The Mu2e experiment at Fermilab: design and status

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On behalf of the Mu2e collaboration

Les Rencontres de Physique de la Vallée d'Aoste

La Thuile, March 5-11, 2017

ROMA TRE UNIVERSITÀ DEGLI STUDI

Fermilab

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

The Mu2e Collaboration

~230 Scientists from 37 Institutions

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 of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, University of Illinois, INFN Genova, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Institute for High Energy Physics Protvino, Kansas State University, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Minnesota, Muons Inc., Northwestern University, Institute for Nuclear Research Moscow, Northern Illinois University, INFN Pisa, Purdue University, Novosibirsk State University/Budker Institute of Nuclear Physics, Rice University, University of South Alabama, University of Virginia, University of Washington, Yale University

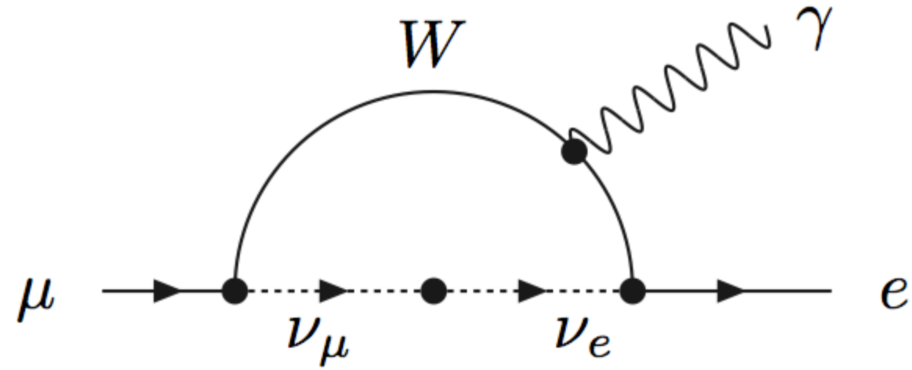
Talk overview

- Charged Lepton Flavor Violation (CLFV)
  - BSM
  - CLFV – Muon sector
  - History
- Muon Conversion
  - Measurement Technique
- Mu2e
  - Goal
  - Design
  - Detectors
- Summary

CLFV

With neutrino mass, we know that lepton flavor is not conserved

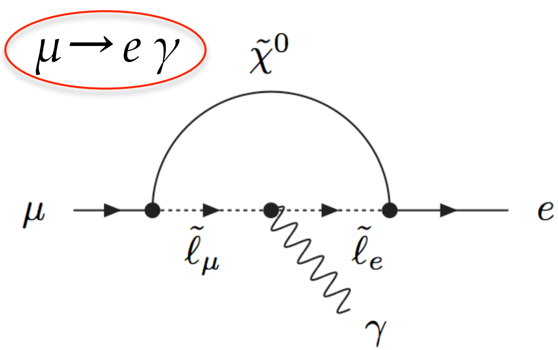
The SM CLFV process would be strongly suppressed:

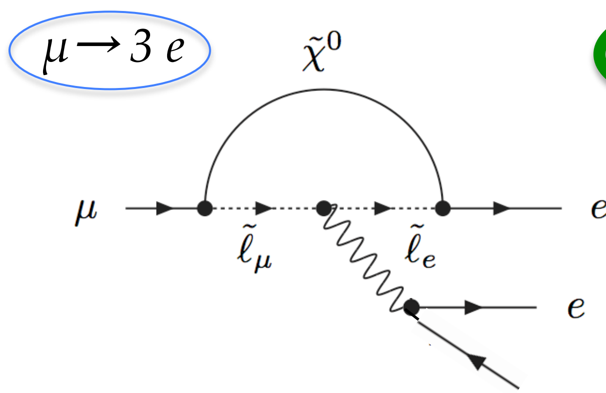


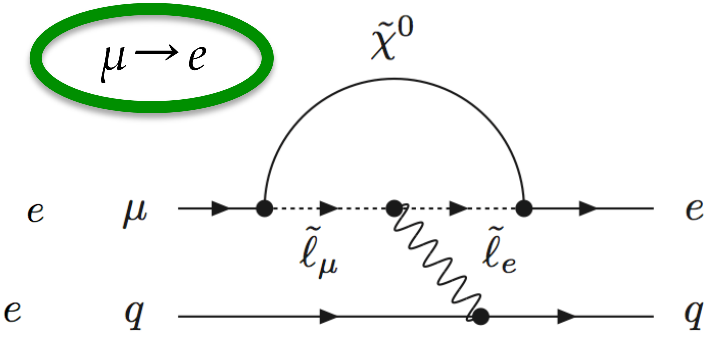
$$\mathcal{B}\left(\mu \to e\gamma\right) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \boxed{\frac{\Delta m^2_{1i}}{M^2_W}}\right|^2 < 10^{-54}$$

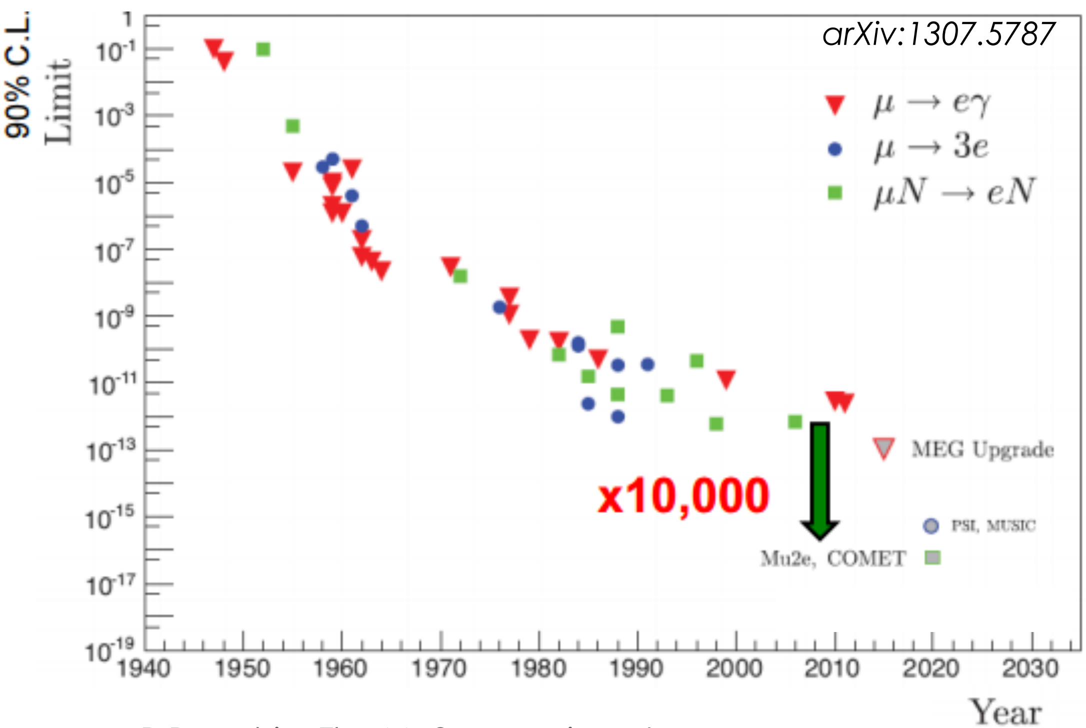
Any observation of CLFV would be new physics Beyond the Standard Model (BSM)!

