The Mu2e Experiment at Fermilab

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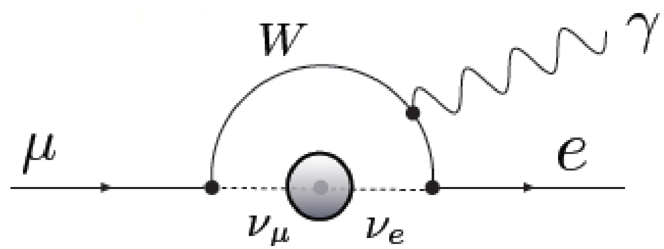
Flavor Violation

- We have known for a long time that quarks mix → (Quark) Flavor Violation
  – Mixing strengths parameterized by CKM matrix
- In last 20 years we have 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)

CLFV in the Standard Model

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

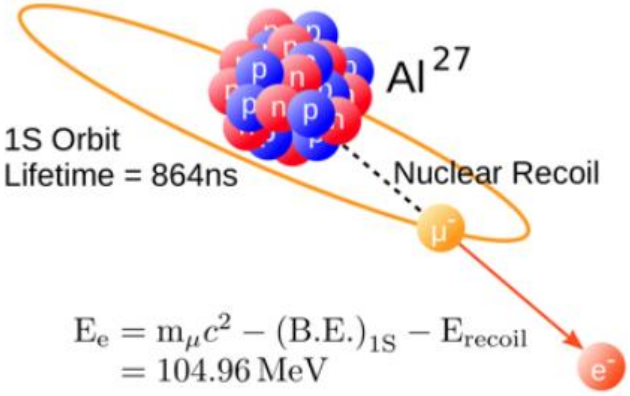
(br~ $\Delta m_{\nu}^2 / M_W^2 < 10^{-50}$)



- Any observation will be signal of New Physics
- However, many New Physics models predict rates observable at next generation CLFV experiments

μ^- Al → e^- Al Conversion

- The muon converts into an electron in the field of a nucleus that is left intact



- The resulting electron has a monochromatic energy slightly below the muon rest mass. For Aluminum E_{ce} = 104.96 MeV

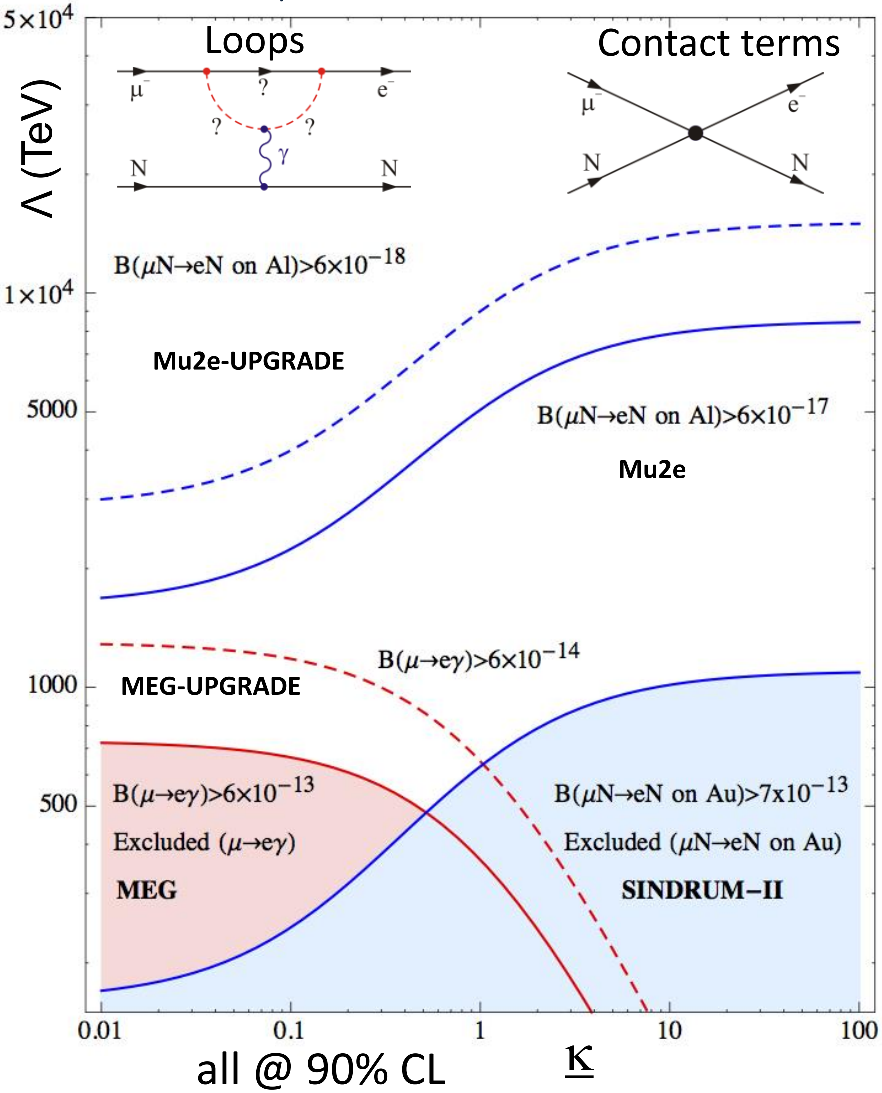
- The mu2e goal is to set an upper limit on the branching ratio normalized to the total muon capture rate of:

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + \mathrm{N(A,Z)}\right) \to e^- + \mathrm{N(A,Z)}}{\Gamma\left(\mu^- + \mathrm{N(A,Z)}\right) \to \text{all muon captures})} \leq 6 \times 10^{-17} \text{ @ } 90\% \text{ C.L.}$$

it represents a 4 order of magnitude improvement on the Sindrum II limit

Probing New Physics with CLFV

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



all @ 90% CL

Effective Lagrangian

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}R\sigma_{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma^\mu q_L$$

- Contact κ, mass scale Λ
- ‘Loops’, κ<<1
- ‘Contact terms’, κ>>1
- **Mu2e will have sensitivity to Λ (mass scale) up to thousands of TeV beyond any existing accelerator!**
- Mu2e is sensitive over the entire κ range

