The Mu2e Experiment at Fermilab

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On behalf of the Mu2e Collaboration

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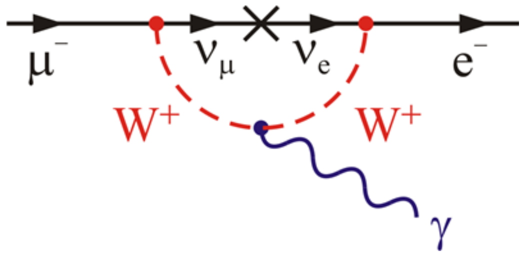
Charged Lepton Flavor Violation

- Charged lepton flavor violation (CLFV) is extremely suppressed in the Standard Model (SM) due to sums over $(\Delta m_{ij}/M_W)^4$, for example $\mu \rightarrow e\gamma$:

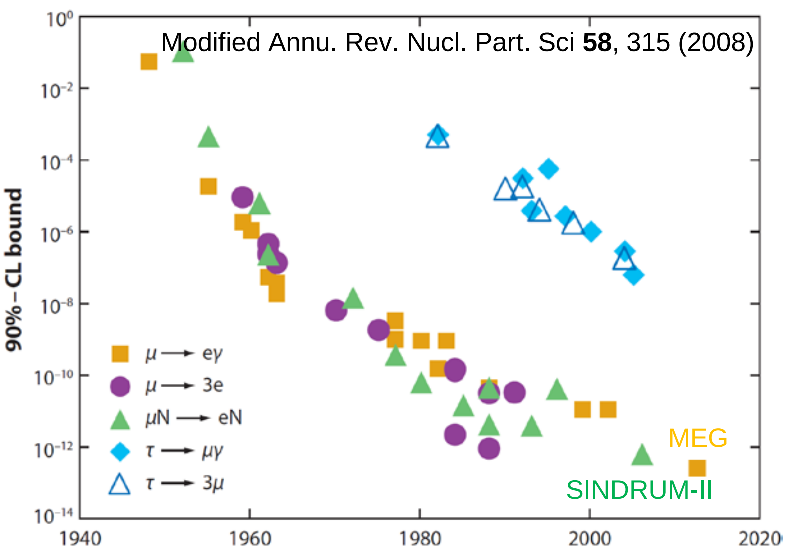
$$\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$



- SM rates of CLFV are below any conceivable experimental sensitivity

  → any detection of a signal is an unambiguous evidence for physics beyond the SM

- Searches for CLFV have a long history:



Most stringent limits for muon decays:

MEG	PRL **110**, 201801 (2013)
$\mathcal{B}(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13}$	

SINDRUM-II	EPJ C **47**, 337 (2006)
$R_{\mu e}(\mu N \rightarrow eN \text{ on Au}) < 7 \times 10^{-13}$	

Sensitivity to Charged Lepton Flavor Violation

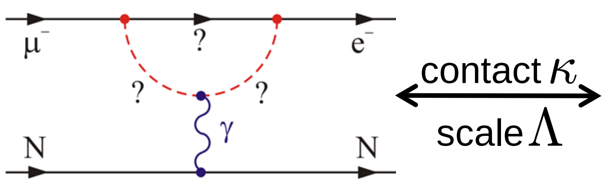
- Model-independent effective Lagrangian allowing for CLFV:

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{\mathrm{m}_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_{\mathrm{R}}\sigma_{\mu\nu}\mathrm{e}_{\mathrm{L}}\mathrm{F}^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_{\mathrm{L}}\gamma_\mu \mathrm{e}_{\mathrm{L}}\left(\sum_{\mathrm{q=u,d}}\bar{\mathrm{q}}_{\mathrm{L}}\gamma^\mu \mathrm{q}_{\mathrm{L}}\right)$$

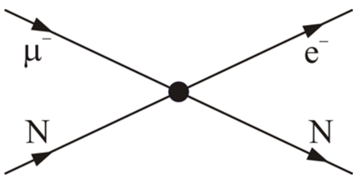
Prog. Part. Nucl. Phys.PRL **71**, 75 (2013)

- Two types of amplitudes contribute to CLFV:

Loops

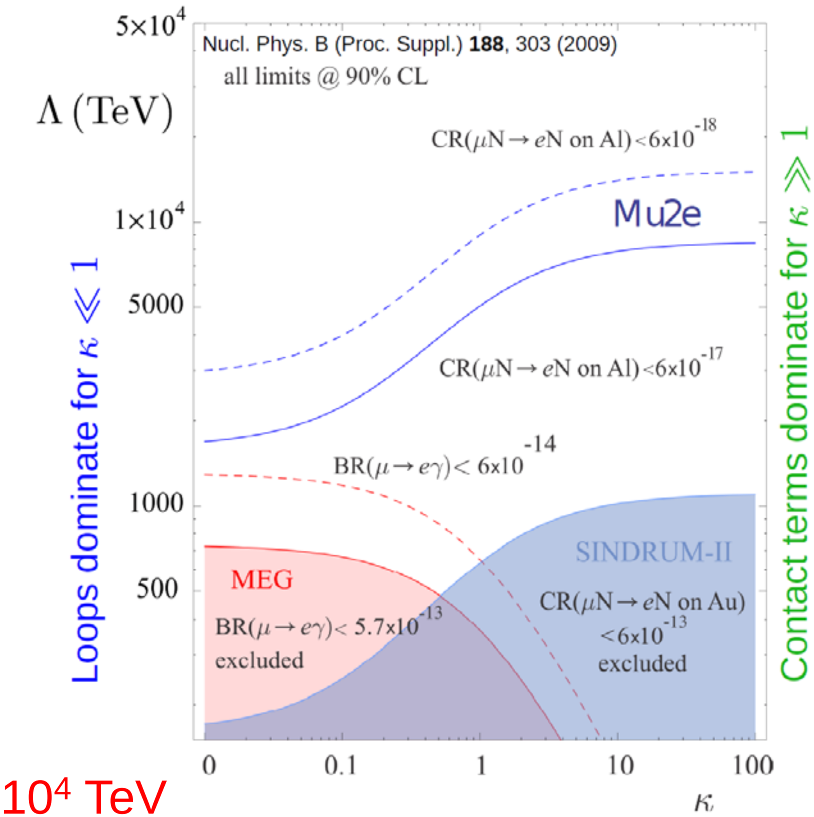


Contact Terms



$\mu \to e\gamma$ | ~~$\mu \to e\gamma$~~

$\mu N \to eN$ | $\mu N \to eN$



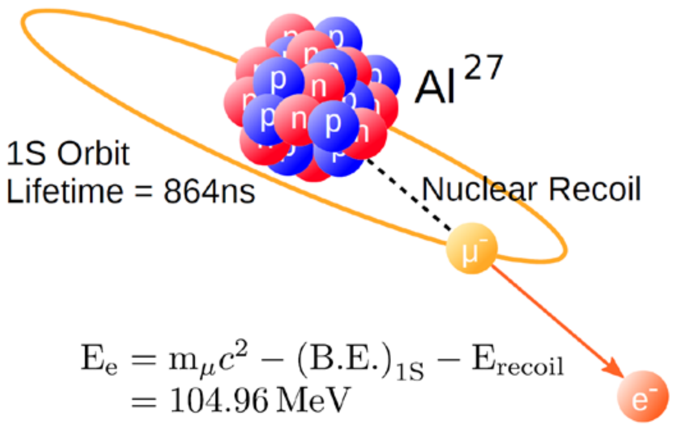
- $\mu \to e\gamma$ and $\mu N \to eN$ have complementary sensitivity to new physics

  → important to search for both processes

- Mu2e can probe at all κ and mass scales up to 10^4 TeV

Conversion of Muons to Electrons

- Mu2e searches for the neutrino-less $\mu^- \to e^-$ conversion in the field of an atomic nucleus:



- Coherent process
- Kinematics of a two-body decay
  → mono-energetic electron
- Lifetime muonic aluminum τ(1S)=864 ns
- Corrected for nuclear recoil and binding energy the signature is a single 105 MeV electron

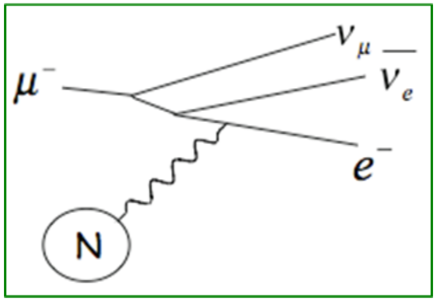
- Observable: Ratio of $\mu^- \to e^-$ conversion rate relative to muon capture by nucleus

