Imperial College London

OSAKA UNIVERSITY

The COMET Muon-to-Electron Conversion Experiment

Yoshi Uchida

PASCOS 2019 at The University of Manchester

4 July 2019

1947

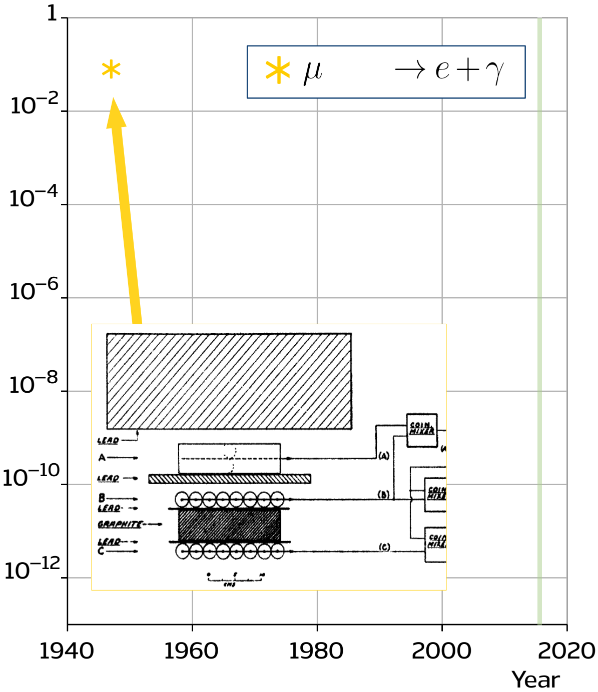
Nuclear Capture of Mesons and the Meson Decay

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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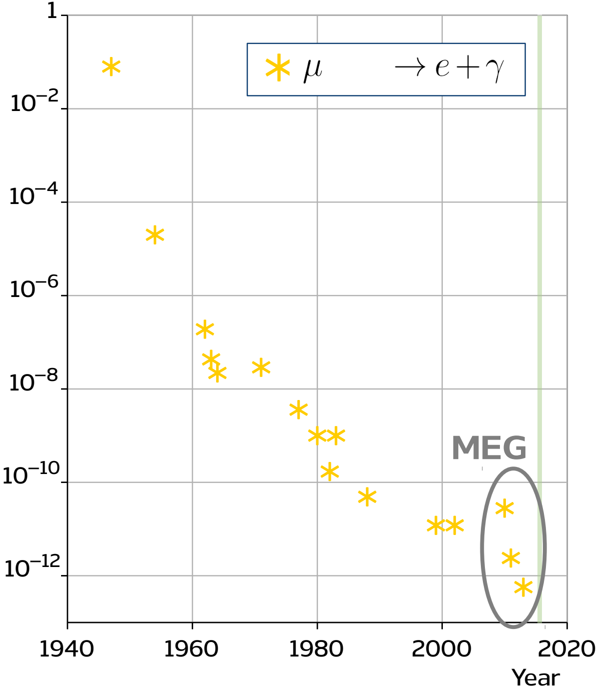

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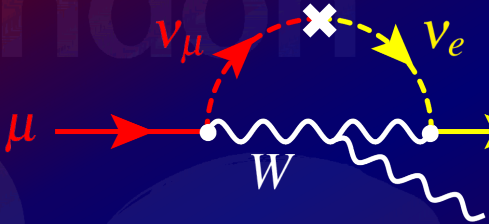
Charged Lepton Flavour Violation

- **Beyond-the-Standard Model Physics** can cause CLFV
  - e.g. **introduction of non-zero neutrino mass**



- but this is ***GIM-suppressed:***

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

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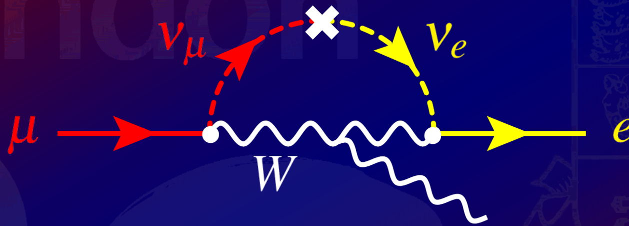