Muon CLFV history









Current best limits:

$BR(\mu \to e\,\gamma) < 5.7 \times 10^{-13}$ MEG2013

$BR(\mu \to 3e) < 1 \times 10^{-12}$ SINDRUM1988

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

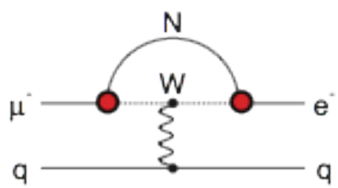
$\boldsymbol{R_{\mu e} = \text{few} \times 10^{-17}}$ **Mu2e goal**

Muon CLFV - BSM

Loop

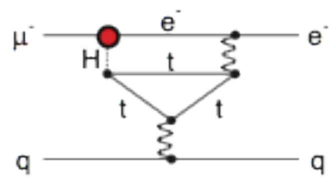
Heavy Neutrinos

$|U_{\mu N} U_{eN}|^2 \sim 8 \times 10^{-13}$



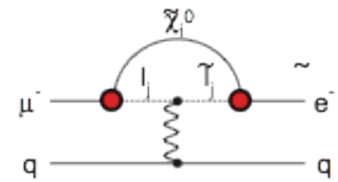
Second Higgs Doublet

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



Supersymmetry

rate ~ 10^{-15}

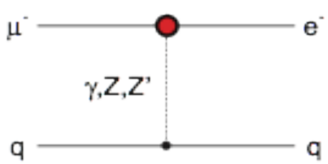


Models which can be probed also by $\mu \rightarrow e\gamma$ *searches*

Contact term

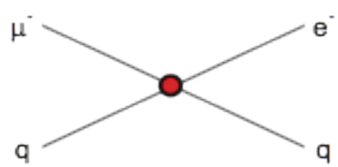
Heavy Z' Anomal. Z Coupling

$M_{Z'} = 3000\ \mathrm{TeV}/c^2$



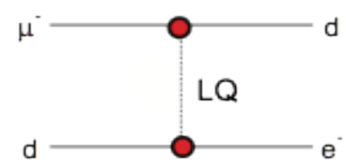
Compositeness

$\Lambda_c \sim 3000$ TeV



Leptoquark

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



Direct coupling between quarks and leptons, better accessed by $\mu N \rightarrow eN$

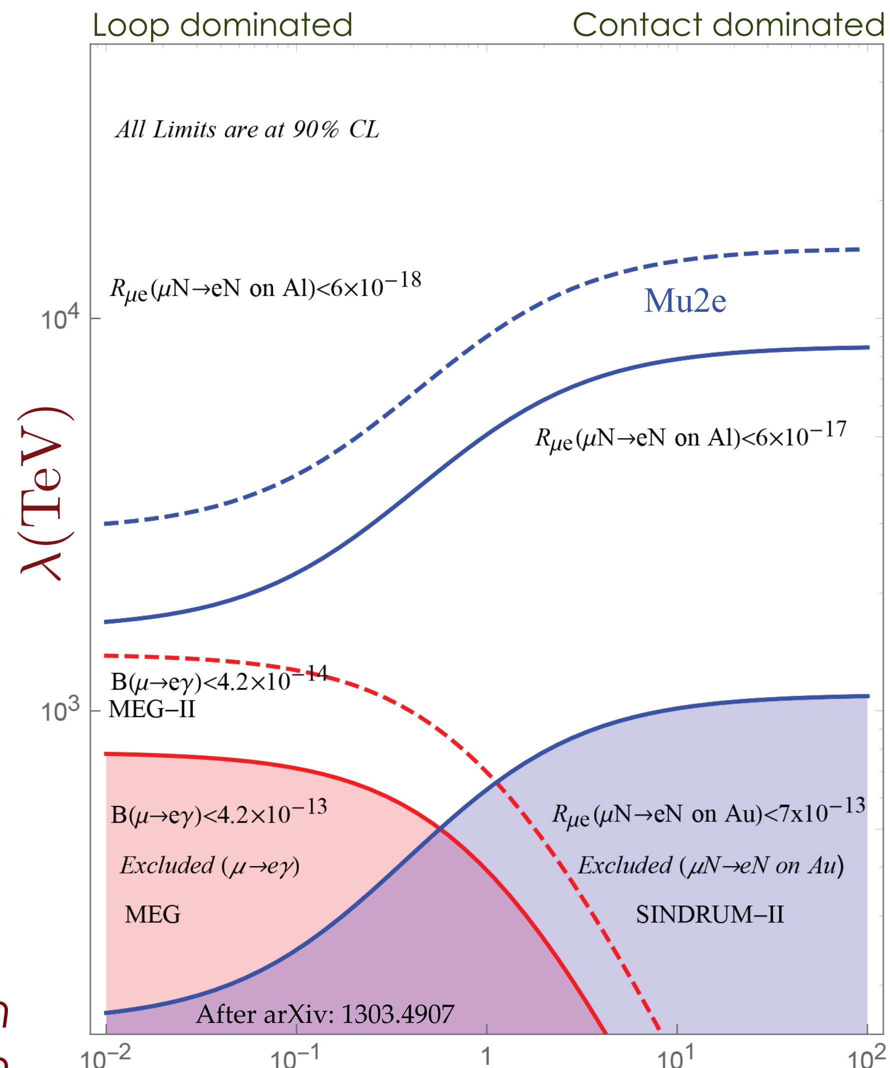
also see *Flavour physics of leptons and dipole moments*, arXiv:0801.1826;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126

Probe mass scales λ 2000~10000 TeV, significantly above the direct reach of LHC

Why muon conversion is unique?

