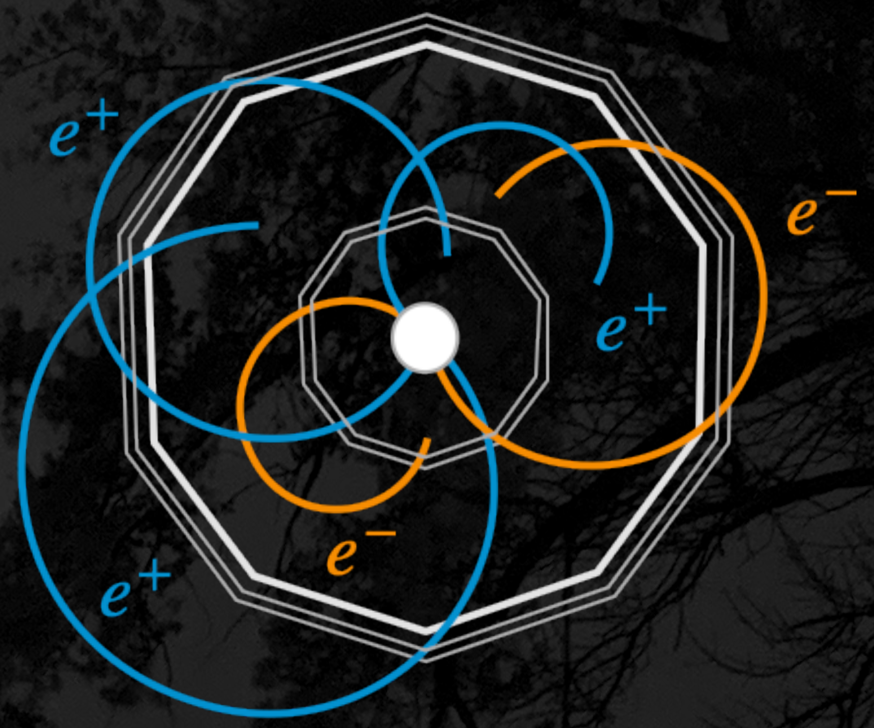

New Particle Production at Muon Facilities

Matheus Hostert
Harvard University
mhostert@g.harvard.edu

Muons in Minneapolis
December 6th, 2023

Going beyond the Standard Model
Light particles

Why search for low-scale extensions?

- Light dark matter (< 10's GeV) and Lee-Weinberg's argument for new weakly-coupled forces.
- UV theories with weakly-coupled Nambu-Goldstone bosons (axion-like particles).
- Neutrino masses from heavy neutrinos with weaker-than-weak interactions.

A new light particle would be revolutionary to our understanding of Particle Physics.

"Low cost, high return" scenario.

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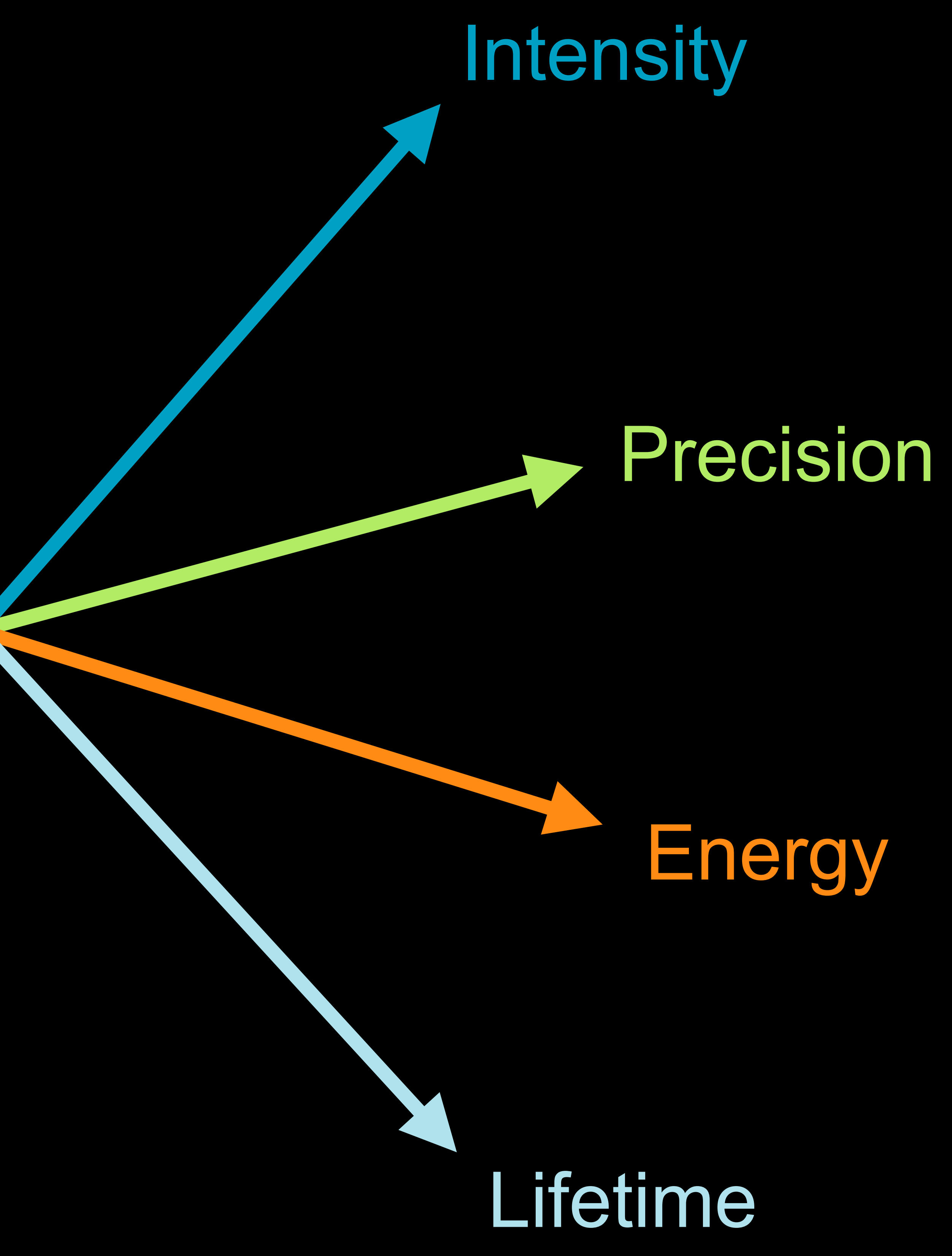
Why muons?

- Lamppost in 2nd generation: high intensities and precision.
- Are the three generations universal?
- Are there new sources of lepton (flavor) violation?

New particles can be open a new window to answer some of these questions.

Going beyond the Standard Model

The “progress axes” for muon facilities



1) Rare decay searches (Intensity & Precision)
   - $10^{15} - 10^{16}$ muons in clean environments

This talk: Five-track events at Mu3e

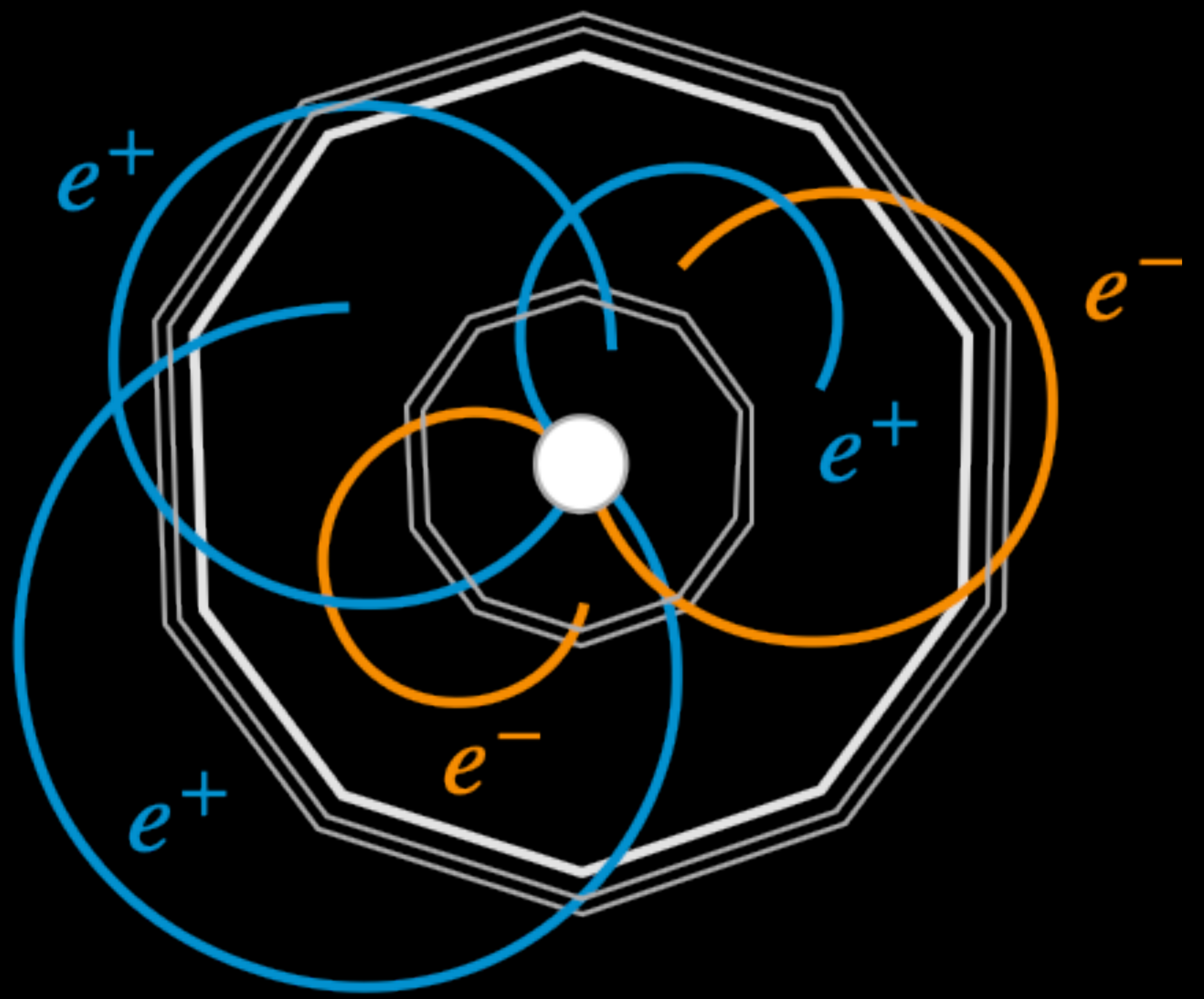
This talk: Some new ideas for dark sectors at Mu2e.

2) Spallation and accelerator neutrino experiment (Intensity & Lifetime)
   - $> 10^{21}$ muons in “dirty” environments, but large detectors.
   - JSNS (J-PARC), SNS (Oak Ridge), Lujan (Los Alamos), ESS (Lund).

This talk: Long-lived particles at spallation sources.

New particle production in μ^+ decays

Multi-electron final states at ~~Mu3e~~ Mu5e



Light particle production at Mu3e
A theorist's overview

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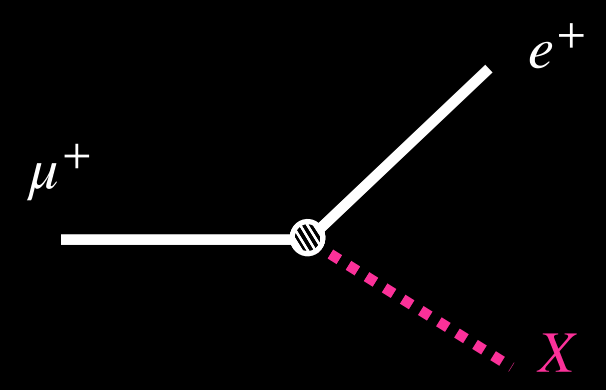

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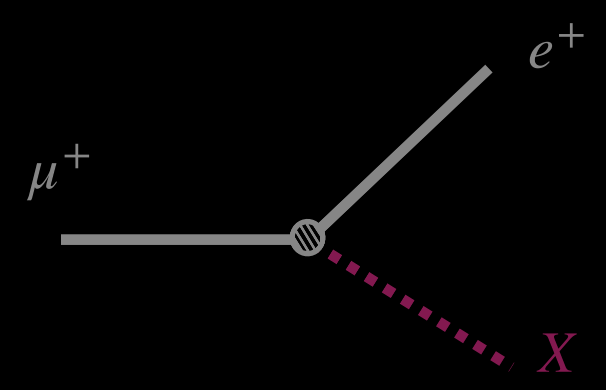

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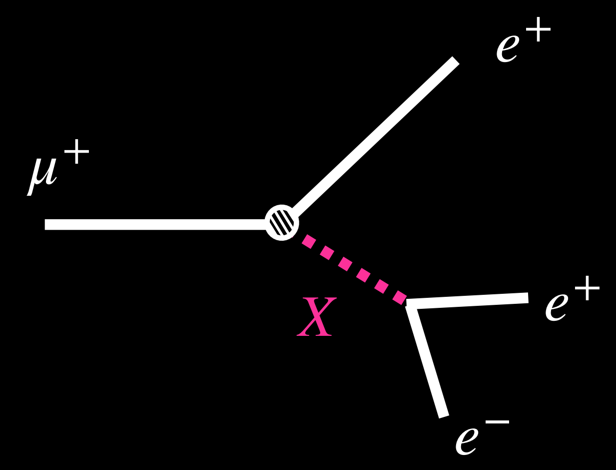

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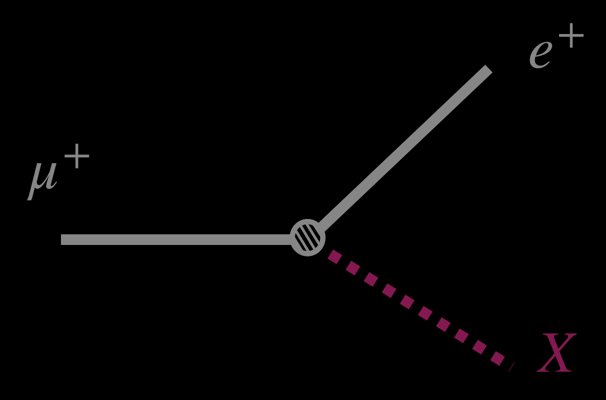

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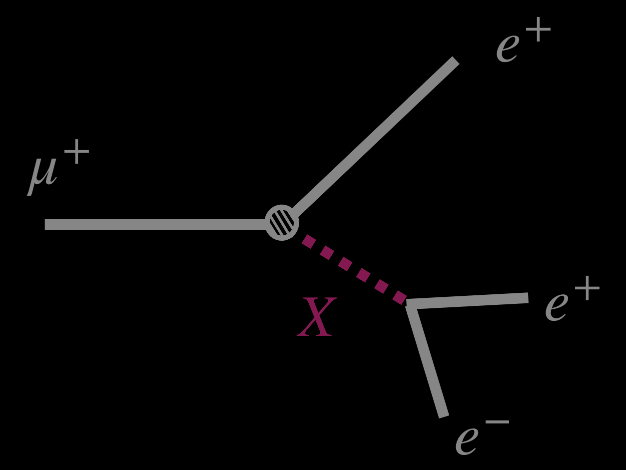

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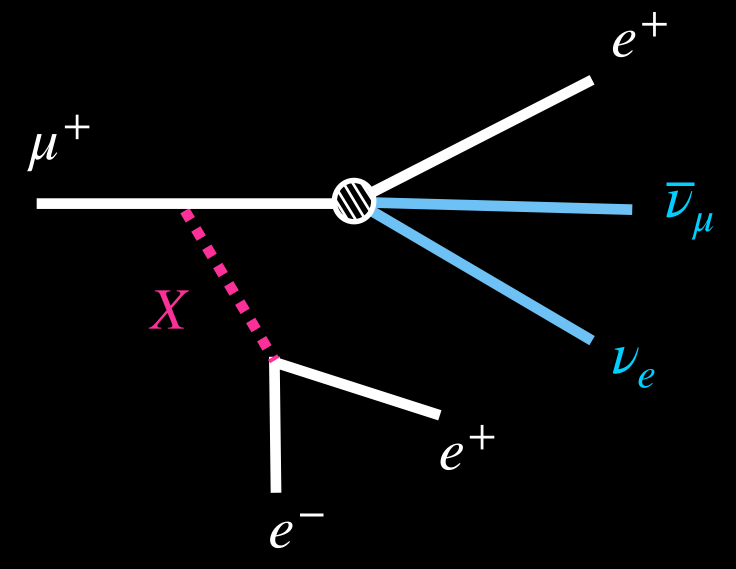

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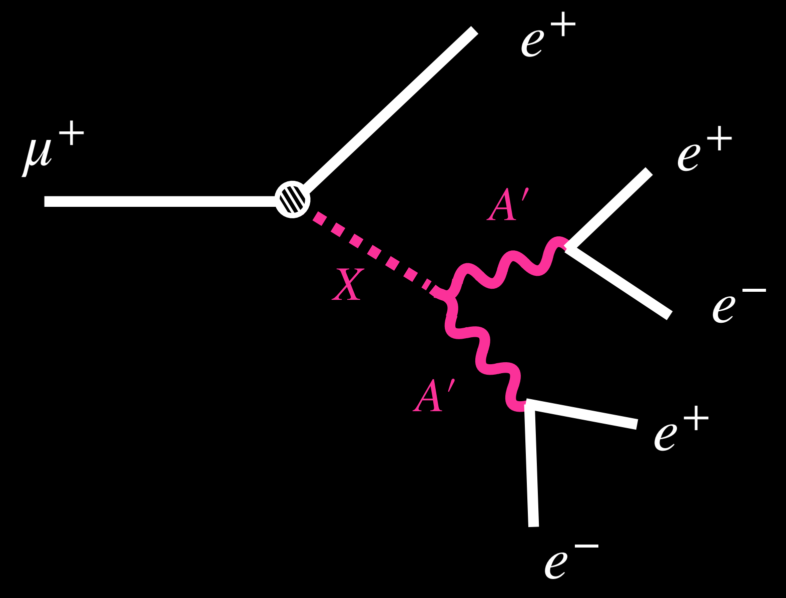

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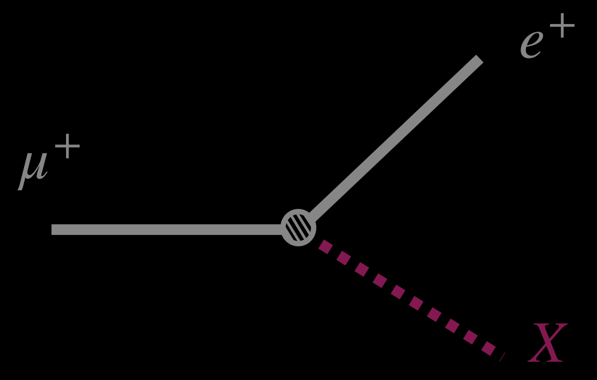

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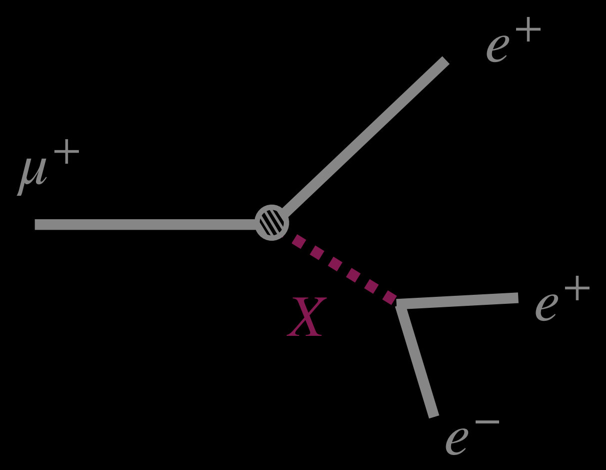

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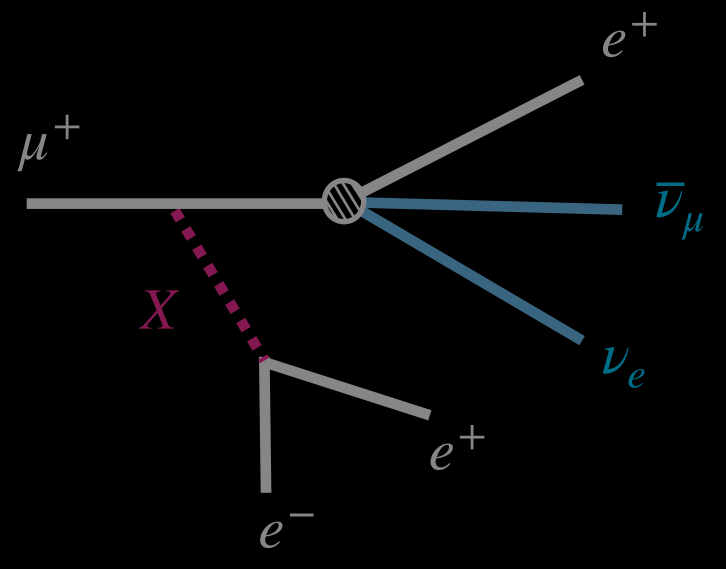

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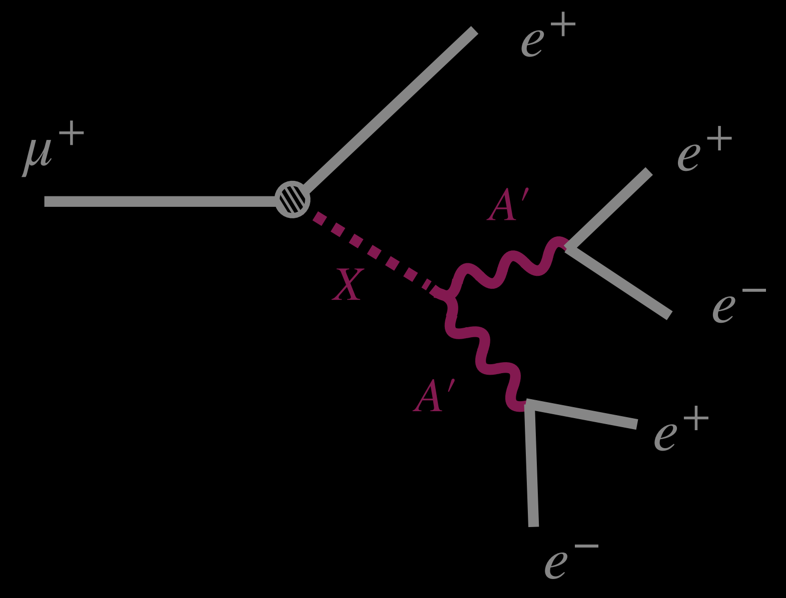

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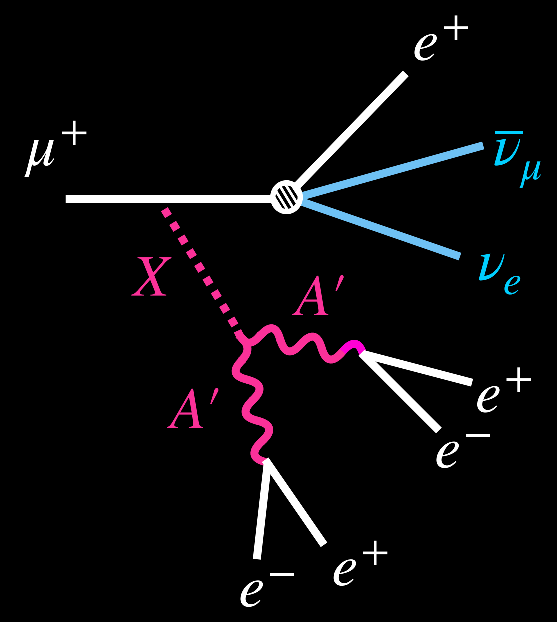