- but this is ***GIM-suppressed:***

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

- if CLFV seen, **unambiguous new physics discovery**
- for other models, CLFV signal can be much larger

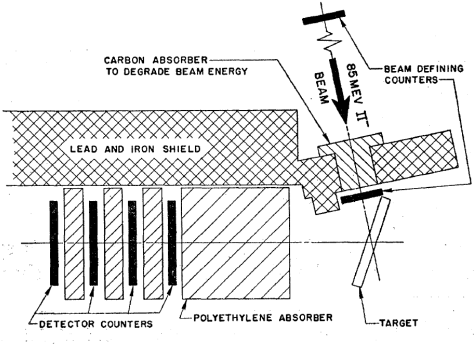
1955

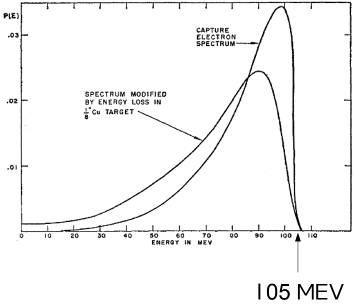
Electrons from Muon Capture*

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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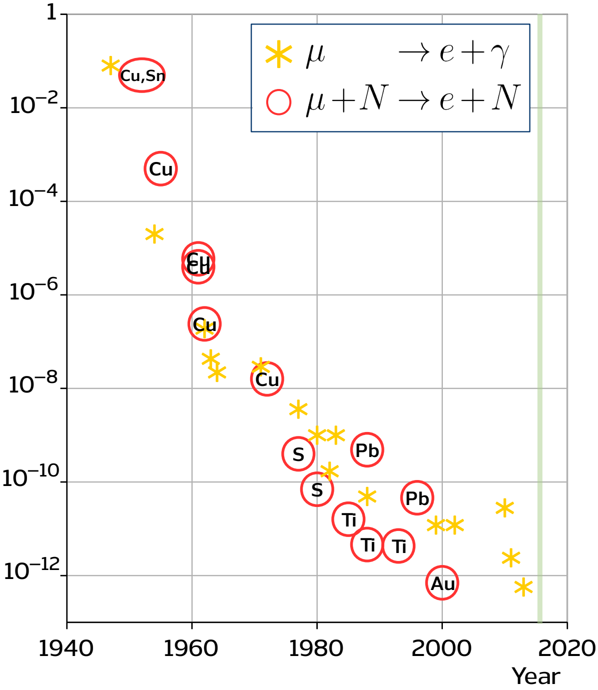

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Muon-to-Electron Conversion

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)

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

Observed signal will be smeared because of detector effects

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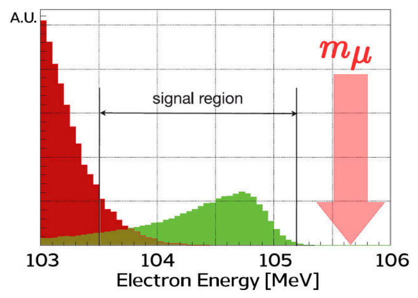

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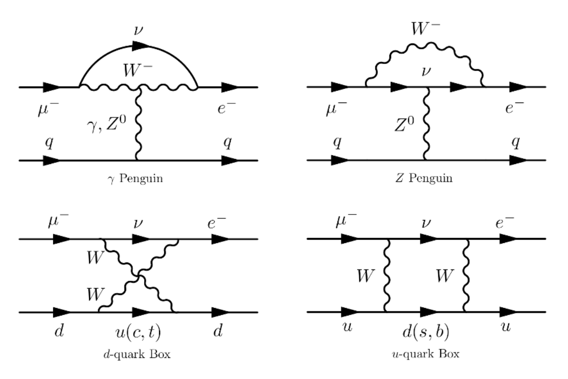
Why Search for Muon-to-Electron Conversion?