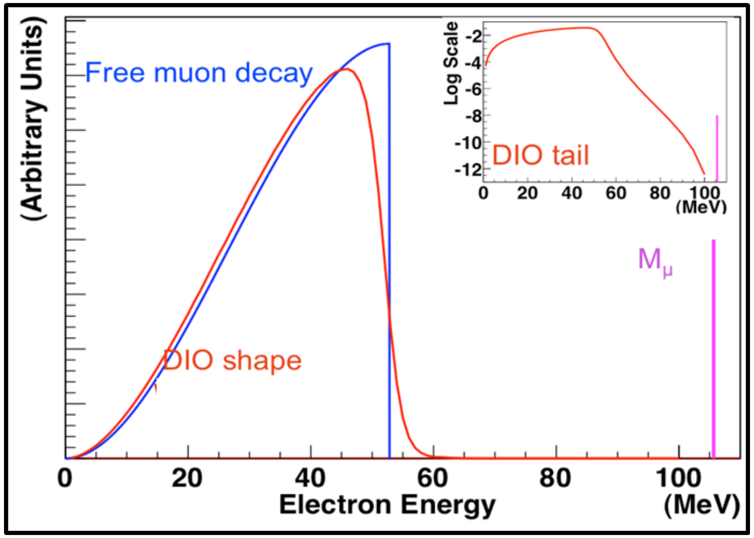
$$R_{\mu e} = \frac{\Gamma(\mu^- + A(Z,N) \to e^- + A(Z,N))}{\Gamma(\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N))}$$

- Mu2e is designed to measure $R_{\mu e}$ with a single-event-sensitivity of 2.9×10^{-17}

→ sensitivity improvement of 4 orders of magnitude compared to SINDRUM-II

Background Processes

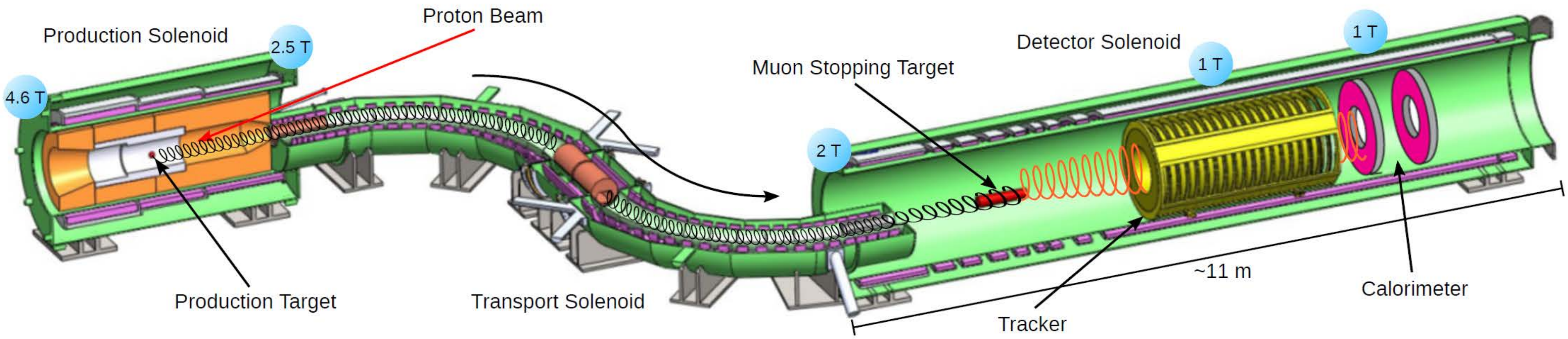




- The dominant irreducible background comes from the decay of bound muons
  - 39% of stopped muons decay in orbit (DIO)
  - recoil of the nucleus causes tail into the signal region
  - spectrum falls rapidly close to the endpoint
- Other backgrounds originate from:
  - radiative pion captures
  - beam-induced backgrounds
  - cosmic ray or antiproton induced backgrounds

