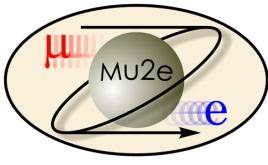


Gianantonio Pezzullo
Yale University

on behalf of the Mu2e Collaboration

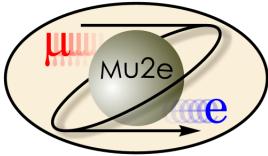


The Mu2e collaboration



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 $\mu \rightarrow e$ conversion

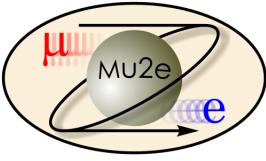
- μ converts to an electron in the presence of a nucleus $\mu^- N \rightarrow e^- N$

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

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

- Signal normalization:

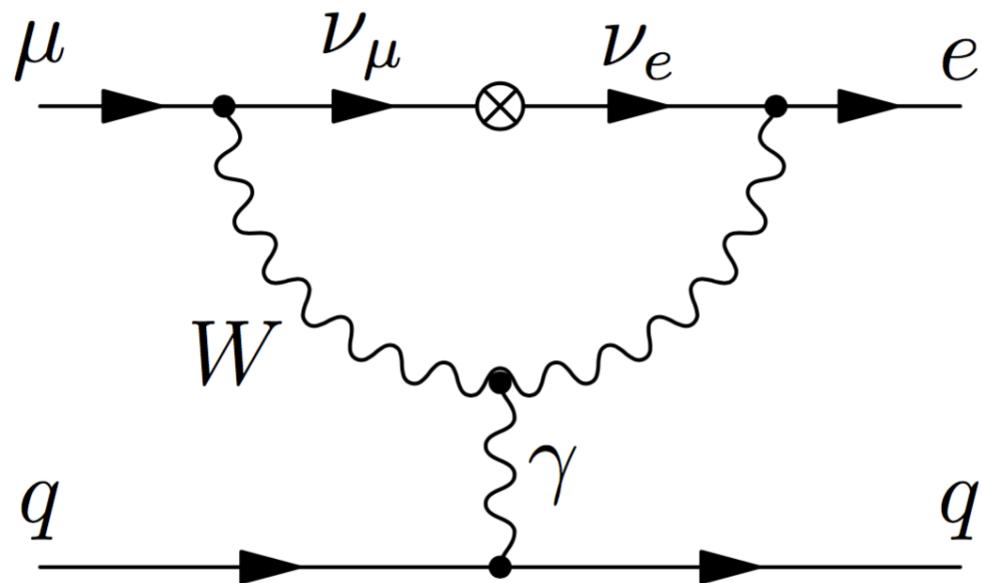
$$R_{\mu e} = \frac{\Gamma(\mu^- + N \rightarrow e^- + N)}{\Gamma(\mu^- + N \rightarrow \text{all captures})}$$



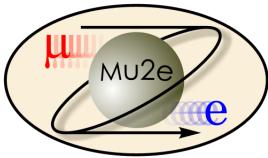
CLFV in SM



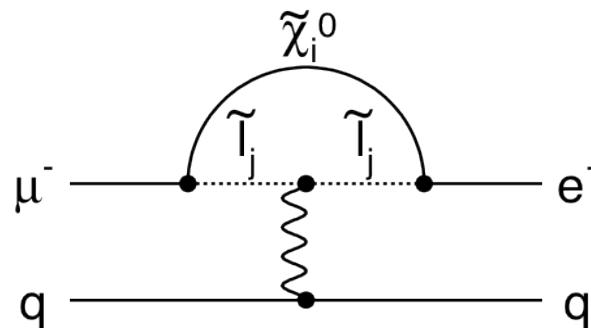
- **CLFV** process forbidden in the **SM**
- μ conversion in the extend-SM is introduced by the **neutrino masses and mixing** at a negligible level $\sim 10^{-52}$



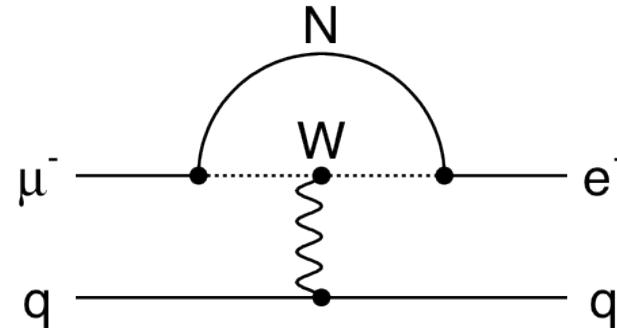
- Many **SM extensions enhance the rate** through mixing in the high energy sector of the theory (other particles in the loop...)



