ALP phenomenology

(in concrete flavor models)

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Implications of LHCb measurements and future prospects

CERN
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Outline

1. What is an ALP?
2. Concrete model: Froggatt-Nielsen ALP
3. Phenomenology
4. Conclusion

1. What is an ALP?

ALP (axion-like particle):

spin-0 particle with an approximate shift symmetry $a \to a + \text{const}$

- Ubiquitous: remnant of spontaneously broken global symmetries
- Possible solution to Strong CP problem (QCD axion)
- Can account for the dark matter in our universe (misalignment)
- Can drive inflation
- Generic prediction of String Theory models ($N \gg 1$)
- …

1. What is an ALP?

SM+a EFT:

$$\mathscr{L}_{\text{SM}+a} = \mathscr{L}_{\text{SM}} + \frac{1}{2}(\partial a)^2$$

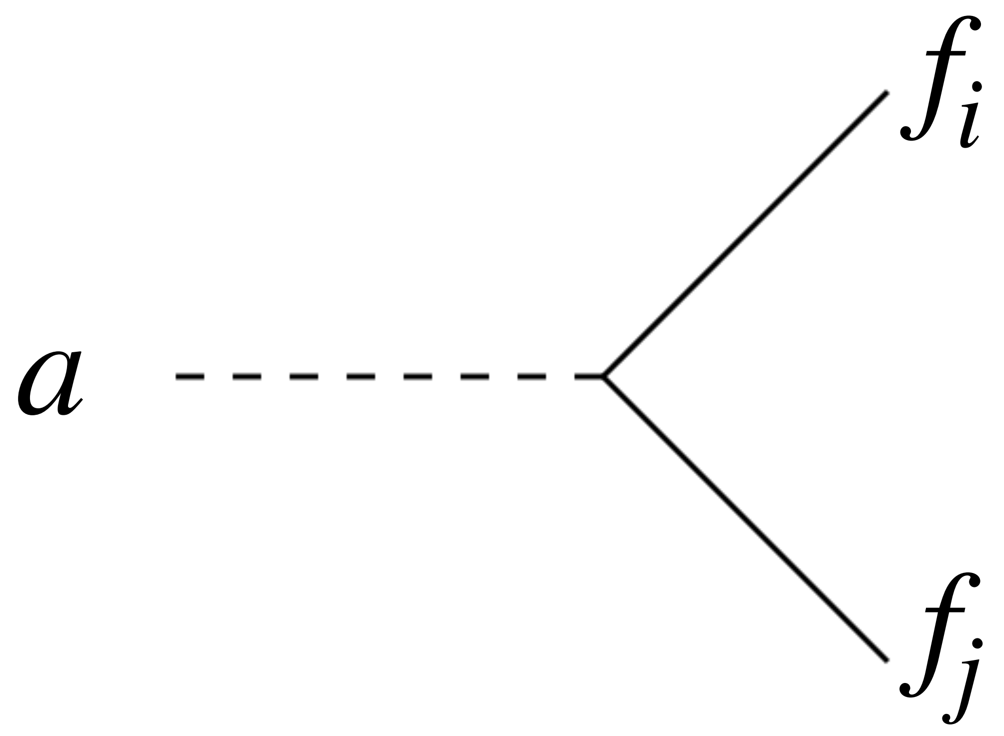
1. What is an ALP?

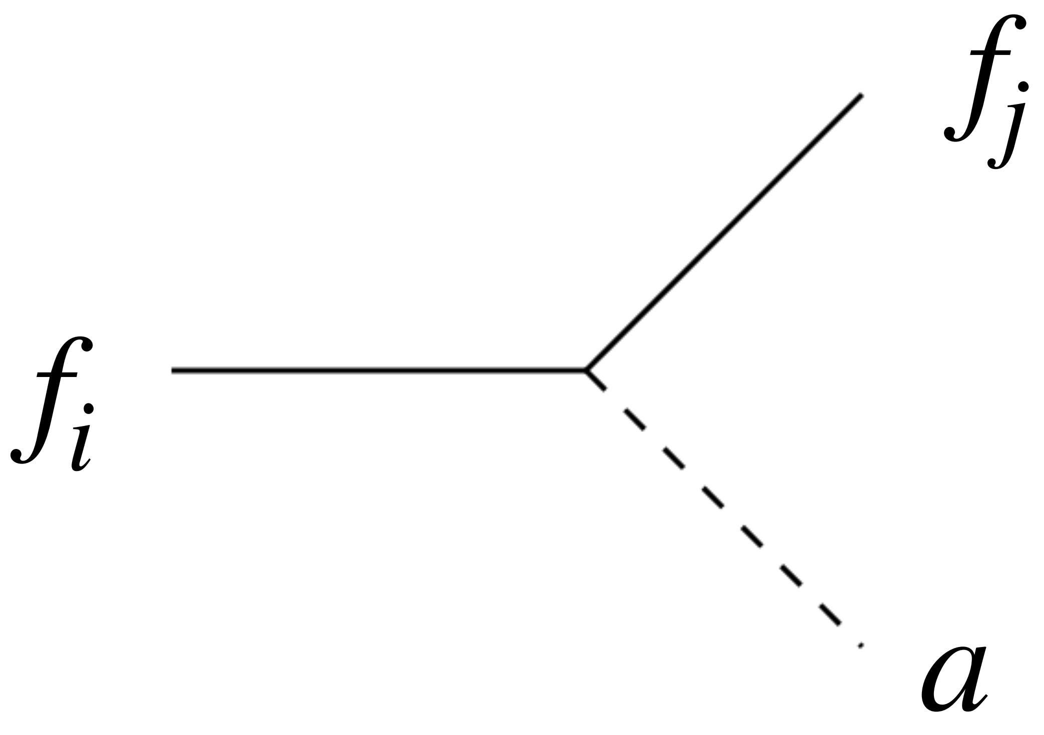
SM+a EFT:

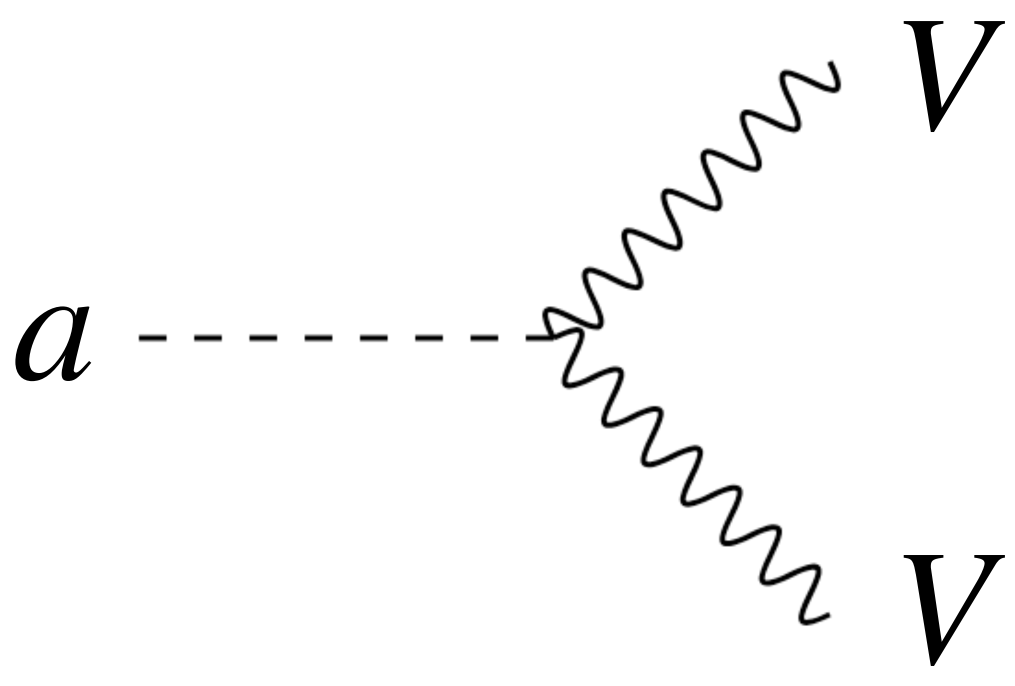
$$\mathscr{L}_{\mathrm{SM}+a} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2$$

soft shift
symmetry breaking

$$- \frac{\partial_\mu a}{f_a}\sum_f c^f_{V(A),ij}\,\bar{f}_i \gamma^\mu(\gamma^5) f_j + \frac{a}{f_a}\frac{c_F}{32\pi^2}F\tilde{F} + \dots$$







2. Froggatt-Nielsen ALP

Very general. Focus on concrete popular flavor scenario.

Froggatt-Nielsen

- New discrete/continuous global symmetry+ SSB $\longrightarrow$ **ALP** *

$f_a(v_\Phi) =$ scale of new physics!

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* If gauged no ALP → see heavy vector bosons pheno

2. Froggatt-Nielsen ALP

Very general. Focus on concrete popular flavor scenario.

Froggatt-Nielsen

- New discrete/continuous global symmetry+ SSB $\longrightarrow$ **ALP** *
- Predictive: c_{ij} fixed by SM flavor parameters

$f_a(v_\Phi) =$ scale of new physics!

