Signatures of light new physics @ muon factories

NuFact 2024
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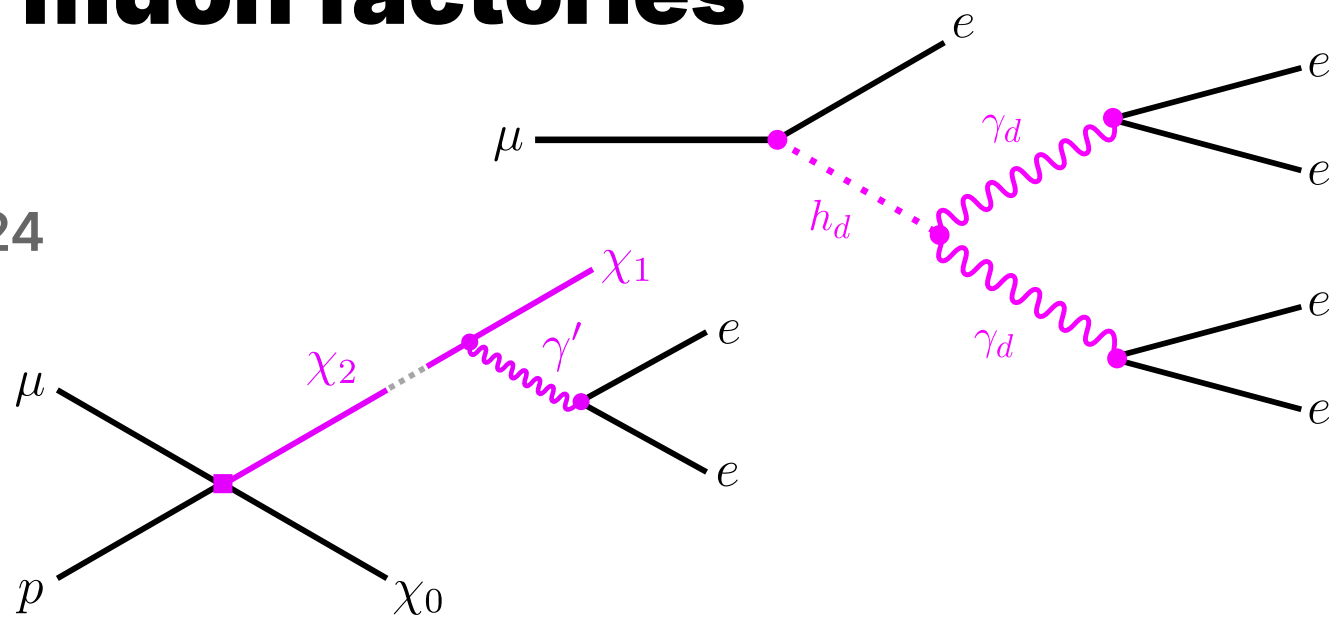


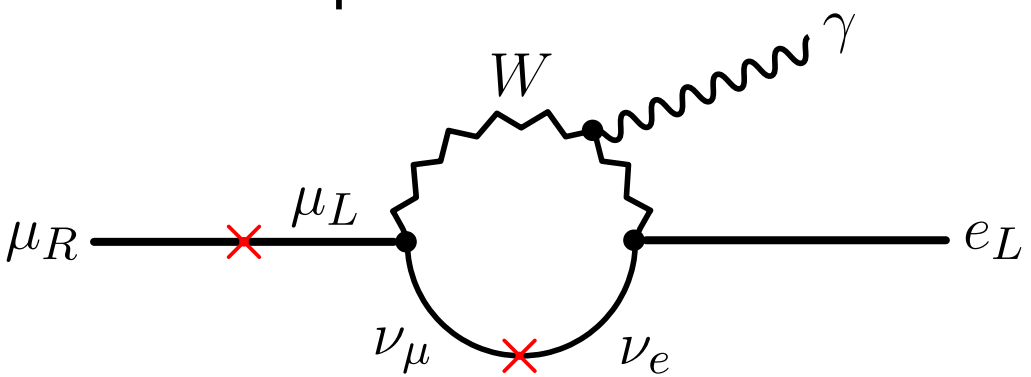
Based on 2306.15631 and 2407.03450 with Patrick Fox, Matheus Hostert, Maxim Pospelov, and Jure Zupan

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



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

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

$$\mathrm{BR}(\mu \to eee) \simeq \frac{\alpha}{3\pi} \left(\log \frac{m_\mu^2}{m_e^2} - 3 \right) \times \mathrm{BR}(\mu \to e\gamma)$$

$$\mathrm{CR}(\mu\,\mathrm{N} \to e\,\mathrm{N}) \simeq \alpha \times \mathrm{BR}(\mu \to e\gamma)\,.$$

Bottom line: Observing CLFV = new physics

Experimental status

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

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

- **Mu3e @ PSI - μ → eee**

  Projected: $\mathrm{BR}(\mu^+ \to e^+e^-e^+) \lesssim 10^{-16}$ $(\Gamma(\mu \to e) \lesssim 10^{-12}\ \mathrm{Hz})$

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

  Projected: $\mathrm{CR}(\mu^-\mathrm{Al} \to e^-\mathrm{Al}) \lesssim 10^{-18} - 10^{-17}$ $(\Gamma(\mu \to e) \lesssim 10^{-13}\ \mathrm{Hz})$

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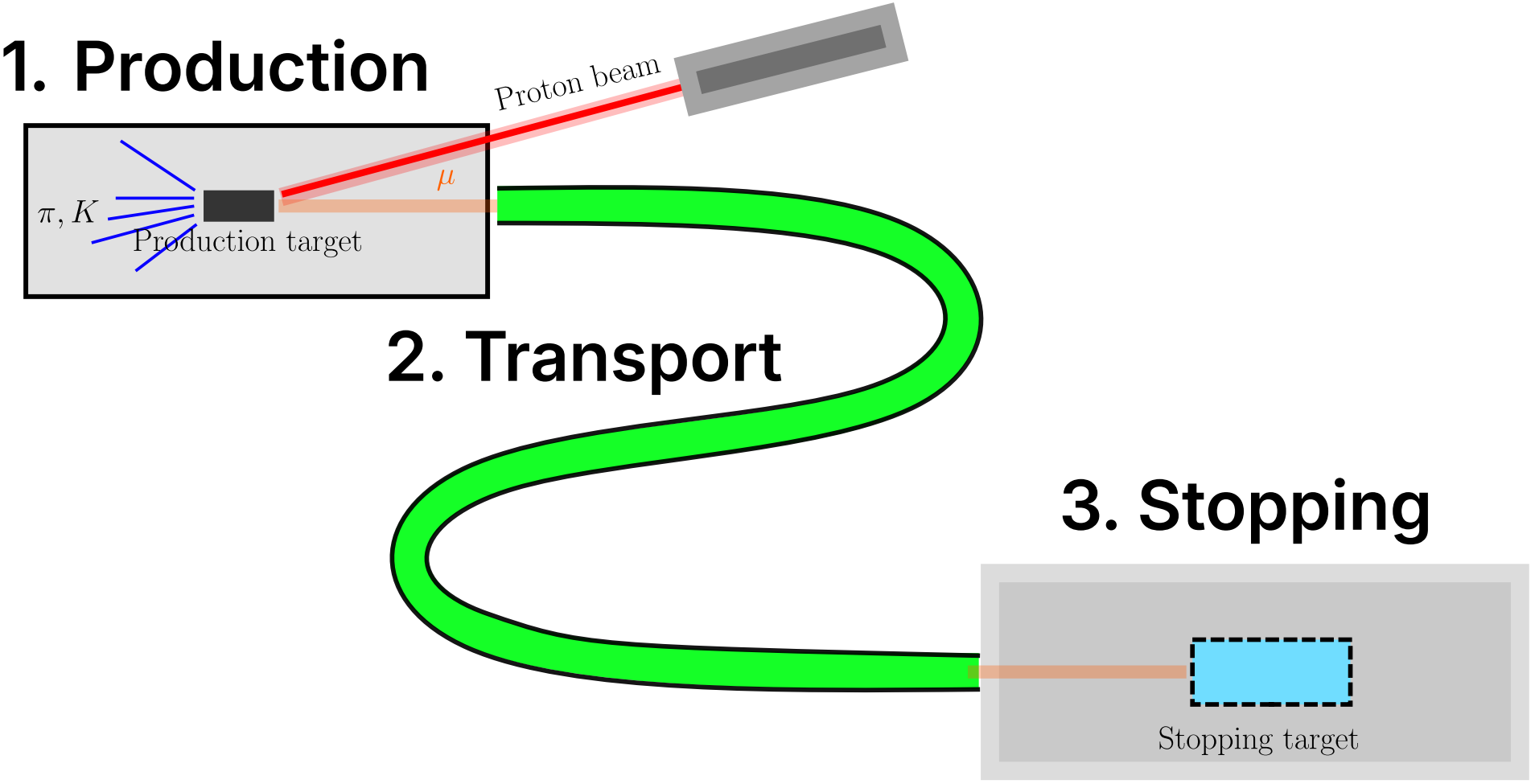
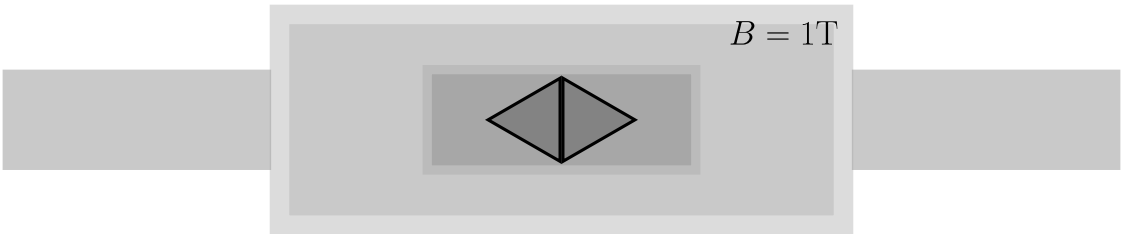

