Imperial College London

The COMET Experiment: Searching for Muon-to-Electron Conversion

Ben Krikler

4th August 2016

High Sensitivity Experiments Beyond the Standard Model

ICISE, Quy Nhon, Vietnam

Overview

Charged Lepton Flavour Violation

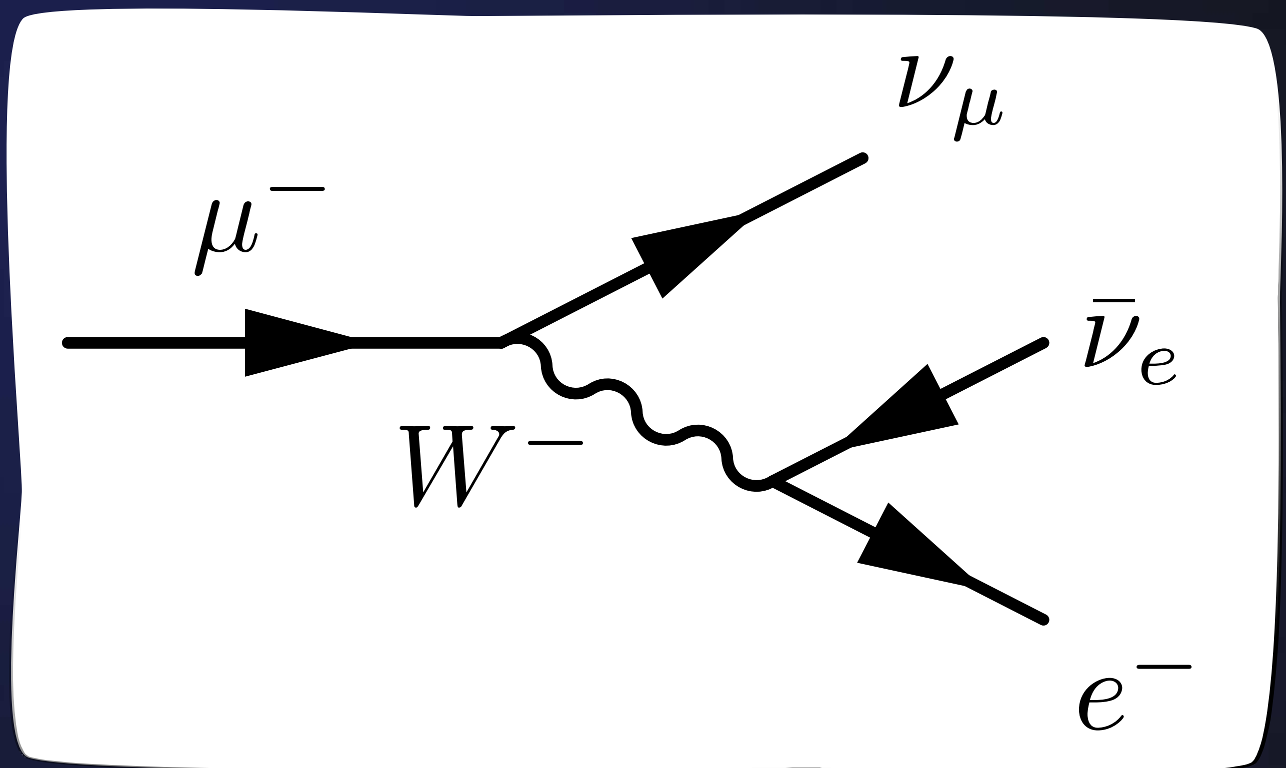
μ-e conversion process

The COMET experiment

COMET Status and R&D

Charged Lepton Flavour Violation

Muon Decay

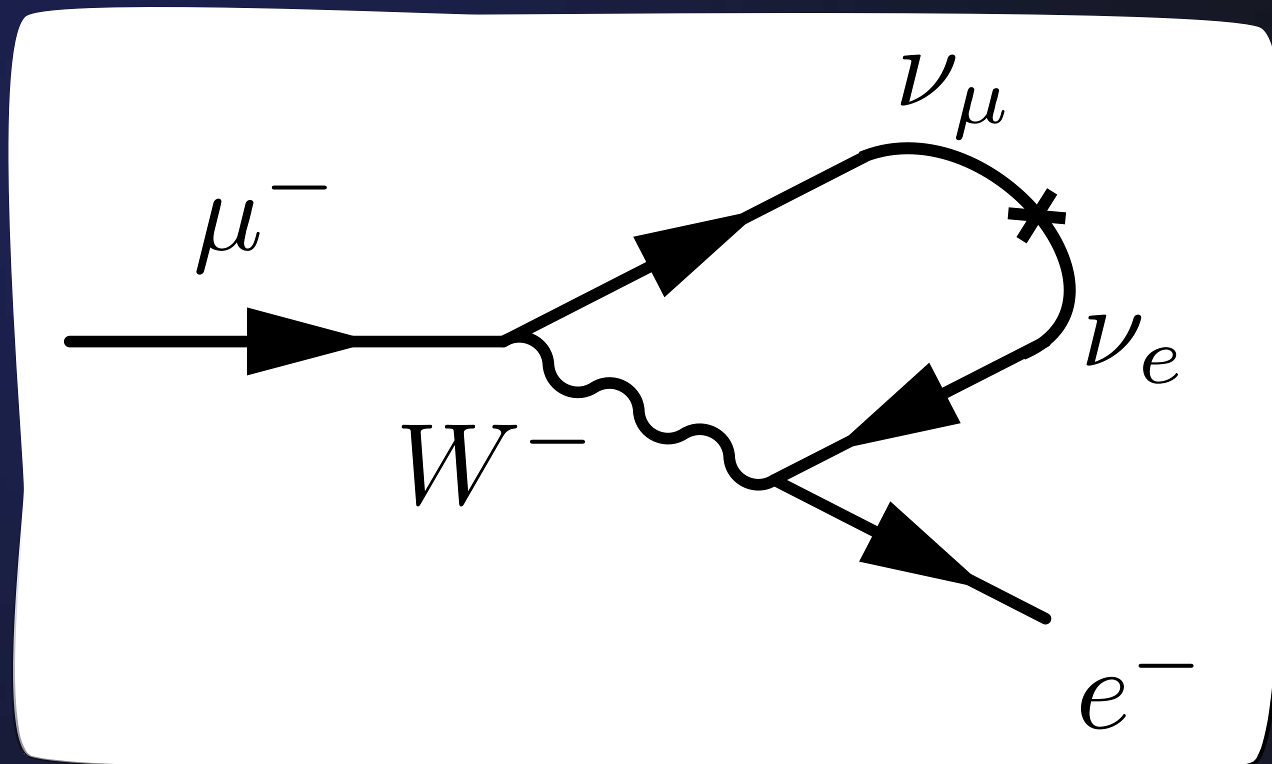


Conservation of Lepton Flavour:

1 muon → 1 muon-neutrino

0 electrons → 1 electron + 1 anti electron-neutrino

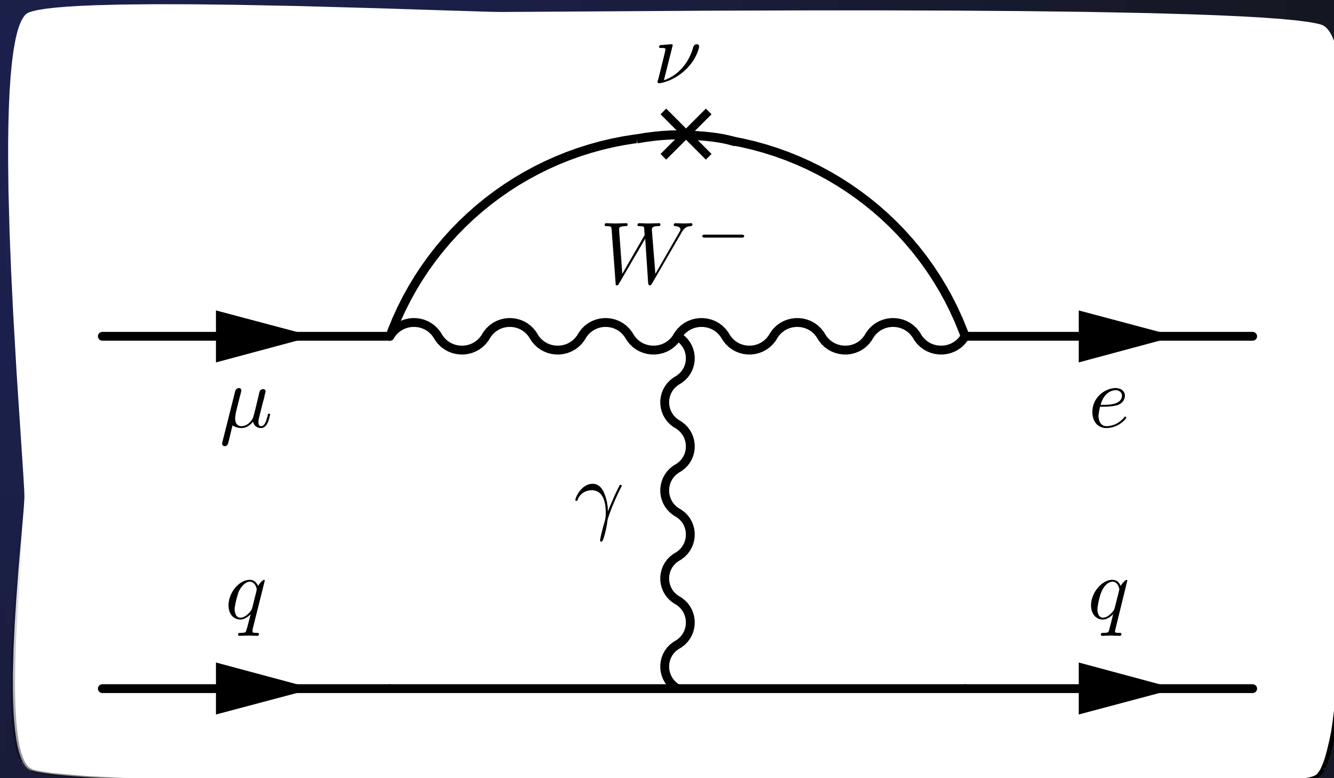
Muon Decay + Neutrino Oscillations



- 1 muon → 1 electron
- No outgoing neutrinos
- BUT: would not conserve energy and momentum

Muon to Electron Conversion

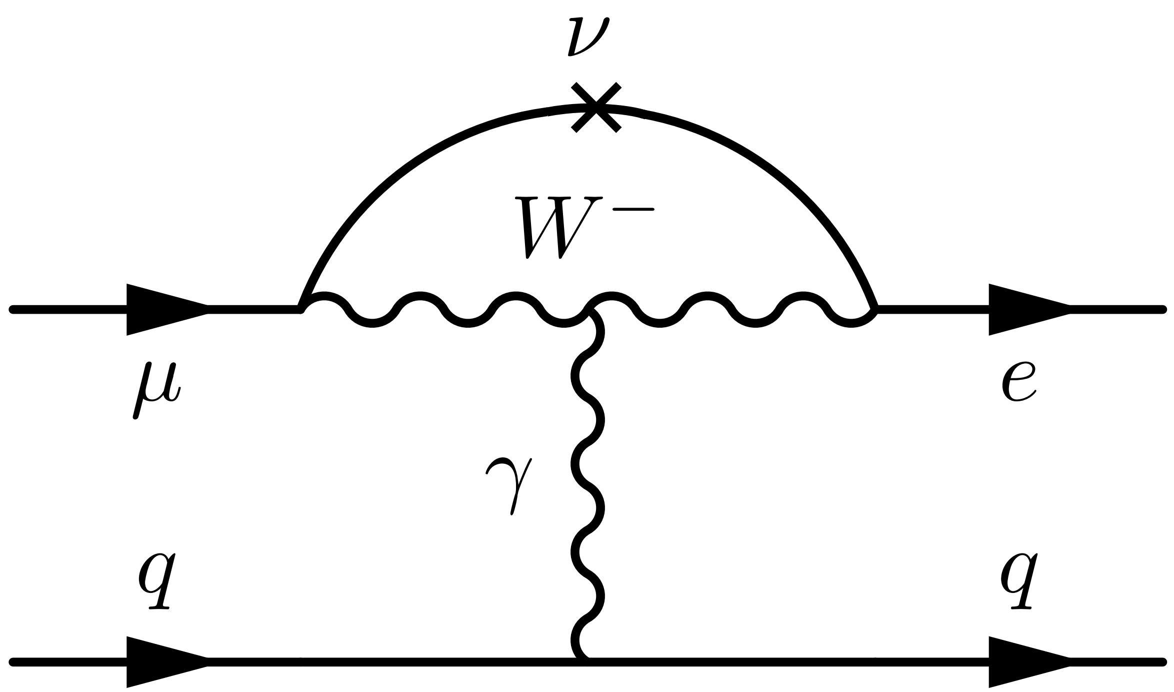
via Neutrino Oscillations



- $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
- No outgoing neutrinos
- Atomic nucleus: conserve energy and momentum
- Violates conservation of Charged Lepton Flavour (CLFV)

Muon to Electron Conversion

via Neutrino Oscillations



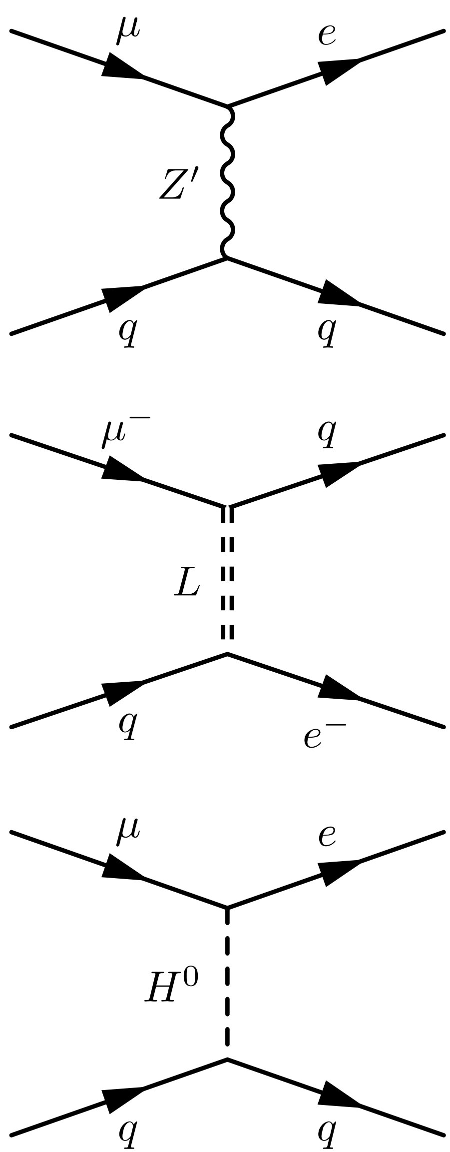
Conversion Rate:

GIM Suppressed

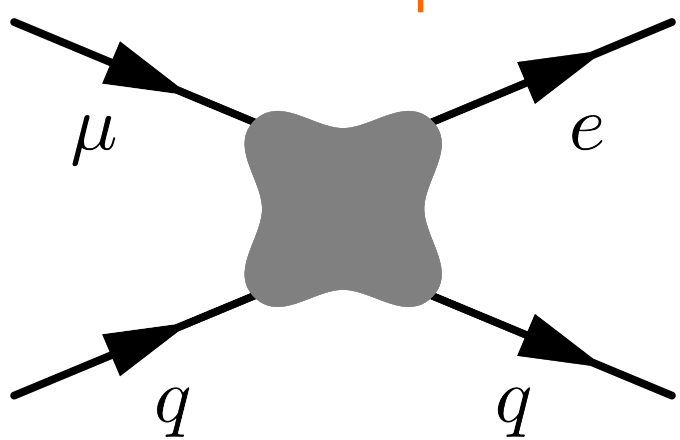
$$\mathcal{R} = \mathcal{O}\left(\frac{(\Delta M_\nu^2)^2}{(M_W^2)^2}\right) \sim 10^{-54}$$

Muon to Electron Conversion

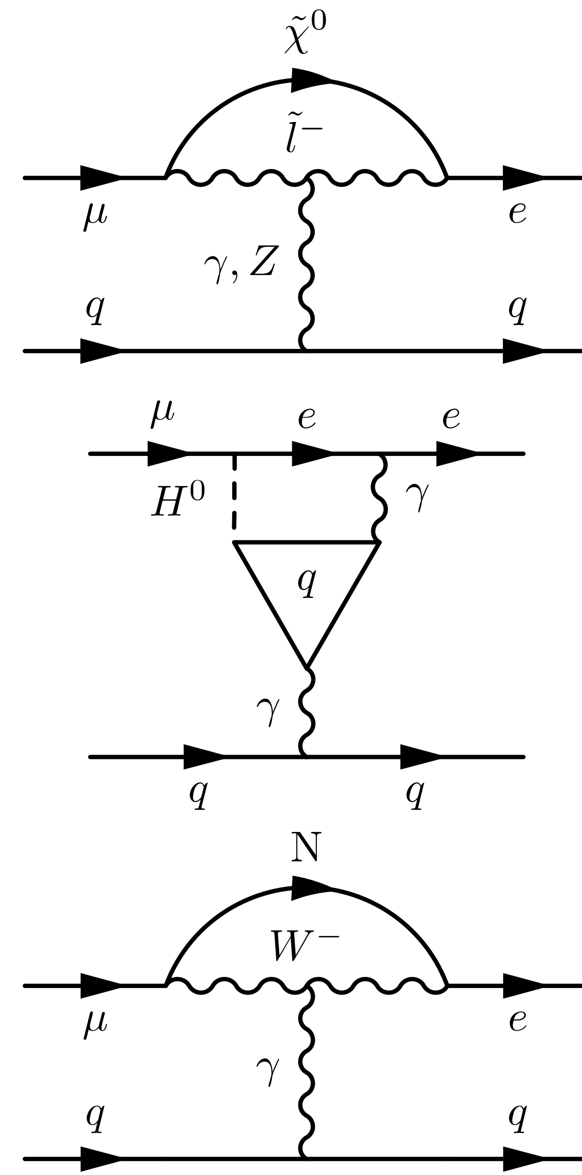
Beyond the Standard Model



- Predicted in many Beyond the Standard Model theories
- Rate is model dependent

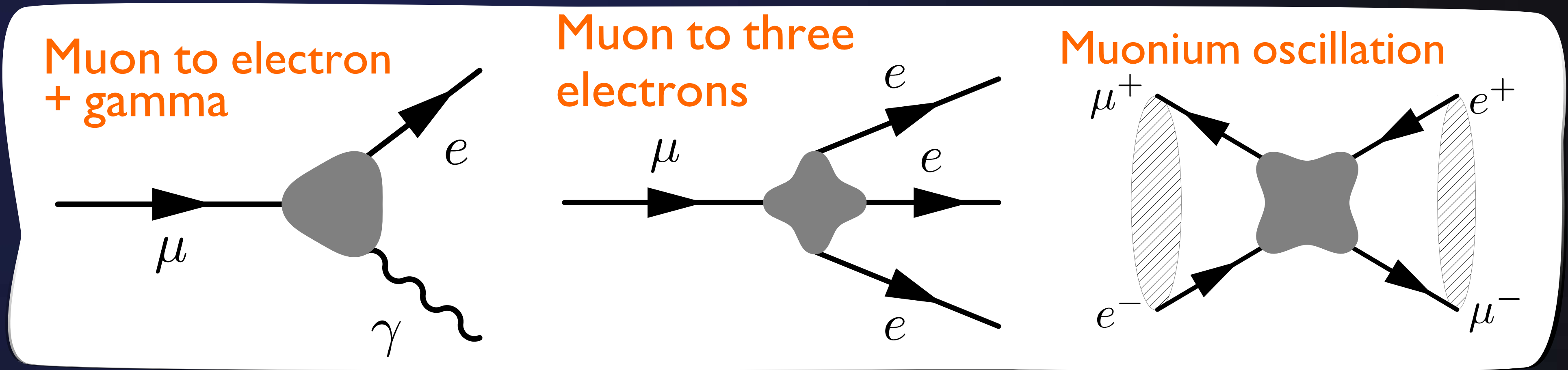


$$\mathcal{R} < \mathcal{O}(10^{-14})$$



CLFV: Beyond mu-e conversion

- Experimentally:



  - Several anomalies at LHCb and B-factories
  - Muon g-2 anomaly
  - Proton radius puzzle
- Charged Lepton Flavour Violation experiments help to understand:
  - The neutrino mass generation mechanism, the scale of the active neutrino masses and the possibility of heavy sterile neutrinos
  - Baryon assymmetry in the universe [Deppisch et al. PRD 92, 036005]
  - Lepton universality in the SM [Glashow et al. PRL 114 (2015) 091801]
  - The validity of Minimal Flavour Violation in BSM models?

Muon-to-electron Conversion

Muon to Electron Conversion

Charged Lepton Flavour Violation:

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

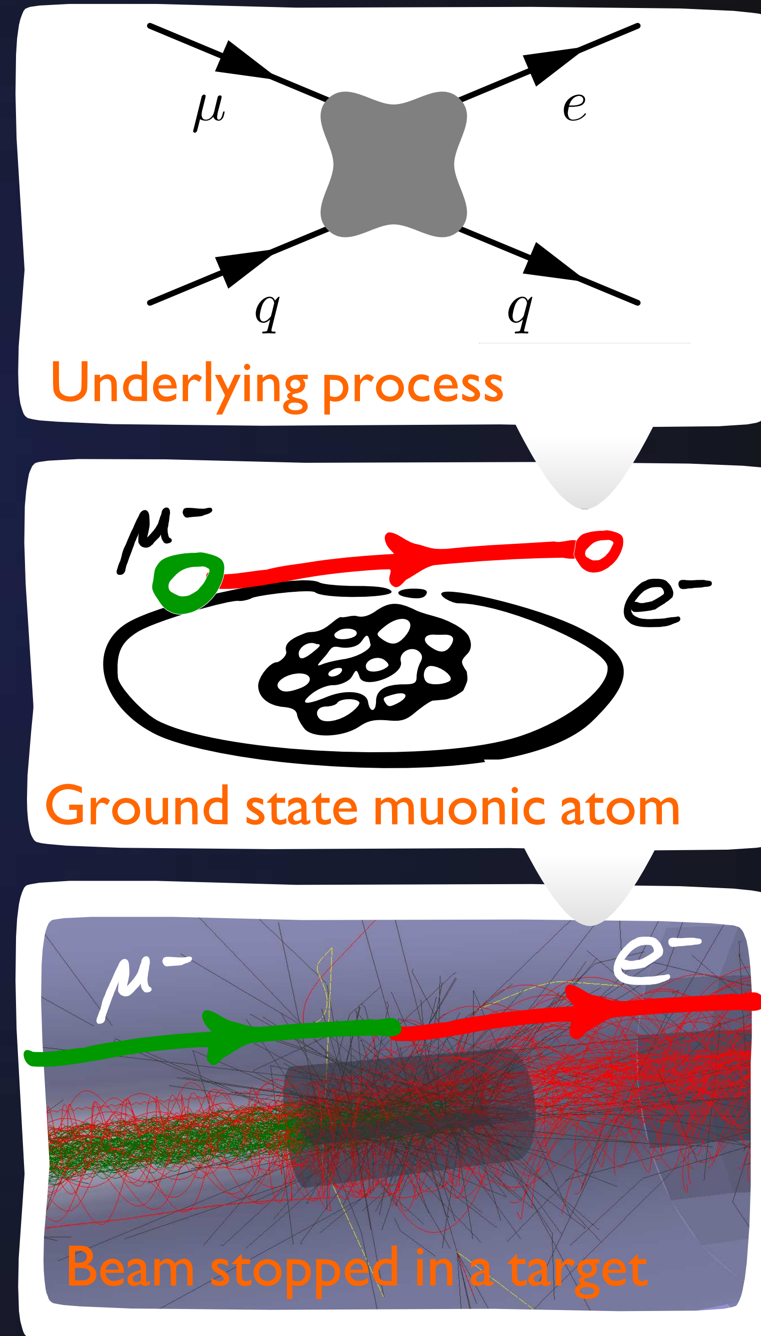
Require that nucleus is unchanged:

- coherent terms dominate
- conversion rate grows with number of nucleons

$$E_e = m_\mu - B_\mu - E_{\mathrm{recoil}}$$

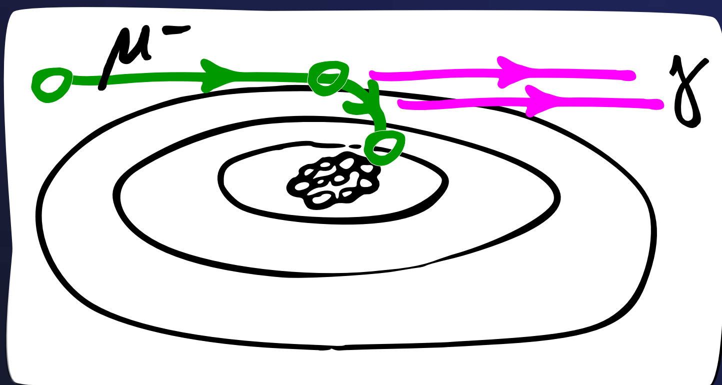
On aluminium, used by COMET:

$$E_e = 104.9\ \mathrm{MeV}$$



Bound Muons

Electromagnetic cascade to the ground state orbital



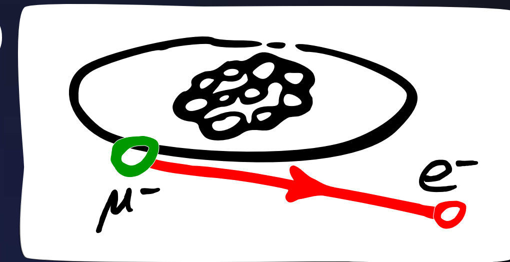
τ = 864 ns in aluminium

Typically define the conversion rate as:

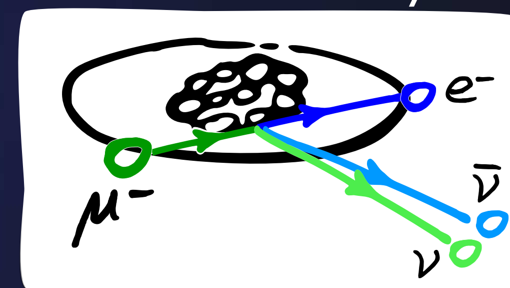
$$\mathcal{R} = \frac{\Gamma(\mu\text{-}e \text{ conversion})}{\Gamma(\mu \text{ capture})}$$

Current limit from SINDRUM-II (90% C.L) on Gold: $\mathcal{R} < 7 \times 10^{-13}$

Muon to Electron Conversion



Bound Muon Decay



$\mathcal{BR} = 39\%$ in aluminium

Standard Model Processes

Muon Nuclear Capture

$\mathcal{BR} = 61\%$ in aluminium

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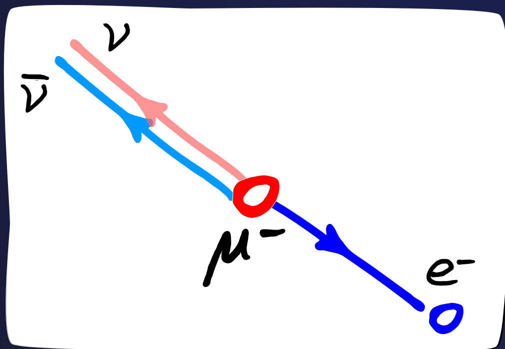
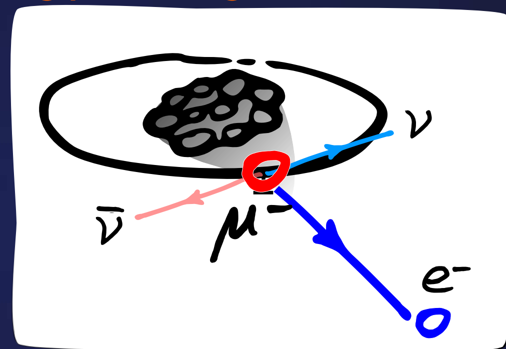
Bound Muon Decay

Maximum electron energy configurations:

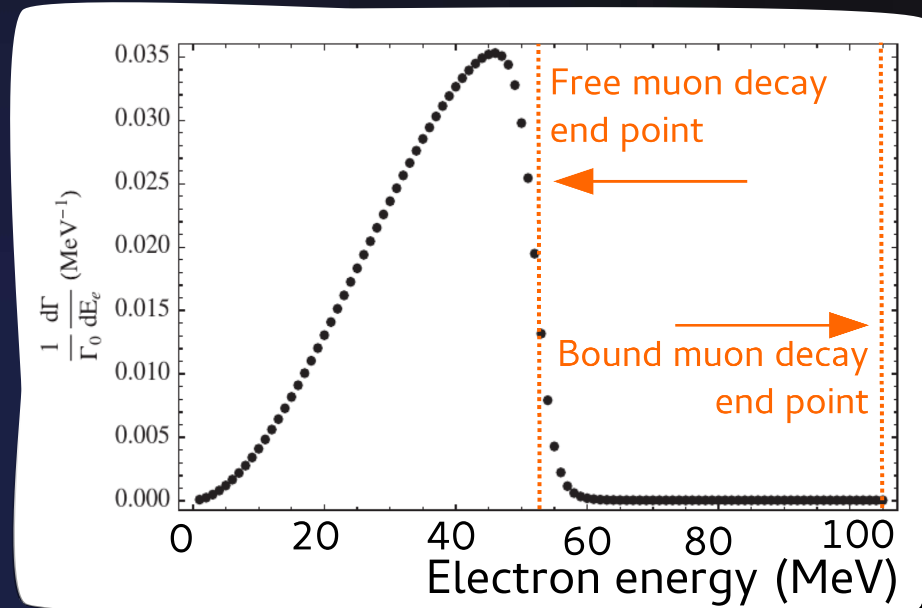


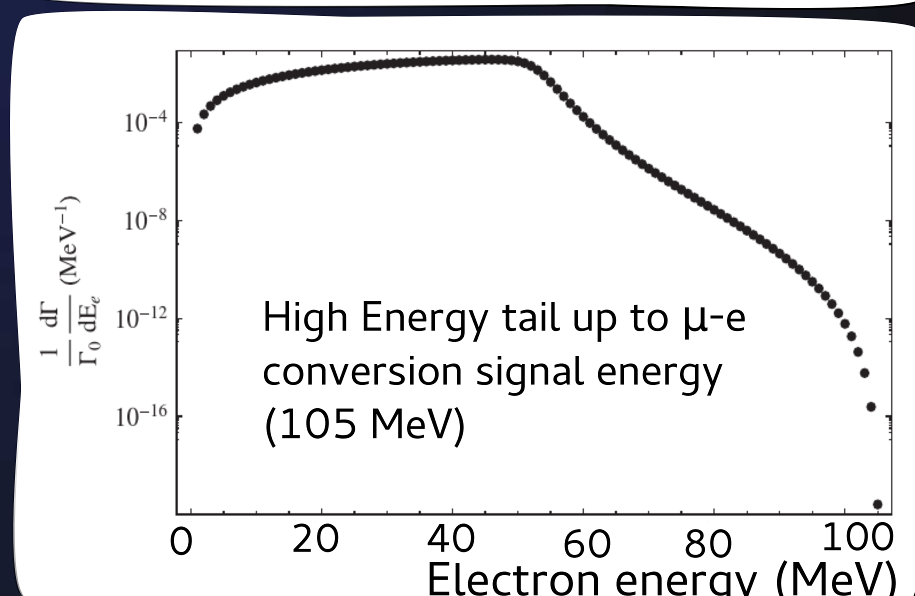
Free muon decay



Bound muon decay

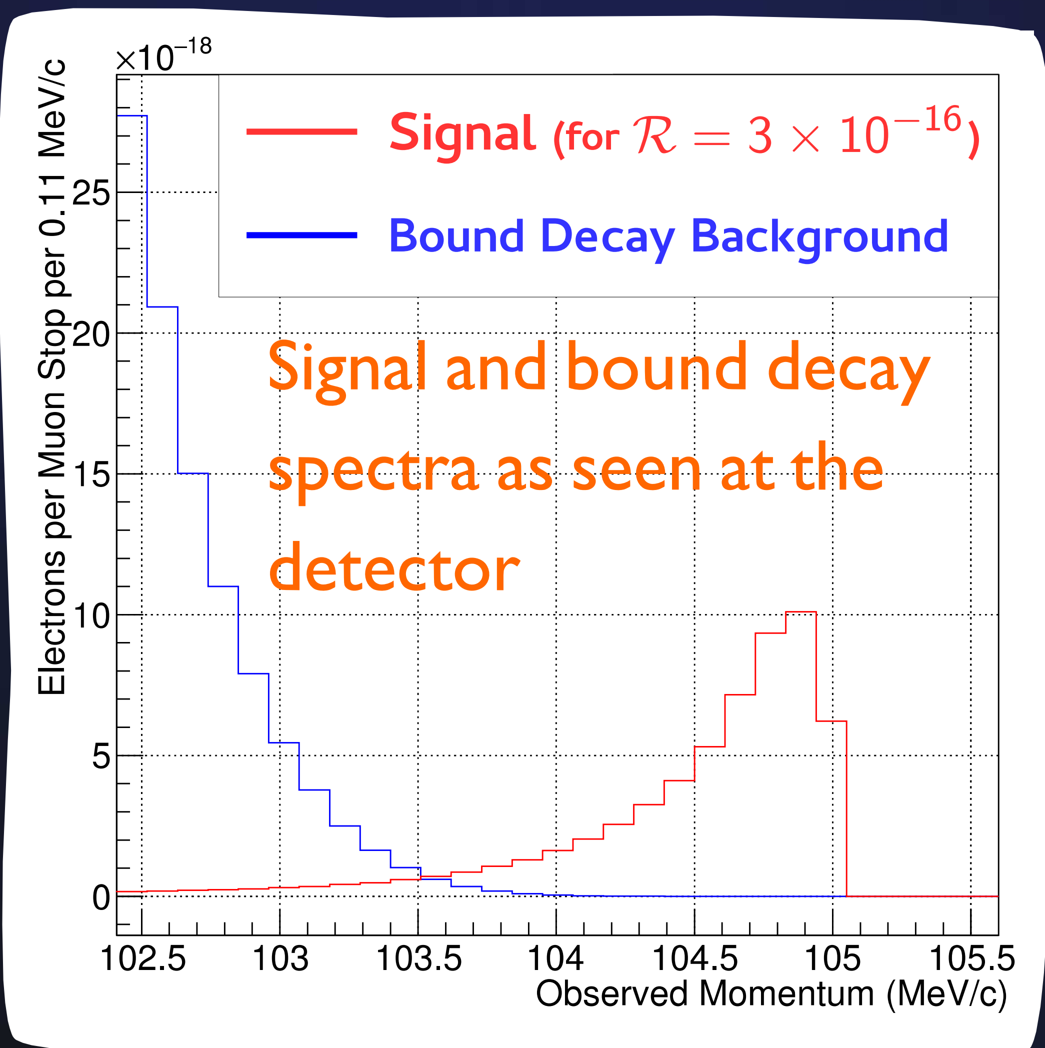
- Maximum energy for electrons from free muon decay = Half of muon mass = 55 MeV
- Bound decay around nucleus
  - End-point close to muon mass
  - Very steeply falling spectrum above 55 MeV
- Theoretical uncertainty on spectrum from initial muon wavefunction
- No accurate measurement at the end point

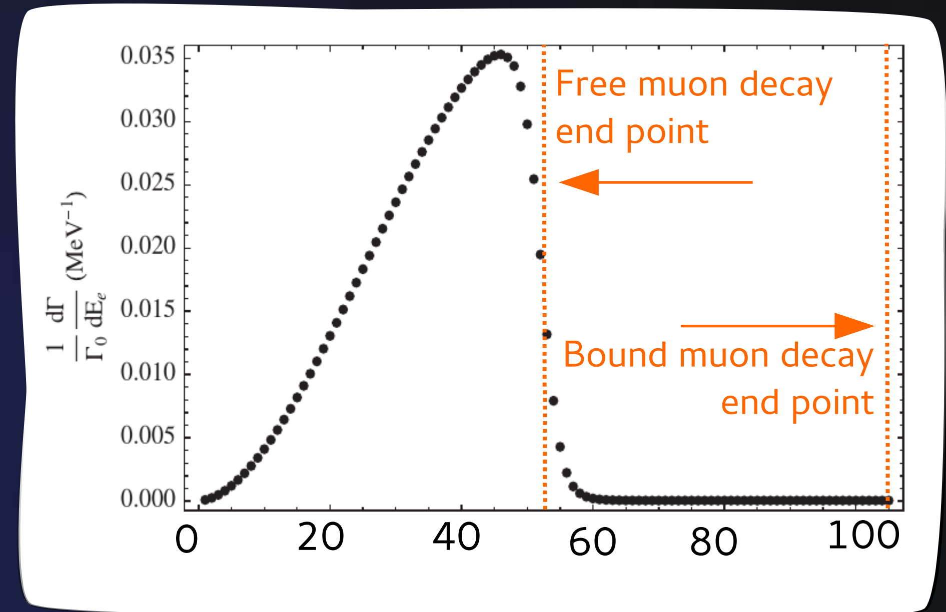


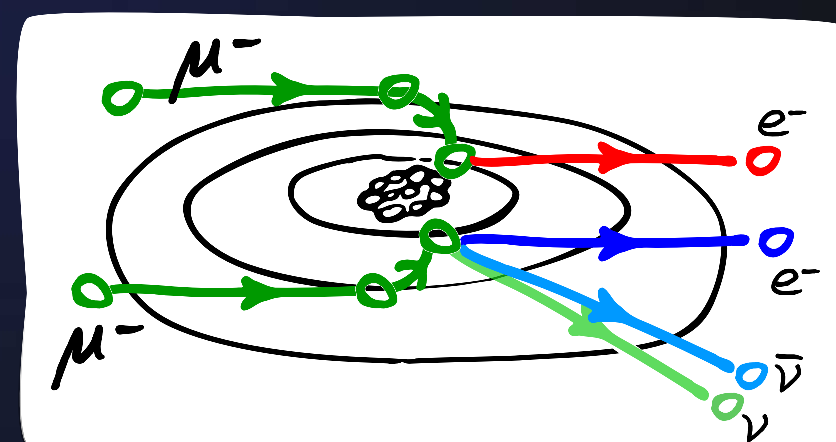


Czarnecki et al. 2011 DOI: 10.1103/PhysRevD.84.013006

Muon to Electron Conversion

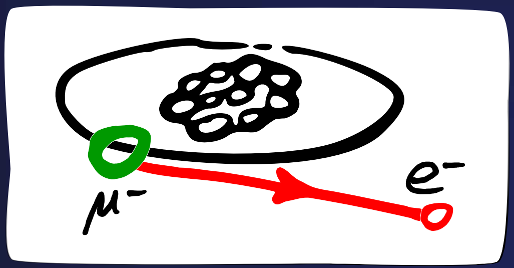






The COMET Experiment

COMET:
COherent Muon to Electron Transitions



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

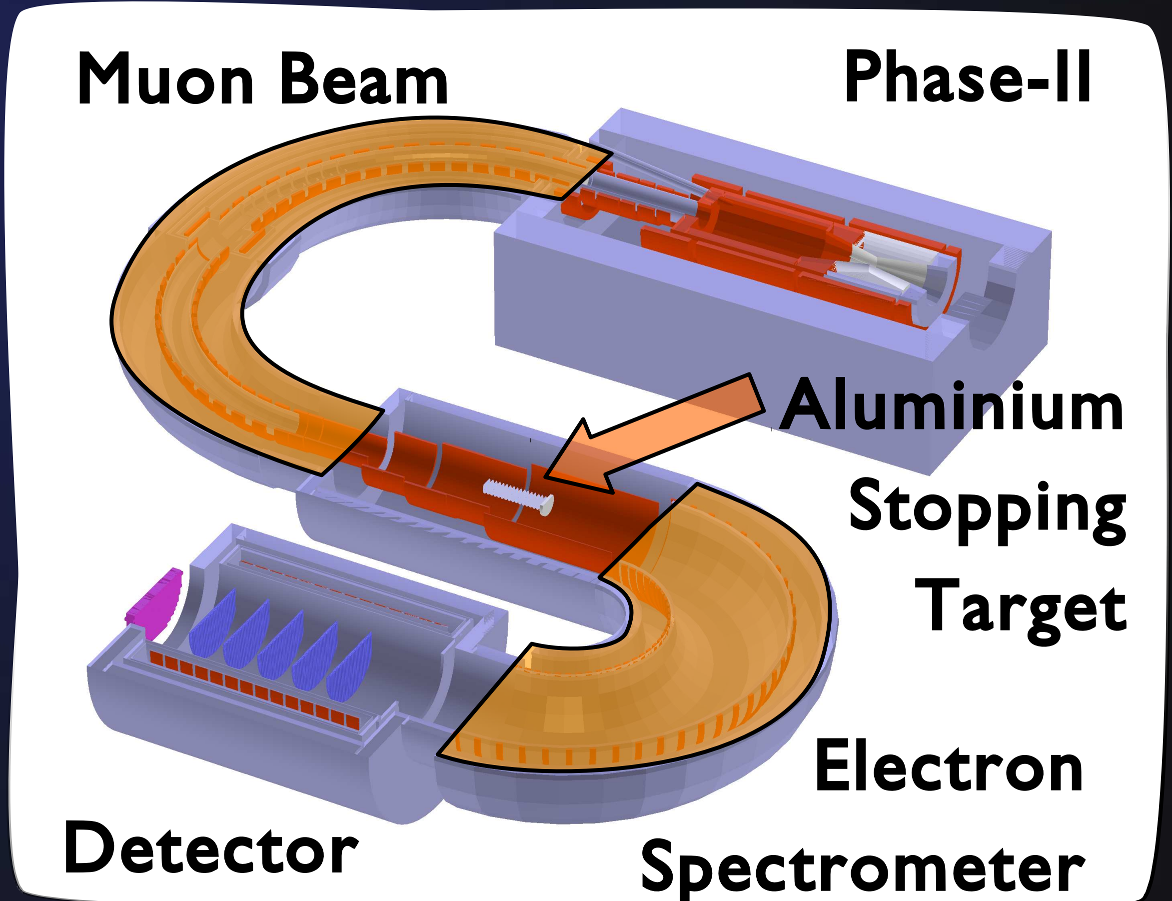
Present limits by SINDRUM-II (2006):

