Muon to electron conversion

The

COMET [J-PARC] **&** **Mu2e** [Fermilab]

Experiments

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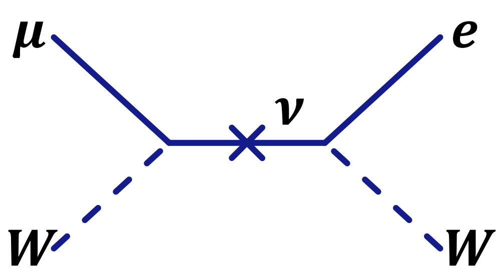
(COMET)

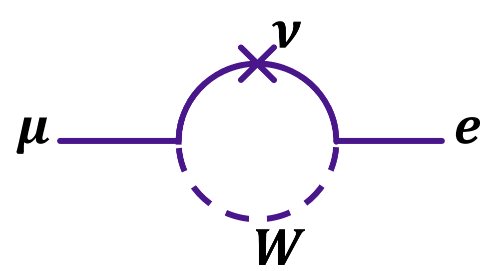
Charged lepton flavour violation

We already know that lepton flavour is not conserved

- Weak mixing mechanism & non-degenerate neutrino masses
- Neutrino (lack of) mass & charge means this is easiest to observe in neutrino oscillations, but can also lead to **CLFV**:



Neutrino oscillation



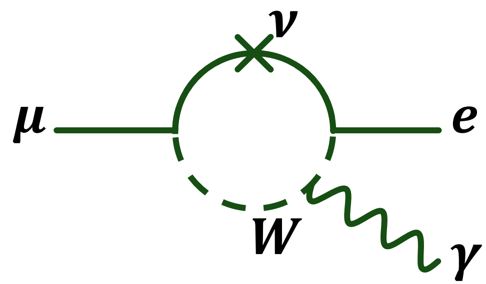
$\mu - e$ transition
(without radiation)

- The basic SM amplitudes can be related to the neutrino oscillation parameters, but requires some radiation to conserve energy & momentum.
- The $\mu - e$ system is particularly simple because the radiated 'mass' must be neutral, and lighter than a muon.

Options for decaying muons

The most obvious candidate for the transition to radiate is a photon, and the branching ratio is:

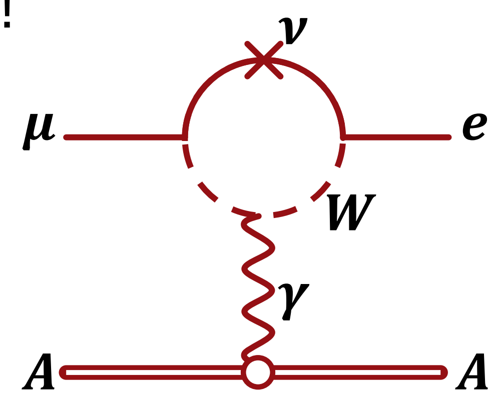
$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\nu)} \propto \left| \sum_i \frac{m_i^2}{m_W^2} U_{\mu i}^* U_{ei} \right|^2 \sim O(10^{-54})$$



$\mu \to e\gamma$ (see note)

For a free muon, this radiation is the only option…

…but in a muonic atom the radiation can be virtual! The nucleus absorbs it, and recoils slightly.



$\mu - e$ conversion

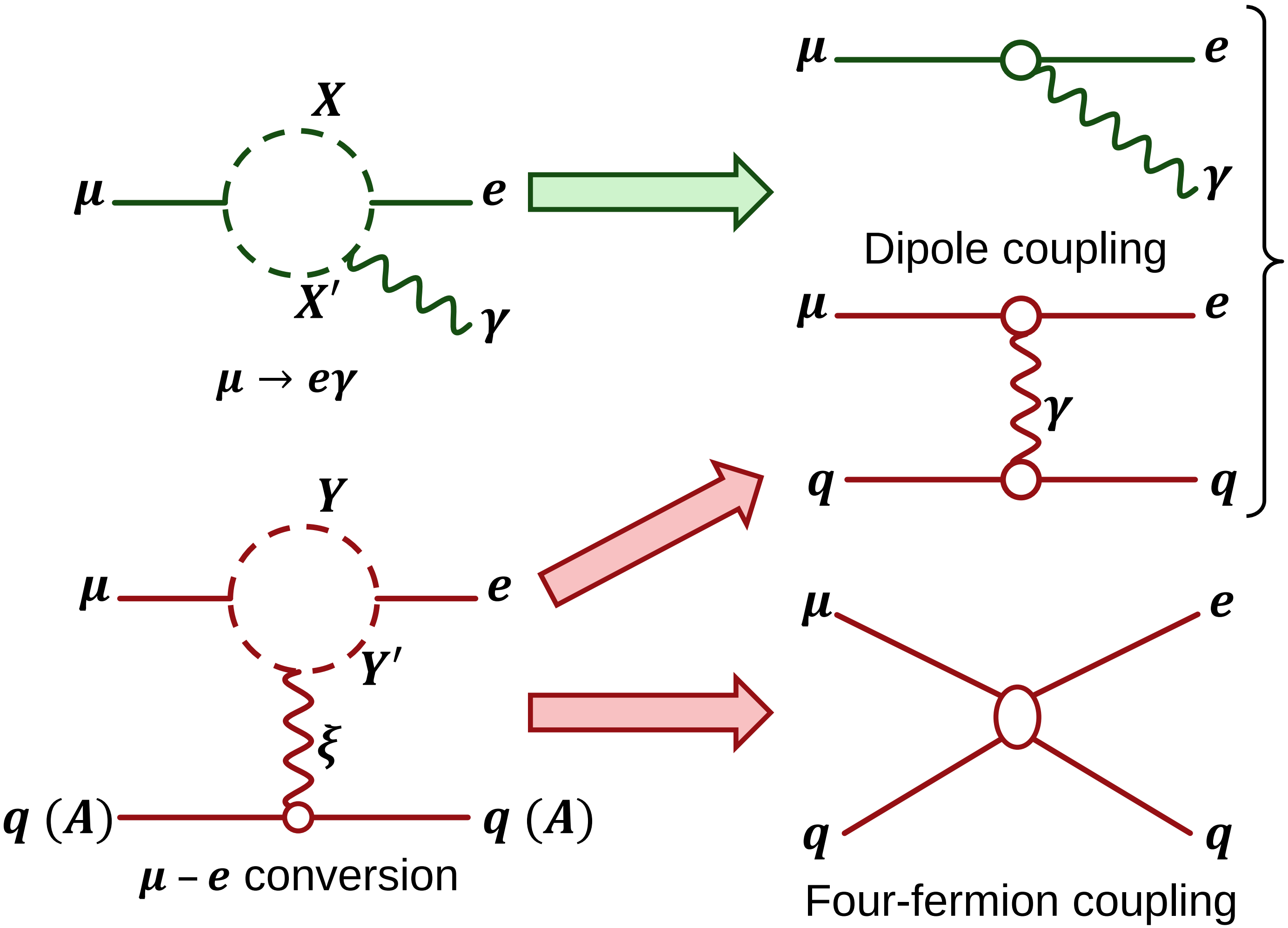
- Because of the relatively large nuclear mass, the electron is effectively mono-energetic.
- Because the process does not require a 'real' photon, other diagrams are possible…

Note: The γ can connect anywhere, not just in the loop

New physics

Similar processes exist in a wide variety of new physics scenarios.