1. Production
Proton beam
μ
π, K
Production target
2. Transport
3. Stopping
Stopping target

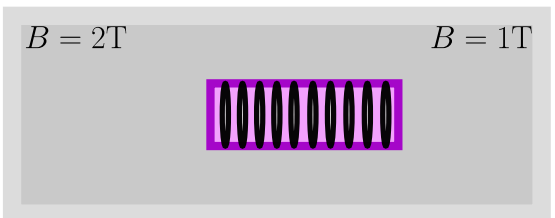
4. Detection (phenomenology is influenced by detector)

Mu3e (μ^+)

* requires $p_T > 10$ MeV



Mu2e (μ^-)



* requires $p_T > 90$ MeV

Exotic μ → e

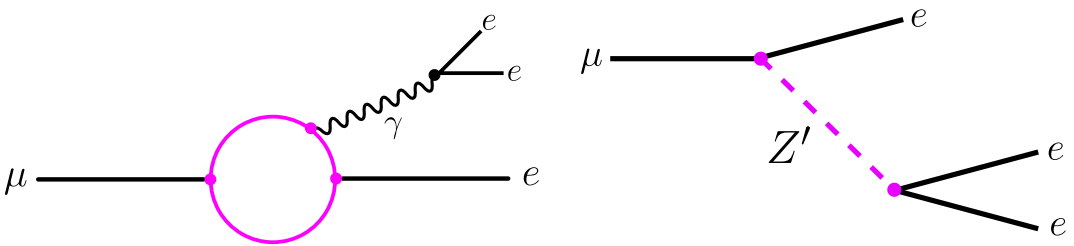
In the *Landscape*, CLFV is common.

The dichotomy:

- Heavy: SM + "irrelevant" operators

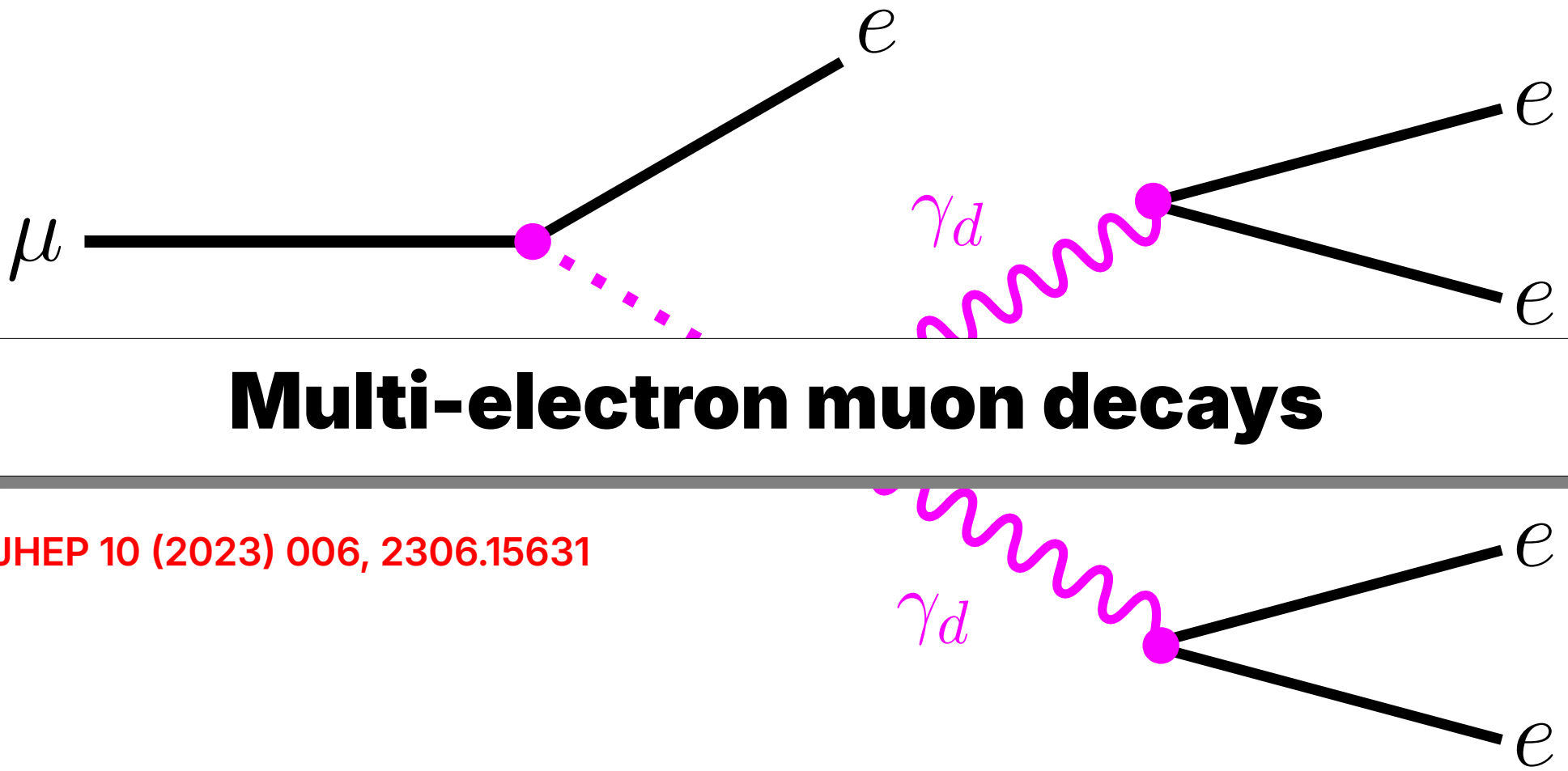
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} O^{(d)}$$

