Searches for μ to e Conversion

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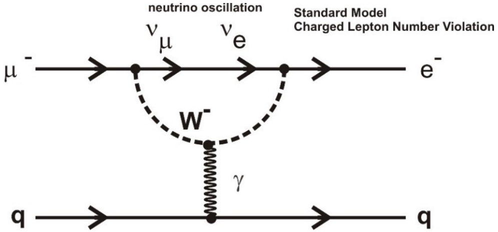
μ to e conversion is a Charged Lepton Flavor Violating process

- Neutrino mixing leads to CLFV in the standard model, but at an undetectable branching ratio $< 10^{-50}$ $\left(\propto (\frac{\Delta m_\nu^2}{M_W^2})^2\right)$

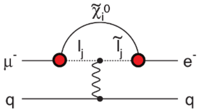


- Any detection of CLFV would be an unambiguous sign of new physics

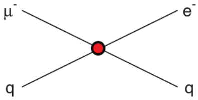
Charged Lepton Flavor Violation

- Many models of new physics predict contributions to CLFV:

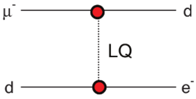
Supersymmetry



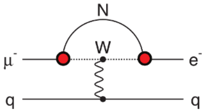
Compositeness



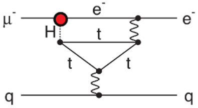
Leptoquark



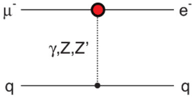
Heavy Neutrinos



Second Higgs Doublet



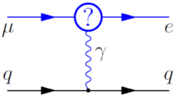
Heavy Z'
Anomal. Z Coupling

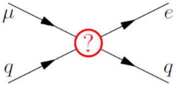


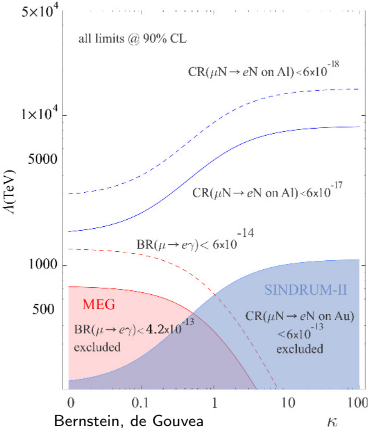
Kuno, Y. and Okada, Y. Rev. Mod. Phys. 73, 151 (2001).
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58 (2008).
M. Raidal et al, Eur.Phys.J.C57:13-182, (2008).
de Gouvea, A., and P. Vogel, arXiv:1303.4097 [hep-ph] (2013).

CLFV Effective Lagrangian

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\overline{\mu}_L\gamma_\mu e_L \left(\sum_{q=u,d}\overline{q_L}\gamma^\mu q_L\right)$$





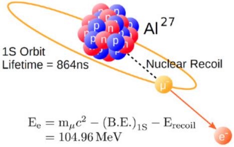


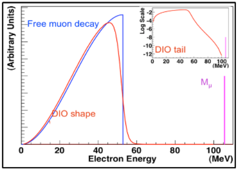
Bernstein, de Gouvea
(MEG from arXiv:1605.05081)

- loop: $\kappa \ll 1$, μN$\to$ eN and $\mu \to e\gamma$
- contact: $\kappa \gg 1$, μN$\to$ eN only
- Complementary to LHC: can probe mass scales up to 10^4 TeV

Designing μ to e conversion experiments

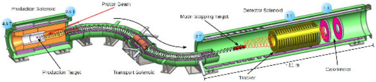
- Look for $\mu^- N \rightarrow e^- N$ conversion using stopped muons

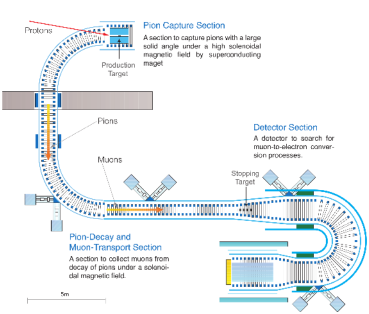




- Once stopped the muon will either:
  - Be captured by the nucleus
  - Decay in orbit (DIO): $\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$
  - Undergo CLFV conversion
- Signal: monoenergetic 105 MeV electrons
- Backgrounds:
  - DIO
    - Energy resolution
  - Cosmic rays
    - Veto
  - Prompt backgrounds
    - Transport design
    - Pulsed proton beam

Next gen μ to e conversion experiments





- Use stopped muons in an Al target (864 ns lifetime)
- Want to measure:

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

- Need very intense muon beam and very low backgrounds
- Will increase sensitivity by 4 orders of magnitude

Mu2e experiment at Fermilab

Argonne National Laboratory
Boston University
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of Illinois
Kansas State University
Lewis University
University of Louisville
University of Minnesota
Muons Inc.
Northern Illinois University
Northwestern University
Purdue University
Rice University
University of South Alabama
University of Virginia
University of Washington
Yale University

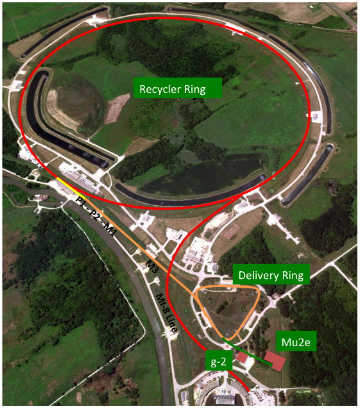
Laboratori Nazionali di Frascati
INFN Genova
INFN Lecce and Universit del Salento
Laboratori Nazionali di Frascati and
Universit Marconi Roma
INFN Pisa

Joint Institute for Nuclear Research, Dubna
Novosibirsk State University/Budker Institute of
Nuclear Physics
Institute for Nuclear Research, Moscow

Helmoltz-Zentrum Dresden-Rossendorf

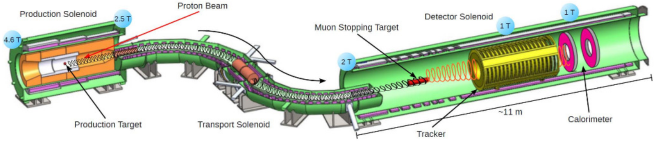
Sun Yat Sen University

Mu2e Proton Beam



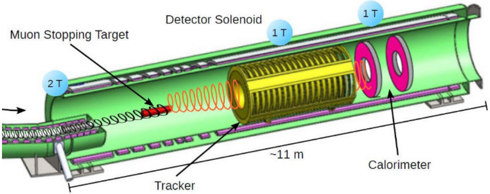
- 8 GeV 8 kW proton beam
- Protons from booster injected into recycler, divided into bunches
- Bunches extracted one at a time into delivery ring (old antiproton debuncher)
- Resonantly extracted from delivery ring in pulses of 4×10^7 protons separated by $1.7\ \mu s$

Mu2e experimental setup



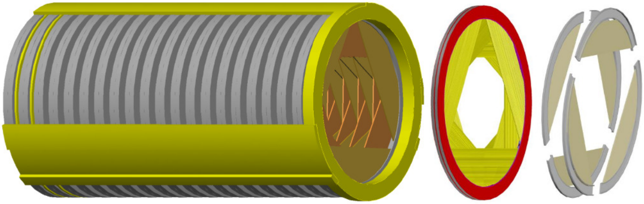
- Production solenoid
  - Proton beam hits tungsten target producing pions
  - Graded field reflects pions and muons back to transport solenoid
- Transport solenoid
  - Toroidal field plus curved shape separates by charge and momentum
  - Collimators to select low momentum muons (40 MeV/c)
- Detector solenoid
  - Muons stop on aluminum target
  - Graded field reflects upstream electrons back to detectors

Detector overview

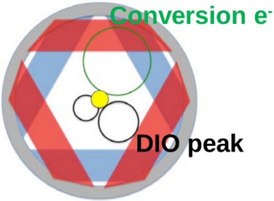


- Muons stop on thin aluminum foils, are captured or decay
  - Decay products emitted isotropically
  - Graded field directs electrons back through detector elements in helical path
  - Flat field in straw tracking volume
- High precision straw tracker for momentum measurement
- Electromagnetic calorimeter for PID

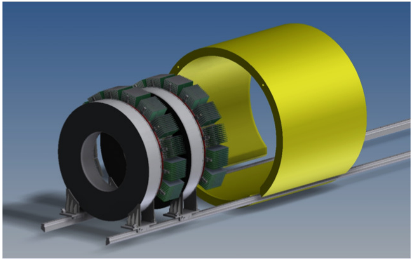
Straw Tracker



- ~21,000 low mass straw tubes in vacuum
  - 5 mm diameter
  - 15 μ thick walls
  - 80/20 ArCO2 gas mixture
  - instrumented on both ends
- 18 stations
- Blind to Michel electron momentum peak and beam flash
- Expected resolution better than 200 keV/c