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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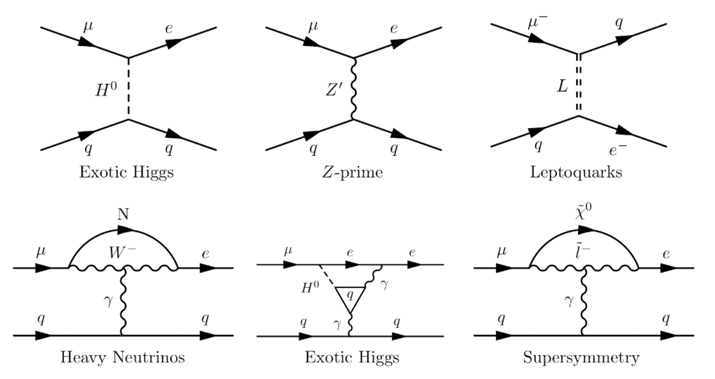

Adapted from B. Krikler, PhD Thesis 2017, Imperial College

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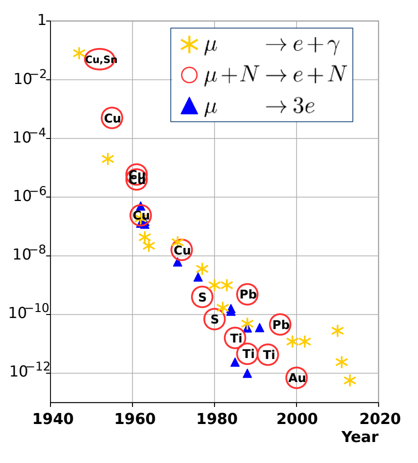
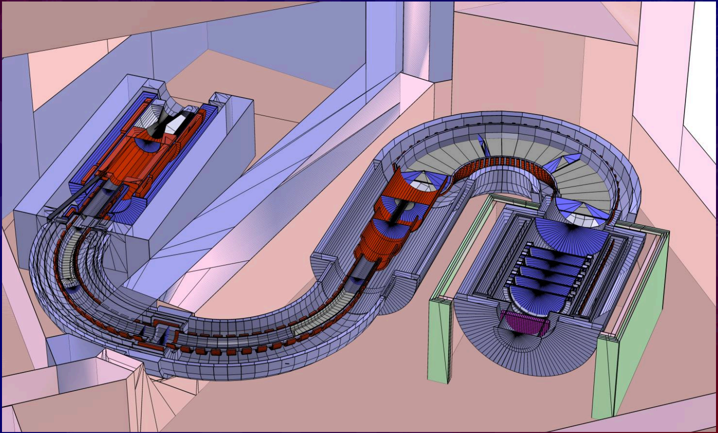


(including another complementary channel, $\mu \rightarrow 3e$)

The COMET Muon-to-Electron Conversion Experiment

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



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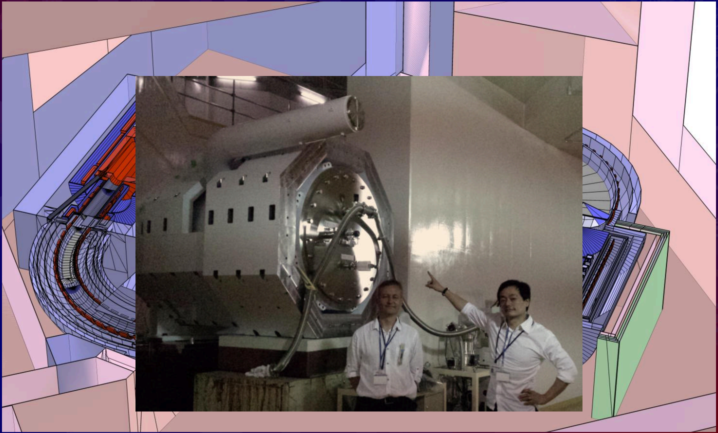
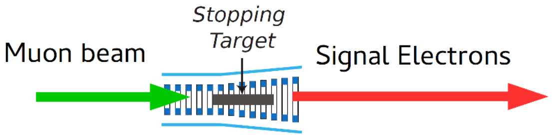
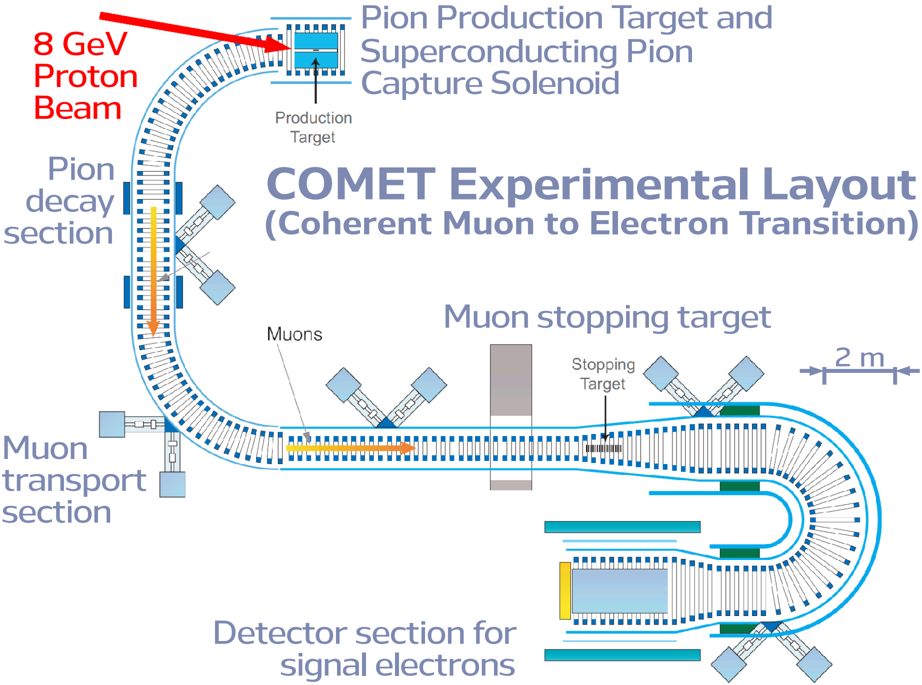