Mu2e Strategy

Generate a low energy muon pulsed beam

↓

Stop 10^{18} muons in aluminum

↓

Muons quickly get to 1S orbit

↓

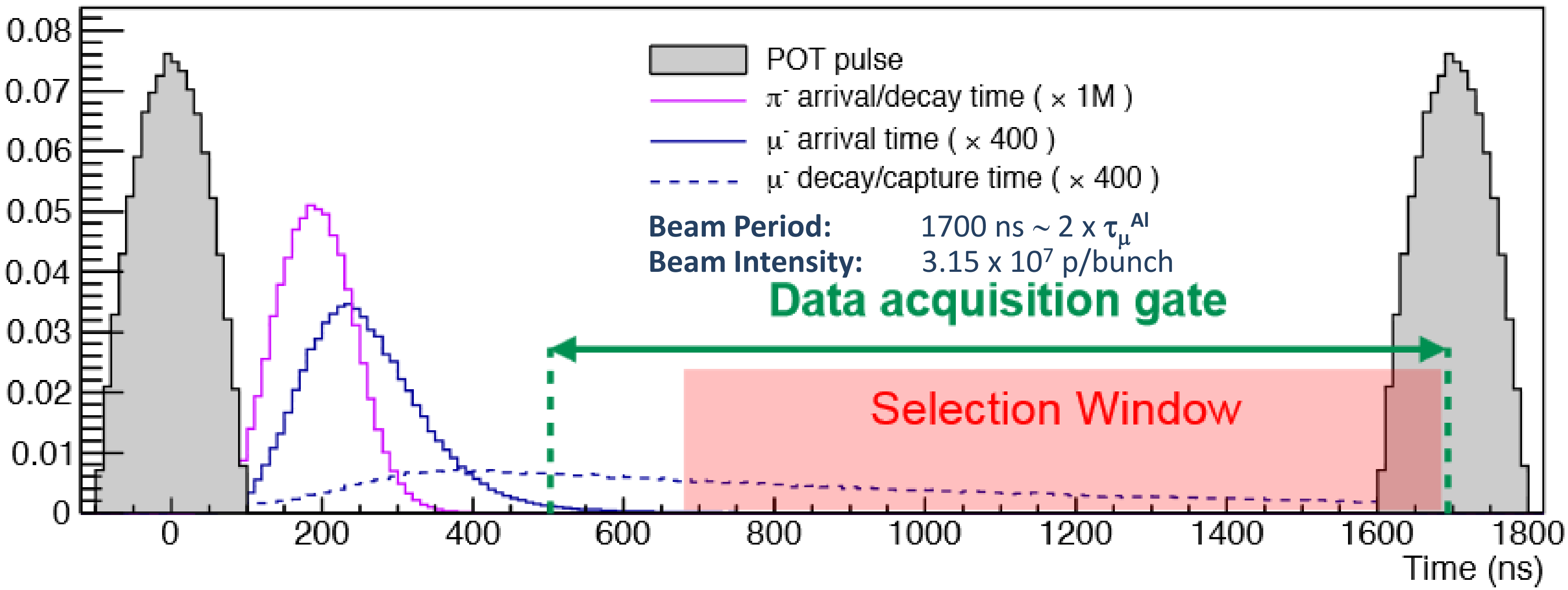
Lifetime of muonic atom is 864 ns

↓

Look for 104.96 MeV electron

Mu2e Beam Structure

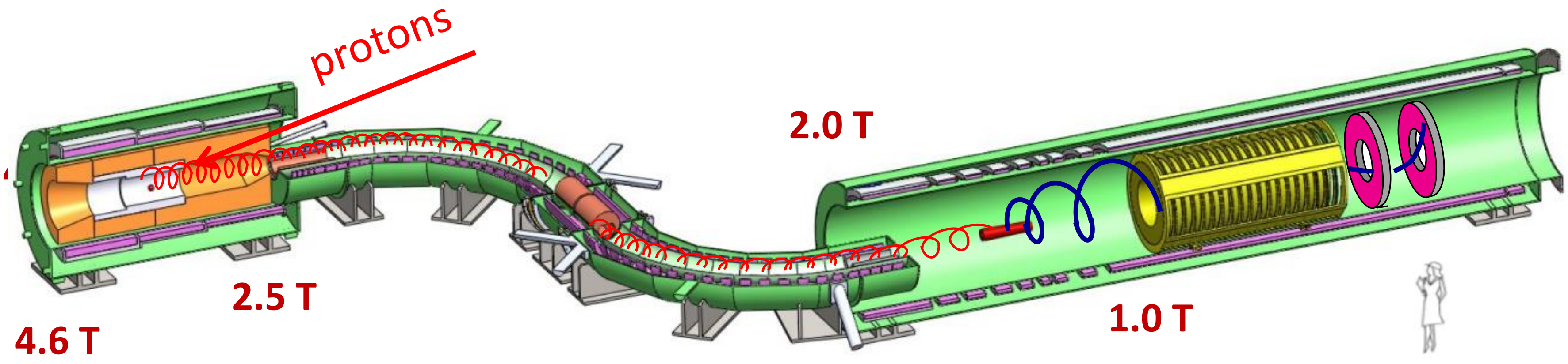
- Mu2e uses a pulsed proton beam and a delayed selection window to suppress the prompt backgrounds coming from proton interactions and pion captures



- A proton extinction factor at the level of **10^{-10}** is needed to avoid out-of-bunch protons that can generate prompt background inside the selection windows.

Experimental Setup

- **Production Solenoid (PS):**
  - 8 GeV protons interact with a tungsten target to produce mostly π- and μ- (from π- decay)
  - Graded magnetic field reflects slow forward π- and μ-



about 25 meters end-to-end

- **Transport Solenoid (TS):**
  - Captures π- and subsequent μ-;
  - Momentum- and sign-selects beam

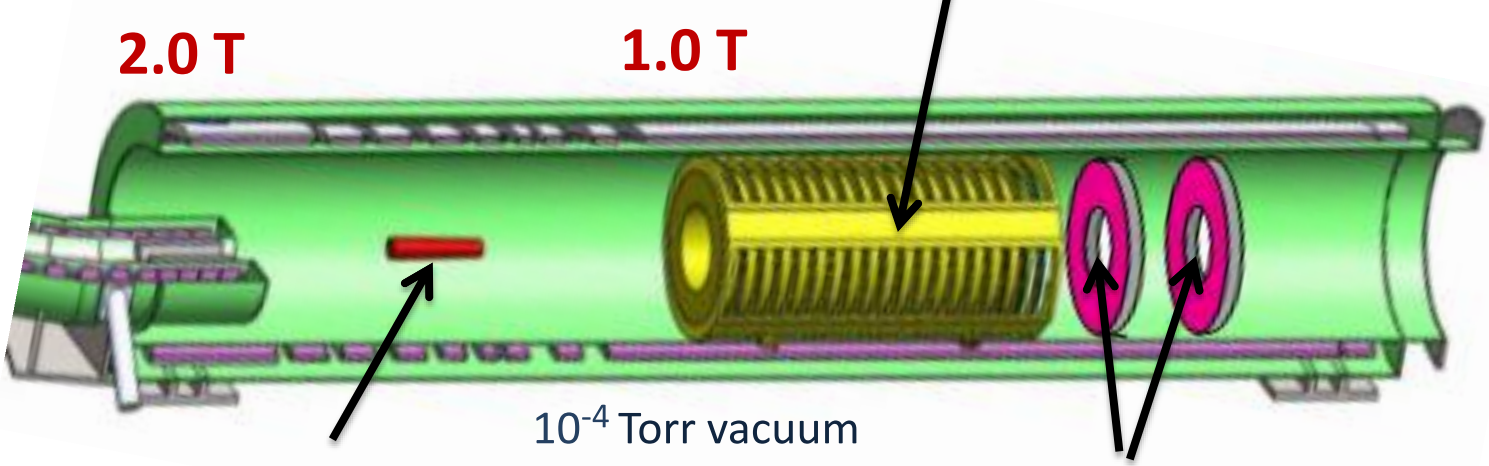
- **Detector Solenoid (DS):**
  - Stops μ- in the target and houses the detector system

The Mu2e Detector

Graded field reflects in the detector region a fraction of conversion electrons emitted on the wrong side, increasing acceptance.

