

Looking for Light Dark States with Taus and/or Time

Patrick Fox

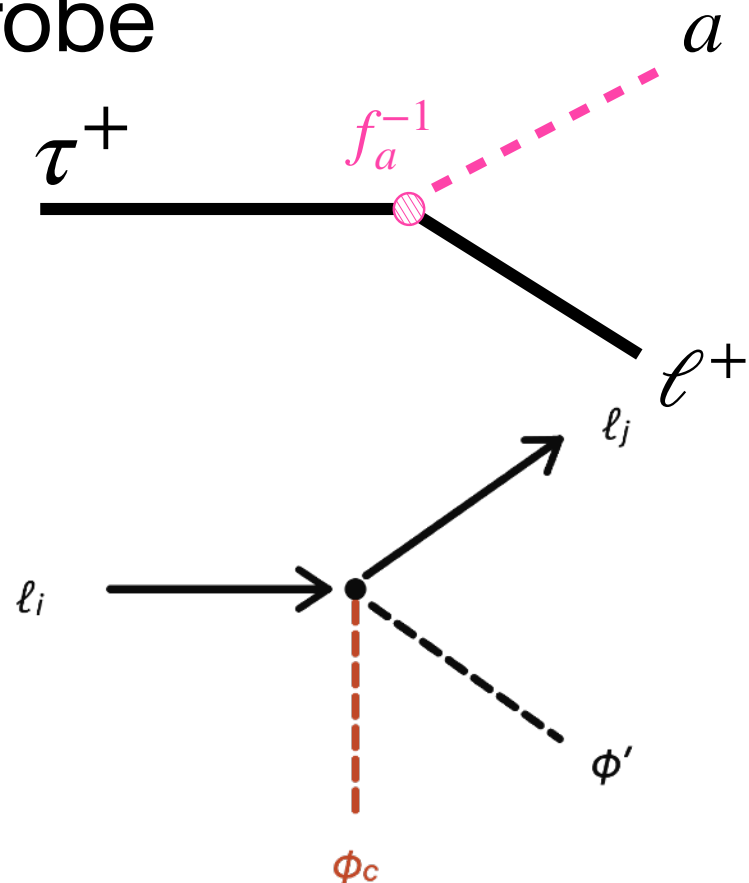


Based on [PRD 112](#) and [2504.01465](#) with Yohei Ema,
Matheus Hostert, Tony Menzo, Maxim Pospelov, Anupam
Ray, Jure Zupan
and
[PRL 136](#) with Innes Bigaran, Yann Gouttenoire, Roni
Harnik, Gordan Krnjaic, Tony Menzo, Jure Zupan

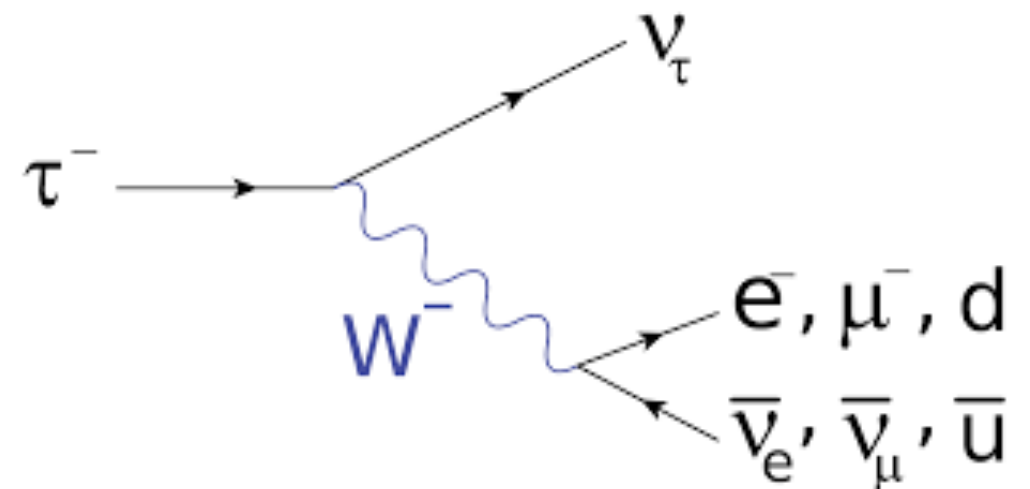
BSM in Tau decays

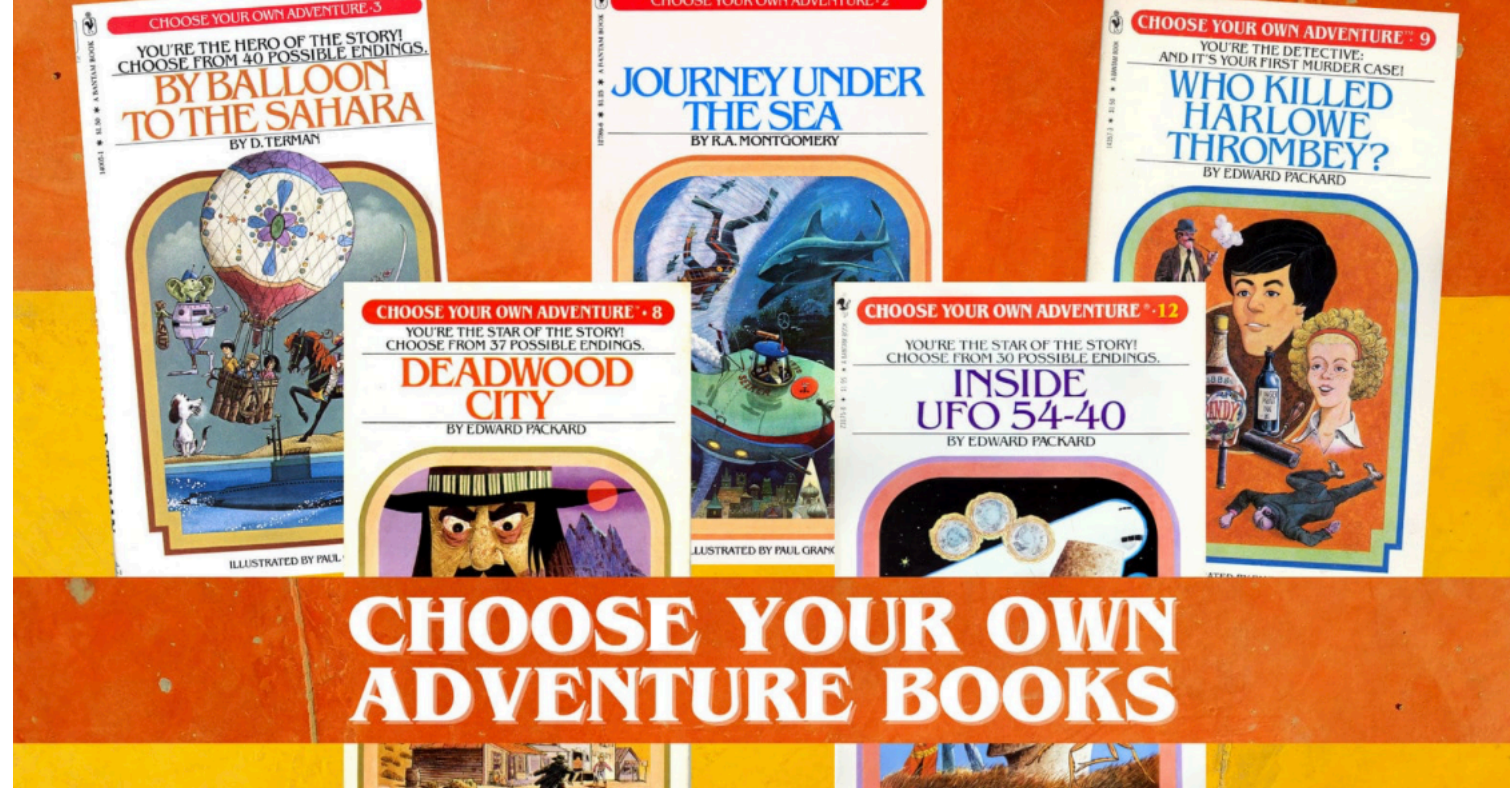
Looking for on-shell (i.e. light) new physics in tau decays:

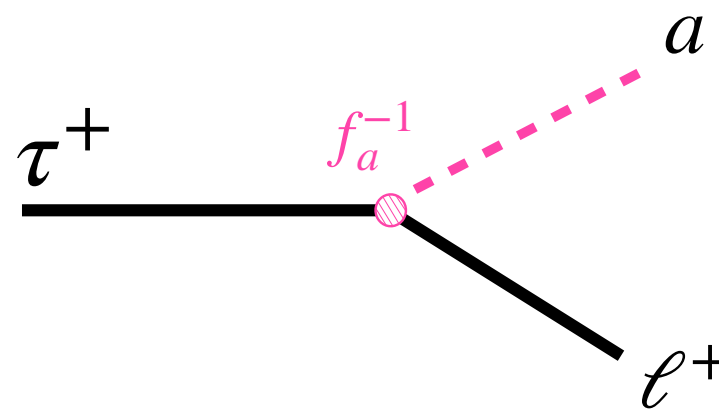
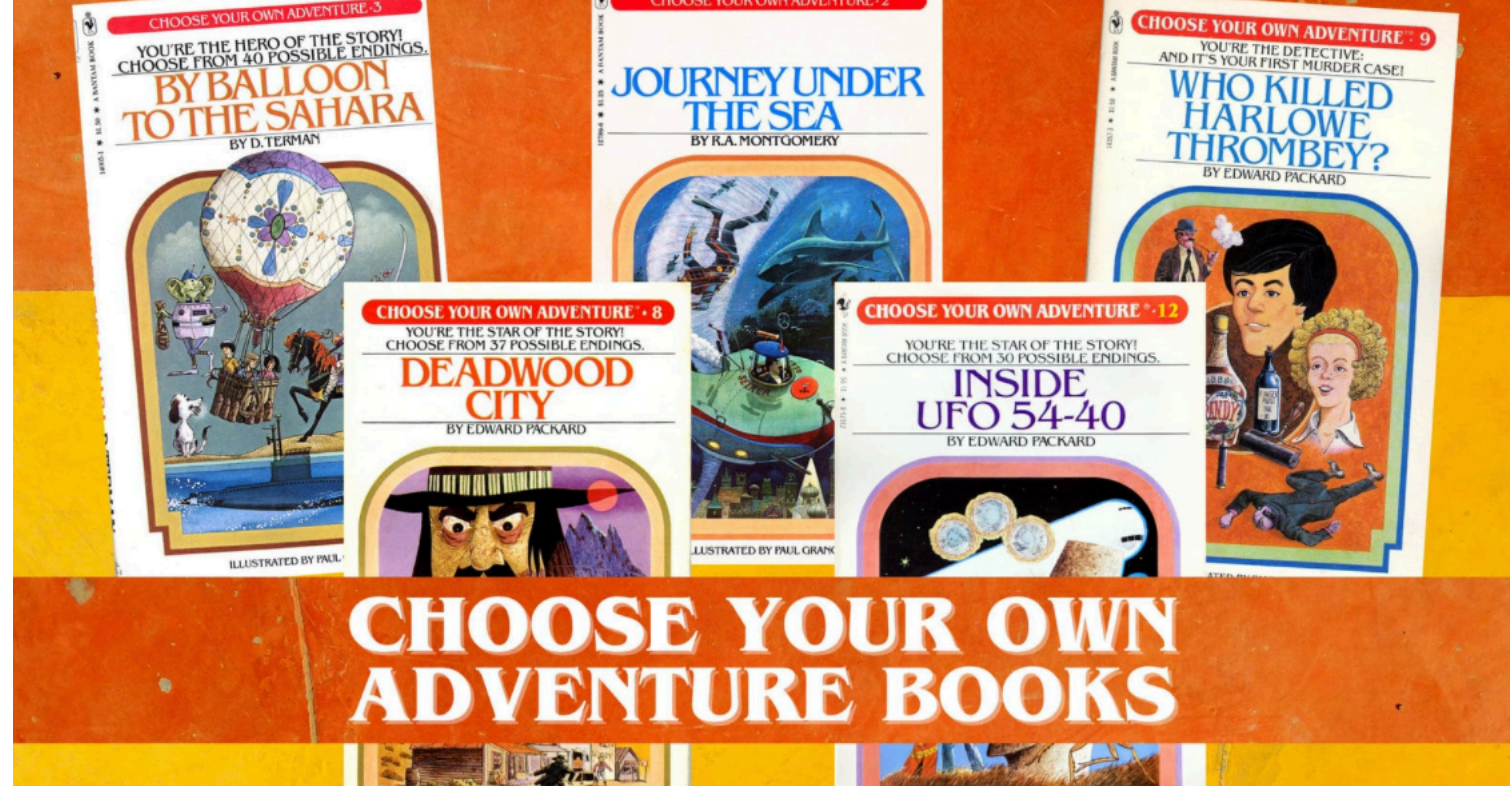
- Taus provide largest leptonic mass reach for “light” BSM states
- Many new and exotic final states
- Tau width narrow in SM, BSM can compete
- Taus less well probed
- Many ongoing and upcoming experiments with potential to probe



vs.

