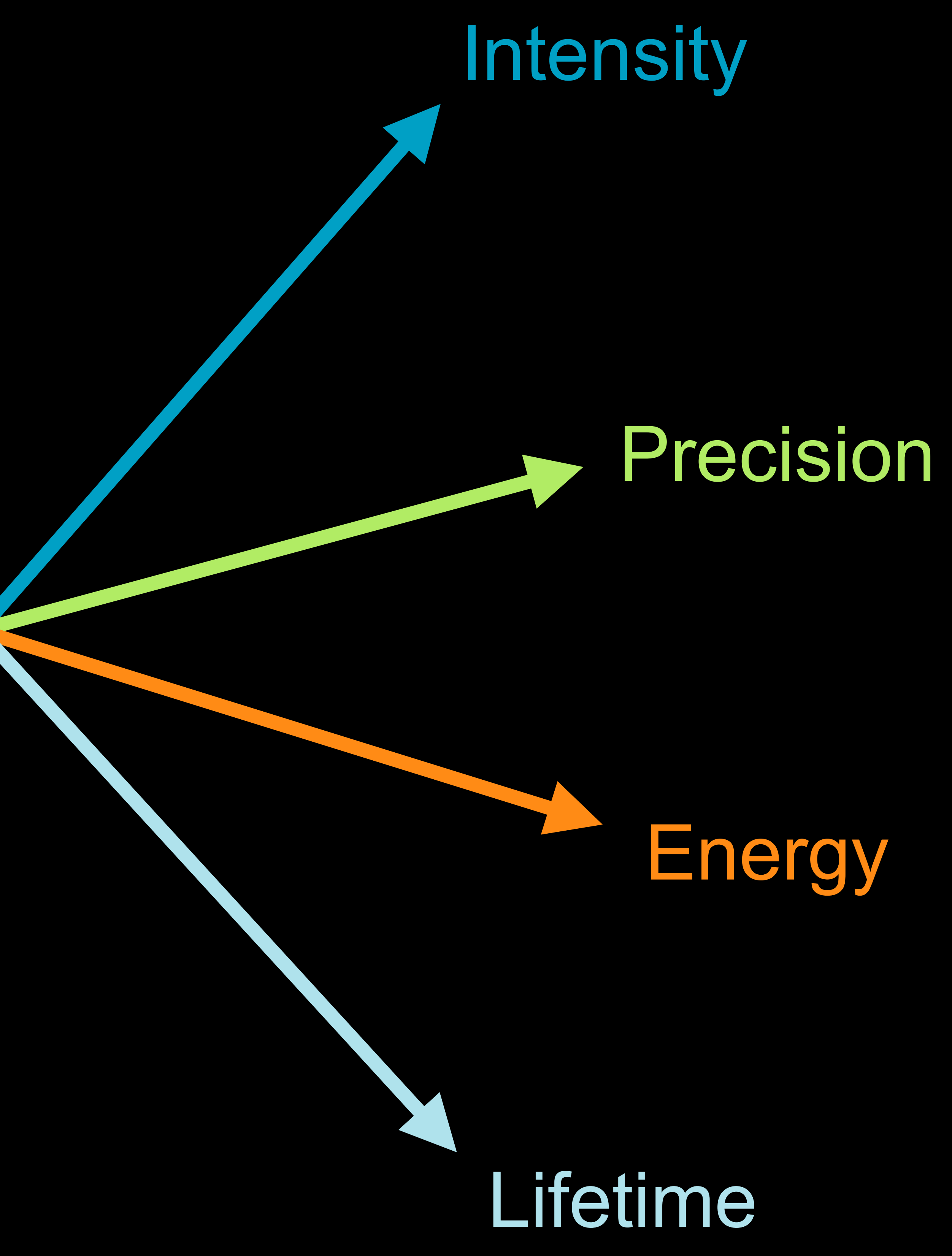
Flavor-violating new physics at the intensity frontier

Matheus Hostert
Harvard University
mhostert@g.harvard.edu

The Mitchell Conference 2024
May 23rd, 2024

Going beyond the Standard Model with Muons

The “progress axes” for muon facilities



Rare decay searches (Intensity & Precision)

$10^{16} - 10^{18}$ muons in clean environments

This talk: Five-track events at the Mu3e experiment

This talk: Muon-induced baryon number violation at Mu2e

Lepton Flavor Beyond the Standard Model

Accidental symmetry in the Standard Model

$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} \quad \text{or} \quad U(1)_{B+L} \times U(1)_{B-L} \times U(1)_{L_e - L_\mu} \times U(1)_{L_e + L_\tau - 2L_\mu}$$

J. Heeck (arXiv:1610.07623)

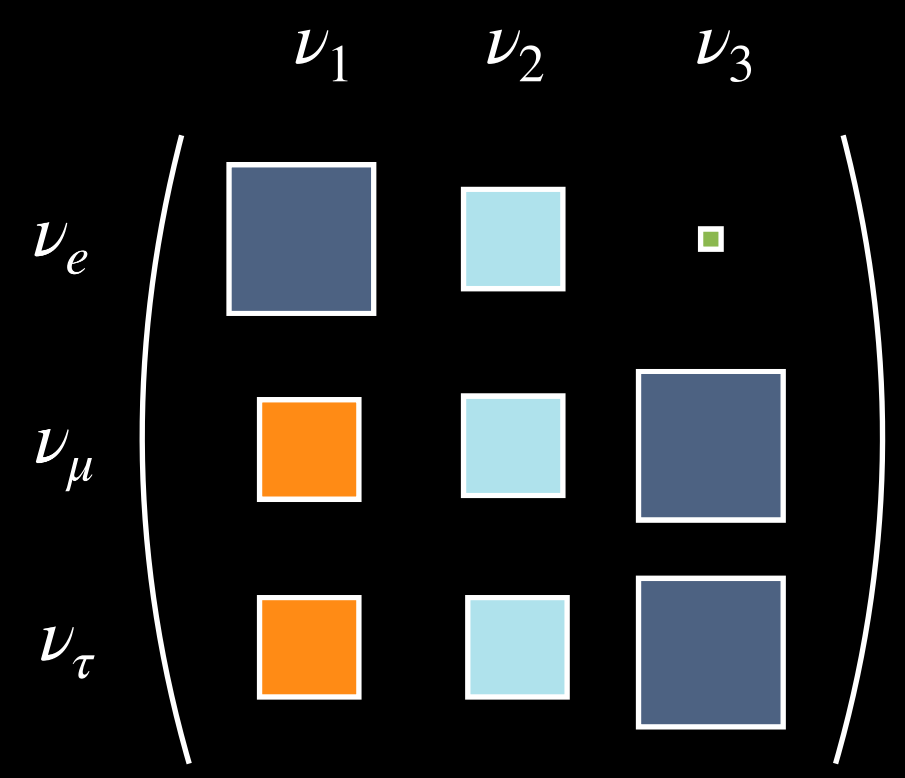
Neutrino masses violate lepton flavor

$$\nu_\alpha \to \nu_\beta$$

Lucky to have discovered this

"Earth-sized flavor interferometers"

Lepton mixing



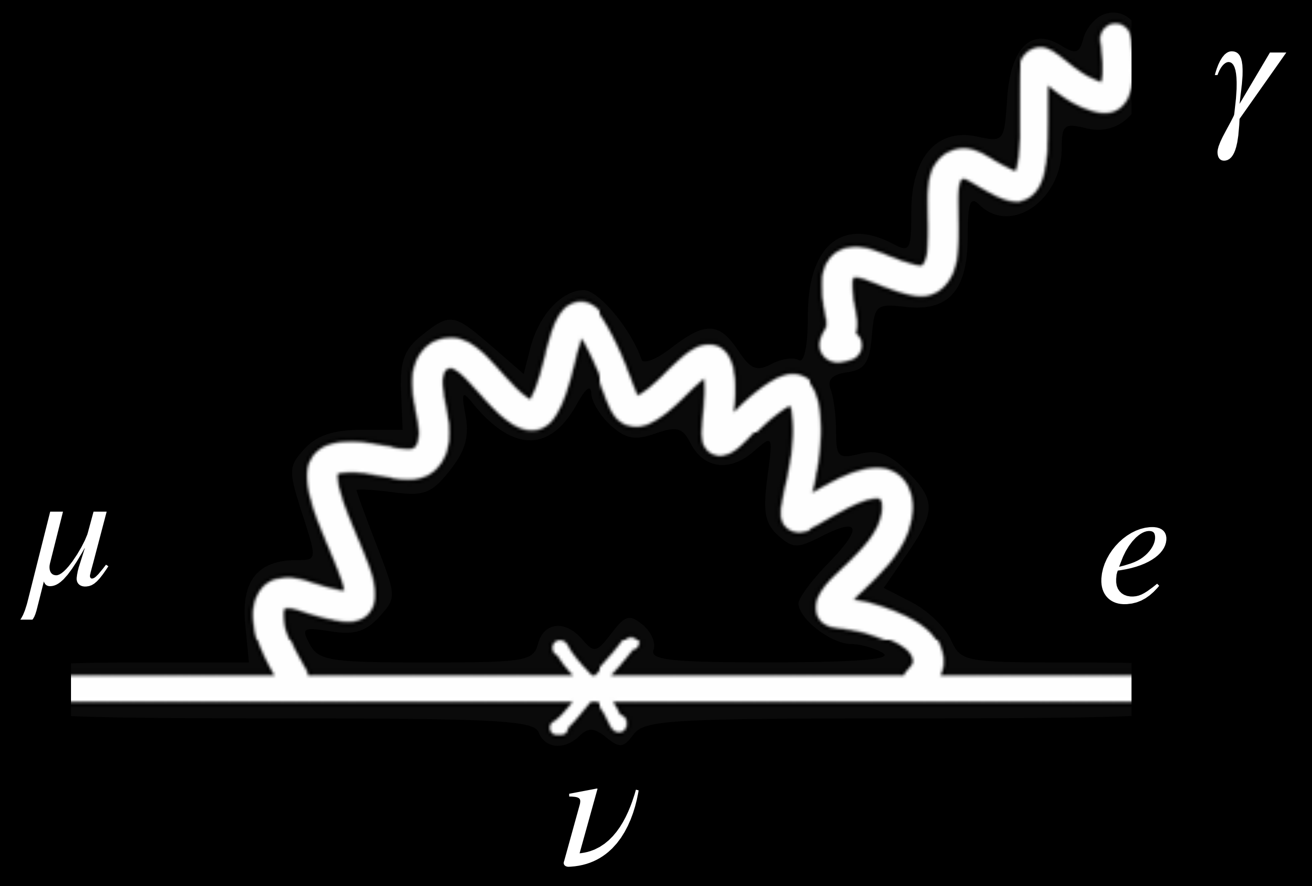
Lepton Flavor Beyond the Standard Model

Accidental symmetry in the Standard Model

$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$ or $U(1)_{B+L} \times U(1)_{B-L} \times U(1)_{L_e - L_\mu} \times U(1)_{L_e + L_\tau - 2L_\mu}$

J. Heeck (arXiv:1610.07623)

But in charged lepton sector, this is unobservable:



$$\mathscr{B}(\mu \to e\gamma) \sim \frac{3\alpha}{32\pi}\frac{m_\nu^4}{M_W^4} \sim 10^{-53}$$

Any measurement of a non-zero rate provides unambiguous evidence for new physics.

Lepton Flavor Beyond the Standard Model

Accidental symmetry in the Standard Model

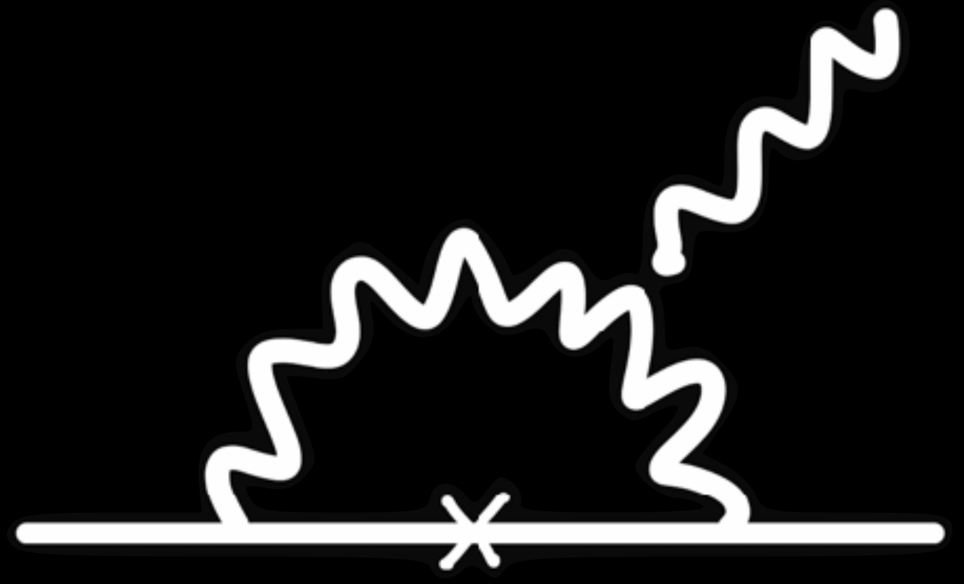
$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} \quad \text{or} \quad U(1)_{B+L} \times U(1)_{B-L} \times U(1)_{L_e-L_\mu} \times U(1)_{L_e+L_\tau-2L_\mu}$$

J. Heeck (arXiv:1610.07623)

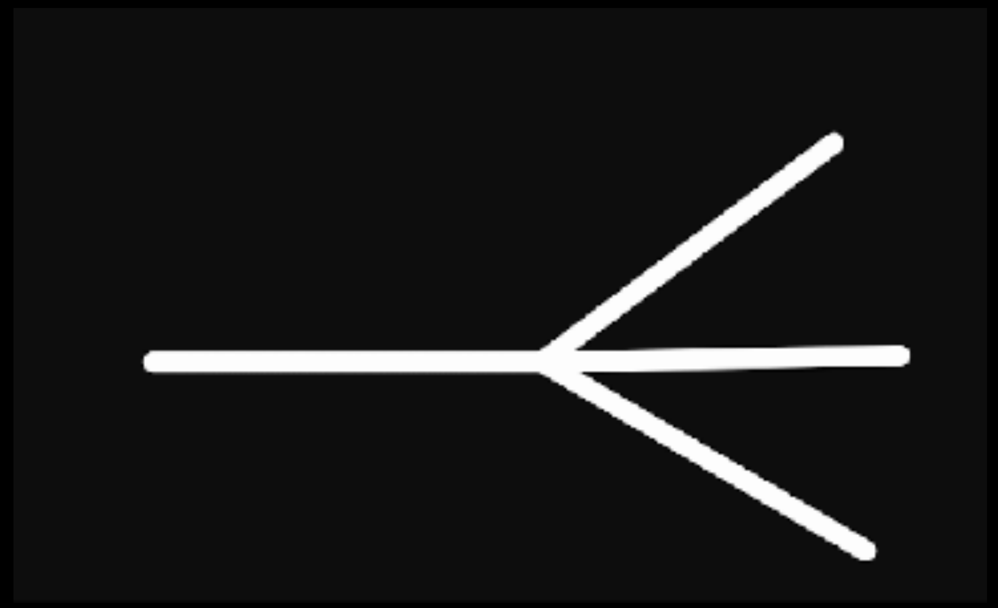
Muons are the lamppost for this symmetry factor:

$$\Delta(L_e - L_\mu) = 2$$

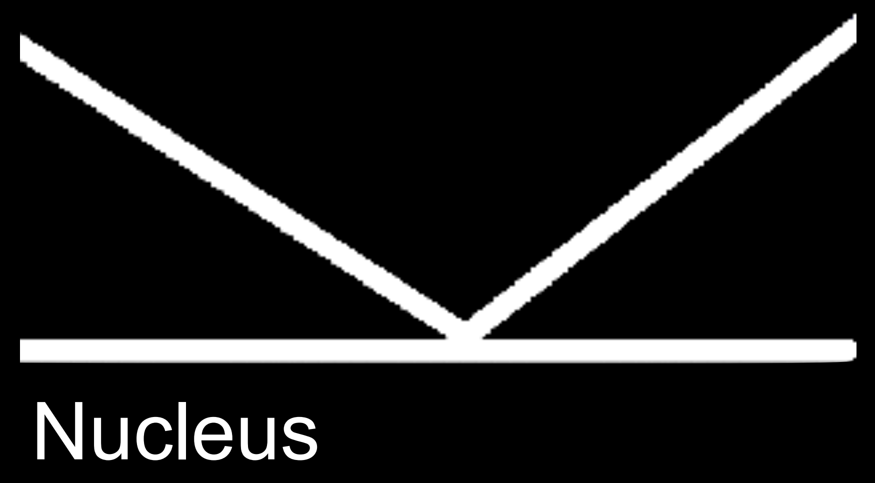
$\mu \to e\gamma$



$\mu \to eee$

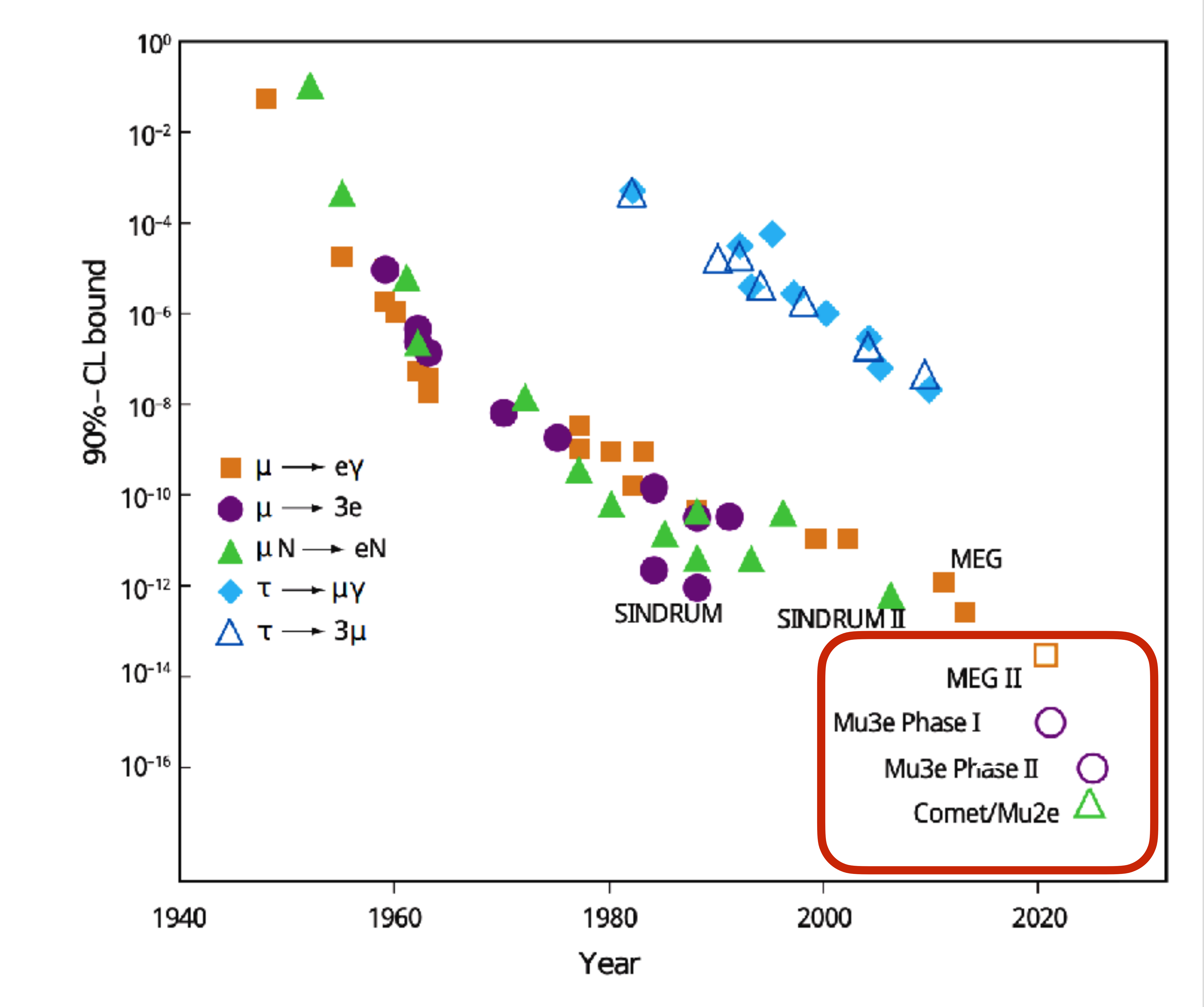


$\mu A \to eA$



Going beyond the Standard Model
Muon facilities

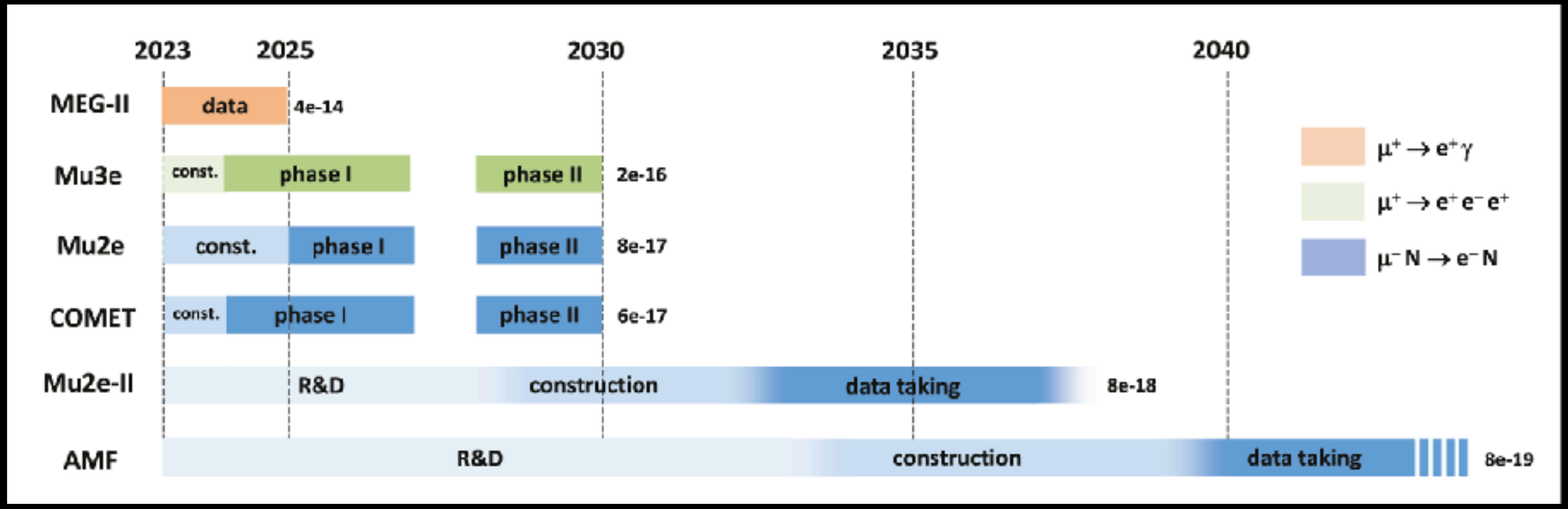
Huge progress is coming. And soon!



L. Calibbi, G. Signorelli, arXiv:1709.00294

Reaction	Present limit	Expected Limit	Experiment
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	5×10^{-14}	MEG II
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	10^{-16}	Mu3e
$\mu^-\mathrm{Al} \to e^-\mathrm{Al}$ †	$< 6.1 \times 10^{-13}$	10^{-17}	Mu2e, COMET
$\mu^-\mathrm{Si/C} \to e^-\mathrm{Si/C}$ †	–	5×10^{-14}	DeeMe

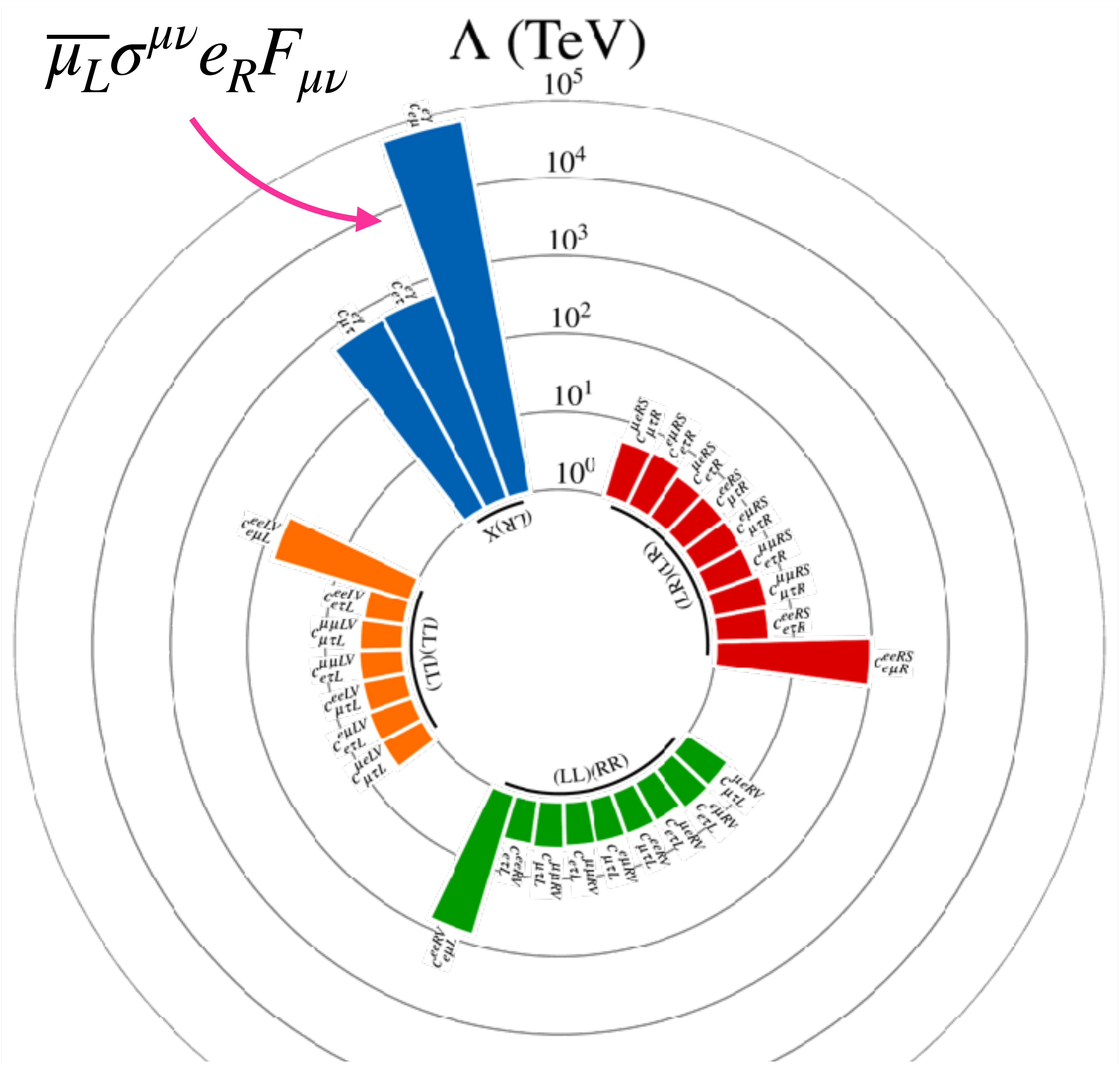
Snowmass 2021 Rare and Precision Frontier Report



Going beyond the Standard Model
Effective Field Theories

Very useful for interpreting cLFV results
but not the only possibility.

Extract information on UV physics from
low-energy observables.



