UCL DEPARTMENT OF PHYSICS AND ASTRONOMY

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

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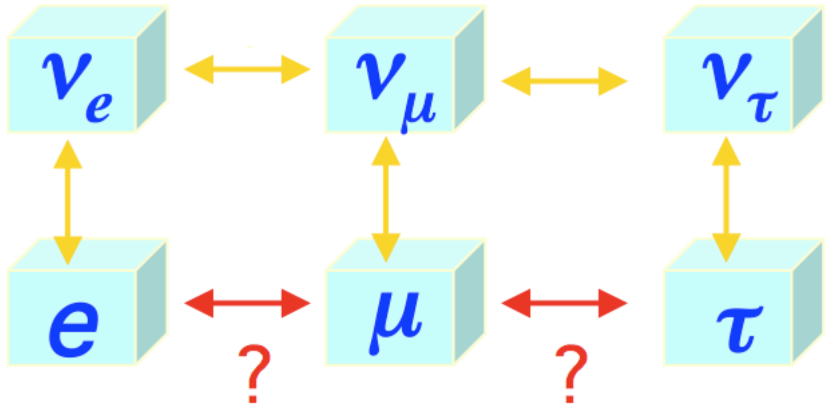
On behalf of the COMET collaboration

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:

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

○ New Physics models (SUSY, GUTs, etc.) increase this BR dramatically to ≈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

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

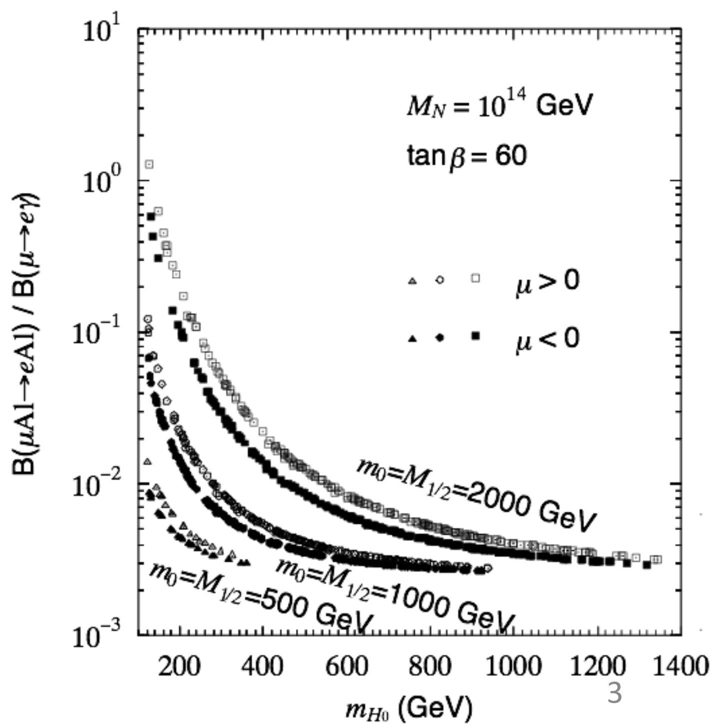
○ The large number of muons available (≈ 10^{18} μ/yr) results in a 'high' sensitivity to LFV.

○ μ->eγ and μ->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.



New Physics search rating

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

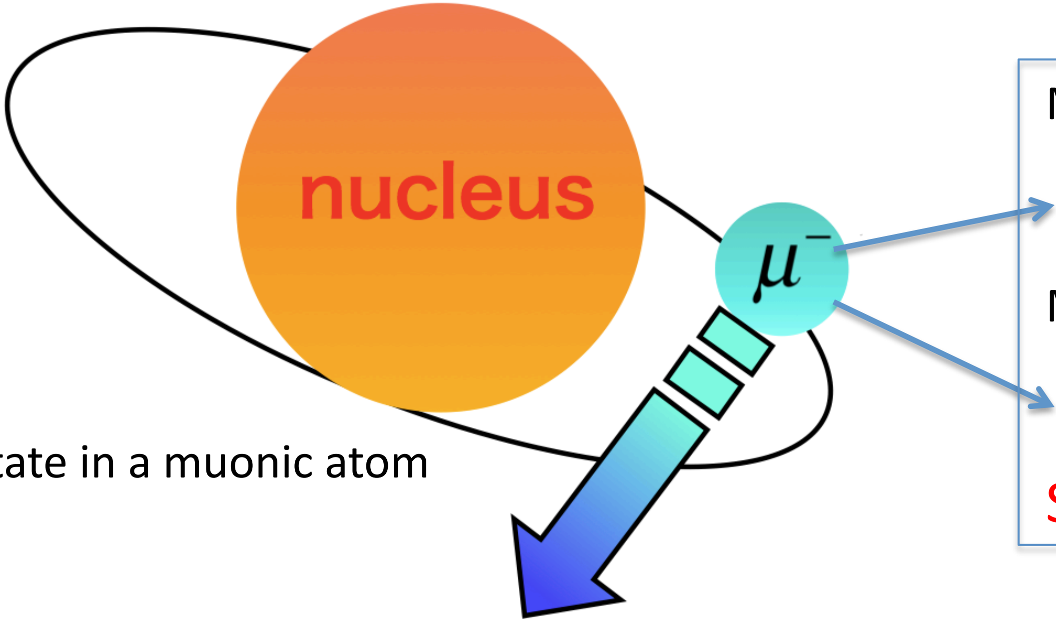
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Different SUSY and non-SUSY new physics models.

All three stars for muon-to-electron conversion in an atom.

Altmannshofer, Buras, Gori, Paradisi, Straub
0909.1333v2 [hep-ph] 26 Jan 2010

What is muon-to-electron conversion?