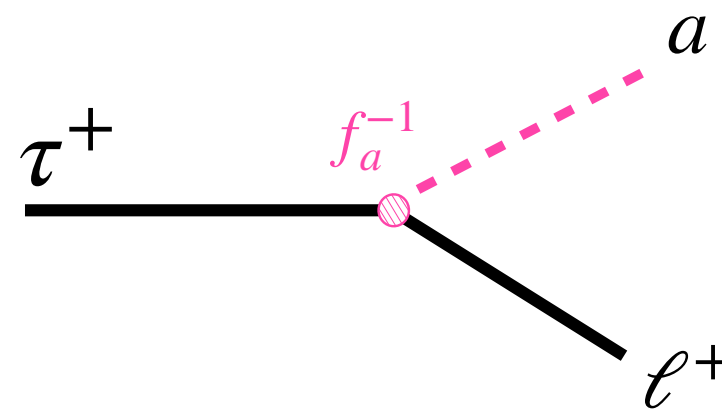
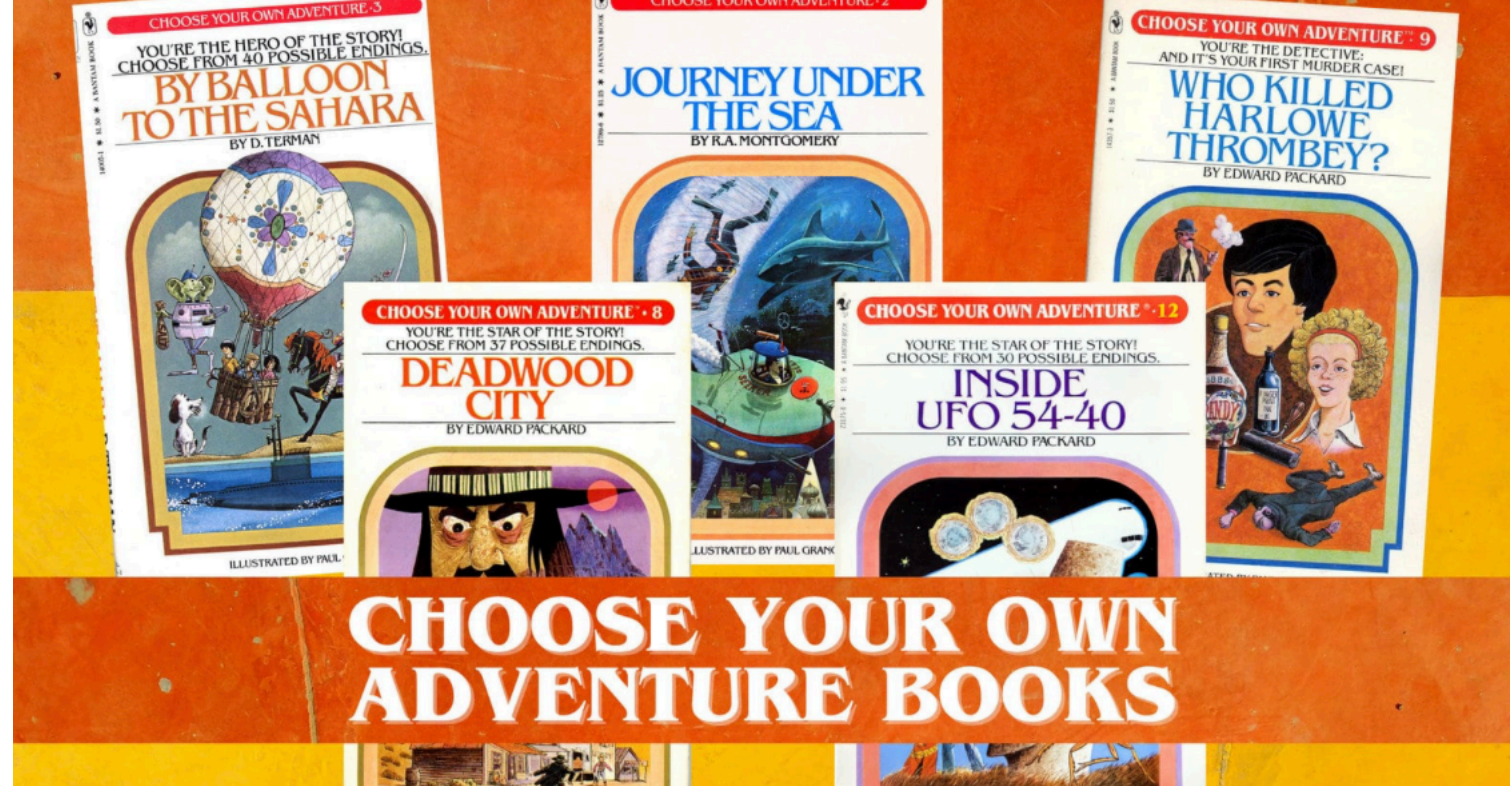






a is long lived

a is prompt



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Axions/ALPs

- pNGB of a spontaneously broken global symmetry
- One of the standard “portals” to the dark sector

$$\mathcal{L}_{\text{eff}}^{D \leq 5} = \frac{1}{2} (\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial^\mu a}{f} \sum_F \bar{\psi}_F \mathbf{c}_F \gamma_\mu \psi_F$$
$$+ c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + c_{BB} \frac{\alpha_1}{4\pi} \frac{a}{f} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

Axions/ALPs

- pNGB of a spontaneously broken global symmetry
- One of the standard “portals” to the dark sector

Breaks shift
symmetry

Generic 3x3
hermitian matrix

$$\mathcal{L}_{\text{eff}}^{D \leq 5} = \frac{1}{2} (\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial^\mu a}{f} \sum_F \bar{\psi}_F \mathbf{C}_F \gamma_\mu \psi_F$$
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Breaking
scale

Axions/ALPs — couplings to fermions

$$\mathcal{L} \supset \frac{\partial^\mu a}{2f_a} \left(C_{\ell_i \ell_j}^V \bar{\ell}_i \gamma_\mu \ell_j + C_{\ell_i \ell_j}^A \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right)$$

No reason for couplings to be diagonal

If PQ charges of SM fermions not aligned with fermion masses axions will have flavour violating couplings e.g.

- DFSZ model with LFV
- Generation dependent PQ charges e.g. Froggatt-Nielsen
- Axiflavor models

[see eg [Calibbi, Redigolo, Ziegler, Zupan JHEP 09, 2021](#)]

$$C_{f_i f_j}^{V,A} = -\frac{1}{2N} \left(V_R^{f\dagger} X_{f_R} V_R^f \pm V_L^{f\dagger} X_{f_L} V_L^f \right)_{ij}$$

Axions/ALPs — couplings to fermions

$$\mathcal{L} \supset \frac{\partial^\mu a}{2f_a} \left(C_{\ell_i \ell_j}^V \bar{\ell}_i \gamma_\mu \ell_j + C_{\ell_i \ell_j}^A \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right)$$

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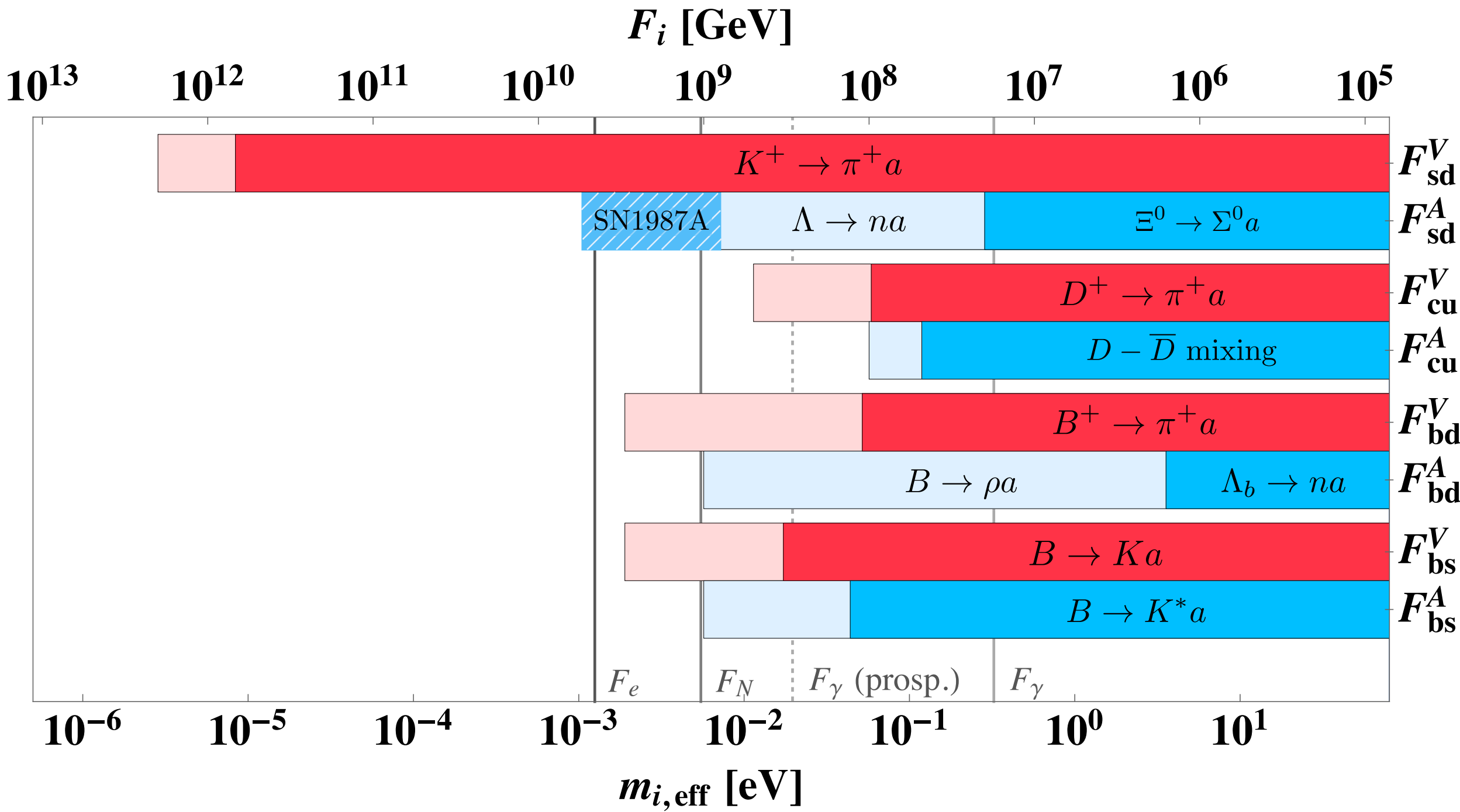
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PQ charge matrix