E. Fernandez-Martinez, X. Marcano D. Naredo-Tuero
arXiv:2403.09772

Beyond Effective Field Theory

New physics exclusively at low scale?

$$\mathscr{L}(\mathrm{SM}) \mathrel{+}= \mathscr{L}(\mathrm{new\ fields})$$

New physics exclusively at high scale?

$$\mathscr{L}(\mathrm{SM}) \mathrel{+}= \frac{1}{\Lambda^{\mathrm{n}}}\mathscr{O}(\mathrm{SM})^{4+\mathrm{n}}$$

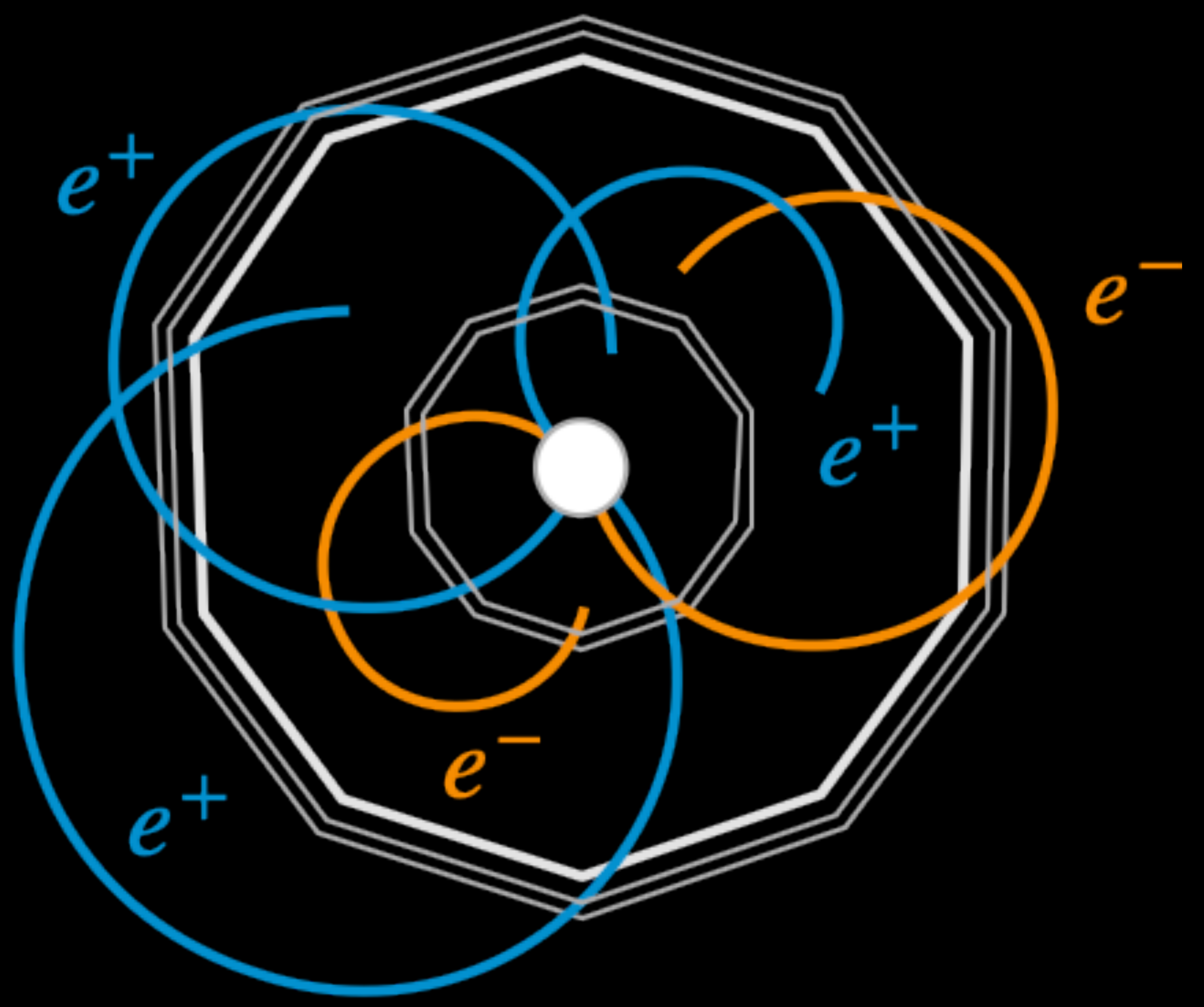
$$\mathscr{L}(\mathrm{SM}) \mathrel{+}= \mathscr{L}(\mathrm{new\ fields}) + \frac{1}{\Lambda^{n}}\mathscr{O}(\mathrm{SM,\ new\ fields})^{4+\mathrm{n}} + \frac{1}{\Lambda^{n}}\mathscr{O}(\mathrm{SM})^{4+\mathrm{n}}$$

E.g., axion-like-particles, $\partial_\mu a(\mu\gamma^\mu e)$, QCD Axions, Majorons, Flavons, etc

L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, 10.1007/JHEP09(2021)173

New particle production in μ^+ decays

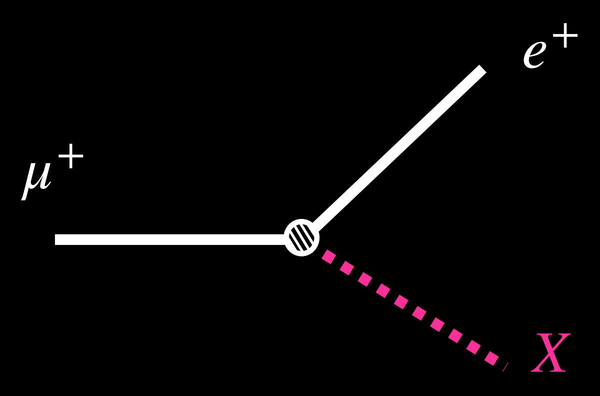
Multi-electron final states at ~~Mu3e~~ **Mu5e**



MH, T. Menzo, M. Pospelov, J. Zupan, 10.1007/JHEP10(2023)006

Light particle production at Mu3e
An overview

(1) $\mu^+ \to e^+ X_{\rm inv}$ — Peak in the Michel spectrum.



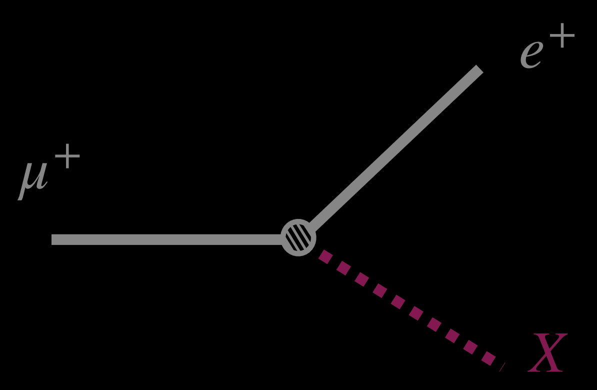
Current limits: $\mathscr{B} \lesssim 10^{-5}$
Projected reach: $\mathscr{B} \lesssim 10^{-8}$

AK. Perrevoort (Ph.D. thesis), 10.11588/heidok.00024585
L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, 10.1007/JHEP09(2021)173

See also $\mu^+ \to e^+ a(\gamma^* \to e^+ e^-)$ for low masses,
S. Knapen, T. Opferkuch, D. Redigolo, arXiv:2311.17915

Light particle production at Mu3e
An overview

(1) $\mu^+ \to e^+ X_{\rm inv}$ — Peak in the Michel spectrum.

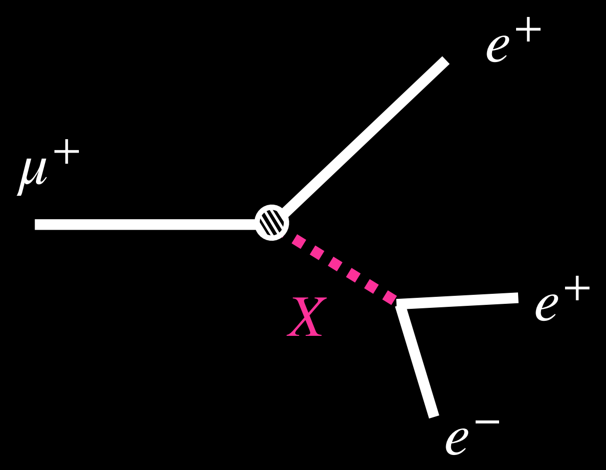


Current limits: $\mathscr{B} \lesssim 10^{-5}$
Projected reach: $\mathscr{B} \lesssim 10^{-8}$

AK. Perrevoort (Ph.D. thesis), 10.11588/heidok.00024585
L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, 10.1007/JHEP09(2021)173

See also $\mu^+ \to e^+ a(\gamma^* \to e^+e^-)$ for low masses,
S. Knapen, T. Opferkuch, D. Redigolo, arXiv:2311.17915

(2) $\mu^+ \to e^+(X \to e^+e^-)$ — Visible resonance

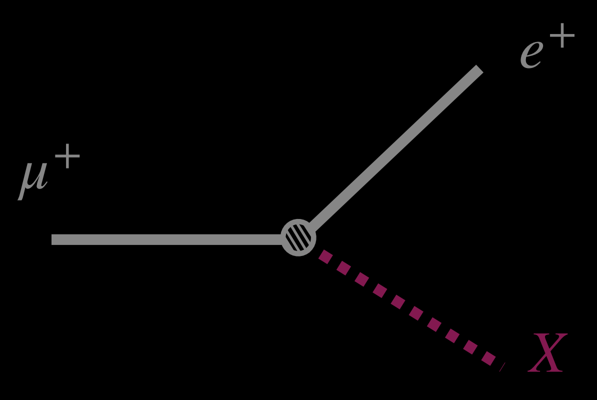


Current limits: $\mathscr{B} \lesssim 3 \times 10^{-12}$
Expected reach: $\mathscr{B} \lesssim 10^{-15}$ or better

J. Heeck, W. Rodejohann, 10.1016/j.physletb.2017.11.067
SINDRUM-I coll., 10.1016/0370-2693(86)90339-4

Light particle production at Mu3e
An overview

(1) $\mu^+ \to e^+ X_{\text{inv}}$ — Peak in the Michel spectrum.

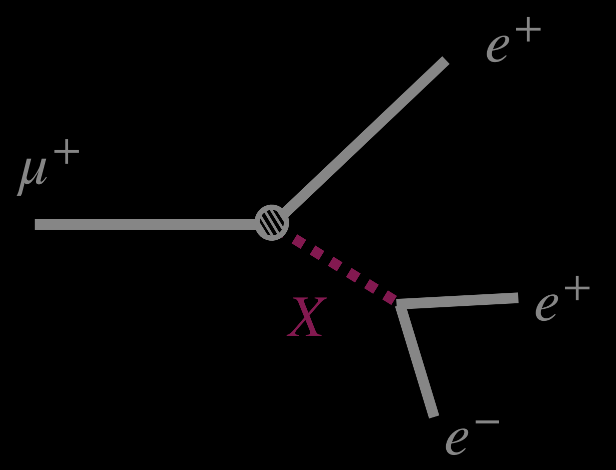


Current limits: $\mathscr{B} \lesssim 10^{-5}$
Projected reach: $\mathscr{B} \lesssim 10^{-8}$

AK. Perrevoort (Ph.D. thesis), 10.11588/heidok.00024585
L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, 10.1007/JHEP09(2021)173

See also $\mu^+ \to e^+ a(\gamma^* \to e^+e^-)$ for low masses,
S. Knapen, T. Opferkuch, D. Redigolo, arXiv:2311.17915

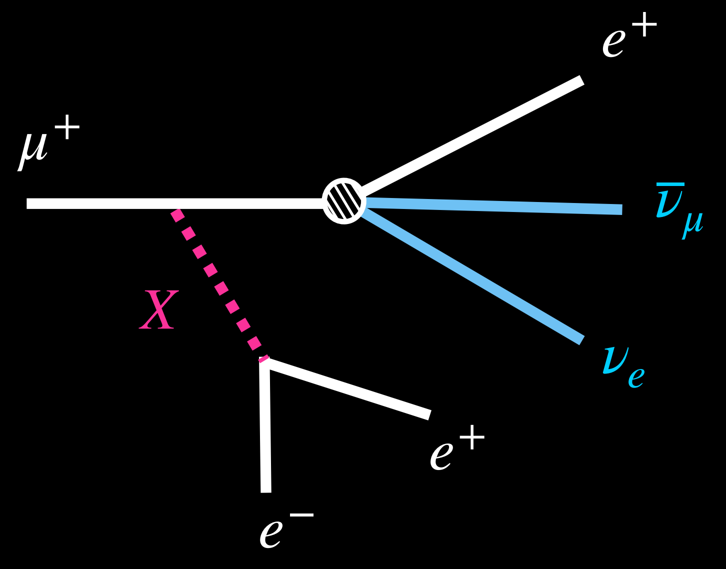
(2) $\mu^+ \to e^+(X \to e^+e^-)$ — Visible resonance



Current limits: $\mathscr{B} \lesssim 3 \times 10^{-12}$
Expected reach: $\mathscr{B} \lesssim 10^{-15}$ or better

J. Heeck, W. Rodejohann, 10.1016/j.physletb.2017.11.067
SINDRUM-I coll., 10.1016/0370-2693(86)90339-4

(3) $\mu^+ \to e^+\nu\nu(X \to e^+e^-)$ — Visible resonance + missing E



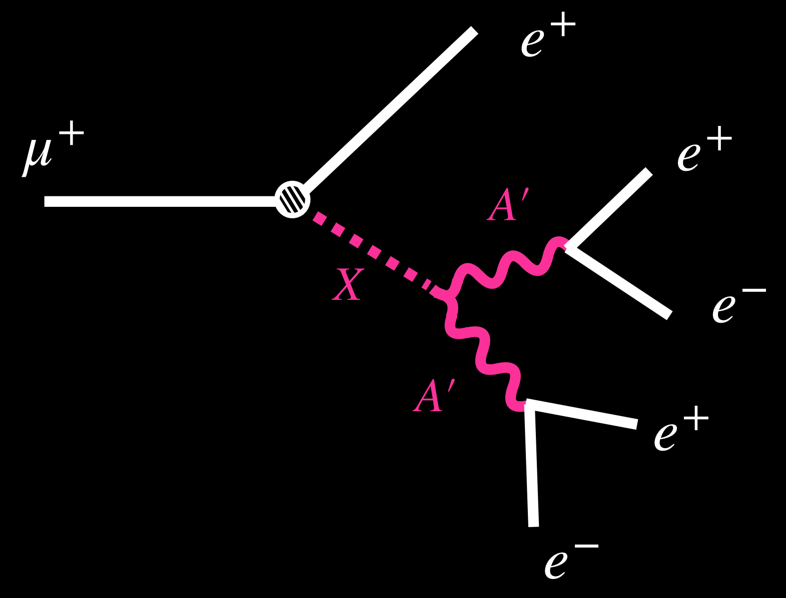
Projected reach: $\mathscr{B} \lesssim 10^{-9} - 10^{-11}$.

B. Echenard, R. Essig, Y.M. Zhong, 10.1007/JHEP01(2015)113
AK. Perrevoort (Ph.D. thesis), 10.11588/heidok.00024585
S. Knapen, T. Opferkuch, D. Redigolo, arXiv:2311.17913

Light particle production at Mu3e

An overview

(4) $\mu^+ \to e^+(X \to e^+e^-e^+e^-)$ — **This talk**



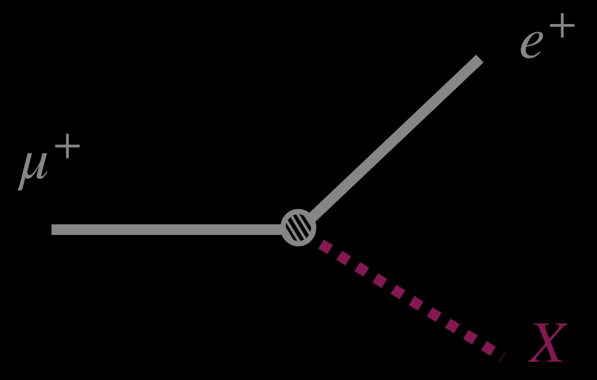
Projected reach: $\mathscr{B} \lesssim 10^{-12} - 10^{-14}$

Cascade of 2-body decays.

Also, the first study of SM five-track rate.

MH, T. Menzo, M. Pospelov, J. Zupan, 10.1007/JHEP10(2023)006

(1) $\mu^+ \to e^+X_{\rm inv}$ — Peak in the Michel spectrum.



Current limits: $\mathscr{B} \lesssim 10^{-5}$

Projected reach: $\mathscr{B} \lesssim 10^{-8}$

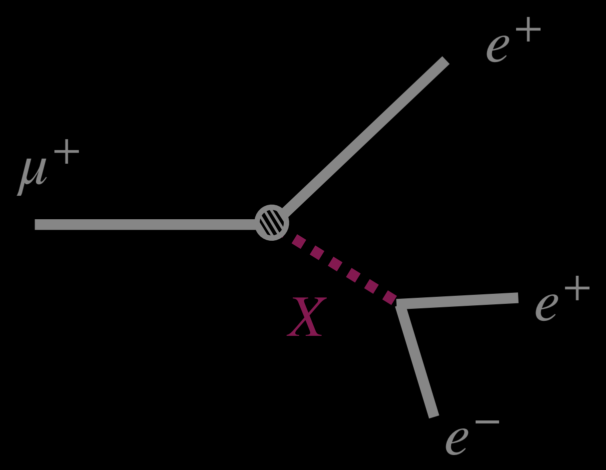
AK. Perrevoort (Ph.D. thesis), 10.11588/heidok.00024585

L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, 10.1007/JHEP09(2021)173

See also $\mu^+ \to e^+a(\gamma^* \to e^+e^-)$ for low masses,

S. Knapen, T. Opferkuch, D. Redigolo, arXiv:2311.17915

(2) $\mu^+ \to e^+(X \to e^+e^-)$ — Visible resonance



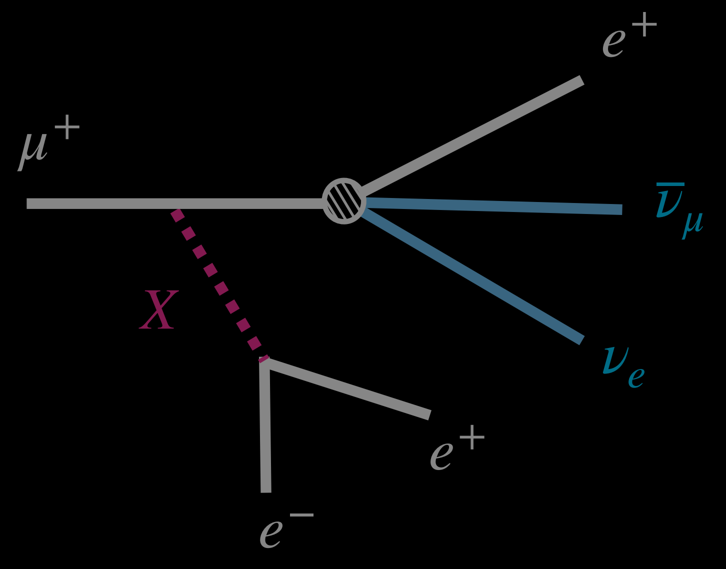
Current limits: $\mathscr{B} \lesssim 3 \times 10^{-12}$

Expected reach: $\mathscr{B} \lesssim 10^{-15}$ or better

J. Heeck, W. Rodejohann, 10.1016/j.physletb.2017.11.067

SINDRUM-I coll., 10.1016/0370-2693(86)90339-4

(3) $\mu^+ \to e^+\nu\nu(X \to e^+e^-)$ — Visible resonance + missing E



Projected reach: $\mathscr{B} \lesssim 10^{-9} - 10^{-11}$.

B. Echenard, R. Essig, Y.M. Zhong, 10.1007/JHEP01(2015)113

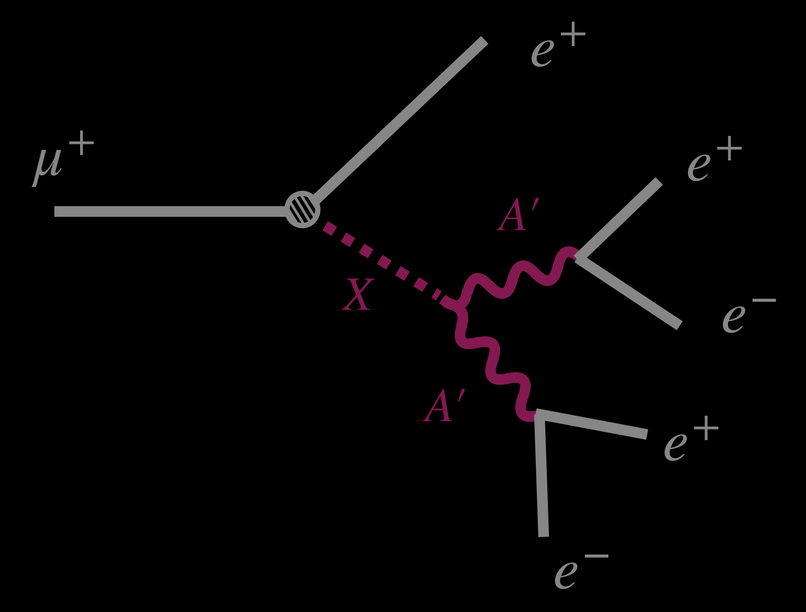
AK. Perrevoort (Ph.D. thesis), 10.11588/heidok.00024585

S. Knapen, T. Opferkuch, D. Redigolo, arXiv:2311.17913

Light particle production at Mu3e

An overview

(4) $\mu^+ \to e^+(X \to e^+e^-e^+e^-)$ — **This talk**



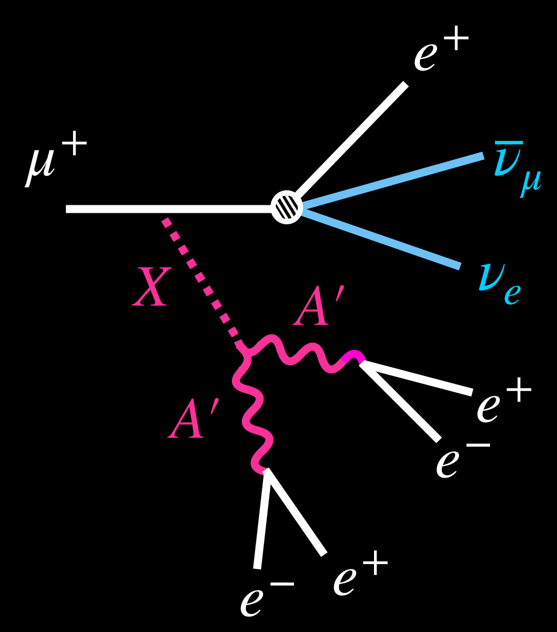
Projected reach: $\mathscr{B} \lesssim 10^{-12} - 10^{-14}$

Cascade of 2-body decays.

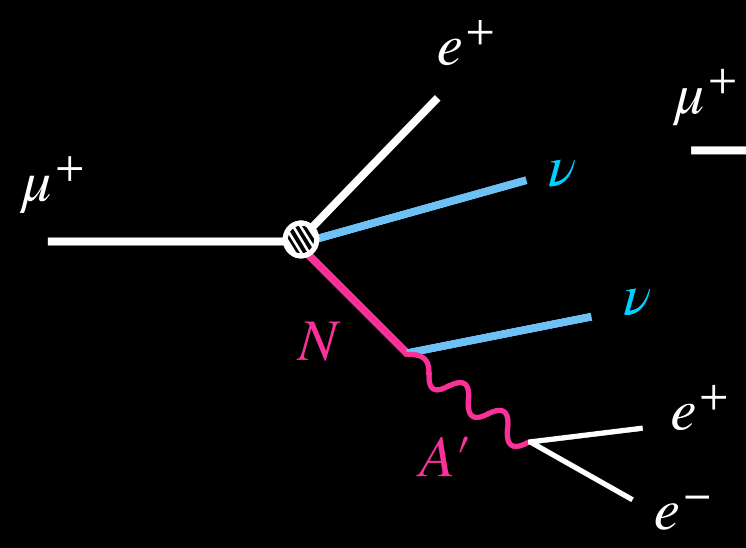
Also, the first study of SM five-track rate.

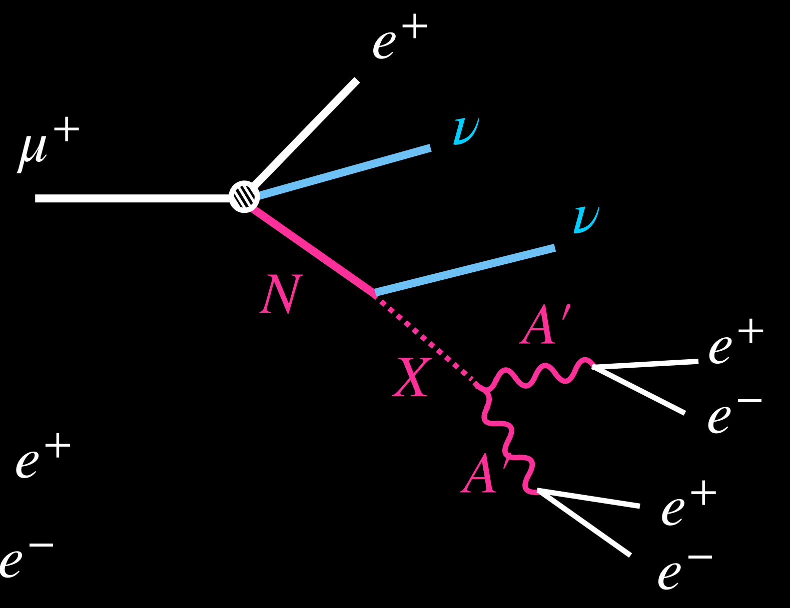
MH, T. Menzo, M. Pospelov, J. Zupan, 10.1007/JHEP10(2023)006

(5) Other modes (not studied)



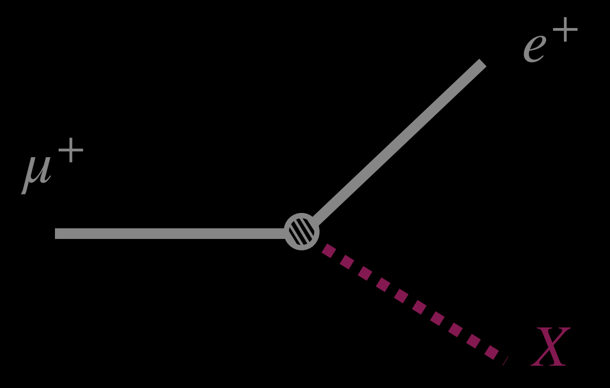
Flavor-preserving version of (4).





Neutrino portal to (3) and (4). Sensitive to mixing of the heavy "dark" neutrino N to electron and muon.

(1) $\mu^+ \to e^+X_{\rm inv}$ — Peak in the Michel spectrum.



