The Mu2e experiment at Fermilab: R&D, design and status

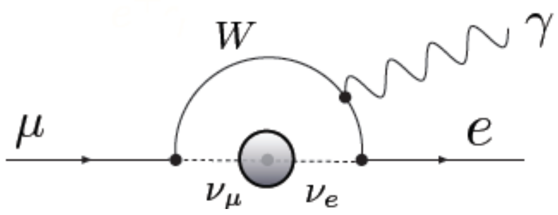
Eleonora Diociaiuti
LNF-INFN and Tor Vergata university
On behalf of the Mu2e collaboration

Outline

- Charged Lepton Flavour Violation (CLFV) processes
- Muon Conversion
- Mu2e experiment
- Conclusion

Charged Lepton Flavour Violation

- CLFV processes are strongly suppressed in the SM
  - Not forbidden due to the neutrino oscillation
  - negligible (rate ~ $\Delta M_\nu^4/M_W^4 < 10^{-50}$)



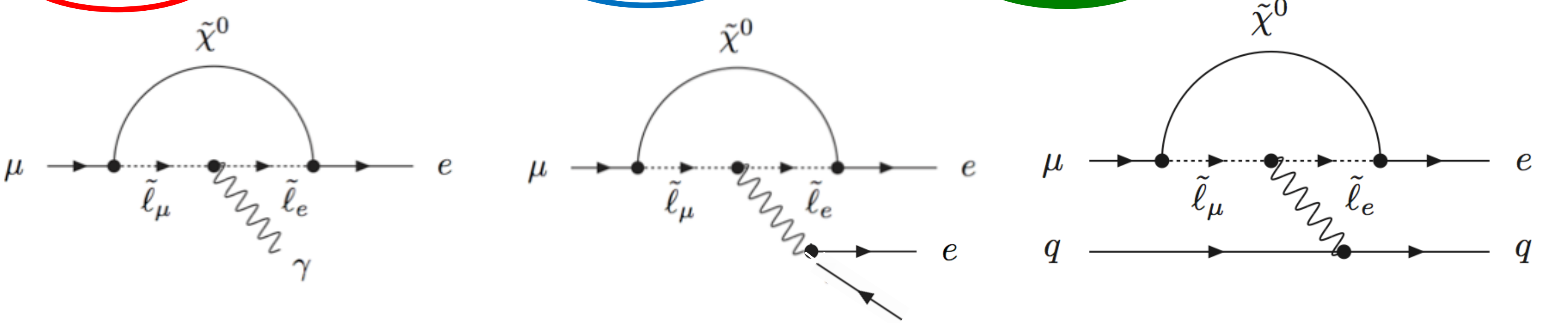
- Different models of New Physics (NP) predict rates observable at next generation CLFV experiments → An observation will be a **clear evidence of Physics Beyond the Standard Model (BSM)**

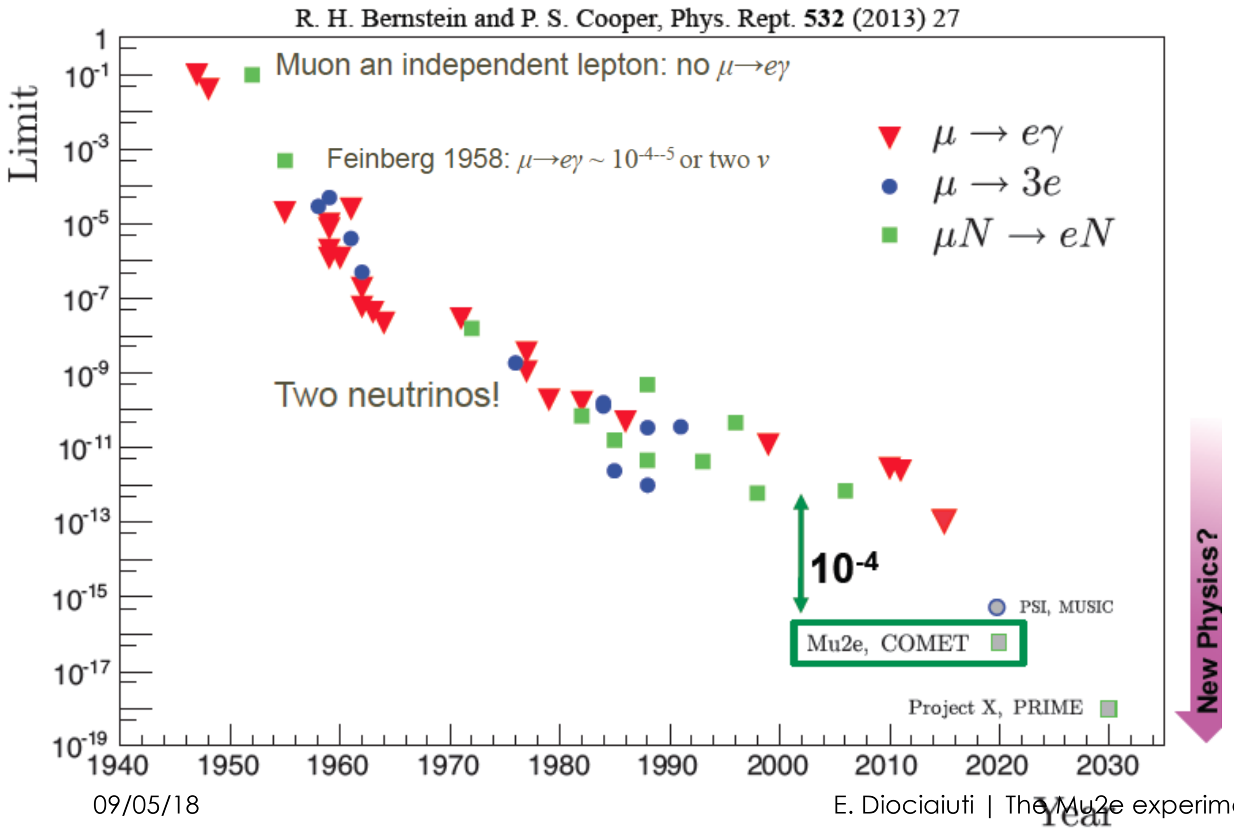
Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\gamma$	BR < 6.8 E-8	
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8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

- Muon channels are ideal for CLFV search
  - Clean topologies
  - Large rates

Muon CLFV - time line

$\mu \to e\gamma$ $\mu \to 3e$ $\mu N \to eN$





Current best limits:

BR($\mu \to e\gamma$) < 4.2×10^{-13} MEG 2016

BR($\mu \to 3e$) < 1×10^{-12} SINDRUM 1998

$R_{\mu e} < 6.1 \times 10^{-13}$ SINDRUM-II 2006

$R_{\mu e} \sim 10^{-17}$ **Mu2e goal**

Muon CLFV – BSM theory

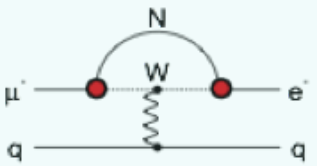
$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