Tracker:

- High precision momentum measurement
- To identify the conversion electron



Stopping Target:

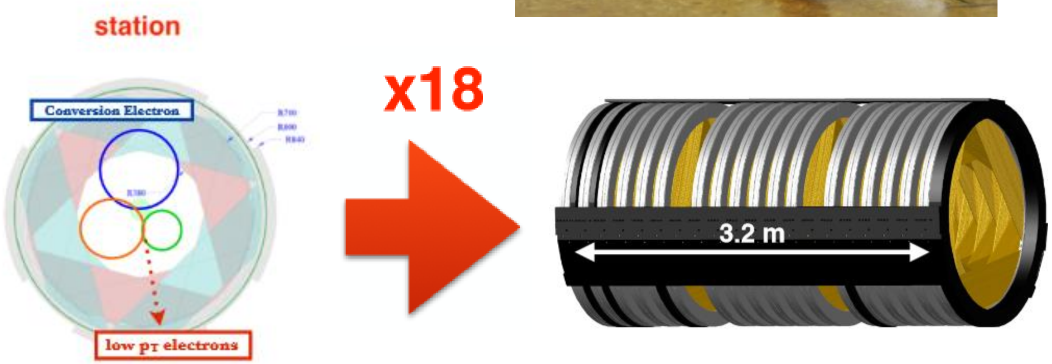
- 34 Al foils (864 ns lifetime)
- **1.6×10^{-3} stopped μ per proton on target**

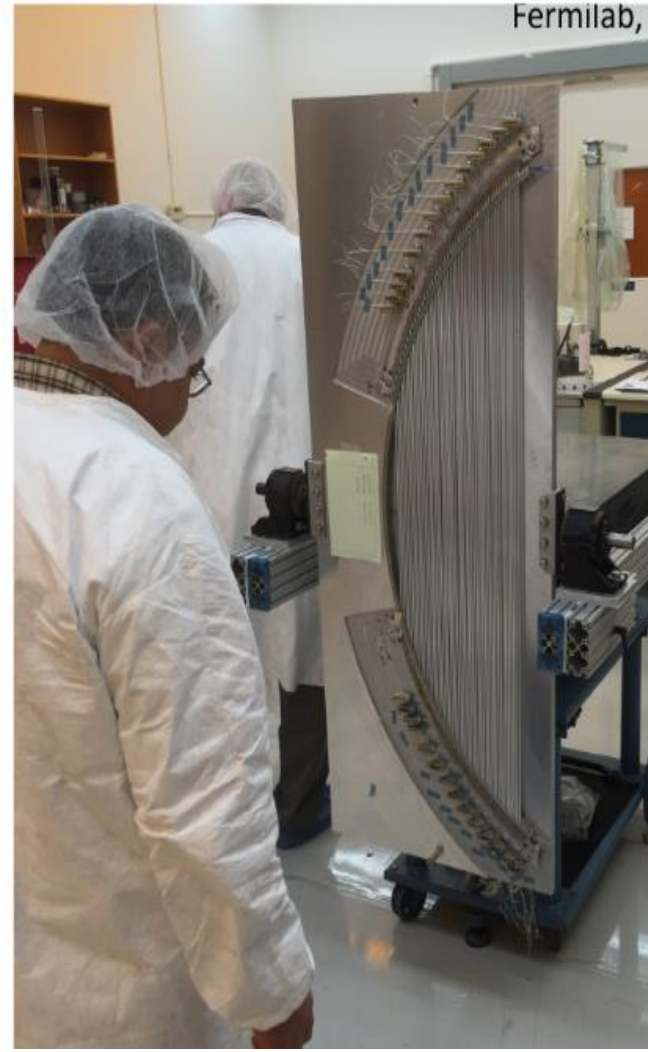
Electromagnetic Calorimeter:

- Energy, time and position measurements
- Particle identification to reject muons

Tracking System

- Low mass straw drift tubes tracker with tubes transverse to the solenoid axis
  - 20k tubes 5 mm diameter, 80/20 Ar/CO_2 gas mixture
  - 15 μm thick straw walls, length 430-1120 mm, dual ended readout
  - 18 stations
  - Inner 38 cm un-instrumented

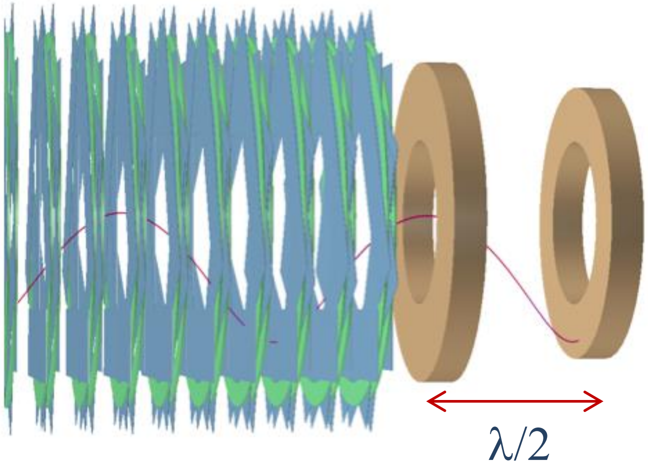


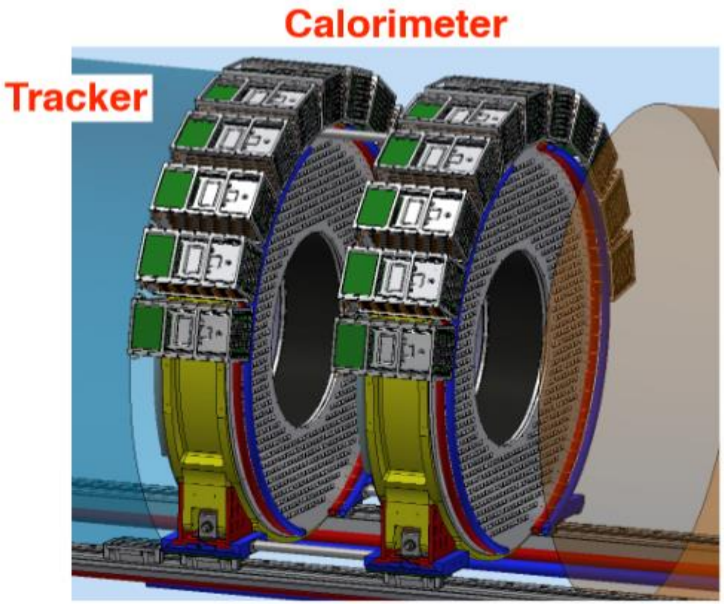


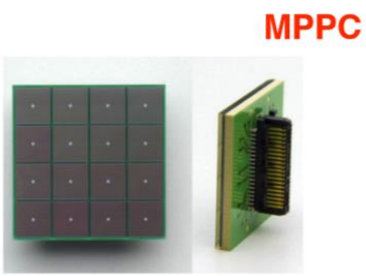
- Expected momentum resolution better than 200 keV/c at the conversion energy