Current limits: $\mathscr{B} \lesssim 10^{-5}$

Projected reach: $\mathscr{B} \lesssim 10^{-8}$

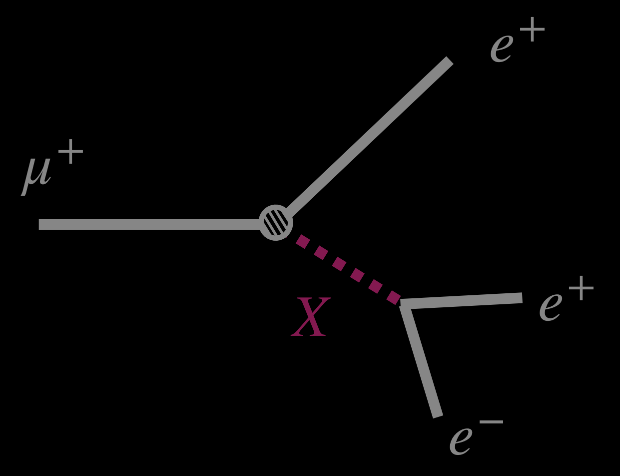
AK. Perrevoort (Ph.D. thesis), 10.11588/heidok.00024585

L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, 10.1007/JHEP09(2021)173

See also $\mu^+ \to e^+a(\gamma^* \to e^+e^-)$ for low masses,

S. Knapen, T. Opferkuch, D. Redigolo, arXiv:2311.17915

(2) $\mu^+ \to e^+(X \to e^+e^-)$ — Visible resonance



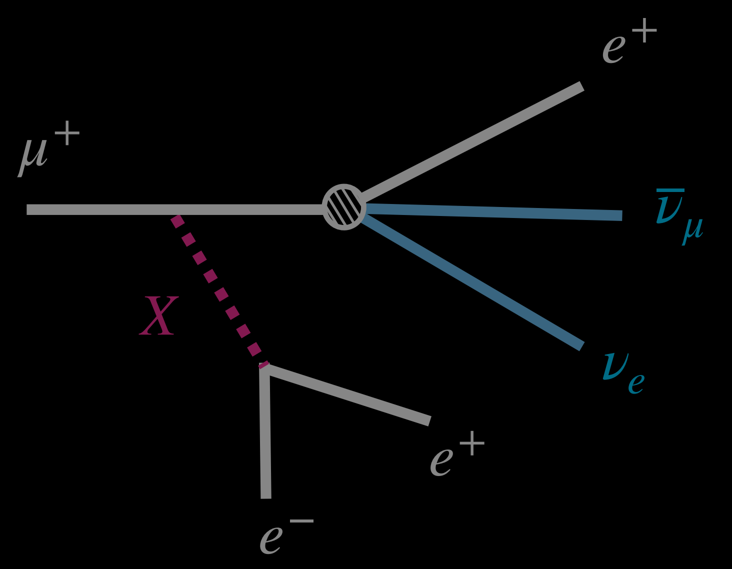
Current limits: $\mathscr{B} \lesssim 3 \times 10^{-12}$

Expected reach: $\mathscr{B} \lesssim 10^{-15}$ or better

J. Heeck, W. Rodejohann, 10.1016/j.physletb.2017.11.067

SINDRUM-I coll., 10.1016/0370-2693(86)90339-4

(3) $\mu^+ \to e^+\nu\nu(X \to e^+e^-)$ — Visible resonance + missing E



Projected reach: $\mathscr{B} \lesssim 10^{-9} - 10^{-11}$.

B. Echenard, R. Essig, Y.M. Zhong, 10.1007/JHEP01(2015)113

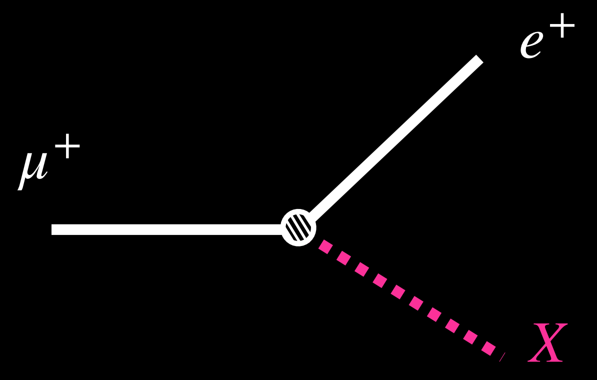
AK. Perrevoort (Ph.D. thesis), 10.11588/heidok.00024585

S. Knapen, T. Opferkuch, D. Redigolo, arXiv:2311.17913

Light particle production at Mu3e

An overview

(1) $\mu^+ \to e^+ X_{\rm inv}$ — Peak in the Michel spectrum.



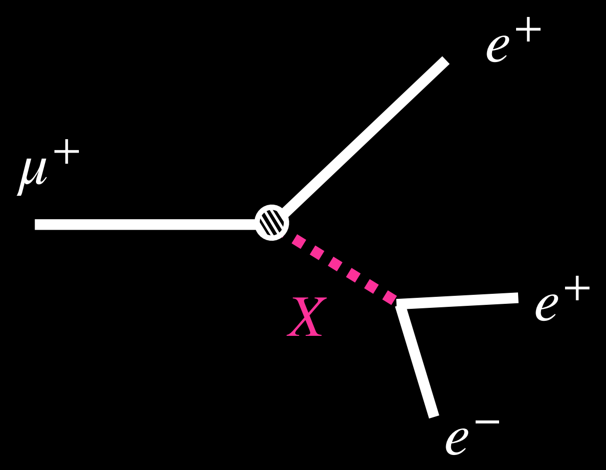
Current limits: $\mathscr{B} \lesssim 10^{-5}$

Projected reach: $\mathscr{B} \lesssim 10^{-8}$

AK. Perrevoort (Ph.D. thesis), 10.11588/heidok.00024585
L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, 10.1007/JHEP09(2021)173

See also $\mu^+ \to e^+ a(\gamma^* \to e^+ e^-)$ for low masses,
S. Knapen, T. Opferkuch, D. Redigolo, arXiv:2311.17915

(2) $\mu^+ \to e^+(X \to e^+ e^-)$ — Visible resonance

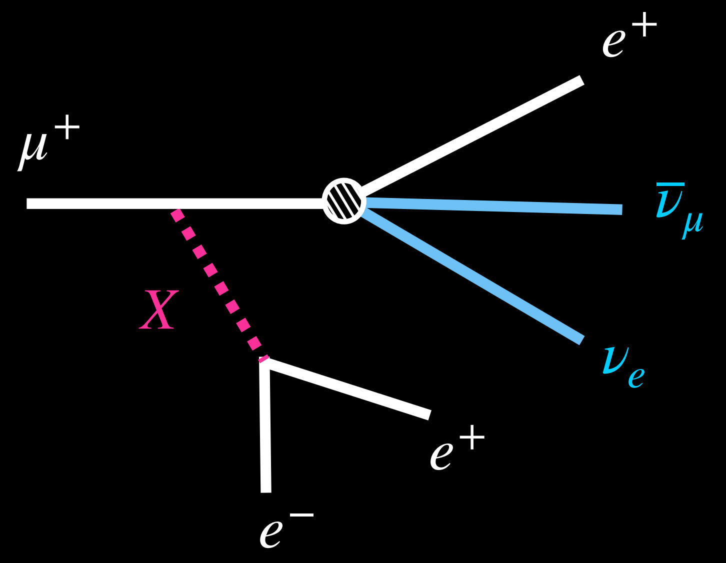


Current limits: $\mathscr{B} \lesssim 3 \times 10^{-12}$

Expected reach: $\mathscr{B} \lesssim 10^{-15}$ or better

J. Heeck, W. Rodejohann, 10.1016/j.physletb.2017.11.067
SINDRUM-I coll., 10.1016/0370-2693(86)90339-4

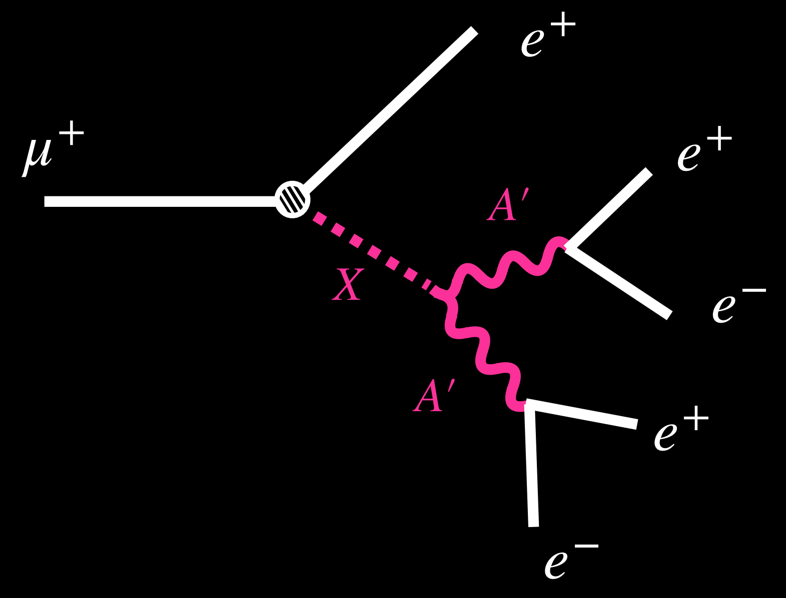
(3) $\mu^+ \to e^+ \nu\nu (X \to e^+ e^-)$ — Visible resonance + missing E



Projected reach: $\mathscr{B} \lesssim 10^{-9} - 10^{-11}$.

B. Echenard, R. Essig, Y.M. Zhong, 10.1007/JHEP01(2015)113
AK. Perrevoort (Ph.D. thesis), 10.11588/heidok.00024585
S. Knapen, T. Opferkuch, D. Redigolo, arXiv:2311.17913

(4) $\mu^+ \to e^+(X \to e^+ e^- e^+ e^-)$ — Two visible resonances



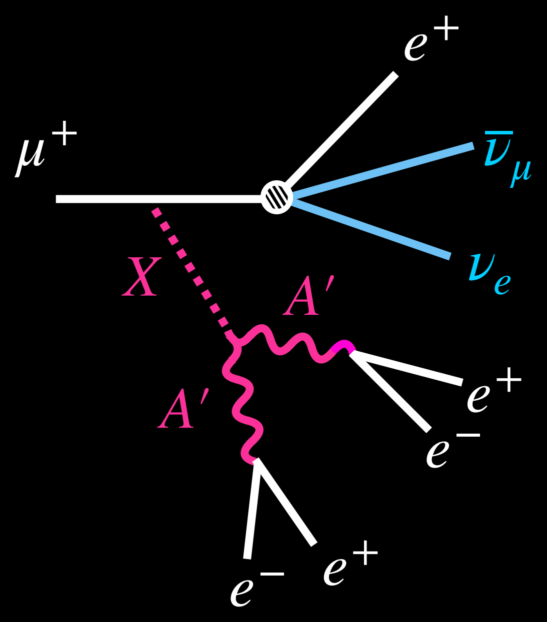
Projected reach: $\mathscr{B} \lesssim 10^{-12} - 10^{-14}$

Cascade of 2-body decays.

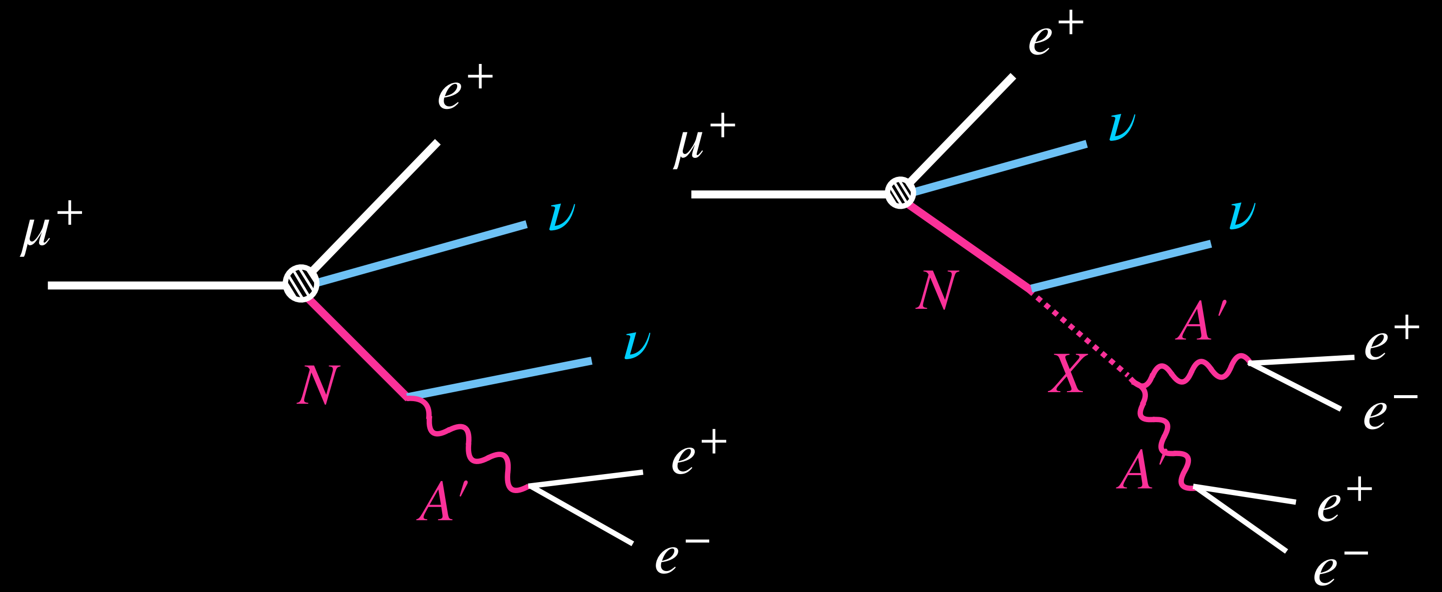
Also, the first study of SM five-track rate.

MH, T. Menzo, M. Pospelov, J. Zupan, 10.1007/JHEP10(2023)006

(5) Other modes (not studied)



Flavor-preserving version of (4).



Neutrino portal to (3) and (4). Sensitive to mixing of the heavy "dark" neutrino N to electron and muon.

Rare muon decays at Mu3e

Higgsed $U(1)_d$ — more is different

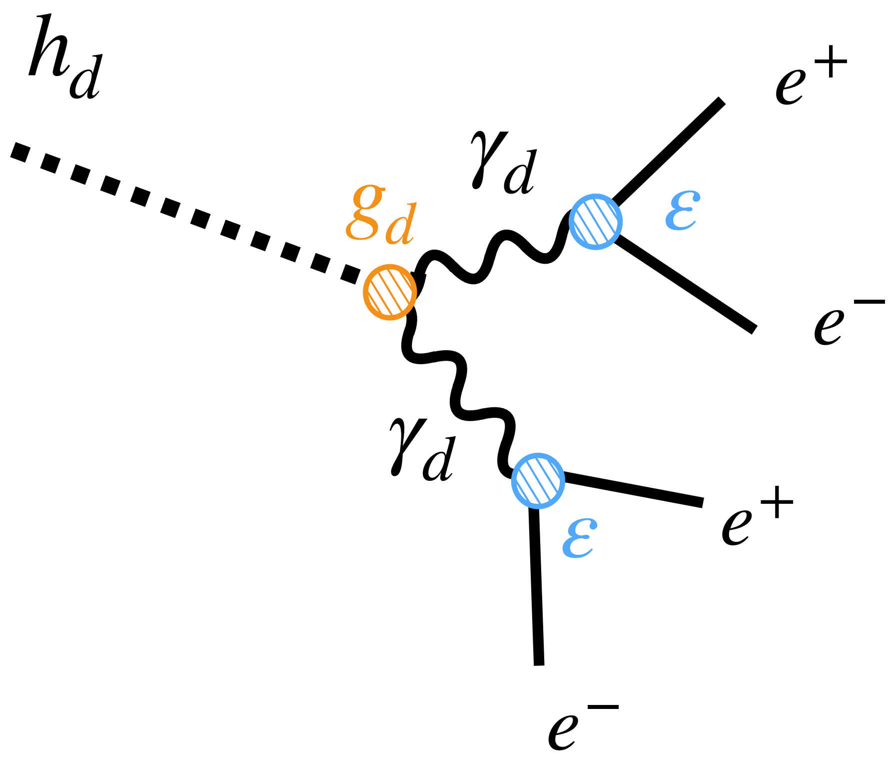
MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

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

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

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

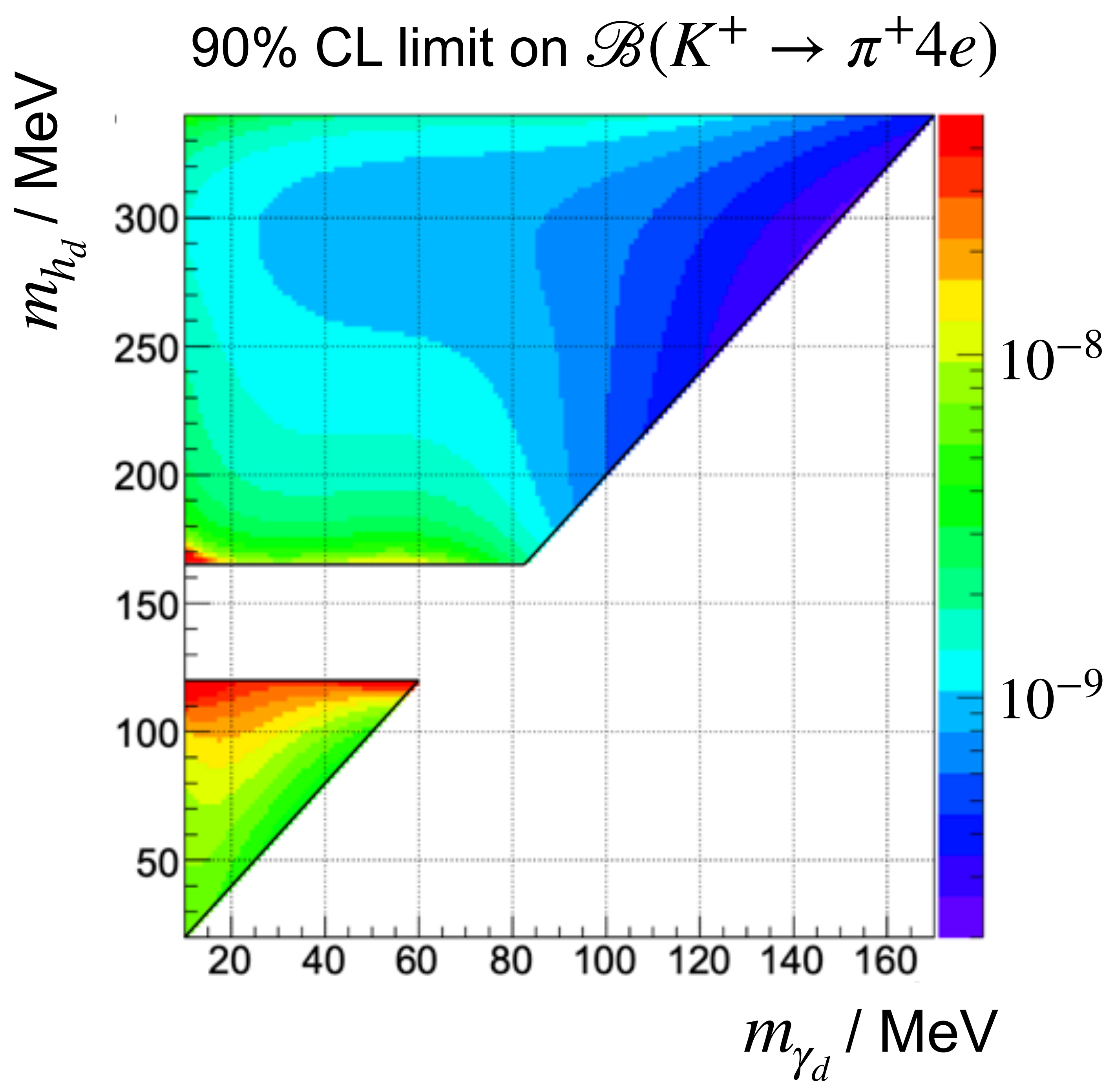
Simple and well-motivated model — multiplication of leptons comes "for free."



Rare muon decays at Mu3e

Higgsed $U(1)_d$ — more is different

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



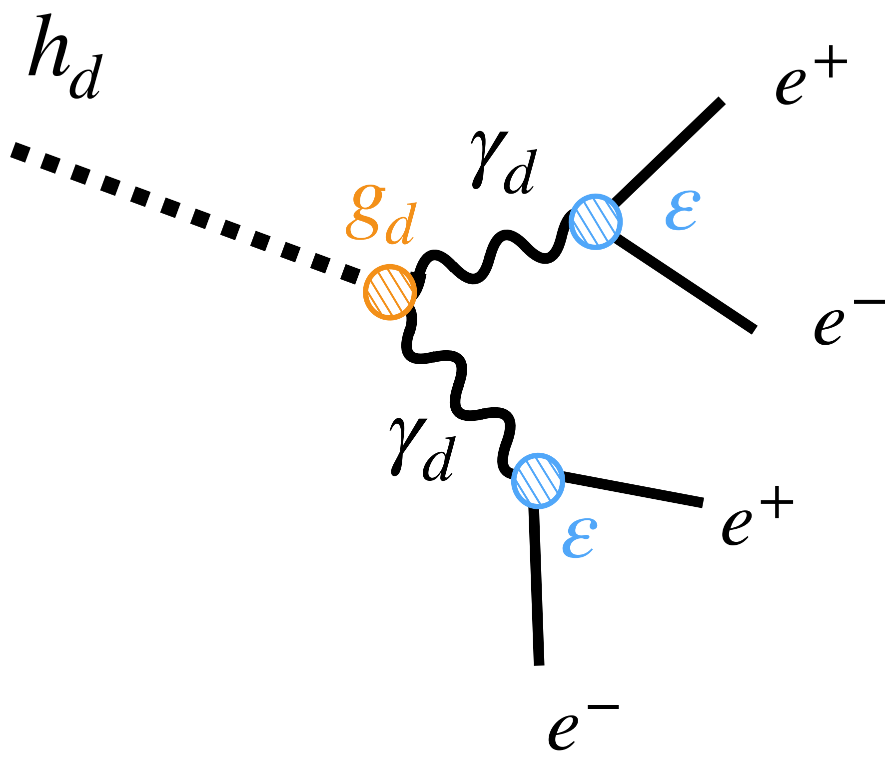
Higgsed dark $U(1)_d$: dark photon (γ_d) gets a mass from the dark Higgs (h_d), and kinetically mixes with hypercharge:

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

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."

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



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

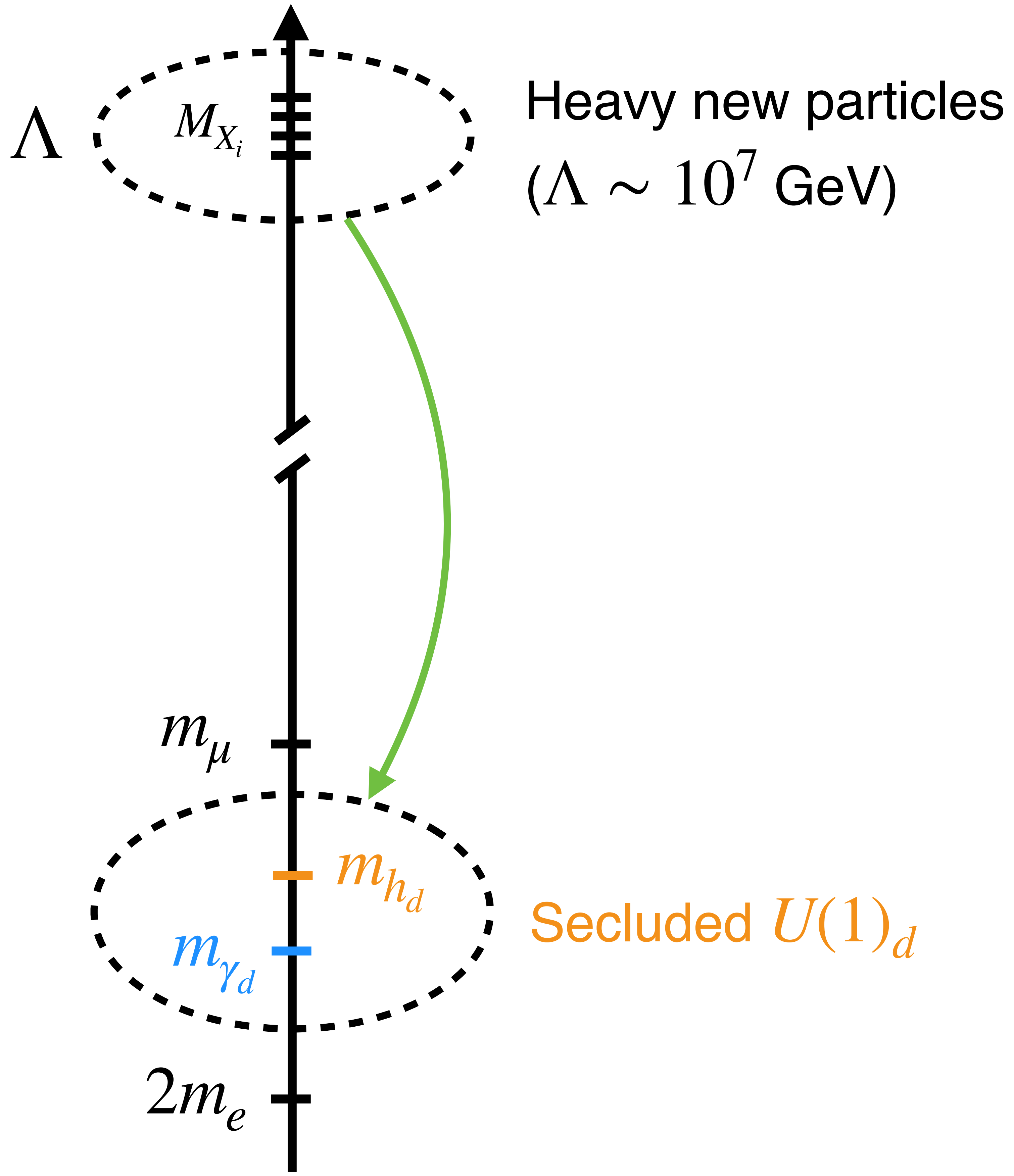
$K^+ \to \pi^+(h_d \to \gamma_d\gamma_d \to 2(e^+e^-))$

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

Consider now new operators with cLFV couplings to leptons.

