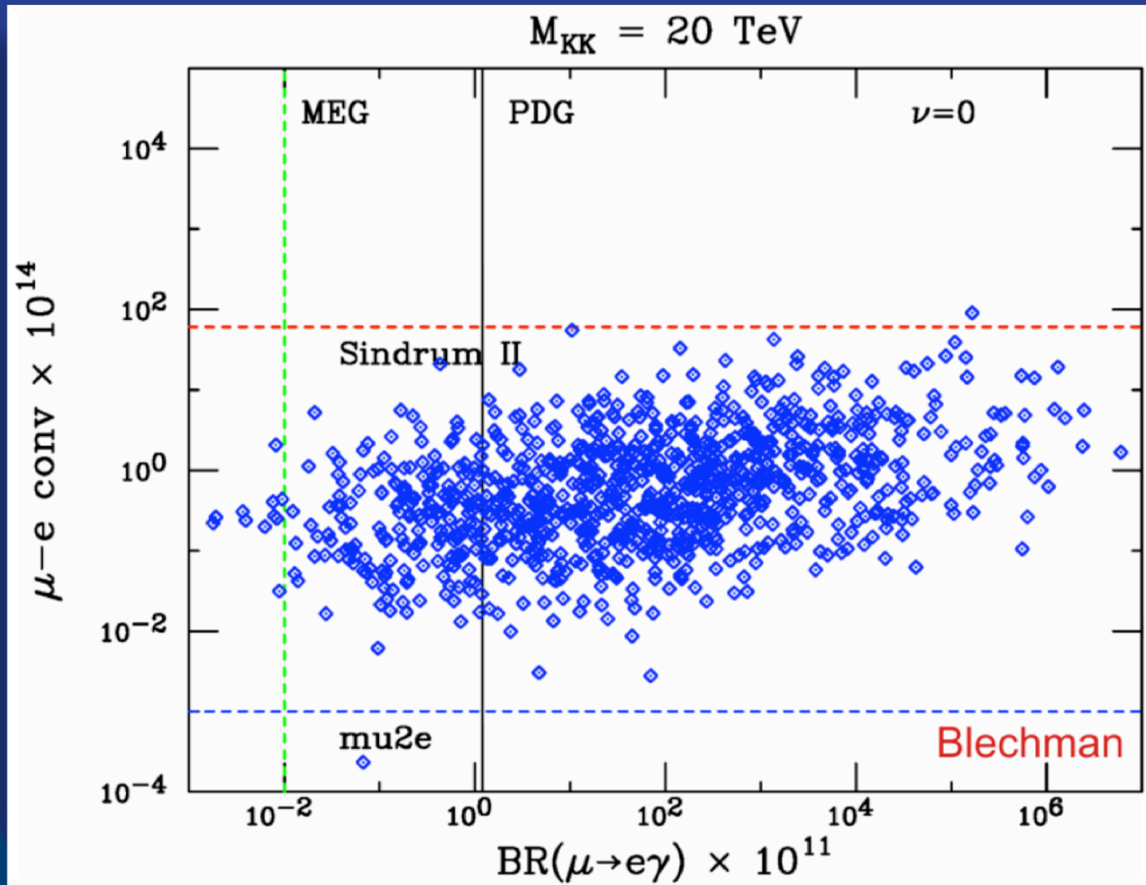
Mu2e Sensitivity



- Mu2e will cover the entire space

D.Glenzinski

Mu2e Sensitivity



hep-ph/0606021v2

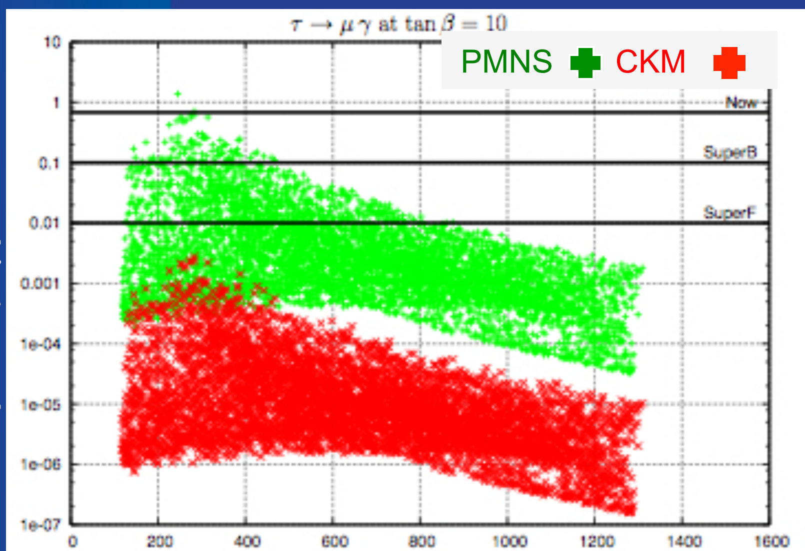
- Mu2e, MEG will each cover entire space

