The Mu2e Experiment at Fermilab

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(On behalf of the Mu2e Collaboration)

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The Mu2e collaboration

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University of California, Berkeley
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California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of Illinois
Kansas State University
Lewis University
University of Louisville
University of Minnesota
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Northern Illinois University
Northwestern University
Purdue University
Rice University
University of South Alabama
University of Virginia
University of Washington
Yale University

Laboratori Nazionali di Frascati

INFN Genova

INFN Lecce and Università del Salento

Laboratori Nazionali di Frascati and Università Marconi Roma

INFN Pisa

Joint Institute for Nuclear Research, Dubna

Novosibirsk State University/Budker Institute of Nuclear Physics

Institute for Nuclear Research, Moscow

Helmoltz-Zentrum Dresden-Rossendorf

San Yat-Sen University

- **Mu2e Home page: http: // mu2e.fnal.gov**
- **Technical Design report: http://arxiv.org/abs/1501.05241**
- **Spokespersons: Doug Glenzinski, Jim Miller**

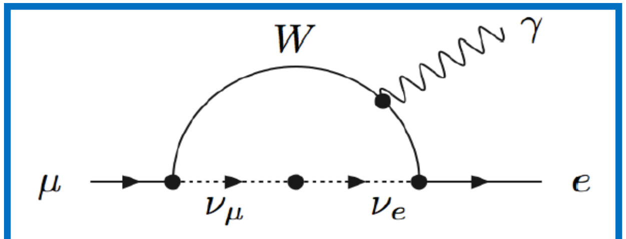
Charged Lepton Flavor violation (CLFV)

- Quark flavor violation has been observed (larger mass quark flavors decay into lower mass quark flavors by weak interaction)

- Neutrino mixing shows lepton flavor is violated.

- What about charged lepton sector?

  Existence of neutrino oscillations implies the possibility of charged lepton flavor violation



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

- Some examples in the muon sector,

$$\mu^+ \to e^+\gamma$$
$$\mu^+ \to e^+e^-e^+$$
$$\mu^- N \to e^- N$$

Mu2e experiment at Fermilab

- **Mu2e will search for the neutrinoless conversion of a muon to electron in the Coulomb field of nucleus (Al)**

$$\mu N \rightarrow eN$$

- **This is extremely suppressed in standard model (BR < 10^{-54}), any observation of a conversion electron signal will be a clear sign of physics beyond standard model**

- **The goal of Mu2e is to improve the sensitivity of the previous best experiment by a factor of 10^4**

- **Many of the leading extensions to the standard model predicts the conversion rates to be within reach of Mu2e experiment**

Probing CLFV

- **Wide range of new physics models predicts muon to electron conversion either through loops or exchange of a heavy intermediate particle**

  - **Contact interactions dominated**

    (Leptoquarks, compositeness, New heavy bosons,…)

  - **Loop dominated**

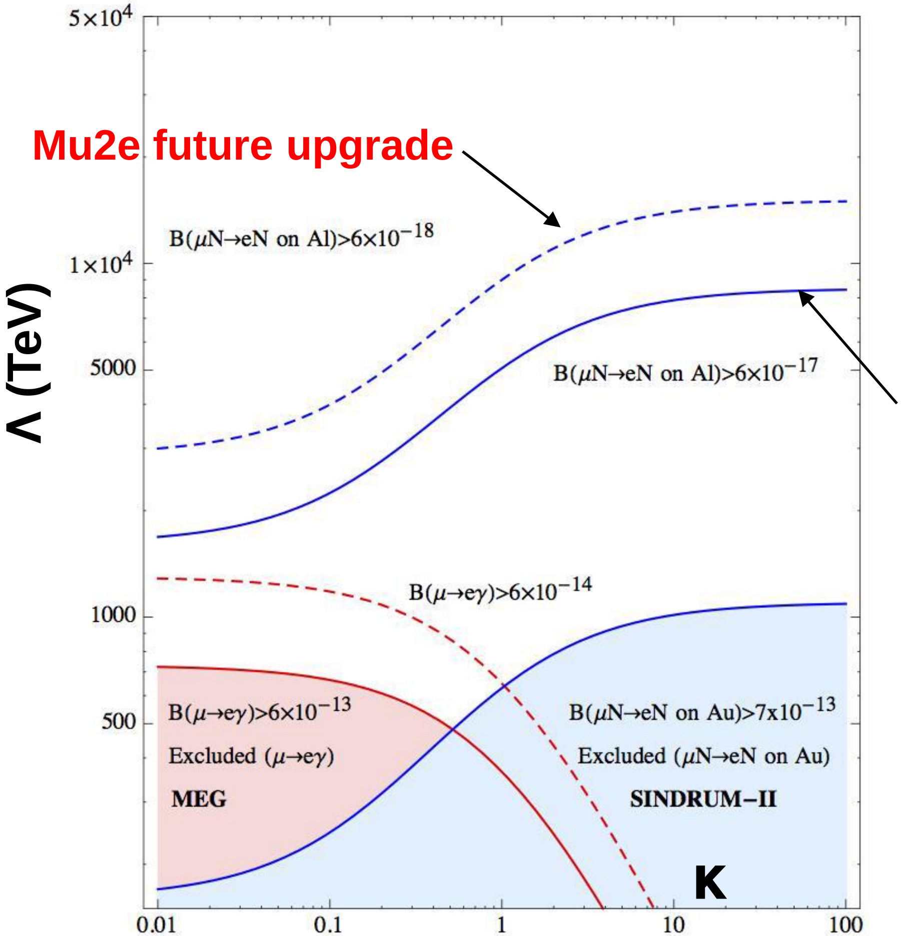
    (supersymmetry, Heavy neutrino, Two Higgs doublet, …)

