Mu2e: a search for charged lepton flavor violation

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on behalf of the Mu2e Collaboration

The Mu2e collaboration

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 for Nuclear Research, Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, University of Illinois, INFN Genova, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce and Università del Salento, Lewis University, University of Louisville, Laboratori Nazionali di Frascati and Università Marconi Roma, University of Minnesota, Muons Inc., Northern Illinois University, Northwestern University, Novosibirsk State University/Budker Institute of Nuclear Physics, Institute for Nuclear Research, Moscow, INFN Pisa, Purdue University, Rice University, University of South Alabama, Sun Yat Sen University, University of Virginia, University of Washington, Yale University

What is μ→e conversion

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

$$\mathrm{E}_e = \mathrm{m}_\mu\ \mathrm{c}^2 - \mathrm{B}_\mu(\mathrm{Z}) - \mathrm{C}(\mathrm{A}) = 104.973\ \mathrm{MeV}$$

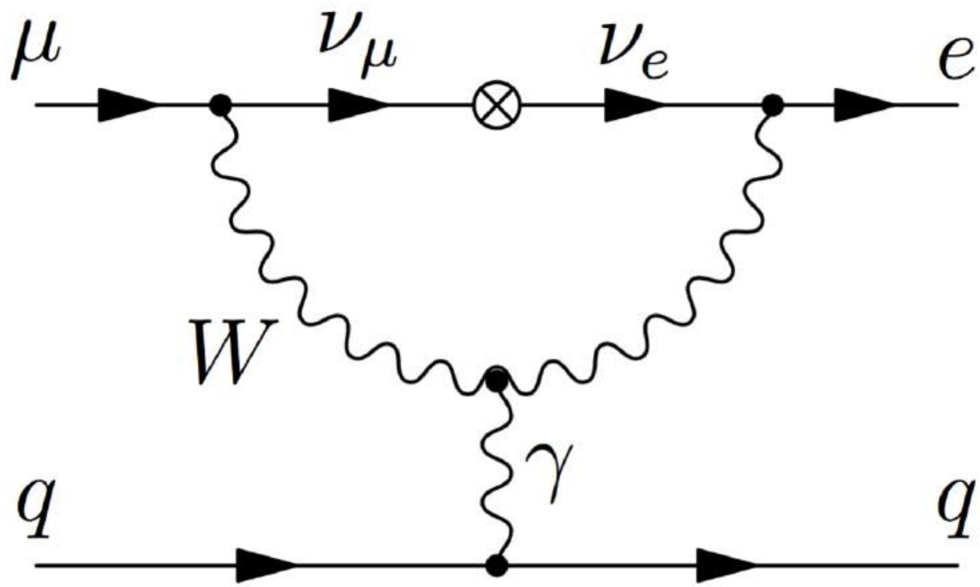
- for Aluminum: $\begin{cases} \mathrm{B}_\mu(\mathrm{Z}) \text{ is the muon binding energy (0.48 MeV)} \\ \mathrm{C}(\mathrm{A}) \text{ is the nuclear recoil energy (0.21 MeV)} \end{cases}$

- Signal normalization:

$$\mathrm{R}_{\mu \mathrm{e}} = \frac{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \mathrm{e}^- + \mathrm{N}\right)}{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \text{all captures}\right)}$$

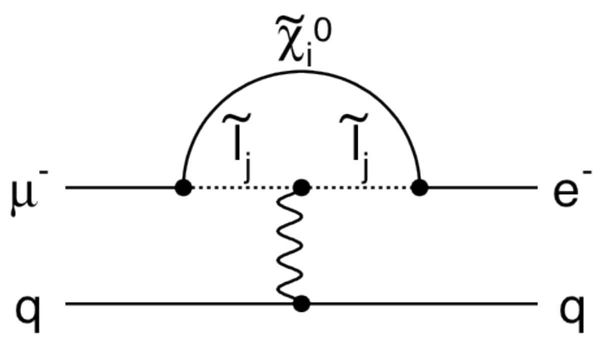
CLFV in SM

- **CLFV** process forbidden in the **SM**
- μ conversion in the extend-SM is introduced by the **neutrino masses and mixing** at a negligible level ~ 10^{-52}

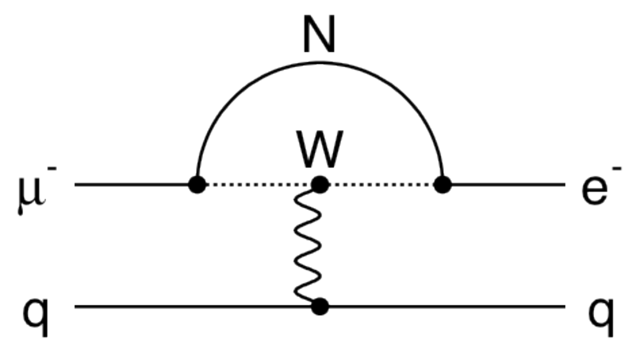


- Many **SM extensions enhance the rate** through mixing in the high energy sector of the theory (other particles in the loop…)