D.Glenzinski

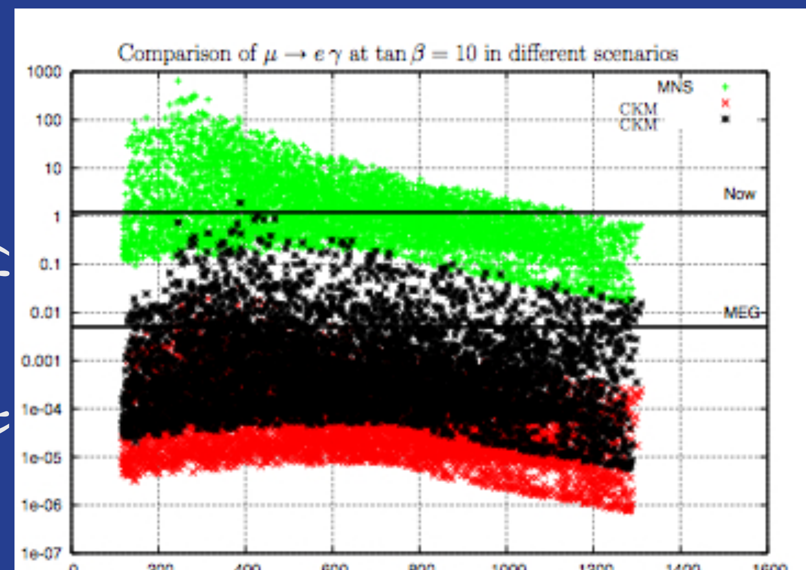
Fermilab

Mu2e Sensitivity

BR(τ→μγ) / 10-7



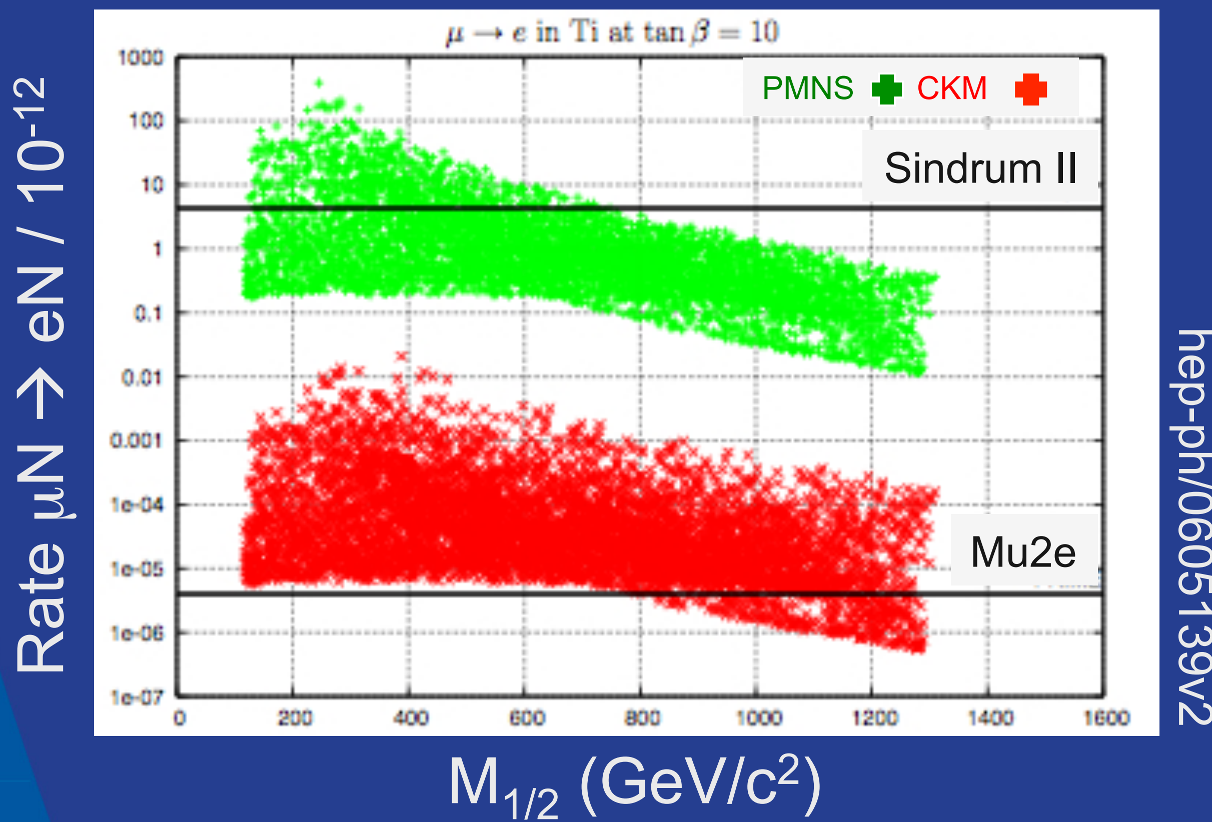
BR(μ→eγ) / 10-11



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

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

Mu2e Sensitivity



- Mu2e will cover (almost) entire space

Mu2e Sensitivity

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

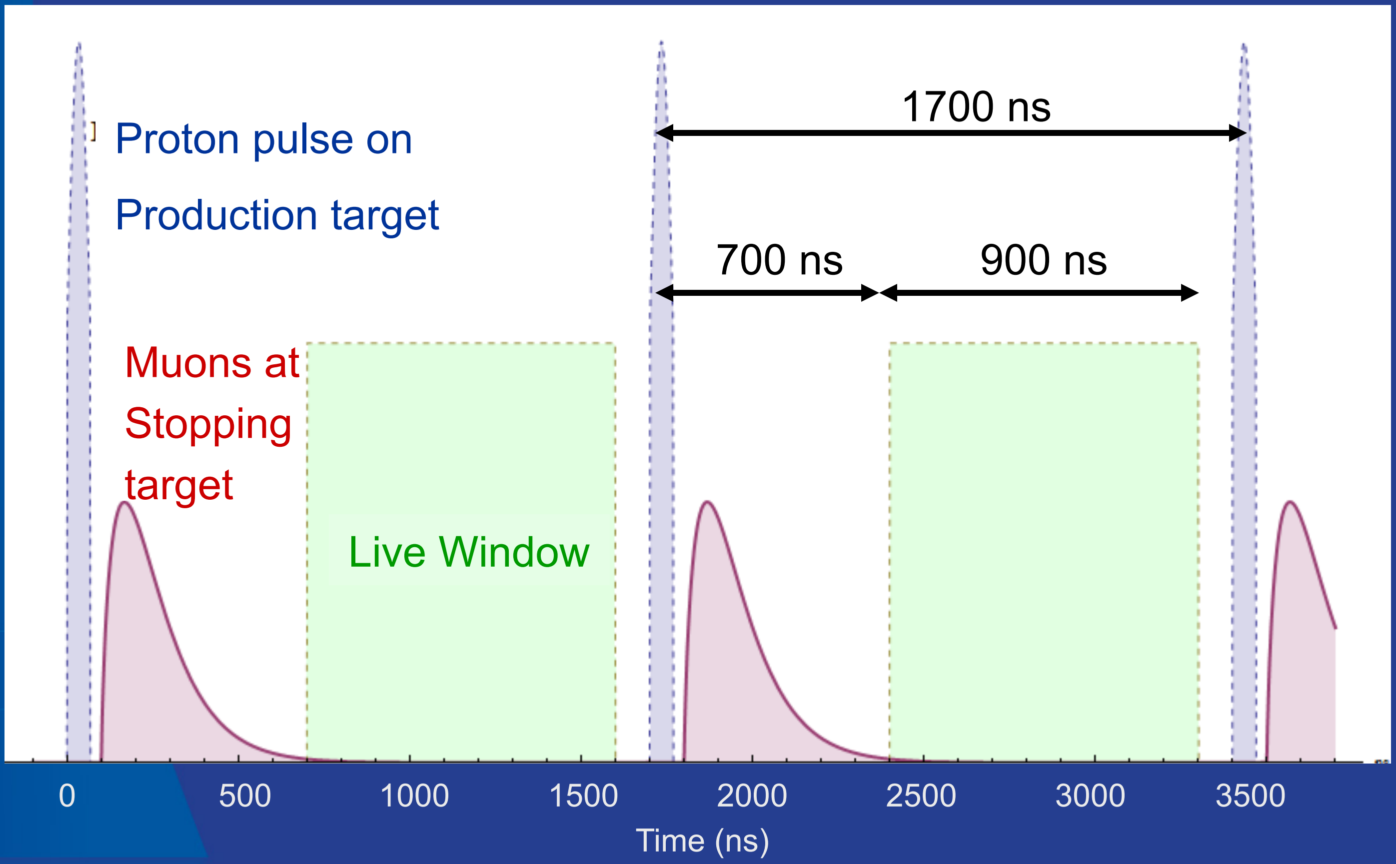
FNAL & Mu2e R BFF

Mu2e Concept

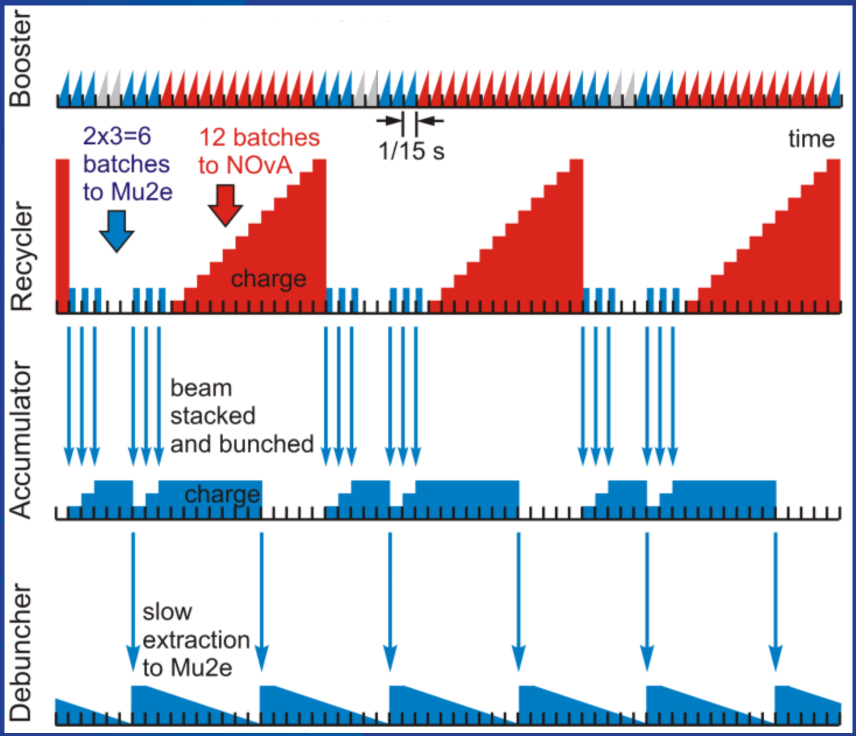
- Generate a beam of low momentum muons (μ^-)
- Stop the muons in a target
  - Mu2e plans to use aluminum