See for example
Kuno, Okada, Rev.Mod.Phys. 73, 151 ,2001
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, 315 ,2008
M. Raidal et al, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, Prog.Part.Nucl.Phys. 71, 2013

Probing CLFV: Mu2e sensitivities

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

all limits at 90% confidence level



Mu2e

Loop dominated

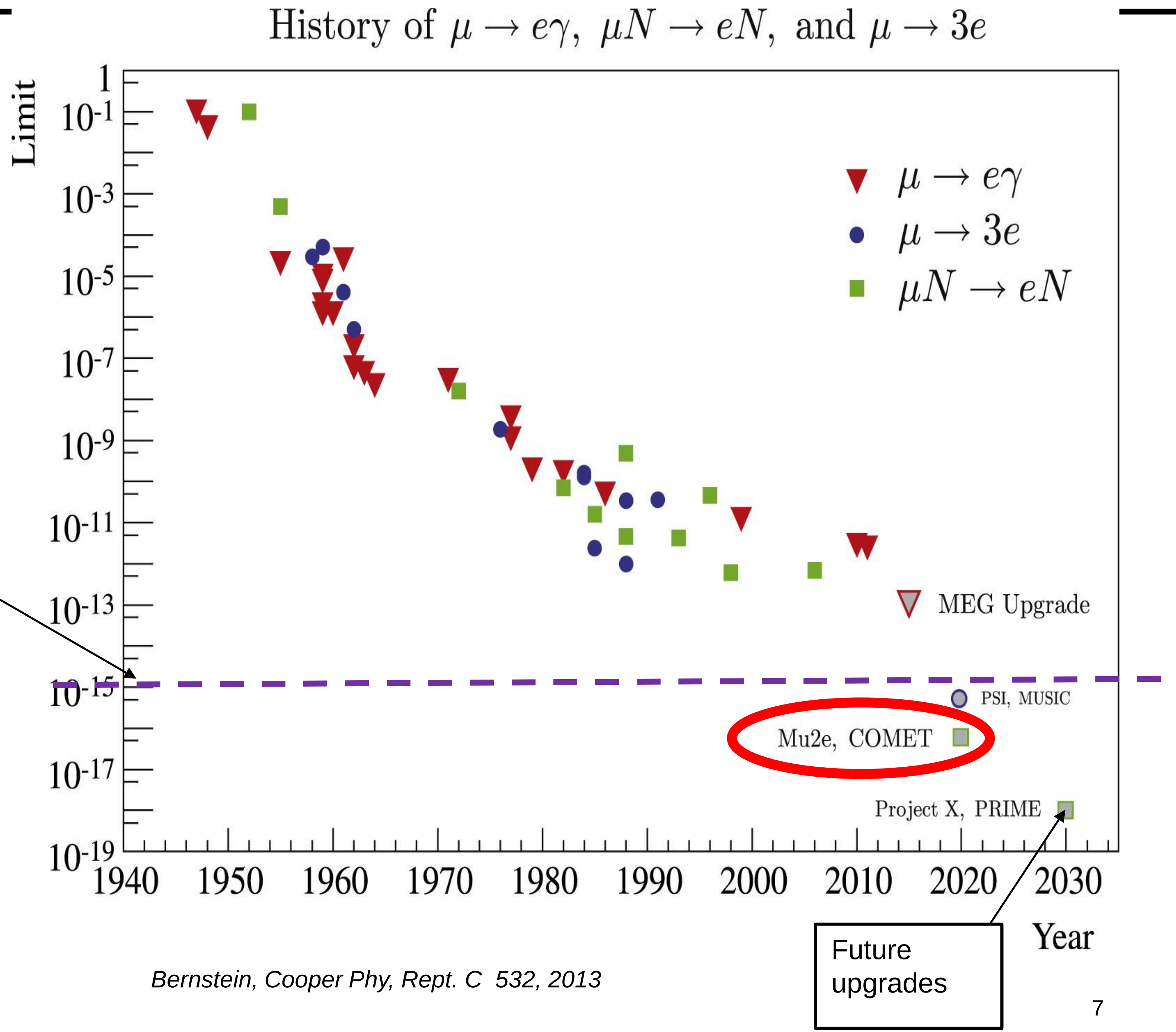
Contact dominated

Loop | Contact

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

- Mu2e will be sensitive over the full K range.
- Mu2e will have sensitivity to mass scales (Λ) up to 10^4 TeV