The Mu2e Experiment

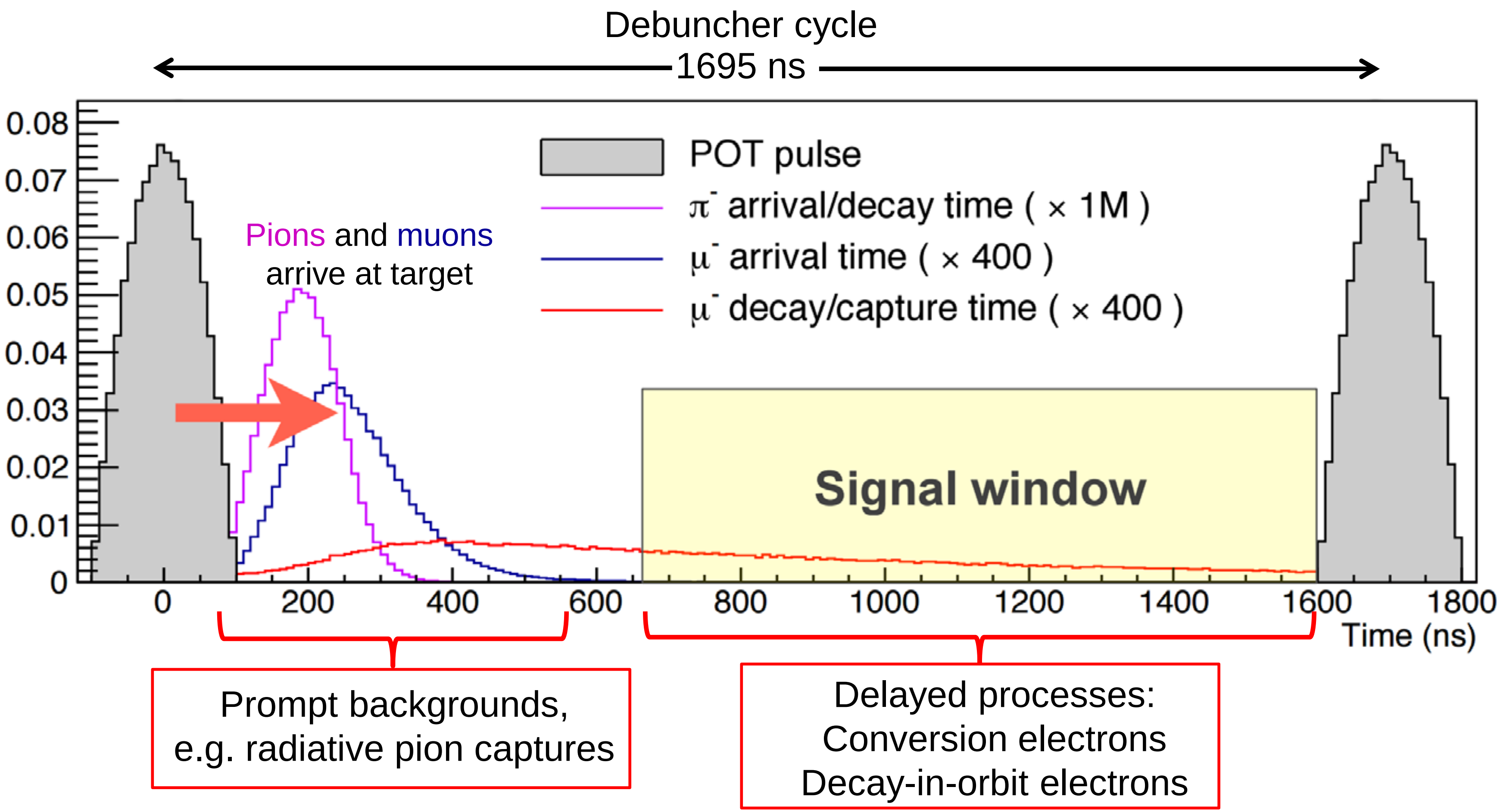
- Key components:
  - Intense 8 GeV proton beam
  - 3 superconducting solenoids (4.6T to 1T)
  - Muon stopping target, tracker and calorimeter



- Measurement principle:
  - Proton beam on tungsten target produces pions and muons
  - Muons are collected and propagated through s-shaped transport solenoid
  - Collimated low energy muons are stopped on an aluminum target
  - Trajectories and energies of electrons from muonic atoms are measured

Mu2e Timing Structure

- FNAL accelerator complex and Mu2e timing structure:

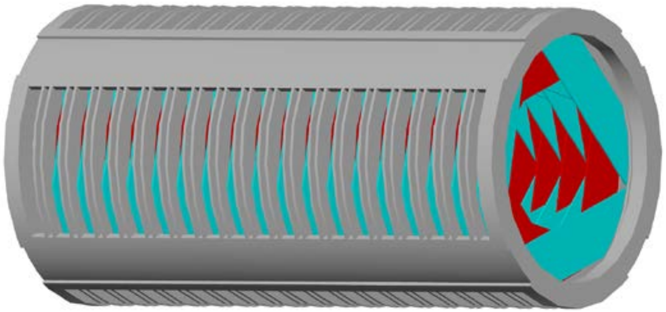


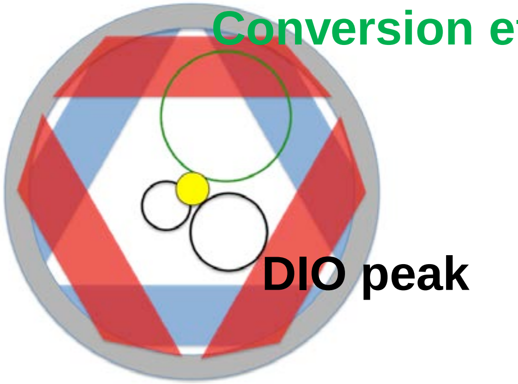
- Utilize the pulsed structure of the proton beam and the lifetime of muonic atoms to suppress prompt backgrounds

