Muon to electron conversion and the Mu2e experiment at Fermilab

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on behalf of the Mu2e Collaboration

EPS EUROPEAN PHYSICAL SOCIETY
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CONFERENCE ON HIGH ENERGY PHYSICS

5-12 July 2017 – Lido di Venezia, Italy

- Astroparticle Physics and Cosmology
- Neutrinos and Dark Matter
- Flavour and CP Violation
- Standard Model and Beyond
- Electroweak Symmetry Breaking
- Quantum Field and String Theory
- QCD and Heavy Ions
- Accelerators and Detectors
- Outreach, Education, and Diversity

The Mu2e Collaboration

~230 Scientists from 37 Institutions

Argonne National Laboratory, Boston University, Brookhaven National Laboratory, University of **California** Berkeley, University of California Irvine, California Institute of Technology, City University of New York, **Joint Institute of Nuclear Research Dubna**, Duke University, Fermi National Accelerator Laboratory, **Laboratori Nazionali di Frascati**, University of Houston**, Helmholtz-Zentrum Dresden-Rossendorf**, University of Illinois**, INFN Genova**, Lawrence Berkeley National Laboratory**, INFN Lecce, University Marconi Rome,** Institute for High Energy Physics Protvino, Kansas State University, Lewis University, **University of Liverpool, University College London,** University of Louisville, **University of Manchester**, University of Minnesota, Muons Inc., Northwestern University**, Institute for Nuclear Research Moscow,** Northern Illinois University**, INFN Pisa,** Purdue University**, Novosibirsk State University/Budker Institute of Nuclear Physics**, Rice University, University of South Alabama, University of Virginia, University of Washington, Yale University

Talk Layout

- The Physics
  - → CLFV processes and BSM reach
  - → Muonic Atom processes: Conversion/capture
- Mu2e experimental technique
- Mu2e Detector Layout
- Status of Mu2e experiment
- Conclusions

CLFV processes

- ✓ **Muon-to-electron conversion is a charged lepton flavor violating process (CLFV)** similar but complementary to other CLFV processes as μ→ eγ and
  μ → 3e, τ→ μγ , τ → 3 e, 3 μ …

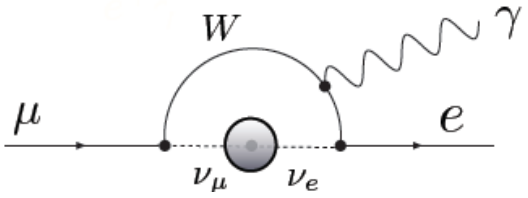
- ✓ The Mu2e experiment searches for **muon-to-electron conversion** in the coulomb field of a nucleus**:** $\mu^- Al \rightarrow e^- Al$

- ✓ CLFV processes are **strongly suppressed**

  in the Standard Model

  → In principle, not forbidden due to neutrino oscillations

  → In practice BR(μ → eγ) ~ 10^{-54} is negligible in the SM!

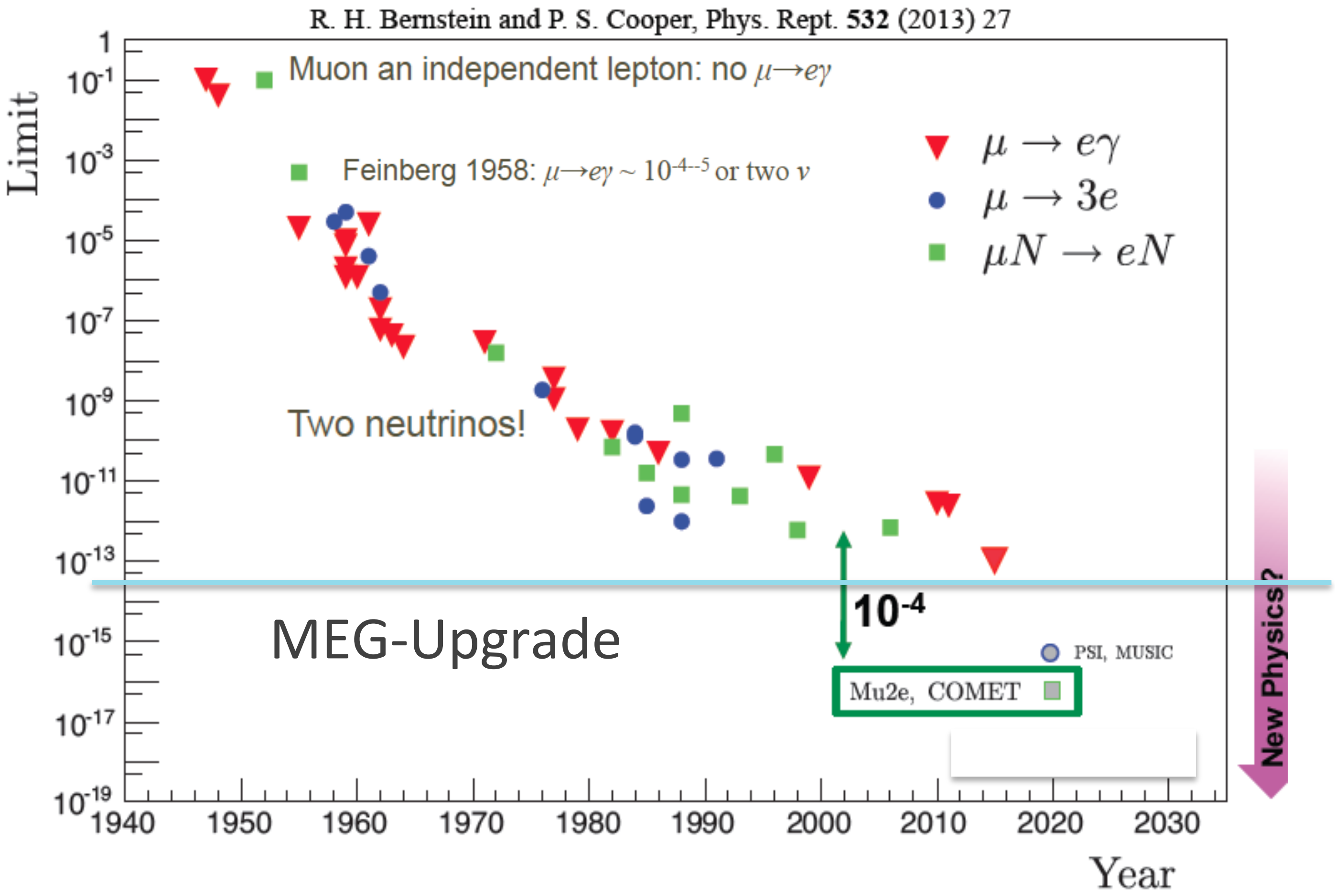


$$\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right| < 10^{-54}$$

- ✓ **New Physics could enhance CLFV rates to observable values**

- ✓ Muon channels are ideal for CLFV search: clean topologies, large rates

CLFV history for muons



Current best limits:

MEG-2016

BR($\mu \to e\gamma$) < 4.2 x 10^{-13}

SINDRUM-1988

BR($\mu \to 3e$) < 1 x 10^{-12}

SINDRUM-II 2006

$R_{\mu e}$ < 6.1 x 10^{-13}

MU2E GOAL

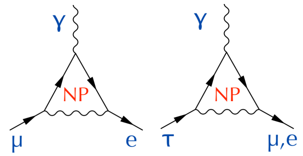
$R_{\mu e}$ = 6 x 10^{-17}

CLFV: Muon channels discovery plane

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

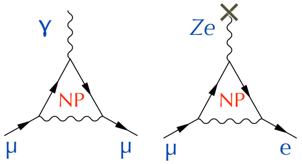
LOOP TERM

$\kappa \ll 1$



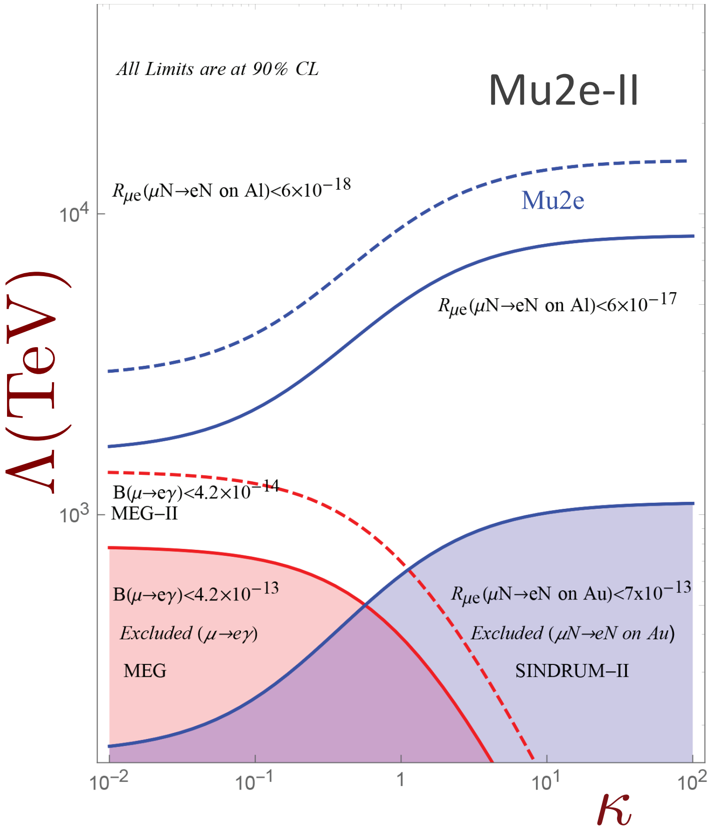
$\mu \to e\gamma$

$\tau \to \mu\gamma$
$\tau \to e\gamma$



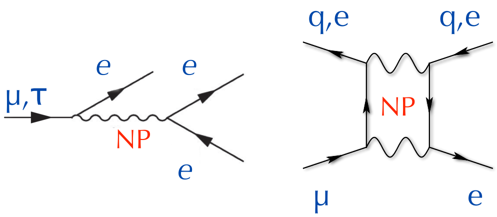
$(g-2)_\mu$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$