Rotations to diagonalize Yukawas

FV ALPs

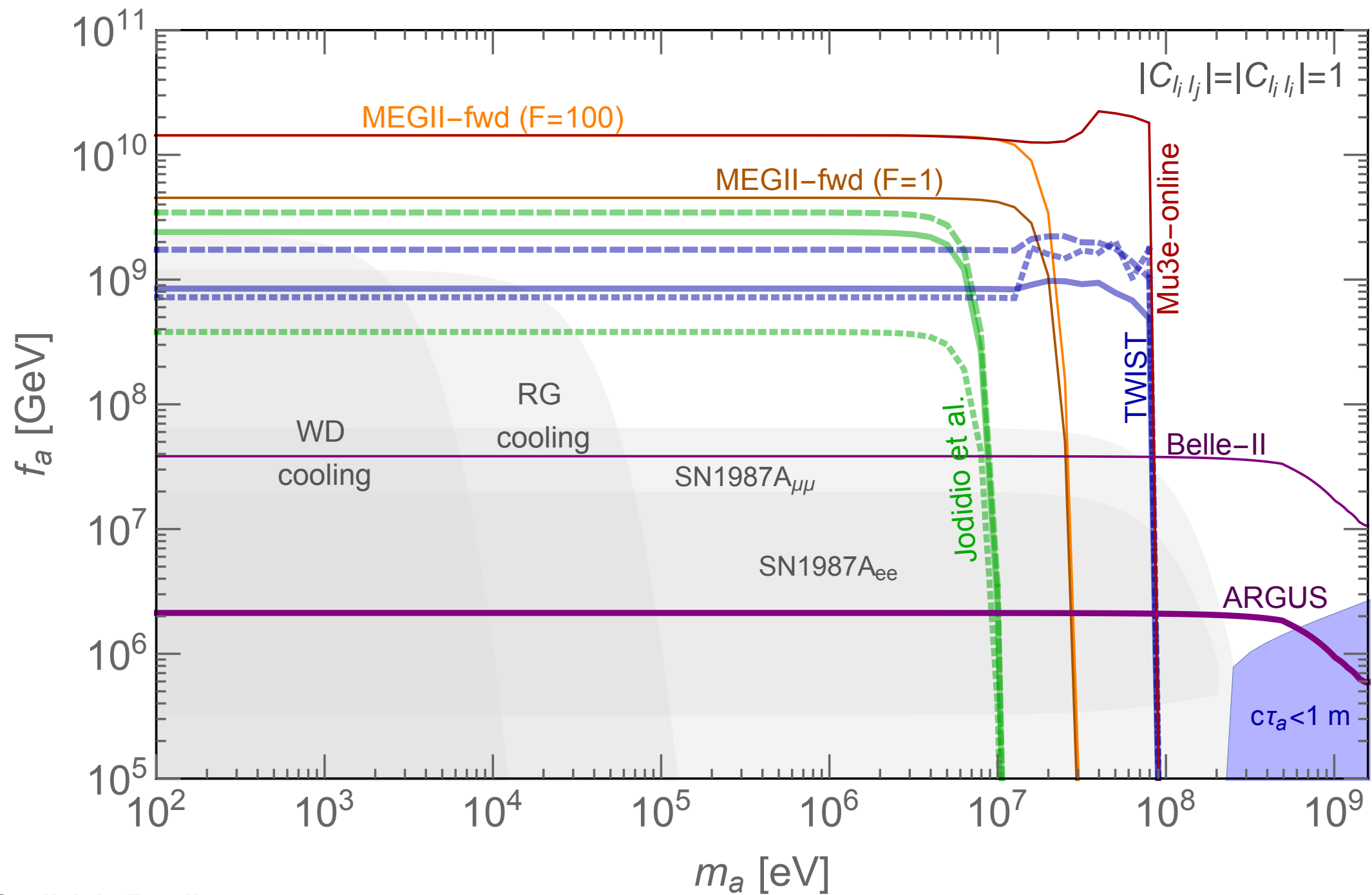
Quark sector



Camalich, Pospelov, et al
(2002.04623)

FV ALPs

Lepton sector



Calibbi, Redigolo, et al
(2006.04795)

Axions/ALPs

- Focus on couplings to **taus**
- Focus on $g_L^{ij} = -g_R^{ij}$

$$\mathcal{L} = \frac{\partial_\mu a}{2f} \sum_{i,j=e,\mu,\tau} g_L^{ij} \bar{L}_i \gamma^\mu L_j + g_R^{ij} \bar{\ell}_i \gamma^\mu \ell_j = \frac{\partial_\mu a}{2f} \sum_{i,j=e,\mu,\tau} g^{ij} [\bar{\ell}_i \gamma^\mu \gamma_5 \ell_j - \bar{\nu}_i \gamma^\mu P_L \nu_j]$$



**Fermion equations
of motion**

$$\mathcal{L} = -\frac{a}{2f} \sum_{i,j=e,\mu,\tau} g^{ij} (m_i + m_j) \bar{\ell}_i \gamma_5 \ell_j$$

1. Axions can be produced in heavy lepton decay

$$\Gamma(\tau \rightarrow \mu a) \propto \frac{m_\tau^3}{f^2} \quad \text{vs.} \quad \Gamma(\tau \rightarrow \mu \nu \bar{\nu}) \propto m_\tau^5 G_F^2$$

2. Axions could be long-lived

$$\Gamma(a \rightarrow \ell^+ \ell^-) \propto m_a \left(\frac{m_\ell}{f} \right)^2$$

Coupling scenarios

$$g^{ij} =$$

LFCV Anarchy



$$\begin{matrix} & e & \mu & \tau \\ \begin{matrix} e \\ \mu \\ \tau \end{matrix} & \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \end{matrix}$$

LFCV Hierarchy



$$\begin{matrix} & e & \mu & \tau \\ \begin{matrix} e \\ \mu \\ \tau \end{matrix} & \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \end{matrix}$$

LFC Universal



$$\begin{matrix} & e & \mu & \tau \\ \begin{matrix} e \\ \mu \\ \tau \end{matrix} & \begin{pmatrix} \blacksquare & \cdot & \cdot \\ \cdot & \blacksquare & \cdot \\ \cdot & \cdot & \blacksquare \end{pmatrix} \end{matrix}$$

LFC non-Universal

$$\begin{matrix} & e & \mu & \tau \\ \begin{matrix} e \\ \mu \\ \tau \end{matrix} & \begin{pmatrix} \blacksquare & \cdot & \cdot \\ \cdot & \blacksquare & \cdot \\ \cdot & \cdot & \blacksquare \end{pmatrix} \end{matrix}$$

μ -phobic

$$\begin{matrix} & e & \mu & \tau \\ \begin{matrix} e \\ \mu \\ \tau \end{matrix} & \begin{pmatrix} \blacksquare & \cdot & \cdot \\ \cdot & \blacksquare & \cdot \\ \cdot & \cdot & \blacksquare \end{pmatrix} \end{matrix}$$

τ -philic

Coupling scenarios — Production

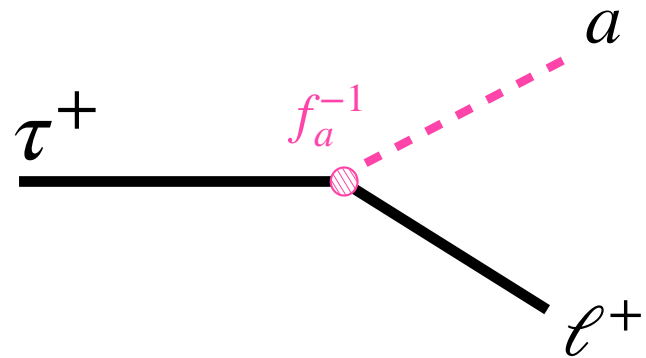
and

Decay

LFV



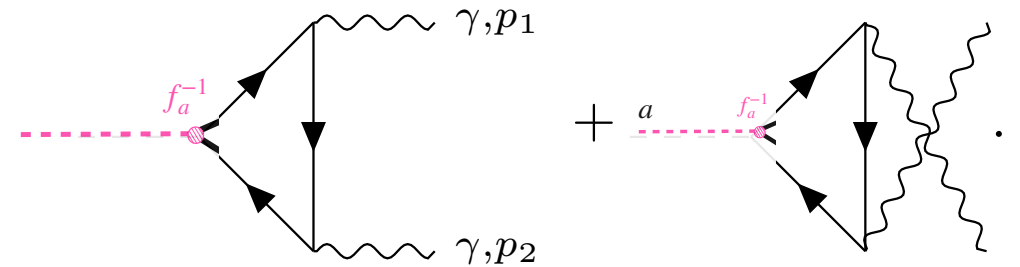
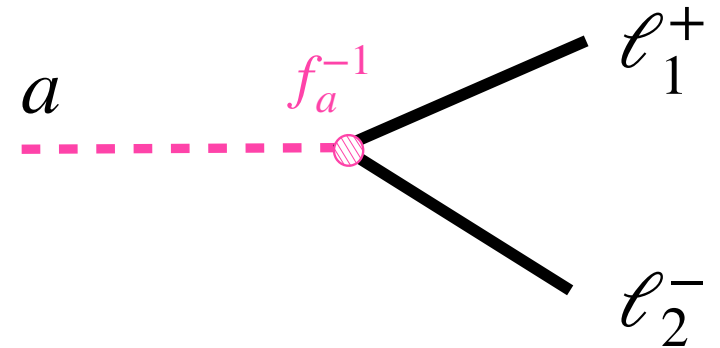
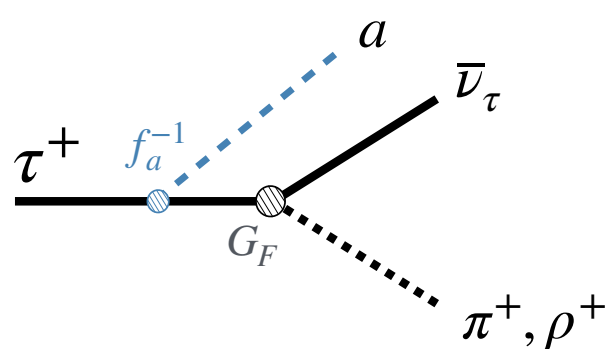
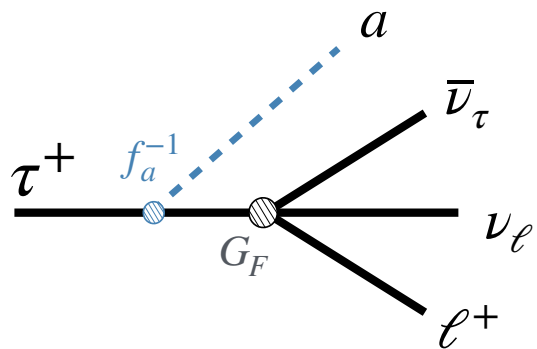
$$\begin{matrix} e & \mu & \tau \\ e & \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \\ \mu & \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \\ \tau & \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \end{matrix} \quad \begin{matrix} e & \mu & \tau \\ e & \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \\ \mu & \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \\ \tau & \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \end{matrix}$$



LFC

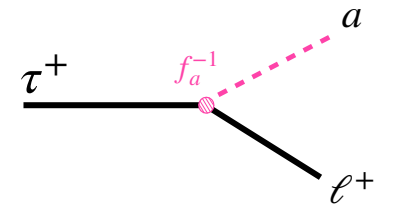


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Coupling scenarios

LFV



$$\Gamma(\tau \rightarrow \ell a) = \frac{|g_{\ell\tau}|^2 m_\tau^3}{64\pi f_a^2} \left(1 + \frac{m_\ell}{m_\tau}\right)^2 \left[\left(1 - \frac{m_\ell}{m_\tau}\right)^2 - \frac{m_a^2}{m_\tau^2} \right] \left[1 - \frac{2(m_\ell^2 + m_a^2)}{m_\tau^2} + \frac{(m_\ell^2 - m_a^2)^2}{m_\tau^4} \right]^{1/2}$$

$$\text{At } 0.1\text{GeV} \quad \text{Br}(\tau \rightarrow \ell a) = 1.2 \times 10^{-4} |g_{\ell\tau}|^2 \left(\frac{10^7 \text{ GeV}}{f_a} \right)^2$$

Can compete because tau is narrow due of weak interactions.