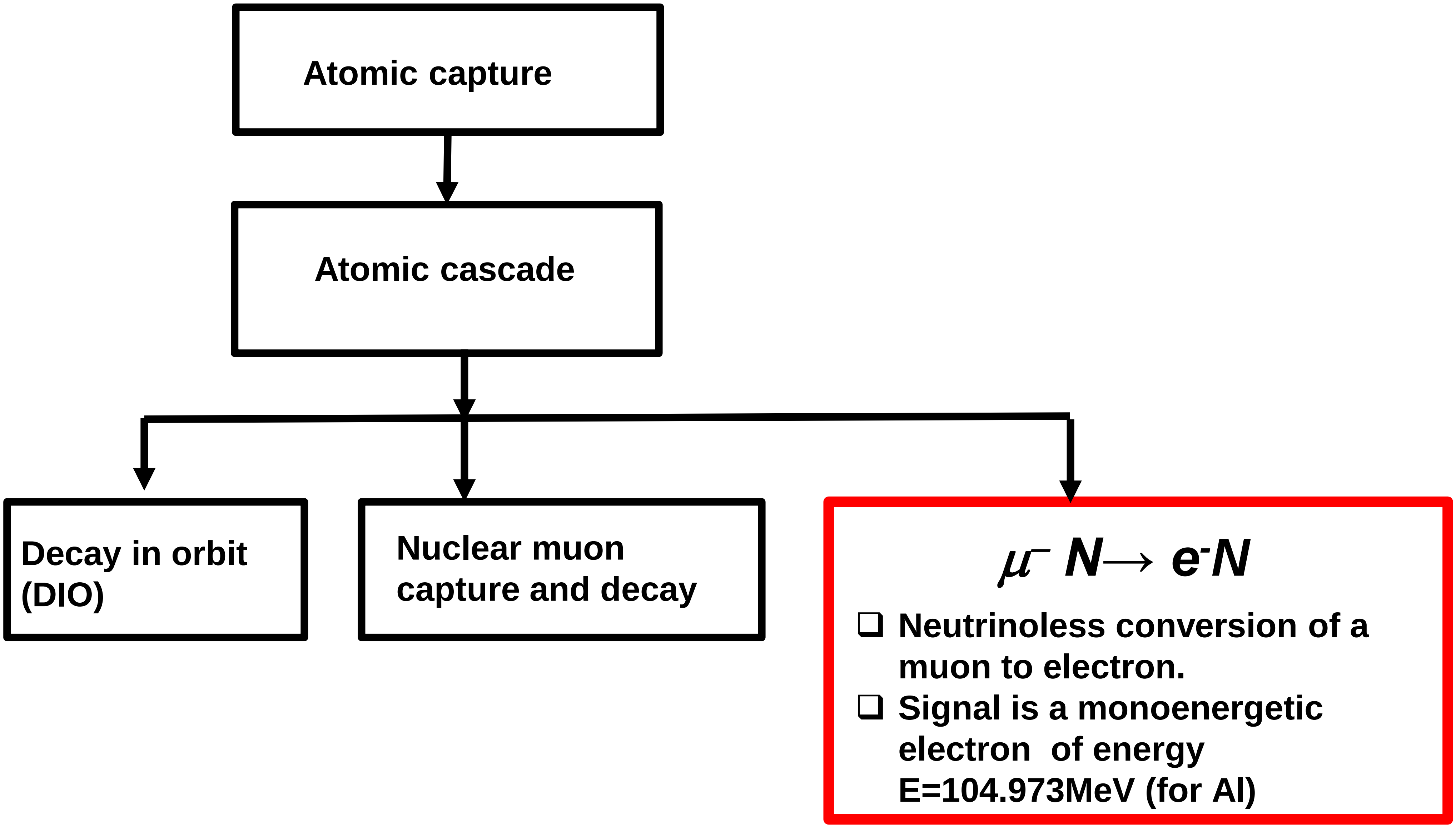
CLFV searches: timeline



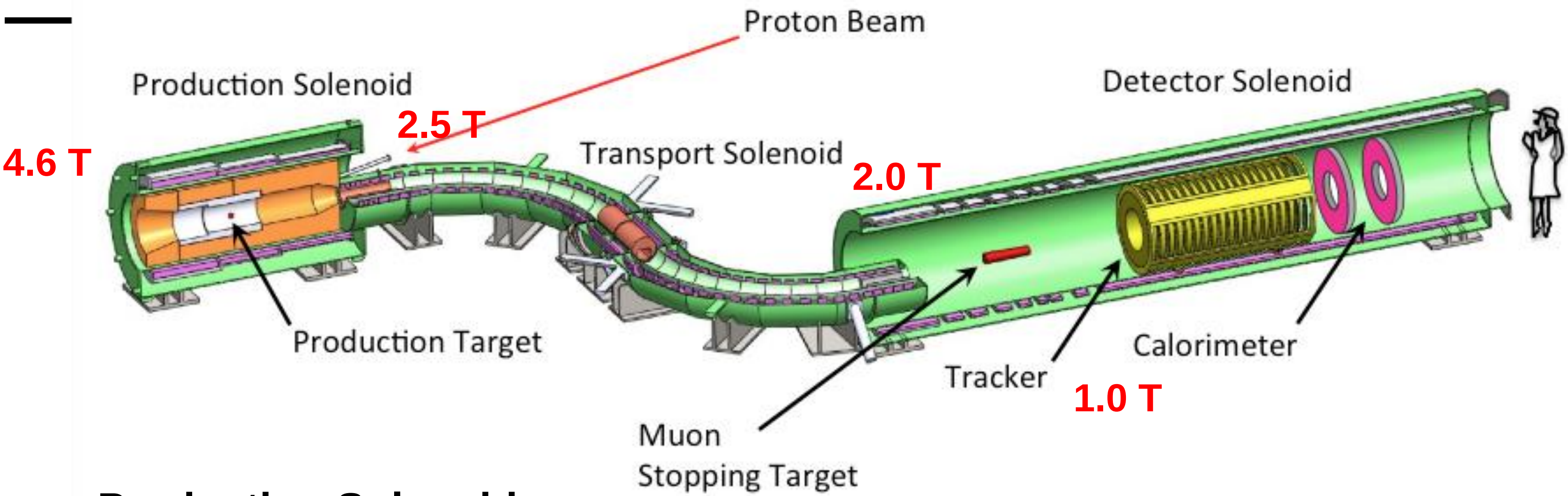
Most of the "New physics" models at the weak scale generically imply CLFV rates of 10^{-15}, within the reach of Mu2e