LOOP TERM

CONTACT TERM

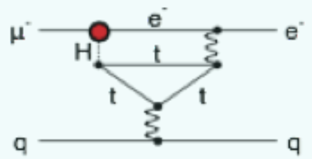
Heavy Neutrinos

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



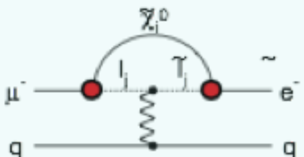
Second Higgs Doublet

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



Supersymmetry

rate ~ 10^{-15}

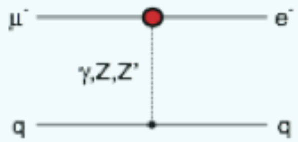


Model which can be probed also by μ→eγ searches

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

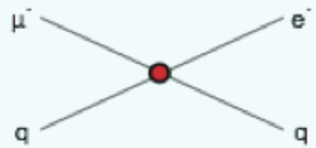
Heavy Z'
Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/c²



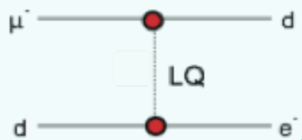
Compositeness

$\Lambda_c \sim 3000$ TeV

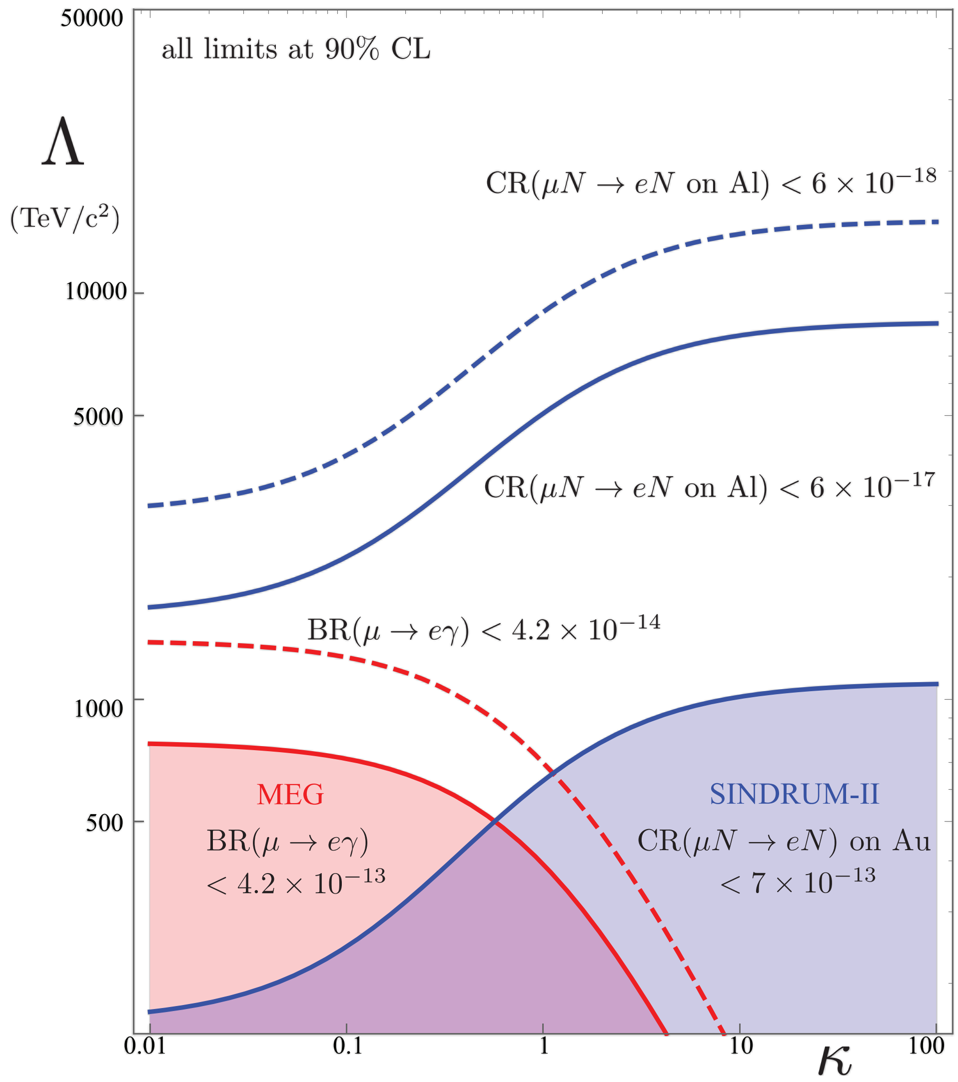


Leptoquark

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



Mu2e physics reach



Muon conversion is a unique probe for physics BSM :

- Broad discovery sensitivity across all models
- Mass scale discovery up to ~10000 TeV, significantly above the direct reach of LHC
- Clear experimental signature: neutrinoless and mono-energetic electron:
  - E_e = 104.96 MeV

Experimental technique

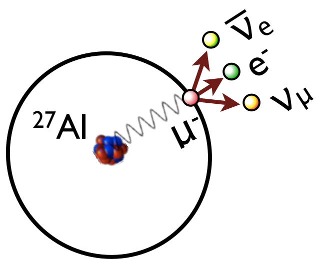
Mu2e will look for coherent muon conversion into a muonic atom

$$\mu^- Al \rightarrow e^- Al$$

- Generation of a μ^- beam
  - Low momentum (<100 MeV/c)
  - High intensity "pulsed" rate
- Stop the beam in a Al target

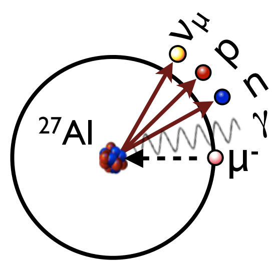
Decay In Orbit (DIO)

(BR=39%)

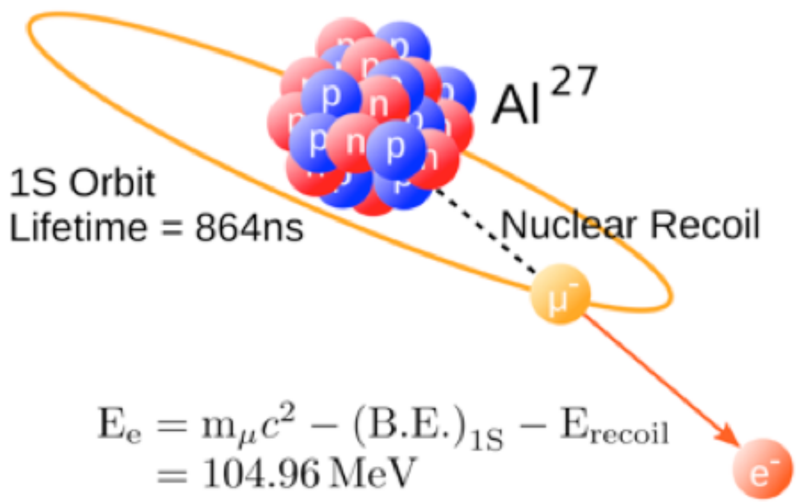


Muon Capture

(BR=61%)