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



- Light: SM + new fields with weakly coupled interactions

***Naturalness demands an explanation! Appeal to high scale physics to explain smallness**



Multi-electron muon decays

JHEP 10 (2023) 006, 2306.15631

Mu3e → Mu5e

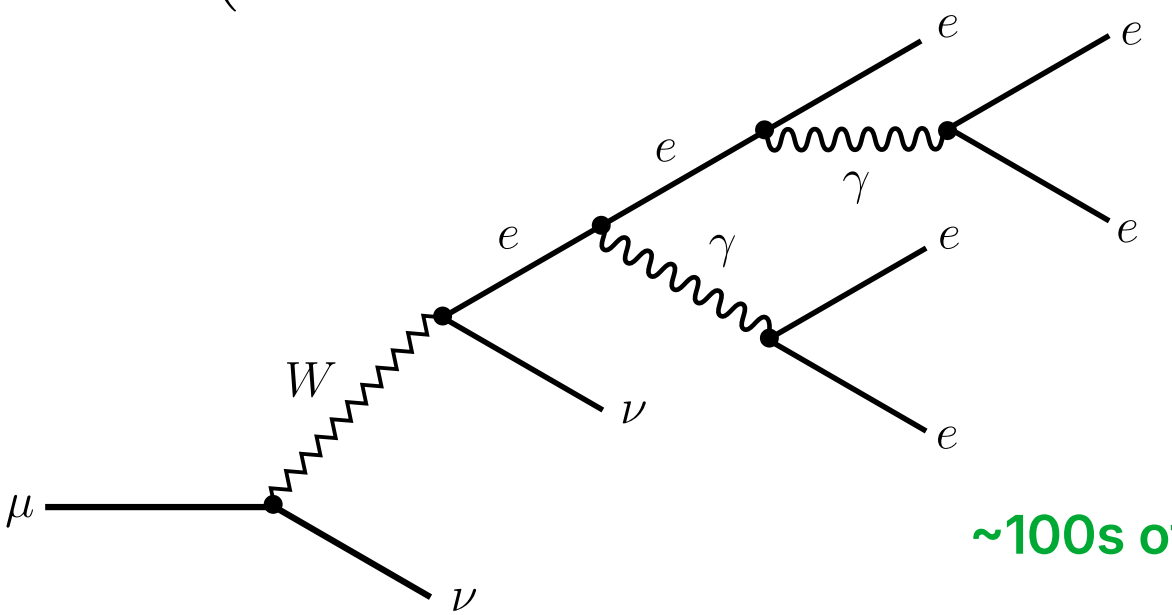
- Mu3e will see ~10^{15} total muon decays from the stopping target.
- With these statistics are there any other interesting channels?
  - What about μ → 5e?

μ → eeeeevv

- **SM background for Mu5e**

From MG5: $\mathcal{B}(\mu^+ \to e^+e^-e^+e^-e^+\nu_e\bar{\nu}_\mu) = (3.929 \pm 0.001) \times 10^{-10}$

$$\mathcal{B}\left(\mu^+ \to e^+e^-e^+e^-e^+\nu_e\bar{\nu}_\mu \,|\, \text{all } p_{e^\pm}^{T,\text{true}} > 10\ \text{MeV}\right) = (1.4 \pm 0.1) \times 10^{-14}$$



$\propto G_F^2\alpha^4$

~100s of μ → 5evv events after cuts!

μ → eeeee

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

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

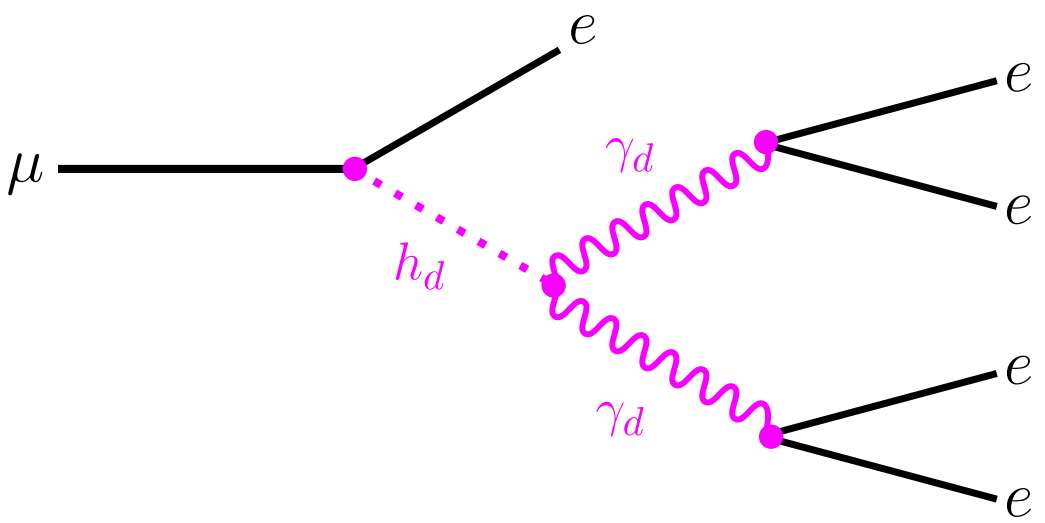
$$\mathscr{L}_{\rm LFV} = -\frac{C_{ij}}{\Lambda} \phi \left(\bar{L}_i H\right) \ell_j + \text{h.c.}$$