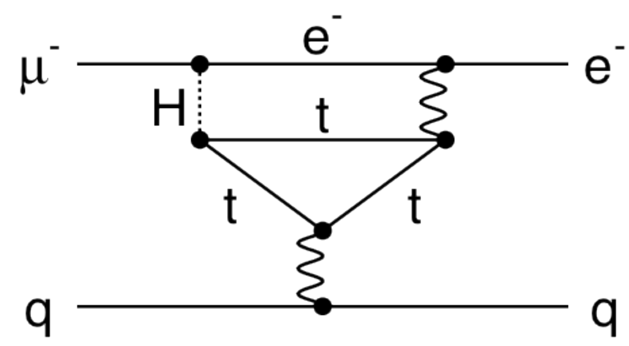
NP contributions to μ→e



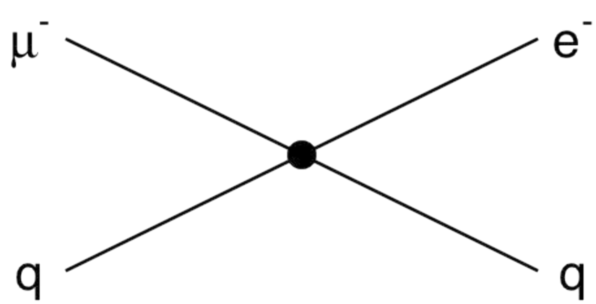
SUSY



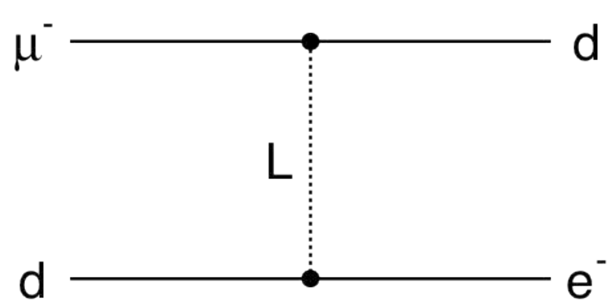
Heavy neutrino



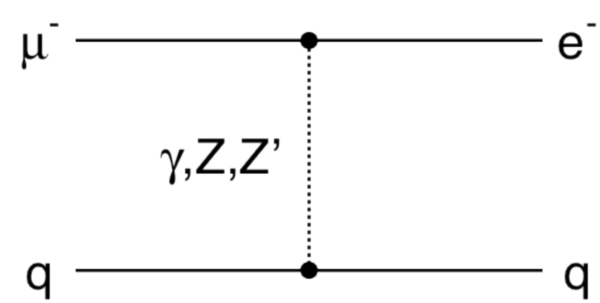
Two Higgs doublet



Compositeness



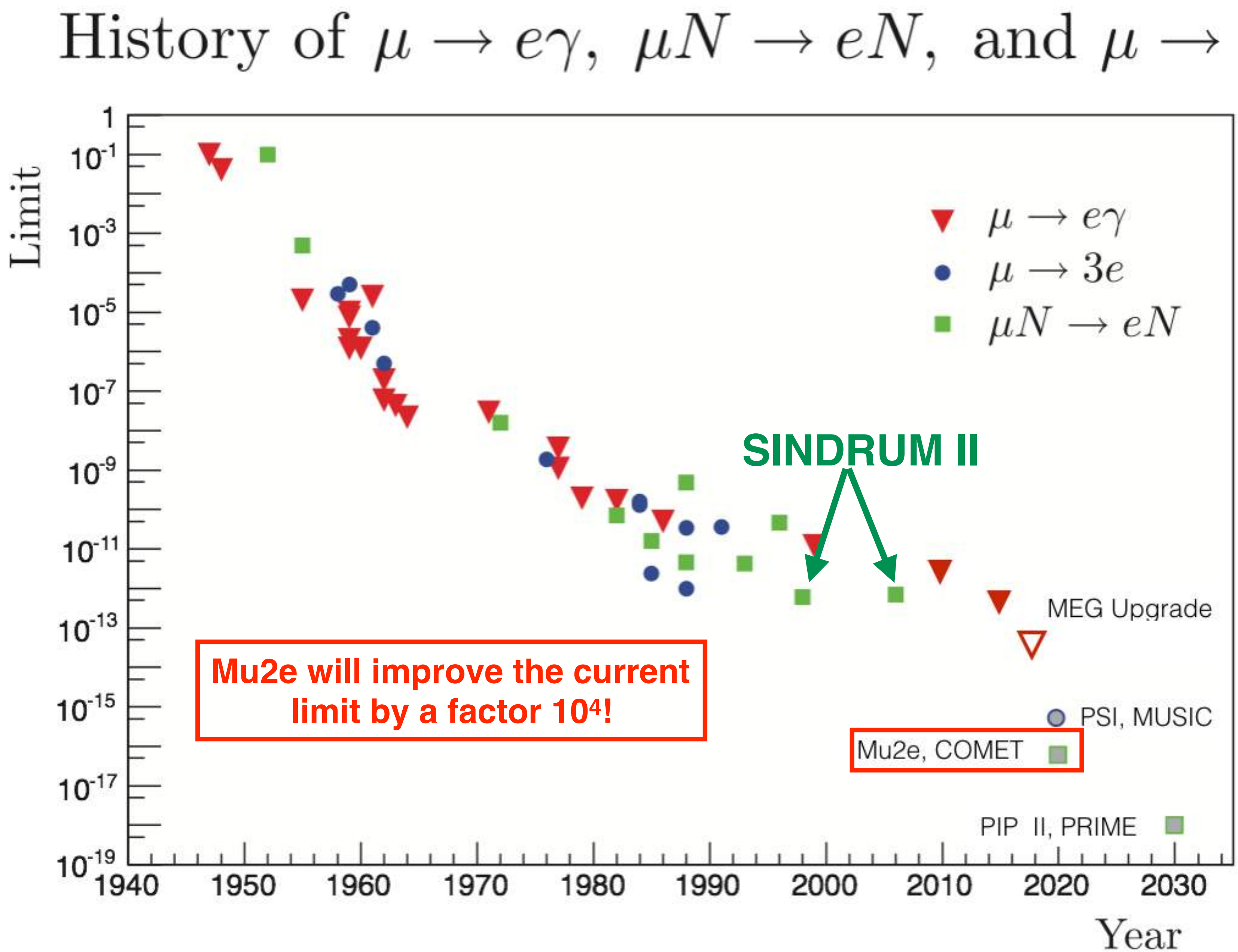
Leptoquarks



Z'/anomalous couplings

- Any signal observation would be an unambiguous sign of **NP**

History of μ→e search

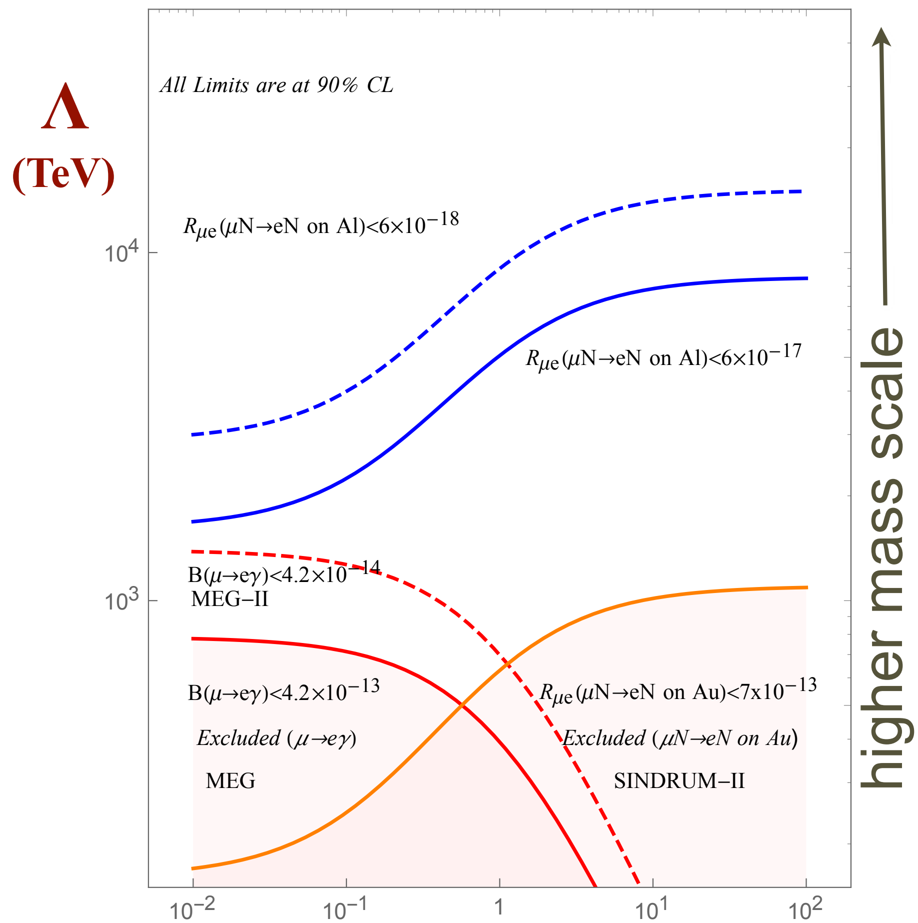


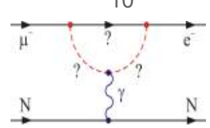
R. Bernstein, P. Cooper https://doi.org/10.1016/j.physrep.2013.07.002

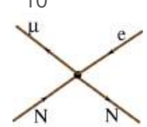
Model independent Lagrangian

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

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







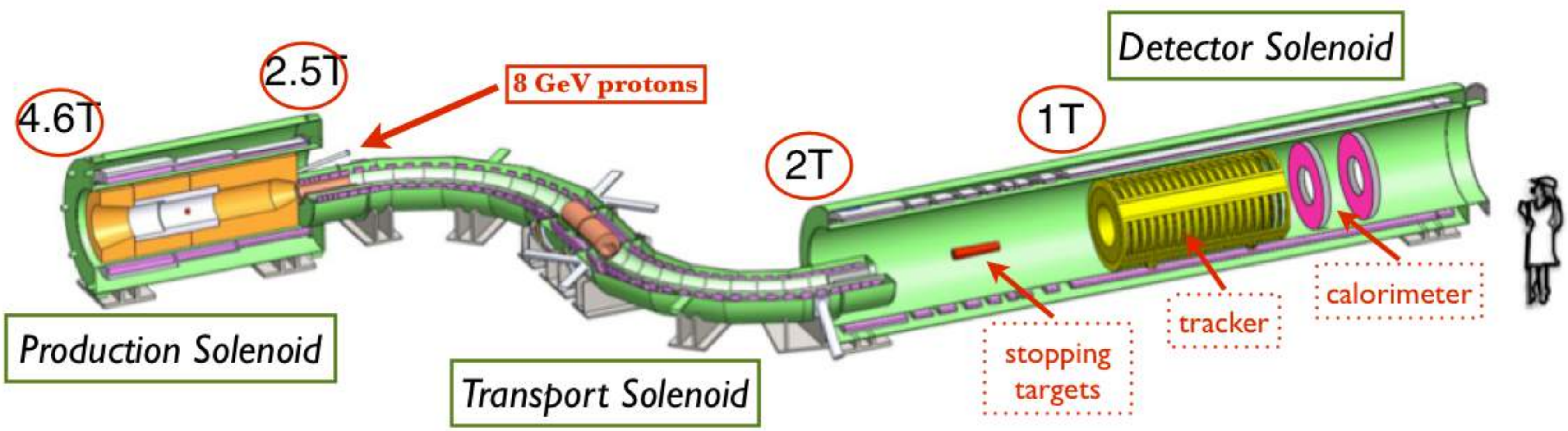
Experimental setup

- ***Production Solenoid:***

➡ Proton beam strikes target, producing mostly π
➡ Graded magnetic field contains backwards π/μ and reflects slow forward π/μ