Bernstein, Cooper Phy, Rept. C 532, 2013

The muon capture process

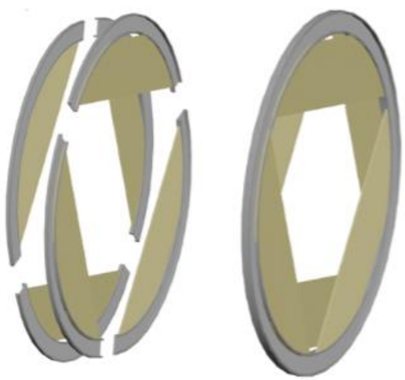


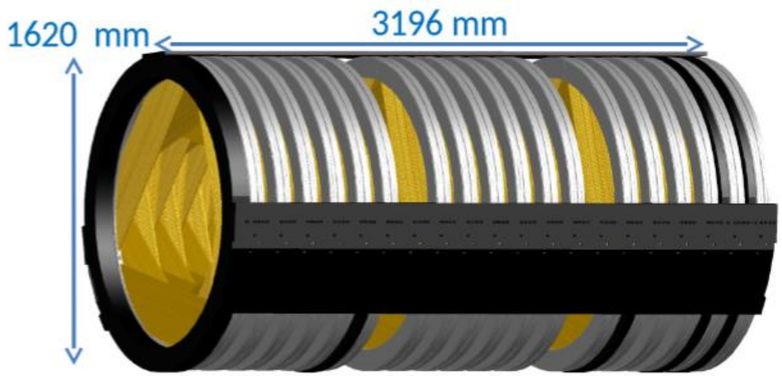
Experimental setup



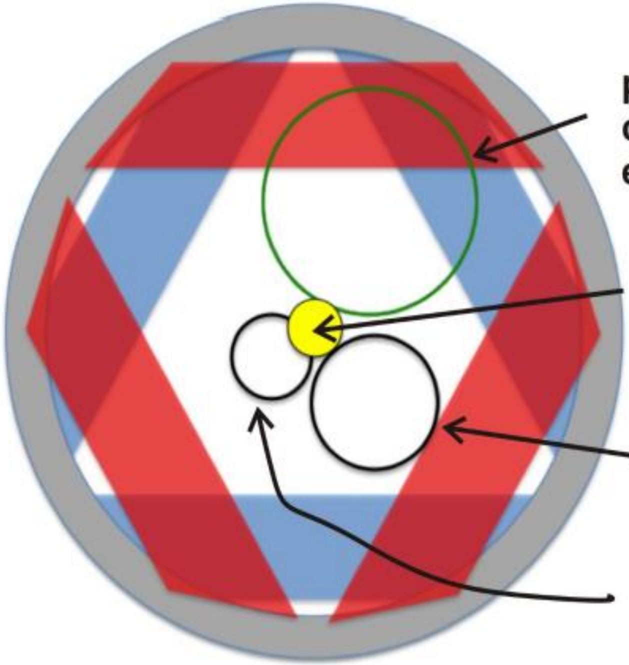
- **Production Solenoid**
  - Proton beam strikes target, producing mostly pions
  - Contains backwards pions/muons; gradient field reflects slow forward pions/muons towards transport solenoid
- **Transport Solenoid**
  - Selects low momentum, negative muons
- **Capture Target, Detector, and Detector Solenoid**
  - Capture muons on target and wait for them to decay
  - Detector blind to ordinary (Michel) decays, with $E \leq \frac{1}{2} m_\mu c^2$
  - Optimized for $E \sim m_\mu c^2$

Straw tracker

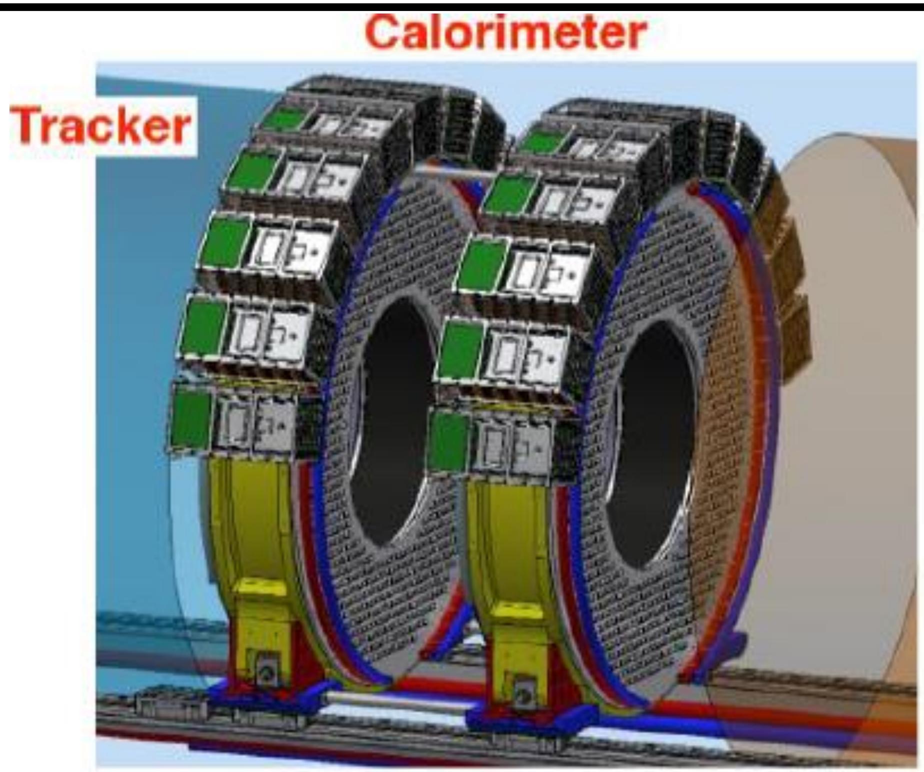




- Low mass straw drift tubes
- About 22, 000 straws, 5mm diameter
- 80/20 Ar/CO_2 gas mixture
- 15um thick straw walls, length varies between 430 mm and 1120 mm, dual ended read out.
- 18 stations
- Blind to most DIO electrons
- Expected momentum resolution better than 200 keV/c at the conversion energy