  - Sensitivity goal requires ~10^{18} stopped muons
- The stopped muons are trapped in orbit around the nucleus
  - In orbit around aluminum: τ_μ^{Al} = 864 ns
  - Large τ_μ^N important for discriminating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

Mu2e Beamline

- Fermilab complex well matched to beam timing requirements for Mu2e

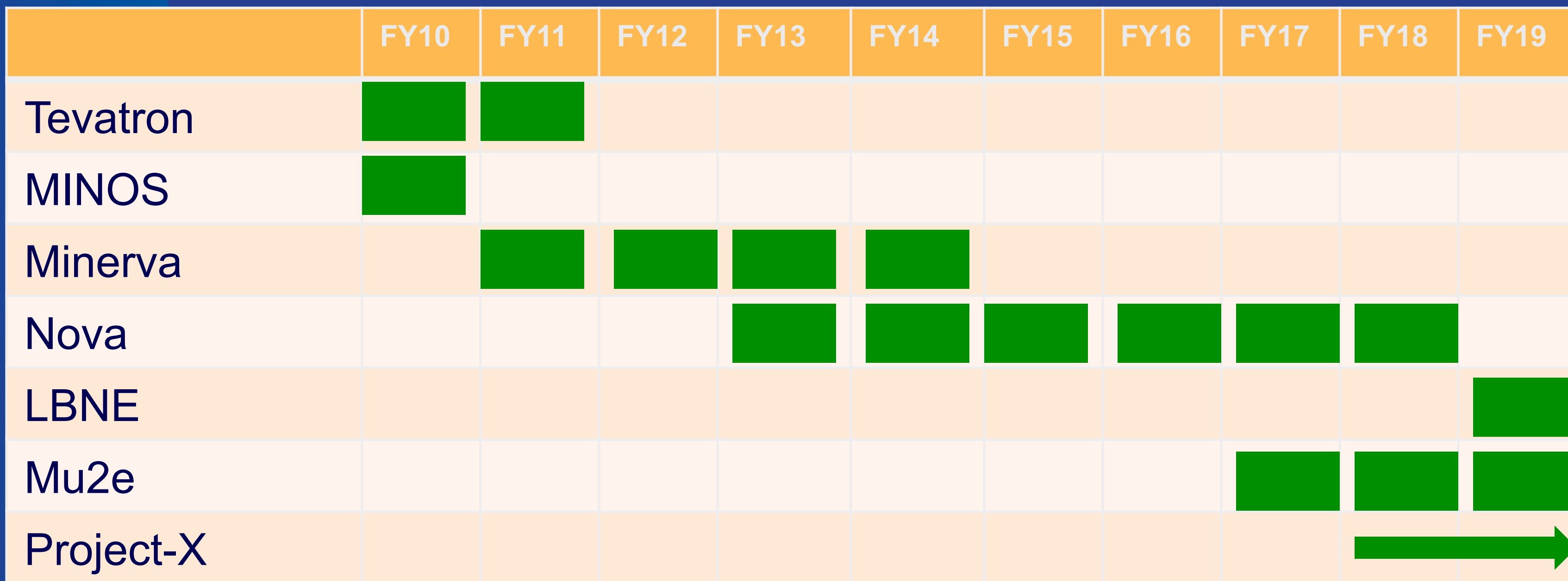


Mu2e Beamline



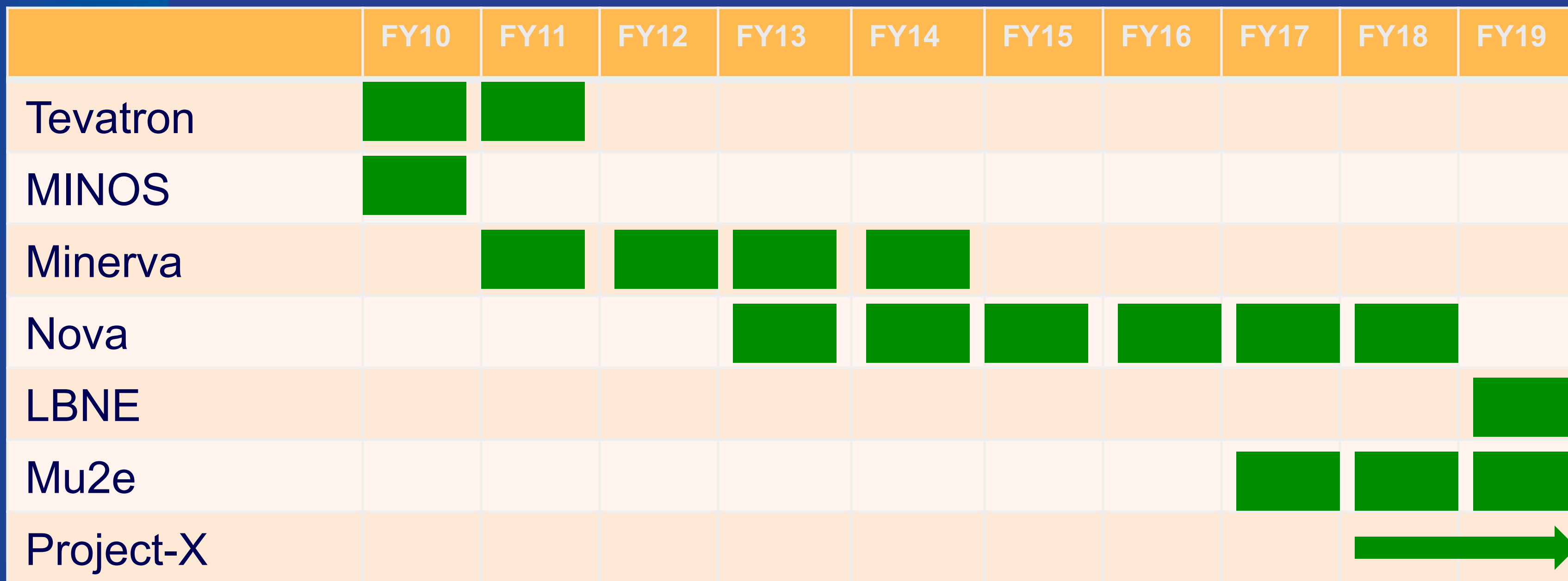
- Use 8 GeV protons from Booster to produce π^-, which decay $\pi^- \rightarrow \mu^- \nu$
- Use a system of solenoids and collimators to momentum and sign-select μ^-
- No impact on Nova
- Aiming for high duty cycle