$\mathcal{R} < 7 \times 10^{-13}$

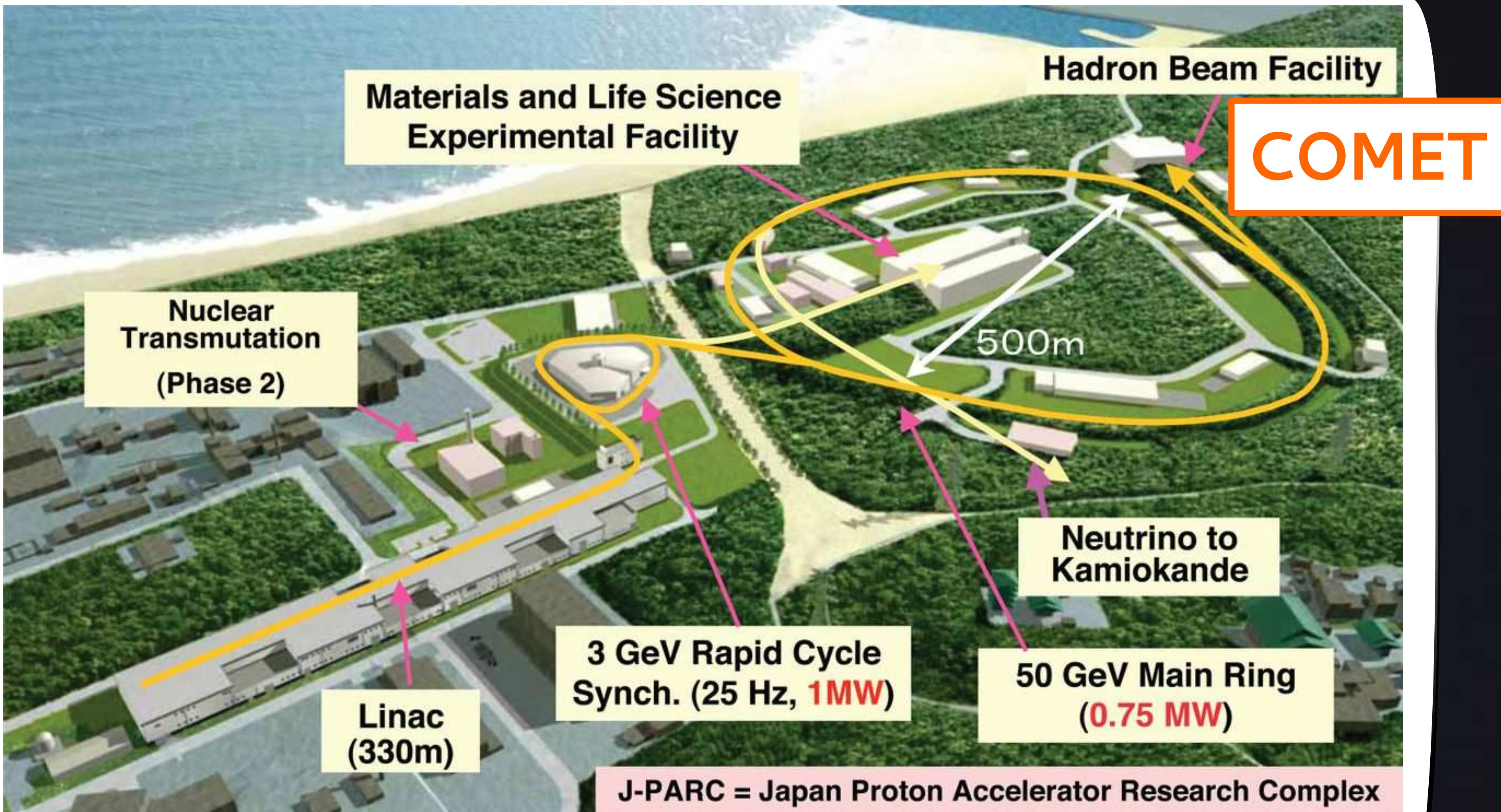
COMET Single-Event-Sensitivity:

Phase-I (2018) = 3×10^{-15}

Phase-II (2021) = 3×10^{-17}

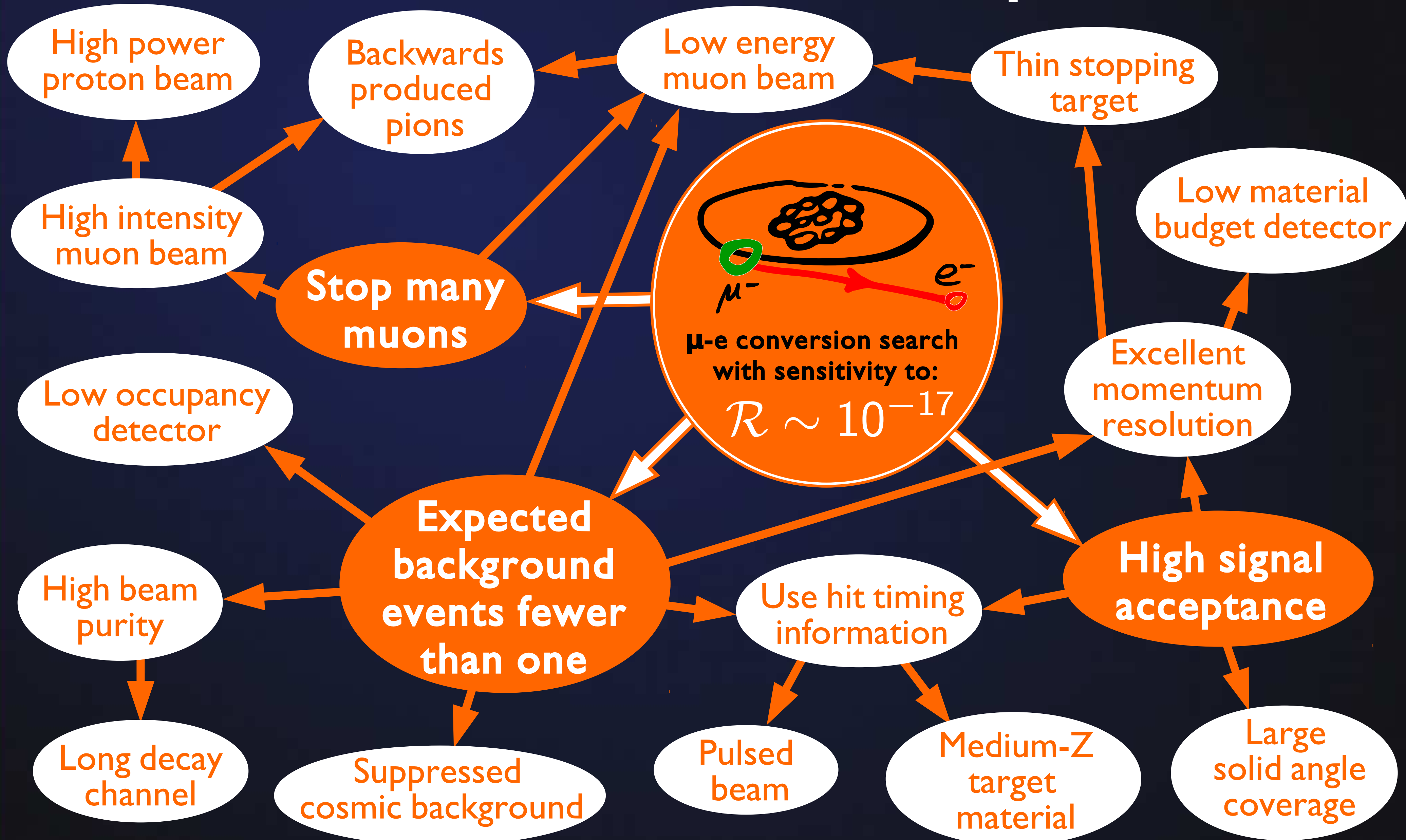


COMET at J-PARC

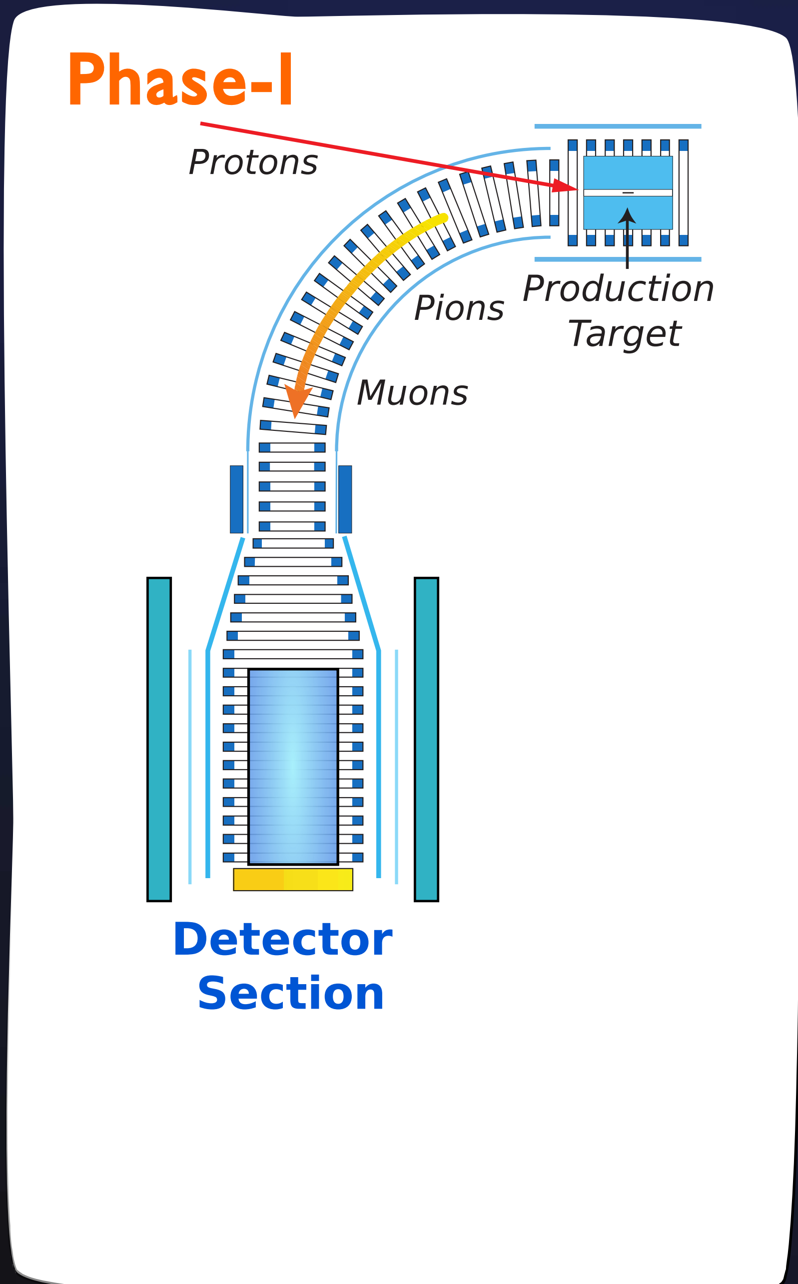


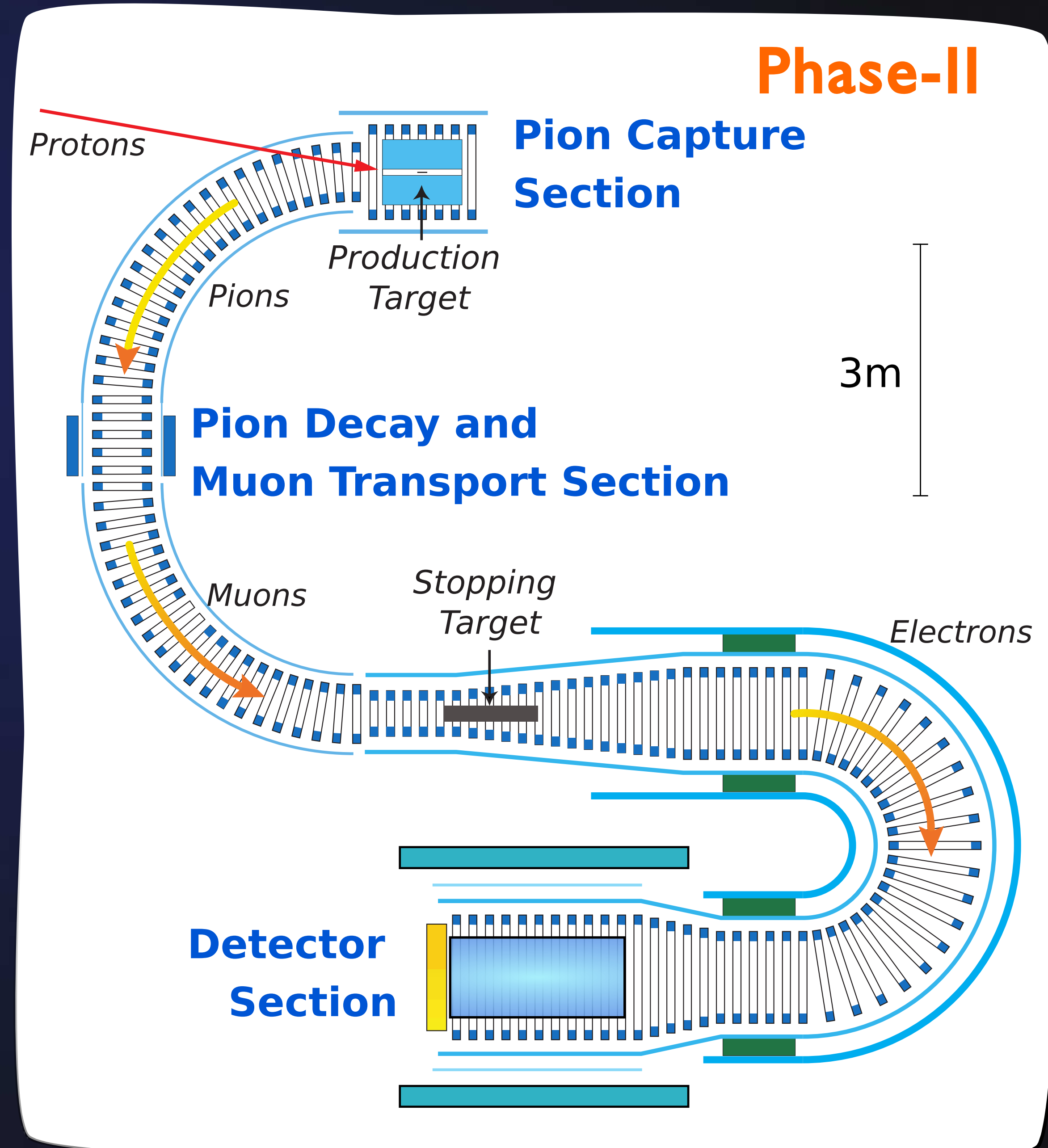
Joint Project between KEK and JAEA

Ben's Mind-map for How to Build a Modern Muon-to-Electron Conversion Experiment©™