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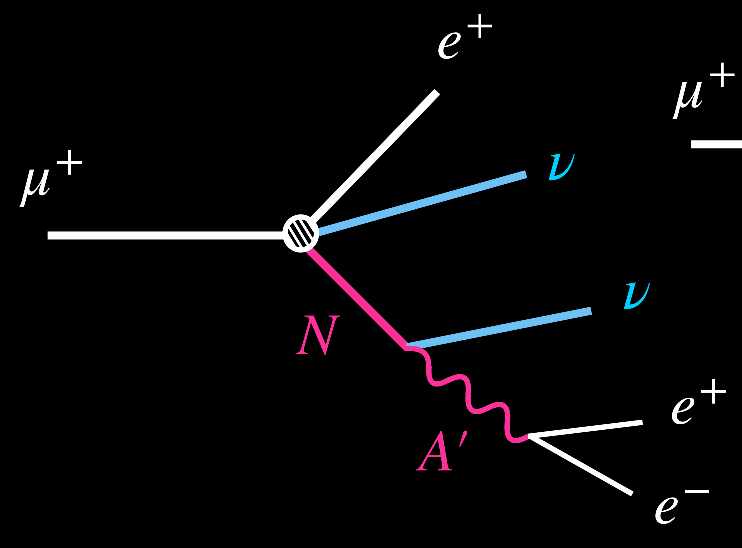

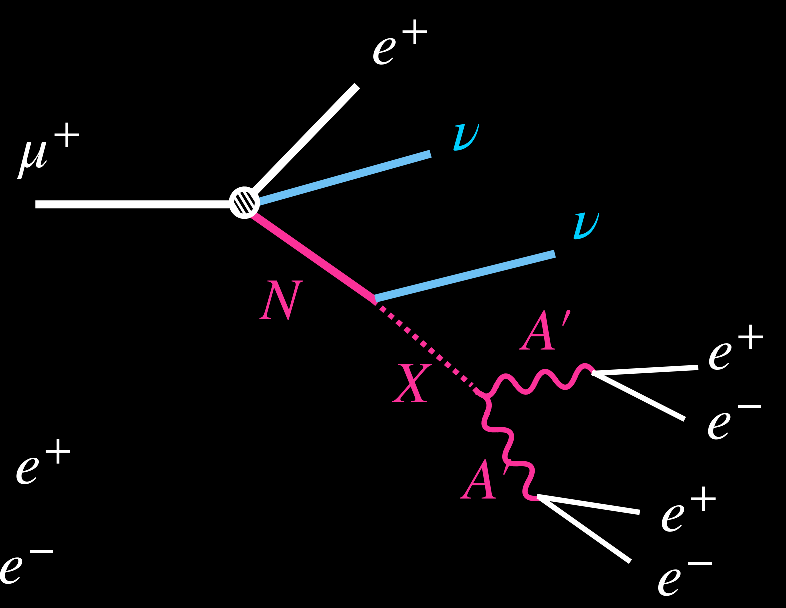

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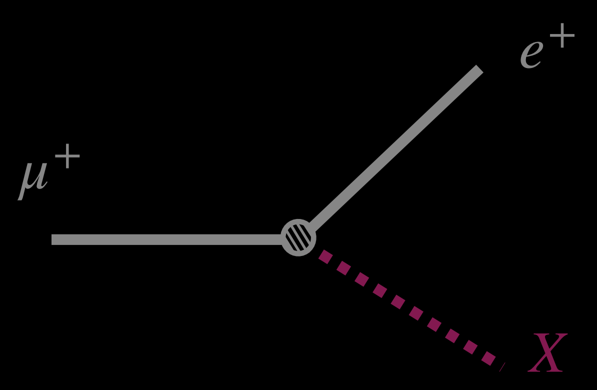

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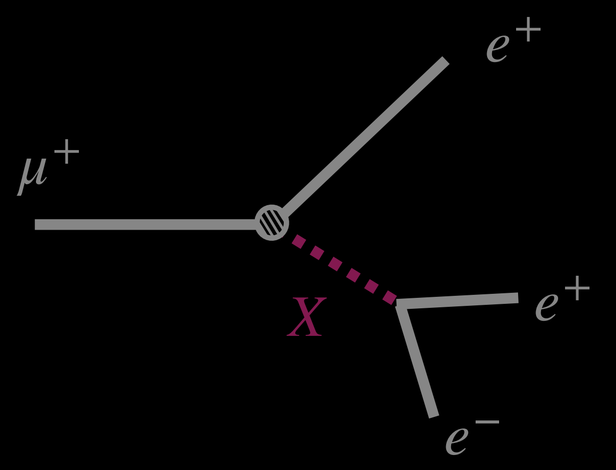

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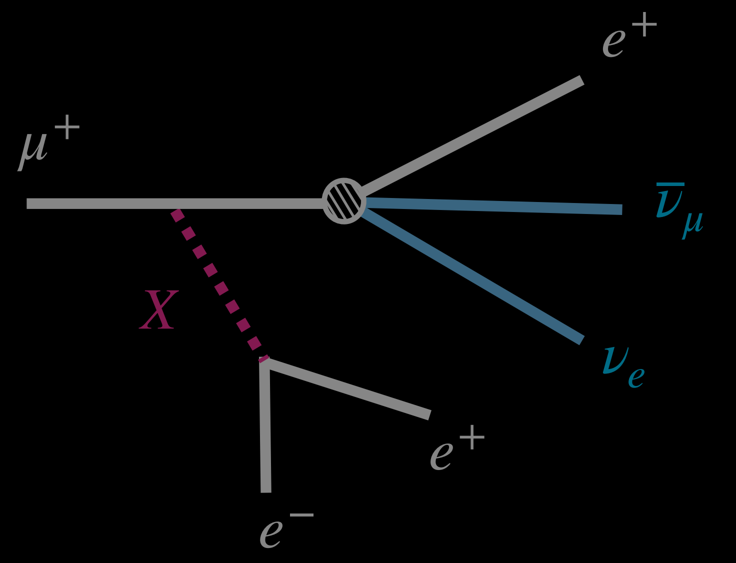

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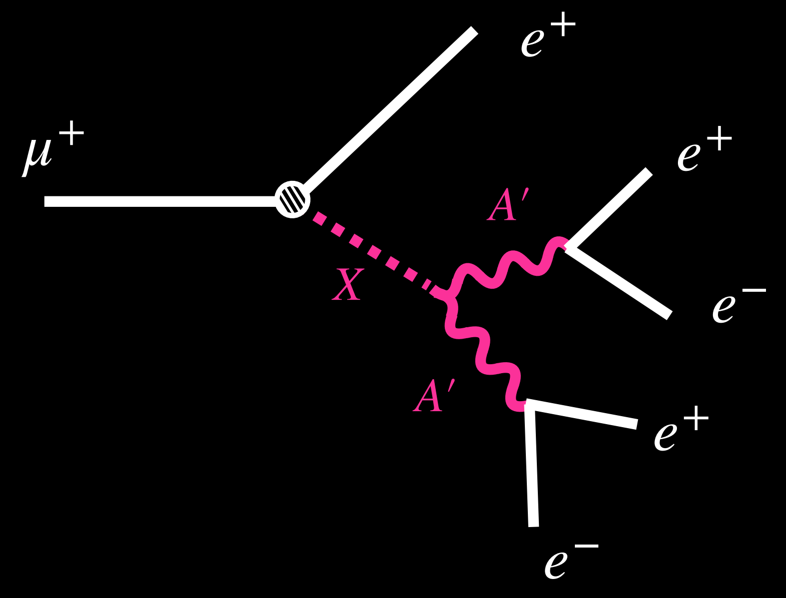

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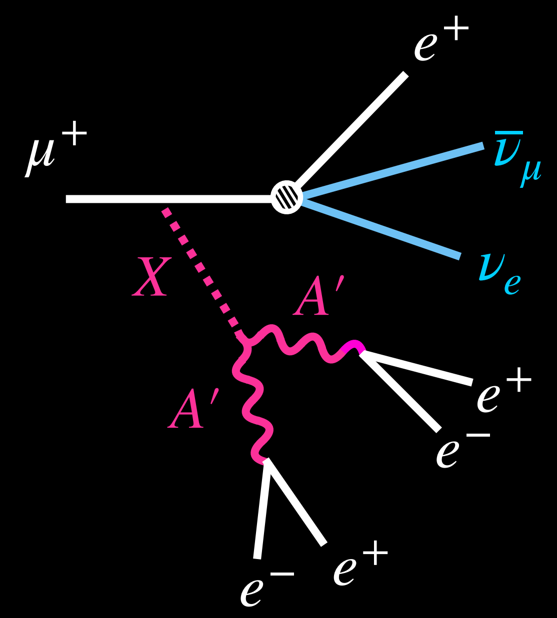

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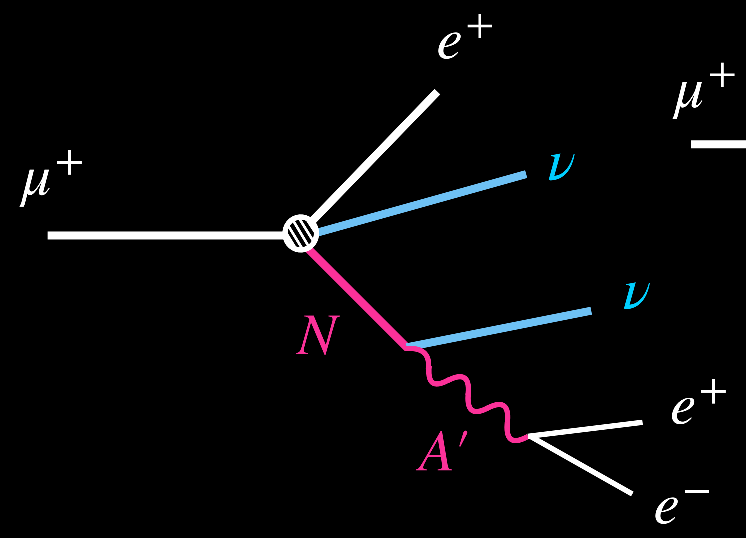

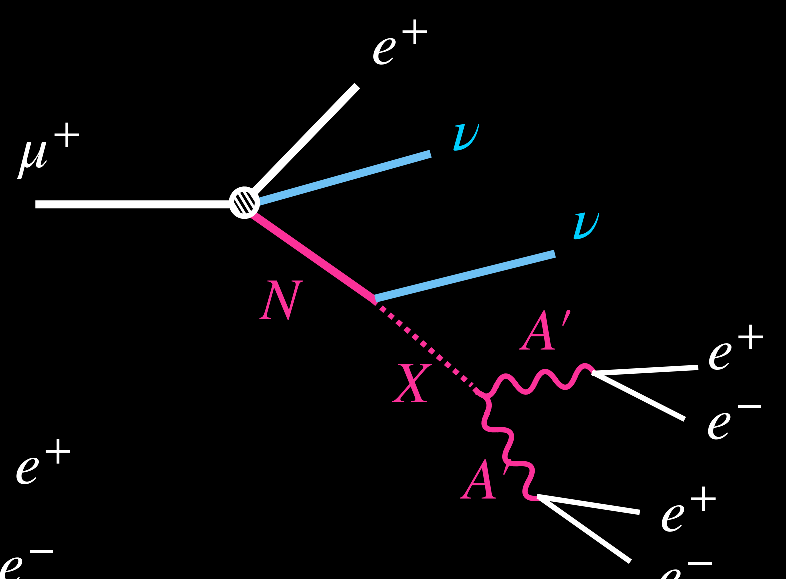

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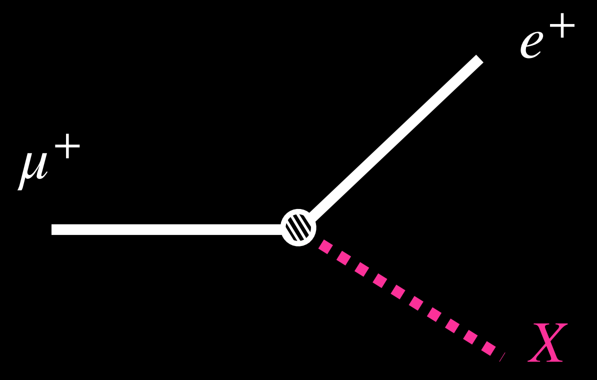

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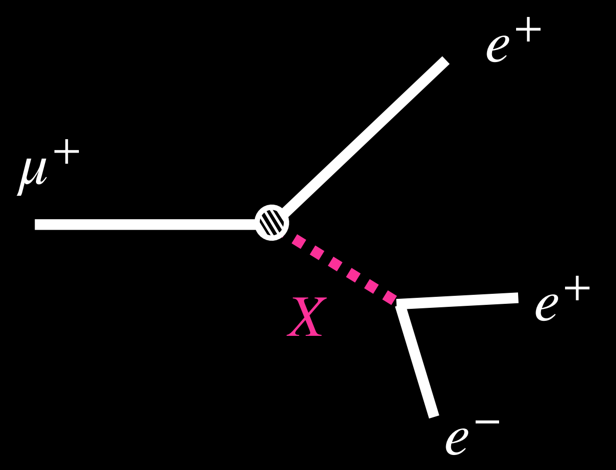

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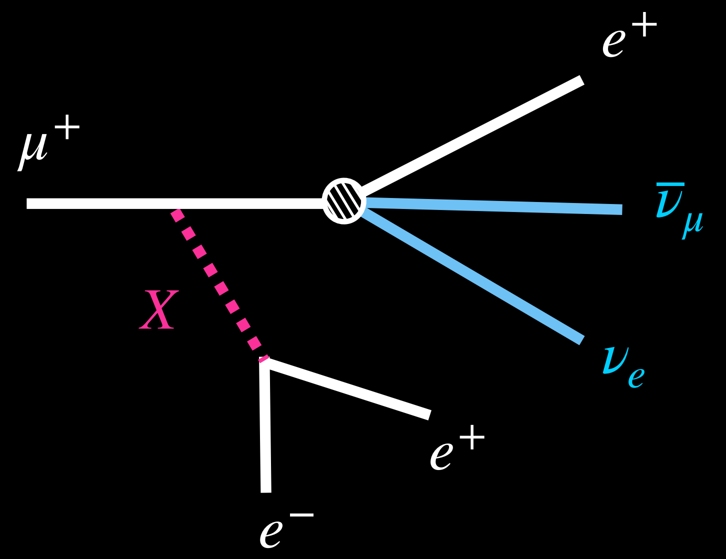

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Rare muon decays at Mu3e
Higgsed $U(1)_d$

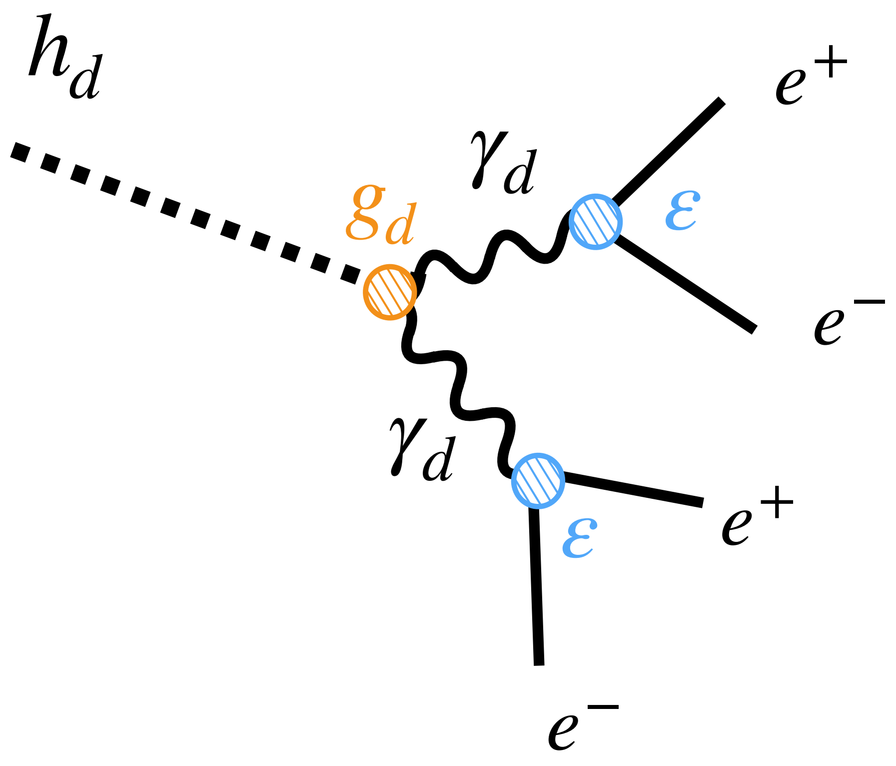
MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

Higgsed dark $U(1)_d$: dark photon (γ_d) gets a mass from the dark Higgs (h_d), and kinetically mixes with hypercharge:

$$\mathscr{L}_{\text{Kin}} \supset -\frac{\varepsilon}{2c_W} F^d_{\mu\nu} B^{\mu\nu}$$

If $m_{h_d} > 2m_{\gamma_d} > 4m_e$, dark Higgs decays to four leptons in cascades of 2-body decays.

Simple and well-motivated model — multiplication of leptons comes "for free."



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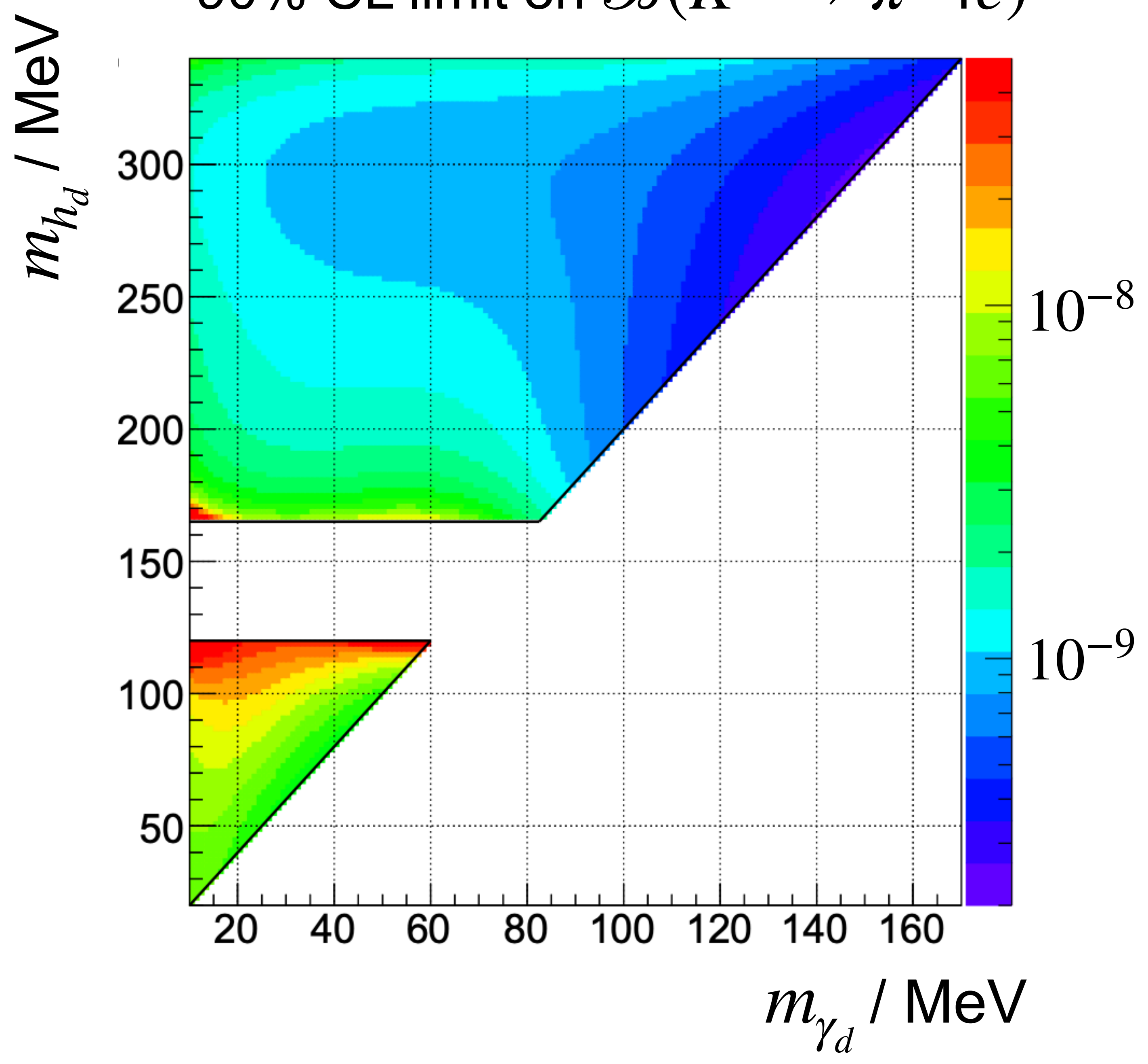
90% CL limit on $\mathscr{B}(K^+ \to \pi^+ 4e)$



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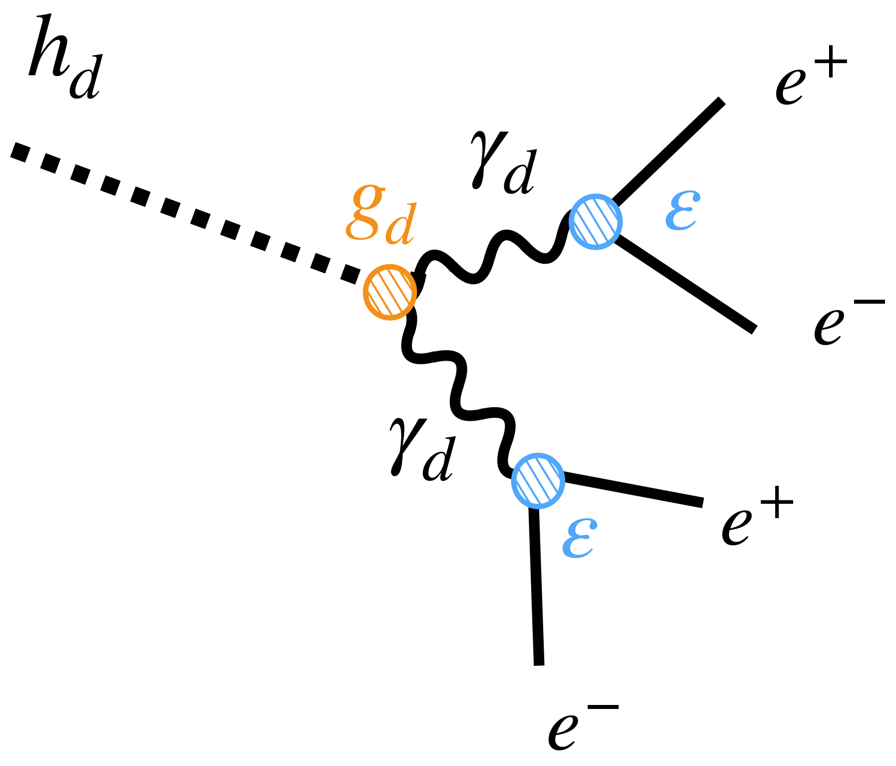
Searches at kaon, e+e- colliders, and LHC target the coupling of h_d with the Higgs and ε, which can be small.



How about potential couplings to leptons?

Recently targeted by a new five-track search at NA62.

