Imperial College London

OSAKA UNIVERSITY

The COMET Muon-to-Electron Conversion Experiment

Yoshi Uchida for the COMET Collaboration

Flavour Changing and Conserving Processes 2019

Anacapri, Italy

30 August 2019

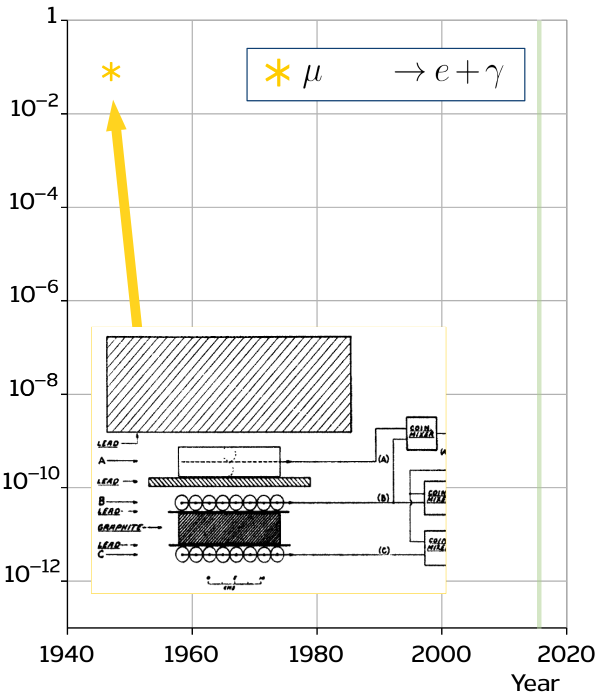
1947

Nuclear Capture of Mesons and the Meson Decay

B. PONTECORVO
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
June 21, 1947

...Returning to the actual decay of the meson, an experiment suggests itself which might answer the following question: Is the electron emitted by the meson with a mean life of about 2.2 microseconds accompanied by a photon of about 50 Mev? This experiment is being attempted at the present time, since it is felt that the available analysis[10] of the soft component in equilibrium with its primary meson component is probably insufficient to decide definitely whether the meson decays into either an electron plus neutral particle(s) or electron plus photon.

Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

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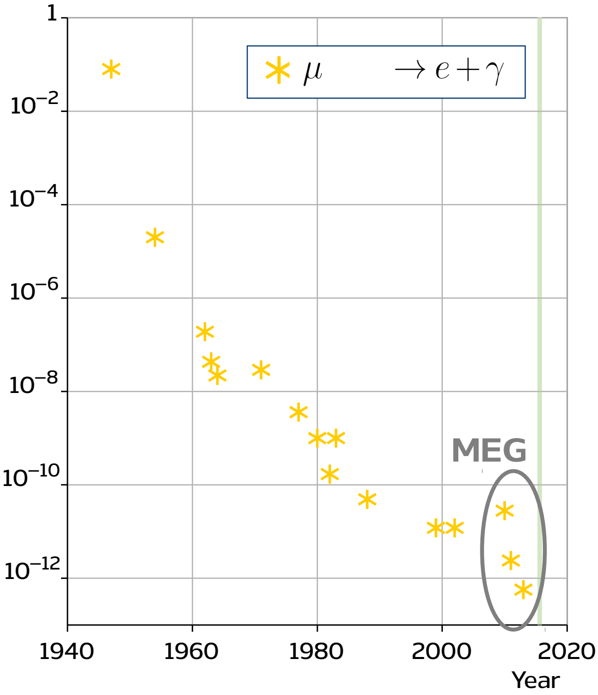

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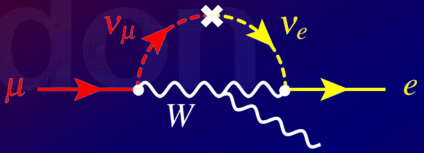
Charged Lepton Flavour Violation

From Beyond-the-Standard Model Physics

- Such as the introduction of non-zero neutrino masses to the SM:



- but this is GIM-suppressed because of the closeness of the neutrino masses:

$$B(\mu \to e + \gamma) = \frac{3\alpha}{32\pi} \left| \sum_\ell V^*_{\mu\ell} V_{e\ell} \frac{\Delta m^2_{\nu_\ell}}{m^2_W} \right|^2$$

- if CLFV is seen: ***unambiguous new physics discovery***
- no SM backgrounds with uncertainties
- for other Beyond-the-SM physics, cancellations need not occur; signal can be much larger

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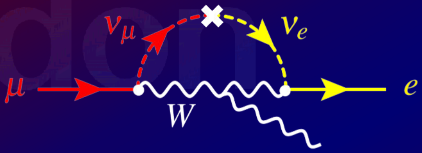

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$$B(\mu \to e + \gamma) \sim 10^{-54} \times \frac{\sin^2 2\theta_{13}}{0.15}$$

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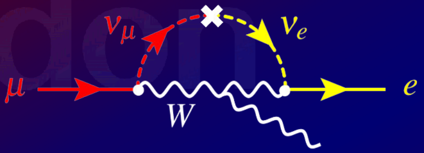

- but this is GIM-suppressed because of the closeness of the neutrino masses:

$$B(\mu \to e + \gamma) \sim 10^{-54} \quad \left(\sim \frac{m_\mu}{30 m_\oplus} \right)$$

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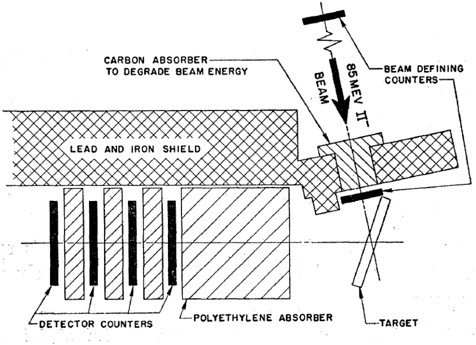
1955

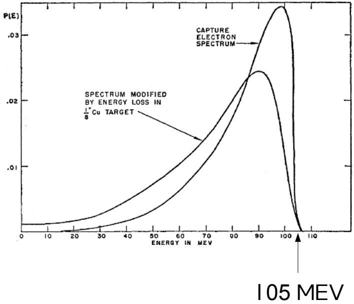
Electrons from Muon Capture*

J. STEINBERGER AND HARRY B. WOLFE
Columbia University, New York, New York

(Received August 31, 1955)

We have searched for the process $\mu^- + p \rightarrow p + e^-$ or $\mu^- + n \rightarrow n + e^-$ for μ mesons stopped in a Cu target. Scintillation counters were employed to detect the electrons from the process. No counts attributable to the electrons were obtained and we place an upper limit of $\sim 5 \times 10^{-4}$ for the relative rate of this process to that for the usual nuclear capture reaction.