- Muon decay is at low energy, so reduce to effective operators:



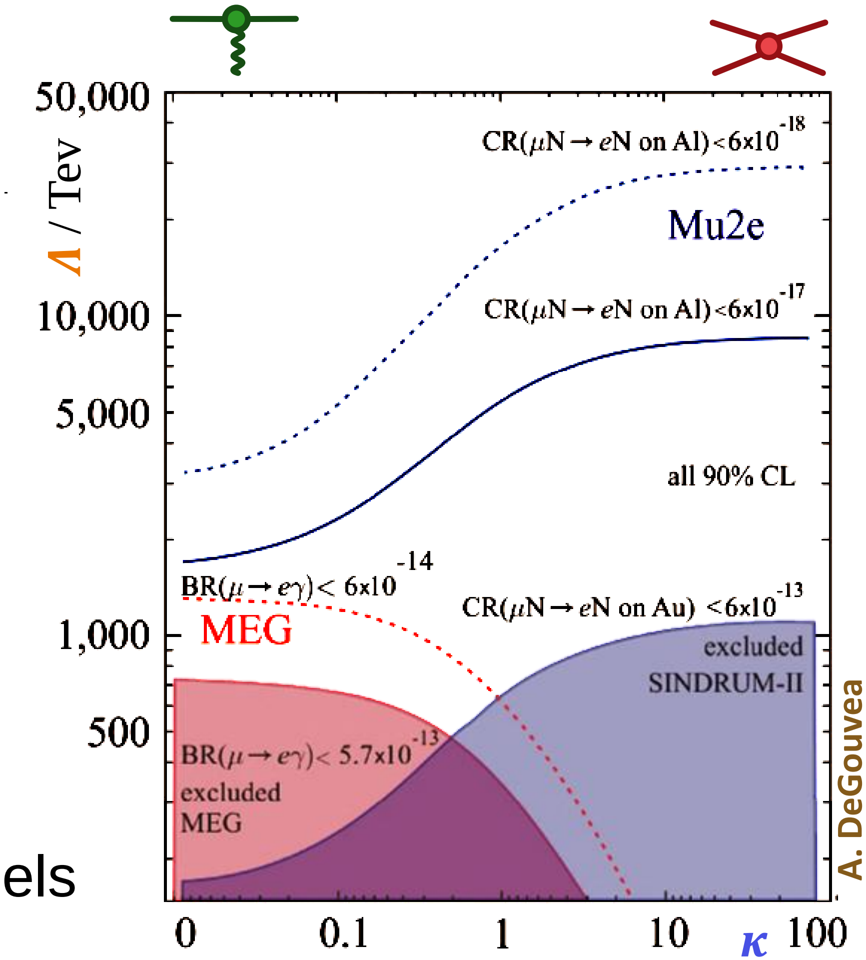
$$\mathcal{L}_{\mathrm{d}} \sim \frac{m_\mu}{\Lambda^2}\, \bar{\mu}\sigma_{\mu\nu} e \cdot F^{\mu\nu}$$

$$\mathcal{L}_4 \sim \frac{1}{\Lambda^2}\, \bar{\mu}\gamma_\mu e \cdot \bar{q}\gamma_\mu q$$

$\mu N \rightarrow eN$ and $\mu \rightarrow e\gamma$

$$\mathcal{L}_{\mu e} \sim \frac{1}{\Lambda^2}\left[\frac{1}{\kappa+1} m_\mu \bar{\mu}\sigma_{\mu\nu} e \cdot F^{\mu\nu} + \frac{\kappa}{\kappa+1} \bar{\mu}\gamma_\mu e \cdot \bar{q}\gamma_\mu q\right]$$

- New physics → CLFV in rare muon decays.
- Energy scale Λ affects the rate of all such processes.
- Parameter κ depends on the nature of the new physics



Both $\mu \rightarrow e\gamma$ and $\mu - e$ conversion are sensitive to dipole terms, but $\mu - e$ conv. is also sensitive to 4-femion terms.

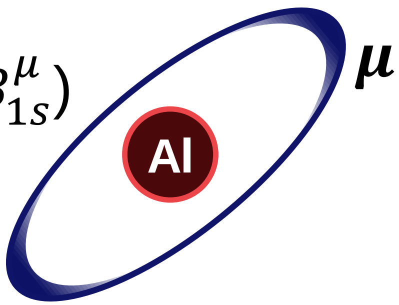
- More sensitive to some models.
- (If signal seen) the comparison allows discrimination between models

Basics of a (modern) $\mu - e$ conversion experiment

Muon decays

Muons allowed stop in suitable target.

- Initially **Aluminium**, but other materials under study.
- Conversion from 1s orbital: $\mu N \rightarrow eN$ gives a ***mono-energetic electron*** at 105MeV ($\approx m_\mu - B_{1s}^\mu$)

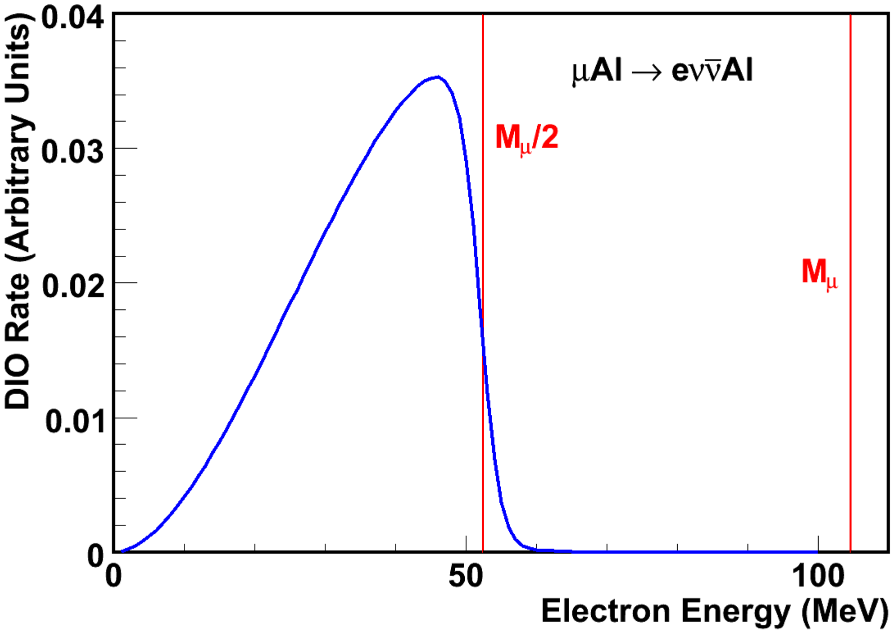


'Normal' decays are backgrounds

- Nuclear muon capture: $\mu N(Z) \rightarrow \nu N(Z-1)$
- **Decay in Orbit [DIO]:**

  $\boldsymbol{\mu \rightarrow e\nu\bar{\nu}}$

  For a free muon, cuts off at $\frac{1}{2}m_\mu$, but bound state has a small tail up to m_μ



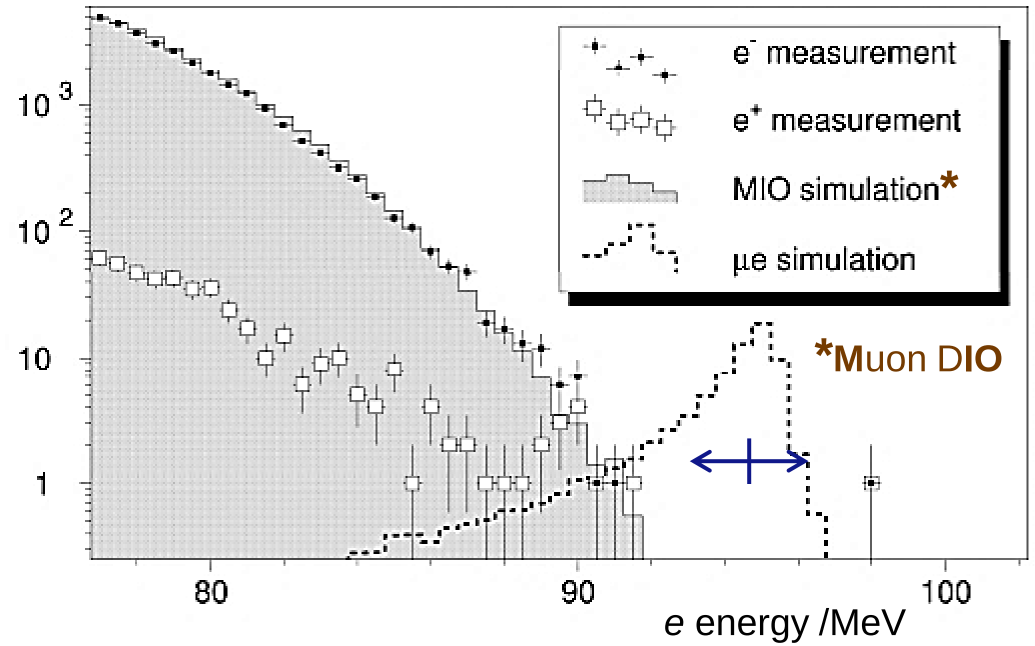
Backgrounds

Three main background processes:

- **Decay in orbit**, as before ▶
  Energy resolution!