$K^+ \to \pi^+(h_d \to \gamma_d \gamma_d \to 2(e^+e^-))$

MH, M. Pospelov, 10.1103/PhysRevD.105.015017
NA62 coll., 10.1016/j.physletb.2023.138193

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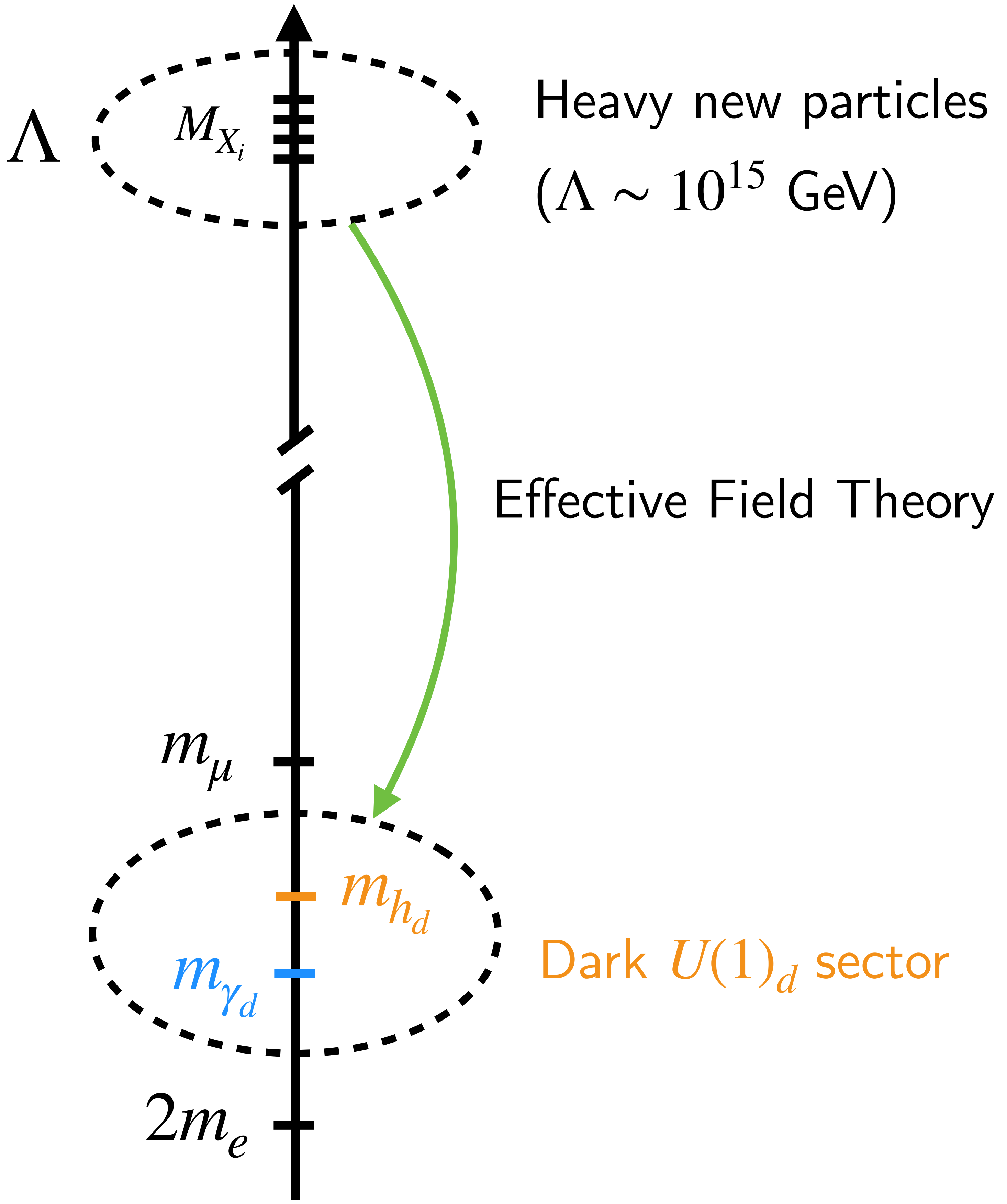


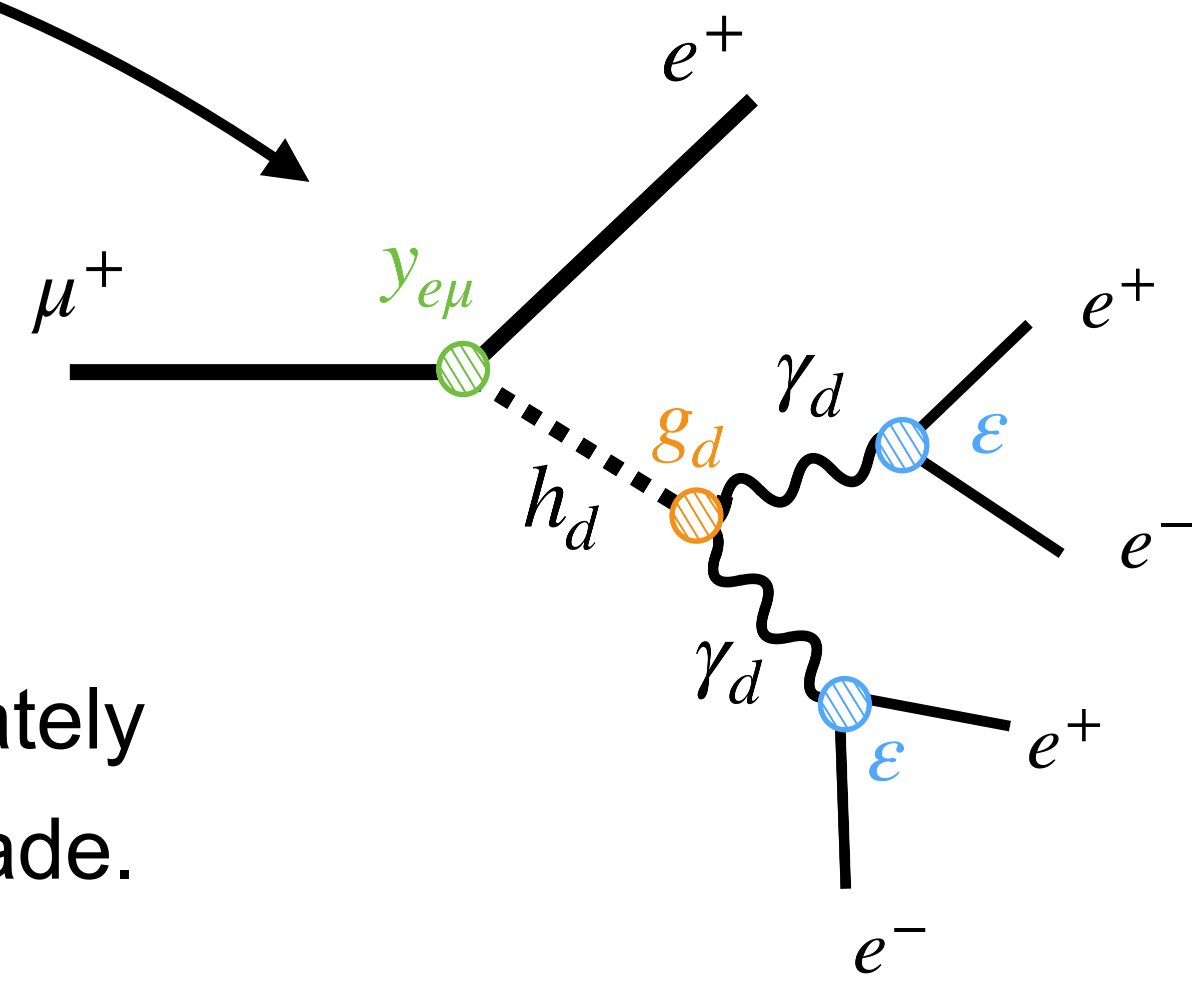
Lowest-dimension operators in the "h_d - EFT" that violate flavor*:

$$\mathscr{L}_{\text{cLFV}} \supset \frac{h_d}{\Lambda}\left(Y_{e\mu}\overline{L}_\mu H e_R + Y_{\mu e}\overline{L}_e H \mu_R\right) \xrightarrow{\cancel{\text{EW}}} h_d\left(y_{e\mu}\overline{\mu}_L e_R + y_{\mu e}\overline{e}_L \mu_R\right), \qquad y_{e\mu} = \frac{Y_{e\mu} v_{\text{EW}}}{\sqrt{2}\Lambda}$$

In mass basis, SM Higgs continues to have diagonal couplings, but **dark Higgs** does not.

If $m_\mu - m_e > m_{h_d} > 2m_{\gamma_d} > 4m_e$:

Muon decays via a 2-body process $\mu^+ \to e h_d$, ultimately leading to a total of five tracks at the end of the cascade.



* Dimension 5 or 6, depending on the lepton charge under $U(1)_d$.

Rare muon decays at Mu3e
Mu3e at PSI

Aiming for $\mathscr{B}(\mu^+ \to e^+e^+e^-) < 10^{-16}$

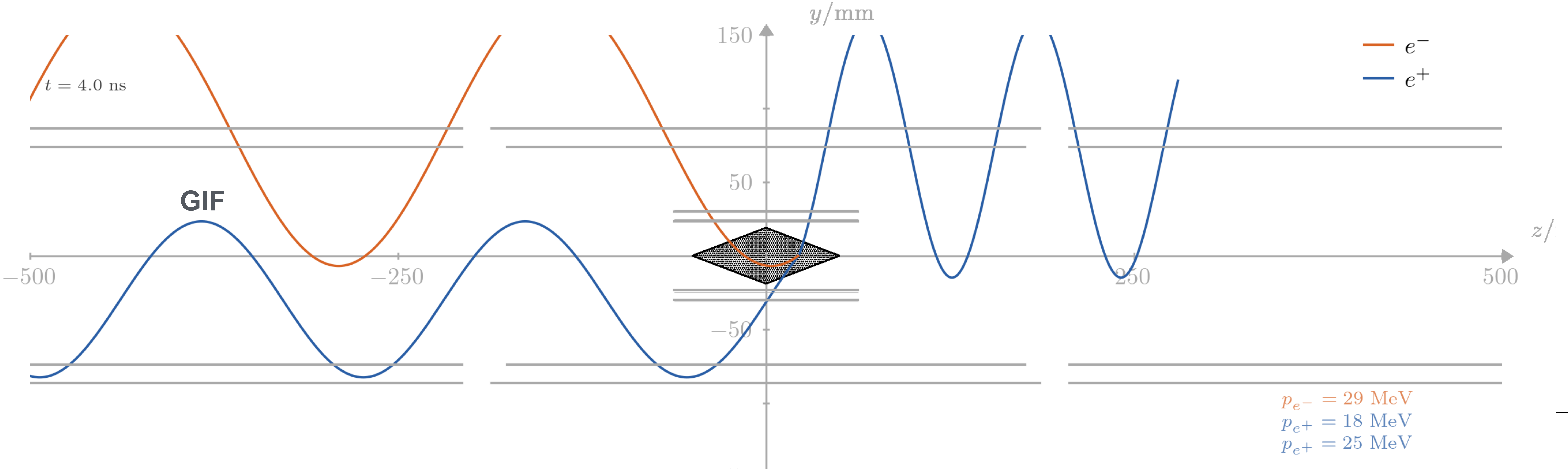
(4 orders of magnitude improvement on current limits).

Phase-I: $\gtrsim 2 \times 10^{15}$ μ^+ decays

Phase-II: $\gtrsim 5 \times 10^{16}$ μ^+ decays

1) About 10^8 muons/s from 2.4 mA proton beam,
2) Low pion contamination, $< 2 \times 10^{-7}$ fraction,
3) Each layer has about $\sim 0.1\%$ radiation length.
4) B = 1 T magnetic field

30 MeV **electrons and positrons** spread by about 2°
in $1\,\%$ of radiation length due to multiple scattering.



Rare muon decays at Mu3e
A theorist's fast MC for the detector

MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

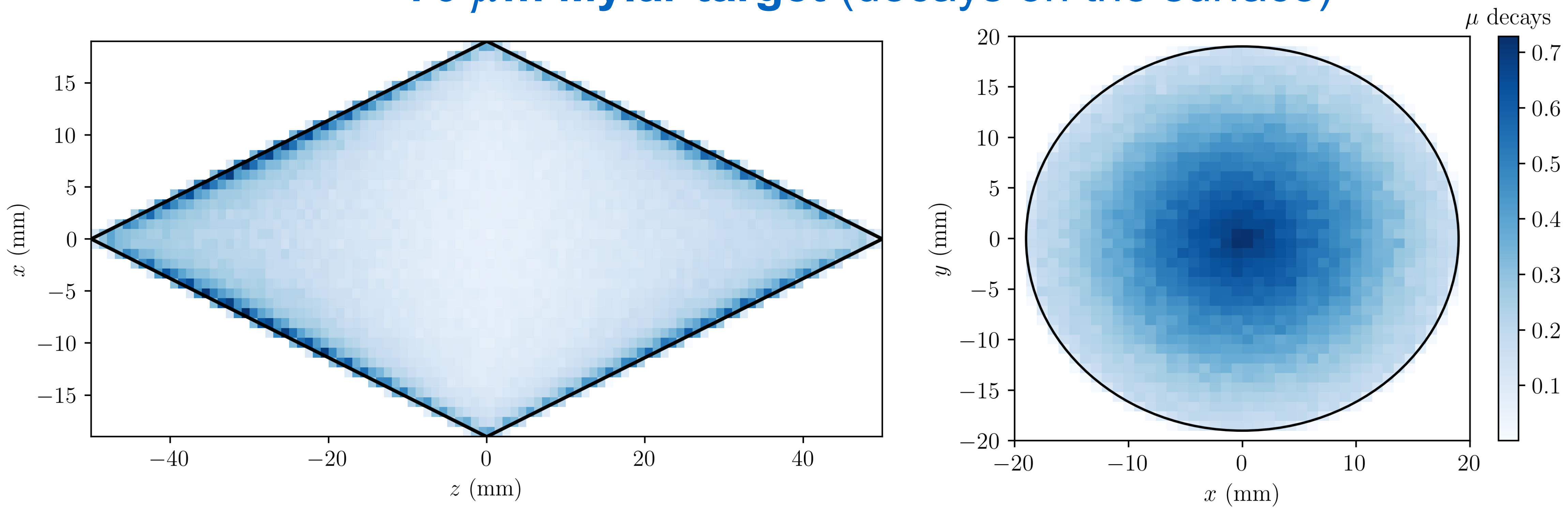
1) Generating muon decays with MadGraph5 v3.5.0 and Scikit-HEP phase-space package. (neglecting polarization).

2) Place muons on surface of Mylar target following TDR*.

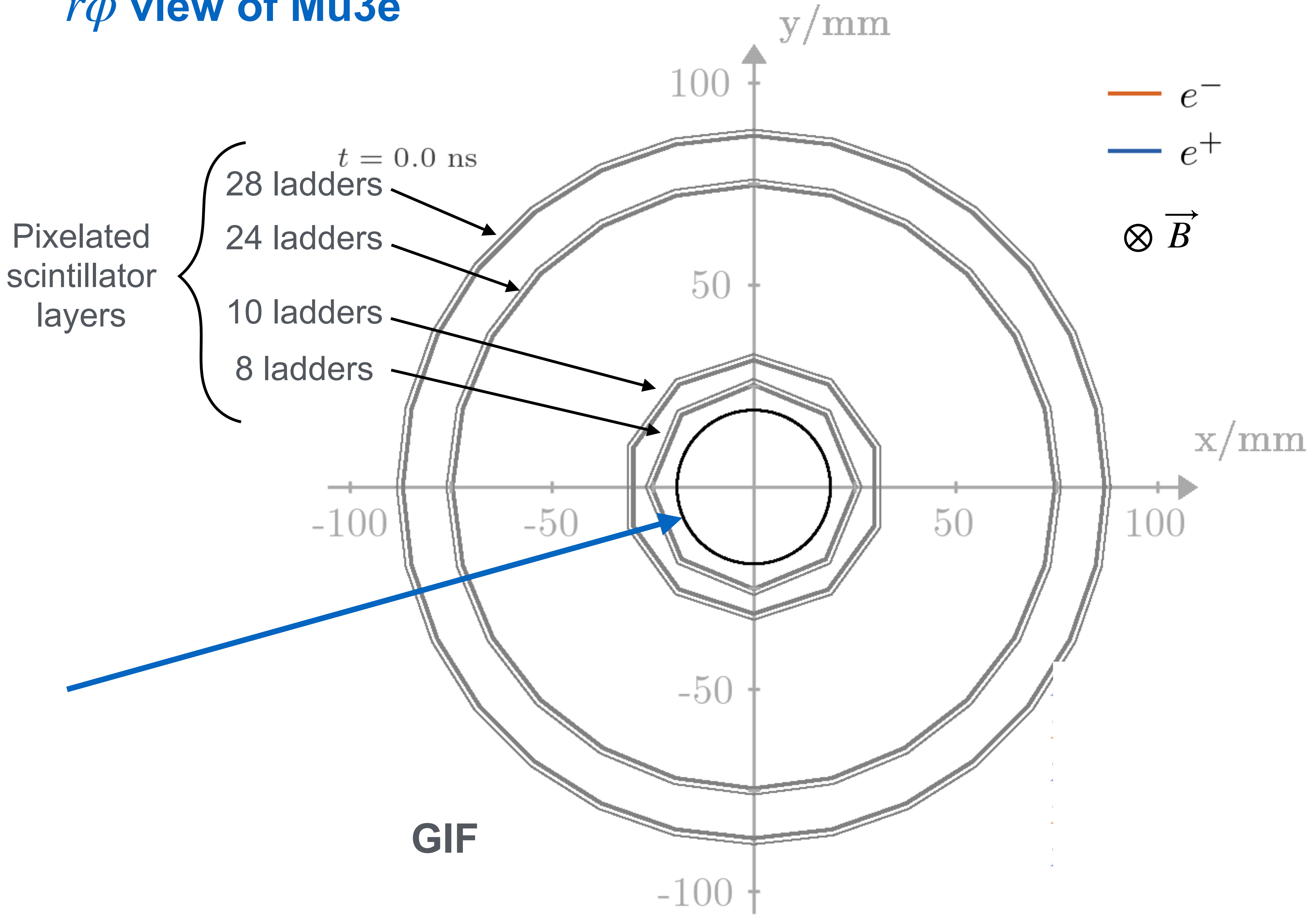
3) Draw helices based (B = 1 T), smearing momentum with energy-dependent Gaussians of TDR.

4) Signal selection based on # of hits on scintillator layers.

70 μm Mylar target (decays on the surface)



$r\phi$ view of Mu3e



* TDR: Technical design of the phase I Mu3e experiment arXiv:2009.11690

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MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

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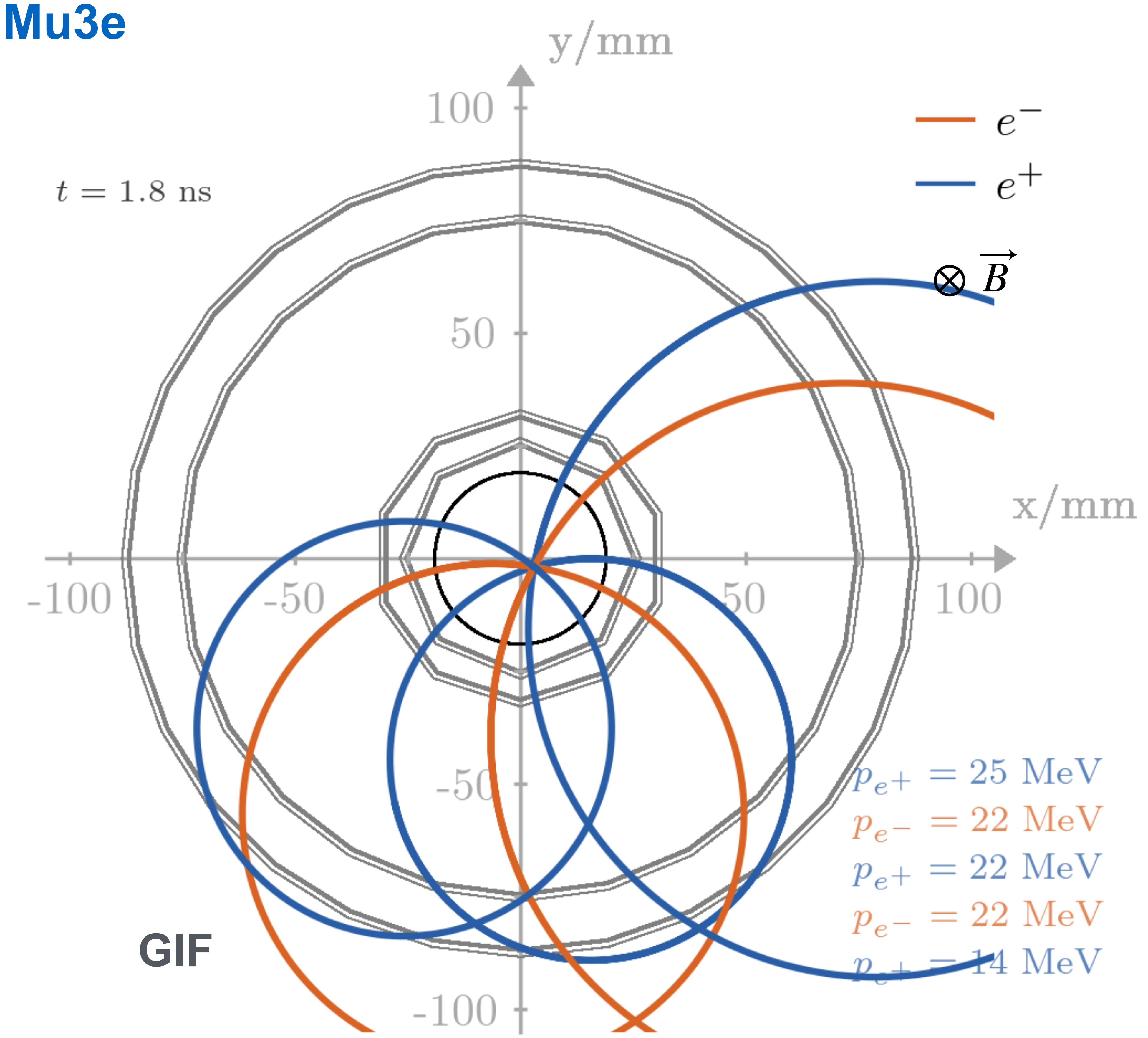
2) Place muons on surface of Mylar target following TDR*.

3) Draw helices based (B = 1 T), smearing momentum with energy-dependent Gaussians of TDR.

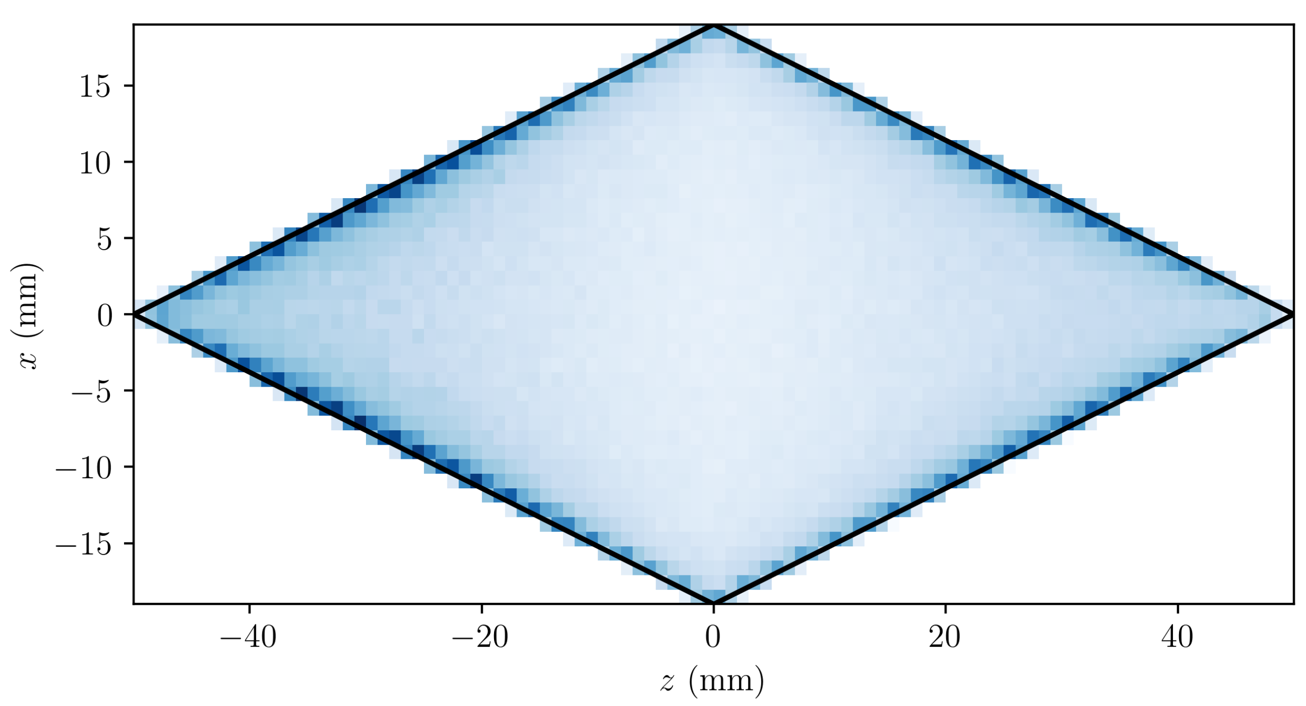
4) Signal selection based on # of hits on scintillator layers.