- ***Detector Solenoid:***

➡ Capture muons on Al target
➡ Measure momentum in tracker and energy in calorimeter
➡ Graded field "focuses" e^- in tracker fiducial



- ***Transport Solenoid:***

➡ Select low momentum, negative muons
➡ Antiproton absorber in the mid-section

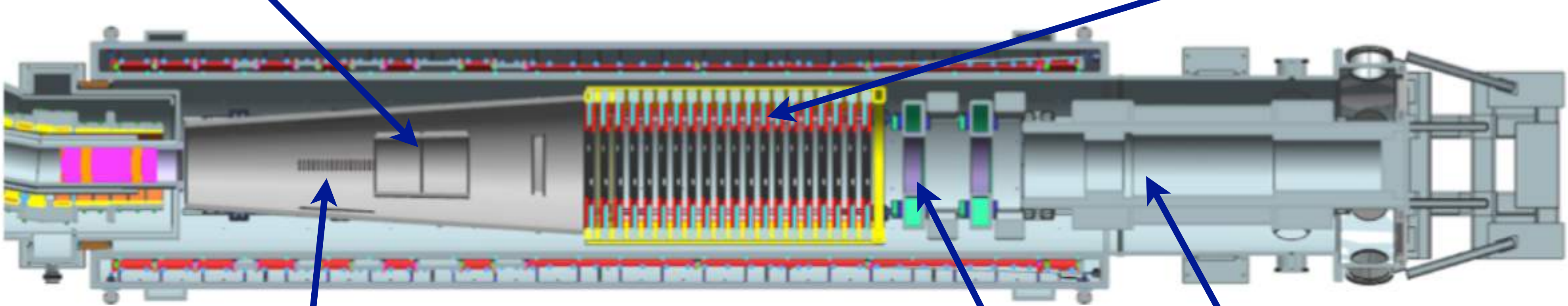
Mu2e detector

- *Proton absorber:*

❖ made of high-density polyethylene
❖ designed in order to reduce proton flux on the tracker and minimize energy loss

- *Tracker:*

❖ ~20k straw tubes arranged in planes on stations, the tracker has 18 stations
❖ Expected momentum resolution < 200 keV/c



- *Targets:*

❖ 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

- *Calorimeter:*

❖ 2 disks composed of undoped CsI crystals

- *Muon beam stop:*

❖ made of several cylinders of different materials: stainless steel and polyethylene

Muonic atom

- Stopped μ^- is captured in atomic orbits
  - ➡ quickly (~fs) cascades into 1S state
- Bohr radius ~20 fm (for Al)
  - ➡ significant overlap between the μ^- and nucleus wave-functions
- For a μ^- in orbit three processes may happen:
  - ➡ **decay** (39%): $\mu^- N \to e^- \bar{\nu}_e \nu_\mu N$, **background**
  - ➡ **capture** (61%): $\mu^- + N \to \nu_\mu + N'$, **normalization**
  - ➡ **conversion** (<10^{-13}): $\mu^- + N \to e^- + N$, **signal**

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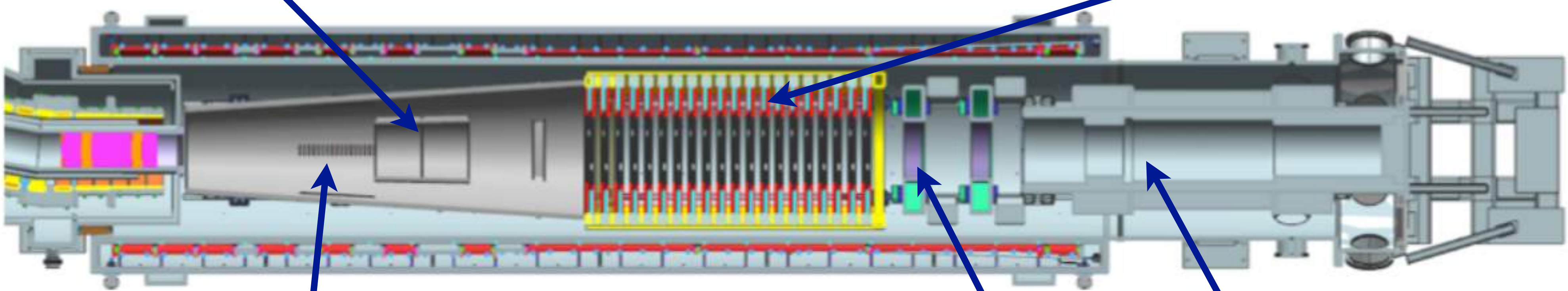

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❖ 2 disks composed of undoped CsI crystals

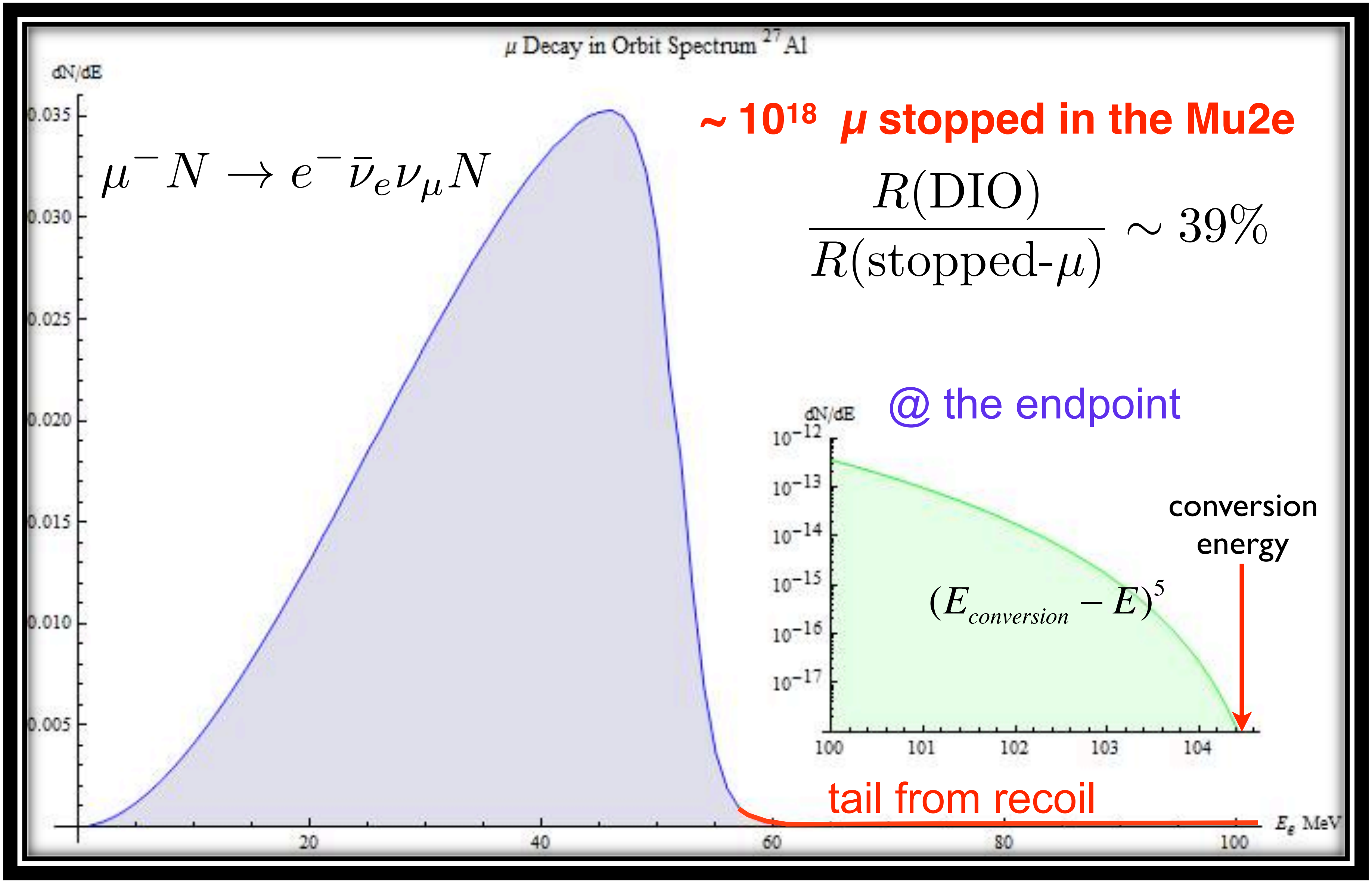
- *Muon beam stop:*

❖ made of several cylinders of different materials: stainless steel, lead and high density polyethylene