$$\downarrow \qquad y_{ij} \simeq \frac{Cv}{\Lambda}$$

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

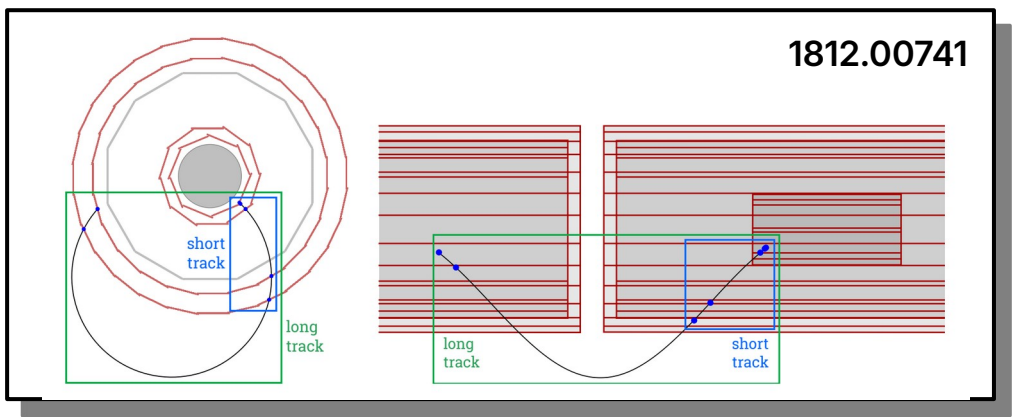
μ → eeeee

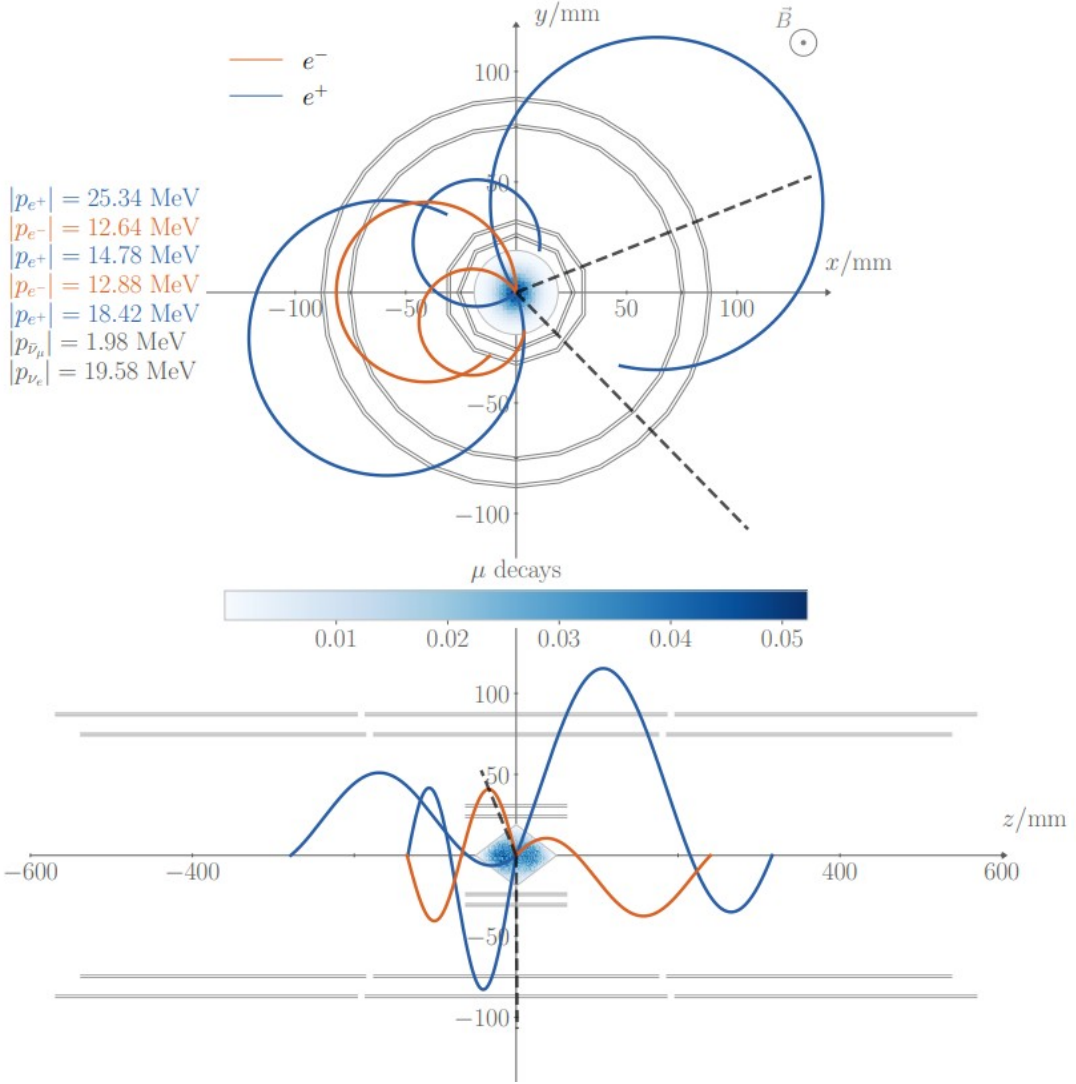
- Leads to cascade decay



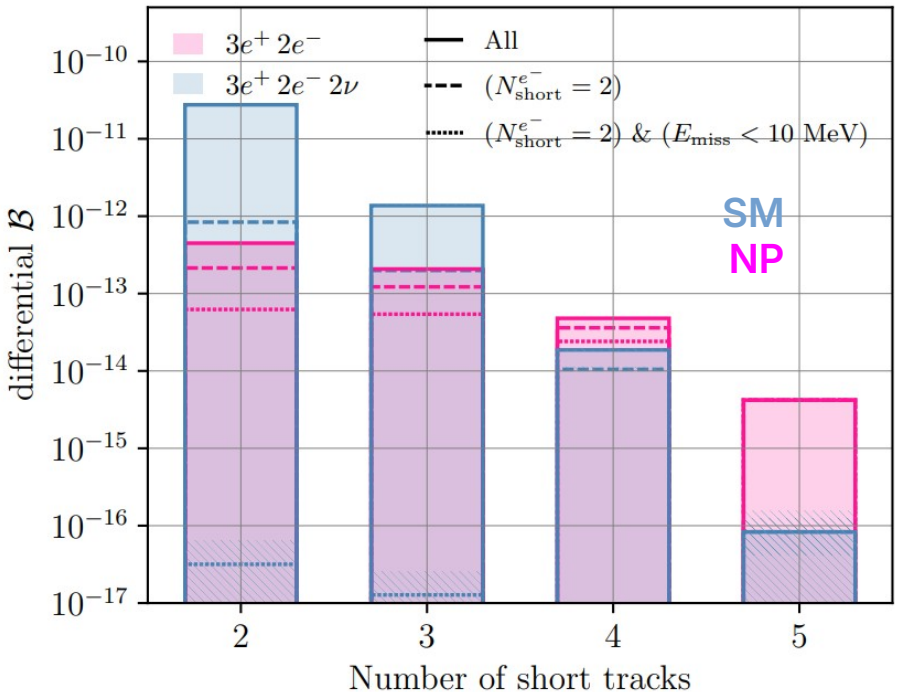
Signatures

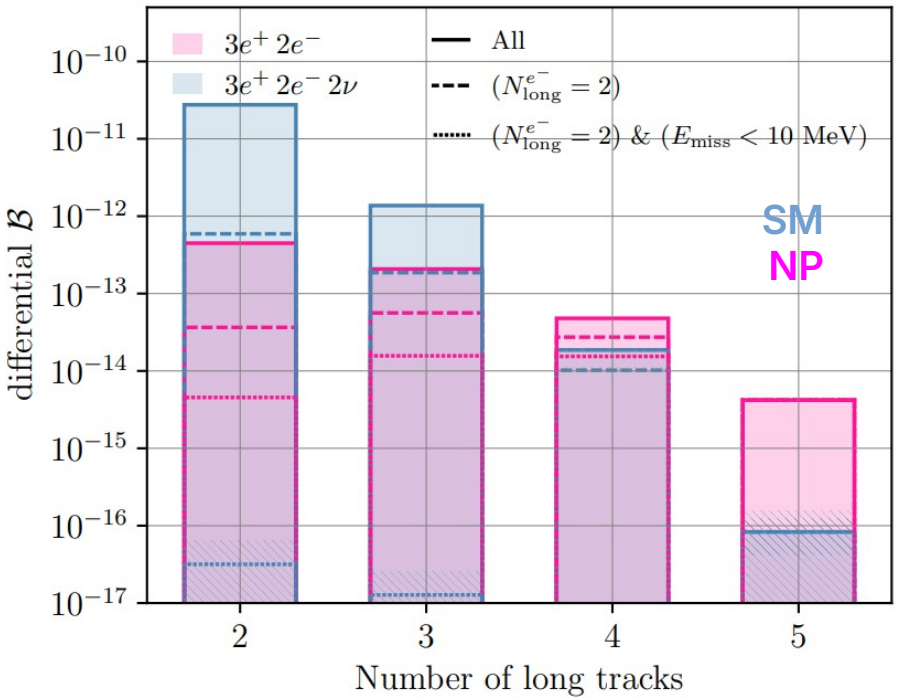
- Momentum of tracks must be reconstructed from energy deposits or ‘hits’ in the layers of the detectors.
- 4 hits = short track
- 6+ hits = long track



