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

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

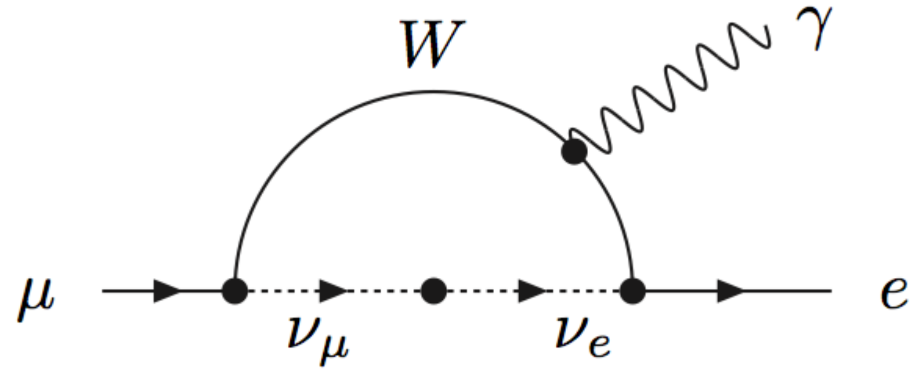
Talk overview

- 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

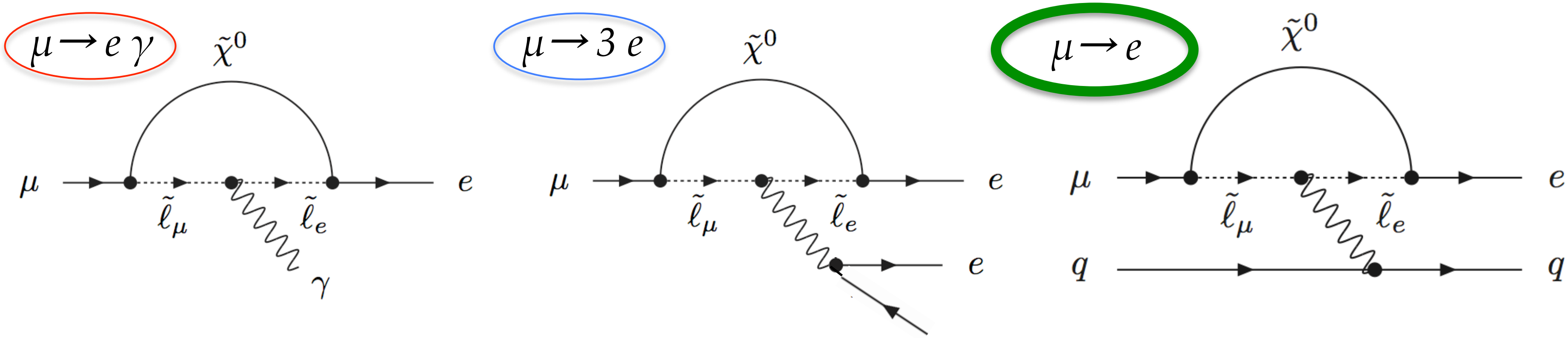
The SM CLFV process would be strongly suppressed:

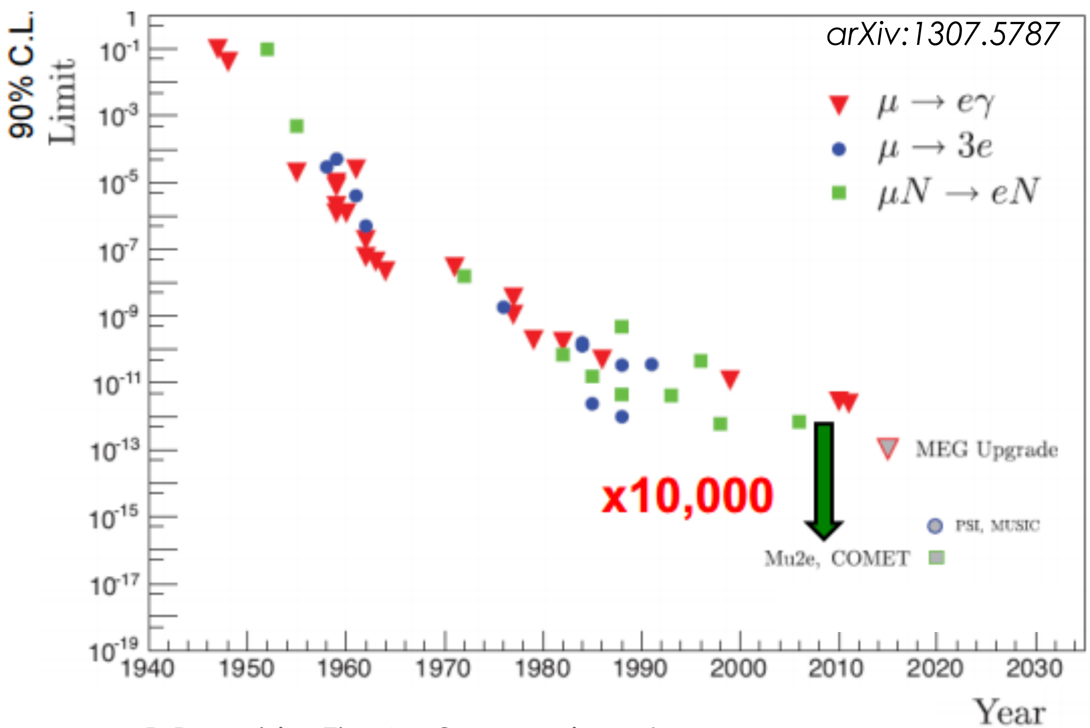


$$\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \boxed{\frac{\Delta m^2_{1i}}{M^2_W}}\right|^2 < 10^{-54}$$

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

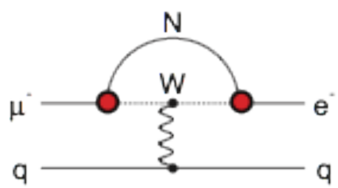
$R_{\mu e}$ = few $\times 10^{-17}$ Mu2e goal

Muon CLFV - BSM

Loop

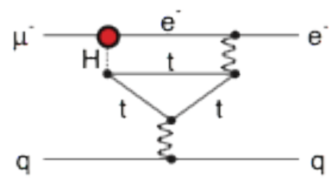
Heavy Neutrinos

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



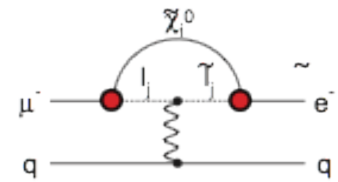
Second Higgs Doublet

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



Supersymmetry

rate ~ 10^{-15}

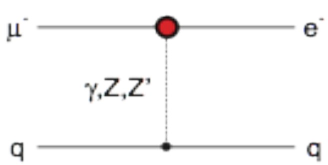


Models which can be probed also by $\mu \to e\gamma$ *searches*

Contact term

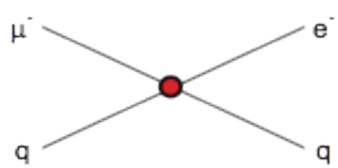
Heavy Z' Anomal. Z Coupling

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



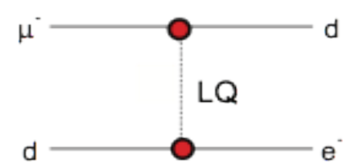
Compositeness

$\Lambda_c \sim 3000$ 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 $\mu N \to eN$

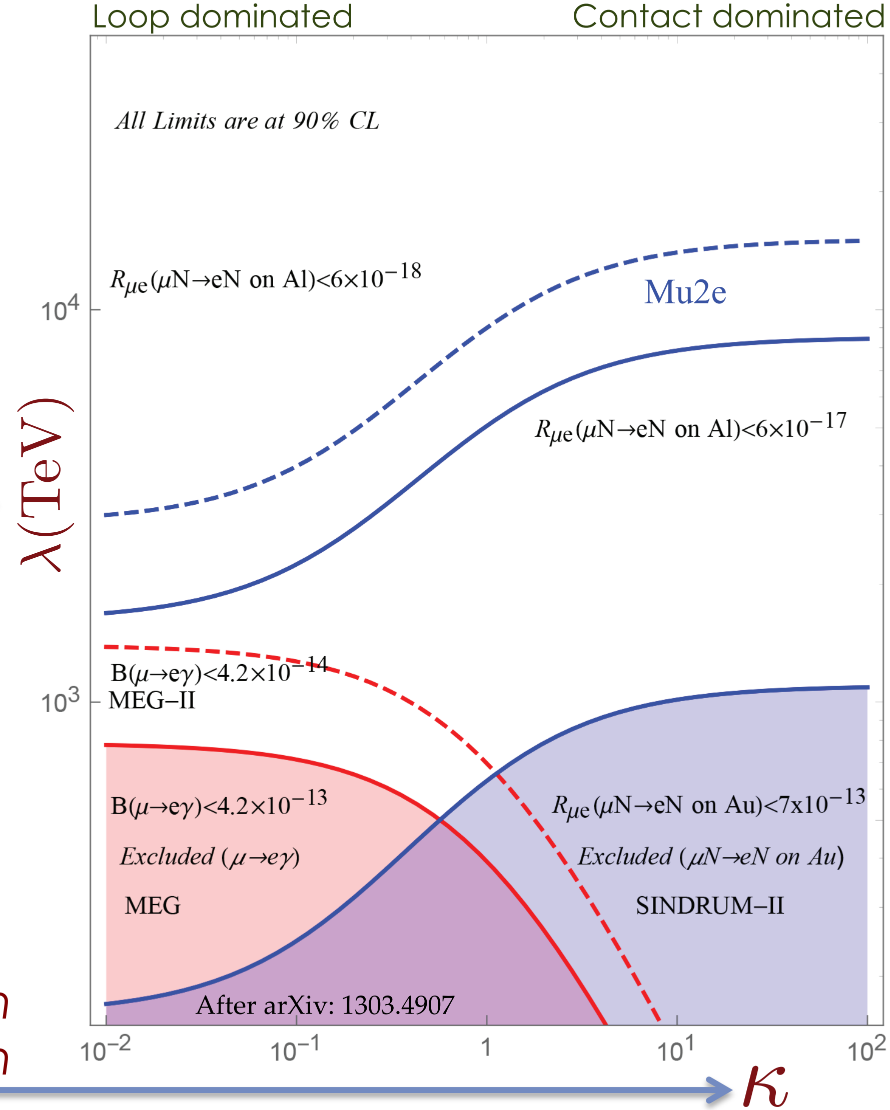
also see *Flavour physics of leptons and dipole moments*, arXiv:0801.1826; Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126

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

Mu2e goal

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

μ-e conversion in the presence of a nucleus

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

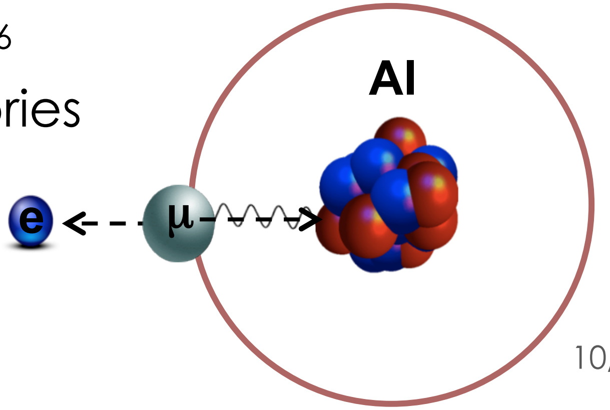
Nuclear captures of muonic Al atoms

- 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)

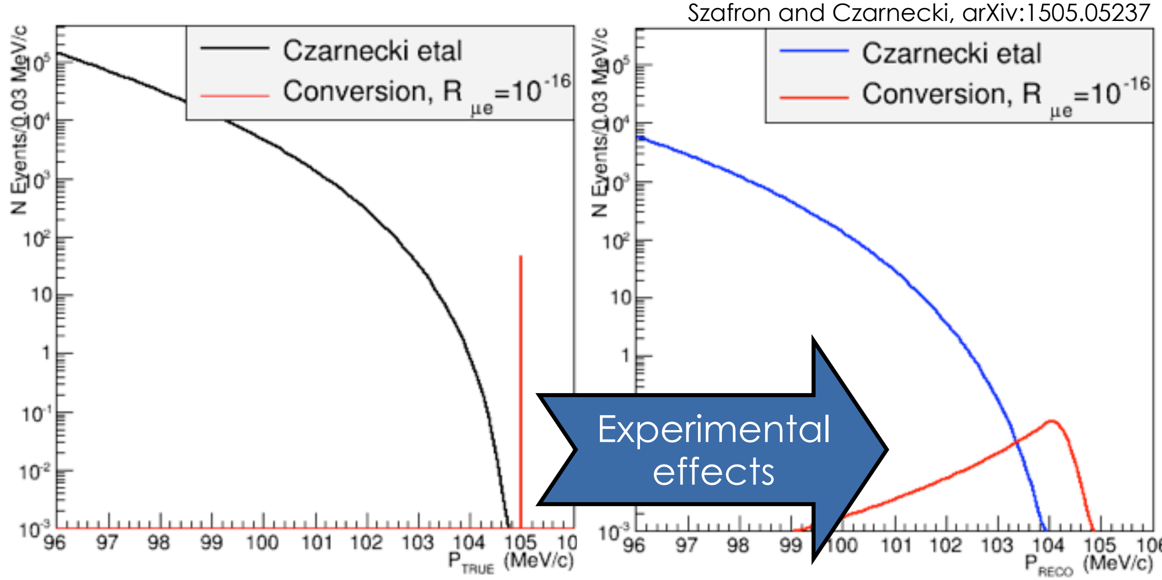
  $$\mu^- + Al \rightarrow e^- + \overline{\nu}_e + \upsilon_\mu + Al$$

