Search for Coherent Muon-to-Electron Transition (COMET) at a sensitivity better than $10^{-16}$

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On behalf of the COMET collaboration

NuFact ‘11 – 01/08/11
Motivation – Lepton Flavour Violation

- Lepton flavour conservation is a fundamental property of the Standard Model (SM).
- LFV of neutrinos has been confirmed.
- LFV of charged leptons is unobserved.
- The SM predicts a branching ratio for LFV processes of $O(10^{-50})$. An example of such a process is:

$$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

- New Physics models (SUSY, GUTs, etc.) increase this BR dramatically to $\approx 10^{-15}$.
- LFV experiments may therefore provide a complimentary probe to beyond SM physics at the LHC, having reach beyond the TeV scale.
Motivation – Charged Lepton Flavour Violation

<table>
<thead>
<tr>
<th>process</th>
<th>present limit</th>
<th>near future</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \to e\gamma$</td>
<td>$1.2 \times 10^{-11}$</td>
<td>$10^{-13}$</td>
<td>MEG at PSI</td>
</tr>
<tr>
<td>$\mu \to eee$</td>
<td>$1.0 \times 10^{-12}$</td>
<td>$10^{-14} - 10^{-15}$</td>
<td>PSI and MUSIC ?</td>
</tr>
<tr>
<td>$\mu N \to eN$ (in Ti)</td>
<td>$7 \times 10^{-13}$</td>
<td>$10^{-18}$</td>
<td>PRISM</td>
</tr>
<tr>
<td>$\mu N \to eN$ (in Al)</td>
<td>none</td>
<td>$10^{-16}$</td>
<td>COMET and Mu2e</td>
</tr>
<tr>
<td>$\tau \to e\gamma$</td>
<td>$1.1 \times 10^{-7}$</td>
<td>$10^{-8} - 10^{-9}$</td>
<td>super B factory</td>
</tr>
<tr>
<td>$\tau \to eee$</td>
<td>$2.7 \times 10^{-7}$</td>
<td>$10^{-8} - 10^{-9}$</td>
<td>super B factory</td>
</tr>
<tr>
<td>$\tau \to \mu\gamma$</td>
<td>$6.8 \times 10^{-8}$</td>
<td>$10^{-8} - 10^{-9}$</td>
<td>super B factory</td>
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<tr>
<td>$\tau \to \mu\mu\mu$</td>
<td>$2 \times 10^{-7}$</td>
<td>$10^{-8} - 10^{-9}$</td>
<td>super B factory</td>
</tr>
</tbody>
</table>

- $\mu \to e\gamma$ and $\mu \to eee$ processes suffer heavily from accidental backgrounds of daughter particles and are thus limited to $O(10^{-13})$.

- Therefore conversion experiments, utilising the process

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

are required as they search for single, monoenergetic signal electrons.

- The large number of muons available ($\approx 10^{18} \mu/yr$) results in a ‘high’ sensitivity to LFV.
## New Physics search rating

<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>δLL</th>
<th>FBMSSM</th>
<th>LHT</th>
<th>RS</th>
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</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow \bar{D}^0$</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>$e_K$</td>
<td>★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
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<td>★</td>
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<tr>
<td>$S_{\phi}$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
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<tr>
<td>$S_{\delta K_3}$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
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<td>★★★</td>
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<tr>
<td>$A_{CP}(B \rightarrow X_s \gamma)$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
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<tr>
<td>$A_{\tau,8}(B \rightarrow K^+ \mu^+ \mu^-)$</td>
<td>★</td>
<td>★</td>
<td>★</td>
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<tr>
<td>$A_{\theta}(B \rightarrow K^\ast \mu^+ \mu^-)$</td>
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</tr>
<tr>
<td>$B \rightarrow K(\eta)\nu\bar{\nu}$</td>
<td>★</td>
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<td>★★★</td>
<td>★★★</td>
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<td>★★★</td>
</tr>
<tr>
<td>$B_s \rightarrow \mu^+ \mu^-$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
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<td>$K^+ \rightarrow \pi^+ \nu\bar{\nu}$</td>
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<tr>
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<tr>
<td>$\mu \rightarrow e\gamma$</td>
<td>★★★</td>
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</tr>
<tr>
<td>$\tau \rightarrow \mu\gamma$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$\mu + N \rightarrow e + N$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
</tbody>
</table>

Table 8: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models. ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.  

- **Different SUSY and non-SUSY new physics models.**

- **All three stars for muon-to-electron conversion in an atom.**
What is muon-to-electron conversion?