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

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



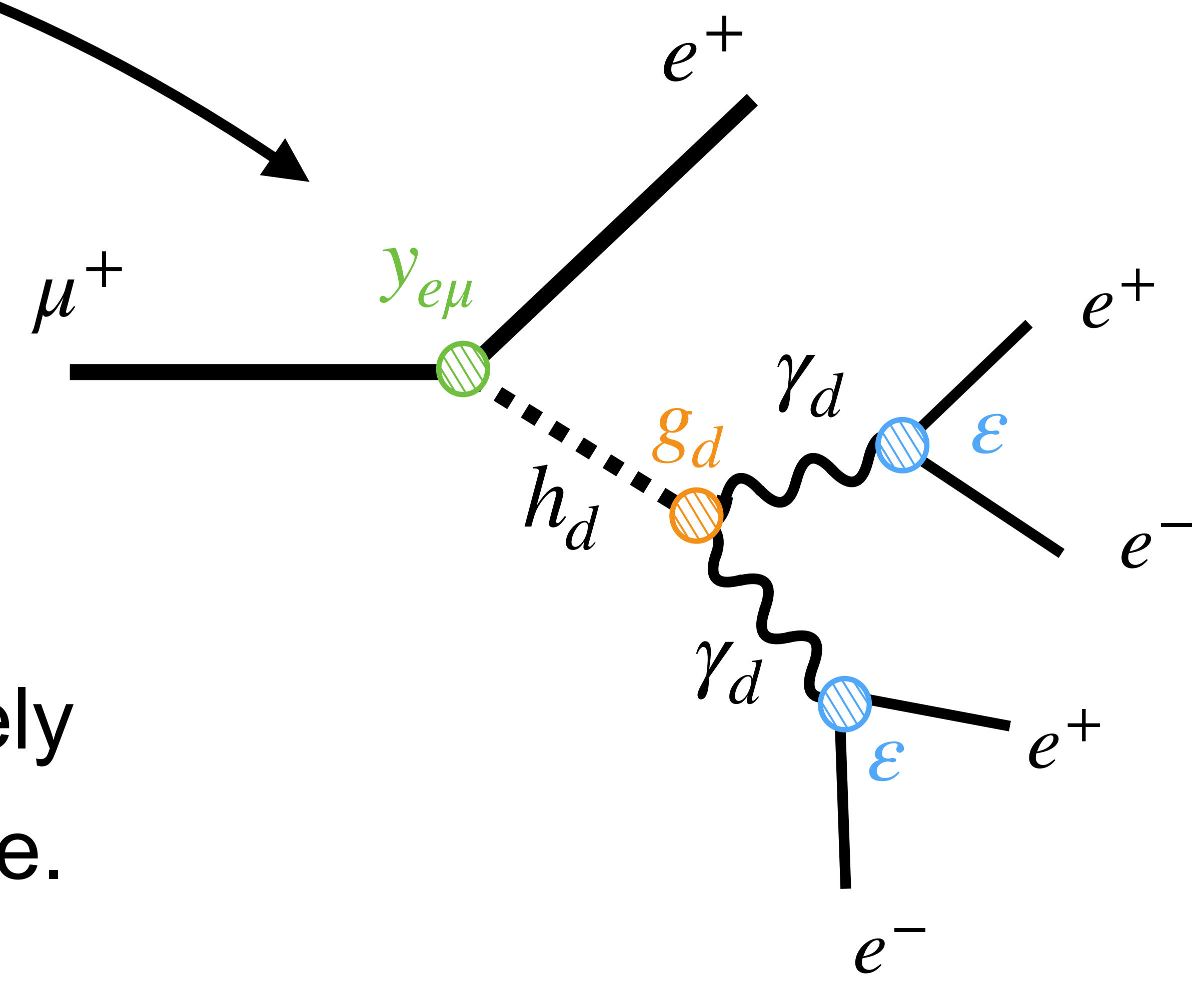
Lowest-dimension operators in the “h_d - EFT” that violate flavor:

$$\mathscr{L}_{\rm cLFV} \supset \frac{|h_d|^2}{\Lambda^2}\left(Y_{e\mu}\overline{L}_\mu H e_R + Y_{\mu e}\overline{L}_e H \mu_R\right) \xrightarrow[\cancel{\rm U(1)_d}]{\cancel{\rm EW}} h_d\left(y_{e\mu}\overline{\mu}_L e_R + y_{\mu e}\overline{e}_L \mu_R\right), \qquad y_{e\mu} = \frac{Y_{e\mu} v_{\rm EW} v_d}{\sqrt{2}\Lambda^2}$$

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

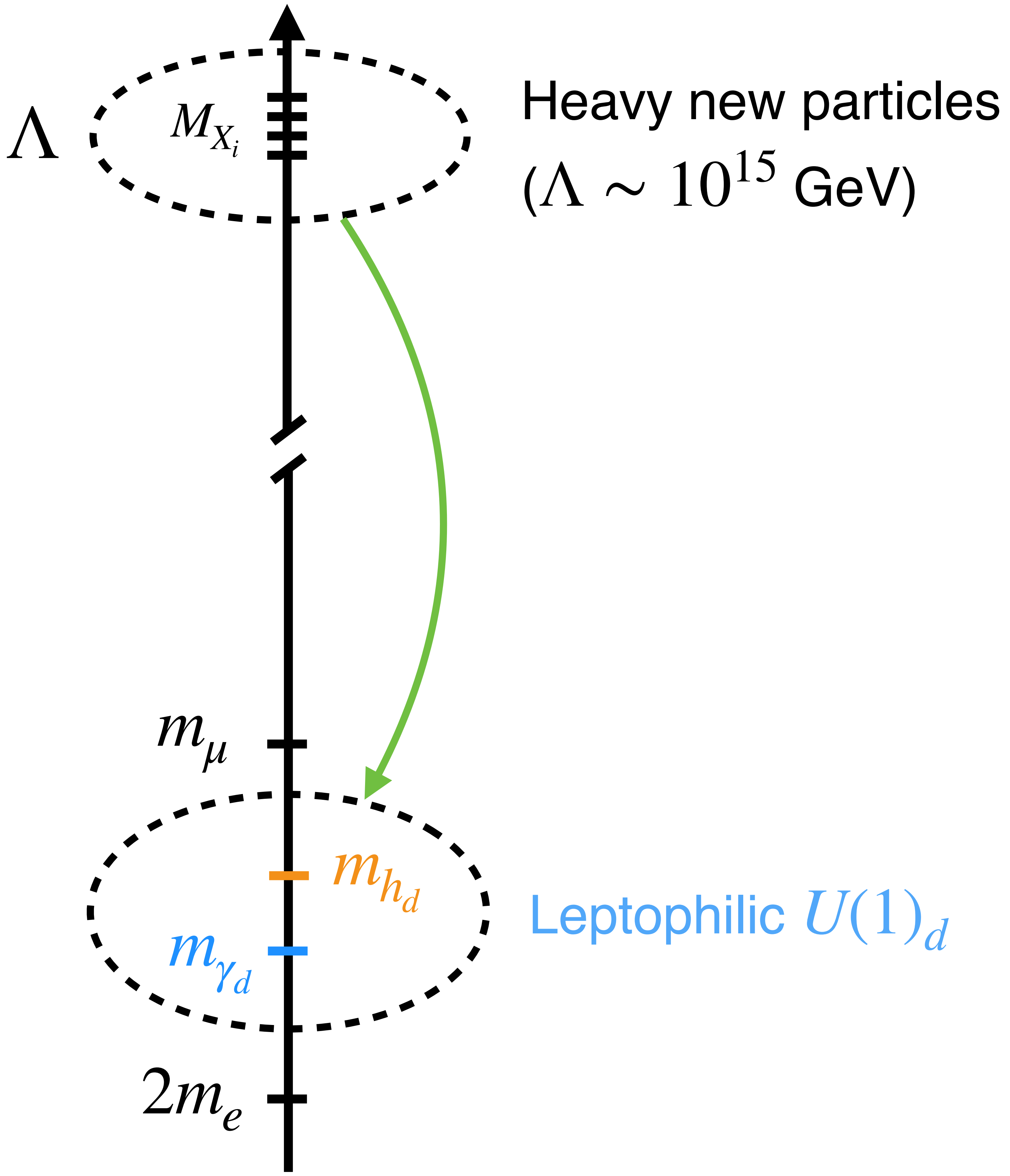
If $m_\mu - m_e > m_{h_d} > 2m_{\gamma_d} > 4m_e$:

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.



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

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



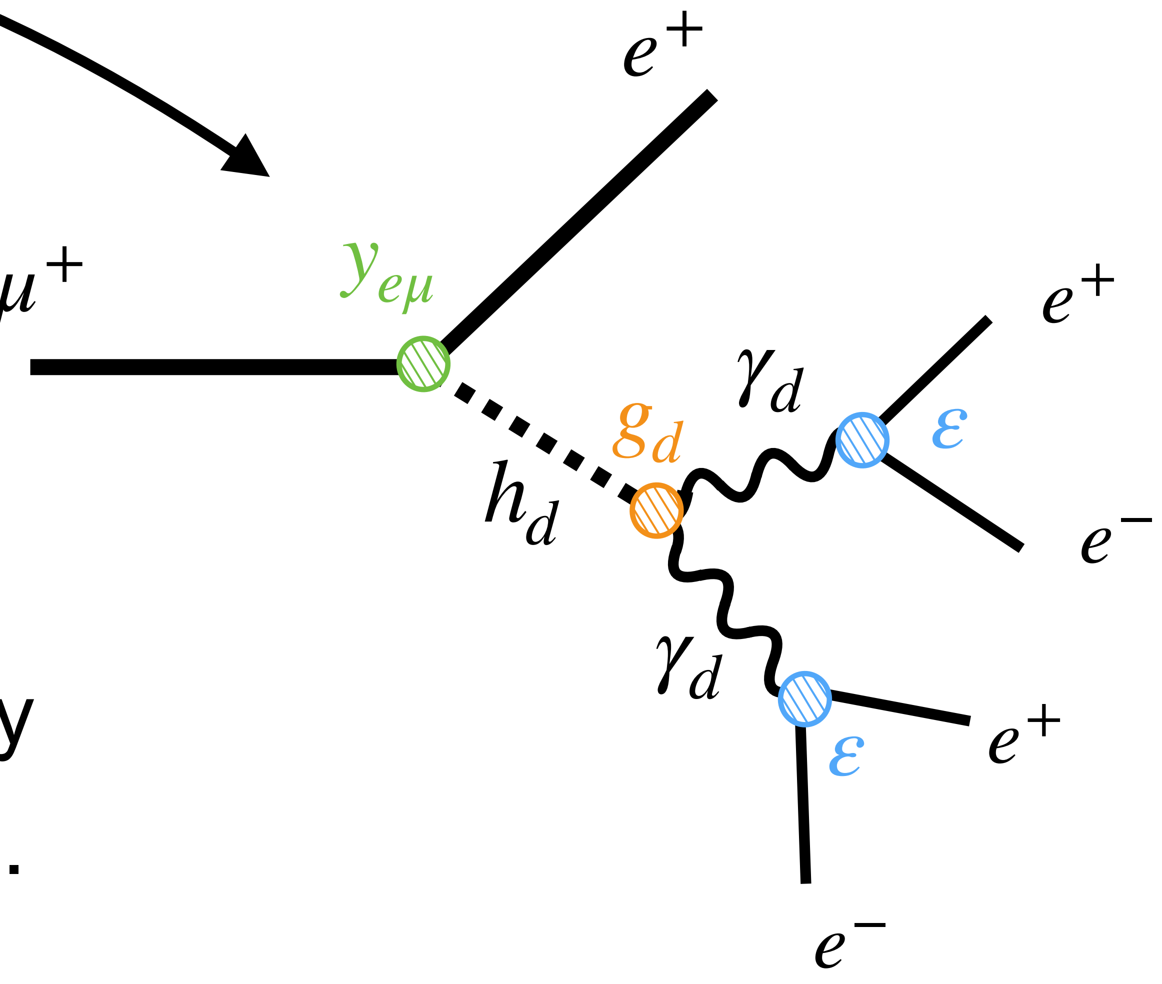
Lowest-dimension operators in the "h_d - EFT" that violate flavor*:

$$\mathscr{L}_{\rm cLFV} \supset \frac{h_d}{\Lambda}\left(Y_{e\mu}\overline{L}_\mu H e_R + Y_{\mu e}\overline{L}_e H \mu_R\right) \xrightarrow[\text{U(1)}_\text{d}]{\text{EW}} h_d\left(y_{e\mu}\overline{\mu}_L e_R + y_{\mu e}\overline{e}_L \mu_R\right), \qquad y_{e\mu} = \frac{Y_{e\mu} v_{\rm EW}}{\sqrt{2}\Lambda}$$

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.



* E.g., $U(1)_d = U(1)_{L_\mu - L_\tau}$ and $|Q(h_d)| = 1$

Rare muon decays at Mu3e
Mu3e at PSI

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

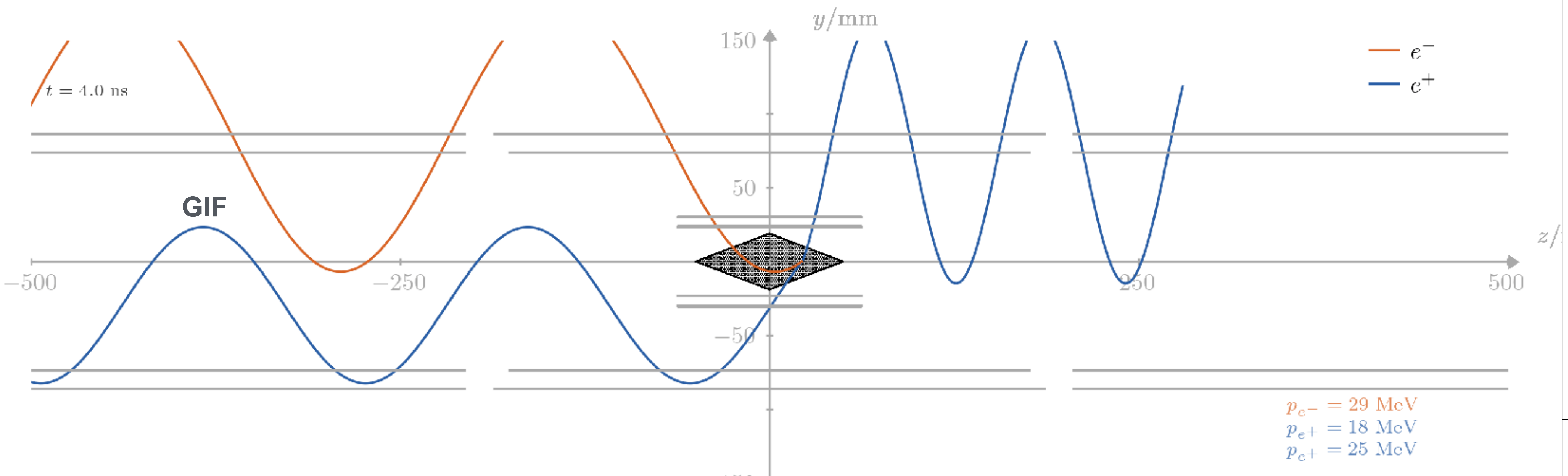
(4 orders of magnitude improvement on current limits).

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

Phase-II: $\gtrsim 5 \times 10^{16}\ \mu^+$ 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 e^+/e^- deflected by about 2° in $1\ \%$ of radiation length due to multiple scattering.

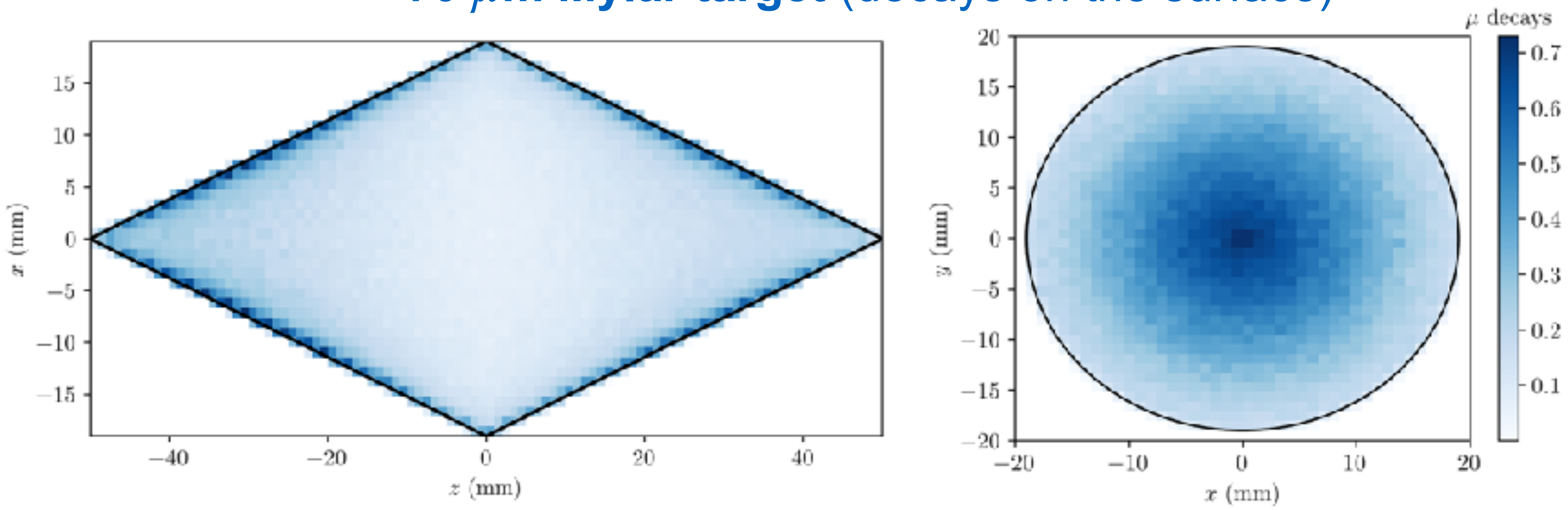


Rare muon decays at Mu3e
A theorist's fast MC for the detector

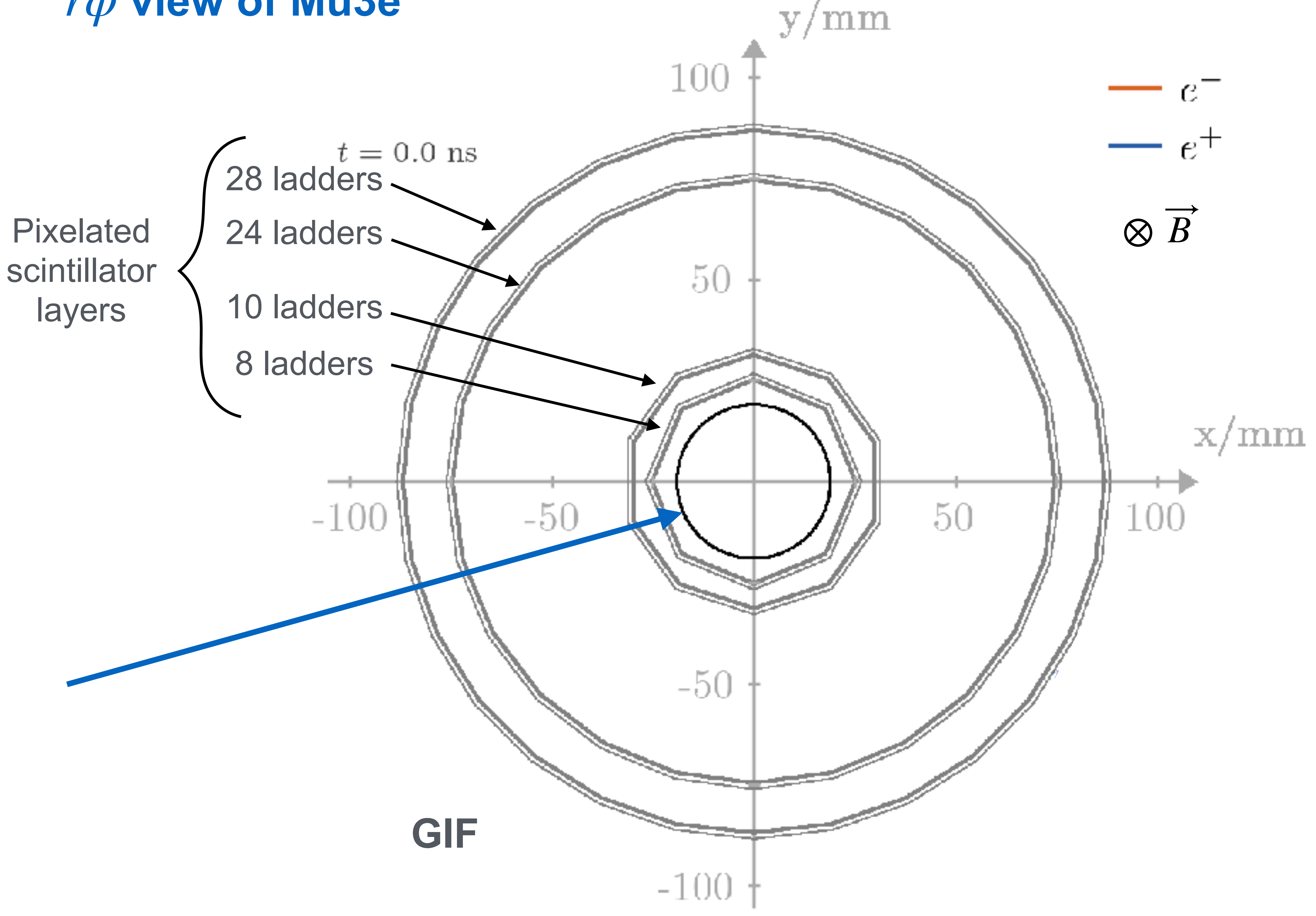
MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

1) Generating muon decays with MadGraph5 v3.5.0 and Scikit-HEP phase-space package (unpolarized μ).
2) Place muons on surface of Mylar target.*
3) Draw helical trajectories with B = 1 T, smearing $|p_e|$ with energy-dependent Gaussians.*
4) Signal selection based on # of hits on scintillator layers.

70 μm Mylar target (decays on the surface)



$r\phi$ view of Mu3e



GIF

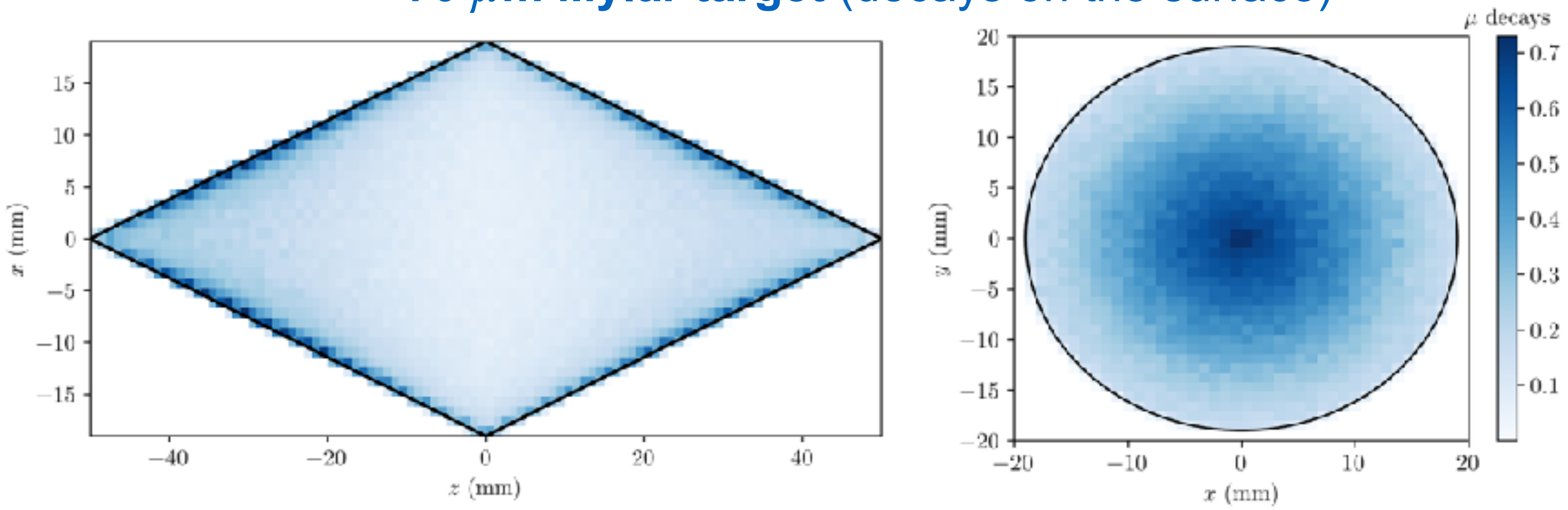
* Technical design of the phase I Mu3e experiment arXiv:2009.11690

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

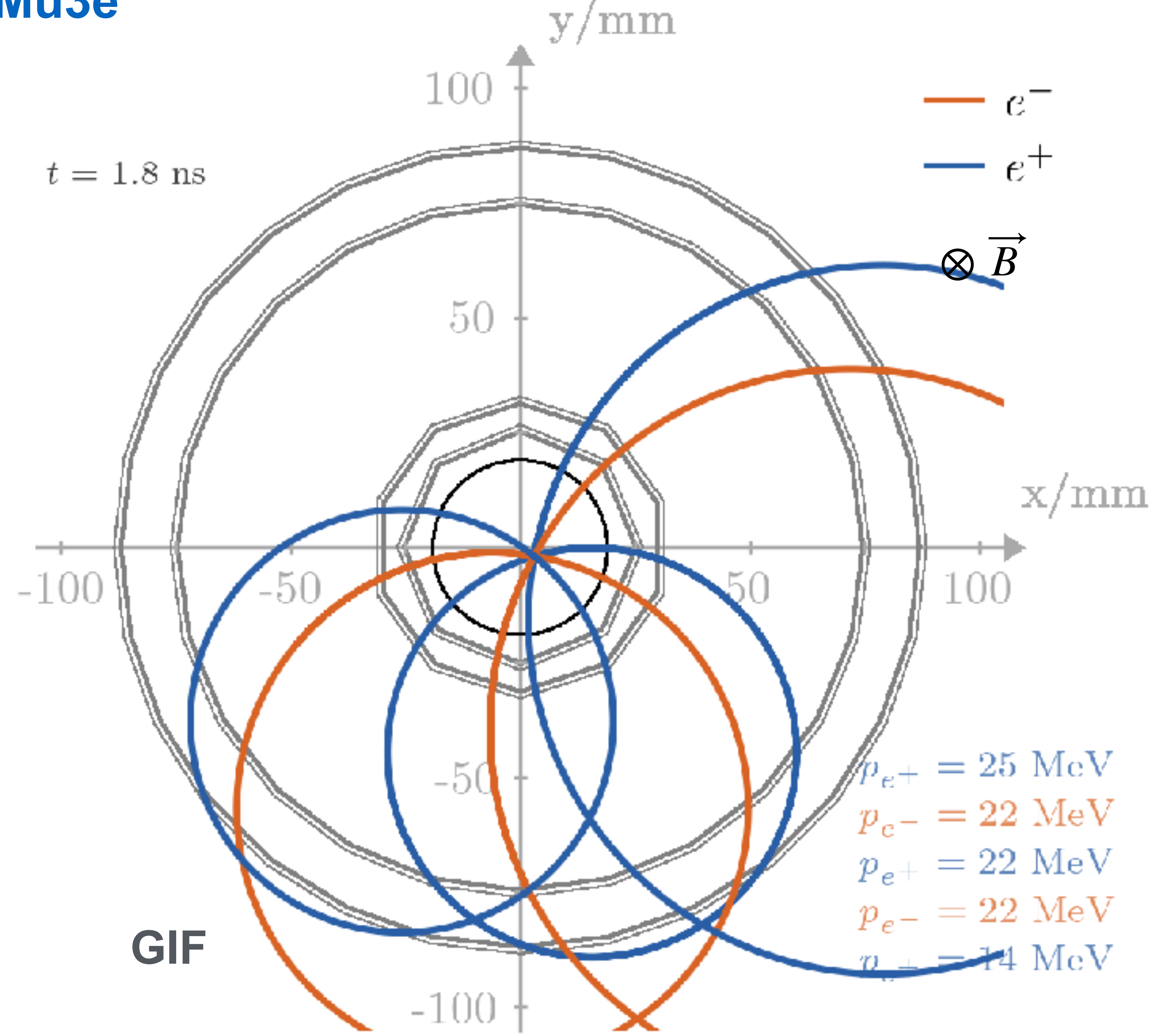
MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

1) Generating muon decays with MadGraph5 v3.5.0 and Scikit-HEP phase-space package (unpolarized μ).
2) Place muons on surface of Mylar target.*
3) Draw helical trajectories with B = 1 T, smearing $|p_e|$ with energy-dependent Gaussians.*
4) Signal selection based on # of hits on scintillator layers.