Calorimeter System

- High granularity crystal based calorimeter:
  - 2 disks separated by 75 cm
  - 1300 CsI crystals, each 3.4x3.4x20 cm^3
  - Inner (Outer) radius of 37.4 (70) cm
  - Double readout with 2 MPPC for redundancy
- Expected performances:
  - $\Delta E/E < 10\%$ and $\Delta t < 500$ ps
  - Position resolution of O(1 cm)







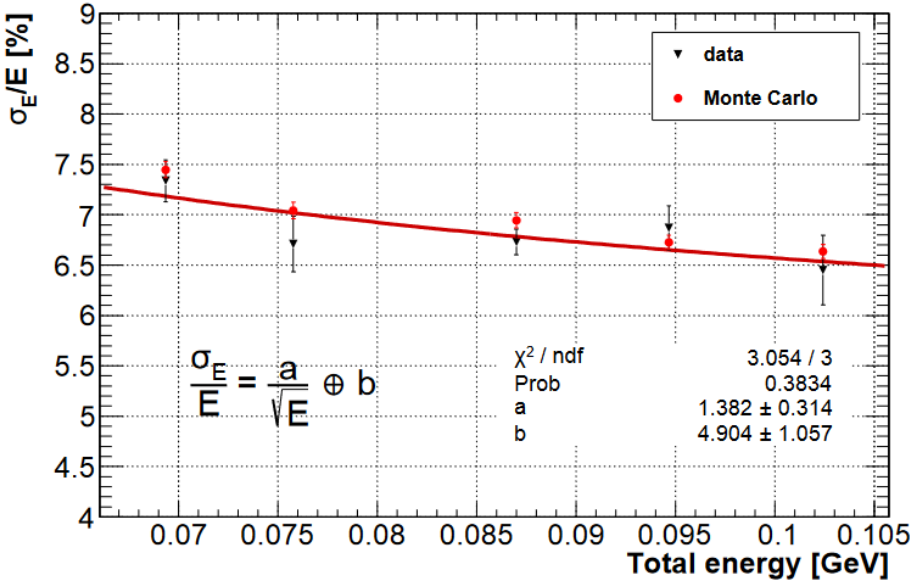
Calorimeter Prototype

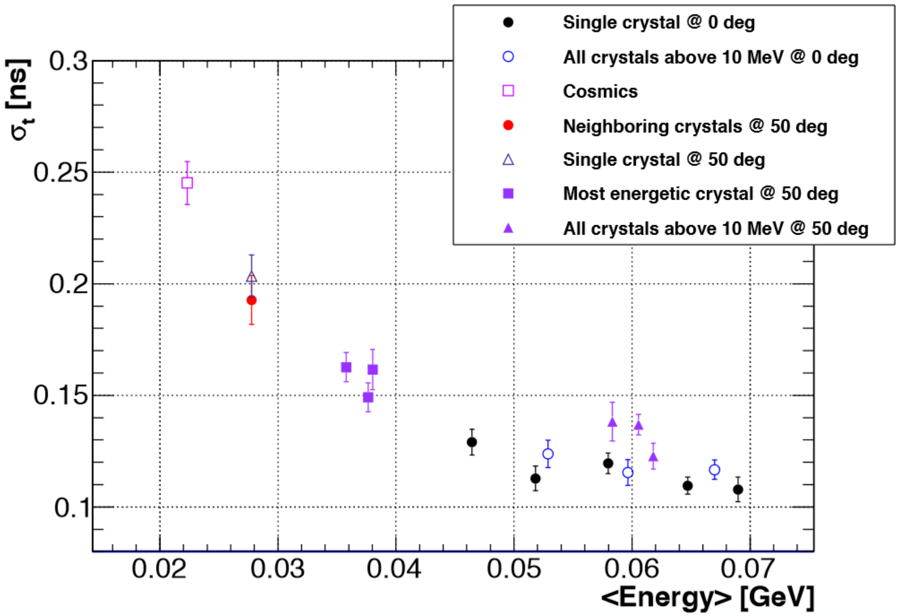
- A small calorimeter prototype has been built and tested in Frascati during April 2015
  - 3x3 matrix of undoped CsI crystals 3x3x20 cm^3 coupled with Hamamatsu MPPC
  - Tested under electrons beam from 80 to 120 MeV

3x3 CsI crystals matrix

Prototype performances

- The obtained energy response and the time resolution well match the calorimeter requirements



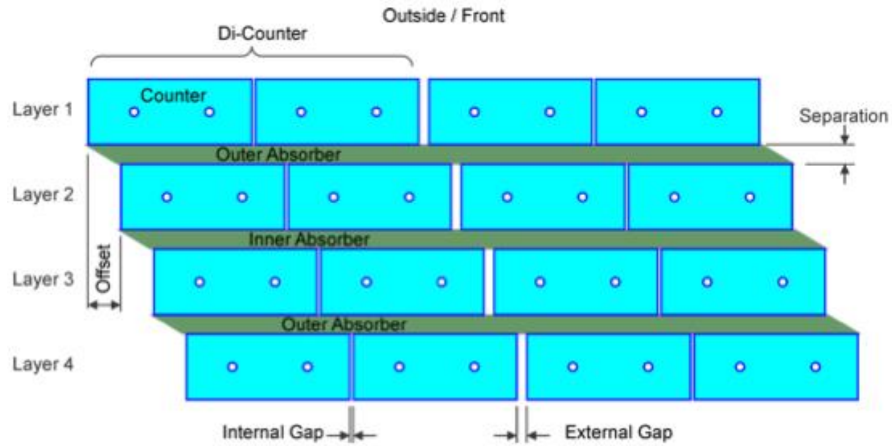


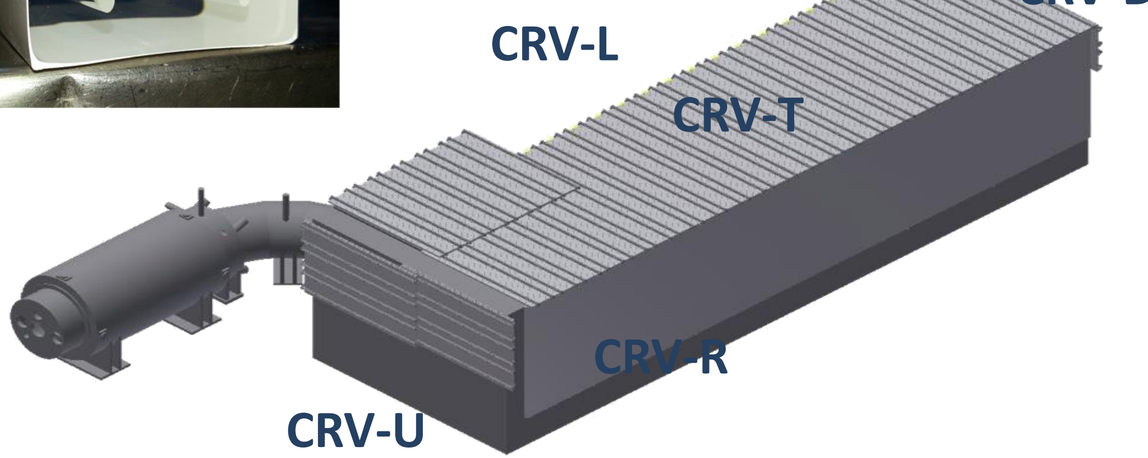
- Another test beam with a larger prototype is planned for the end of the year