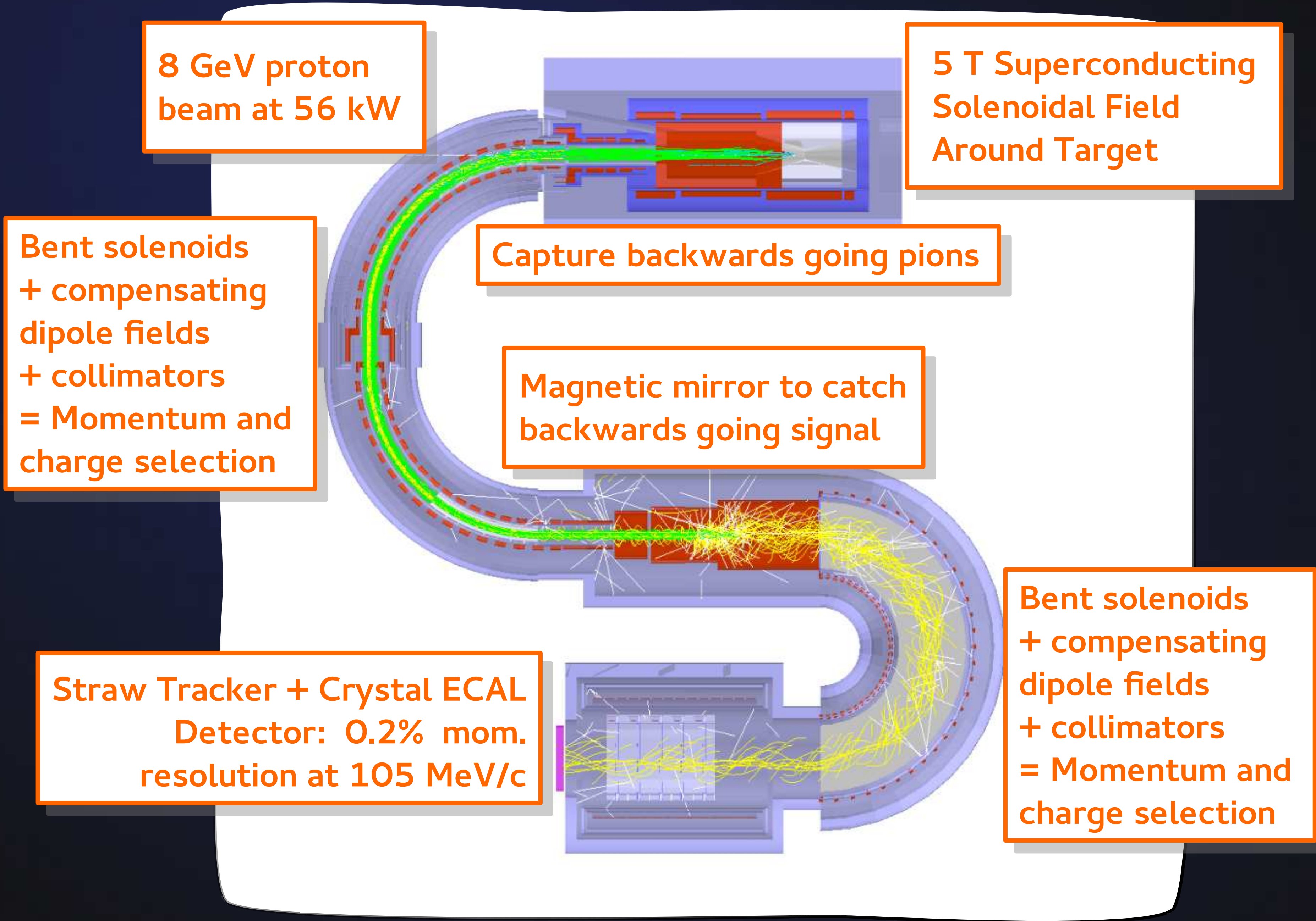


The COMET Experiment

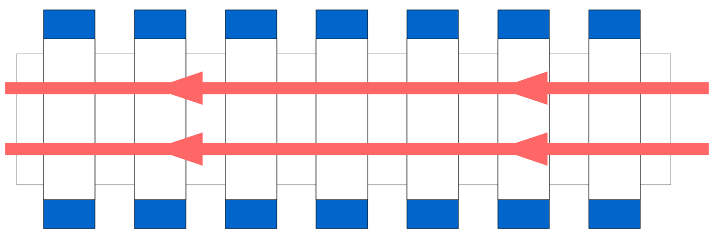




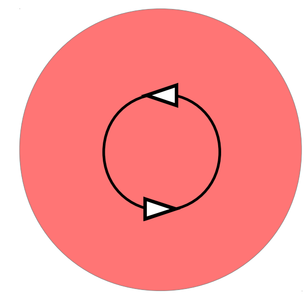
The COMET Experiment Phase-II



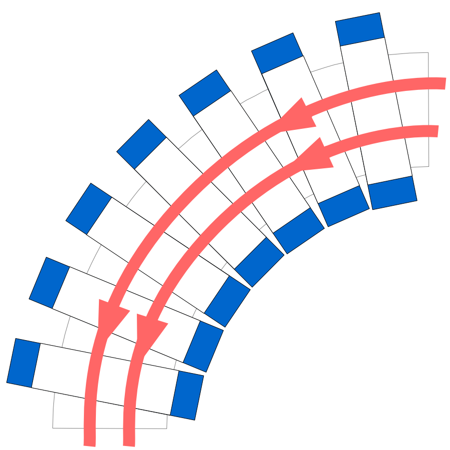
Bent Solenoid Drifts



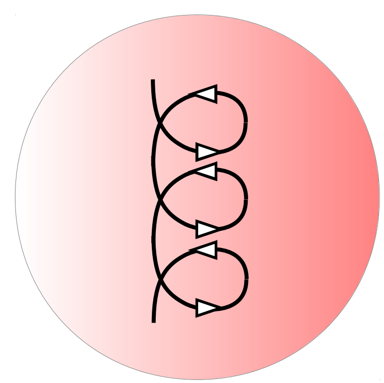
- Uniform B field
- Linear field lines



Circular motion about field lines



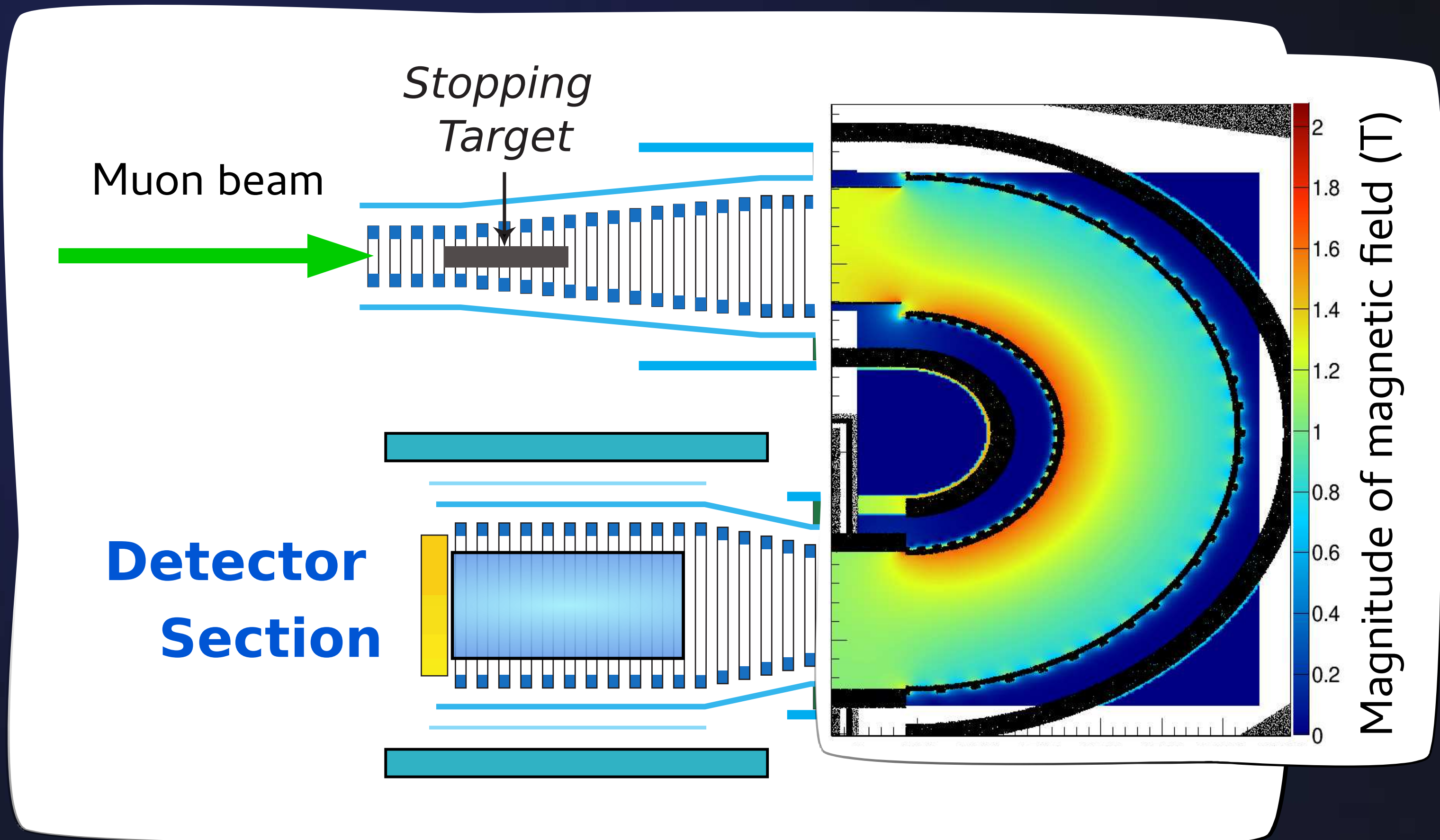
- Radial gradient in magnetic field
- Cylindrical field lines



Circular motion about a drifting centre:

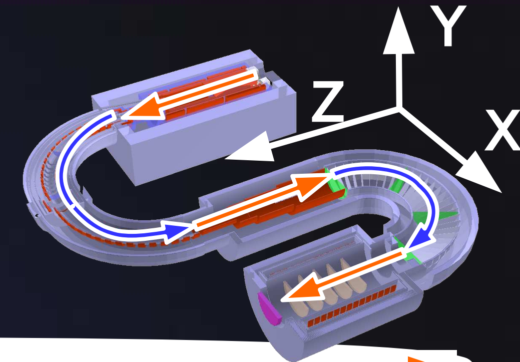
$$D \propto \frac{p}{qB} f(\theta)$$

Phase-II Electron Spectrometer



- No line of sight between detector and target
- Select for high momentum electrons using bent solenoid and tuneable dipole field

Bent solenoids + Dipole

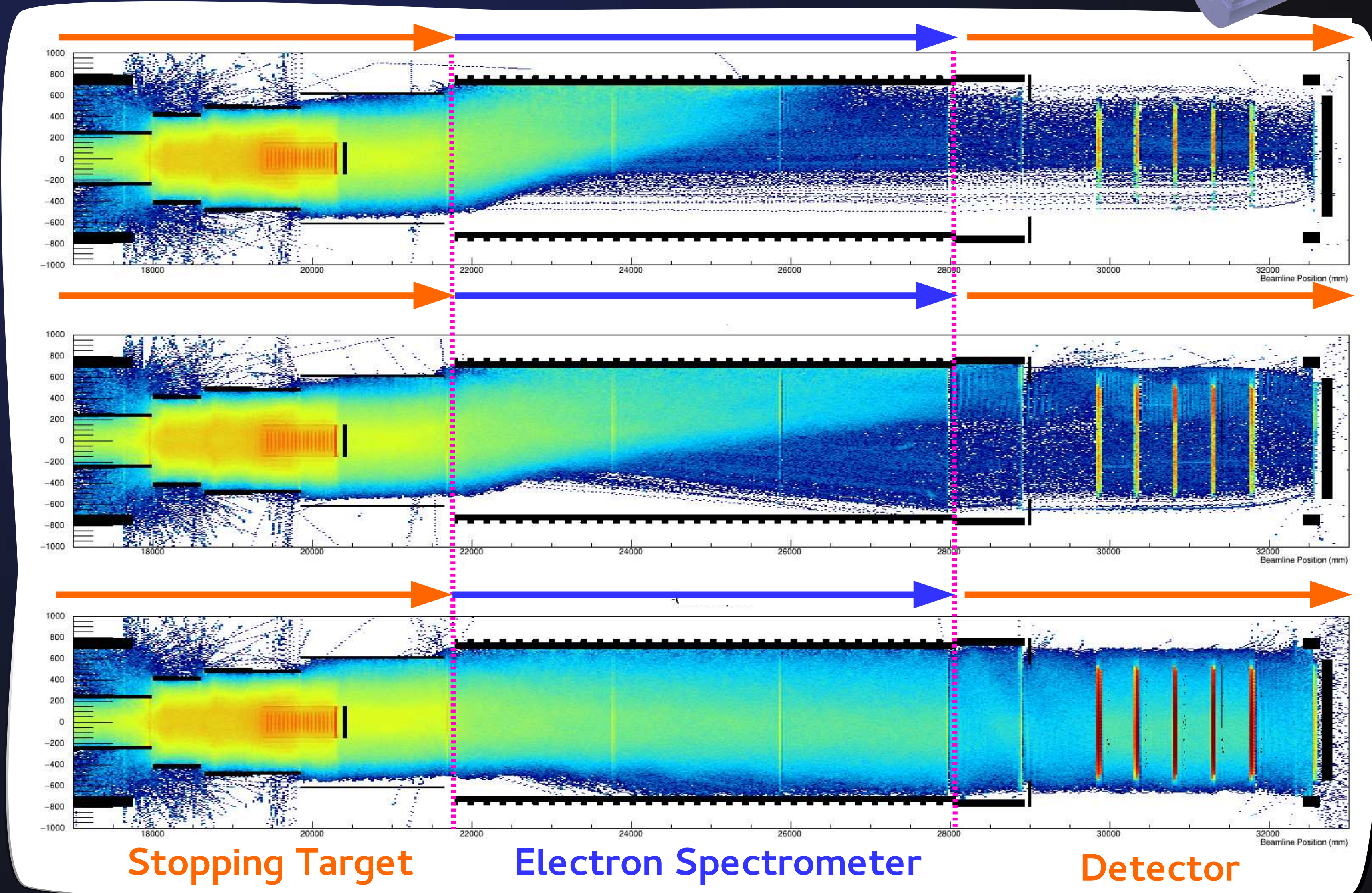


A correcting dipole field allows us to select the momentum that remains on axis. Eg. 105 MeV/c:

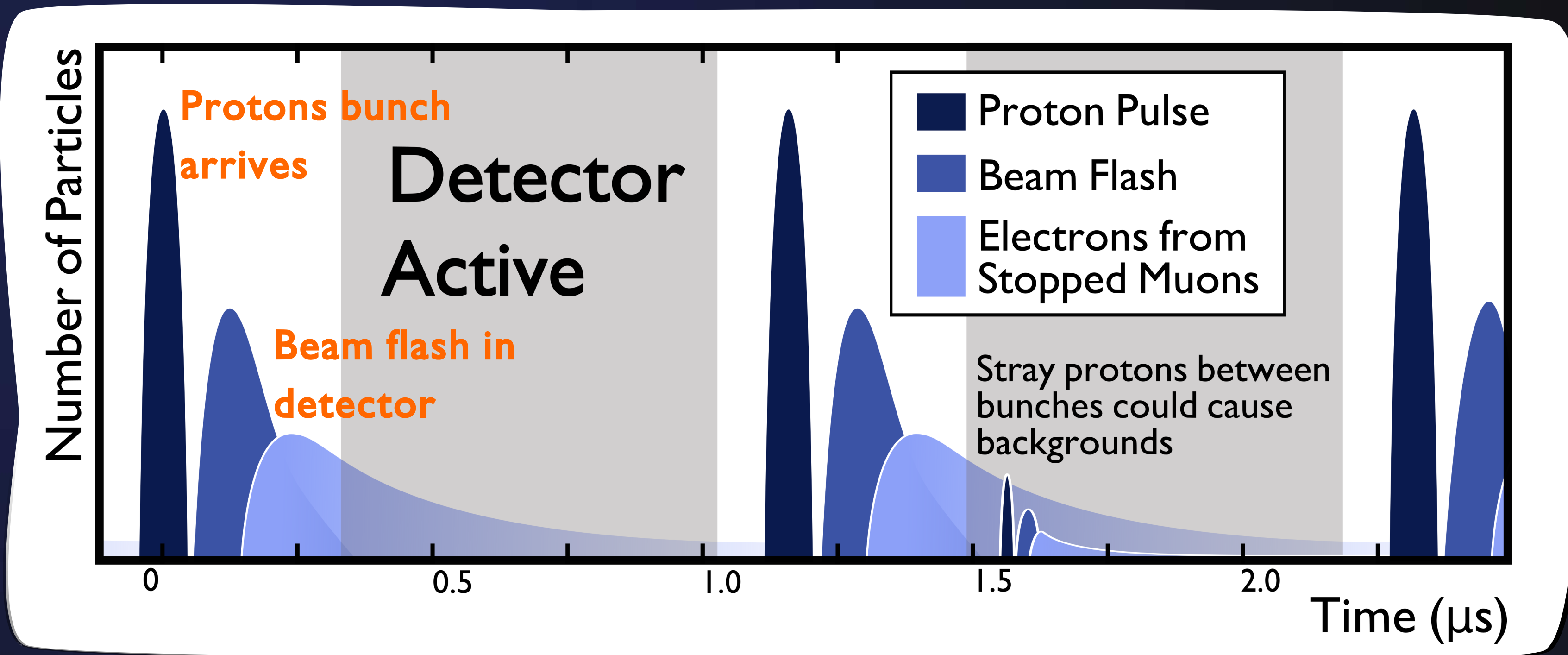
No Dipole

-0.08 T Dipole

-0.22 T Dipole



Pulsed Beam and Timing Information

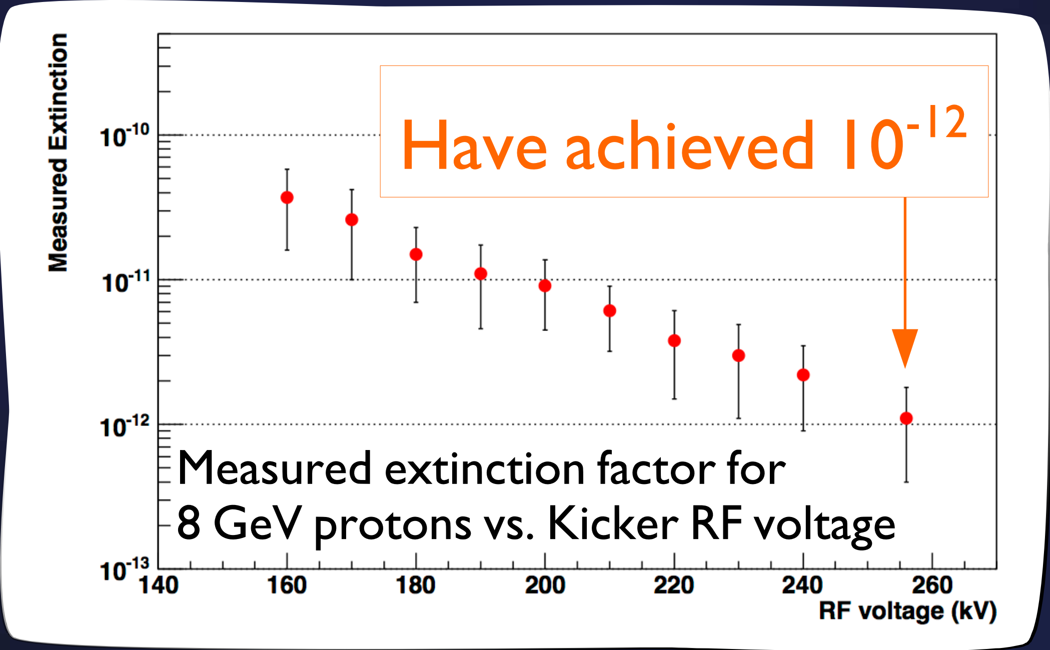


- Muon lifetime on Aluminium: 864 ns
- Pulsed beam removes beam-related backgrounds, typically up to 200 ns
- Few protons between pulses as possible:
  - Extinction factor:

$$\text{Extinction} = \frac{\text{N(Protons between pulse)}}{\text{N(Protons in bunch)}}$$

  - Originally aiming for 10^{-9}
- Diamond detector to measure extinction during running

Pulsed Beam and Timing Information



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Backgrounds

From Phase-I TDR (2016)

From Phase-II CDR (2009)

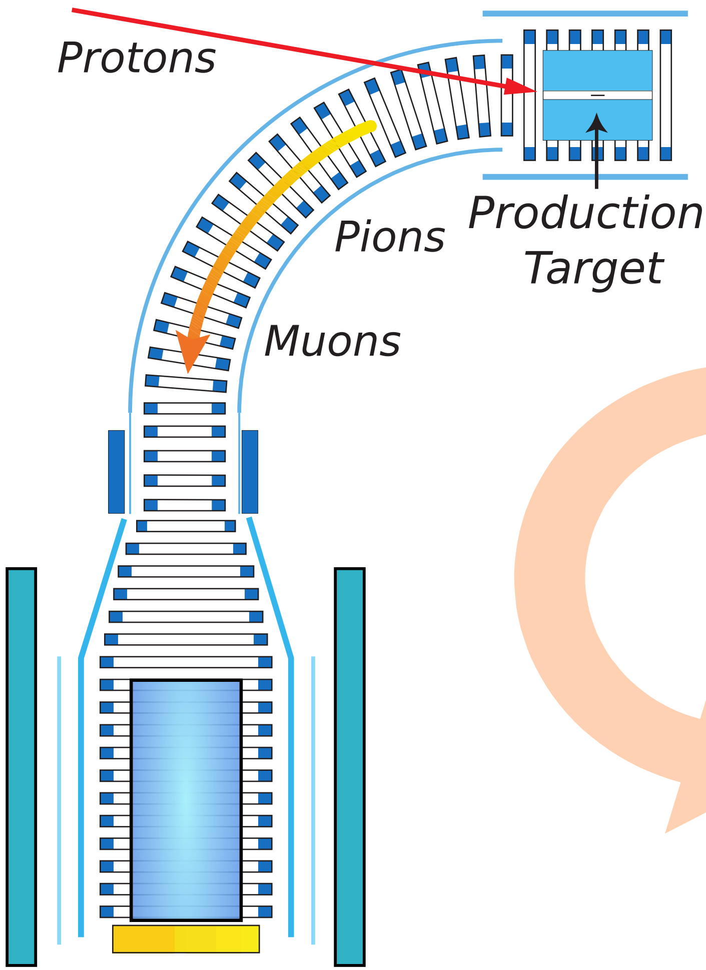
Type	Background	Number of events during run Phase-I [28]	Phase-II [14]
Intrinsic	Muon Decay-in-Orbit	$0{\cdot}01$	$0{\cdot}15$
	Radiative Muon Capture	$0{\cdot}0019$	$< 0{\cdot}001$
	μ^- Capture w/ n Emission	$< 0{\cdot}001$	$< 0{\cdot}001$
	μ^- Capture w/ Charged Part. Emission	$< 0{\cdot}001$	$< 0{\cdot}001$
Prompt	Radiative Pion Capture	$0{\cdot}00028$	$0{\cdot}05$
	Beam Electrons	≤ 0.0038 (Beam Electrons, Muon Decay in Flight, Pion Decay in Flight combined)	$< 0{\cdot}1^*$
	Muon Decay in Flight		$< 0{\cdot}0002$
	Pion Decay in Flight		$< 0{\cdot}0001$
	Neutron Induced	$\sim 10^{-9}$	$0{\cdot}024$
Delayed	Delayed Radiative Pion Capture	~ 0	$0{\cdot}002$
	Anti-proton Induced	$0{\cdot}0012$	$0{\cdot}007$
	Other delayed B.G.	~ 0	–
Cosmic	Cosmic Ray Muons	≤ 0.01 (Cosmic Ray Muons and Electrons from Cosmic Ray Muons combined)	$0{\cdot}002$
	Electrons from Cosmic Ray Muons		$0{\cdot}002$
	Total background	$< 0{\cdot}032$	$< 0{\cdot}34$
	Signal (Assuming $B = 1 \times 10^{-16}$)	$0{\cdot}31$	$3{\cdot}8$

Assumed extinction factors:
Phase-I: 10^{-11}
Phase-II: 10^{-9} (to be updated)

Run times:
Phase-I: 150 days
Phase-II: 1 year

COMET Phase-I Status and R&D

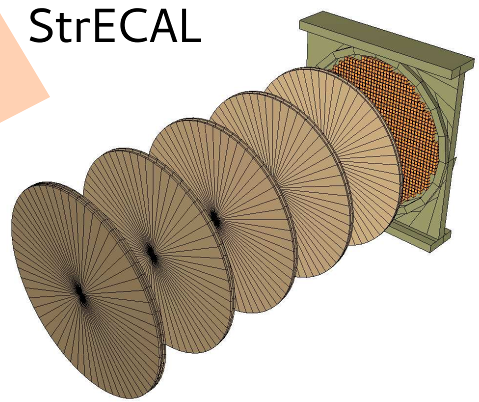
COMET: Phase-I



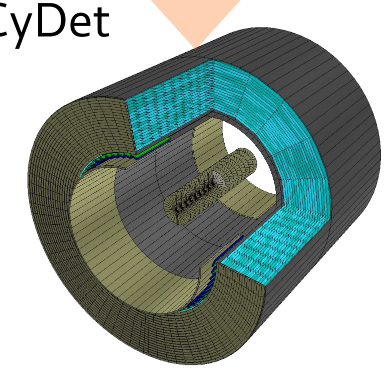
Goals of Phase-I

- Understand production system
- Understand bent solenoid dynamics
- Prototype the detector
- Measurement of background sources
- μ-e conversion search at: 3×10^{-15}