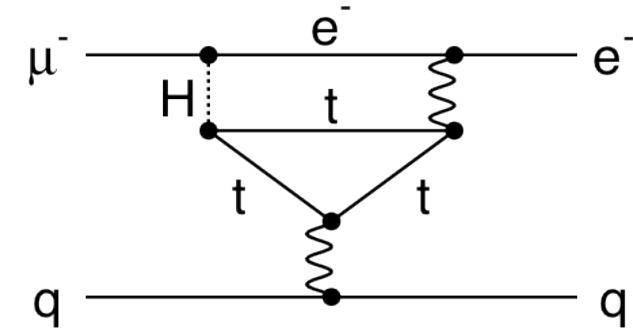
NP contributions to $\mu \rightarrow e$



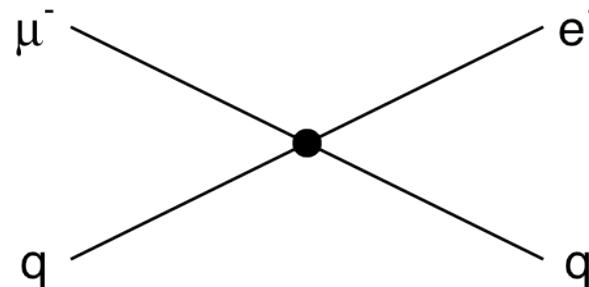
SUSY



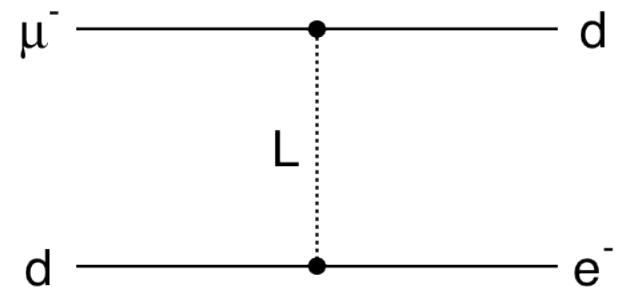
Heavy neutrino



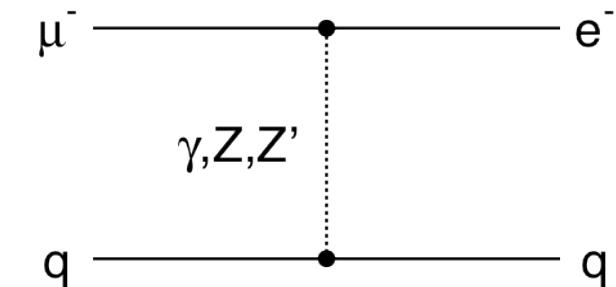
Two Higgs doublet



Compositeness

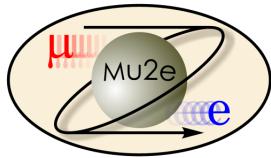


Leptoquarks



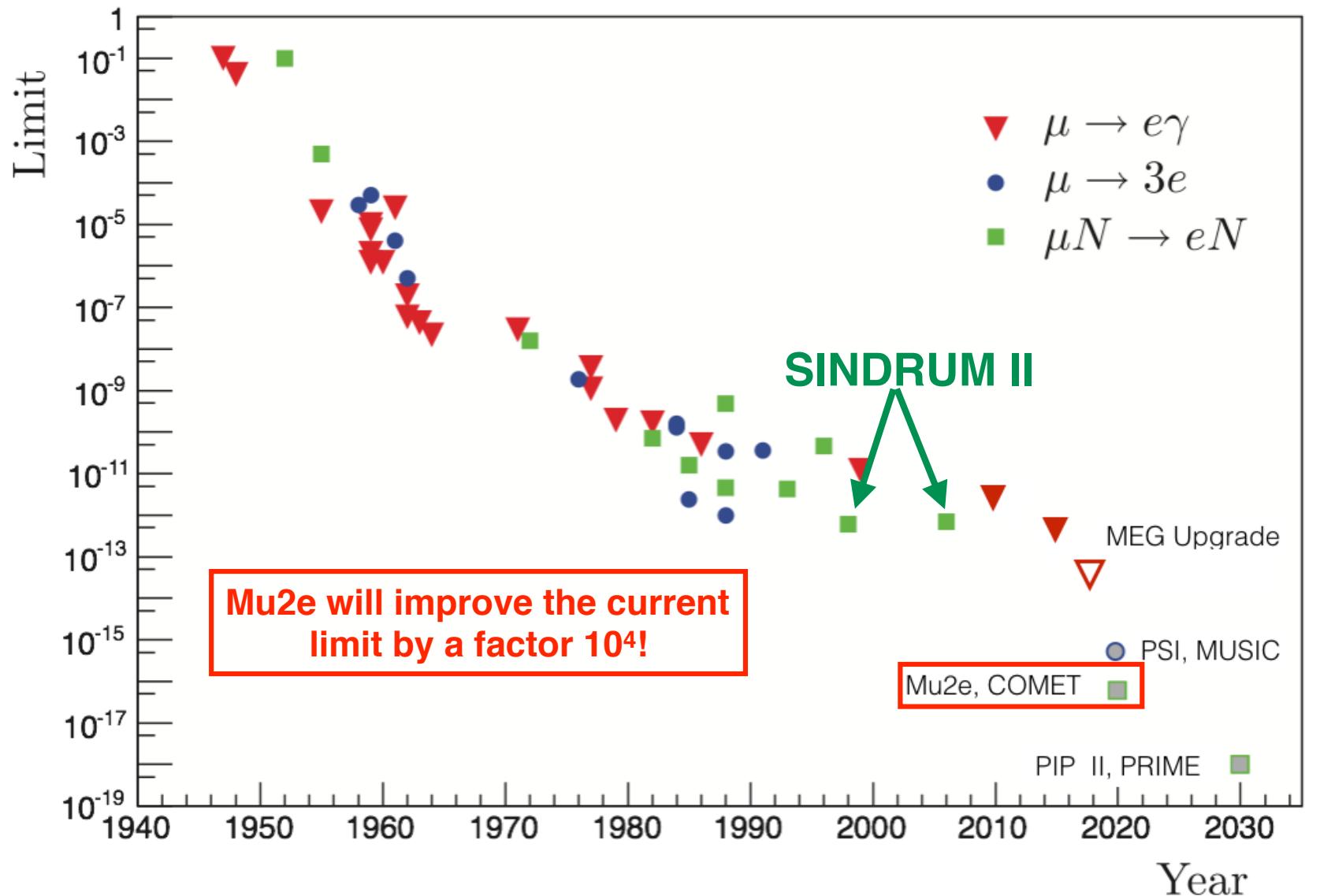
**Z' /anomalous
couplings**

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

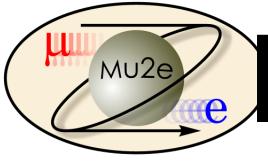


History of $\mu \rightarrow e$ search

History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$



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



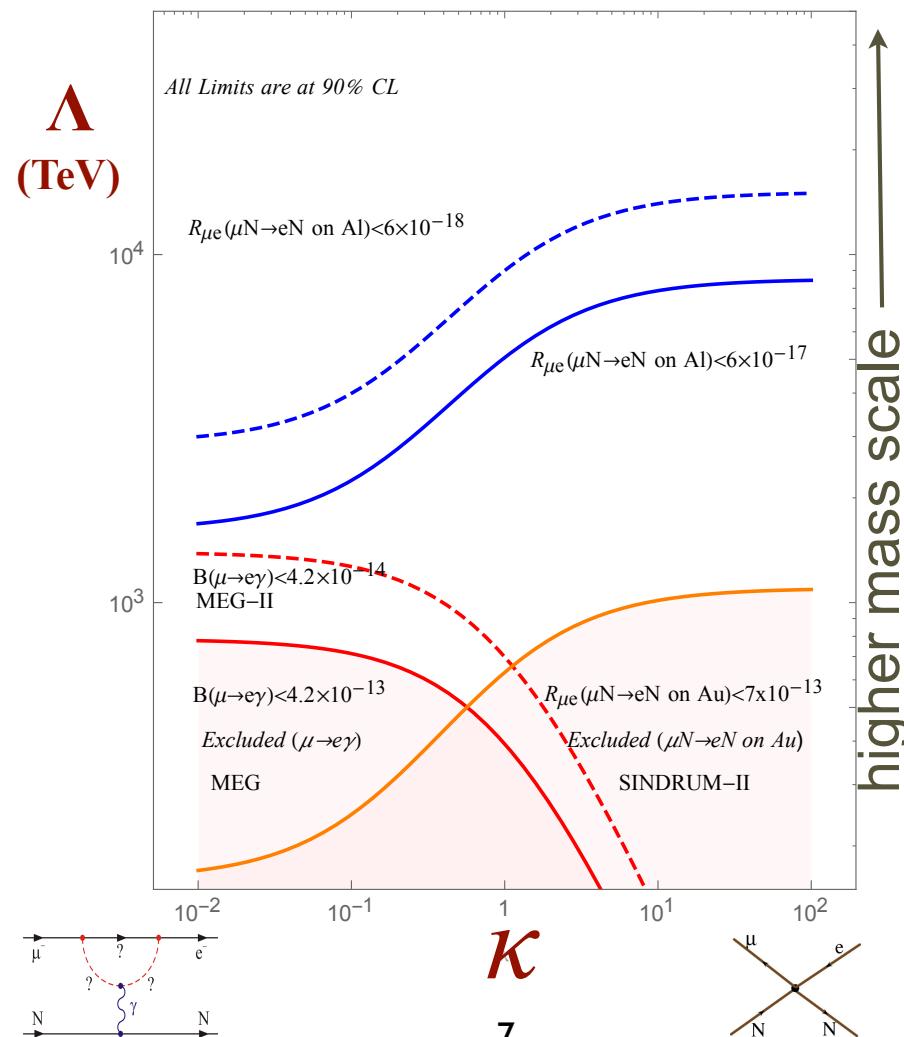
Model independent Lagrangian

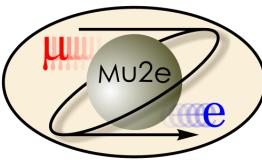


$$L_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa + 1)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{e} \gamma^\mu e)$$

“dipole term”

“contact term”