Cosmic-Ray Veto System

Cosmic Ray Veto System:

- 4 layers of scintillators separated by 10 mm absorber
- Read-out both ends of each fiber with SiPM
- Covers the entire DS and half TS
- **Veto inefficiency < 10^{-4}**



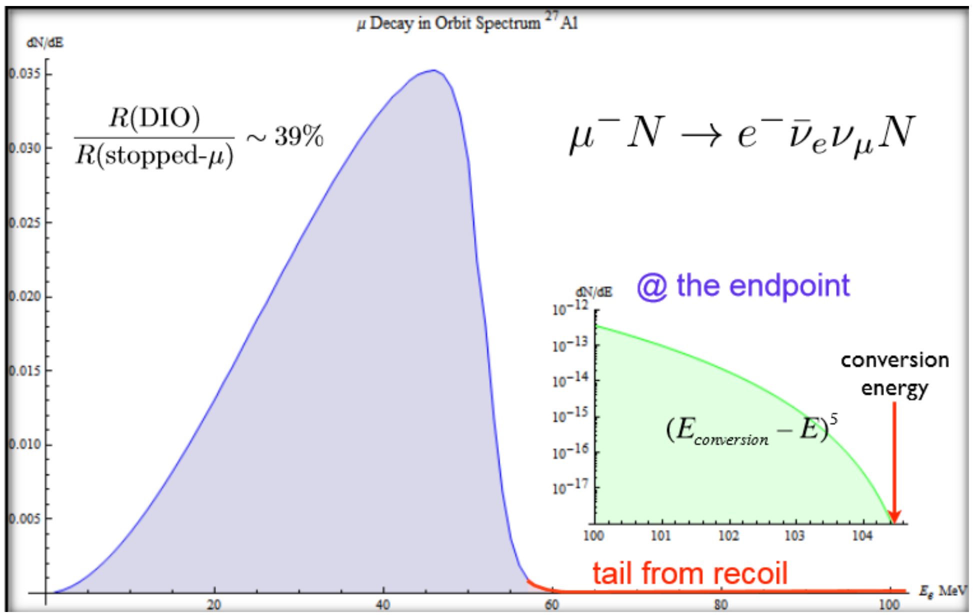


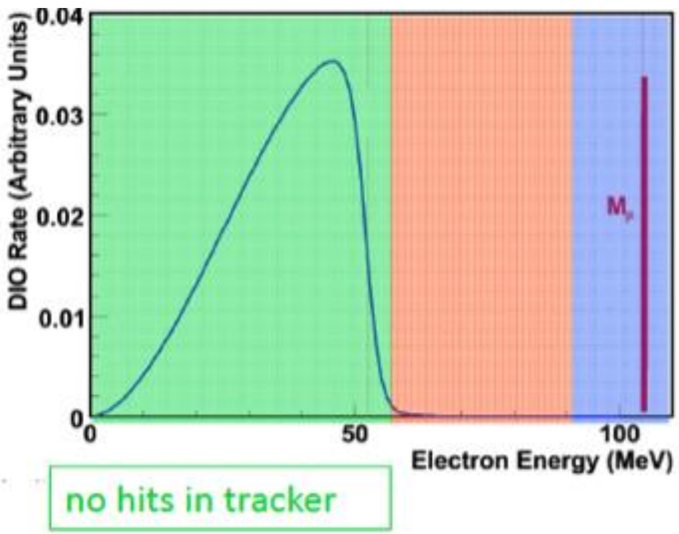
Main Mu2e Backgrounds

1. **μ Decay-in-Orbit (DIO)**
2. Cosmic-ray induced
3. Radiative pion capture (RPC)
4. Anti-proton induced

DIO Background

- For decay-in-orbit muons, the maximum energy of the electron is equal to the energy of a conversion electron
- Near the endpoint the high energy tail falls as **(Ece–Ee)^5**
- 10^{-17} of the spectrum is within 1 MeV on left the endpoint
- An excellent momentum resolution is needed to suppress this background





Main Mu2e Backgrounds

1. μ Decay-in-Orbit (DIO)
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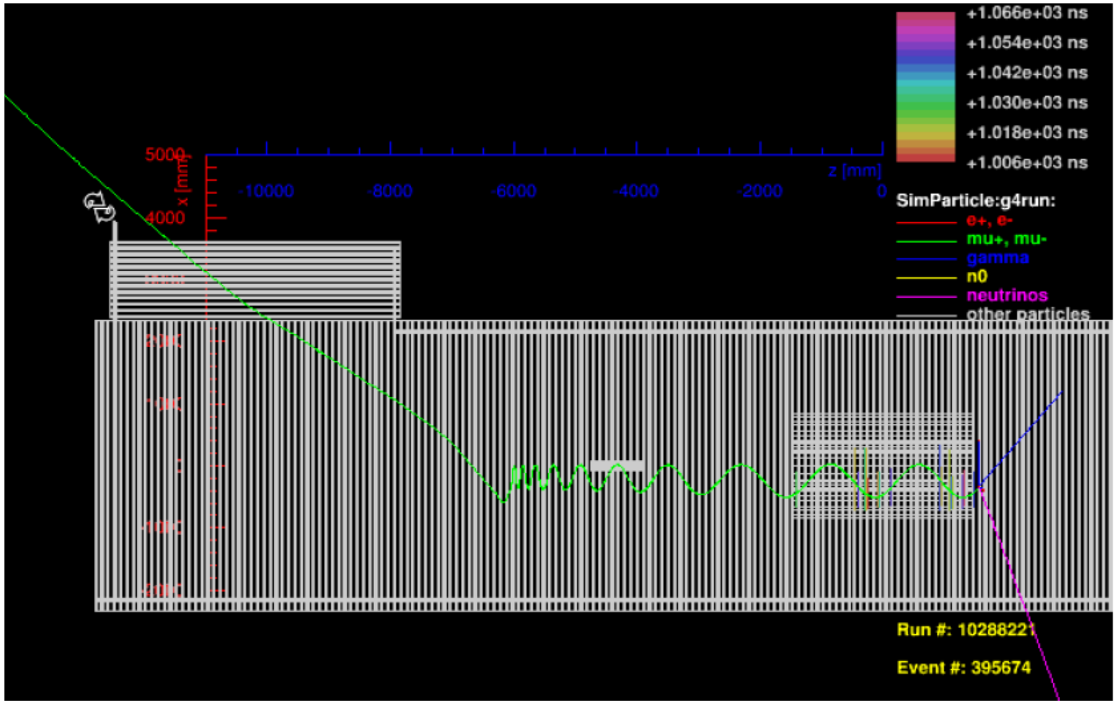
Cosmic Rays Background