CONTACT TERM

$\kappa \gg 1$



$\mu \to eee$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$

Probing mass scales
λ 2000~10000 TeV,
significantly above the
direct reach of LHC

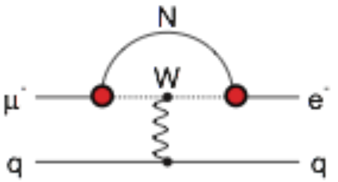
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \to e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \to \text{ all muon capture})} \leq 6\times10^{-17}\ (@90\%\text{CL})$$

Mu2e physics reach & goal

Loop

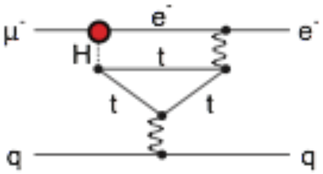
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\times10^{-13}$



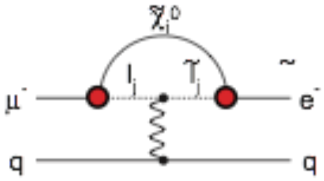
Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



Supersymmetry

rate ~ 10^{-15}

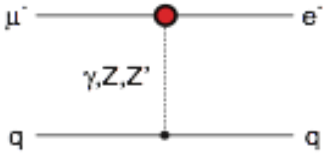


Models which can be probed also by *μ→eγ searches*

Contact term

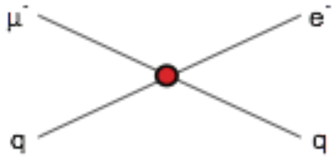
Heavy Z'
Anomal. Z Coupling

$M_{Z'} = 3000$ TeV/c²



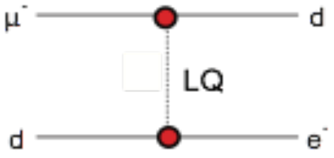
Compositeness

$\Lambda_c \sim 3000$ TeV



Leptoquark

$M_{LQ} = 3000 (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c²



Direct coupling between quarks and leptons, better accessed by *μN→eN*

Sensitivity reach:
10^4 improvement with respect to previous muon to electron
conversion experiment (Sindrum-II)

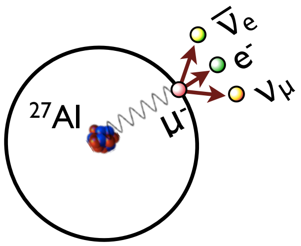
Test of Physics BSM:
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, arXiv:1303.4097

Mu2e experimental Technique

- ☐ Low momentum μ beam (< 100 MeV/c)
- ☐ High intensity “pulsed” rate
  - → **10^{10}/s muon stop on Al. target**
  - → **1.7 μsec micro-bunch**
- ☐ Formation of muonic atoms that can make a:

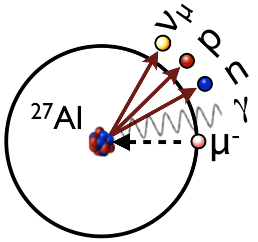
Decay in Orbit (DIO)

(BR=39%)

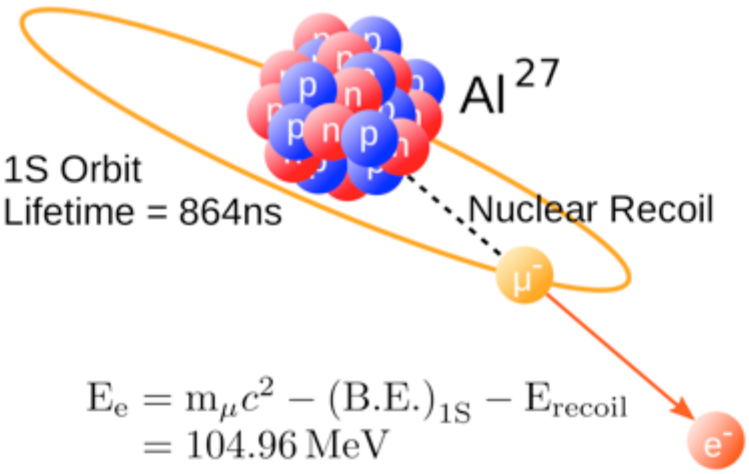


Muon Capture Process

(BR=61%)



Conversion Process



$$\mathrm{E_e} = \mathrm{m}_\mu c^2 - (\mathrm{B.E.})_{1\mathrm{S}} - \mathrm{E_{recoil}}$$
$$= 104.96\,\mathrm{MeV}$$

The conversion process results in a clear signature of a single electron, CE, with a mono-energetic spectrum close to the muon rest mass

Mu2e backgrounds

- **Intrinsic – scale with number of stopped muons**
  - **μ Decay-in-Orbit (DIO)**
  - Radiative muon capture (RMC)

- **Cosmic-ray induced**

- **Late arriving – scale with number of late protons**
  - **Radiative pion capture (RPC)**
  - $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$ **and** $\pi^- N \rightarrow e^+e^- N'$
  - **μ and π decay-in-flight (DIF)**

- **Miscellaneous**

  Anti-proton induced

  produce pions when they annihilate in the target ..

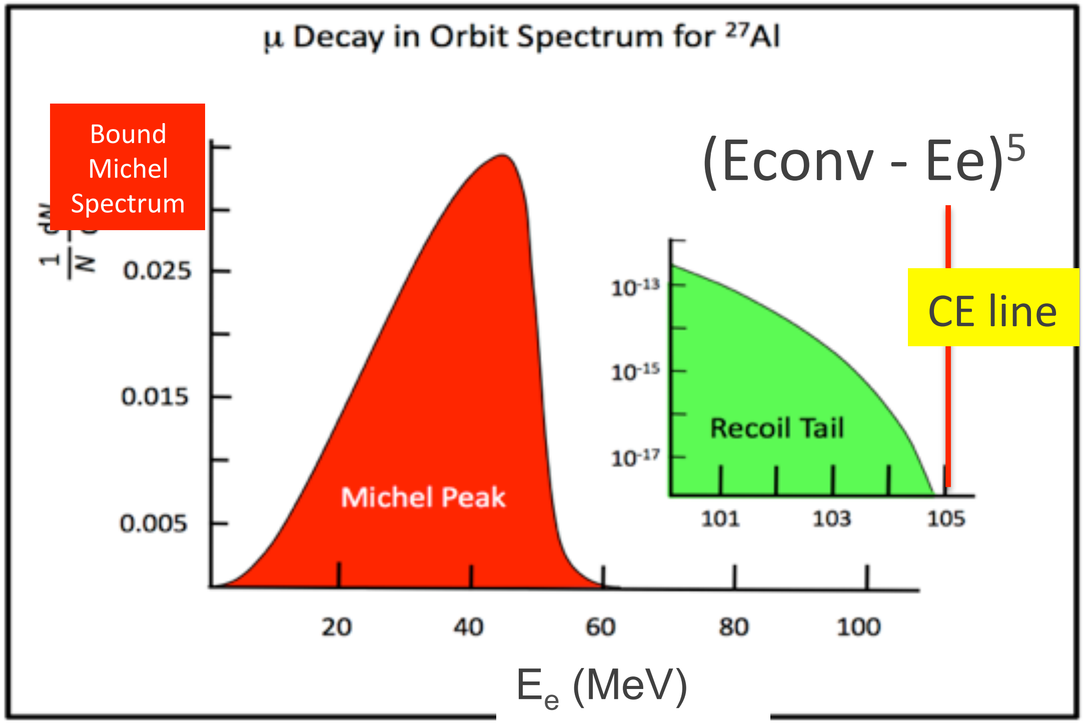
  antiprotons are negative and they can be slow!