Example: Z_4 model

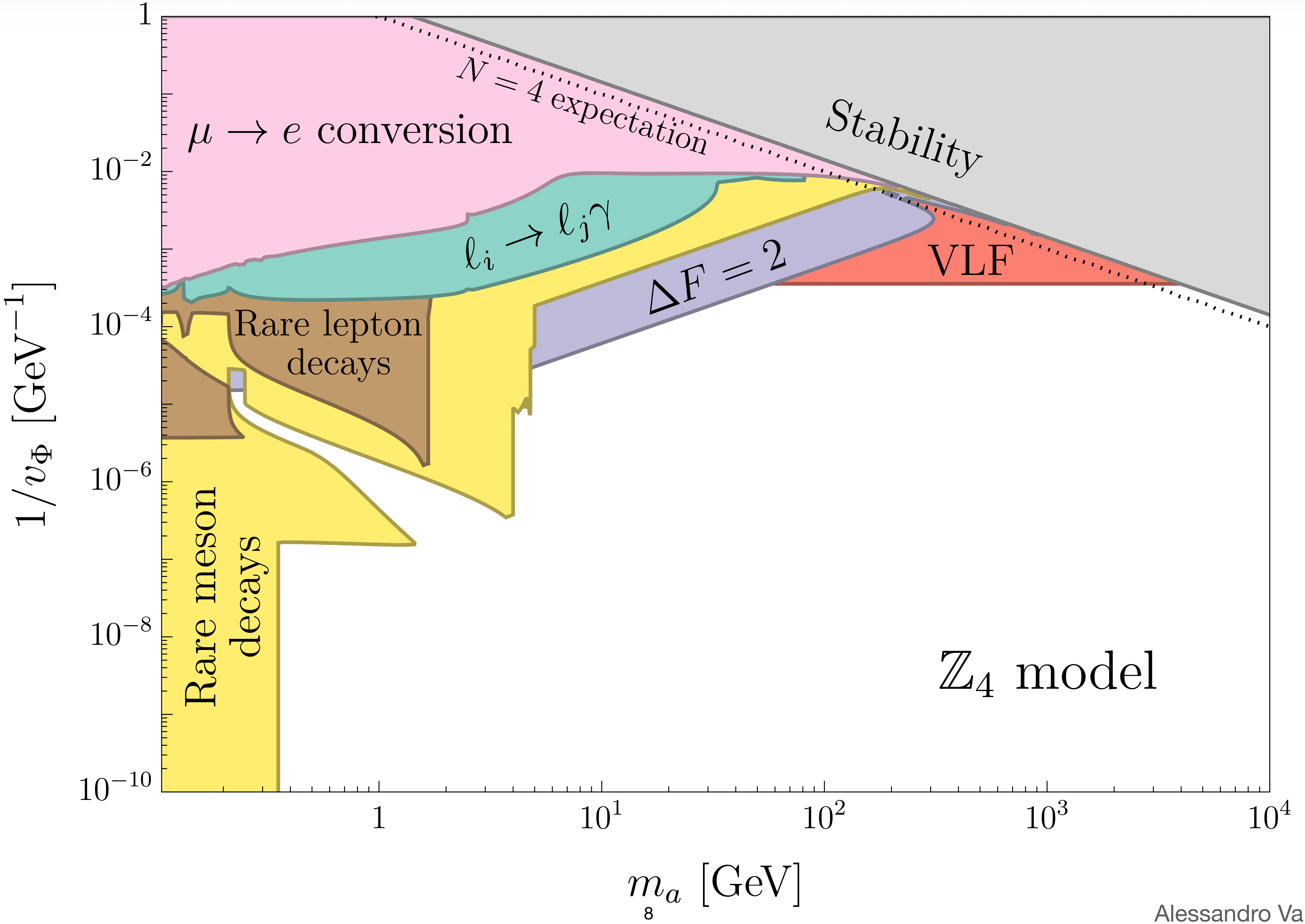
$$c^d \sim \begin{pmatrix} 1 & \frac{m_d}{m_s} & \frac{m_d}{m_b} \\ \frac{m_d}{m_s} & 1 & \frac{m_s}{m_b} \\ \frac{m_d}{m_d} & \frac{m_s}{m_b} & \frac{m_s^2}{m_b^2} \end{pmatrix}, \quad c^u, c^e \sim c^d$$

$$\left(\frac{m_d}{m_s} \sim \lambda_c, \frac{m_s}{m_b} \sim \lambda_c^2, \frac{m_d}{m_b} \sim \lambda_c^3\right)$$

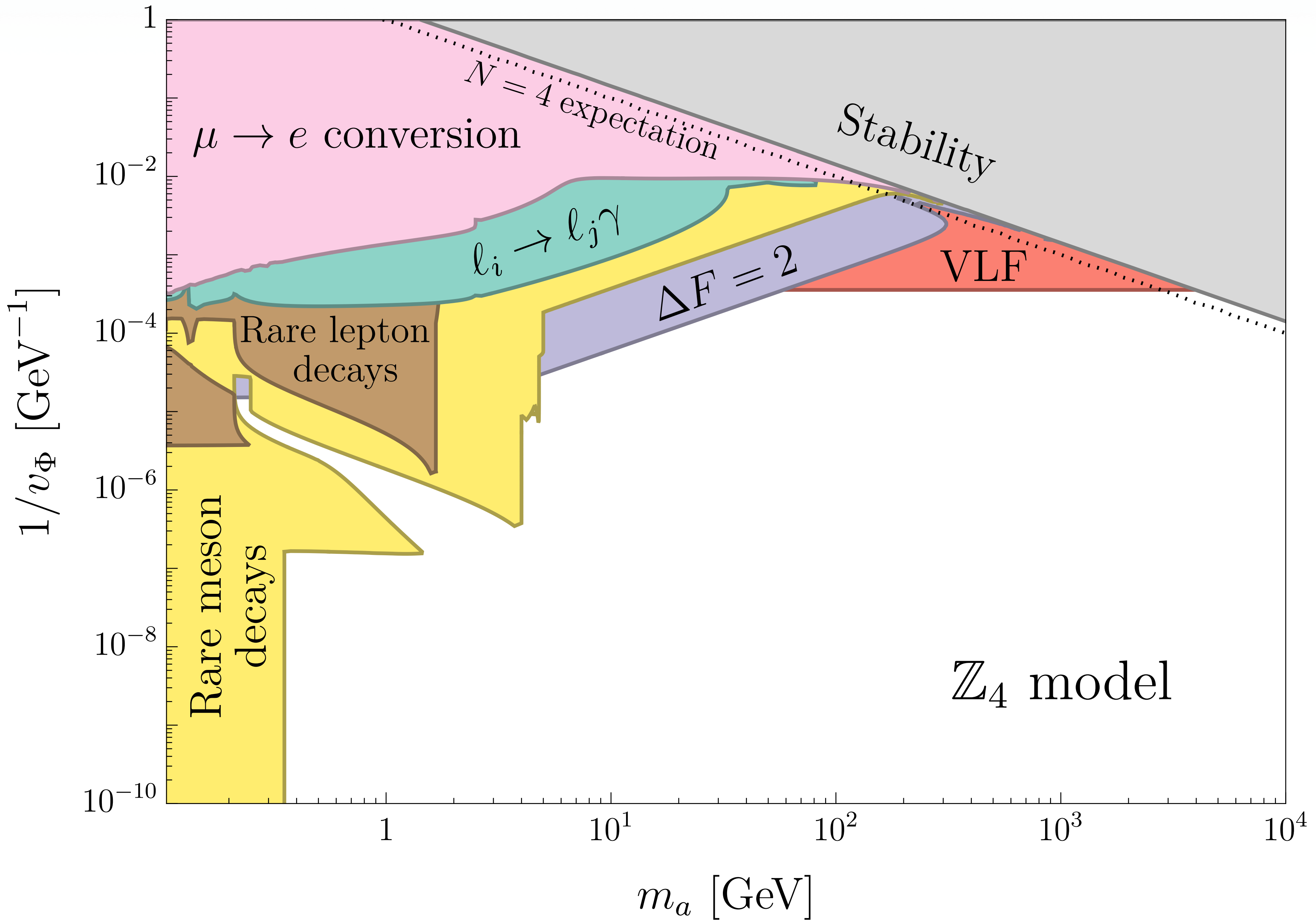
$$\mathscr{L} \supset -\frac{\partial_\mu a}{f_a} \sum_{f=q,u,d,l,e} c^f_{V(A),ij}\, \bar{f}_i \gamma^\mu (\gamma^5) f_j$$

* If gauged no ALP → see heavy vector bosons pheno

3. ALP pheno


$\mu \to e$ conversion
$N = 4$ expectation
Stability
$\ell_i \to \ell_j \gamma$
$\Delta F = 2$
VLF
Rare lepton decays
Rare meson decays
$\mathbb{Z}_4$ model
$1/v_\Phi$ [GeV^{-1}]
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
m_a [GeV]
1
10^1
10^2
10^3
10^4