Experimental setup

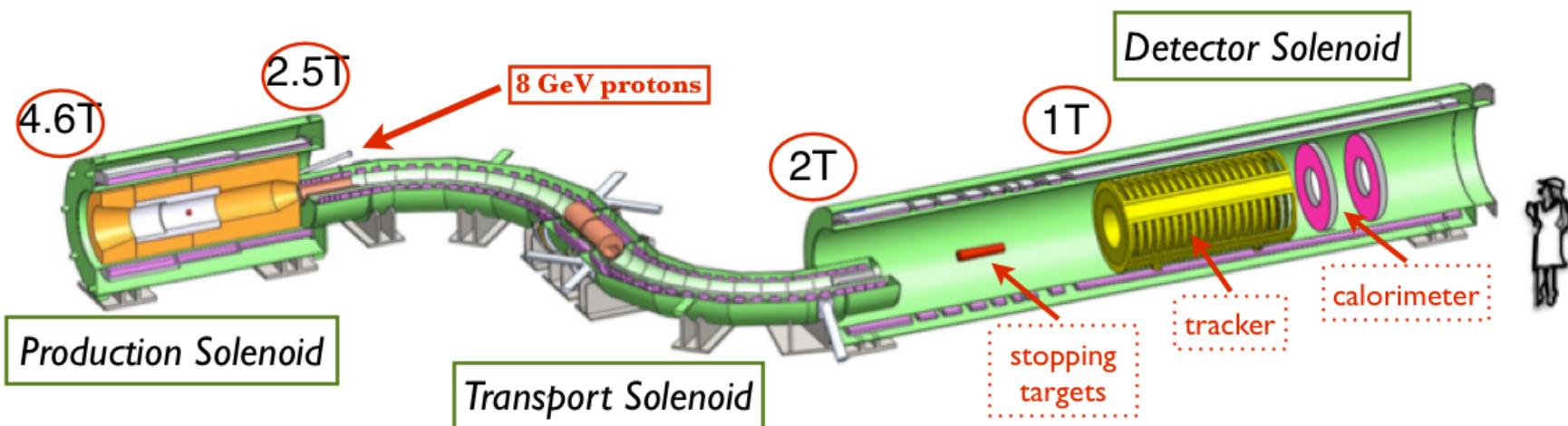


- **Production Solenoid:**

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

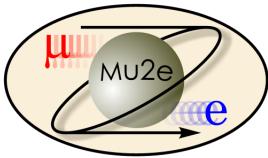
- **Detector Solenoid:**

- 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

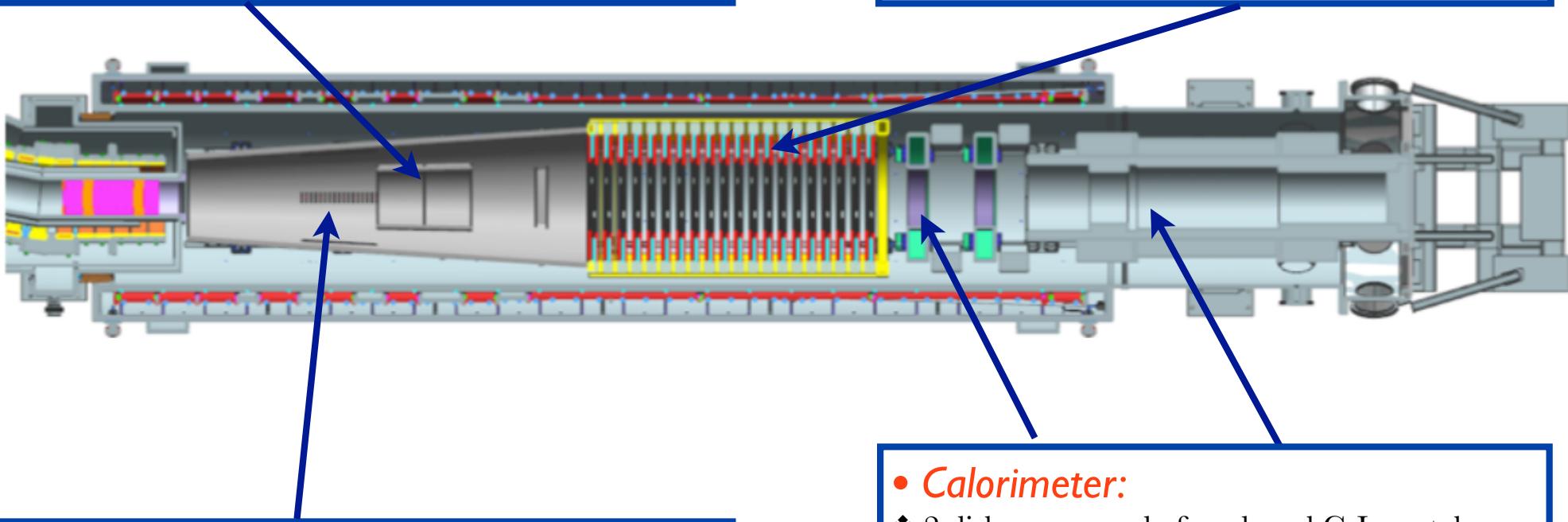


- **Proton absorber:**

- ❖ 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:**

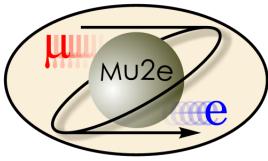
- ❖ 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

- **Calorimeter:**

- ❖ 2 disks composed of undoped CsI crystals

- **Muon beam stop:**

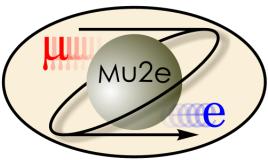
- ❖ made of several cylinders of different materials: stainless steel and polyethylene



Muonic atom



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



Mu2e detector

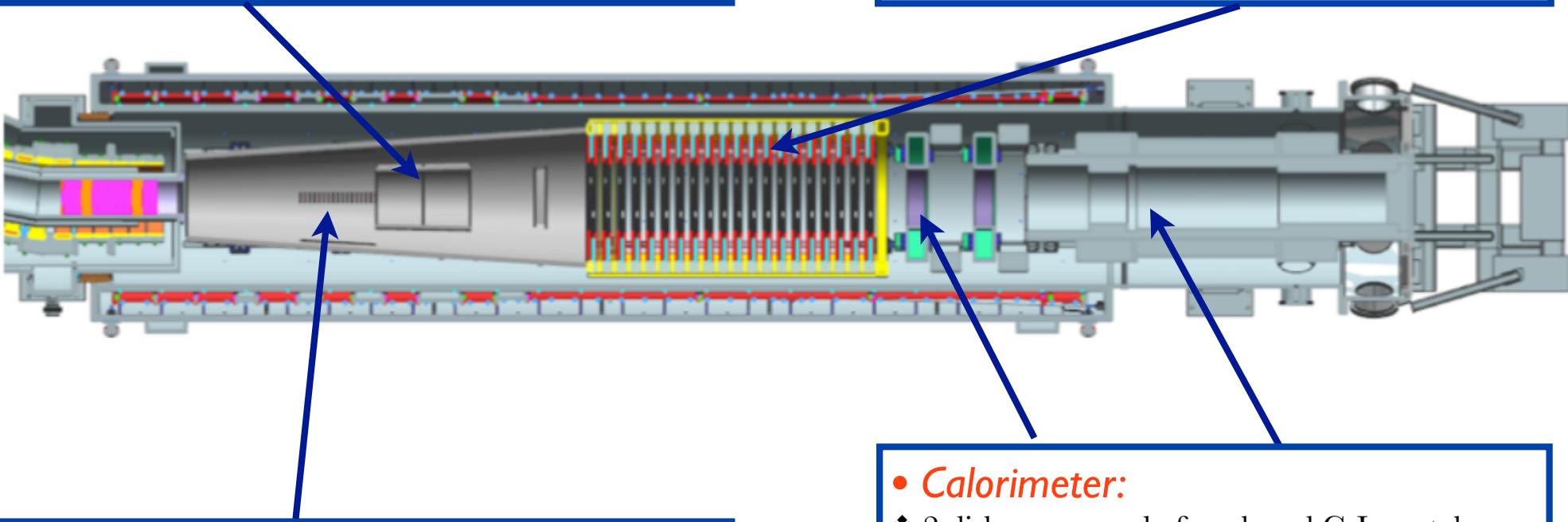


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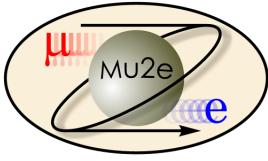
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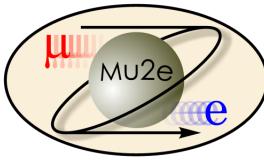
- ❖ made of several cylinders of different materials: stainless steel, lead and high density polyethylene



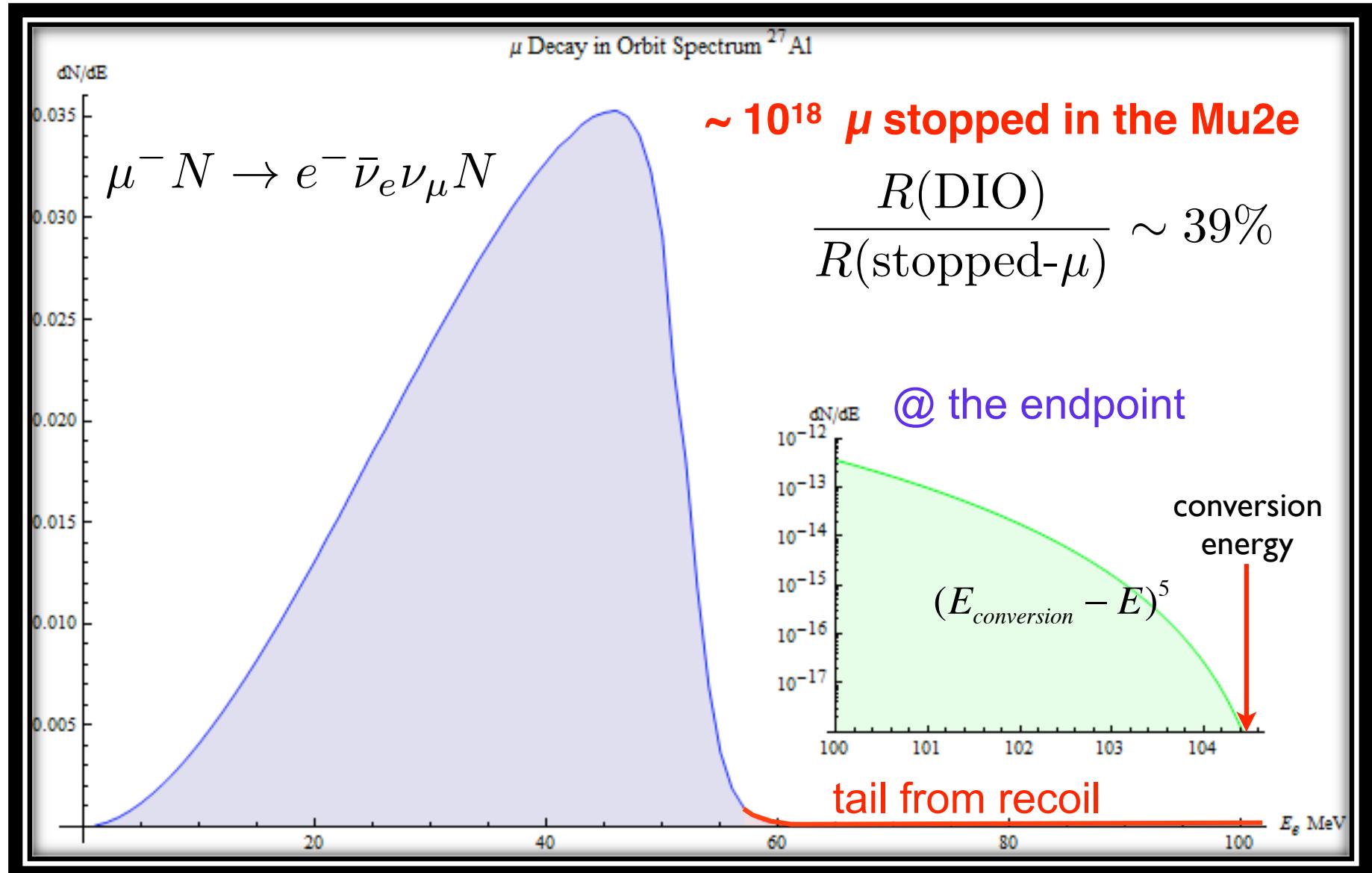
Physics background



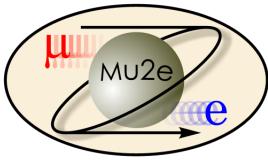
- **μ decay-in-orbit:**
 - ✓ low-mass tracker with high performance
- Cosmic-induced background:
 - ✓ cosmic ray veto and PID
- Antiproton-induced background
 - ✓ absorbers in the beam line to annihilate p-bar and PID
- Radiative π capture: $\pi^- N_z \rightarrow N_{z-1}^* \gamma$, asymmetric $\gamma \rightarrow e^- e^+$
 - ✓ 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>