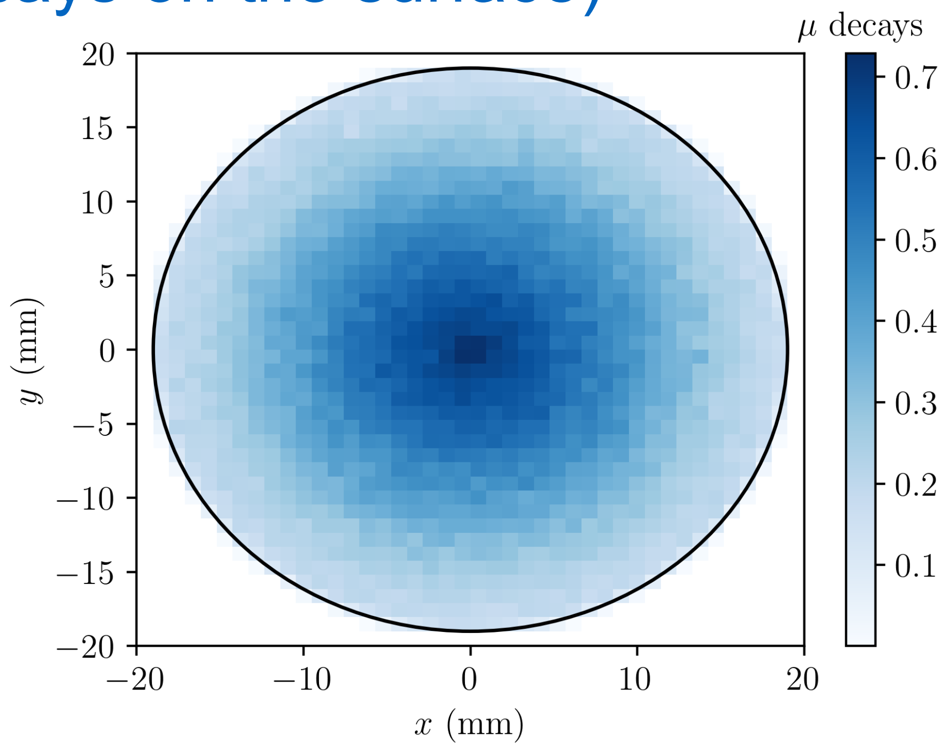
$r\phi$ view of Mu3e



GIF

70 μm Mylar target (decays on the surface)





* TDR: Technical design of the phase I Mu3e experiment arXiv:2009.11690

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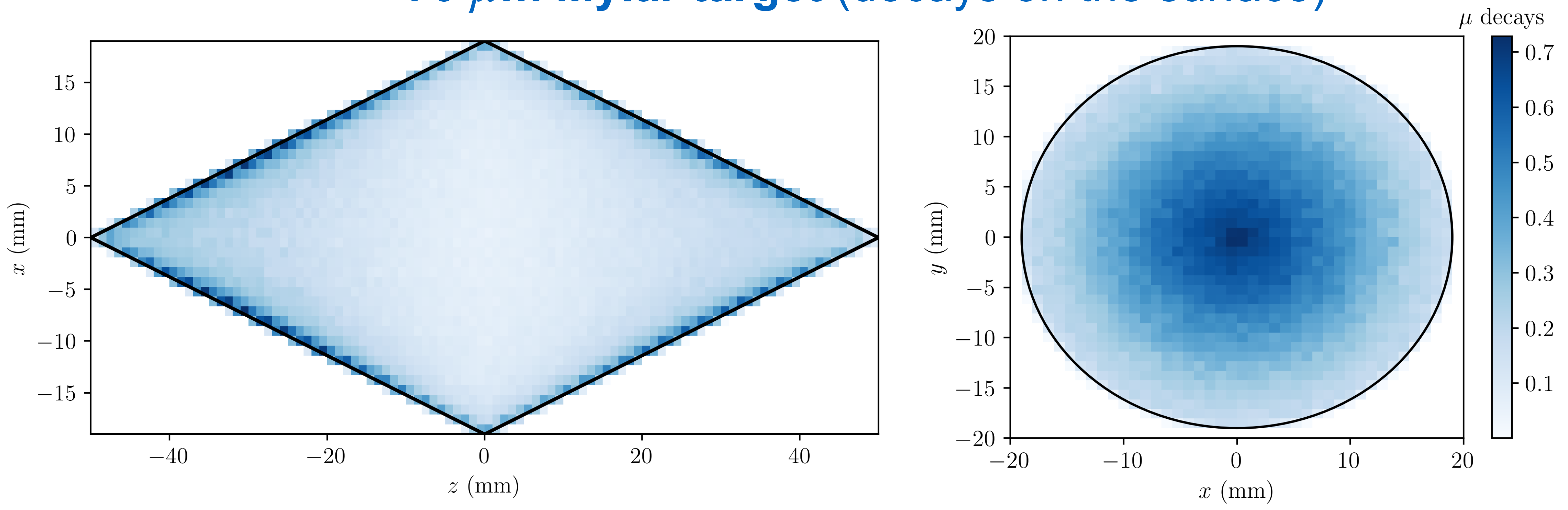

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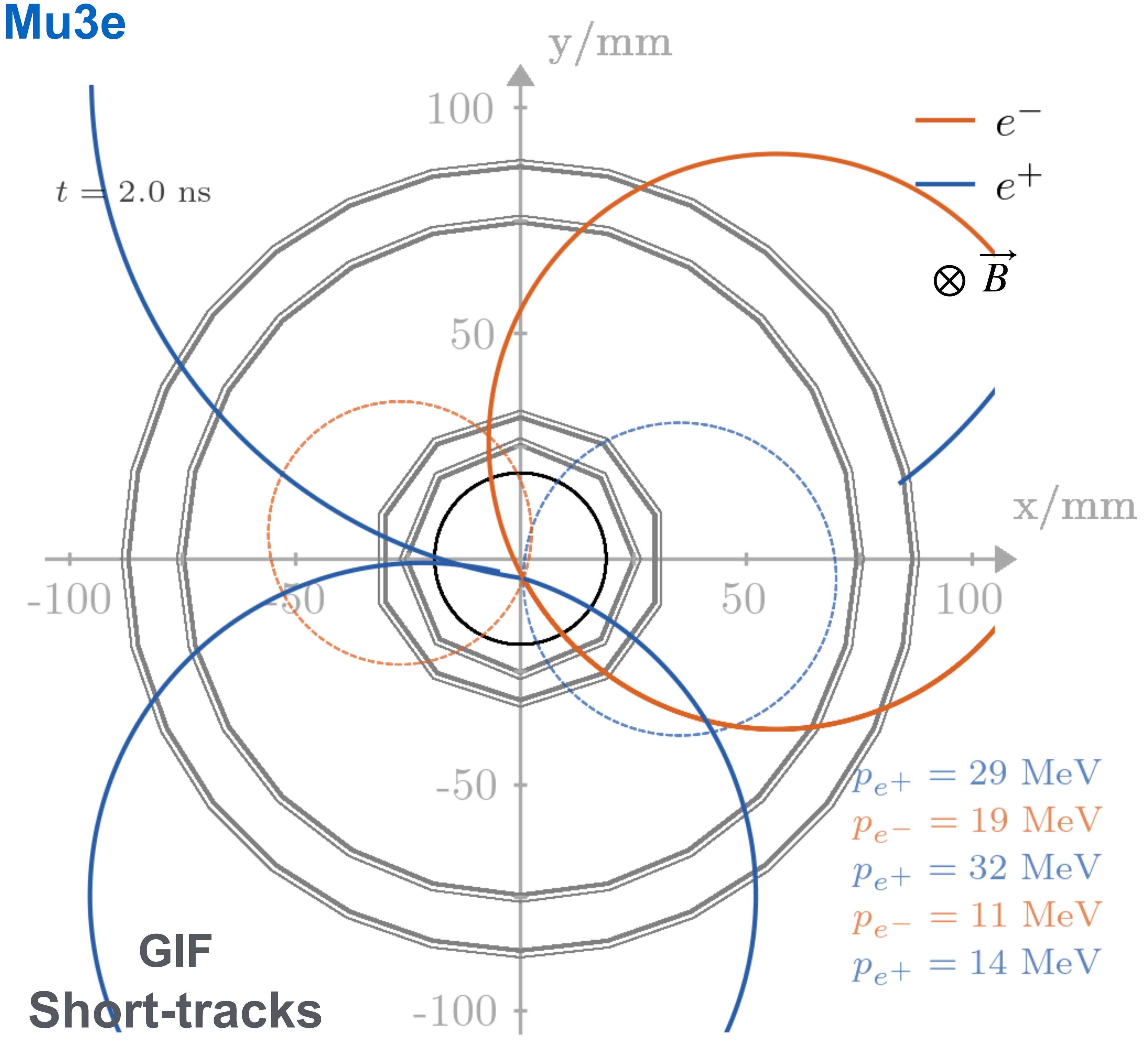

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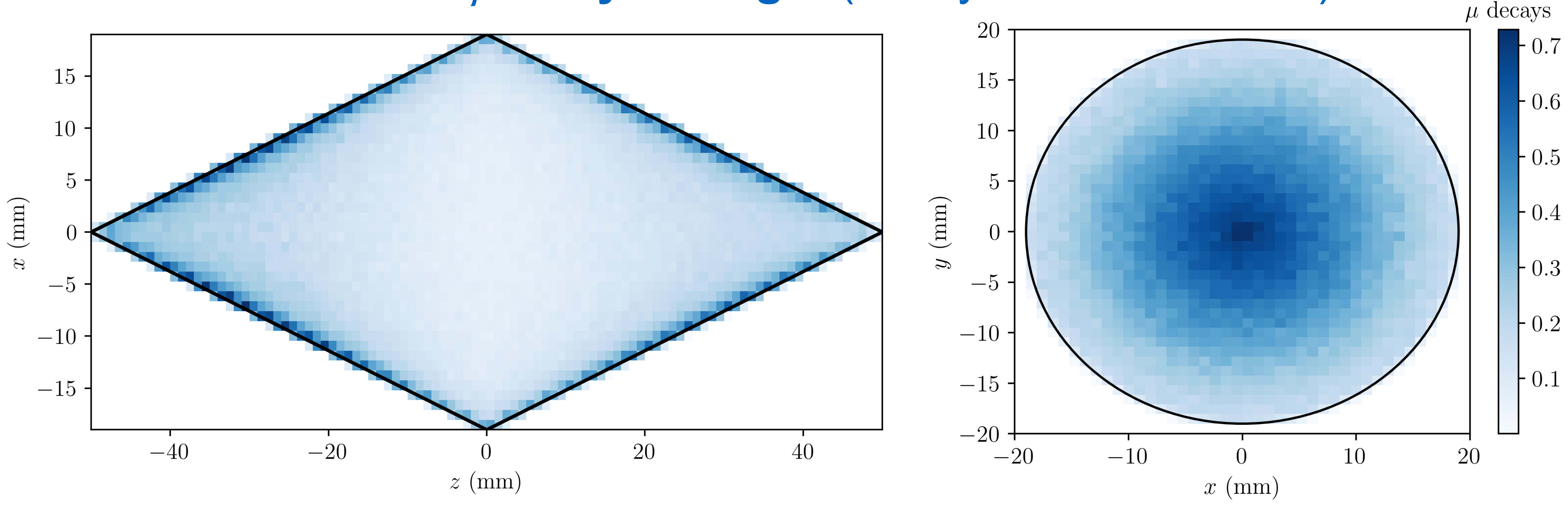

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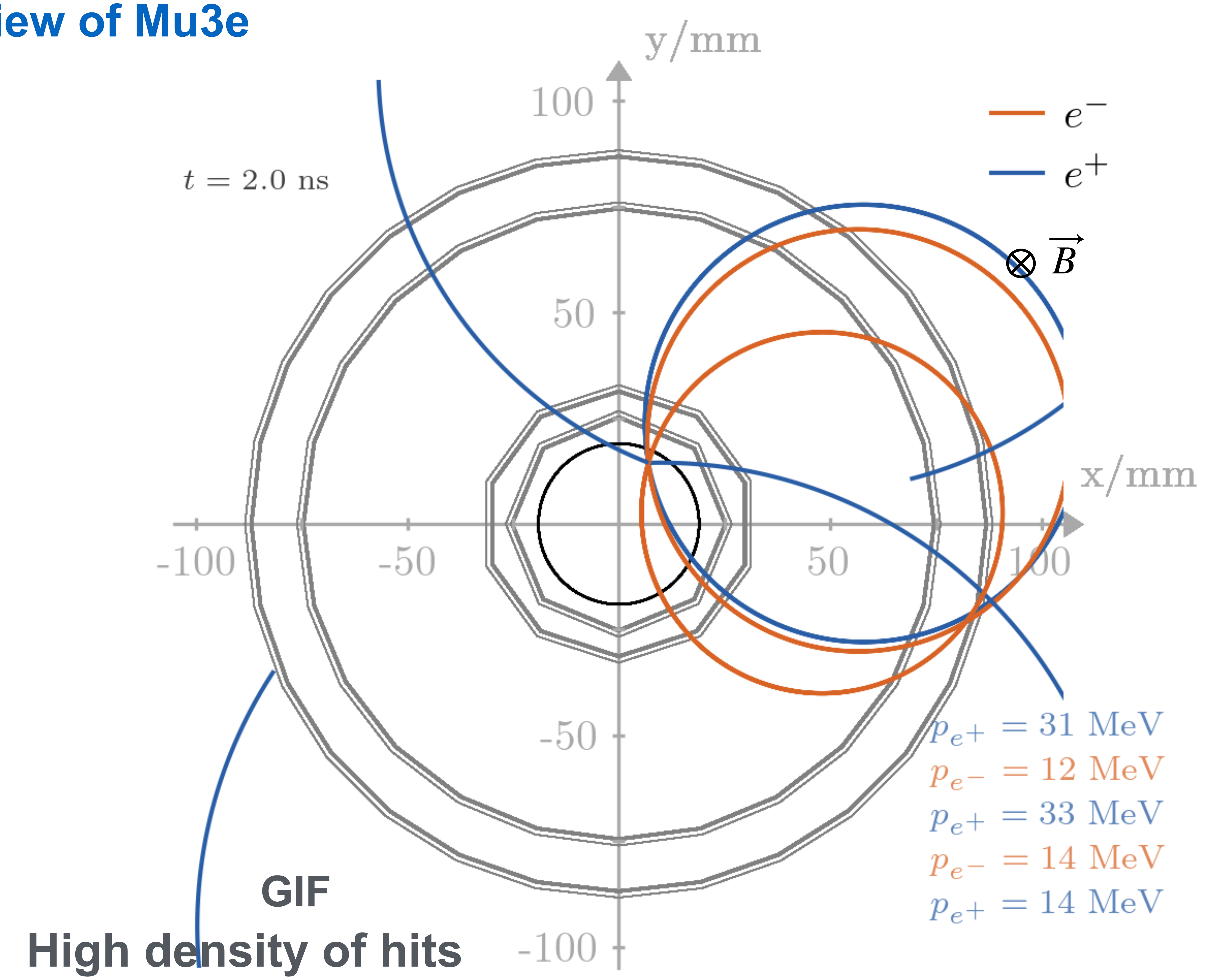

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The Standard Model rate

MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

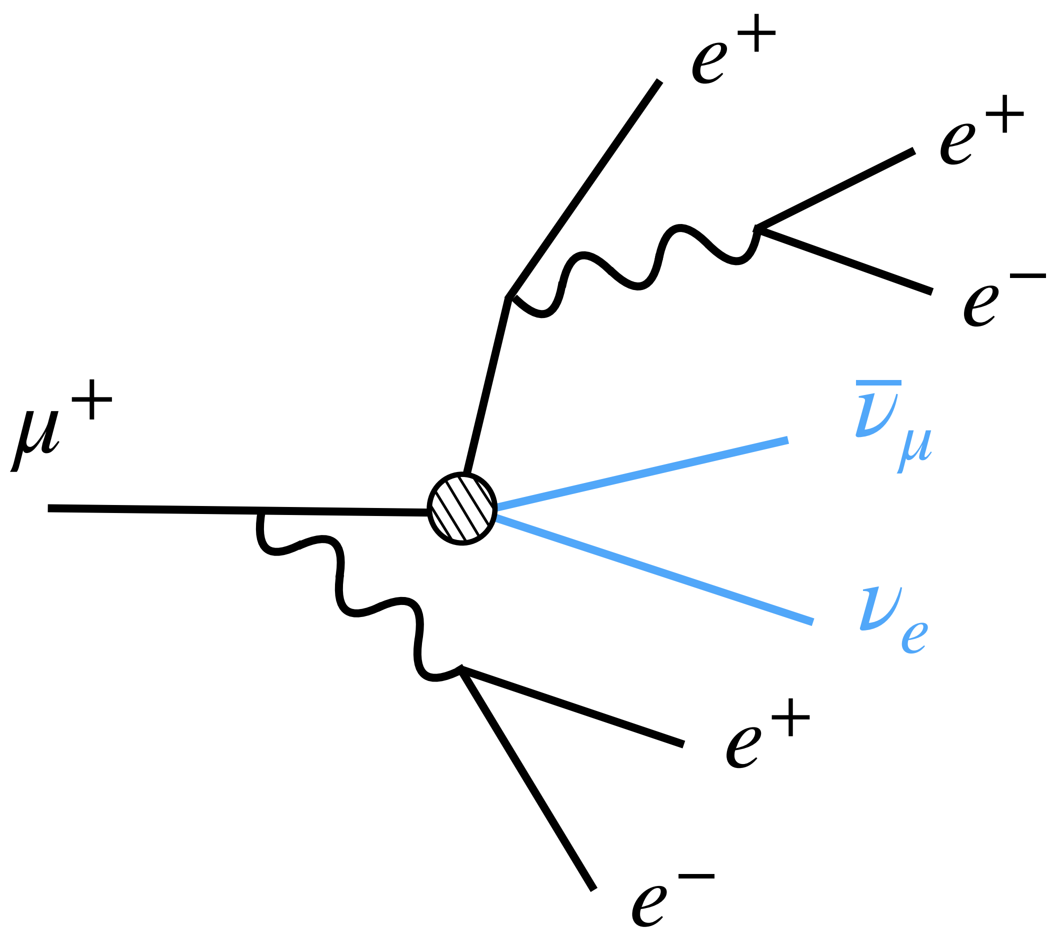
From $\mathrm{MadGraph5\ v3.5.0}$, we can calculate the total rate:

Leading order in G_F and α — negligible MC stats error

$$\mathscr{B}(\mu^+ \to e^+e^+e^-e^+e^-\nu\nu) \simeq 3.9 \times 10^{-10},$$

but this is not all observable. Some simple truth-level cuts illustrate the challenge:

$$\mathscr{B}\left(\mu^+ \to e^+e^+e^-e^+e^-\nu\nu \,|\, \mathrm{all}\, p_{e^\pm}^{\mathrm{T,true}} > 10\,\mathrm{MeV}\right) = (1.4 \pm 0.1) \times 10^{-14}.$$



1 of 84 diagrams

The smallest decay rate measurement for fundamental particles involving 2nd and 3rd generation?

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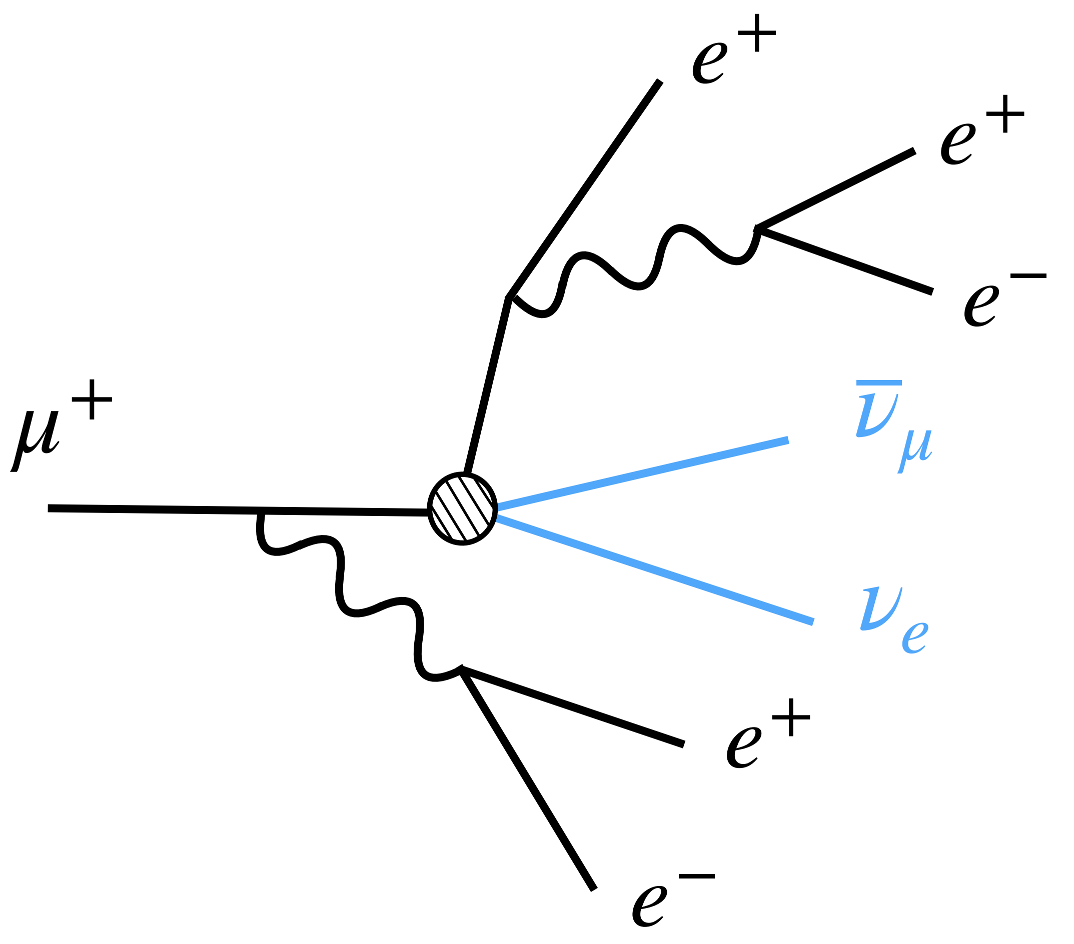


1 of 84 diagrams

The smallest decay rate measurement for fundamental particles involving 2nd and 3rd generation?