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: $\pi^- N_Z \rightarrow N^*_{Z-1}\,\gamma$, asymmetric $\gamma \rightarrow e^- e^+$
  - ✓ pulsed beam and extinction of out-of-time protons

μ decay-in-orbit (DIO)



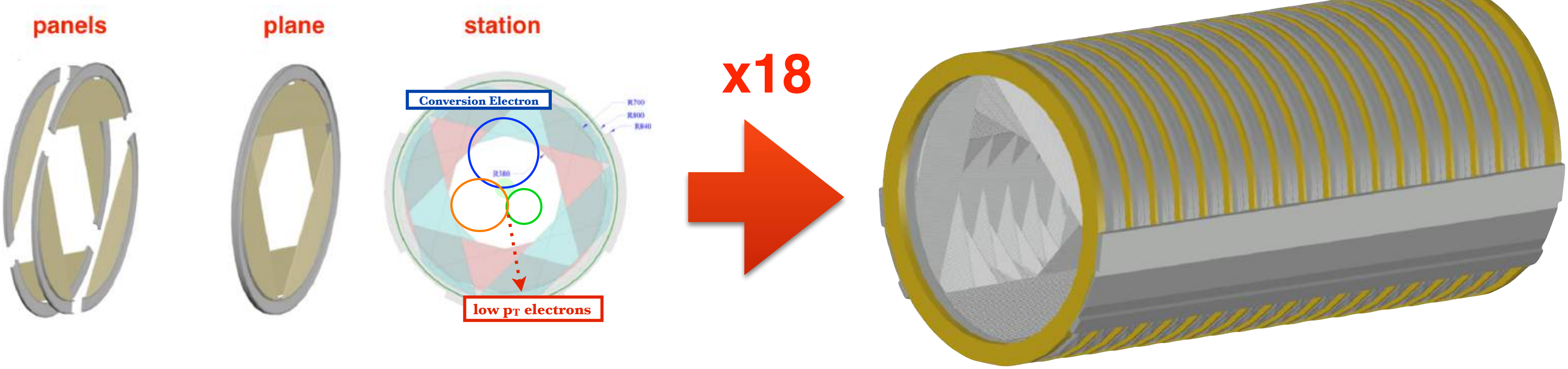
R. Szafron, A. Czarnecki https://doi.org/10.1016/j.physletb.2015.12.008

Tracker design

- 18 stations equally spaced with straws transverse to the beam
- Straw technology employed:
  - ✓ 5 mm diameter, 12 μm Mylar walls
  - ✓ 25 μm Au-plated W sense wire
  - ✓ 80/20 Ar/CO_2 with HV ~ 1500 V
- Inner 38 cm un-instrumented:
  - ✓ blind to beam flash
  - ✓ blind to **low** pT particles, almost all the DIO

straw tube

panel



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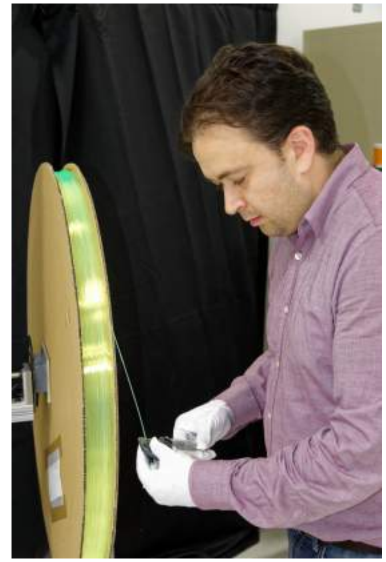
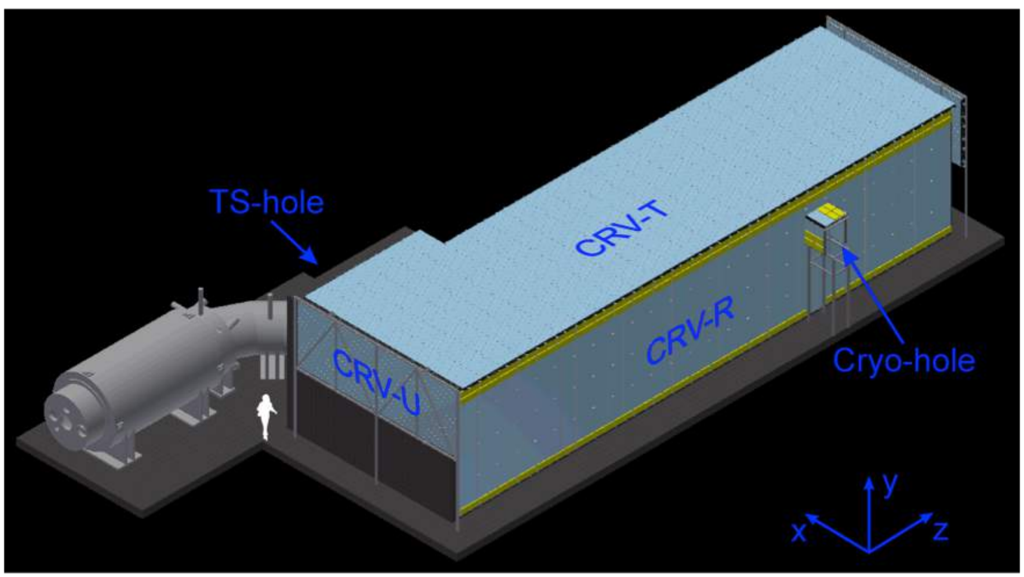
Cosmic Ray Veto

- 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}

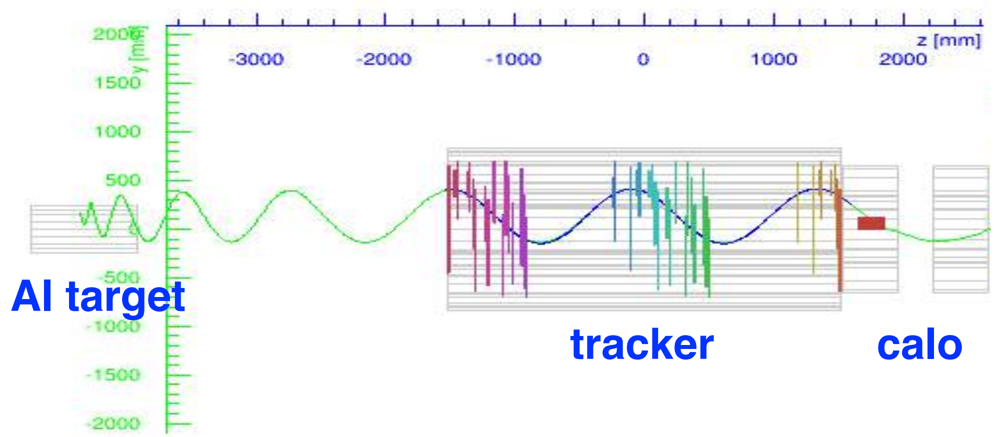
WLS fiber



Prototype



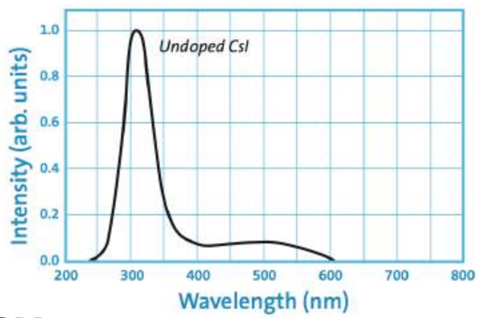
μ mimicking the CE



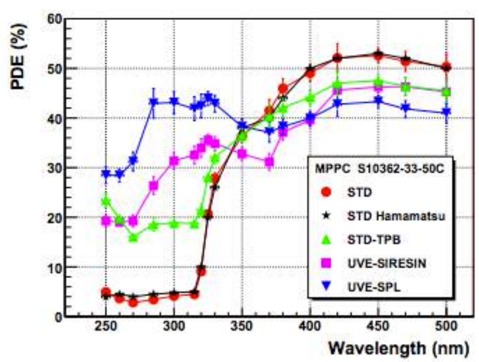
Calorimeter

- 2 disks; each disk contains 674 undoped CsI crystals 20 x 3.4 x 3.4 cm^3
- Disk separation ~ 70 cm
- Inner/outer radii: 37.4/66 cm
- Readout system:
  - 2 large area SiPM-array/crystal
  - 12 bit, 250 MHz waveform-based digitizer boards