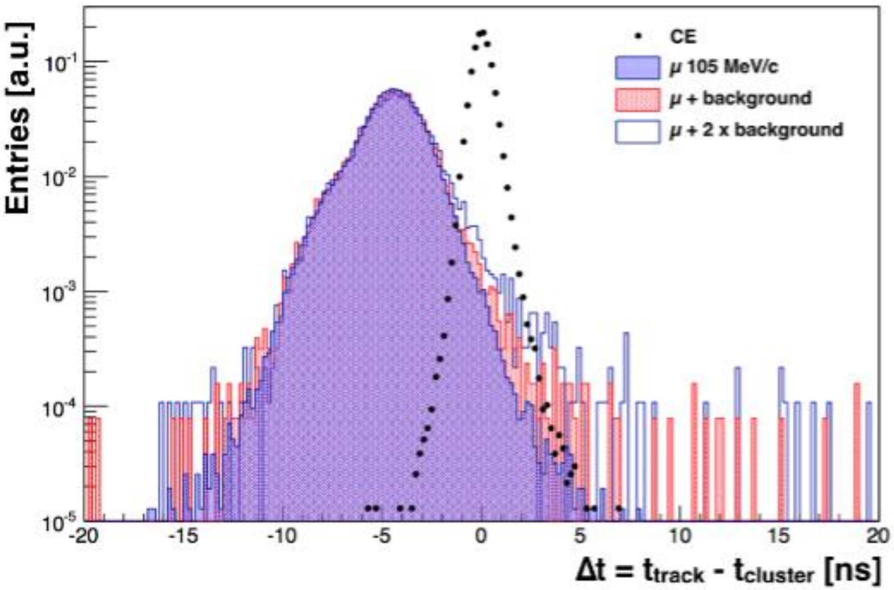
- Cosmic rays can:
  1. interact in the detector material producing 105 MeV delta rays
  2. be trapped by the graded magnetic field and directly mimic a conversion electron



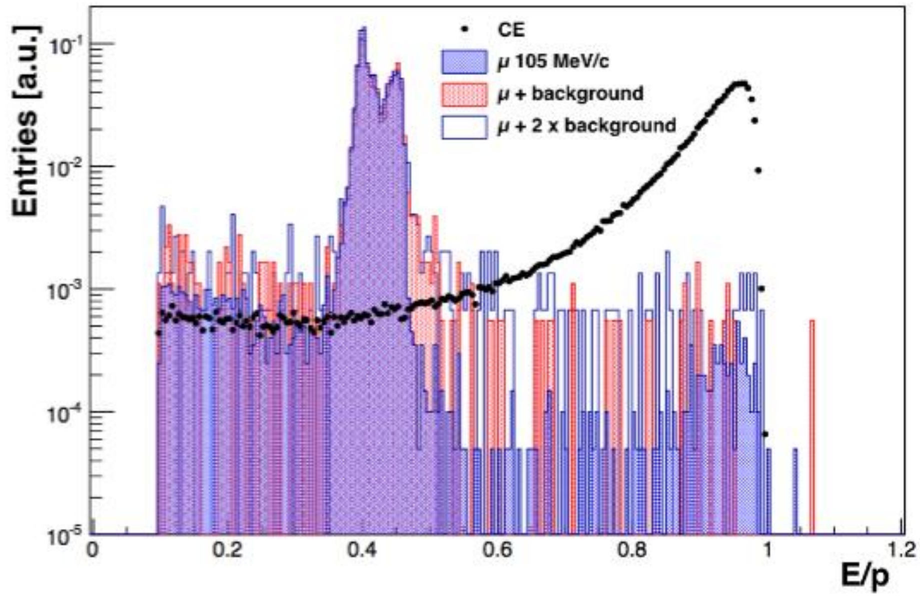
- While for 1. the CR veto is enough, to keep 2. at a reasonable level is needed another 200 muons rejection factor

Calorimeter Particle ID

- To distinguish cosmic muons from CE, the time difference between the tracker and the calorimeter is combined with the e/p ratio in a likelihood



Time difference between tracker track and calorimeter cluster



Ratio of calorimeter energy over tracker momentum

- The requested rejection factor is obtained with an efficiency on the signal of about 95%

Main Mu2e Backgrounds

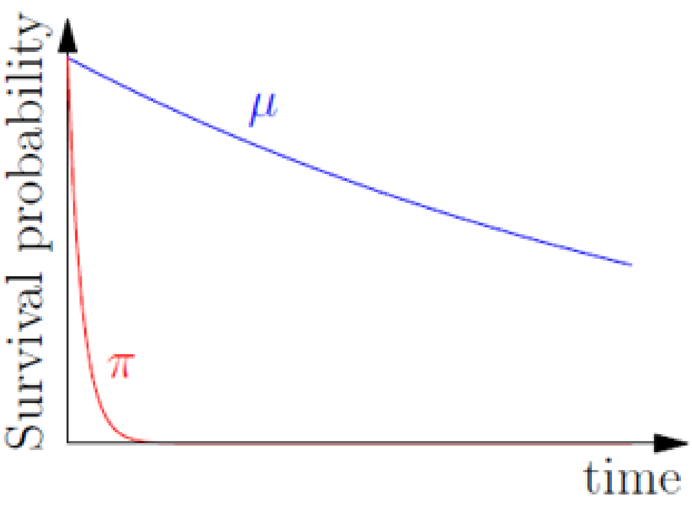
1. μ Decay-in-Orbit (DIO)
2. Cosmic-ray induced
3. **Radiative pion capture (RPC)**
4. Anti-proton induced

RPC Background

- Muons are produced from pions decay, therefore there are residual pions in the muon beam

- **Radiative π Capture:** π^{-}Al --> $Mg^{*} + \gamma$
  - Pions stop at the target and promptly annihilate on the nucleus
  - E_{γ} extends out to ~m_{π}
  - Asymmetric γ —-> $e^{+}e^{-}$ pair production
  - 2% of total π captures

- Mitigated by **pulsing the proton beam** and defining a delayed **signal timing window**