1s state in a muonic atom

Muon-to-electron conversion
\[ \mu^- + (A, Z) \rightarrow e^- + (A, Z) \]

Beyond Standard Model Process

Signal:
A single mono-energetic electron with energy

\[ E_e = m_\mu - B_\mu (\text{Al}) \approx 105 \text{MeV} \]

Muon decay in orbit (DIO)
\[ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \]

Muon coherent capture (MC)
\[ \mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1) \]

Standard Model Processes

Other backgrounds:
- Prompt background
- Muon decay in flight (DIF)
- Beam electrons
Current status of cLFV

SINDRUM-II at PSI (target – Au)
Muon beam intensity $\sim 10^{7-8}$/sec
Upper limit of $7 \times 10^{-13}$
✓ published result 2004

MEG at PSI ($\mu^+ \rightarrow e^+ \gamma$)
Upper limit of $2.4 \times 10^{-12}$
✓ published result 2011

COMET at J-PARC (target – Al)
Muon beam intensity $\sim 10^{11}$/sec
Proposed sensitivity of $< 10^{-16}$

(SINDRUM results published in 2004)
Improvements (background rejection)

Beam-related backgrounds

Beam pulsing with separation of 1 μsec

Muon DIO background

Curved solenoids and DIO beam scrapers

Muon DIF background

Curved solenoids for momentum selection

Muon extinction = #protons between pulses/#protons in a pulse < 10⁻⁹

vastly decreases prompt background

improve electron energy resolution

eliminate energetic muons (>75 MeV/c)
The COMET (J-PARC - E21) Experiment

- **COherent Muon-to-Electron Transition** experiment.

- COMET / PRISM is a two stage experiment with a proposed sensitivity to cLFV of $10^6$ times better than current limits.

- Unique curved solenoidal beamline design for momentum selection.

- Pion capture and muon transport by novel superconducting solenoid system.

$$BR(\mu^- + A_1 \rightarrow e^- + A_1) < 10^{-16}$$
COMET Collaboration List

80 people from 20 institutes (March 2011)

**Imperial College London, UK**
- A. Kurup, J. Pasternak,
- Y. Uchida, P. Dauncey,
- U. Egede, P. Dornan

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**University of Glasgow**
- P. Soler

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- G. Macharashvili, J. Pontecorvo,
- B. Sabirov, Z. Tsamalaidze,
- and P. Evtuikhovich

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- Fedotovich, A. Ryzhanikov, D.
- Shemyakin

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**Institute for Nuclear Science and Technology**
- T.H. Hoang
- Chau Vau Tao

**University of Science, HoChi Minh**

**University of Malaya**
- Wan Ahmad Tajuddin

**University Technology Malaysia**
- Md. Imam Hossain

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**Department of Physics, Osaka University, Japan**
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**Department of Physics, Saitama University, Japan**
- M. Kojima, and J. Sato

**High Energy Accelerator Research Organization (KEK), Japan**
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- T. Nakamoto, T. Ogitsu, C. Ohmori, Y. Takubo, M. Tomizawa,
- A. Yamamoto, M. Yamanaka, M. Yoshida, M. Yoshii,
- K. Yoshimura
Mu2e at Fermilab

- Similar sensitivity to COMET with similar ideas (curved solenoids yet with slightly different geometry).
- Built on the ideas and groundwork of the MECO experiment.
- Collaborations between COMET and Mu2e are prosperous (e.g. radiation damage to superconductors R&D)
## Design Differences between Mu2e and COMET

<table>
<thead>
<tr>
<th>Component</th>
<th>Mu2e</th>
<th>COMET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam</td>
<td>Fermilab (pulsed)</td>
<td>J-PARC (pulsed)</td>
</tr>
<tr>
<td>Muon beamline</td>
<td>S-shape</td>
<td>C-shape</td>
</tr>
<tr>
<td>Electron Spectrometer</td>
<td>Straight solenoid</td>
<td>Curved solenoid</td>
</tr>
</tbody>
</table>

![Diagram of Mu2e and COMET setups](image-url)
Proton Beam (pulsed)

- A pulsed proton beam is needed to reject beam-related prompt background.

- Requirements:
  - pulse separation > 1 μsec (muon lifetime in Al is 880ns)
  - pulse width < 100 nsec

- Beam parameters:
  - beam power – 56 kW
  - beam energy – 8 GeV
  - avg. current – 7 μA

- Beam extinction:

\[ R_{\text{Ext}} = \frac{\text{number of protons between pulse}}{\text{number of protons in a pulse}} < 10^{-9} \]
Proton Beam (extinction)

- Muonic lifetime is dependent on target material (Z number). For Al the lifetime is 880ns.

- Bunch structure:
  - separation – 1.3 μs
  - length – 100 ns
  - protons/bunch – $1.2 \times 10^8$
  - extinction – $10^{-9}$

- Without extinction we would encounter problems with prompt background from proton interactions. This problem is reduced with bunching.