DIO background

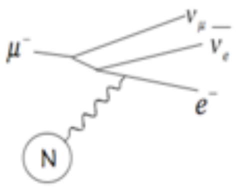
- Electron energy distribution from the decay of bound muons follows a modified-Michel spectrum:

→ Presence of atomic nucleus and momentum transfer create a recoil tail with a fast falling slope close to the endpoint

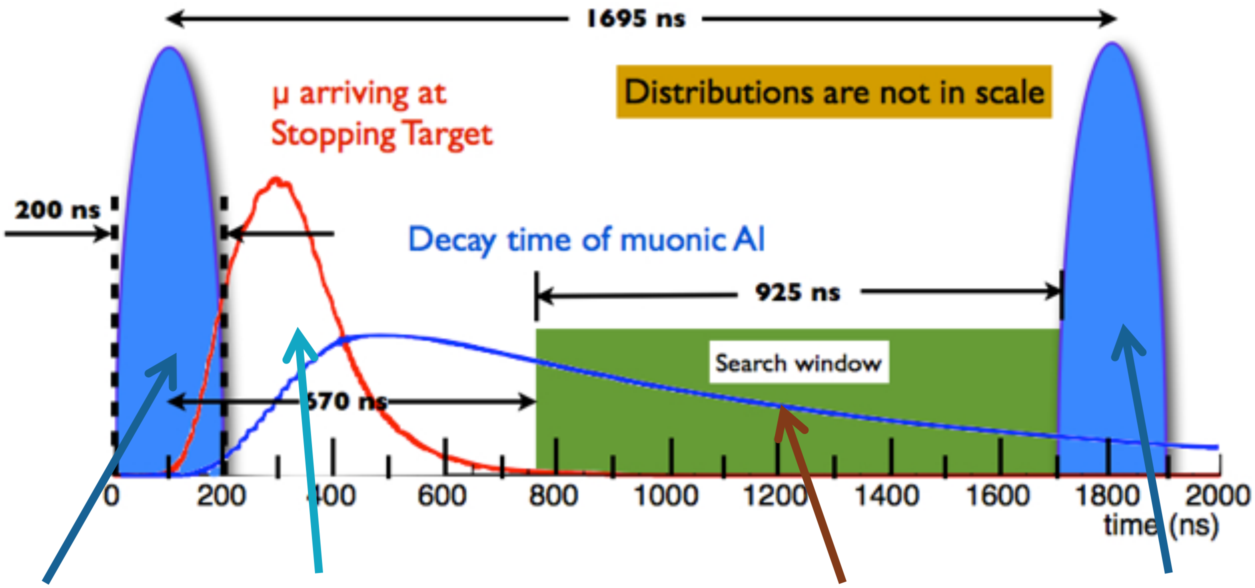
→ **To separate DIO endpoint from CE line we need a high Resolution Spectrometer**



Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv: 1106.4756v2



Beam structure → prompt background



Beam hits target

Prompt bkg like radiative pion capture

Mainly Decay In Orbit background

Next bunch

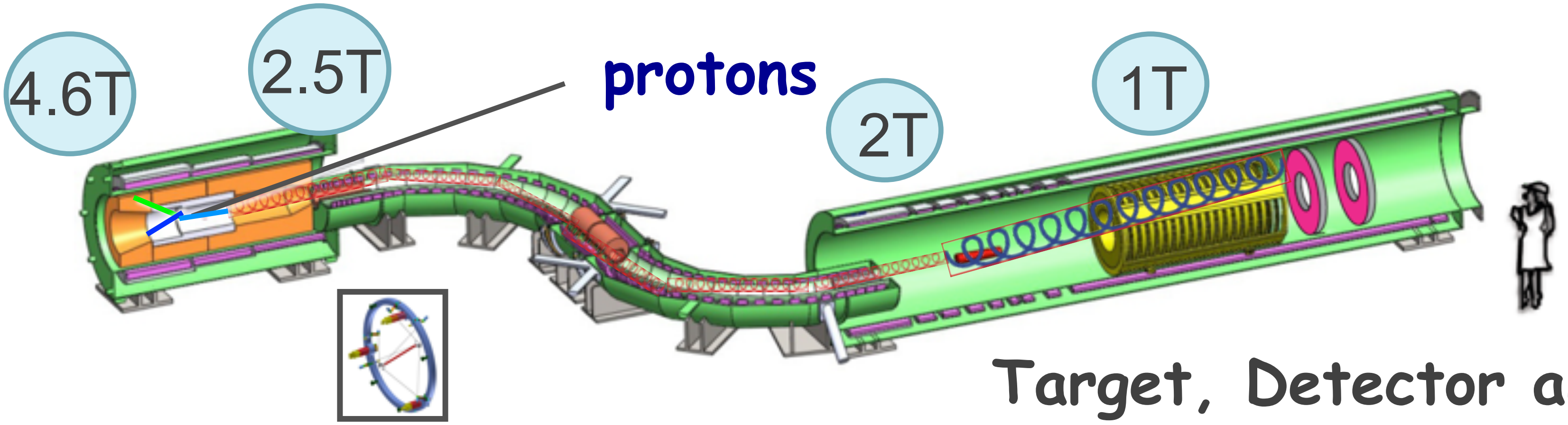
The trick is … muonic atomic lifetime > prompt background

Need a pulsed beam to wait for prompt background to reach acceptable levels ➔ **Fermilab provides the beam we need !**

Muon Beam-line and solenoids

Production Target / Solenoid (PS)

- 8 GeV Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons



→ Heat and radiation shielding
→ Tungsten target.

Transport Solenoid (TS)

Selects low momentum, negative muons
Antiproton absorbers in the mid-section

Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- CRV to veto Cosmic Rays event

Mu2e @ on campus: civil construtions done

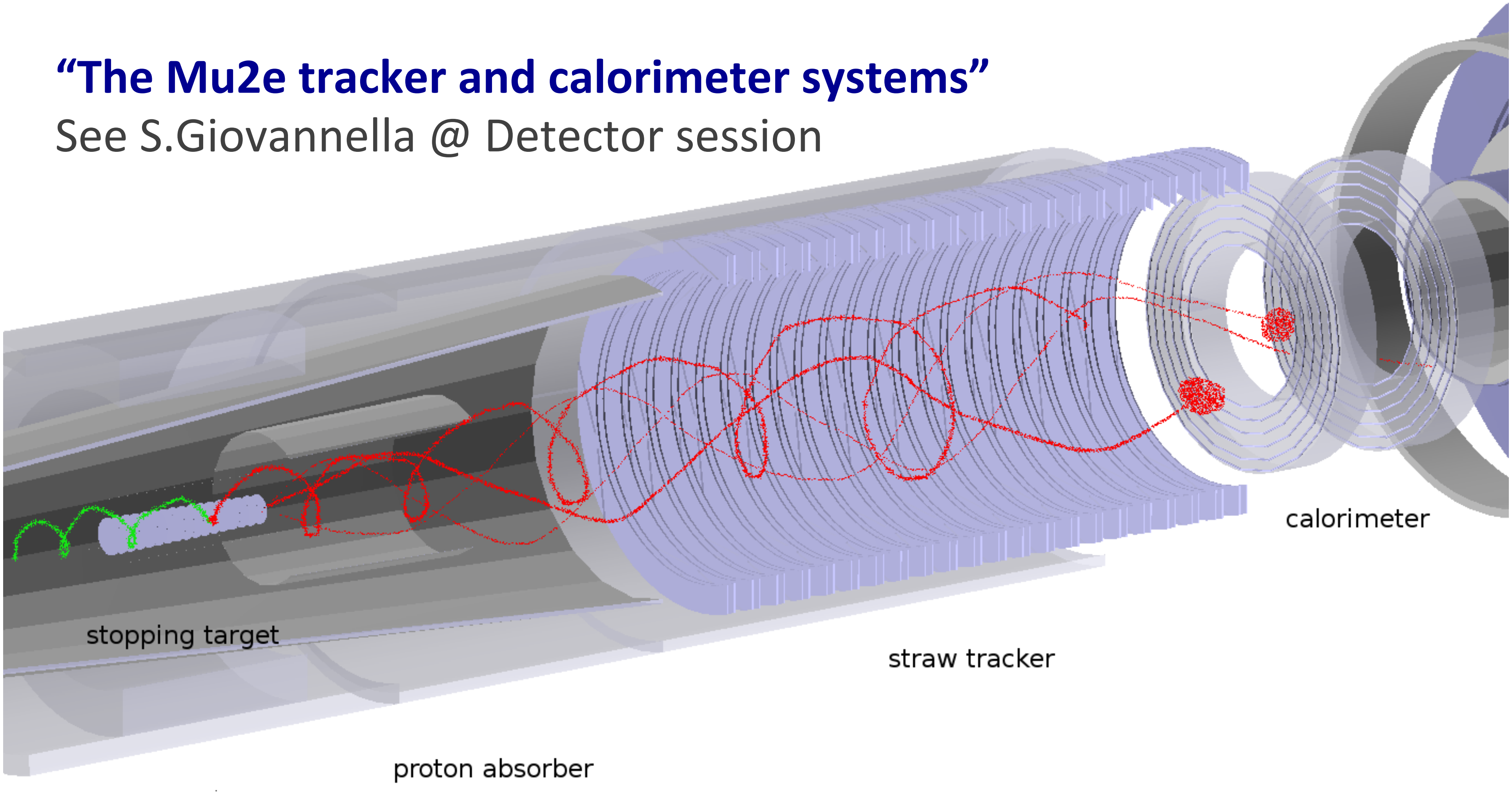
Mu2e Solenoids

- 75 km of superconducting cable procured and tested.
- Solenoids' designs completed
- TS fabrication has begun at ASG Superconducting in Genova (Italy).
- PS, DS fabrication started at GA (USA).