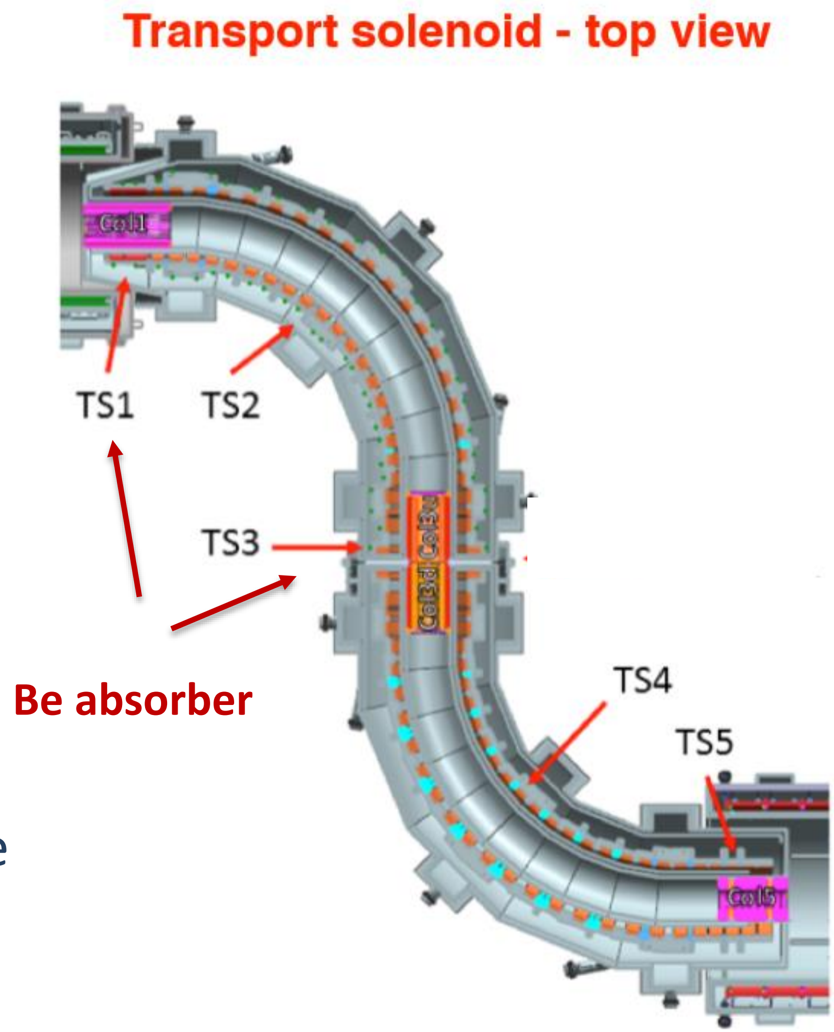
Main Mu2e Backgrounds

1. μ Decay-in-Orbit (DIO)
2. Cosmic-ray induced
3. Radiative pion capture (RPC)
4. **Anti-proton induced**

Anti-Proton Background

- Proton beam is just above **antiproton** production threshold:
  - These low momentum antiprotons wander slowly until they annihilate
  - Annihilations produce high multiplicity final states e.g. π^- can undergo RPC to yield a background electron

- To stop antiprotons, two 200 um thick Beryllium absorber are placed at the entrance and in the middle of the Transport Solenoid



Mu2e Backgrounds

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

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	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	0.092 ± 0.020
	Total	0.37 ± 0.10

Designed to be nearly background free

Upper Limit < 6×10^{-17} @ 90% C.L.

Summary

- ✓ Mu2e will improve the current limit on the muon conversion by 4 orders of magnitude
- ✓ If signal is found, it will be proof of new Physics and it will provide data complementar to LHC and to the other CLFV experiments
- ✓ If no signal is found, it will set constrains on mass scale up to thousands of TeV
- ✓ R&D phase is completed for all the subdetectors
- ✓ Test beams of first large scale prototypes are scheduled for this year
- ✓ Data taking will start in 2021

Backup Slides

Other CLFV Predictions

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

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$0.8 \ldots 2.0$	~ 5	$0.3 \ldots 0.5$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$0.7 \ldots 1.6$	~ 0.2	$5 \ldots 10$
$\frac{R(\mu\mathrm{Ti} \to e\mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$

arXiv:0909.5454v2[hep-ph]

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.*

- **Relative rates are model dependent**
- **Measure ratios to pin-down theory details**

Stopping Target Monitor

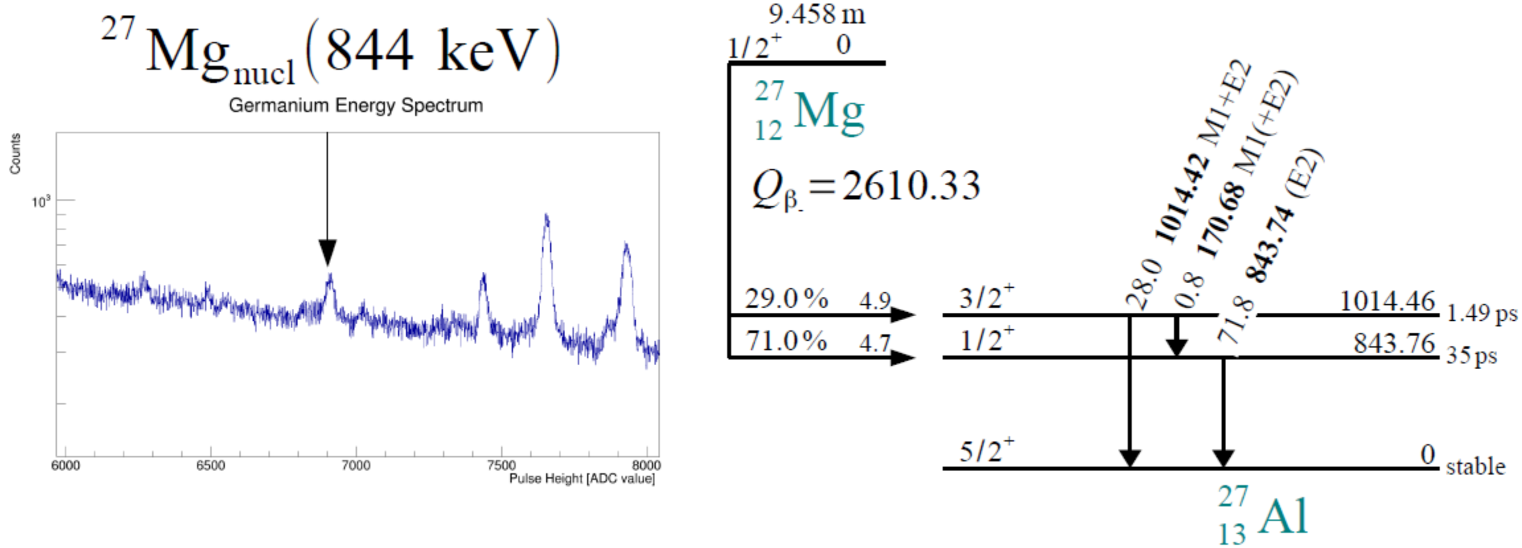
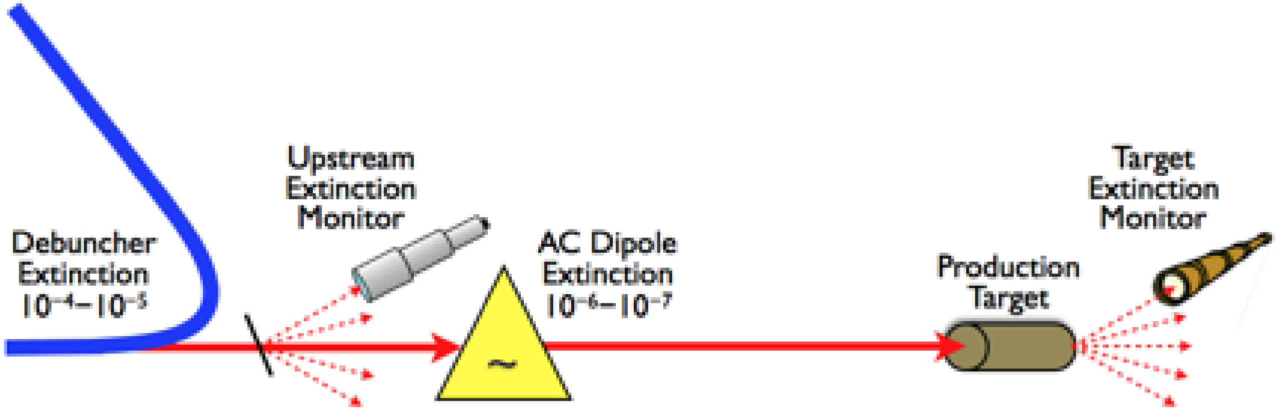


Figure 7.18. Preliminary singles germanium spectrum from the AlCap experiment at PSI. When muons stop in aluminum, they capture on the nucleus 60% of the time. A fraction of the captures produce ^{27}Mg in the ground state, which has a half-life of 9.5 minutes. In the decay, an 844 keV gamma is produced 72% of the time.