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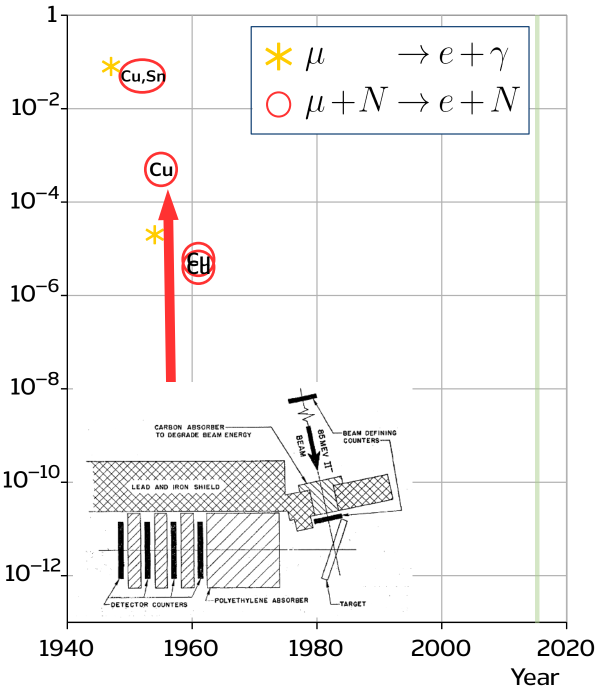

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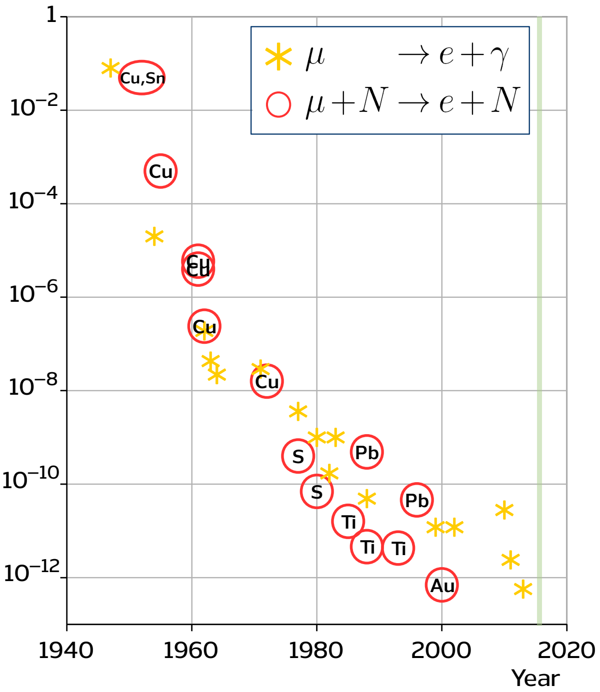

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Muon-to-Electron Conversion

Search for the process:

$$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$$

muonic atom

mono-energetic electron

Time available: up to about 1 μs (864 ns for Al)

$$\begin{aligned} E_e &= m_\mu \\ &- E_{\text{binding}} - E_{\text{recoil}} \\ &= 104.97 \text{ MeV for Al} \end{aligned}$$

Observed signal will be smeared because of detector effects

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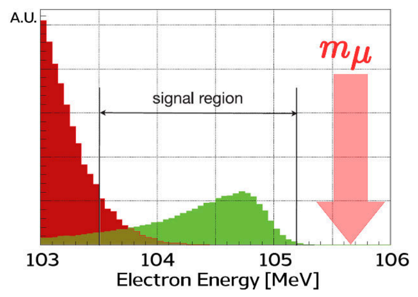
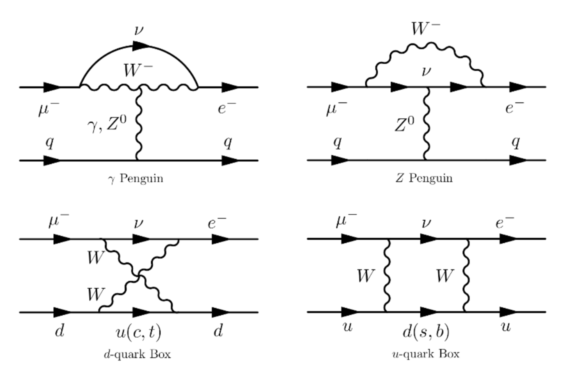


Why Search for Muon-to-Electron Conversion?

instead of only $\mu \to e + \gamma$

- $\mu \to e + \gamma$ requires BSM coupling with on-shell photon
- For muon-to-electron conversion, nuclear environment provides other potential ways to couple:



Adapted from B. Krikler, PhD Thesis 2017, Imperial College

Contributions from the SM with non-zero neutrino masses inserted

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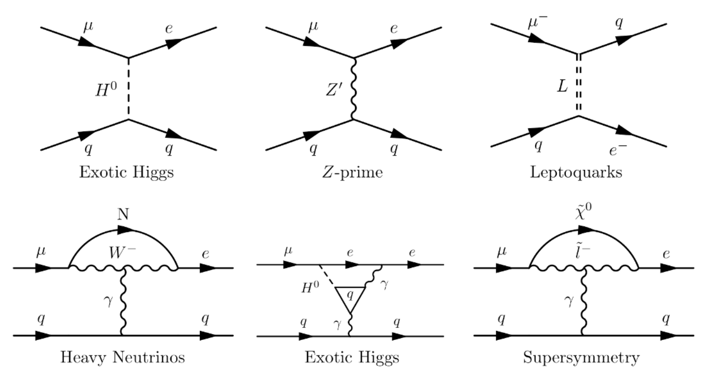