- **Decay in flight**:
  Electrons from energetic free muons can be boosted to 105MeV.
  - Use momentum selection in muon transport (see later)

Results from SINDRUM-II



- **Beam backgrounds**:
  Significant number of prompt e^- and π^- produced by beam. Can eliminate this with timing *if* we have reliably beam-free time windows.

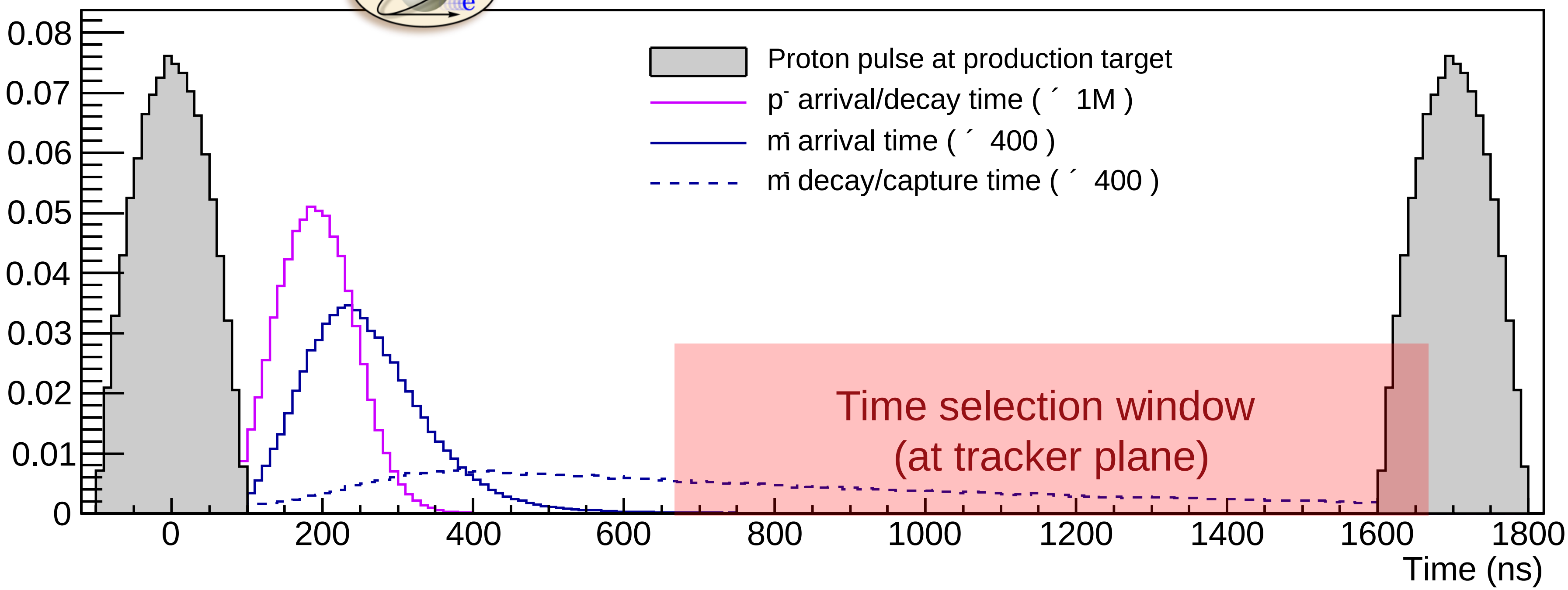
Beam-free windows?

Naïvely, this sounds easy, but…

- High intensity pulsed muon beams are uncommon → new facilities
- Need $\tau_\mu \gg \sigma_{Pulse}$ so choose stopping targets with long lifetime
  ↳ low Z, conflicts with high A preferred for coherent signal.

Aluminium ($Z = 13, \tau_\mu = 0.88\mu s$) preferred

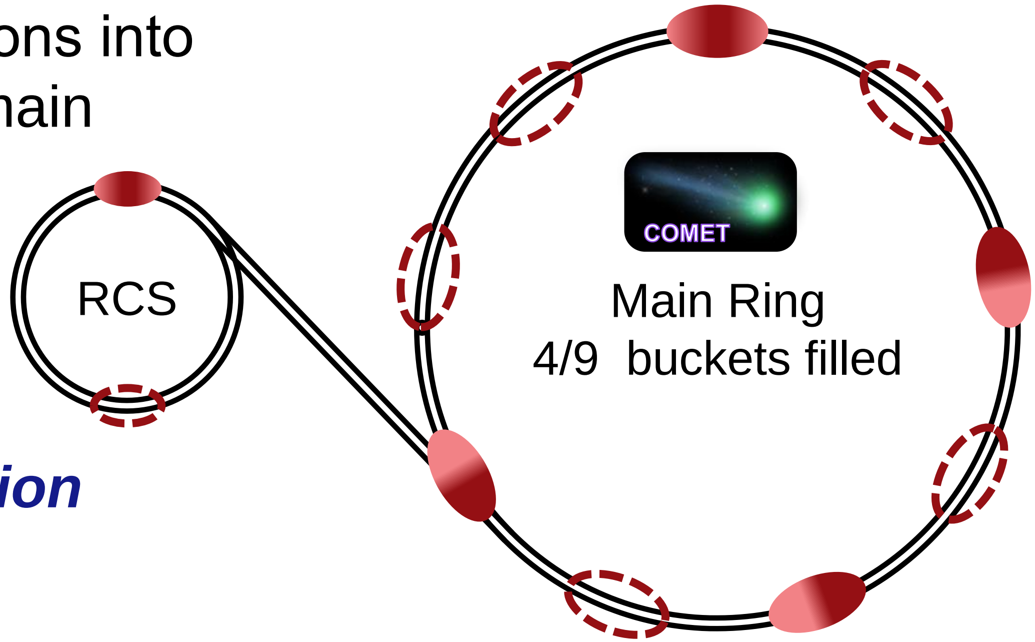
Cartoon from



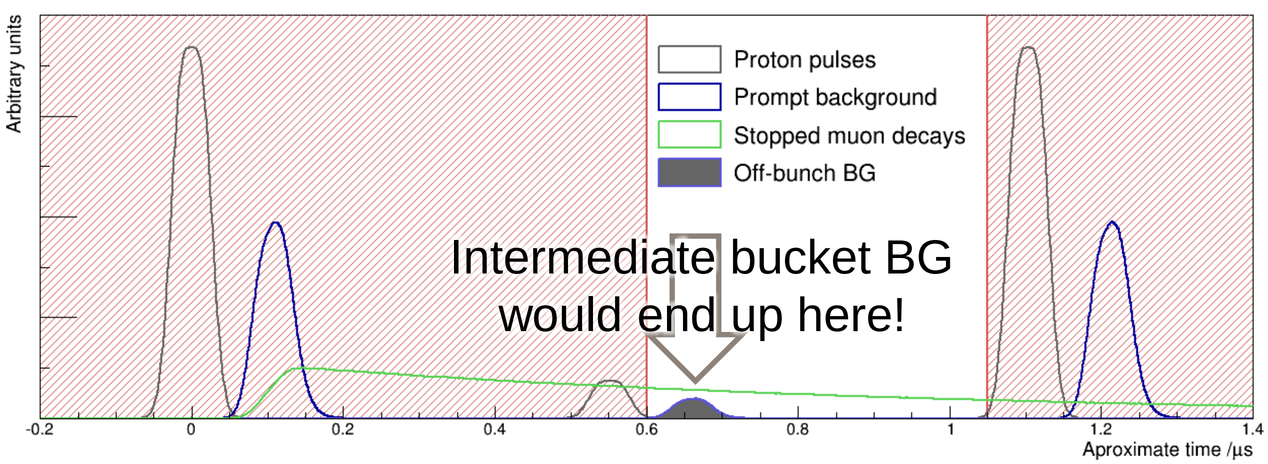
Really beam-free windows?

Synchrotrons have stable acceleration buckets

- Even if you don't inject protons into them, stray protons can remain in stable acceleration.