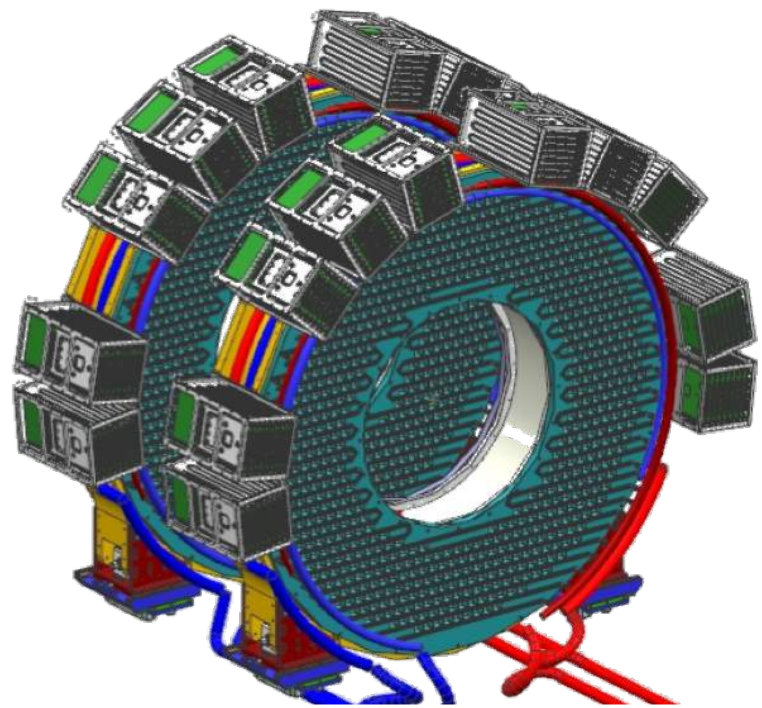
undoped CsI



SiPM array



Calorimeter



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: $\pi^- N_Z \rightarrow N^*_{Z-1}\,\gamma$, asymmetric $\gamma \rightarrow e^- e^+$

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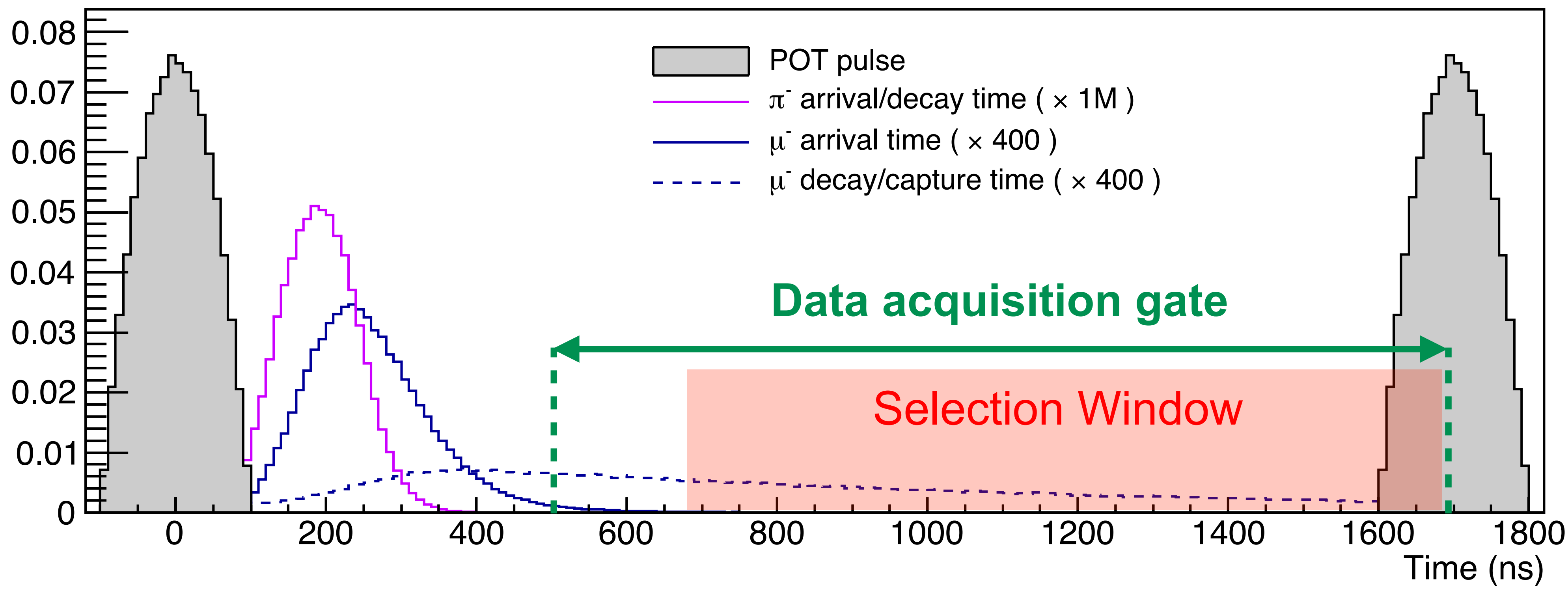
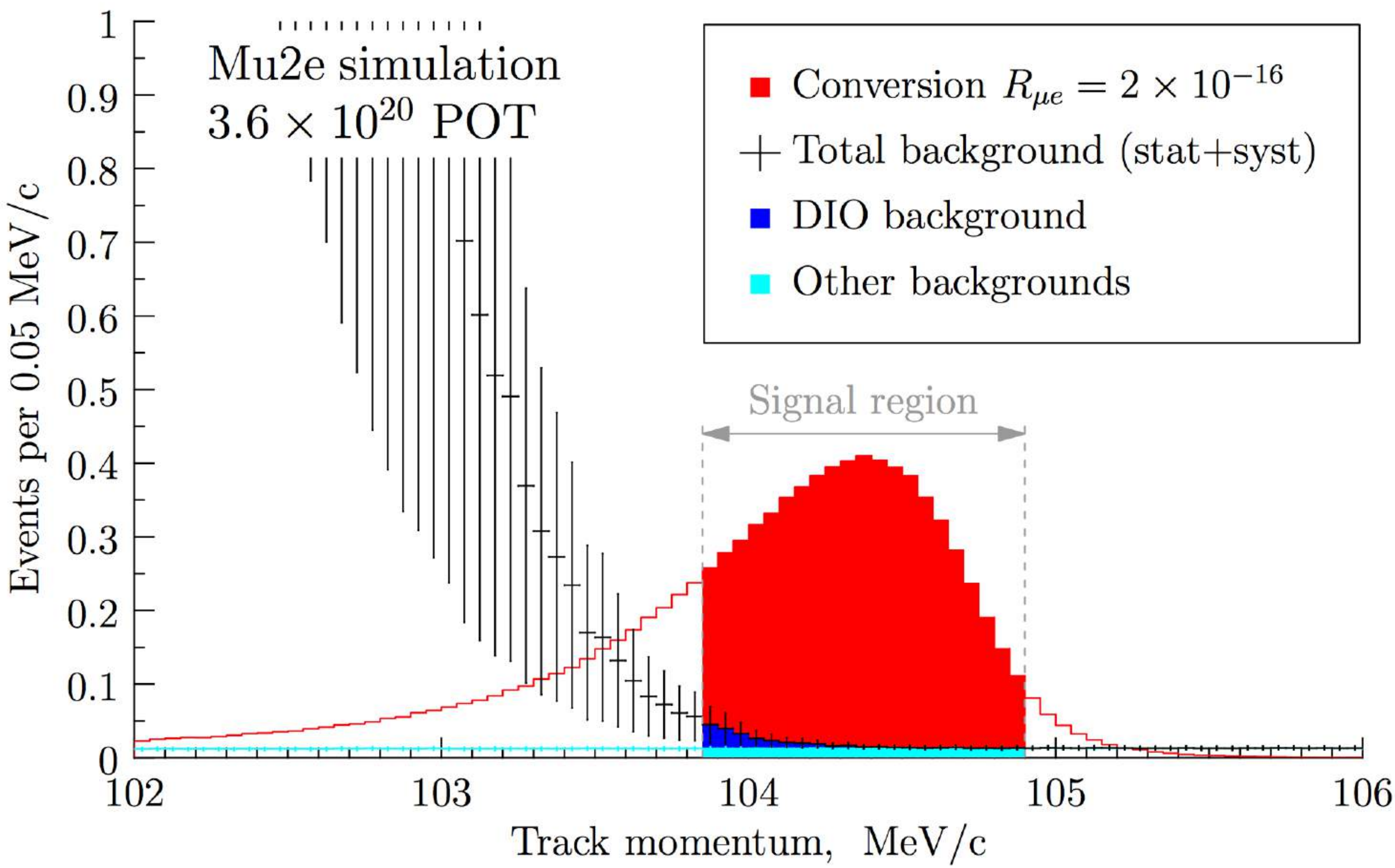
  ✓ pulsed beam and extinction of out-of-time protons

