Multi-electron muon decays

(μ → eeeee)

PIKIMO
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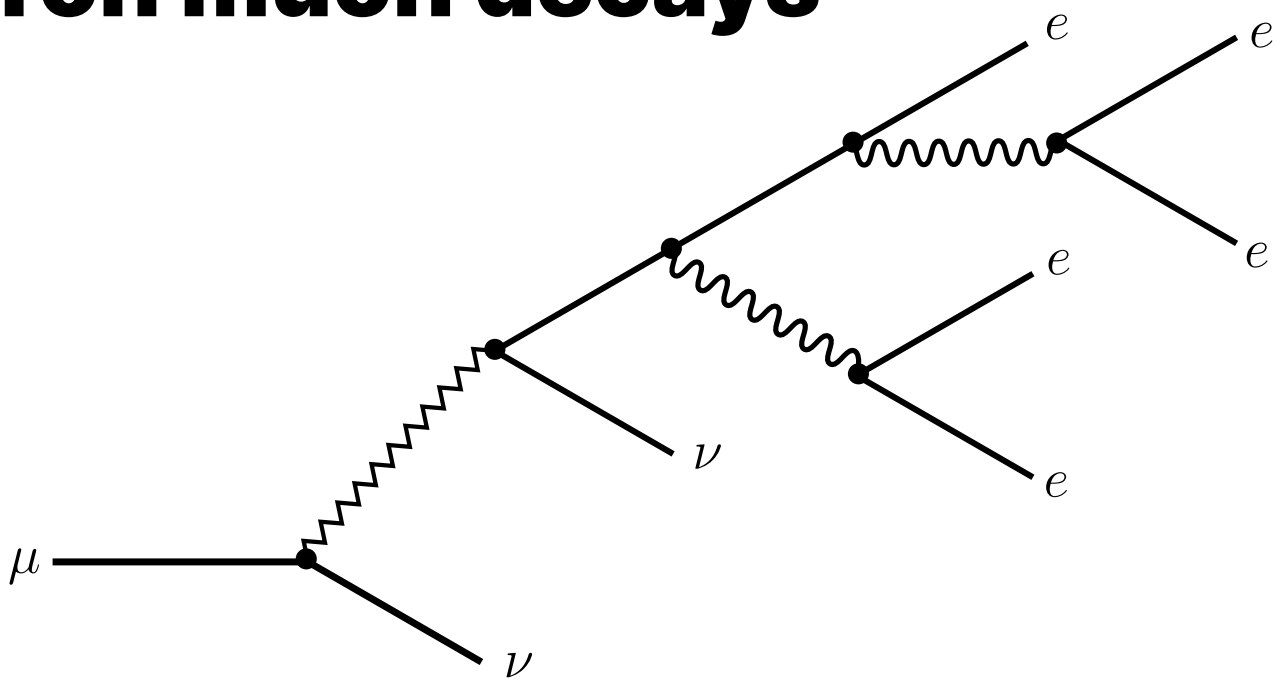
University of Cincinnati



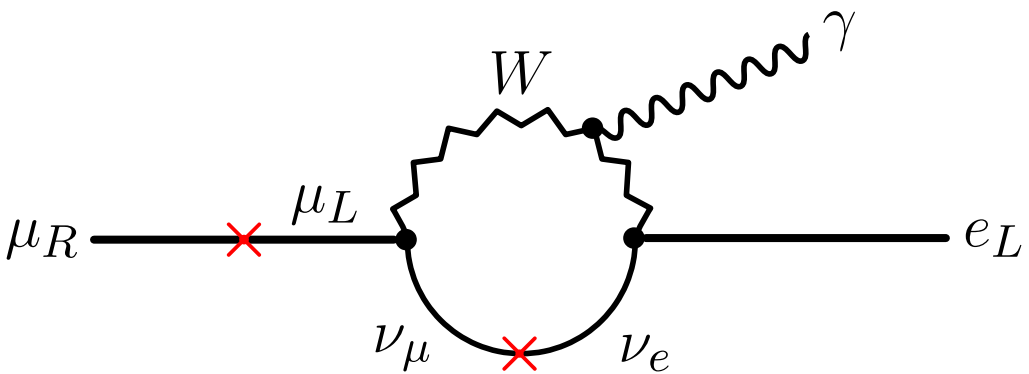
Based on 2306.15631 with Matheus Hostert, Maxim Pospelov, and Jure Zupan

μ → e

- The Standard Model (SM) has an accidental global flavor symmetry

$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$

- Because $m_\nu \neq 0$ charged-lepton-flavor violation (CLFV) can occur at one-loop



$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{3\alpha}{32\pi M_W^4} |U_{\mu 3} U_{e3}^* \Delta m_{31}^2 + U_{\mu 2} U_{e2}^* \Delta m_{21}^2|^2$$

$$\simeq 10^{-54}$$

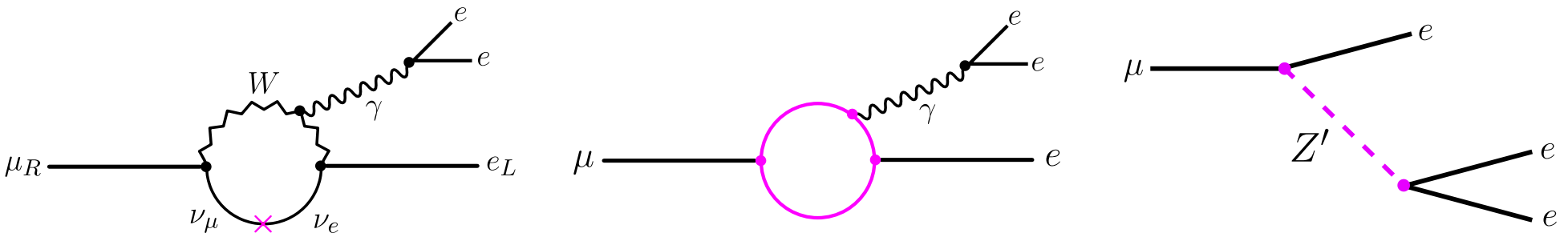
Bottom line: Observing CLFV = new physics

Exotic μ → e

In the space of all UV models, CLFV is common. For heavy new physics:

- **"Photonic" – e.g. SUSY, massive neutrinos, …**
- **"Contact" – e.g. Z', leptoquarks, …**

New physics



Motivates an extensive experimental program

Upcoming experiments

- **Mu → E Gamma (MEG) @ PSI - μ → eɣ**

  Projected: $\mathrm{BR}(\mu^+ \to e^+\gamma) \lesssim 6 \times 10^{-14}$

- **Mu3e @ PSI - μ → eee**

  Projected: $\mathrm{BR}(\mu^+ \to e^+e^-e^+) \lesssim 10^{-16}$

- **Mu2e @ Fermilab, COMET @ J-PARC - Nμ → Ne**

  Projected: $\mathrm{CR}(\mu^- \mathrm{Al} \to e^- \mathrm{Al}) \lesssim 10^{-18} - 10^{-17}$