Conversion process



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 sensitivity

- Measure the ratio of the μ-e conversion wrt the conventional μ capture

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

- To obtain a Single Event Sensitivity of 3×10^{-17}
  - 10^{18} stopped muons
  - High background suppression

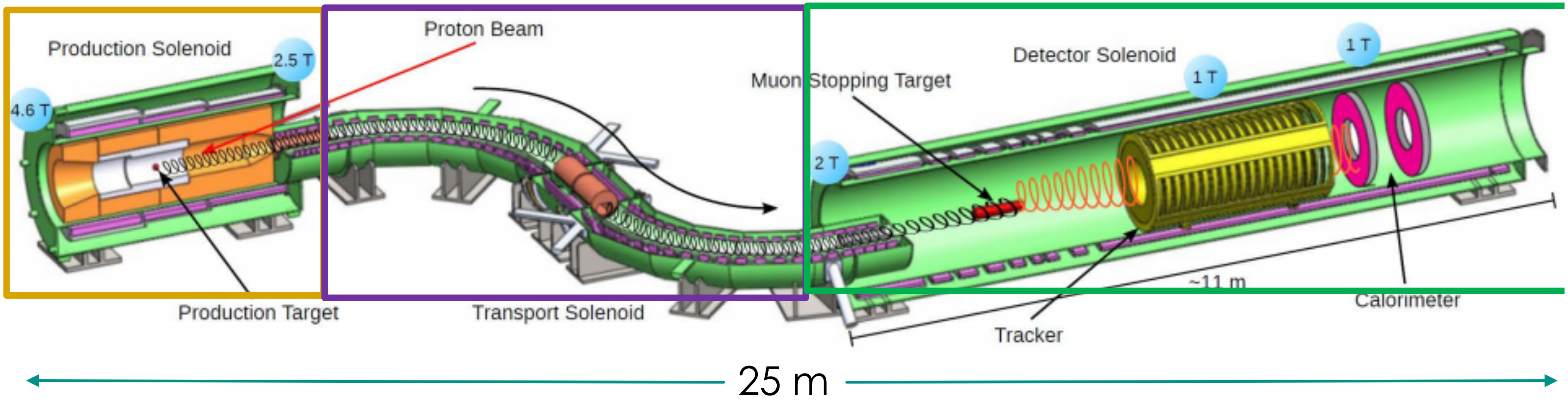
Mu2e Design

PRODUCTION SOLENOID

- Protons hitting the target and producing mostly π
- Graded magnetic field reflects slow forward π

TRANSPORT SOLENOID

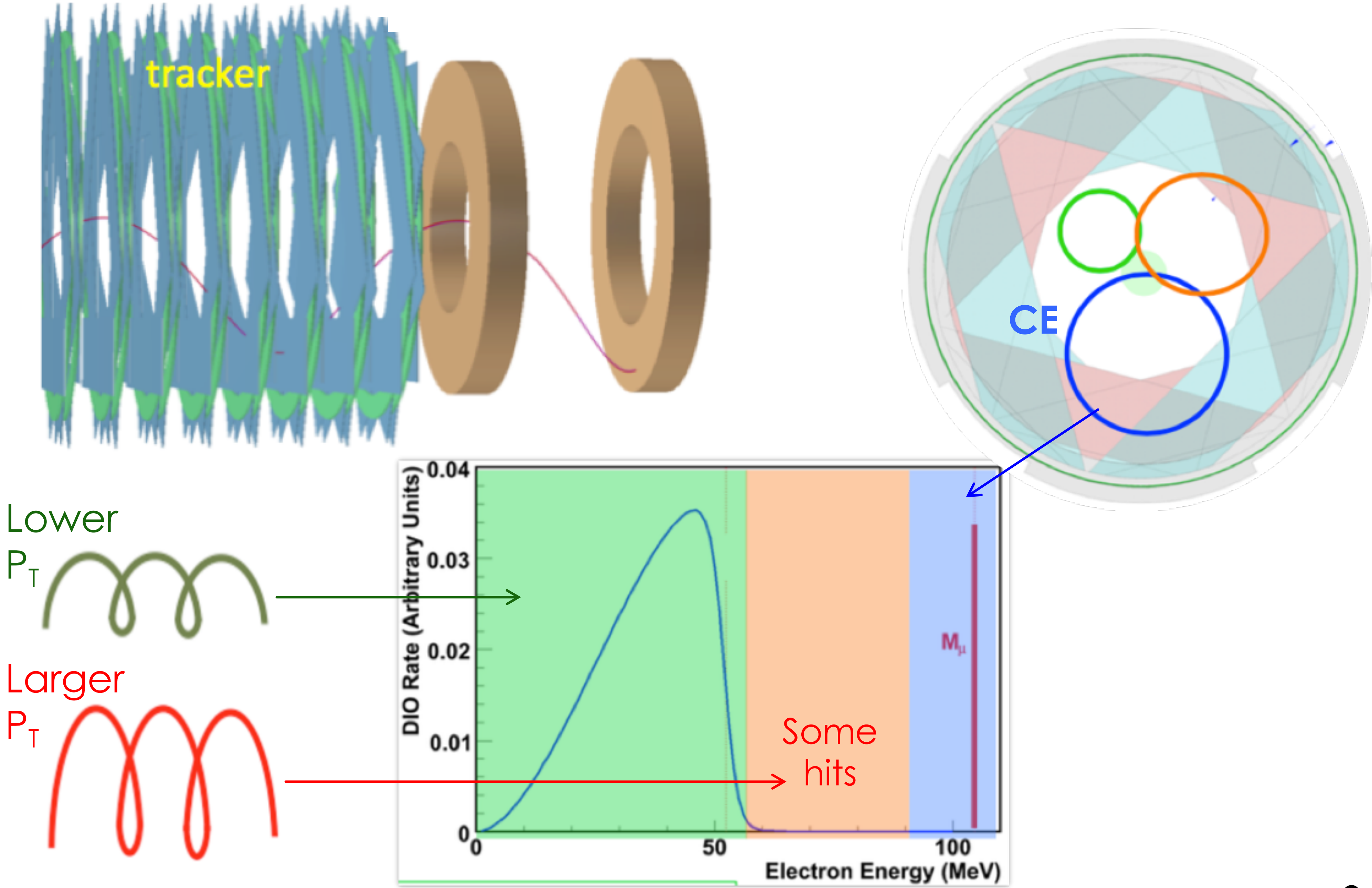
- Selection and transportation of low momentum μ^-