- Radiative μ / π capture

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

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

Szafron and Czarnecki, arXiv:1505.05237



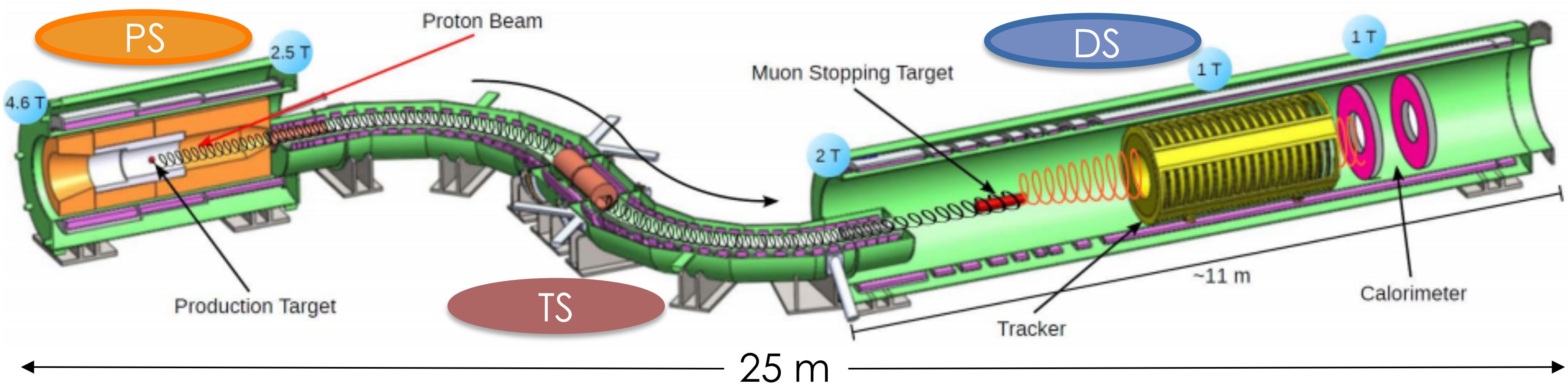
Mu2e design

Production Solenoid / Target

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

Transport Solenoid

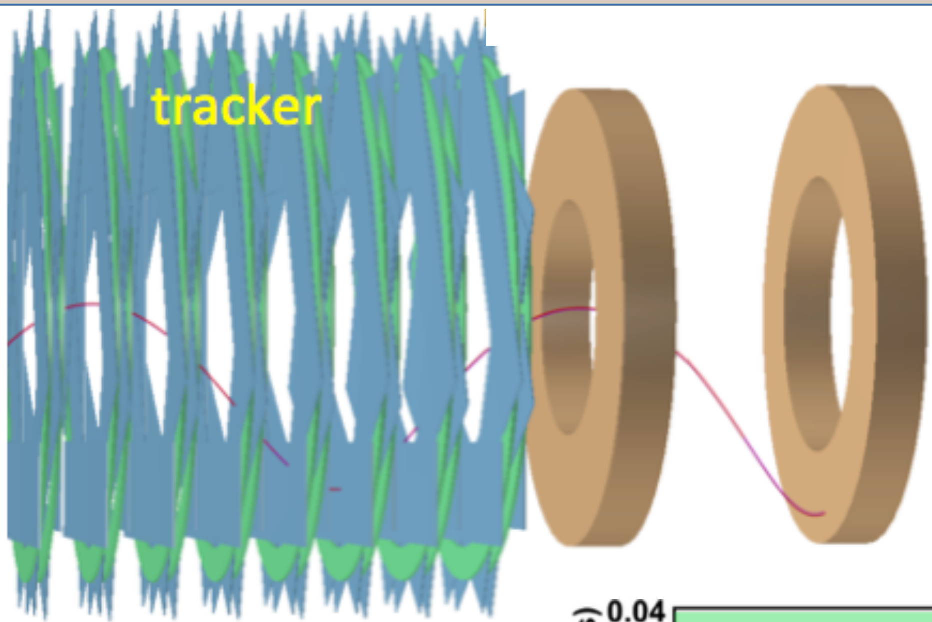
- Selects and transports low momentum μ^-

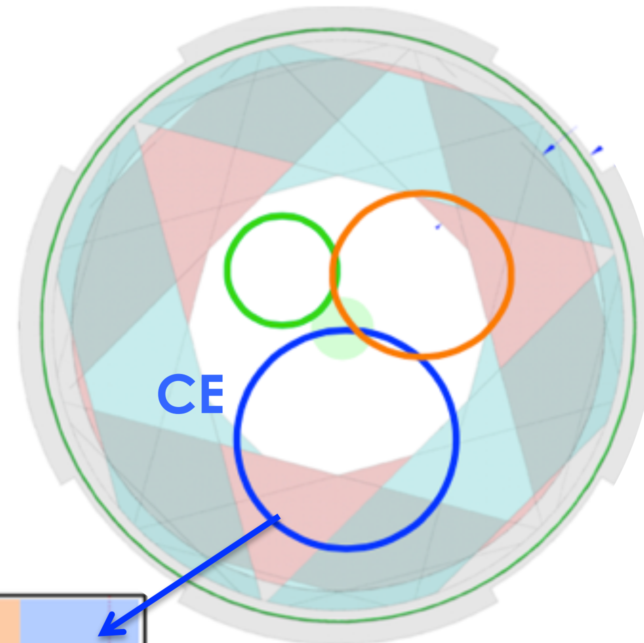


Detector Solenoid: stopping target and detectors

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

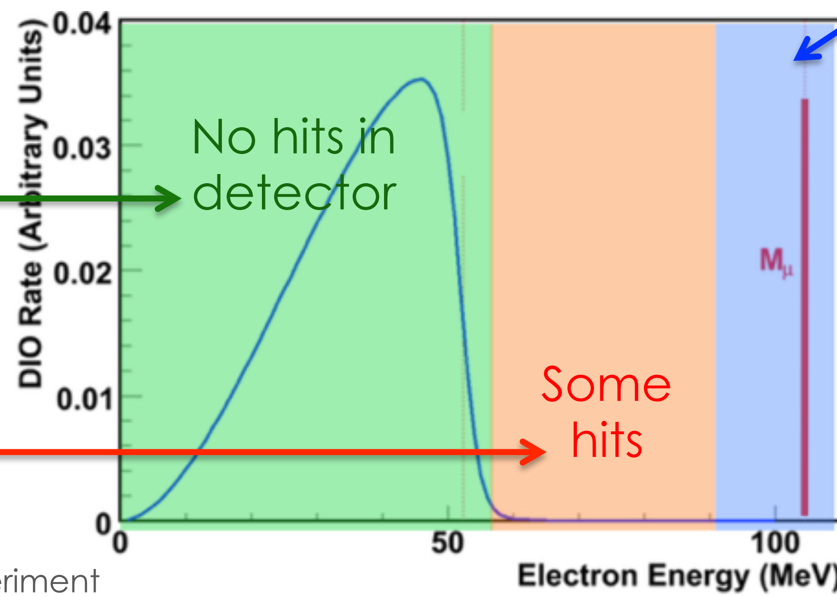
Detectors



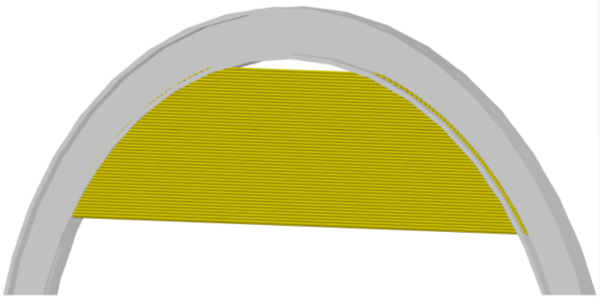
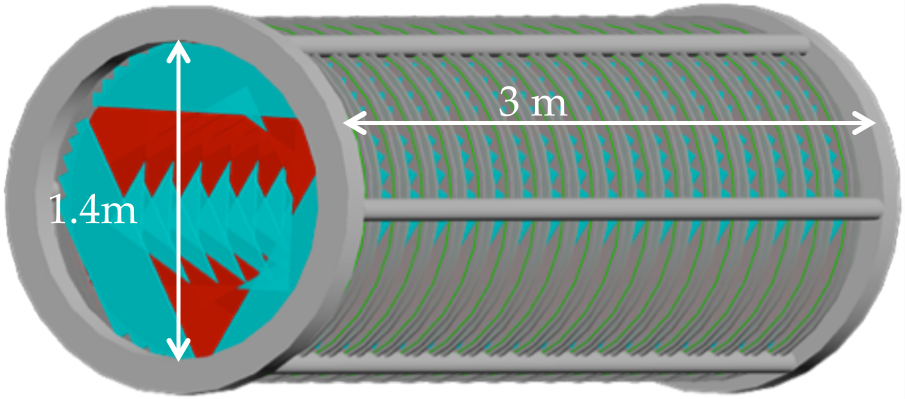


Lower P_T

Larger P_T



Straw Tracker

Straw tubes on a panel	One station	Tracker Structure
		

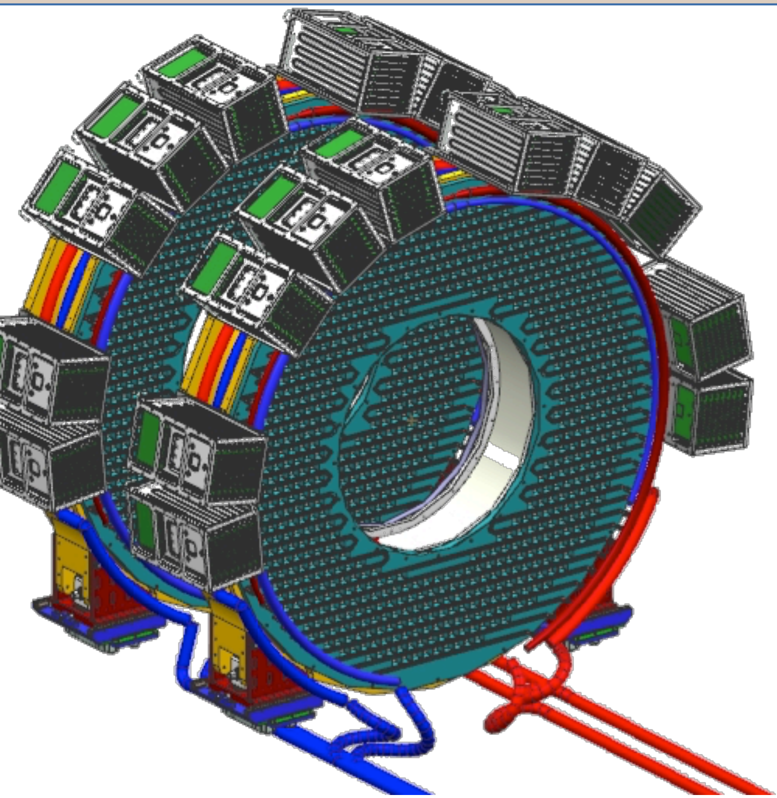
- ~ 20000 straw drift tubes, divided in 18 stations, 2 planes/station
- Each straw is 5 mm diameter, with 25 μm sense wire, 15 μm thick mylar walls
- 3 m long, 1.4 m diameter, in a uniform 1 T magnetic field

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

Timing resolution ~ 1 ns

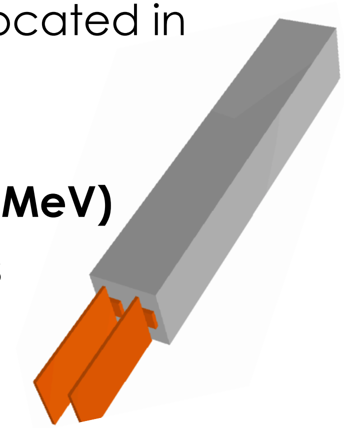
Spatial resolution ~ 100 μm

EM Calorimeter



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

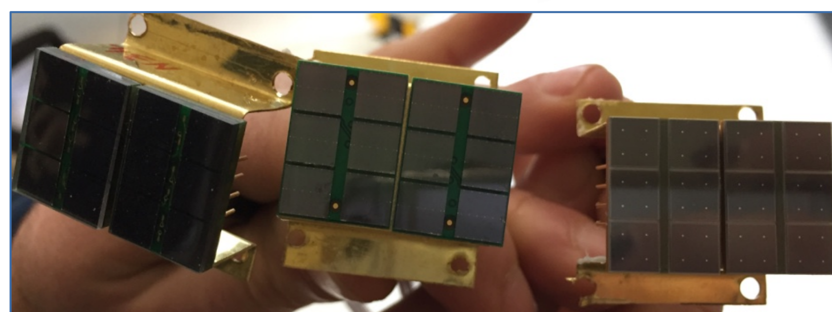
- R_{IN} = 374 mm, R_{OUT} = 660 mm
  Depth = 10 X_0 (200 mm), Distance 70 cm
- Readout: 2 UV-extended SiPMs/crystal
- Analog FEE and digital electronics located in near-by electronics crates



Energy resolution < 5% (@ 100 MeV)