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  Projecte

$$\Gamma(\mu \to e\nu\nu) \approx 10^{-19}\mathrm{GeV}$$

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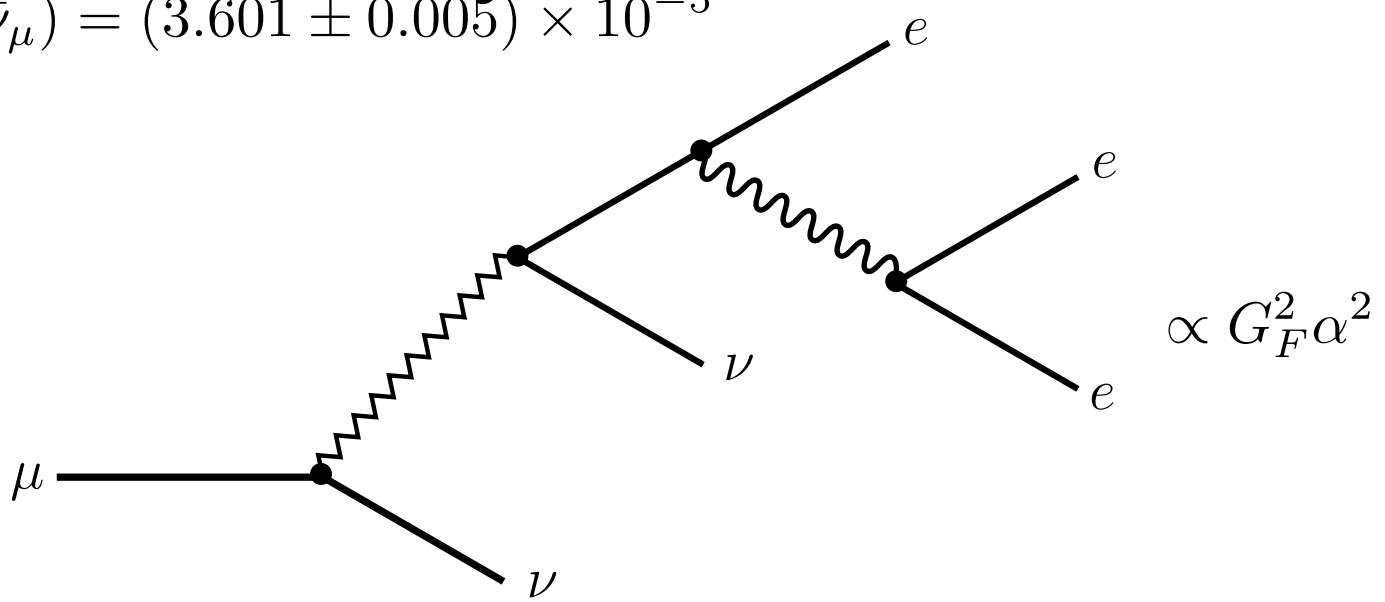
μ → eeevv

- **SM background for Mu3e**

$$\mathcal{B}(\mu^+ \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu) = (3.601 \pm 0.005) \times 10^{-5}$$

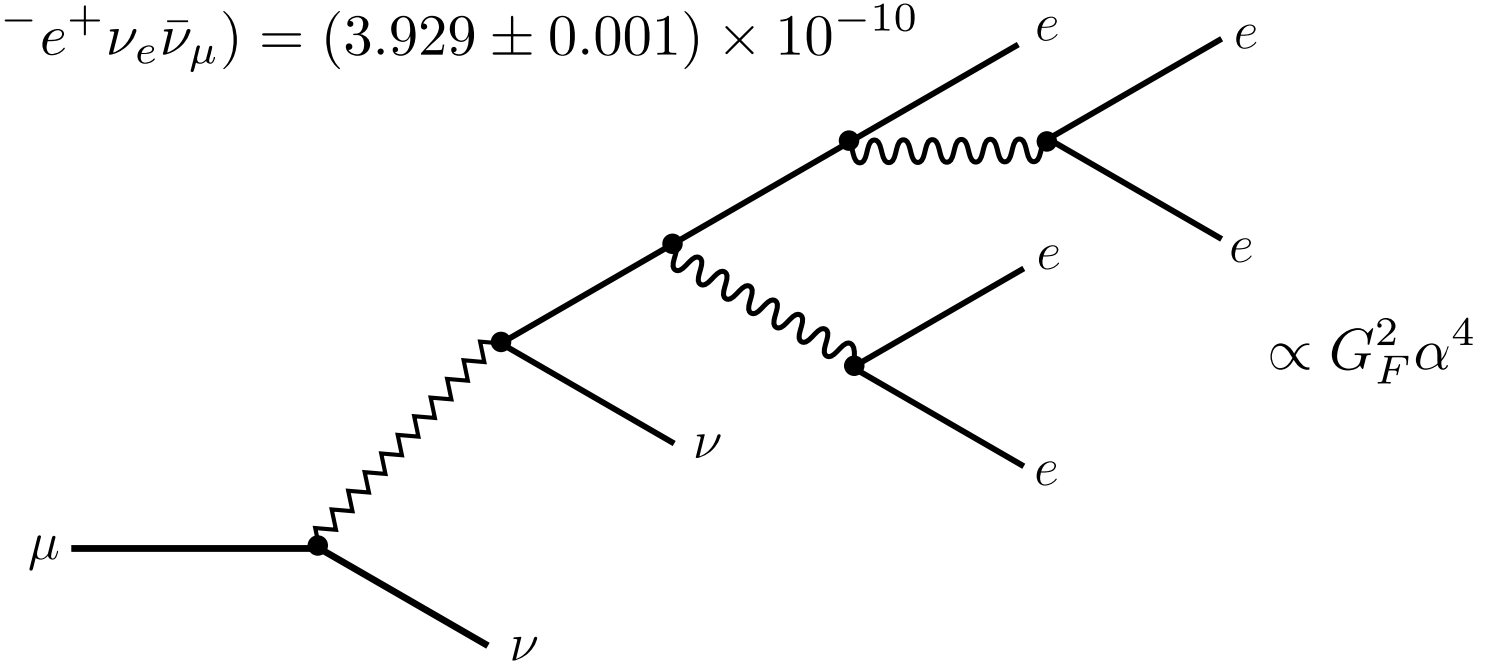


$$\propto G_F^2 \alpha^2$$

μ → eeeeevv

- **SM background for Mu5e**

$$\mathcal{B}(\mu^+ \to e^+e^-e^+e^-e^+\nu_e\bar{\nu}_\mu) = (3.929 \pm 0.001) \times 10^{-10}$$



$$\propto G_F^2\alpha^4$$

μ → eeeee

- Higgsed $U(1)_D$ + SM portal via kinetic mixing

$$\mathscr{L}_{\mathrm{DS}} = (D_\mu \phi)^\dagger D^\mu \phi - \frac{1}{4} F_d^{\mu\nu} F_{d\,\mu\nu} - \frac{\varepsilon}{2} F_d^{\mu\nu} F_{\mu\nu} - \mu^2 \left(\phi^\dagger \phi\right) - \lambda \left(\phi^\dagger \phi\right)^2$$