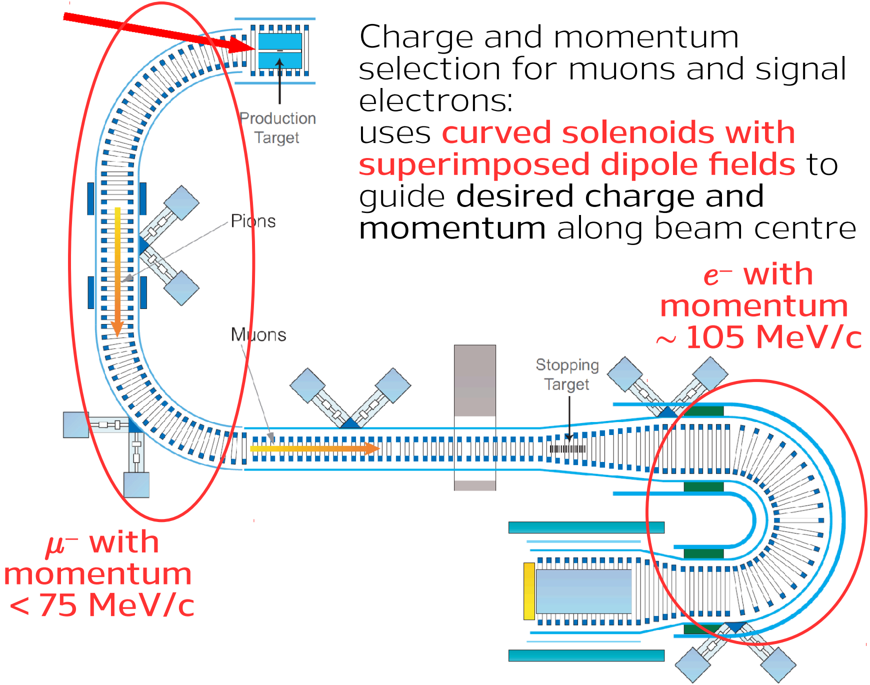


Stopping
Target
Muon beam
Signal Electrons



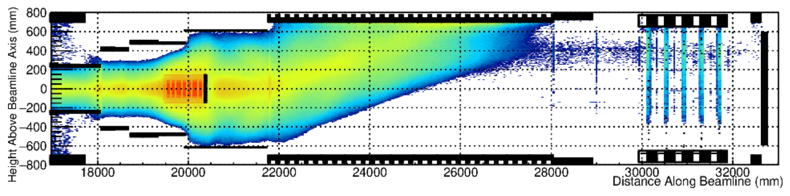
8 GeV Proton Beam
Pion Production Target and Superconducting Pion Capture Solenoid
Production Target
COMET Experimental Layout
(Coherent Muon to Electron Transition)
Pion decay section
Muon stopping target
Muons
Stopping Target
2 m
Muon transport section
Detector section for signal electrons