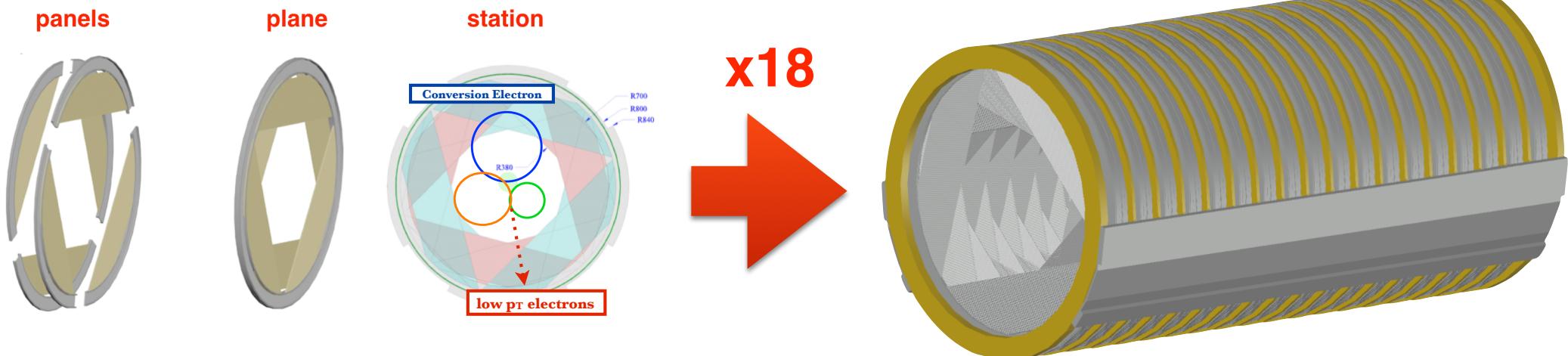


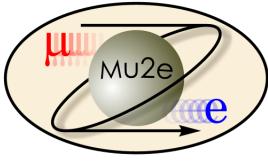
Tracker design



- 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/CO₂ with HV \sim 1500V
- Inner 38 cm un-instrumented:
 - ✓ blind to beam flash
 - ✓ blind to **low** pT particles, almost all the DIO

straw tube

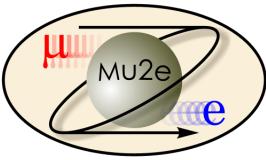




Physics background



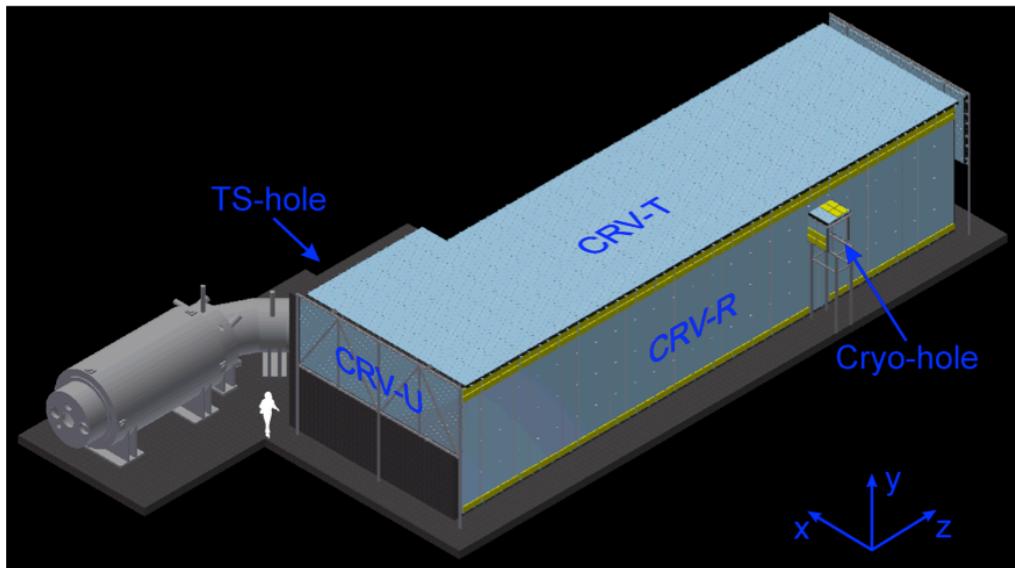
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 - ✓ pulsed beam and extinction of out-of-time protons



Cosmic Ray Veto



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



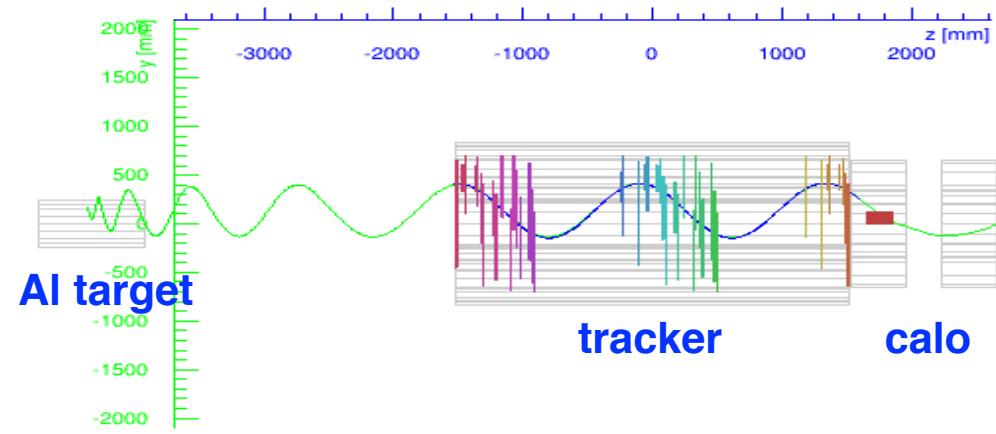
WLS fiber

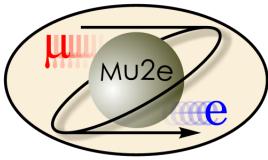


Prototype



μ mimicking the CE



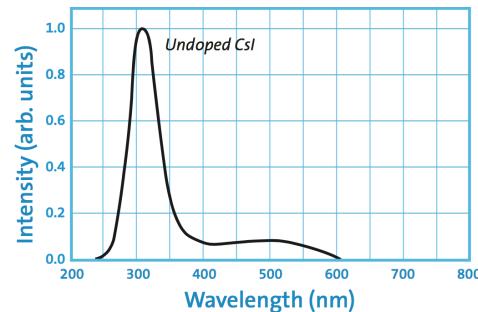


Calorimeter

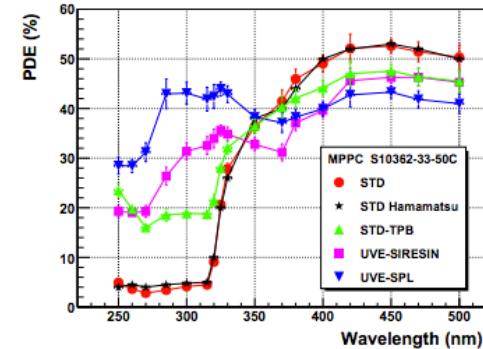


- 2 disks; each disk contains 674 undoped CsI crystals $20 \times 3.4 \times 3.4 \text{ cm}^3$
- Disk separation $\sim 70 \text{ cm}$
- Inner/outer radii: 37.4/66 cm
- Readout system:
 - 2 large area SiPM-array/crystal
 - 12 bit, 250 MHz waveform-based digitizer boards