Timing resolution < 0.5 ns

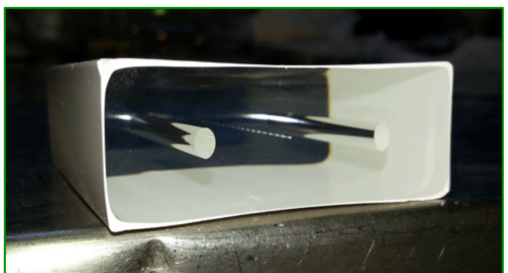
Spatial resolution < 1 cm

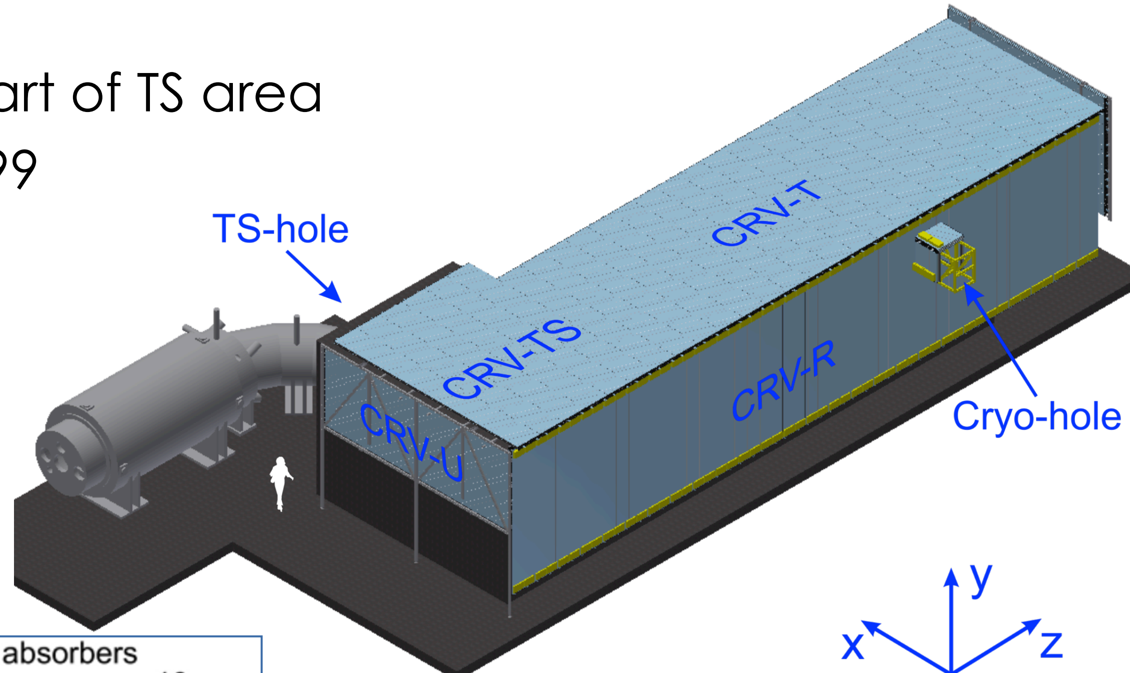


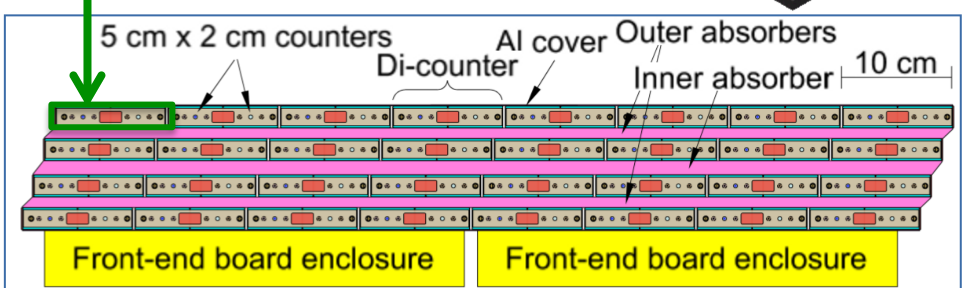
Cosmic Ray Veto

Cosmic Rays are a major sources of background → CRV required

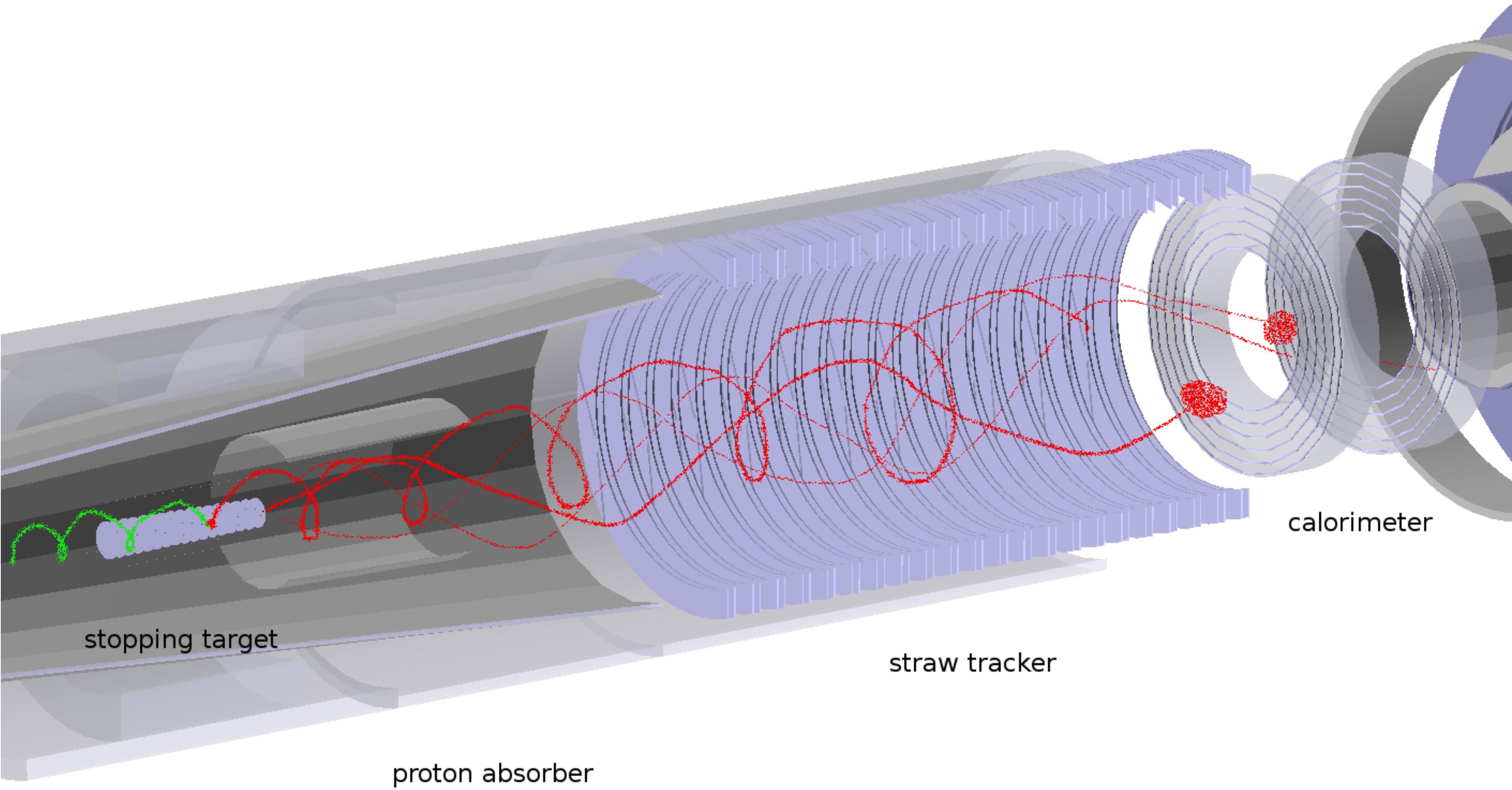
- Composed of 4 layers of overlapping scintillators (a coincidence of 3 out of 4 is used)
- Placed around DS and part of TS area
- Required efficiency: 0.9999