Adapted from B. Krikler, PhD Thesis 2017, Imperial College

Contributions from further BSM Physics beyond neutrino masses

How do we look for Muon-to-Electron Conversion?

compared to $\mu \to e + \gamma$

$\mu \to e + \gamma$

- Require ***free*** muons: μ^+
- Coincidence measurement
  - background suppression from coincidence
  - need good detector resolutions (timing/kinematics)
  - higher instantaneous intensity more difficult

$\Rightarrow$ continuous-wave beam

Muon-to-electron conversion

- Require ***bound*** muons: μ^-
- Single signal particle
  - no intrinsic SM backgrounds
  - background suppression through delay and energy
  - no accidental coincidences; high intensity acceptable

$\Rightarrow$ pulsed beam with delayed signal timing window

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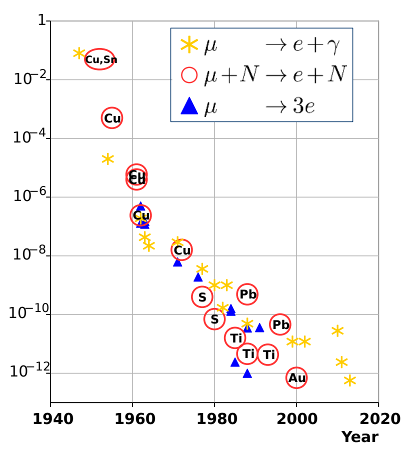
Muon-to-Electron Conversion

current status

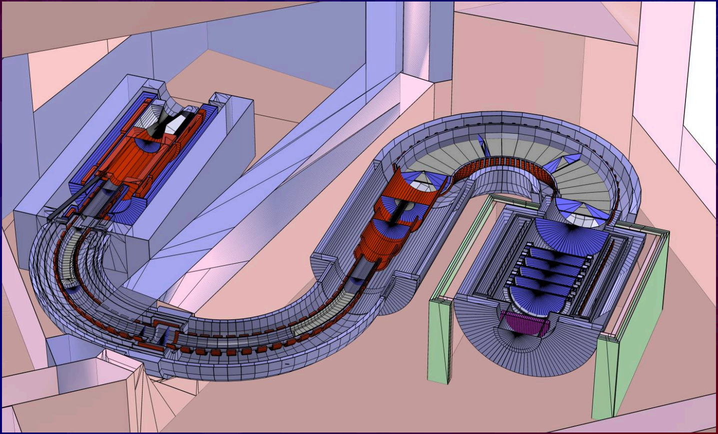
- Present limit from the SINDRUM-II experiment at PSI (2006)
    - from data taken in 2000, with Au as the target
    - CR($\mu + \text{Au} \rightarrow e + \text{Au}$) $< 7 \times 10^{-13}$ (90% C.L.)
- No new results since then
- Three experiments currently under construction
    - DeeMe at J-PARC
    - COMET at J-PARC
    - Mu2E at Fermilab



(including another complementary channel, $\mu \rightarrow 3e$)

The COMET Muon-to-Electron Conversion Experiment

Superconducting solenoidal channel from 5 T (pion production) gradually decreasing to 1 T



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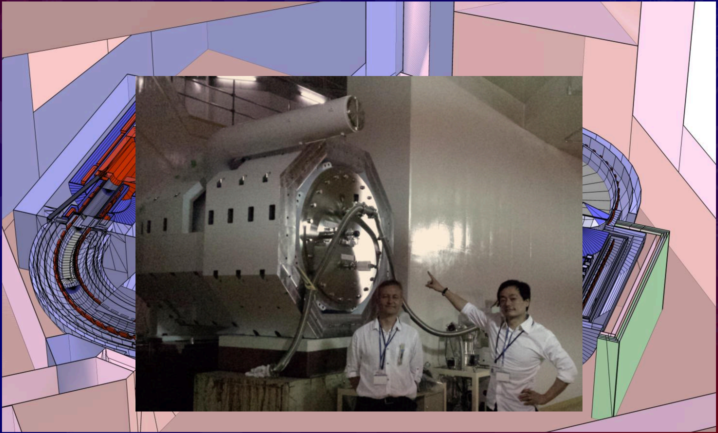
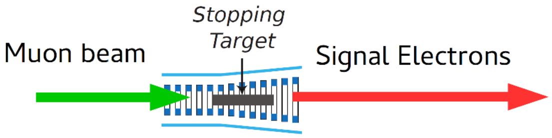
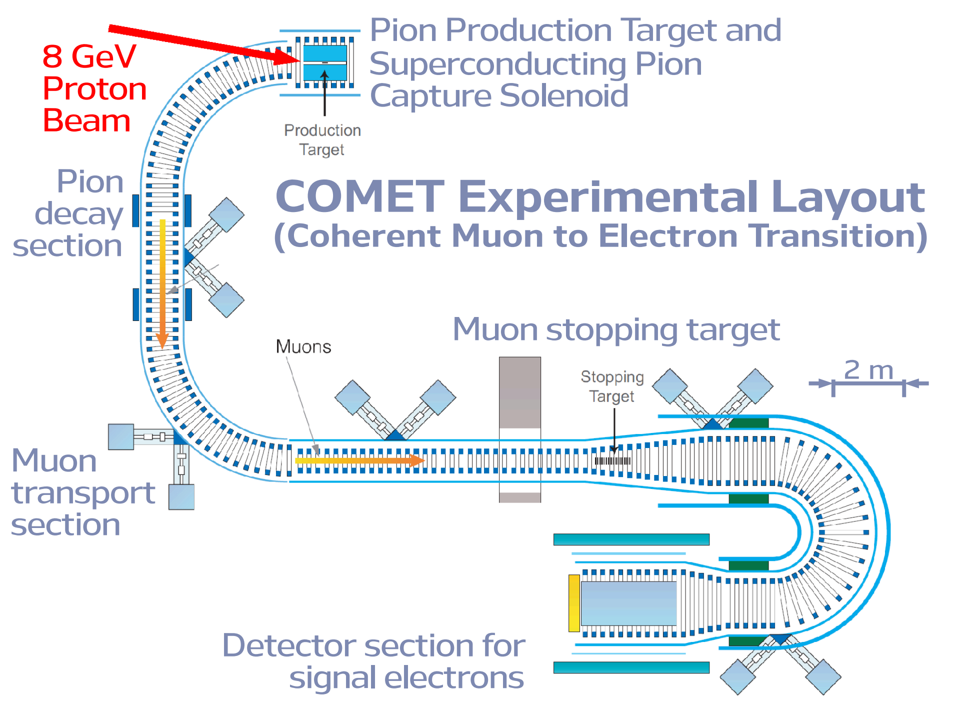
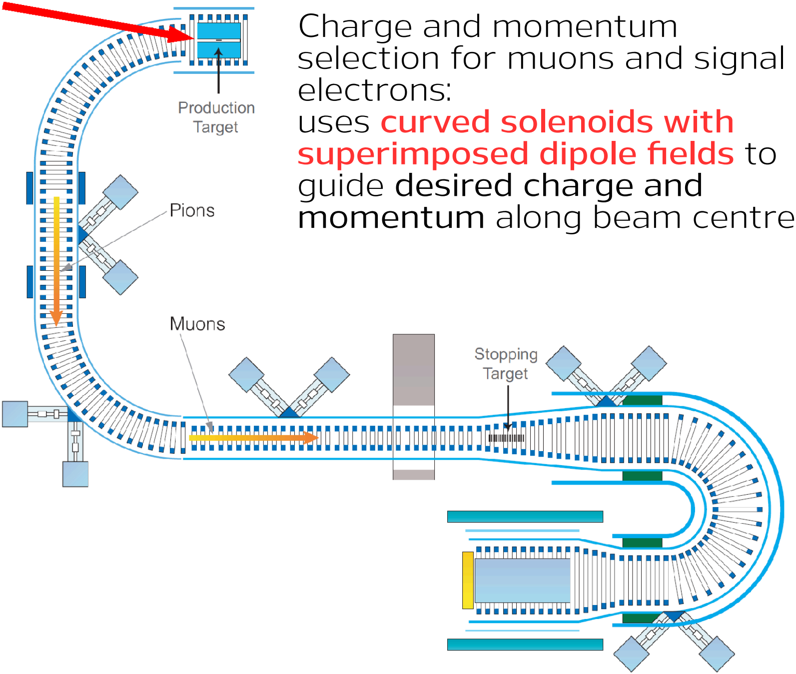