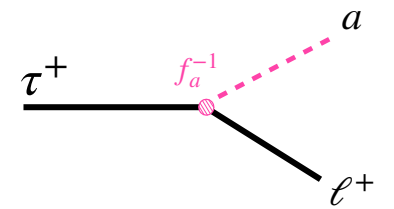
Axions long lived

Coupling scenarios

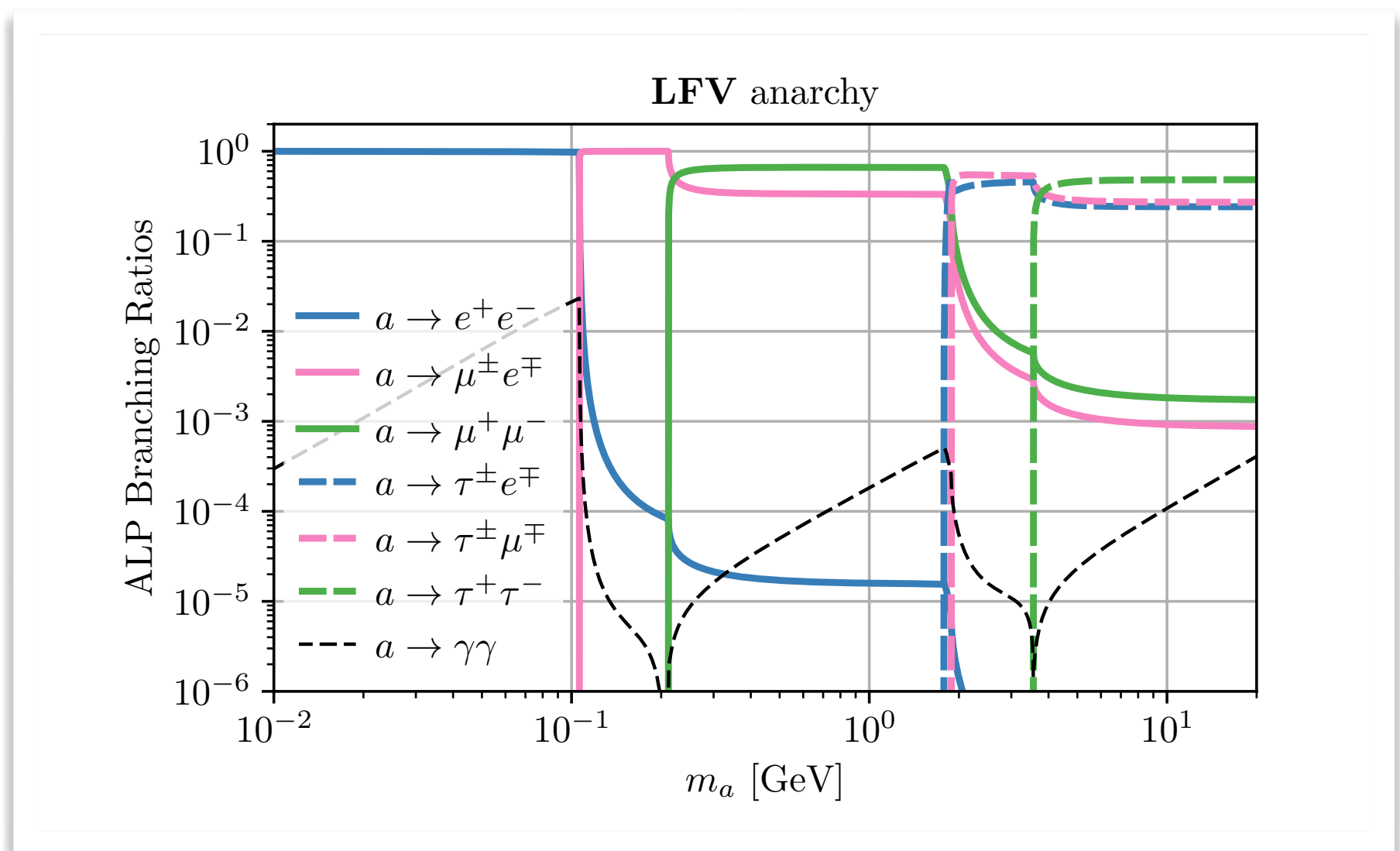
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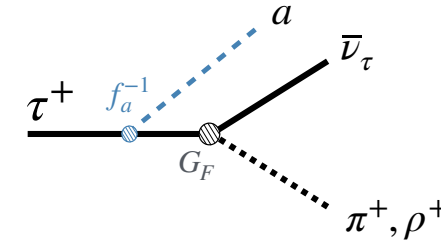
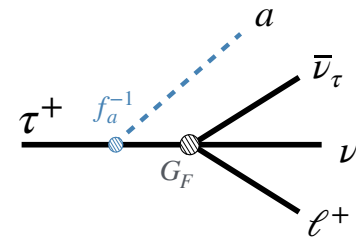


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Axions long lived



Coupling scenarios

LFC



$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{ud}^* f_\pi (\partial_\mu \pi^-) \bar{\tau} \gamma^\mu (1 - \gamma_5) \nu_\tau + (\text{h.c.})$$

$$\frac{d\Gamma(\tau \rightarrow \pi \nu_\tau a)}{dE_a} = \frac{|g_{\tau\tau}|^2 G_F^2 |V_{ud}|^2 f_\pi^2 m_\tau^2 (\bar{m}_\tau^2 - m_\pi^2)^2}{256\pi^3 f_a^2 \bar{m}_\tau^2} \left[1 - \frac{m_a^2 (m_\tau^2 + \bar{m}_\tau^2)}{(m_\tau^2 - \bar{m}_\tau^2)^2} \right] v(m_\tau, \bar{m}_\tau, m_a)$$

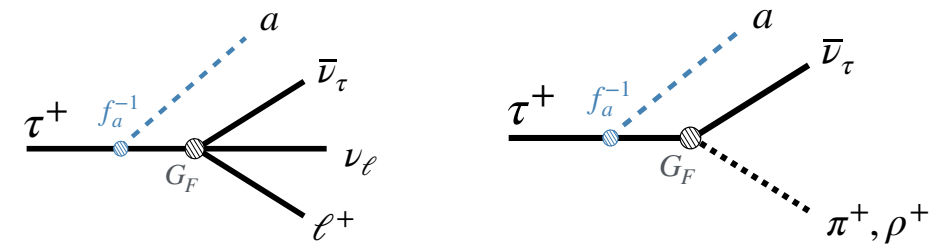
At 0.1 GeV $\text{Br}(\tau \rightarrow \pi \nu_\tau a) = 1.5 \times 10^{-12} |g_{\tau\tau}|^2 \left(\frac{10^4 \text{ GeV}}{f_a} \right)^2$,

These decays are suppressed by GF and f_a

So only long lived below muon threshold, or for muon-phobic

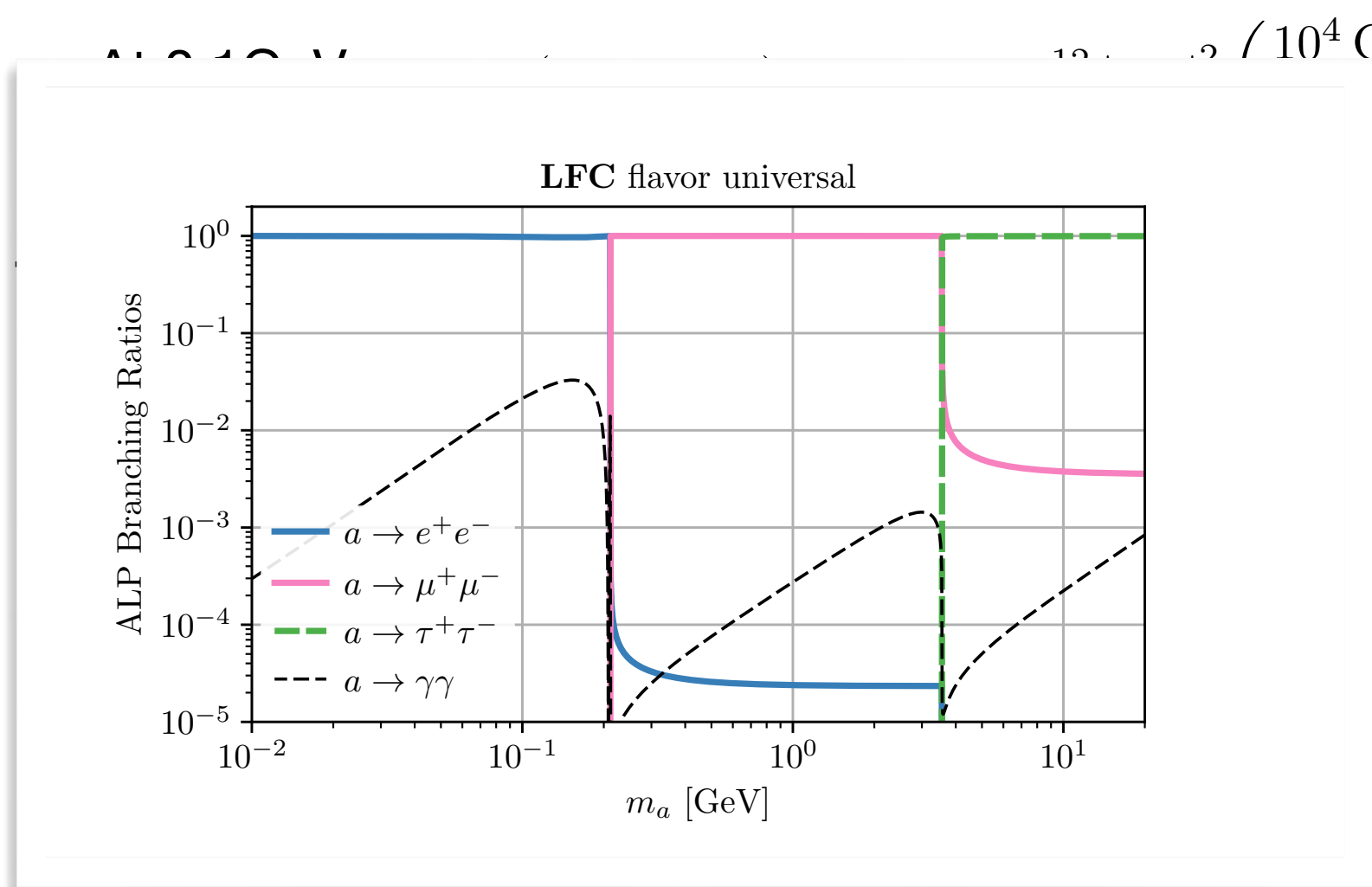
Coupling scenarios

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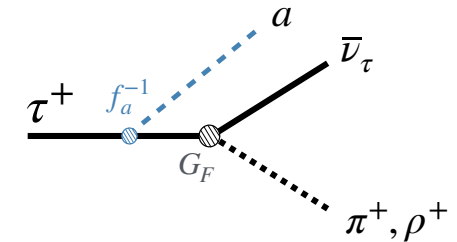
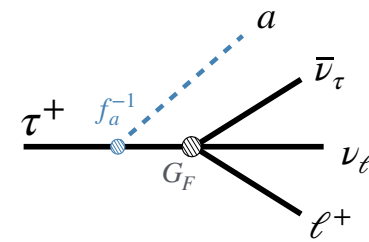
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for muon-phobic