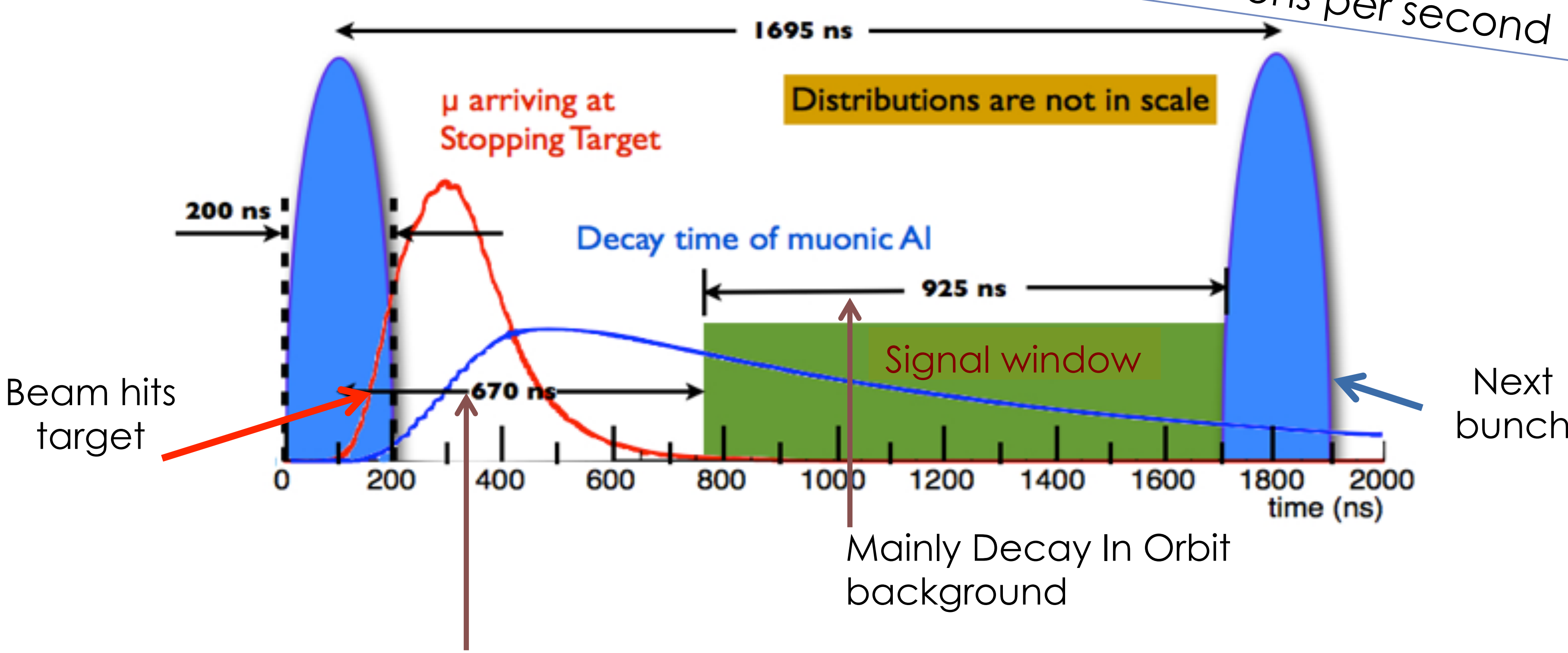


Conversion electron trajectory



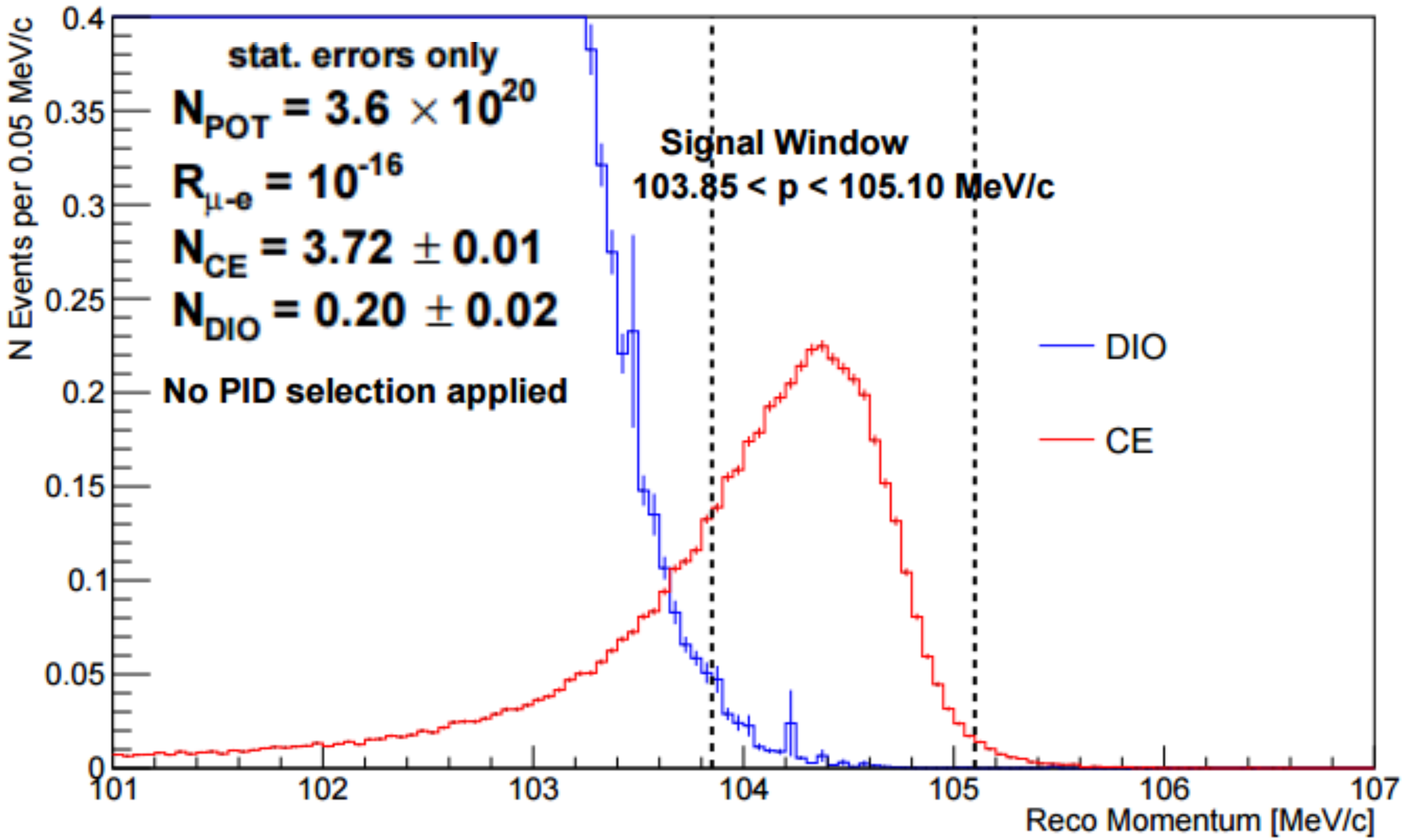
Signal window

~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

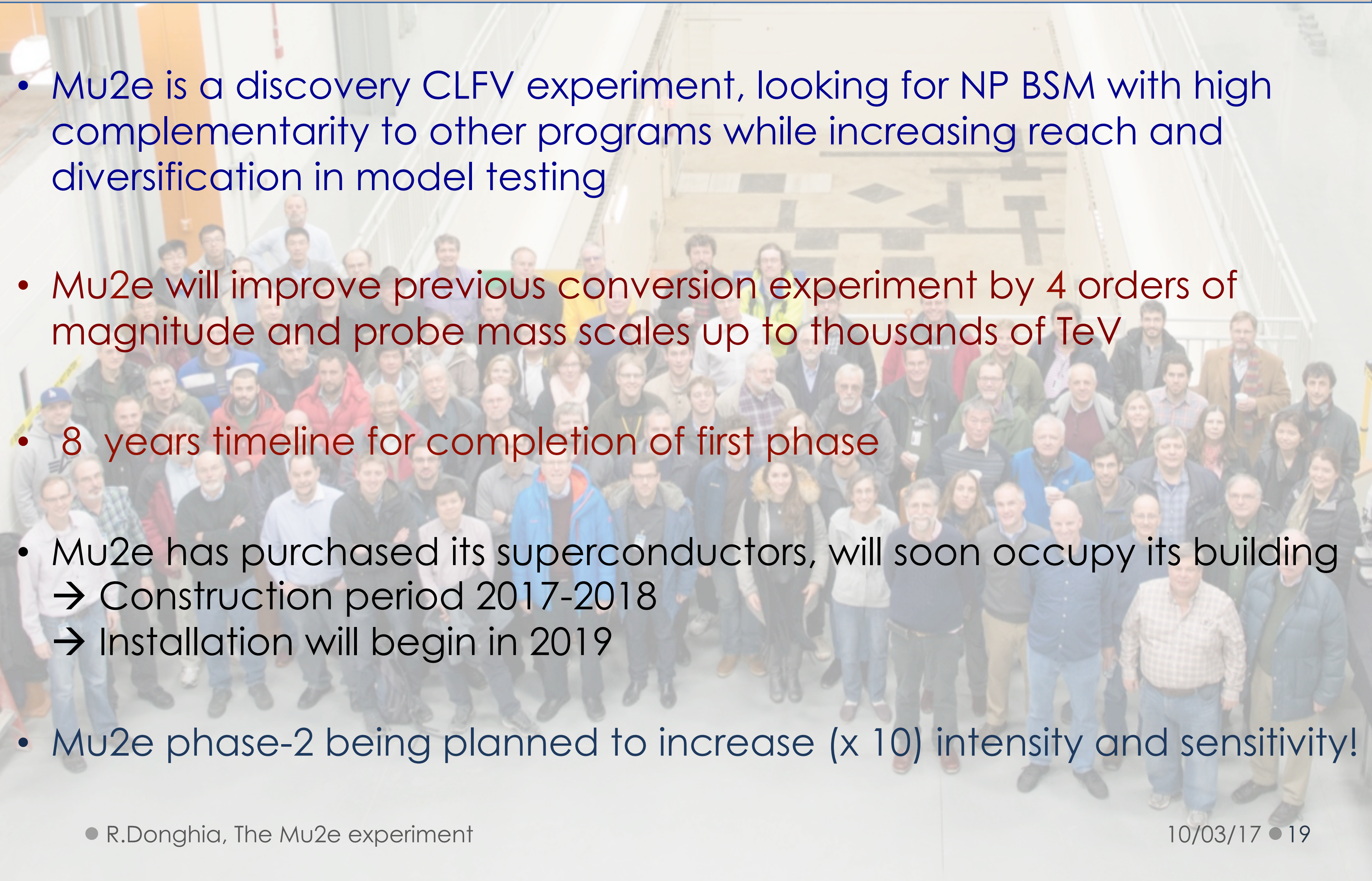
Upgrade proton source and detector to achieve precision

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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On behalf of the Mu2e collaboration

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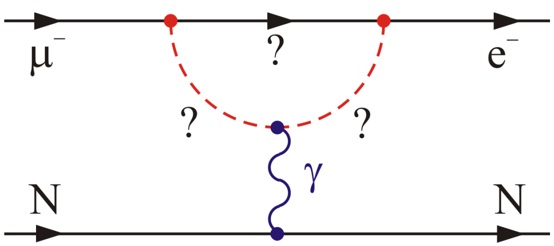
ROMA TRE UNIVERSITÀ DEGLI STUDI
Fermilab
INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

CLFV Lagrangian

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

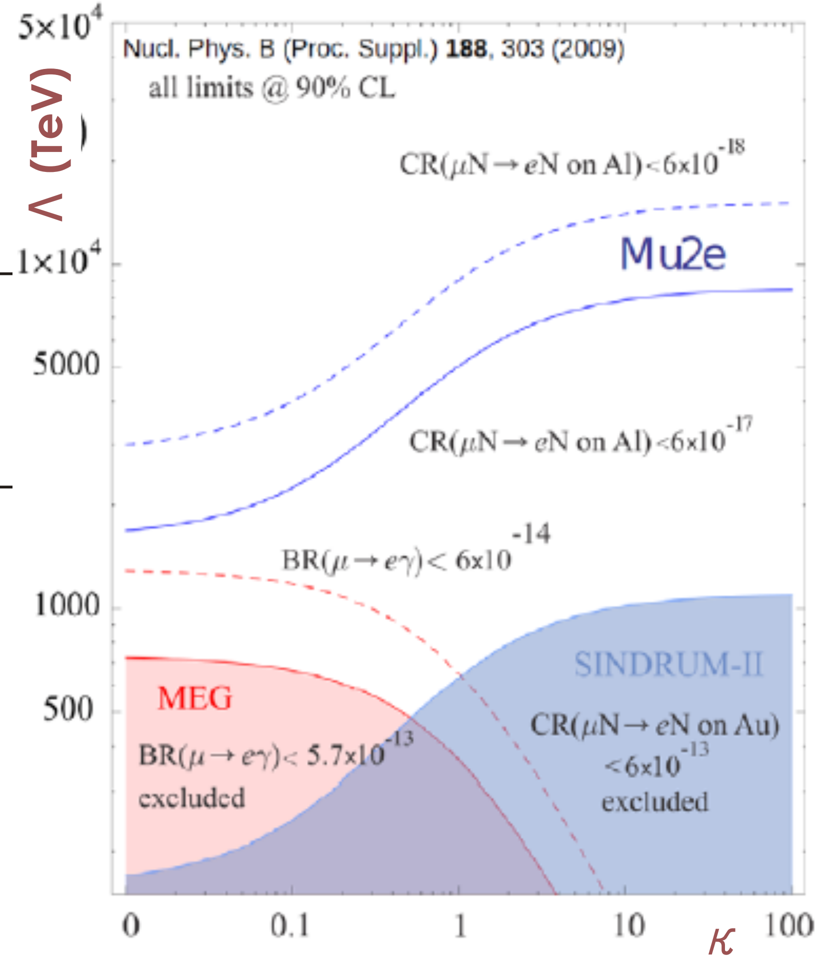
Loops dominate for
κ << 1



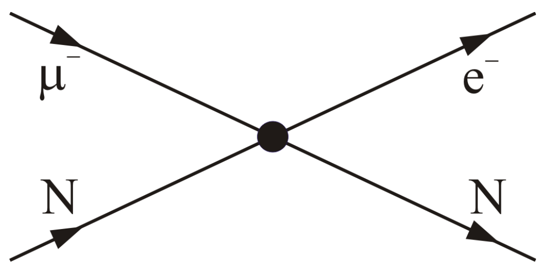
$\mu \rightarrow e\gamma$

μ N→eN

$\mu \rightarrow eee$



Contact terms dominate for
κ >> 1



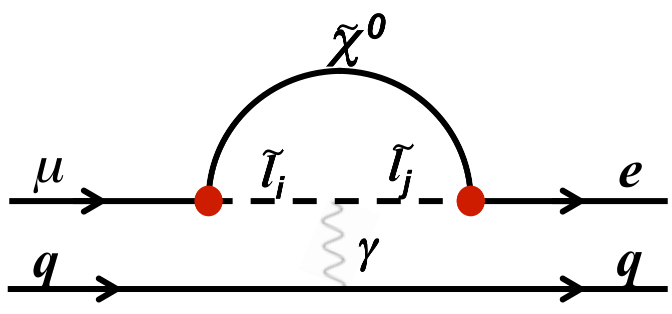
$\cancel{\mu \rightarrow e\gamma}$

μ N→eN

$\mu \rightarrow eee$

Specific Example: SUSY

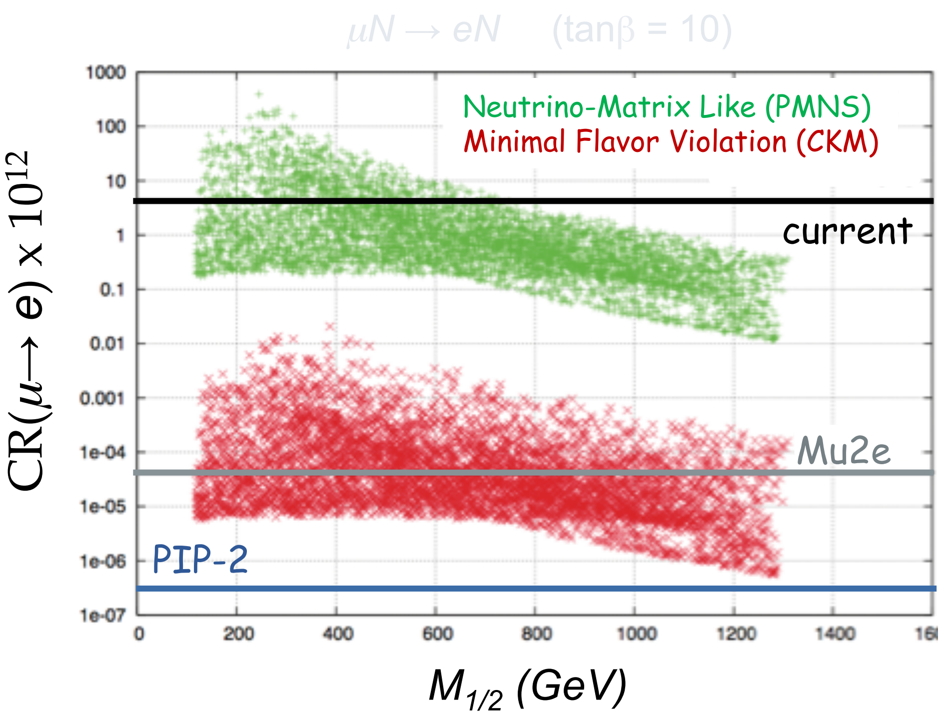
Probe SUSY through loops



If SUSY seen at LHC → rate ~10^{-15}

Implies ~ 40-50 signal events with negligible background in Mu2e for many SUSY models.

SUSY GUT in an SO(10) framework



L. Calibbi et al., hep-ph/0605139

Complementary with the LHC experiments while providing models' discrimination

Other CLFV prediction

M.Blanke, A.J.Buras, B.Duling, S.Recksiegel, C.Tarantino, arXiv:0909.5454v2[hep-ph]

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to\mu^-\mu^+\mu^-)}{Br(\tau\to\mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^-\to\mu^-e^+e^-)}{Br(\tau\to\mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2.0$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^-\to\mu^-\mu^+\mu^-)}{Br(\tau^-\to\mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$

- Relative rates are model dependent
- Measure ratios to pin-down theory details

Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\mathrm{TeV}$) and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

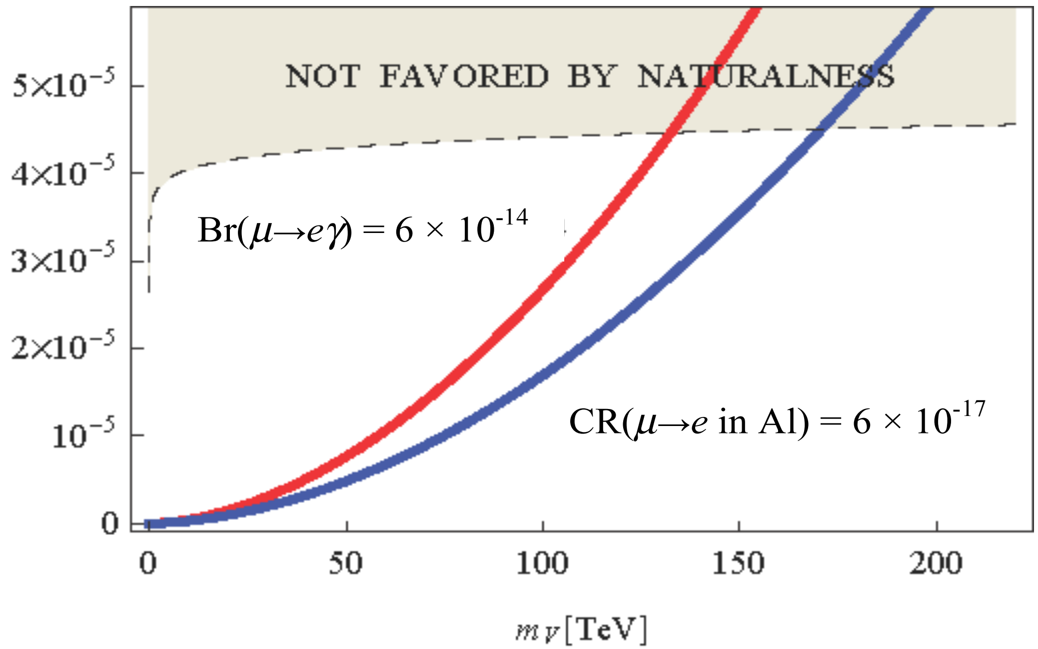
Points vs LHC

TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME, Super Flavour factory) highlighted in italics.