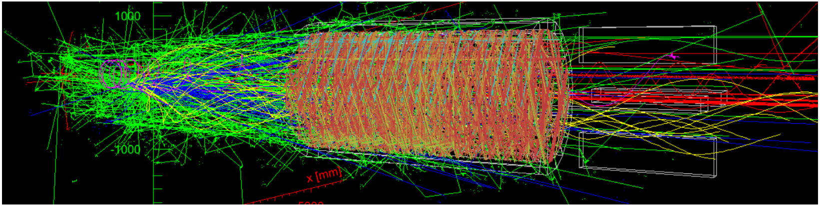


Calorimeter



- Two annular disks separated by half a “wavelength” (70cm) of electron’s helical path
  - Maximize probability to hit as least one disk
- Each disk contains 860 CsI crystals read out by SiPMs
- 5% energy, 0.5 ns time, 1 cm position measurement independent of straw tracker
- Provides particle ID for track rejection
- Can be used as seed for tracking algorithm

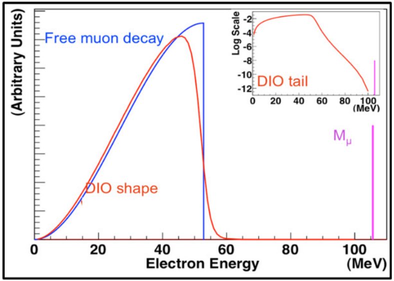
Mu2e Detector Simulation

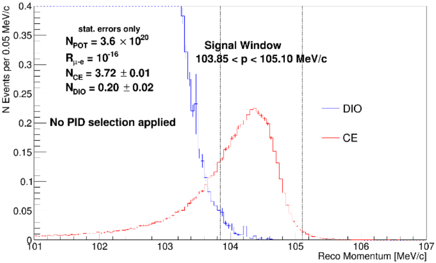


1 μs selection window after beam flash

- Detailed Geant4 simulation of full detector
- Simulate from production target forward (including backgrounds)
- Response tuned to data and detector prototype measurements

Backgrounds: Decay in Orbit

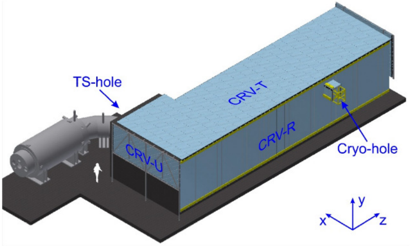


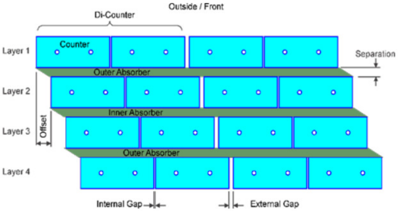


- Free muon decay has an energy cutoff at 52.8 MeV (Michel spectrum)
- DIO interactions with nucleus allow for much higher energies
  - Near endpoint fast falling slope: $(E_{\text{conv}} - E)^5$
    (Czarnecki et al., Phys. Rev. D 84, 013006 (2011))
- Spectrum from results of reconstructing full simulation
- Track reconstruction based on BaBar Kalman Filter algorithm

Backgrounds: Cosmic ray induced

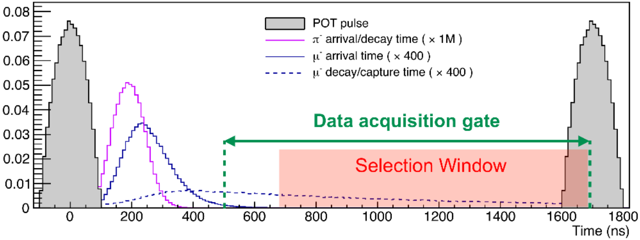
- Cosmic rays can produce delta rays or decay to electrons with the same momentum as conversion electrons
- Expect cosmic rays to produce 1 conversion-like event per day
- 4 overlapping layers of scintillator, read out on both ends with SiPMs
- Covers entire DS, half of TS, better than 10^{-4} inefficiency





Backgrounds: Radiative pion capture

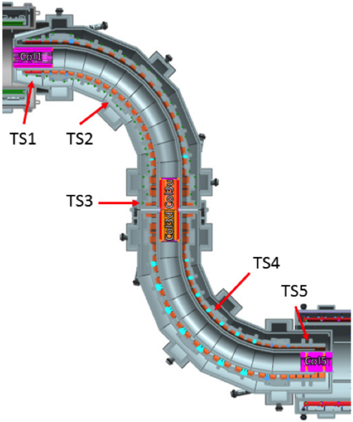
- π^- Al $\rightarrow$ Mg* + γ
- Gamma can convert, can create conversion like electrons
- Suppressed by pulsing proton beam and using delayed signal timing window