70 μm Mylar target (decays on the surface)



$r\phi$ view of Mu3e



GIF

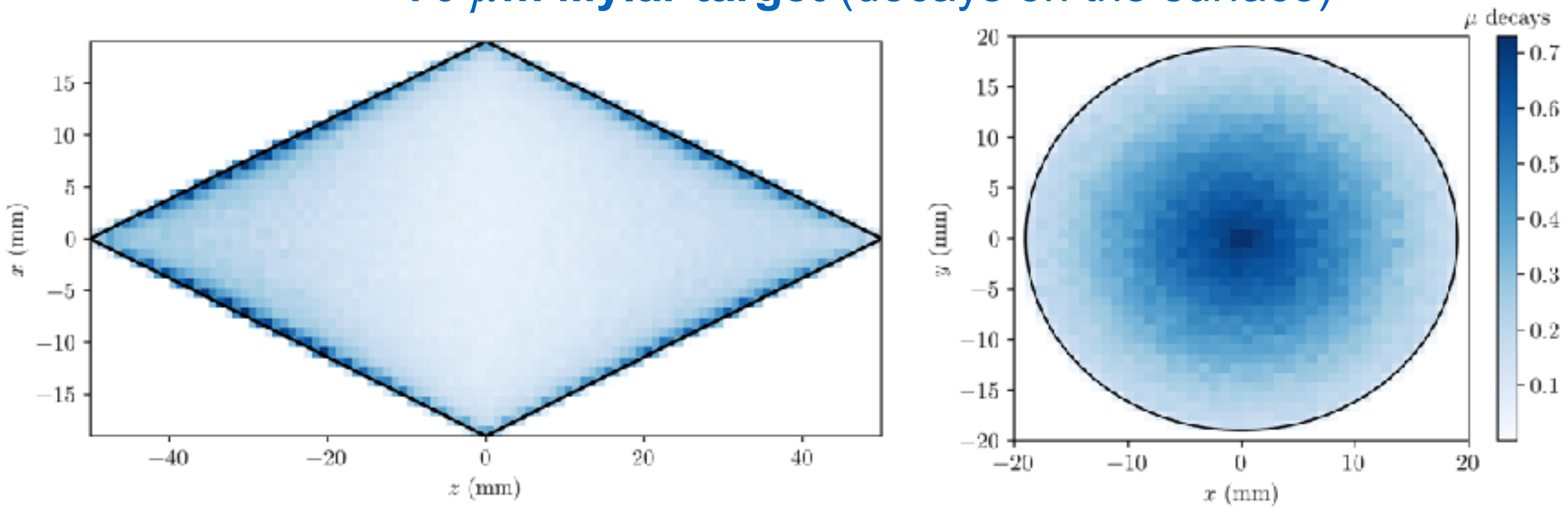
* Technical design of the phase I Mu3e experiment arXiv:2009.11690

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

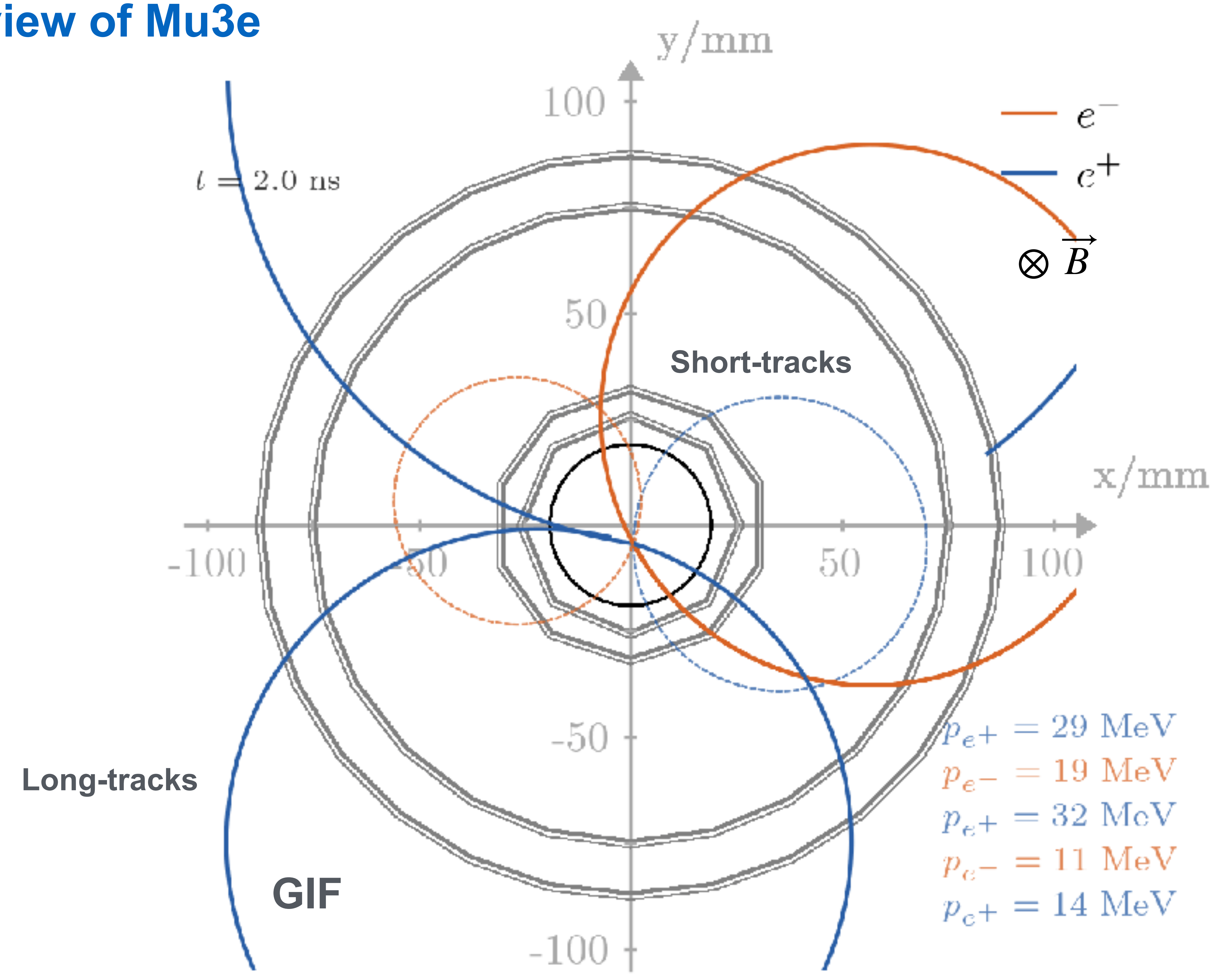
MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

1) Generating muon decays with MadGraph5 v3.5.0 and Scikit-HEP phase-space package (unpolarized μ).
2) Place muons on surface of Mylar target.*
3) Draw helical trajectories with B = 1 T, smearing $|p_e|$ with energy-dependent Gaussians.*
4) Signal selection based on # of hits on scintillator layers.

70 μm Mylar target (decays on the surface)



$r\phi$ **view of Mu3e**



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

Rare muon decays at Mu3e
The Standard Model rate

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

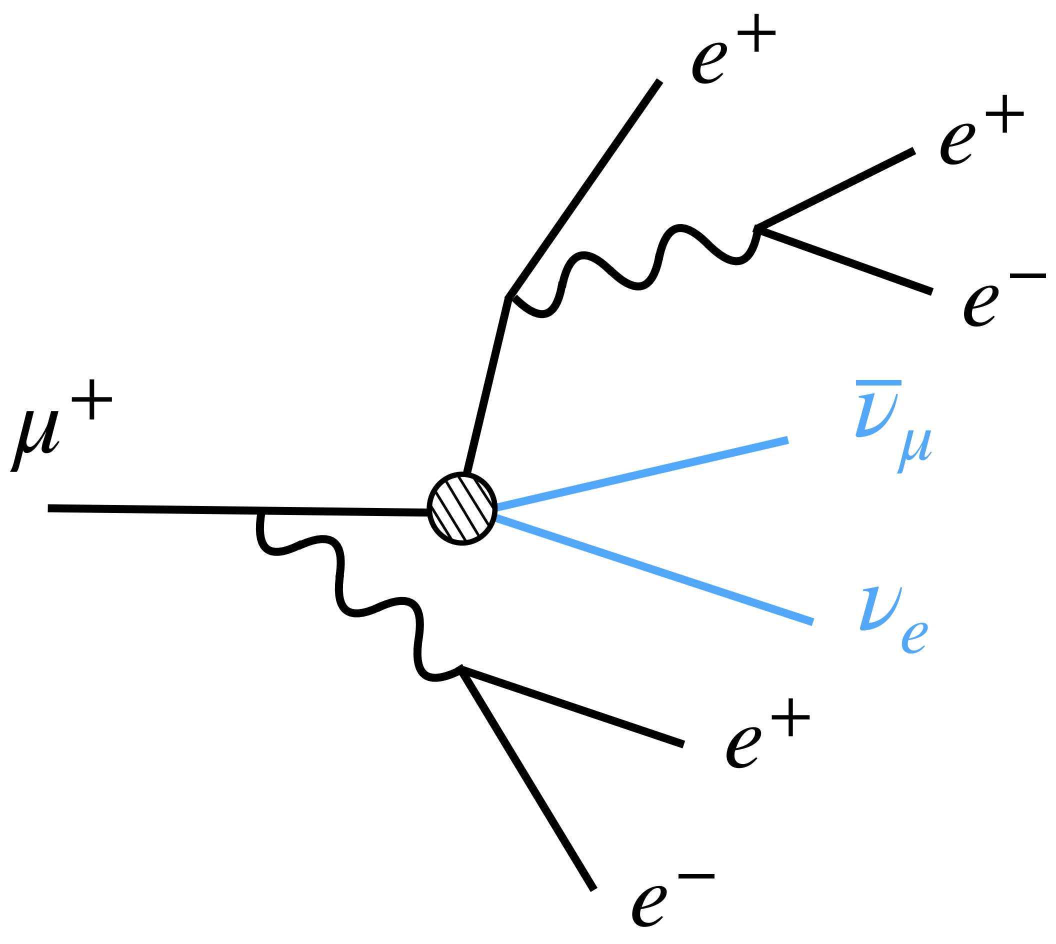
From MadGraph5 v3.5.0, we can calculate the total rate:

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?

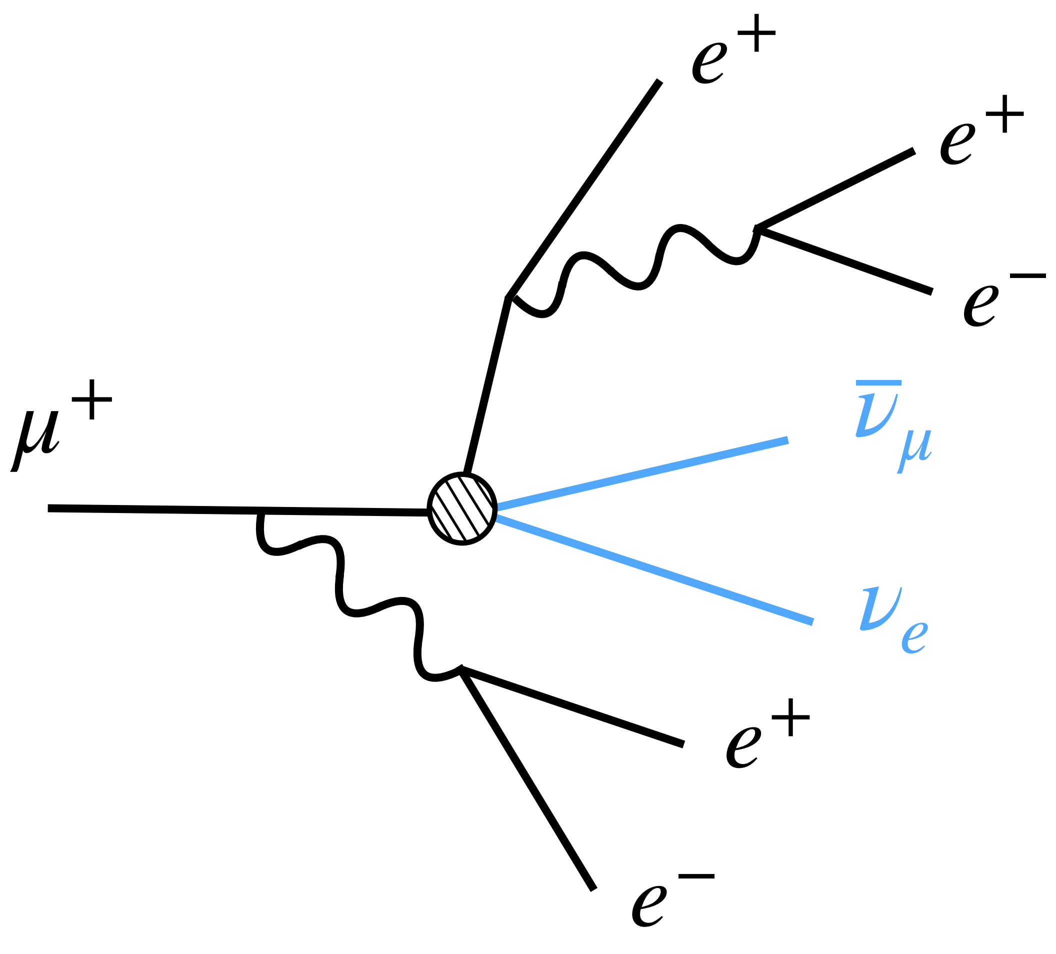
Rare muon decays at Mu3e
The Standard Model rate

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

From MadGraph5 v3.5.0, we can calculate the total rate:

Leading order in G_F and α — negligible MC stats error

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



1 of 84 diagrams

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

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

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

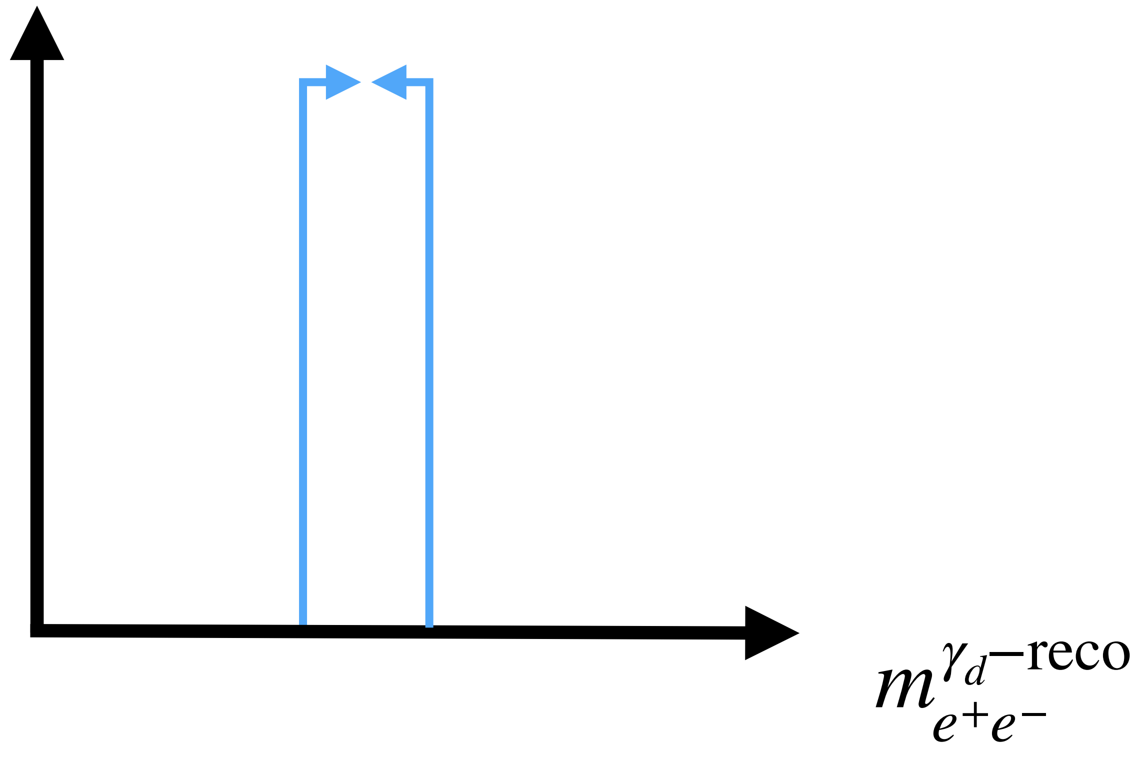
When looking for neutrino-less channels, this SM rate will not be an issue. Missing energy cuts are very effective:

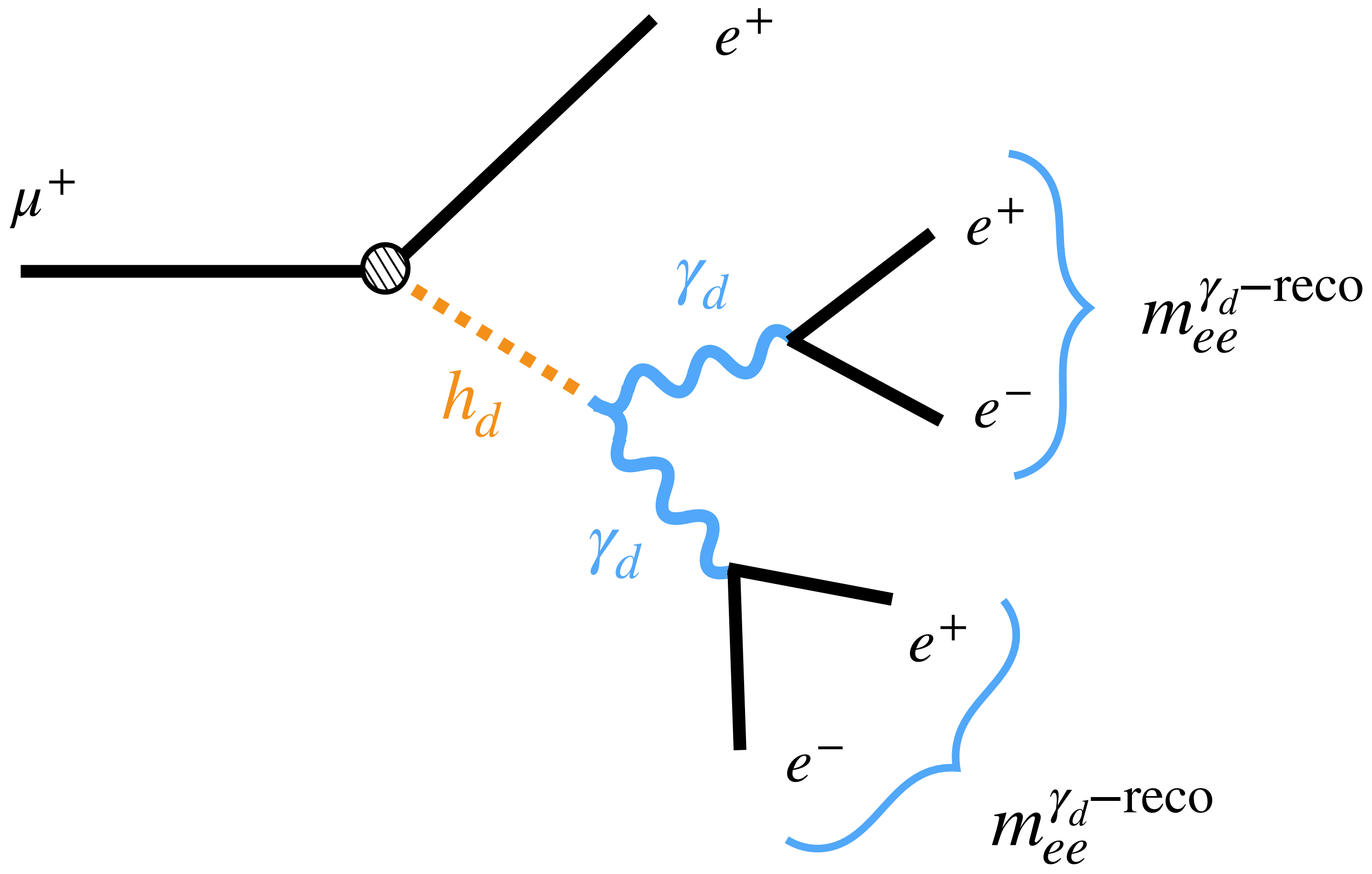
$$\mathscr{B}\left(\mu^+ \to e^+e^+e^-e^+e^-\nu\nu \,|\, E_{\text{missing}}^{\text{true}} < 20\text{ MeV}\right) = (8.9 \pm 0.3) \times 10^{-14}$$
$$\mathscr{B}\left(\mu^+ \to e^+e^+e^-e^+e^-\nu\nu \,|\, E_{\text{missing}}^{\text{true}} < 10\text{ MeV}\right) = (1.1 \pm 0.2) \times 10^{-15}$$

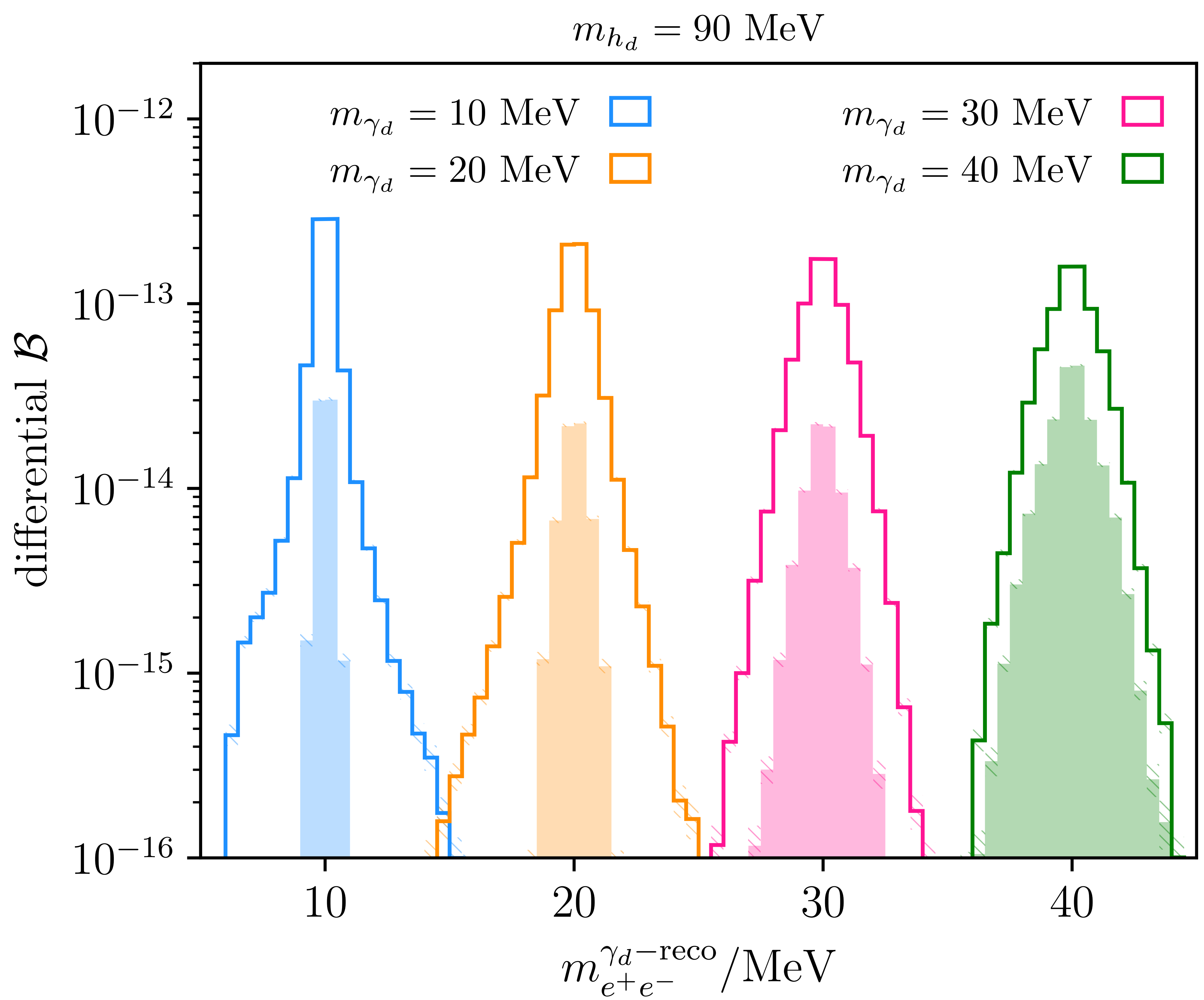
Rare muon decays at Mu3e
Neutrinoless five-track events

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

Double bump hunt





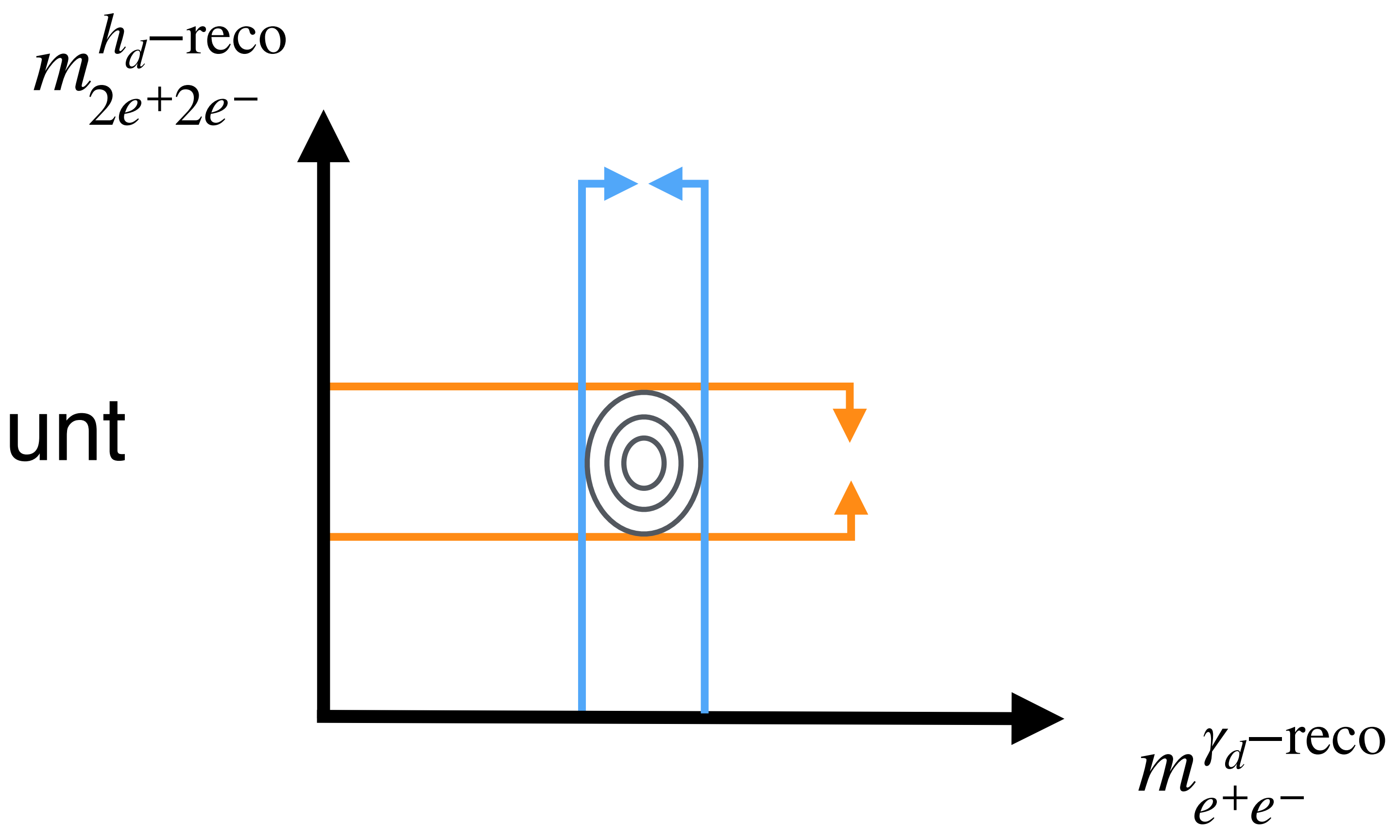


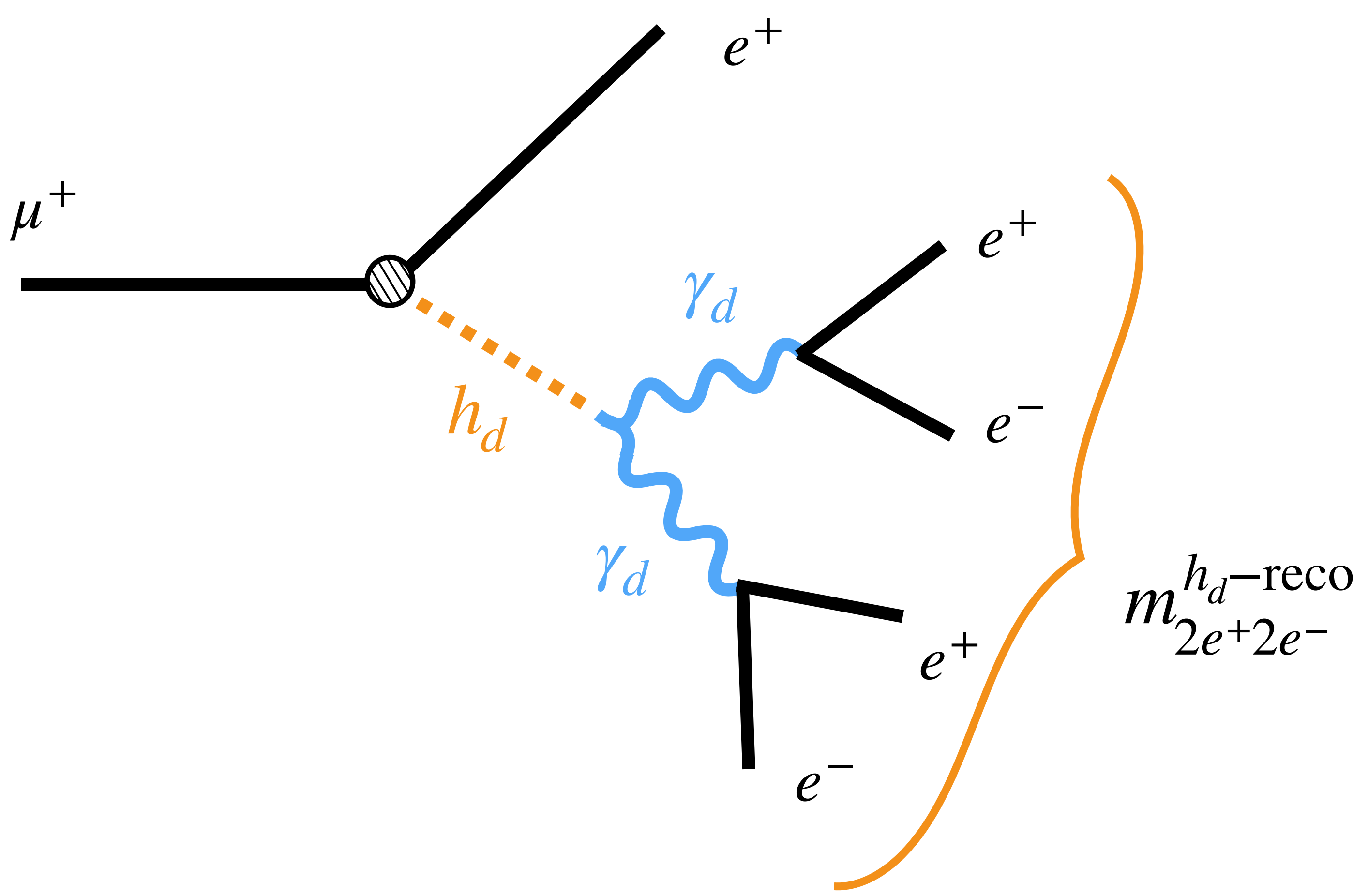
We find: $\sigma_{m_{\gamma_d}}/m_{\gamma_d} = 2.3\%$