Muon conversion is an unique probe for BSM:

- Broad discovery sensitivity across all models
- Sensitivity to λ (mass scale) up to thousands of TeV
- Clear experimental signature Neutrinoless and mono-energetic electron
  E_e = 104.97 MeV



Interpolation factor between contact and loop interaction κ

Mu2e goal

- Measure the ratio of μ - e conversions to conventional muon captures

μ-e conversion in the presence of a nucleus

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

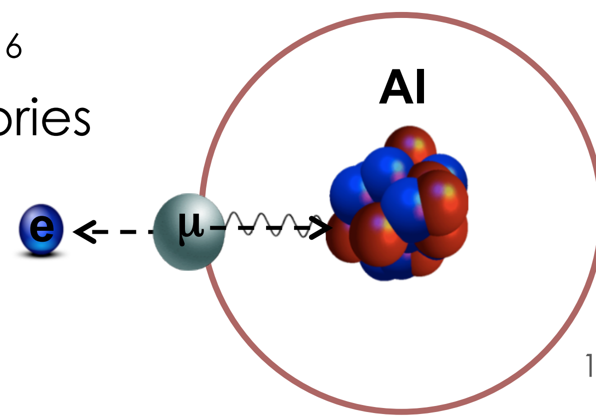
Nuclear captures of muonic Al atoms

- And set an upper limit:

$R_{\mu e}$ < 6 x 10^{-17} (@ 90% CL, with ~ 10^{18} stopped muons in 3 years of running)

- Discovery sensitivity: all $R_{\mu e}$ > few x 10^{-16}

Covers broad range of new physics theories



Measurement technique

1. Generate low momentum μ^- beam
2. Stop the muons in an Al target → trapped in orbit around the nucleus
3. Look for an excess around 104.97 MeV/c in the electron spectrum

Main Backgrounds

- Muon decay in orbit (DIO)

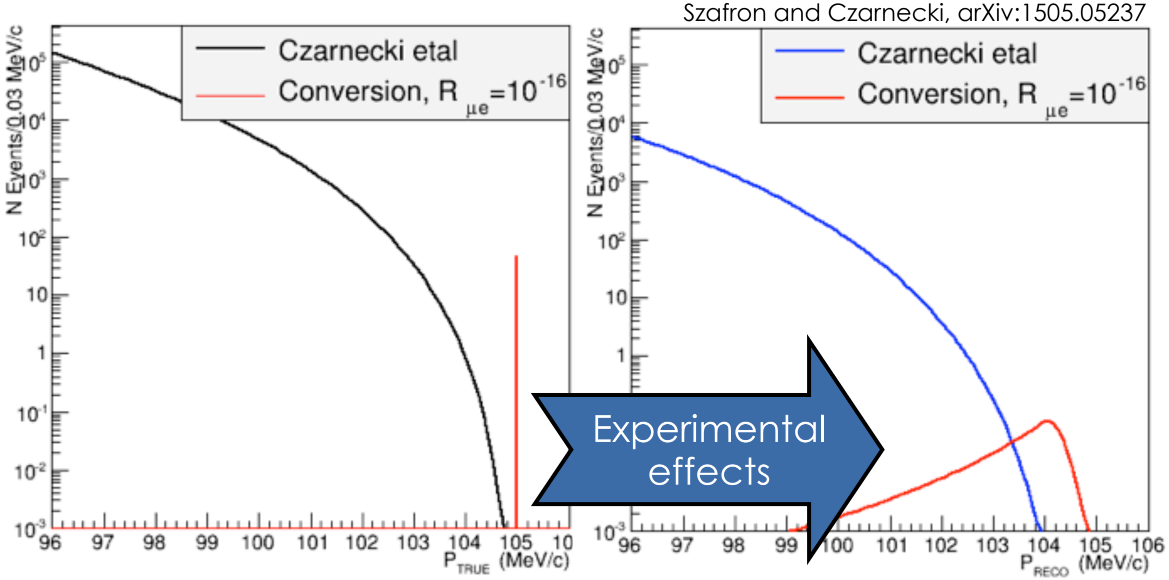
$$\mu^- + Al \rightarrow e^- + \overline{v}_e + v_\mu + Al$$

- Radiative μ / π capture

$$\mu^- + Al \rightarrow v_\mu + \gamma + Mg$$
$$\pi^- N \rightarrow \gamma N^*, \gamma \rightarrow e^+ e^-$$
$$\pi^- N \rightarrow e^+ e^- N^*$$

- π / μ decay in flight
- Antiproton annihilation
- Electrons from beam, cosmic rays

Szafron and Czarnecki, arXiv:1505.05237



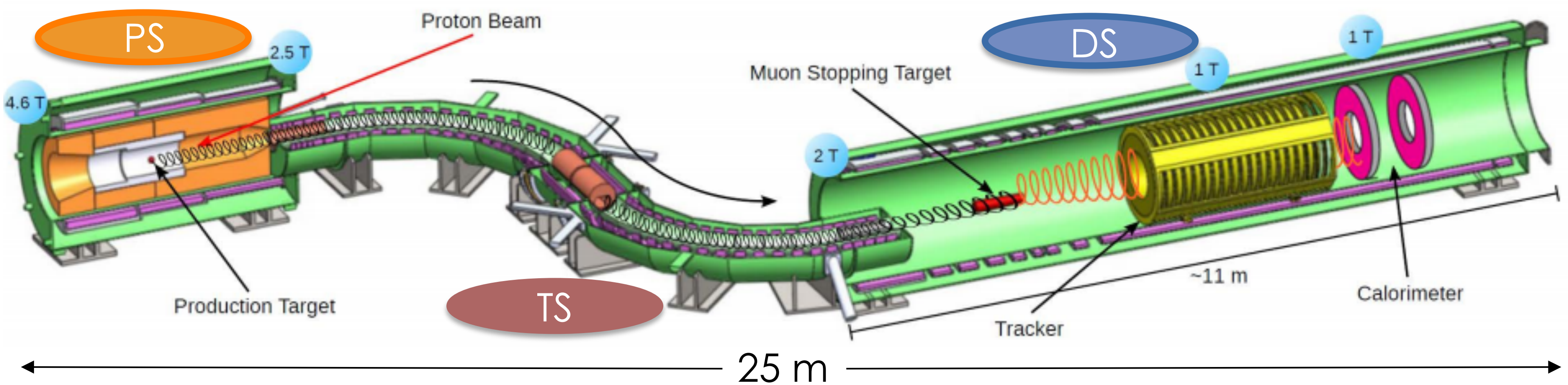
Mu2e design

Production Solenoid / Target

- Protons hitting target and producing mostly π
- Solenoid reflects slow forward μ / π and contains backward μ / π