MESON DECAYS

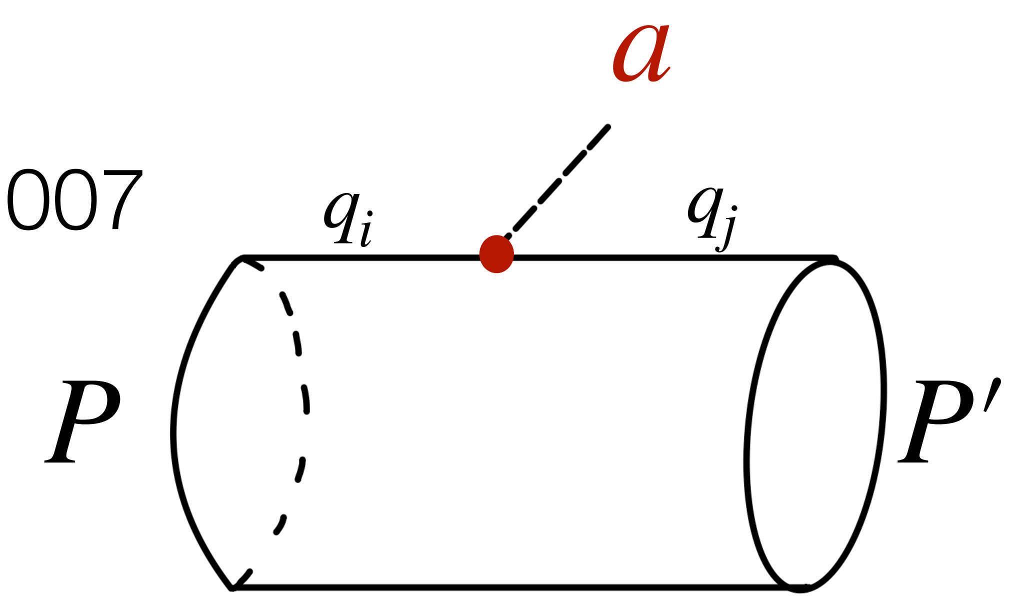


3. ALP pheno

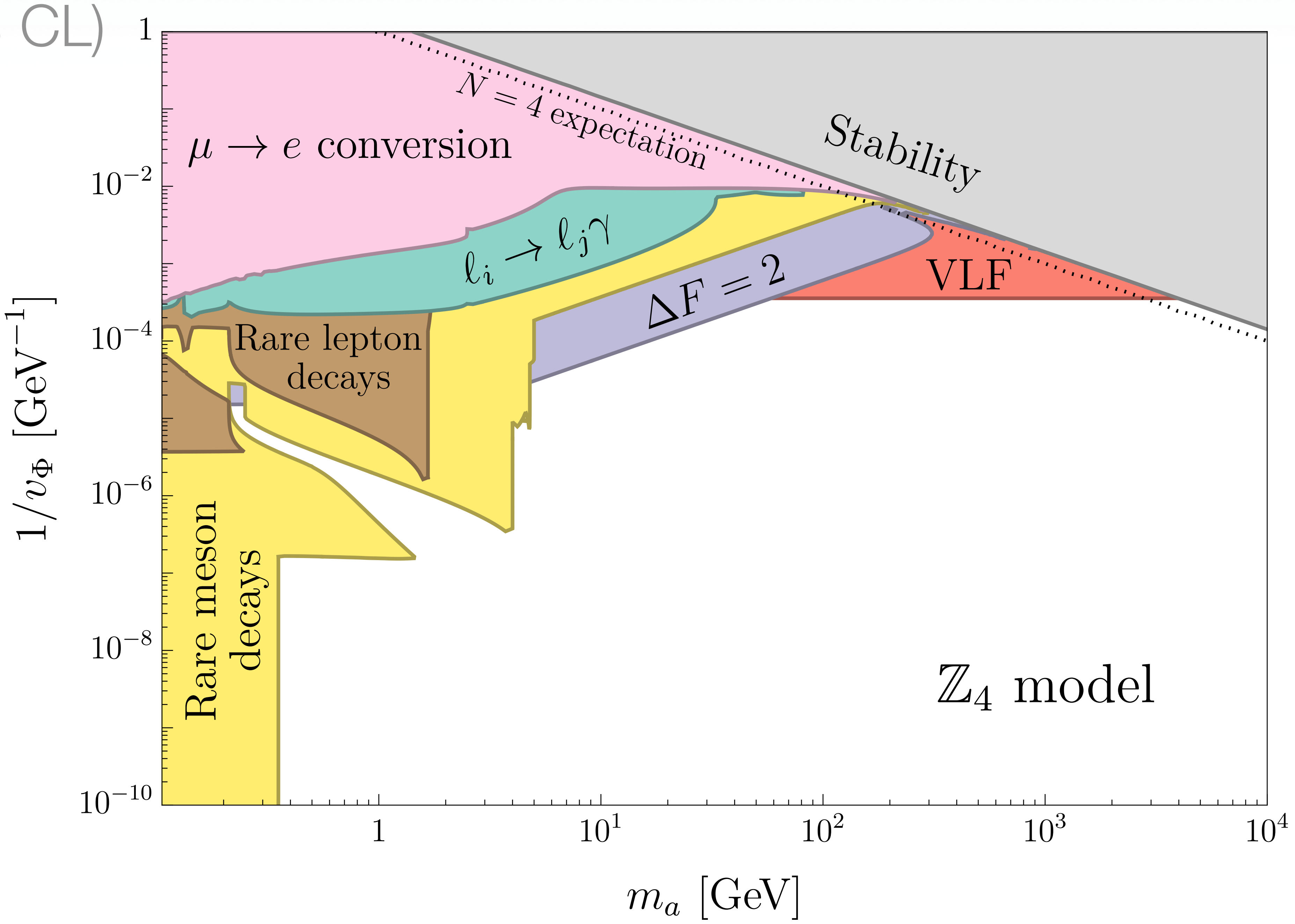
MESON DECAYS

Invisible

Br$(K^+ \to \pi^+ + a) < 9.5 \times 10^{-11}$ @ E787+E949 2007
Br$(B_0 \to K_0^* + a) < 1.0 \times 10^{-4}$ @ BaBar 2013
Br$(B^+ \to K^+ \bar{\nu}\nu) = (2.3 \pm 0.7) \times 10^{-5}$ @ Belle II 2023
⋮



(Bounds at 95% CL)



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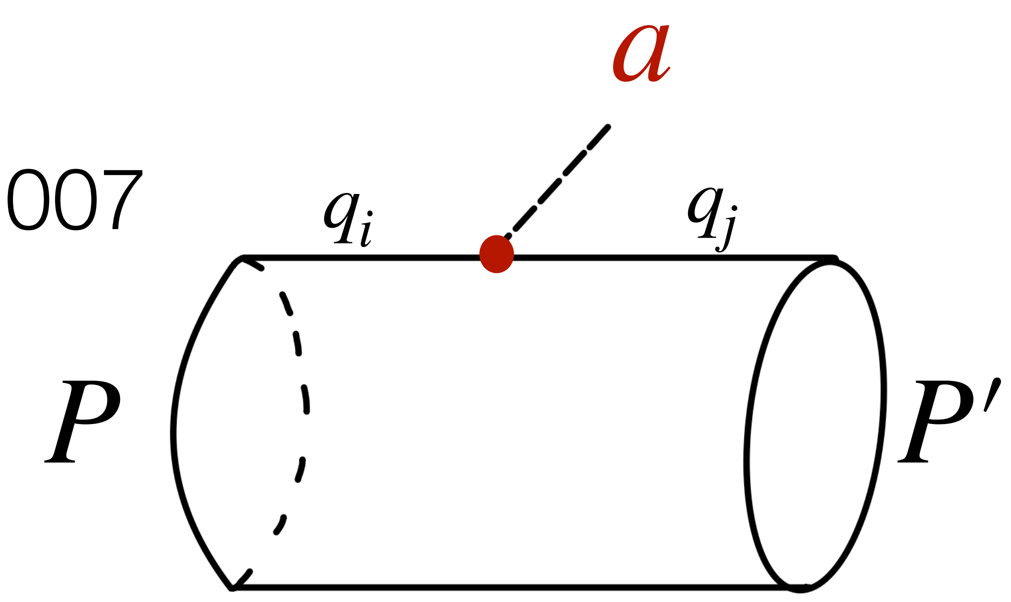
⋮

Visible - purely leptonic

Br($K_L \to \mu\mu) = (6.8 \pm 0.1) \times 10^{-11}$ @ E871 2000

Br($K_L \to \mu e) < 6.3 \times 10^{-12}$ @ E871 1998

⋮



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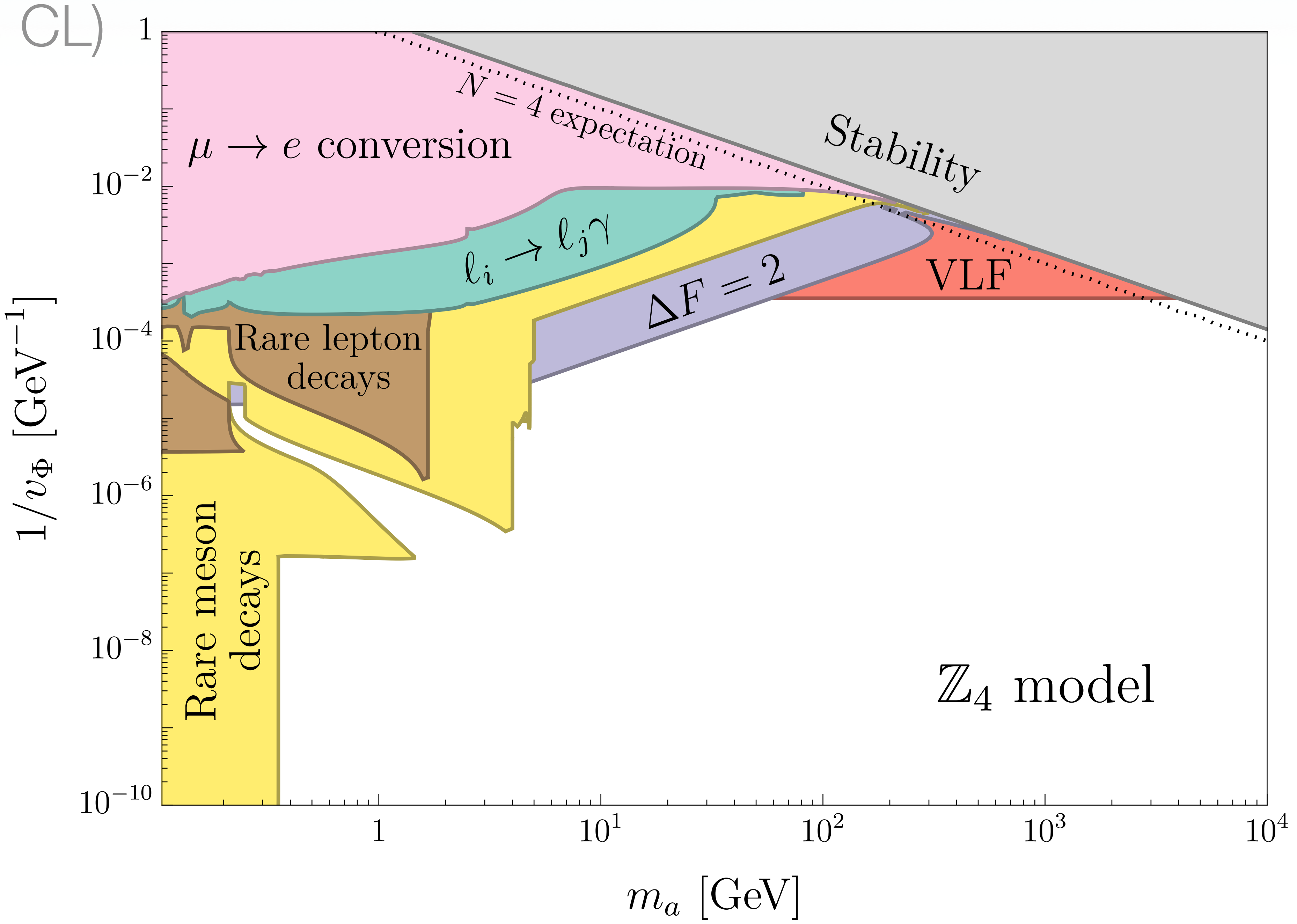