- Extinction factor (ratio of out-of-time protons to in-time protons) of 10^{-10} is needed
- 700 ns delay followed by 1 μs livegate

Backgrounds: Antiprotons

- Proton beam energetic enough to produce low energy antiprotons
- Can enter TS slowly, delayed annihilation creating late π^-
- Thin Beryllium absorber in center of TS suppresses this background

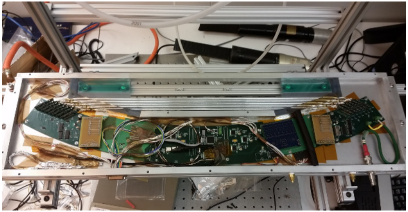


Background table and Sensitivity

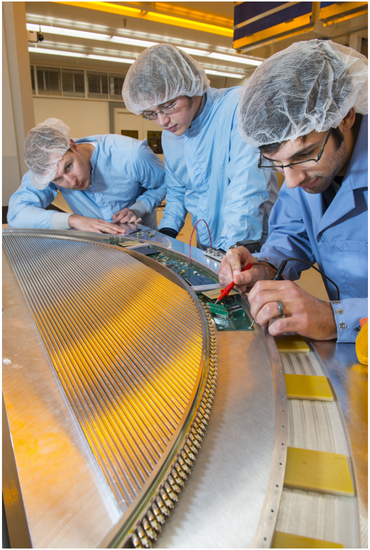
Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	0.001 ± <0.001
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10

- Fewer than $\sim$0.5 background events expected over entire run
- 3.6 x 10^{20} protons on target over 3 years $\rightarrow \sim 10^{18}$ stopped muons
- Single event sensitivity: $R_{\mu e} = 2.4x10^{-17}$
- Typical SUSY prediction of $10^{-15} \rightarrow \sim$50 signal events

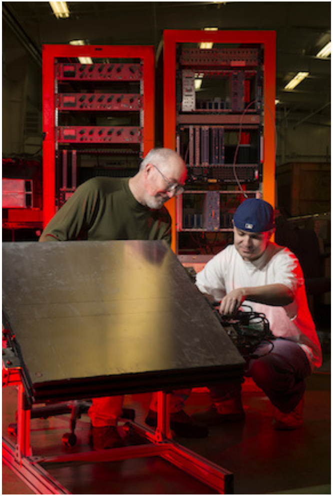
Mu2e Status: Tracker prototypes



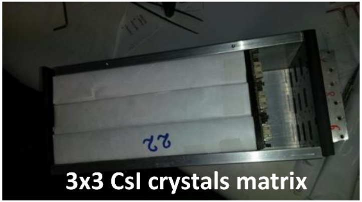
- Tracker resolution shown to meet specifications
  - $< 200\ \mu$m resolution
  - $> 95\%$ single straw hit efficiency
  - Current simulations include these results
- Prototype undergone beam and radiation tests



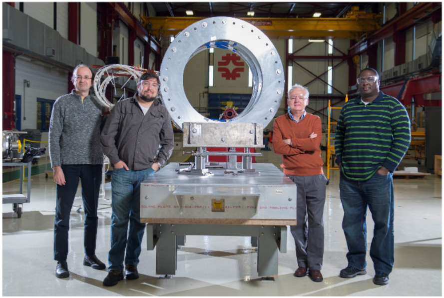
Mu2e Status: CRV, Calorimeter, Transport Solenoid prototypes



CRV prototype



Calorimeter prototype



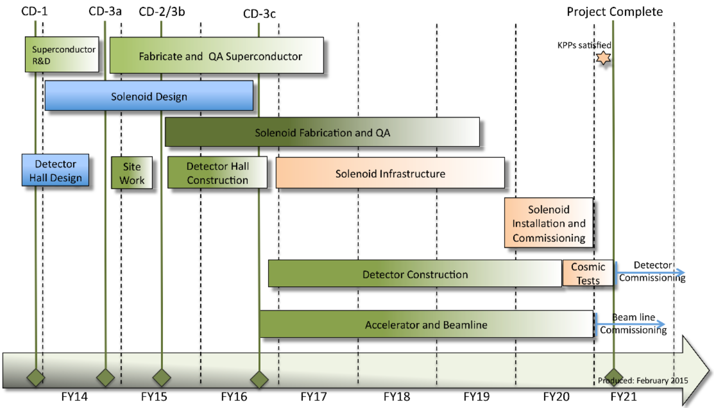
TS prototype module

Mu2e civil construction well underway

Experimental hall - March 2016

Beamline enclosure - Feb 2016

Mu2e Timeline



COMET experiment at J-PARC

High Energy Accelerator Research Organization (KEK)
Institute for Chemical Research, Kyoto University
Kyushu University
Nagoya University
Osaka University
Research Reactor Institute, Kyoto University
Saitama University
Utsunomiya University

