The Mu2e Experiment at Fermilab

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U.S. DEPARTMENT OF ENERGY

Fermilab

Introduction

- We expect that colliders might soon yield direct observation of New Physics particles/interactions
  - Tevatron is probing mass scales of ~1 TeV
  - LHC will probe mass scales of a few TeV

- To get a full understanding of the New Physics will require measurements the colliders can't do
  - Determining the parameters of the PMNS matrix
  - Determining whether or not mixing occurs in the charged lepton sector (Charged Lepton Flavor Violation - CLFV)
  - Proton decay, CKM matrix, DM Searches, etc.

Introduction

- Mu2e experiment is a search for Charged Lepton Flavor Violation (CLFV)
  - Coherent conversion $\mu^- N \rightarrow e^- N$
- Strictly speaking, forbidden in Standard Model
  - But since $m_\nu > 0$ we now know it's allowed
  - Rate proportional to $(\Delta m_\nu^2 / M_W^2)^2$ so practically still absent from SM
    e.g. $BR(\mu \rightarrow e\gamma) \sim 10^{-54}$
  - Observation thus offers unambiguous evidence for New Physics
- In wide array of New Physics models CLFV processes occur at rates we can observe with next generation experiments
  - sensitive to effective mass scales well beyond collider energies

Some CLFV Processes

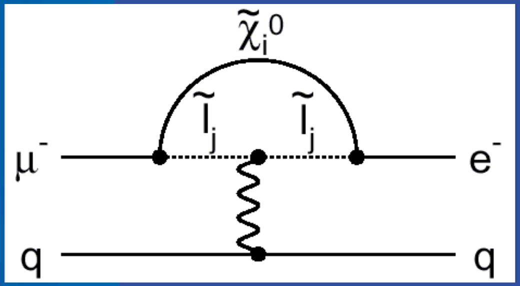
Process	Current Limit	Next Generation exp
τ --> $\mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (SuperB)
τ --> $\mu\gamma$	BR < 6.8 E-8	
τ --> $\mu\mu\mu$	BR < 3.2 E-8	
τ --> eee	BR < 3.6 E-8	
K_L --> $e\mu$	BR < 4.7 E-12	
K^+ --> $\pi^+e^-\mu^+$	BR < 1.3 E-11	
B^0 --> $e\mu$	BR < 7.8 E-8	
B^+ --> $K^+e\mu$	BR < 9.1 E-8	
μ^+ --> $e^+\gamma$	BR < 1.2 E-11	10^{-13} - 10^{-14} (MEG)
μ^+ --> $e^+e^+e^-$	BR < 1.0 E-12	
μN --> eN	$R_{\mu e}$ < 4.3 E-12	10^{-16} (Mu2e, COMET)

(current limits from the PDG)

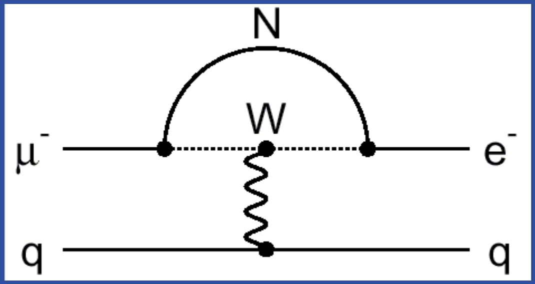
- Relative sensitivities model dependent
- Measure several to pin-down NP details