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



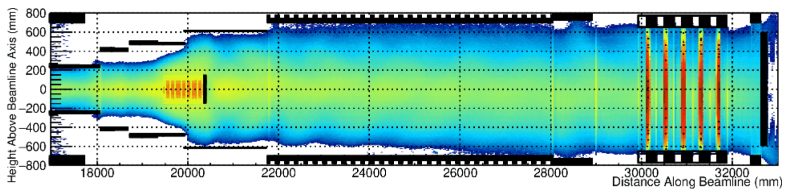
COMET Phase-II

"Steering of signal (105 MeV) electrons"



Vertical compensation/steering fields OFF

B. Krikler, PhD Thesis, 2017



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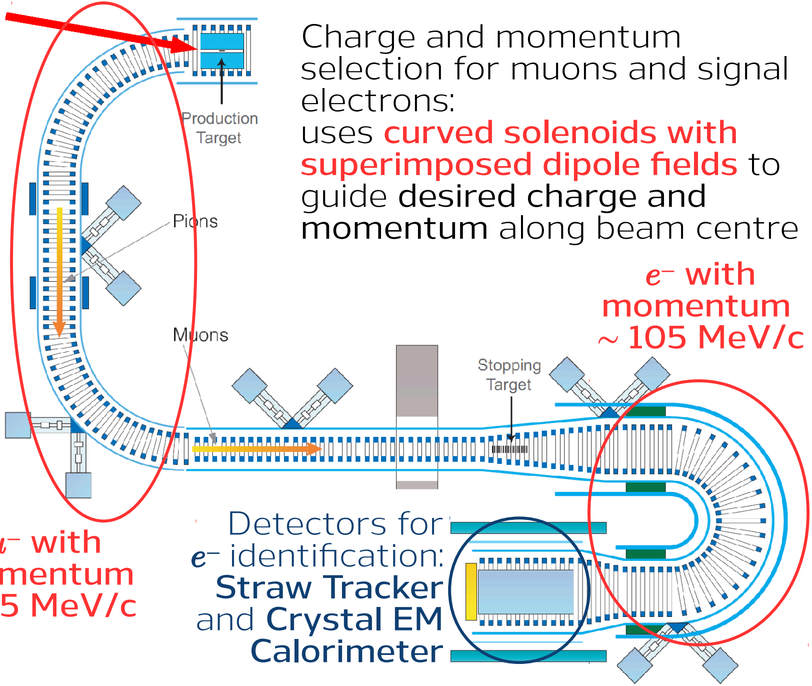
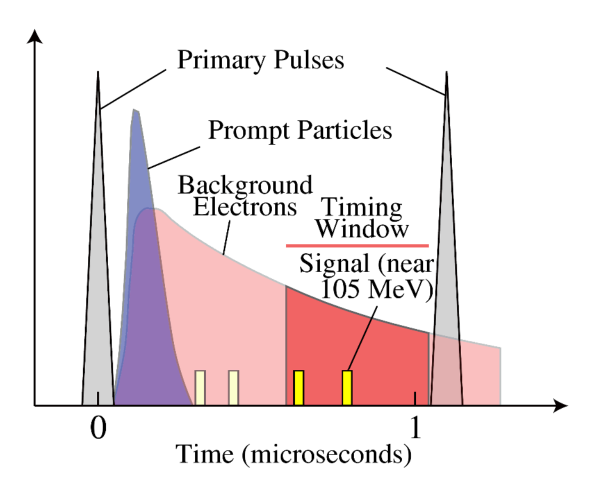