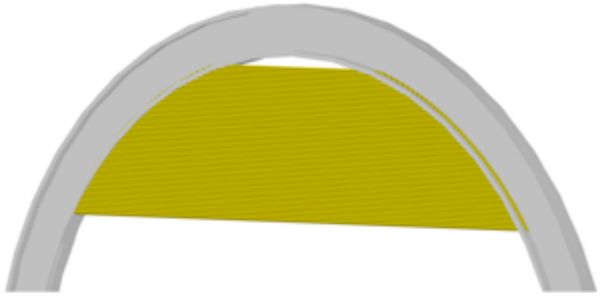
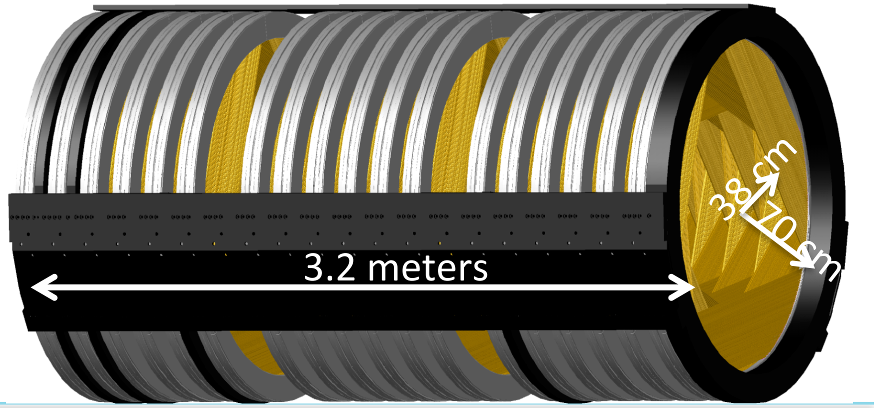
Mu2e apparatus: CE trajectories

"The Mu2e tracker and calorimeter systems"

See S.Giovannella @ Detector session



Mu2e apparatus: the tracker system

2x48 Straw tubes on a panel	One station 2 planes	Tracker Structure
		

Low mass straw drift tubes design:

- 20000 straws
- 5 mm diameter, 33 – 117 cm length
- 15 μm Mylar wall, 25 μm Au-plated W wire
- 80:20 Ar:CO_2 @ 1 atm
- Dual-ended readout
- Momentum resolution core < 180 keV for 105 MeV electrons.
- dE/dX capability to distinguish e/p

Mu2e apparatus: the calorimeter system

Calorimeter provides :

PID: : e/μ separation

✗ seeding for track finder

✗ standalone EMC trigger

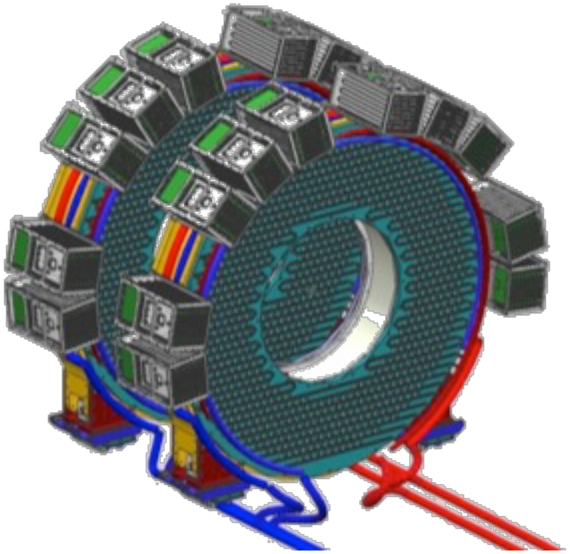
with O(5%) energy resolution

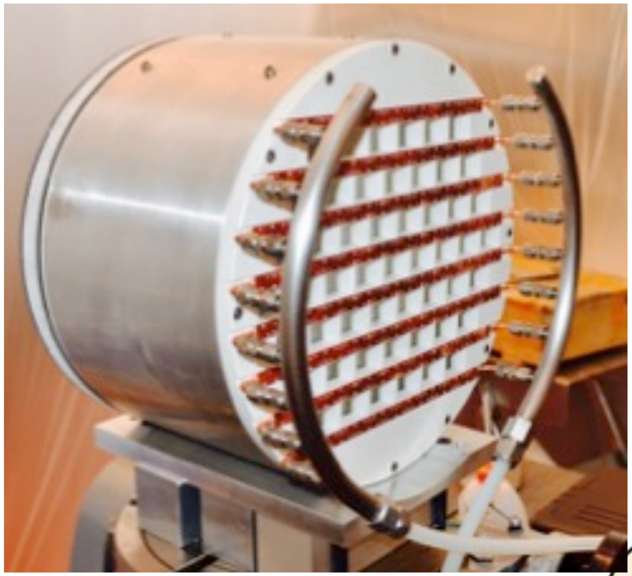
and < 500 ps timing resolution

✗ Two disks, of 674+674 square **pure CsI crystals**, each one readout with two custom **large area UV-extended SiPMs**

✗ Analog FEE directly mounted on SiPM, WD on crates

✗ Calibration/Monitoring with 6 MeV radioactive source, MIPs and laser system

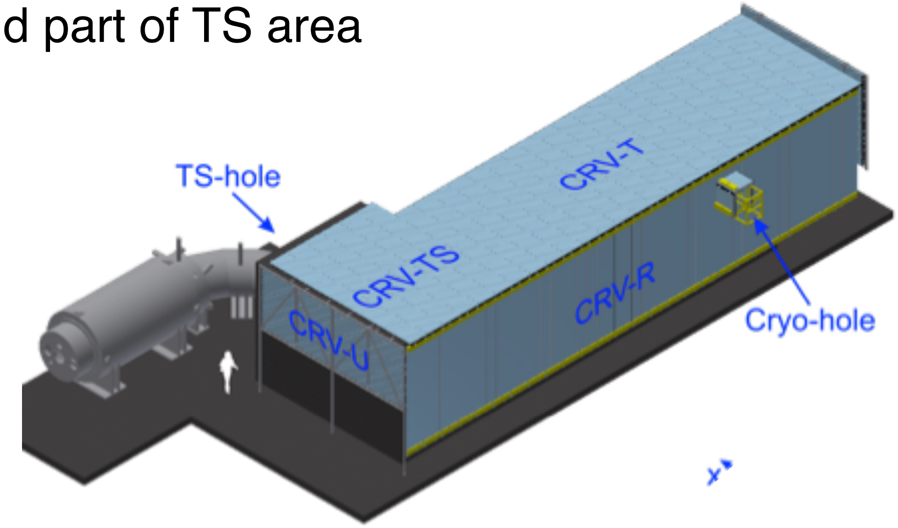


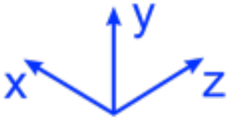


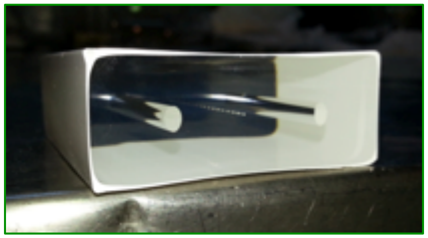
Mu2e apparatus: the CRV system

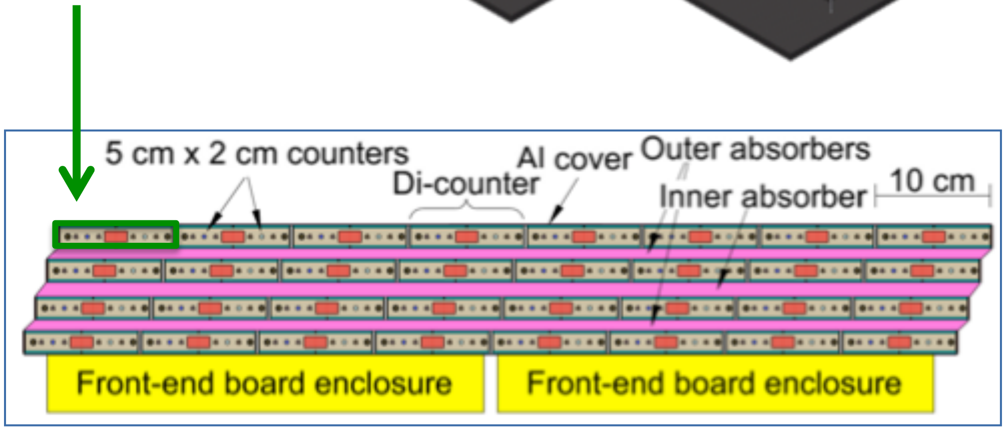
Cosmic Rays are one of two largest backgrounds → high efficiency (0.9999) veto needed

- ✓ Composed of 4 layers of overlapping scintillator bars (3 out of 4 coincidence used)
- ✓ 2 WLS fibers (1.4 mm diameter) per counter, 1-side readout with 2x2 mm^2 SIPMs.
- ✓ CRV covers all DS and part of TS area