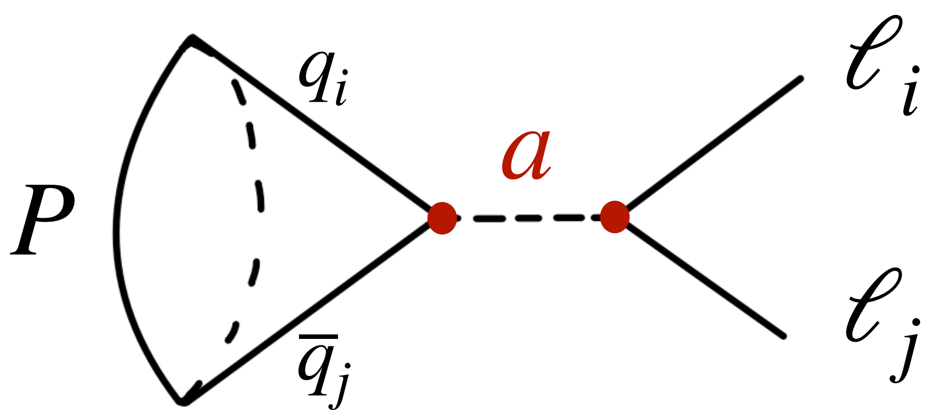

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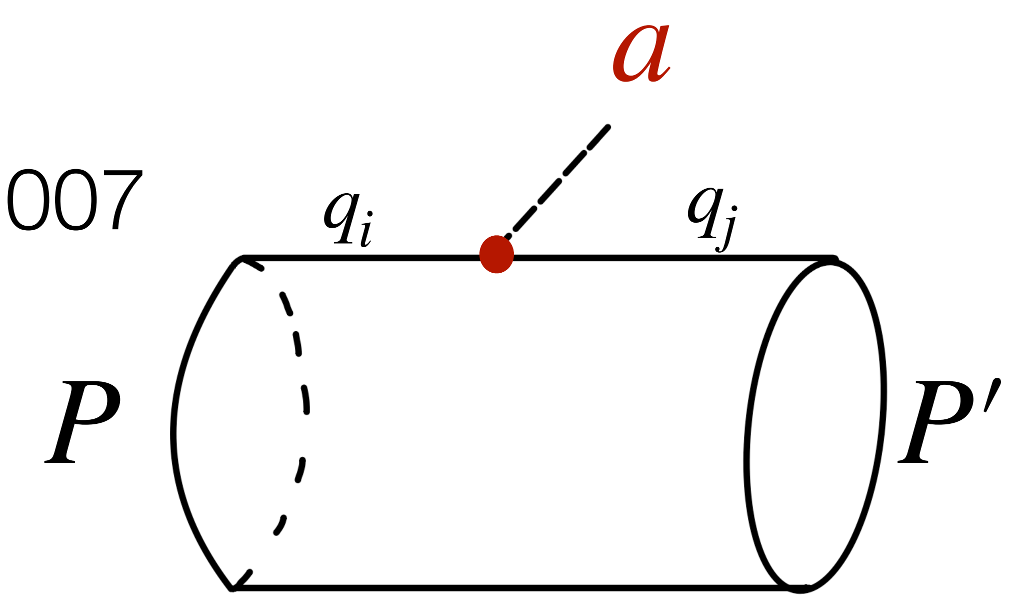

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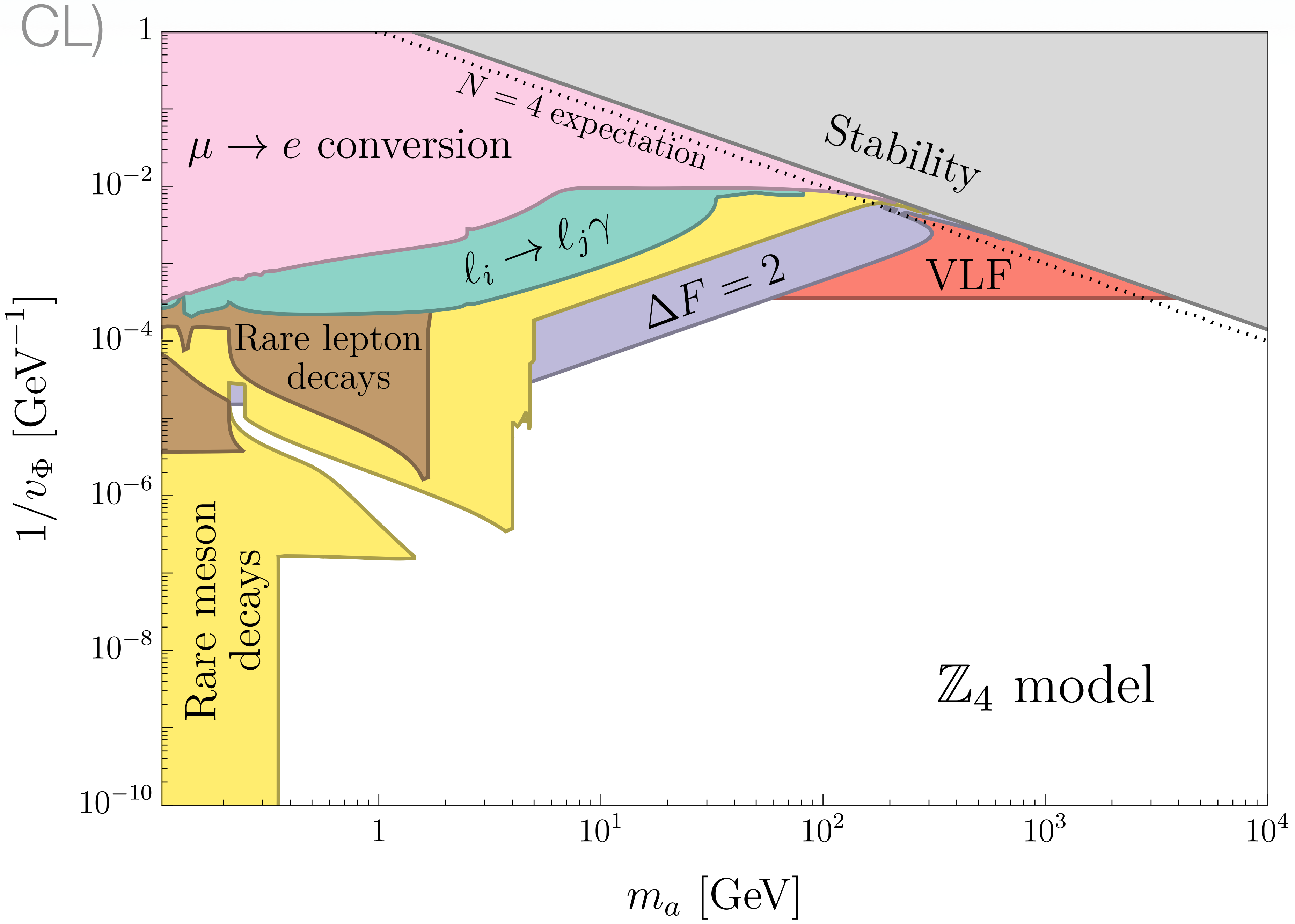

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$\mathrm{Br}(K_L \to \mu e) < 6.3 \times 10^{-12}$ @ E871 1998

$\vdots$

Visible - prompt

$\mathrm{Br}(B^+ \to K^+ \tau\mu) < 7.7 \times 10^{-6}$ @ Belle 2022, …

$\mathrm{Br}(B_0 \to K_0^* \tau\mu) < 9.8 \times 10^{-6}$ @ LHCb 2022

R_K, R_{K^*} @ LHCb 2022

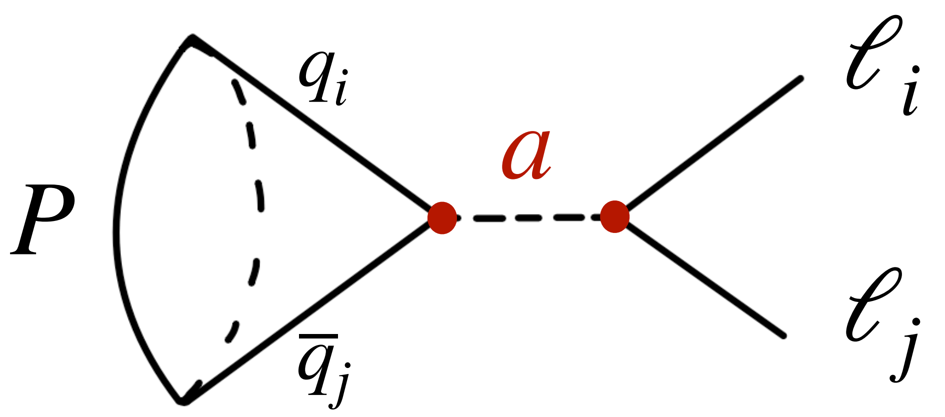
$\vdots$

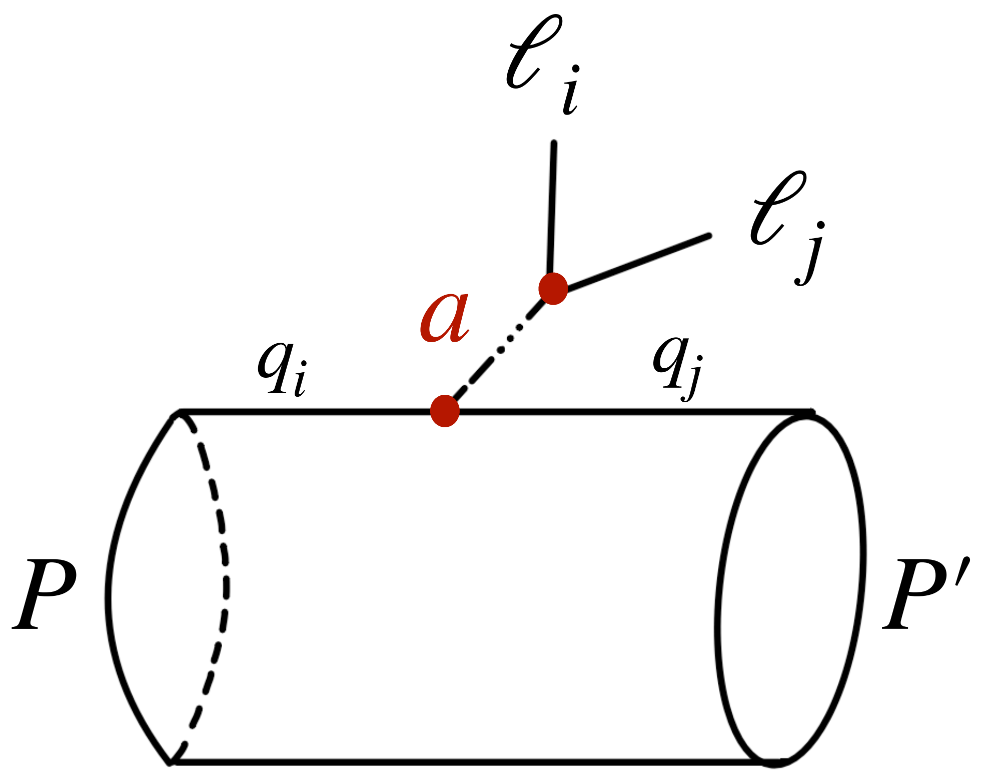
Visible - displaced $\longrightarrow$ D **decays?**

$\mathrm{Br}(B_0 \to K_0^* \mu\mu) \lesssim 10^{-10} f(m_a, \tau_a)$ @ LHCb 2015

$\mathrm{Br}(B^+ \to K^+ \mu\mu) \lesssim 10^{-10} f(m_a, \tau_a)$ @ LHCb 2016

$\vdots$





3. ALP pheno

LEPTON DECAYS

Invisible

Br$(\tau \to \mu + a) < 10^{-4} - 10^{-3}$ @ Belle II 2022
Br$(\tau \to e + a) < 10^{-4} - 10^{-3}$ @ Belle II 2022
Br$(\mu \to e + a) \lesssim 10^{-5}$ @ TRIUMF 1986, 2014 (TWIST)
$\vdots$