	SPS 1a		SPS 1b		SPS 2		SPS 3		Future
Process	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	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($\mu \to e$ 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 points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/Belle-2
- All of these will be observable by Mu2e

Specific Example: Leptoquarks



Leptoquarks

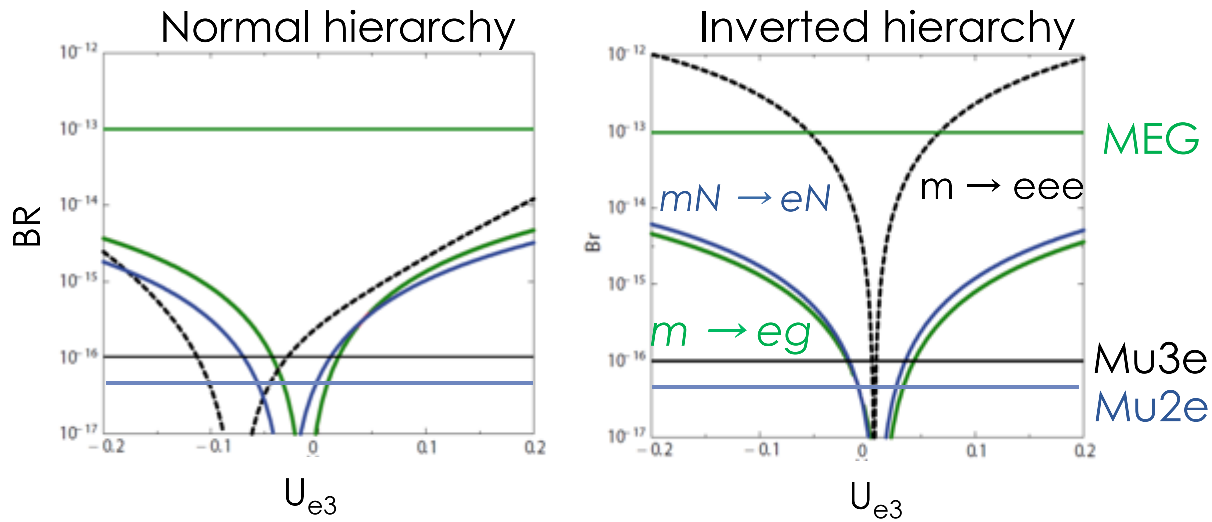
Presenza di leptoquarks alla scala del TeV potreb indurre processi CLFV con una costante di accoppiamento λ.

- Rosso: MEG-II
- Blu: Mu2e

Specific Example: Higgs triplet and LHT

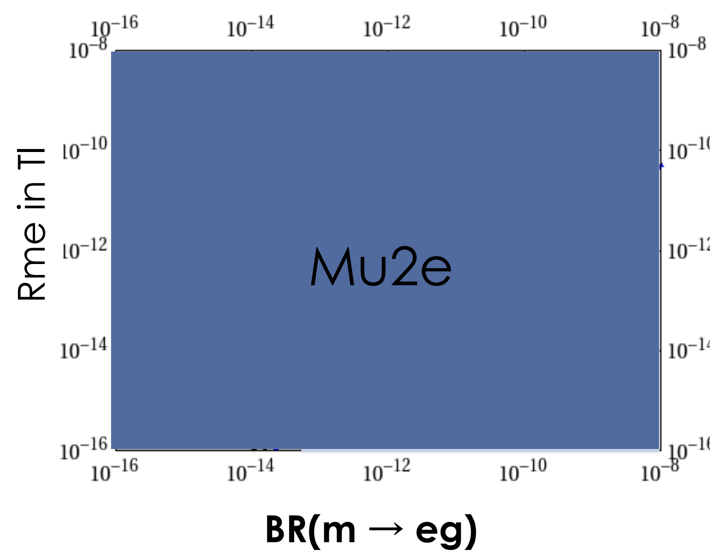
Higgs triplet model

Dependence on neutrino mass hierarchy and θ_{13}



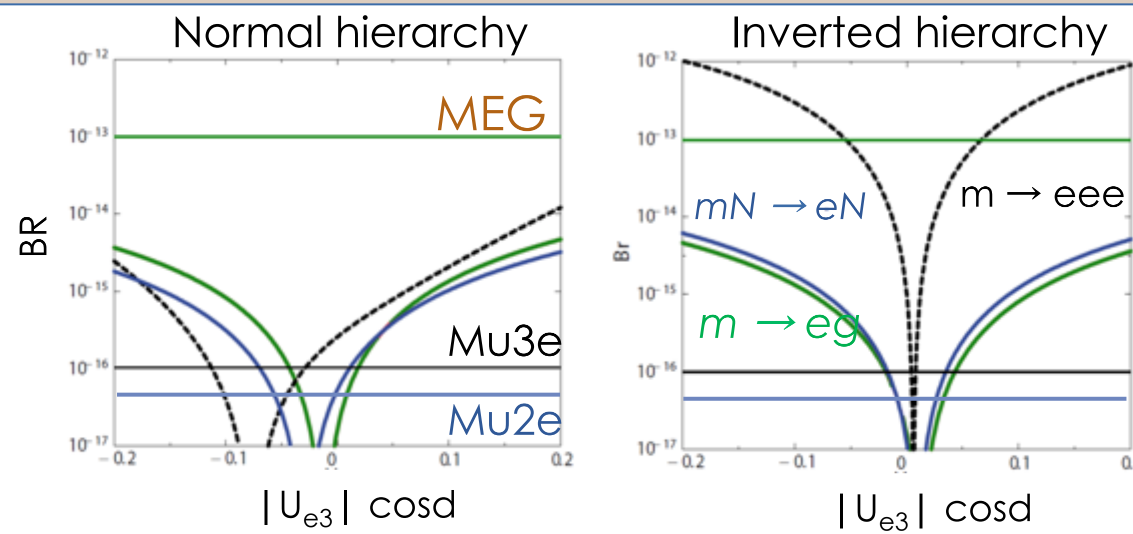
Littlest Higgs with T-parity

M. Blanke et al., Acta Phys.Polon.B41:657,2010

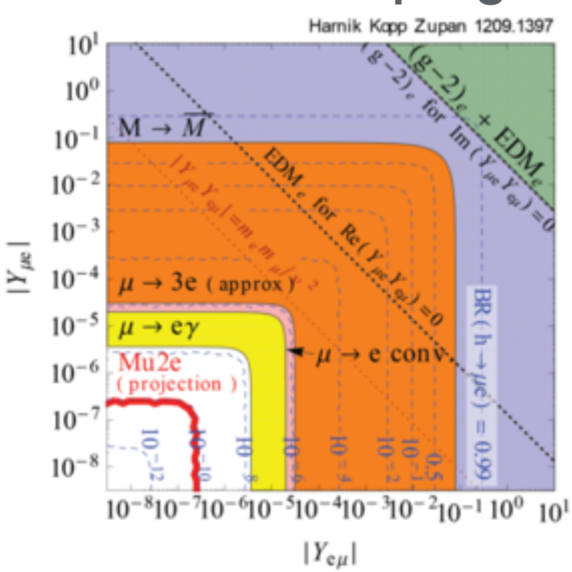


A few more models

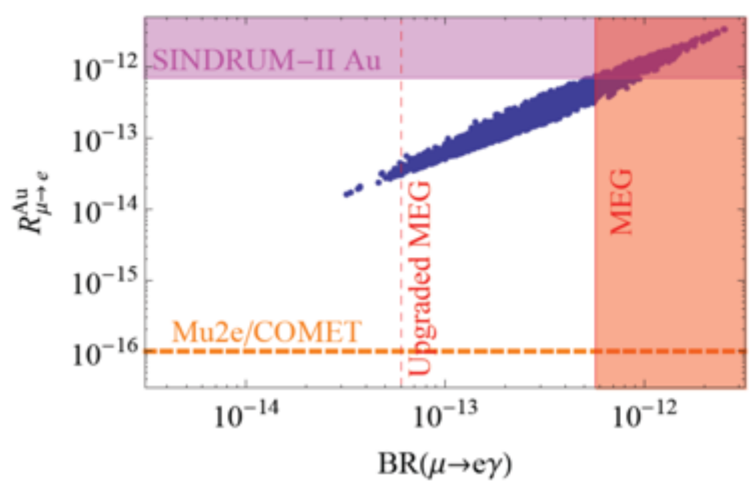
Higgs triplet model



Flavor violating Yukawa couplings

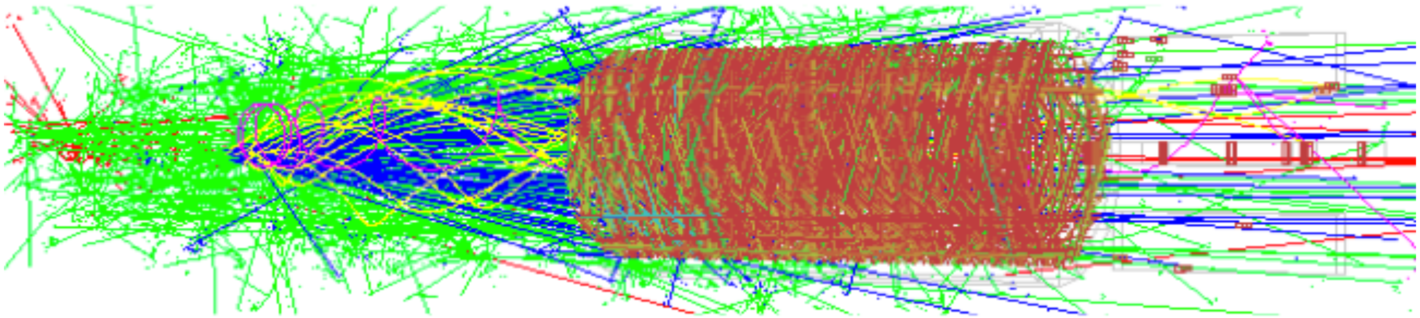


Left-right symmetric models

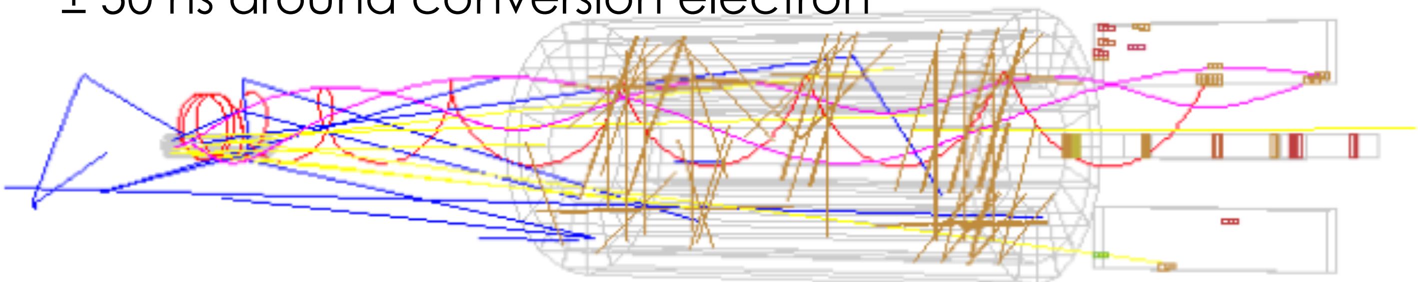


A few more models

500 – 1695 ns window



± 50 ns around conversion electron



- ❑ Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters (| ΔT | < 50 ns) → simplification of pattern recognition
- ❑ Add search of an Helix passing through cluster and selected hits + use calorimeter time to calculate tracking Hit drift times.
  → Reduce the wrong drift sign assignments i.e. smaller positive momentum tail

Background

Process	TDR Yield	CD3 Yield	Comment
DIO	0.199 ± 0.092	0.19 ± 0.08	Fixed by the procedure. Instead one can compare tracker-only SES for the fixed DIO background: 2.6×10^{-17} (TDR), 2.69×10^{-17} (CD3).
RMC	$0.000^{+0.004}_{-0.000}$	$\Leftarrow$ same	not updated
Pion capture	0.023 ± 0.006	0.030	assumes 10^{-10} extinction
Muon DIF	< 0.003	$\Leftarrow$ same	not updated
Pion DIF	$0.001 \pm < 0.001$	$\Leftarrow$ same	not updated
Beam electrons	0.003 ± 0.001	$< 5 \times 10^{-4}$	assumes 10^{-10} extinction
Antiprotons	0.047 ± 0.024	$\Leftarrow$ same	consistent with TDR to 10%
Cosmic rays	0.082 ± 0.018	0.247 ± 0.055	assumes CRV inefficiency 10^{-4}
Total	0.36 ± 0.10	0.52±?	

Assuming 6 x 10^{17} stopped muons in 6 x 10^{7} sec of beam tine

- Tracker digitization tuned to prototype performance
- New CsI calorimeter
- Better cosmic background estimate (much higher statistics)
- Largest background in Mu2e:
  .DIO, according to the TDR numbers
  .Cosmic, as we currently think

Less than 1 background event allows us to reach desired single event sensitivity

Why muon conversion is unique?