New Physics Contributions to Mu2e

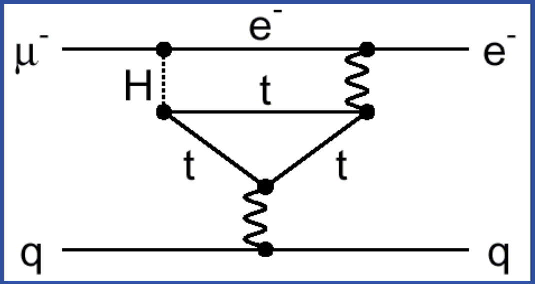
Loops



Supersymmetry

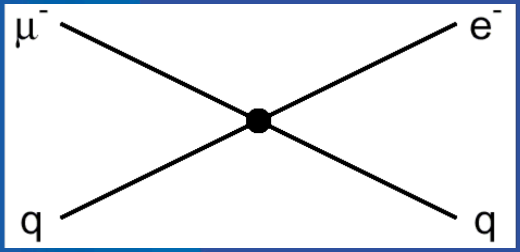


Heavy Neutrinos

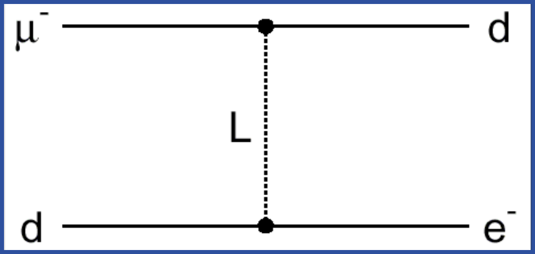


Two Higgs Doublets

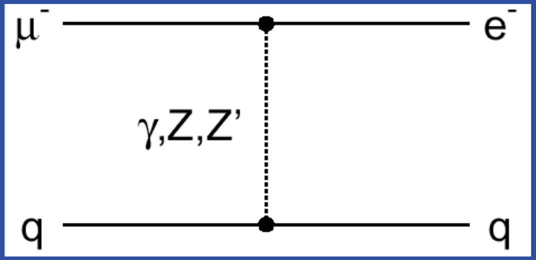
Contact Terms



Compositeness



Leptoquarks



New Heavy Bosons /
Anomalous Couplings

- The μN-->eN process is sensitive to wide array of New Physics processes

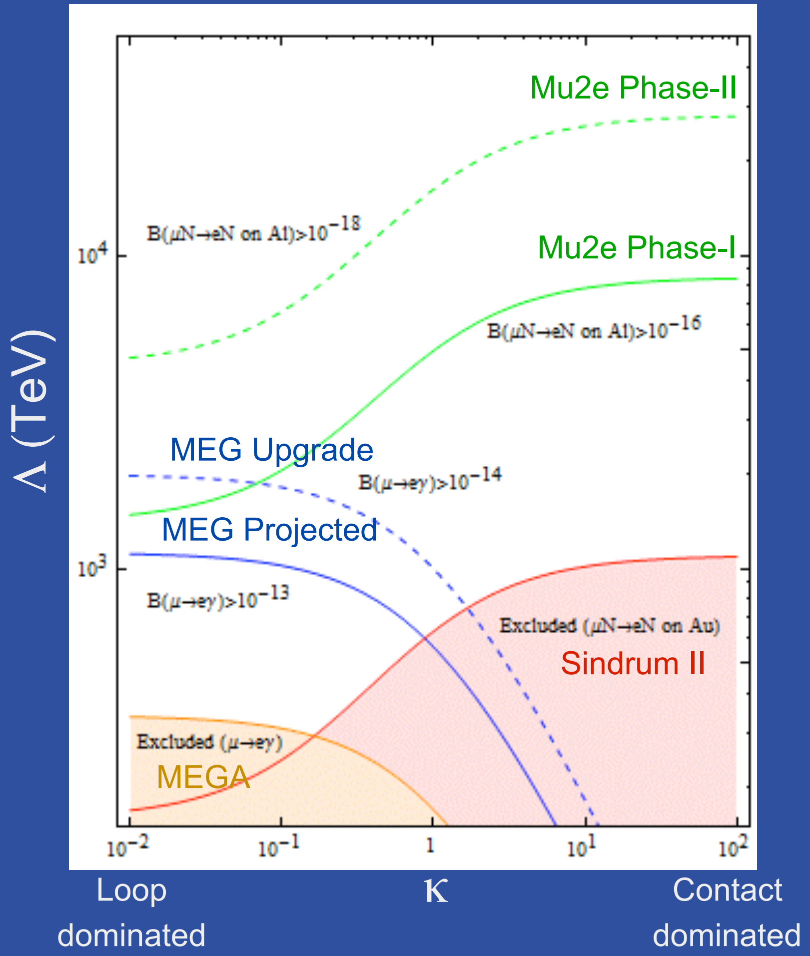
Mu2e Experiment

- Anticipate a phased program at Fermilab
  - Phase I: use Booster cycles left unused by Noνa
  - Phase II: use spare protons from Project-X
- Presently optimizing (Phase-I) experiment and beam line
  - At present, largely based on MECO proposal
  - Account for differences between BNL/FNAL accelerator complex
  - Take advantage of technological advances
- Strongly endorsed by Fermilab PAC and P5

Mu2e Sensitivity

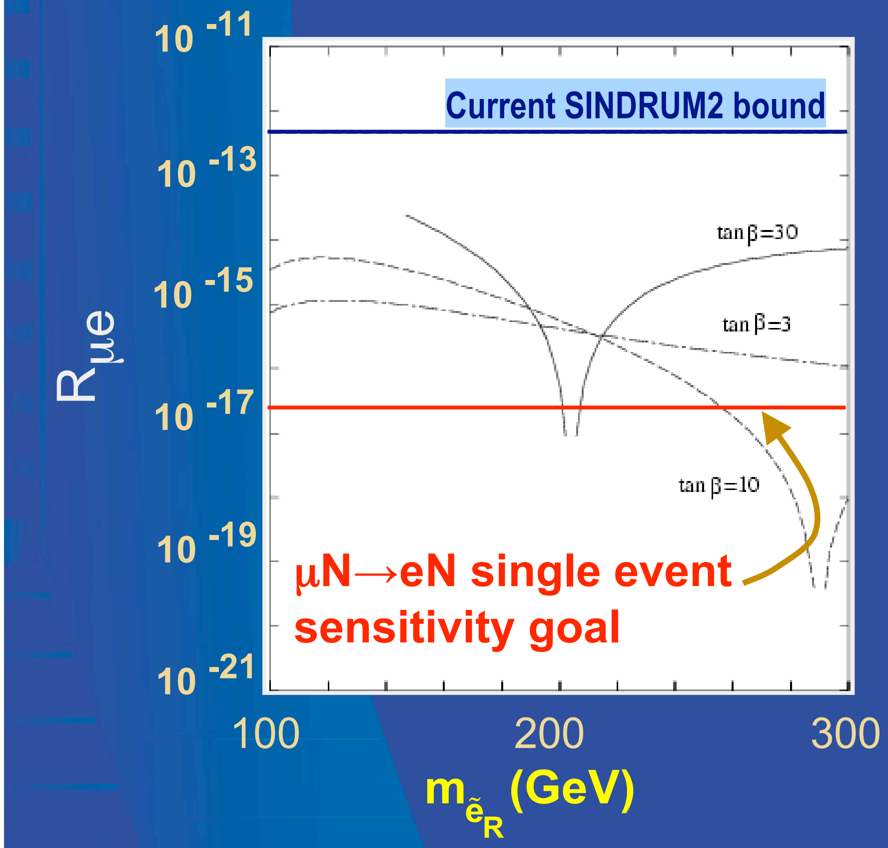
- Single Event Sensitivity = 2×10^{-17}
  - For 10^{18} stopped muons
  - If $R_{\mu e} = 10^{-15}$ will observe ~50 events
  - If $R_{\mu e} = 10^{-16}$ will observe ~ 5 events
- Expected background < 0.5 event
  - Assuming 2×10^{7} seconds of run time
- Expected limit < 6×10^{-17} @ 90% CL
- >5σ sensitivity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

