The Mu2e experiment at Fermilab: a search for lepton flavor violation

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Flavor Violation

- We've known for a long time that quarks mix

✓**Mixing strengths parameterized by V_{CKM}**

$$\mathrm{V_{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

- In last 15 years also neutrinos (neutral leptons) mixing was measured

✓**Mixing strengths parameterized by PMNS matrix**

- **Is there violation for charged leptons?**

Some CLFV processes

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8	
$\tau \rightarrow eee$	BR < 3.6 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 7.8 E-8	
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \rightarrow eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

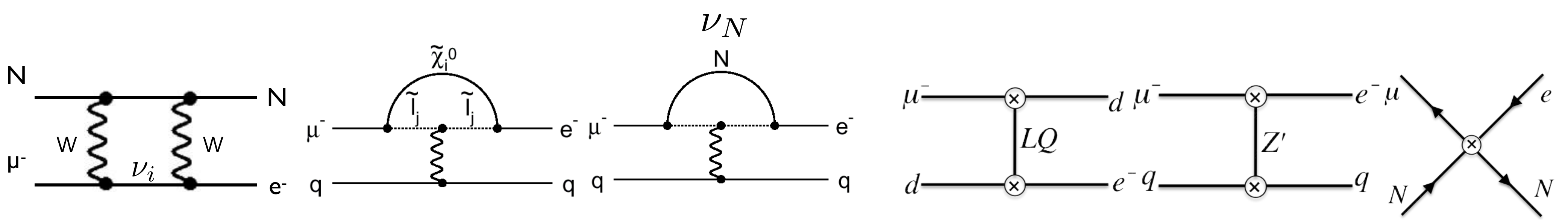
- Global interest in CLFV

What is μ→e conversion

- μ could convert to an electron in the presence of a nucleus $\mu^- N \rightarrow e^- N$

$$E_e = m_\mu c^2 - B_\mu(Z) - C(A) = 104.973 \text{ MeV}$$

- for Aluminum: $\begin{cases} B_\mu(Z) \text{ is the muon binding energy (0.48 MeV)} \\ C(A) \text{ is the nuclear recoil energy (0.21 MeV)} \end{cases}$
- new interaction in nature if there are no neutrinos!



nuMSM Muon conversion: R≈10^{-52}

Supersymmetry : R ≤10^{-13}

Heavy neutrino

Lepto-quark exchange

Z' exchange

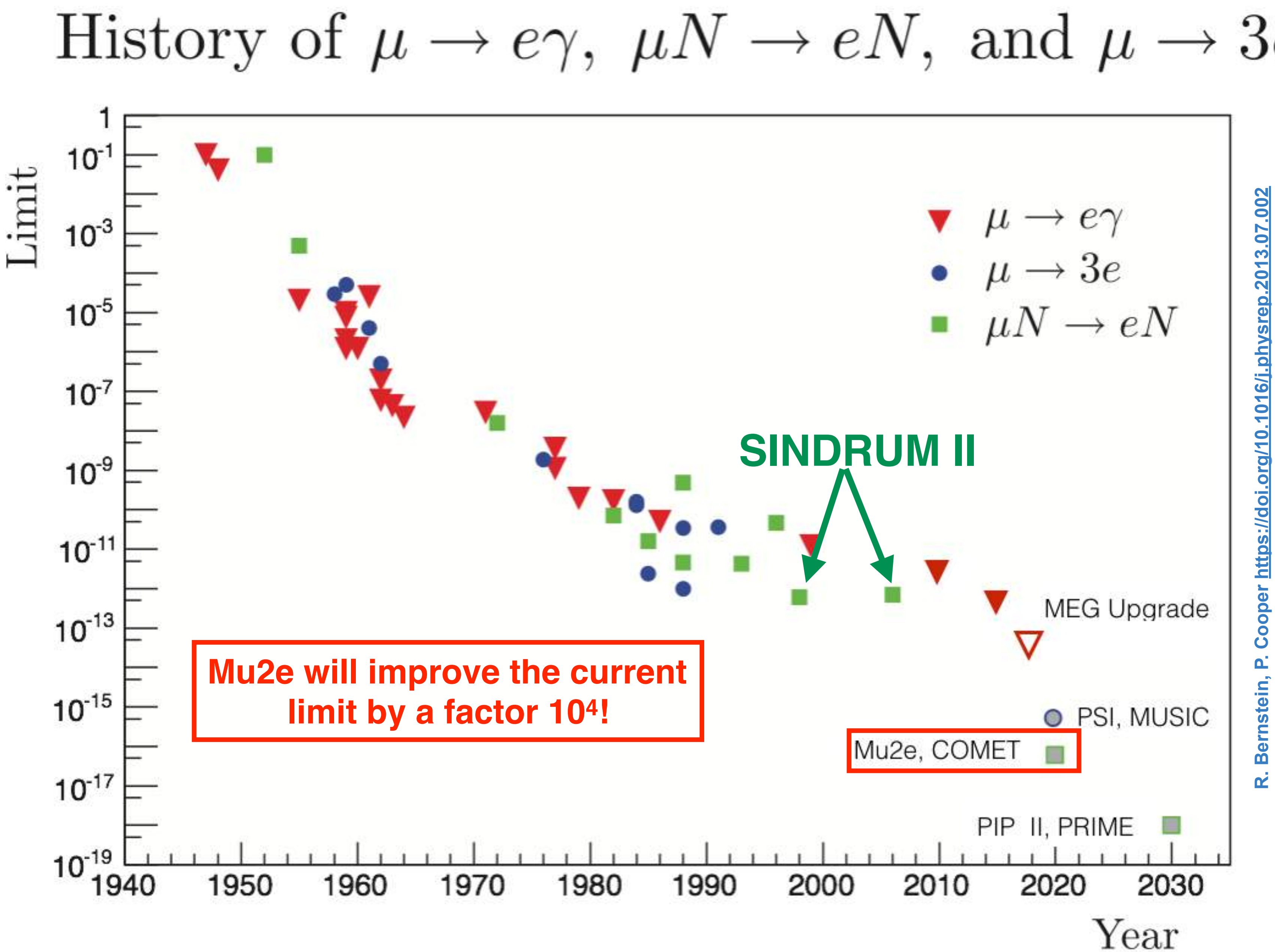
Eff contact interaction

Mu2e goal

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)\right)}{\Gamma\left(\mu^- + N(A,Z) \rightarrow \text{all muon captures}\right)} = 8 \cdot 10^{-17} \text{ @ } 90\% \text{C.L.}$$

Mu2e will start data taking at Fermilab in 2021

History of μ→e search



Experimental setup

(1) Production Solenoid:

➡ Proton beam strikes target, producing mostly pions

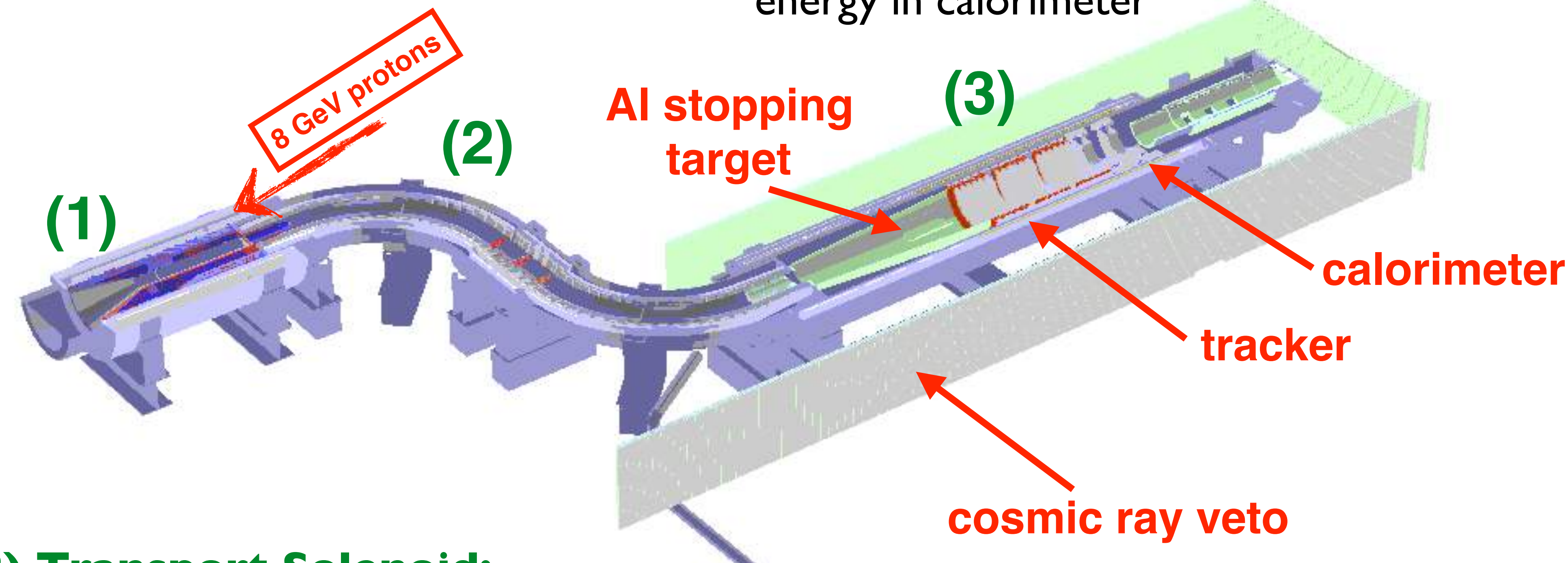
➡ Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