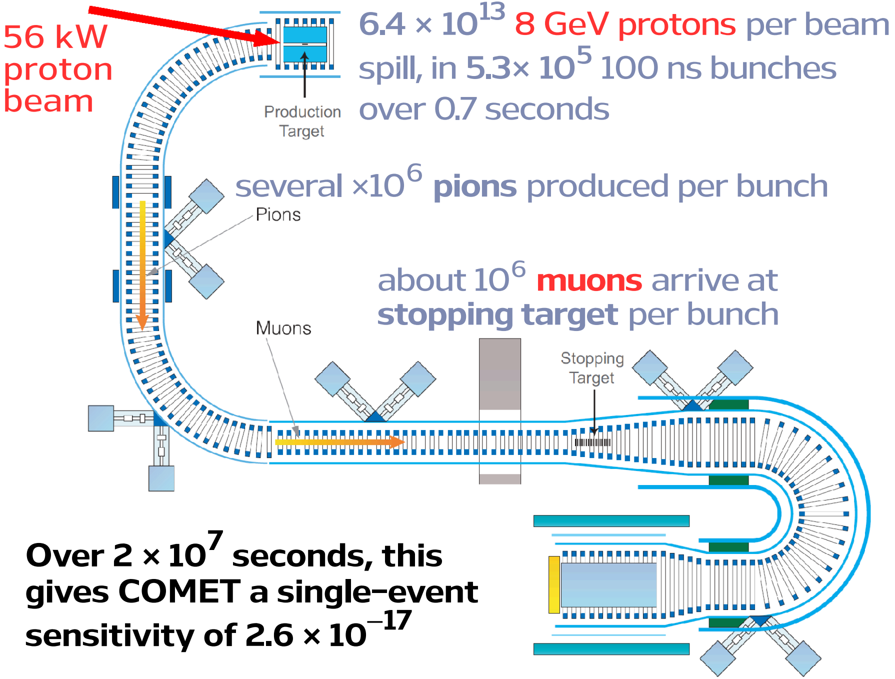
Charge and momentum selection for muons and signal electrons:
uses curved solenoids with superimposed dipole fields to guide desired charge and momentum along beam centre
Production Target
Pions
Muons
Stopping Target
e^- with momentum $\sim$ 105 MeV/c
μ^- with momentum < 75 MeV/c
Detectors for e^- identification:
Straw Tracker and Crystal EM Calorimeter