1s state in a muonic atom

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

Muon-to-electron conversion

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

Beyond Standard Model Process

Other backgrounds:

- Prompt background
- Muon decay in flight (DIF)
- Beam electrons

Signal:

A single mono-energetic electron with energy $E_e = m_\mu - B_\mu(\mathrm{Al}) \simeq 105\mathrm{MeV}$

Current status of cLFV

SINDRUM-II at PSI (target – Au)

Muon beam intensity ~ $10^{7\text{-}8}$/sec

Upper limit of 7×10^{-13}

- ✓ published result 2004

MEG at PSI ($\mu^+ \rightarrow e^+\gamma$)

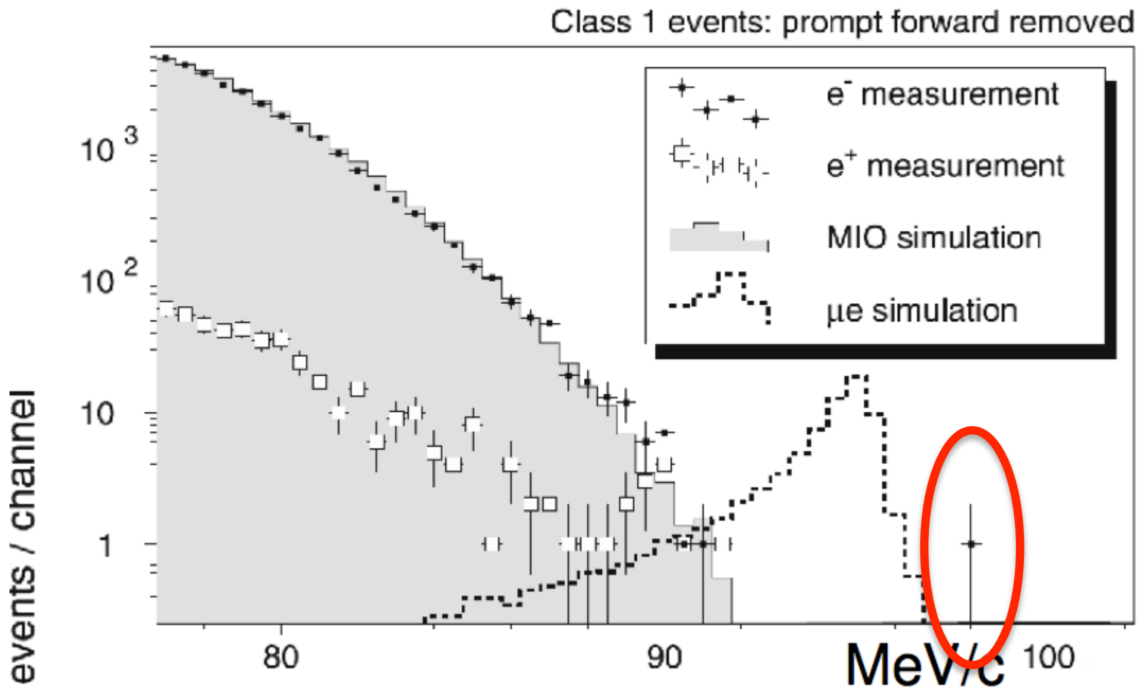
Upper limit of 2.4×10^{-12}

- ✓ published result 2011

COMET at J-PARC (target – Al)

Muon beam intensity ~ 10^{11}/sec

Proposed sensitivity of $< 10^{-16}$



(SINDRUM results published in 2004)

Improvements (background rejection)

Beam-related backgrounds → Beam pulsing with separation of 1μsec — vastly decreases prompt background

proton extinction = #protons between pulses/#protons in a pulse < 10^{-9}

Muon DIO background → Curved solenoids and DIO beam scrapers — improve electron energy resolution

Muon DIF background → Curved solenoids for momentum selection — eliminate energetic muons (>75 MeV/c)

The COMET (J-PARC - E21) Experiment

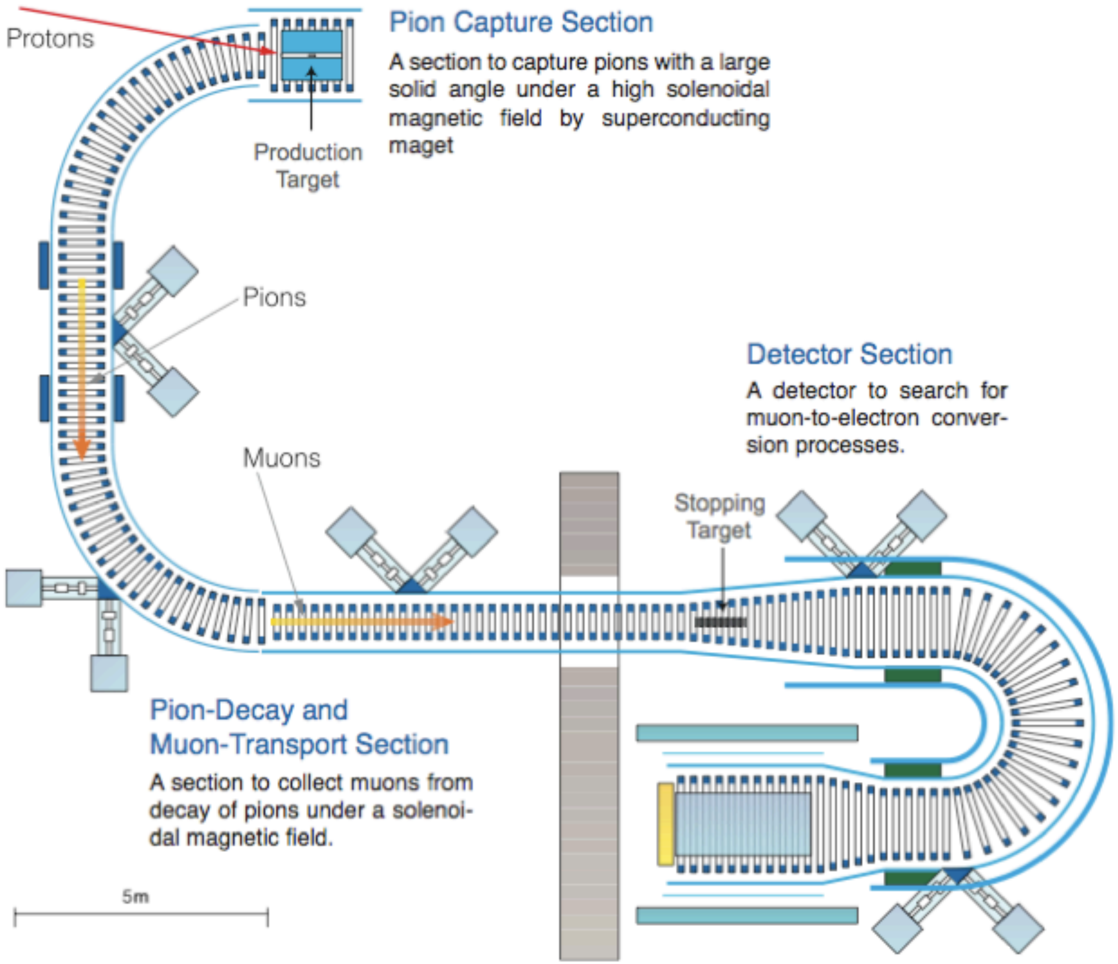
○ **CO**herent **M**uon-to-**E**lectron **T**ransition experiment.