DETECTOR SOLENOID

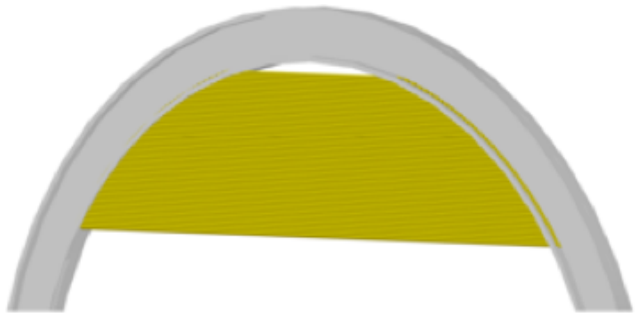
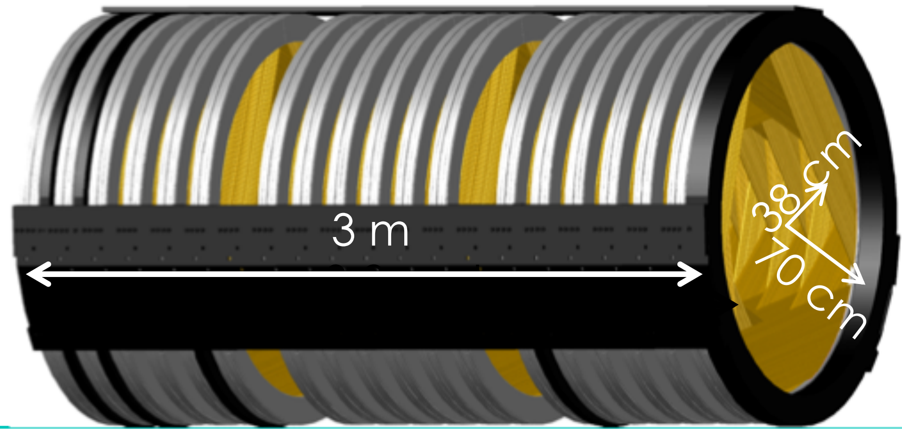
- Capture μ on the Al target
- Momentum measurement in the tracker and energy reconstruction with calorimeter
- CRV to veto cosmic rays events

Detectors



tracker
CE
Lower
P_T
Larger
P_T
DIO Rate (Arbitrary Units)
0.04
0.03
0.02
0.01
0
0
50
100
Electron Energy (MeV)
M_μ
Some
hits

Tracker

Straw tubes on a panel	One station	Tracker Structure
		

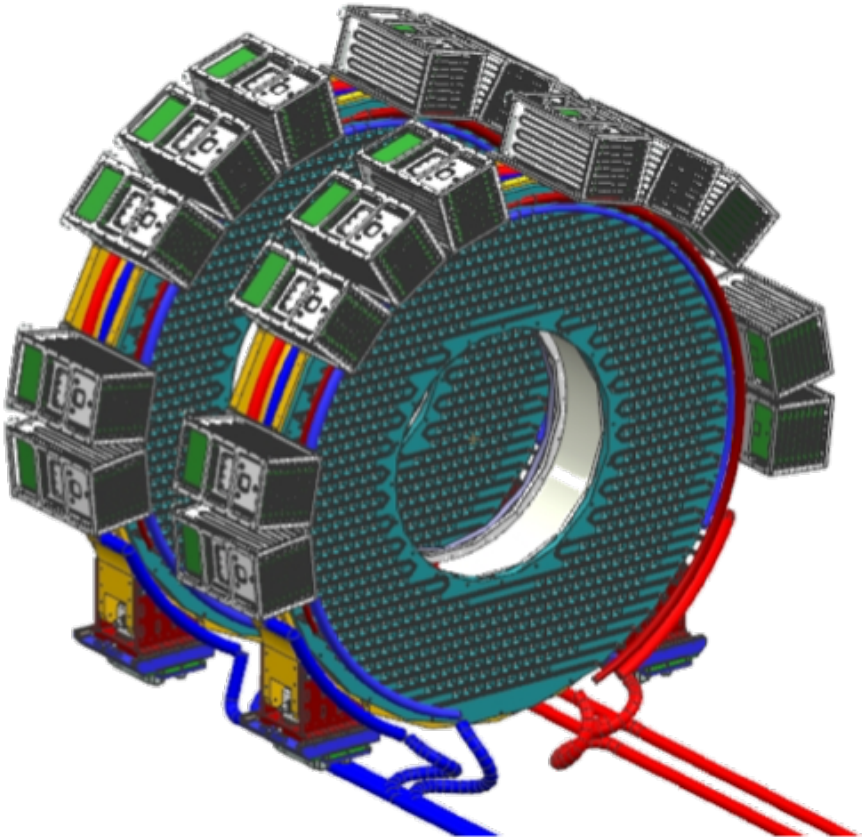
- 3 m long , 1.4 m diameter in a 1 T uniform B field
- Maximize/minimize the acceptance for CE/DIO
- ~20000 straw drift tubes organized into 18 stations, 2 planes per station
- Each straw is 5 mm diameter, with 25 μm sense wire , 15 μm Mylar wall

Momentum resolution <170 keV/c (@100 MeV/c)

Timing resolution ~ 1 ns

Spatial resolution ~ 100 μm

Electromagnetic Calorimeter



Energy resolution < 5% (@ 100 MeV)