Muon conversion is a unique probe for BSM:

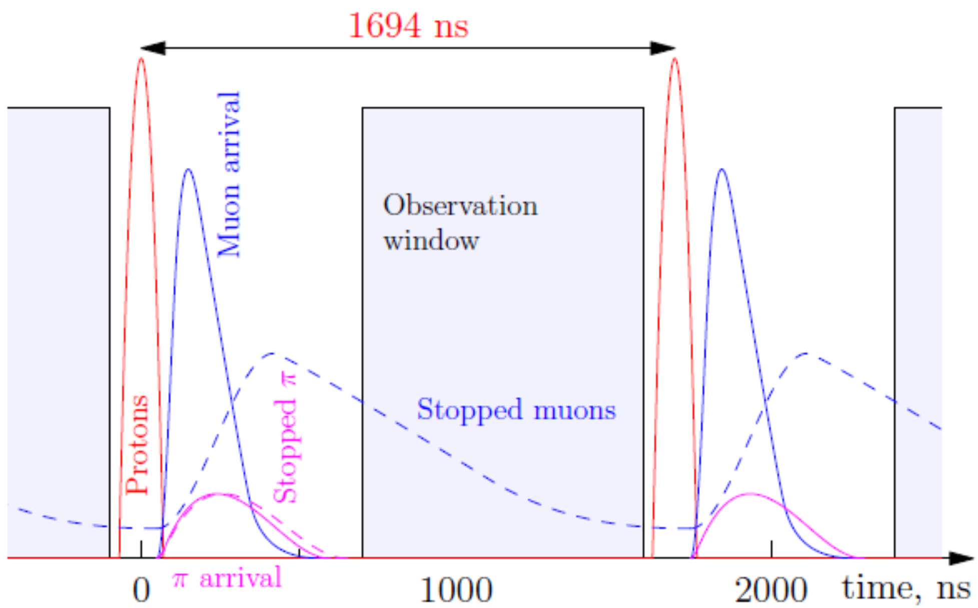
- Broad discovery sensitivity across all models:

  → Sensitivity to the same physics of MEG but with better mass reach
  → Sensitivity to physics that MEG is not
  → If MEG observes a signal, MU2E/COMET do it with improved statistics.
  Ratio of the BR allows to pin-down physics model
  → If MEG does not observe a signal, MU2E/COMET have still a reach to do so

- Sensitivity to λ (mass scale) up to hundreds of TeV beyond any current existing accelerator

Year

Background – Signal window

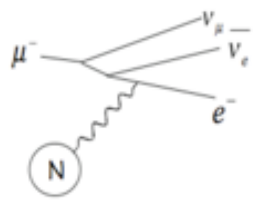


- **Use the fact that muonic atomic lifetime >> prompt background**
  Need a pulsed beam to wait for prompt background to reach acceptable levels → Fermilab provides the beam we need !

- **OUT of time protons are also a problem.**
  To keep associated background low we need proton extinction of 10^{-10} :
  proton extinction (between pulses): # protons out of beam/# protons in pulse

Background – DIOs

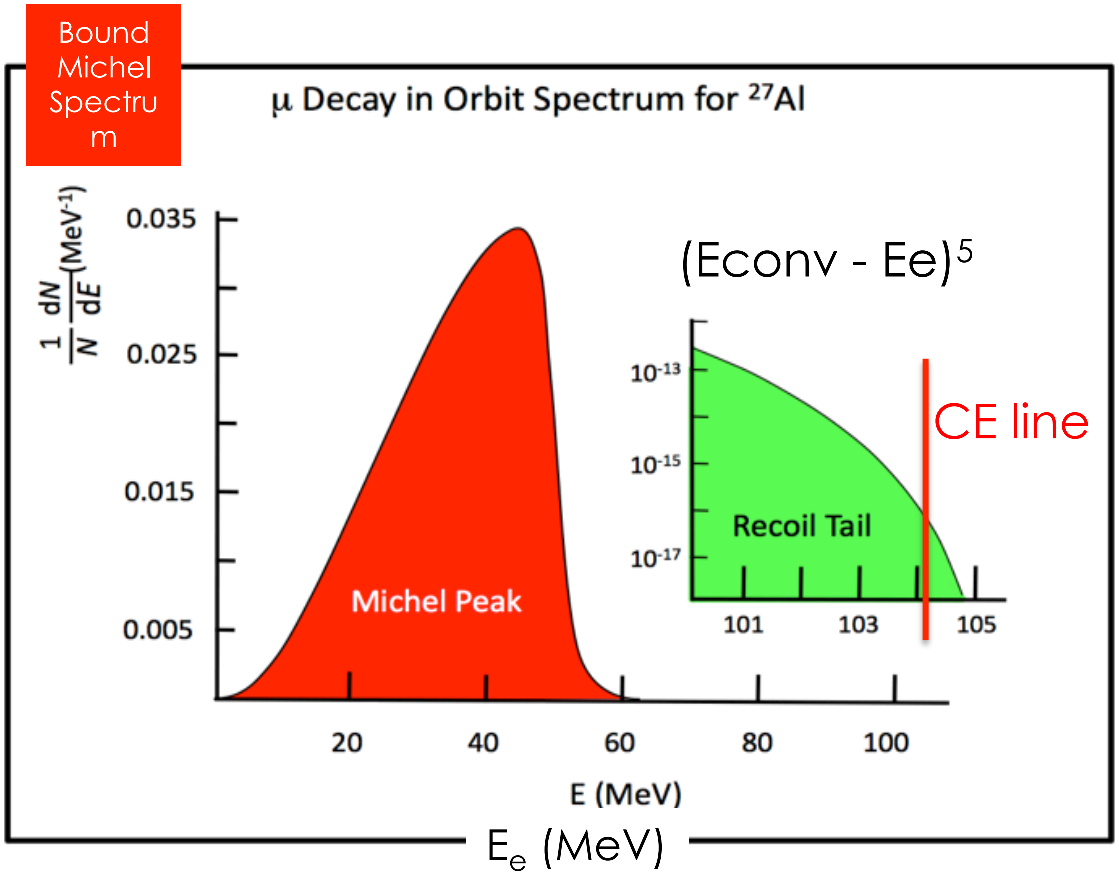
The DIO background is the most difficult one



- ❑ Electron energy distribution from the decay of bound muons is a (modified) Michel spectrum:

→ Presence of atomic nucleus and momentum transfer create a recoil tail with a fast falling slope close to the endpoint

→ To separate DIO endpoint from CE line we need a high Resolution Spectrometer



Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv:1106.4756v2

Stopping Monitor

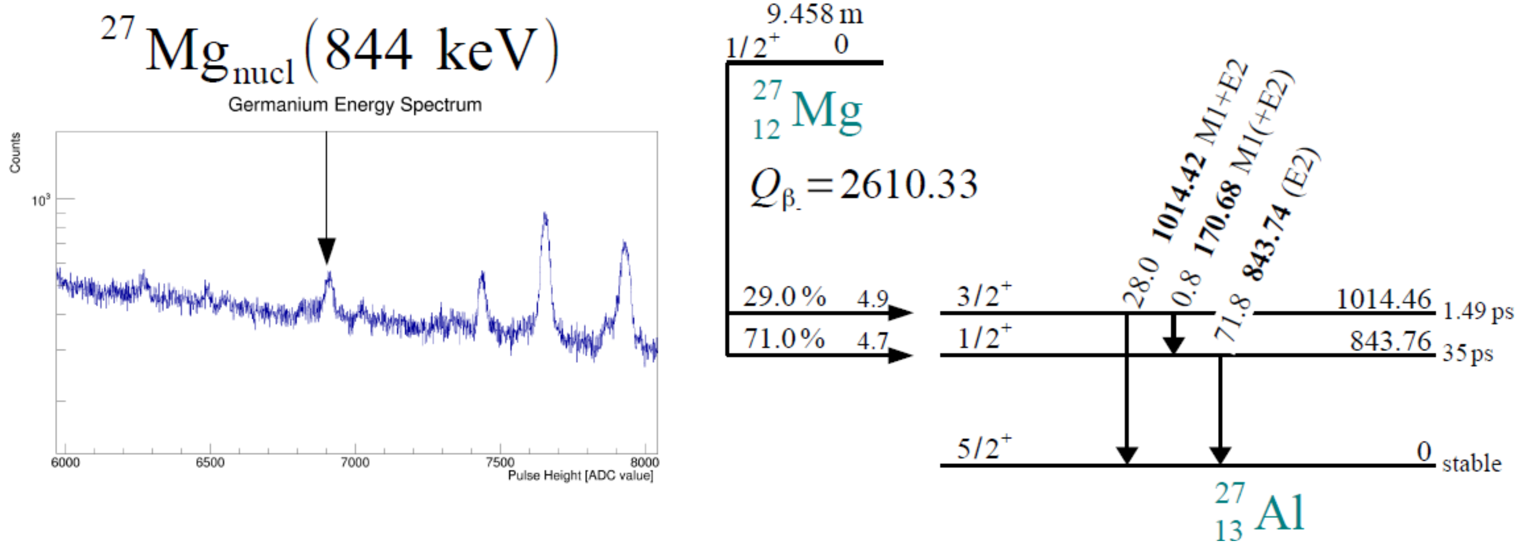


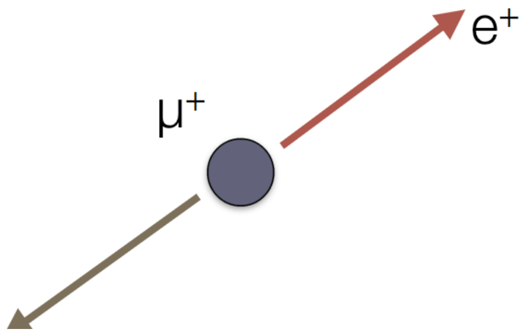
Figure 7.18. Preliminary singles germanium spectrum from the AlCap experiment at PSI. When muons stop in aluminum, they capture on the nucleus 60% of the time. A fraction of the captures produce ^{27}Mg in the ground state, which has a half-life of 9.5 minutes. In the decay, an 844 keV gamma is produced 72% of the time.

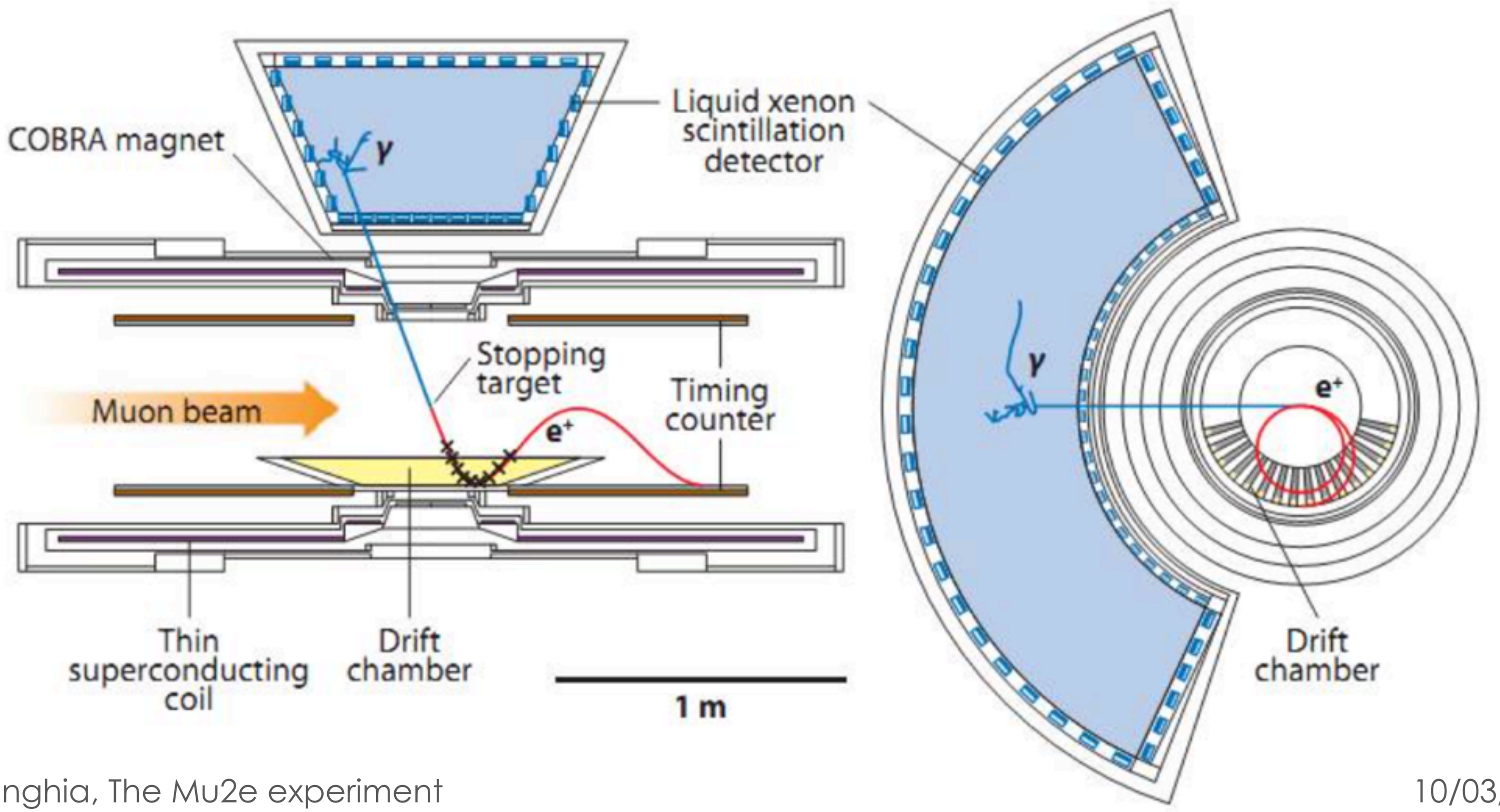
- Need a high precise gamma detector (HpGe)
- Energy of gamma ray is unique to the detector
- Detecting the delayed gamma rays eliminate problems related to beam flash
- Proton beam structure is 0.5 s on followed by 0.8 s idle. Gamma spectrum wil be acquired during idle time.
- Hpge should view the target far from the source and beyond DS