Coupling scenarios

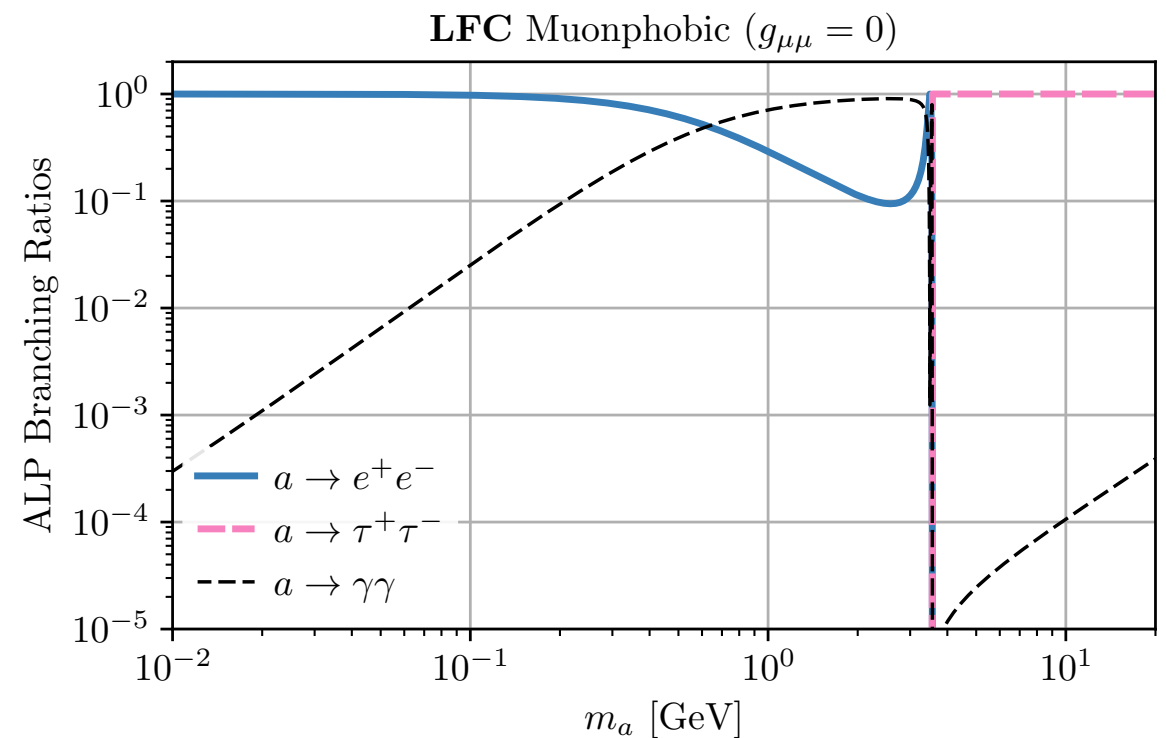
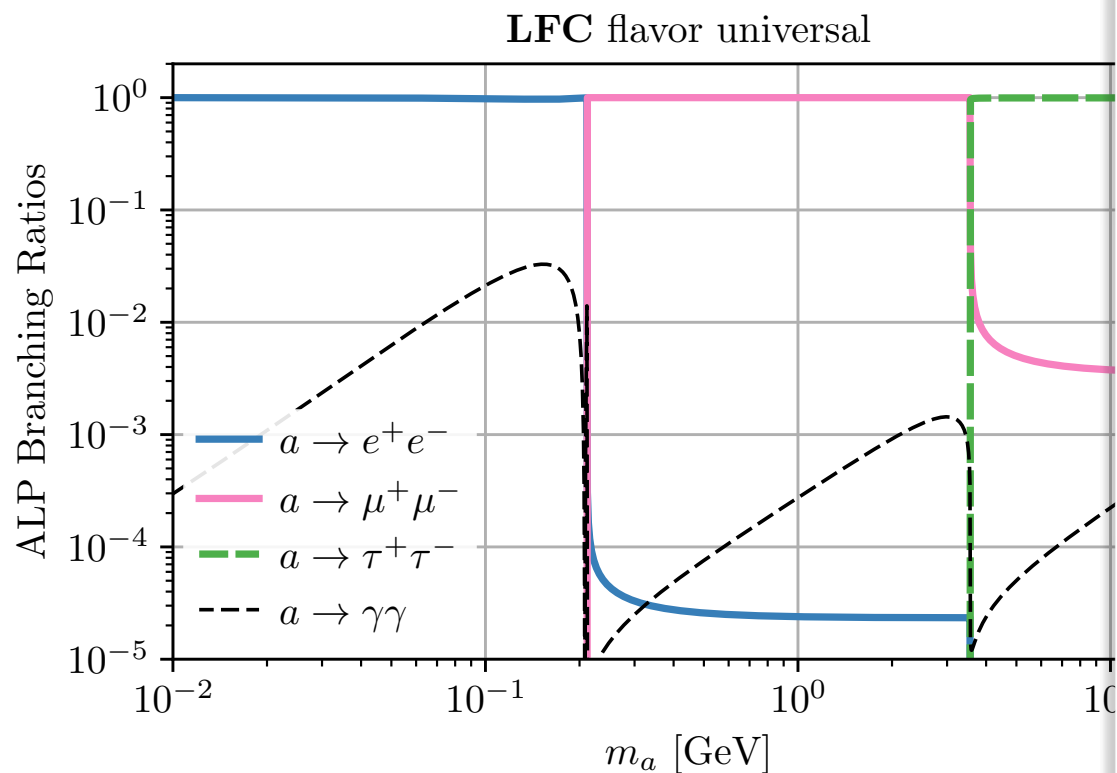
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ALP Branching Ratios / $(10^4 \text{ GeV})^2$

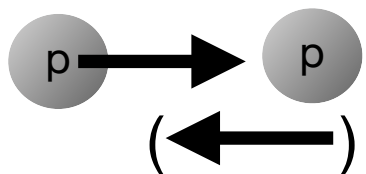


ALP production & Detection

ALP production & Detection

PYTHIA

SoftQCD:all

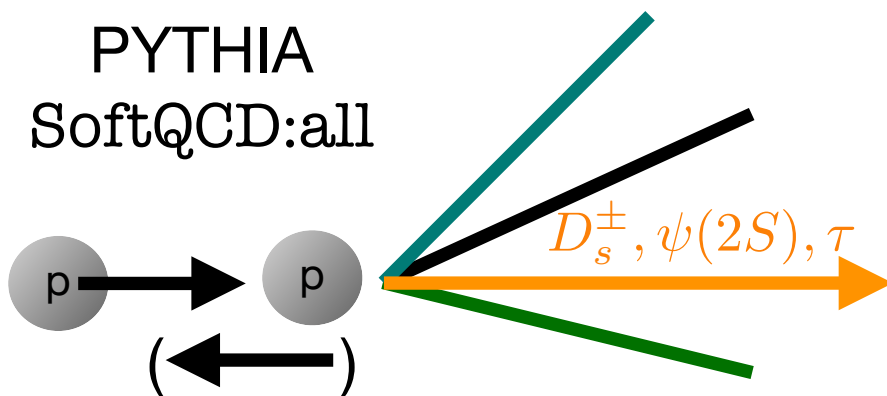


NuMI: 120 GeV beam

SPS: 400 GeV beam

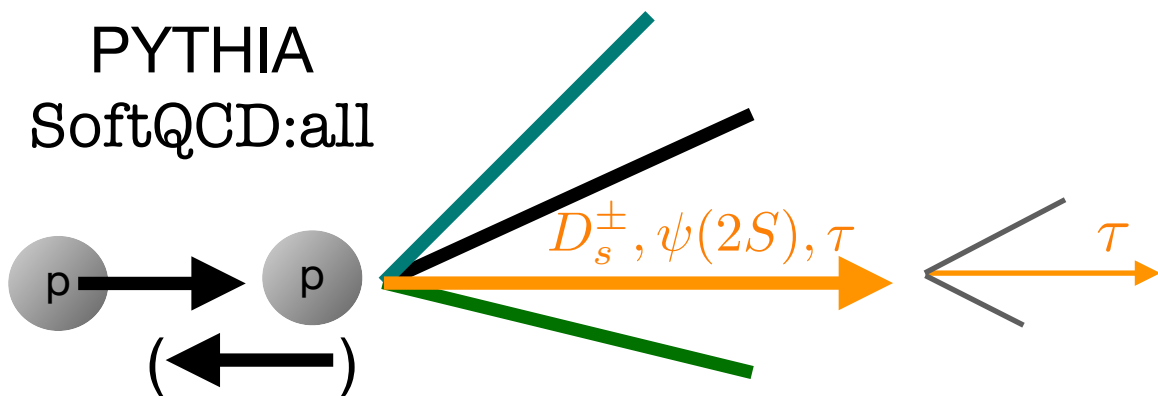
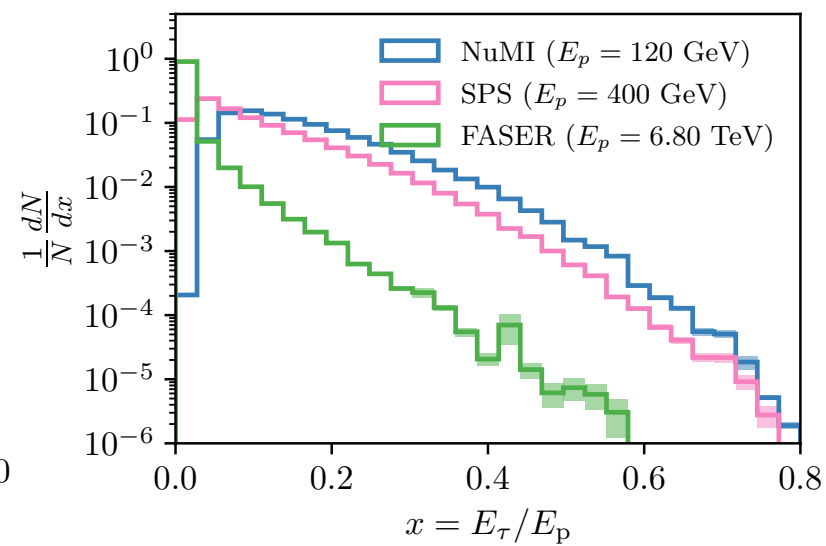
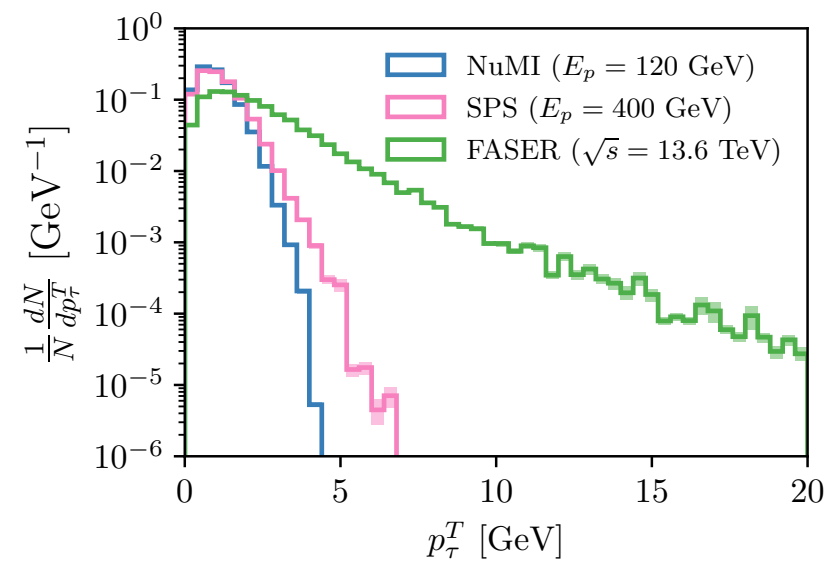
LHC: $\sqrt{s} = 13.6$ TeV