Pulsed beam

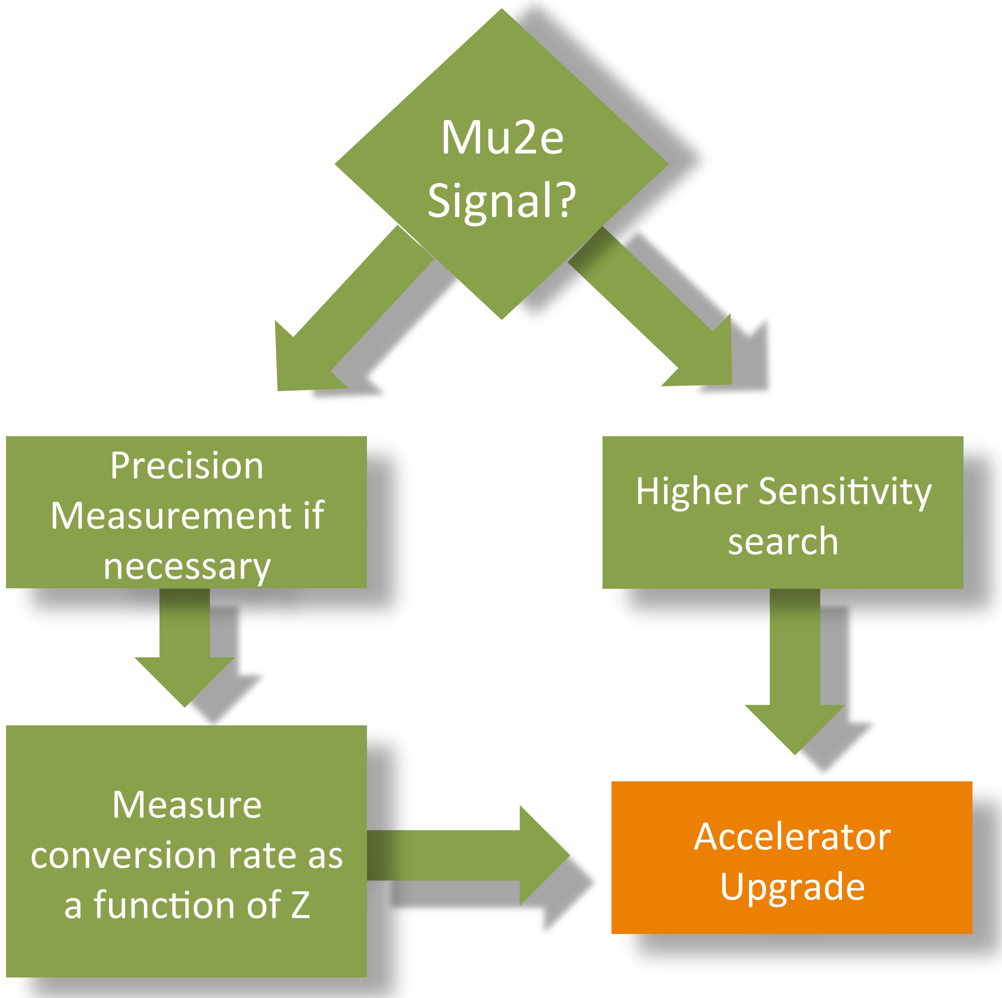
- Beam period : 1.7 μs ~ 2 x τ_{μ}^{Al}
- Beam intensity: 3.9 x 10^7 p/bunch
- duty cycle : ~ 30%
- **Extinction: out-of-time protons / in-time protons < 10^{-10}**



Mu2e sensitivity



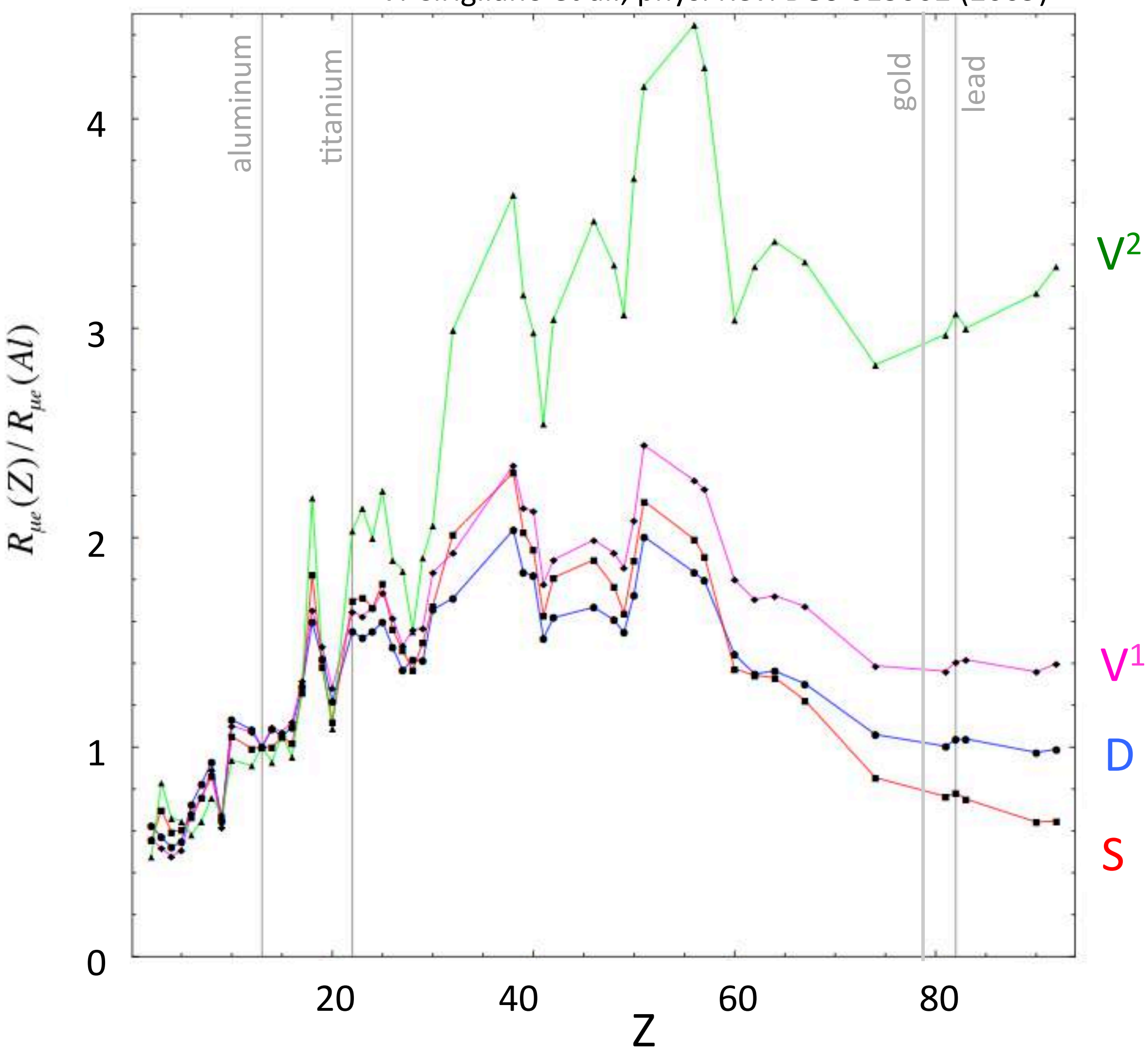
Mu2e signal?