μ → eeeee

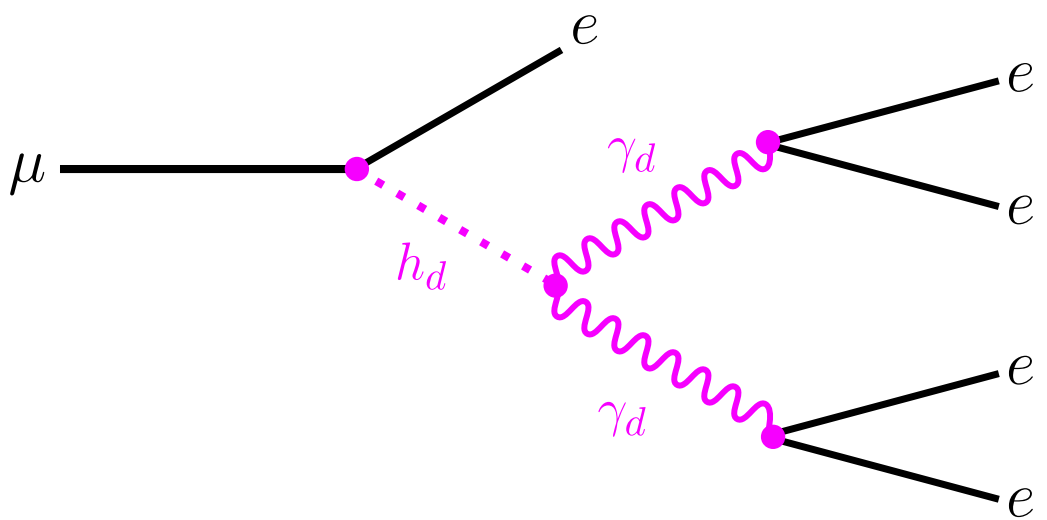
- Higgsed $U(1)_D$ + SM portal via kinetic mixing

$$\mathscr{L}_{\mathrm{LFV}} = -\frac{C_{ij}}{\Lambda}\phi\left(\bar{L}_i H\right)\ell_j + \mathrm{h.c.}$$

μ → eeeee

- **Higgsed $U(1)_D$ + SM portal via kinetic mixing**

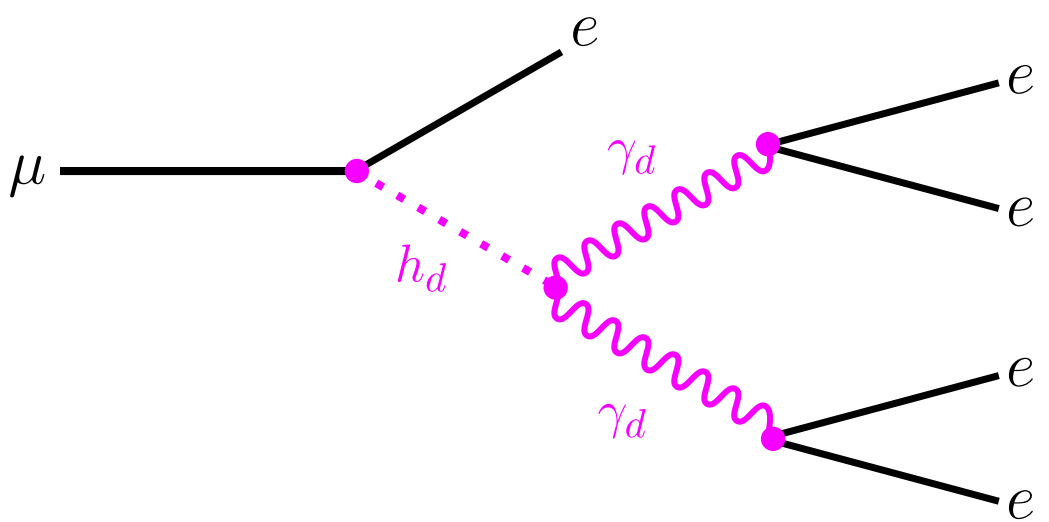
$$\mathscr{L} \supset -m_{\ell_i}\bar{\ell}_{Li}\ell_{Ri}\left(1+\frac{h}{v}\right) - y_{ij}\bar{\ell}_{Li}\ell_{Rj}h_d\left(1+\frac{h}{v}\right) + \text{h.c.},$$



μ → eeeee

- Higgsed $U(1)_D$ + SM portal via kinetic mixing

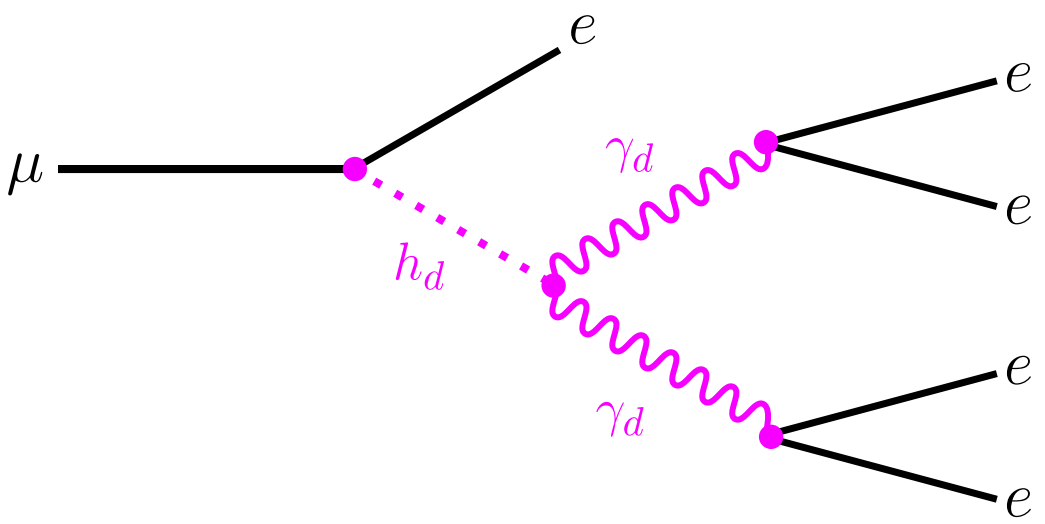
$$\mathcal{B}(\mu \to e h_d) = \frac{1}{\Gamma_\mu}\left(|y_{\mu e}|^2 + |y_{e\mu}|^2 + 4\mathrm{Re}\left(y_{\mu e} y_{e\mu}^*\right) r_e\right) \frac{m_\mu}{32\pi}\left[(1+r_e)^2 - r_{h_d}^2\right] \lambda^{1/2}(1, r_e^2, r_{h_d}^2)$$