Fermilab Accelerator Plan



- In the mid-term, Mu2e offers the possibility of exploiting the *current* Fermilab Accelerator Complex to perform a world class experiment

Fermilab Accelerator Plan

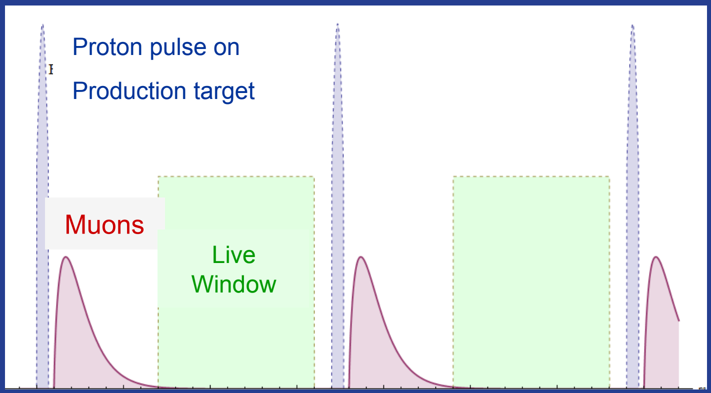


- In the long term, “next generation” Mu2e experiment would require Project-X intensities

The Challenges of Mu2e

Mu2e Background

- Three basic categories
  - Intrinsic
    - These, like the signal, scale with the number of stopped μ
  - Late Arriving
    - These arise from out-of-time (ie. late) protons on the production target



  - Miscellaneous
    - These include Long Transit, CR induced, Patt. Rec. errors

Mu2e Background

Category	Source	Events
	μ Decay in Orbit	0.225
Intrinsic	Radiative μ Capture	<0.002
	Radiative π Capture	0.072
	Beam electrons	0.036
	μ Decay in Flight	<0.063
Late Arriving	π Decay in Flight	<0.001
	Long Transit	0.006
	Cosmic Ray	0.016
Miscellaneous	Pat. Recognition Errors	<0.002
Total Background		0.42

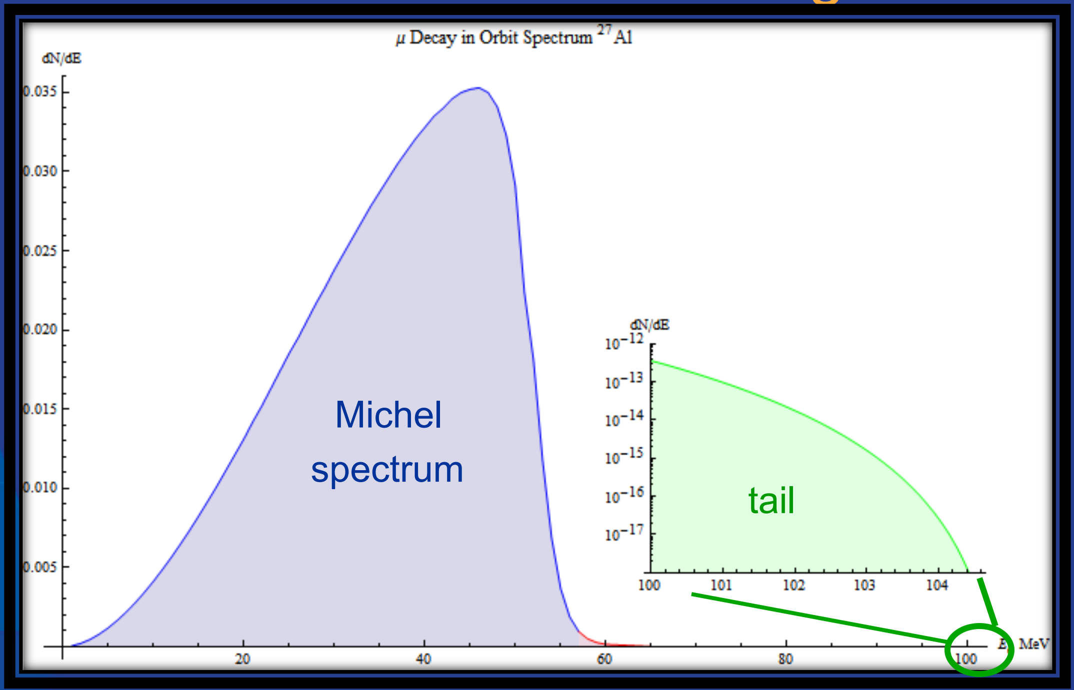
(assuming 1E18 stopped muons in 2E7 s of run time)

- 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

Fermilab

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 $< 10^{-9}$

Mu2e Late Arriving Backgrounds

- Contributions from
  - Radiative π Capture
    - $\pi^- N_Z$ --> $N^*_{Z-1} + \gamma$
    - For Al. RπC fraction: 2%
    - E_γ extends out to ~m_π
    - Asymmetric γ --> 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 ~40% 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
    - 200 μm mylar window in decay volume absorbs them all
    - Annihilations produce lots of stuff 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%

Inputs to Mu2e Background Estimates

- For each category of background

$$B_{DIO} = N_{POT} \cdot \left\{ \sigma\left(pN \to \pi^- X\right)(\vec{P},\vec{x},t)_\pi \cdot (\vec{P},\vec{x},t)_\mu^{\pi\to\mu X} \otimes [PS \cdot TS] \cdot f_{stop} \right\} \cdot f_{DIO} \cdot (\vec{P},\vec{x},t)_e^{DIO} \cdot A\left(\vec{P},\vec{x},t \middle| \Delta P, \Delta t\right)$$

$$= N_{POT} \cdot \left\{ N_{stop-\mu} / POT \right\} \cdot f_{DIO} \cdot (\vec{P},\vec{x},t)_e^{DIO} \cdot A\left(\vec{P},\vec{x},t \middle| \Delta P, \Delta t\right)$$

- $\sigma(pN \to \pi X)(P,x,t)_\pi$: fits to fixed target data (e.g. HARP)
- $(P,x,t)_\mu^{\pi\to\mu X}$: known
- [PS*TS] : modeled G4Beamline
- f_{stop} : modeled GEANT
- f_{DIO} : measured
- $(P,x,t)_e^{DIO}$: calculated and measured to 100 MeV
  approximate calculation for E>100 MeV
- $A(P,x,t \mid \Delta P, \Delta t)$: detector acceptance, modeled GEANT

Inputs to Mu2e Background Estimate

- For the RPC estimate:

$$B_{RPC} = N_{POT} \cdot \left\{ \sigma\left(pN \to \pi^- X\right)(\vec{P},\vec{x},t)_\pi \otimes [PS \cdot TS] \cdot f_{stop}^{\pi} \right\} \cdot X_{bm} \cdot f_{RPC} \cdot (\vec{P},\vec{x},t)_\gamma^{RPC} \cdot \sigma_{\gamma \to ee}(\vec{P},\vec{x},t)_e^{\gamma \to ee} \cdot A\left(\vec{P},\vec{x},t \middle| \Delta P, \Delta t\right)$$

$$= N_{POT} \cdot \left\{ N_{stop\text{-}\pi} / POT \right\} \cdot X_{bm} \cdot f_{RPC} \cdot (\vec{P},\vec{x},t)_\gamma^{RPC} \cdot \sigma_{\gamma \to ee}(\vec{P},\vec{x},t)_e^{\gamma \to ee} \cdot A\left(\vec{P},\vec{x},t \middle| \Delta P, \Delta t\right)$$