Calorimeter system

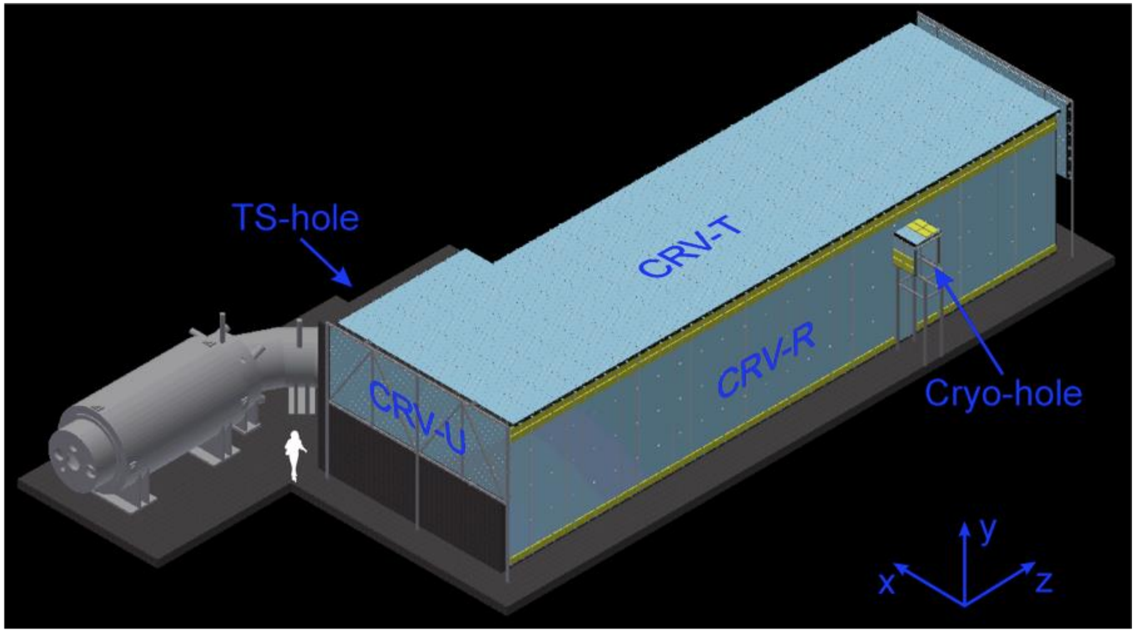


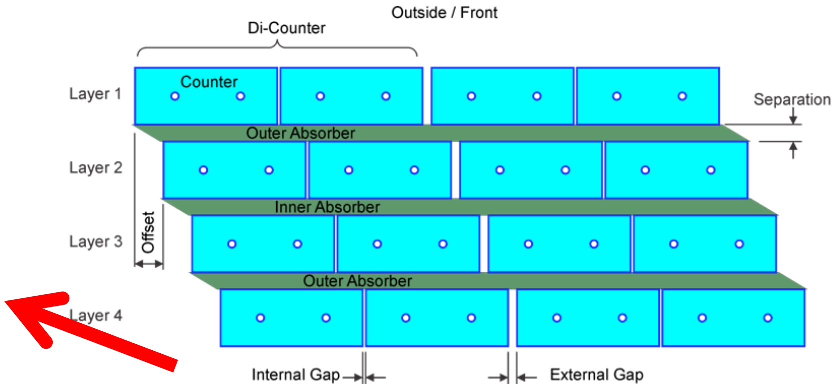
High granularity crystal based calorimeter

- **Two disks separated by 75 cm**
- **Each annulus is made of about 700 pure CsI crystals, readout by SiPM**
- **Provides independent measurement of energy (about 5%) , time (about 0.5ns) and position (about 1cm)**
- **Particle ID**
- **Seed for tracking algorithm in a complicated reconstruction environment**

Cosmic Ray Veto (CRV)

- Cosmic ray background can mimic conversion electrons, which happens about 1 per day
- Multiple layers of scintillator panels surround detector to veto cosmic rays





- Two wavelength shifting fibers per bar, readout both ends by SiPM
- Efficiency achieved by test beam : > 99.4% per layer