(3) Detector Solenoid:

➡ Capture muons on Al target

➡ Graded field "focuses" e- in tracker fiducial

➡ Measure momentum in tracker and energy in calorimeter



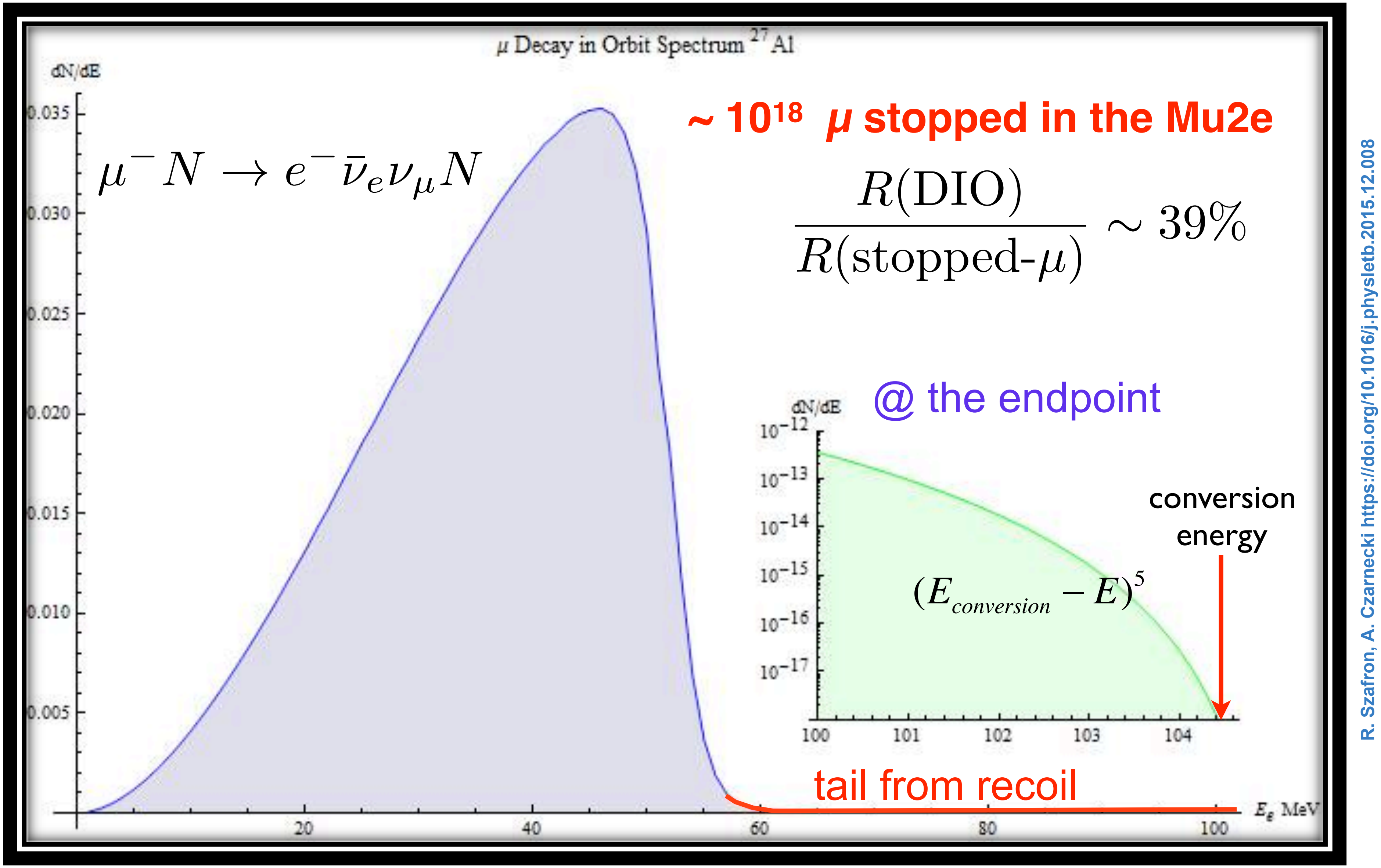
(2) Transport Solenoid:

➡ Select low momentum, negative muons

Physics background

- **μ decay-in-orbit**
- Cosmic-induced background
- Antiproton-induced background
- Radiative π capture

μ decay-in-orbit (DIO)



Physics background

- **μ decay-in-orbit:**

  ✓ **low-mass tracker with high performance**

Mu2e Tracker talk
Kate Ciampa & Fawzi Abusalma!

- Cosmic-induced background
- Antiproton-induced background
- Radiative π capture

Physics background

- μ decay-in-orbit:

  ✓ low-mass tracker with high performance

- **Cosmic-induced background:**

  ✓ **cosmic ray veto and PID**

- Antiproton-induced background

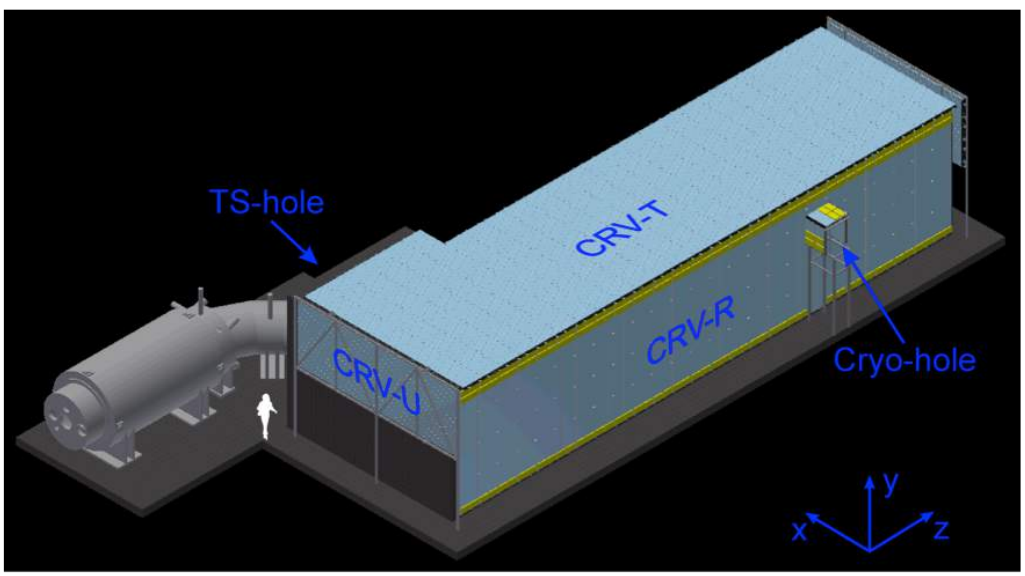
- Radiative π capture

Cosmic Ray Veto

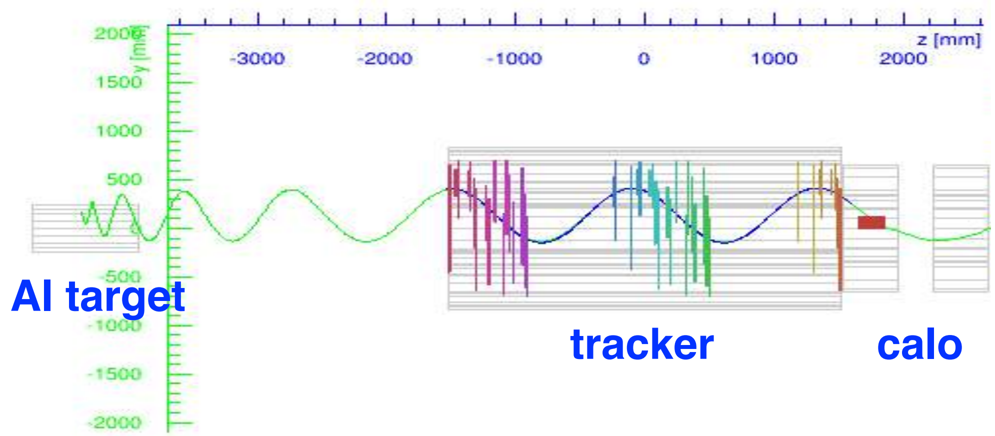
- Veto system covers entire DS and half TS
- 4 layers of scintillator
  - each bar is 5x2x~450 cm^3
  - 2 WLS fibers/bar
  - read out at both ends with SiPM
- required inefficiency ~ 10^{-4}

WLS fiber

Prototype



μ mimicking the CE



Physics background

- μ decay-in-orbit:

  ✓ low-mass tracker with high performance

- Cosmic-induced background:

  ✓ cosmic ray veto and PID

- **Antiproton-induced background**

  ✓ **absorbers in the beam line to annihilate p-bar and PID**

- Radiative π capture

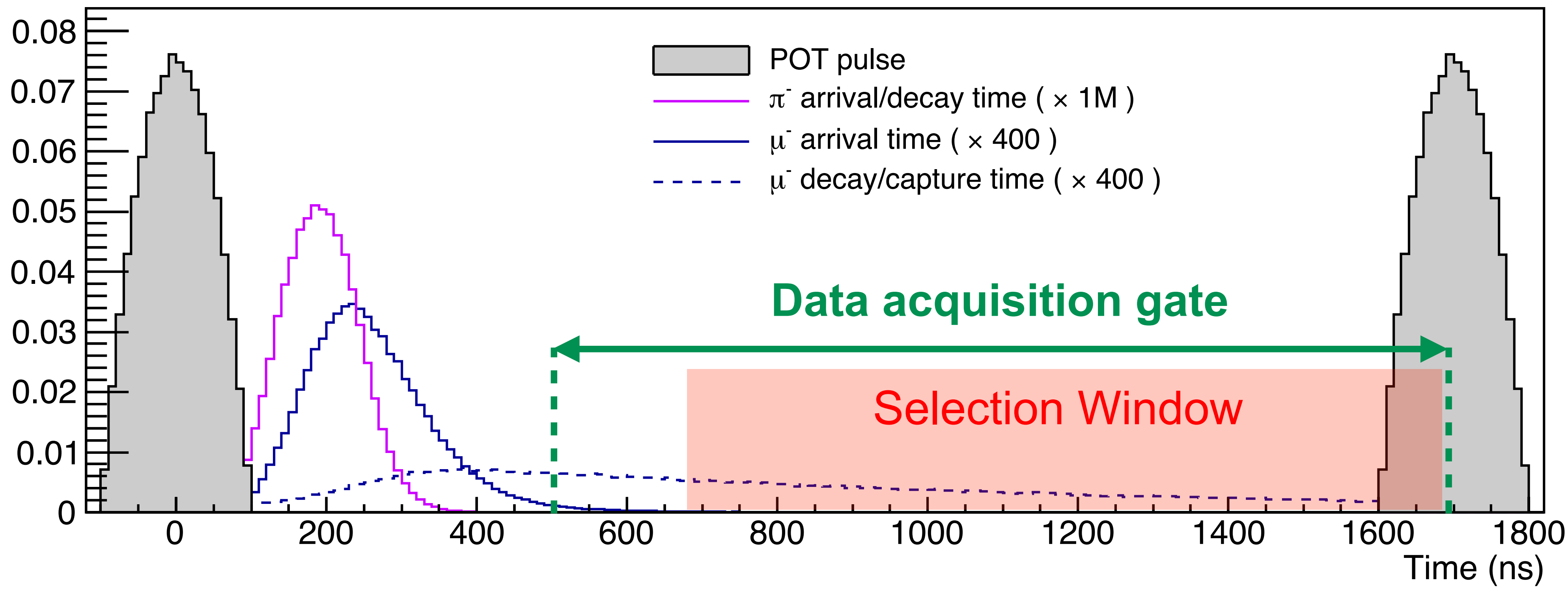
Physics background

- μ decay-in-orbit:
  - ✓ low-mass tracker with high performance
- Cosmic-induced background:
  - ✓ cosmic ray veto and PID
- Antiproton-induced background
  - ✓ 3 thin absorbers in the beam line and PID
- **Radiative π capture: $\pi^- N_Z \rightarrow N^*_{Z-1}\, \gamma$, asymmetric $\gamma \rightarrow e^- e^+$**
  - ✓ **pulsed beam and extinction of out-of-time protons**

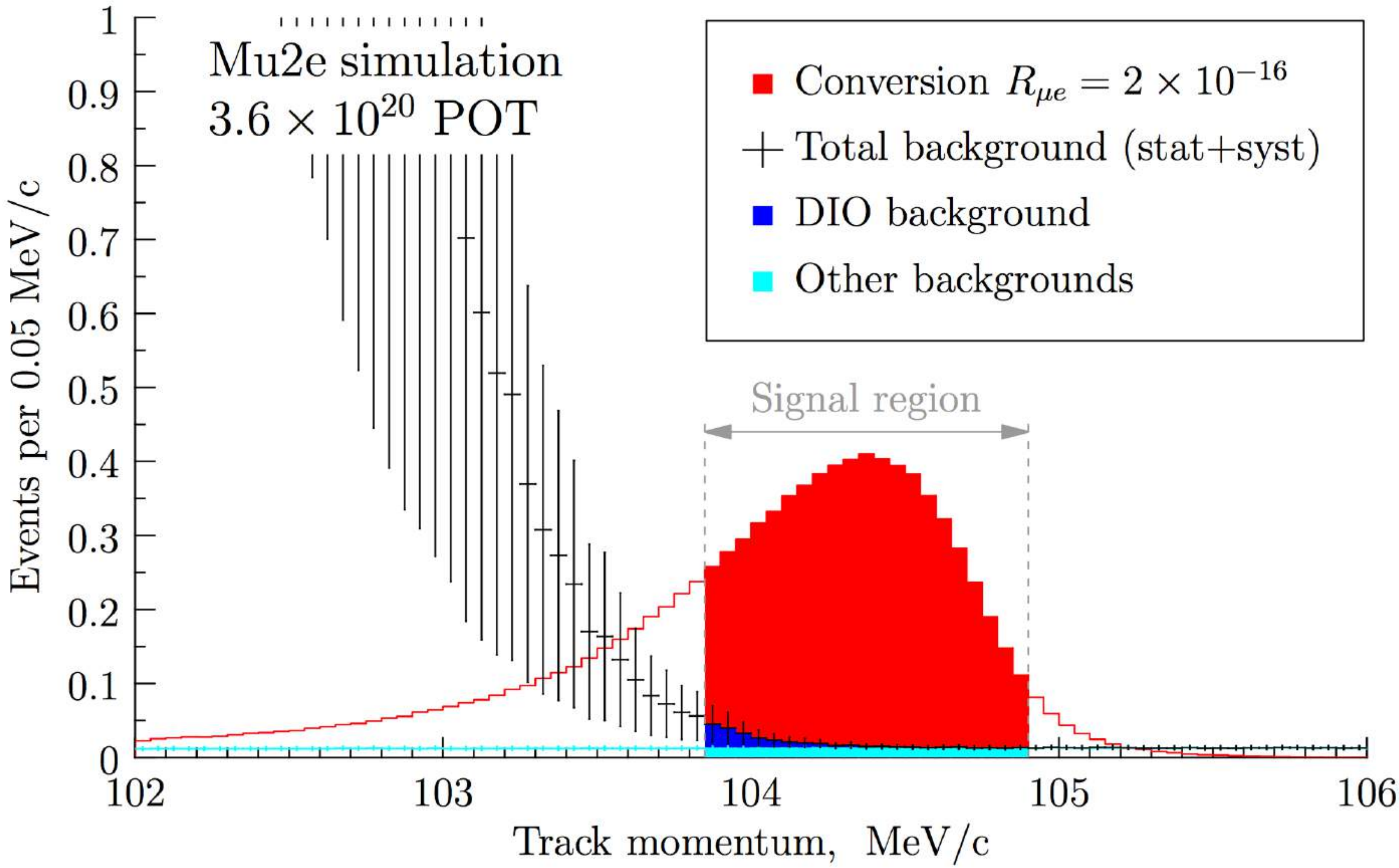
Pulsed beam

- Beam period : 1.7 μs ~ 2 x τ_{μ}^{Al}
- Beam intensity: 3.9 x 10^7 p/bunch
- duty cycle : ~ 30%
- **out-of-time protons / in-time protons < 10^{-10}**