Timing resolution < 0.5 ns

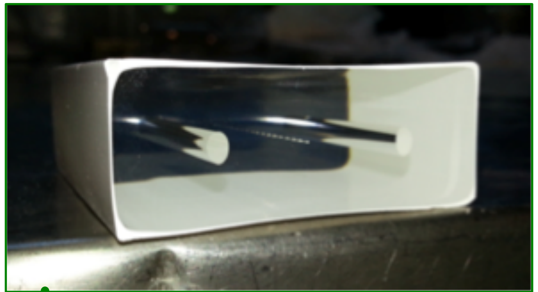
Spatial resolution < 1 cm

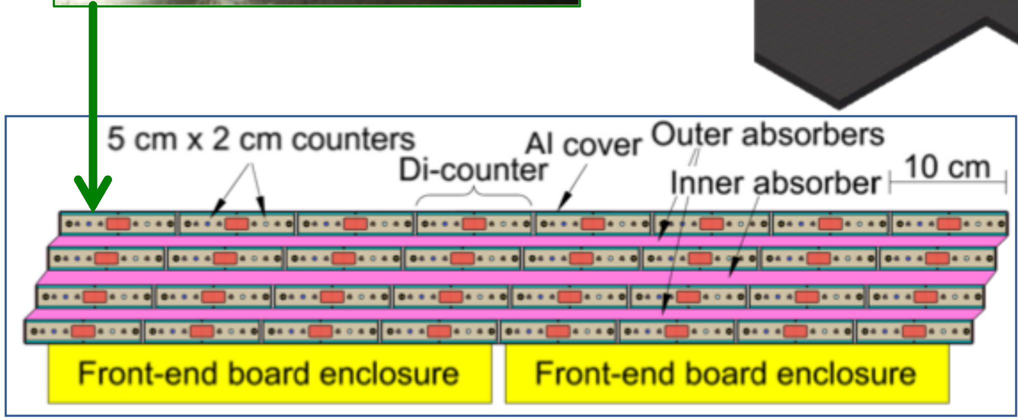
- 2 annular disks with 674 CsI (30x30x200) mm^3 crystals each
- Crystal read-out by 2 custom SiPMs
- Work in vacuum and B = 1T

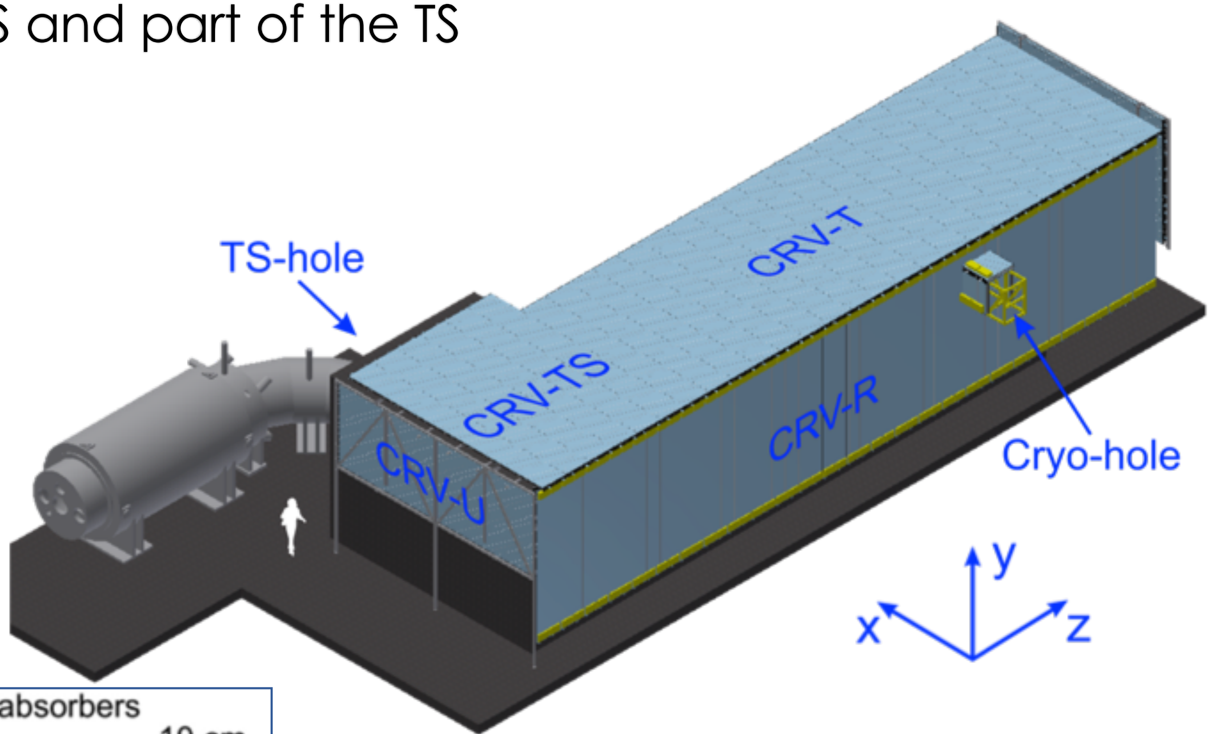
- Acceptance optimized to observe conversion electron Ee~105 MeV
- PID and e/μ discrimination
- Help the track reconstruction

Cosmic Ray Veto (CRV)

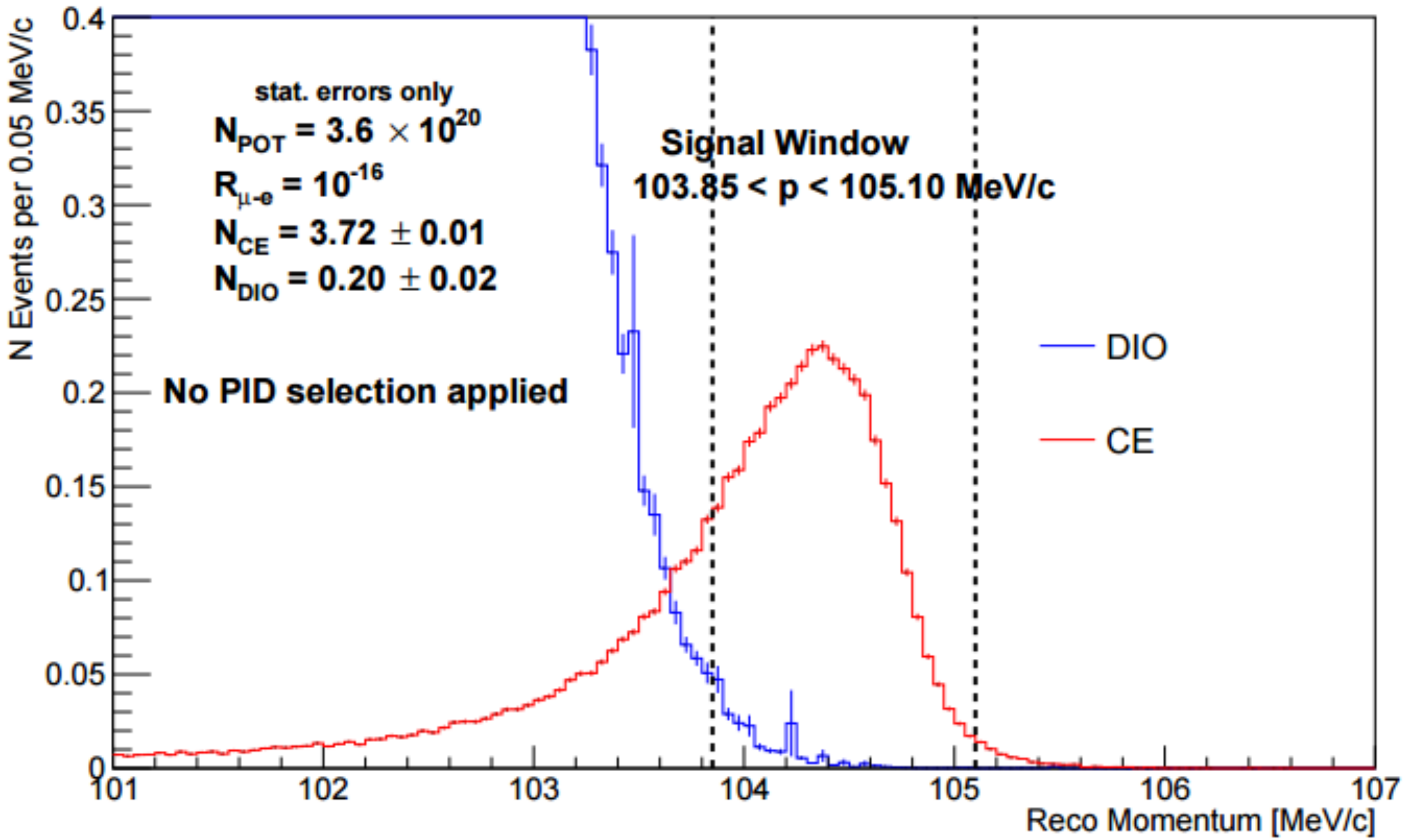
- CR are the major source of background (1 fake CE event per day)
- CRV composed of 4 layers of overlapping scintillator
- CRV is placed around the DS and part of the TS
- Required efficiency 0.9999