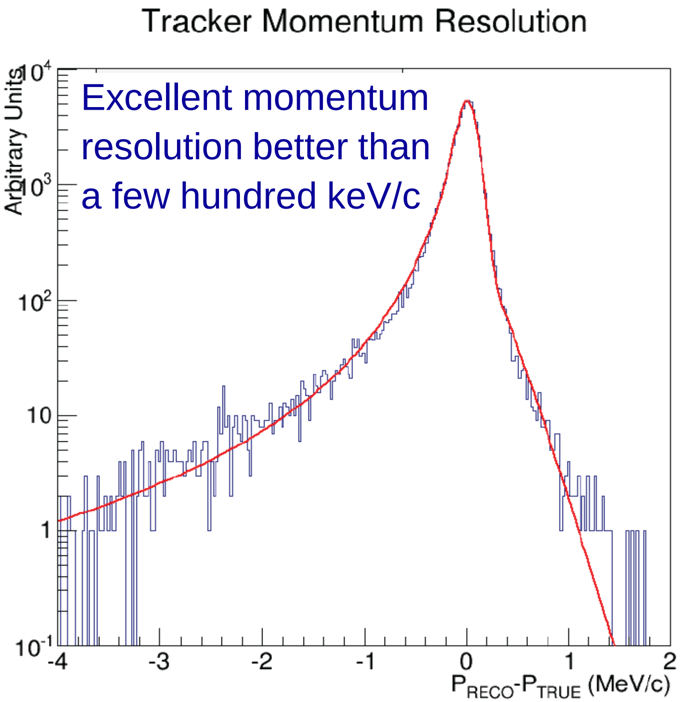
Tracker

- ≈20,000 straw tubes:
  - 5 mm diameter
  - 25 µm sense wire
  - 15 µm thick mylar walls
  - 80/20 Ar:CO_2

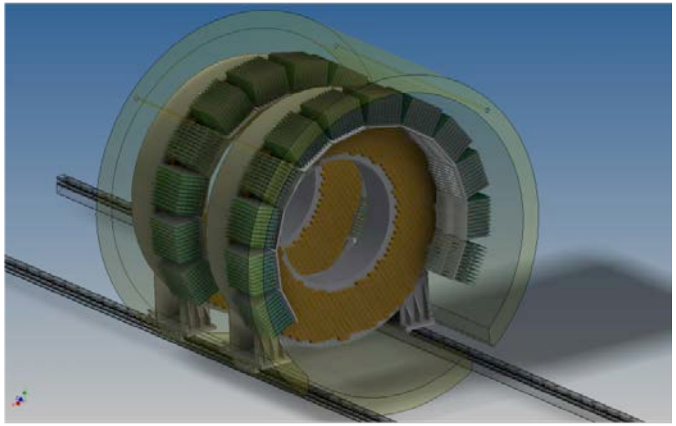
- 18 stations of straw chambers
  - 3 m long
  - low effective mass
  - insensitive to <53 MeV electrons



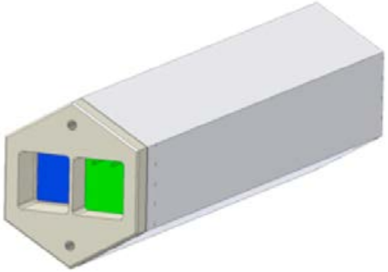


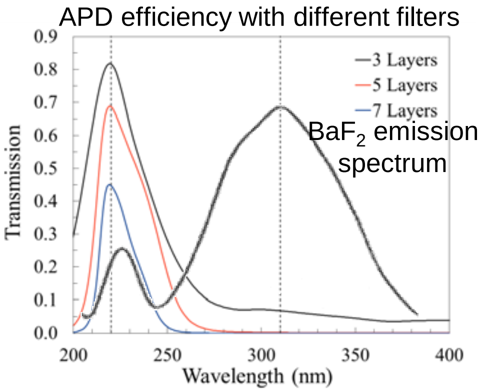


Calorimeter



- Two disks placed behind the tracker
  - radii 36 to 70 cm
  - each disk: ≈800 BaF_2 crystals
  - crystals 3x3x20 cm (10 X_0)





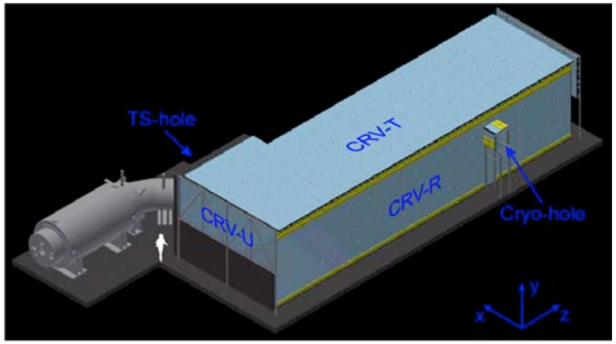
- Each BaF_2 crystal is readout by 2 APDs
  - APDs tailored to discriminate between fast and slow scintillating components
  - unprecedented sensitivity in the UV
  - capable of high rates