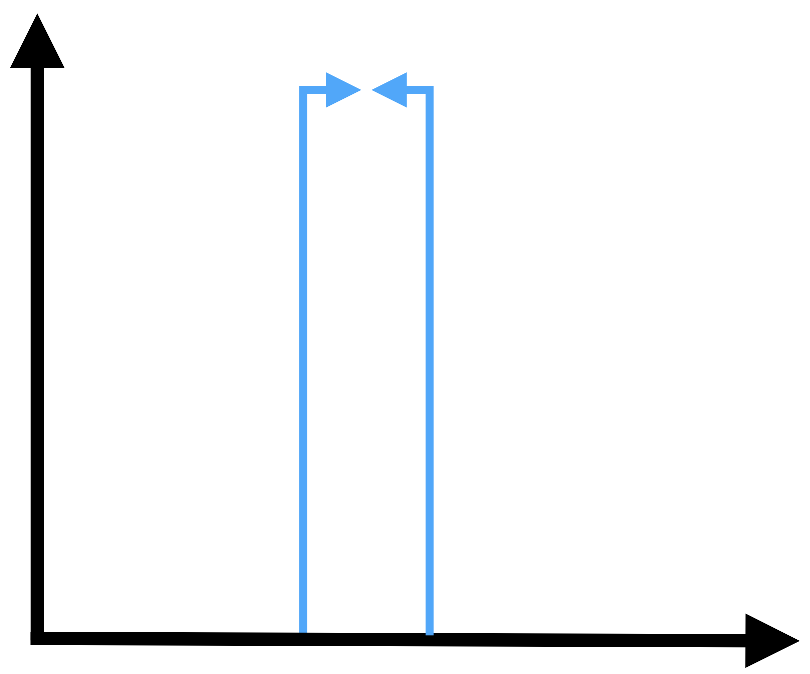
When looking for neutrino-less channels, this SM rate will not be an issue. Missing energy cuts are very effective:

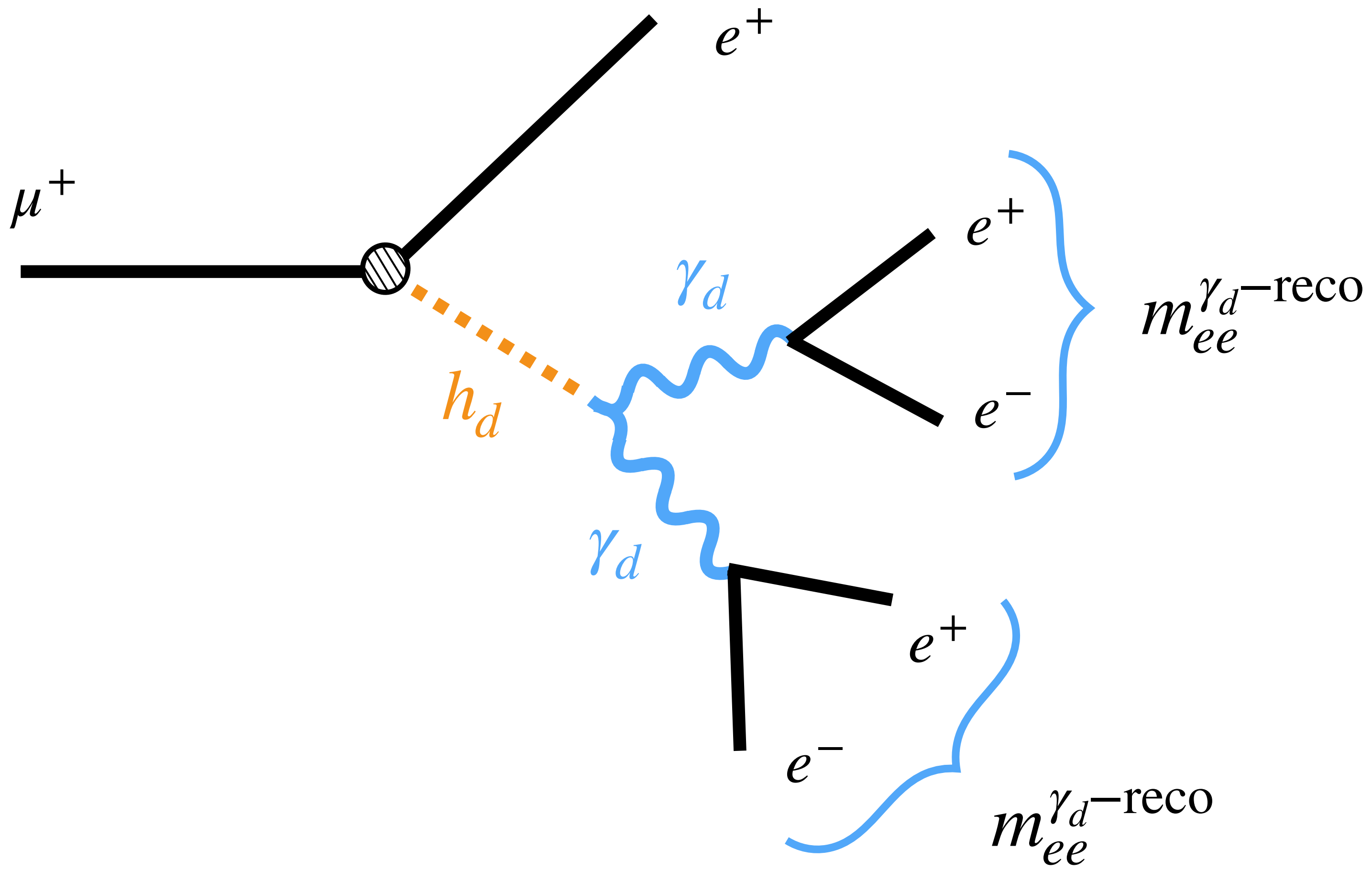
$$\mathscr{B}\left(\mu^+ \to e^+e^+e^-e^+e^-\nu\nu \,|\, E_{\mathrm{missing}}^{\mathrm{true}} < 20\ \mathrm{MeV}\right) = (8.9 \pm 0.3) \times 10^{-14}$$
$$\mathscr{B}\left(\mu^+ \to e^+e^+e^-e^+e^-\nu\nu \,|\, E_{\mathrm{missing}}^{\mathrm{true}} < 10\ \mathrm{MeV}\right) = (1.1 \pm 0.2) \times 10^{-15}$$

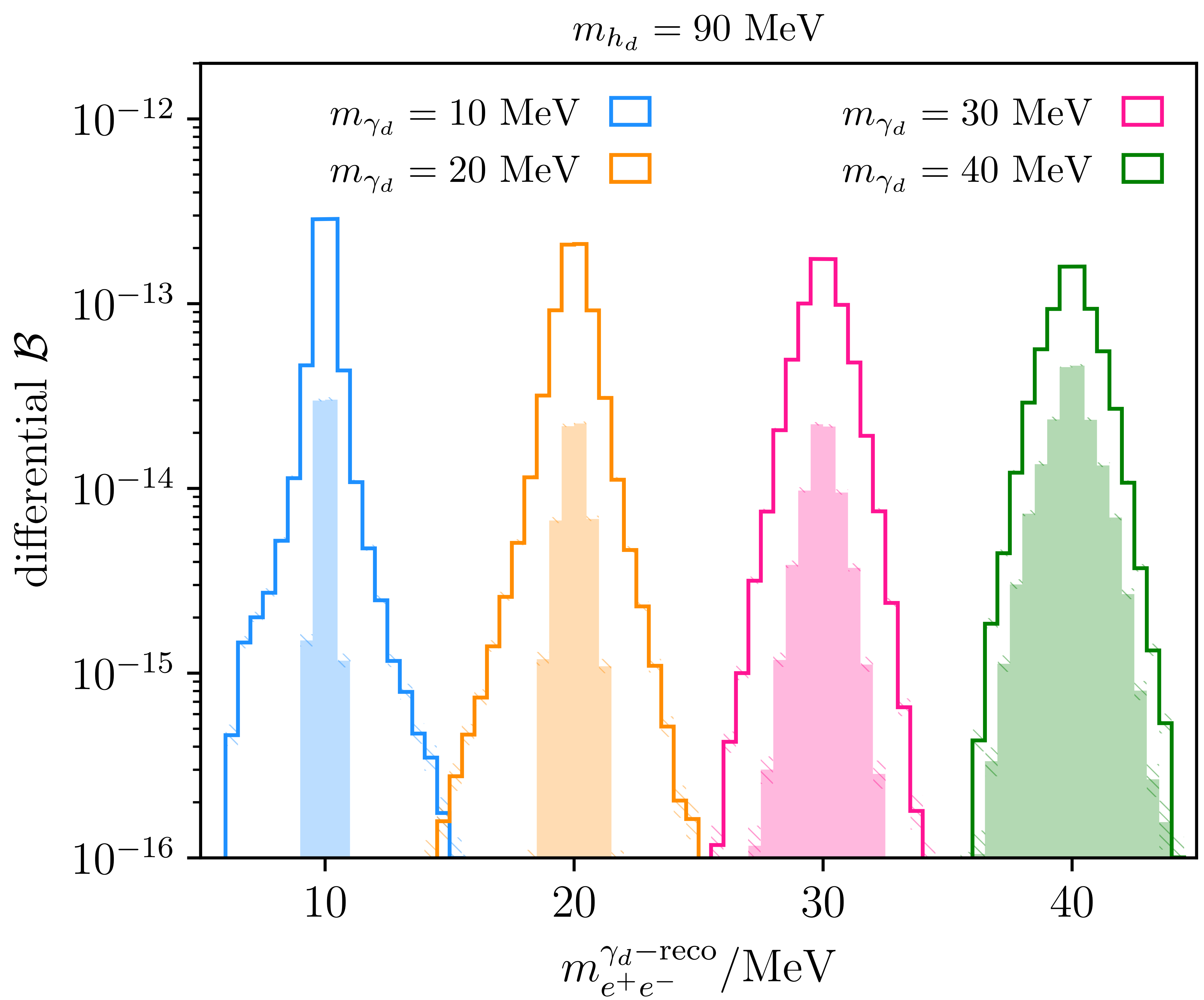
Rare muon decays at Mu3e
Neutrinoless five-track events

MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

Double bump hunt







We find: $\sigma_{m_{\gamma_d}}/m_{\gamma_d} = 2.3\%$

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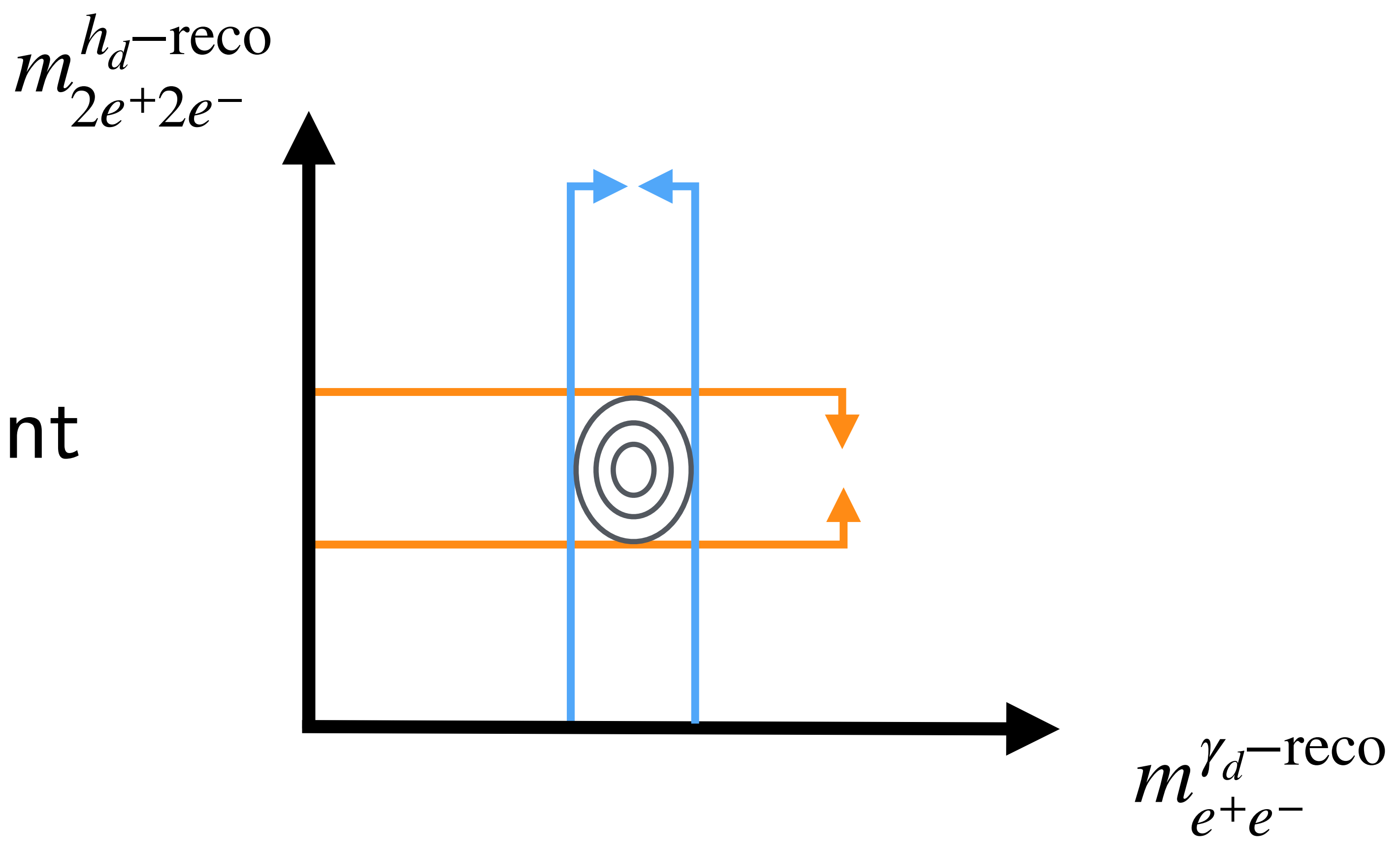
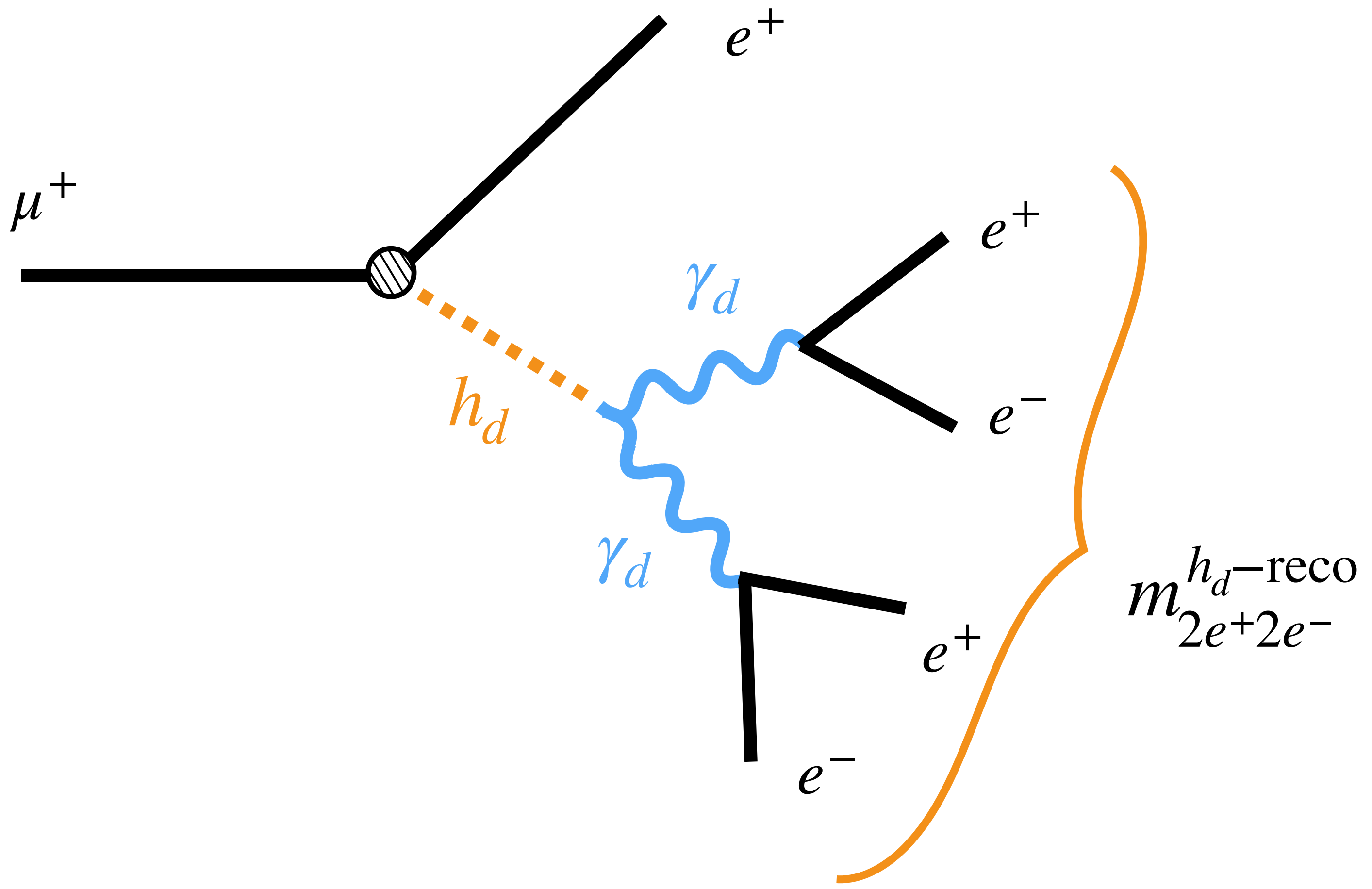
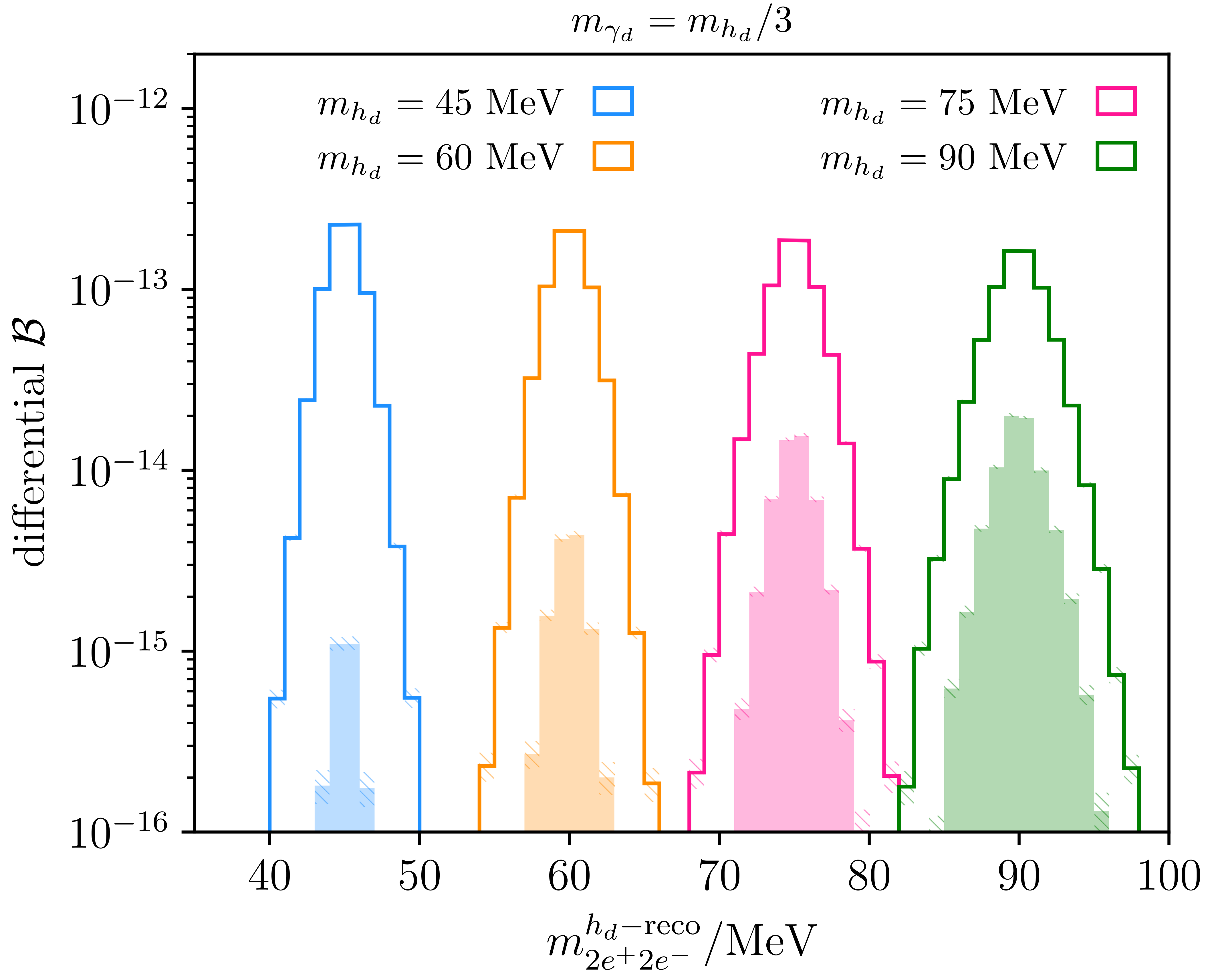