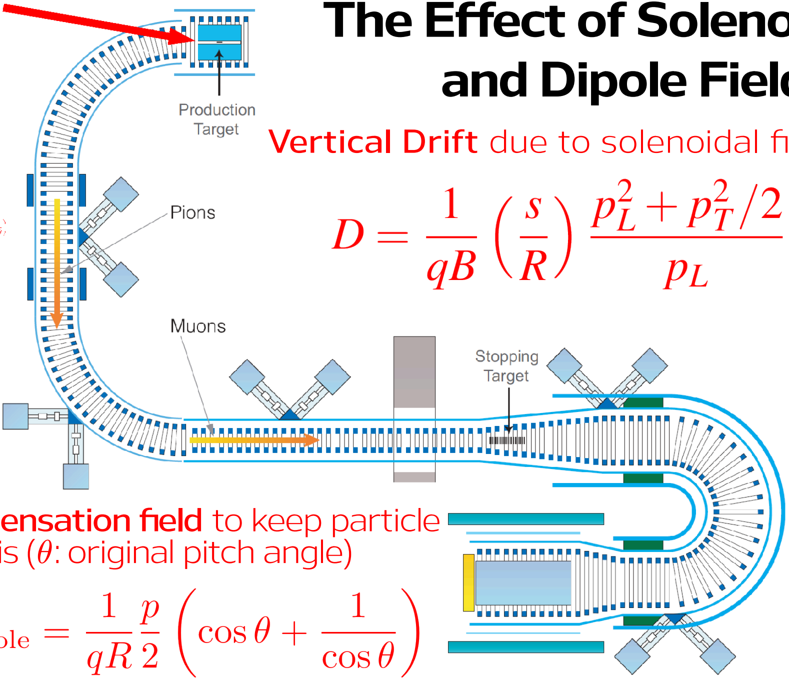

Stopping
Target
Muon beam
Signal Electrons


8 GeV Proton Beam
Pion Production Target and Superconducting Pion Capture Solenoid
Production Target
COMET Experimental Layout
(Coherent Muon to Electron Transition)
Pion decay section
Muon stopping target
Muons
Stopping Target
2 m
Muon transport section
Detector section for signal electrons

Charge and momentum selection for muons and signal electrons:
uses **curved solenoids with superimposed dipole fields** to guide **desired charge and momentum** along beam centre



The Effect of Solenoid and Dipole Fields



Vertical Drift due to solenoidal field:

$$D = \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p_L^2 + p_T^2/2}{p_L}$$

Compensation field to keep particle on-axis (θ: original pitch angle)

$$B_{\mathrm{dipole}} = \frac{1}{qR}\frac{p}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

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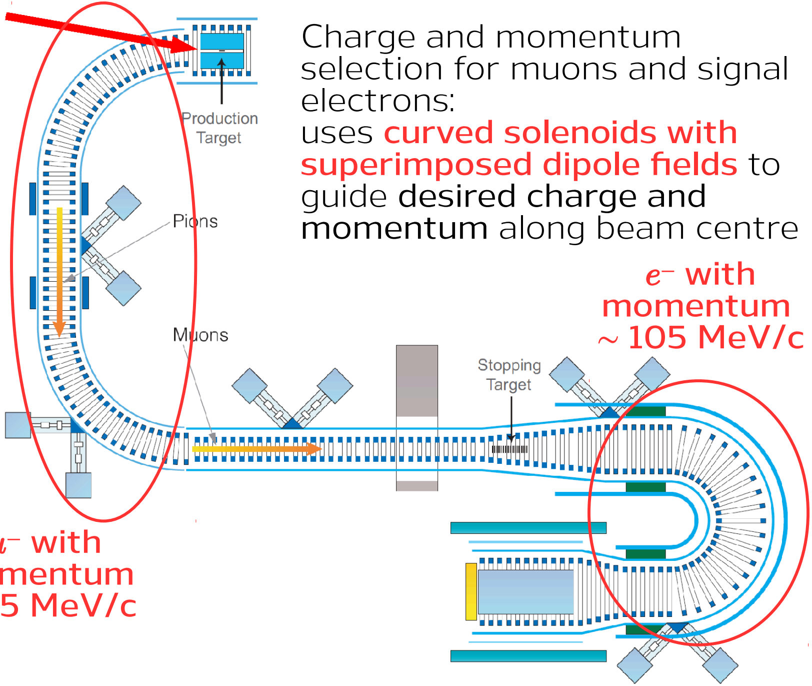