Mu2e Sensitivty



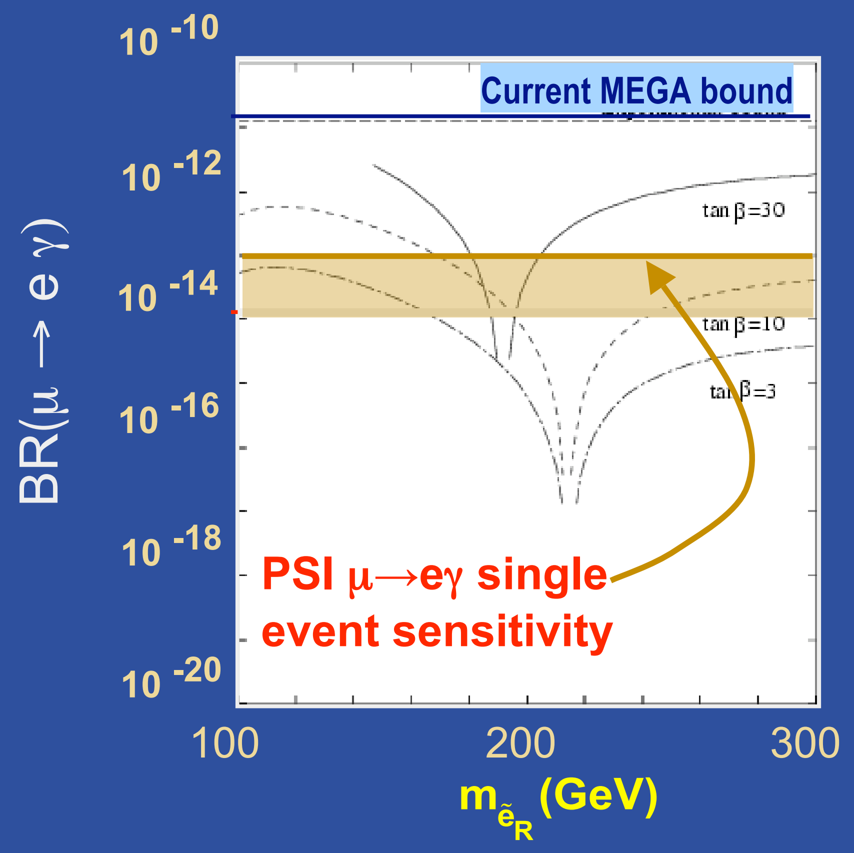
- Target Mu2e Sensitivity best in all scenarios