Mu2e: signal, backgrounds

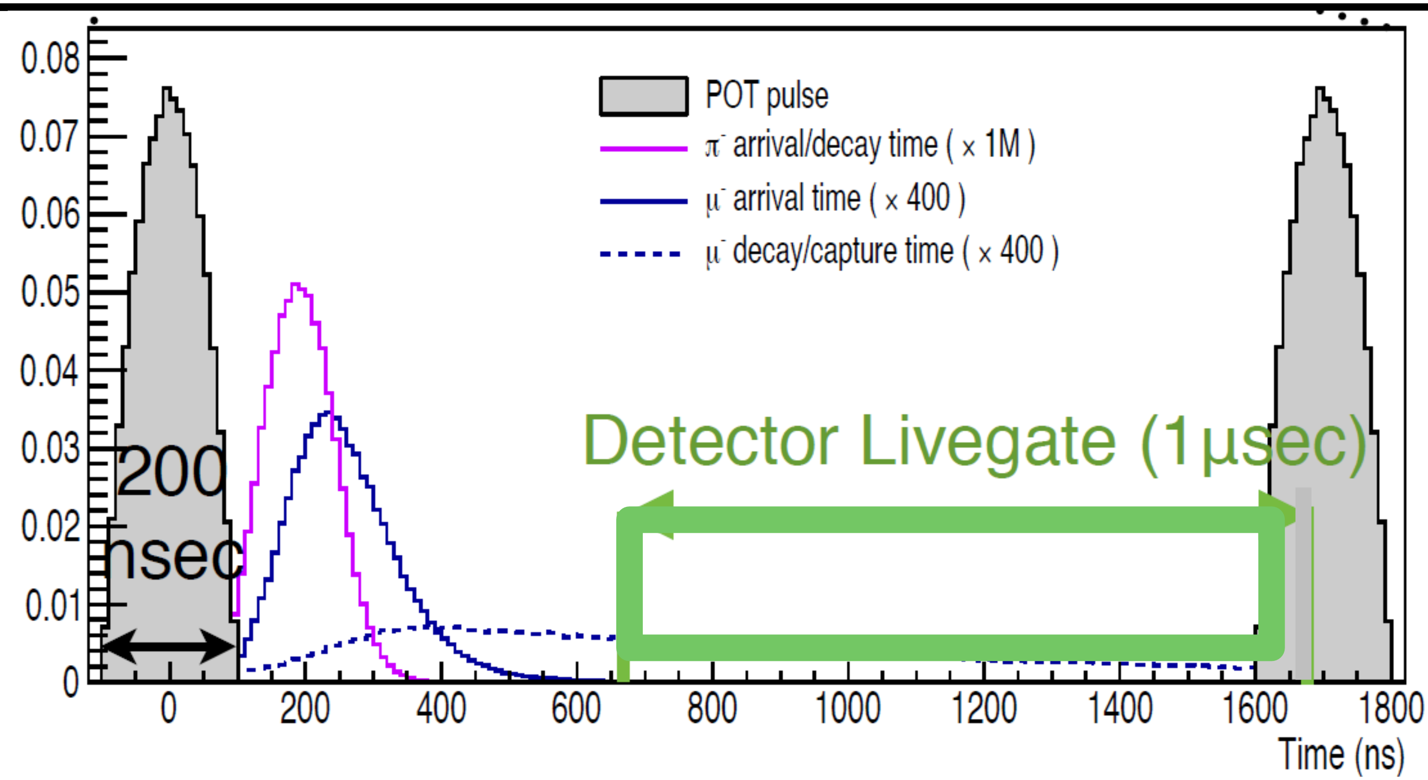
- **Signal is a mono-energetic electron**

$$
\begin{aligned}
E_{\mu e} &= m_\mu c^2 - E_b - E_{\mathrm{recoil}} \\
&= 104.973\ \mathrm{MeV} \quad (\mathrm{for\ Al})
\end{aligned}
$$

- **Measure the rate of μ to *e* conversion relative to ordinary μ capture (ie., total number of muons captured)**

$$
Branching\ \ ratio,\ R_{\mu e} \equiv \frac{\Gamma\left(\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}\right)}{\Gamma\left(\mu^- + \mathrm{Al} \rightarrow \left(\mathrm{All\ Captures}\right)\right)}
$$

Beam timing:

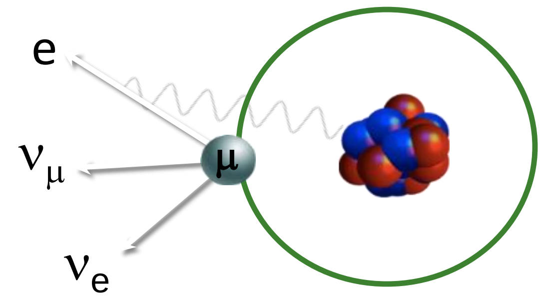


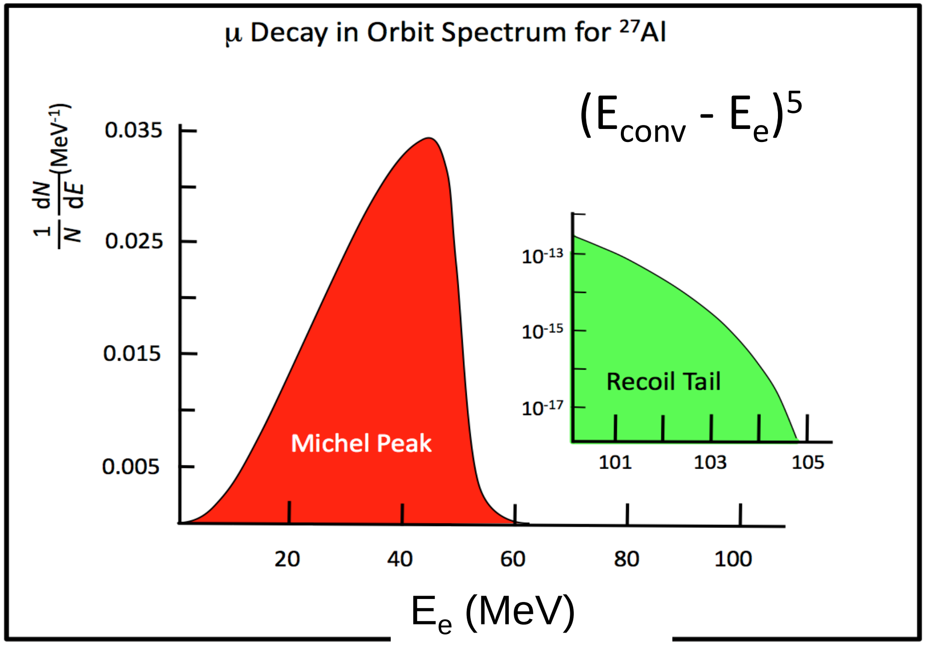
- Mu2e uses a pulsed proton beam and a delayed selection window to suppress prompt backgrounds
- Beam delivered in 1.7us cycle
- Detector live for about 1us
- 700nsec delay avoids beam backgrounds, proton extinction factor is < 10^{-10}
- Beam flash in first ~300 ns, huge detector rate, no data acquisition during this period