Mu2e expectation with full simulation



Discovery sensitivity accomplished with 3 year of running and background suppression to <0.4 event total

Conclusions

- The Mu2e experiment is a discovery experiment looking for the CLFV event of a coherent conversion of muon into electron in the electric field of a nucleus
- Mu2e will improve the sensitivity on conversion experiment of ~ 4 order of magnitude
- It provides discovery capabilities over a wide range on NP model
- Construction phase: 2017-2019
- Installation in 2020
- Commissioning phase will begin in 2021
- Start thinking about Mu2e-II →increase the intensity x10 and the sensitivity

SPARES

SUSY benchmark point

Process	SPS 1a CKM	SPS 1a $U_{e3}=0$	SPS 1b CKM	SPS 1b $U_{e3}=0$	SPS 2 CKM	SPS 2 $U_{e3}=0$	SPS 3 CKM	SPS 3 $U_{e3}=0$	Future Sensitivity
$BR(\mu \to e\gamma)$	$\mathbf{3.2 \cdot 10^{-14}}$	$\mathbf{3.8 \cdot 10^{-13}}$	$\mathbf{4.0 \cdot 10^{-13}}$	$\mathbf{1.2 \cdot 10^{-12}}$	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
$BR(\mu \to e\,e\,e)$	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
$CR(\mu \to e \text{ in Ti})$	*$2.0 \cdot 10^{-15}$*	*$2.4 \cdot 10^{-14}$*	*$2.6 \cdot 10^{-15}$*	*$7.6 \cdot 10^{-14}$*	*$1.0 \cdot 10^{-16}$*	*$6.7 \cdot 10^{-16}$*	*$1.0 \cdot 10^{-16}$*	*$8.4 \cdot 10^{-16}$*	$\mathcal{O}(10^{-18})$
$BR(\tau \to e\gamma)$	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
$BR(\tau \to e\,e\,e)$	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
$BR(\tau \to \mu\gamma)$	$5.0 \cdot 10^{-11}$	$\mathbf{1.1 \cdot 10^{-8}}$	$7.3 \cdot 10^{-11}$	$\mathbf{1.3 \cdot 10^{-8}}$	$2.9 \cdot 10^{-12}$	*$7.8 \cdot 10^{-10}$*	$2.7 \cdot 10^{-12}$	*$6.0 \cdot 10^{-10}$*	$\mathcal{O}(10^{-9})$
$BR(\tau \to \mu\,\mu\,\mu)$	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

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

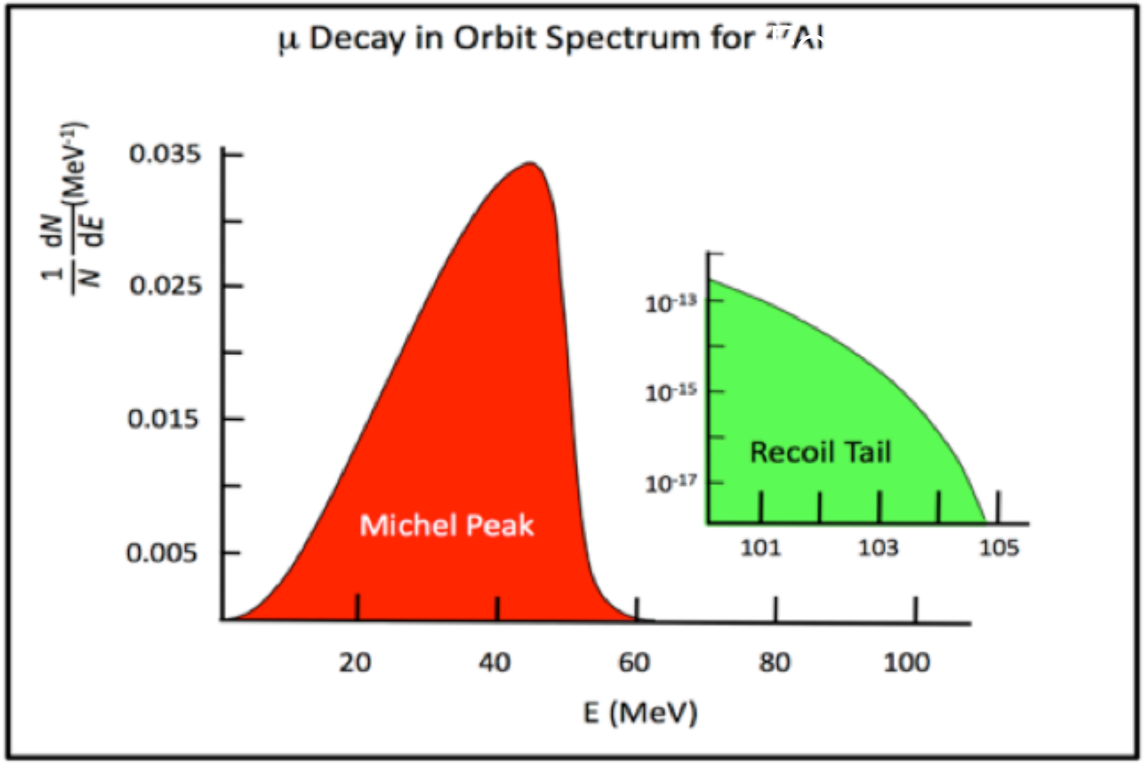
Background for Mu2e

- Intrinsic physics background:
  - Muon Decay in Orbit (DIO)→ end point @ signal energy
  - Radiative Muon Capture →πN → γN'; γ→e^+e^-
  - Neutron from muon nuclear capture
  - Proton from muon nuclear capture
- Beam related backgrounds:
  - Radiative Pion Capture (RPC)
  - Beam electron
  - Muon decay in flight
  - Neutron
  - Antiprotons producing pions when annihilating in the target
- Cosmic rays