ALP production & Detection



NuMI: 120 GeV beam
SPS: 400 GeV beam
LHC: $\sqrt{s} = 13.6$ TeV

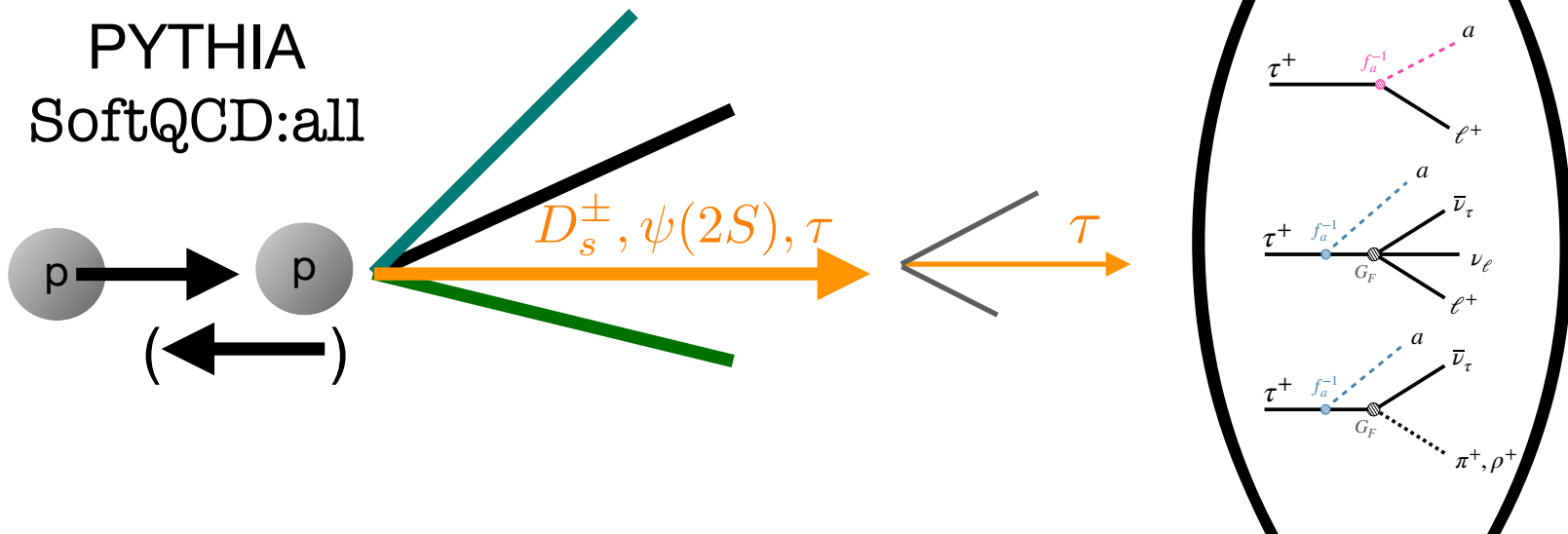
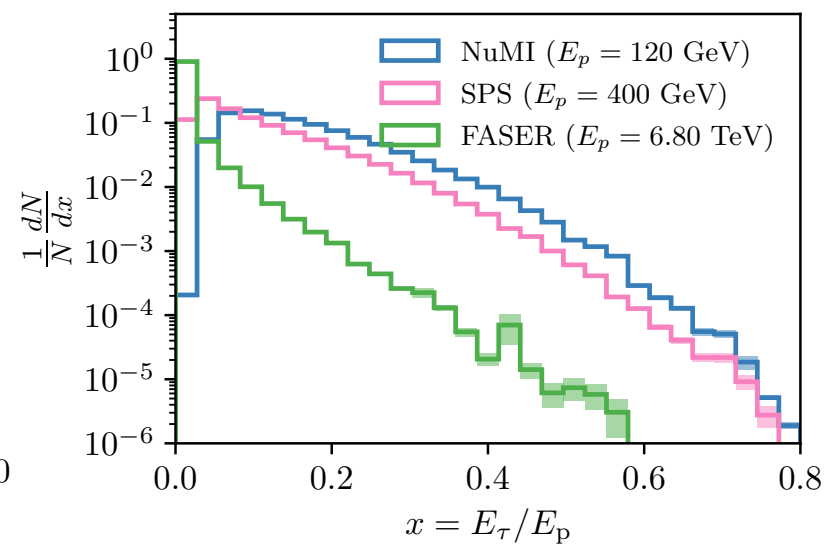
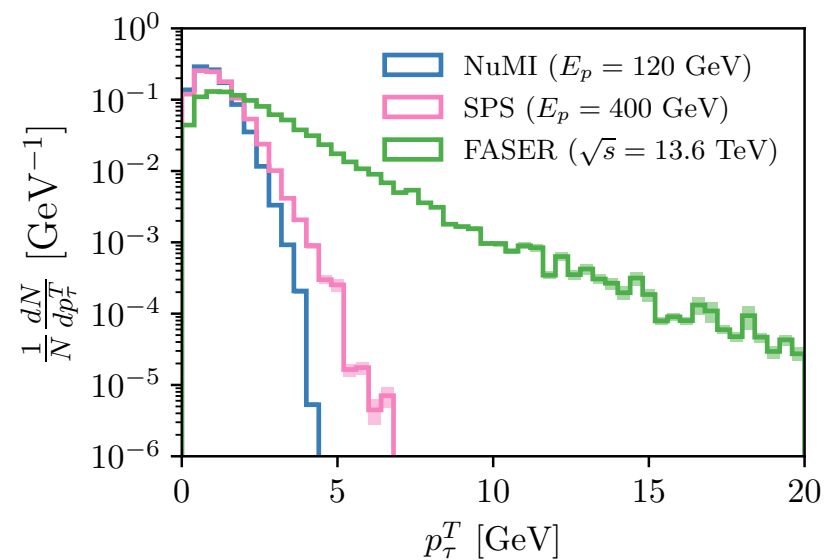
ALP production & Detection



NuMI: 120 GeV beam
SPS: 400 GeV beam
LHC: $\sqrt{s} = 13.6 \text{ TeV}$

$$\mathcal{B}(D_s \rightarrow \tau) = 5.4\%$$

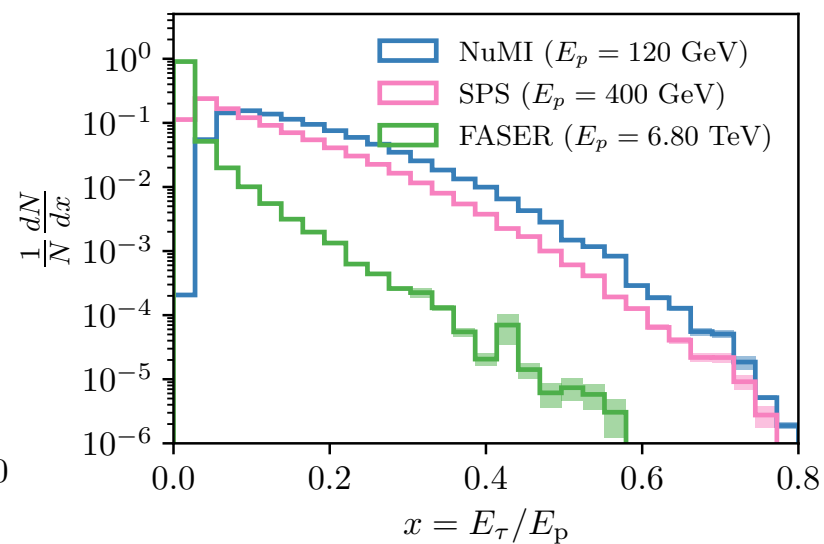
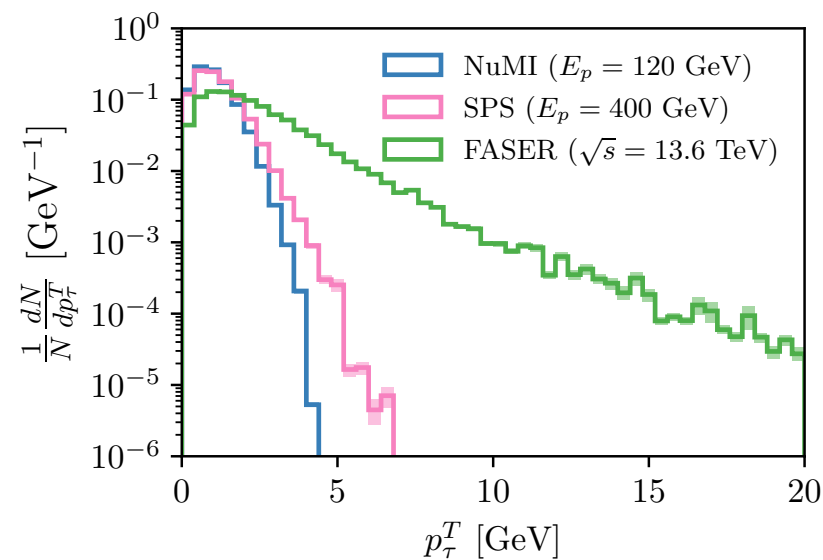
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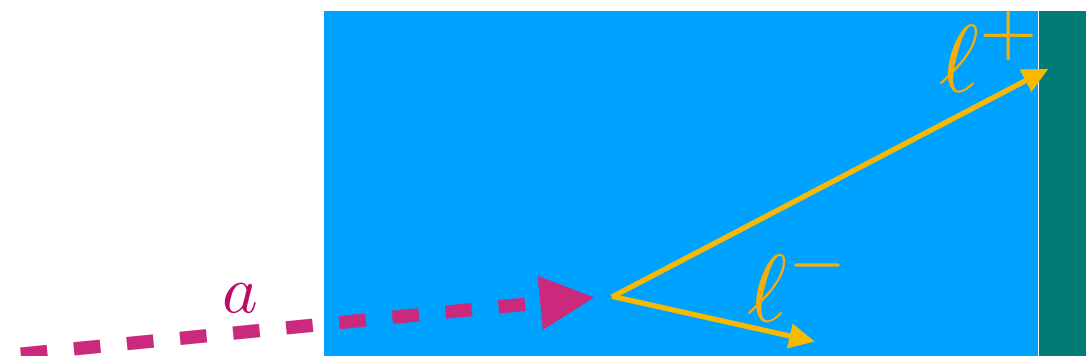
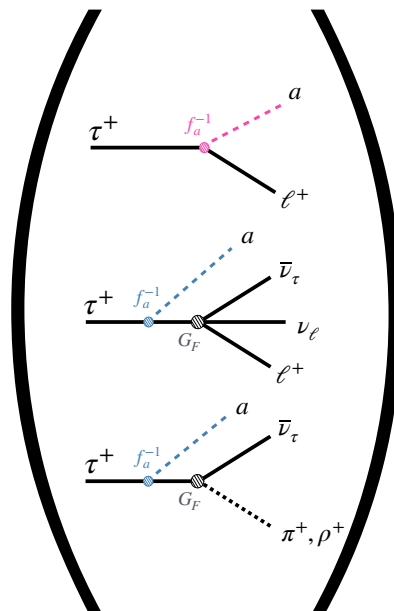
ALP production & Detection