Transport Solenoid

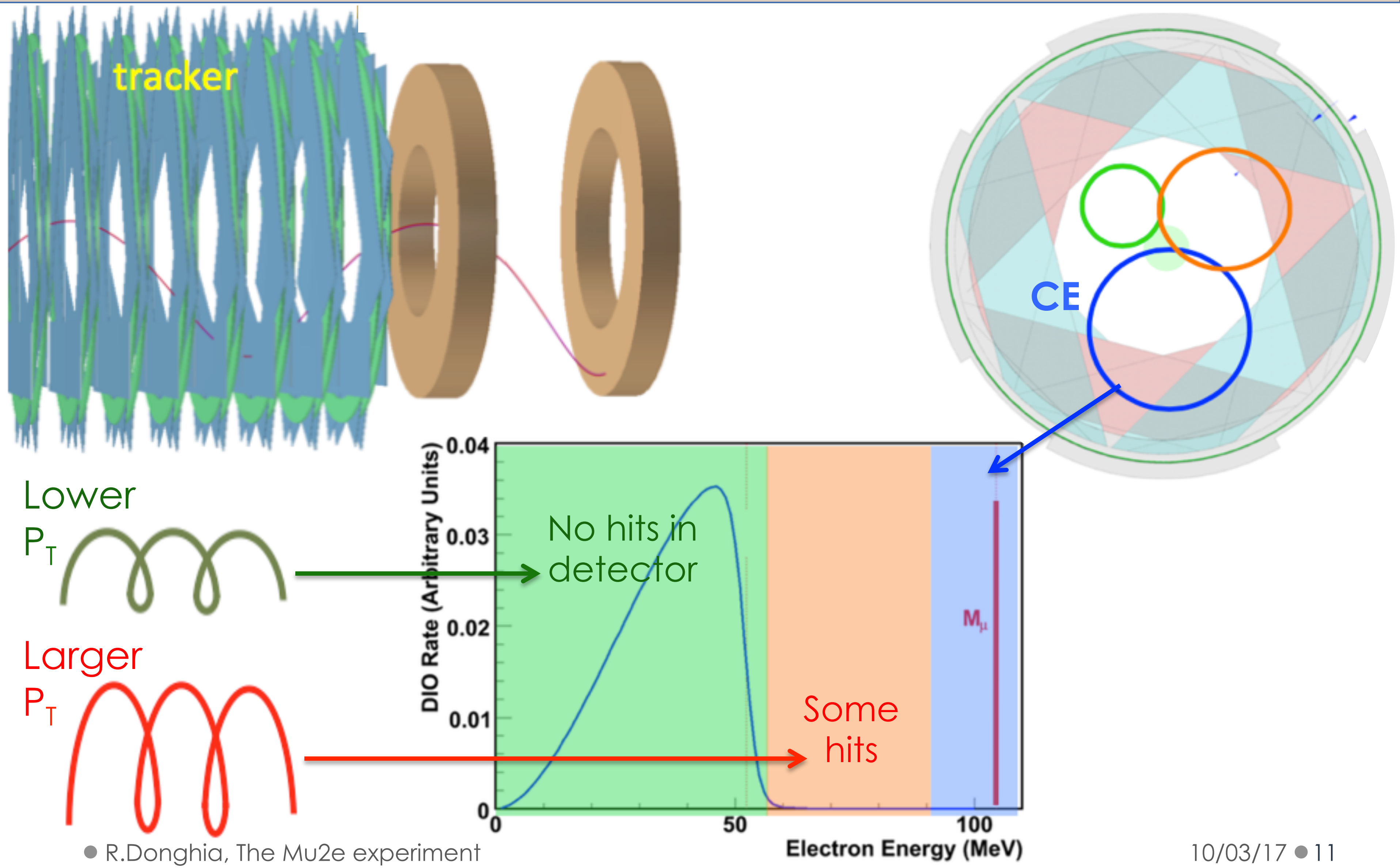
- Selects and transports low momentum μ^-



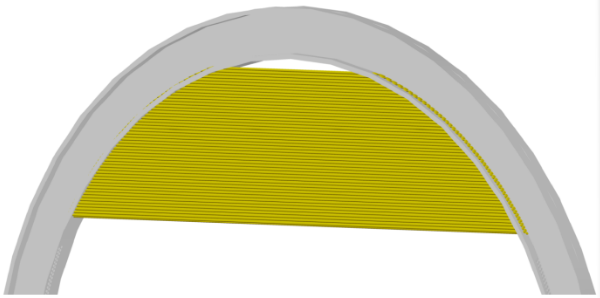
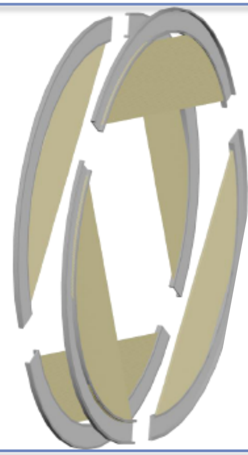
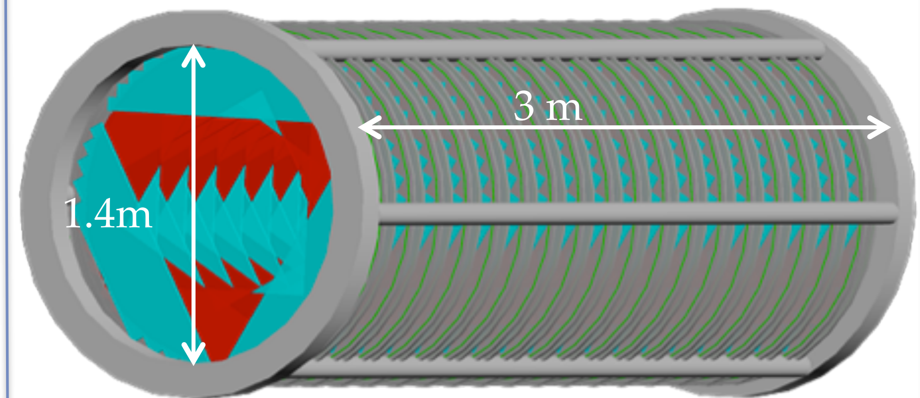
Detector Solenoid: stopping target and detectors