e^- with momentum ~ 105 MeV/c

μ^- with momentum < 75 MeV/c

Motion of Charged Particles in Magnetic Fields

Uniform B-Field

- Negatively-charged particle
- Initial direction to the right and 6 degrees into the plane
- Uniform B-Field
- "Inside a straight solenoid"

Motion of Charged Particles in Magnetic Fields

B-Field with a Gradient

- B-Field still parallel, but magnitude varies
- Stronger to the left, weaker to the right

Motion of Charged Particles in Magnetic Fields

B-Field with a Gradient

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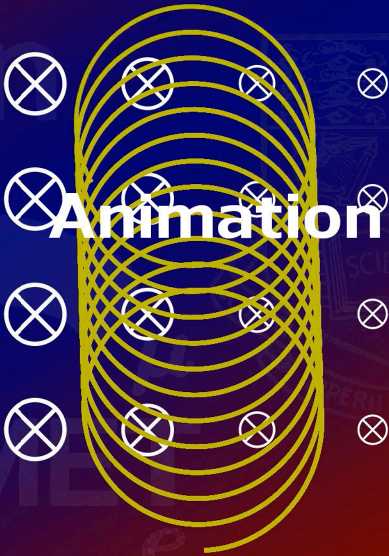
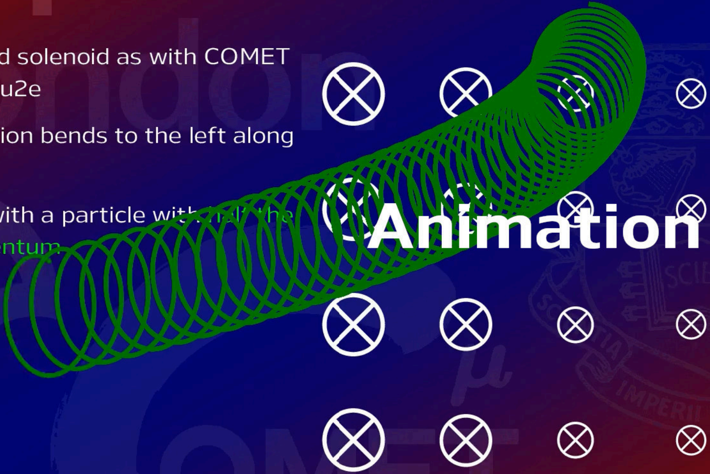
- Stronger to the left, weaker to the right
- Now for a particle of the ***opposite charge***



Motion of Charged Particles in Magnetic Fields

B-Field in a Curved Solenoid

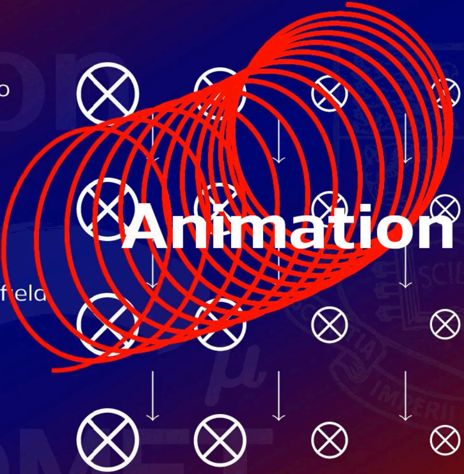
- Curved solenoid as with COMET and Mu2e
- Direction bends to the left along field
- Also with a particle with half the momentum



Motion of Charged Particles in Magnetic Fields

B-Field in a Curved Solenoid with a Compensating Field

- Curved solenoid with compensating field unique to COMET
- Vertical compensating field (dipole field) superimposed
- Particle remains the same
- ***Gradually increasing*** dipole field



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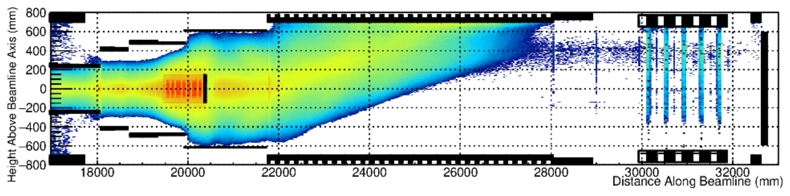
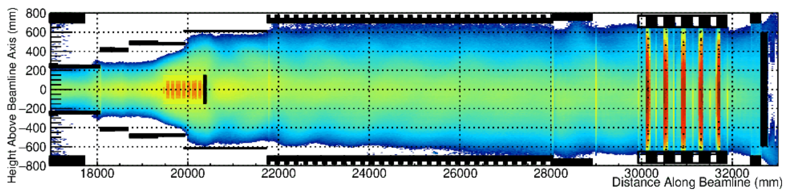
COMET Phase-II

“Steering of signal (105 MeV) electrons”