○ 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.

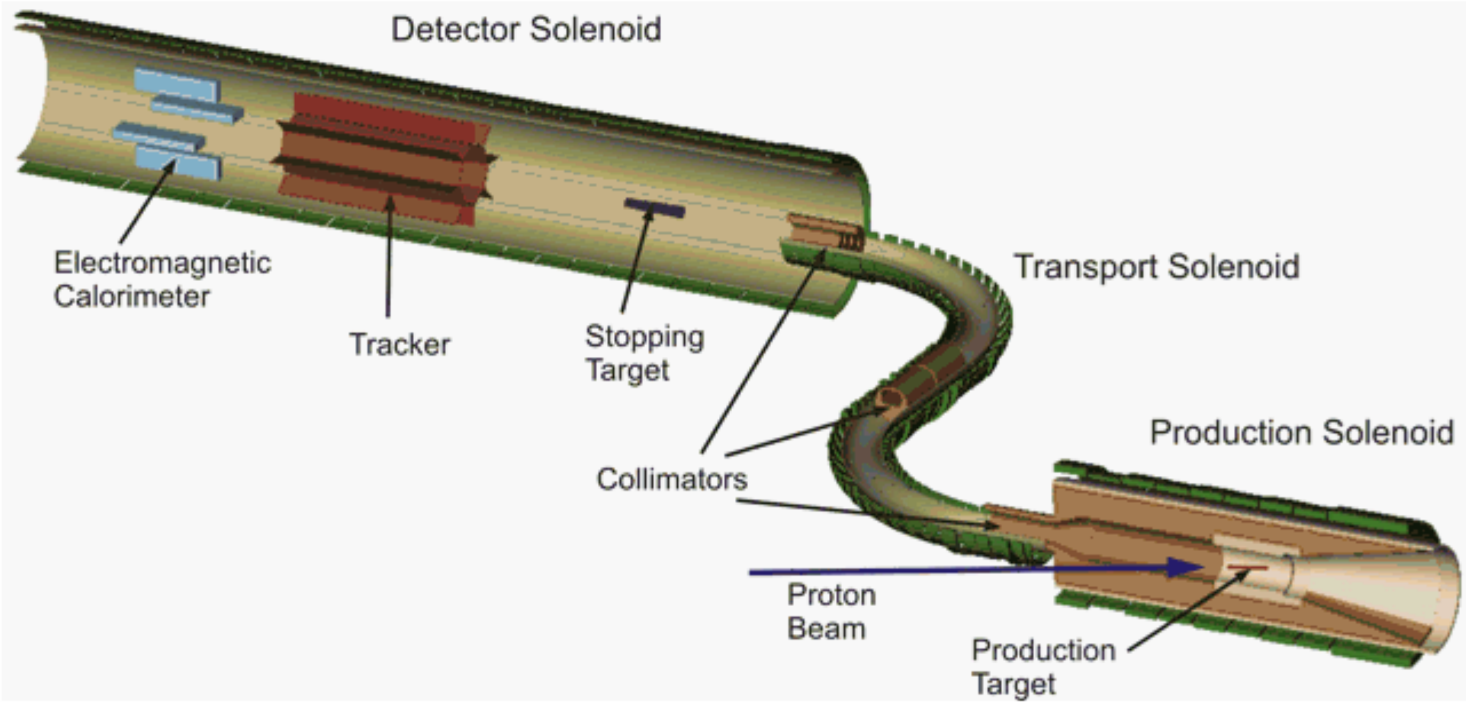
○ Pion capture and muon transport by novel superconducting solenoid system.