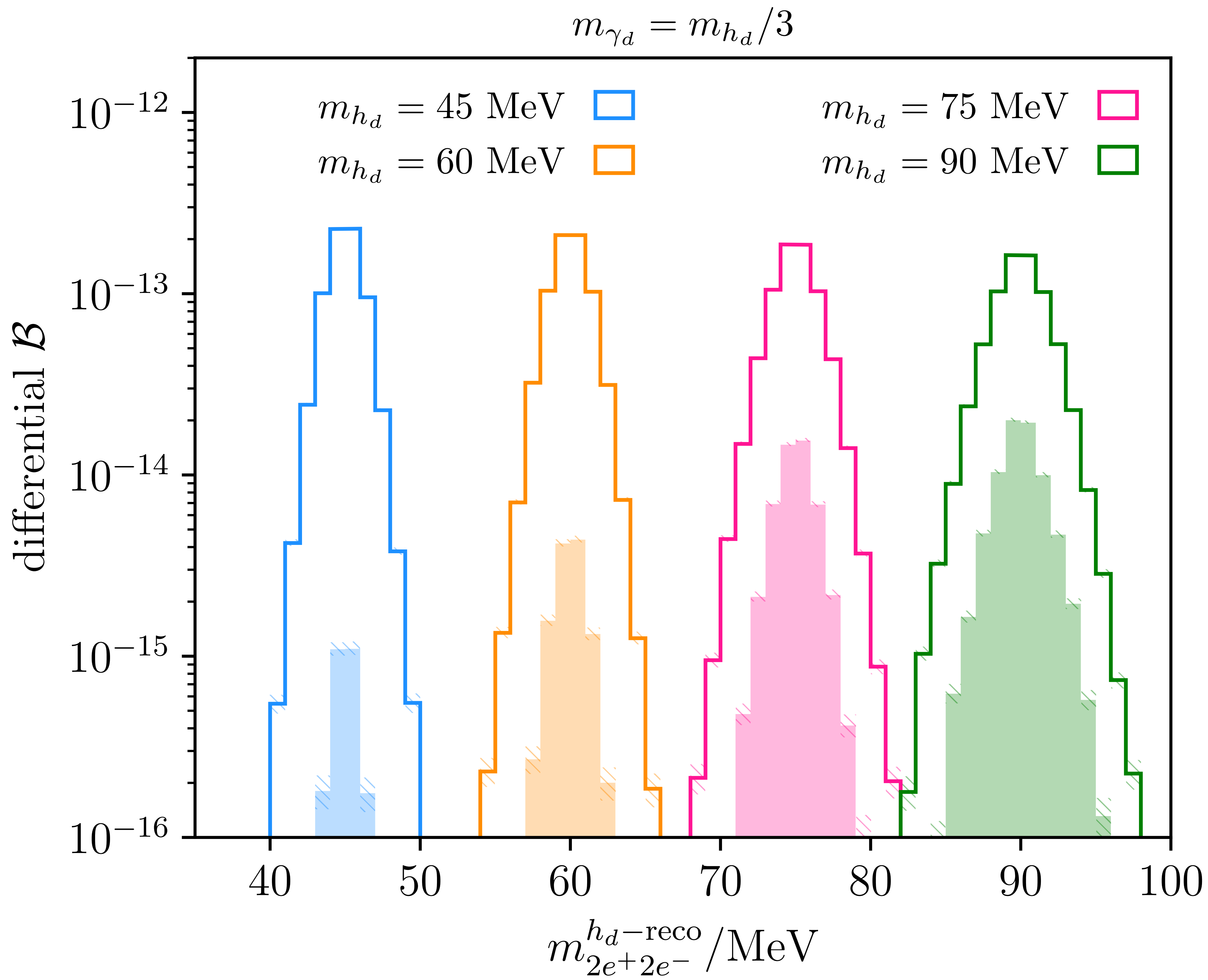
Rare muon decays at Mu3e
Neutrinoless five-track events

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

Double bump hunt





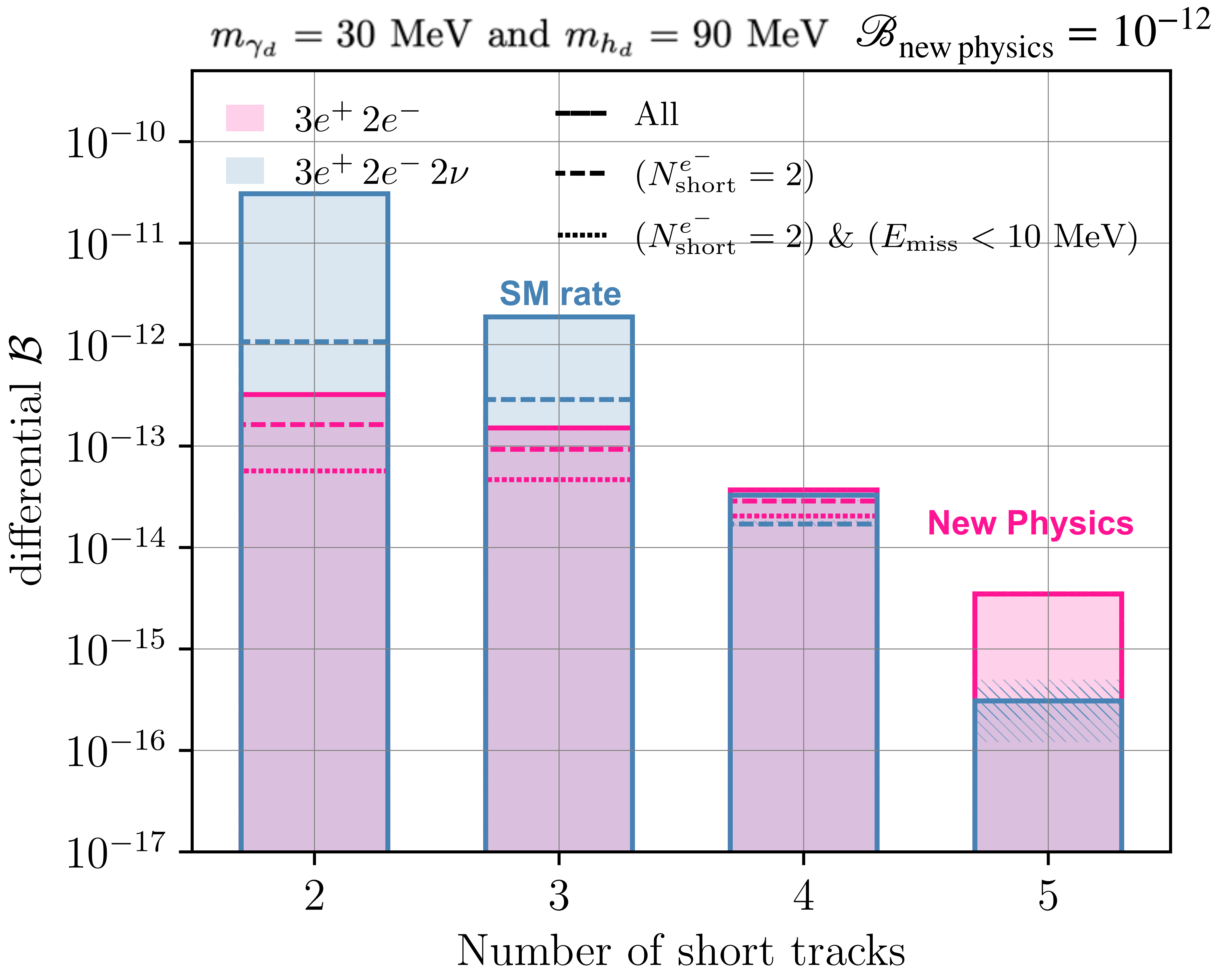


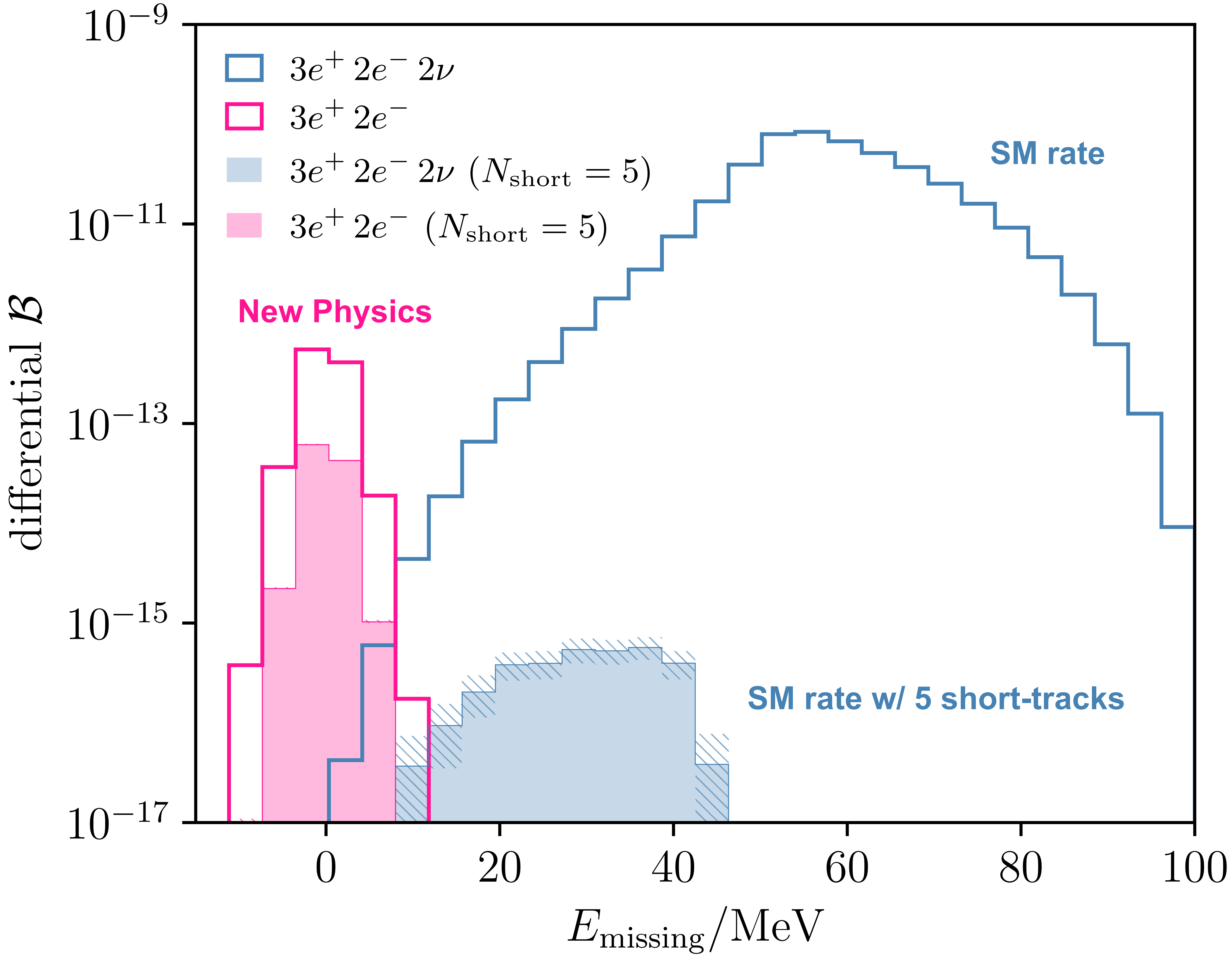
We find: $\sigma_{m_{\gamma_d}}/m_{\gamma_d} = 2.3\%$ and $\sigma_{m_{h_d}}/m_{h_d} = 1.5\%$

Rare muon decays at Mu3e
Signal selection for new physics

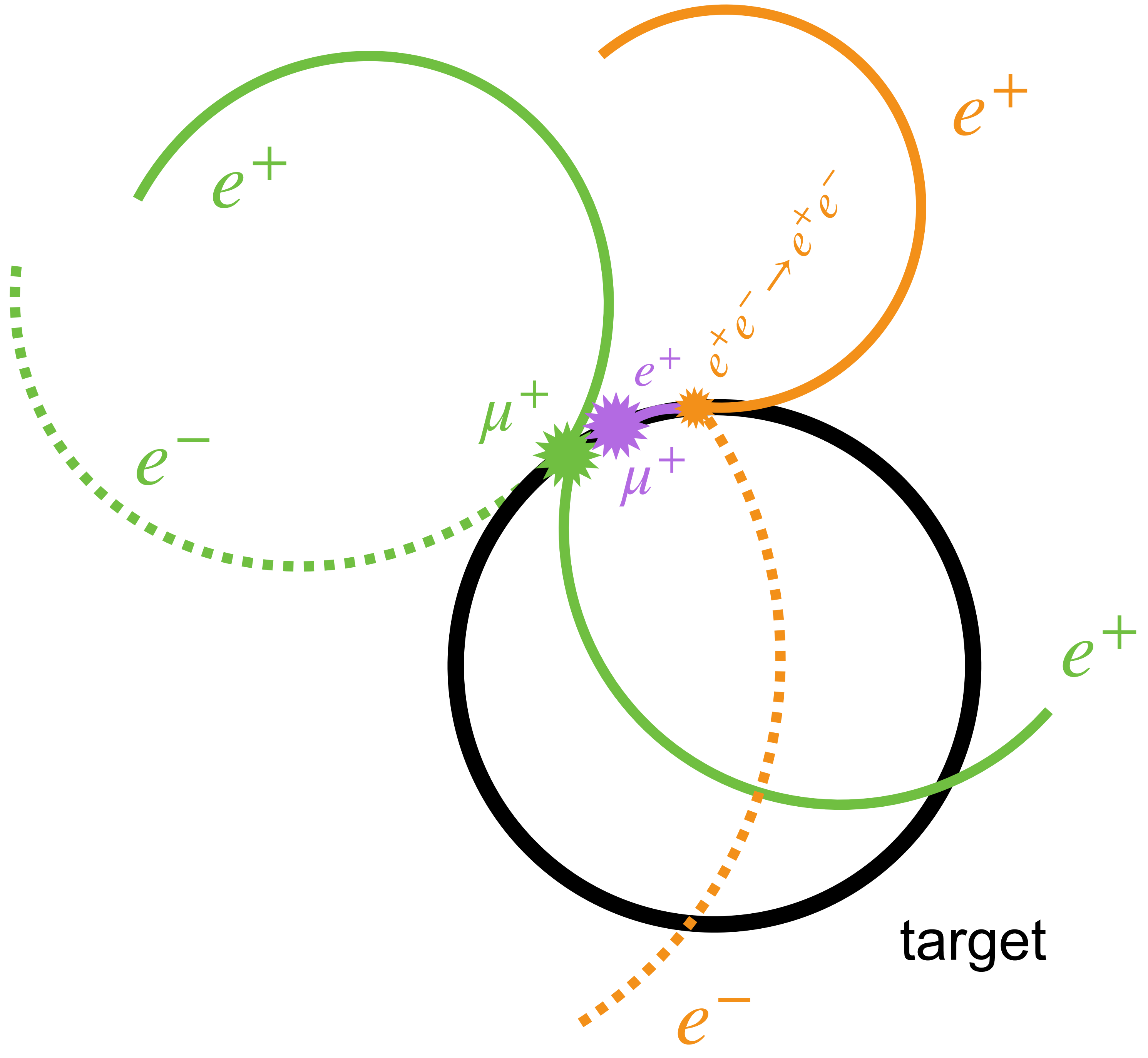
MH, T. Menzo, M. Pospelov, J. Zupan, JHEP 10 (2023) 006

Short-tracks: $\geq$ 4 hits





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.

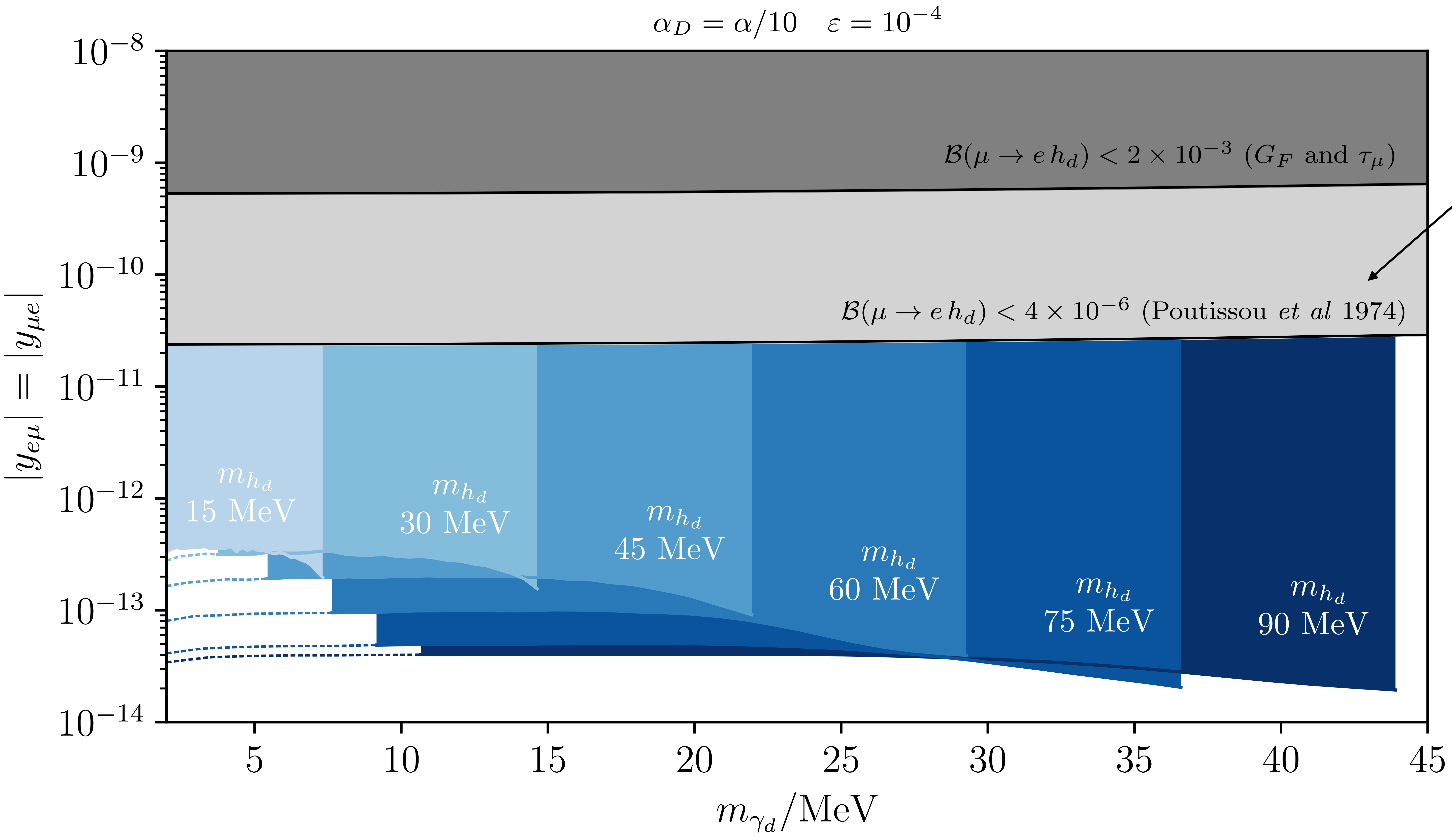
Further experimental studies are needed, but a background-free search may be possible.

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

Rare muon decays @ Mu3e

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

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



Calorimetric search for $E_{\text{vis}} \simeq m_\mu$

Conservatively showing corresponding reach of

1 **decay out of 10^{12} muons,**

after signal selection.

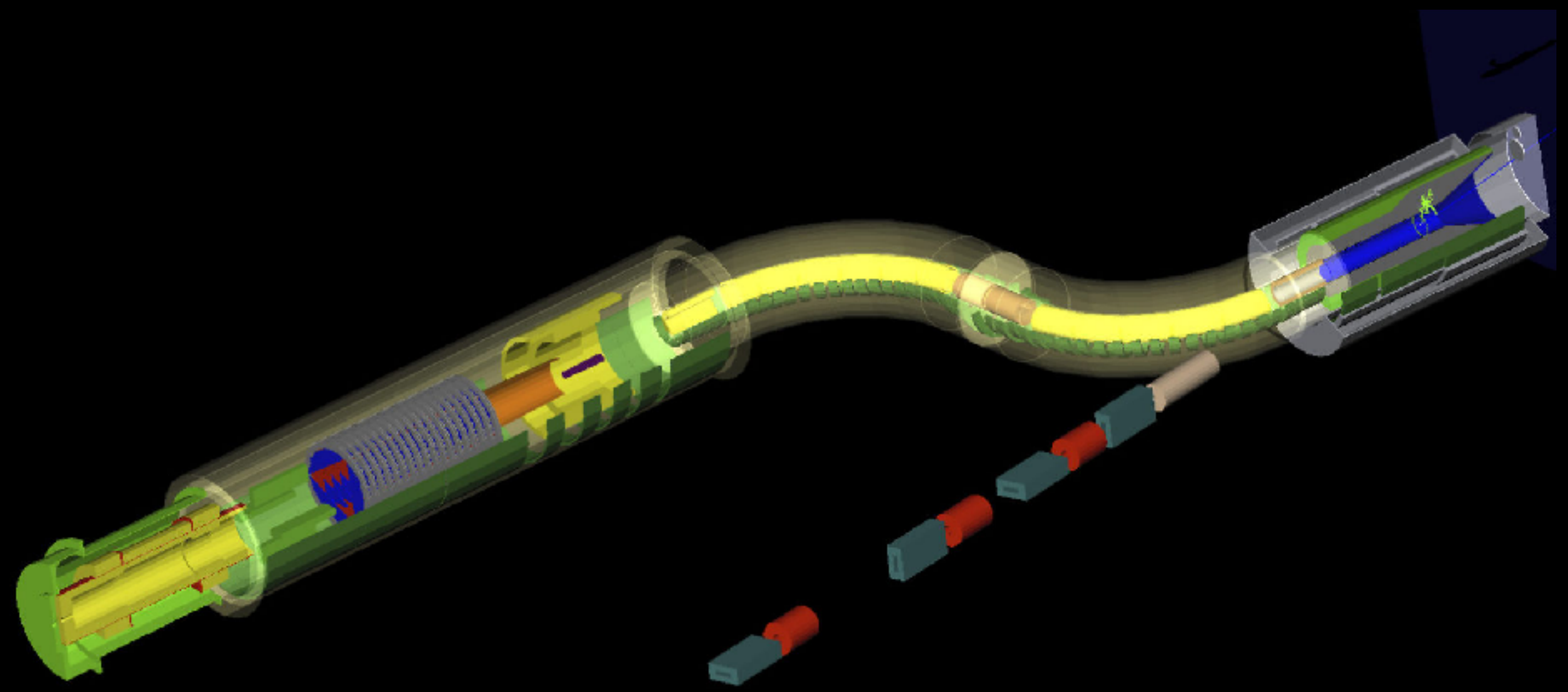
New physics scale as high as:

$\Lambda < 10^7$ GeV if secluded

$\Lambda < 10^{15}$ GeV if leptophilic

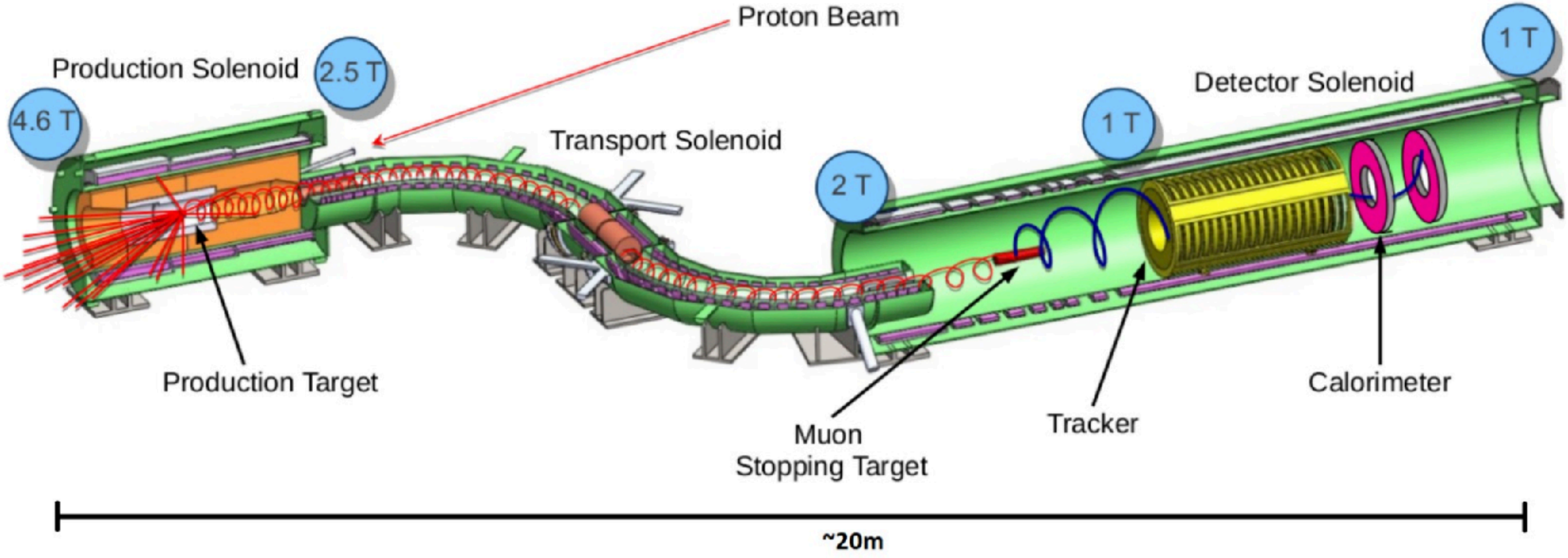
Extracting more energy out of μ^- capture