Imperial College London
STFC Rutherford Appleton Laboratory (RAL)
University College London

Budker Institute of Nuclear Physics (BINP)
Institute of Theoretical and Experimental Physics (ITEP)
Joint Institute for Nuclear Research (JINR)

Georgian Technical University
Institute of High Energy Physics of I. Javakhishvili State University (HEPI-TSU)

Institute of High Energy Physics (IHEP)
Nanjing University
North China Electric Power University
Peking University

TRIUMF

Indian Institute of Technology (IIT)

Technical University Dresden

College of Natural Science, National Vietnam University

National Center for Particle Physics, University of Malaysia

Laboratory of Nuclear and High Energy Physics (LPNHE)
CC-IN2P3

Institute for Basic Science (IBS) and Korea Advanced Institute of Science and Technology (KAIST)

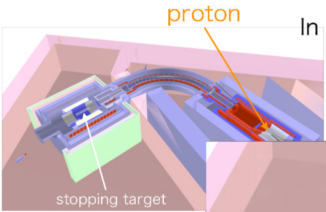
Belarusian State University
B.I. Stepanov Institute of Physics, National Academy of Science of Belarus

Charles University in Prague
Czech Technical University in Prague

King Abdulaziz University

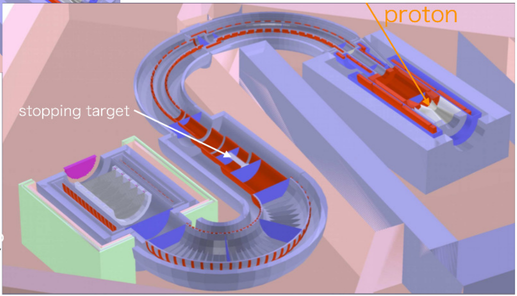
COMET Phase I and II

- 8 GeV proton beam - 100 ns wide pulses separated by 1.1 μs



In Phase-I setup

- 3.2 kW proton beam operation
- 90 degree muon transport solenoid
- CDC in a spectrometer solenoid



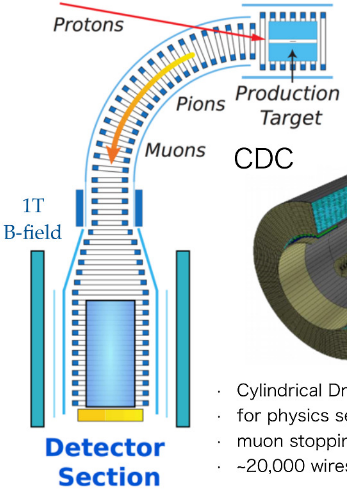
In **Phase-II** setup

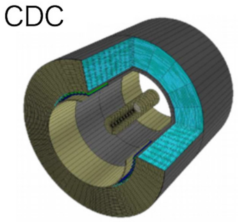
- 56 kW proton beam
- 180 degree transport solenoid for muon
- 180 degree spectrometer solenoid for electron
- StrawECAL detector

S-Shape Design in Phase-II

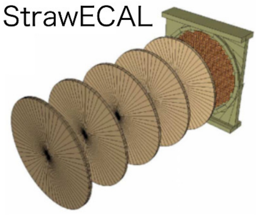
Slides from Hisataka Yoshida

COMET Phase I detector





- Cylindrical Drift Chamber
- for physics search in Phase-I
- muon stopping target at center
- ~20,000 wires with He base gas



- Straw Tracker
  + Energy Calorimeter
- for background measurement
- also as R&D for Phase-II

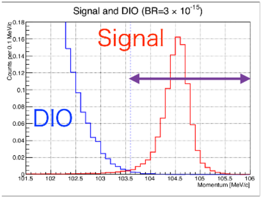
Slides from Hisataka Yoshida

COMET Phase I sensitivity

Signal Acceptance

Table 28: *Breakdown of the $\mu^- N \to e^- N$ conversion signal acceptance.*

Event selection	Value	Comments
Geometrical acceptance	0.37	
Track quality cuts	0.66	
Momentum selection	0.93	103.6 MeV/c < P_e <106.0 MeV/c
Timing window	0.3	700 ns < t < 1100 ns
Trigger efficiency	0.8	
DAQ efficiency	0.8	
Track reconstruction efficiency	0.8	
Total	0.043	