Vertical compensation/steering fields OFF

B. Krikler, PhD Thesis, 2017



Vertical compensation/steering fields ON

B. Krikler, PhD Thesis, 2017

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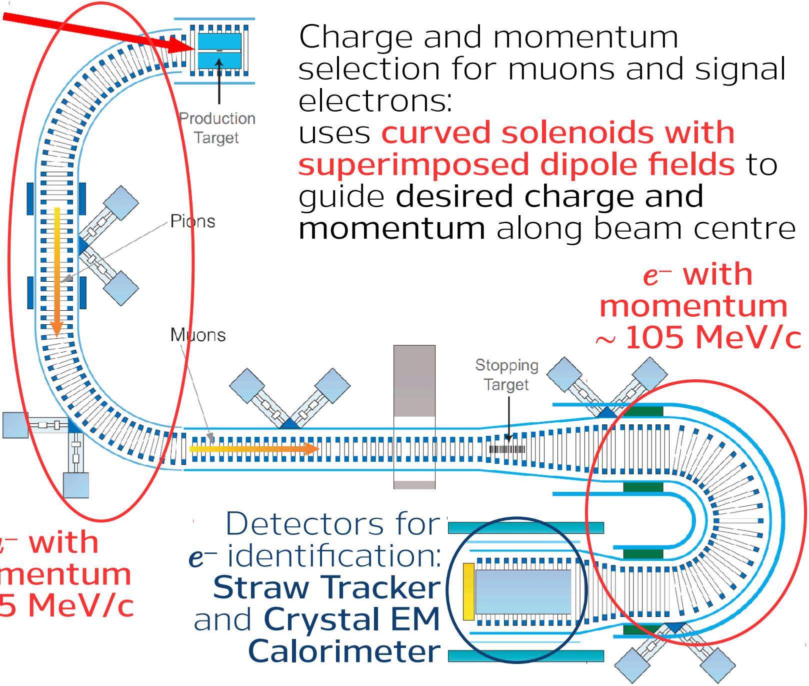
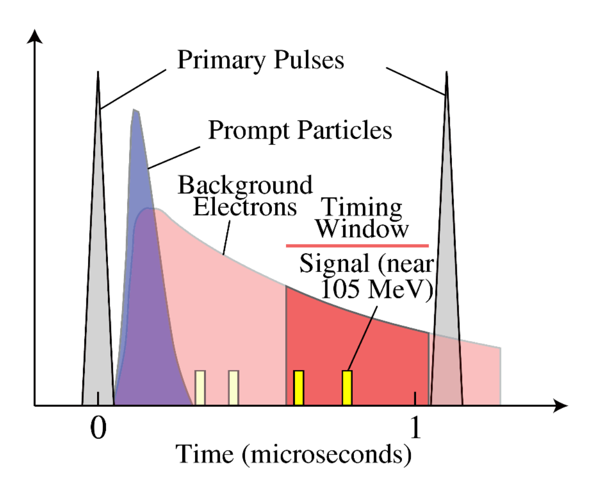


COMET: Pulsed Proton Beam

Background Suppression Through Timing



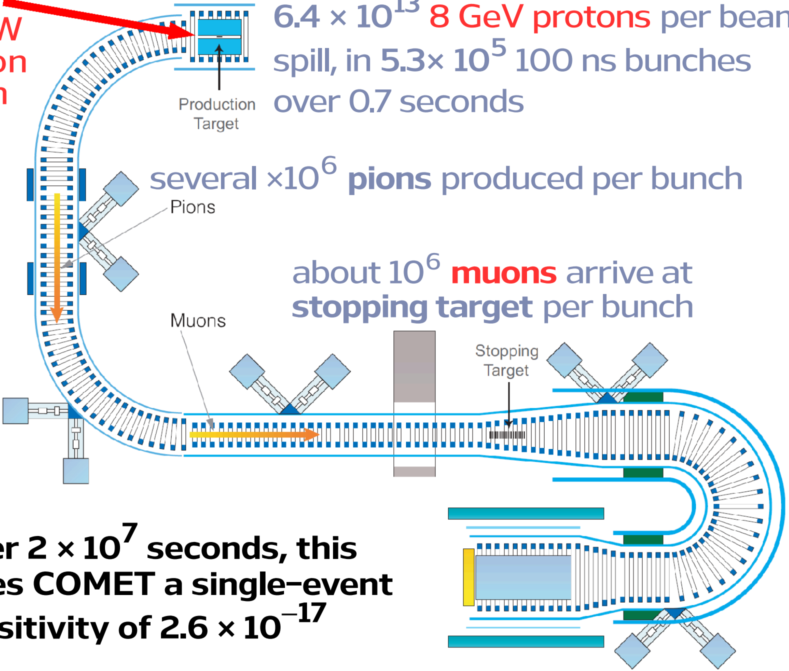
Time profile of COMET beam and signal window

56 kW proton beam

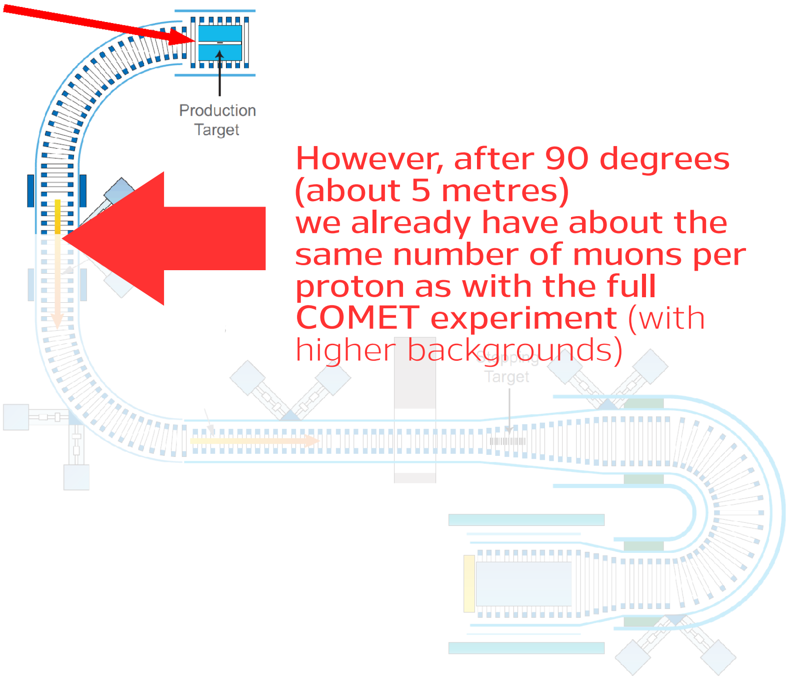
6.4×10^{13} 8 GeV protons per beam spill, in 5.3×10^{5} 100 ns bunches over 0.7 seconds

several $\times 10^{6}$ **pions** produced per bunch

about 10^{6} **muons** arrive at **stopping target** per bunch



Over 2×10^{7} seconds, this gives COMET a single-event sensitivity of 2.6×10^{-17}