Mu2e Sensitivity



Current SINDRUM2 bound

μN→eN single event sensitivity goal

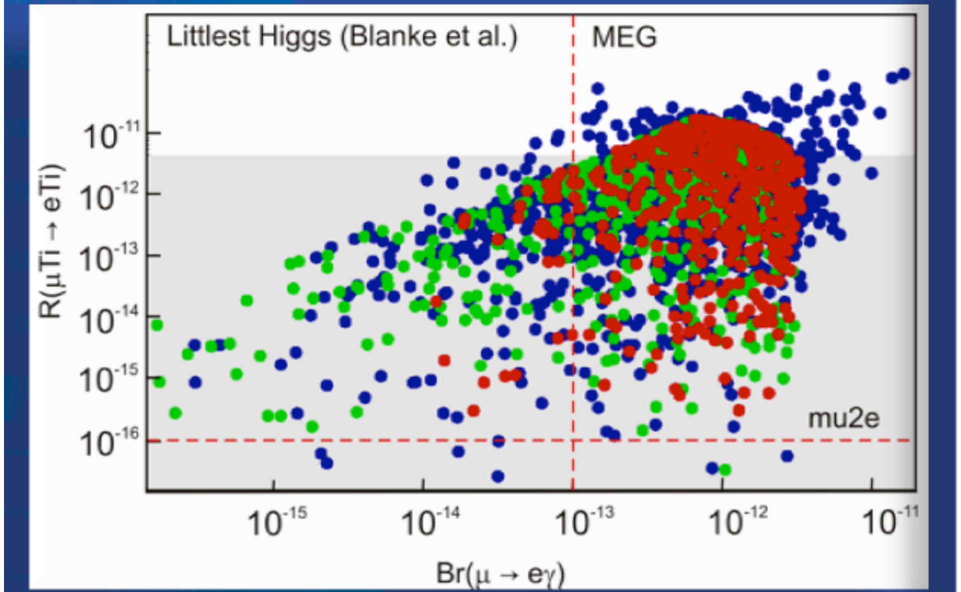


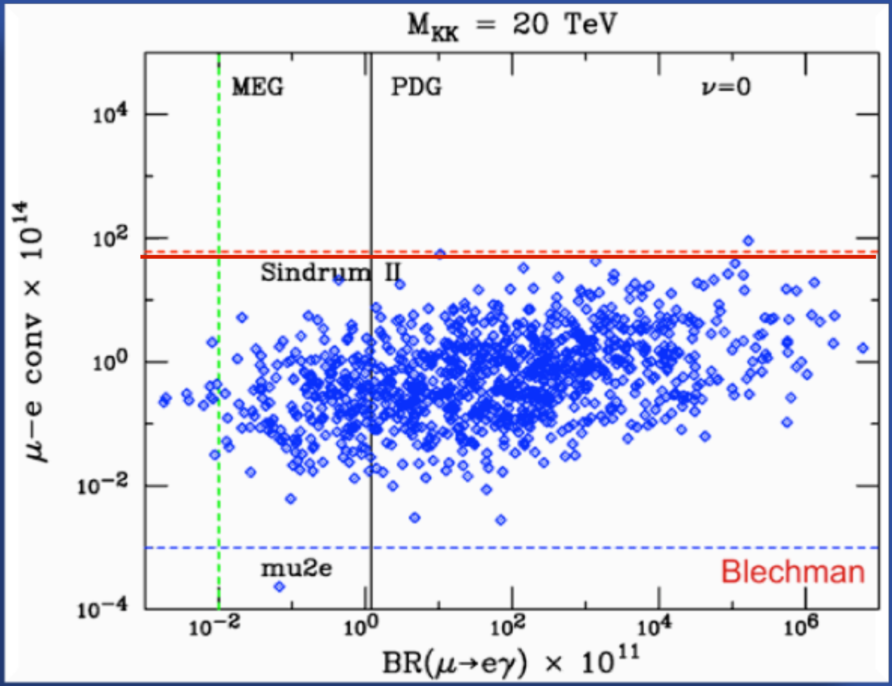
Current MEGA bound

PSI μ→eγ single event sensitivity

- A specific example in the context of SuSy

Mu2e Sensitivity





- Some more specific examples

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 μN --> eN
  - Use a delayed timing window to suppress bgd

Mu2e Signal

- Proceeds from the 1S state
  - Use x-rays as muons transition to 1S from atomic excited states to monitor rate of stopped-μ in situ

- 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
  - Signal window: 103.6-105.1 MeV accepts 62% signal

Mu2e Background

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

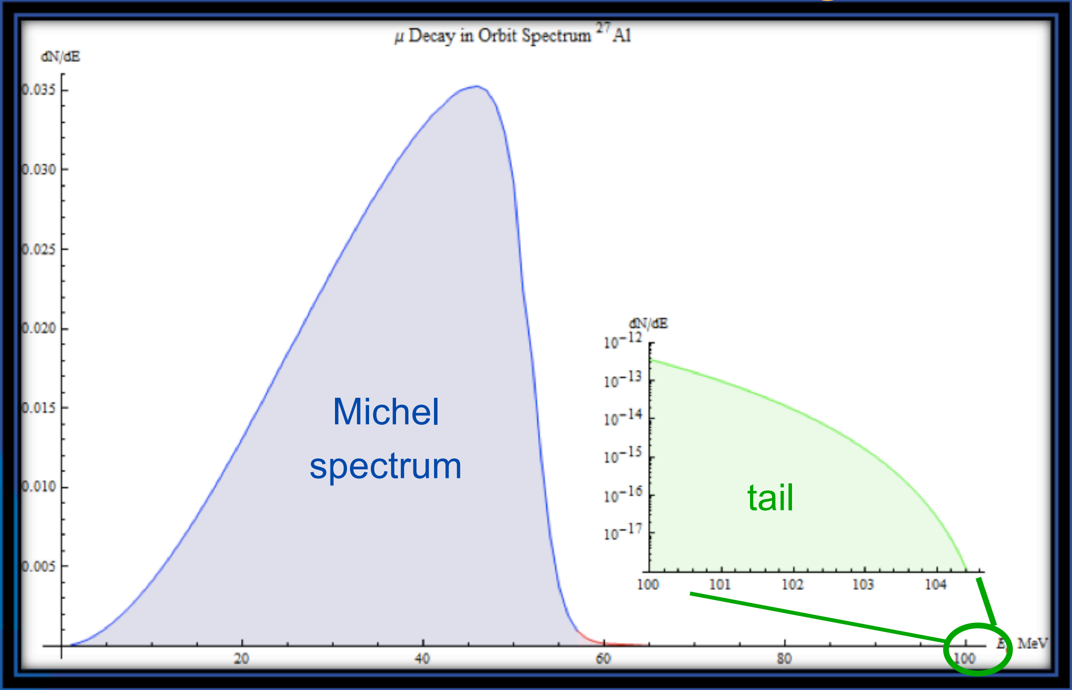
(assuming 1E18 stopped muons in 2E7 s of run time)

- Designed to be nearly background free

Mu2e Intrinsic Backgrounds

Once trapped in orbit, muons will:

1) Decay in orbit (DIO): $\mu^- N \text{ --> } e^- \nu_\mu \nu_e N$
   - For Al. DIO fraction is 39%
   - Electron spectrum has tail out to 105 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
  - $\mu^{-}N_{Z} \dashrightarrow \nu N_{Z-1}$
  - Used for normalization
- Radiative μ capture
  - $\mu^{-}N_{Z} \dashrightarrow \nu N_{Z-1} + \gamma$
  - (# Radiative / # Ordinary) ~ 1 / 100,000
  - E_{γ} kinematic end-point ~102 MeV
  - Asymmetric $\gamma \dashrightarrow e^{+}e^{-}$ 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

$$\text{out-of-time protons / in-time protons} < 10^{-9}$$

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 ~45% of the total background and scale *linearly* with the number of out-of-time protons