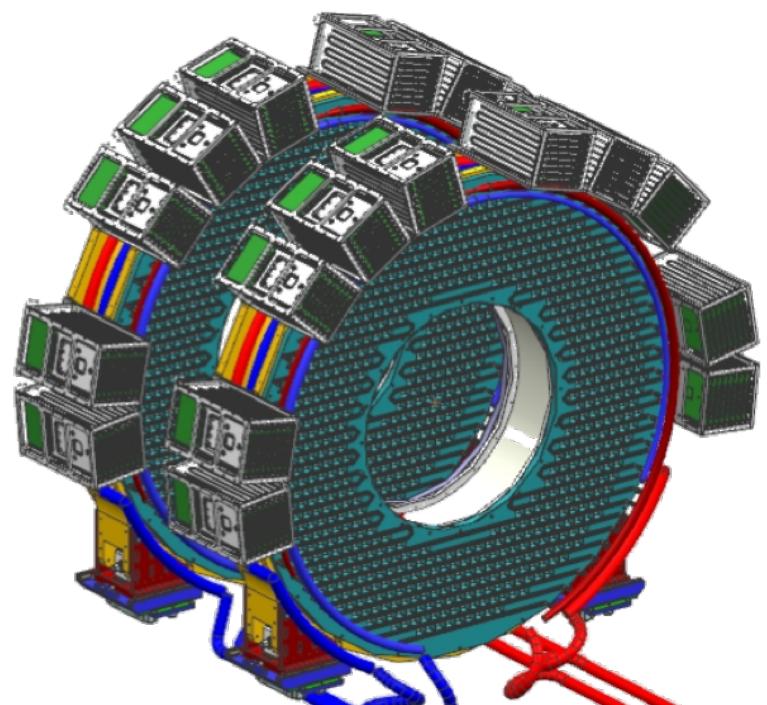
undoped CsI

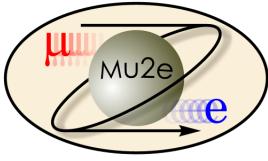


SiPM array



Calorimeter

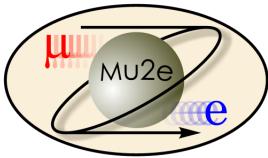




Physics background



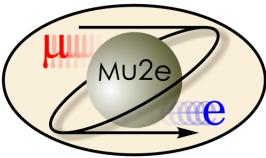
- μ decay-in-orbit:
 - ✓ low-mass tracker with high performance
- Cosmic-induced background:
 - ✓ cosmic ray veto and PID
- **Antiproton-induced background**
 - ✓ absorbers in the beam line to annihilate $p\bar{p}$ and PID
- Radiative π capture: $\pi^- N_z \rightarrow N_{z-1}^* \gamma$, asymmetric $\gamma \rightarrow e^- e^+$
 - ✓ pulsed beam and extinction of out-of-time protons



Physics background



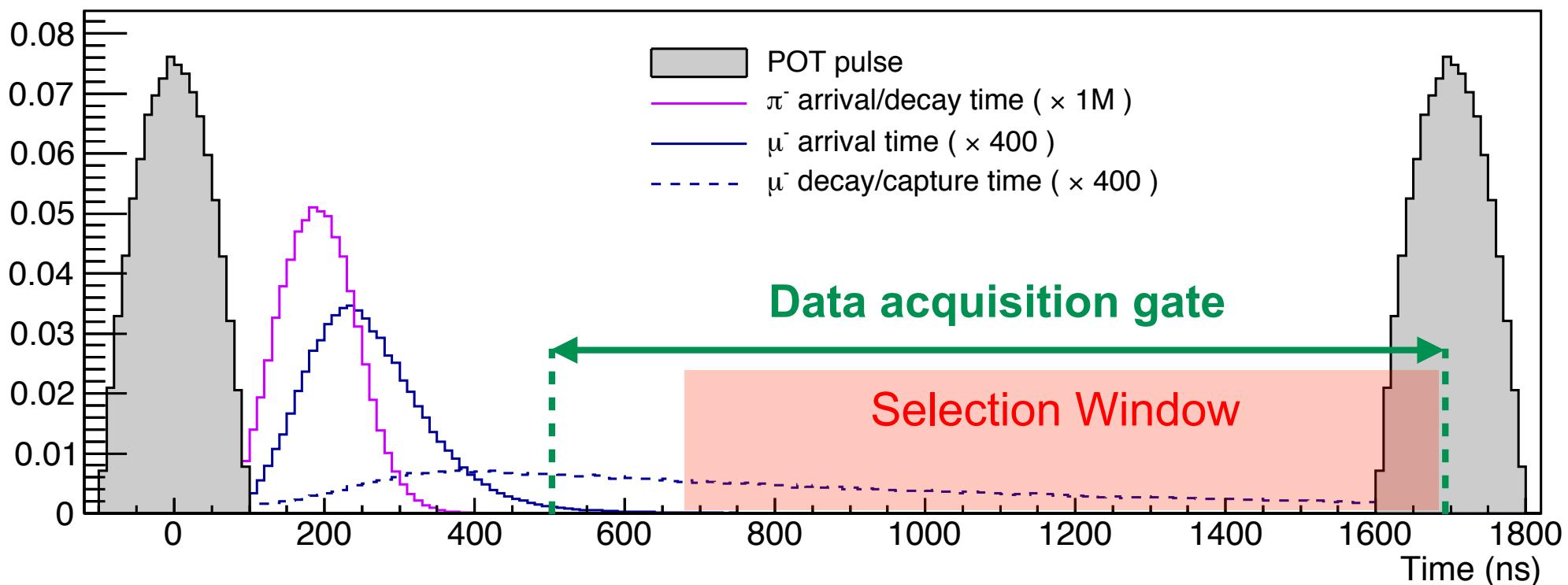
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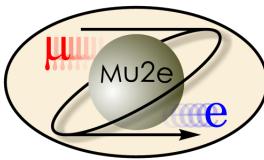


Pulsed beam

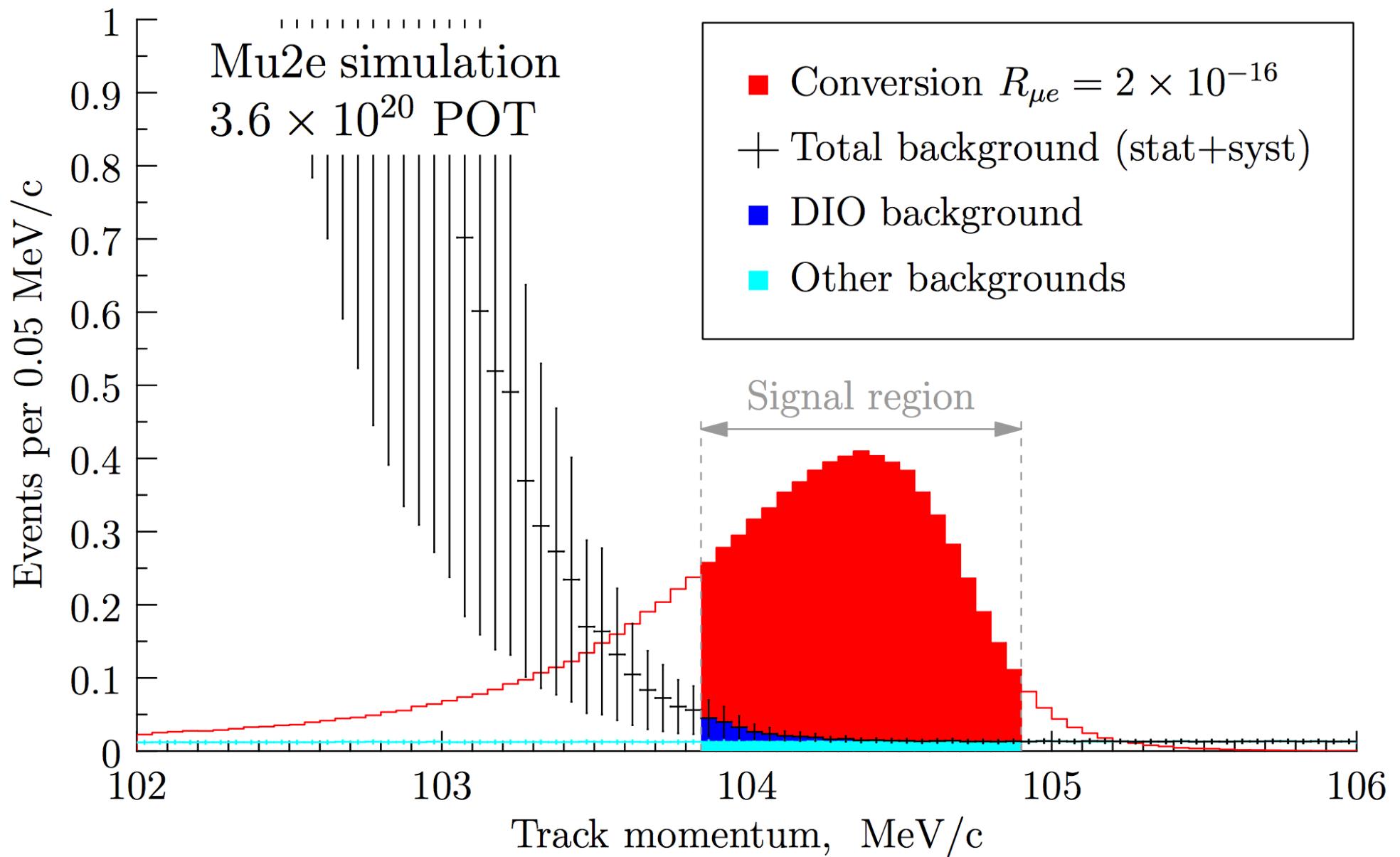


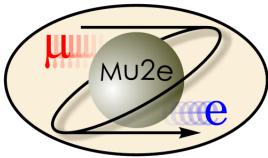
- Beam period : $1.7 \mu\text{s} \sim 2 \times \tau_\mu^{Al}$
- Beam intensity: $3.9 \times 10^7 \text{ p/bunch}$
- duty cycle : $\sim 30\%$
- **Extinction: out-of-time protons / in-time protons < 10^{-10}**