However, after 90 degrees
(about 5 metres)
we already have about the
same number of muons per
proton as with the full
COMET experiment (with
higher backgrounds)

COMET Phase-I

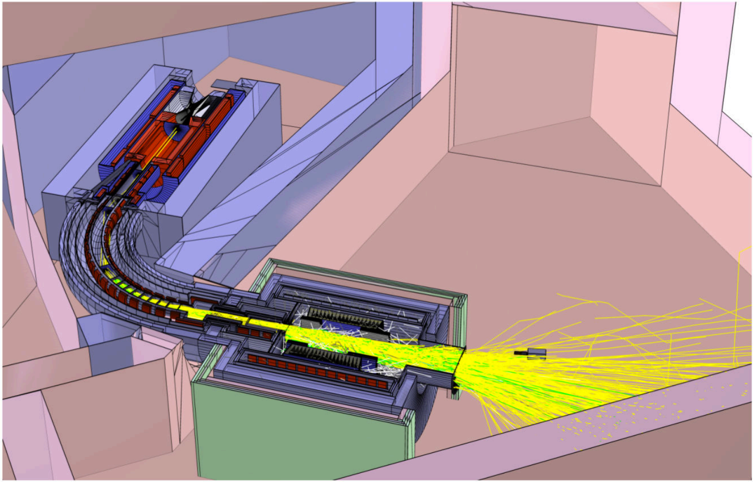
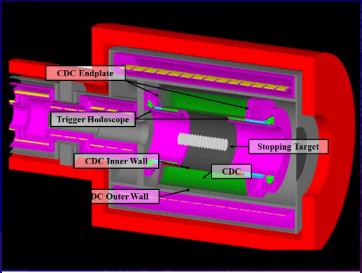


Figure 4.2.: Phase-I event display of 8e6 proton-on-target events, one half of a bunch, in the CyDet system. This image also includes the experimental hall in which the Phase-I beamline is placed. Only the trajectories that reach the Detector Solenoid are rendered.

E. Gillies, PhD Thesis, 2018

COMET Phase-I Detectors: CyDet

The Cylindrical Detector, specifically designed for Phase-I physics measurements. Consists of the:

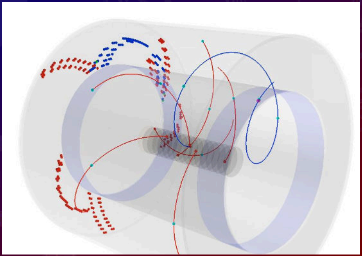


Cylindrical Drift Chamber (CDC)

- All-stereo layers: z information for tracks
- Helium-based gas to minimize multiple scattering
- Large inner bore to avoid beam flash and lower-energy electrons.

Cylindrical Trigger Hodoscope (CTH)

- Plastic scintillator layers for timing
- Cherenkov layers for electron tagging

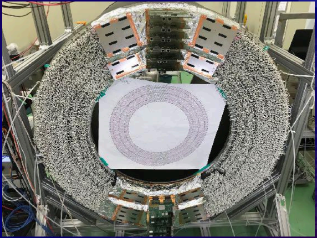


COMET Phase-I Detectors: CyDet

Status

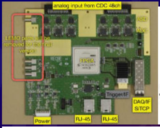
Detector

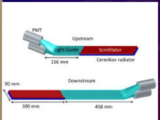
- Prototype tests in 2015; 150 micron spatial resolution, 99% hit efficiency
- Main drift chamber completed in 2016
- Undergoing cosmic ray tests



Front-end electronics

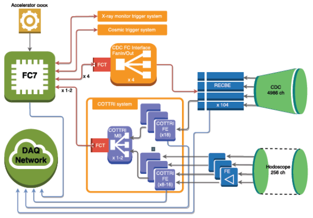
- Based on Belle-II boards
- 108 boards completed and tested
- Radiation testing paper to be published





Trigger system

- Hodoscope mechanical designs being finalised
- Trigger logic and board design (FC7-based) finalised and being tested



COMET Phase-I Detectors: StrECAL

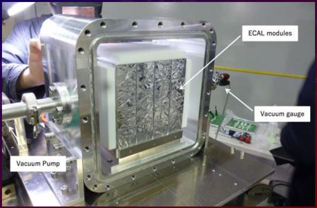
Straw-Tube Tracker and ECAL System. Primarily for studying muon beam characteristics, but conceptually identical to Phase-II physics detector
Consists of the:

Straw-Tube Tracker

- Vacuum tests with **20 micron-thick tube walls**
- Phase-I Production run complete
- 150 micron resolution with 100 MeV electron beam

Electromagnetic Calorimeter

- GSO and LYSO crystals tested
- LYSO chosen (4.6% resolutions)



Front-end electronics

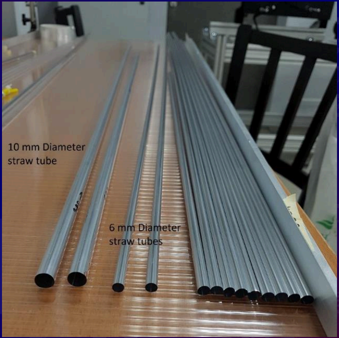
- Design complete
- Radiation test results published