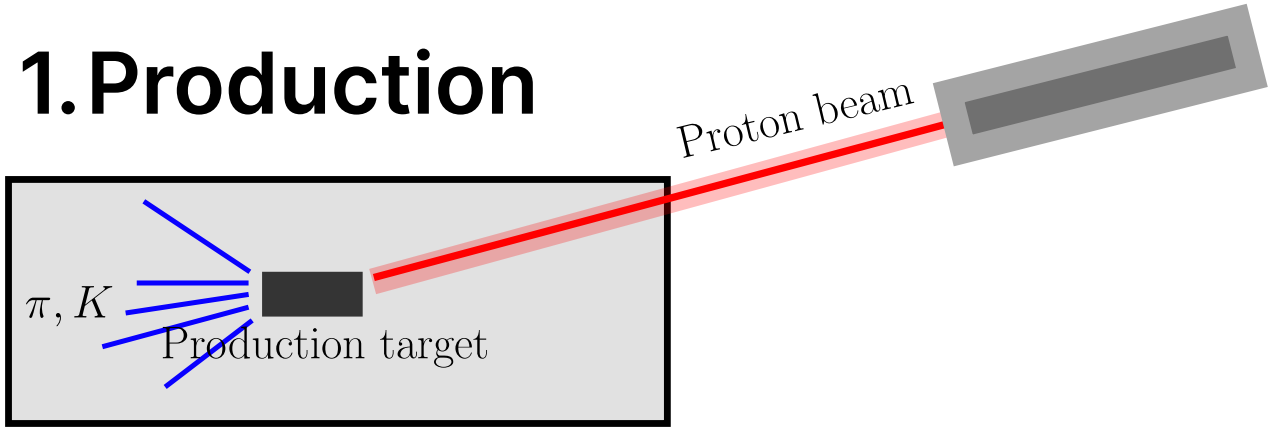
μ → eeeee

- **Higgsed $U(1)_D$ + SM portal via kinetic mixing**

$$\mathcal{B}(\mu^+ \to e^+ h_d \to e^+ 2(e^+e^-)) = 3.5 \times 10^{-3} \left(\frac{\sqrt{|y_{\mu e}|^2 + |y_{e\mu}|^2}}{10^{-9}} \right)^2 (1 - r_{h_d}^2)^2$$