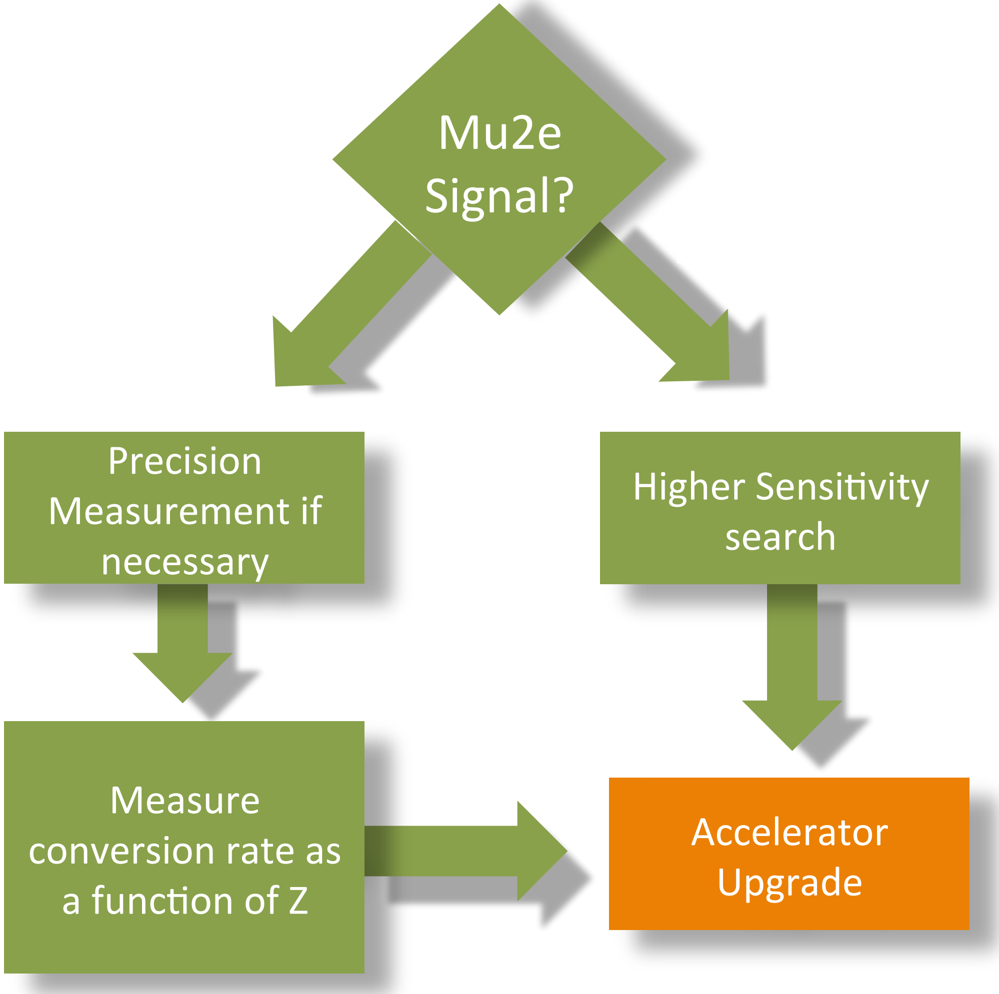
Mu2e extinction monitor talk -> Avery Archer!



Mu2e sensitivity



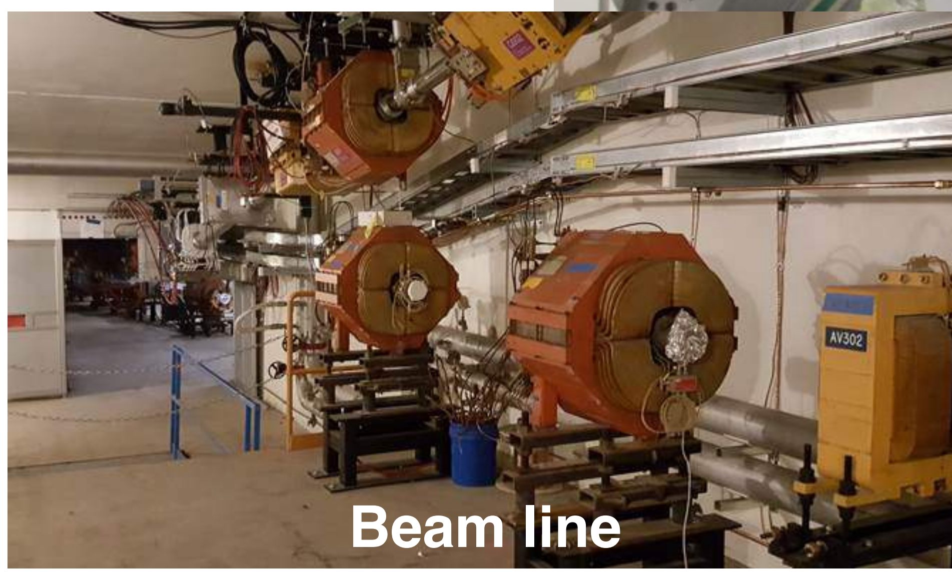
Mu2e signal?



- A next-generation Mu2e experiment makes sense in all scenarios:
  - ✓ Push sensitivity or
  - ✓ Study underlying new physics
  - ✓ Will need more protons upgrade accelerator
  - ✓ **Snowmass** white paper, arXiv:1802.02599

Fermilab Muon campus

Mu2e detector hall



Summary

- Mu2e will improve the sensitivity by four orders of magnitude
- Provides discovery capabilities over a wide range of new Physics Models
- **R&D mature with data taking scheduled on 2021**
- More info: **`http://mu2e.fnal.gov`**

Within this session checkout:

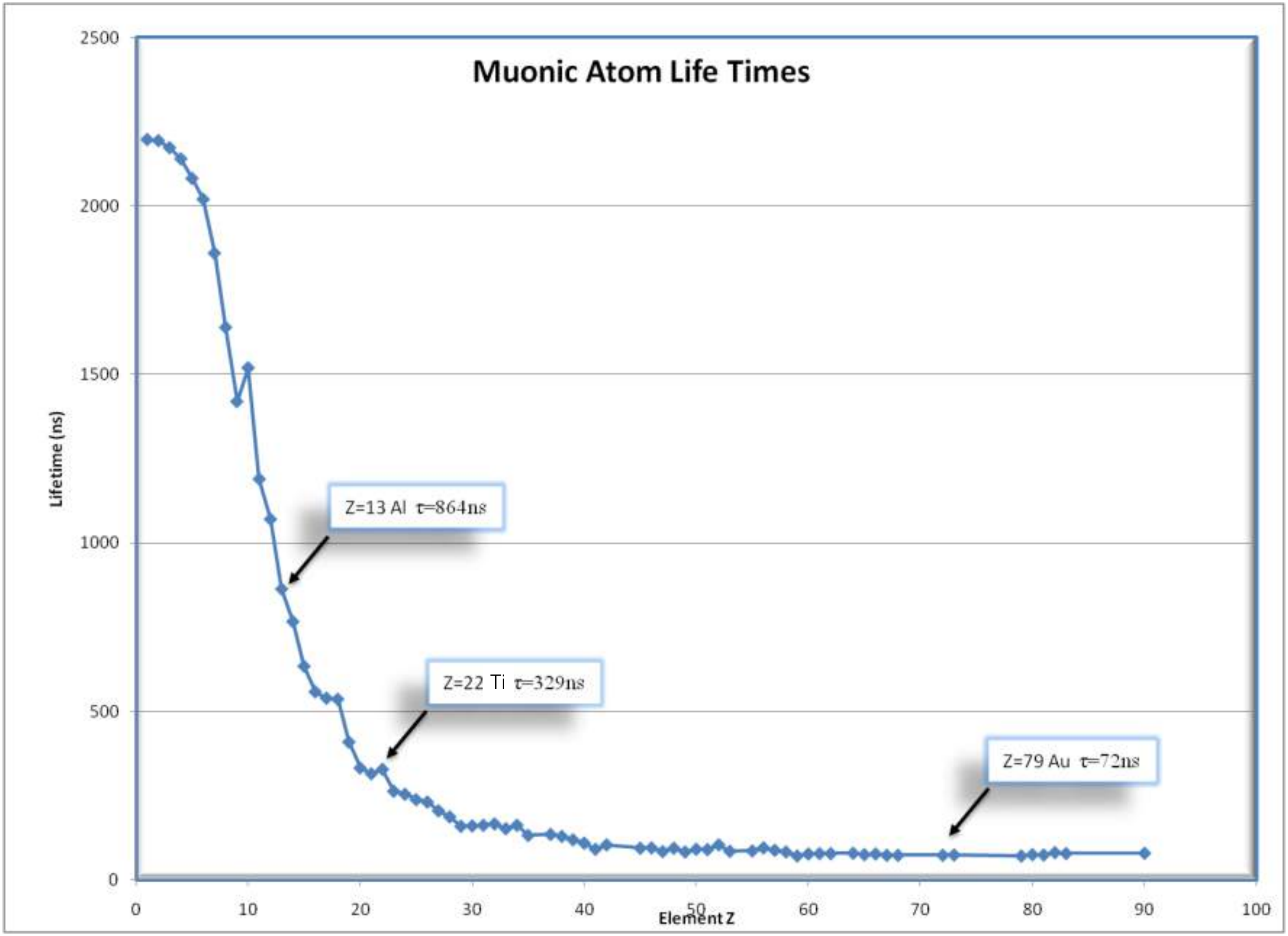
➡ Mu2e extinction monitor from Avery Archer

➡ Mu2e Straw Tracker design from Kate Ciampa & Fawzi Abusalma

➡ Mu2e Calorimeter clustering studies from Emma Castiglia

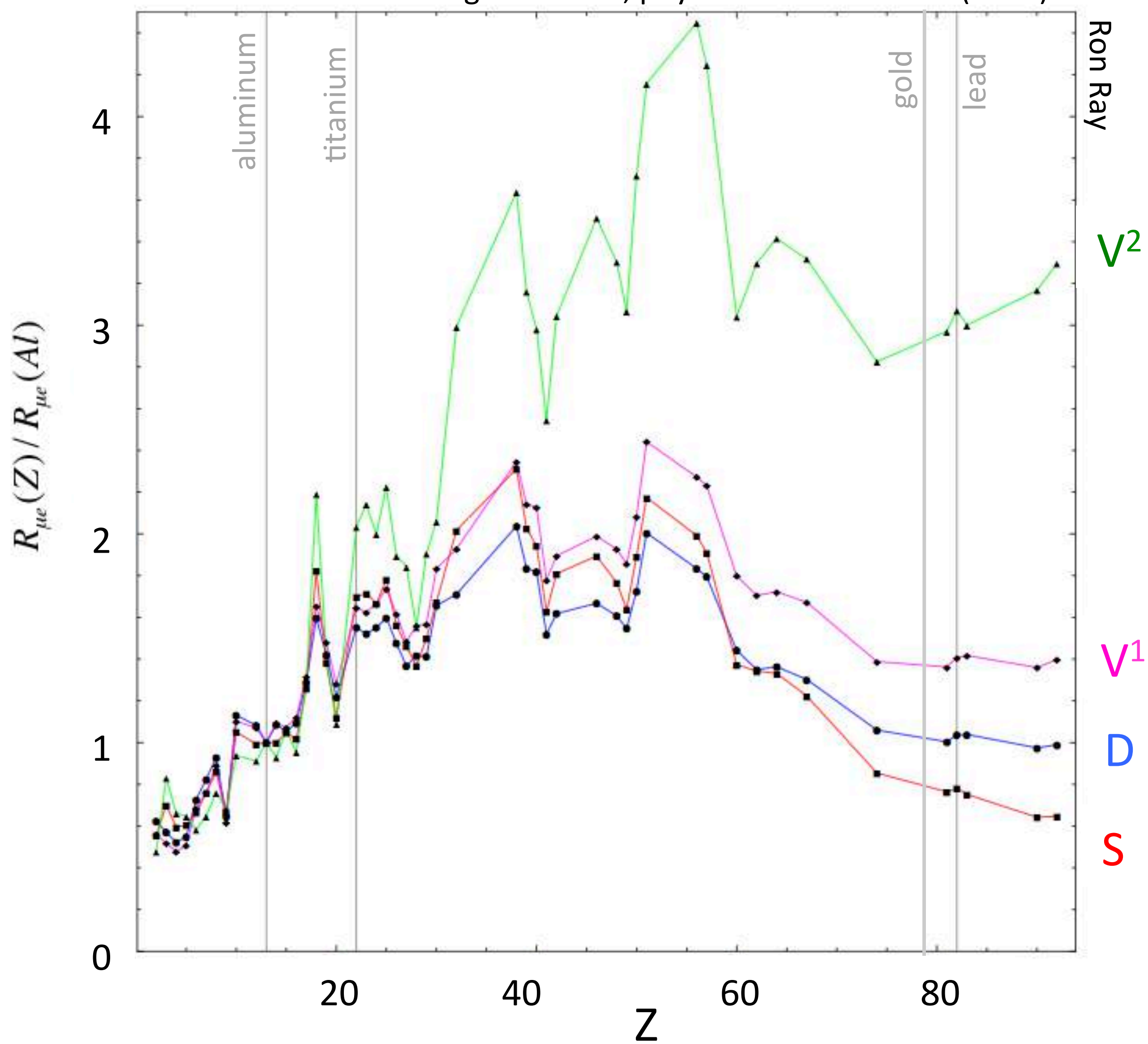
backup slides

Muonic atom life times



$R_{\mu e}$ rate vs Z

V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)