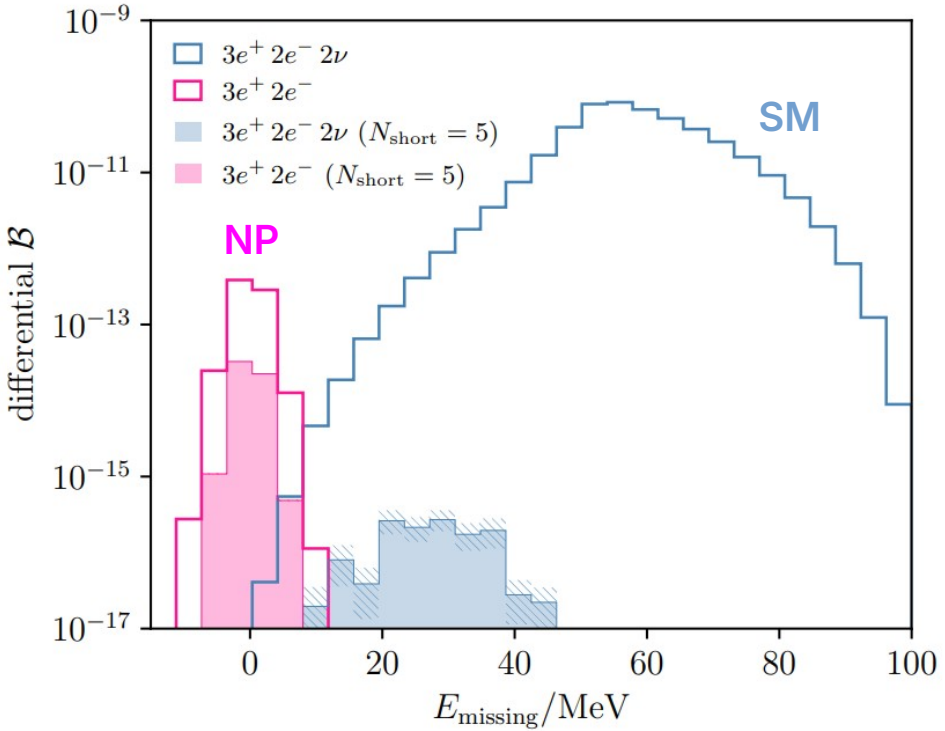


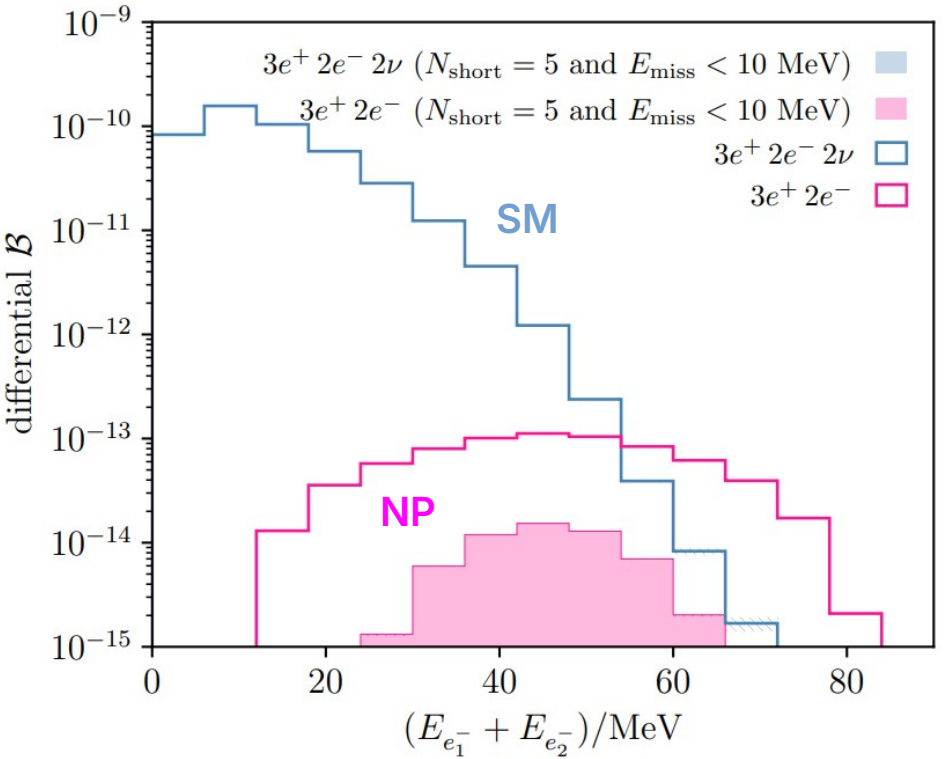
Signatures


$3e^+\,2e^-$
$3e^+\,2e^-\,2\nu$
All
$(N^{e^-}_{\rm short}=2)$
$(N^{e^-}_{\rm short}=2)$ & $(E_{\rm miss}<10$ MeV$)$
SM
NP
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

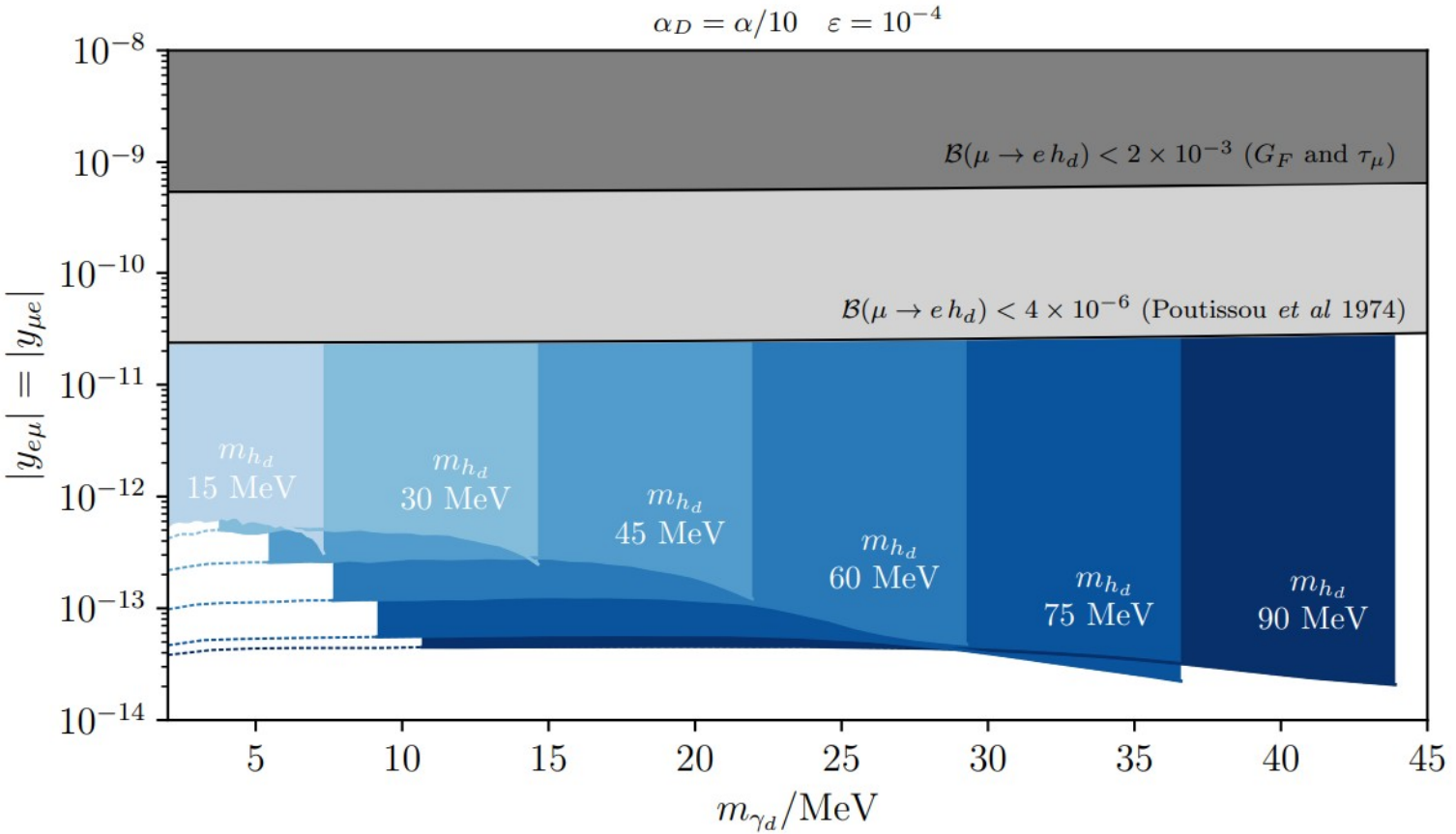

$3e^+\,2e^-$
$3e^+\,2e^-\,2\nu$
All
$(N^{e^-}_{\rm long}=2)$
$(N^{e^-}_{\rm long}=2)$ & $(E_{\rm miss}<10$ MeV$)$
SM
NP
differential $\mathcal{B}$
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
2
3
4
5
Number of long tracks