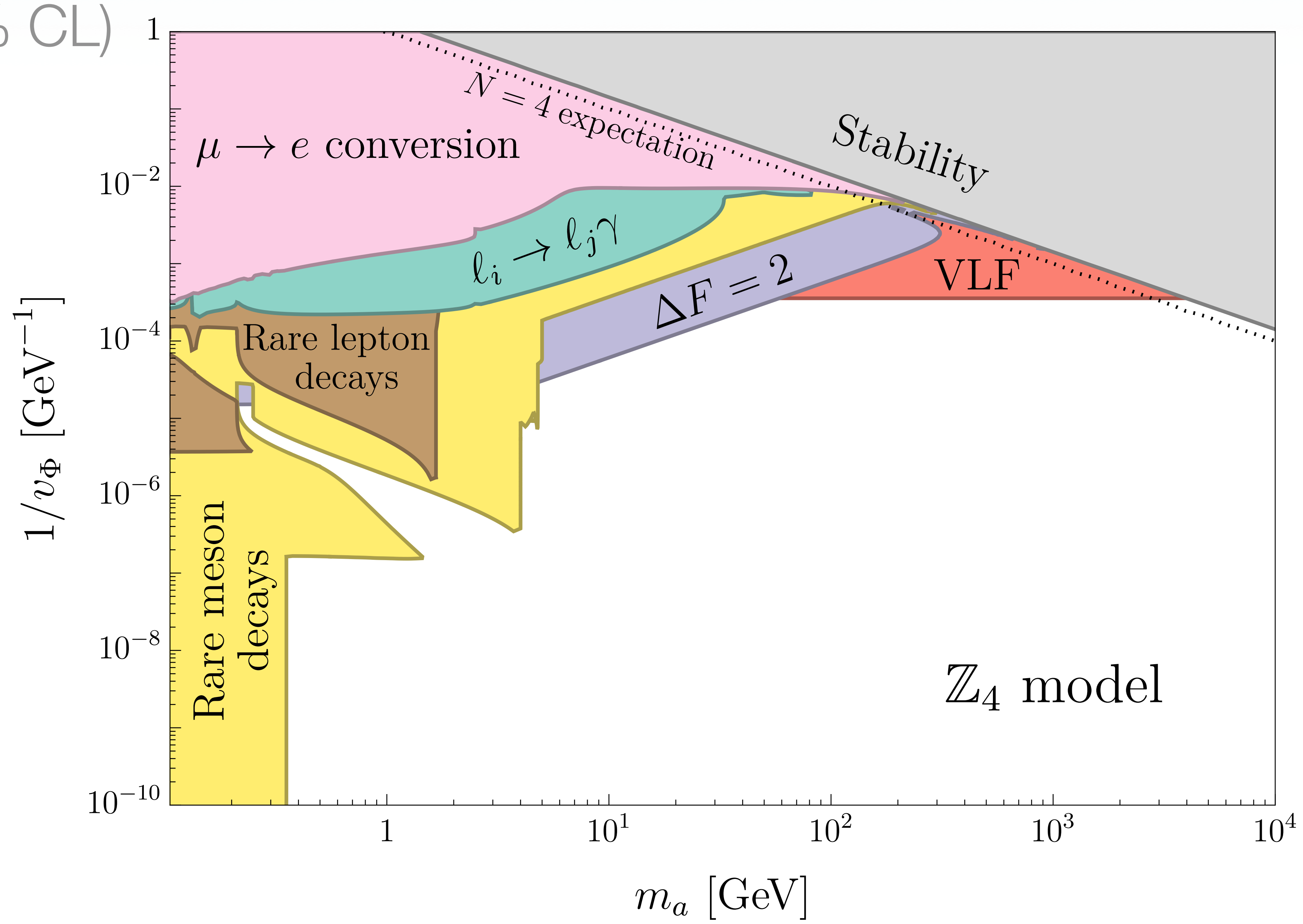
Visible - prompt

Br$(\tau \to K\mu) < 3 \times 10^{-8}$ @ Belle 2010, BaBar 2009, …
Br$(\tau \to 3\mu) < 2.5 \times 10^{-8}$ @ Belle II 2024, LHCb 2015, …
Br$(\tau \to \mu\mu e) < 2.2 \times 10^{-8}$ @ Belle 2010, BaBar 2010, …
$\vdots$

Visible - displaced

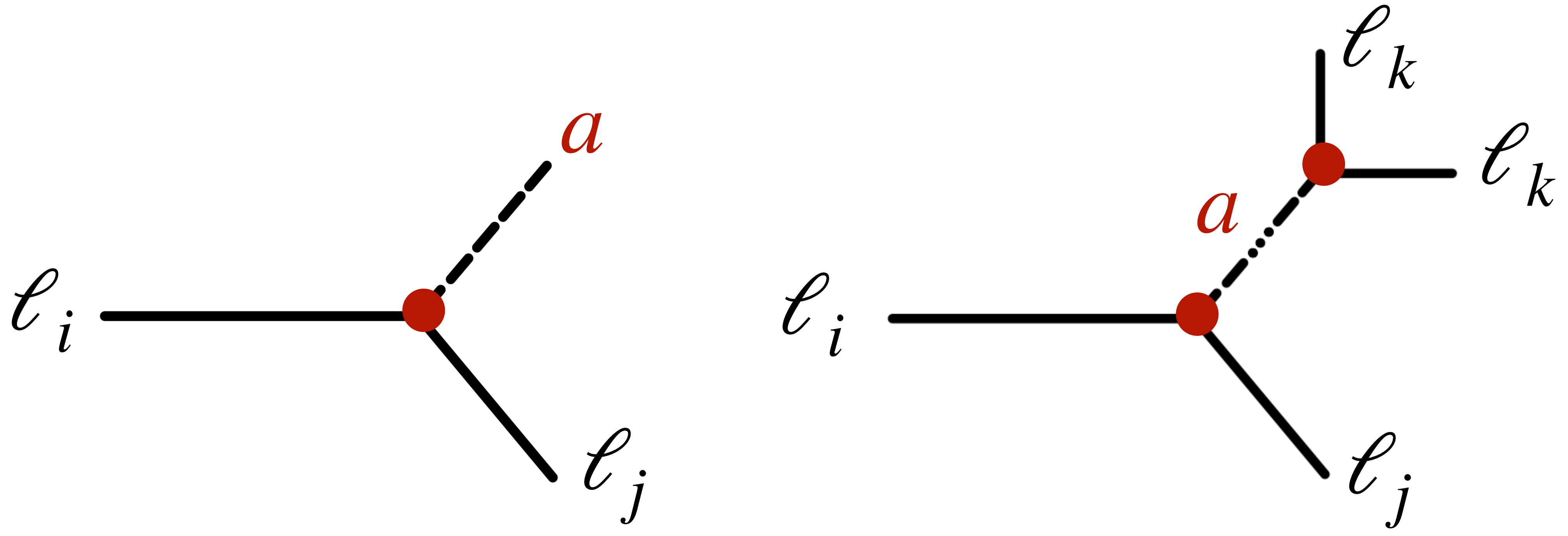
Br$(\mu \to 3e) \lesssim 10^{-12} f(m_a, c\tau_a)$ @ SINDRUM 1986
Br$(\mu \to e\gamma\gamma) \lesssim 10^{-11} f(m_a, c\tau_a)$ @ CrystalBox 1988, MEG 2020

(Bounds at 95% CL)



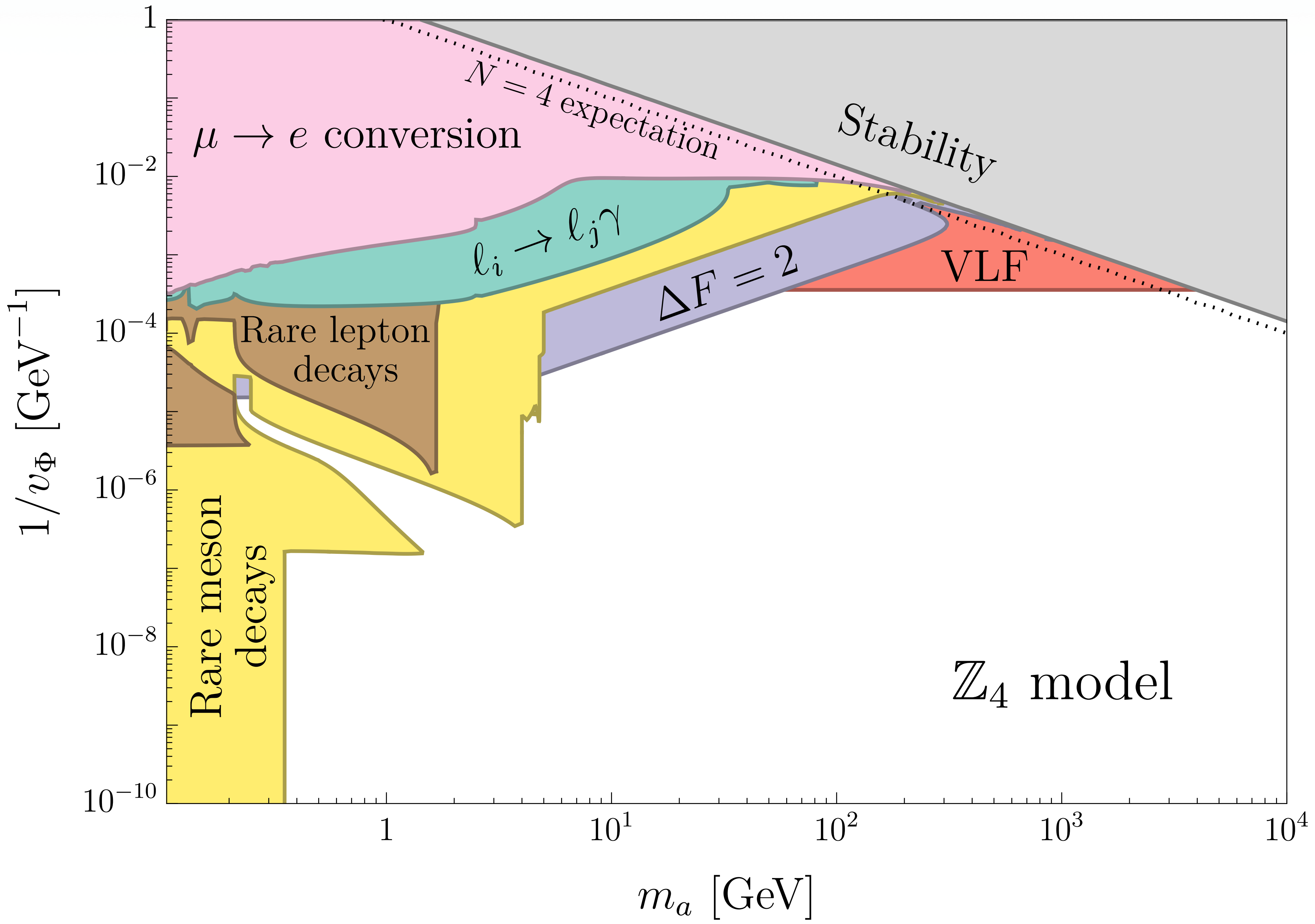
Heeck, Rodejohann (2017)