The signal process is rare,
so requirements on the ***extinction***
between pulses is very strict

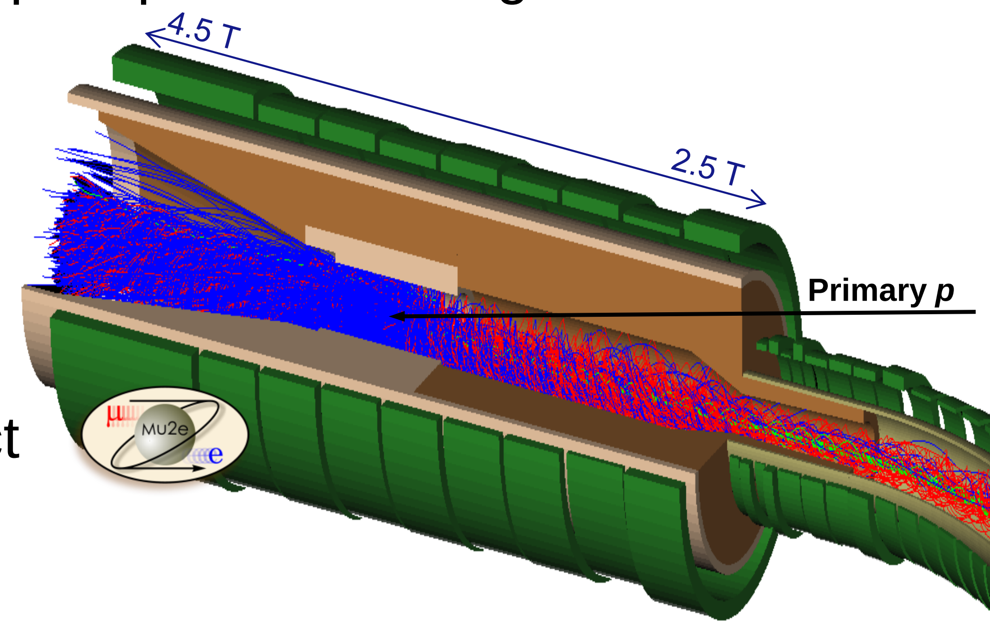


Muon source

Main driver of sensitivity: Need lots of low energy muons!

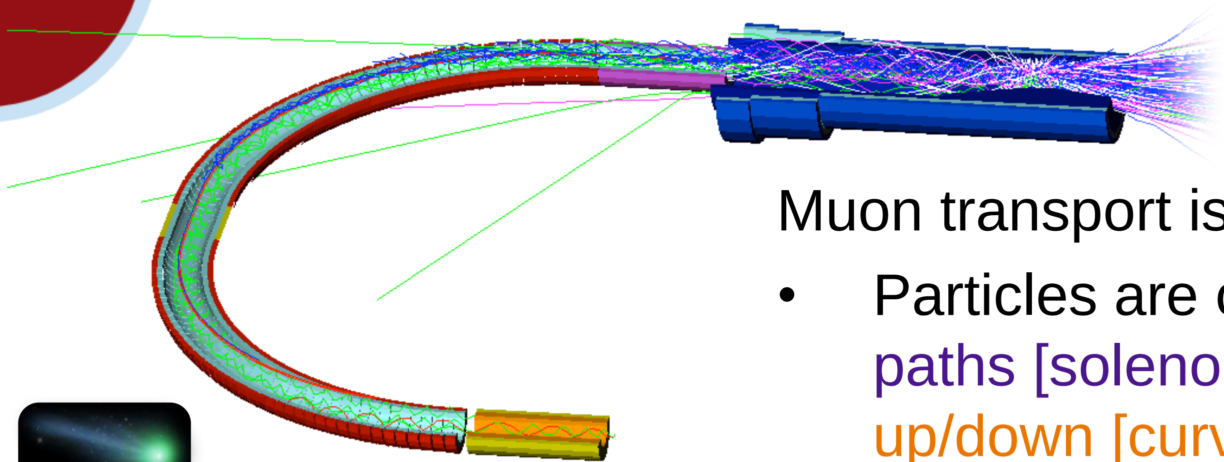
- Use dedicated high-power *pulsed* proton beam lines (~8 GeV)
- Resonant slow extraction onto pion production target

- Collect *backward*-going pions with capture solenoid
- Requires high mag field to maximise collection
- Can use gradient field to reflect low-energy forward pions.



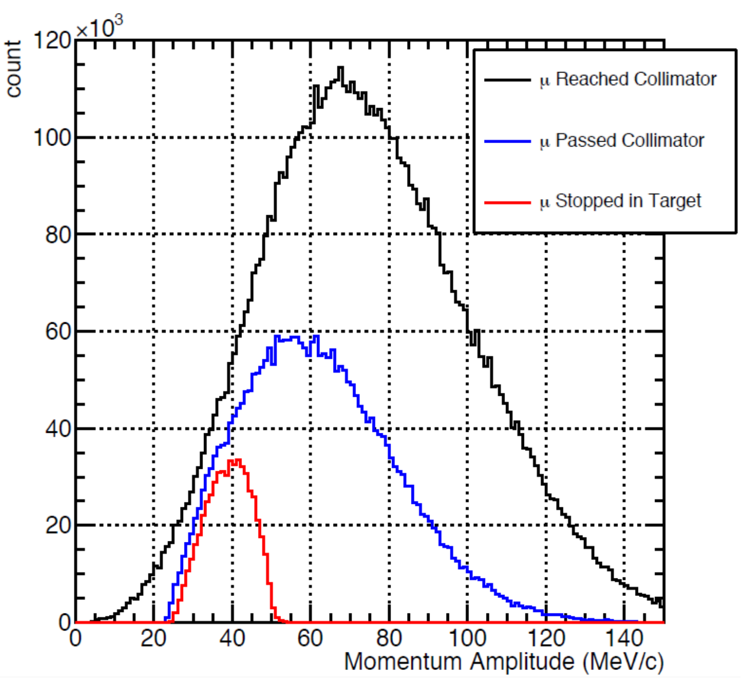
- Pions decay to muons en-route to stopping target.
- Many neutrons produced, requires careful shielding. The curved transport line helps to eliminate direct line-of sight.

Muon transport



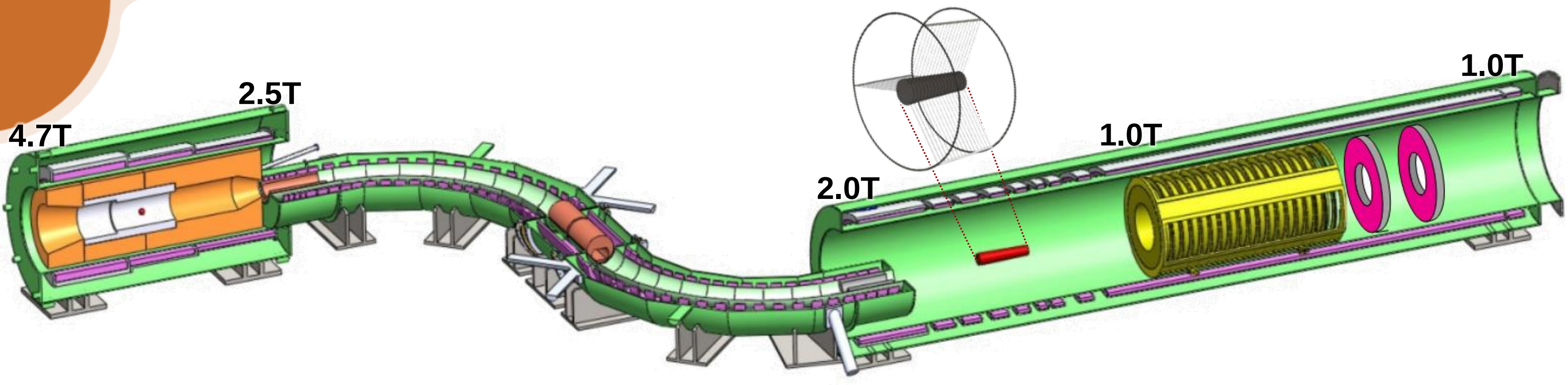
Muon transport is a curved solenoid

- Particles are channelled in spiral paths [solenoid], which naturally tend up/down [curvature] depending on momentum and charge
- Gives charge sign and momentum selection, which can be enhanced by using a collimator.
- Use to eliminate high momentum muons, other particles.
- Eliminates line-of-sight from production target