DIO background

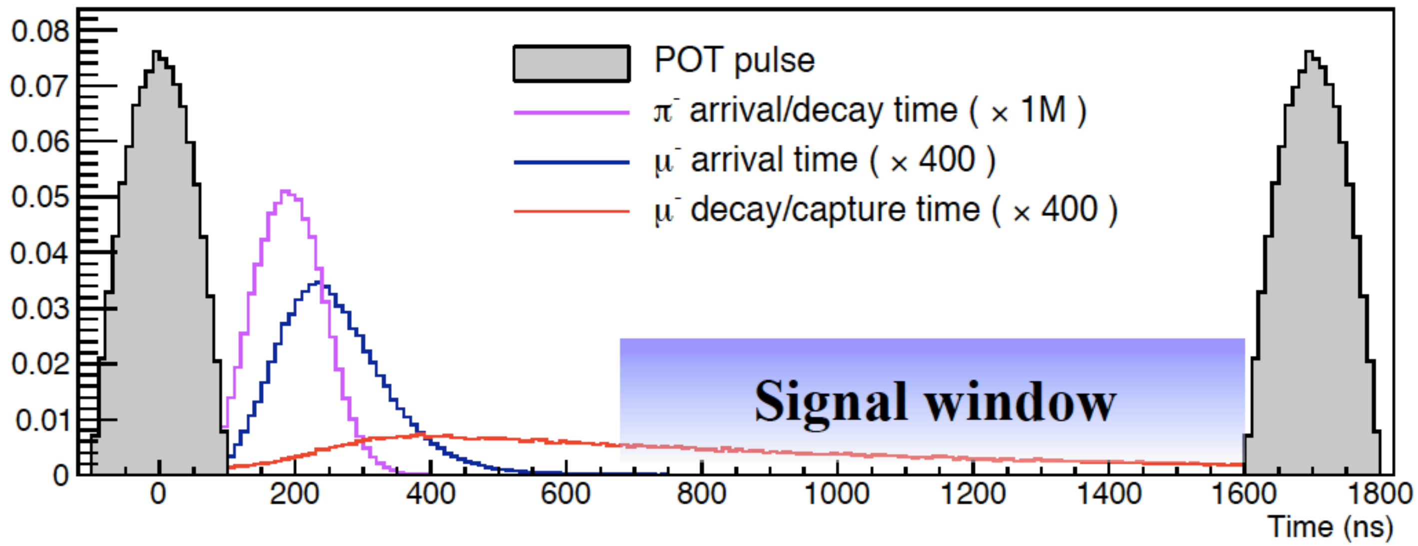
- Electron energy distribution from the decay of bound muons follows a modified-Michel spectrum:
- The Michel spectrum is distorted by the presence of the nucleus and the electron can have an energy similar to the one of CE if neutrino are almost at rest

→ **To separate DIO endpoint from CE line Mu2e needs an high Resolution Spectrometer**



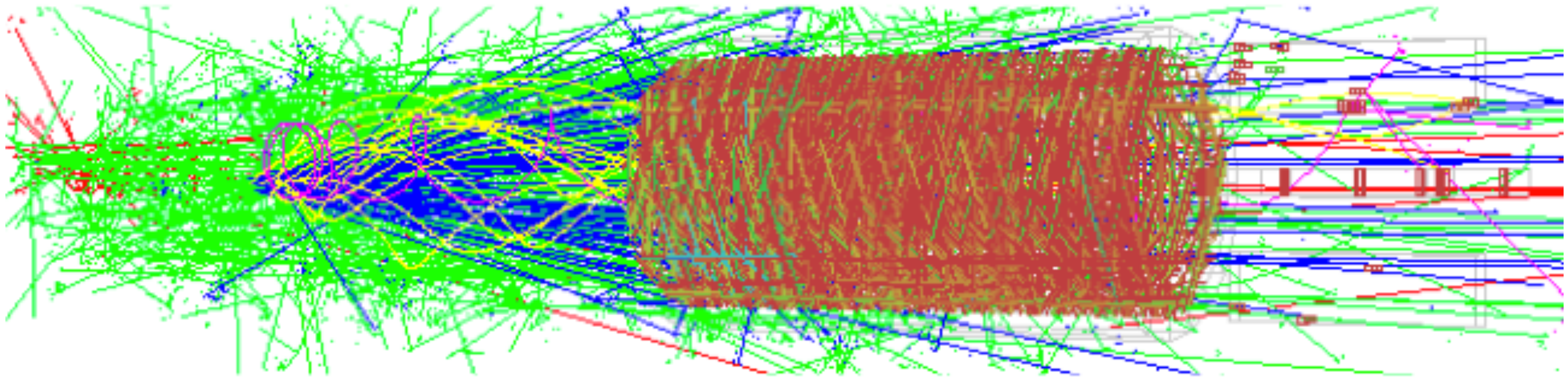
Minimizing prompt background

- Prompt backgrounds arise from the interaction occurring at the stopping target
  - Radiative Pion Capture (τ_{π}^{Al} = 26 ns) $\pi^- N \to \gamma N^* \to e^+ e^- N^*$
  - π/μ decay in flight
- **Muonic atomic life>> prompt background**
- Narrow pulsed proton beam
- Delayed signal window starting 700 ns after the initial proton pulse
- Out-of-time proton suppressed by $O(10^{10})$