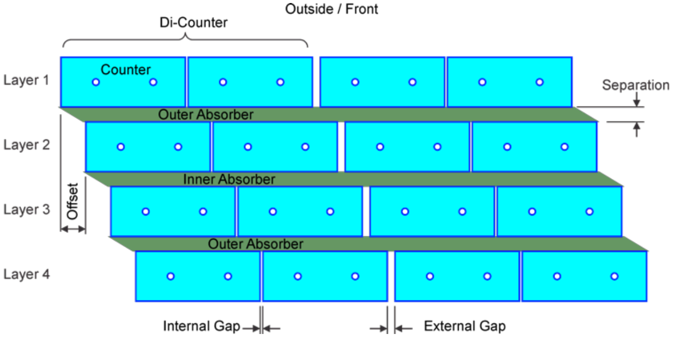
- The calorimeter provides independent timing and energy measurements (resolution $\sigma(t)=0.5$ ns and $\sigma(E)/E=5\%$)

- The calorimeter contributes to particle identification and the trigger

Further Instrumentation

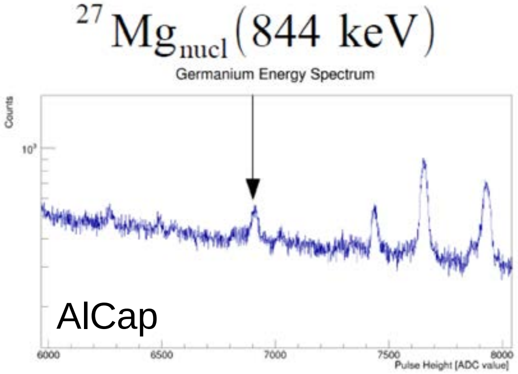
- Cosmic ray veto
  - Covers whole detector solenoid and downstream end of the transport solenoid
  - 4 layers of long scintillator strips with wavelength shifter and aluminum absorbers





- Muon stopping target monitor
  - measures delayed γ-rays from radioactive nuclei produced by nuclear muon captures
  - enables to determine the number of captured muons

  → important as normalization for $R_{\mu e}$

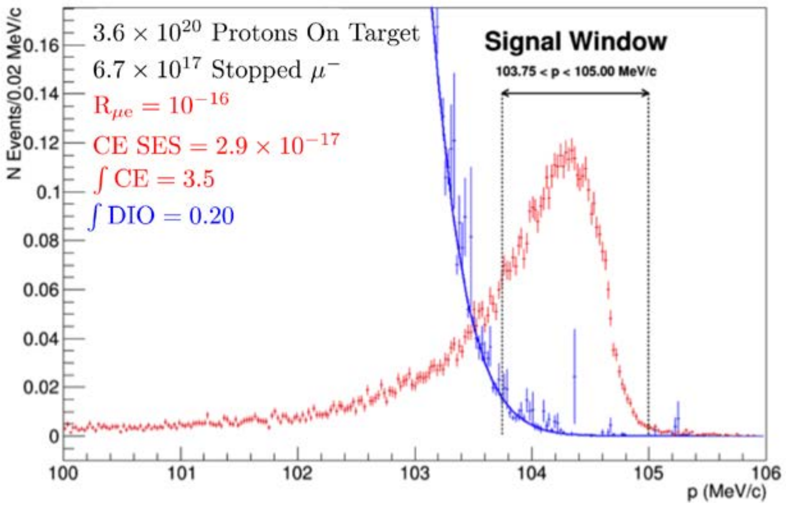


Background Estimates and Detection of the Signal

- Mu2e background estimates for 3 years of running:

	Category	Background process	Estimated yield (events)
54%	Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Late Arriving	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
		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
13%	Miscellaneous	Antiproton induced	0.047 ± 0.024
25%		Cosmic ray induced	0.092 ± 0.020
		Total	0.37 ± 0.10

- Reconstructed simulated momentum spectra assuming $R_{\mu e} = 10^{-16}$



Separation of conversion from DIO electrons due to excellent momentum resolution

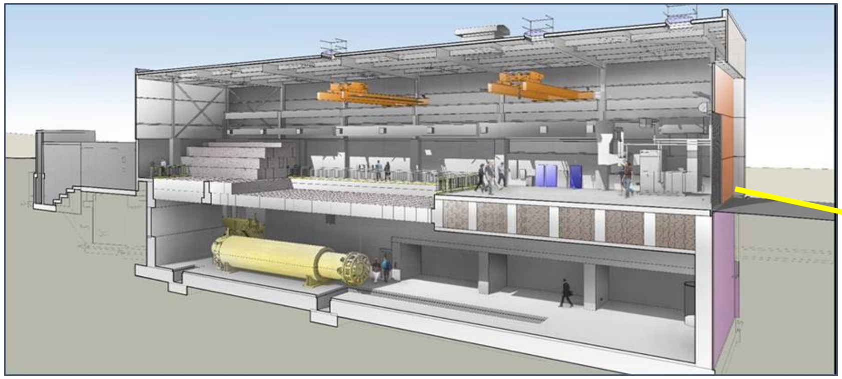
→ Signal is a peak over the background close to the endpoint