$\sigma = 30-40\text{ns}$
Proton Beam (extinction measurement)

Bunched slow extraction:
- Measurements taken from the J-PARC secondary beamline – K1.1BR
- Extinction: $(5.4 \pm 0.6) \times 10^{-7}$
Proton Beam (extinction measurements)

Abort beamline measurements
Secondary beamline measurements
Double injection kicking
External extinction device

Consistent with $O(10^{-7})$ in the J-PARC MR

$\times$ additional factor of $O(10^{-6})$

$\times$ additional factor of $O(10^{-3})$

The COMET collaboration is confident of achieving proton extinction of $< O(10^{-9})$
Curved solenoids

- In a curved solenoid the centre of the helical trajectory of a charged particle drifts towards the perpendicular direction to the curved solenoid plane.

\[ D = \frac{p}{qB} \theta_{bend} \left( \frac{1}{2} \left( \cos \theta + \frac{1}{\cos \theta} \right) \right) \]

- \( D \) : drift distance
- \( B \) : Solenoid field
- \( \theta_{bend} \) : Bending angle of the solenoid channel
- \( p \) : Momentum of the particle
- \( q \) : Charge of the particle
- \( \theta \) : \( \text{atan}(P_T/P_L) \)

- A compensating magnetic field is introduced, according to:

\[ B_{comp} = \frac{p}{qr} \left( \frac{1}{2} \left( \cos \theta + \frac{1}{\cos \theta} \right) \right) \]

- \( p \) : Momentum of the particle
- \( q \) : Charge of the particle
- \( r \) : Major radius of the solenoid
- \( \theta \) : \( \text{atan}(P_T/P_L) \)

This can be used for charge and momentum selection.
Curved solenoids (muon transport)

- Muon transport consists of two $90^\circ$ bent solenoids:
  - magnetic field – 3 T
  - total bend – $180^\circ$
  - radius of curvature – 3 m
- Designed to eliminate muons with high momentum.
- Momentum selection proportional to bending angle.
Curved solenoids (muon transport)

- COMET simulation method:
  - protons incident on a graphite target (MARS)
  - subsequent particle distribution tracked through a model of the experiment (Geant4)

No high energy muons after 180° bend selection
Curved solenoids (electron transport)

- Electron transport consists of one 180° bent solenoid:
  - magnetic field – 1 T
  - total bend – 180°
  - radius of curvature – 2 m

- Designed to eliminate:
  - positively charged particles (e.g. protons from muon capture)
  - negatively charged particles $p < 60$ MeV/c

- And select signal electrons of $p > 60$ MeV/c.

- Detector rates are drastically reduced as a result of this.
Curved solenoids (electron transport efficiency)

- Prompt background is small due to extinction, therefore other backgrounds dominate (DIO, DIF, etc.).

- The electron spectrometer provides huge suppression of DIO electrons (augmented by a series of DIO blockers).

- The plot of transmission efficiency is produced with the DIO blockers placed 20cm below the beamline axis.

- The collimators and blockers require optimisation to achieve a detector rate of 1-10 kHz within the timing window.
Sensitivity and Background

**Sensitivity:**

\[
\text{Single event sensitivity} = (N_p \cdot N_{\mu/p}^{\text{stop}} \cdot f_{\text{cap}} \cdot A_{\mu-e})^{-1}
\]

90% confidence level upper limit

Events per $1 \times 10^{-16}$ BR

<table>
<thead>
<tr>
<th>Source</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiative Pion Capture</td>
<td>0.05</td>
</tr>
<tr>
<td>Beam Electrons</td>
<td>$&lt; 0.1^\dagger$</td>
</tr>
<tr>
<td>Muon Decay in Flight</td>
<td>$&lt; 0.0002$</td>
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<tr>
<td>Pion Decay in Flight</td>
<td>$&lt; 0.0001$</td>
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<tr>
<td>Neutron Induced</td>
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<tr>
<td>Delayed-Pion Radiative Capture</td>
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<td>Anti-proton Induced</td>
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<td>Muon Decay in Orbit</td>
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<tr>
<td>Radiative Muon Capture</td>
<td>$&lt; 0.001$</td>
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<tr>
<td>$\mu^-$ Capt. w/ n Emission</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>$\mu^-$ Capt. w/ Charged Part. Emission</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Cosmic Ray Muons</td>
<td>0.002</td>
</tr>
<tr>
<td>Electrons from Cosmic Ray Muons</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.34</td>
</tr>
</tbody>
</table>

**Background:**
Proton extinction in the secondary beamline at J-PARC has been measured.

Design of superconducting solenoid cavities has been realised.

A prototype of the first ever superconducting pion capture solenoid has been built at Osaka University. Experiments (MuSIC, etc.) are currently in progress, utilising this and the first 36° of muon transport solenoids.

Conceptual design report (CDR) submitted, receiving Stage-1 approval as E21 at J-PARC PAC, 2009 - vindication of physics motivation and feasibility.

Stage-2 approval will be assessed in the coming months following submission of a technical design report (TDR) to J-PARC PAC.
Summary

- Physics motivation for cLFV is robust, allowing a probe of beyond-LHC energy scales.

- Muon-to-electron conversion provides the current best chance of observing cLFV with $> 10^{18} \mu/yr$.

- COMET/conversion experiments can achieve sensitivity beyond $10^{-13}$ because:
  - Pulsed proton beam for background rejection
  - Curved solenoid magnets for momentum rejection and signal selection

- New collaborators are welcome!