Mu2e Miscellaneous Backgrounds

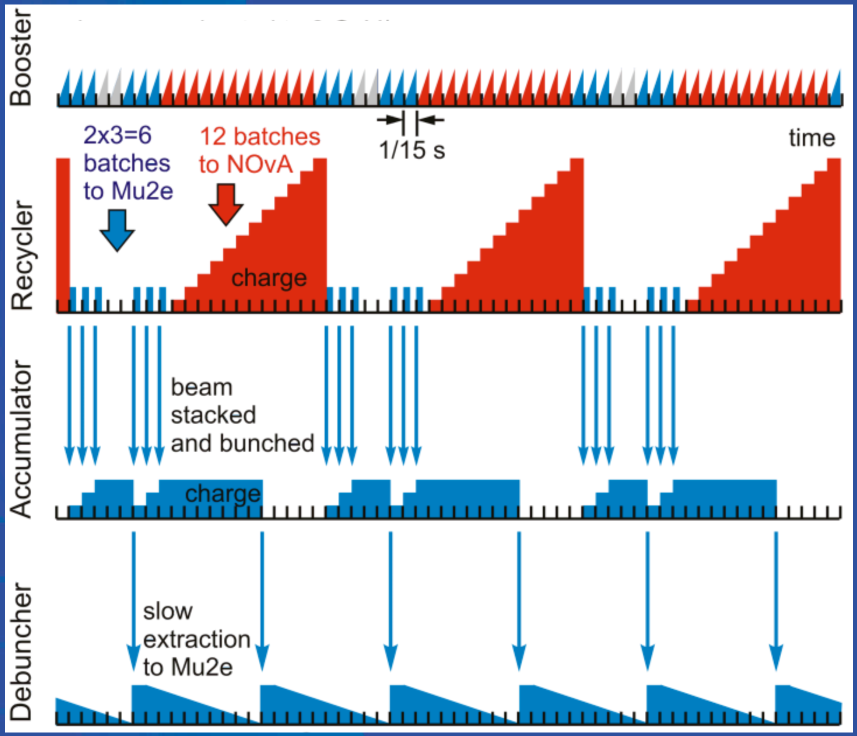
- Several additional miscellaneous sources can contribute background - most importantly
  - Anti-protons
    - Proton beam is just above pbar production threshold
    - These low momentum pbars wander until they annihilate
    - 150 μm mylar window in decay volume absorbs them all
    - Annihilations 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%

Mu2e Experimental Requirements

- Beamline
  - Narrow pulses (<100ns full width) of ~10^8 protons each, delivered every ~$2^*\tau_\mu^{Al}$ ~ 1700 ns
  - Stringent out-of-time requirements for POT
  - High duty cycle preferred

- Detector
  - Excellent spectrometer resolution (< 1MeV FWHM)
  - High efficiency (99.99%) cosmic veto shield
  - In situ monitoring of stopped-μ rate
  - Capable of handling high rates