Muon-induced baryon number violation



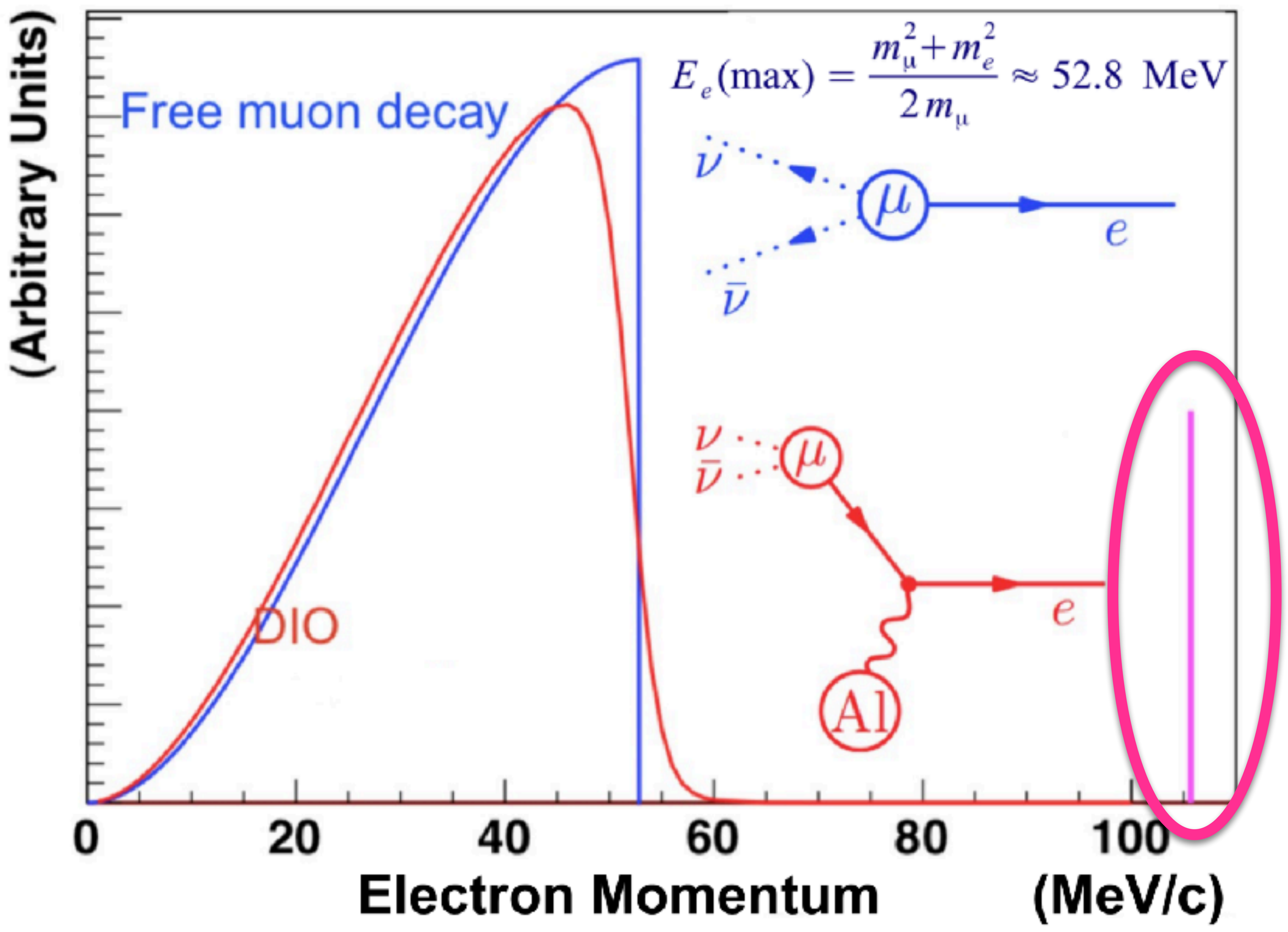
Mu2e on $\mu \to e$ conversion

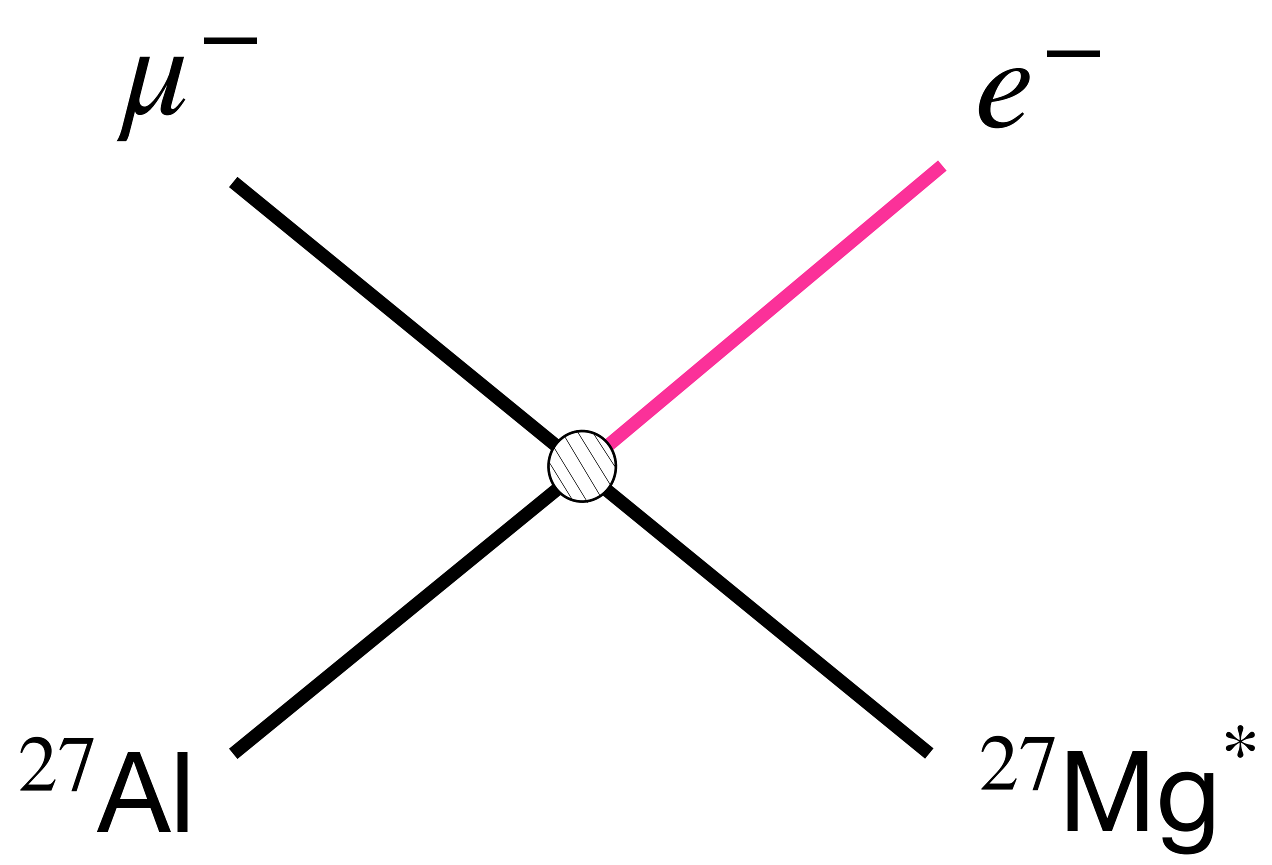
Mono-energetic conversion electrons



Mu2e on $\mu \to e$ conversion

Mono-energetic conversion electrons





Conversion Electron: $E_{\rm cap} \sim 104.9$ MeV

Can we overshoot this value with new physics?

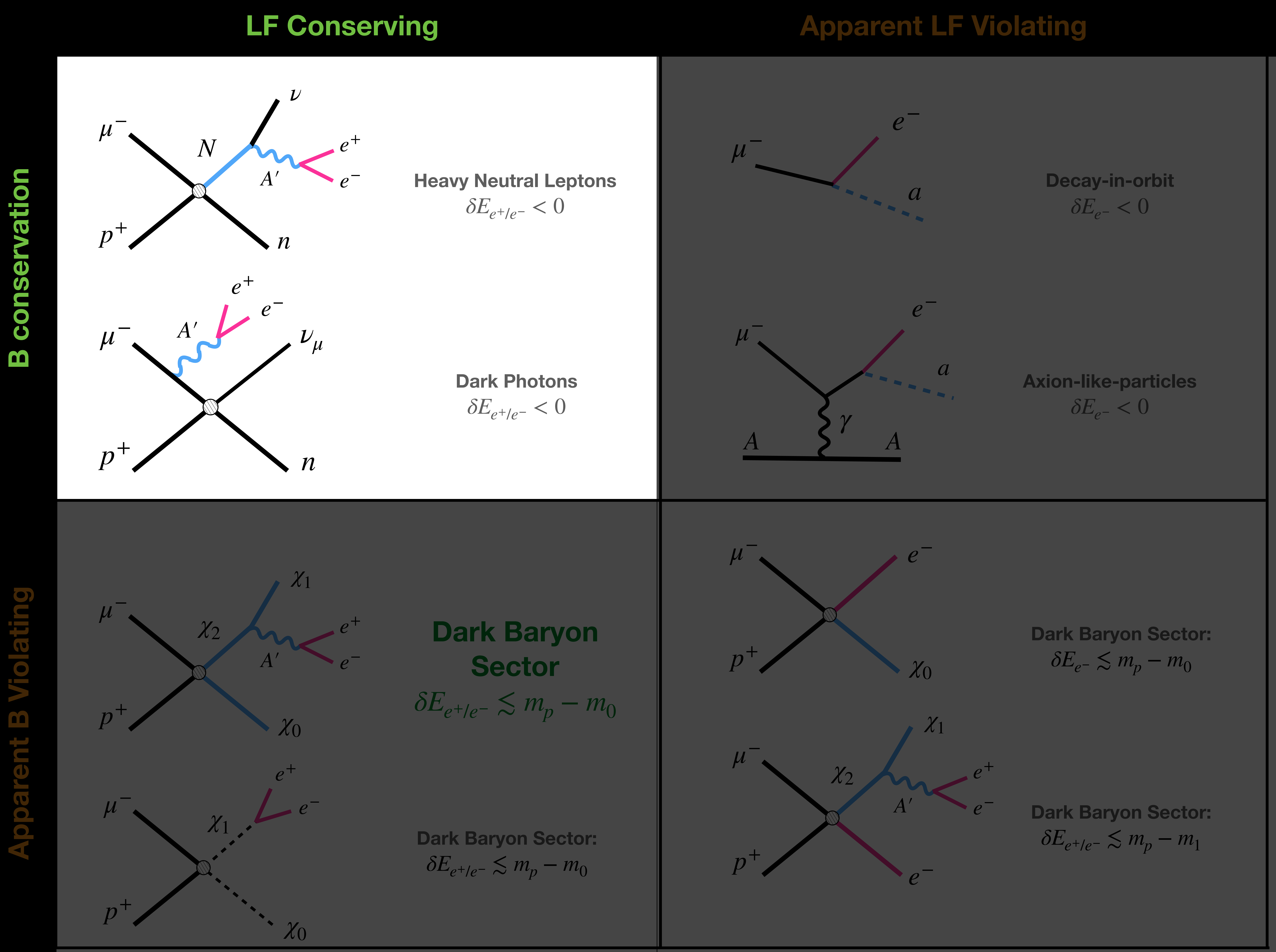
A genuine source of $E_{e^-} > E_{\rm cap}$ in muon capture can arise if we destroy a baryon.

New light particles at Mu2e/COMET

Soft spectrum under μ DIO

Electron energy

$$\delta E_{e^-} = E_{e^-} - m_\mu$$



New light particles at Mu2e/COMET

Soft spectrum under μ DIO

Electron energy

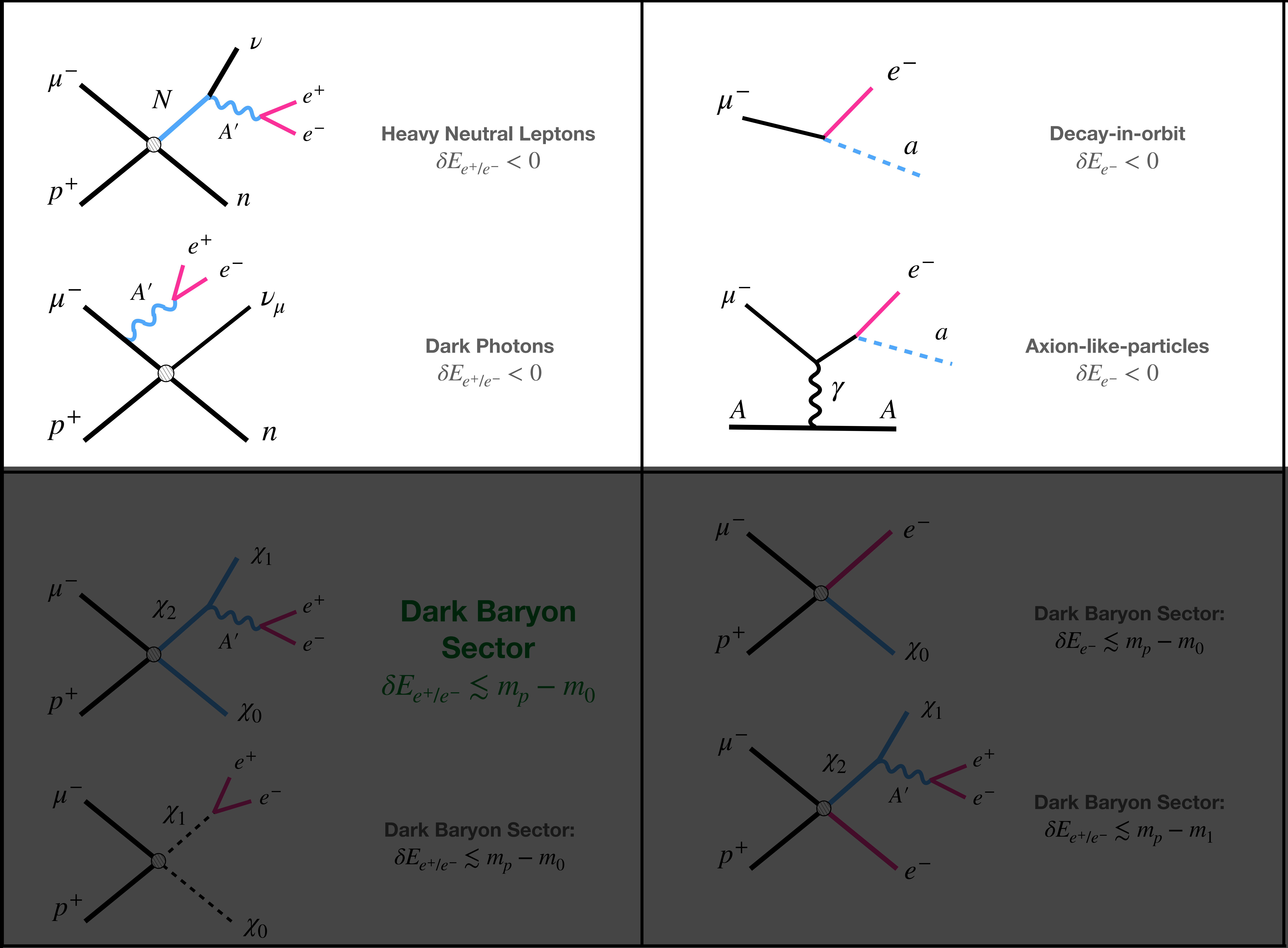
$$\delta E_{e^-} = E_{e^-} - m_\mu$$

LF Conserving

Apparent LF Violating

B conservation

Apparent B Violating



New light particles at Mu2e/COMET

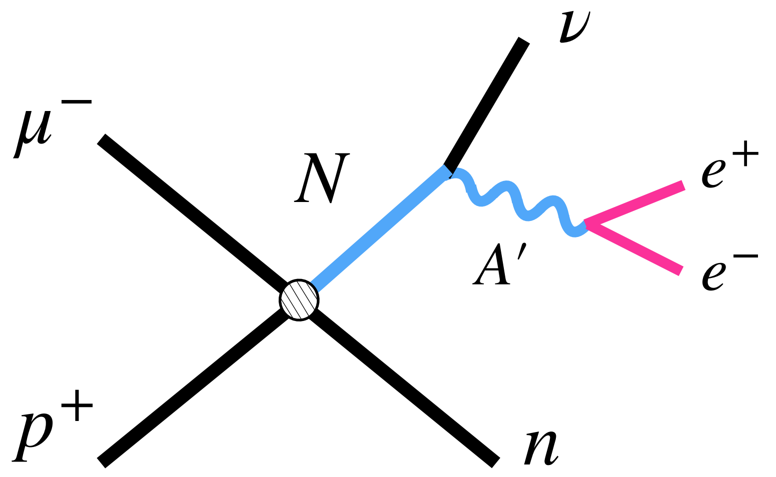
Harder spectrum above μ DIO

Electron energy

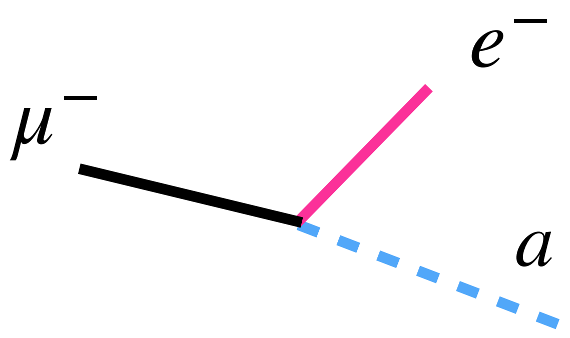
$$\delta E_{e^-} = E_{e^-} - m_\mu$$

LF Conserving | **Apparent LF Violating**

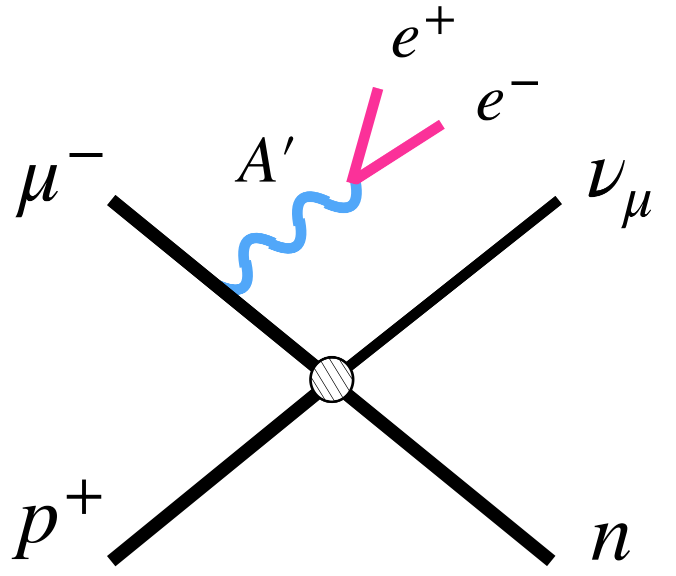
B conservation



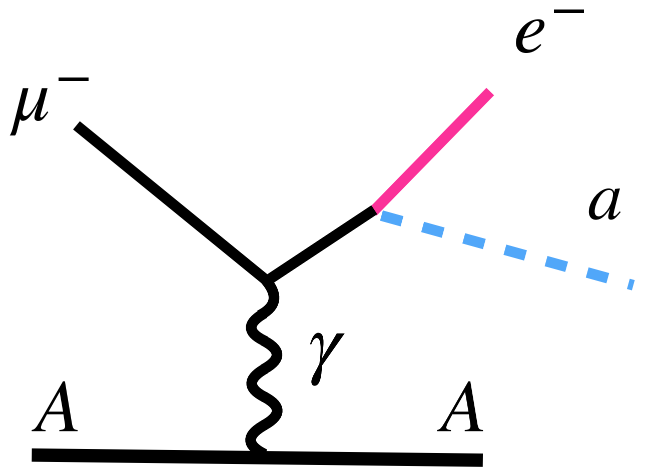
Heavy Neutral Leptons
$\delta E_{e^+/e^-} < 0$



Decay-in-orbit
$\delta E_{e^-} < 0$

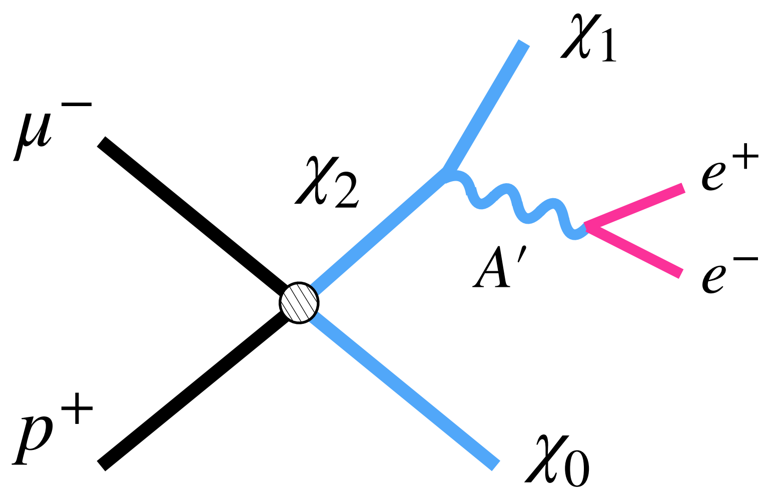


Dark Photons
$\delta E_{e^+/e^-} < 0$

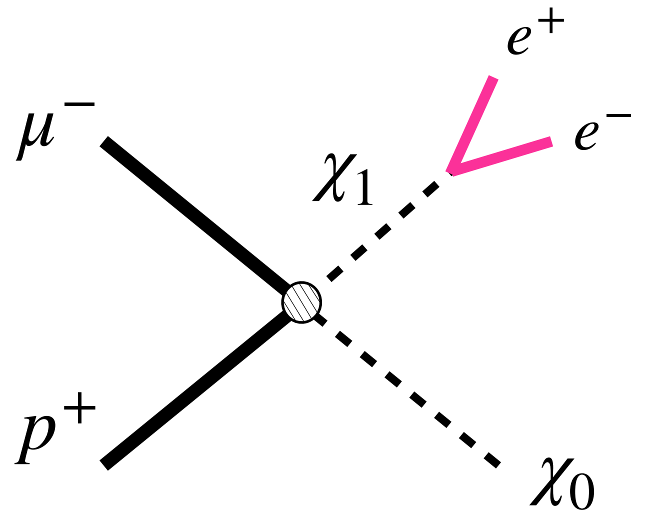


Axion-like-particles
$\delta E_{e^-} < 0$

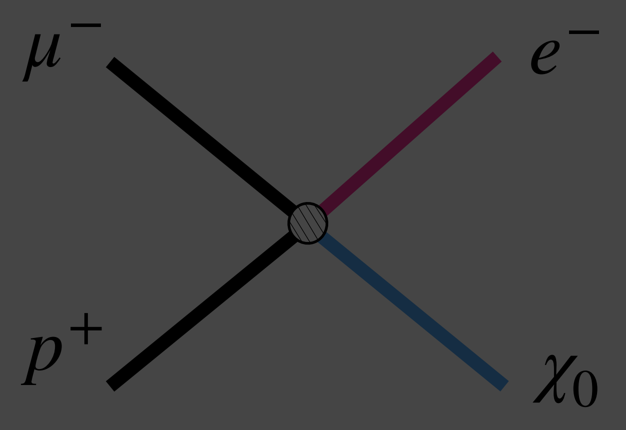
Apparent B Violating



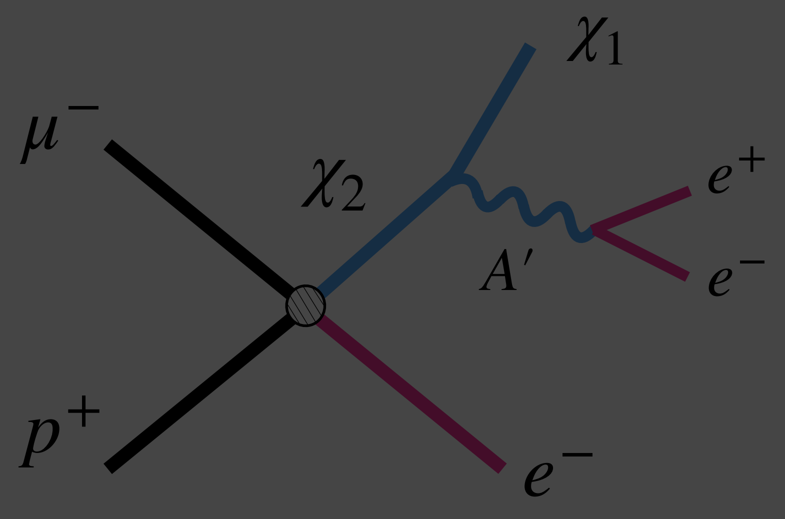
Dark Baryon Sector
$\delta E_{e^+/e^-} \lesssim m_p - m_0$



Dark Baryon Sector:
$\delta E_{e^+/e^-} \lesssim m_p - m_0$



Dark Baryon Sector:
$\delta E_{e^-} \lesssim m_p - m_0$



Dark Baryon Sector:
$\delta E_{e^+/e^-} \lesssim m_p - m_1$

LF Conserving | Apparent LF Violating

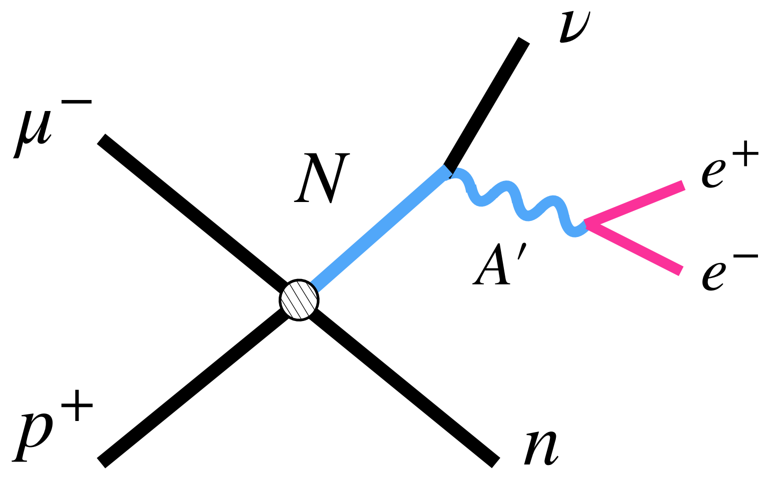
New light particles at Mu2e/COMET

Harder spectrum above μ DIO

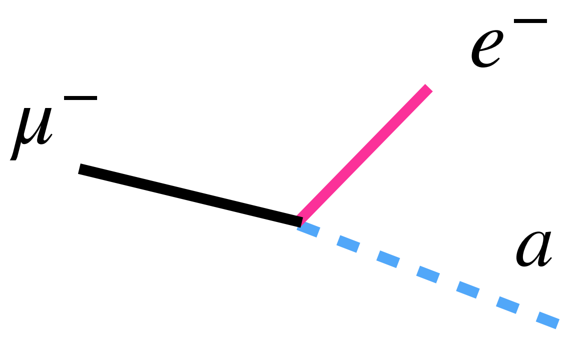
Electron energy

$$\delta E_{e^-} = E_{e^-} - m_\mu$$

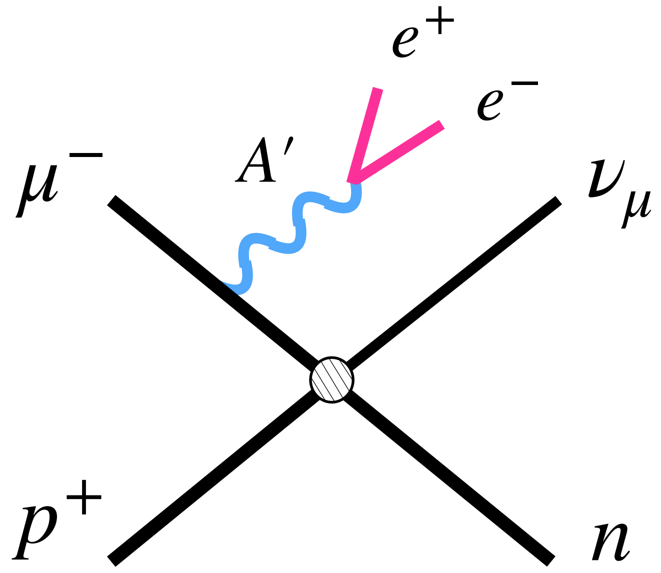
B conservation



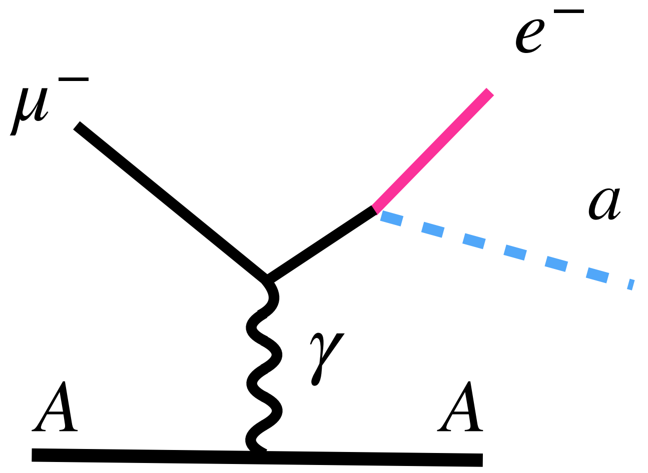
Heavy Neutral Leptons
$\delta E_{e^+/e^-} < 0$