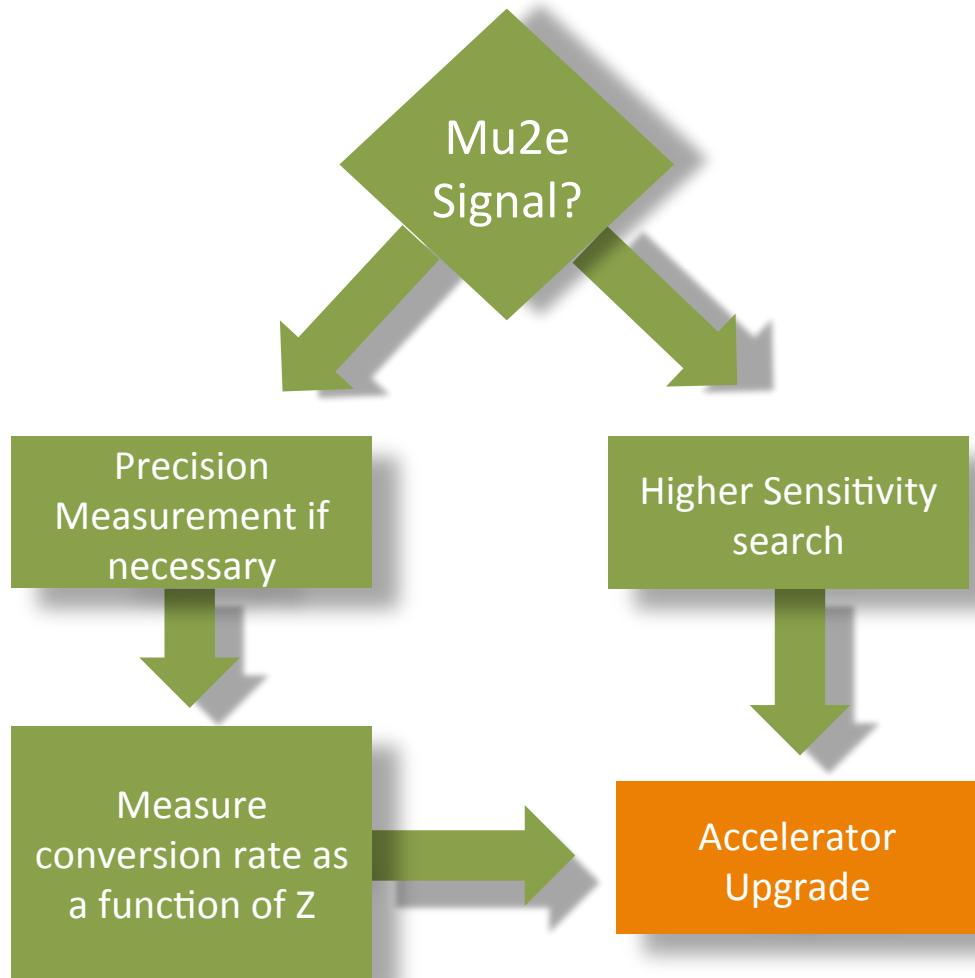


Mu2e sensitivity

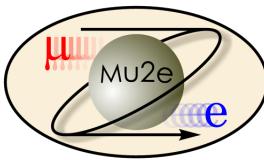




Mu2e signal?



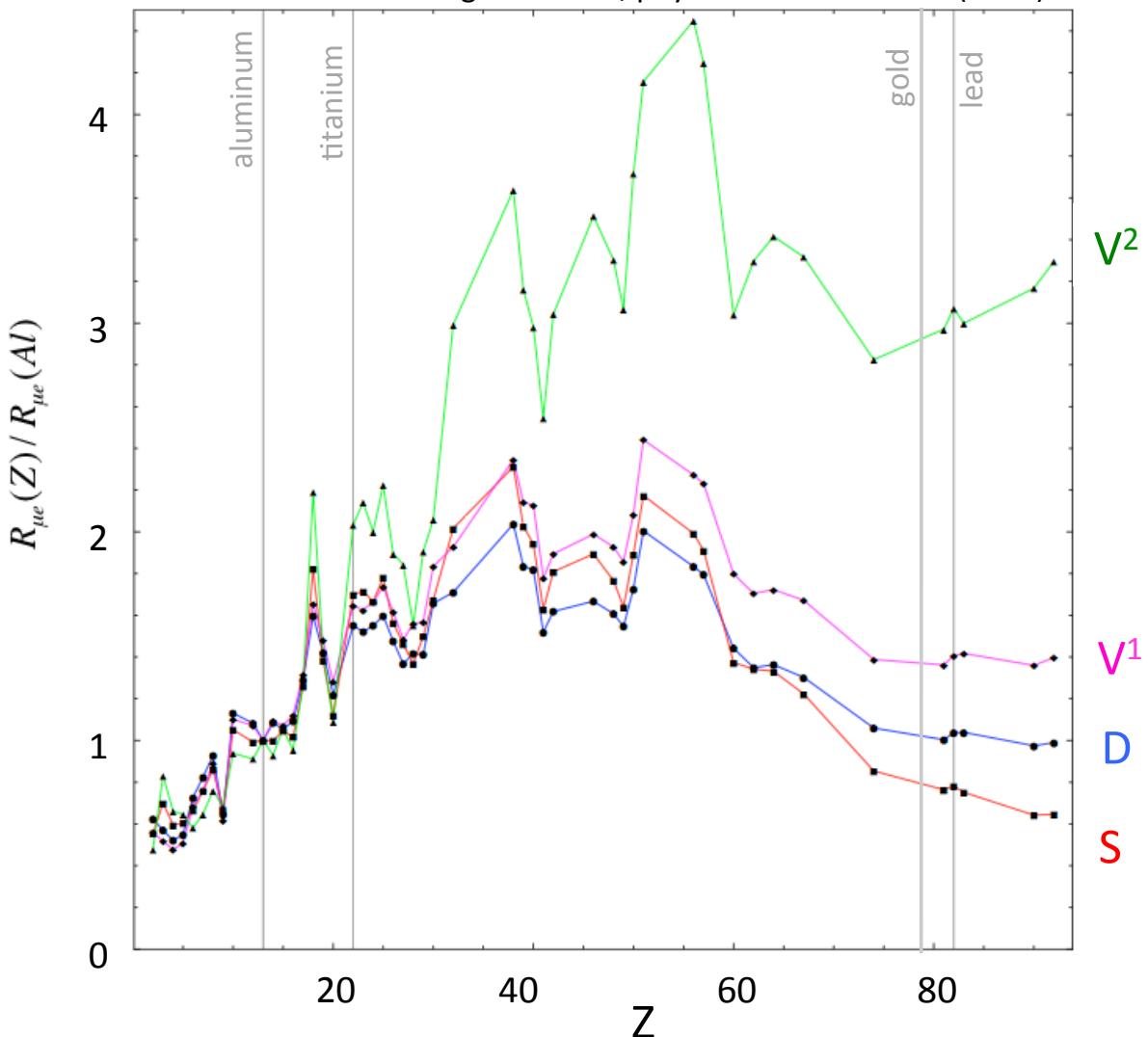
- A next-generation Mu2e experiment makes sense in all scenarios:
 - ✓ Push sensitivity or
 - ✓ Study underlying new physics
- Will need more protons upgrade accelerator