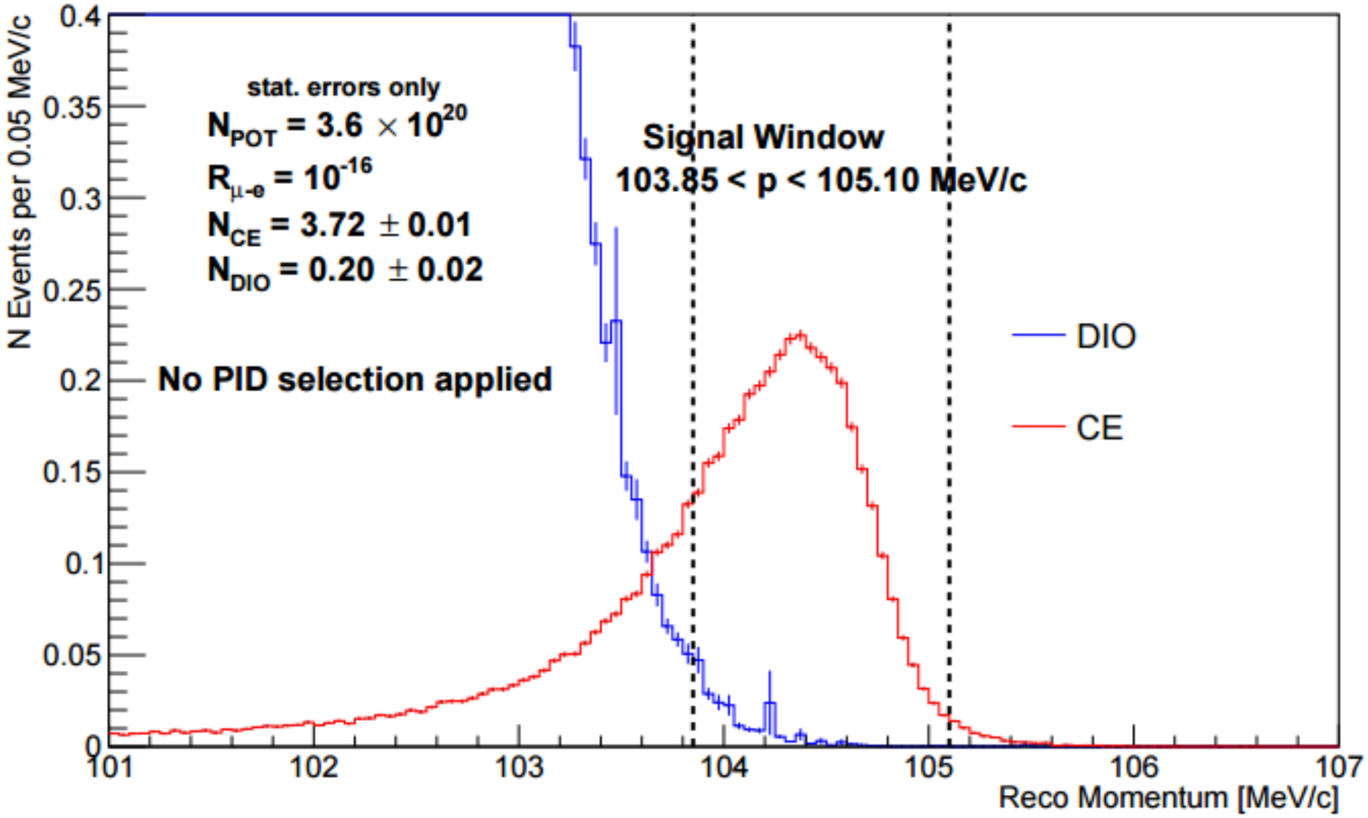








Mu2e expectation with full simulation

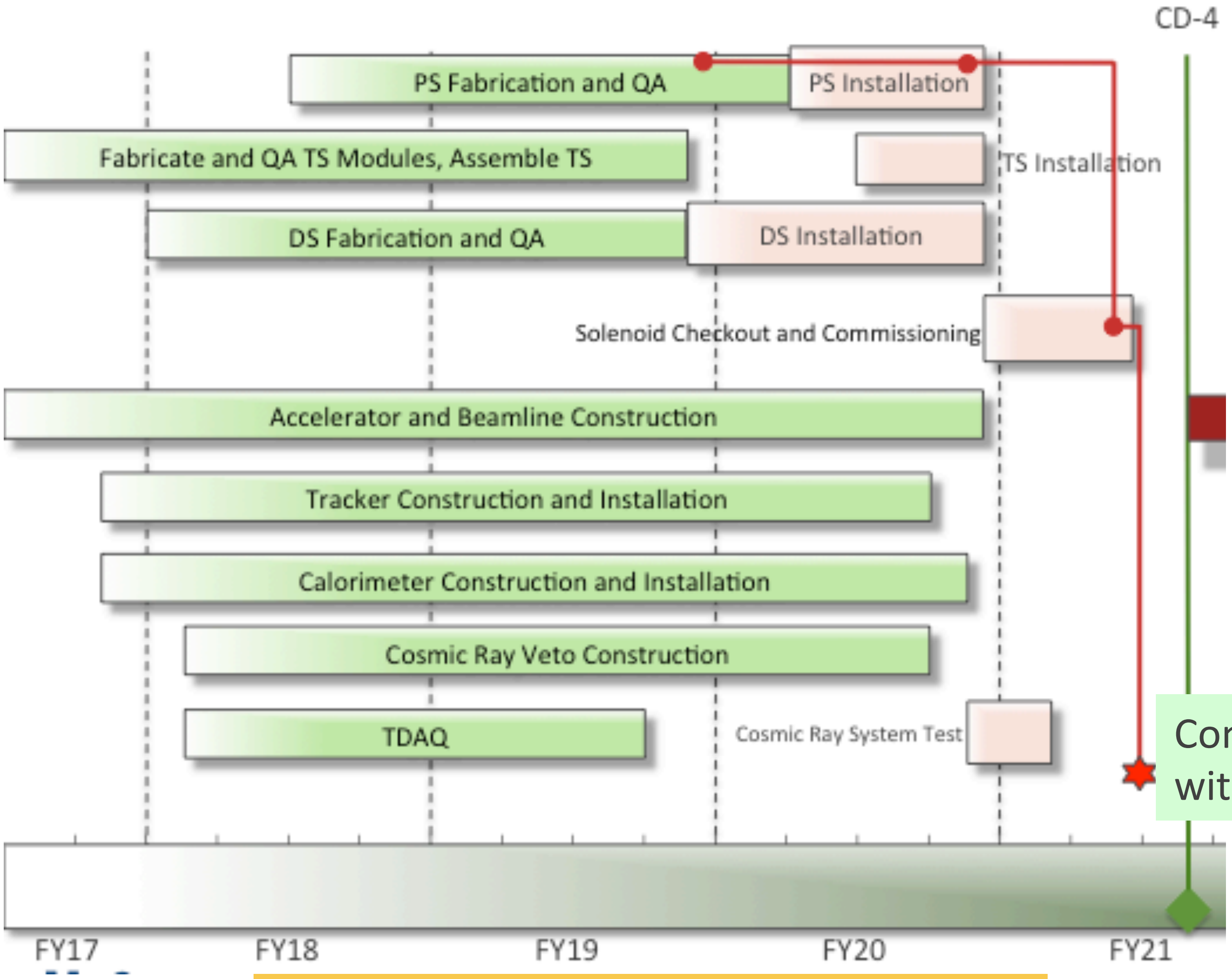


@ BR=10^{-15}
40 events
<0.4 bkg

Discovery sensitivity accomplished with 3 years of running and suppressing backgrounds to < 0.4 event total

Upper Limit < 6 x 10^{-17} @ 90% C.L.

Mu2e schedule



Commissioning with beams

3 years run expected 2022-2025

Conclusions

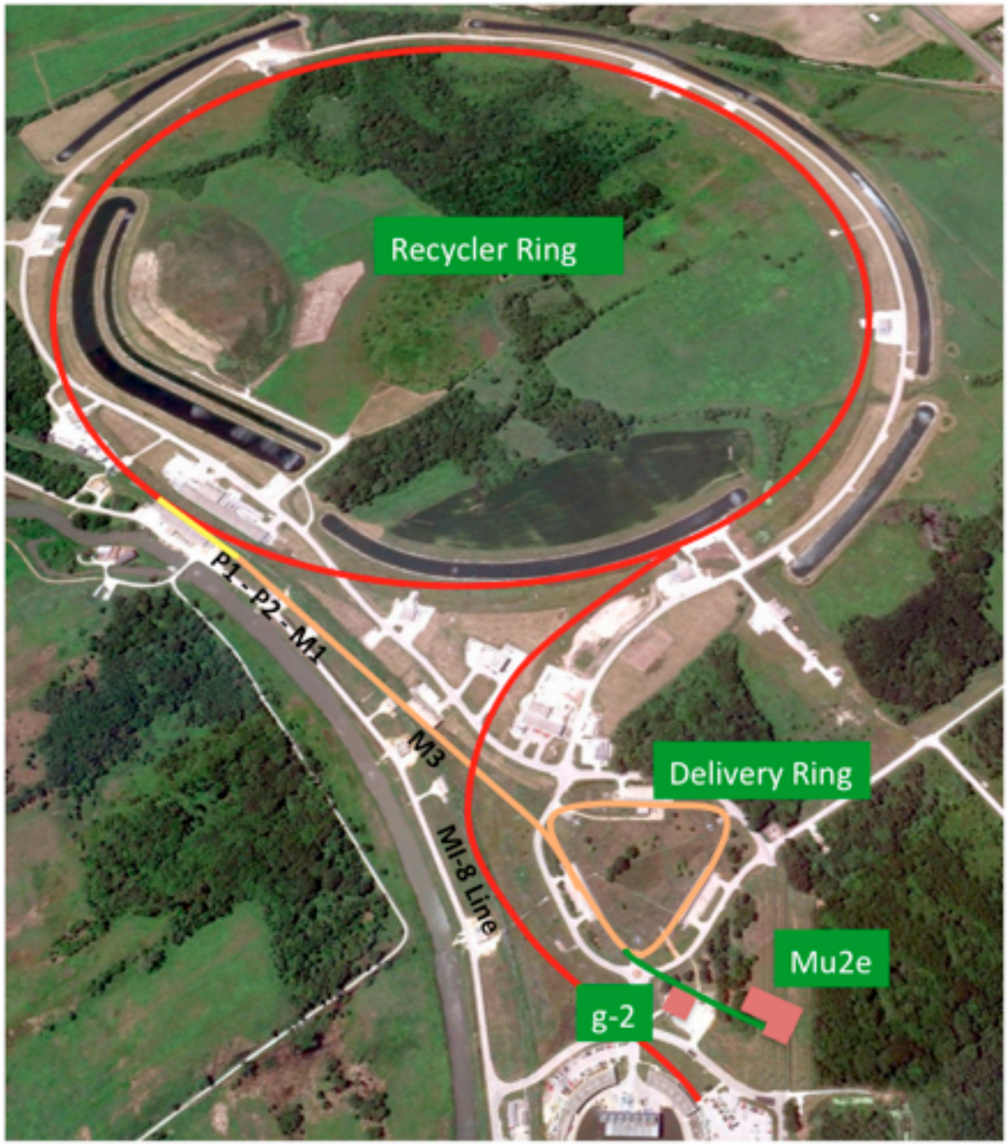
The Mu2e experiment:

- Improves sensitivity on conversion exp. by a factor of 10^4
- Provides *discovery capability* over wide range of New Physics models
- Is complementary to LHC, heavy-flavor, dark matter, and neutrino experiments
- Is progressing on schedule… will begin commissioning in 2021
- Start discussing about Mu2e-II

ADDITIONAL INFORMATION

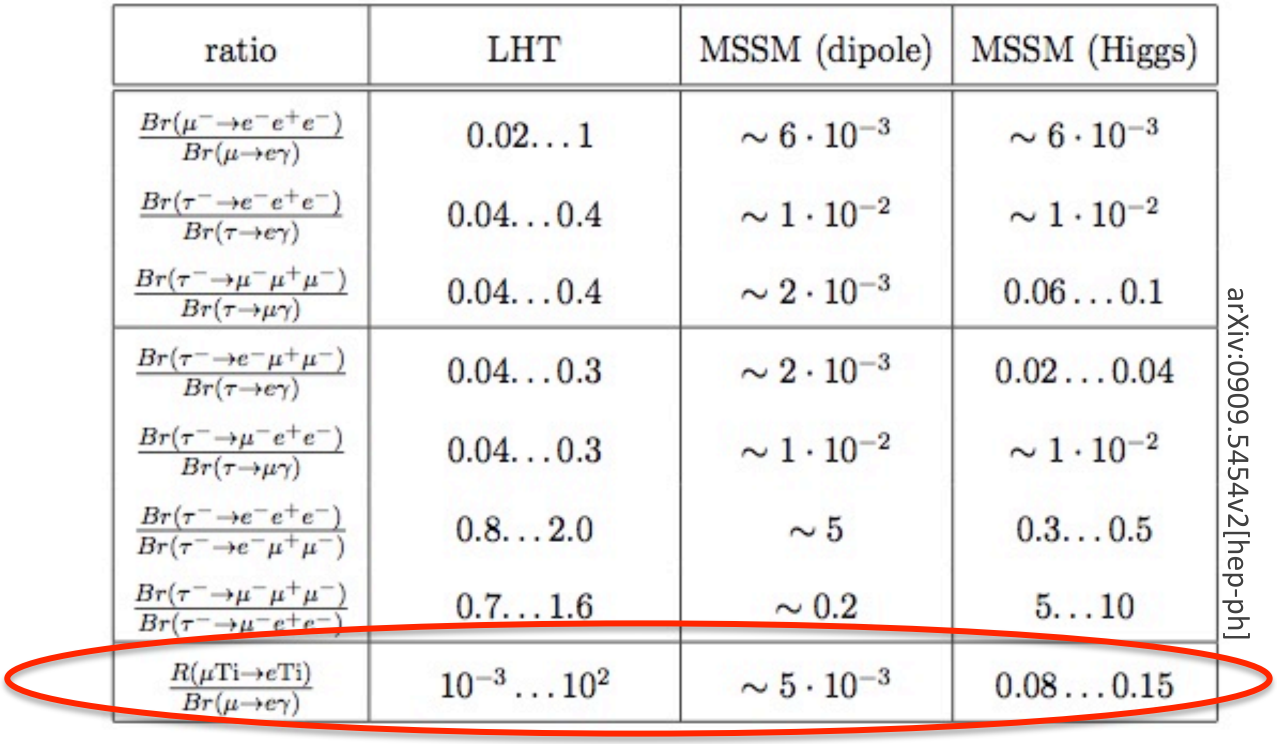
Fermilab accelerator scheme for Mu2e

- ❑ Booster: batch of 4×10^{12} protons every 1/15th second
- ❑ Booster "batch" is injected into the Recycler ring
- ❑ Batch is re-bunched into 4 bunches
- ❑ These are extracted one at a time to the Debuncher/Delivery ring
- ❑ As a bunch circulates, protons are extracted to produce the desired beam structure
- ❑ **Produces bunches of ~3x10^7 protons each, separated by 1.7 μs (debuncher ring period)**



Other CLFV Predictions

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



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

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 Conversions/MEG are model dependent**
  - **Measure ratios to pin-down theory details**

SUSY benchmark points vs LHC

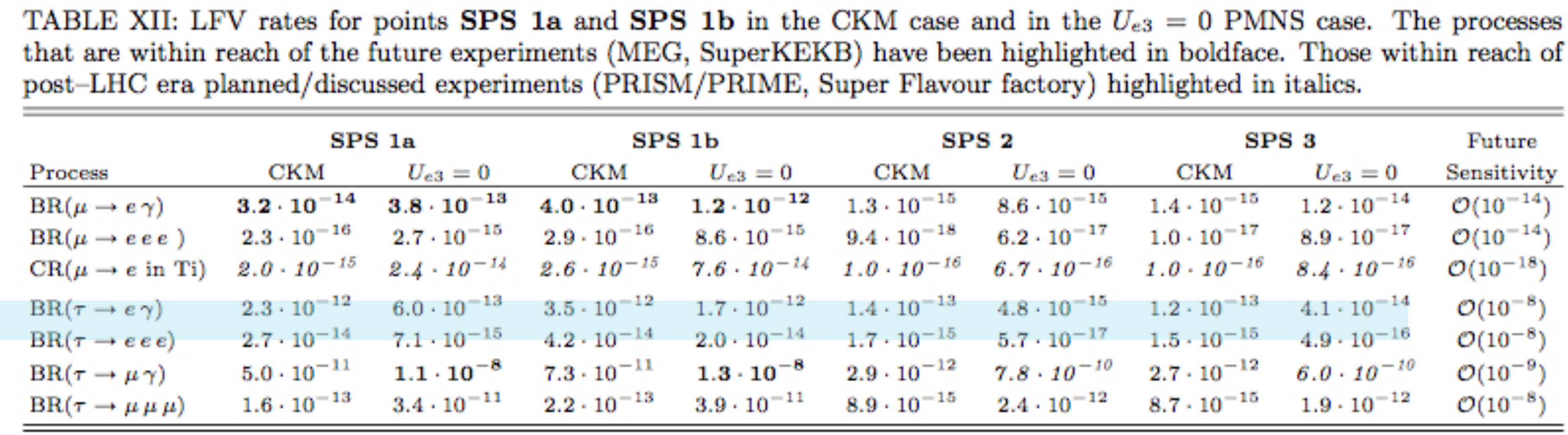


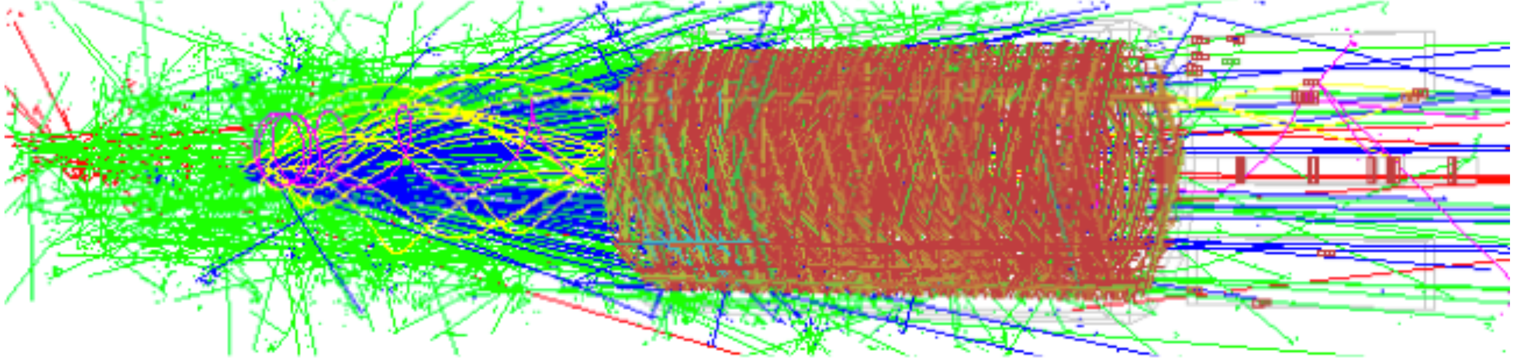
TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME, 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
$\mathrm{BR}(\mu \to e\,\gamma)$	$\mathbf{3.2 \cdot 10^{-14}}$	$\mathbf{3.8 \cdot 10^{-13}}$	$\mathbf{4.0 \cdot 10^{-13}}$	$\mathbf{1.2 \cdot 10^{-12}}$	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
$\mathrm{BR}(\mu \to e\,e\,e\,)$	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
$\mathrm{CR}(\mu \to e \text{ in Ti})$	$\mathit{2.0 \cdot 10^{-15}}$	$\mathit{2.4 \cdot 10^{-14}}$	$\mathit{2.6 \cdot 10^{-15}}$	$\mathit{7.6 \cdot 10^{-14}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{6.7 \cdot 10^{-16}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{8.4 \cdot 10^{-16}}$	$\mathcal{O}(10^{-18})$
$\mathrm{BR}(\tau \to e\,\gamma)$	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to e\,e\,e)$	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to \mu\,\gamma)$	$5.0 \cdot 10^{-11}$	$\mathbf{1.1 \cdot 10^{-8}}$	$7.3 \cdot 10^{-11}$	$\mathbf{1.3 \cdot 10^{-8}}$	$2.9 \cdot 10^{-12}$	$\mathit{7.8 \cdot 10^{-10}}$	$2.7 \cdot 10^{-12}$	$\mathit{6.0 \cdot 10^{-10}}$	$\mathcal{O}(10^{-9})$
$\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