$$BR(\mu^- + \text{Al} \rightarrow e^- + \text{Al}) < 10^{-16}$$



COMET Collaboration

Mu2e at Fermilab

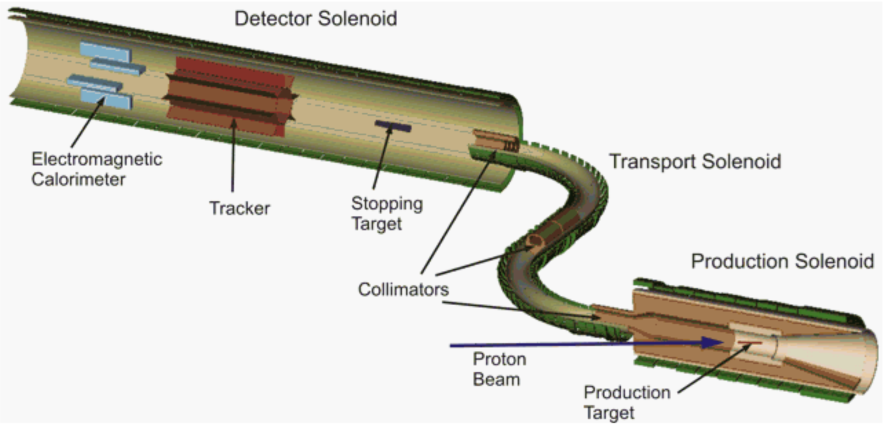


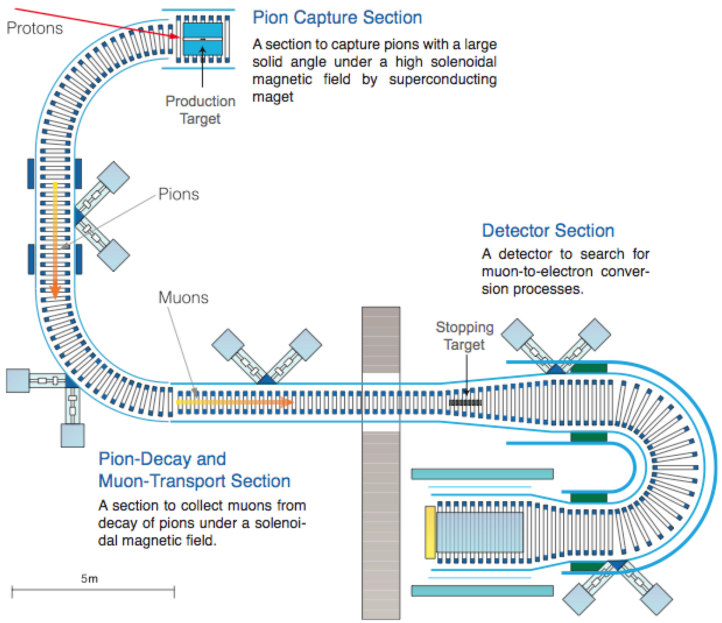
○ Similar sensitivity to COMET with similar ideas (curved solenoids yet with slightly different geometry).

○ 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





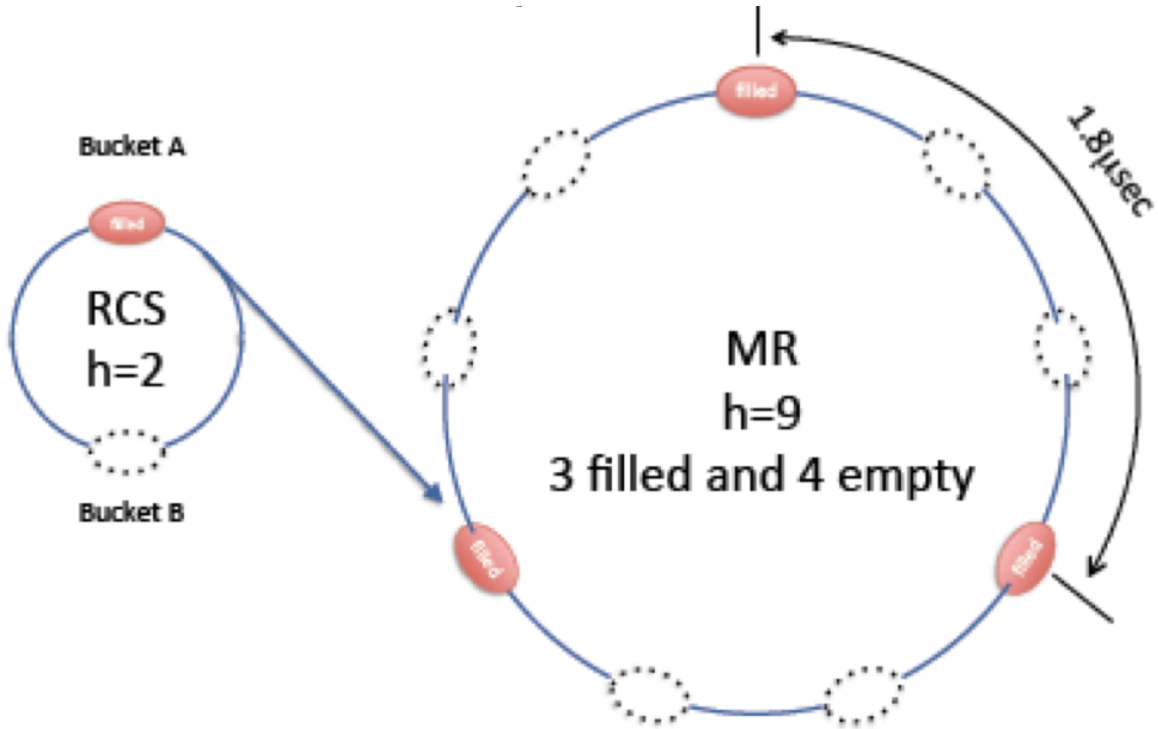
	Mu2e	COMET
Proton beam	Fermilab (pulsed)	J-PARC (pulsed)
Muon beamline	S-shape	C-shape
Electron Spectrometer	Straight solenoid	Curved solenoid

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:

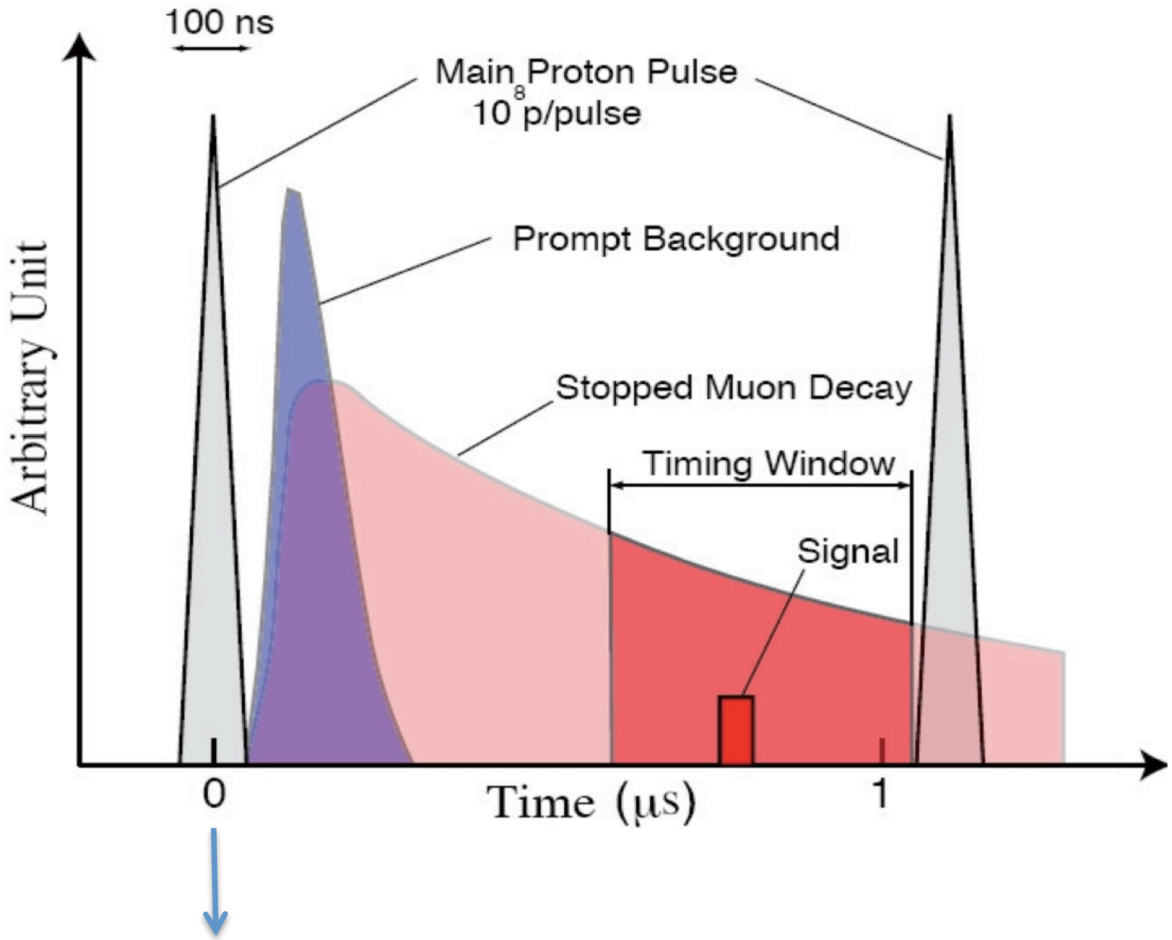
$$R_{Ext} = \frac{\text{number of protons between pulse}}{\text{number of protons in a pulse}} < 10^{-9}$$