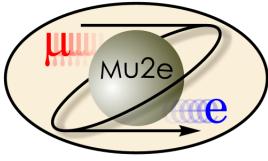
$R_{\mu e}$ rate vs Z



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



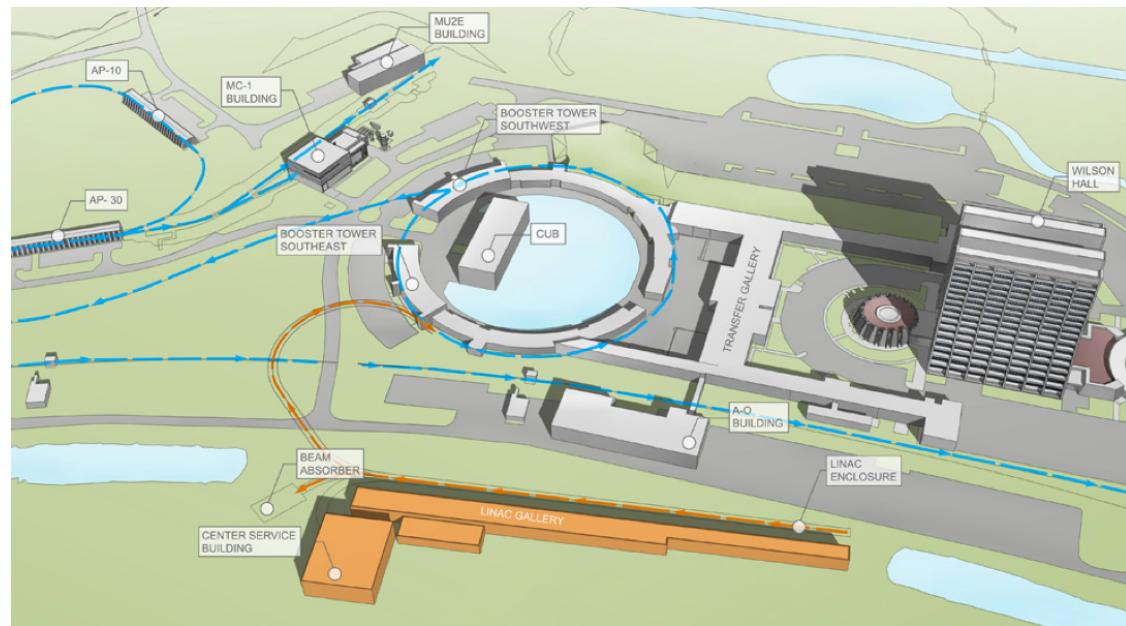
- Can use ratio of rates to determine dominant operator contribution
- Life time of the μ -atom plays also a role in the Z choice:
 - ✓ $\tau_\mu(\text{Al}) = 864 \text{ ns}$
 - ✓ $\tau_\mu(\text{Ti}) = 338 \text{ ns}$
 - ✓ $\tau_\mu(\text{Au}) = 74 \text{ ns}$

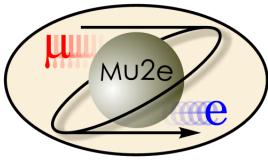


Mu2e Upgrade



- Studies for $\times 10$ improvement with Ti look promising and will be continued; EOI written (1307.11168 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