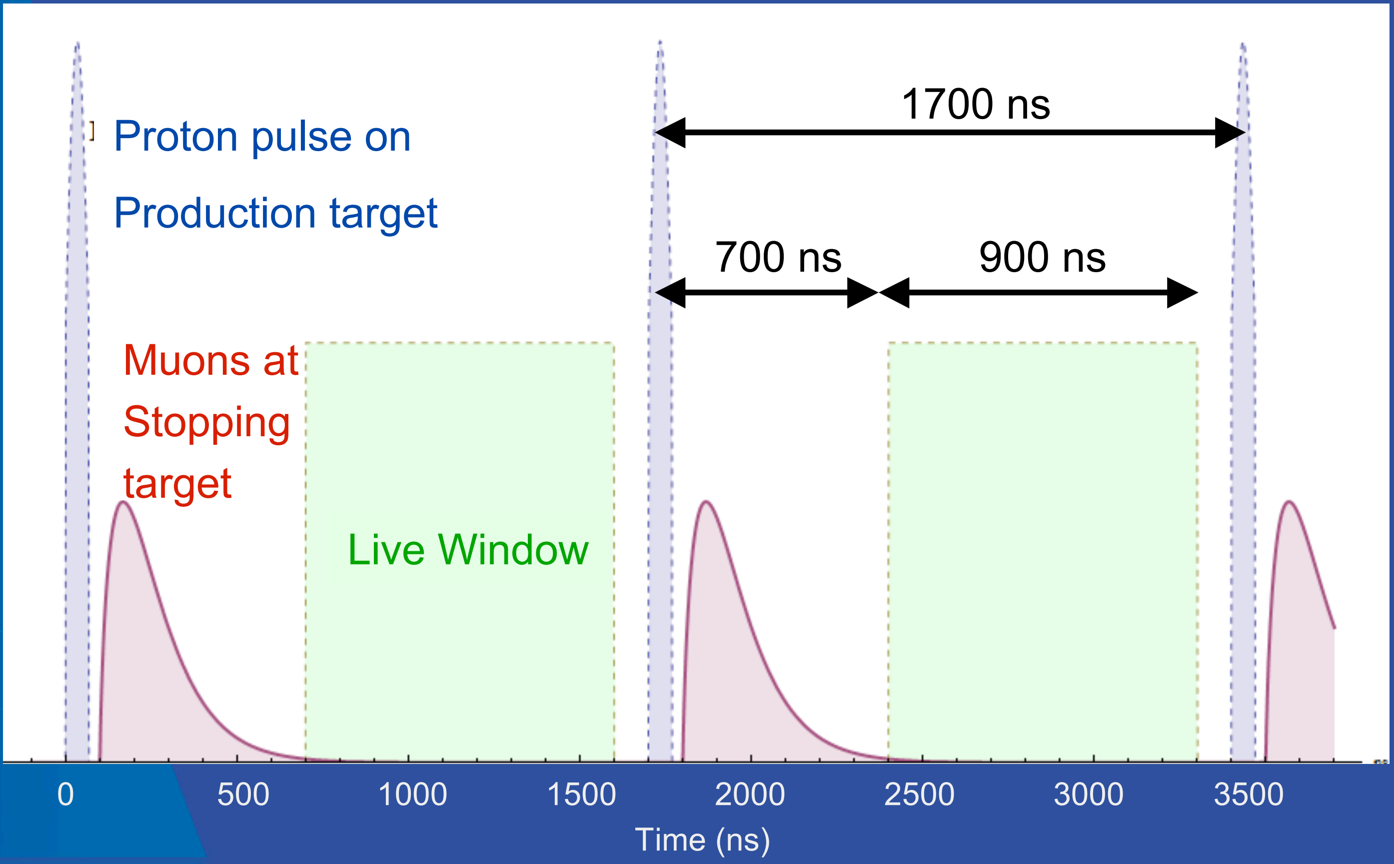
Mu2e Beamline



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

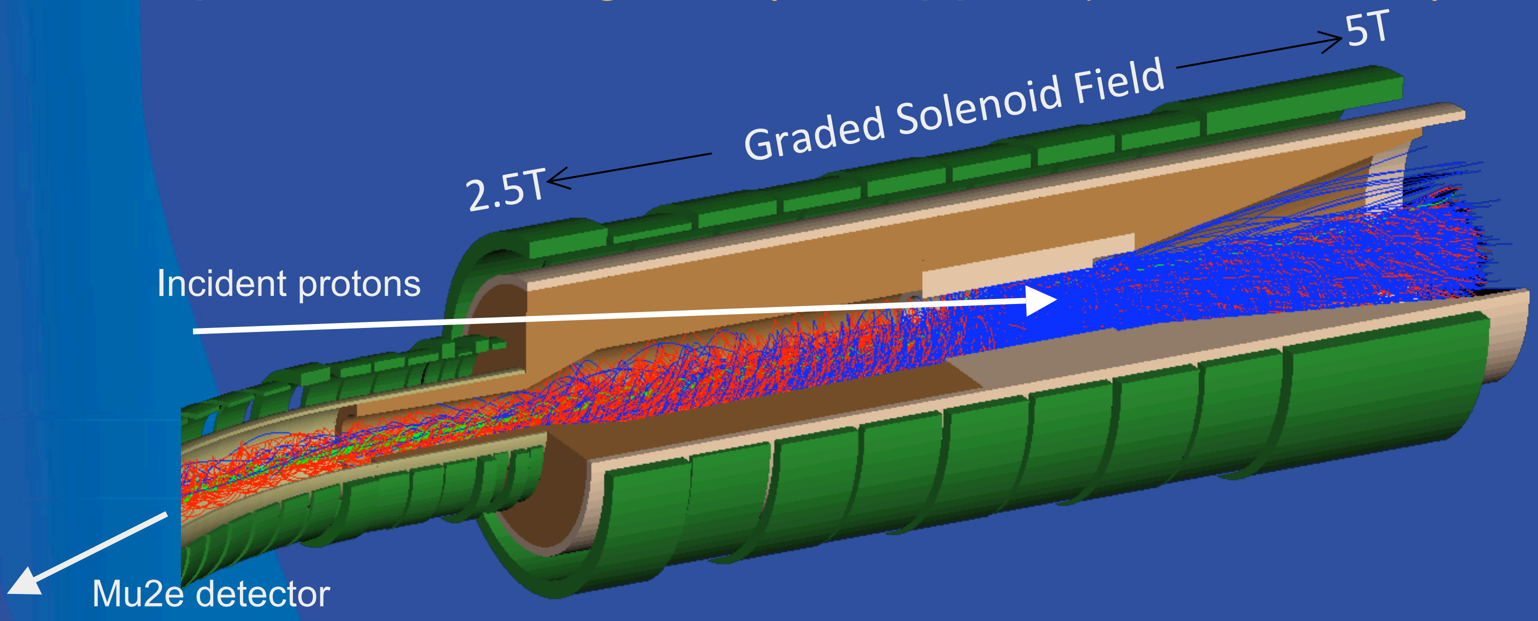
Mu2e Beamline