- $\sigma(pN \to \pi X)(P,x,t)_\pi$: fits to fixed target data (e.g. HARP)
- [PS*TS] : modeled G4Beamline
- f_{stop}^{π} : modeled GEANT
- X_{bm} : beam "extinction" (ie. suppression of out-of-time p)
- f_{RPC} : calculated and measured
- $(P,x,t)_\gamma^{RPC}$: calculated+measured (but not very well)
- $\sigma(\gamma \to ee)\ (P,x,t)_e^{\gamma \to ee}$: modeled GEANT
- A(P,x,t | ΔP, Δt) : detector acceptance, modeled GEANT

Inputs to Mu2e Background Estimate

- For the RPC estimate:

$$B_{RPC} = N_{POT} \cdot \left\{ \sigma\left(pN \to \pi^- X\right)(\vec{P},\vec{x},t)_\pi \otimes [PS \cdot TS] \cdot f_{stop}^{\pi} \right\} \cdot X_{bm} \cdot f_{RPC} \cdot (\vec{P},\vec{x},t)_\gamma^{RPC} \cdot \sigma_{\gamma \to ee}(\vec{P},\vec{x},t)_e^{\gamma \to ee} \cdot A\left(\vec{P},\vec{x},t | \Delta P, \Delta t\right)$$

$$= N_{POT} \cdot \left\{ N_{stop\text{-}\pi} / POT \right\} \cdot X_{bm} \cdot f_{RPC} \cdot (\vec{P},\vec{x},t)_\gamma^{RPC} \cdot \sigma_{\gamma \to ee}(\vec{P},\vec{x},t)_e^{\gamma \to ee} \cdot A\left(\vec{P},\vec{x},t | \Delta P, \Delta t\right)$$

- Ignoring the beam extinction for the moment, you'd get

$B_{RPC} = 7 \times 10^7$ events

All prompt, so remove by the 700 ns delayed signal window

But this sets the specification for X_{bm}… suppression must be large enough to reduce all Late Arriving backgrounds to negligible level:

If $X_{bm} <= 10^{-9}$, $B_{RPC} <= 0.07$

Inputs to Mu2e Background Estimate

- This exercise produces a long list of things to worry about e.g.
  - π- production known to a factor of ~2
  - DIO driven by spectrometer resolution (which is scattering dominated)
  - Material in detector affects RMC, RPC, DIO
  - Nuclear resonance effects for RMC, RPC
  - Will $X_{bm} < 10^{-9}$ be achieved? (cf. 40% of background scales linearly with X_{bm})
  - etc.
- How do these affect Mu2e sensitivity?

My Personal Investigation (MPI)

- Built a ToyMC to investigate
  - Model n_s as a Poisson distribution with mean S
  - Model n_b as a Poisson distribution with mean B
  - Incorporate uncertainties in s and b using Gaussians
  - So, for a given toy experiment
    1) Choose S from a Gaussian(μ=s, σ_s)
    2) Choose B from a Gaussian(μ=b, σ_b)
    3) Choose n_s from a Poisson(μ=S)
    4) Choose n_b from a Poisson(μ=B)
    5) $n_{obs} = n_s + n_b$

MPI: The inputs

- My baseline/default:
  - b = 0.45
  - single-event-sensitivity (ses) = 2E-17
    s = R(μN→eN)/ses, so R=1E-16 gives s=5
  - Used σ_b/b = σ_s/s = 33% (seemed reasonable)
- Also considered these variations
  - σ_b/b = 10%, 68% (roughly corresponds to dflt *0.5 and *2)
  - σ_s/s = 15%, 45% (corresponds to default +/- 0.5*dflt)
  - b = 1.0, 2.0
- Looked at R(μN→eN) = 5, 8, 10, 15, 20, 25, 30 E-17

MPI: Adding some sophistication

- The background is the sum of various components
  - Some better understood than others
  - Some correlated to each other
  - Some correlated to signal

- Estimate b like this
  - $b = b_{dio} + b_{rmc} + b_{rpc} + b_{beam\text{-}e} + b_{\mu dif} + b_{\pi dif} + b_{cosmic} + b_{other}$
  - For now, just Gaussian smear this total

- Consider what happens if extinction, π-production, μ-stopping, e-scatter in target, conversion probability are each wrong

MPI: Adding some sophistication

- Include correlations by estimating b like this:

$$
\begin{aligned}
b = \; & b_{\mathrm{DIO}} \\
& + b_{\mathrm{RMC}} * F_{\gamma \to e^+ e^-} \\
& + b_{\mathrm{RPC}} * F_{\gamma \to e^+ e^-} * F_{\mathrm{extinction}} \,/\, F_{\mu\text{-stop}} \\
& + b_{\mu\mathrm{DIF}} * \left(\frac{3}{7} + \frac{4}{7} F_{e^- \mathrm{scatter}}\right) * F_{\mathrm{extinction}} \,/\, F_{\mu\text{-stop}} \\
& + b_{\pi\mathrm{DIF}} * F_{e^-\ \mathrm{scatter}} * F_{\mathrm{extinction}} \,/\, F_{\mu\text{-stop}} \\
& + b_{\mathrm{beam}\ e^-} * F_{\mathrm{extinction}} \,/\, F_{\pi\ \mathrm{Production}} \,/\, F_{\mu\text{-stop}} \\
& + b_{\mathrm{cosmics}} * F_{\mathrm{CRV\ inefficiency}} \,/\, F_{\pi\ \mathrm{Production}} \,/\, F_{\mu\text{-stop}} \\
& + b_{\mathrm{other}} \,/\, F_{\pi\ \mathrm{Production}} \,/\, F_{\mu\text{-stop}}
\end{aligned}
$$

- Have incorporated mistakes in π-prod, μ-stop such that ses is fixed at 2E-17; thus this includes the correlation with the signal

MPI: Adding some sophistication

- The default is obtained by setting all F=1
  - "other" = pbar, pattern recognition errors, late arriving particles

$$b = b_{DIO} + b_{RMC} + b_{RPC} + b_{\mu DIF} + b_{\pi DIF} + b_{\text{beam } e^-} + b_{cosmics} + b_{other}$$
$$= 0.250 + 0.005 + 0.071 + 0.070 + 0.001 + 0.040 + 0.013 + 0.004$$
$$= 0.454$$

MPI: Background Scenarios

- Considered the following
  A. F(π production rates) = 0.5
  B. F(μ-stopping fraction) = 0.5
  C. F(μ-stopping fraction) = 0.2
  D. F(extinction factor) = 5
  E. F(extinction factor) = 10
  F. F(conversion probability) = 5
  G. F(target scatters) = 5
  H. F(CRV inefficiency) = 100