PYTHIA
SoftQCD:all

$D_s^\pm, \psi(2S), \tau$

τ

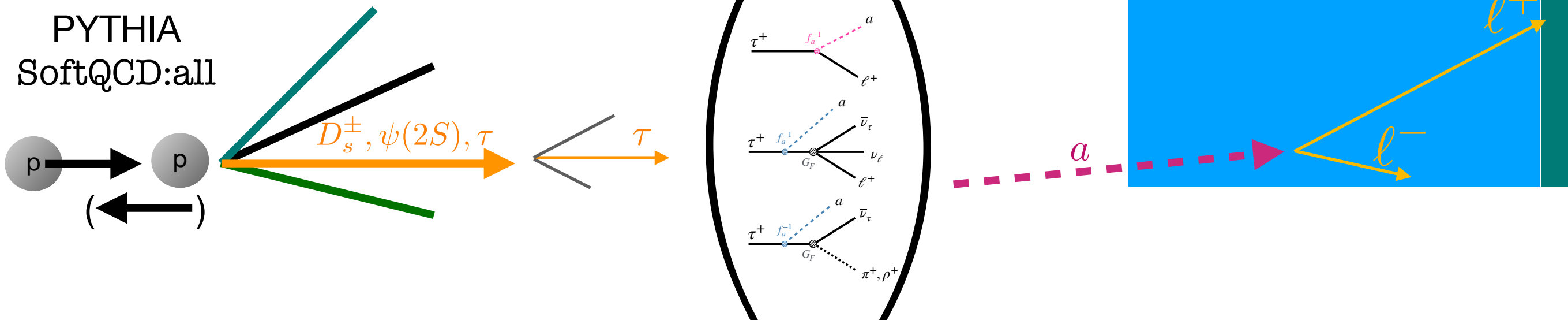


NuMI: 120 GeV beam
SPS: 400 GeV beam
LHC: $\sqrt{s} = 13.6 \text{ TeV}$

$$\mathcal{B}(D_s \rightarrow \tau) = 5.4\%$$

$$P_{\text{decay}} = \mathcal{B}(a \rightarrow \ell_1 \ell_2) \exp \left[-\frac{\Gamma_a L}{\gamma_a \beta_a} \right] \left[1 - \exp \left[-\frac{\Gamma_a \lambda}{\gamma_a \beta_a} \right] \right]$$

ALP production & Detection

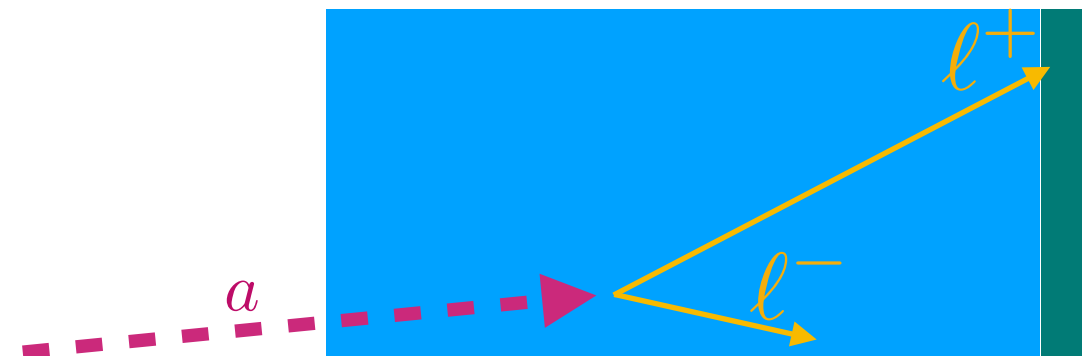
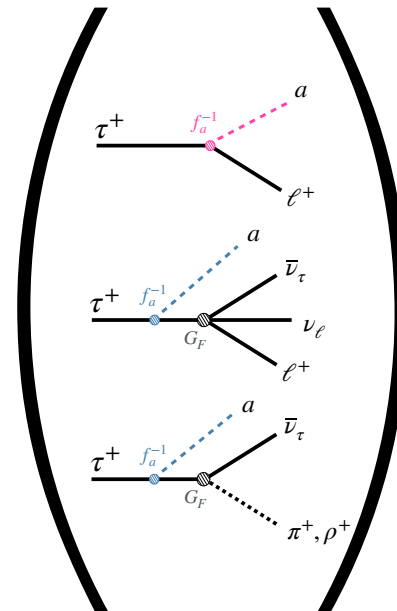
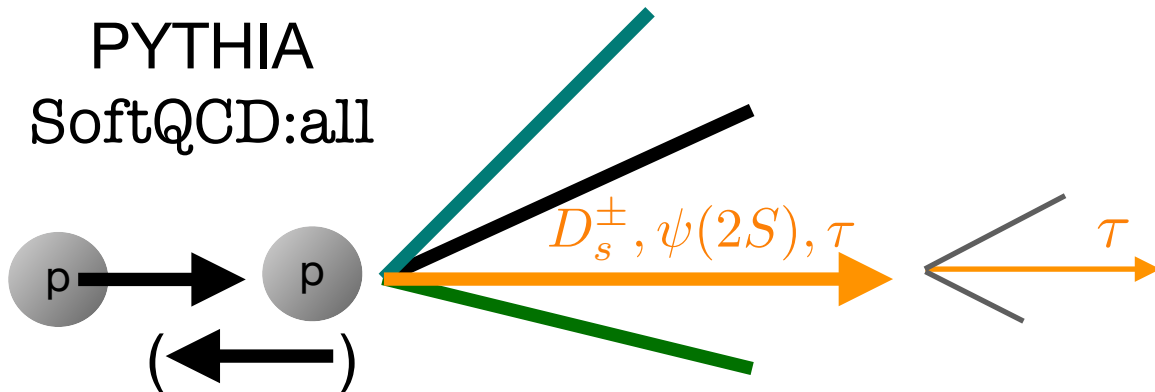
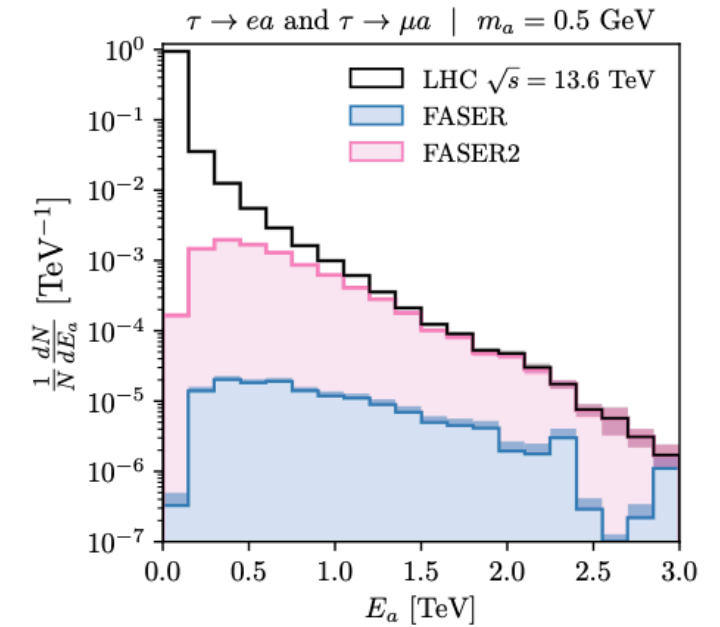
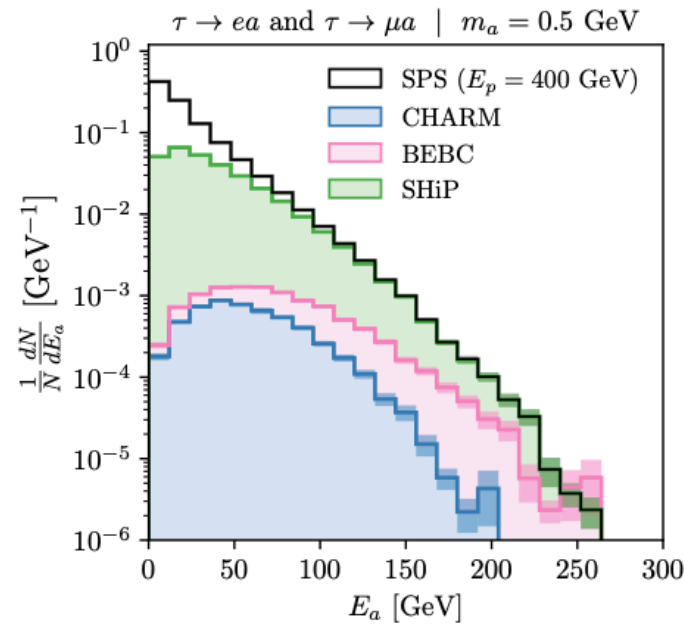
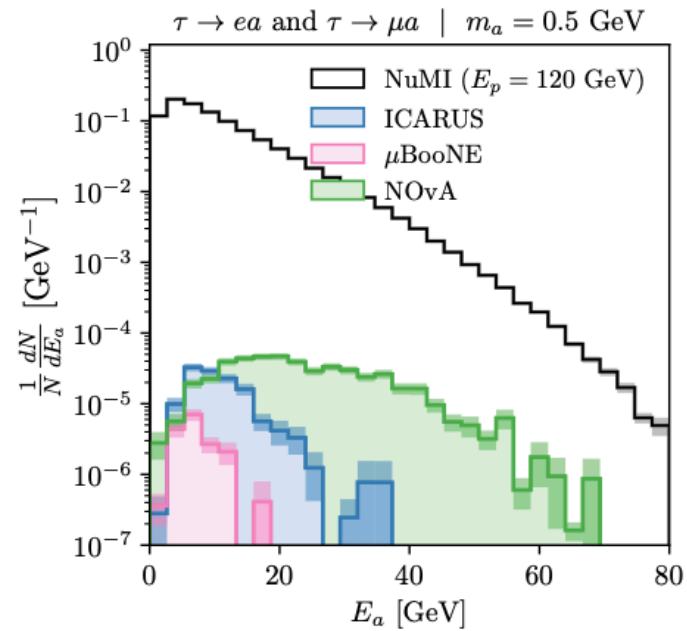


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LHC: $\sqrt{s} = 13.6$ TeV

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$$P_{\text{decay}} = \mathcal{B}(a \rightarrow \ell_1 \ell_2) \exp \left[-\frac{\Gamma_a L}{\gamma_a \beta_a} \right] \left[1 - \exp \left[-\frac{\Gamma_a \lambda}{\gamma_a \beta_a} \right] \right]$$