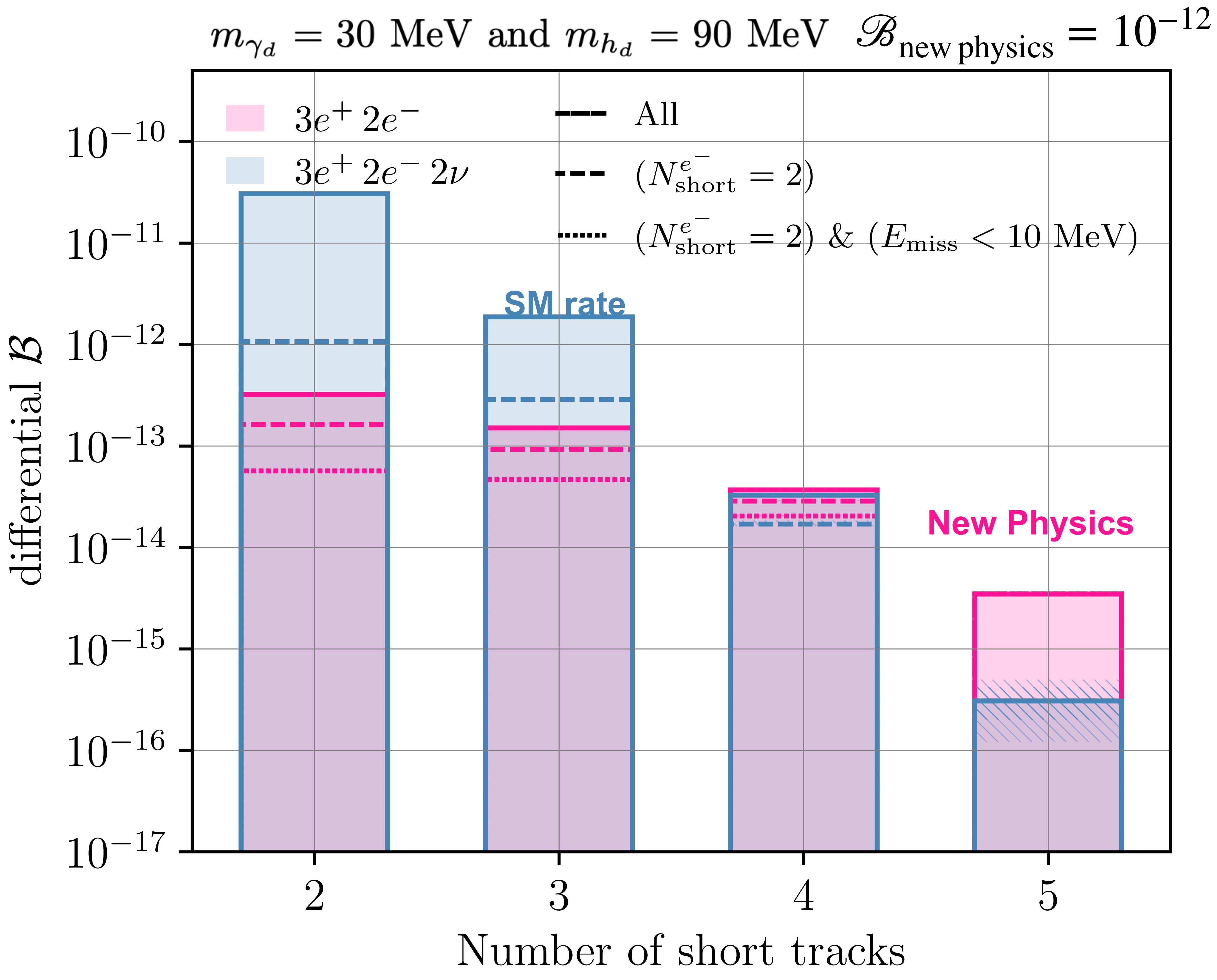


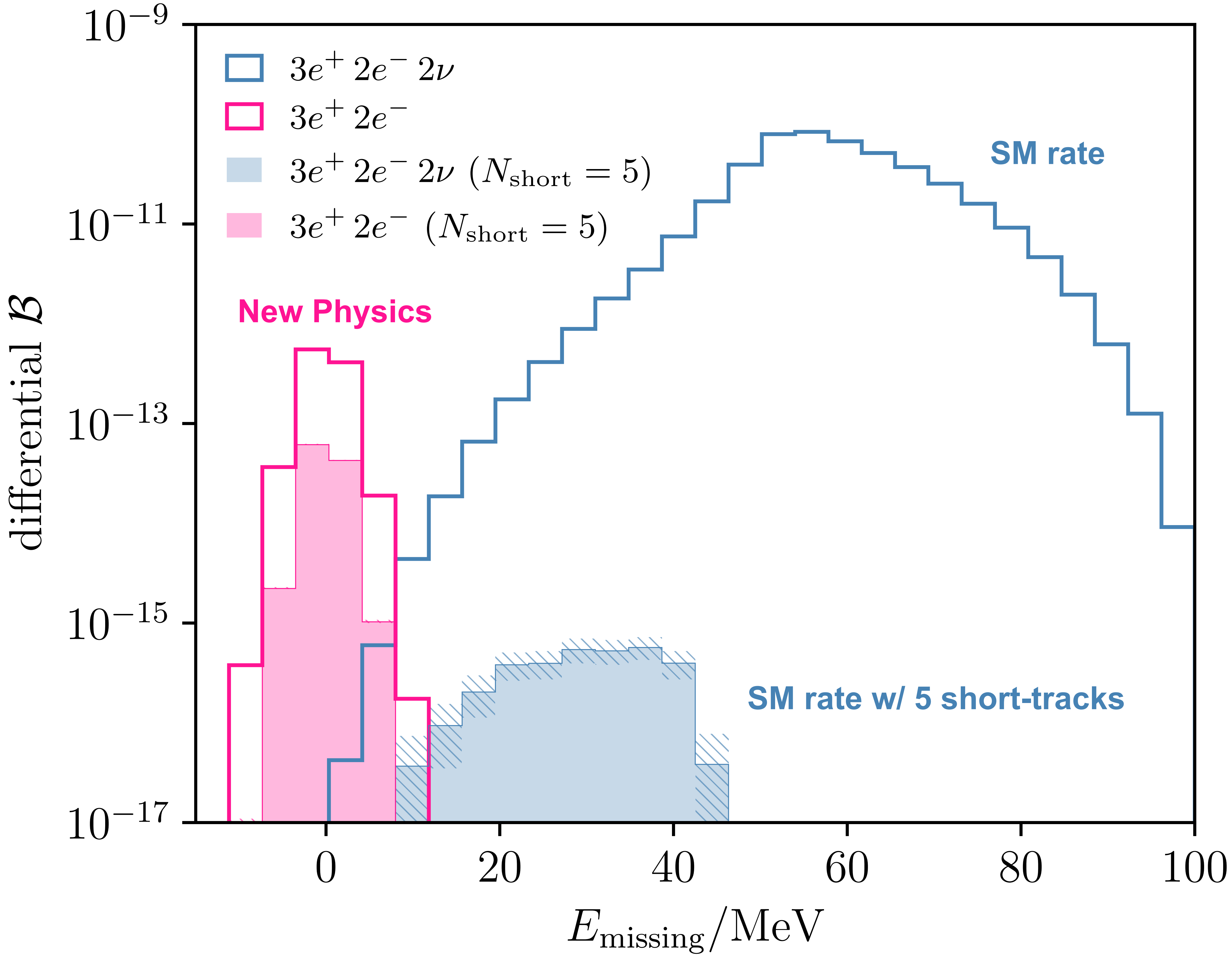
We find: $\sigma_{m_{\gamma_d}}/m_{\gamma_d} = 2.3\%$ and $\sigma_{m_{h_d}}/m_{h_d} = 1.5\%$

Rare muon decays at Mu3e
Signal selection for new physics

MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

Short-tracks: ≥ 4 hits





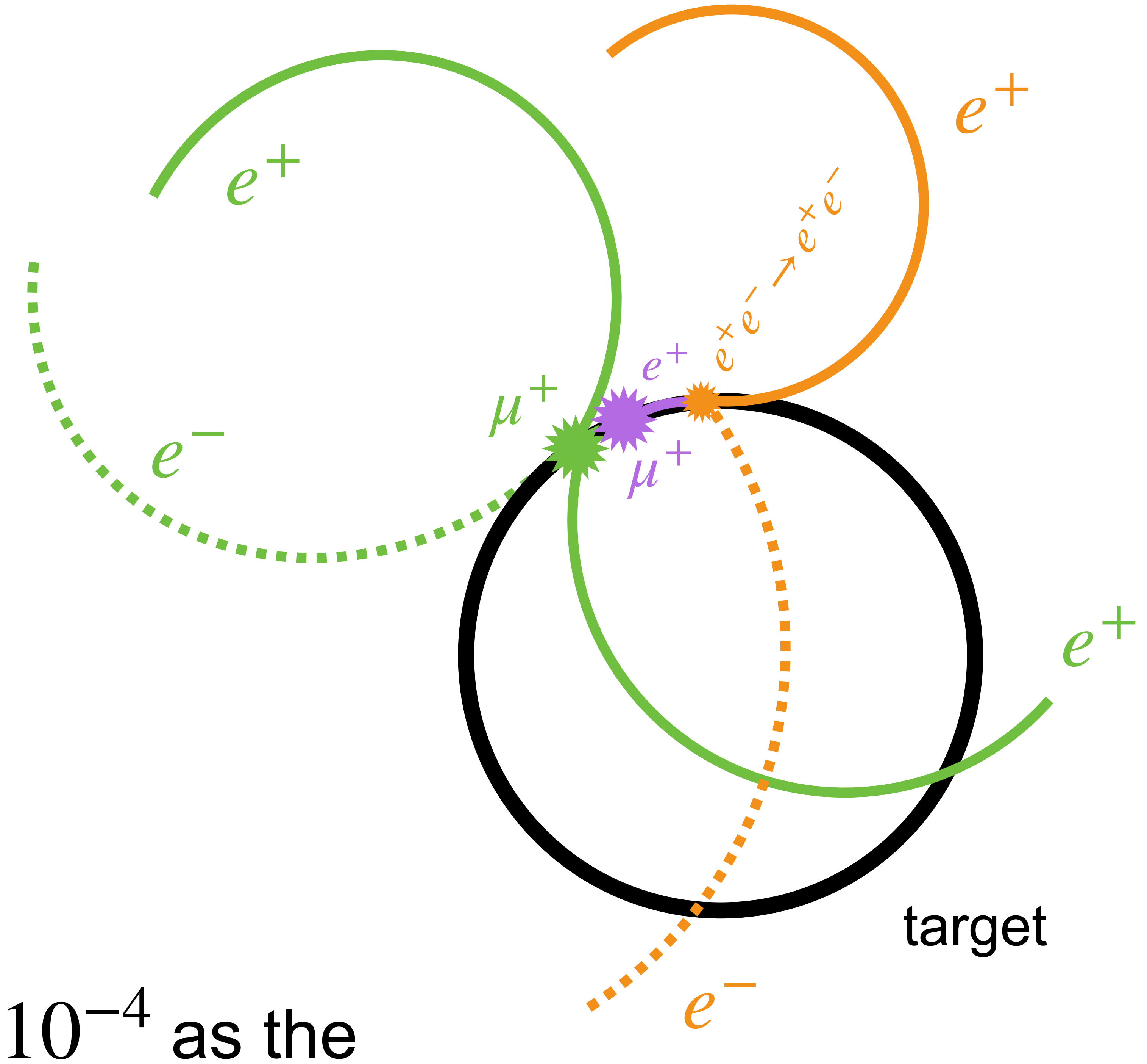
Rare muon decays at Mu3e
Backgrounds

MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

Five-track SM decay is not going to be a show-stopper.

The most worrisome backgrounds, however, will arise from **accidentals.**

- $\mu^+ \to e^+ e^+ e^- \nu\nu$ in coincidence with $\mu^+ \to e^+ \nu\nu$, where one of the positrons produces a Bhabha electron.



Before any kinematical cuts, we estimate this rate to be around

3 out of 10^{12} muon decays

with a stopped muon rate of 10^8 μ/s. This assumes a constant $P_{\text{Bhabha}} \sim 10^{-4}$ as the probability for an observable Bhabha scattered e^+e^- pair given a e^+ from within the target.

Further experimental studies are needed, but a background-free search may be possible.

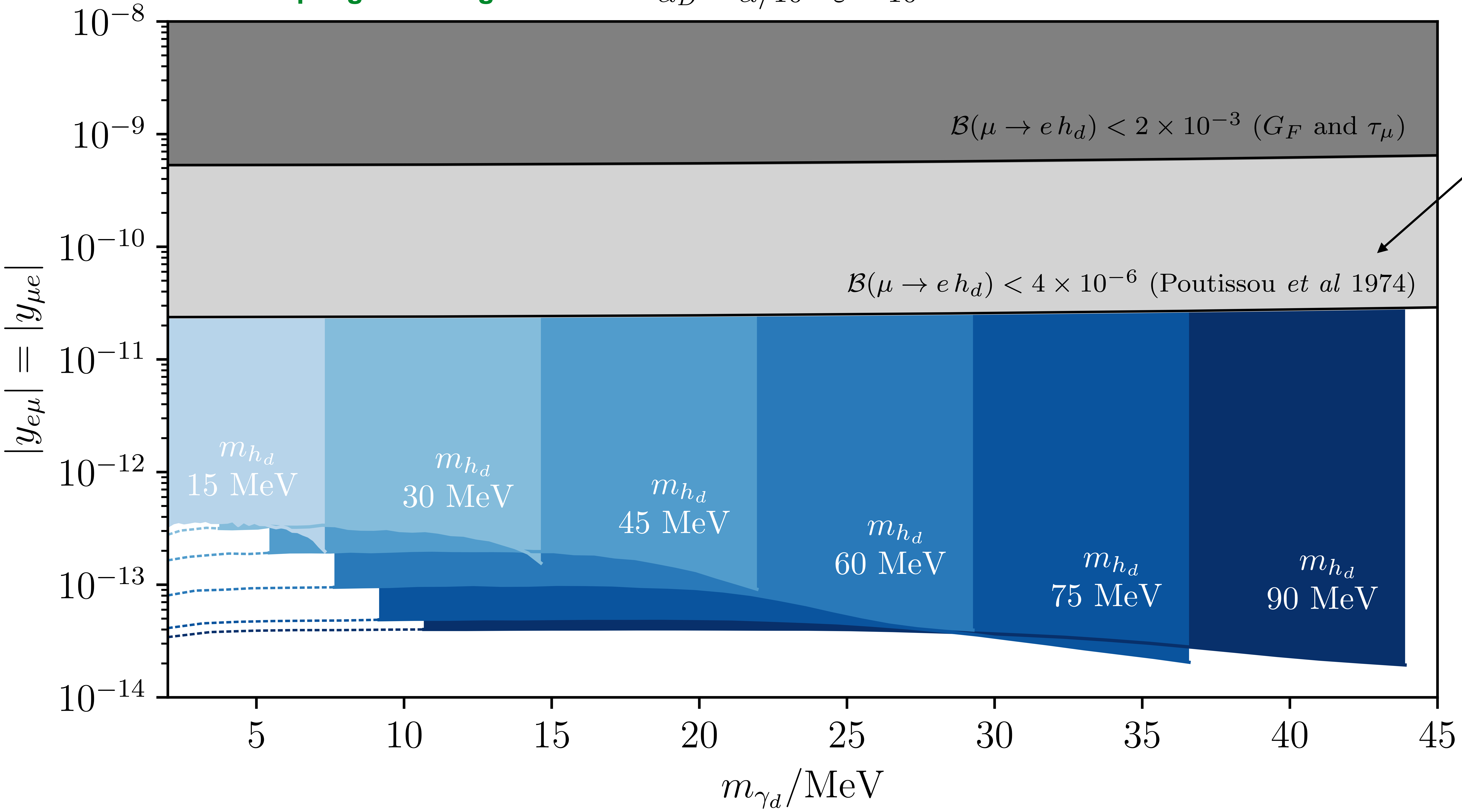
It would also be interesting to investigate four-track events with only 2(e^-e^+).

Rare muon decays @ Mu3e

$U(1)_X$ with charged Lepton Flavor Violation

MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

With sampling from target surface: $\alpha_D = \alpha/10 \quad \varepsilon = 10^{-4}$



Calorimetric search for $E_{\text{vis}} \simeq m_\mu$
(see D. Bryman's talk tomorrow.)

Conservatively showing corresponding reach of

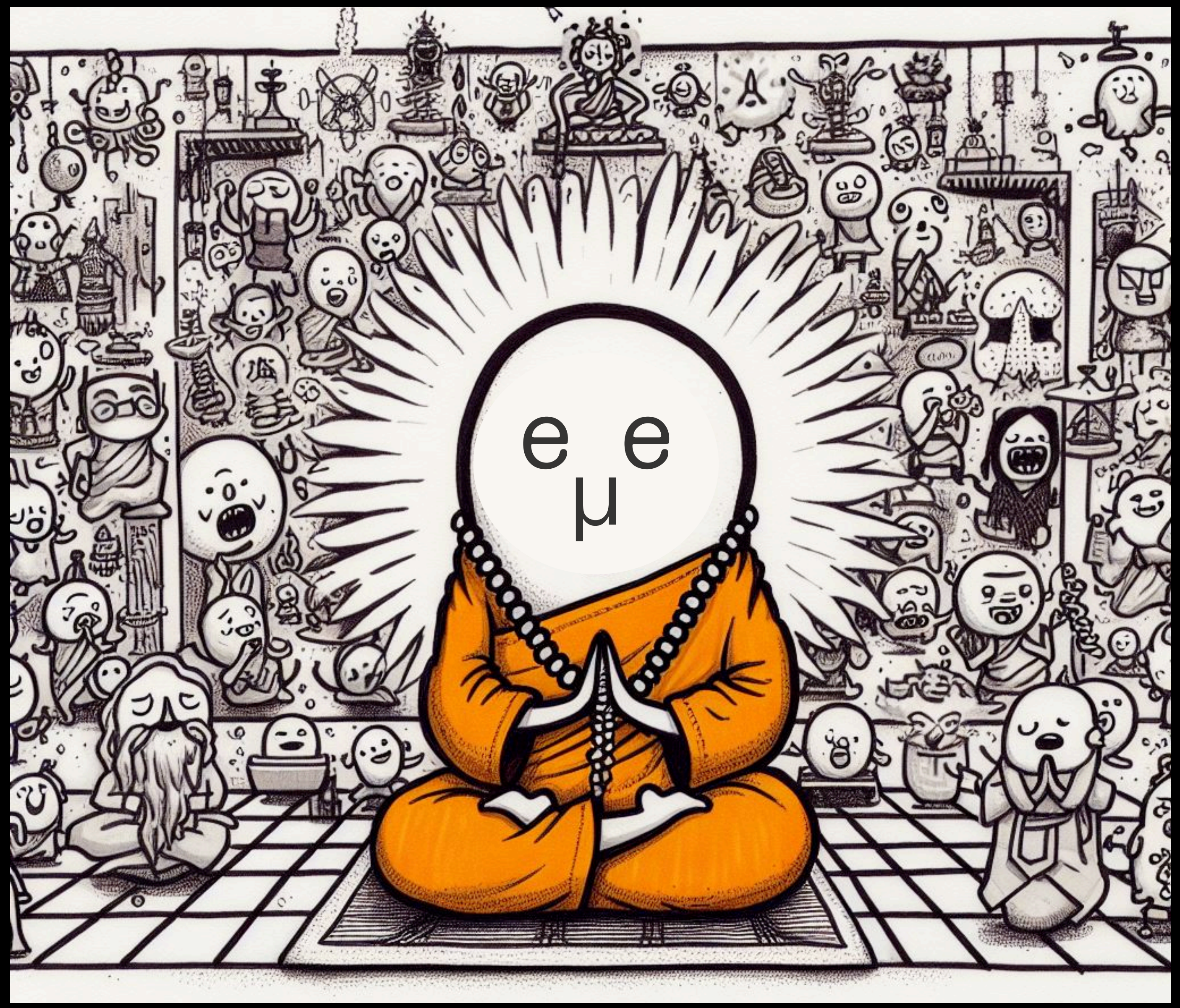
1 **decay out of 10^{12} muons,** after signal selection.

New physics scale as high as:

$\Lambda < 10^{15} - 10^{16}$ GeV.

Some new ideas for $\mu^- \to e^-$ conversion

e^+e^- pairs from dark particles



DALL·E 3: muon conversion

Dark particle production in $\mu \to e$ conversion

Borrowing energy from the proton

P. Fox, **MH**, T. Menzo, M. Pospelov, J. Zupan (in progress)

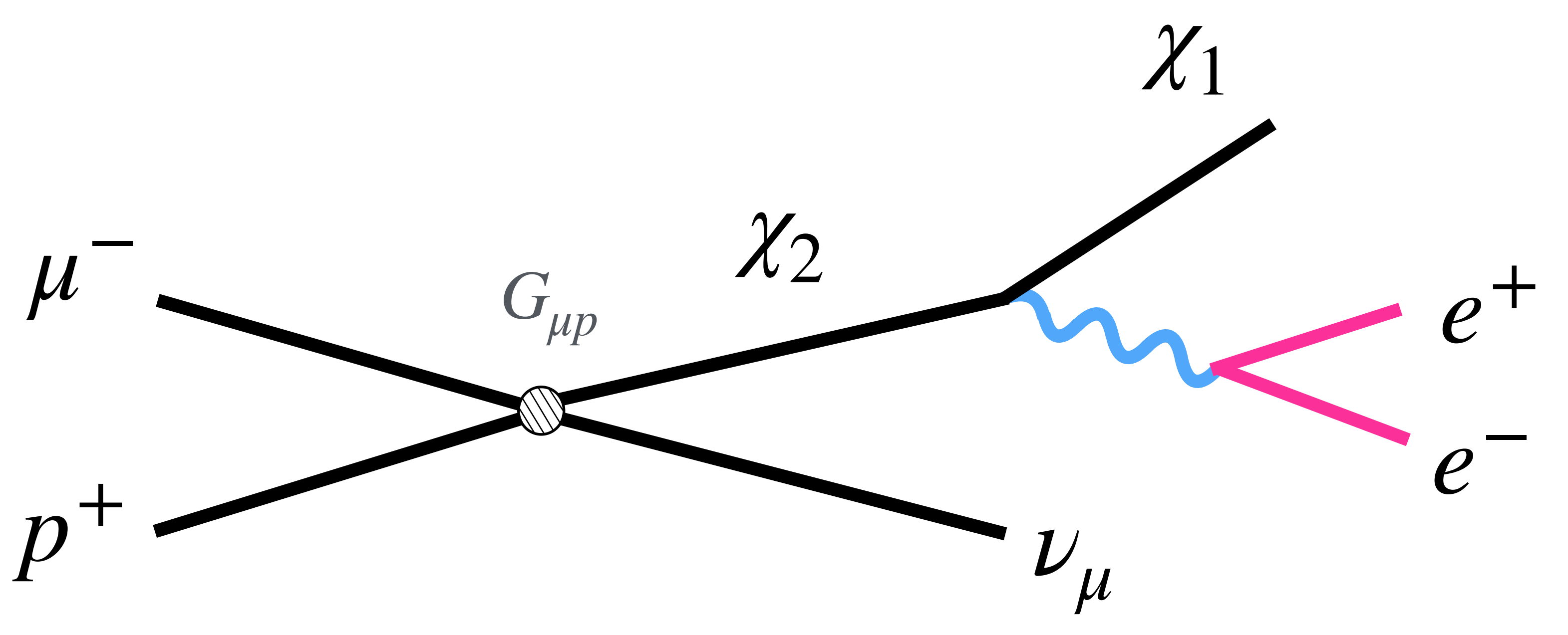
Mu2e conversion happens in the presence of an energy reservoir: M_N

Can we borrow some of this energy to produce higher energy e^-?

Let us consider a toy model to illustrate the point.