Signatures

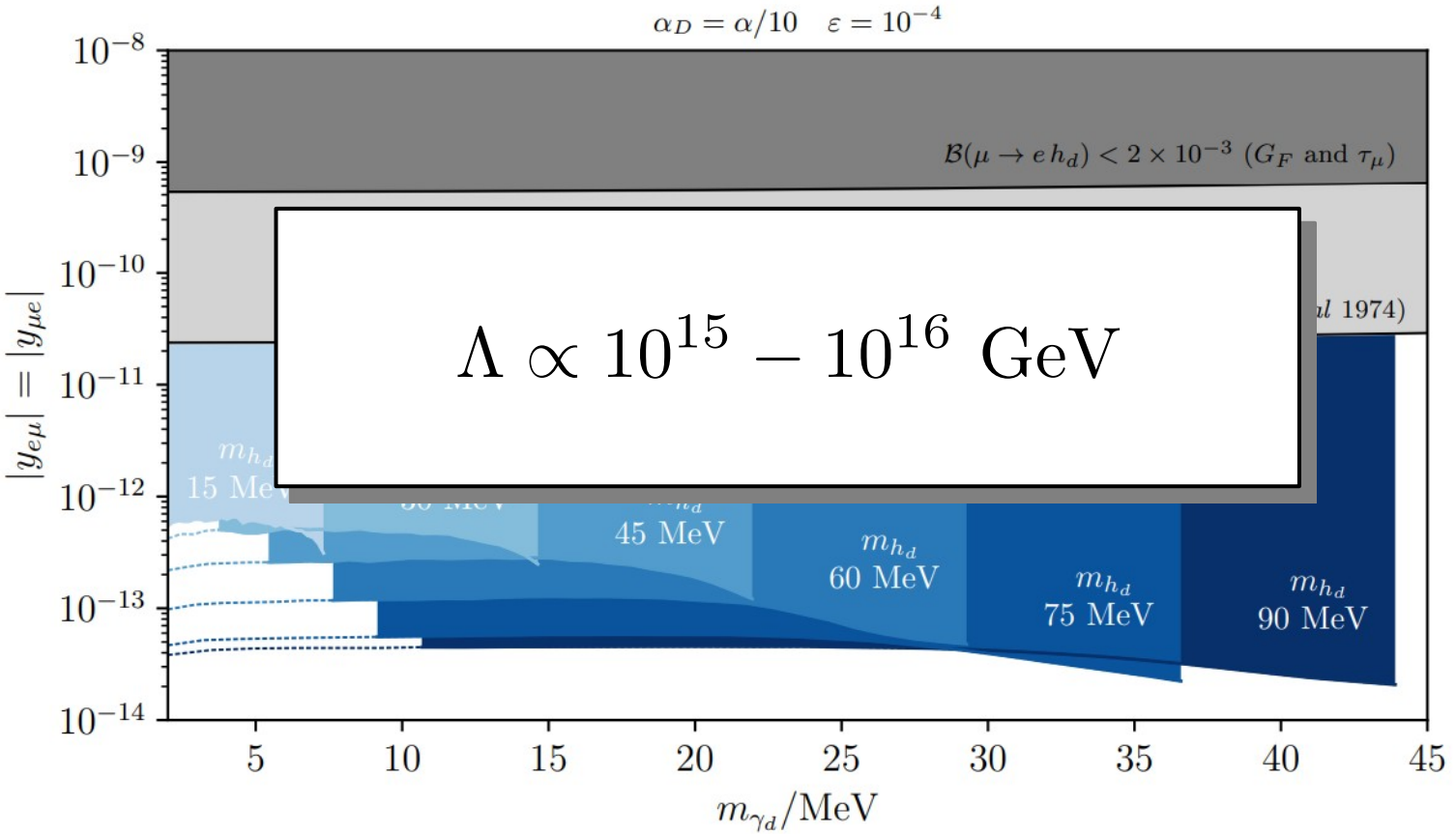

$3e^+\,2e^-\,2\nu$
$3e^+\,2e^-$
$3e^+\,2e^-\,2\nu$ ($N_{\rm short}=5$)
$3e^+\,2e^-$ ($N_{\rm short}=5$)
NP
SM
differential $\mathcal{B}$
$E_{\rm missing}$/MeV