- A next-generation Mu2e experiment makes sense in all scenarios:
  - ✓ Push sensitivity or
  - ✓ Study underlying new physics
- Will need more protons upgrade accelerator

$R_{\mu e}$ rate vs Z

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



- Can use ratio of rates to determine dominant operator contribution
- Life time of the μ-atom plays also a role in the Z choice:

  ✓ $\tau_\mu(Al)$ = 864 ns

  ✓ $\tau_\mu(Ti)$ = 338 ns

  ✓ $\tau_\mu(Au)$ = 74 ns

Mu2e Upgrade

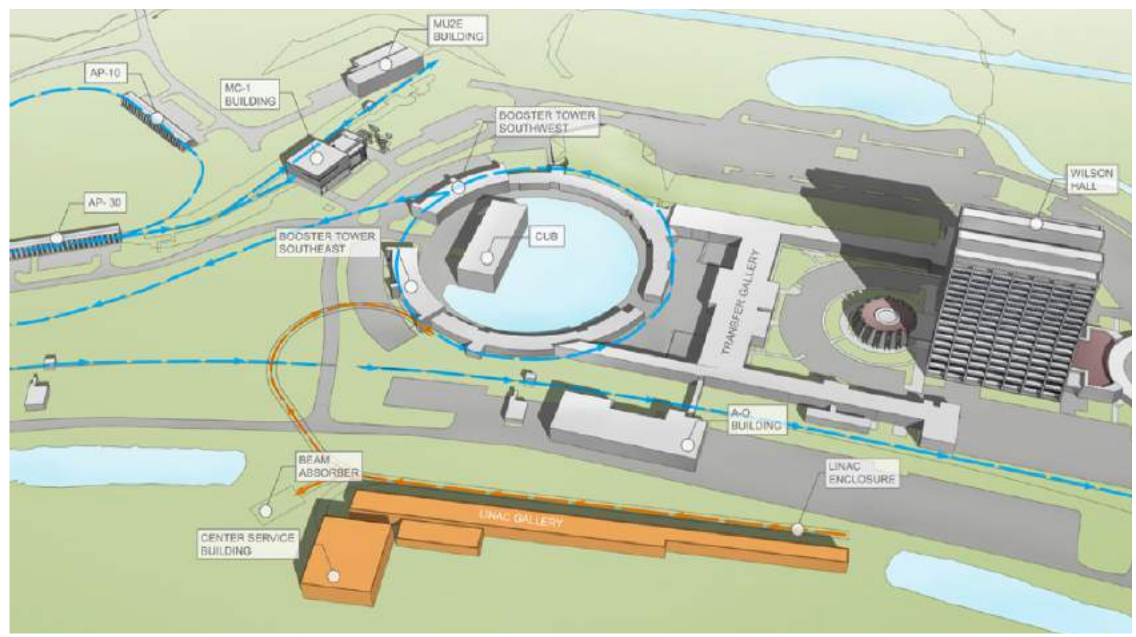
- Studies for x10 improvement with Ti look promising and will be continued; EOI written (1307.1168 and EOI at 1802.02599)

- Investigating $\mu^{-}N \rightarrow e^{+}N$ related to Majorana neutrino physics

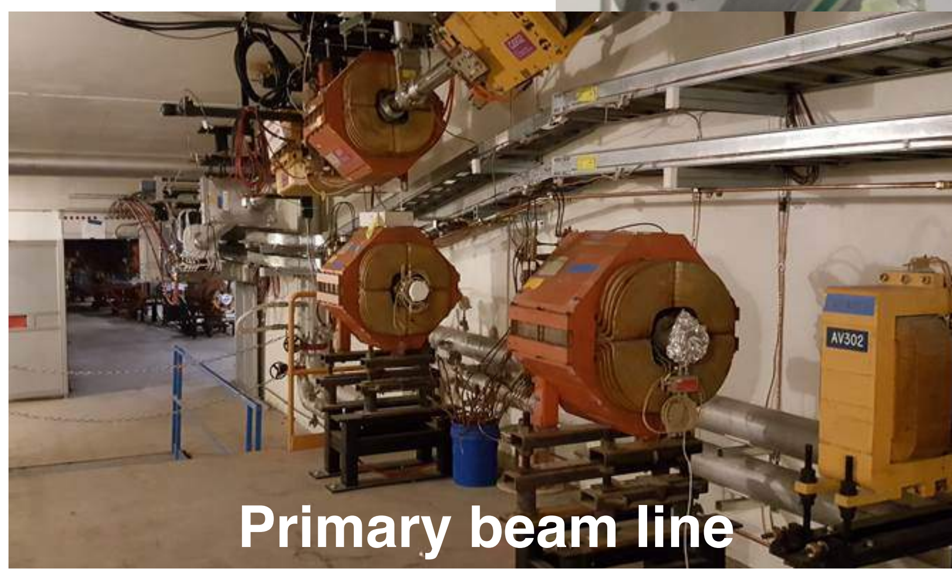
- We need detector and solenoid improvements

  ➡ may need new production solenoid to handle lower energy beam and higher power.

- FNAL PIP-II natural for both pulsed and non-pulsed CLFV, could do $\mu^{-}N \rightarrow e^{\pm} N$, $\mu \rightarrow e\, \gamma$, $\mu \rightarrow 3e$, $\mu^{-}e^{-} \rightarrow e^{-}e^{-}$



Mu2e detector hall



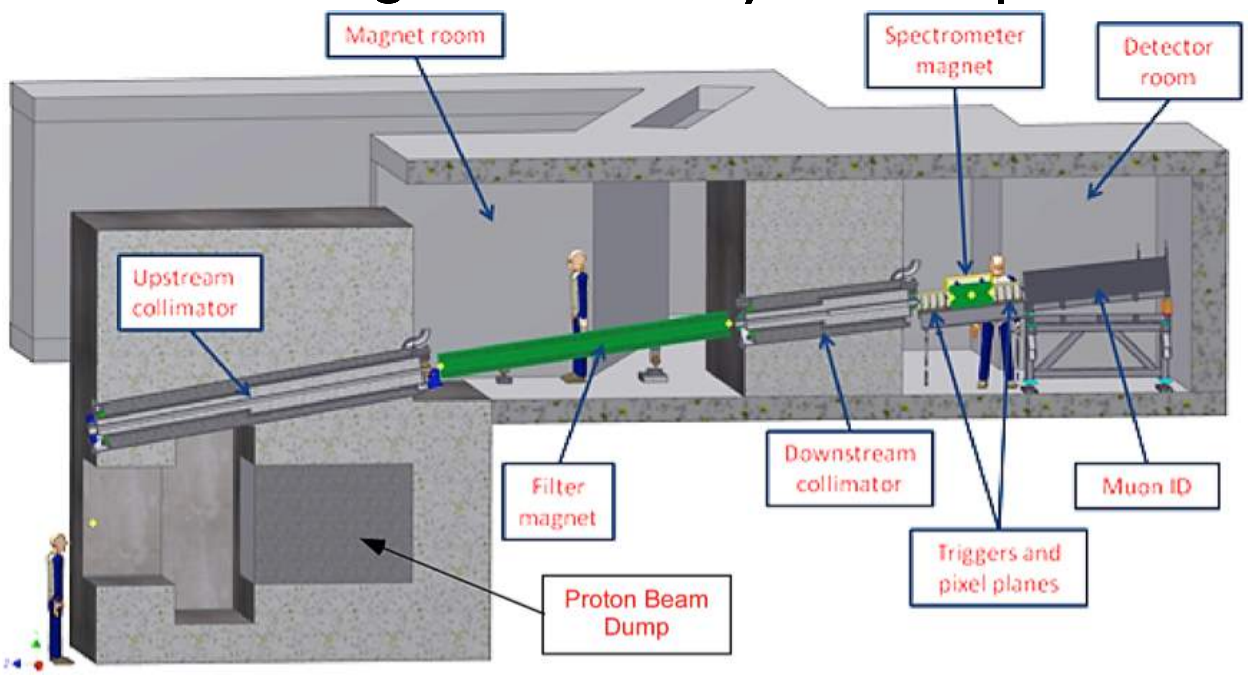
Summary

- 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 2022**
- More info: **http://mu2e.fnal.gov**