Consider new dark baryons $\chi_{2,1}$. Schematically:

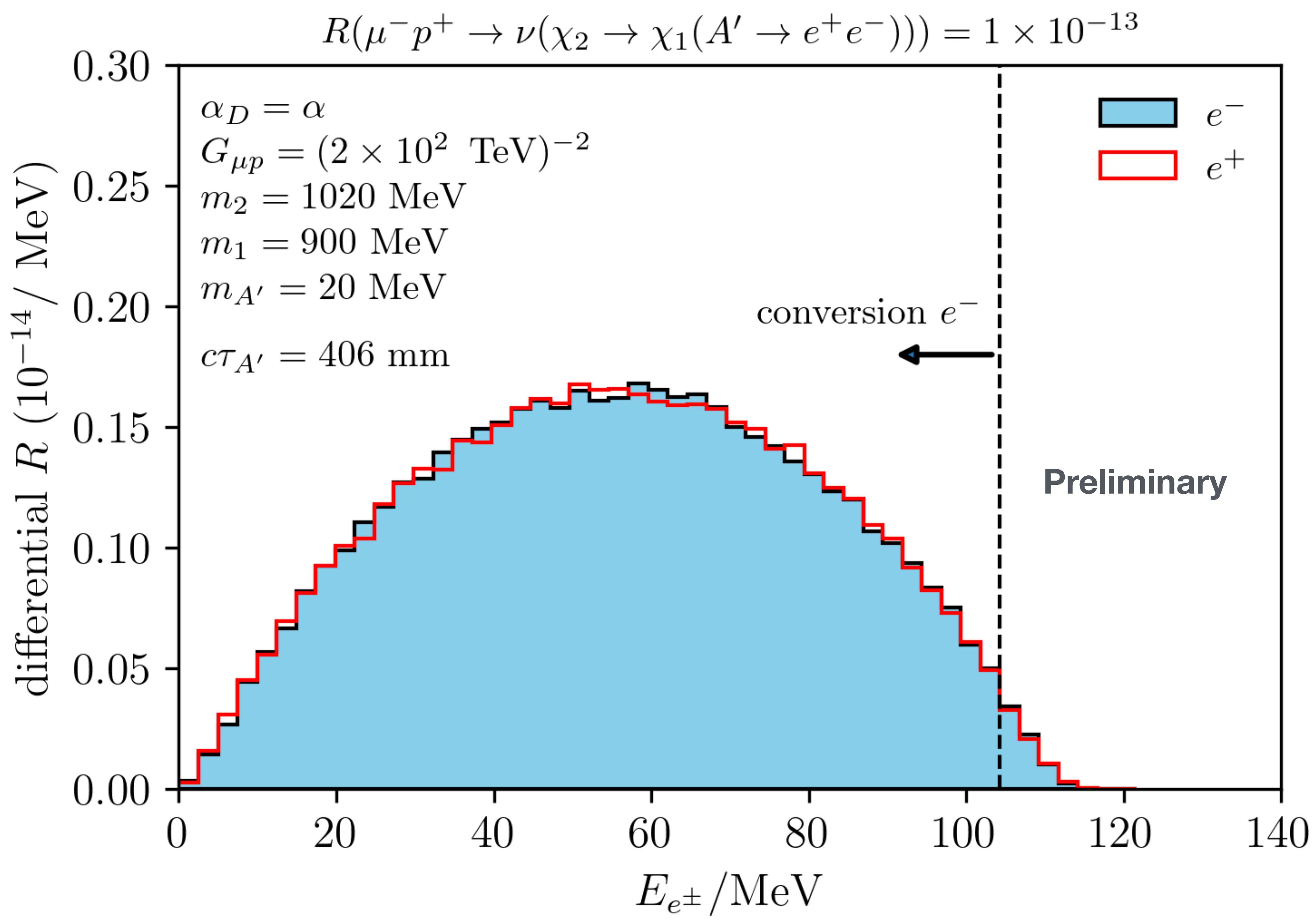
$$\mathscr{L} \supset G_{\mu p}(\overline{\mu}\nu_\mu)(\overline{p}\chi_2) + A'_\mu \left(g_D \overline{\chi_2}\gamma^\mu \chi_1 + e\varepsilon J_{\mathrm{EM}}\right)$$



Muon capture on a proton

$m_2 = 1020$ **MeV**

$m_1 = 900$ **MeV**



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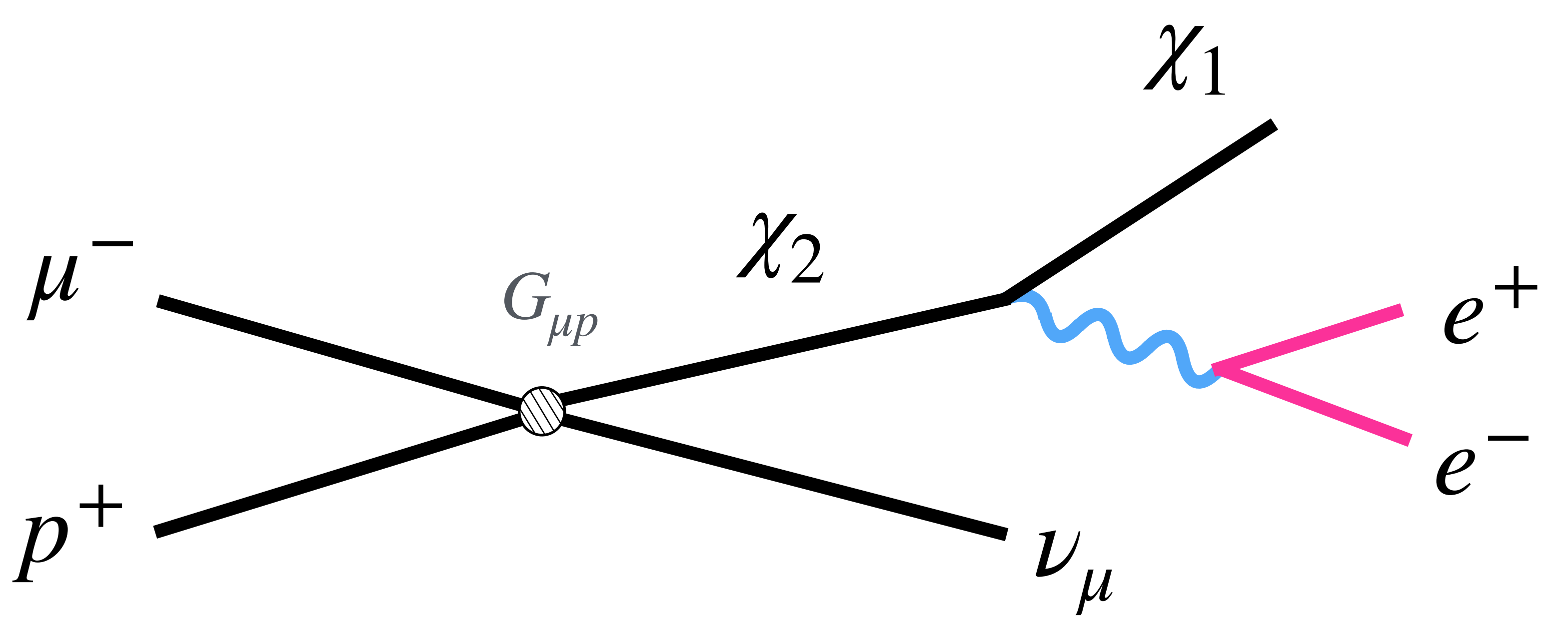
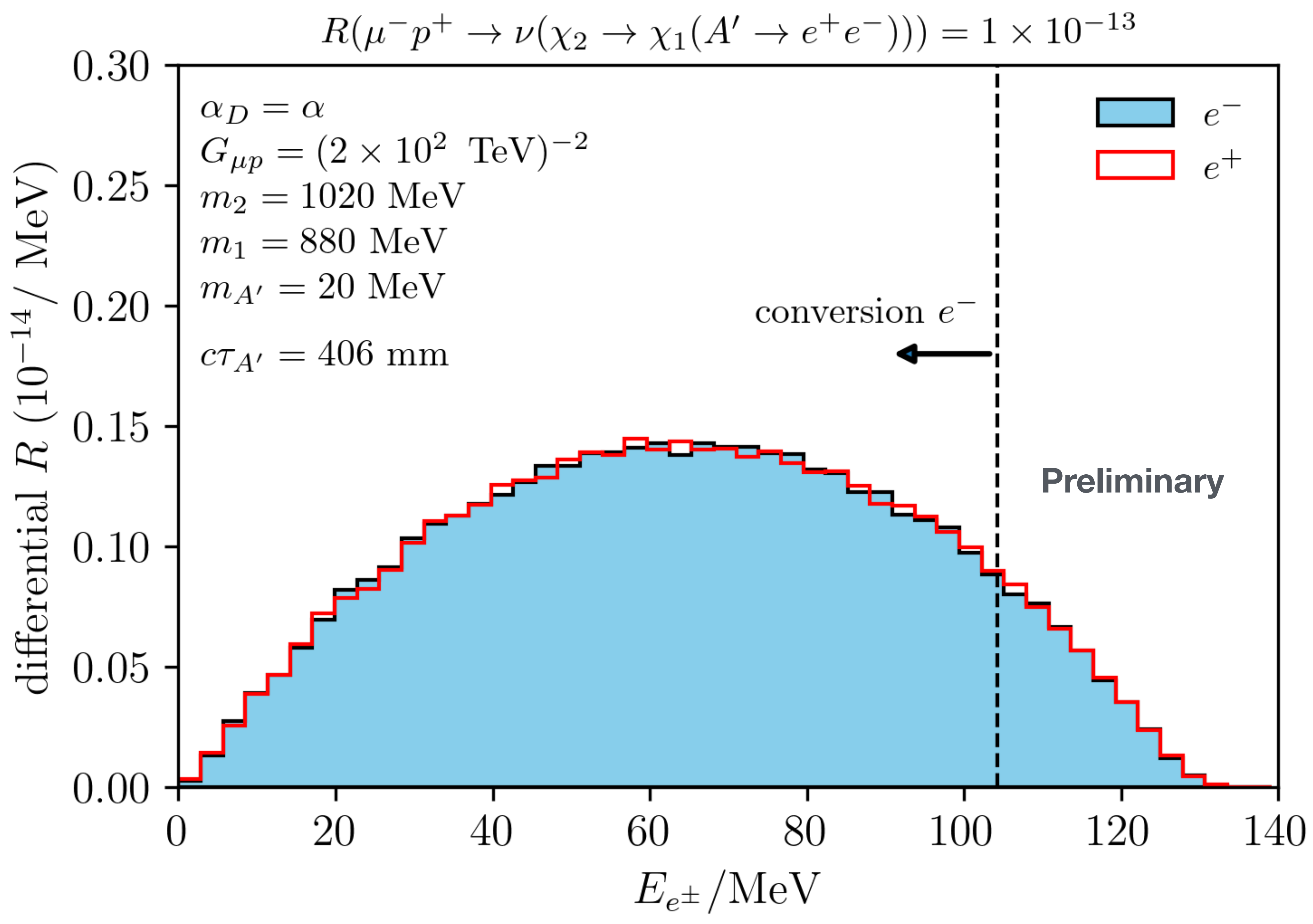


Muon capture on a proton

$m_2 = 1020$ **MeV**

$m_1 = 880$ **MeV**



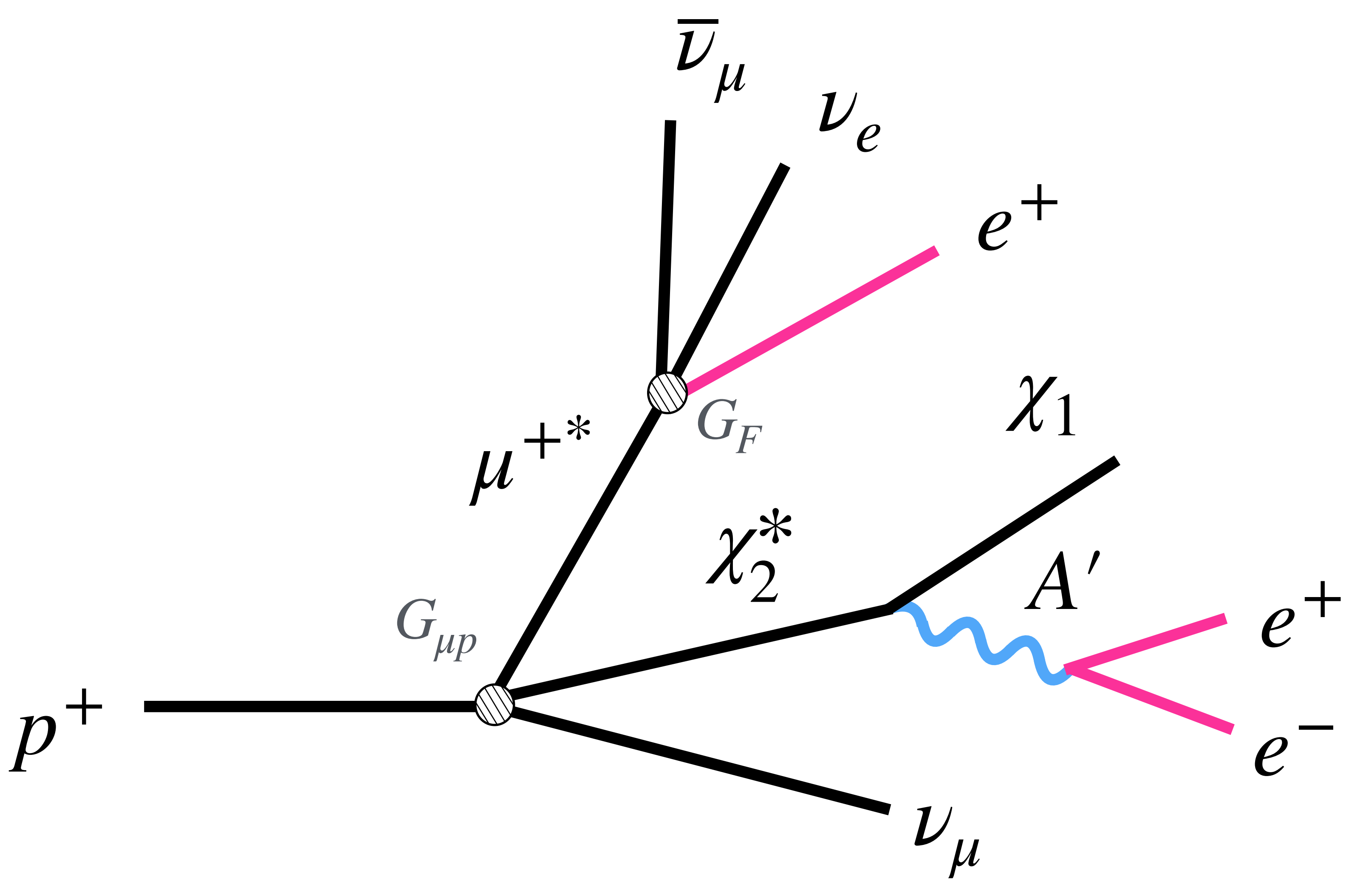
Proton decay

P. Fox, **MH**, T. Menzo, M. Pospelov, J. Zupan (in progress)

Proton decay is suppressed by "off-shellness" and the small Q-value.

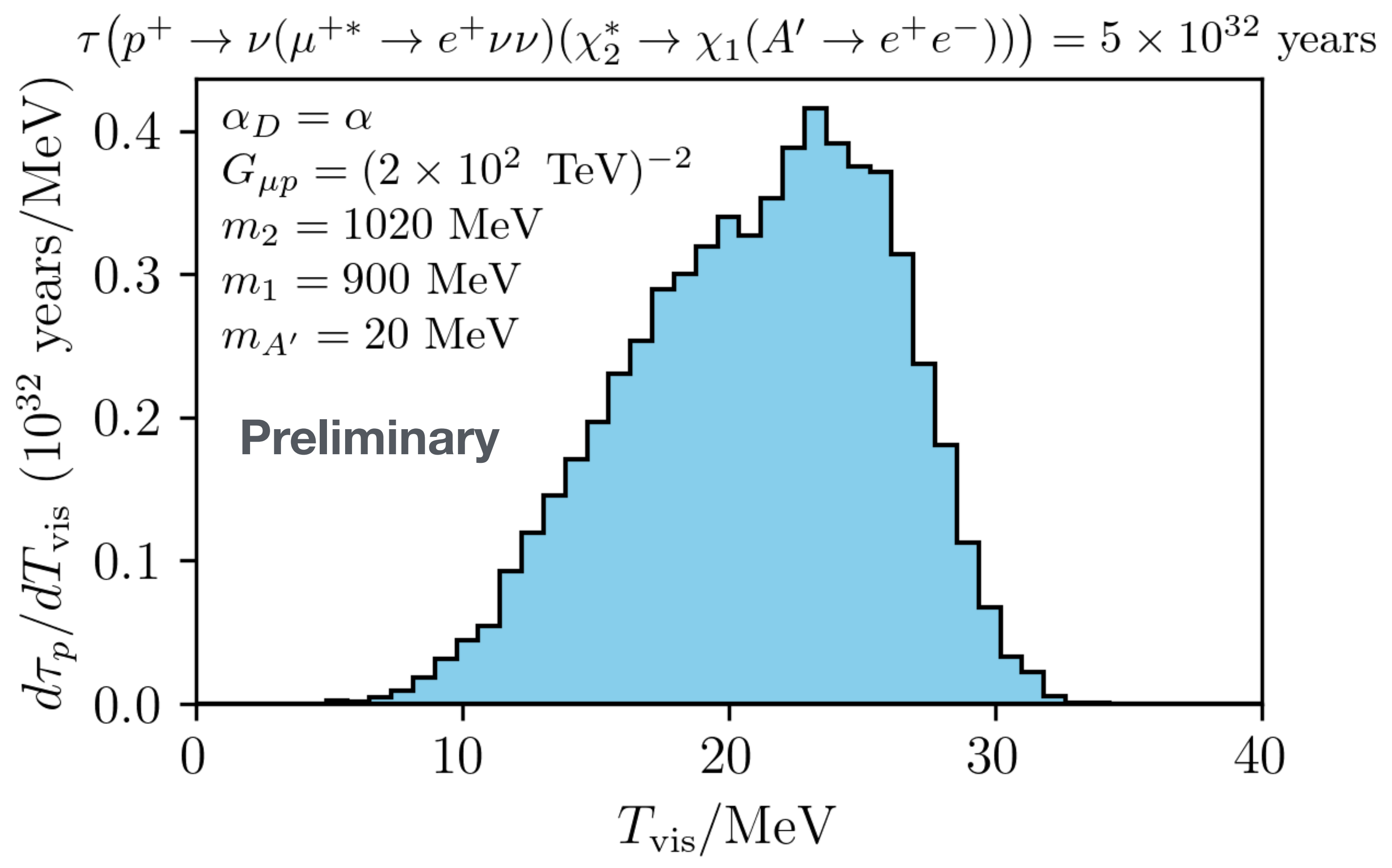
The resulting event is a soft collection of tracks.

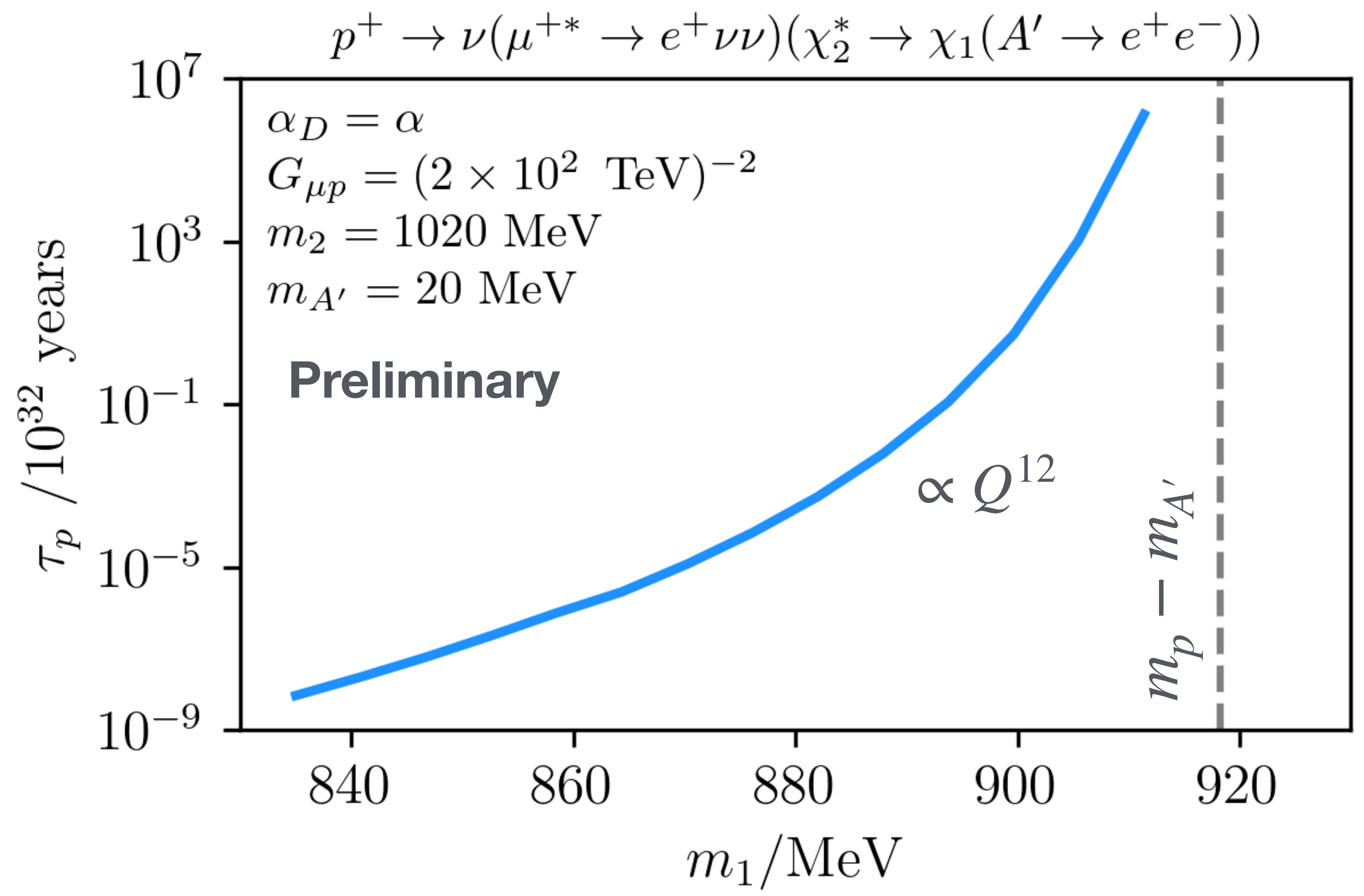
Super-Kamiokande limits relaxed $\gtrsim 2$ orders of magnitude.