Experimental signature:

- Simultaneous back-to-back e^+ and γ

  $E_\gamma = E_{e+} = 52.8 MeV$



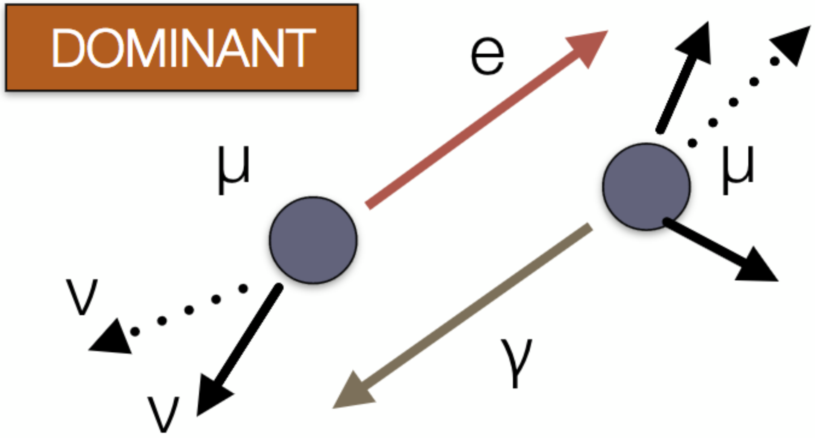


MEG - Backgrounds

- **Accidental coincidence of e^+ and γ:**

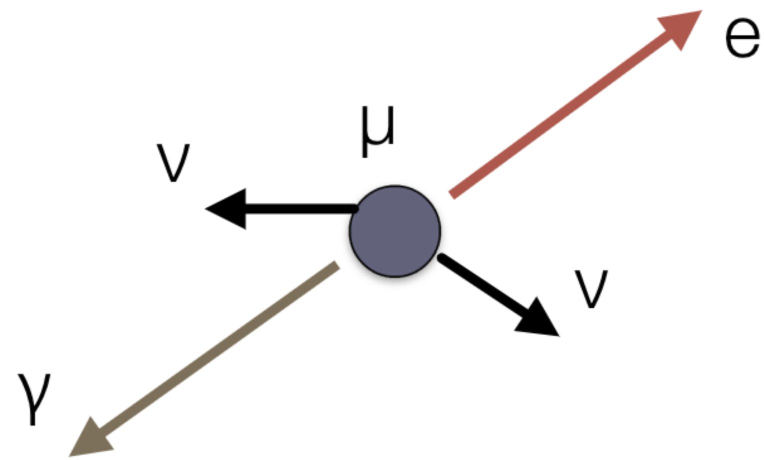
Proportional to I^2_μ (while signal proportional to I_μ)

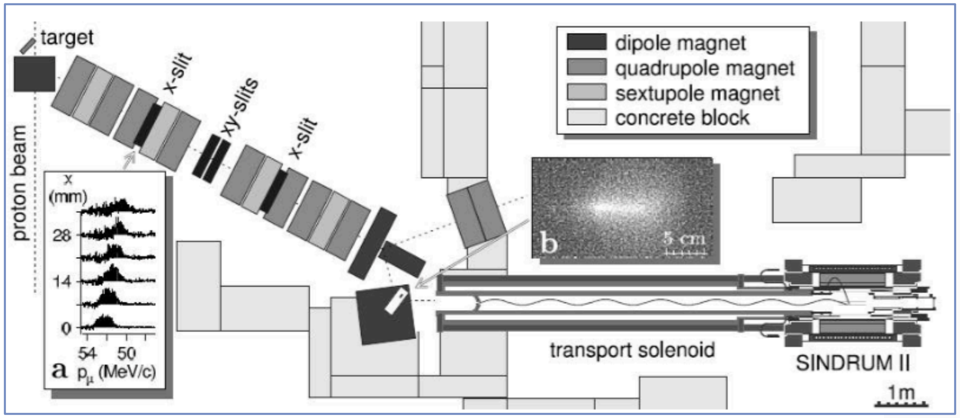
- Compromise between high intensity and low background



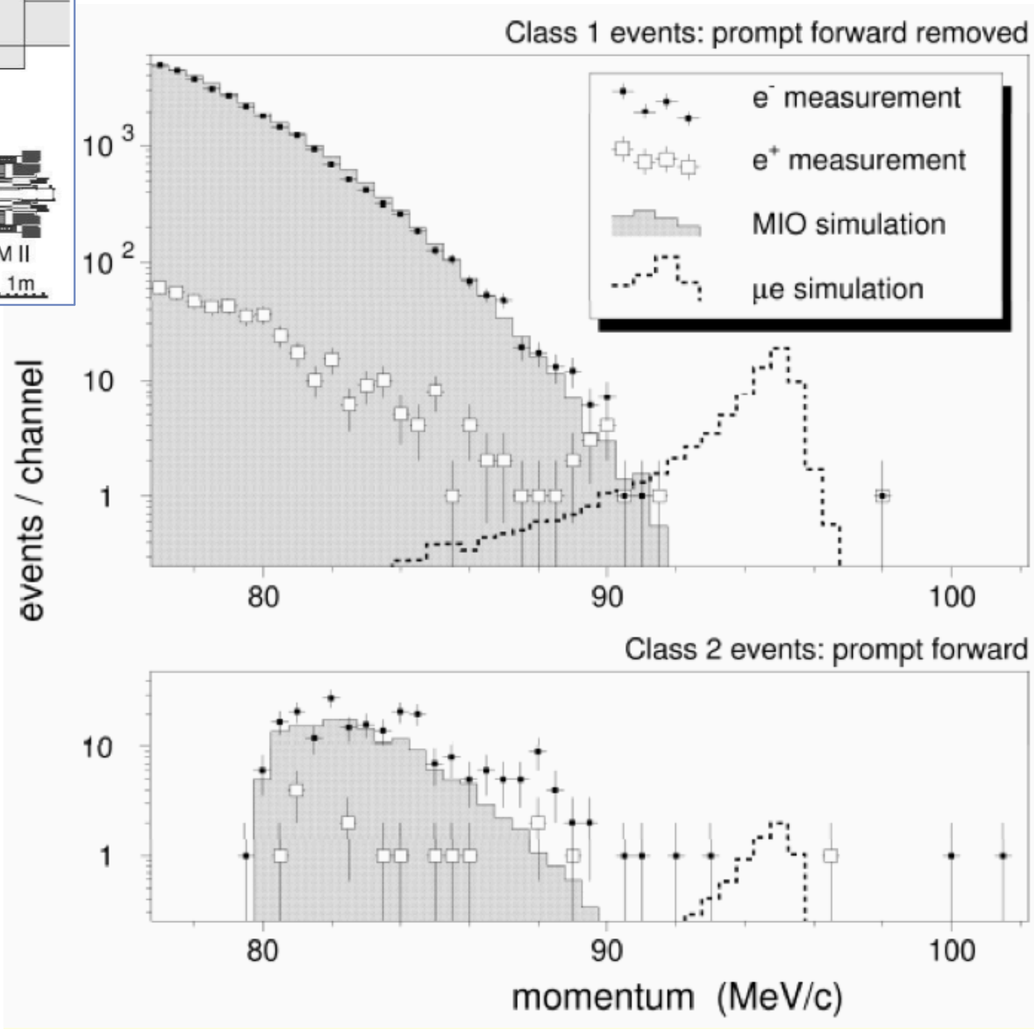
- **Radiative muon decay background**

- Proportional to I_μ
- Note: e^+ and γ simultaneous as for signal





Proton beam: 590 MeV, time structure: bursts 0.3 ns wide every 19.75 n

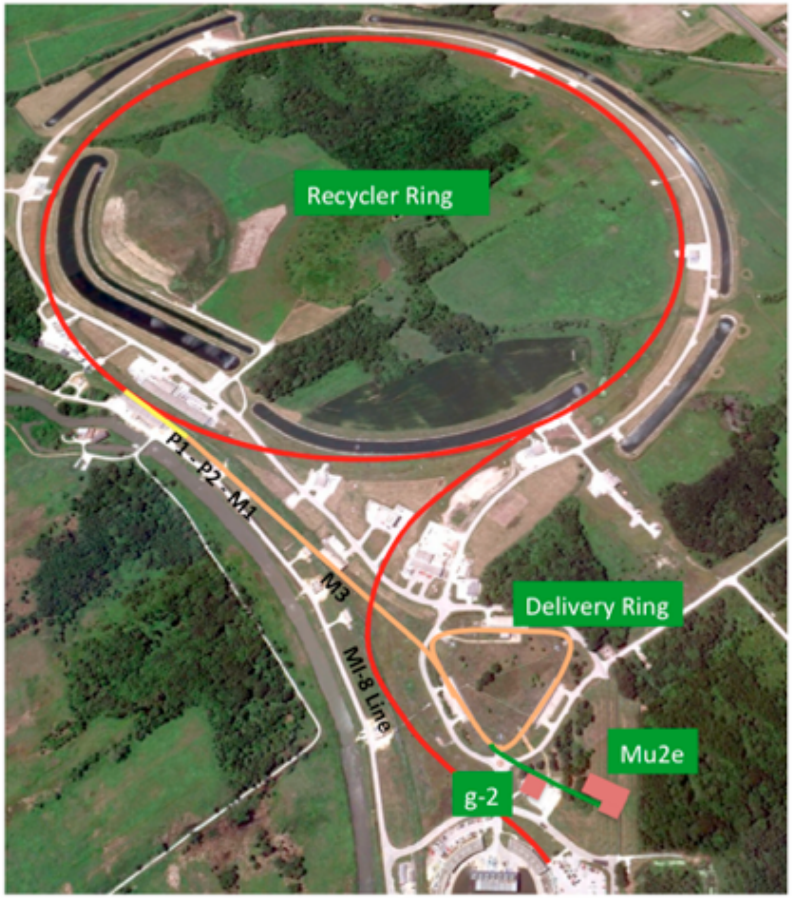


2 event classes defined based on polar angle Θ and rf-phase t_{rf} :

- Class 1: No sign for μ -e conversion events
- Class 2: Approximately flat high energy component as expected from pion induced background

Accelerator scheme and proton extinction

- Booster: batch of 4×10^{12} protons every $1/15^{th}$ second
- Booster "batch" is injected into the Recycler ring and re-bunched into 4 bunches
- These are extracted one at a time to the Delivery ring
- As a bunch circulates, protons are extracted to produce the desired beam structure → **bunches of ~3×10^7 protons each, separated by 1.7 μs**



Proton Extinction

achieving 10^{-10} is hard; normally get $10^{-2} - 10^{-3}$

- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole

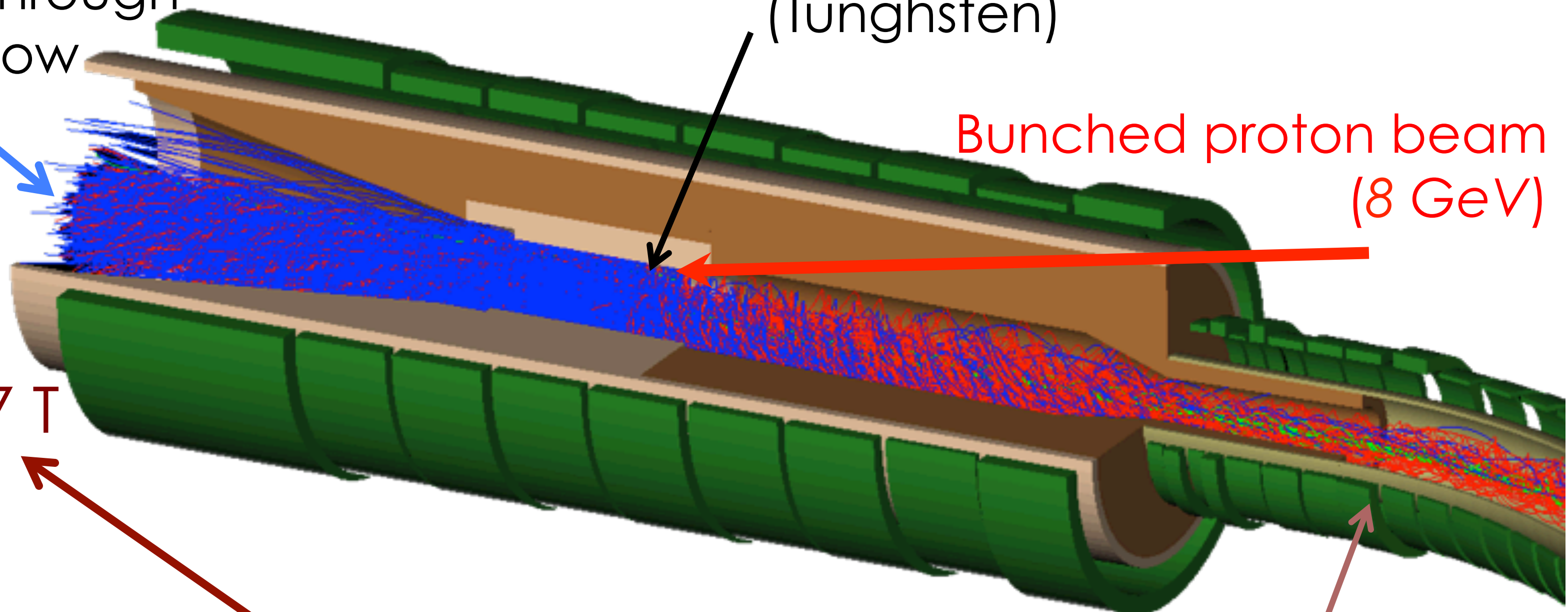
Calculations based on accelerator models
That take into account collective effects
Shows that this combination gets ~ 10^{-12}