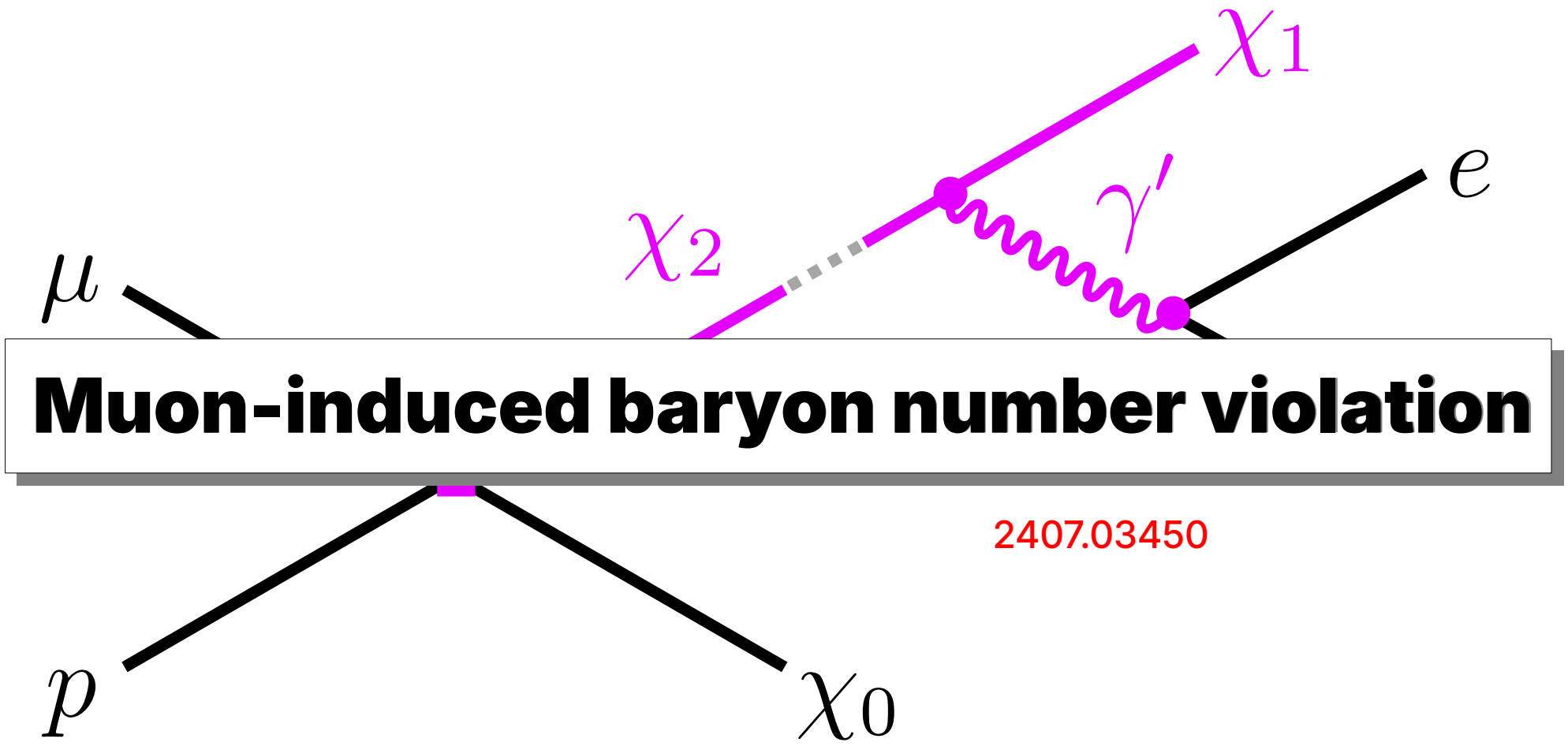

$3e^+\,2e^-\,2\nu$ ($N_{\rm short}=5$ and $E_{\rm miss}<10$ MeV)
$3e^+\,2e^-$ ($N_{\rm short}=5$ and $E_{\rm miss}<10$ MeV)
$3e^+\,2e^-\,2\nu$
$3e^+\,2e^-$
SM
NP
differential $\mathcal{B}$
$(E_{e_1^-}+E_{e_2^-})$/MeV

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} 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



Muon-induced baryon number violation

2407.03450

Widening the view

- Can the CLFV signal @ Mu2e stem from non-CLFV physics?
- NP scenarios where E_e>105 MeV?
  - Can we take advantage of the huge energy reservoir that is the nucleus?

$\mu\,^{27}\mathrm{Al} \to {}^{26}\mathrm{Mg}^{(*)}\chi_0\chi_1 ee$

- **Three dark states + $U(1)_D$ + SM portal via kinetic mixing**

$$\mathcal{L}_{\mu p} = G_{\mu p}(\bar{p}\chi_2)(\bar{\mu}\chi_0) + \text{h.c.}$$

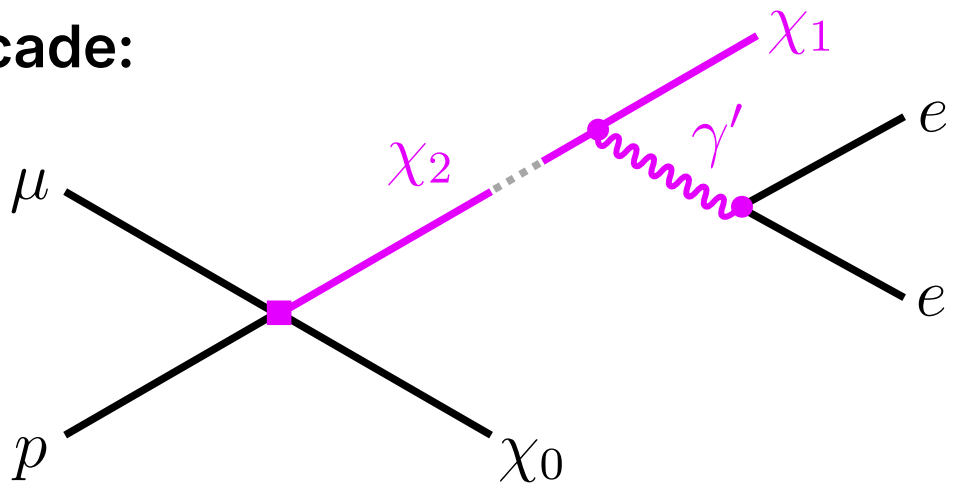
$$\mathcal{L}_{eA'} = e\varepsilon A'_\mu J^\mu_{\text{EM}}$$

$$\mathcal{L}_\chi = g_D\left(\bar{\chi}_2\gamma^\mu\chi_1\right)A'_\mu + \text{h.c.}$$

$\mu\,^{27}\mathrm{Al} \to {}^{26}\mathrm{Mg}^{(*)}\chi_0\chi_1 ee$

Benchmark: $m_2 = 1030\ \mathrm{MeV},\ m_1 = 900\ \mathrm{MeV}, m_0 = 0,\ m_{A'} = 20\ \mathrm{MeV},$
$G_{\mu p} = (300\ \mathrm{TeV})^{-2},\ \varepsilon = 10^{-4},\ \alpha_D = 10^{-3}$