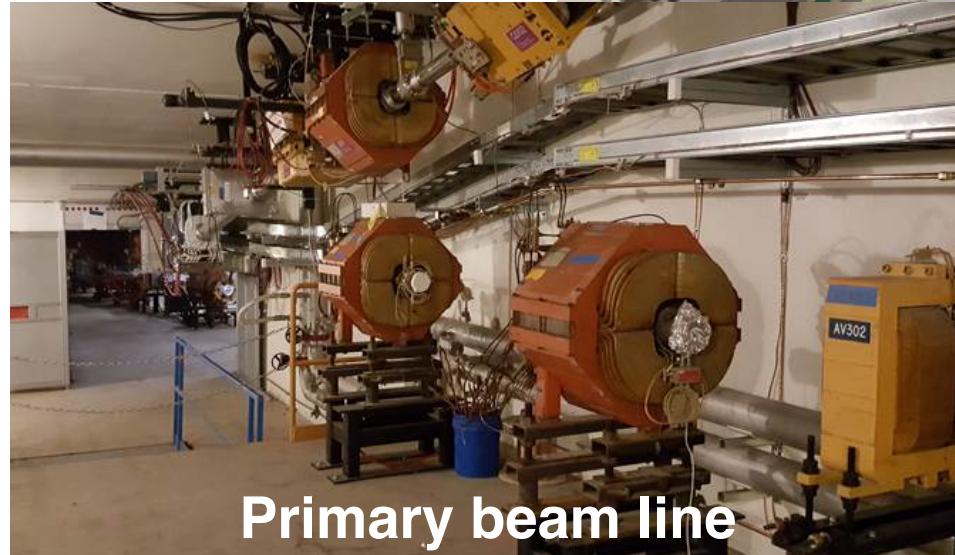
North face



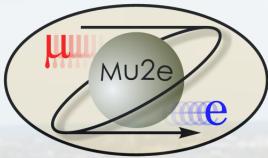
Splice between
solenoids @ GA



Coils module @ ASC



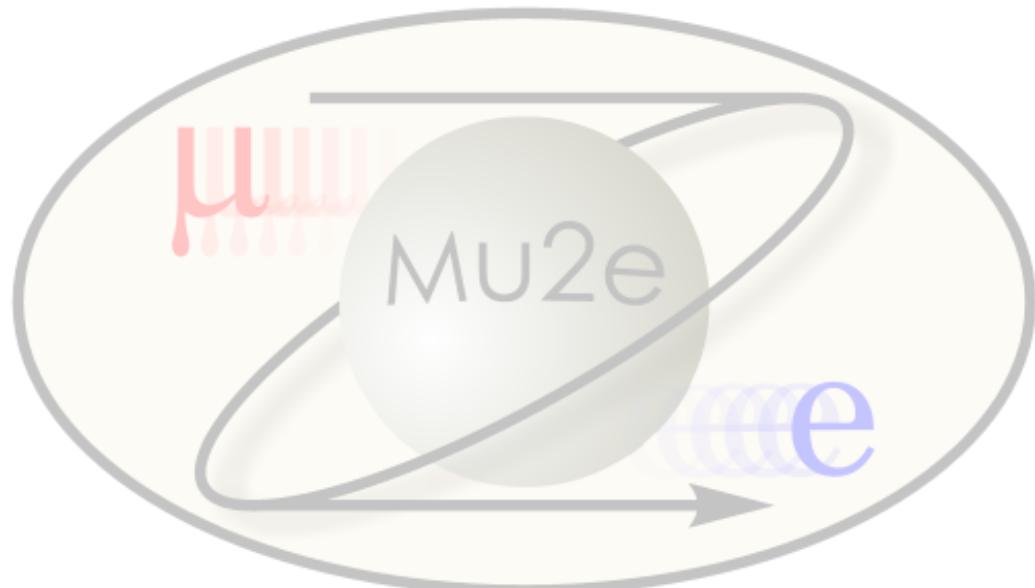
Primary beam line

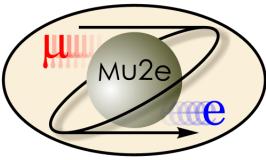


Summary

- 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

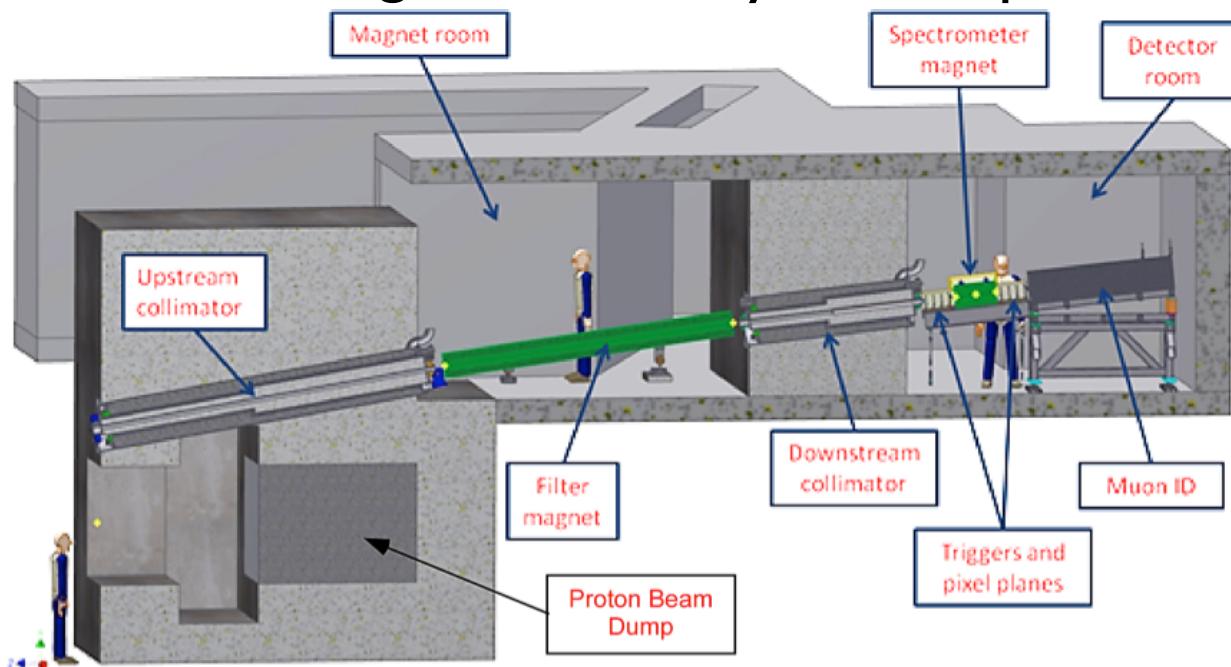


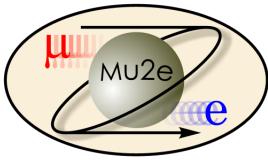


Extinction of out-of-time protons

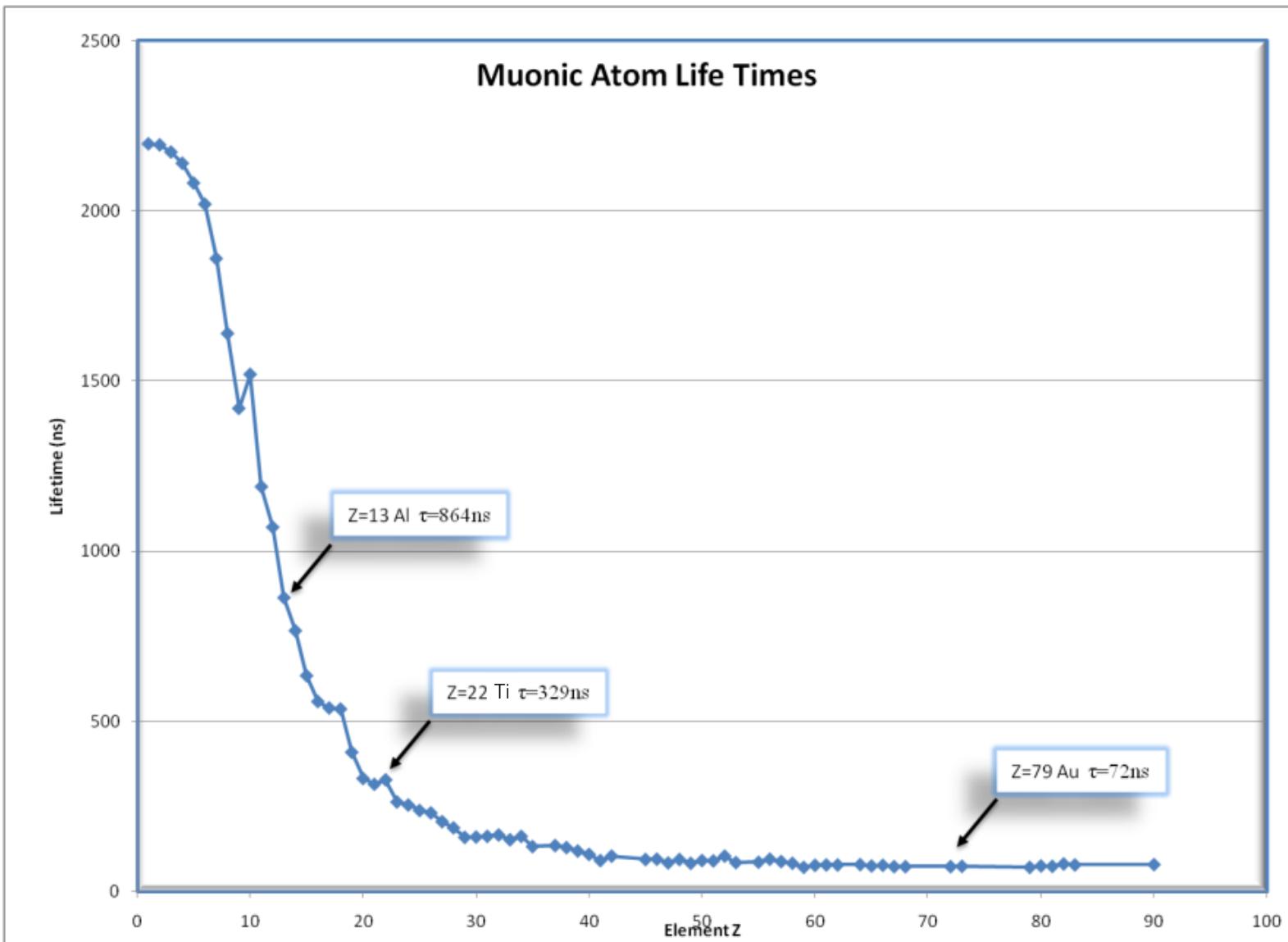


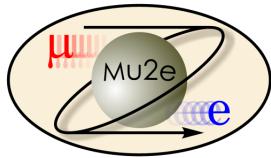
- The RF structure of the Recycler provides some “intrinsic” extinction:
✓ **Intrinsic extinction $\sim 10^{-5}$**
- A custom-made AC dipole placed just upstream of the production solenoid provides additional extinction:
✓ **AC dipole extinction $\sim 10^{-6} - 10^{-7}$**
- Together they provide a total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





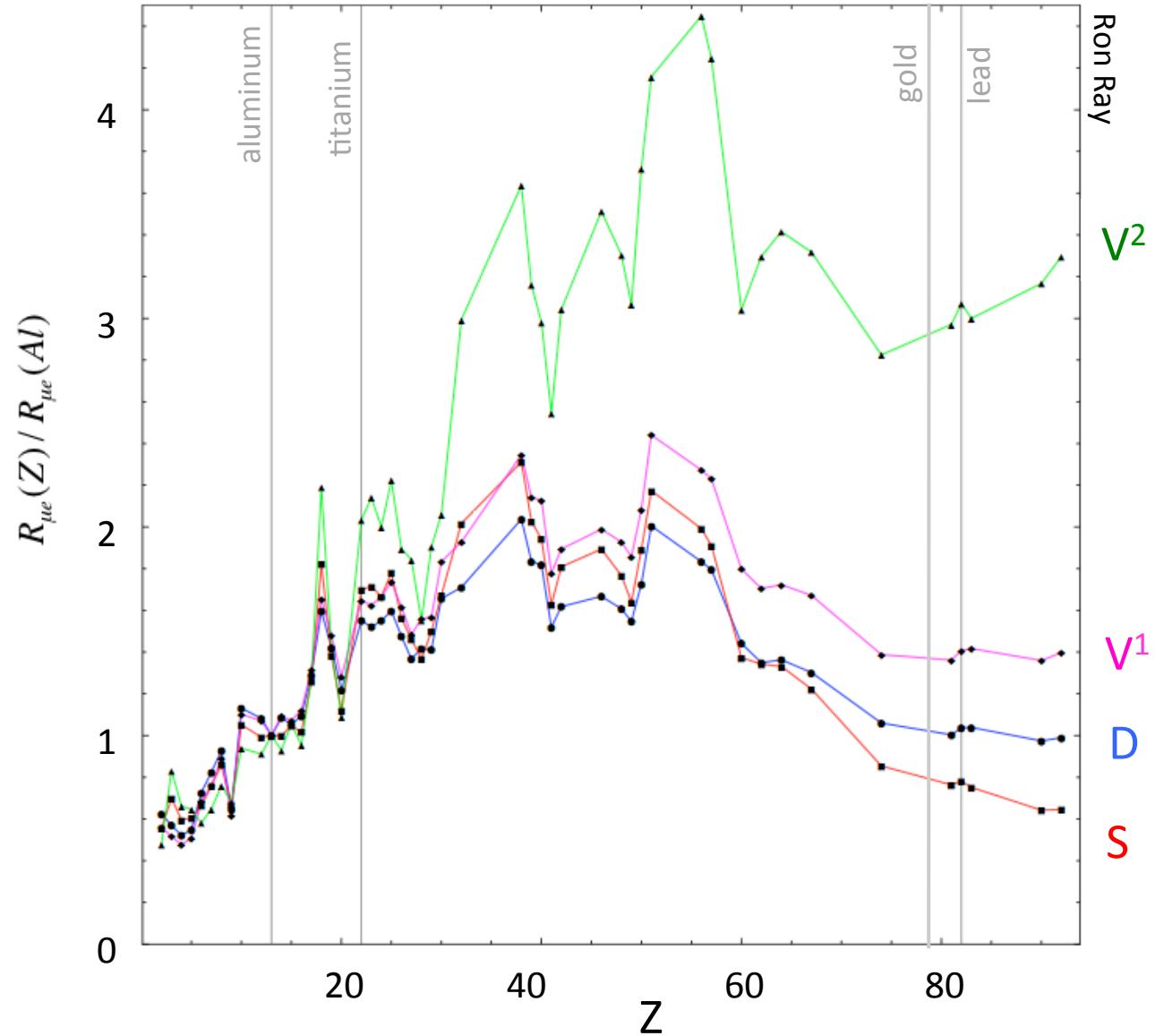
Muonic atom life times

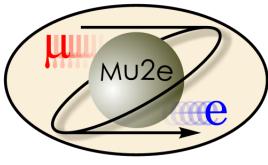




$R_{\mu e}$ rate vs Z

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





Mu2e sensitivity

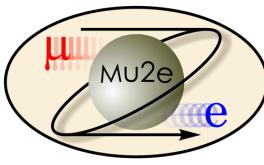
W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

arXiv:0909.1333[hep-ph]

★★★ = Discovery Sensitivity

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

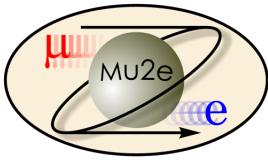
Table 8: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models. ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.



CLFV limits I



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



CLFV limits 2



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