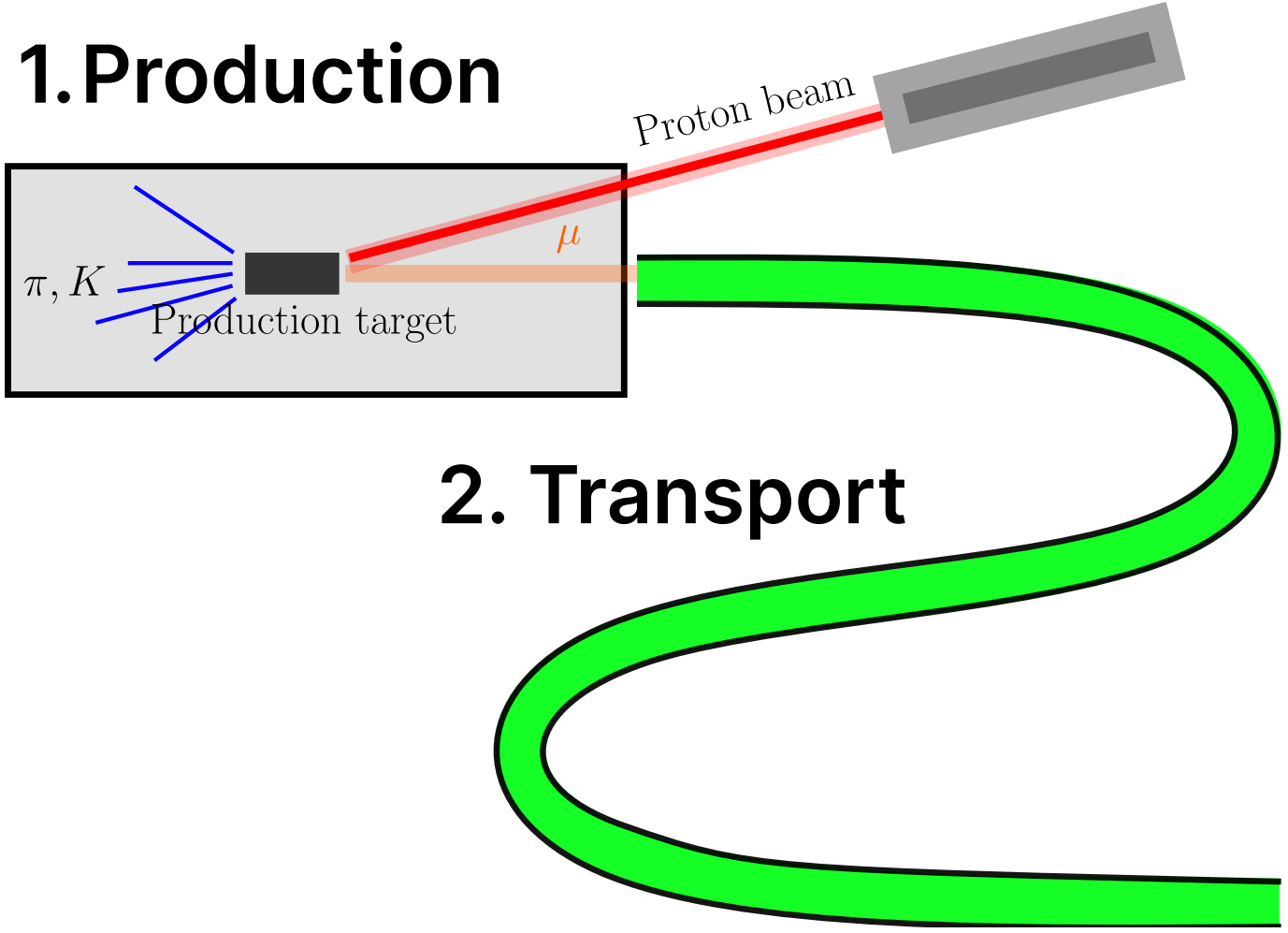
1. Production



Mu3e

1. Production

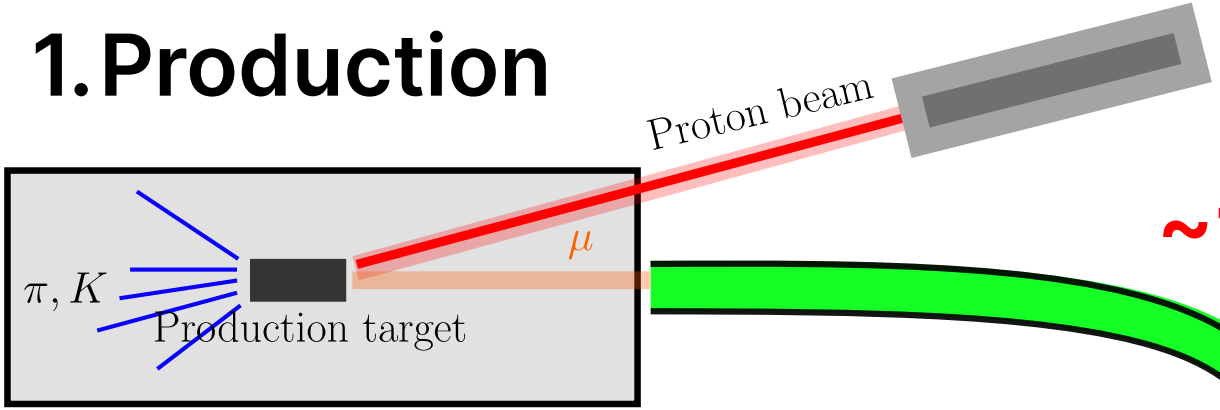
Mu3e



2. Transport

1. Production

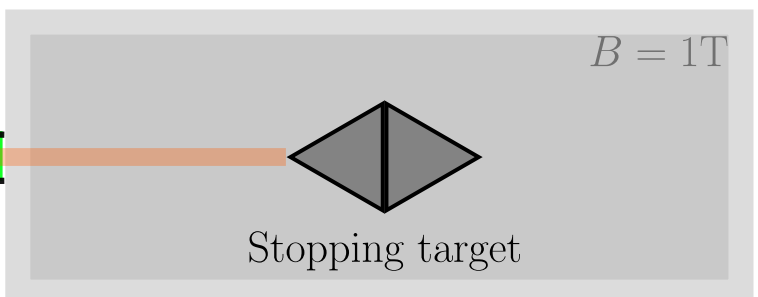
Mu3e



~10^8 stopped μ/sec

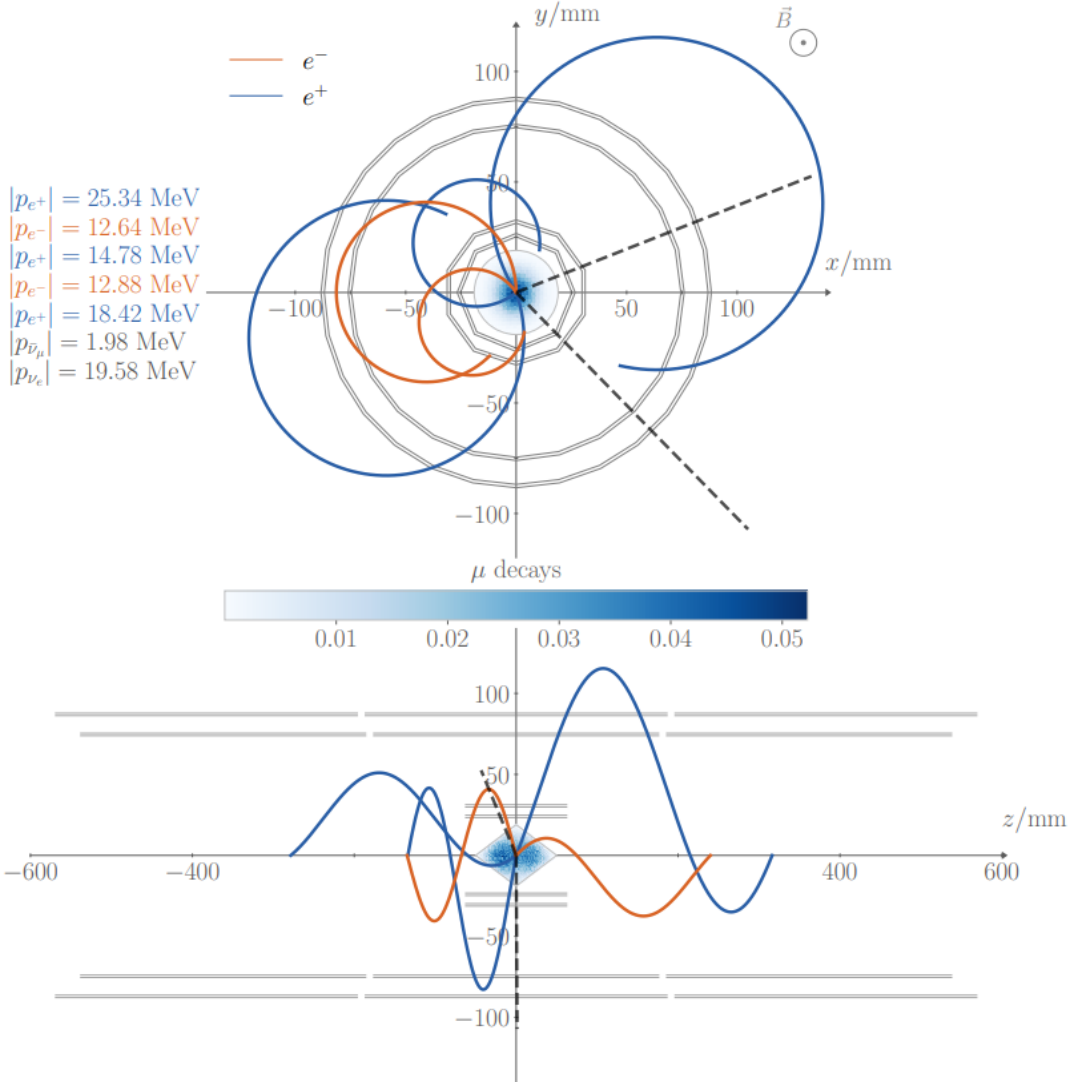
2. Transport

3. Stopping



Simulation

- Momentum of tracks must be reconstructed from energy deposits or ‘hits’ in the layers of the detectors.
- 4 hits = short track
- 6+ hits = long track