Signal Sensitivity

$$B(\mu^- + Al \to e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

- $f_{cap} = 0.6$
- $A_e = 0.043$
- $N_\mu = 1.23 \times 10^{16}$ muons

$$B(\mu^- + Al \to e^- + Al) = 3.1 \times 10^{-15} \quad \text{(S.E.S)}$$
$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

Muon intensity

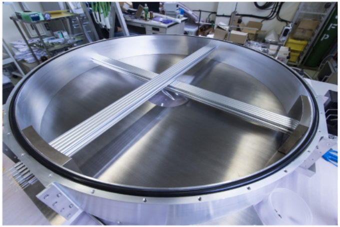
about 0.00052 muons stopped/proton

With 0.4 μA, a running time of about 110 days is needed.

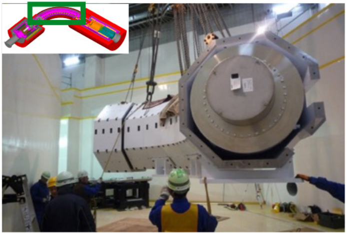
Slides from Hisataka Yoshida

COMET Phase I status

CDC



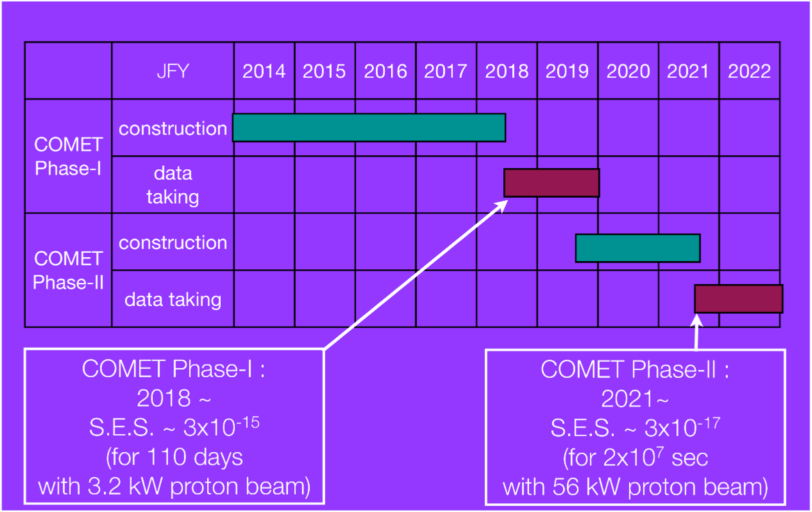
Prototype straw station



Transport system

Experimental hall

COMET Timeline



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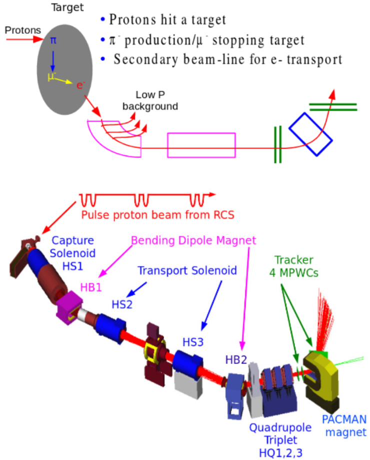
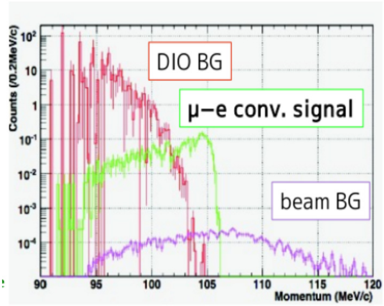
DeeMe Overview



- Planned to run at J-PARC using 3 GeV proton beam
- Thick target for production, decay, and muon stopping
- Collaboration:

Osaka University
UBC
Osaka City University
KEK Accelerator
KEK MUSE
JAEA
KEK IPNS
TRIUMF
Okayama University
PSI

DeeMe Sensitivity and status



- Plan to start data taking 2016
- SES:
  - 1×10^{-13} with Graphite target (one year)
  - 2×10^{-14} with SiC target (one year)
  - 5×10^{-15} with SiC target (four years)

Conclusion

- μ to e conversion measurements are sensitive to a broad range of models of new physics
- Any signal would be unambiguous proof of physics beyond the standard model
- Next generation experiments will increase sensitivity by a factor of 10^4