Proton Beam (extinction)

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

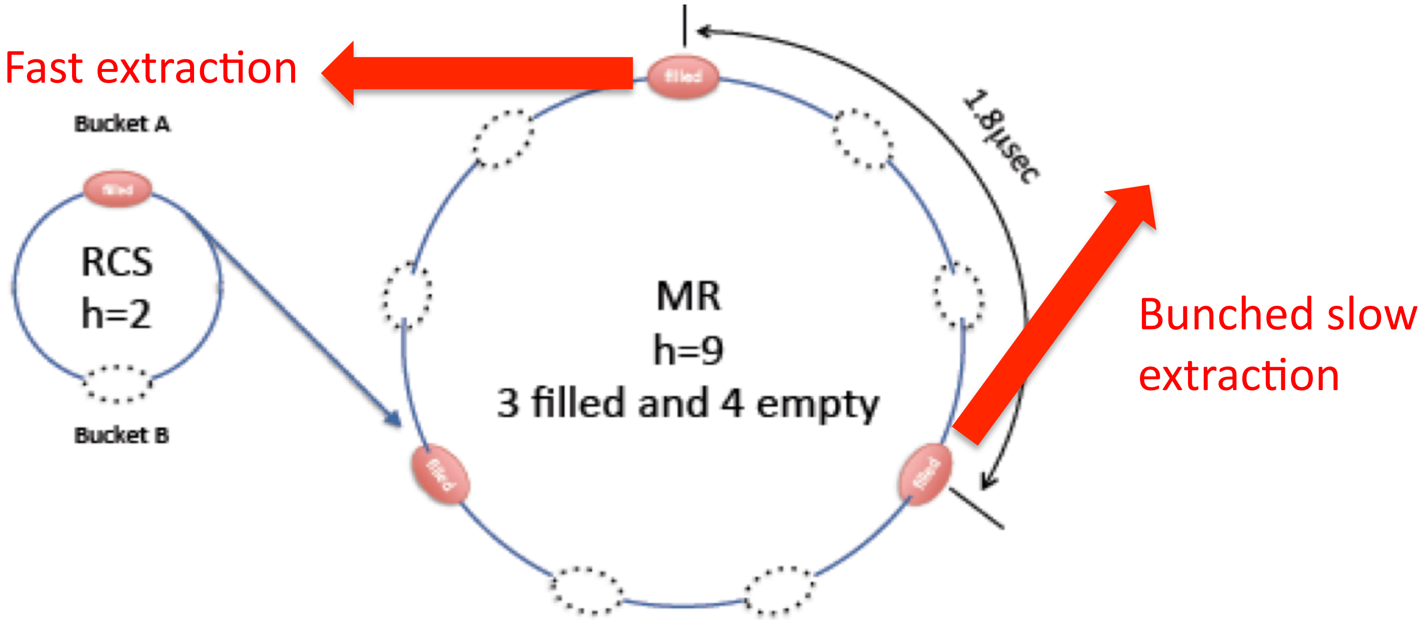
- Bunch structure:
  - separation – 1.3 μs
  - length – 100 ns
  - protons/bunch – 1.2×10^8
  - extinction – 10^{-9}

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



σ = 30-40ns

Proton Beam (extinction measurement)

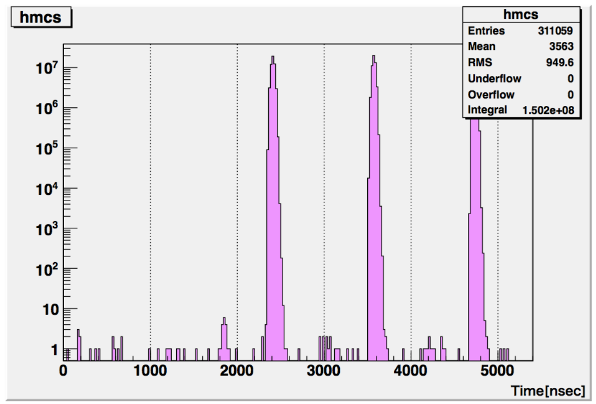


Bunched slow extraction:

○ 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

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

Double injection kicking

× additional factor of $O(10^{-6})$

External extinction device

× additional factor of $O(10^{-3})$

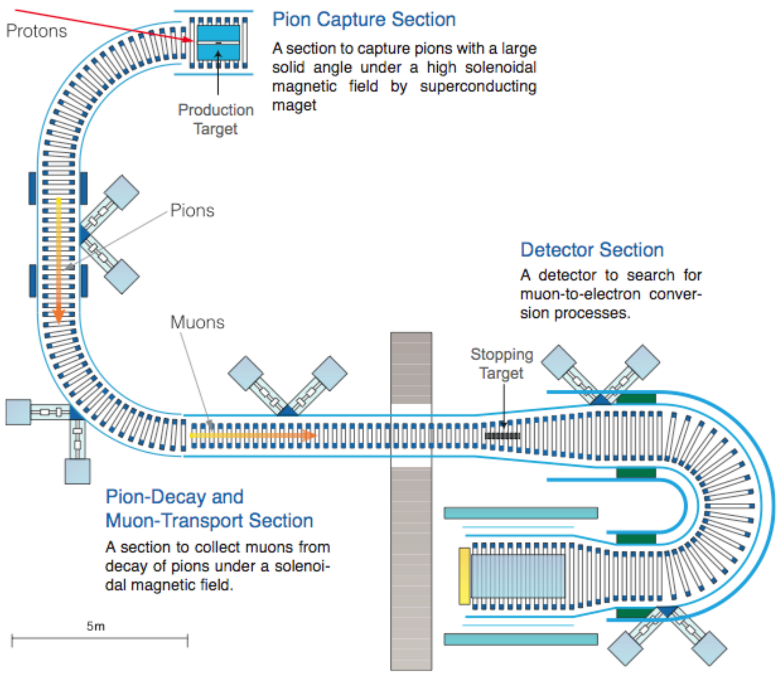
The COMET collaboration is confident of achieving proton extinction of < $O(10^{-9})$

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.

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

D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*



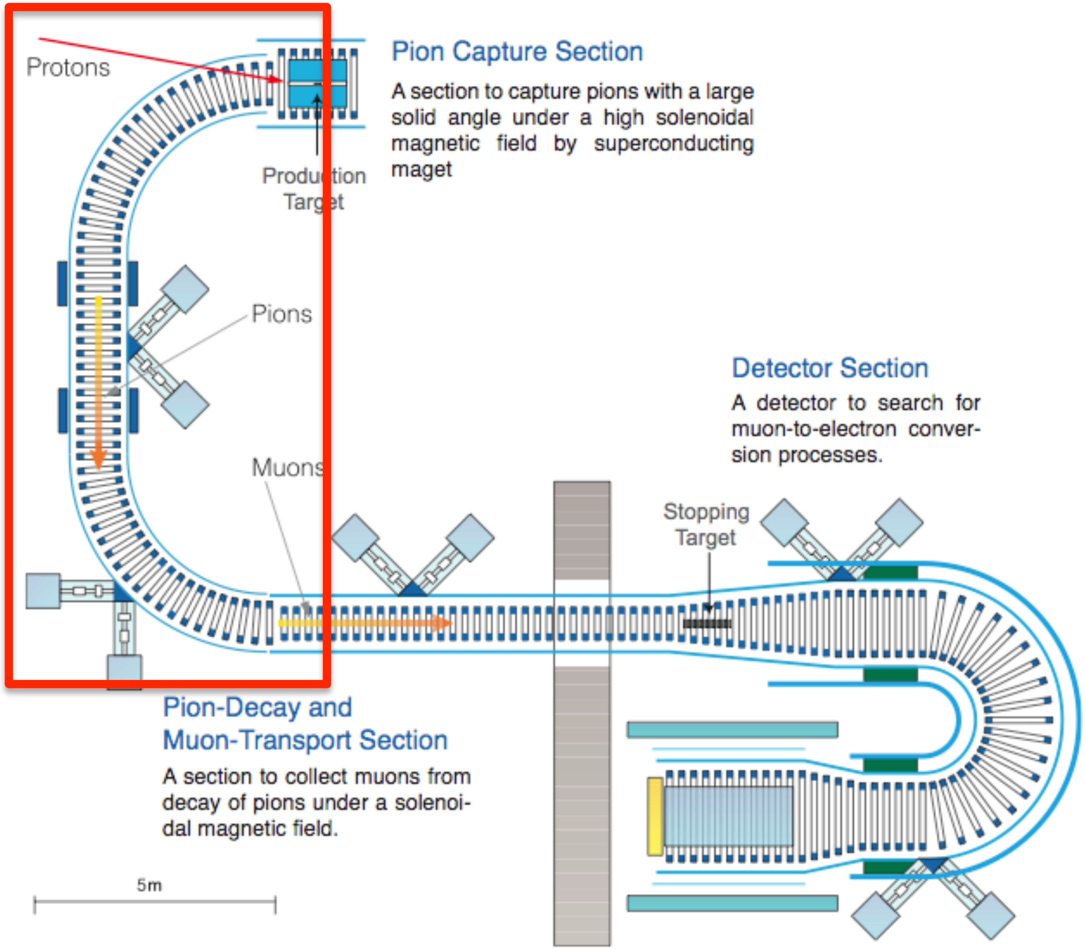
○ A compensating magnetic field is introduced, according to:

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

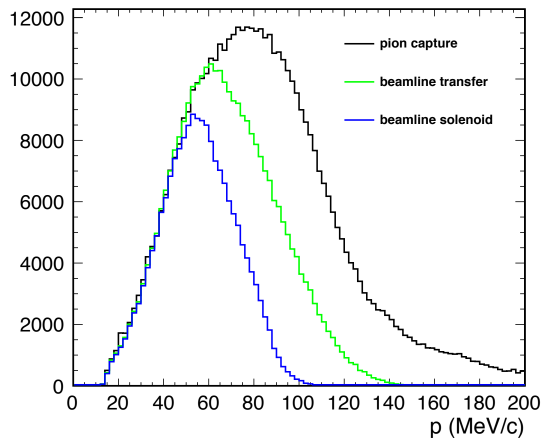
p : Momentum of the particle
q : Charge of the particle
r : Major radius of the solenoid
θ *: atan(*P_T/P_L*)*

→ This can be used for charge and momentum selection.