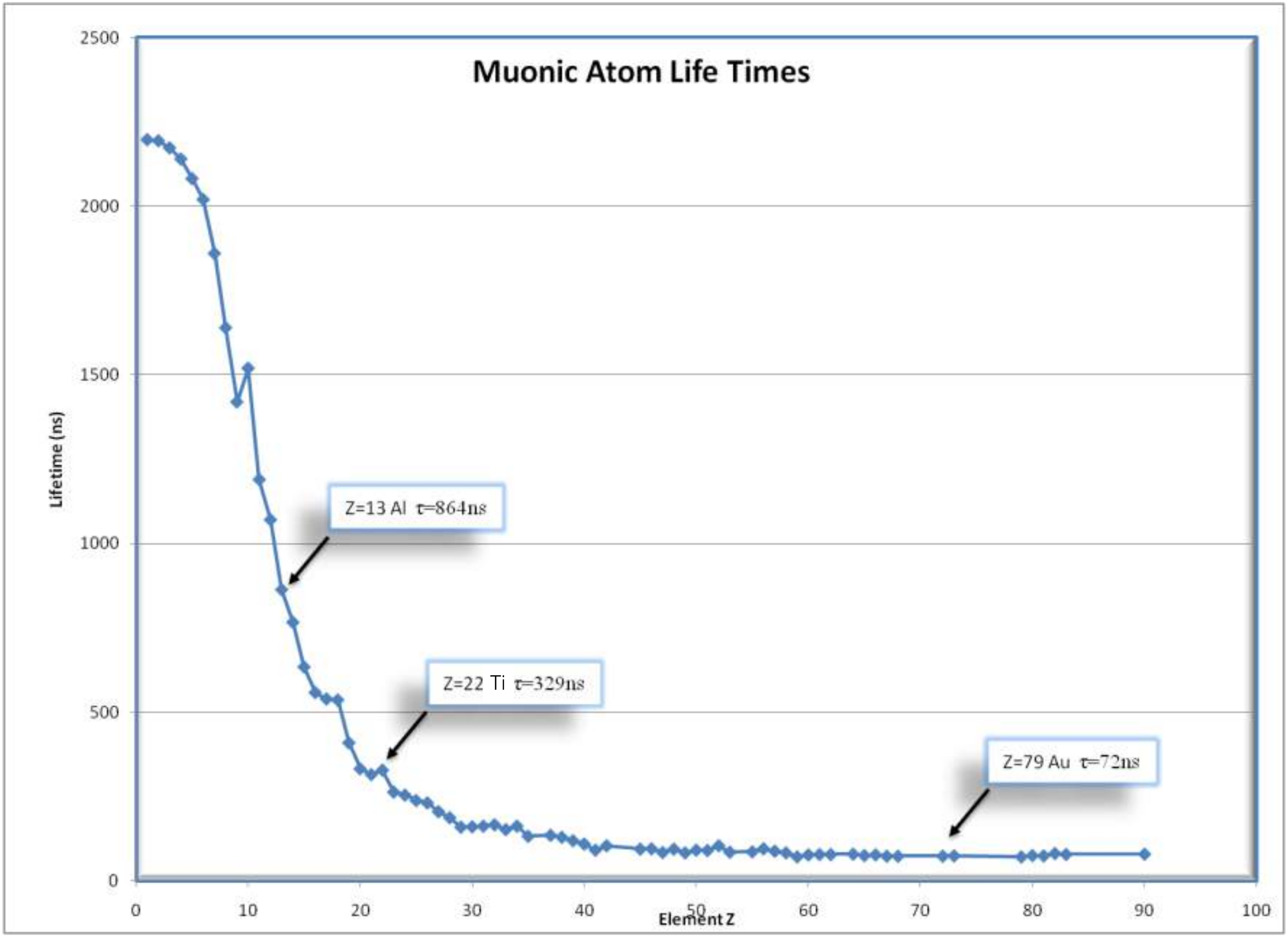
backup slides

Extinction of out-of-time protons

- The RF structure of the Recycler provides some "intrinsic" extinction:
  ✓ **Intrinsic extinction ~10^{-5}**
- A custom-made AC dipole placed just upstream of the production solenoid provides additional extinction:
  ✓ **AC dipole extinction ~ 10^{-6} - 10^{-7}**
- Together they provide a total extinction:
  ✓ **Total extinction ~ 10^{-11} - 10^{-12}**
- Extinction measured using a detector system: Si-pixel + sampling EMC



Muonic atom life times



$R_{\mu e}$ rate vs Z

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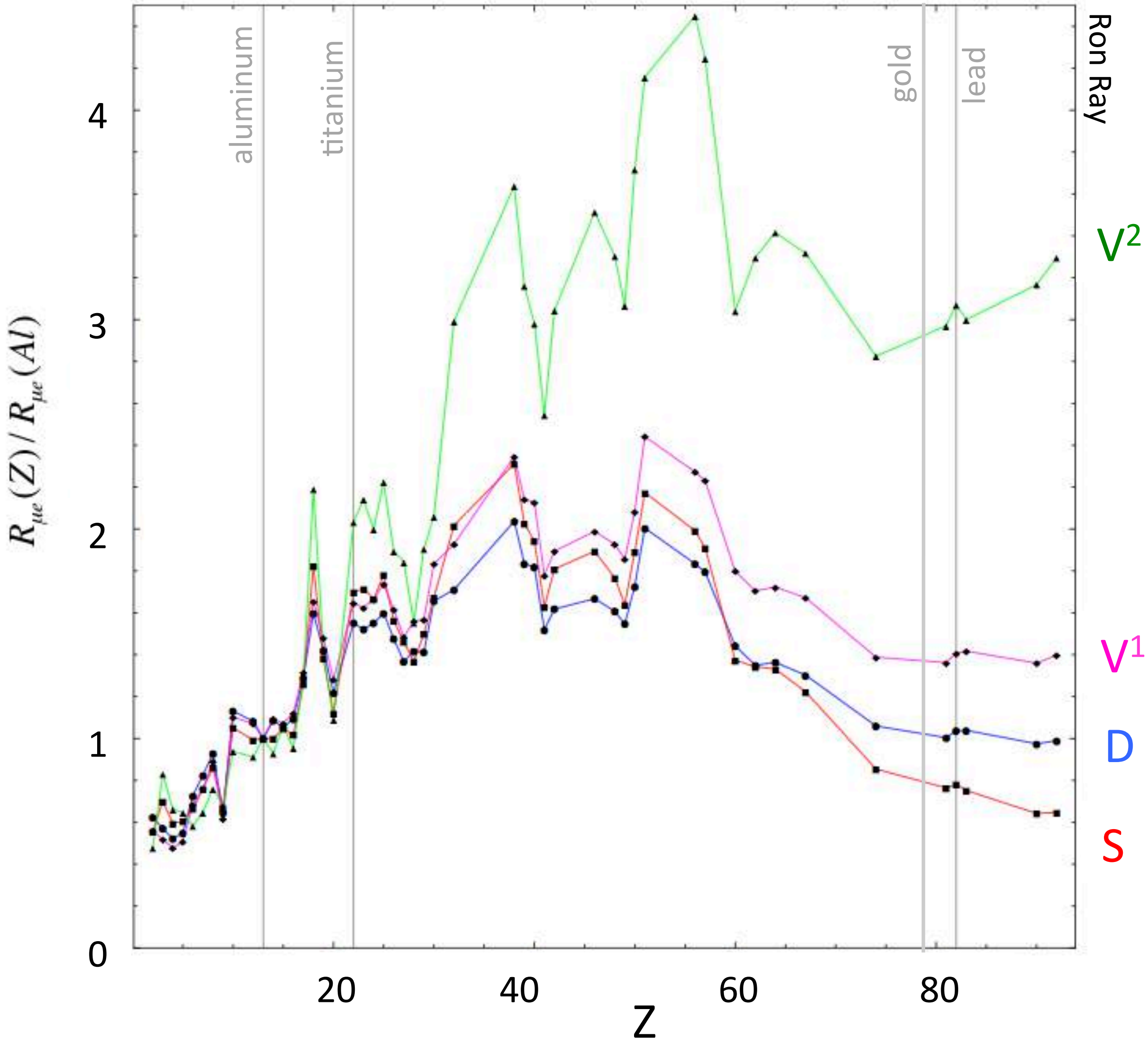

Mu2e sensitivity

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]

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