- Stops μ^- on Al foils (decay time ~ 864 ns)
- Events reconstructed by detectors, optimized for 105 MeV momentum

Detectors


tracker
CE
Lower
P_T
Larger
P_T
No hits in detector
Some hits
0.04
0.03
0.02
0.01
0
DIO Rate (Arbitrary Units)
0
50
100
Electron Energy (MeV)
M_μ

Straw Tracker

Straw tubes on a panel	One station	Tracker Structure
		

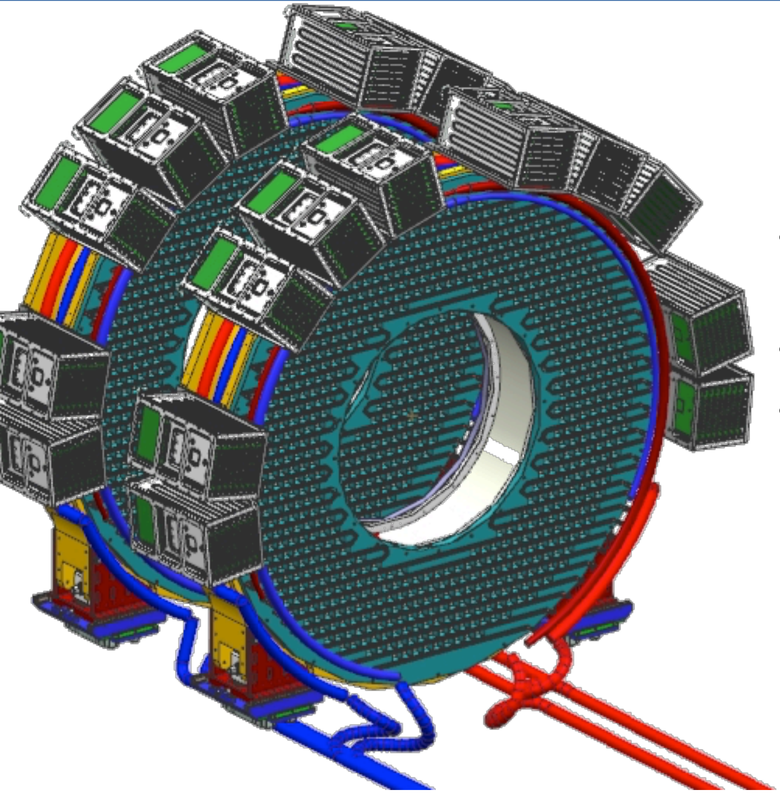
- ~ 20000 straw drift tubes, divided in 18 stations, 2 planes/station
- Each straw is 5 mm diameter, with 25 μm sense wire, 15 μm thick mylar walls
- 3 m long, 1.4 m diameter, in a uniform 1 T magnetic field

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

Timing resolution ~ 1 ns

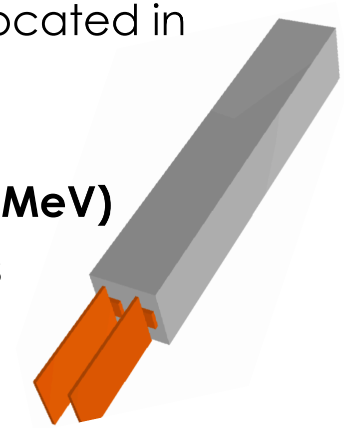
Spatial resolution ~ 100 μm

EM Calorimeter



2 annular disks with 674 CsI (30x30x200) mm^3 square crystals each

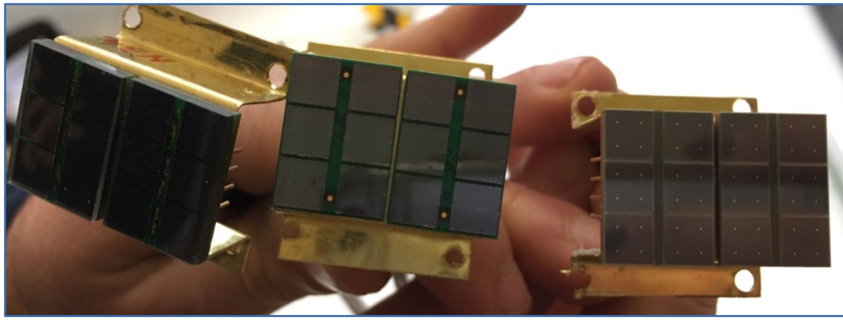
- R_{IN} = 374 mm, R_{OUT} = 660 mm
  Depth = 10 X_0 (200 mm), Distance 70 cm
- Readout: 2 UV-extended SiPMs/crystal
- Analog FEE and digital electronics located in near-by electronics crates



Energy resolution < 5% (@ 100 MeV)