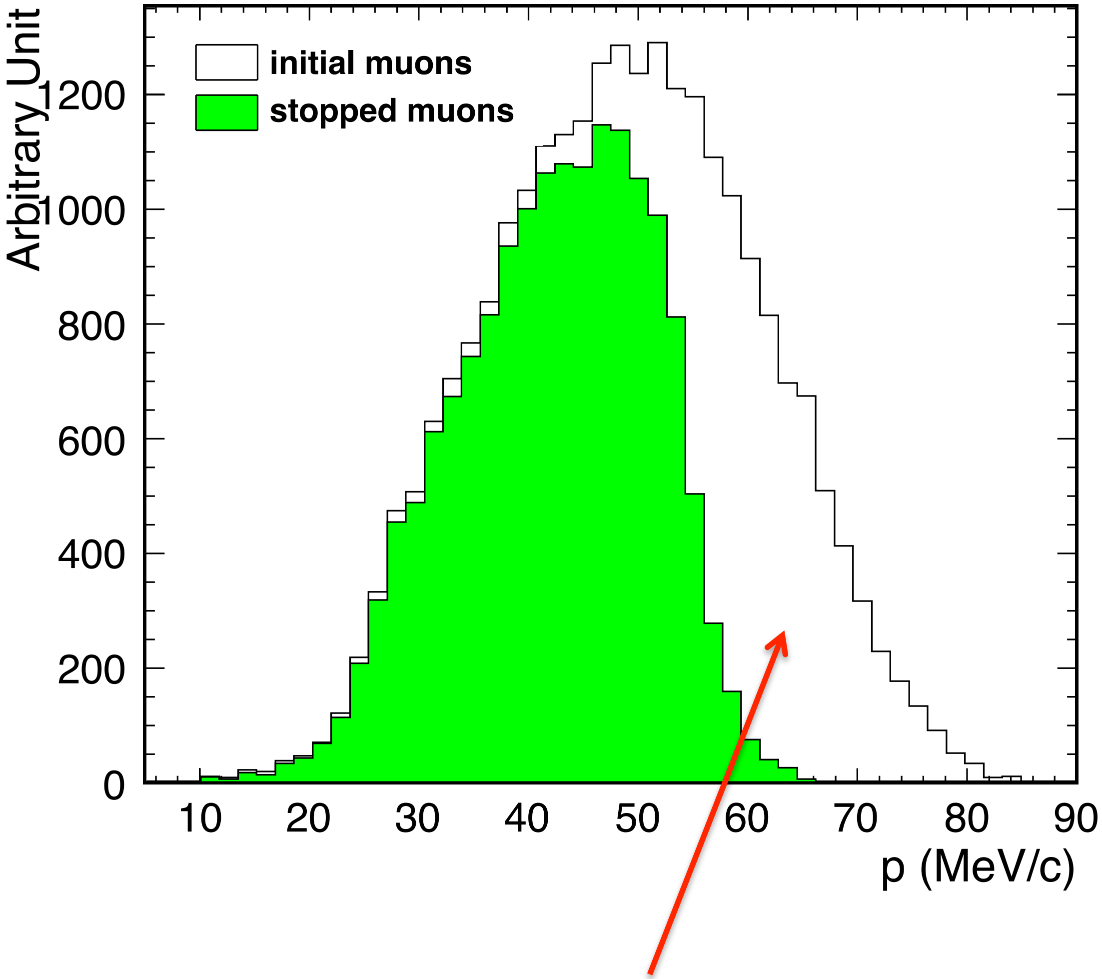
Curved solenoids (muon transport)



- ○ Muon transport consists of two 90° bent solenoids:
  - magnetic field – 3 T
  - total bend – 180°
  - radius of curvature – 3 m
- ○ Designed to eliminate muons with high momentum.
- ○ Momentum selection proportional to bending angle.



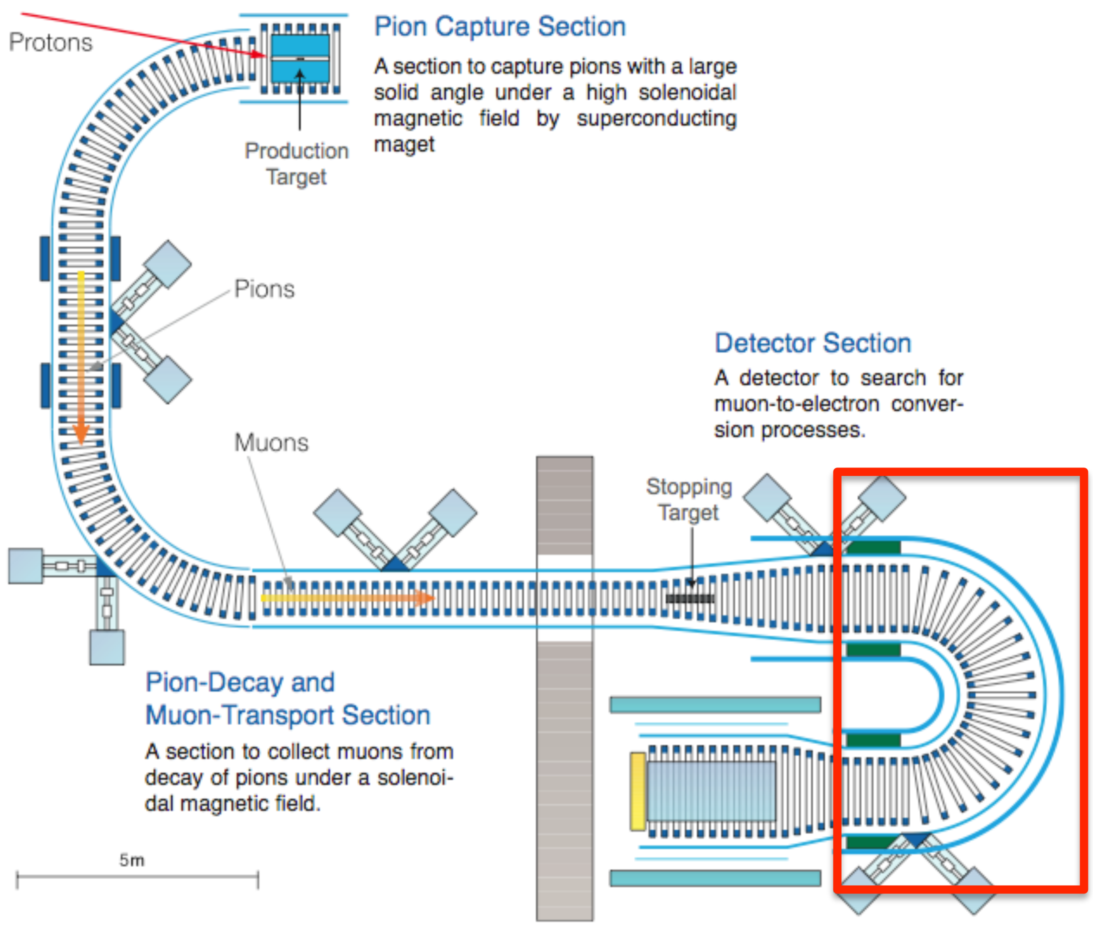
Curved solenoids (muon transport)