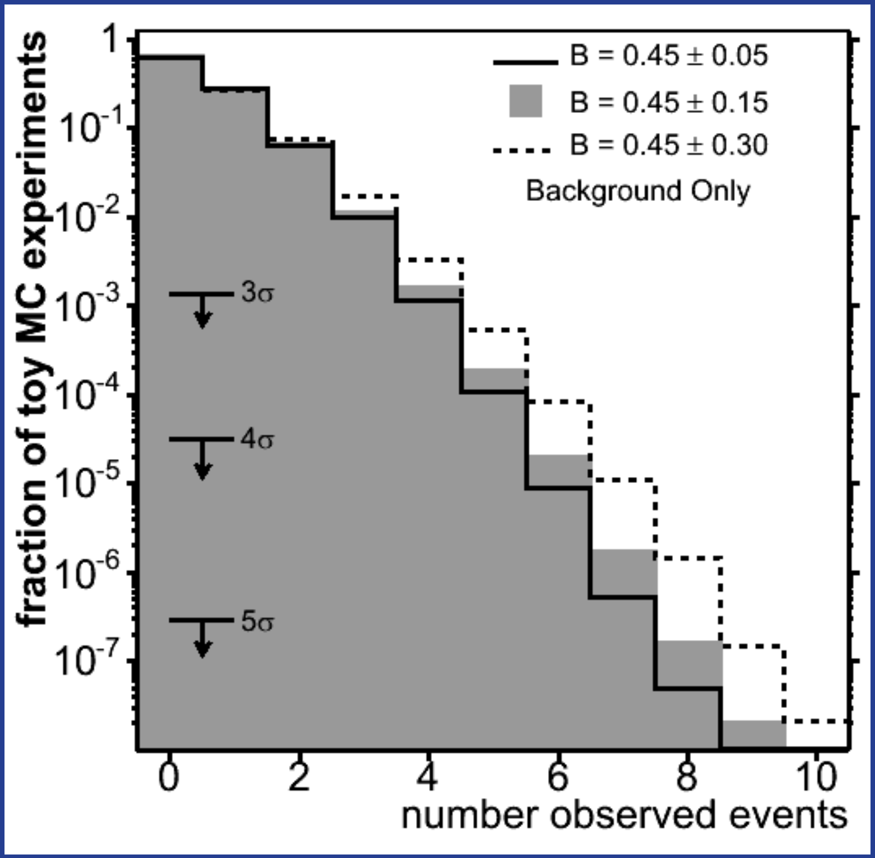
- Looked at how discovery sensitivities changed

MPI:Background Scenarios

- Considered the following
  A. F(π production rates) = 0.5 → b = 0.51
  B. F(μ-stopping fraction) = 0.5 → b = 0.65
  C. F(μ-stopping fraction) = 0.2 → b = 1.25
  D. F(extinction factor) = 5 → b = 1.18
  E. F(extinction factor) = 10 → b = 2.09
  F. F(conversion probability) = 5 → b = 0.76
  G. F(target scatters) = 5 → b = 0.62
  H. F(CRV inefficiency) = 100 → b = 1.74

- All these bracketed by studies shown next

MPI: The background distributions

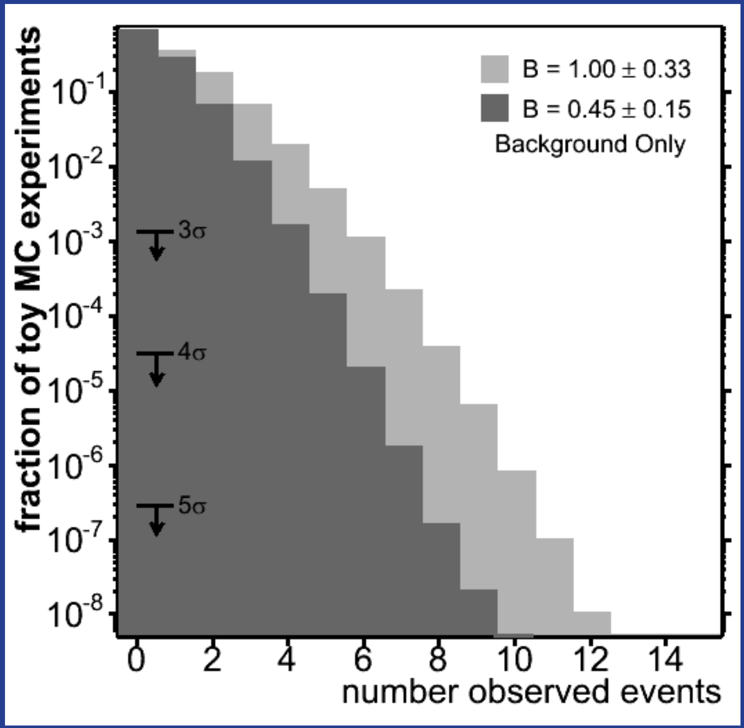


- Gaussian smearing mildly important for discovery

D.Glenzinski

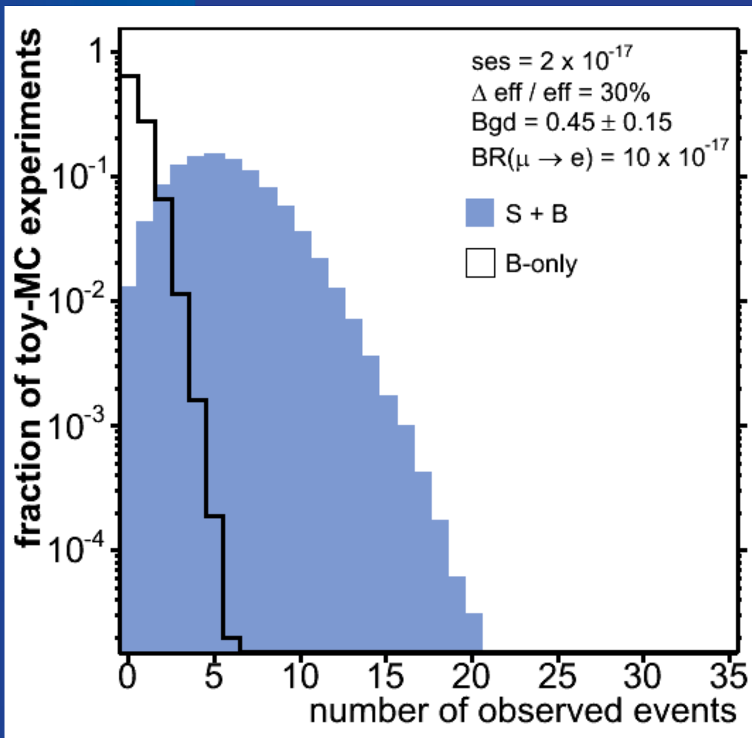
Fermilab

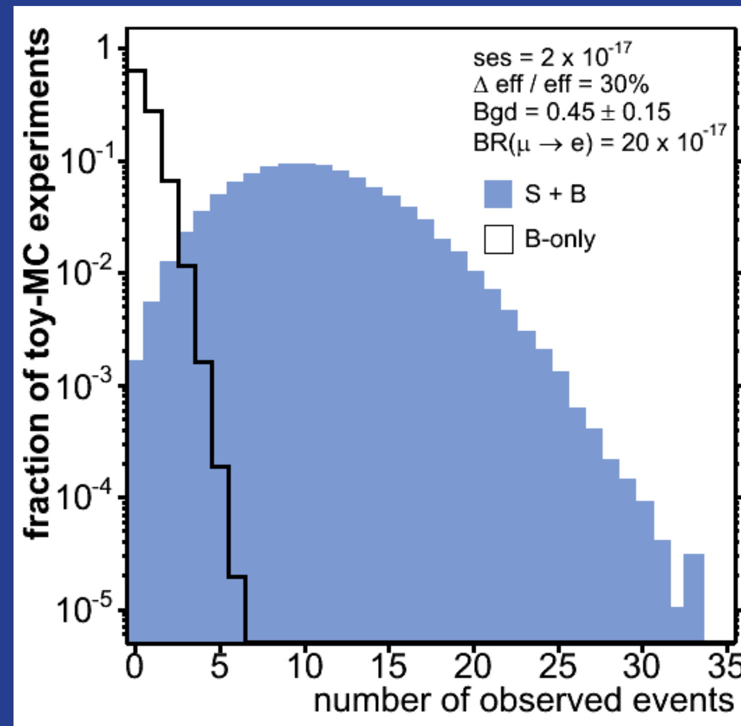
MPI: The background distributions



- Shifts in mean expected background more important
  - For b=0.45 : $n_{3\sigma}$=5, $n_{5\sigma}$=8
  - For b=1.00 : $n_{3\sigma}$=6, $n_{5\sigma}$=11
  - For b=2.00 : $n_{3\sigma}$=9, $n_{5\sigma}$=15