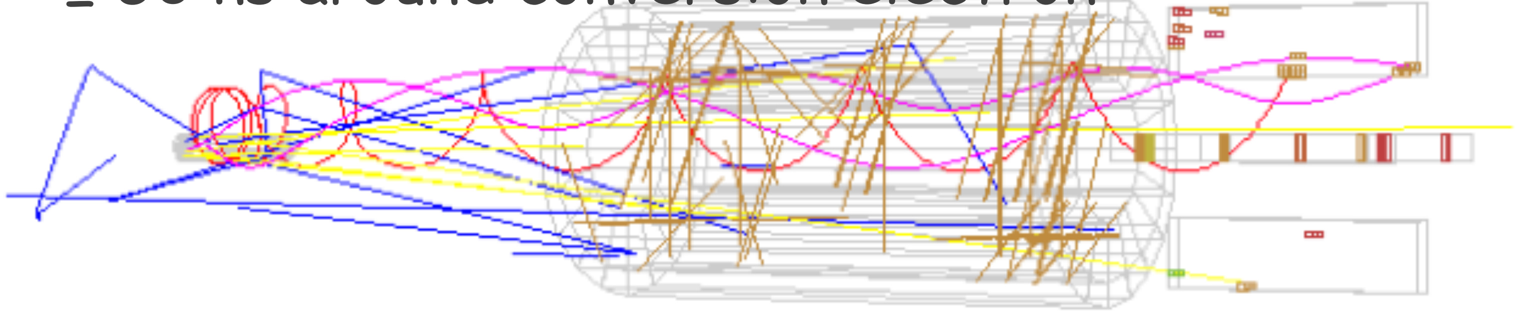
- These are SuSy benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/Belle-2
- All of these will be observable by Mu2e

A typical Mu2e event: Calo track seeding

500 - 1695 ns window



± 50 ns around conversion electron



Search for tracking hits with time and azimuthal angle compatible with the calo clusters (|ΔT| < 50 ns) → **simpler pattern recognition**

Mu2e Expected Background (TDR)

(assuming ~ 10 GHz muon stops, 6×10^{17} stopped muons in 6×10^{7} s of beam time)

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.20 (0.09)
	Radiative μ Capture	<0.001
Late Arriving	Radiative π Capture	0.023
	Beam electrons	0.003(0.001)
	μ Decay in Flight	<0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton induced	0.047 (0.024)
	Cosmic Ray induced	0.082(0.018)
Total Background		0.36 (0.10)

Discovery sensitivity accomplished by suppressing backgrounds to < 0.5 event total

Upper Limit < 6×10^{-17} @ 90% C.L.

Mu2e Expected Background (CD3 +)

(assuming ~ 10 GHz muon stops, 6×10^{17} stopped muons in 6×10^{7} s of beam time)

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.14 (0.11)
	Radiative μ Capture	<0.001
Late Arriving	Radiative π Capture	0.025(0.003)
	Beam electrons	2.5E-4
	μ Decay in Flight	<0.003
	π Decay in Flight	0.001
Miscellaneous	Anti-proton induced	0.047(0.024)
	Cosmic Ray induced	0.247(0.055)
Total Background		0.46(0.11)

Discovery sensitivity accomplished by suppressing backgrounds to < 0.5 event total

Upper Limit < 6×10^{-17} @ 90% C.L.

(WhatNext?) Mu2e → Mu2e-II

Project-X re-imagined to match Budget constraints:

1) PIP-2 plans:

→ 1 MW at LNBF at start (2025)

→ 2 MW at regime at LNBF

→ **x 10 at Mu2e**

Projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232

CLVF-snowmass →Arxiv.1311.5278

Mu2e-2 → Arxiv.1307.1168v2.pdf

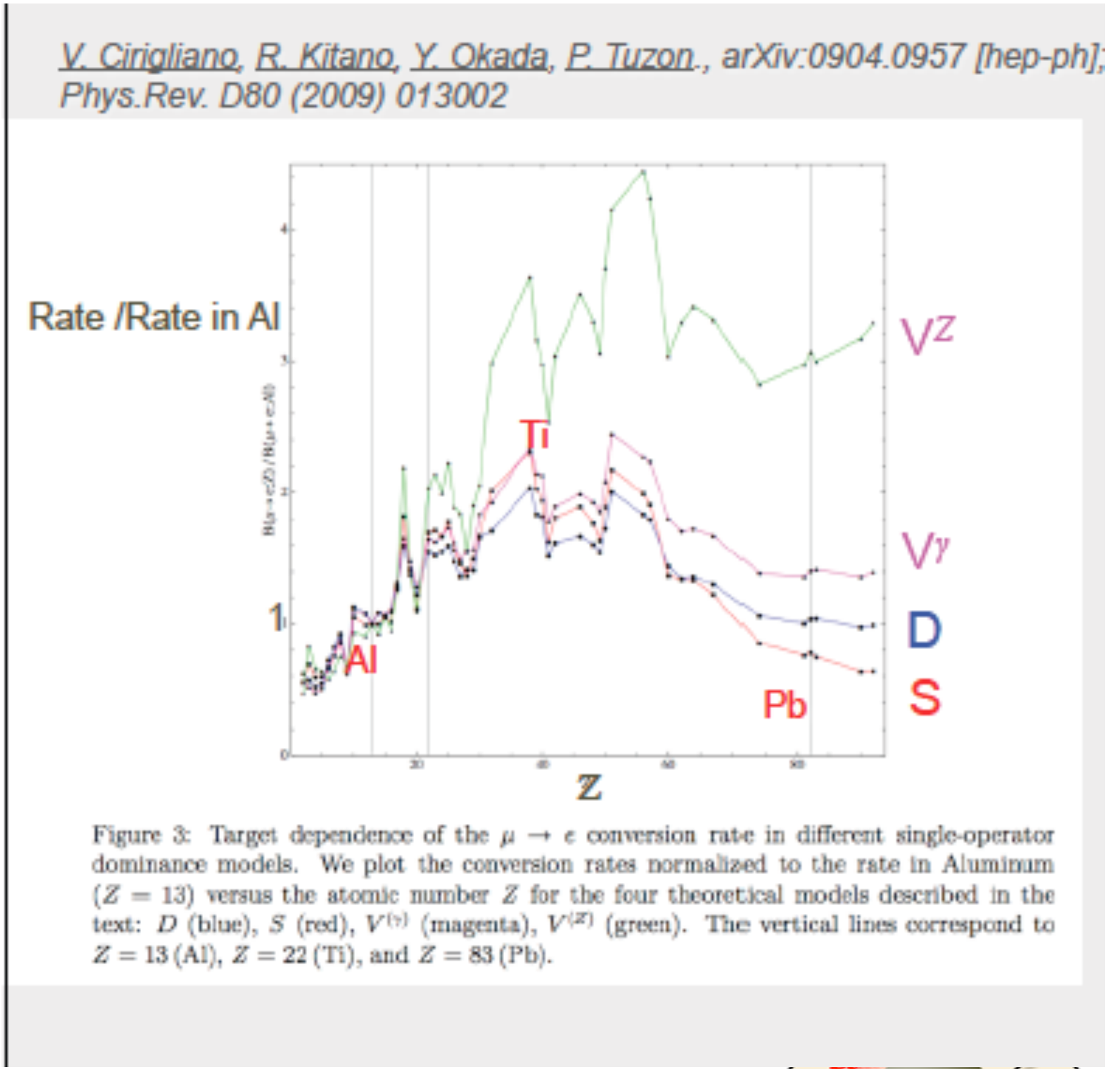
2) **Depending on the beam Structure available:**

→ study Z dependence if signal is observed

3) If no signal is observed

Use x 10 events in Mu2e-II

Some R&D and modifications of detector and shielding → **BR < 6 x 10^{-18}**



V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon., arXiv:0904.0957 [hep-ph];