Mu2e sensitivity

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

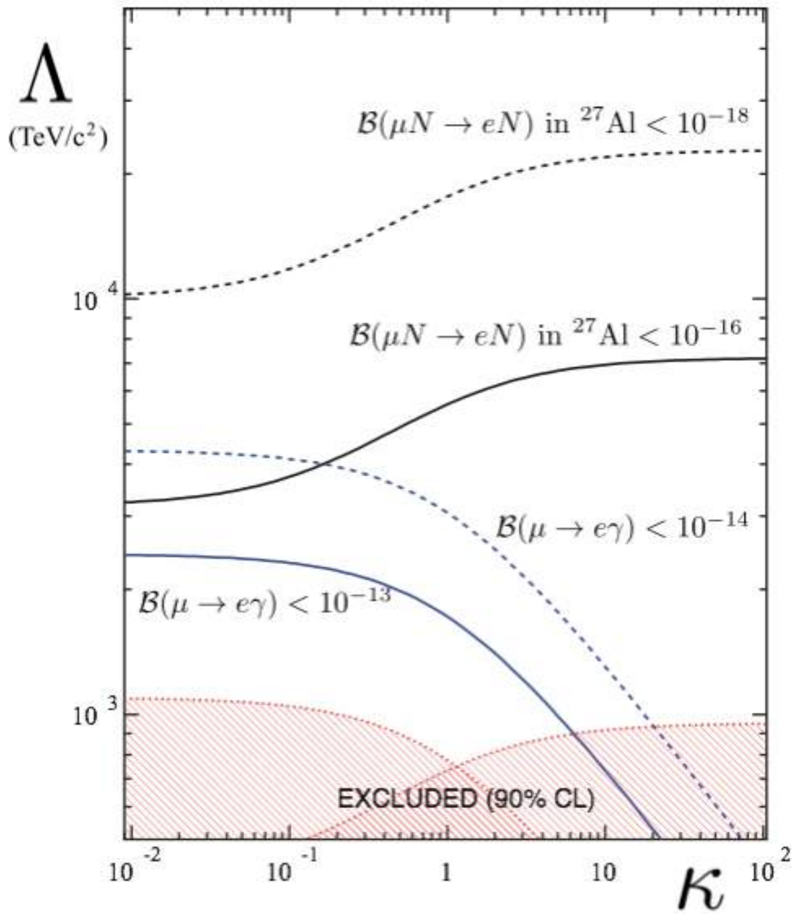
★★★ = Discovery Sensitivity

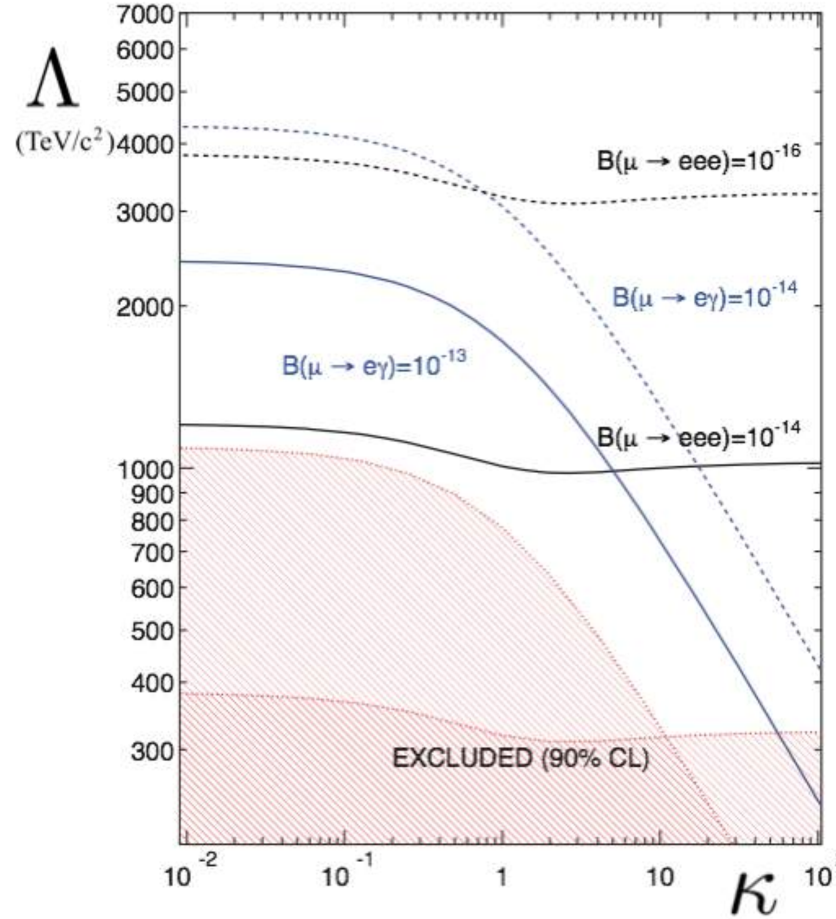
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

arXiv:0909.1333[hep-ph]

Model independent Lagrangian





$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{e}\gamma^\mu e\right)$$

"dipole term" **"contact term"**

CLFV limits I

Process	Upper limit
$\mu^+ \to e^+\gamma$	$< 5.7 \times 10^{-13}$
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$	$< 1.7 \times 10^{-12}$
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 3.0 \times 10^{-13}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau^- \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau^- \to e^-e^+e^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to \mu^-\mu^+\mu^-$	$< 2.1 \times 10^{-8}$
$\tau^- \to e^-\mu^+\mu^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to \mu^-e^+e^-$	$< 1.8 \times 10^{-8}$
$\tau^- \to e^+\mu^-\mu^-$	$< 1.7 \times 10^{-8}$
$\tau^- \to \mu^+e^-e^-$	$< 1.5 \times 10^{-8}$

CLFV limits 2

Process	Upper limit
$\pi^0 \to \mu e$	$< 8.6 \times 10^{-9}$
$K^0_L \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+ \mu^+ e^-$	$< 2.1 \times 10^{-10}$
$K^0_L \to \pi^0 \mu^+ e^-$	$< 4.4 \times 10^{-10}$
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \to \tau \mu$	$< 1.2 \times 10^{-6}$

Particle identification

Why Particle Identification is needed

- **Cosmic ray** and **antiproton** induced background can be divided into 2 main categories:
    1. e^- generated via interactions producing a track mimicking the CE
    2. non-electron particles (μ and π) that are reconstructed as track mimicking the CE
- (1) represents the irreducible background, while (2) can be suppressed using a PID

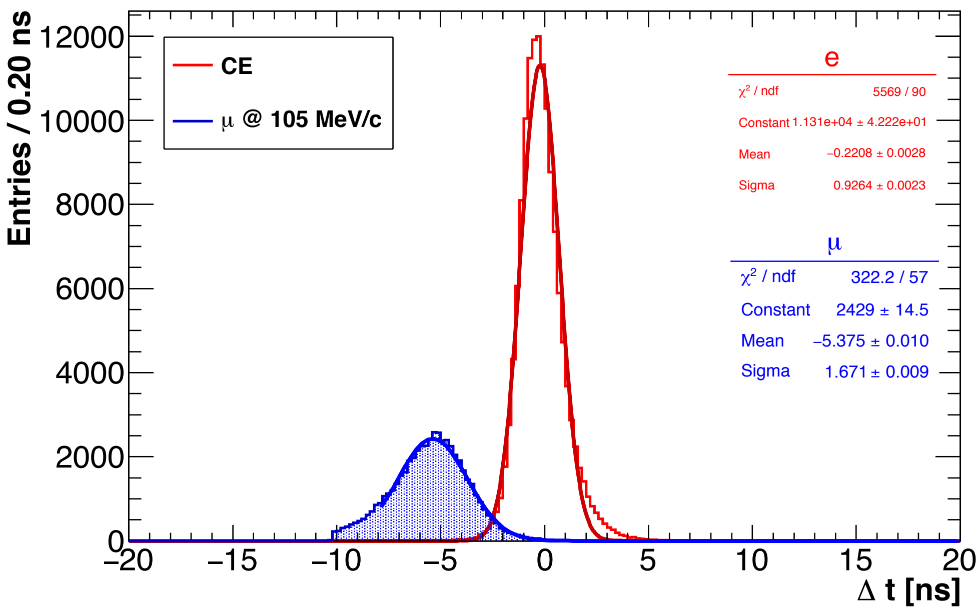
Mu2e PID method:

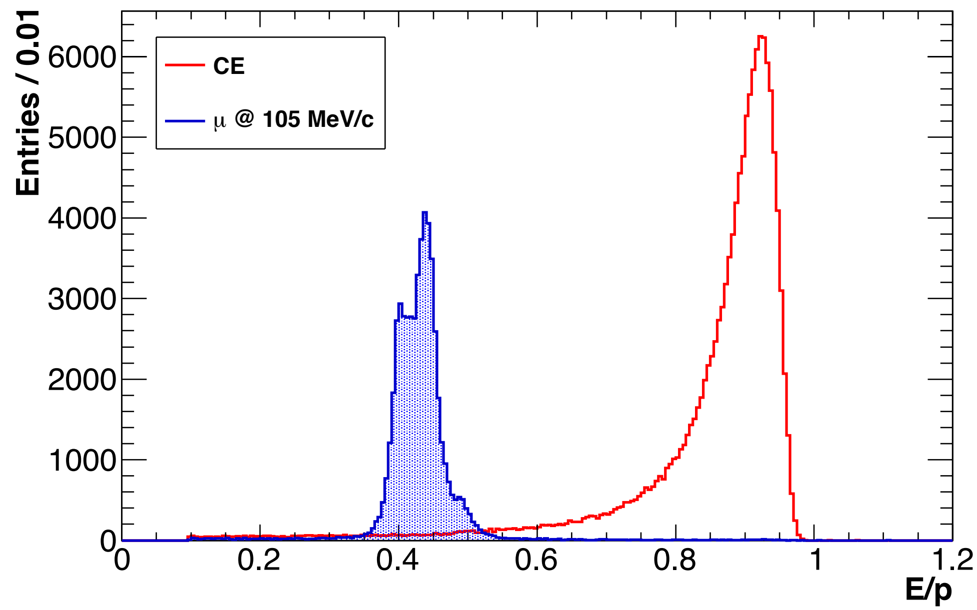
- Information from reco tracks and calorimeter clusters is combined
- We require contribution from mis-identified μ to smaller than the irreducible background from cosmic μ.
- That results **μ-rejection factor of about 200**