No high energy muons after 180^{o} bend selection

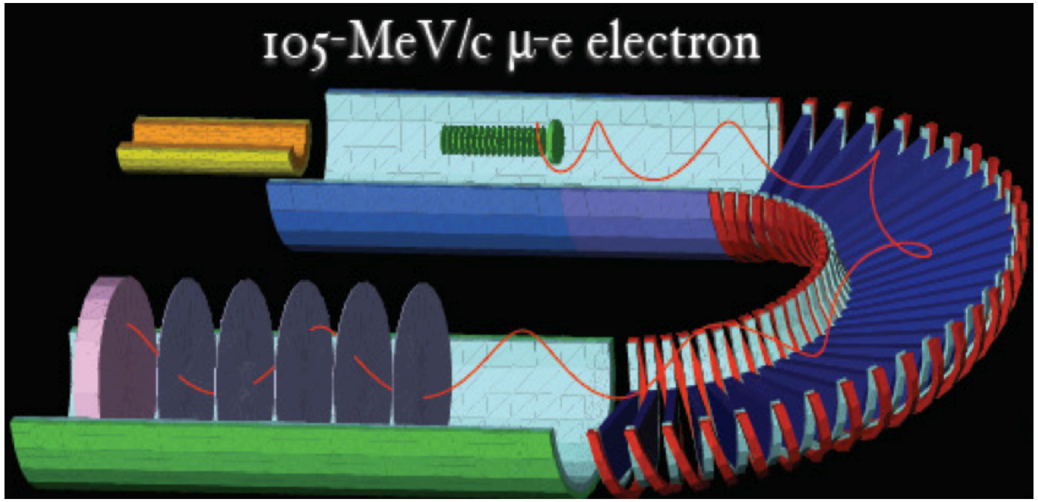
- COMET simulation method:
  - protons incident on a graphite target (MARS)
  - subsequent particle distribution tracked through a model of the experiment (Geant4)

Curved solenoids (electron transport)



- Electron transport consists of one 180º bent solenoid:
  - magnetic field – 1 T
  - total bend – 180º
  - 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)

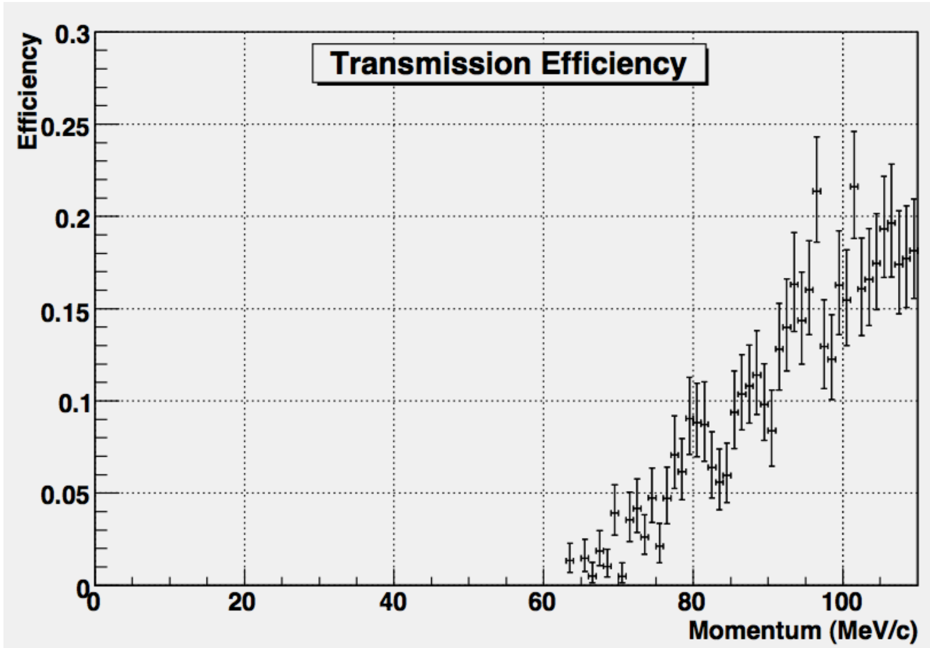


○ Prompt background is small due to extinction, therefore other backgrounds dominate (DIO, DIF, etc.).

○ 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:

Single event sensitivity $= (N_p \cdot N_{\mu/p}^{stop} \cdot f_{cap} \cdot A_{\mu\text{-}e})^{-1}$	2.6×10^{-17}
90% confidence level upper limit	6.0×10^{-17}
Events per 1×10^{-16} **BR**	**3.8**

Background:

Radiative Pion Capture	0.05
Beam Electrons	$< 0.1^{\ddagger}$
Muon Decay in Flight	< 0.0002
Pion Decay in Flight	< 0.0001
Neutron Induced	0.024
Delayed-Pion Radiative Capture	0.002
Anti-proton Induced	0.007
Muon Decay in Orbit	0.15
Radiative Muon Capture	< 0.001
μ^- Capt. w/ n Emission	< 0.001
μ^- Capt. w/ Charged Part. Emission	< 0.001
Cosmic Ray Muons	0.002
Electrons from Cosmic Ray Muons	0.002
Total	0.34

Status

- 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^{o} 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} μ/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!