Phys.Rev. D80 (2009) 013002

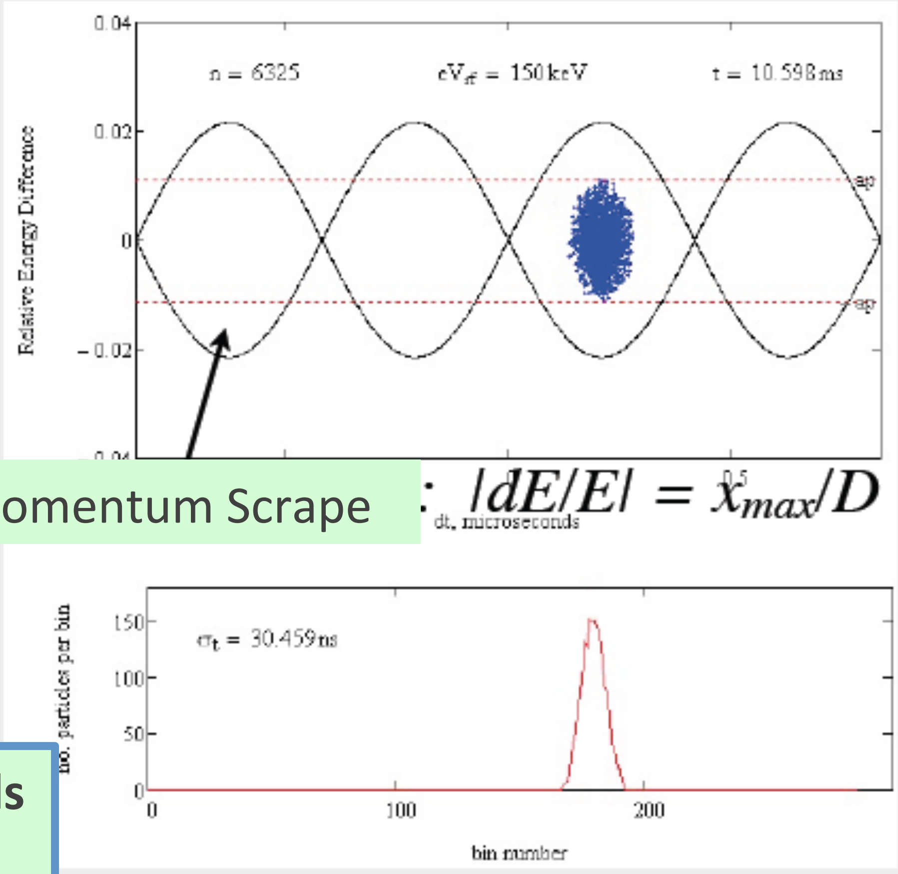
Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$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

Out of Time proton → Extinction Method

Proton extinction between pulses → # protons out of beam/# protons in pulse

achieving 10^{-10} is hard; normally get $10^{-2} – 10^{-3}$

- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
  - Sweep Unwanted Beam into collimators

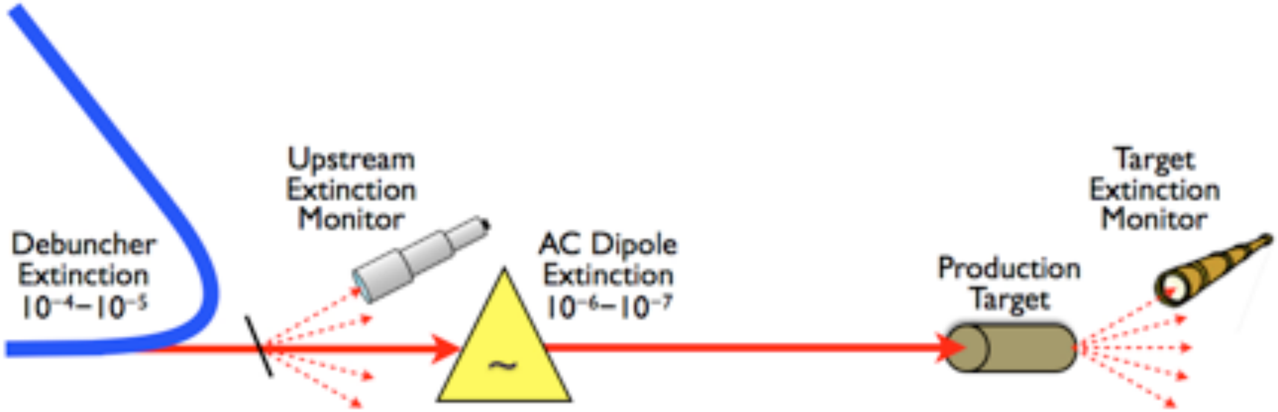


Momentum Scrape

$: |dE/E| = x_{max}/D$

Calculations based on accelerator models that take into account collective effects Shows that this combination gets ~ 10^{-12}

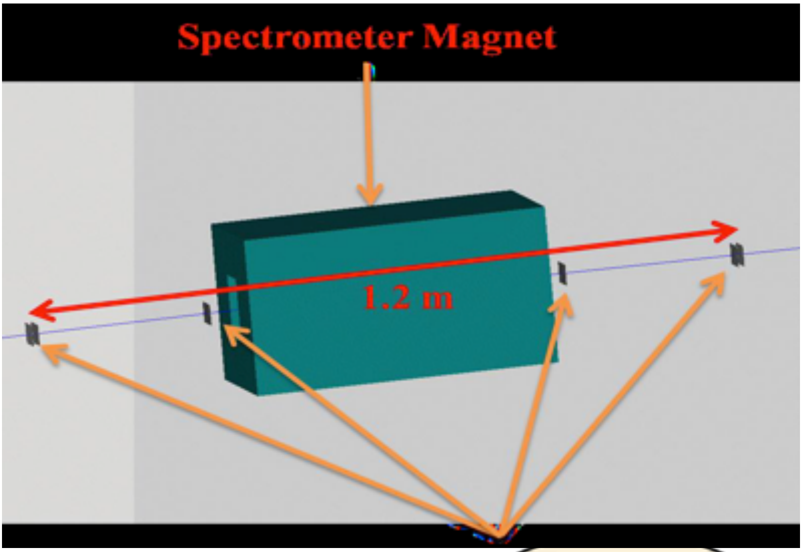
Extinction Monitor



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

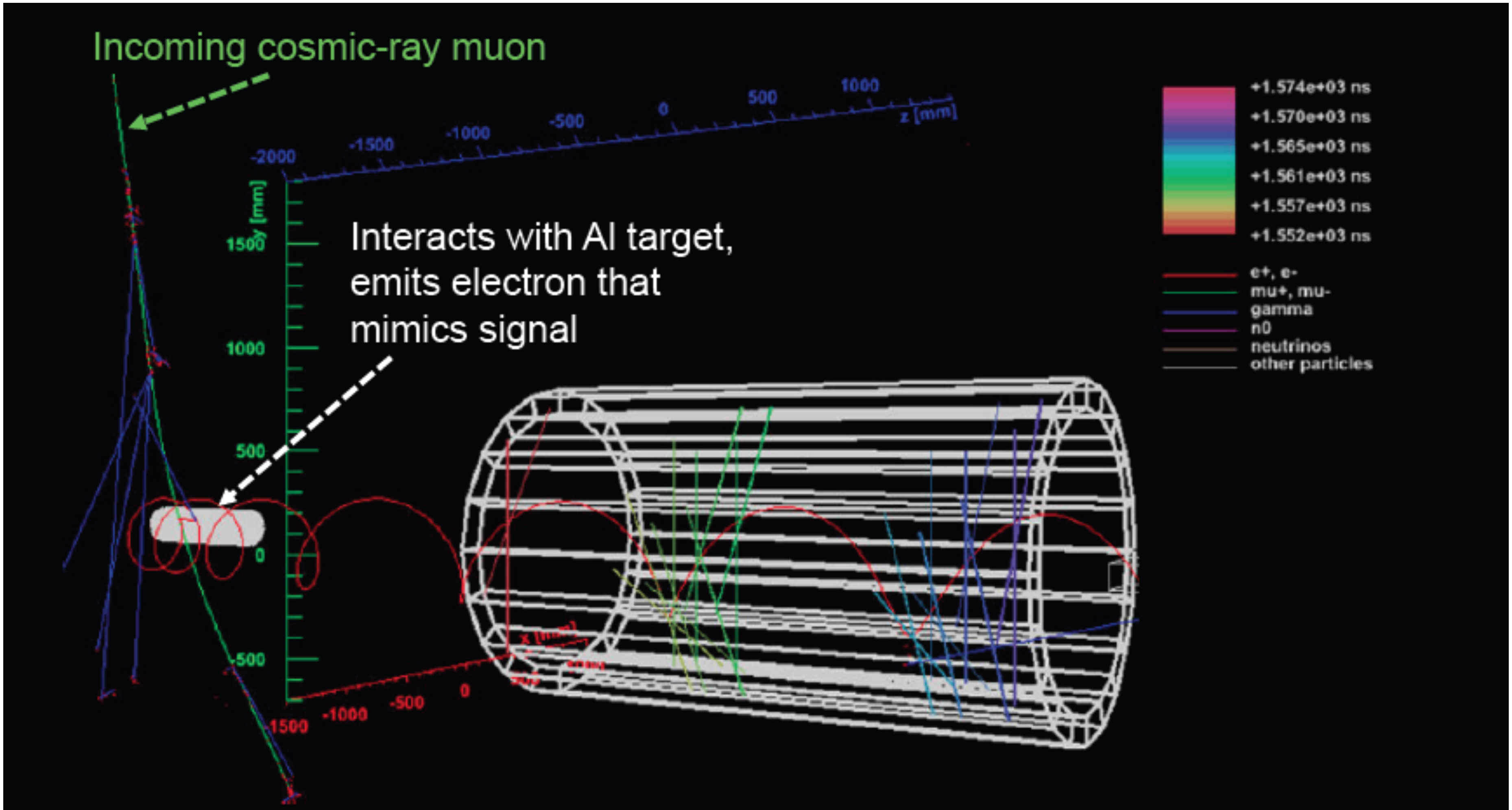
Spectrometer based on ATLAS pixel detector

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



collimator exit

Cosmic Rays are a problem


Incoming cosmic-ray muon

Interacts with Al target, emits electron that mimics signal

- This happens once per day!