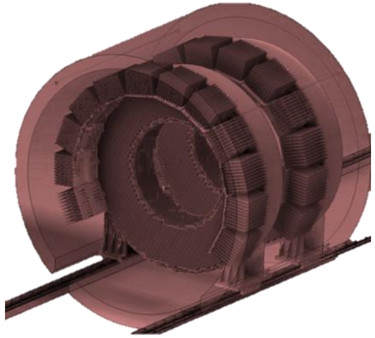
Mu2e

Mu2e overview



- S-shape and off-centre collimators that can rotation for BG studies
- Stopping **target** is 17 × 0.2mm Al foils

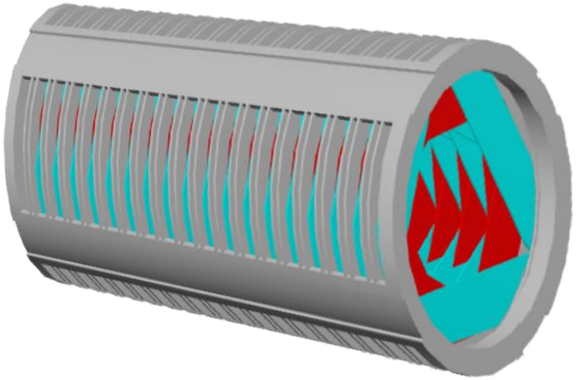
- Target & detector surrounded by solenoid
  - Electron transport
  - Magnetic mirror

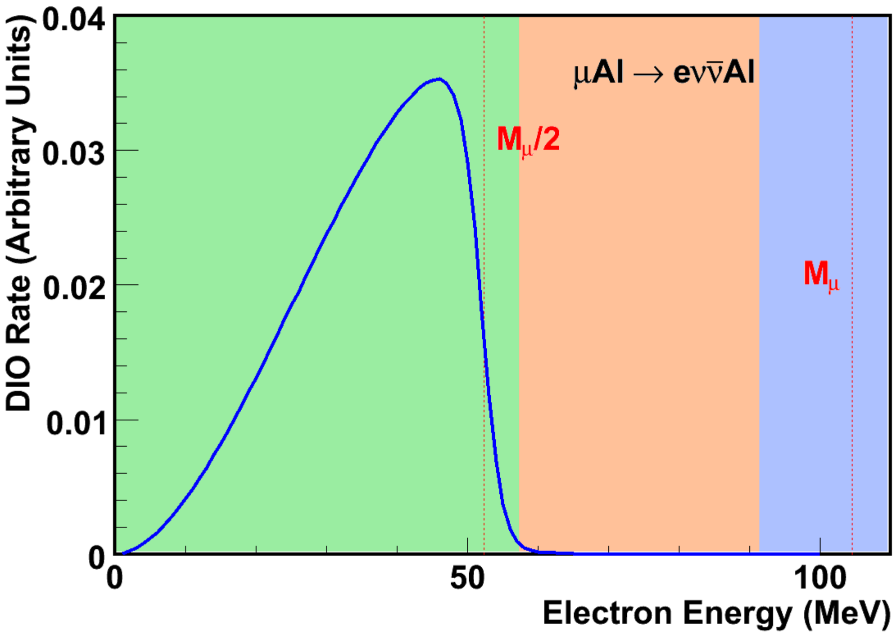



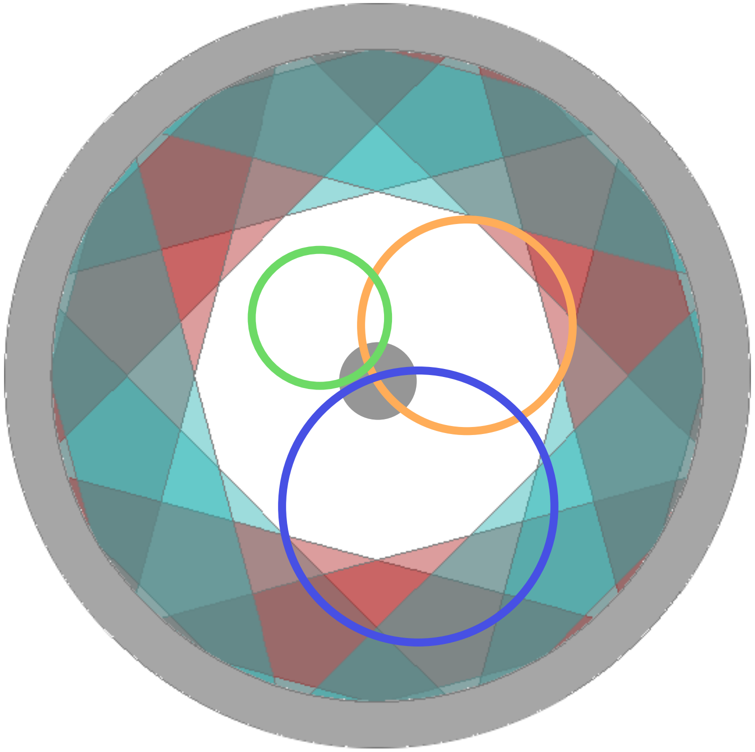
- Electrons spiral from target to **tracker** and **EM calorimeter**

Mu2e Tracker

- Tracker made from straw tubes to measure particle momentum
- Minimum radius of 380mm corresponds to momentum ~ 60MeV
- ‘Complete’ tracks need mom > 90 MeV