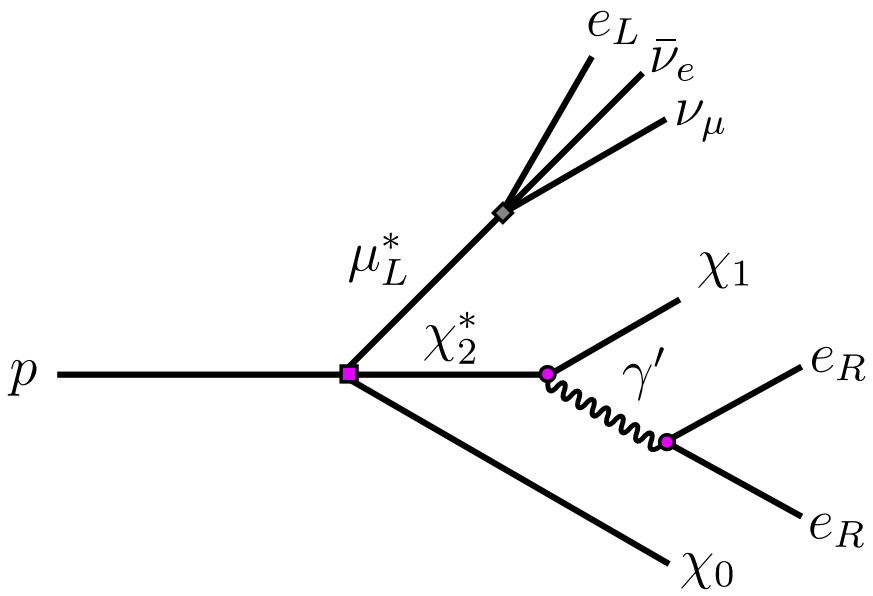
- **Leads to the cascade:**



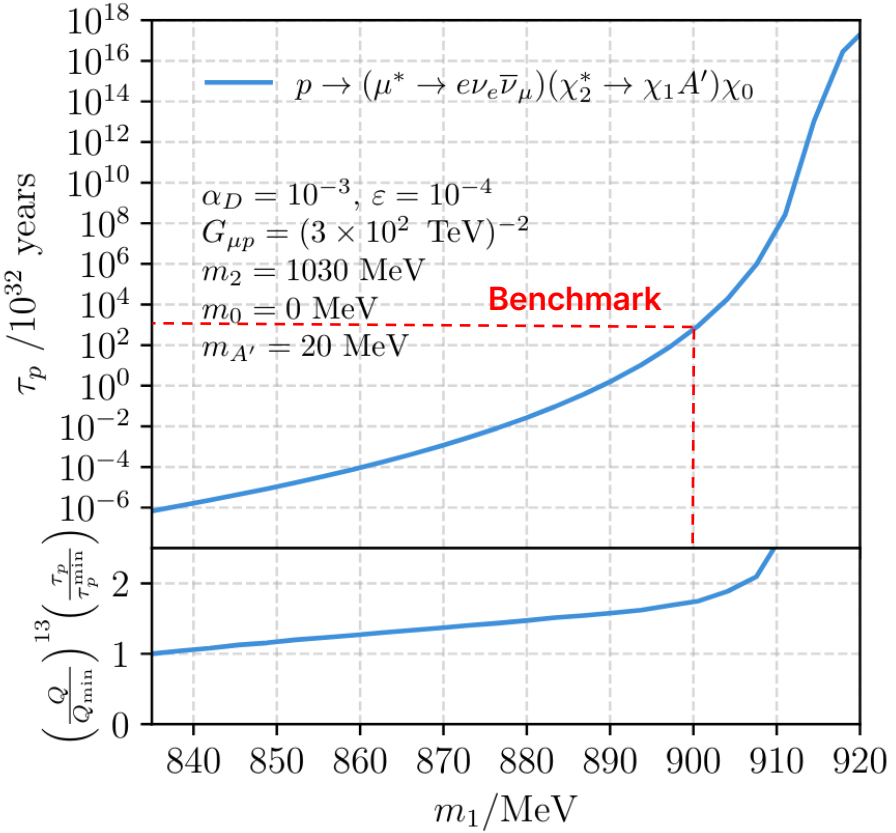
~4 × 10⁻³

$$\Gamma(\mu\,^{27}\mathrm{Al} \to \chi_0\chi_2\,^{26}\mathrm{Mg}) \simeq r_{\mathrm{p.s.}}\frac{G_{\mu p}^2}{G_F^2}\Gamma(\mu\,^{27}\mathrm{Al} \to \nu_\mu n\,^{26}\mathrm{Mg}) \longrightarrow R \equiv \frac{\Gamma_{\mathrm{exotic}}}{\Gamma_{\mu\mathrm{Al}}} \sim 10^{-15}$$

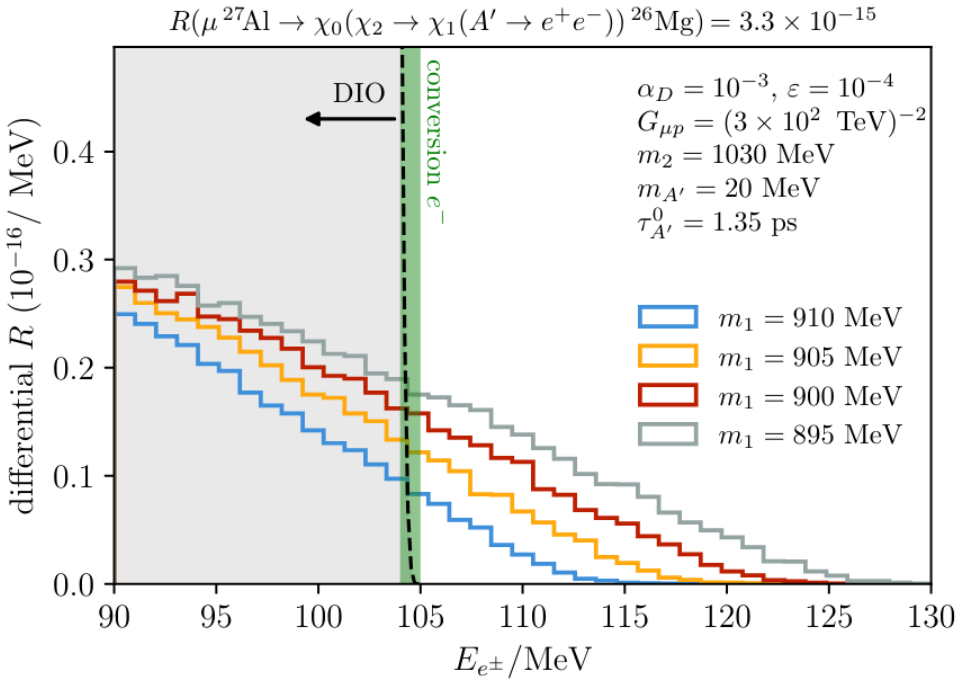
Tug-of-war with nucleon decay

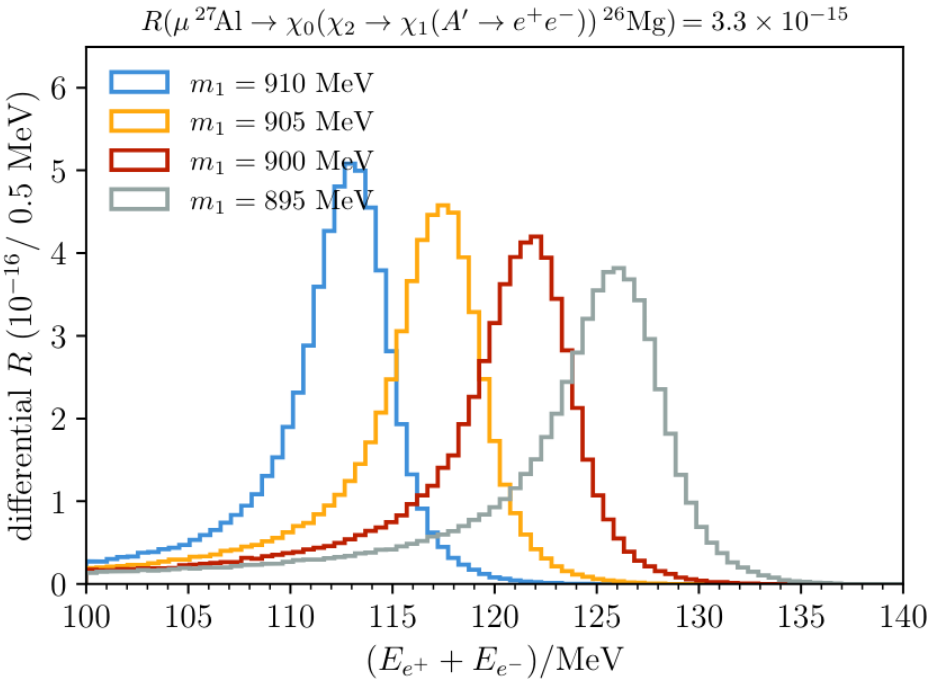


$$\Gamma_p \propto \frac{G_{\mu p}^2 G_F^2 \alpha_D Q^{13}}{(16\pi^2)^4 m_\mu^2 m_2^2}$$



Signature


$R(\mu\,^{27}\mathrm{Al} \to \chi_0(\chi_2 \to \chi_1(A' \to e^+e^-))\,^{26}\mathrm{Mg}) = 3.3 \times 10^{-15}$
DIO
conversion e^-
$\alpha_D = 10^{-3}$, $\varepsilon = 10^{-4}$
$G_{\mu p} = (3 \times 10^2\ \mathrm{TeV})^{-2}$
$m_2 = 1030$ MeV
$m_{A'} = 20$ MeV
$\tau^0_{A'} = 1.35$ ps
$m_1 = 910$ MeV
$m_1 = 905$ MeV
$m_1 = 900$ MeV
$m_1 = 895$ MeV
differential R (10^{-16}/ MeV)
$E_{e^\pm}$/MeV


$R(\mu\,^{27}\mathrm{Al} \to \chi_0(\chi_2 \to \chi_1(A' \to e^+e^-))\,^{26}\mathrm{Mg}) = 3.3 \times 10^{-15}$
$m_1 = 910$ MeV
$m_1 = 905$ MeV
$m_1 = 900$ MeV
$m_1 = 895$ MeV
differential R (10^{-16}/ 0.5 MeV)
$(E_{e^+} + E_{e^-})$/MeV

Conclusions

- Mu3e should be able to see ~100s of $\mu \rightarrow eeeeevv$ events and potentially ~1000 new physics events (for the described model).
- We hope Mu3e adds the $\mu \rightarrow eeeee$ channel to their analysis pipeline
- … Mu7e? Let's not get greedy!
- Interesting non-CLFV physics at Mu2e (and COMET)
- We hope Mu2e + COMET add highly energetic electrons (above the conversion energy) to their analysis pipeline

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Thank you :)