Need searches for displaced τ decays! ($\tau \to 3\mu, \mu\mu e, \ldots$)



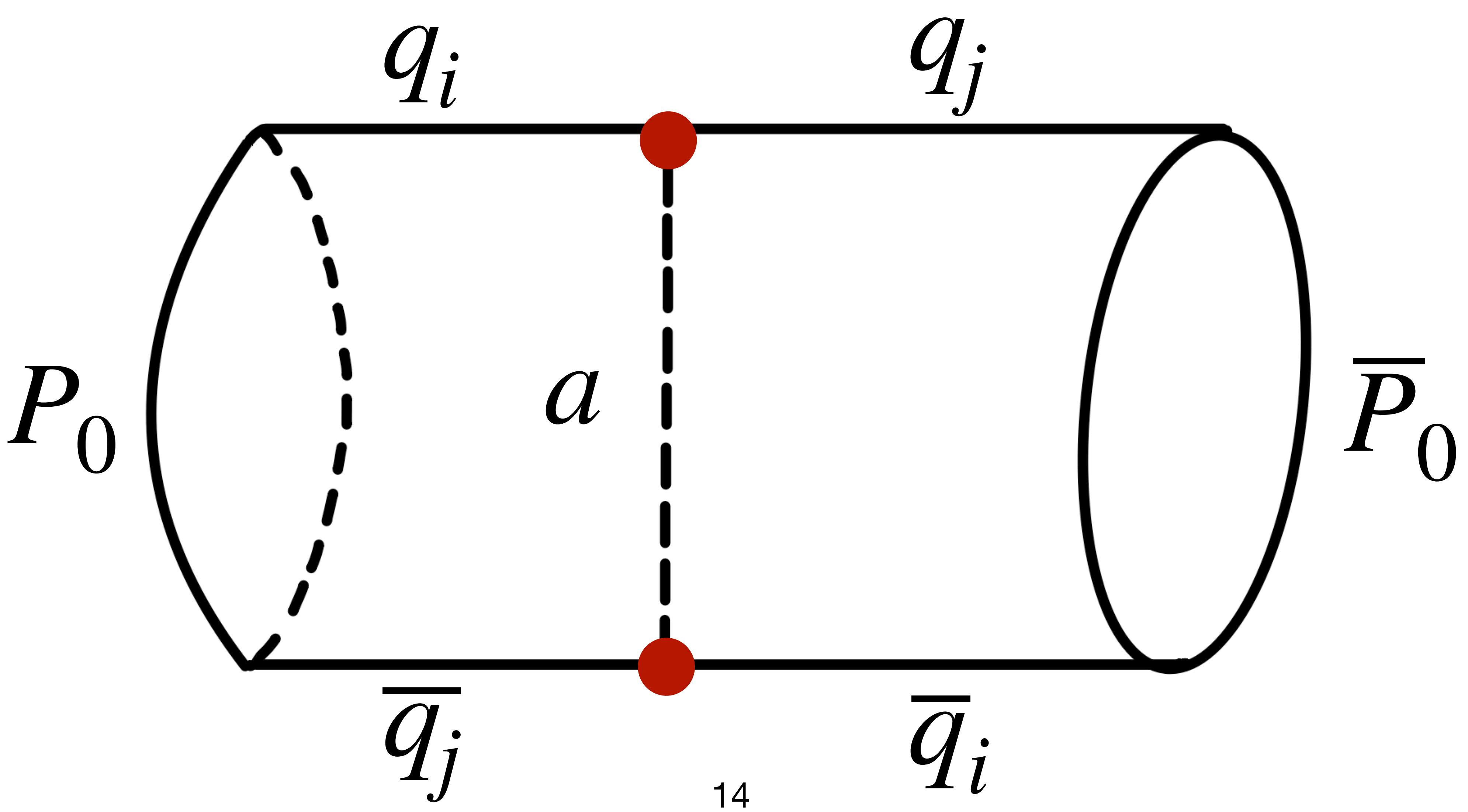
MESONS MIXING

$P_0 - \overline{P}_0$ oscillations with $P = K, B, B_s, D$



$\epsilon_K = (2.23 \pm 0.01) \times 10^{-3}$
$\Delta M_s = 17.765 \pm 0.006$ ps^{-1}
$\Delta M_d = 0.506 \pm 0.002$ ps^{-1}
$\vdots$

@ PDG world average 2024
(LHCb dominating $\Delta M_d, \Delta M_s$)



3. ALP pheno

(Bounds at 95% CL)

Lepton dipoles

Br$(\tau \to \mu\gamma) < 5.7 \times 10^{-8}$ @ BaBar 2009, Belle 2008, …

Br$(\tau \to e\gamma) < 4.3 \times 10^{-8}$ @ BaBar 2009, Belle 2008, …

Br$(\mu \to e\gamma) < 5.5 \times 10^{-13}$ @ MEG 2016

$\mu \to e$ in nuclei

Br$(\mu \to e) < 9 \times 10^{-13}$ @ SINDRUM II 2006 (Au)