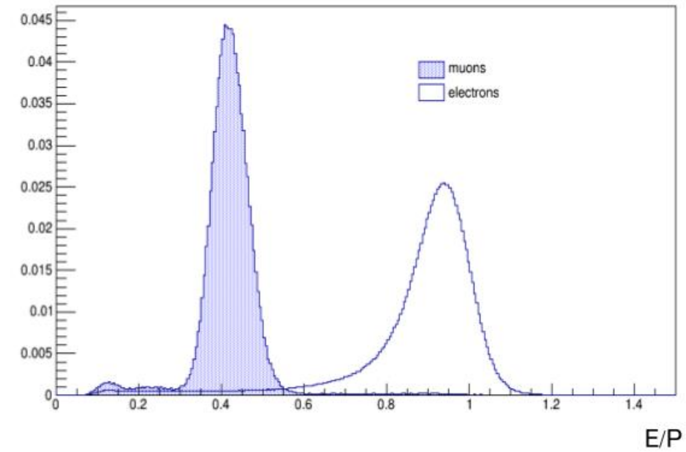


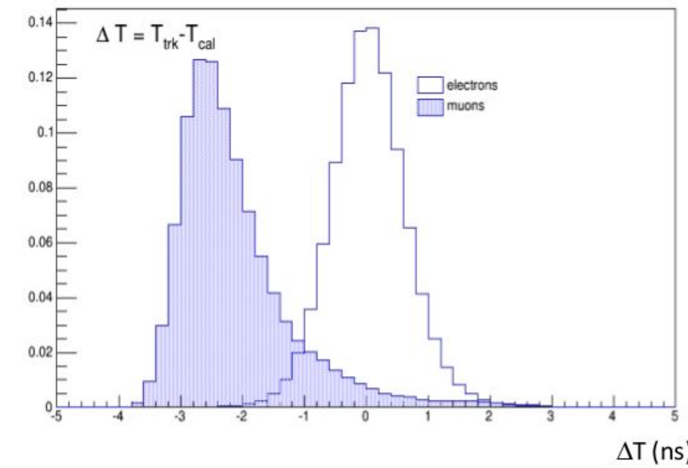


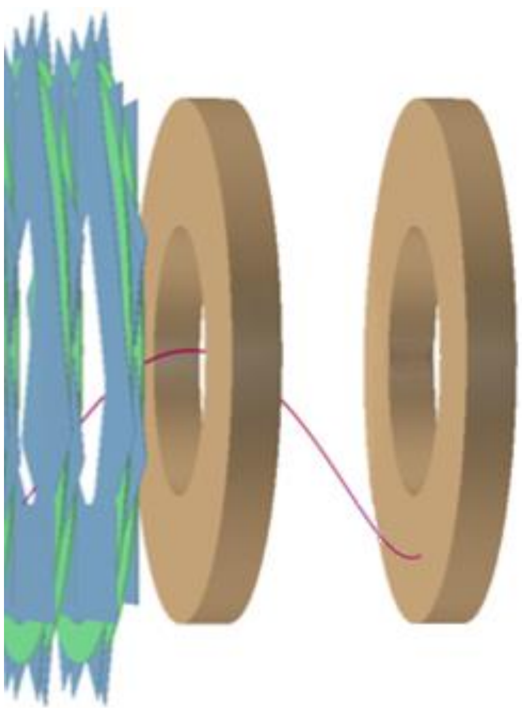


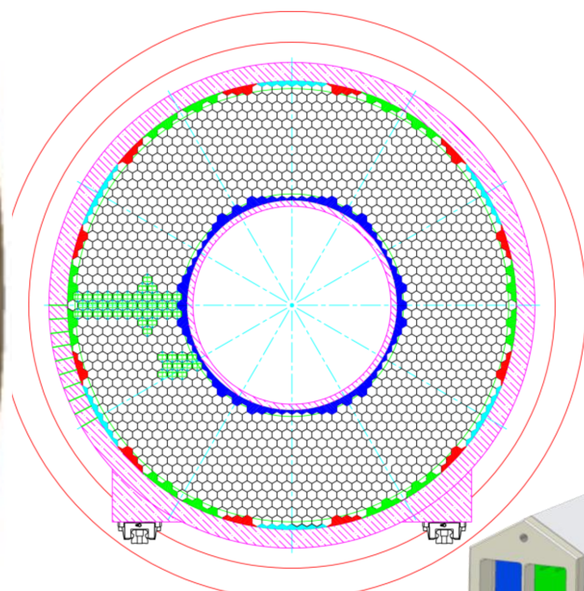
Mu2e calorimeter

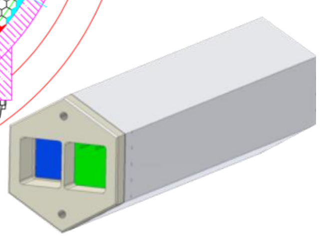
- Inorganic scintillator crystals
- Provides fast response for trigger
- Energy measurement combined with momentum from tracker gives excellent μ/e discrimination