COMET: Pulsed Proton Beam

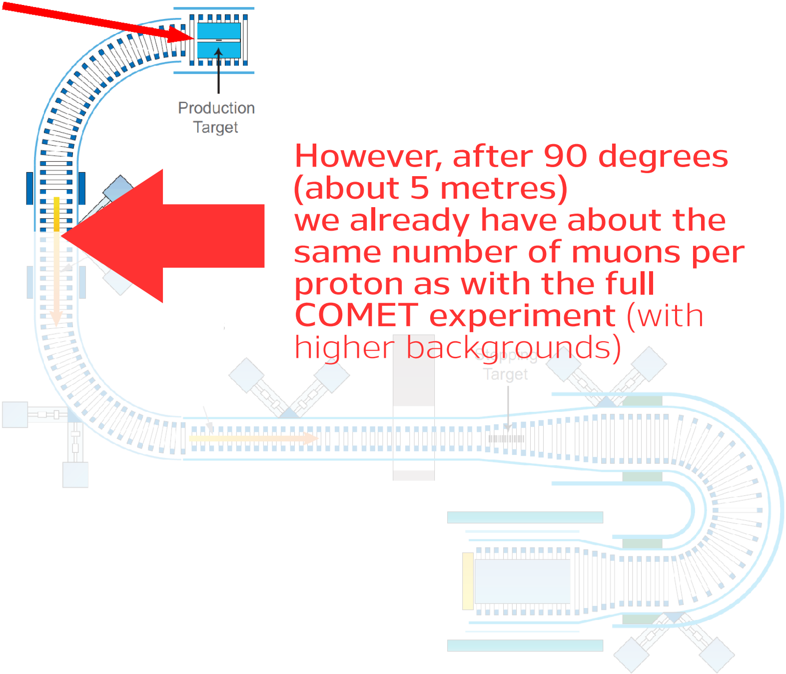
Background Suppression Through Timing



Time profile of COMET beam and signal window



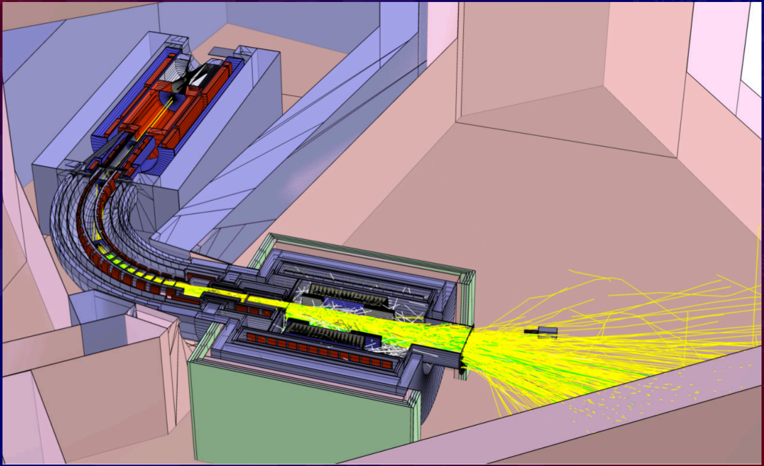
56 kW proton beam
6.4 × 10^13 8 GeV protons per beam spill, in 5.3× 10^5 100 ns bunches over 0.7 seconds
Production Target
several ×10^6 pions produced per bunch
Pions
about 10^6 muons arrive at stopping target per bunch
Muons
Stopping Target
Over 2 × 10^7 seconds, this gives COMET a single-event sensitivity 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

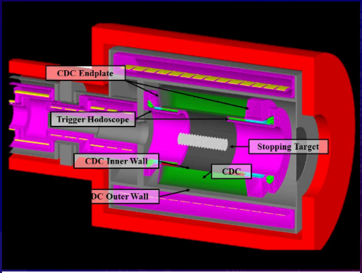
Study novel pion/muon production physics in detail, whilst also making a CLFV measurement



Approximately one beam bunch (100 ns duration) in Phase-I running

COMET Phase-I Detectors: CyDet

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

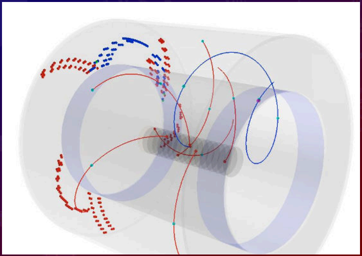


Cylindrical Drift Chamber (CDC)

- 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

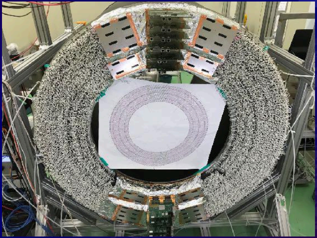
- Prototype tests in 2015; 150 micron spatial resolution, 99% hit efficiency
- Main drift chamber completed in 2016
- Undergoing cosmic ray tests

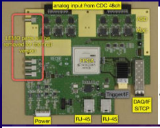
Front-end electronics

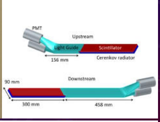
- Based on Belle-II boards
- 108 boards completed and tested
- Radiation testing paper to be published

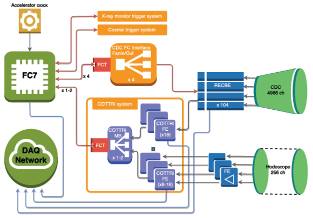
Trigger system

- 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

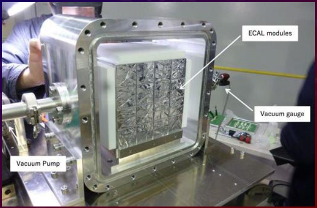
- Vacuum tests with 20 micron-thick tube walls
- Phase-I Production run complete
- 150 micron resolution with 100 MeV electron beam

Electromagnetic Calorimeter)

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

Front-end electronics)