StrECAL

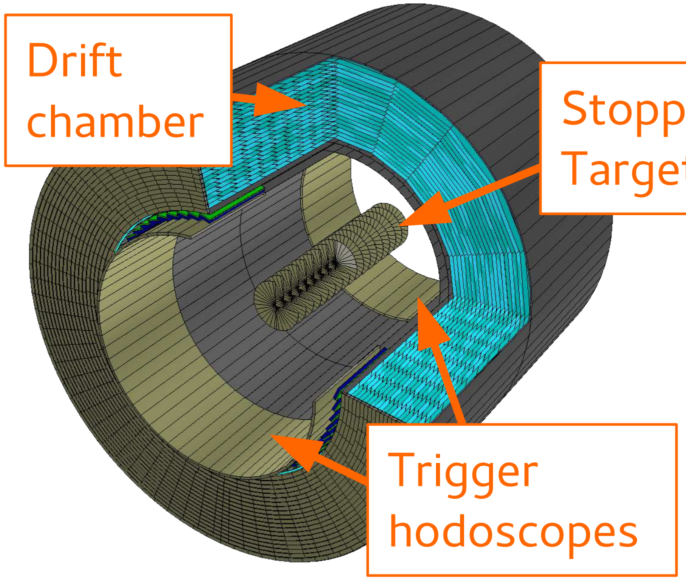


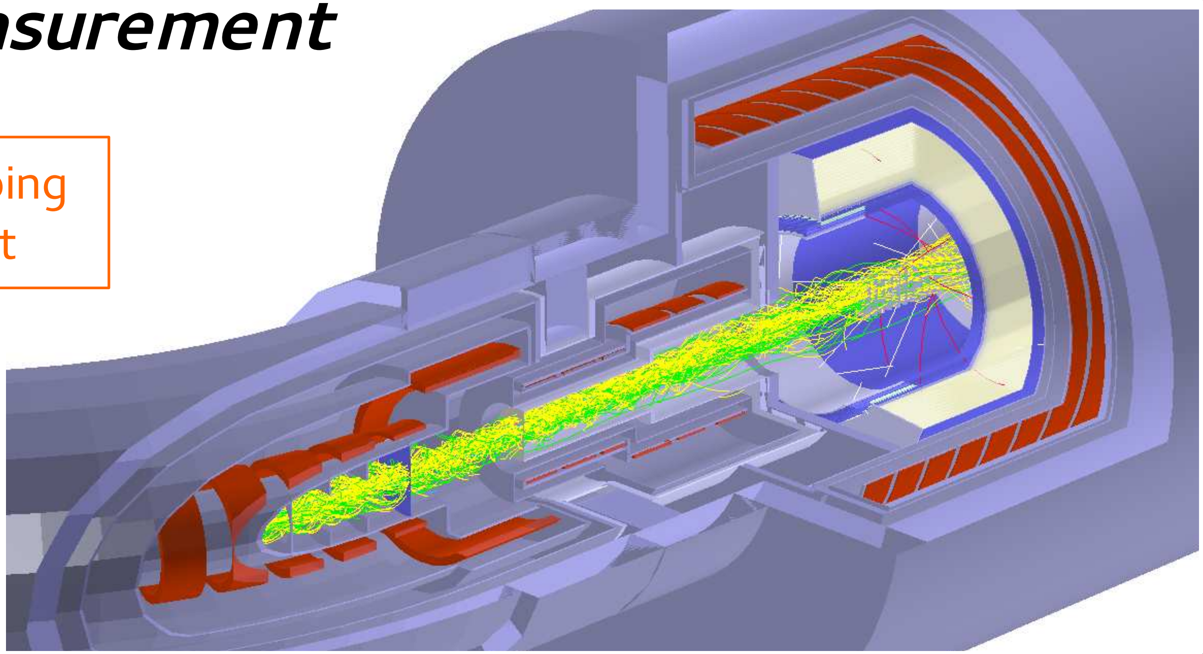
CyDet



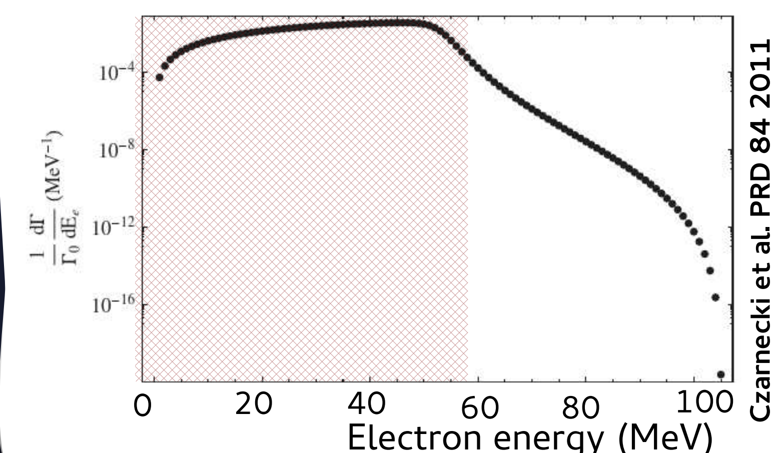
Cylindrical Detector (CyDet)

Phase-I Physics Measurement



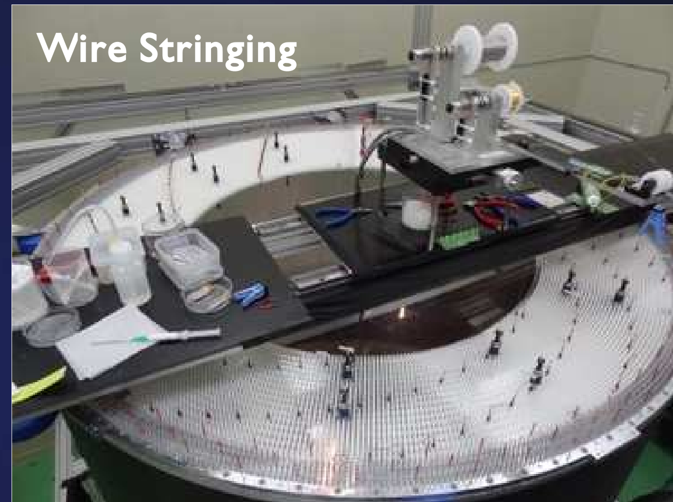


- Cylindrical Drift Chamber (CDC) triggered from hodoscopes made of Cherenkov counters and plastic scintillators
- 60 cm inner radius
  - Only accept particles with momentum greater than 60 MeV/c
  - Avoids beam flash and most electrons from bound muon decay
- Momentum measurement using drift chamber
  - Low material budget improves resolution
  - All stereo wires to recover Z information

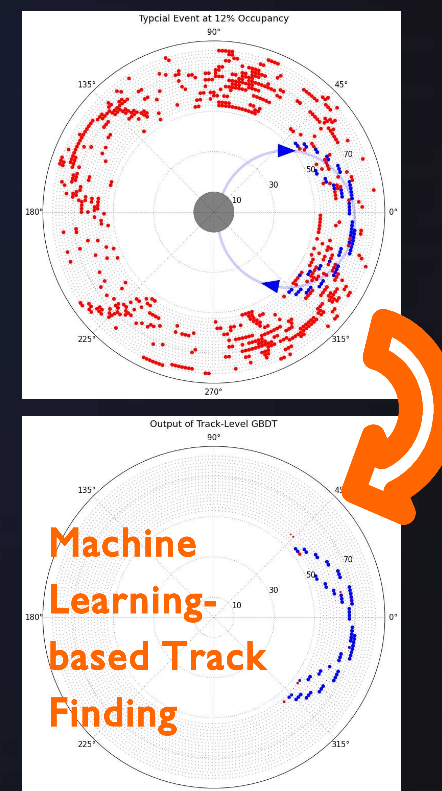


Electrons from Bound Muon Decay

Cylindrical Drift Chamber (CDC)



- 20 layers with alternating stereo angles of ±4°
- 20,000 wires total
- Fully strung as of November 2015
- Resonance-based wire tension checking completed in March
- CDC completed in July with installation of inner wall
- Reconstruction software being prepared
- Cosmic and beam tests to optimise gas choice and study resolution and drift time
  - Achieving the 200 keV/c resolution



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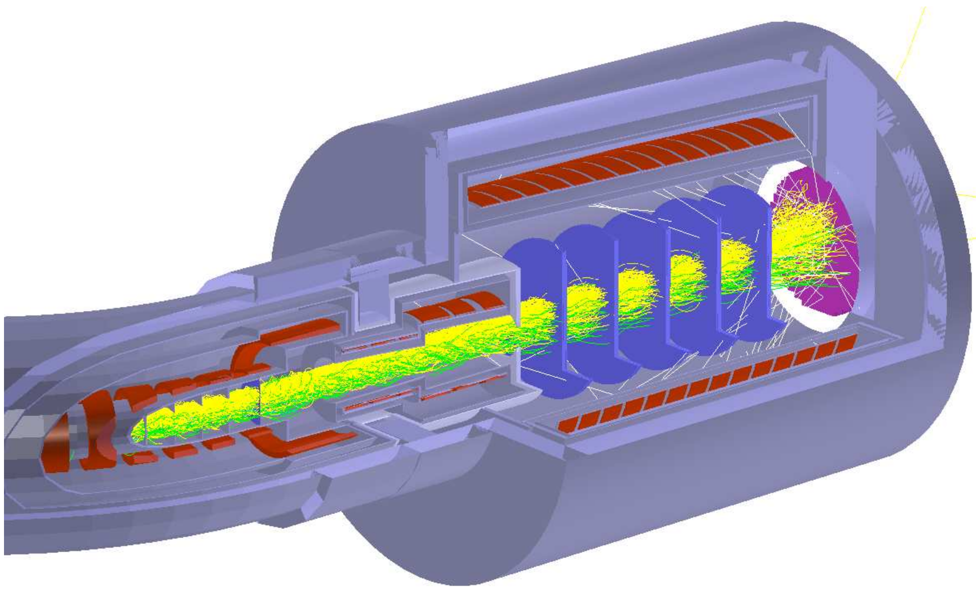
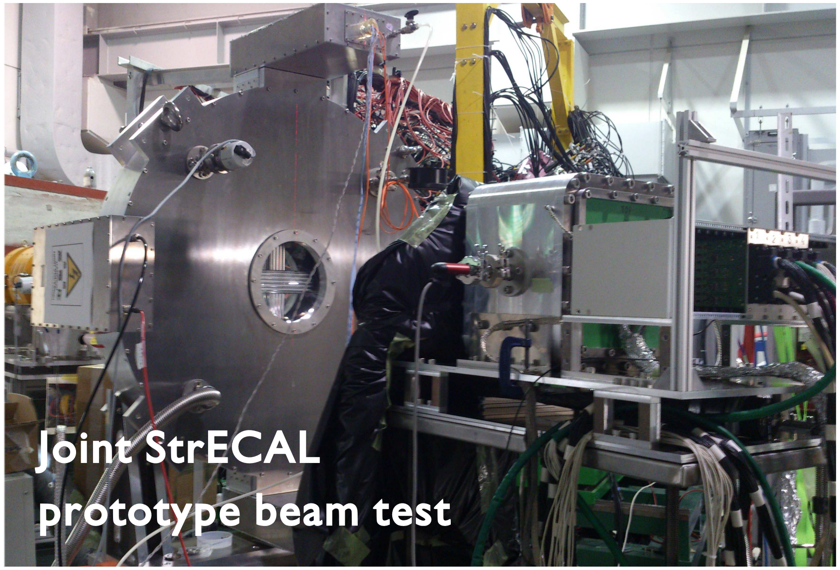
StrECAL Detector

Straw Tracker + ECAL





Joint StrECAL prototype beam test

- Phase-II Detector prototype
- Used to characterise beam in Phase-I

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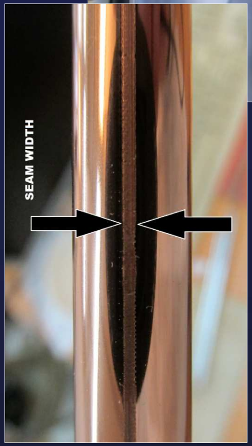
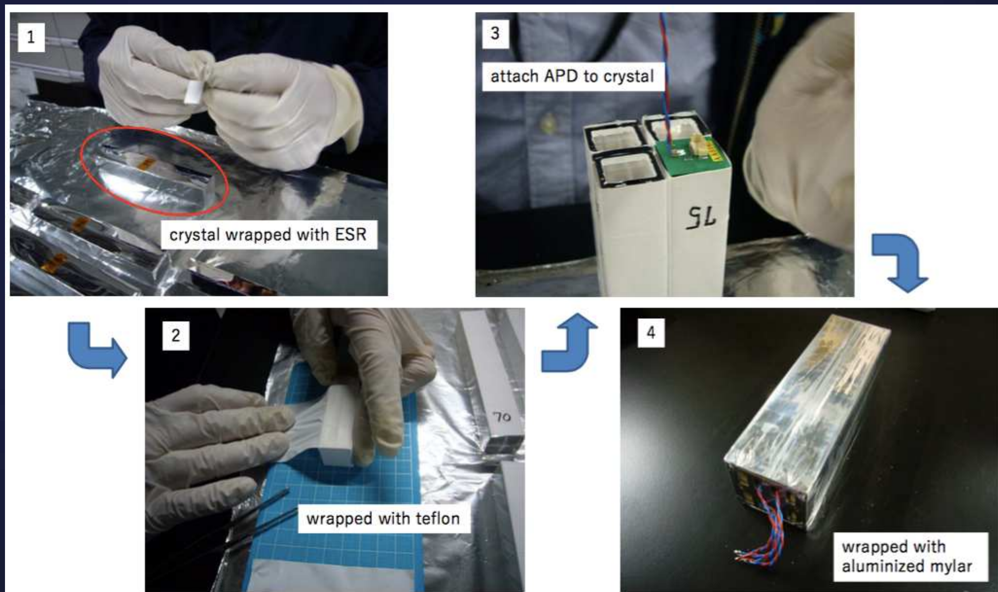
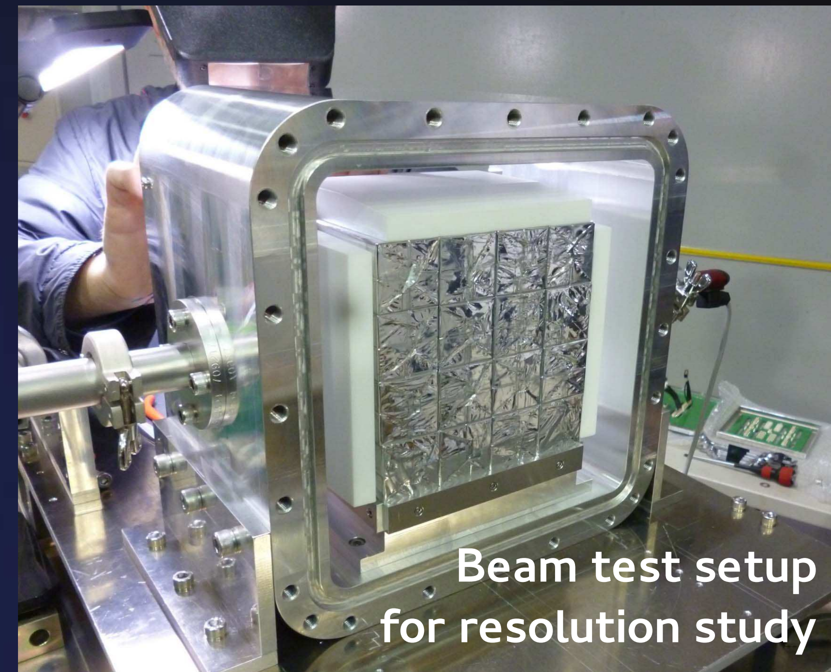
Straw Tracker