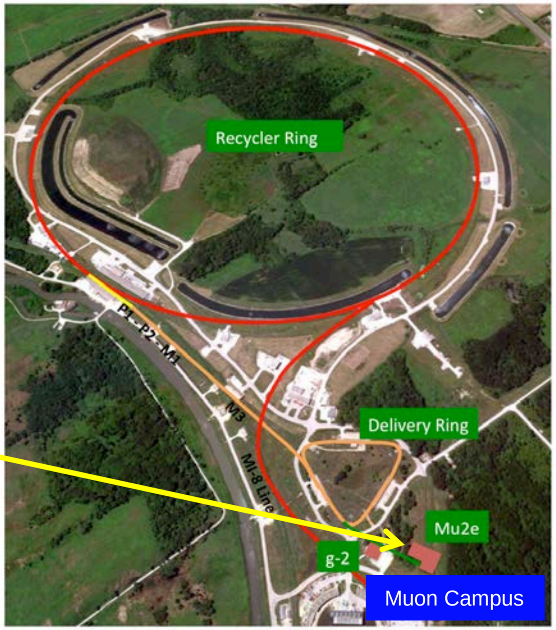
Current Status

- Mu2e received the DOE critical decision (CD-2/3b) approval in March 2015
  → the budget, timeline and baseline are fixed;
  i.e. for civil construction and magnet fabrication

- Testing of a transport solenoid coil prototype has started

- Construction of the detector building has started





- Preparations for DOE CD-3c "proceed with construction" review in early 2016

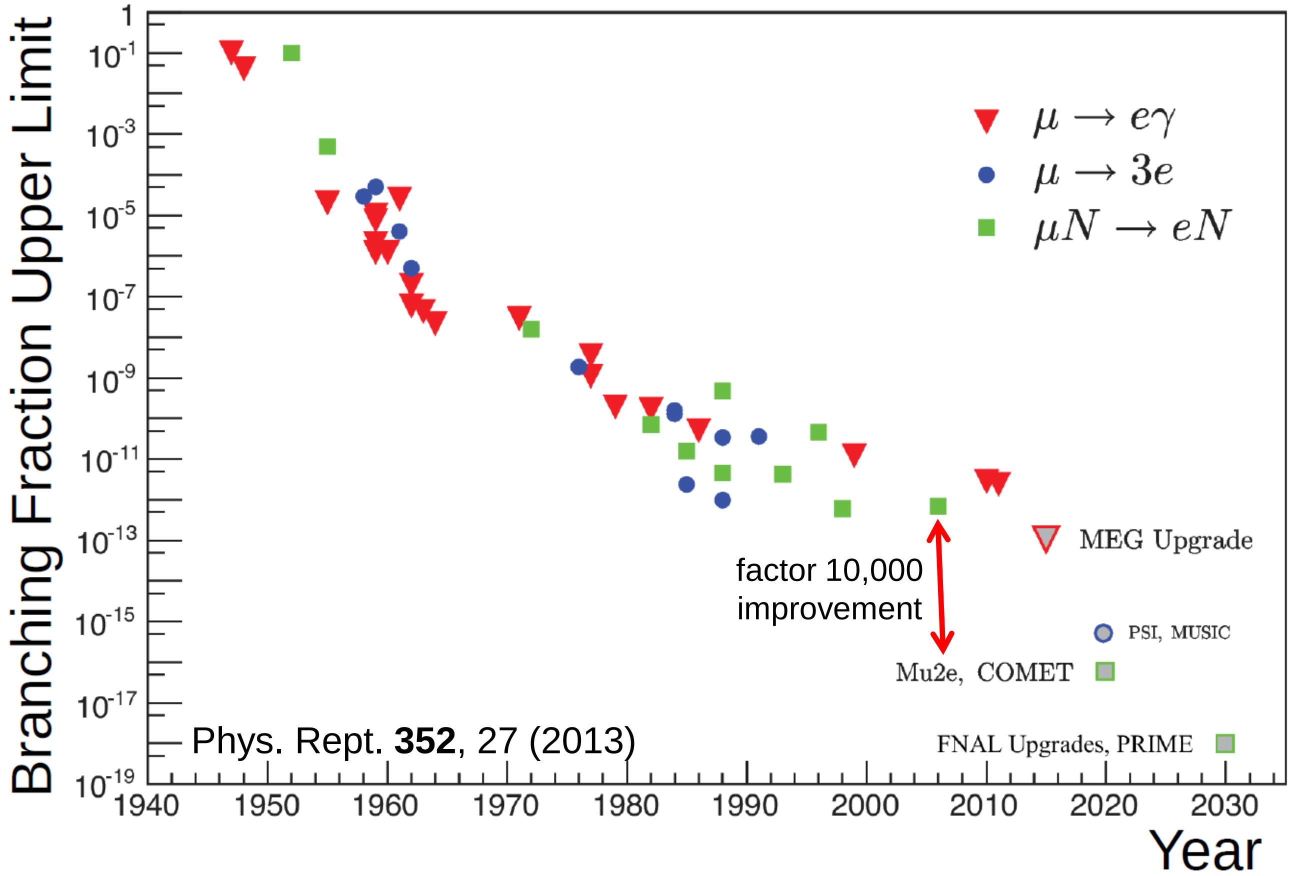
- The commissioning of the beam-line and detector are scheduled for 2020