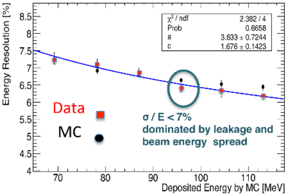
DeeMe	(2016)	SES $= 2\text{x}10^{-14}$	1 year run
COMET Phase I	(2017)	SES $= 3\text{x}10^{-15}$	110 day run
COMET Phase II	(2021)	SES $= 2.6\text{x}10^{-17}$	1 year run
Mu2e	(2021)	SES $= 2.4\text{x}10^{-17}$	3 year run

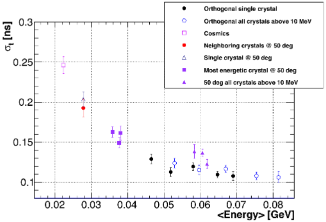
Backup

Mu2e Sensitivity

Parameter	Value
Physics run time @ 2×10^7 s/yr.	3 years
Protons on target per year	1.2×10^{20}
μ^- stops in stopping target per proton on target	0.0019
μ^- capture probability	0.609
Total acceptance x efficiency for the selection criteria of Section 3.5.3	$\left(8.5 \pm^{1.1}_{0.9}\right)\%$
Single-event sensitivity with Current Algorithms	$\left(2.87 \pm^{0.32}_{0.27}\right) \times 10^{-17}$
Goal	2.4×10^{-17}

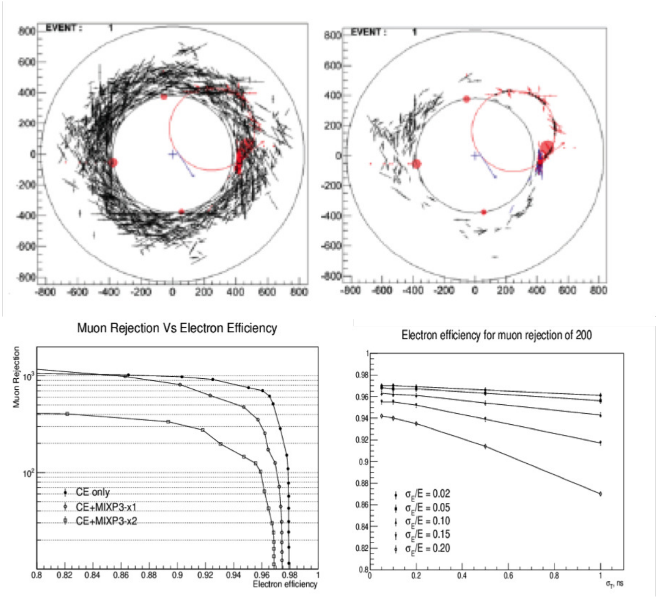
Calorimeter prototype





- 3x3 matrix of undoped CsI crystals 3x3x20 cm^3
- Tested under 80 to 120 MeV electron beam
- Energy response (7%) and time resolution (110 ps) meet specifications

Calorimeter Track Cuts



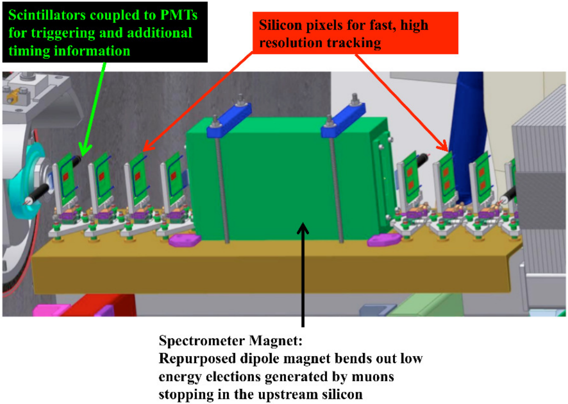
Stopping Target

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

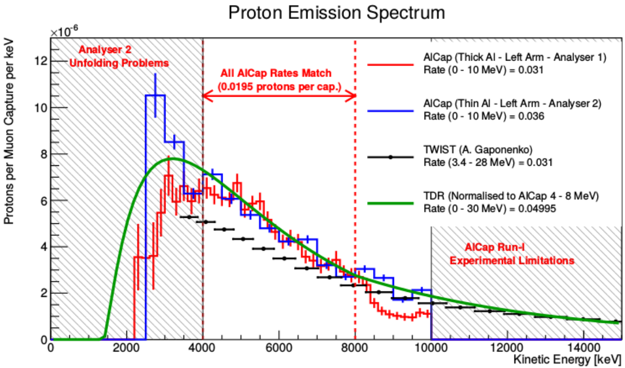
- Measure number of stopped (captured) muons to within 10%
- Detect x-rays and gammas emitted from muonic atom using HPGe
  - 2p→1s 347 keV (79.7% of stopped muons)
  - 1809 keV gamma from muon capture (delayed)
  - 844 keV gamma from ^{27}Mg decay (9.5 minute halflife)
- Series of collimators and a sweeping magnet reduce rate to tolerable levels