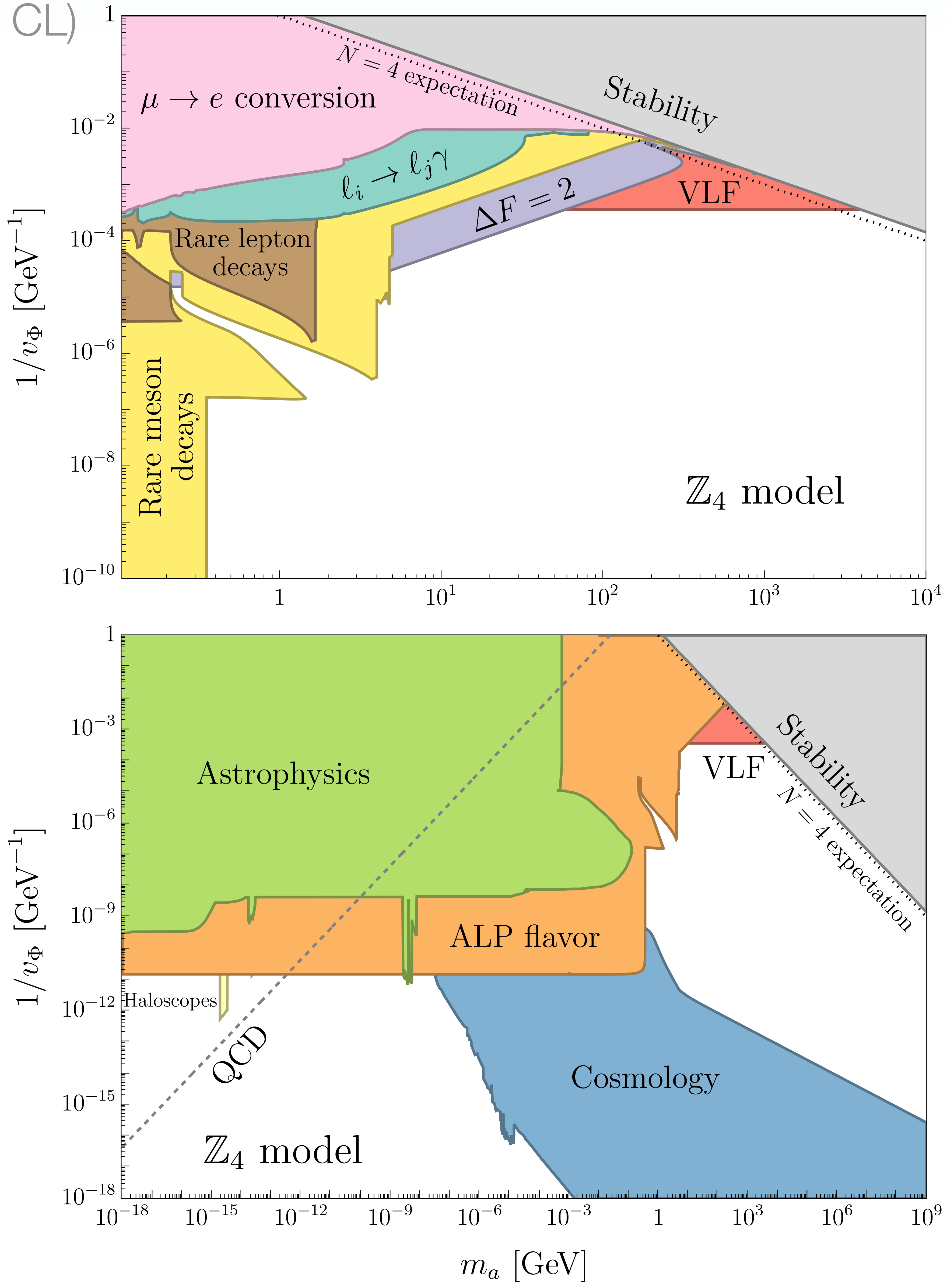
Lepton EDMs

$|d_e|/e < 5.4 \times 10^{-30}$ cm @ Cornell et al. 2022

Neutron EDM

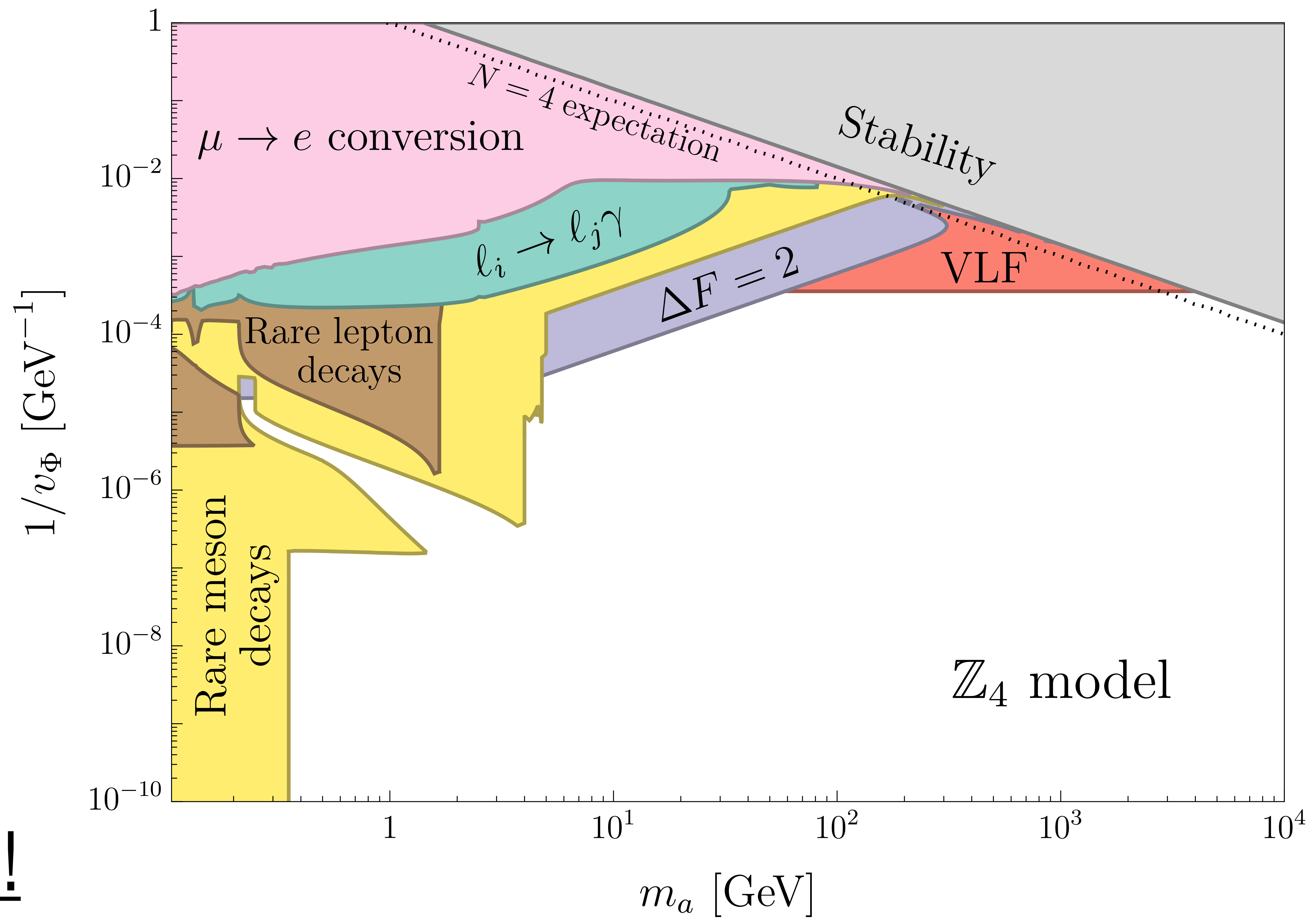
$|d_n|/e < 2.6 \times 10^{-26}$ cm @ Abel et al. 2020

Astrophysics, Cosmology, Haloscopes, …



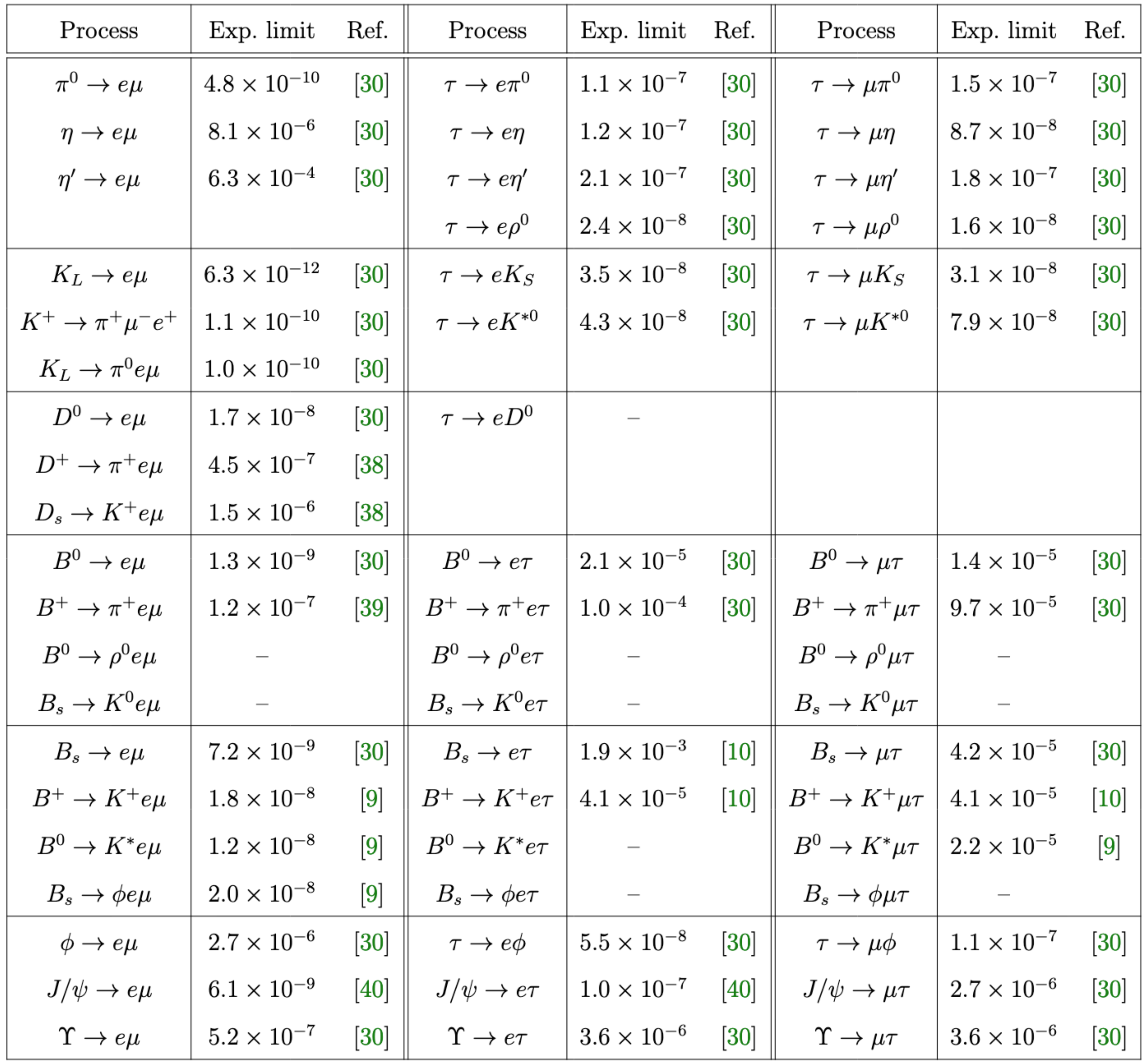
4. Conclusion

- ALPs: very popular, theoretically motivated particles
- Concrete models (FN) able to provide guidelines and correlations in observables
- LHCb + other experiments delivered key observations for constraining/discovering ALPs
- Would be nice: displaced τ, D (and more) decays searches!



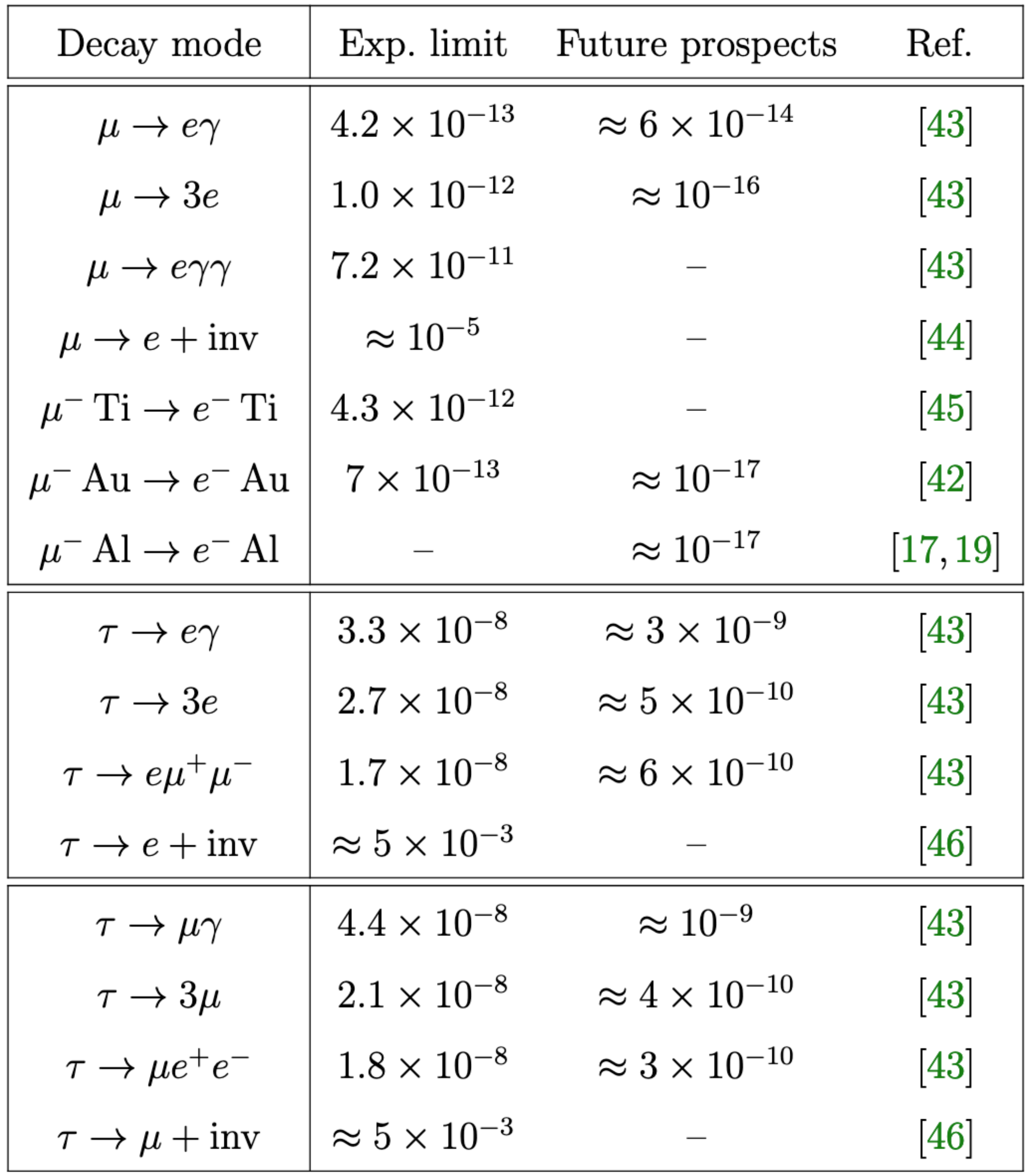
Thank you for your attention!