Cosmic μ rejection

- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines $\Delta t = t_{track} - t_{cluster}$ and E/p:

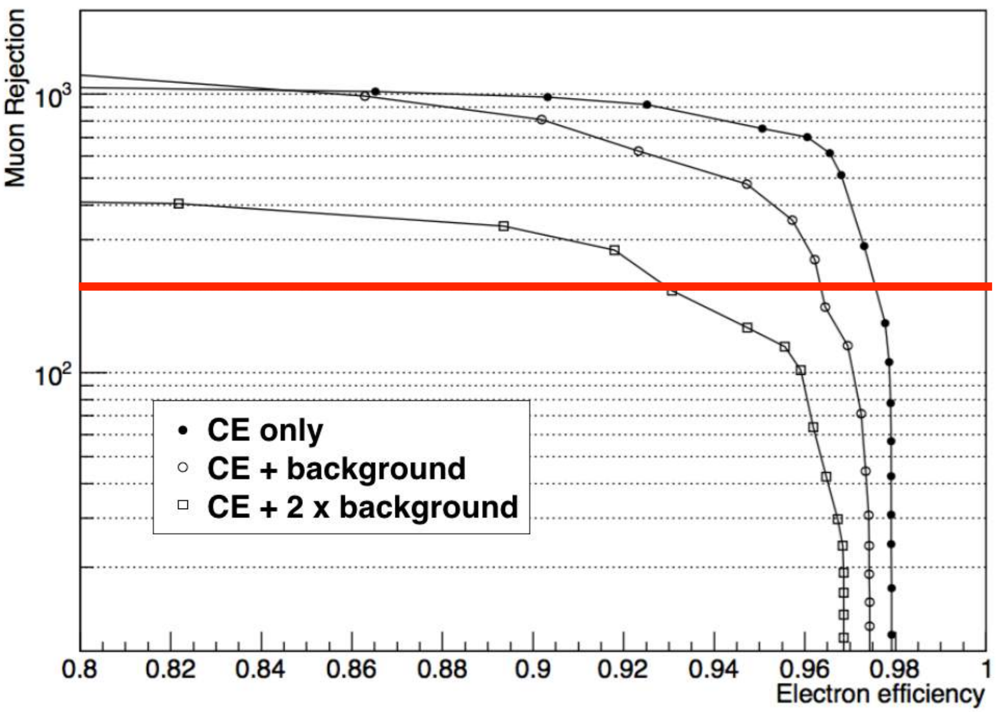
$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta \mathrm{t}) + \ln P_{e,\mu}(\mathrm{E/p})$$



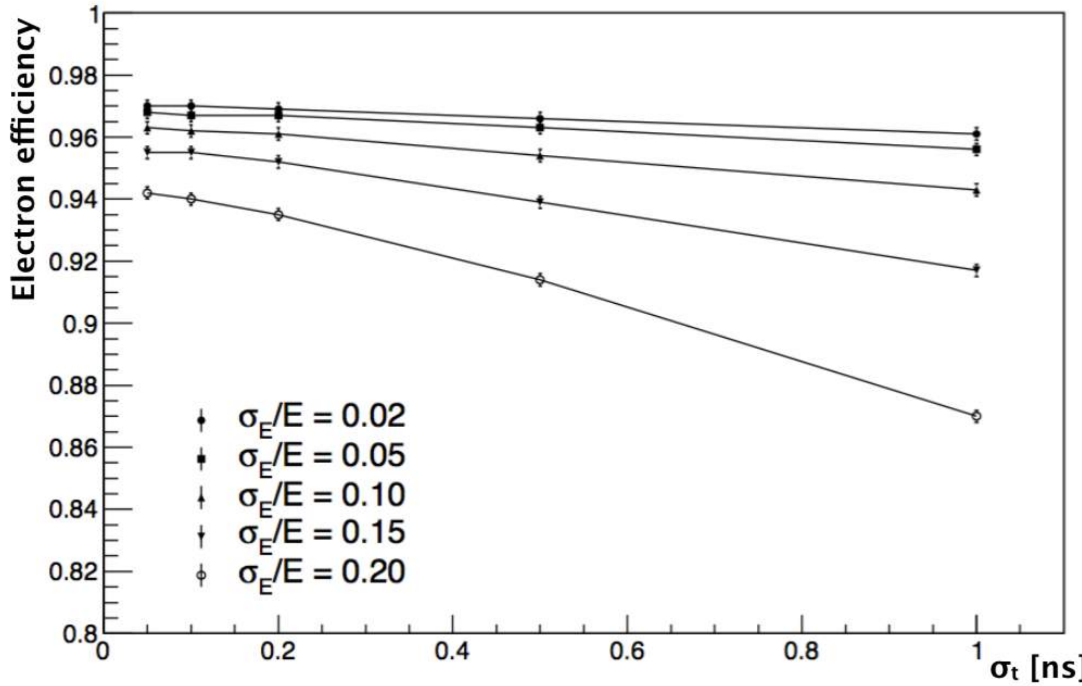


DOI:10.1016/j.nuclphysbps.2014.02.030

PID performance



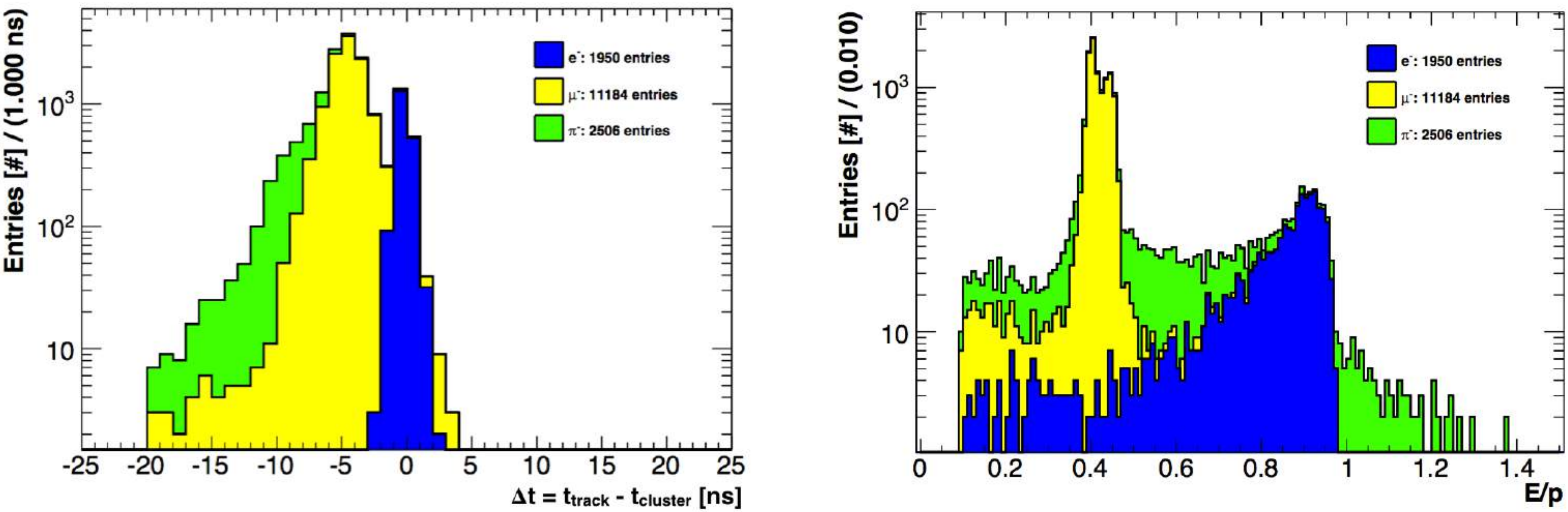
μ-rejection = 200



- A muon-rejection of 200 corresponds to a cut at ln $L_{e/\mu}$ > 1.5 and an e^- efficiency of ~ 96%
- In the range $\sigma_E/E<10\%$ and $\sigma_t<0.5$ ns the e^- ϵ varies by less than 2%