Proton decay to 6 particles via **off-shell** μ^+ **and** χ_2**!**

Low energies ⟶





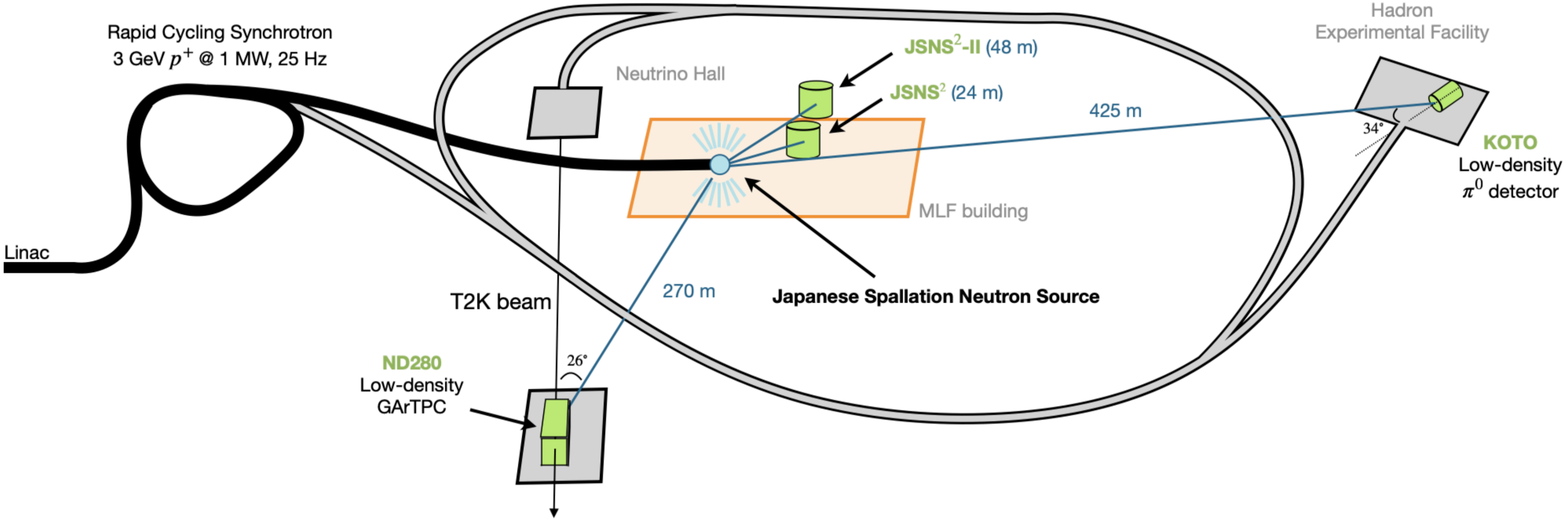
New particle production in μ^+ decays at spallation sources

Long-lived particles at neutrino detectors

Muons at Spallation Sources
Long-lived particles @ J-PARC

C. Argüelles, MH, S. Urrea, in preparation

J-PARC complex:



C. Argüelles, MH, S. Urrea, in preparation

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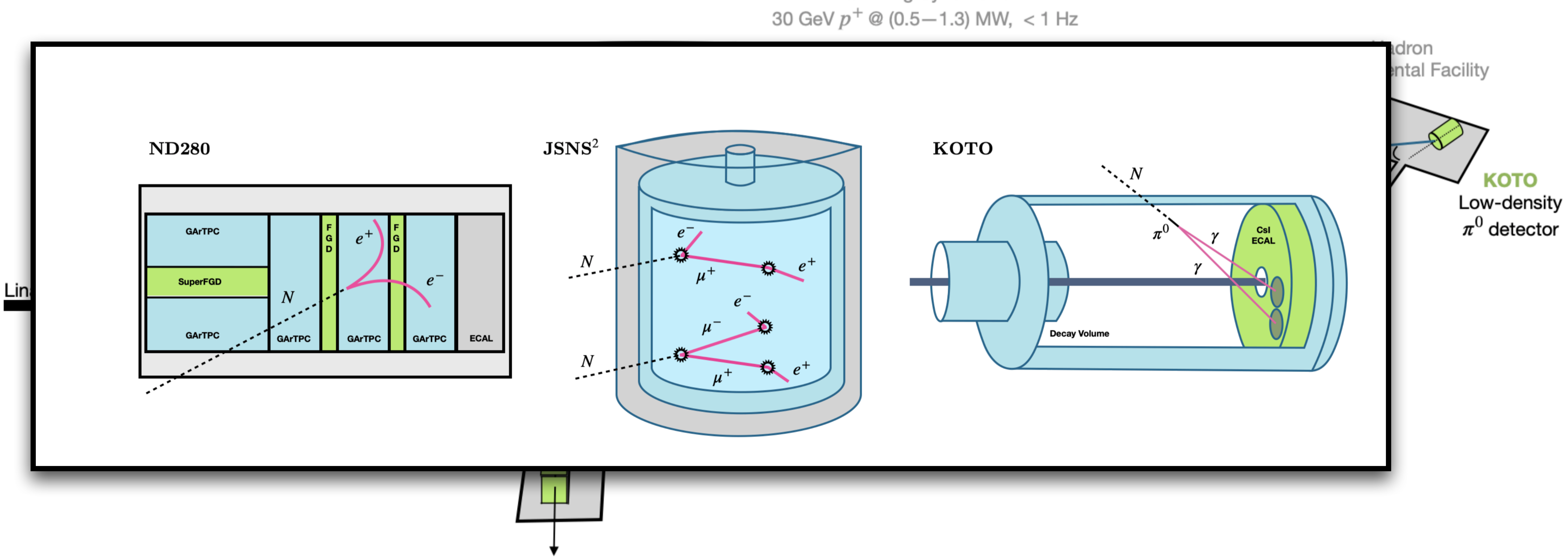
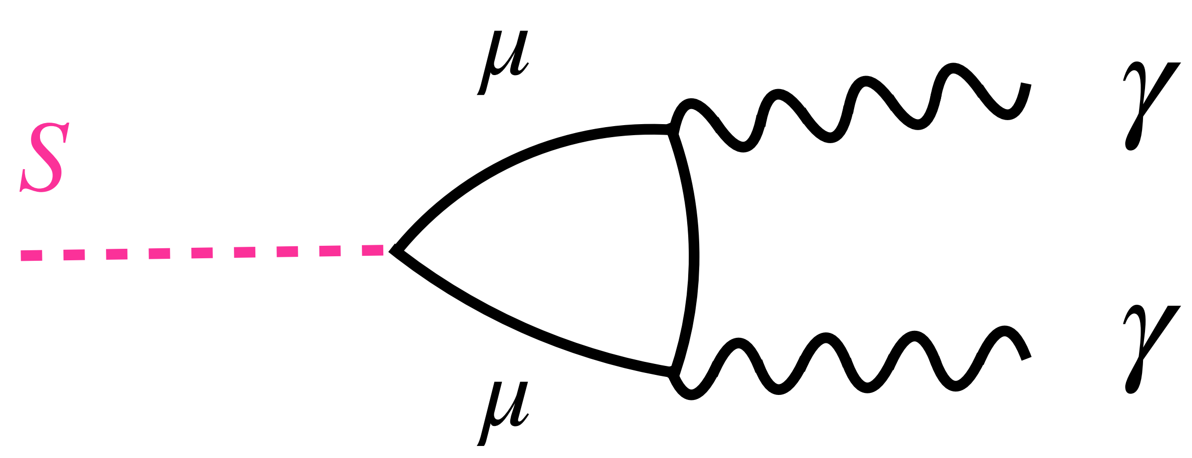


C. Argüelles, **MH**, S. Urrea, in preparation

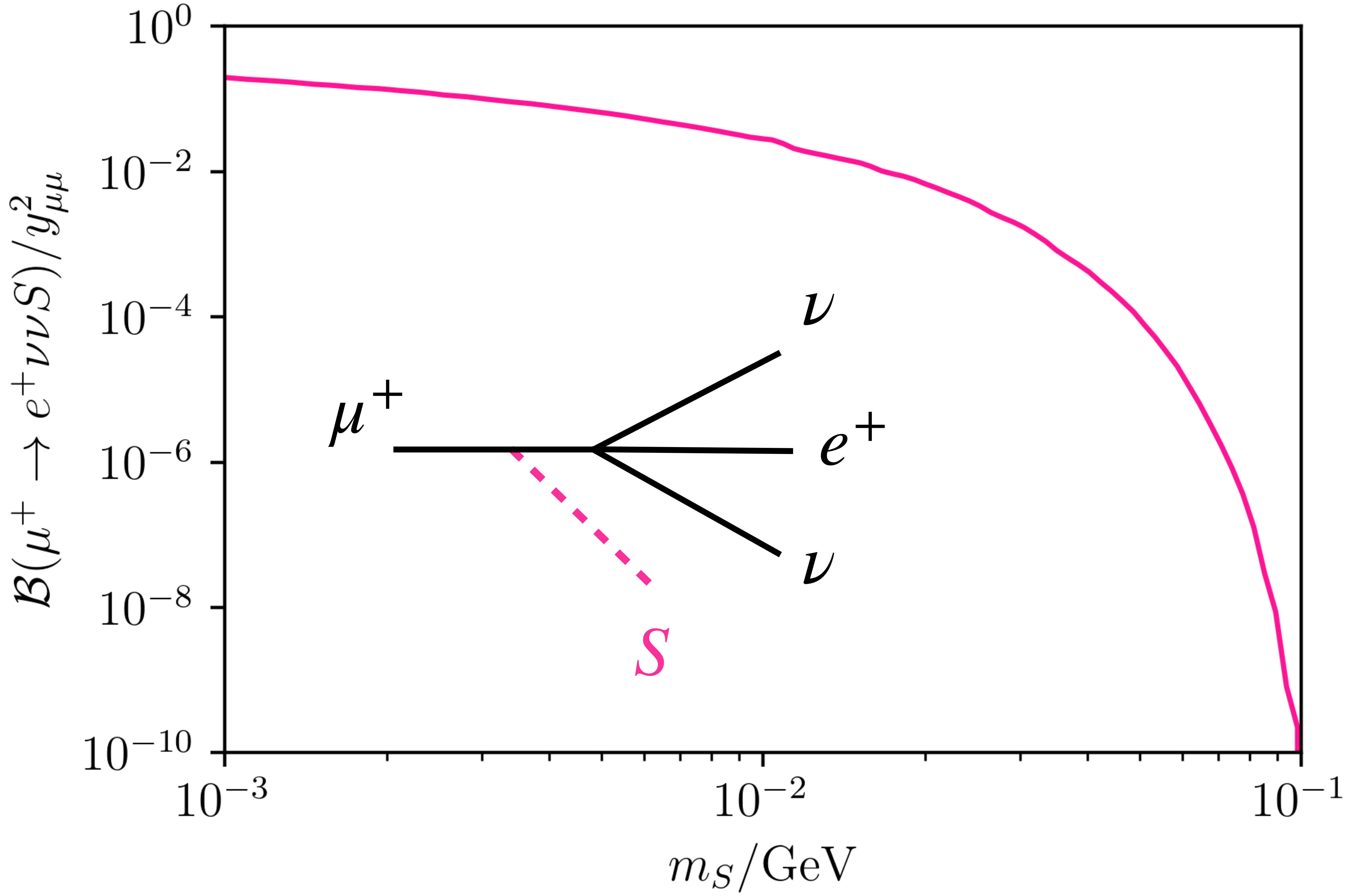
A toy model of muon-philic scalars:

$$\frac{Y_{\mu\mu}}{\Lambda} S \overline{L} H \mu_R \to y_{\mu\mu} S \overline{\mu_L} \mu_R, \qquad y_{\mu\mu} = \frac{Y_{\mu\mu} v_{\text{EW}}}{\sqrt{2}\Lambda}$$

Below dimuon threshold ($m_S < 2m_\mu$), the scalar is long-lived:



Scalar production in 4-body muon decays:



C. Argüelles, **MH**, S. Urrea, in preparation

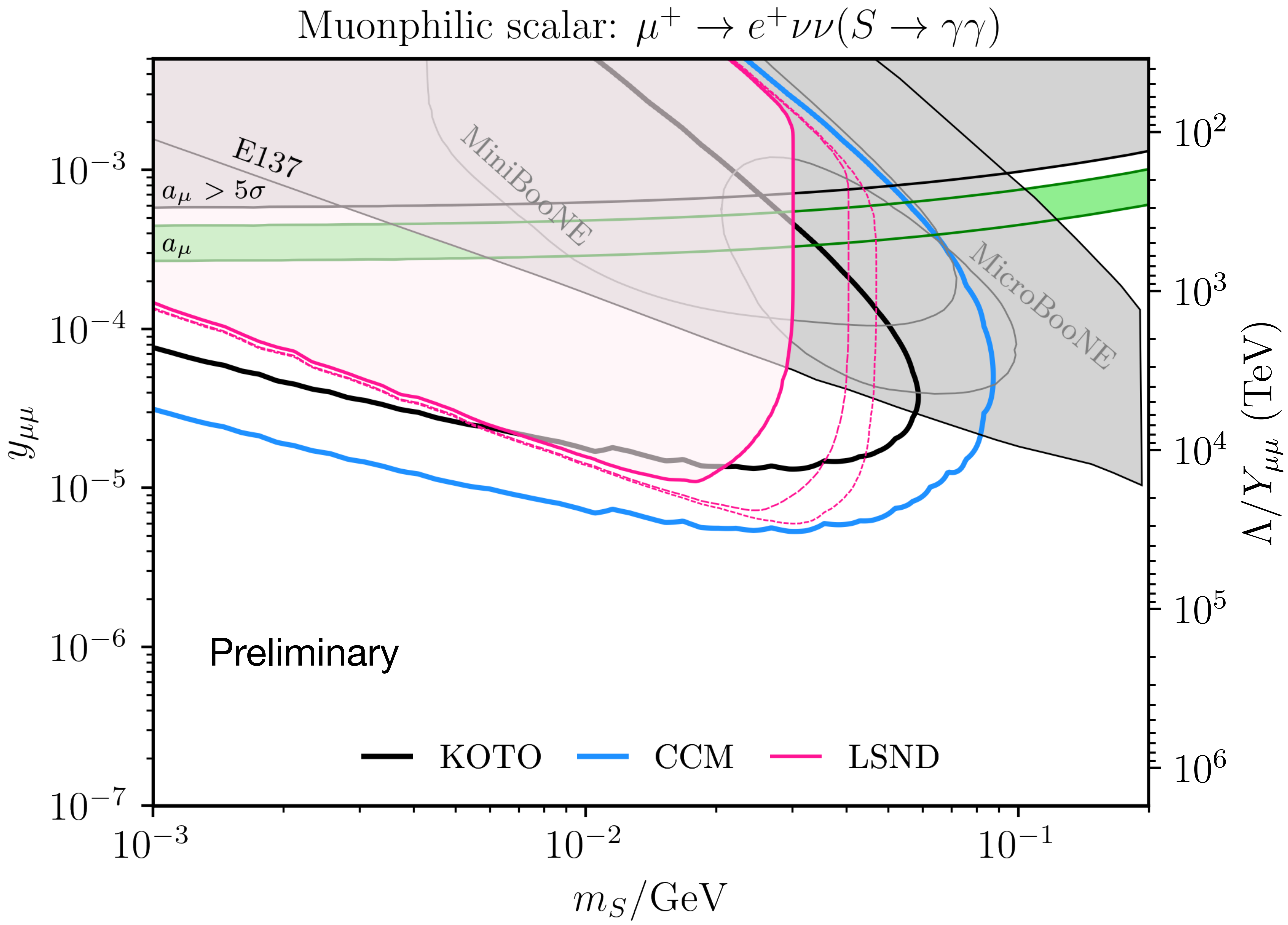
Spallation sources and neutrino detectors provide the best limits in this mass range.

To fall in the $(\nu - e)$-like event sample, we require photons to be energy-asymmetric or angle-overlapping. We use three examples:

1) $E_{e_{inv}} < 5$ MeV or $\theta_{ee} < 5°$ (weakest limit, solid pink region)
2) $E_{e_{inv}} < 10$ MeV or $\theta_{ee} < 10°$
3) $E_{e_{inv}} < 15$ MeV or $\theta_{ee} < 15°$ (strongest limit)

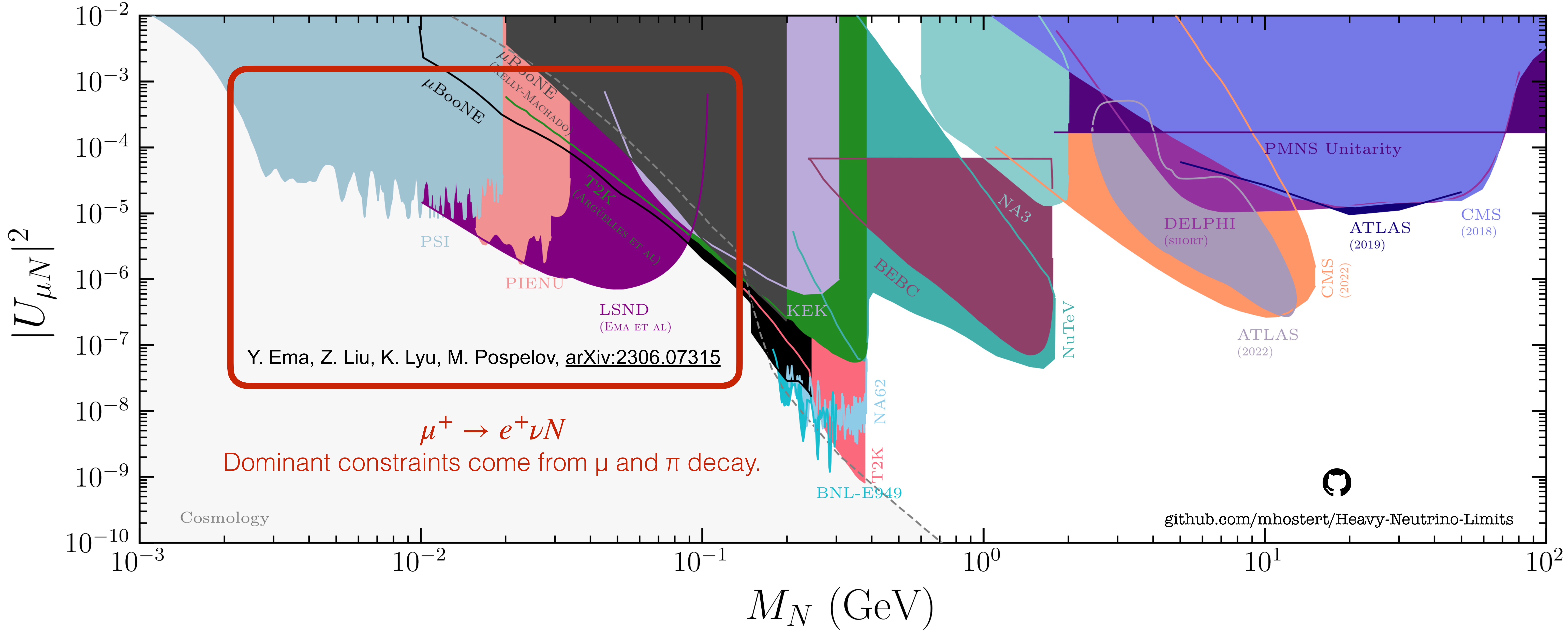
All events must also satisfy signal selection criterion:
18 MeV $< E_{\rm vis} < 50$ MeV and $\cos\theta_{\rm vis} > 0.9$

* Supernovas can also provide strong limits. There may be potential energy injection in the outer envelopes of the star.



Muons at Spallation Sources

Heavy Neutral Leptons



E. Fernández-Martínez, M.González-López, J. Hernández-García, **MH**, J. Lópes-Pavón, 10.1007/JHEP09(2023)001

Muons at Spallation Sources
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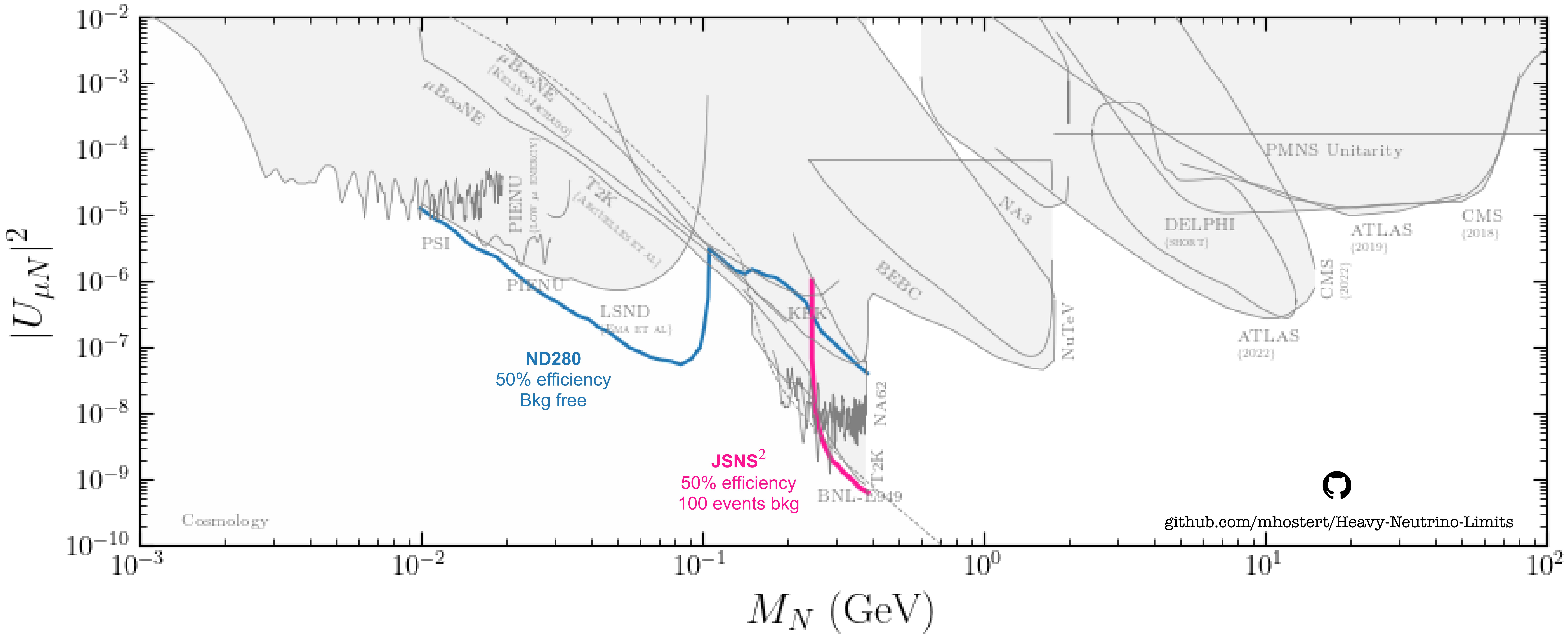

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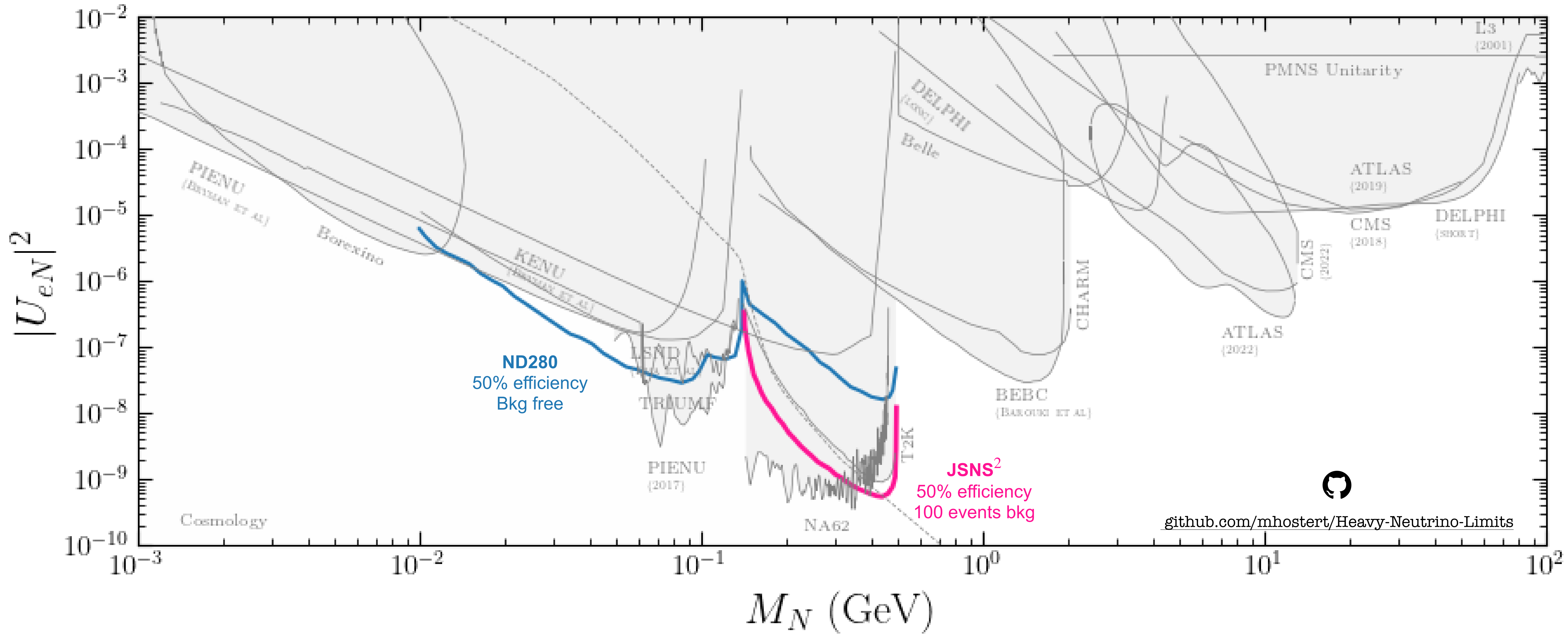

Summary

Matheus Hostert (mhostert@g.harvard.edu)

Muon facilities offer a new lamppost in the second generation of the SM.

1) **Several opportunities for dark particle searches at Mu3e and $\mu \to e$ conversion experiments:**
   1) Considered for the first time $\mu \to 5e$ decays within and beyond the SM.
   2) With the right light particles, sensitivity to new physics scale can be as strong as $\Lambda \sim 10^{15}$ GeV.
   3) Measurement of the SM rate is more challenging, but perhaps not impossible
   4) Need to investigate relaxing the requirement of observing **all** five tracks and focusing on the presence of 2 electrons.

2) **Spallation sources provide even more muons! Despite the dirtier environment, it is still incredibly useful for long-lived particle searches**
   1) New LSND limits, J-PARC and CCM sensitivities limits to muon-philic scalars (excludes part of $(g-2)_\mu$ explanation).
   2) J-PARC experiments sensitive to heavy neutrinos coupled to muon and electron flavors.

Back-up slides

Rare muon decays at Mu3e
Relaxing requirements to just 2 electrons?

MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006