- Design complete
- Radiation test results published

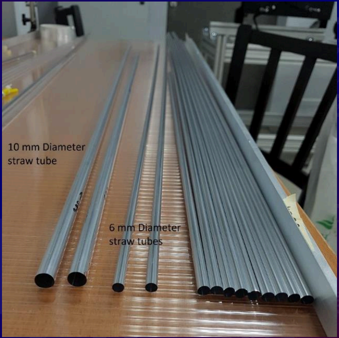


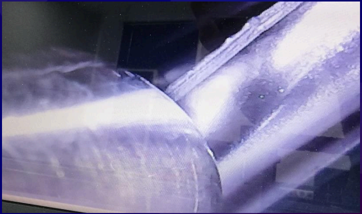
COMET Phase-II Detector R&D

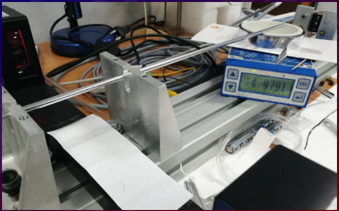
Straw-Tube Tracker

Successfully developed tubes with 12 micron-thick walls

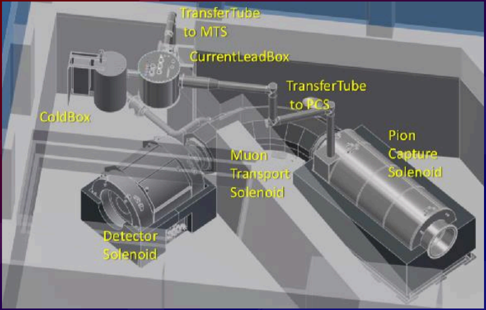
- Diameter 5 mm (half of Phase-I)
- Overpressure of 1 bar: 0.1 micron-level accuracy
- Tested at more than 4 bar overpressure







COMET Solenoids

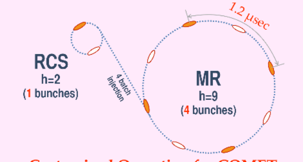


- Pion capture solenoid: final coil being wound
- Transport solenoid: installed and ready for cryogenics tests
- "Bridge" solenoid: coil delivered
- Detector solenoid: coil and cryostat ready
- Cryogenic system: Refrigerator tests completed, He transfer tube being built

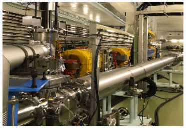
Accelerator Status and Inter–Bunch Beam Extinction

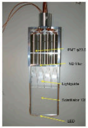
as reported by H. Nishiguchi at IPAC19, May 2019

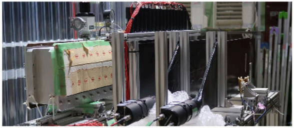
- J-PARC Main Ring Synchrotron needs to run in dedicated configuration:
  - 8 GeV operation (not 30 GeV)
  - 1.2 μs bunch separation (0.6 μs)
  - Fraction of protons arriving between bunches, the **extinction rate**, should be less than $\mathbf{10^{-10}}$
- Beam extinction is a quantity that is not 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



Customized Operation for COMET


【MR Abort Line】


【Abort Monitor】


【Hodoscopes in Secondary Beam Line】

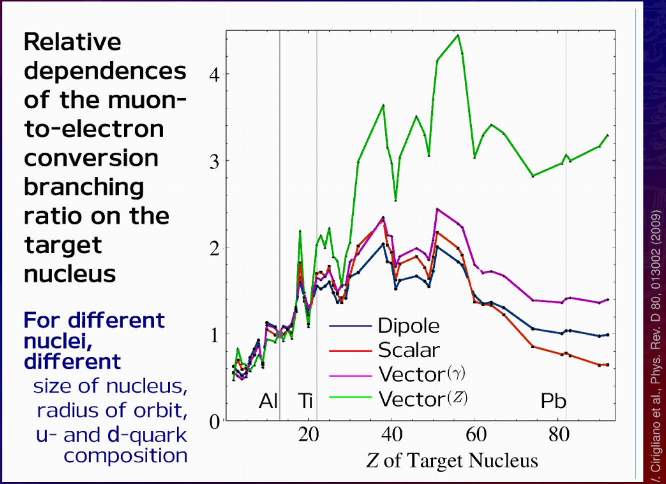
⇒ "J-PARC MR is ready for COMET" (H. Nishiguchi, KEK/J-PARC)

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



Other Possible Physics Channels at COMET

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

- 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)

$$\mu^- + e^- \rightarrow e^- + e^-$$

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

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

- X can be a new light boson or axion etc.
- feasibility being studied

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** (×100 improvement over present)
- **Phase-II data-taking over one year** (×10000 improvement over present)
- Further Phase-II optimisation underway; likely to improve sensitivity by a further factor of 10 for the same beam power