Simulation

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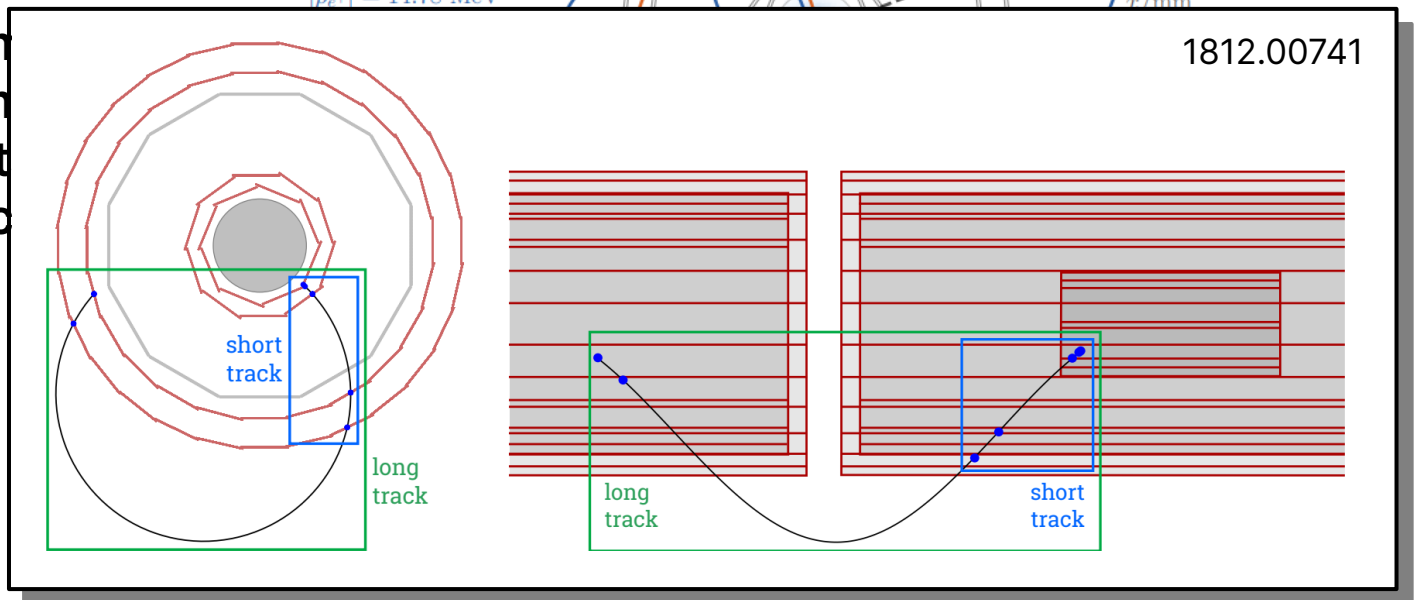
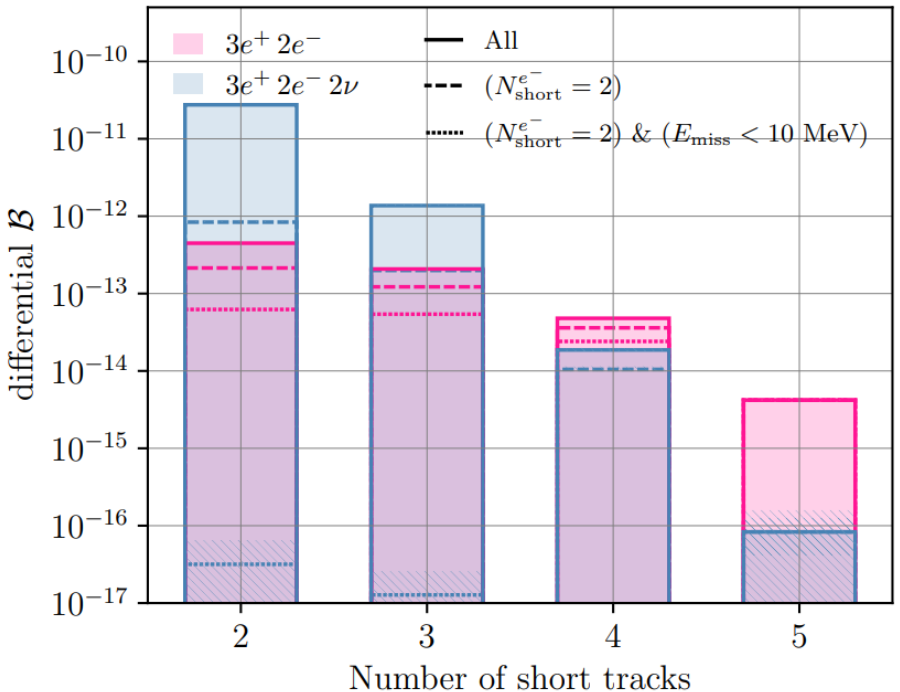
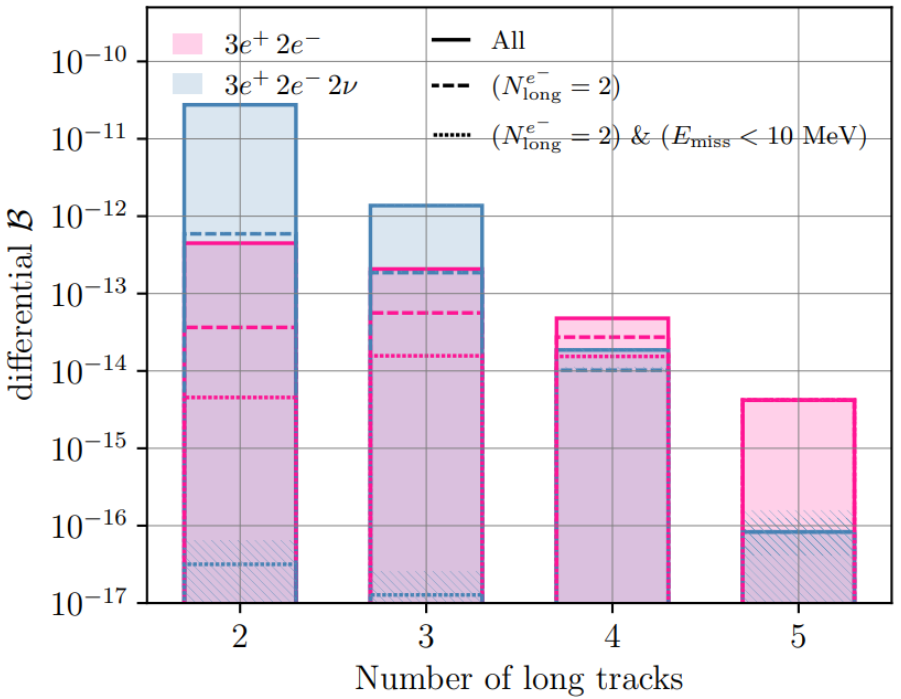
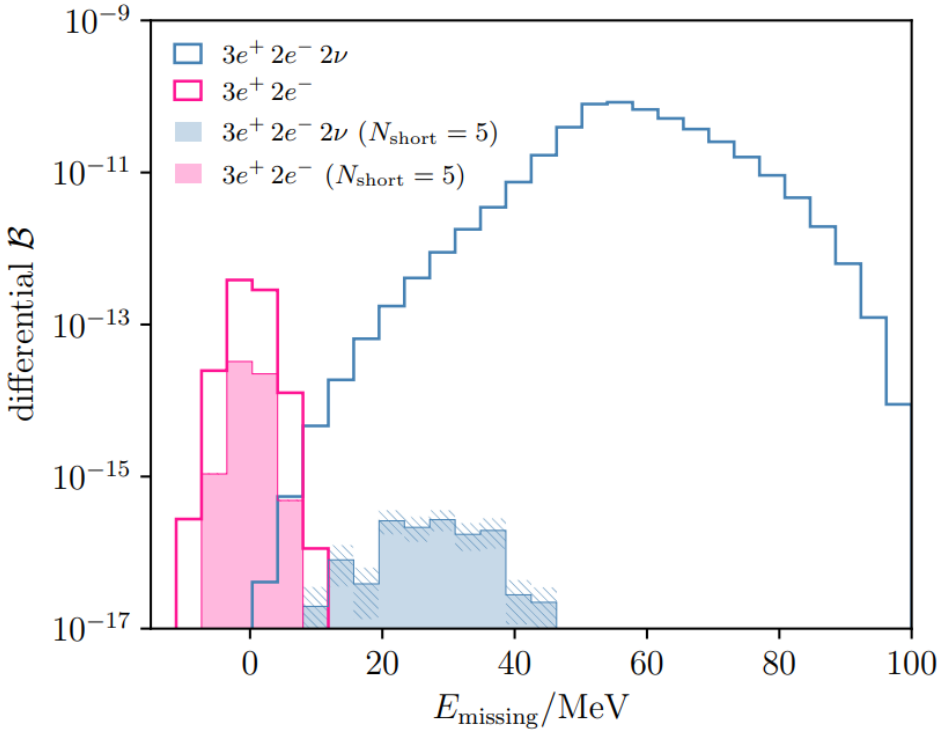