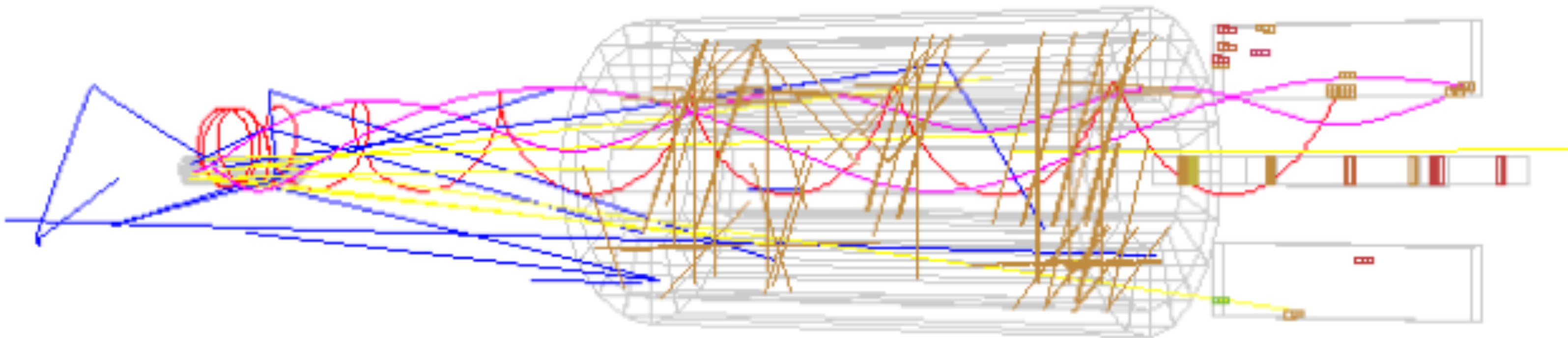


A typical Mu2e event: calo track seeding

500 -1695 ns windows

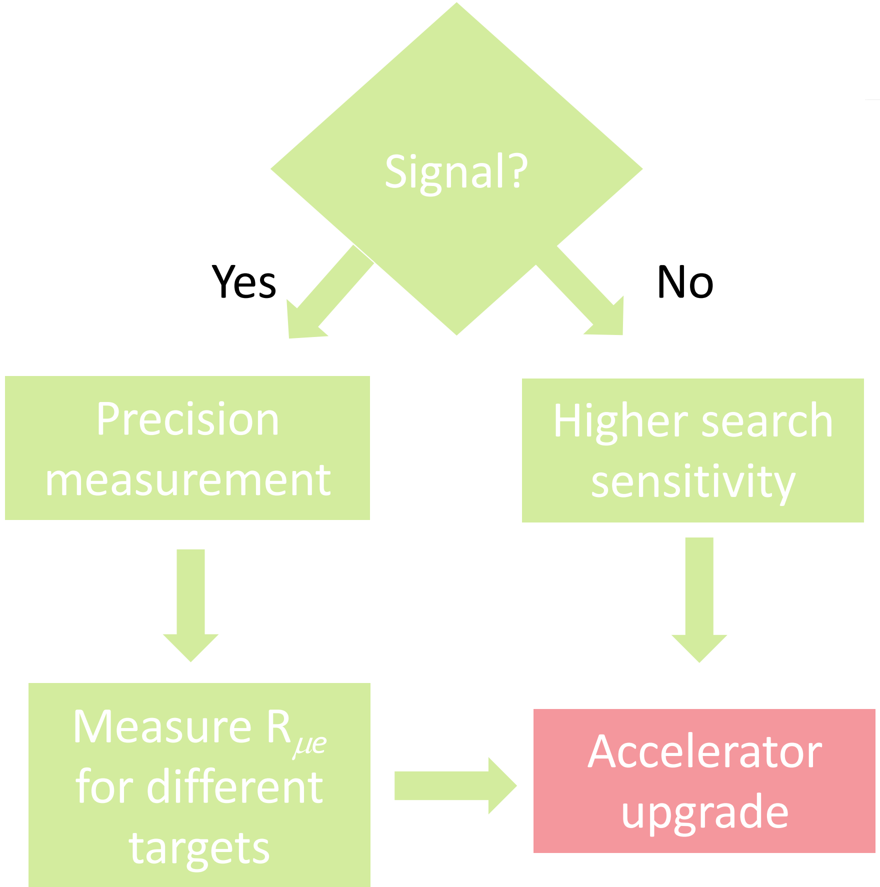


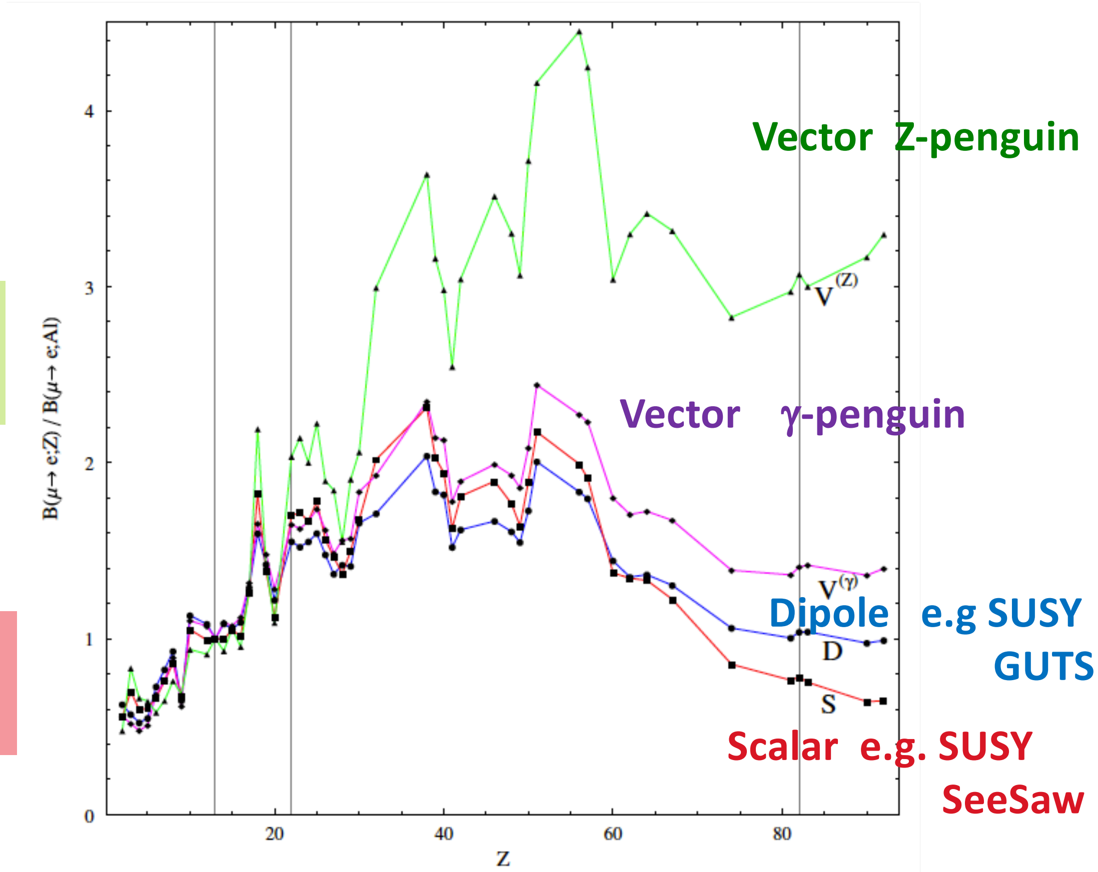
± 50 ns around conversion electron



- Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters ($|\Delta T| < 50$ ns) → **simpler pattern recognition**

What’s next





Cirigliano, *et al*, PRD **80**, 013002 (2009)