Mu2e backgrounds: Decay in orbit

- **Muon decay in orbit** (~39% for Al)

$$\mu \to e\ \nu_\mu\ \nu_e$$





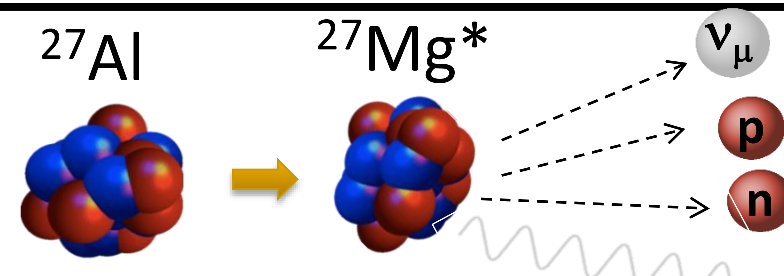
See e.g. Czarnecki et al., Phys. Rev. D 84, 013006 (2011)

- **Free muon decay (Michel decay); cut off at 52.8MeV**
- **However, free muon decay spectrum is distorted by the presence of the nucleus and the electron can be at the conversion energy**
- **Suppressed by energy resolution of the tracker**

Mu2e backgrounds: from nuclear muon capture

- **Nuclear capture** (~61% for Al)

$$\mu N \rightarrow \nu_\mu N'^*$$



decay products could produce electrons

Protons	Neutrons	Gammas
- Generate hits in the detector which affect track finding algorithms and affect tracking efficiency - Cross-talk between channels - If proton flux is high, DAQ may be saturated which reduces the efficiency	- Fast neutrons may cause single event upset and damages to Front-end electronics - Defects in calorimeter crystal - False positives in cosmic ray veto	- What is the best way to count the number of stopped or captured muons for normalization?.

Mu2e: R&D ('Al'uminum 'Cap'ture) experiment at PSI

- It is crucial to understand the rate and spectrum of these BG products from muon capture with some improved precision
- AlCap experiment at PSI

AlCap Collaboration

- Spokespersons P. Kammel and Y. Kuno
- ANL, BU, BNL, FNAL, ICL, IHEP, INFN, LBL, OU, UCL, UH, UW
- Joint project between COMET and Mu2e

Status of AlCap

- Three run periods focusing on charged and neutral particle emission after muon capture.
- Alternative normalization schemes being investigated
- Data analysis underway
- Preliminary results indicate that proton emission rate is much less than (about 3.5% per muon captured) than the 15% estimated from previous old data