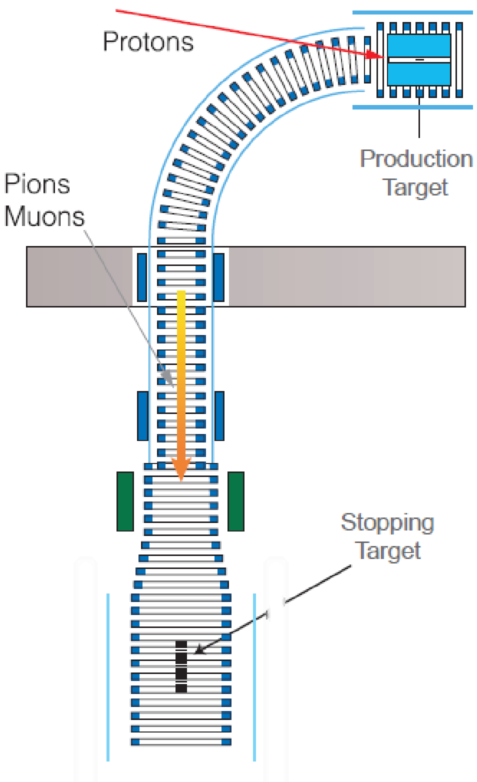




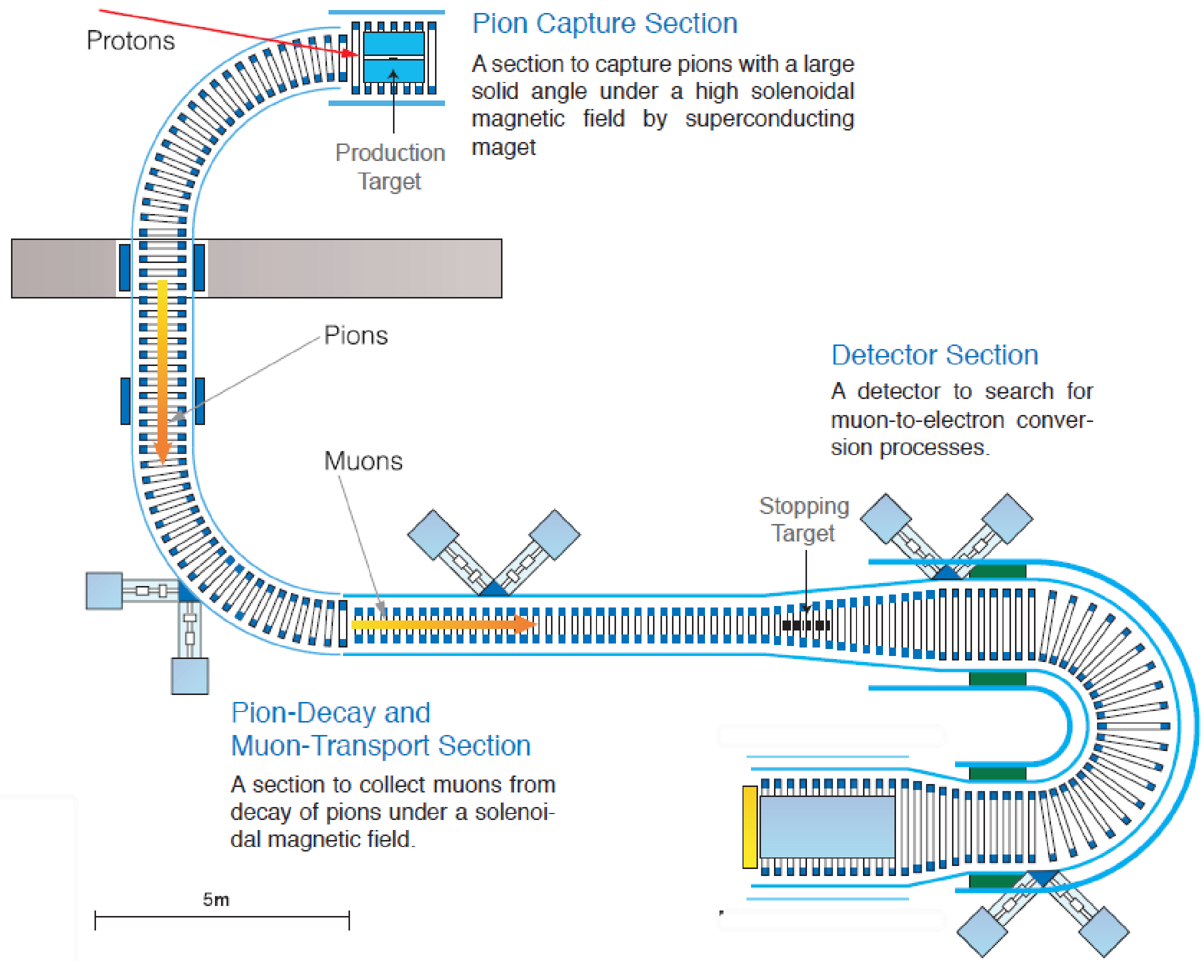
COMET

Two phases of COMET

Phase I

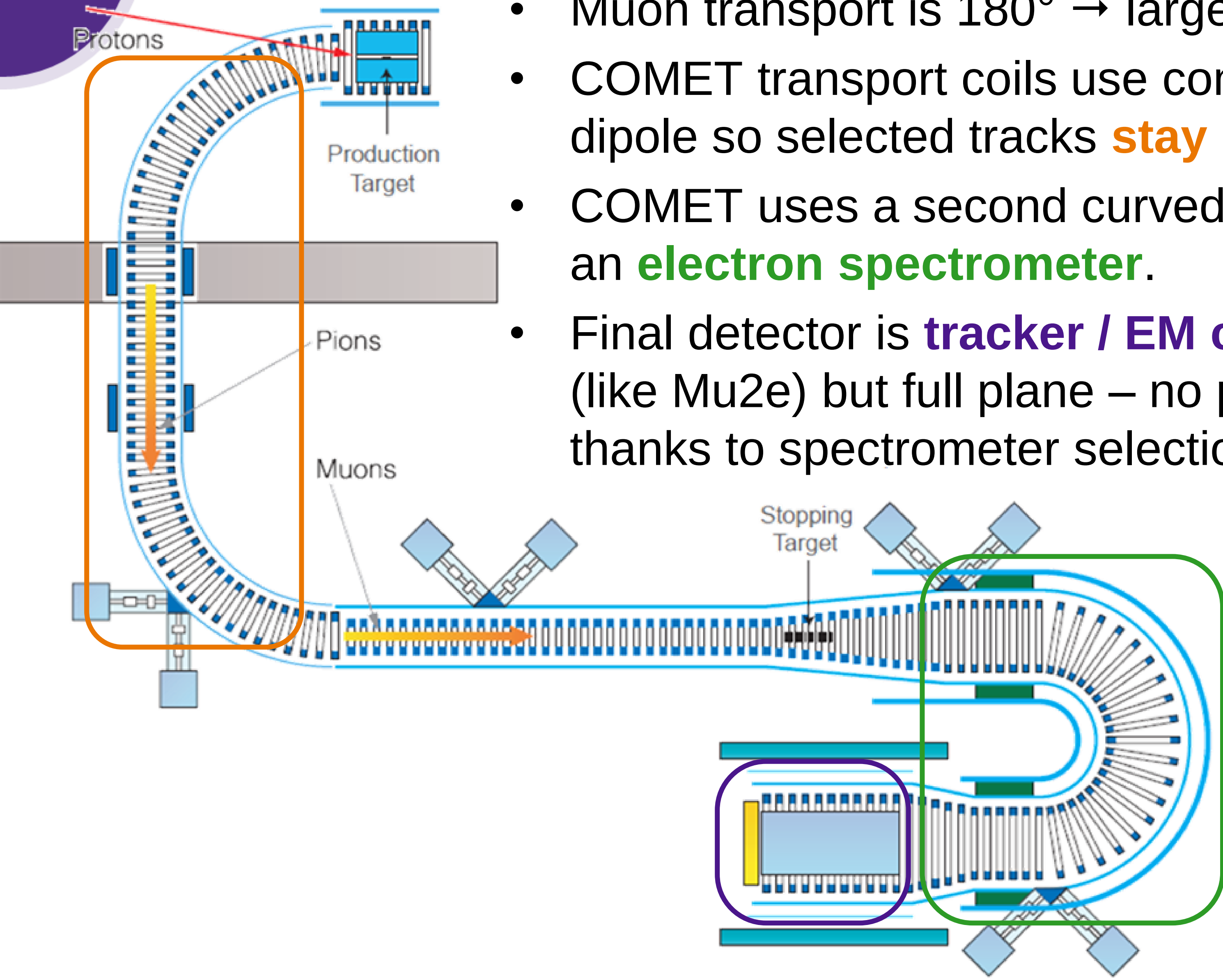


Phase II

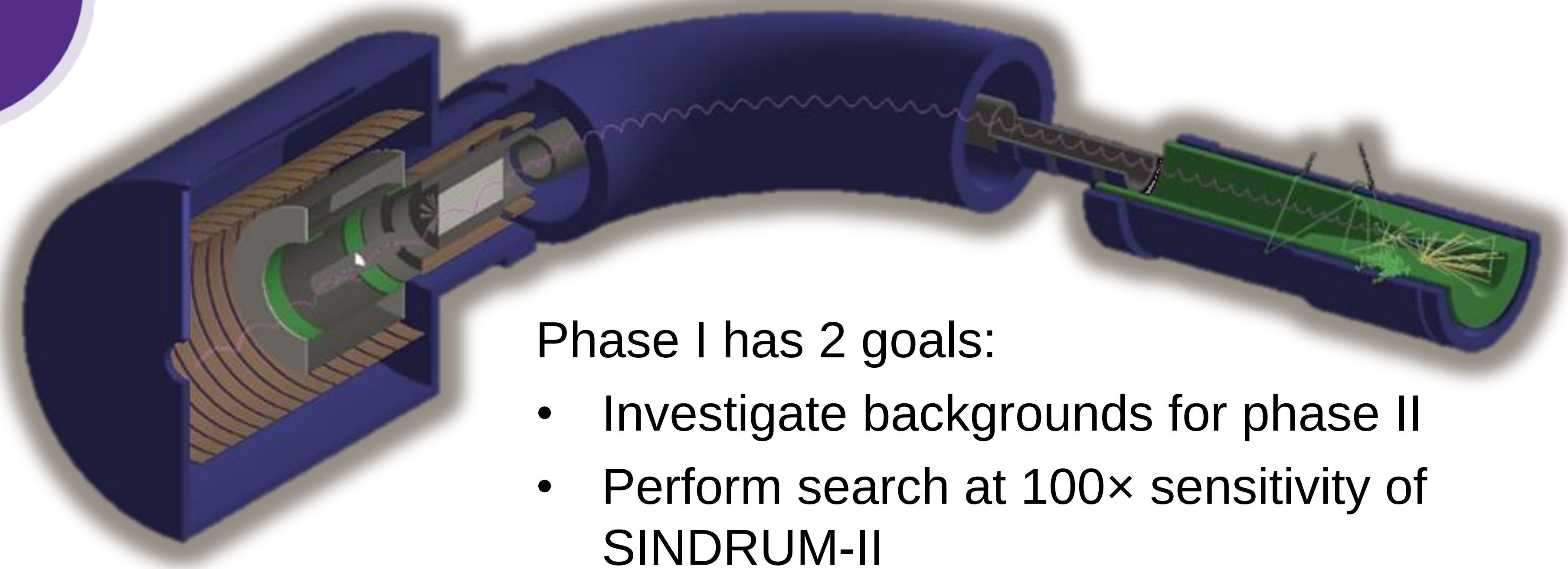


In time-revered order: Phase II…

- Muon transport is 180° → larger dispersion.
- COMET transport coils use compensating dipole so selected tracks **stay level**.
- COMET uses a second curved solenoid as an **electron spectrometer**.
- Final detector is **tracker / EM calorimeter** (like Mu2e) but full plane – no proton BG, thanks to spectrometer selection.



…and Phase I



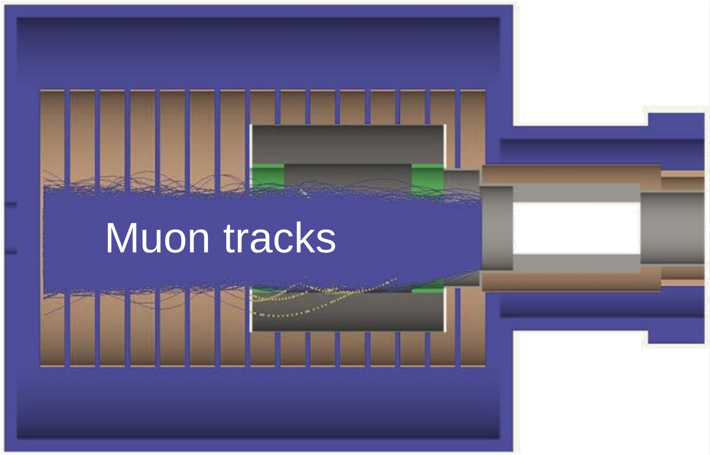
Phase I has 2 goals:

- Investigate backgrounds for phase II
- Perform search at 100× sensitivity of SINDRUM-II

For Phase I measurement use a **cylindrical drift chamber** around the stopping target.