- Phase-I Straw Design
  - Based on NA62 Straws with single seam weld
  - 20 micron aluminised mylar
  - 9.8 mm diameter tubes
- Phase-II possibilities:
  - 5 mm diameter
  - 12 micron Al-mylar
- Status
  - Phase-I production finished (2500 straws)
  - Aging and vacuum tests at KEK
  - Resolution studies from beam tests:
    - Better than 200 micron resolution across straw

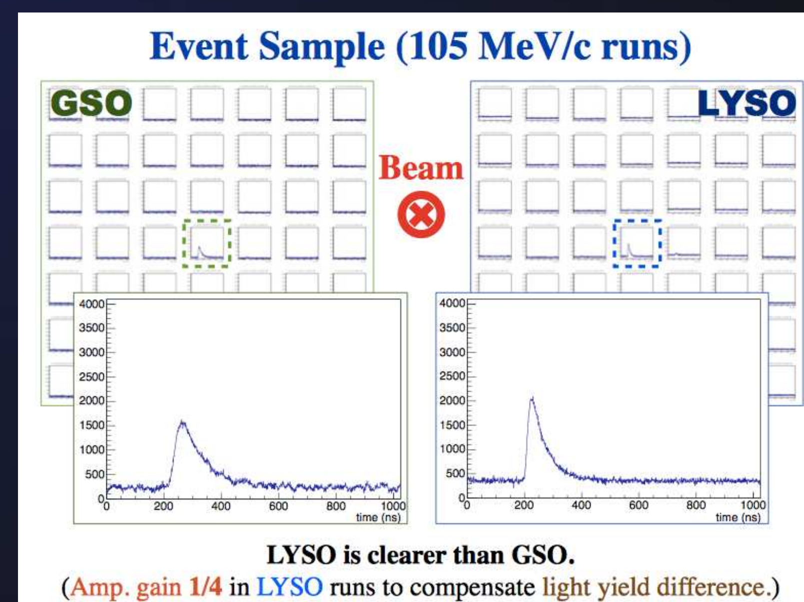


LYSO Crystal Calorimeter



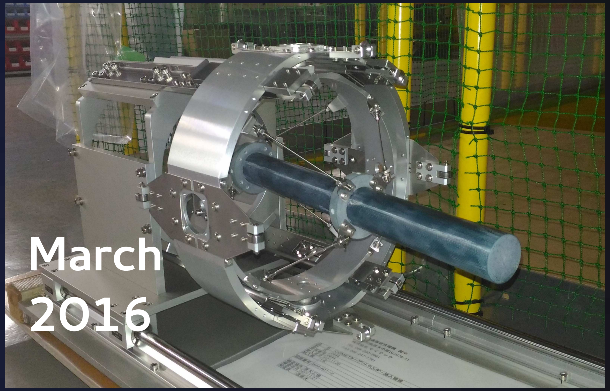


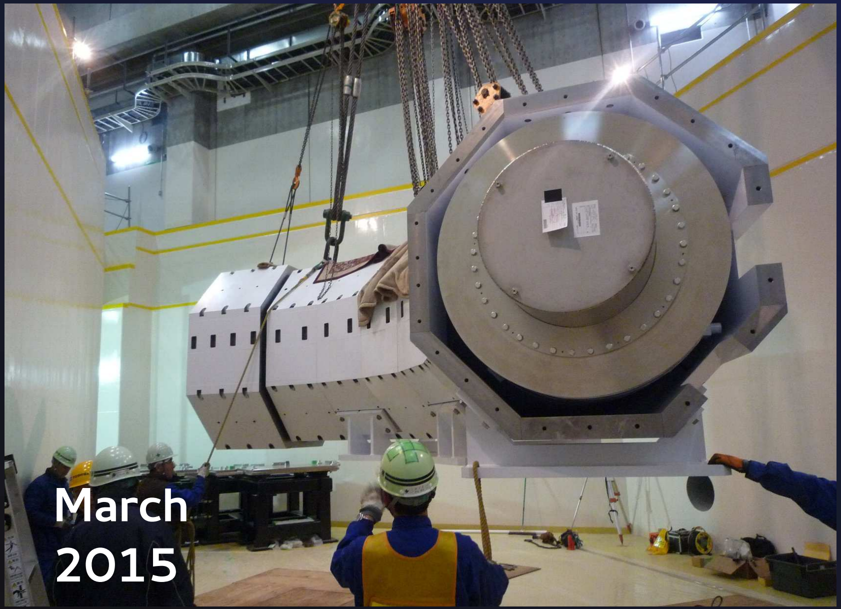
- 2272 LYSO Crystals
  - Dimensions: 2x2x12 cm
- Status:
  - Crystal purchasing on-going
  - Test bench being built
  - Beam tests for resolution studies, PID and DAQ underway
  - Calibration system being designed



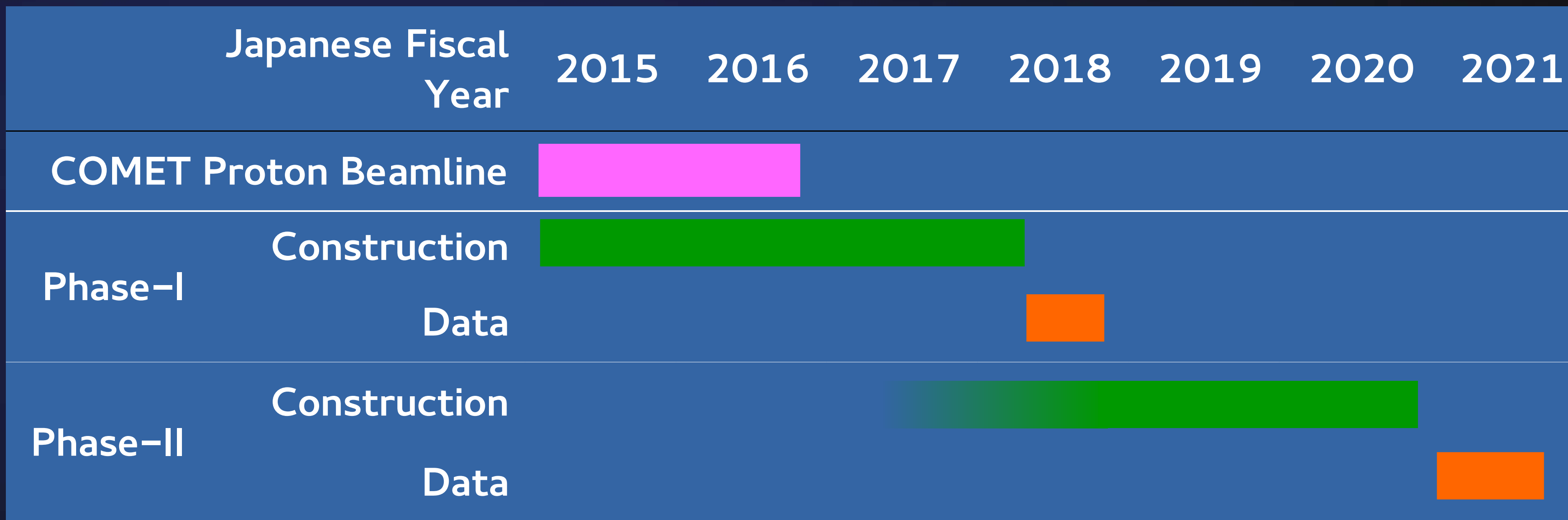
Facility Status and Beamline

- Building and hall completed
- Phase-I bent solenoid built and installed
- Detector solenoid under construction





Schedule and Collaboration

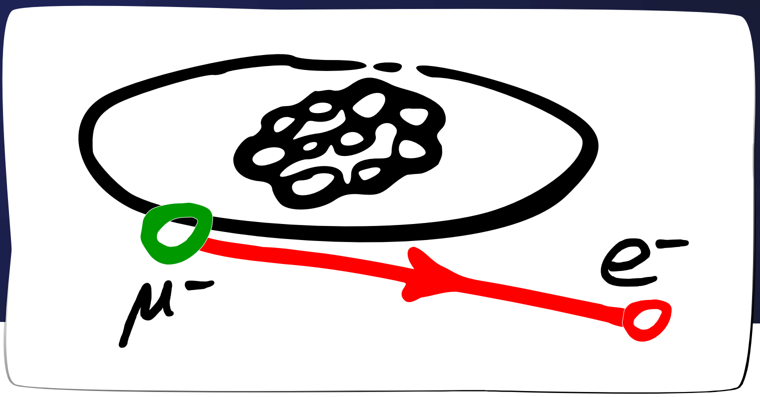


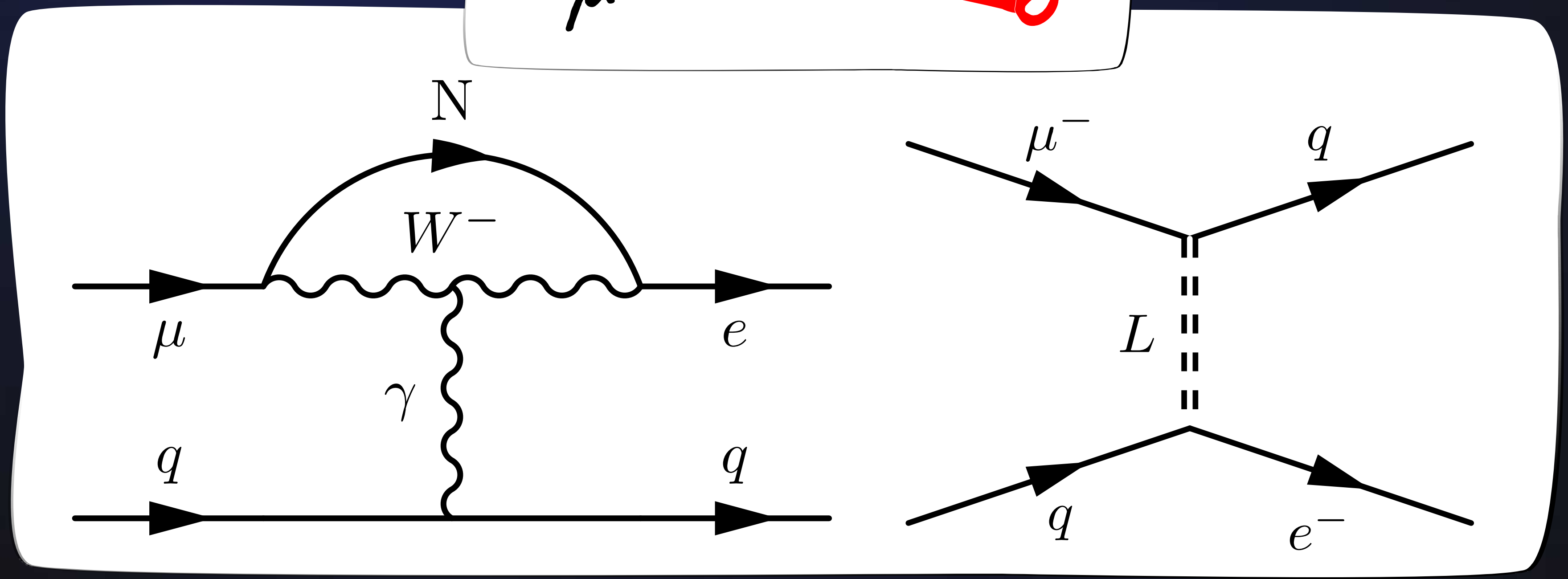
15 Countries, 33 institutes

176 participants

Summary

Muon-to-electron conversion is a strong probe of new physics





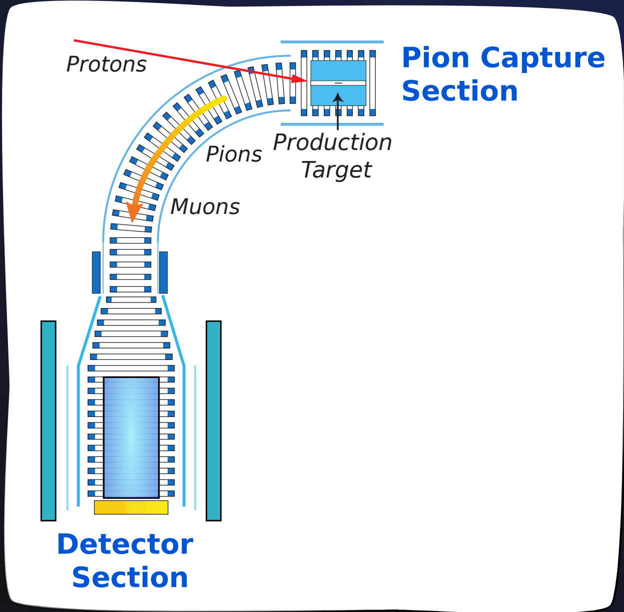
Summary

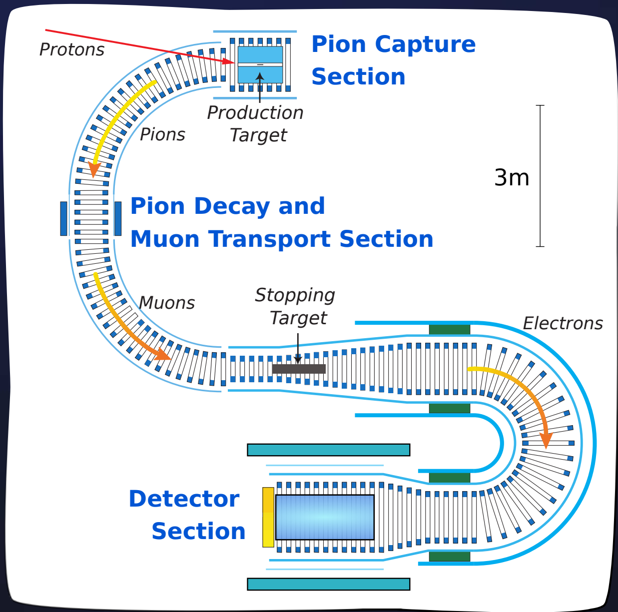
Muon-to-electron conversion is a strong probe of new physics

COMET's staged approach and unique design makes it highly sensitive to this process

COMET Phase-I
2018, for 150 days
Sensitivity $< 3 \times 10^{-15}$
3.2 kW proton beam

COMET Phase-II
2021, for 1 year
Sensitivity $< 3 \times 10^{-17}$
56 kW proton beam





Summary

Muon–to–electron conversion is a strong probe of new physics

COMET's staged approach and unique design makes it highly sensitive to this process

Development and construction are well under way

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