Mu2e: expected sensitivity

3 years running period with 1.2×10^{20} protons on target per year

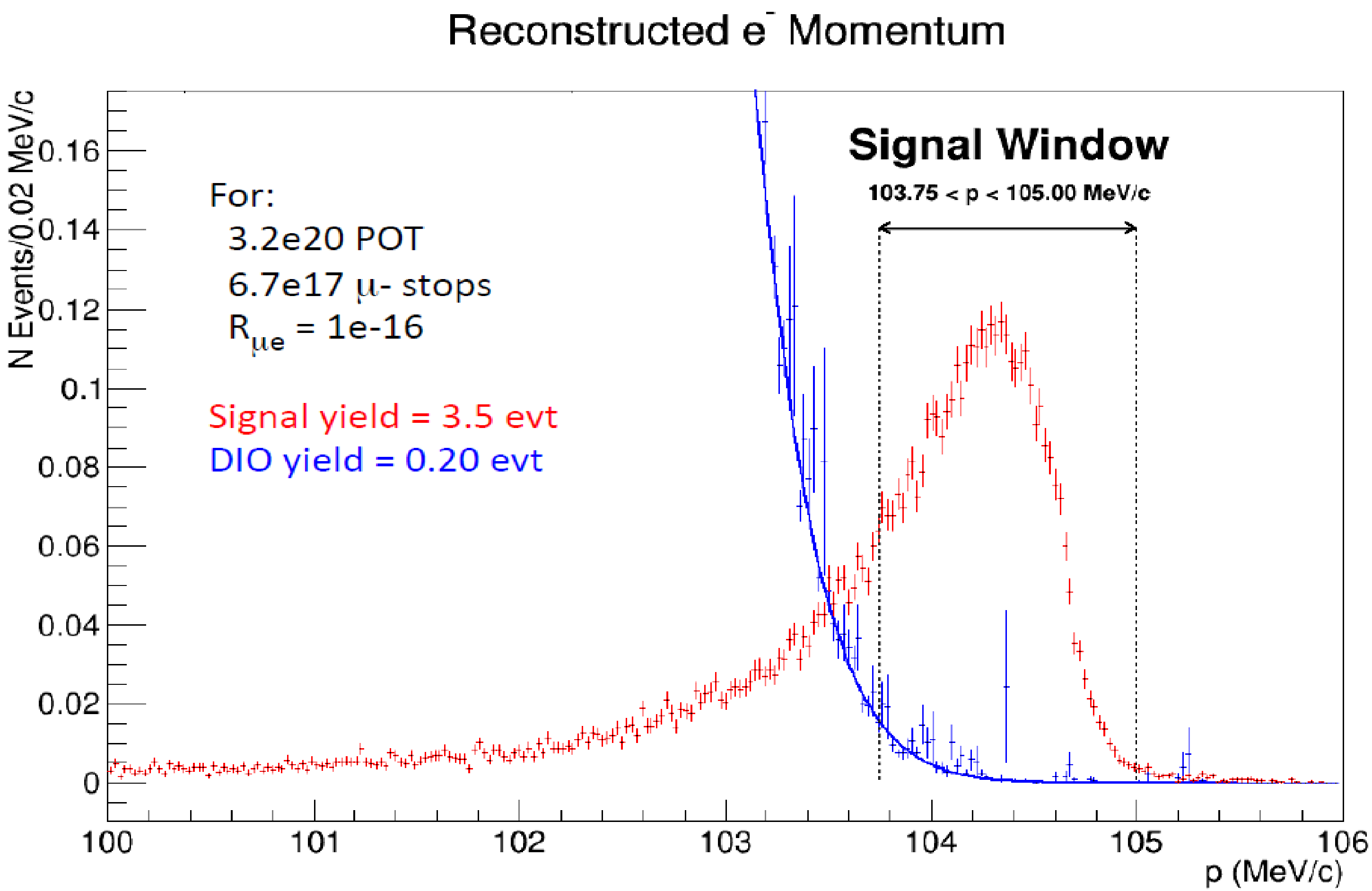
Estimated background

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	$\boxed{0.37 \pm 0.10}$

- ❑ **Background < 0.5 event**

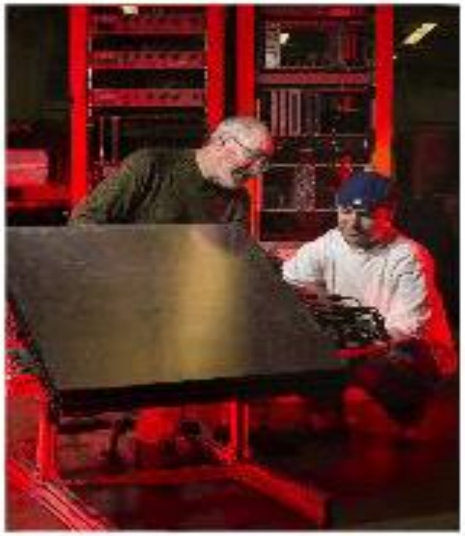
Mu2e: expected sensitivity

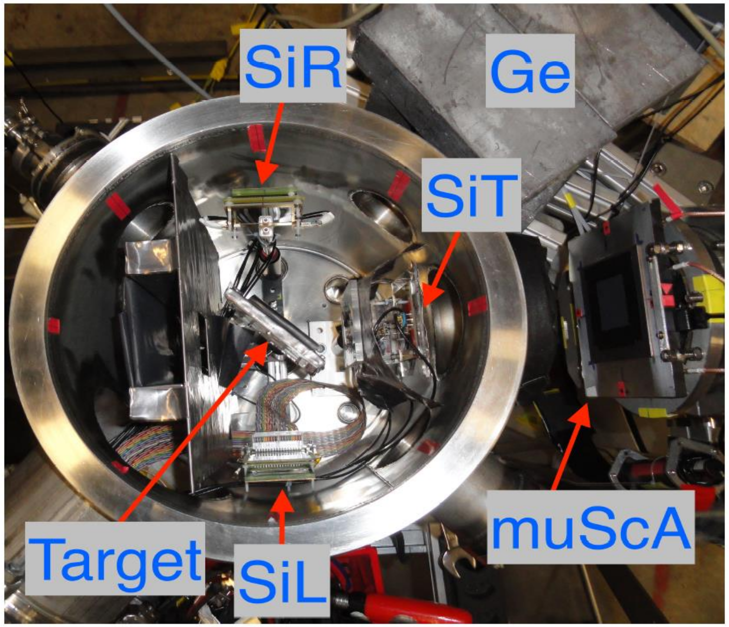
3 years running period with 1.2×10^{20} protons on target per year



- ❑ **Background < 0.5 event**
- ❑ **Single event sensitivity: $R_{\mu e} = 2.9\times10^{-17}$ (goal is 2.5×10^{-17})**
- ❑ **If $R_{\mu e} = 10^{-16}$, we would see about 3.5 conversion electrons (typical SUSY signal ~50 events or more for rate 10^{-15})**

Mu2e: civil construction, some representative R&D, …





Mu2e: Summary

Mu2e will attempt to measure

$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}\right)}{\Gamma\left(\mu^- + \mathrm{Al} \to \left(\mathrm{All\ Captures}\right)\right)}$$

- **Single event sensitivity of $R_{\mu e} = 2.5\text{x}10^{-17}$**
- **This represents an improvement of *four orders of magnitude compared to the existing limit.***
- **Any signal would be unambiguous proof of physics beyond the Standard Model. The absence of a signal would be a very important constraint on proposed new models.**
- **R&D phase is mostly completed, civil construction almost done.**
- **Experiment begins from 2021 onwards.**