Summary

- Mu2e will search charged lepton flavor violation at unprecedented sensitivity
- Mu2e has a 5σ discovery sensitivity to all $\mu \rightarrow e$ conversion rates greater than 2×10^{-16} and probes effective mass scales of new physics up to the 10^4 TeV scale
- Expected sensitivity is $R_{\mu e}(\mu N \rightarrow eN \text{ on Al}) < 6 \times 10^{-17}$ in 3 years running
  (improvement of 4 order of magnitude to previous experiments)
- Mu2e construction and next approval steps are proceeding on schedule
- Commissioning is scheduled for 2020

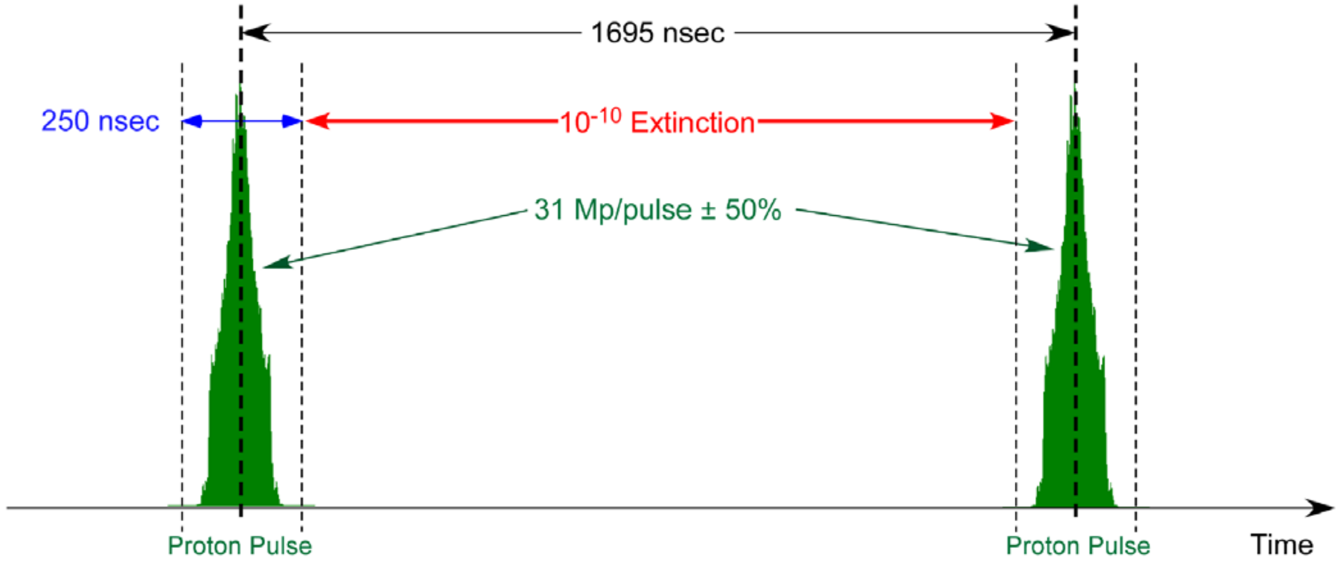
BACKUP

Prospects of Charged Lepton Flavor Violation



Extinction Monitor

- Extinction defined as number of protons striking the production target between beam pulses to the number of protons striking during the beam pulses



- For Mu2e an extinction of about 10^{-10} is required to reduce the backgrounds induced by out of time particles to an accectable level
- An extinction monitor will estimate the overall performance by monitoring the beam hitting the primary target