- Triggering by **auxillary hodoscopes**

Also include prototypes/partial elements of Phase II detectors for development and characterising backgrounds at low current

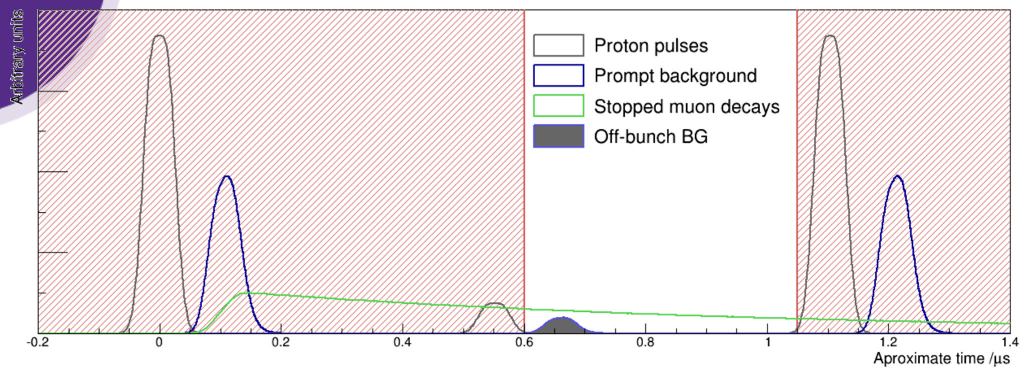


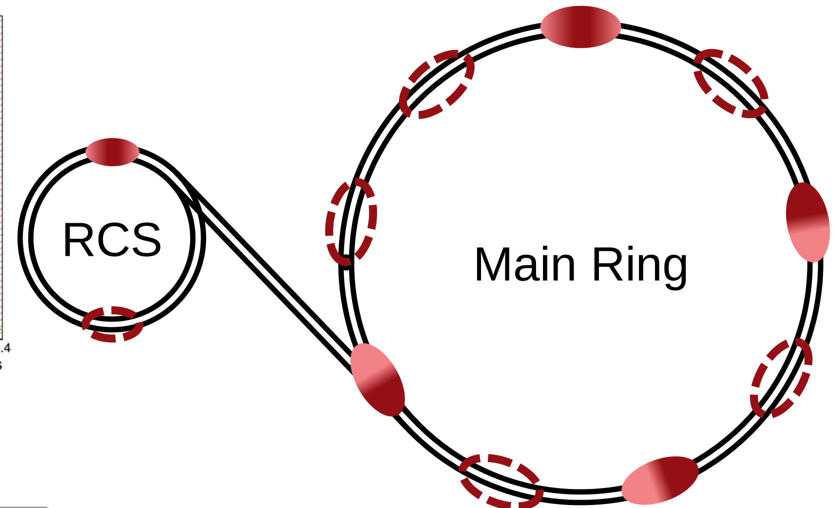
COMET developments

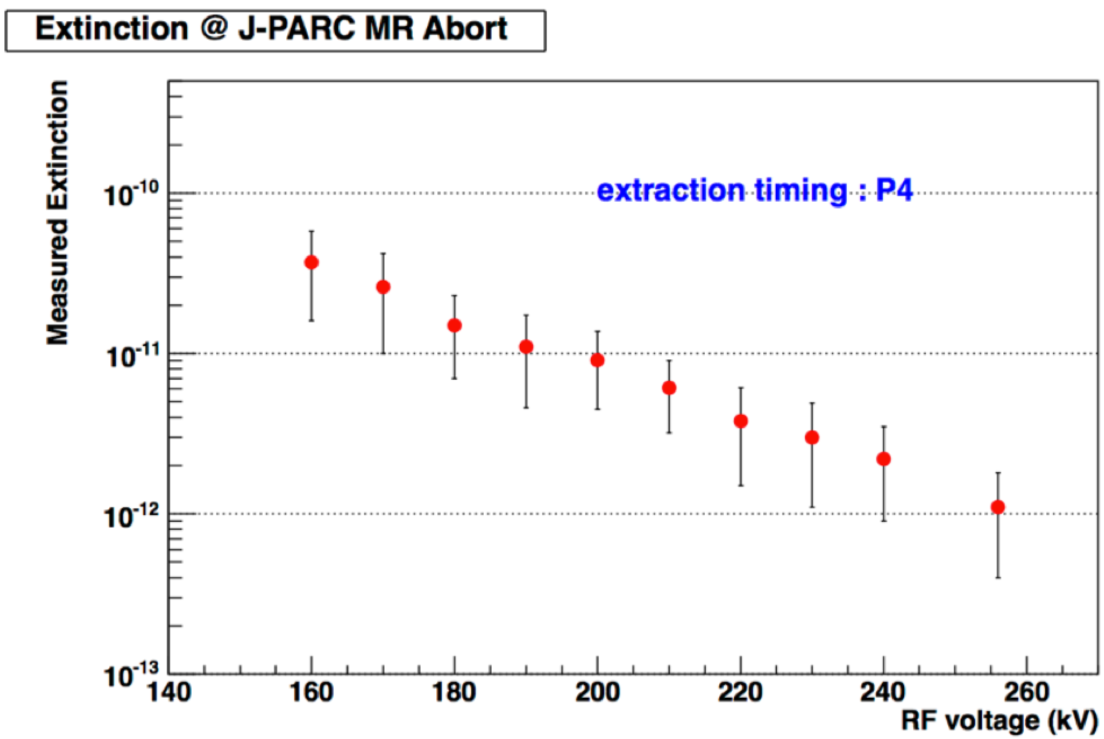
- COMET hall construction proceeding well

- Magnets laid-out for new beam switchyard

Extinction test







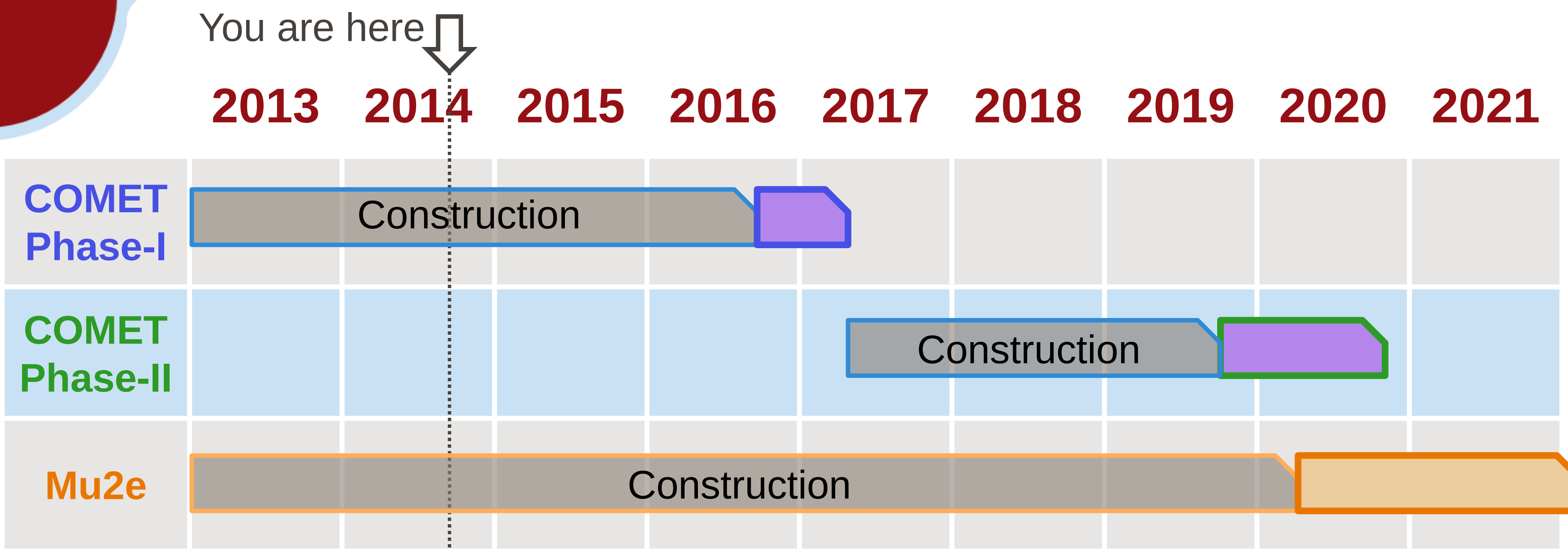
Comet requires extinction:

$$E = \frac{N_{Empty}}{N_{Filled}} < 10^{-9}$$

Important test in May 2014:

Excellent results!

Timelines



2014: 7×10^{-13} **90% U.L.** [SINDRUM-II] (since 2004)

~2017: 3×10^{-15} **S.E.S.** [COMET Phase-I]

~2021: 3×10^{-17} **S.E.S.** [COMET Phase-II & Mu2e]

beyond 2021: PRISIM /PRIME @J-PARC**?**

Mu2e × ProjectX @FNAL**?**

Summary

- **Charged lepton flavour violation** is ‘natural’ in new physics scenarios.
- The (arguably) SM process is driven by neutrino mixing, and is **hugely suppressed**: $\mathbf{O(10^{-54})}$
- Complimentary approaches from $\mu \rightarrow e\gamma$ and $\boldsymbol{\mu - e}$ **conversion**
- Current limit is $\mathbf{O(10^{-12})}$ from SINDRUM-II
- COMET & Mu2e can improve on this by **4 orders of magnitude** in 5~10 years
- Information on *what* the NP is through similar experiments.