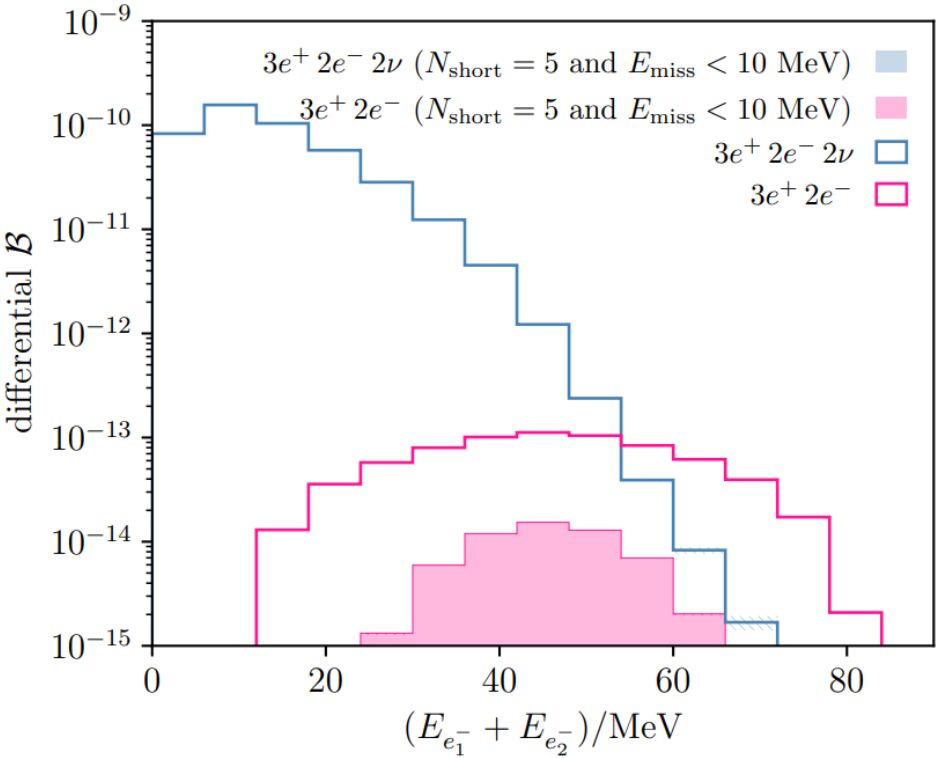
Simulation


$3e^+\,2e^-$
$3e^+\,2e^-\,2\nu$
All
$(N^{e^-}_{\text{short}} = 2)$
$(N^{e^-}_{\text{short}} = 2)$ & $(E_{\text{miss}} < 10\ \text{MeV})$
differential $\mathcal{B}$
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
2
3
4
5
Number of short tracks

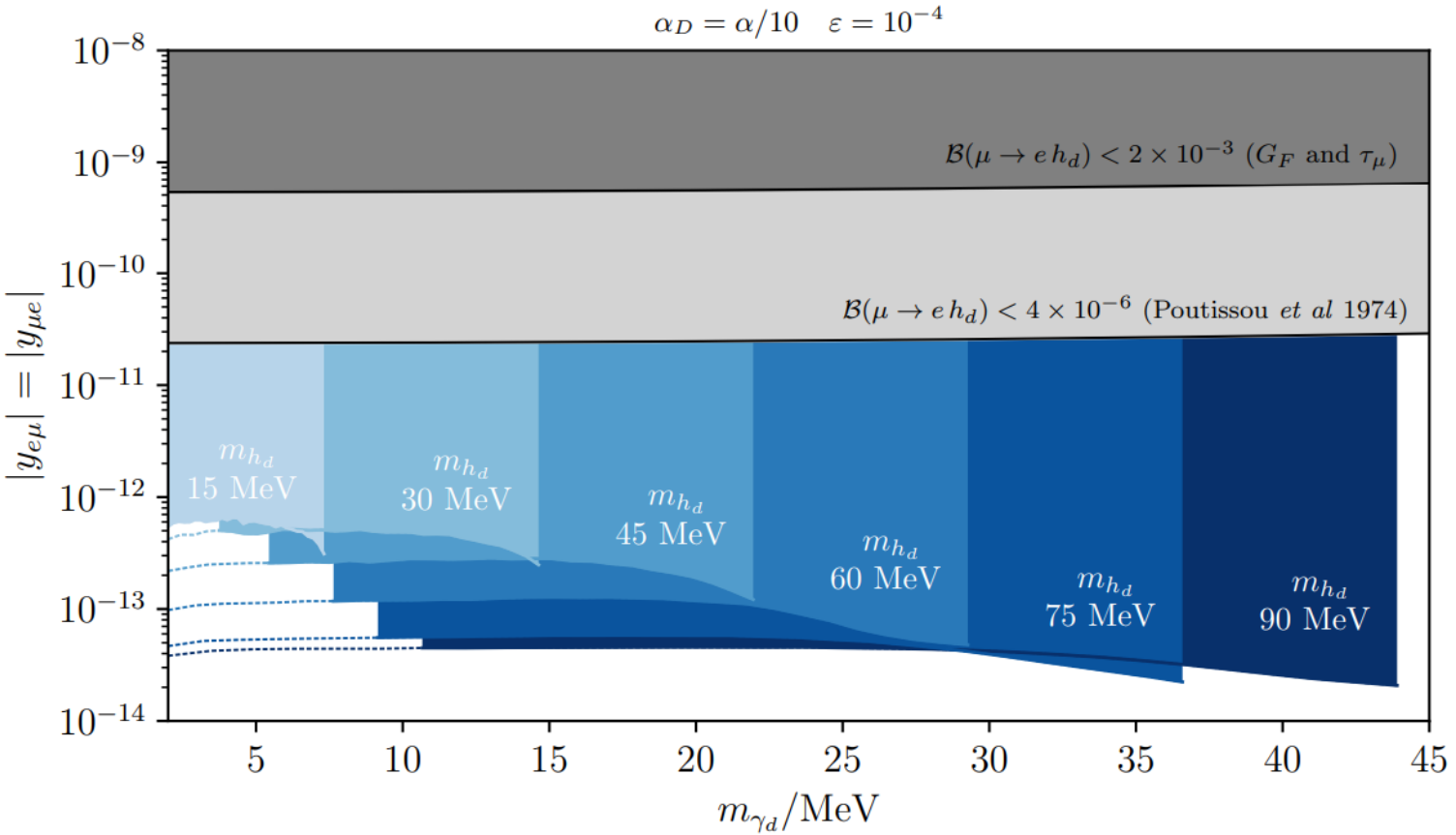

$3e^+\,2e^-$
$3e^+\,2e^-\,2\nu$
All
$(N^{e^-}_{\text{long}} = 2)$
$(N^{e^-}_{\text{long}} = 2)$ & $(E_{\text{miss}} < 10\ \text{MeV})$
differential $\mathcal{B}$
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
2
3
4
5
Number of long tracks