The Production Solenoid

Not absorbed protons exit through thin window

Proton Target (Tunghsten)

Bunched proton beam (8 GeV)



4.7 T

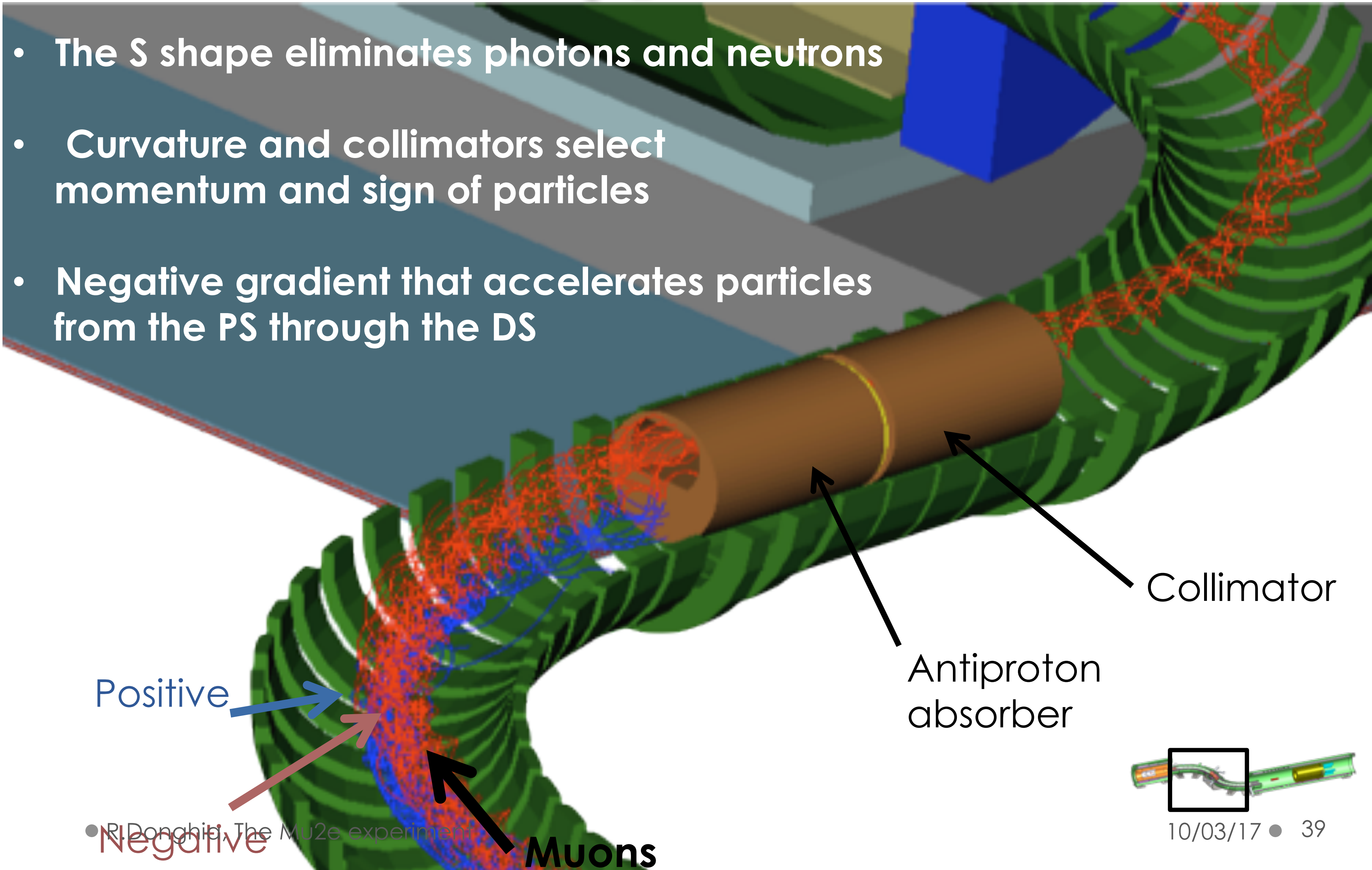
2.5 T

Graded magnetic field contains backwards pions/muons and reflects forward pions/muons (with production angle more than 30°)

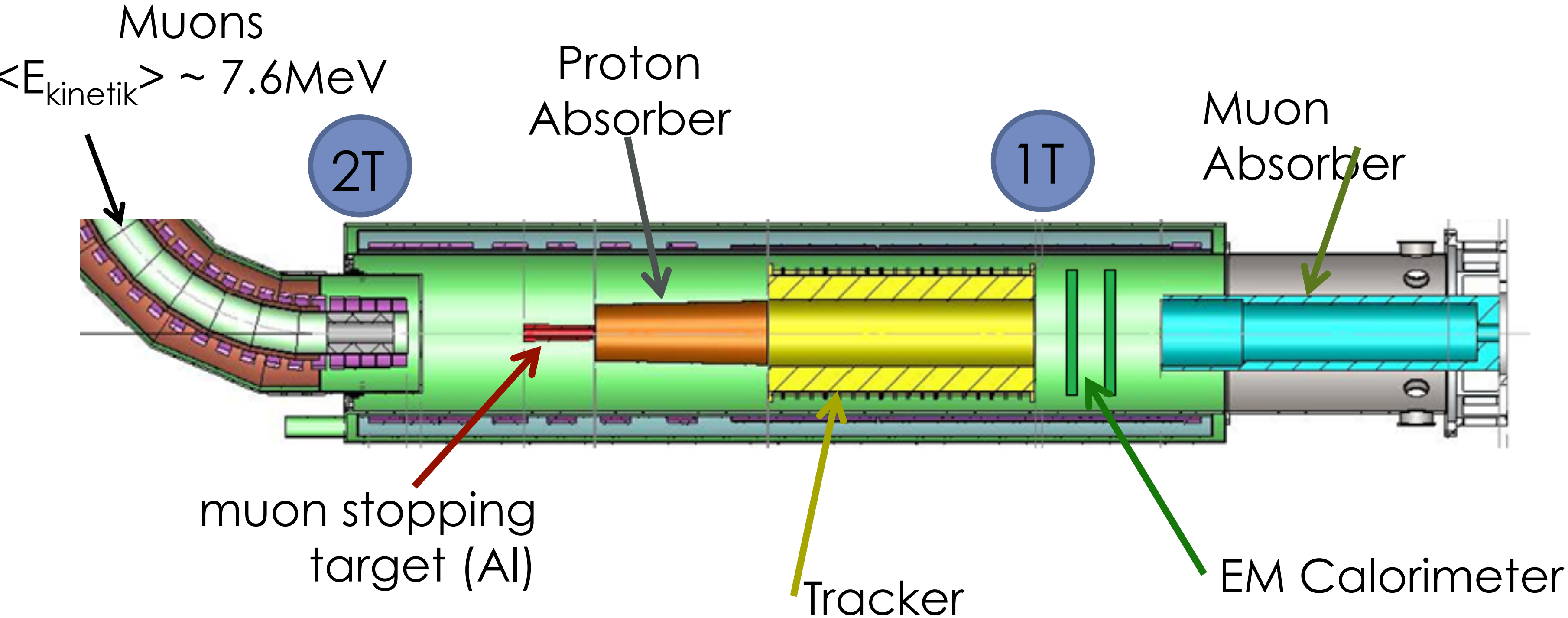
Muons leave to TS

The Transport Solenoid

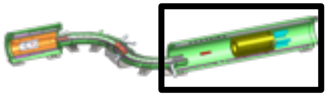
- The S shape eliminates photons and neutrons
- Curvature and collimators select momentum and sign of particles
- Negative gradient that accelerates particles from the PS through the DS



The Detector Solenoid

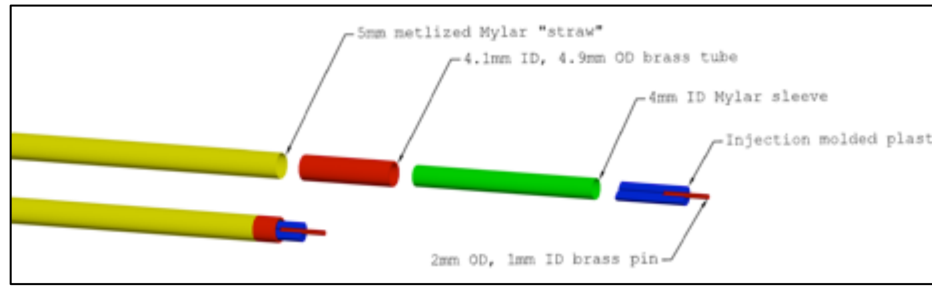


- Graded field "reflects" downstream a fraction of conversion electrons emitted upstream (isotropic process)
- For the sensitivity goal → ~ 6 x 10^{17} stopped muons for 3 years run → 10^{10} stopped muon/s (10 GHz)

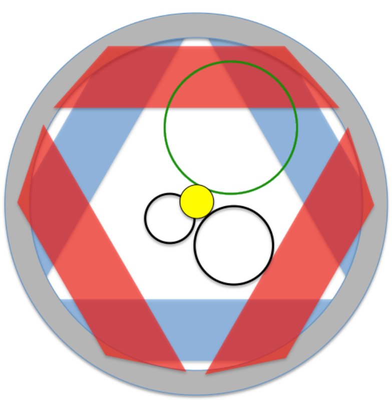


Straw Tracker (2)

- Tracker is made of arrays of straw drift tubes
- 20000 tubes arranged in planes on stations, the tracker has 18 stations
- Tracking at high radius only ensures operability (beam flash produces a lot of low momentum particles + DIO background)

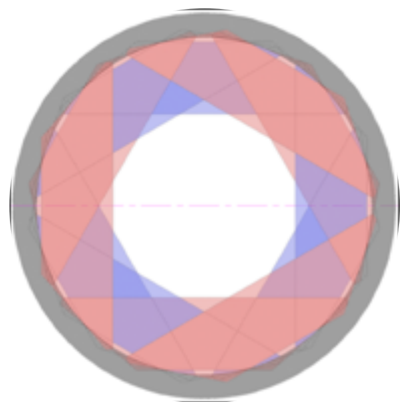


Tracker station



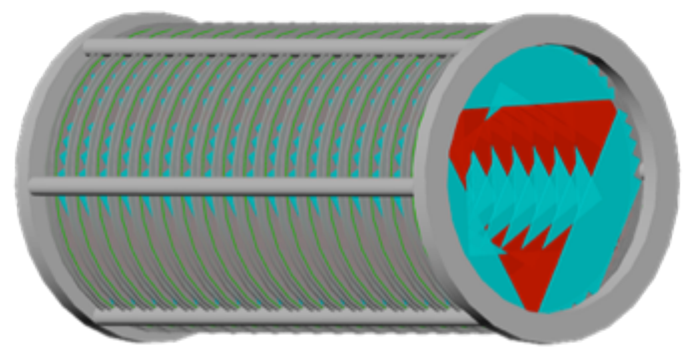
→

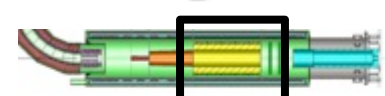
Stations are rotated



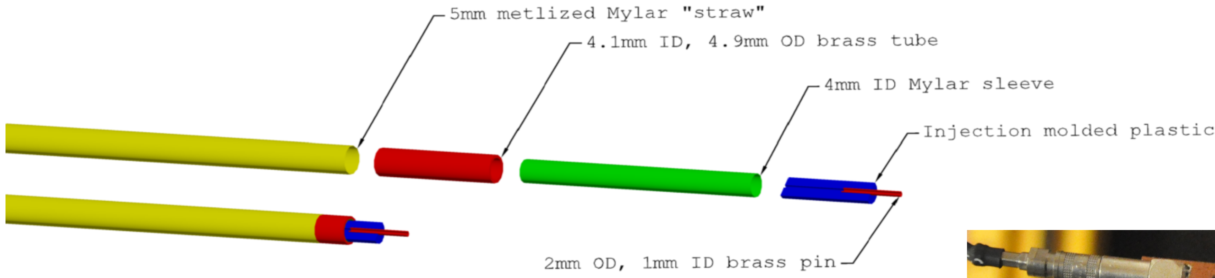
→

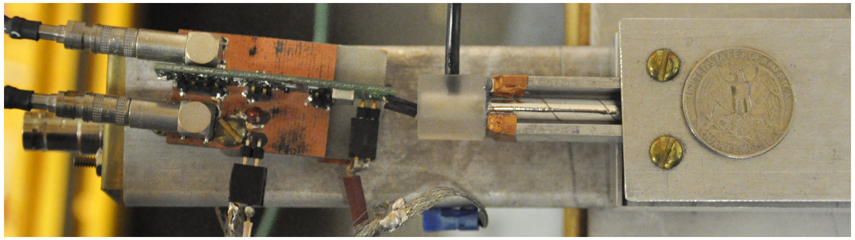
Tracker





Straw tubes





- 5 mm diameter;
- wall thickness of 15 μm
  - two layers of ~6 μm (25 gauge) Mylar, spiral wound, with a ~3 μm layer of adhesive between layers. The inner surface has 500 Å aluminum overlaid with 200 Å gold as the cathode layer. The outer surface has 500 Å of aluminum to act as additional electrostatic shielding and improve the leak rate
    The straws will be tensioned to 500 g
- sense wire is 25 μm gold plated tungsten, centered in the straw
  - The wire will be tensioned to 80 g
- The drift gas is tentatively taken as 80:20 Argon:CO_2 with an operating voltage of ~1500 V, with maximum drift time of ~50 ns and gain of ~$3*10^4$

CsI Test beam