Timing resolution < 0.5 ns

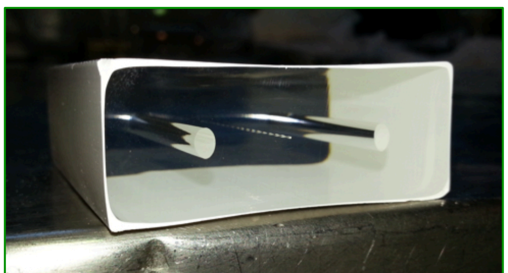
Spatial resolution < 1 cm

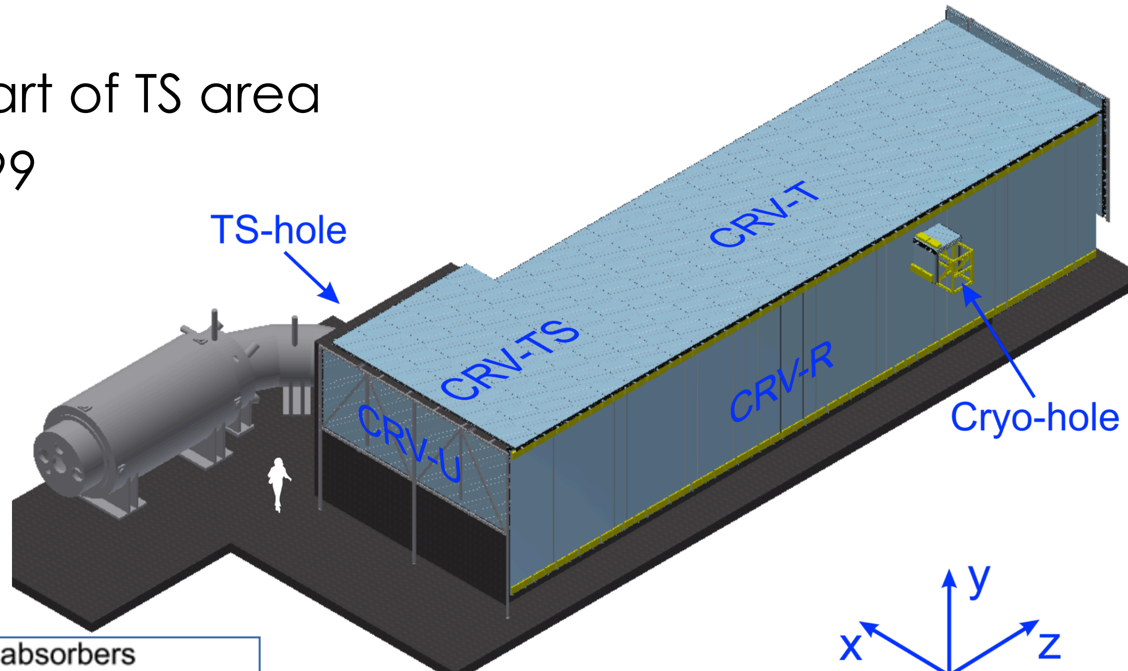


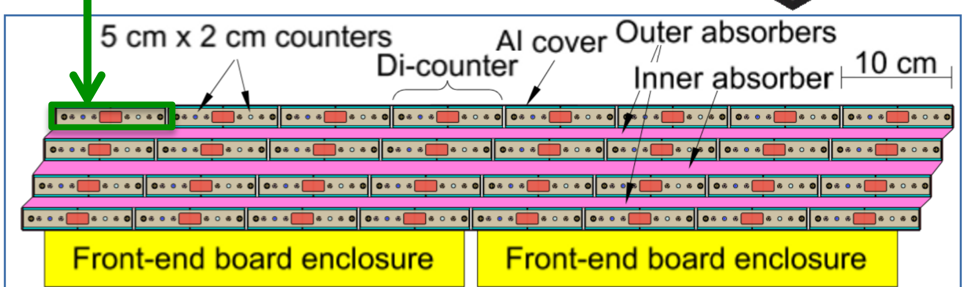
Cosmic Ray Veto

Cosmic Rays are a major sources of background → CRV required

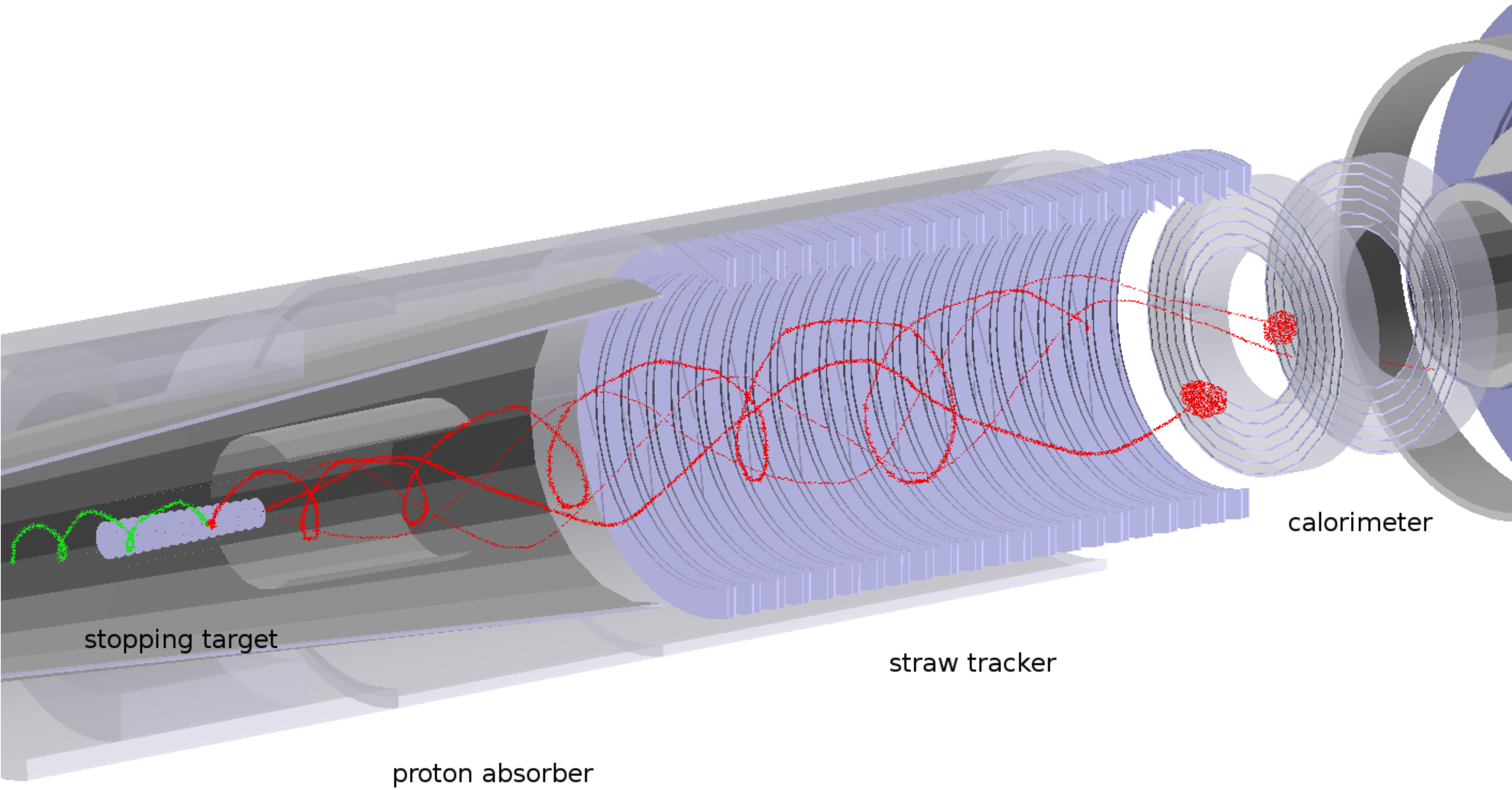
- Composed of 4 layers of overlapping scintillators (a coincidence of 3 out of 4 is used)
- Placed around DS and part of TS area
- Required efficiency: 0.9999