MPI: The s+b distributions





- With default assumptions, clearly have good chance for a significant observation for $R(\mu N \rightarrow eN) << 10^{-12}$ (current best limit)

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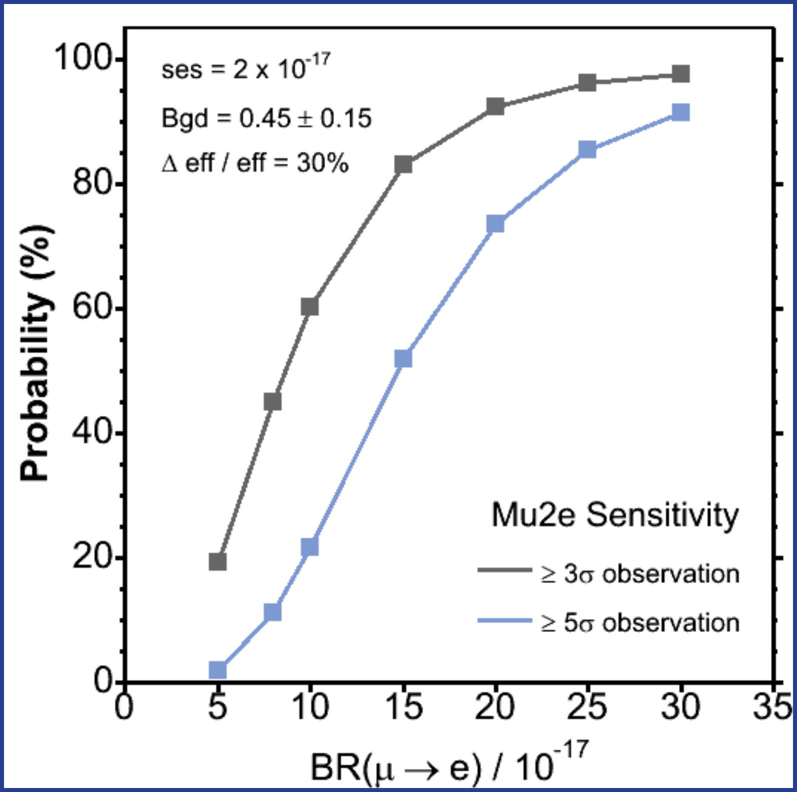
MPI: Discovery Sensitivities



- >50% chance of >5σ observation for all R>15E-17
- >50% chance of >3σ evidence for all R>8E-17

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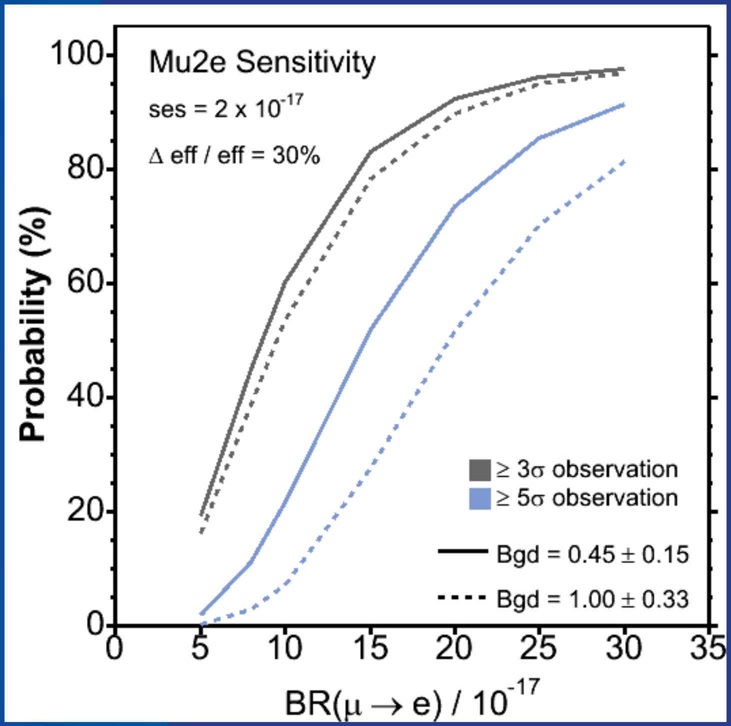
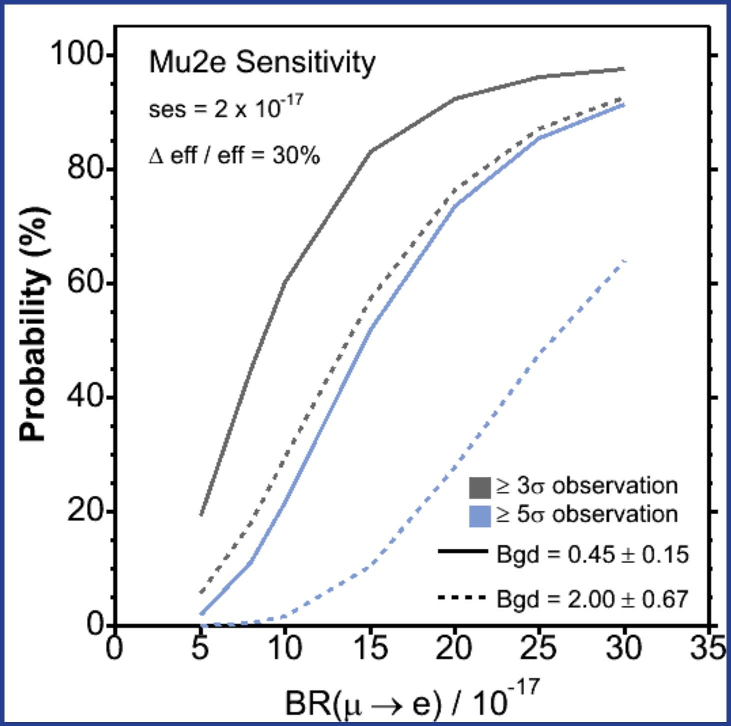
MPI: Discovery Sensitivities





- If Background is worse by a factor of 2-4,
  - 5σ sensitivity down to 20-25E-17
  - 3σ sensitivity down to 10-15E-17

MPI: What I took away from MPI

- Mu2e has an impressive discovery sensitivity
- That sensitivity fairly robust to the uncertainties in the background I investigated
- Things I didn't include
  - Surprise nuclear resonances in capture processes
    - Will use e+ spectrum *in situ* to investigate
  - Degradation of spectrometer resolution
    - Since DIO spectrum falling so steeply, can make stricter E_e requirements w/o affecting Acceptance too much
  - Your favorite worry

Mu2e R&D

- Broad R&D campaign identified
  - Design and Specifications of Solenoids
  - Optimization of the production and transport regions
  - Demonstrating resolution and rate capabilities of various tracker options
  - Rethinking calorimeter and trigger requirements
  - Demonstrating cosmic ray veto efficiency and characterizing response to neutrons
  - Developing robust monitoring of out-of-time protons
  - Developing thorough and accurate simulation
  - Measuring proton, neutron rates from stopped muons
- New collaborators welcome!