- Fermilab complex well matched to beam timing requirements for Mu2e



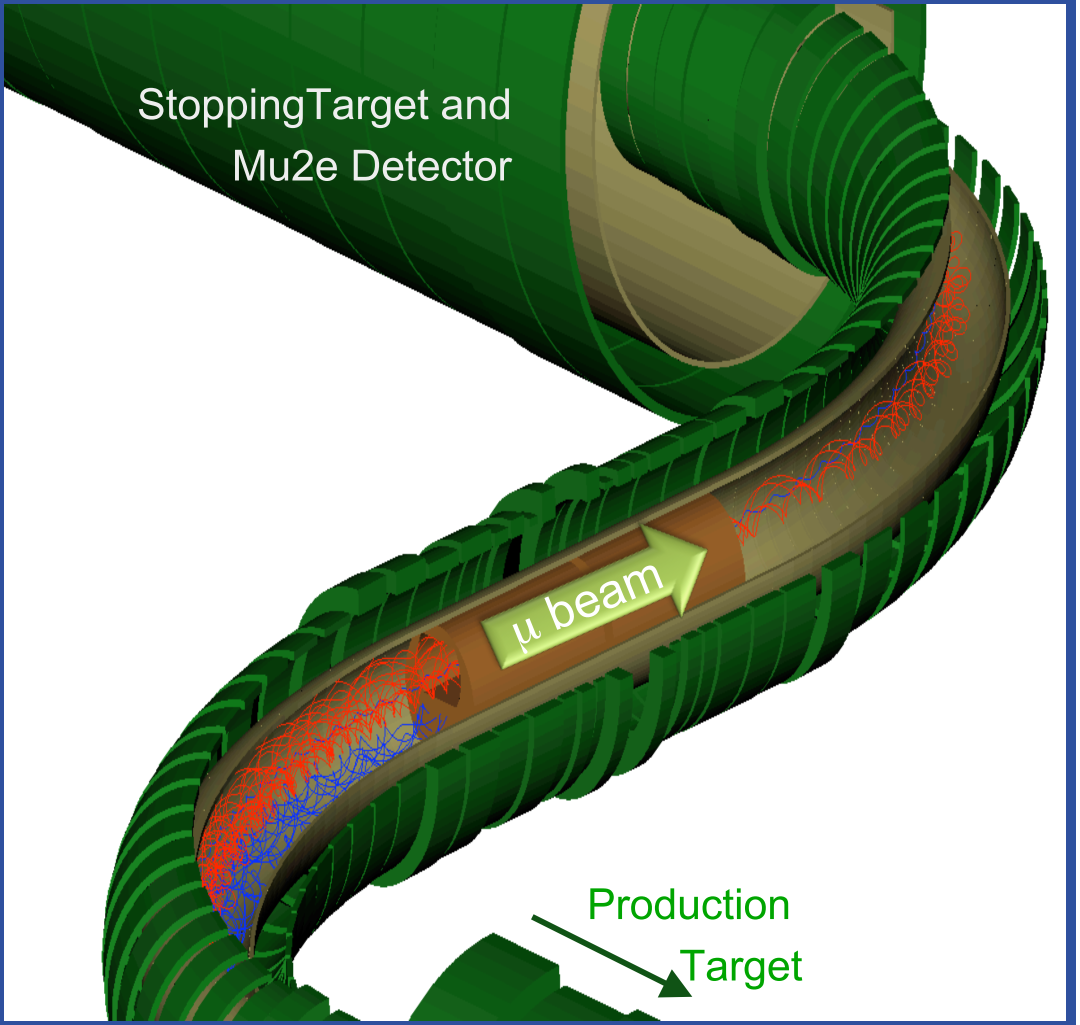
Mu2e Production Target

- 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)