Extinction Monitor

- Beam coming from delivery ring starts with 10^{-4} extinction
- 2 AC dipoles coupled with collimators expected to bring up to 10^{-12}
- Monitor downstream and off-axis of production target

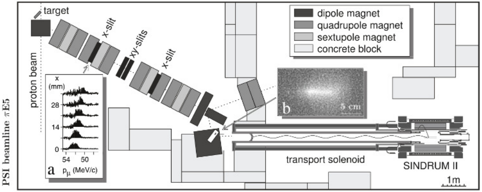


AlCap



- Joint project by Mu2e and COMET
- Measure particles emitted after muon capture on Al

SINDRUM-II



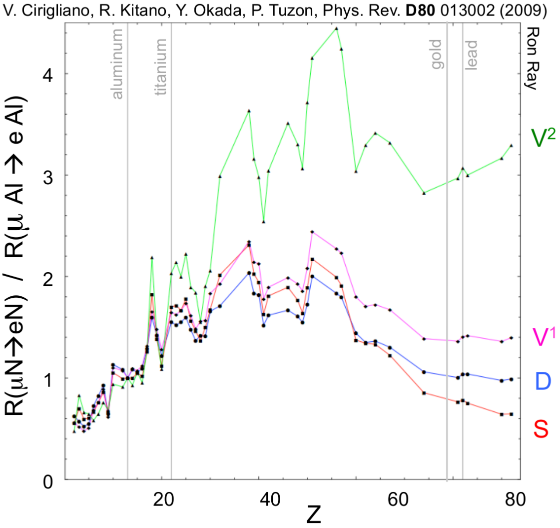
- 0.3 ns beam pulse every 19.75 ns
  - can't wait for pions to decay
  - prompt veto limits statistics
- 8 mm thick CH2 degrader
- Limit: 7x10^{-13} (90% confidence) on Au

CLFV detection processes

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

arXiv:0909.1333[hep-ph]

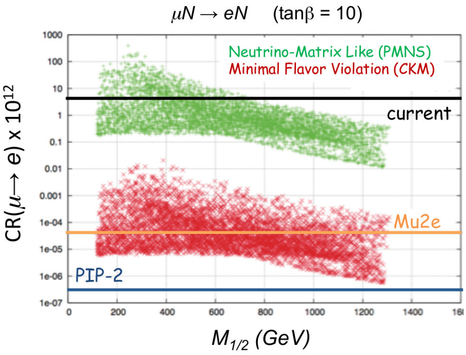
Determining model with CLFV



CLFV detection processes

Process	Current Limit	Next Generation exp.
$\tau \to \mu\eta$	BR $<$ 6.5 E-8	10^{-9} - 10^{-10} (Belle II, LHCb)
$\tau \to \mu\gamma$	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	
$B^+ \to K^+ e\mu$	BR $<$ 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR $<$ 5.7 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR $<$ 1.0 E-12	10^{-16} (PSI)
$\mu^- N \to e^- N$	$R_{\mu e} <$ 7.0 E-13	10^{-17} (Mu2e, COMET)

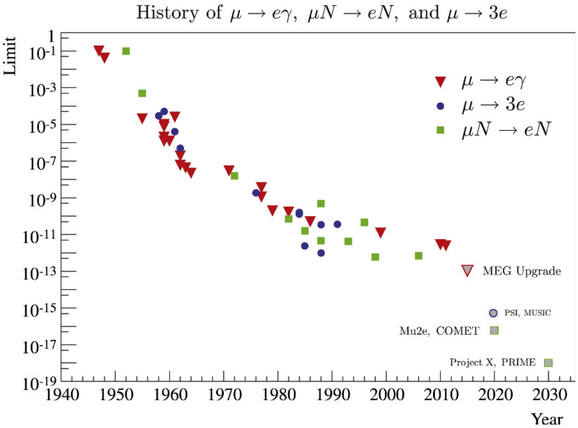
μ to e SUSY



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

- SUSY GUT in an SO(10) framework

Current Limits



R.H. Bernstein and P.S. Cooper. Phys. Rept. C 532, 2013

- Will improve upon current best limit by 4 orders of magnitude