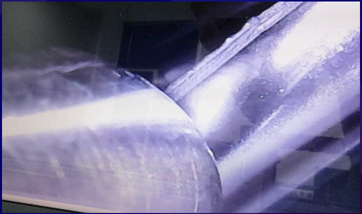
COMET Phase-II Detector R&D

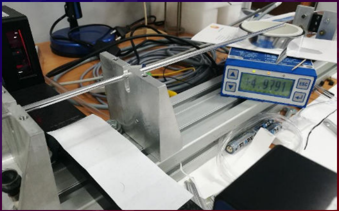
Straw-Tube Tracker

Successfully developed tubes with ***12 micron-thick walls***

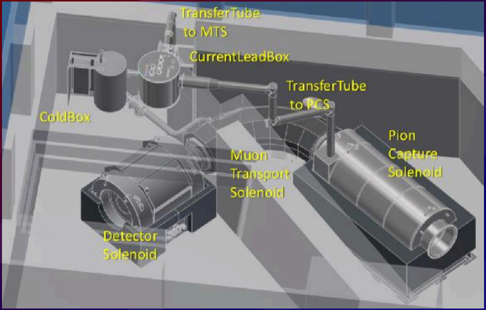
- Diameter 5 mm (half of Phase-I)
- Overpressure of 1 bar: 0.1 micron-level accuracy
- Tested at more than 4 bar overpressure







COMET Solenoids

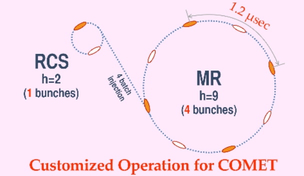


- Pion capture solenoid: final coil being wound
- Transport solenoid: installed and ready for cryogenics tests
- “Bridge” solenoid: coil delivered
- Detector solenoid: coil and cryostat ready
- Cryogenic system: Refrigerator tests completed, He transfer tube being built

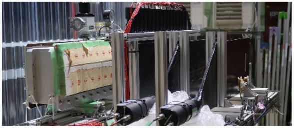
Accelerator Status and Inter-Bunch Beam Extinction

as reported by H. Nishiguchi at IPAC19, May 2019

- J-PARC Main Ring Synchrotron needs to run in dedicated configuration:
  - 8 GeV operation (not 30 GeV)
  - 1.2 μs bunch separation (0.6 μs)
  - Fraction of protons arriving between bunches, the **extinction rate**, should be less than $\mathbf{10^{-10}}$
- Beam extinction is a quantity that is not normally controlled strongly
- MR injection kicker timing adjusted to ensure good extinction
- Measurements made using actual beam configurations
- Ability to run at extinction levels of better than $\mathbf{6 \times 10^{-11}}$ demonstrated



【MR Abort Line】 【Abort Monitor】



【Hodoscopes in Secondary Beam Line】

⇒ "J-PARC MR is ready for COMET" (H. Nishiguchi, KEK/J-PARC)

Other Possible Physics Channels at COMET

$\mu^- + N(Z) \to e^+ + N(Z-1)$

- Lepton number-violating channel
- Difficult with Al target, but other choices may help
- Phys. Lett. B422 334 (1998)
- Phys. Lett. B764 157 (2017)
- Phys. Rev. D96 075027 (2017)

$\mu^- + e^- \to e^- + e^-$

- CLFV channel
- proportional to Z^3
- Phys. Rev. Lett. 105 (2010)
- Phys. Rev. D93 076006 (2016)
- Phys. Rev. D97 015017 (2018)

$\mu^- \to e^- + X$

- X can be a new light boson or axion etc.
- feasibility being studied
- See Uesaka at KEK-PH2018

COMET Phases I and II

Over 150 collaborators from 41 institutions in 17 countries:

- Proton beam to arrive at upstream point of COMET in early 2020
- **Phase-I data-taking over five months** ($\times$100 improvement over present)
- **Phase-II data-taking over one year** ($\times$10000 improvement over present)
- Further Phase-II optimisation underway; likely to improve sensitivity by a further factor of 10 for the same beam power

Z-Dependence of Muon-to-Electron Conversion

Disentangling the BSM Physics

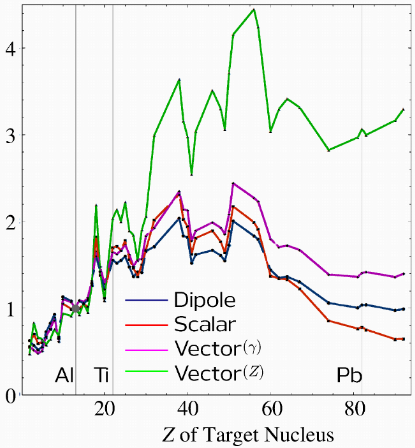
Z-Dependence of Muon-to-Electron Conversion

- differs according to type of New Physics interaction

Relative dependences of the muon-to-electron conversion branching ratio on the target nucleus

For different nuclei, different

size of nucleus,
radius of orbit,
u- and d-quark composition



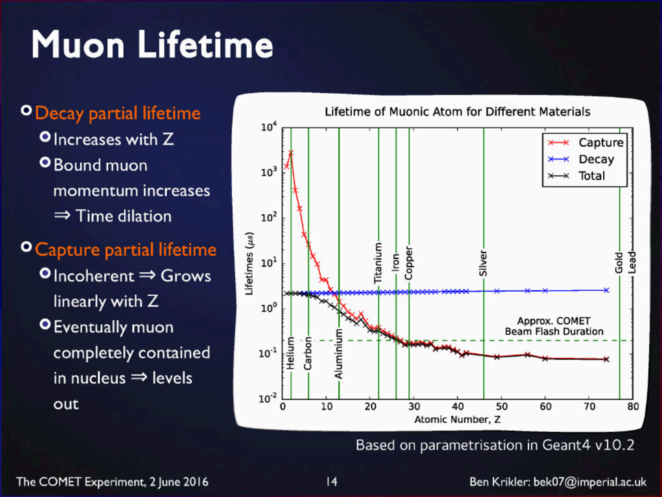
V. Cirigliano et al., Phys. Rev. D 80, 013002 (2009)

Z-Dependence of Muon-to-Electron Conversion

Disentangling the BSM Physics

Z-dependence of the bound muon lifetime

- Competing effects on bound muon lifetime
- Becomes very short above, say, Titanium or Iron



Ben Krikler

COMET Phase-I TDR 2019

List of Backgrounds

Summary of the estimated background events for a single-event sensitivity of 3×10^{-15} in COMET Phase-I with a proton extinction factor of 3×10^{-11}.

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Antiproton-induced backgrounds	0.0012
Others	Cosmic rays[†]	< 0.01
Total		0.032

Official Timeline for Muon CLFV Experiments