Decay-in-orbit
$\delta E_{e^-} < 0$

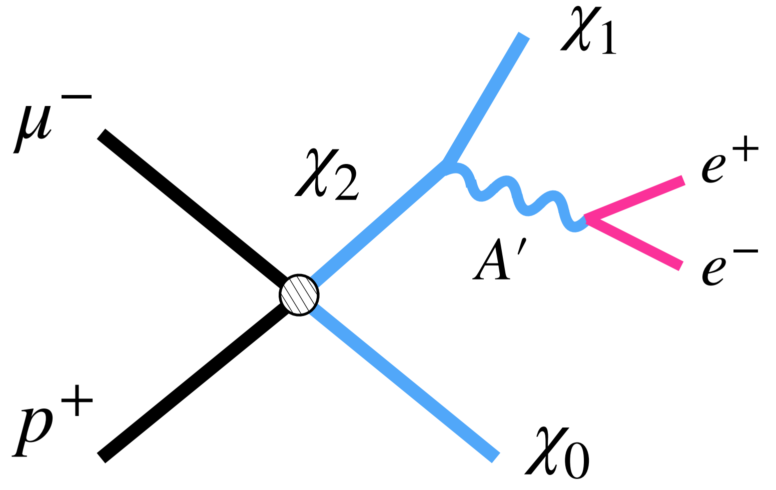


Dark Photons
$\delta E_{e^+/e^-} < 0$

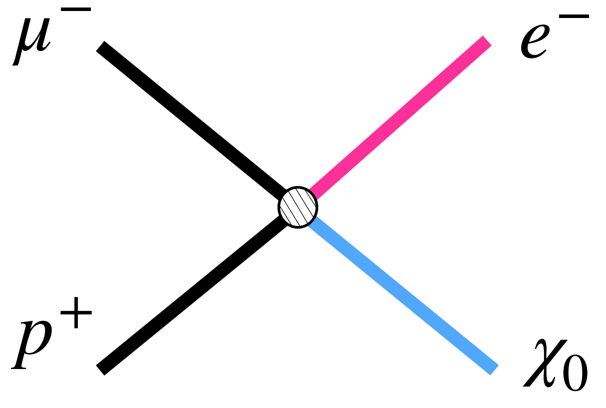


Axion-like-particles
$\delta E_{e^-} < 0$

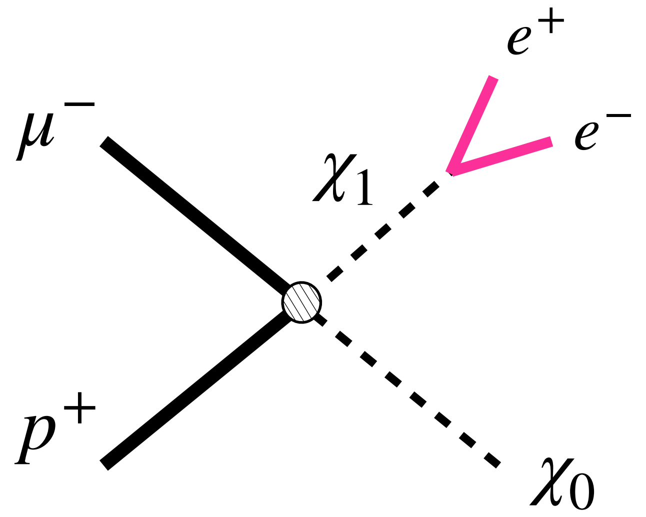
Apparent B Violating



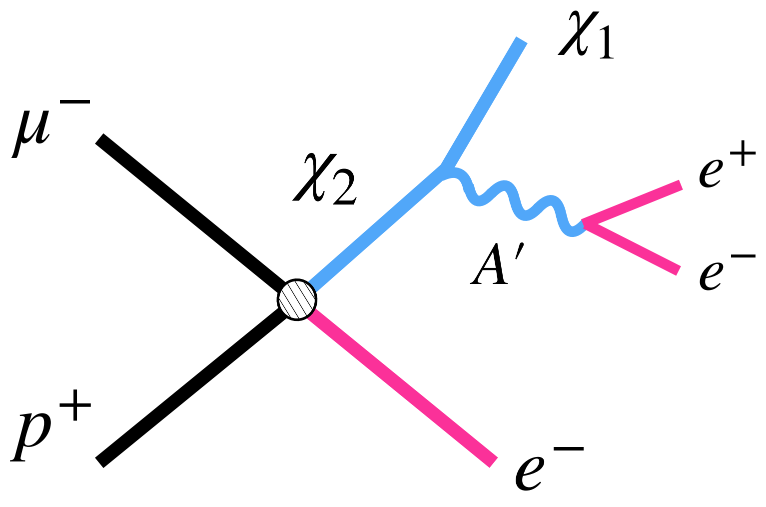
Dark Baryon Sector
$\delta E_{e^+/e^-} \lesssim m_p - m_0$



Dark Baryon Sector:
$\delta E_{e^-} \lesssim m_p - m_0$



Dark Baryon Sector:
$\delta E_{e^+/e^-} \lesssim m_p - m_0$



Dark Baryon Sector:
$\delta E_{e^+/e^-} \lesssim m_p - m_1$

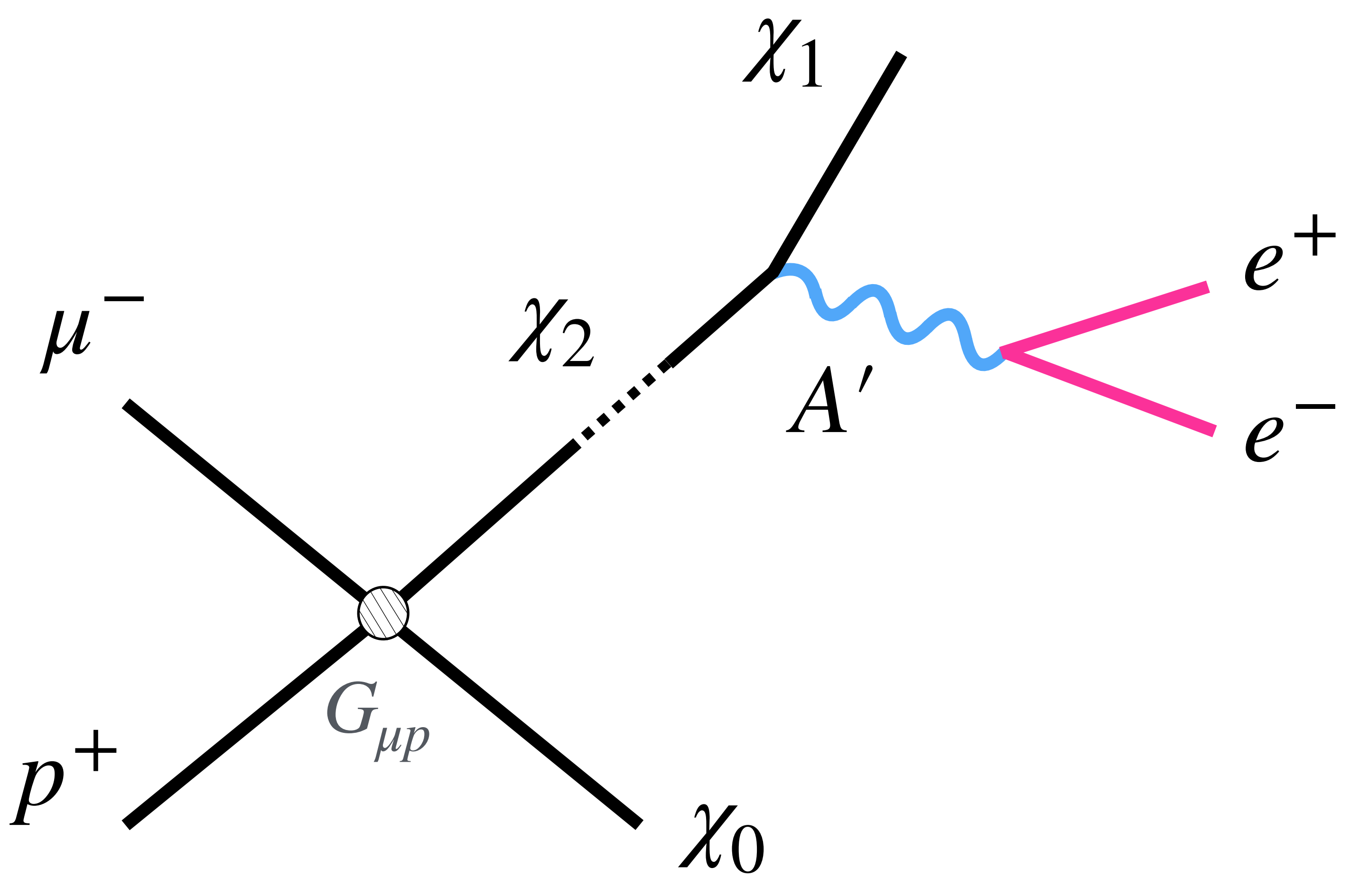
Dark particle production in $\mu \to e$ conversion

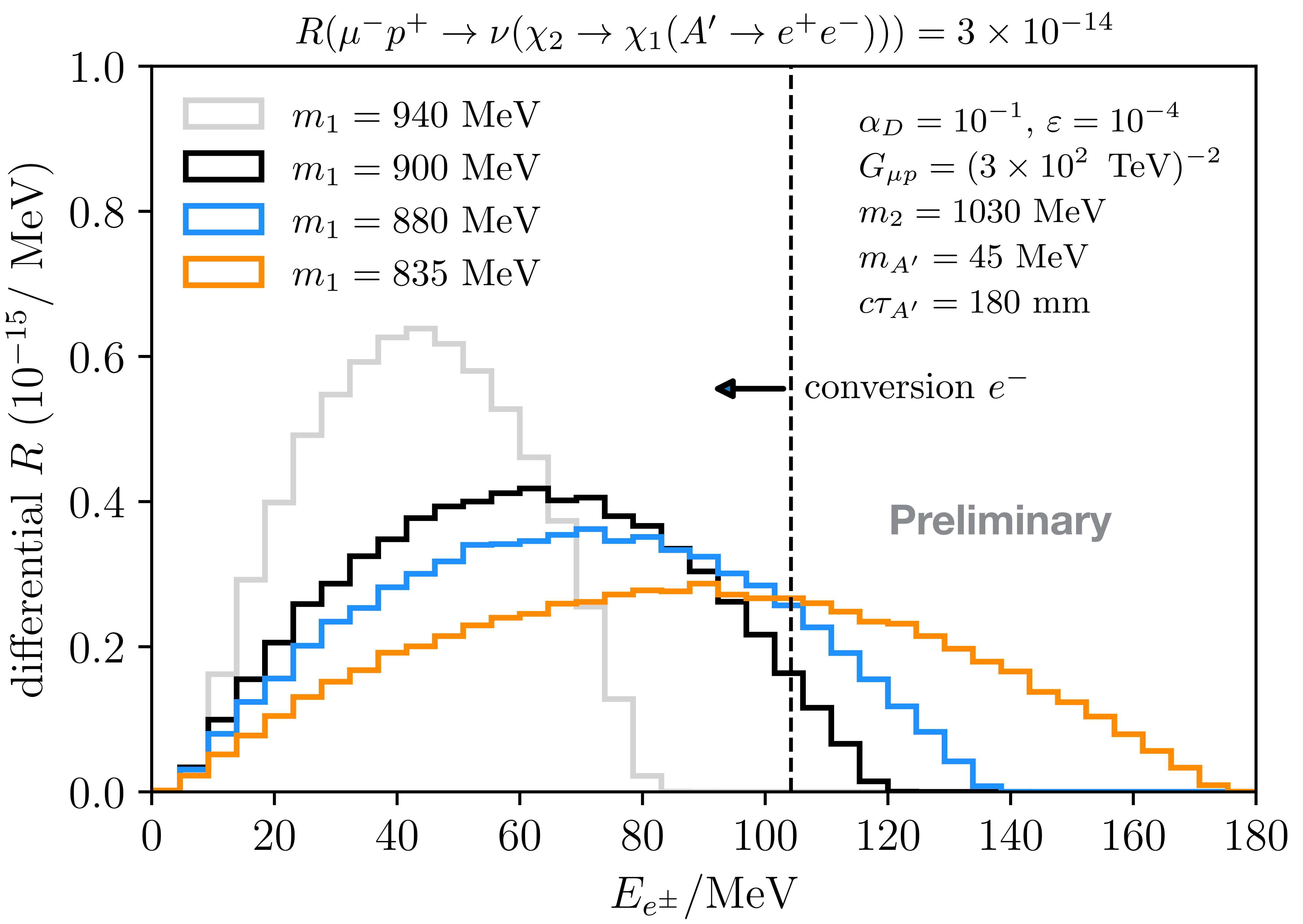
Borrowing energy from the proton

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

Consider new dark particles χ_2, χ_1, and χ_0. Schematically:

$$\mathscr{L} \supset G_{\mu p}(\overline{\mu}\chi_2)(\overline{p}\chi_0) + A'_\mu \left(g_D \overline{\chi_2}\gamma^\mu \chi_1 + e\varepsilon J_{\mathrm{EM}}\right)$$



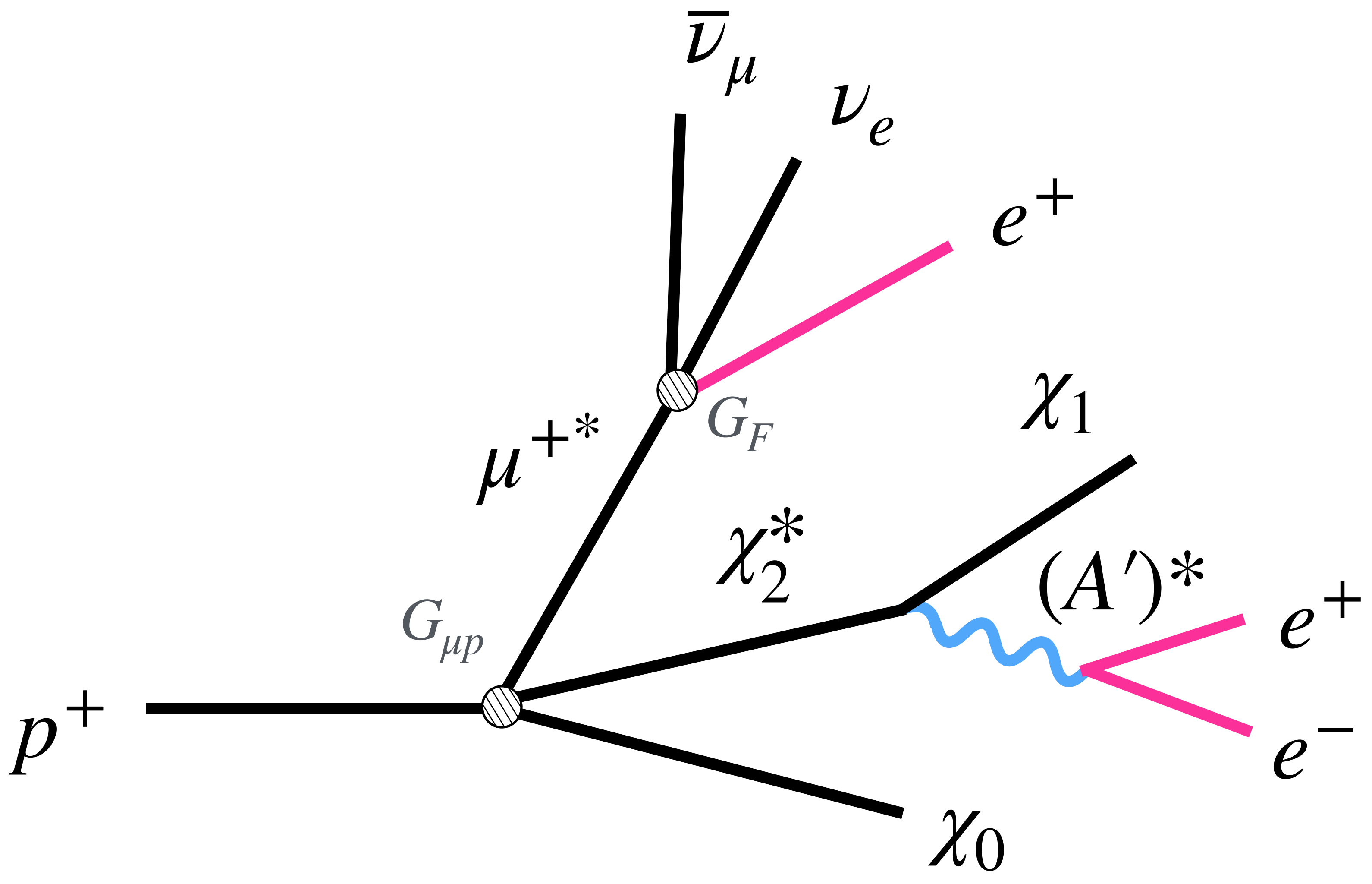


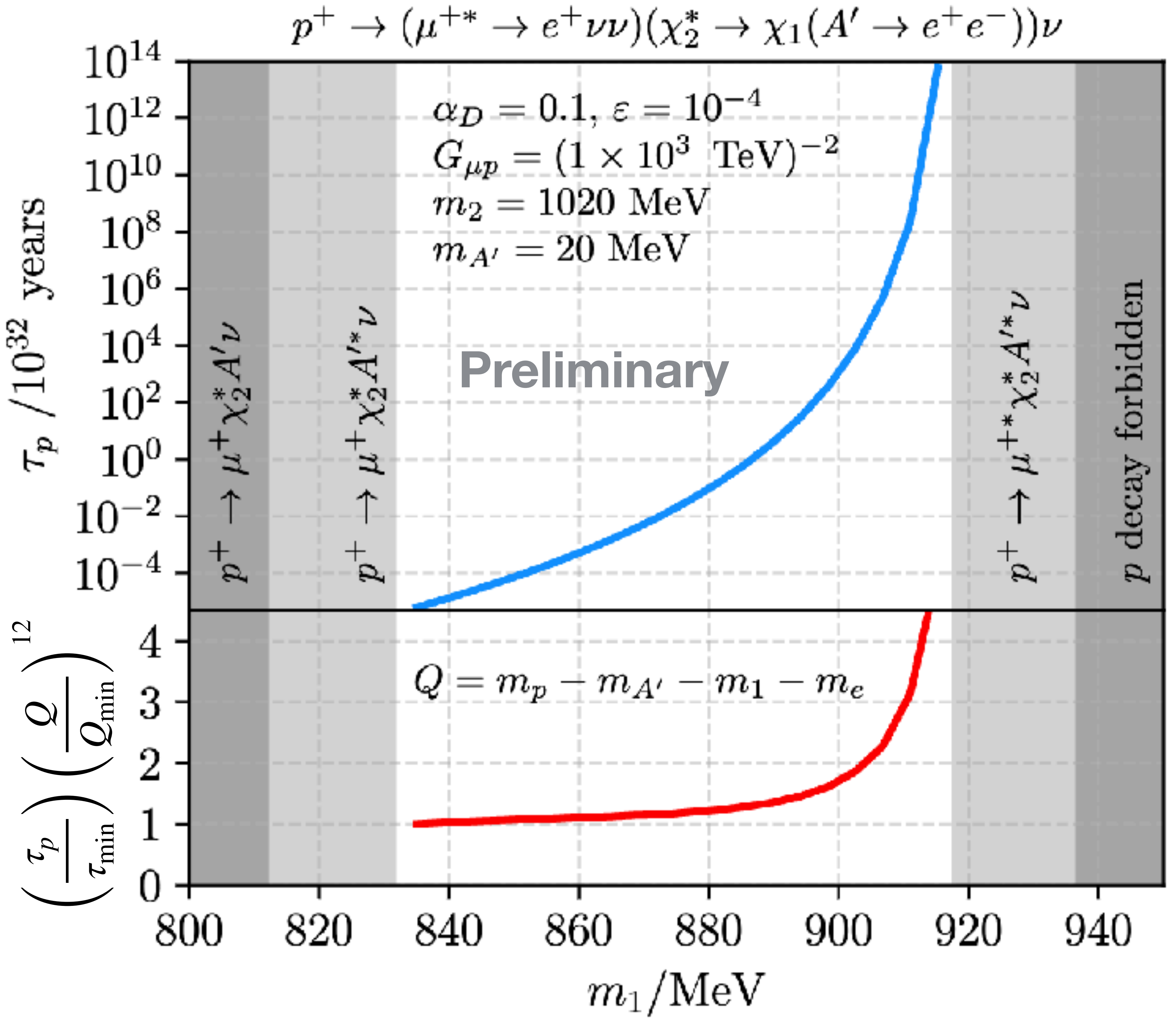
Challenge 1) Proton decay
Suppression by fine tuning the spectrum

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

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

Even if $\tau_p \sim 10^{32}$ years, not excluded as protons decay to very soft tracks.





Proton decay to 7 particles via **off-shell** μ^+ **and** χ_2 (possibly A')

Challenge 2) Neutron stars
Muon capture leads to a new equilibrium

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

The core of a Neutron Star may have as much as $5\,\%$ of its particle number in muons.

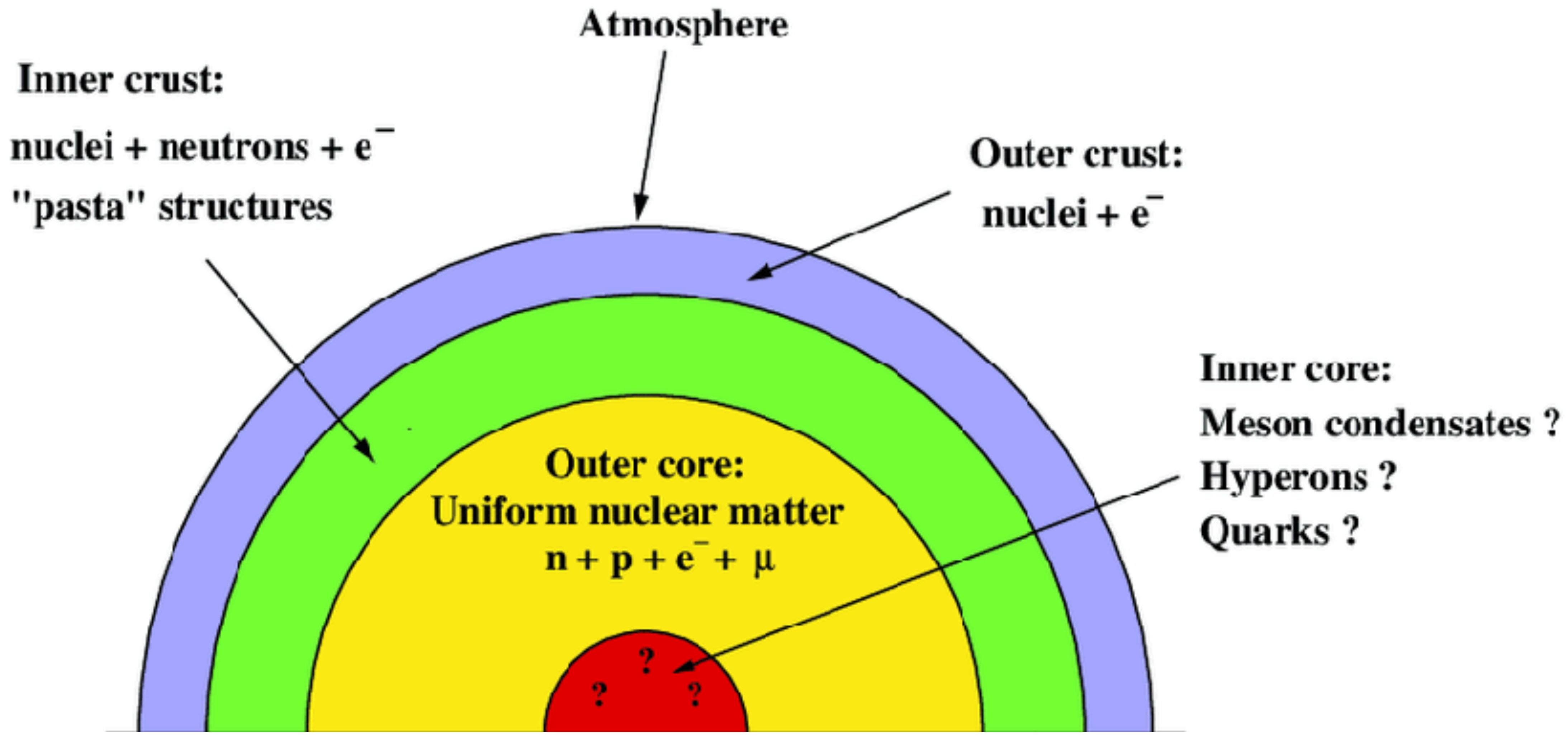
The muons in the Neutron Star will destroy protons/neutrons

This process happens “fast” in the history of the star

$$\Gamma^{\rm NS}_{\mu^- p^+ \to \chi_1 \chi_2} = \langle \sigma_{\mu p} v \rangle n_p \simeq \Gamma^{\rm Lab}_{\mu^- p^+} \frac{n_p}{|\psi(0)|^2} > \frac{1}{10^6\,{\rm s}}$$

A new equilibrium is then found and the pressure drops.

To support observed mass-radius relations, χ_1 particles must have self-interactions.



Summary

Thank you for listening!

Matheus Hostert (mhostert@g.harvard.edu)

Charged Lepton Flavor Violation is exotic enough and we are looking for it hard enough that new particles, light or heavy, may be first discovered through their flavor-violating couplings.

1) **Suggested an additional muon decay target for Mu3e: $\mu \to 5e$ within and beyond the SM.**

2) Sensitivity to new physics scale can be as strong as $\Lambda \sim 10^7/10^{15}$ GeV.

3) Measurement of the SM rate is more challenging, but may not be impossible.

4) **New speculations for $\mu \to e$: tap into baryonic energy reservoir in muon capture**

5) Experimental implication: spectrum of e^- as well as e^+ with higher energy endpoint.

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