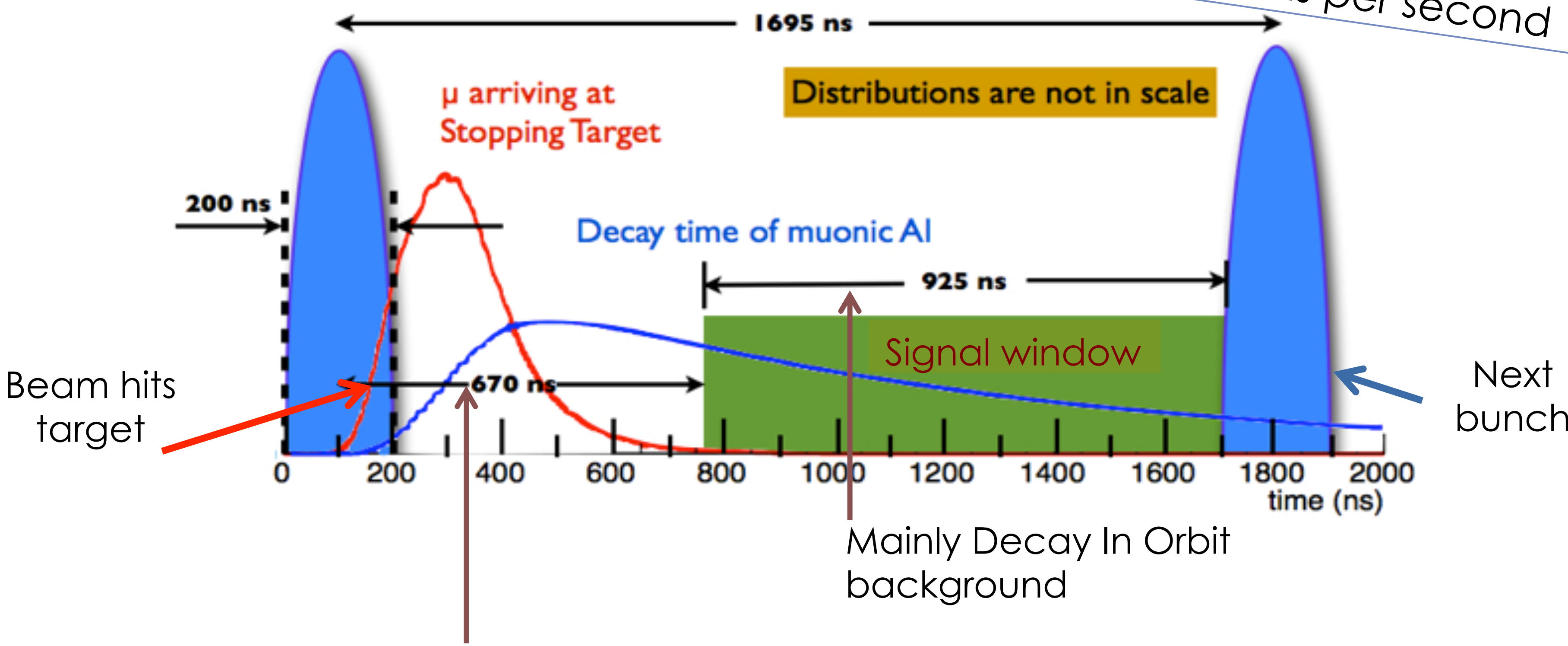


Conversion electron trajectory



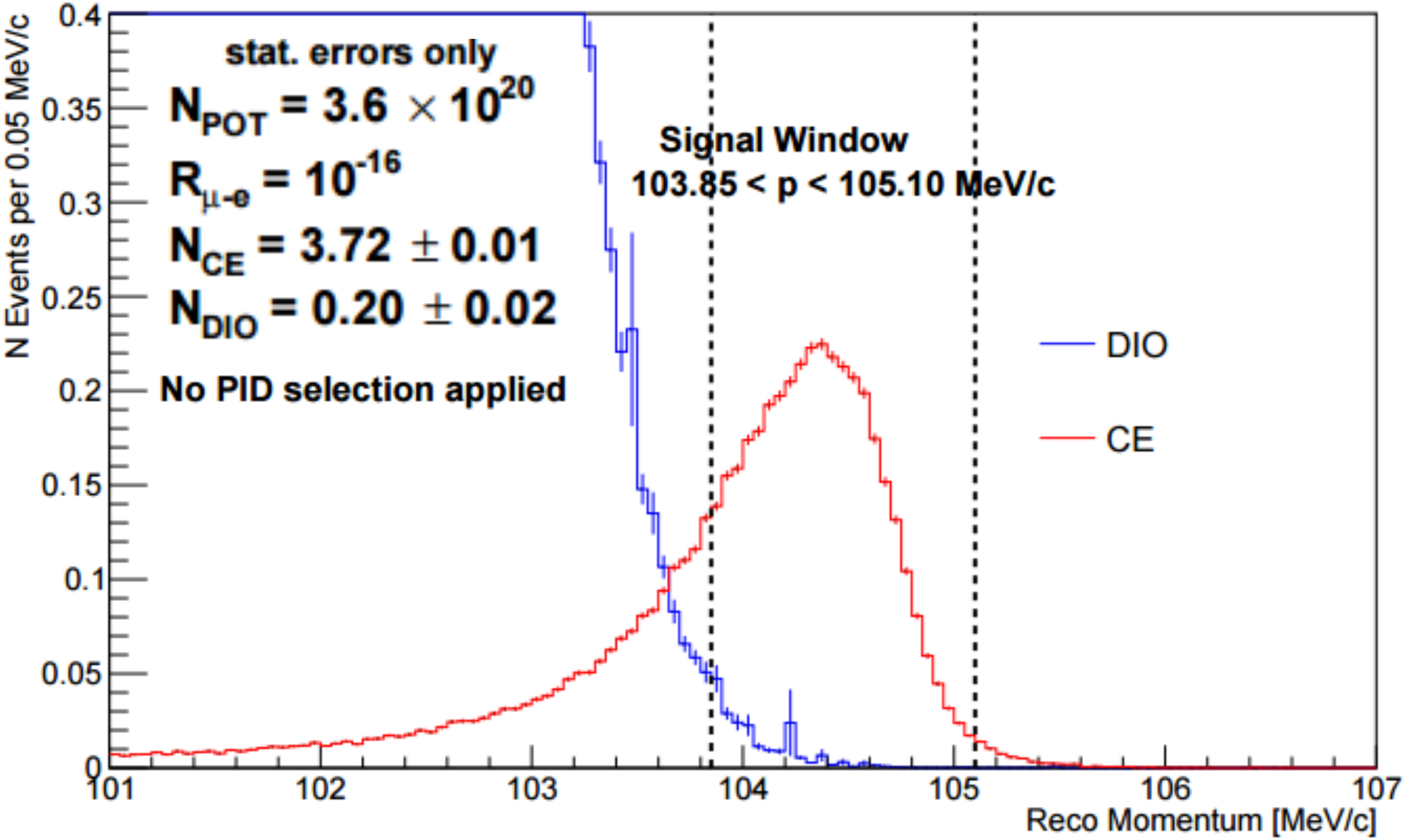
Signal window

~20,000 muons per bunch
10^{10} muons per second



Prompt bkg: almost all protons, unstopped muons, stopped and unstopped pions will arrive at the detector before observation window

Three years run
Expectation by full Simulation



Possible upgrade

Signal?

Yes

Let's party!

Change the target to study the underlying NP

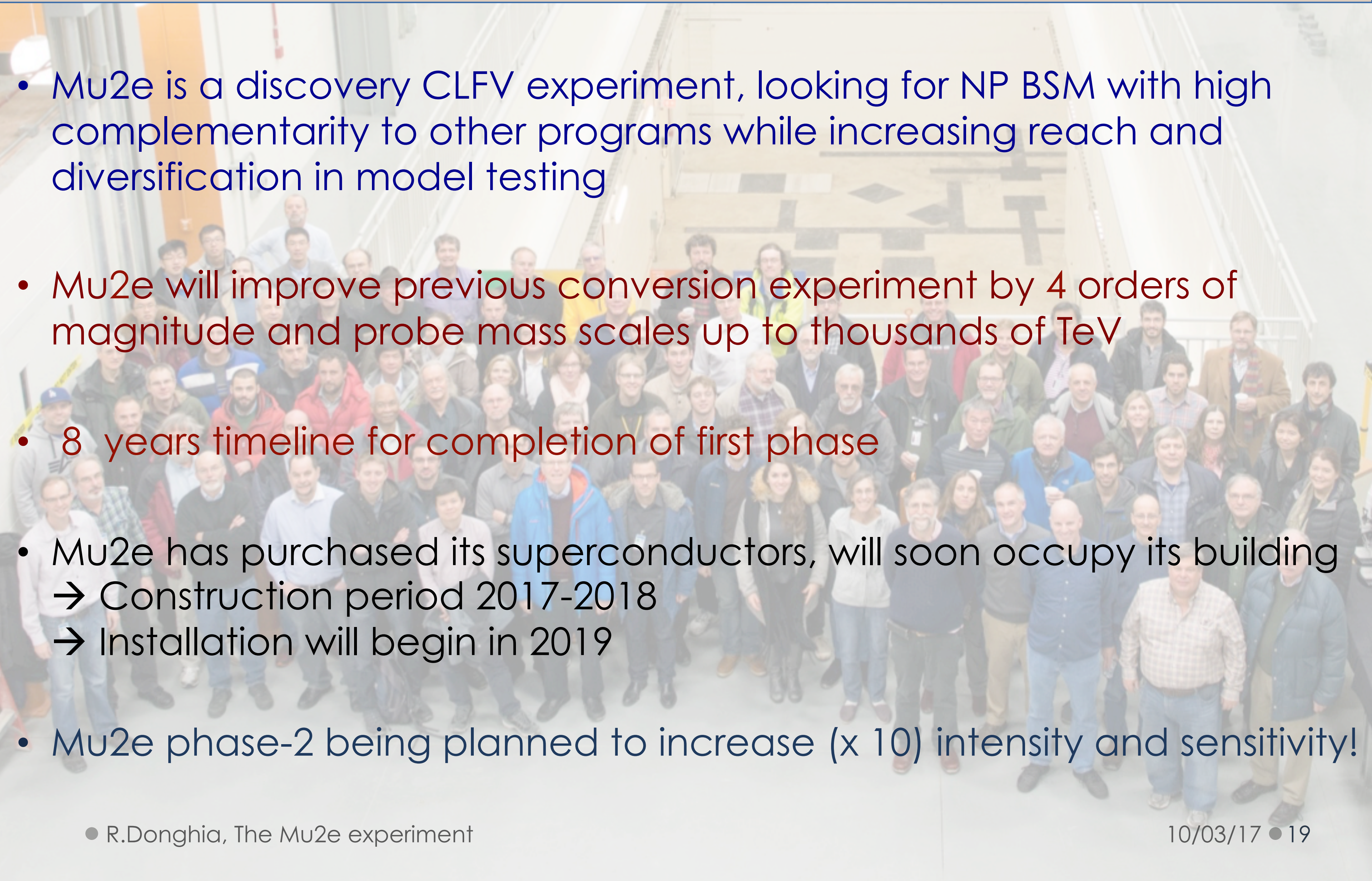
Upgrade proton source and detector to achieve precision

No

Higher rates, background must decrease to measure $R_{\mu e}$ at 10^{-18}

Upgrade proton source and detector to improve sensitivity

Conclusion



- Mu2e is a discovery CLFV experiment, looking for NP BSM with high complementarity to other programs while increasing reach and diversification in model testing

- Mu2e will improve previous conversion experiment by 4 orders of magnitude and probe mass scales up to thousands of TeV

- 8 years timeline for completion of first phase

- Mu2e has purchased its superconductors, will soon occupy its building
  → Construction period 2017-2018
  → Installation will begin in 2019

- Mu2e phase-2 being planned to increase (x 10) intensity and sensitivity!

Spares

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