Some observables (not exhaustive)



Process	Exp. limit	Ref.	Process	Exp. limit	Ref.	Process	Exp. limit	Ref.
$\pi^0 \to e\mu$	4.8×10^{-10}	[30]	$\tau \to e\pi^0$	1.1×10^{-7}	[30]	$\tau \to \mu\pi^0$	1.5×10^{-7}	[30]
$\eta \to e\mu$	8.1×10^{-6}	[30]	$\tau \to e\eta$	1.2×10^{-7}	[30]	$\tau \to \mu\eta$	8.7×10^{-8}	[30]
$\eta' \to e\mu$	6.3×10^{-4}	[30]	$\tau \to e\eta'$	2.1×10^{-7}	[30]	$\tau \to \mu\eta'$	1.8×10^{-7}	[30]
			$\tau \to e\rho^0$	2.4×10^{-8}	[30]	$\tau \to \mu\rho^0$	1.6×10^{-8}	[30]
$K_L \to e\mu$	6.3×10^{-12}	[30]	$\tau \to eK_S$	3.5×10^{-8}	[30]	$\tau \to \mu K_S$	3.1×10^{-8}	[30]
$K^+ \to \pi^+\mu^-e^+$	1.1×10^{-10}	[30]	$\tau \to eK^{*0}$	4.3×10^{-8}	[30]	$\tau \to \mu K^{*0}$	7.9×10^{-8}	[30]
$K_L \to \pi^0 e\mu$	1.0×10^{-10}	[30]						
$D^0 \to e\mu$	1.7×10^{-8}	[30]	$\tau \to eD^0$	–				
$D^+ \to \pi^+ e\mu$	4.5×10^{-7}	[38]						
$D_s \to K^+ e\mu$	1.5×10^{-6}	[38]						
$B^0 \to e\mu$	1.3×10^{-9}	[30]	$B^0 \to e\tau$	2.1×10^{-5}	[30]	$B^0 \to \mu\tau$	1.4×10^{-5}	[30]
$B^+ \to \pi^+ e\mu$	1.2×10^{-7}	[39]	$B^+ \to \pi^+ e\tau$	1.0×10^{-4}	[30]	$B^+ \to \pi^+ \mu\tau$	9.7×10^{-5}	[30]
$B^0 \to \rho^0 e\mu$	–		$B^0 \to \rho^0 e\tau$	–		$B^0 \to \rho^0 \mu\tau$	–	
$B_s \to K^0 e\mu$	–		$B_s \to K^0 e\tau$	–		$B_s \to K^0 \mu\tau$	–	
$B_s \to e\mu$	7.2×10^{-9}	[30]	$B_s \to e\tau$	1.9×10^{-3}	[10]	$B_s \to \mu\tau$	4.2×10^{-5}	[30]
$B^+ \to K^+ e\mu$	1.8×10^{-8}	[9]	$B^+ \to K^+ e\tau$	4.1×10^{-5}	[10]	$B^+ \to K^+ \mu\tau$	4.1×10^{-5}	[10]
$B^0 \to K^* e\mu$	1.2×10^{-8}	[9]	$B^0 \to K^* e\tau$	–		$B^0 \to K^* \mu\tau$	2.2×10^{-5}	[9]
$B_s \to \phi e\mu$	2.0×10^{-8}	[9]	$B_s \to \phi e\tau$	–		$B_s \to \phi \mu\tau$	–	
$\phi \to e\mu$	2.7×10^{-6}	[30]	$\tau \to e\phi$	5.5×10^{-8}	[30]	$\tau \to \mu\phi$	1.1×10^{-7}	[30]
$J/\psi \to e\mu$	6.1×10^{-9}	[40]	$J/\psi \to e\tau$	1.0×10^{-7}	[40]	$J/\psi \to \mu\tau$	2.7×10^{-6}	[30]
$\Upsilon \to e\mu$	5.2×10^{-7}	[30]	$\Upsilon \to e\tau$	3.6×10^{-6}	[30]	$\Upsilon \to \mu\tau$	3.6×10^{-6}	[30]

Plakias, Sumensari (2023)



Decay mode	Exp. limit	Future prospects	Ref.
$\mu \to e\gamma$	4.2×10^{-13}	$\approx 6 \times 10^{-14}$	[43]
$\mu \to 3e$	1.0×10^{-12}	$\approx 10^{-16}$	[43]
$\mu \to e\gamma\gamma$	7.2×10^{-11}	–	[43]
$\mu \to e + \mathrm{inv}$	$\approx 10^{-5}$	–	[44]
$\mu^- \mathrm{Ti} \to e^- \mathrm{Ti}$	4.3×10^{-12}	–	[45]
$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$	7×10^{-13}	$\approx 10^{-17}$	[42]
$\mu^- \mathrm{Al} \to e^- \mathrm{Al}$	–	$\approx 10^{-17}$	[17, 19]
$\tau \to e\gamma$	3.3×10^{-8}	$\approx 3 \times 10^{-9}$	[43]
$\tau \to 3e$	2.7×10^{-8}	$\approx 5 \times 10^{-10}$	[43]
$\tau \to e\mu^+\mu^-$	1.7×10^{-8}	$\approx 6 \times 10^{-10}$	[43]
$\tau \to e + \mathrm{inv}$	$\approx 5 \times 10^{-3}$	–	[46]
$\tau \to \mu\gamma$	4.4×10^{-8}	$\approx 10^{-9}$	[43]
$\tau \to 3\mu$	2.1×10^{-8}	$\approx 4 \times 10^{-10}$	[43]
$\tau \to \mu e^+e^-$	1.8×10^{-8}	$\approx 3 \times 10^{-10}$	[43]
$\tau \to \mu + \mathrm{inv}$	$\approx 5 \times 10^{-3}$	–	[46]

Cornella, Paradisi, Sumensari (2019)

flavio observables

flav-io.github.io/docs/observables

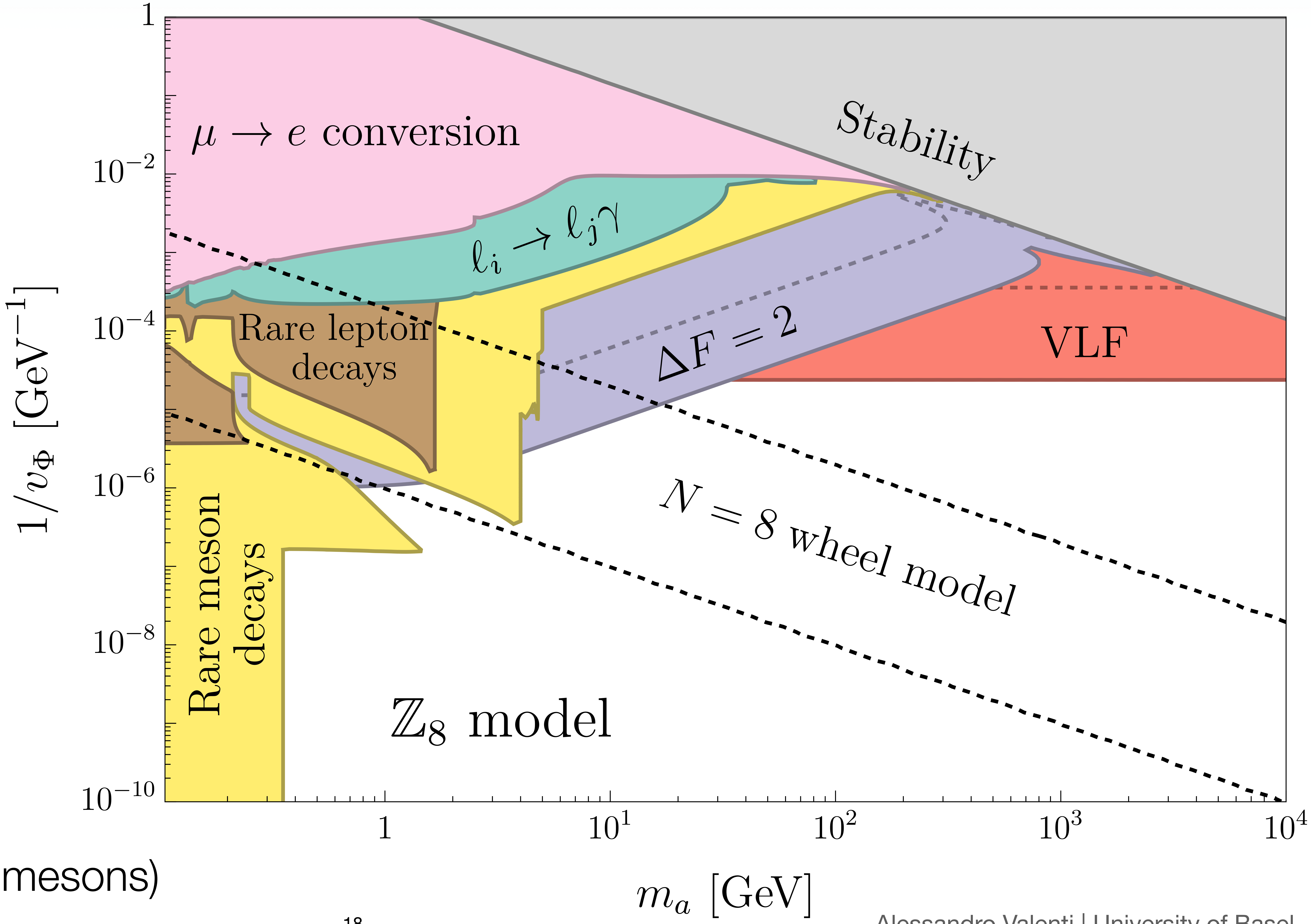
Backup

Z_8 model

$$c^d \sim \begin{pmatrix} 1 & \frac{m_d}{m_s} & \frac{m_d}{m_b} \\ \frac{m_d}{m_s} & 1 & \frac{m_s}{m_b} \\ \frac{m_d}{m_d} & \frac{m_s}{m_b} & 1 \end{pmatrix}$$

$$c^e \sim c^d$$

$$c^u \sim \begin{pmatrix} 1 & \sqrt{\frac{m_u}{m_c}} & \sqrt{\frac{m_u}{m_t}} \\ \sqrt{\frac{m_u}{m_c}} & 1 & \sqrt{\frac{m_c}{m_t}} \\ \sqrt{\frac{m_u}{m_t}} & \sqrt{\frac{m_c}{m_t}} & \frac{m_c}{m_t} \end{pmatrix}$$



Better masses fit

Up physics more important! (D mesons)