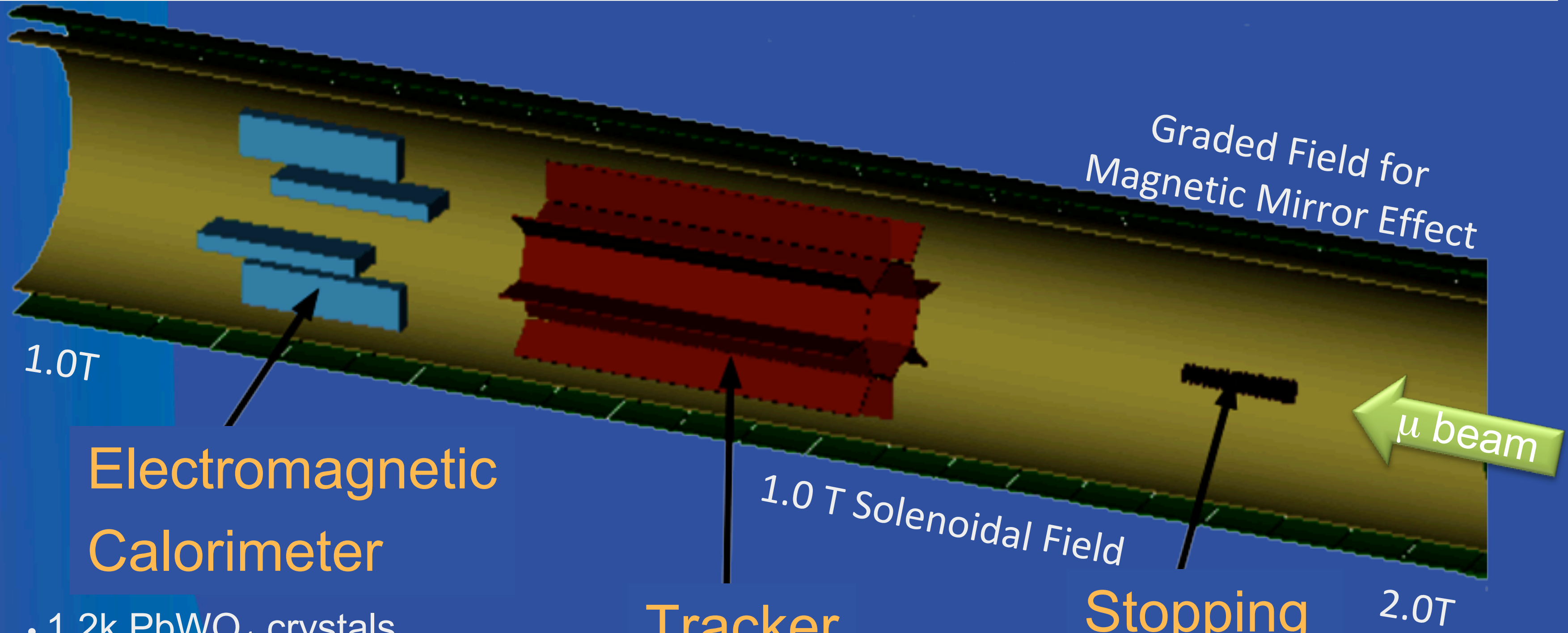


Mu2e Transport Solenoid

- 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

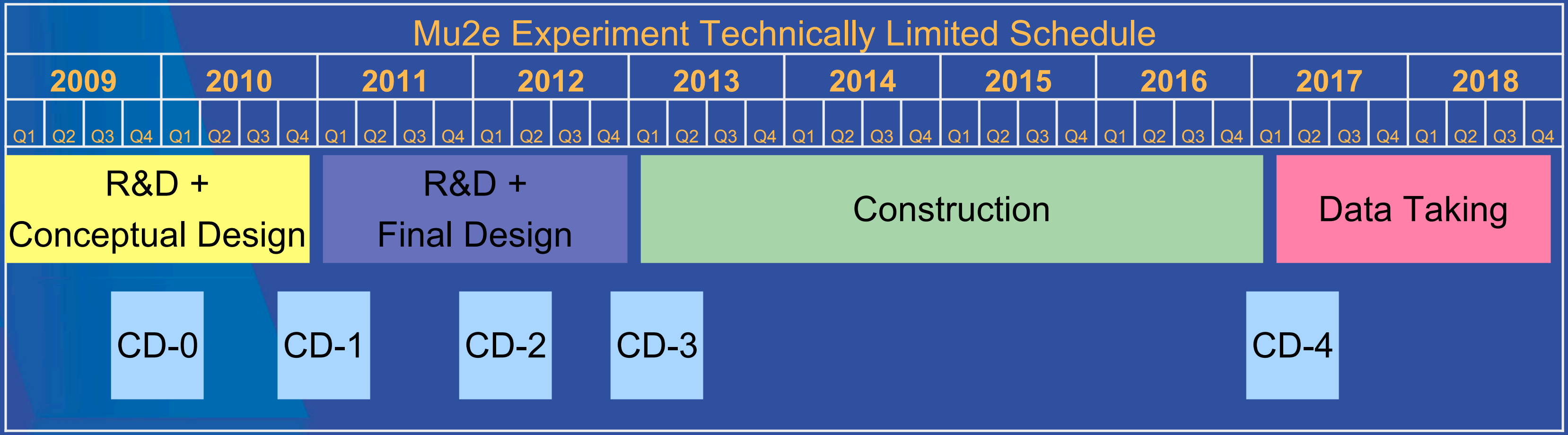
Stopping Target

- 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 Status and Schedule

- Have Stage-1 approval from Fermilab PAC
- Expect DOE CD-0 approval this summer and aim for CD-1 in 2010
- Cost estimated at $ 200M (fully loaded, escalated, and including contingencies)



Mu2e Experiment Technically Limited Schedule

2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

Q1 Q2 Q3 Q4 (each year)

R&D + Conceptual Design

R&D + Final Design

Construction

Data Taking

CD-0 CD-1 CD-2 CD-3 CD-4

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
- μN --> 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 world's best by 10^4
  - Probes mass scales well beyond LHC's capabilities
  - Two year run starting as early as 2016
  - Clear upgrade path using Project-X

Mu2e Collaboration

http://www-mu2e.fnal.gov

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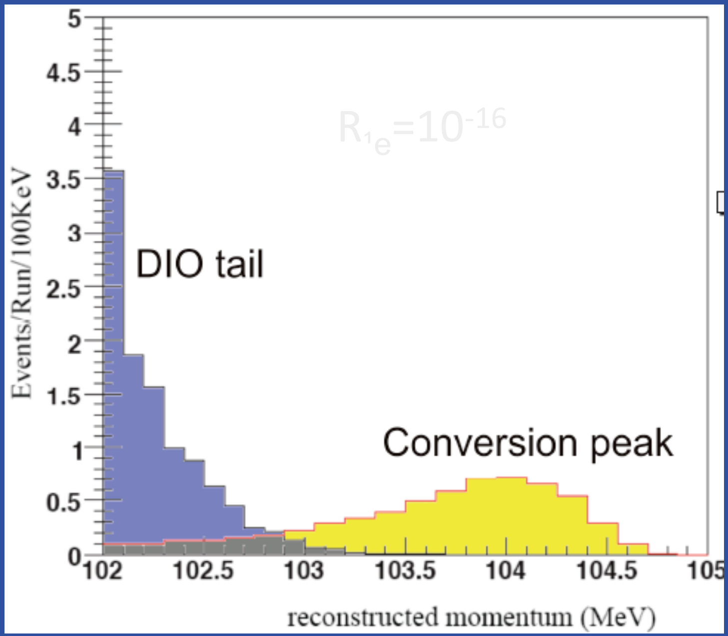
Backup Slides

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 μN-->eN measurements