Conclusions

- Understanding charged lepton flavor physics necessary to fully illuminate New Physics
- $\mu N \rightarrow eN$ among most sensitive probes of Charged Lepton Flavor Violating processes
- Fermilab complex well suited to delivering the necessary beam for a phase-I experiment
- Mu2e experiment with a single-event-sensitivity of 2E-17 being enthusiastically pursued
  - Improves current best by 10^4 (Discovery Oriented)
  - Probes mass scales well beyond LHC's capabilities
  - Two year run starting as early as 2017
  - Clear upgrade path using Project-X

Backup Slides

Mu2e Sensitivity

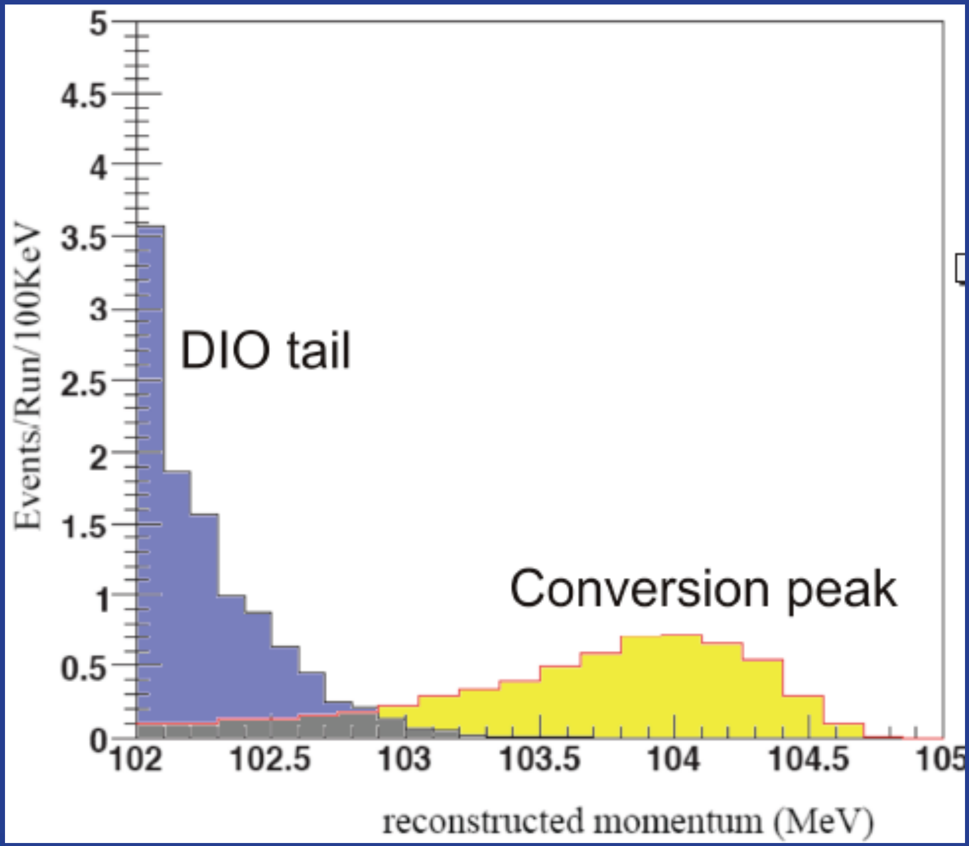
$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}$$

$$+ \quad \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

- Augment SM with some effective operators which enable CLFV
- Other (Dim-6) operators also possible, but these two alone do a good job of generically describing all CLFV predictions from concrete NP models

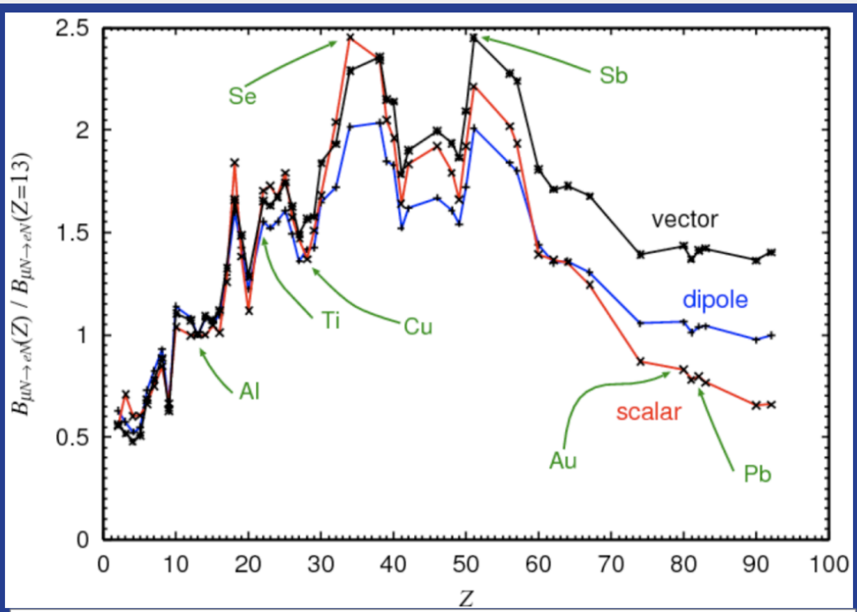
Mu2e Signal vs Background

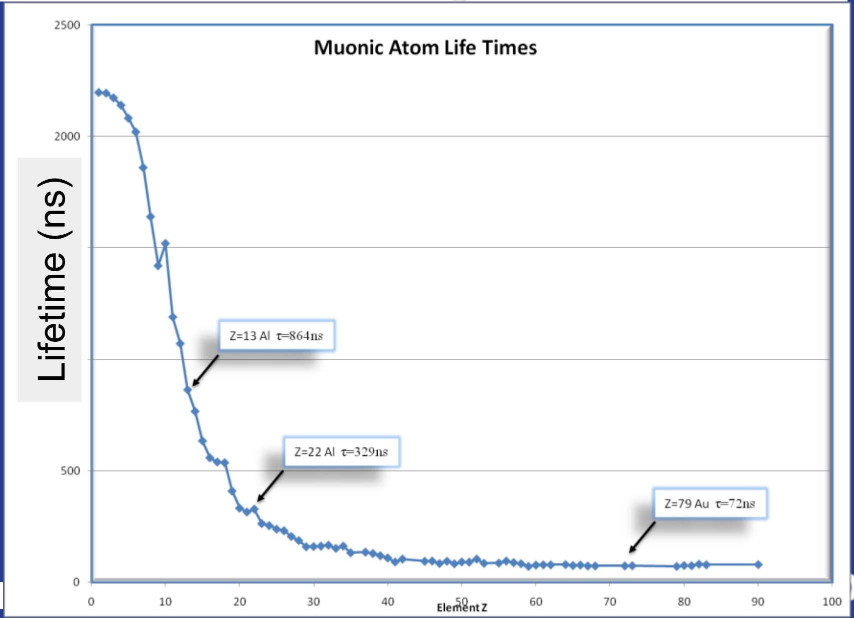
- DIO vs Signal E spectrum



Mu2e Phase-II Possibilities

- If Phase-1 Observes a signal:
  - Change target to probe coupling (vector, scalar, etc)
  - Need to go to high Z
  - Hard because τ small for large Z (τ_{μ}^{Au} =72ns)
  - But DIO backgrounds are suppressed and signal rate increases
- This is a unique feature of the $\mu N \rightarrow eN$ measurements





A Clarification

- “Mu2e is complimentary…”

A Clarification

- “Mu2e is complementary…”

$$L_{\mathrm{NP}} = L_{\mathrm{LHC}} + L_{\mathrm{PMNS}} + L_{\mathrm{Mu2e}} + \ldots$$