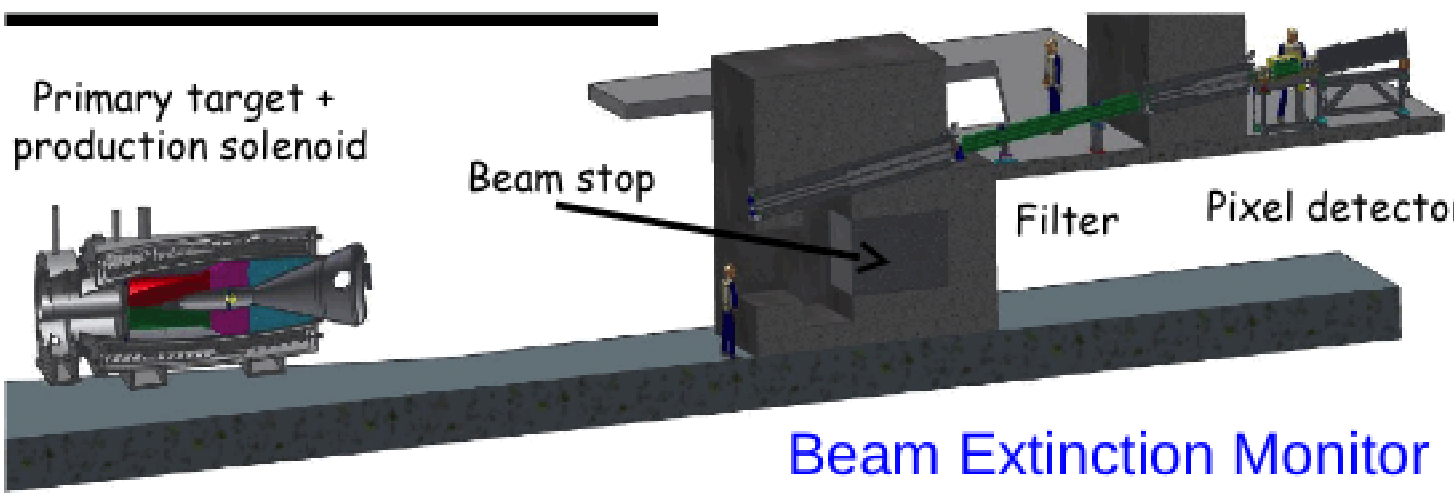
- Need a high precise gamma detector (HpGe)
- Energy of gamma ray is unique to the detector
- Detecting the delayed gamma rays eliminate problems related to beam flash
- Proton beam structure is 0.5 s on followed by 0.8 s idle. Gamma spectrum wil be acquired during idle time.
- HpGe should view the target far from the source and beyond DS

Extinction Monitor



- Thin foils in the debuncher → Mu2e production target transport line (fast feedback)
- Off-axis telescope looking at the production target (slow feedback – timescale of hours)

Reach a 10^{-10} extinction sensitivity in an hour or so



Mu2e → Mu2e-2

1) **Depending on the beam Structure available:**
→ study Z dependence if signal is observed

2) If no signal is observed
Use x 10 events in Mu2e-2

Minor modifications of the detector → **BR < 6 x 10^{-18}**

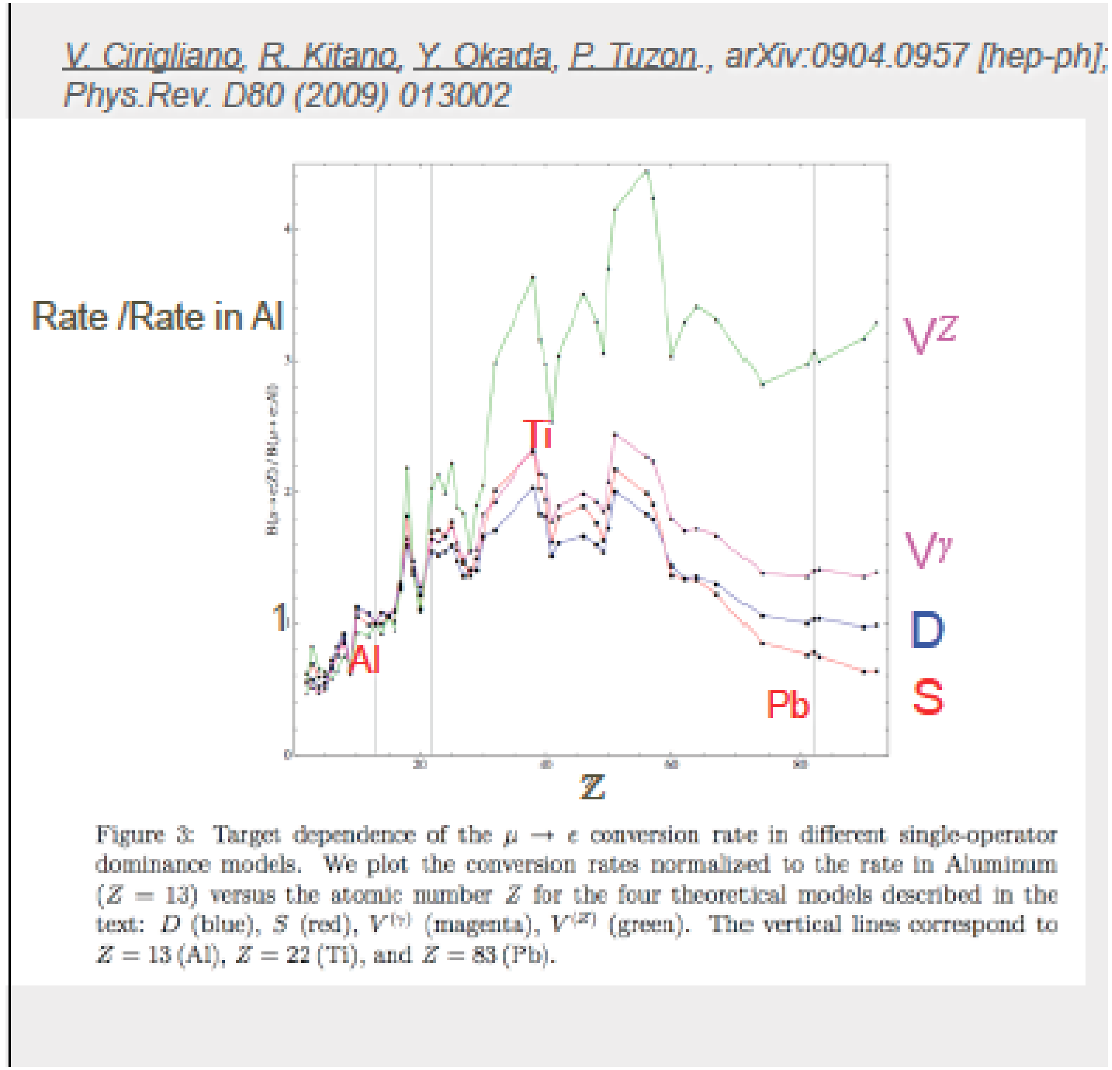


Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).