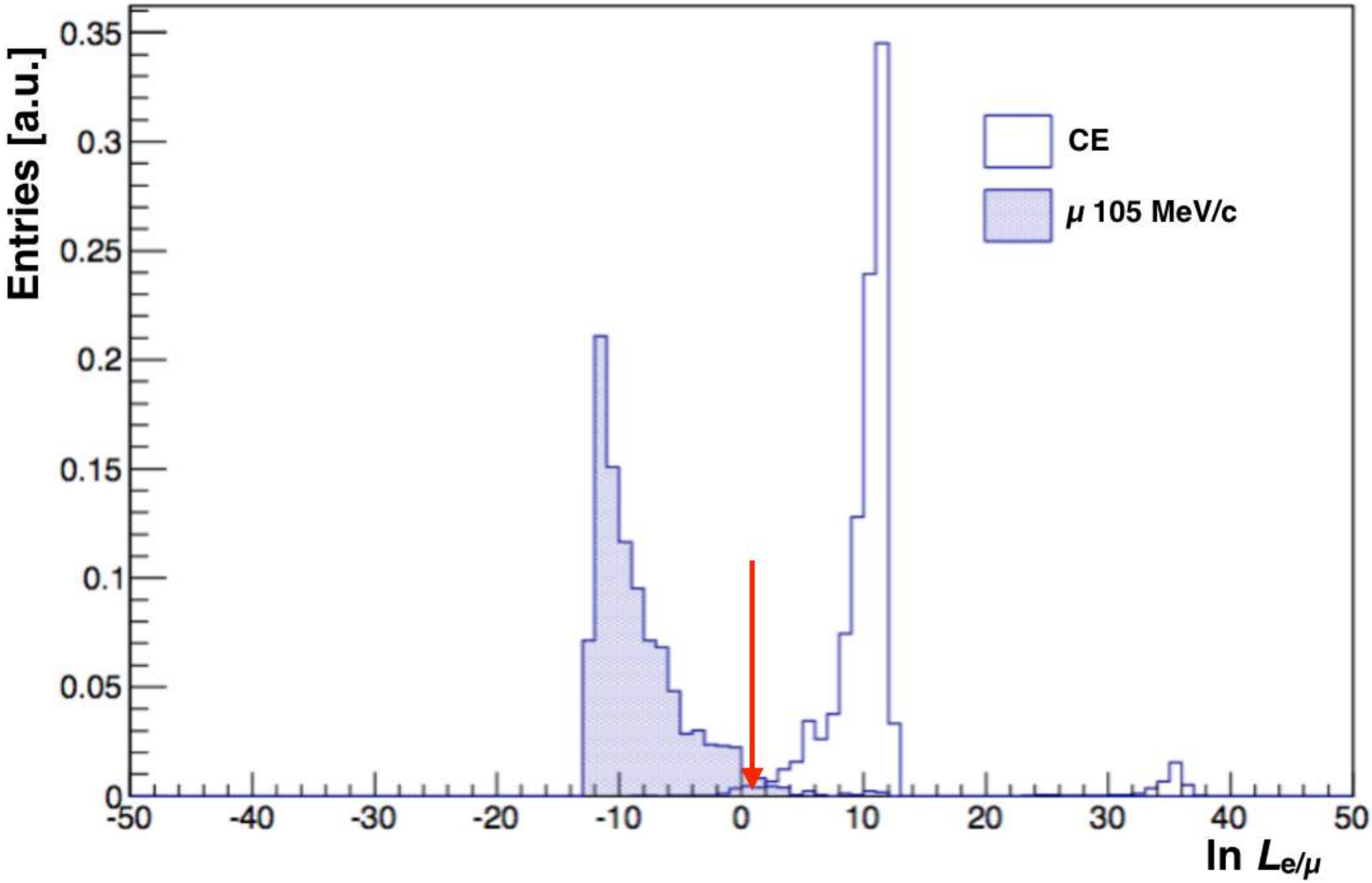
PID for antiproton induced background

- Same procedure tested on μ and π from antiproton annihilation, and reconstructed under the e^- hypothesis with p in [101,106] MeV/c

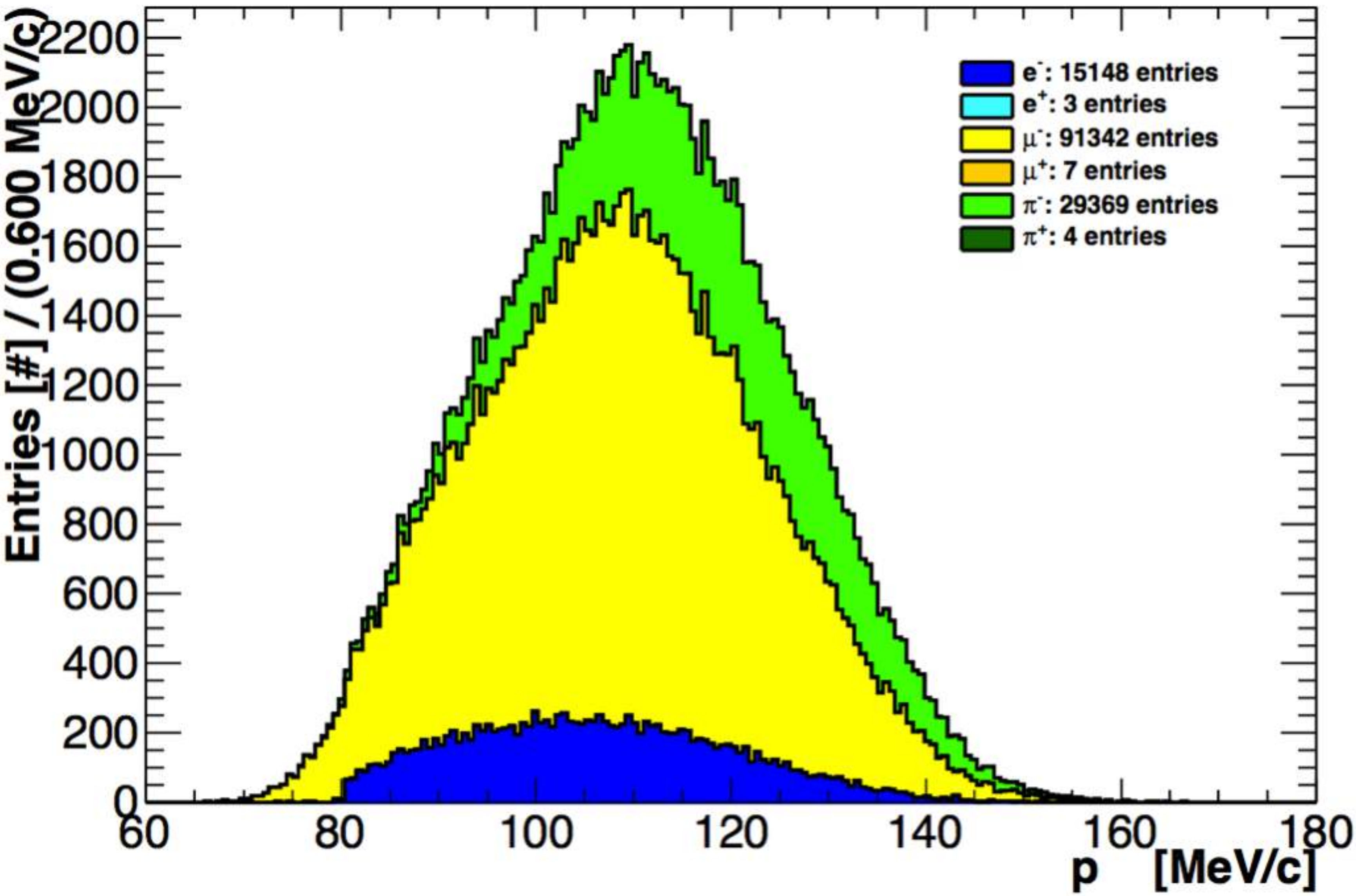


- Applying the same cut @ ln $L_{e/\mu}$ > 1.5 used for the Cosmic, **results in < 4x10^{-3}** induced background events in 3 years of run

Cosmic μ likelihood ratio



Antiproton products



Antiproton likelihood ratio