Simulation

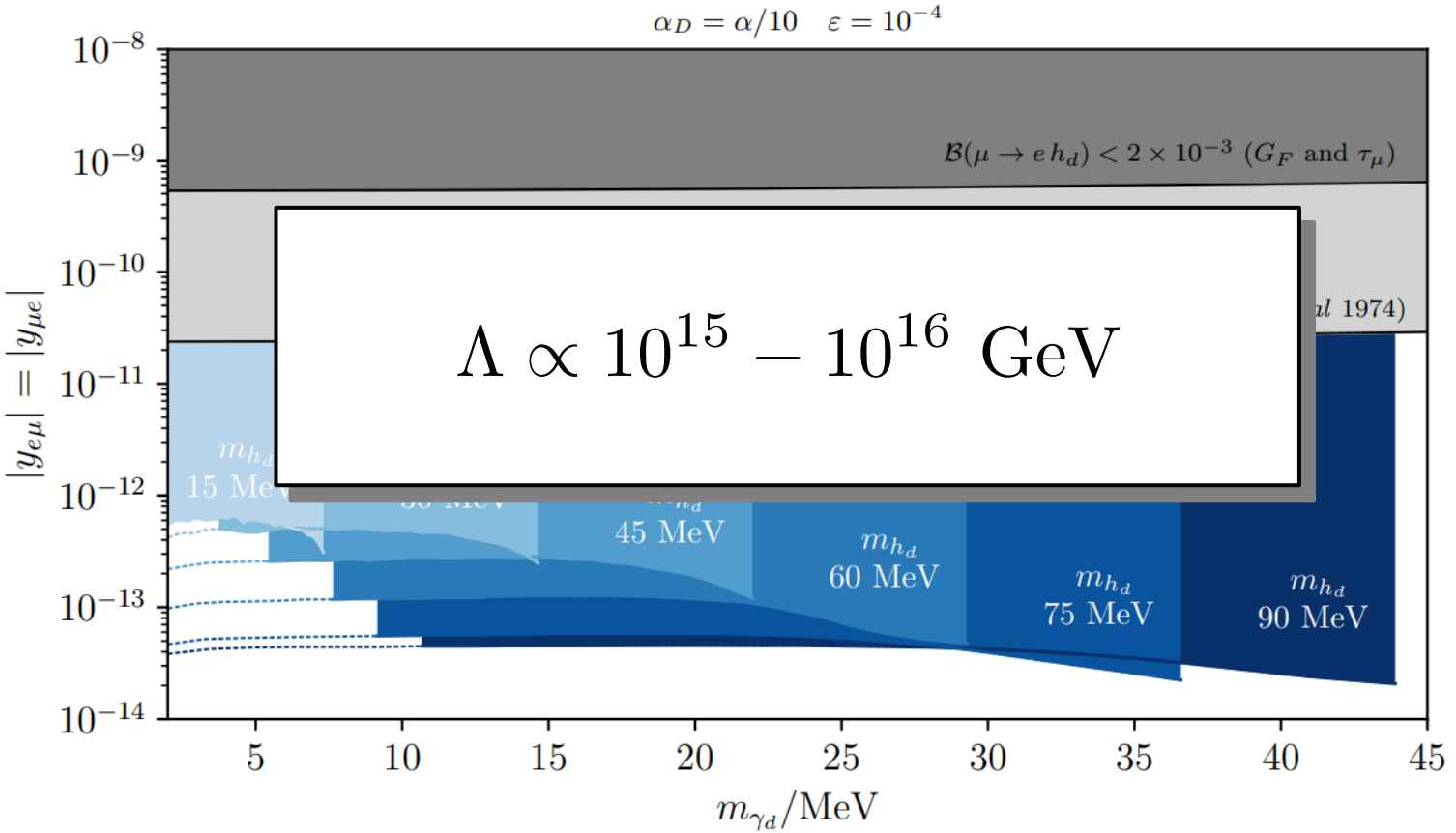

$3e^+\,2e^-\,2\nu$
$3e^+\,2e^-$
$3e^+\,2e^-\,2\nu$ ($N_{\text{short}} = 5$)
$3e^+\,2e^-$ ($N_{\text{short}} = 5$)
differential $\mathcal{B}$
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
0
20
40
60
80
100
$E_{\text{missing}}/\text{MeV}$


$3e^+\,2e^-\,2\nu$ ($N_{\text{short}} = 5$ and $E_{\text{miss}} < 10$ MeV)
$3e^+\,2e^-$ ($N_{\text{short}} = 5$ and $E_{\text{miss}} < 10$ MeV)
$3e^+\,2e^-\,2\nu$
$3e^+\,2e^-$
differential $\mathcal{B}$
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
0
20
40
60
80
$(E_{e_1^-} + E_{e_2^-})/\text{MeV}$

Reach


$\alpha_D = \alpha/10 \quad \varepsilon = 10^{-4}$
$\mathcal{B}(\mu \to e\, h_d) < 2 \times 10^{-3}$ (G_F and τ_μ)
$\mathcal{B}(\mu \to e\, h_d) < 4 \times 10^{-6}$ (Poutissou *et al* 1974)
m_{h_d} 15 MeV
m_{h_d} 30 MeV
m_{h_d} 45 MeV
m_{h_d} 60 MeV
m_{h_d} 75 MeV
m_{h_d} 90 MeV
$|y_{e\mu}| = |y_{\mu e}|$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
5
10
15
20
25
30
35
40
45
m_{γ_d}/MeV

Reach


$\alpha_D = \alpha/10 \quad \varepsilon = 10^{-4}$
$\mathcal{B}(\mu \to e\, h_d) < 2 \times 10^{-3}$ (G_F and τ_μ)
$\Lambda \propto 10^{15} - 10^{16}$ GeV
m_{h_d} 15 MeV
45 MeV
m_{h_d} 60 MeV
m_{h_d} 75 MeV
m_{h_d} 90 MeV
$|y_{e\mu}| = |y_{\mu e}|$
m_{γ_d}/MeV

Conclusions

- Mu3e should be able to see ~100s of μ → eeeeevν events and ~1000 new physics events.
- BR sensitivity of ~10^{-12} for μ → eeeee signal
- We hope Mu3e adds the μ → eeeee channel to their analysis pipeline

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Thank you :)