ALP production & Detection



NuMI: 120 GeV beam
SPS: 400 GeV beam
LHC: $\sqrt{s} = 13.6$ TeV

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Experiment	p^+ Energy	Exposure	Baseline	Fiducial Volume	Material(s)	Cuts	Refs.
				Pyramidal frustum			
SHiP	400 GeV (SPS)	$6 \cdot 10^{20}$ POT	33.7 m	$(1 \cdot 2.7 \rightarrow 4 \cdot 6) \cdot$ 49.6 m ³	He, Ecal	$E_{\ell,\gamma} > 0.5$ GeV	[20]
DUNE ND	120 GeV (NuMI/LBNF)	$11 \cdot 10^{21}$ POT (10 yrs)	574 m	$(5 \cdot 5 \cdot 5.88)$ m ³	LAr	$E_{\ell,\gamma} > 0.5$ GeV	[21]
protoDUNE NP02 [NP04]	400 GeV (SPS)	$1.75 \cdot 10^{19}$ POT (5 yrs)	677 [723] m T2	$(6 \cdot 7 \cdot 6)$ m ³ $\delta x = +3[-3]$ m, $\delta y = +1.5$ m	LAr	$E_{\ell,\gamma} > 0.5$ GeV	[22]
FASER	$\sqrt{s} = 13.6$ TeV (LHC)	$\mathcal{L} = 150$ fb ⁻¹	480 m	$R = 0.1$ m, $z = 1.5$ m $\delta y = 6.5$ cm	Air, Ecal	$E_{\ell,\gamma} > 50$ GeV	[23]
FASER2	$\sqrt{s} = 13.6$ TeV (LHC)	$\mathcal{L} = 3$ ab ⁻¹	650 m	$2.6 \cdot 1 \cdot 10$ m ³	Air, Ecal	$E_{\ell,\gamma} > 50$ GeV	[24]
ICARUS	120 GeV (NuMI)	$3 \cdot 10^{21}$ POT	803 m (5.6°)	$2 \times (2.67 \cdot$ $\cdot 2.86) \cdot 17.0$ m ³	LAr	$E_{\ell,\gamma} > 0.1$ GeV	[25, 26]
NOvA ND	120 GeV (NuMI)	$4.2 \cdot 10^{21}$ POT (2024)	990 m (14.6 mrad)	$3.9 \cdot 3.9 \cdot$ $\cdot 12.7$ m ³	Liquid Scint.	$E_{\ell,\gamma} > 0.1$ GeV	[27]
MicroBooNE	120 GeV (NuMI)	$2 \cdot 10^{21}$ POT	685 m (8°)	$2.26 \cdot 2.03 \cdot$ $\cdot 9.42$ m ³	LAr	$E_{\ell,\gamma} > 0.1$ GeV	[28]
BEBC	400 GeV (SPS)	$2.72 \cdot 10^{18}$ POT	404 m	$3.57 \cdot 2.52 \cdot$ $\cdot 1.85$ m ³	Ne/H ₂	$ \vec{p}_{\ell,\gamma} > 0.5$ GeV	[29, 30]
CHARM	400 GeV (SPS)	$2.4 \cdot 10^{18}$ POT	480 m	$3 \cdot 3 \cdot 35$ m ³ $\delta x = 5$ m	Air, Ecal	$E_{\ell,\gamma} > 0.5$ GeV	[31, 32]

Existing Limits

Exotic Tau decays

$$\mathcal{B}(\tau^- \rightarrow e^- e^+ e^-) < 2.7 \times 10^{-8},$$

$$\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 1.9 \times 10^{-8}.$$

etc [Belle, Belle-II, BaBar,
CMS, ATLAS, LHCb]

Invisible Tau decays

$$\mathcal{B}(\tau \rightarrow \ell a_{\text{inv}}) \lesssim 10^{-3}$$

[ARGUS, Belle, Belle-II]

Tau lifetime

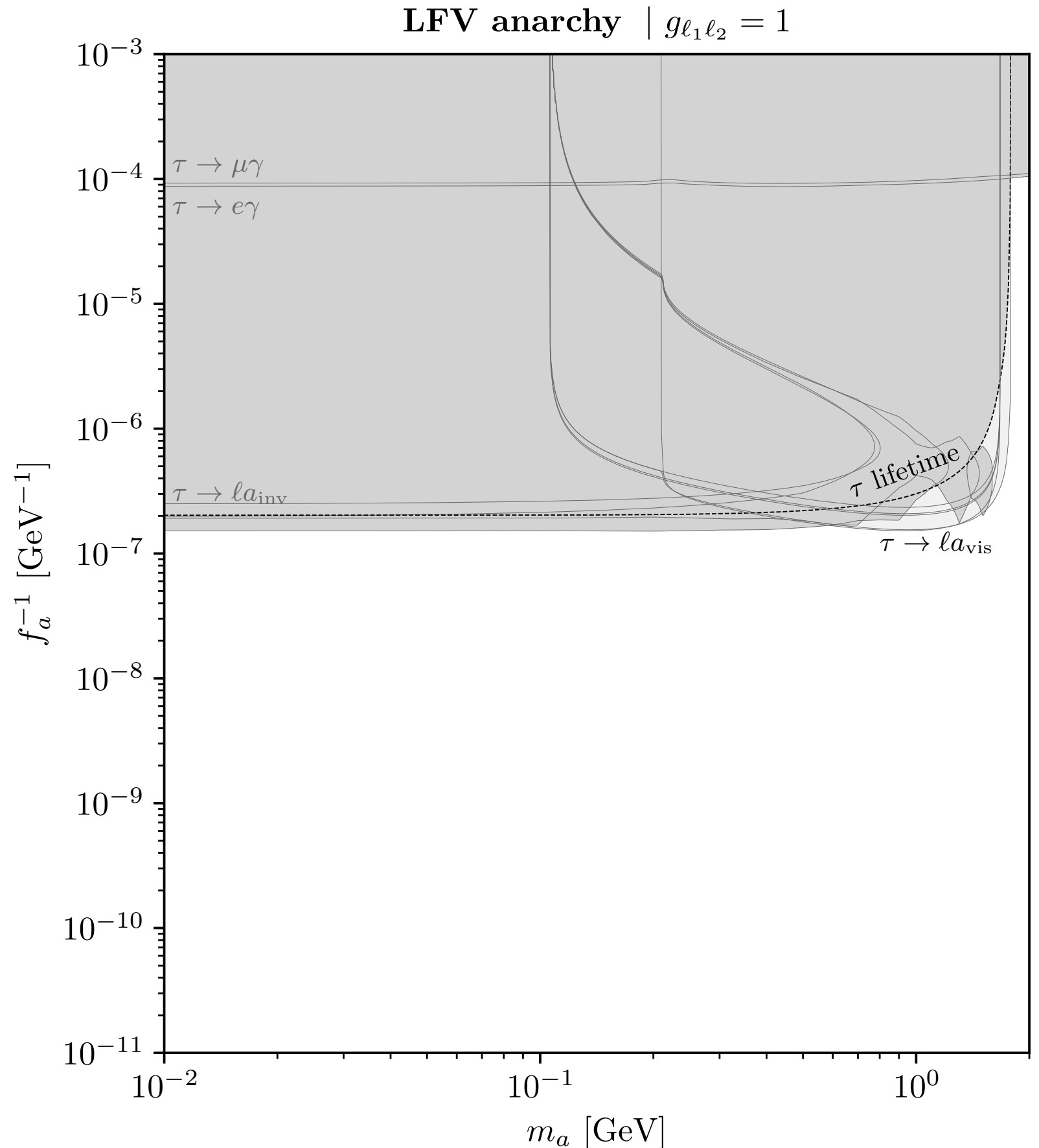
$$\mathcal{B}(\tau \rightarrow \ell a) < 10^{-3}$$

Loop decays

$$\mathcal{B}(\tau \rightarrow e \gamma) < 3.3 \times 10^{-8}$$

$$\mathcal{B}(\tau \rightarrow \mu \gamma) < 4.2 \times 10^{-8}$$

[BaBar, Belle]



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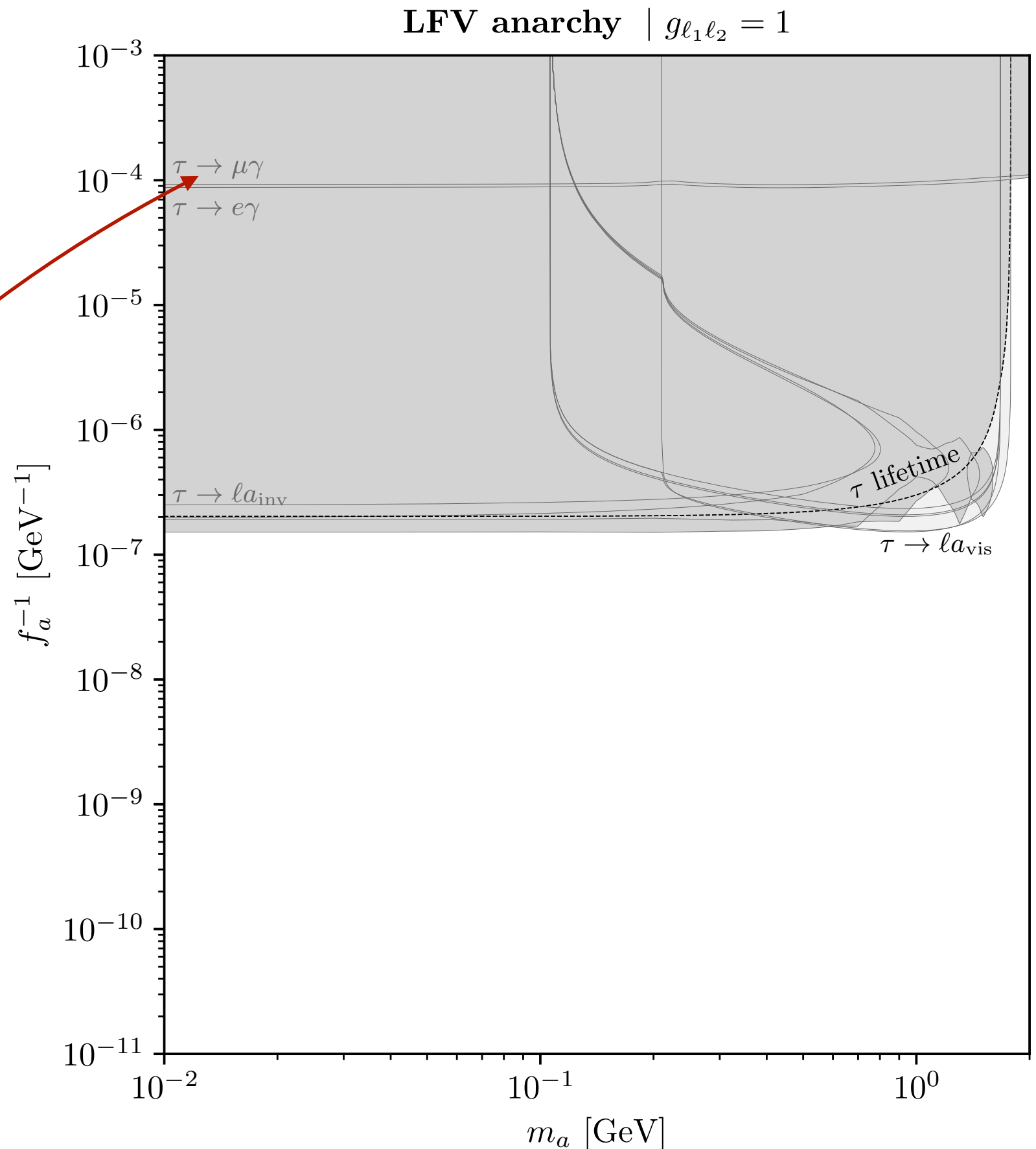
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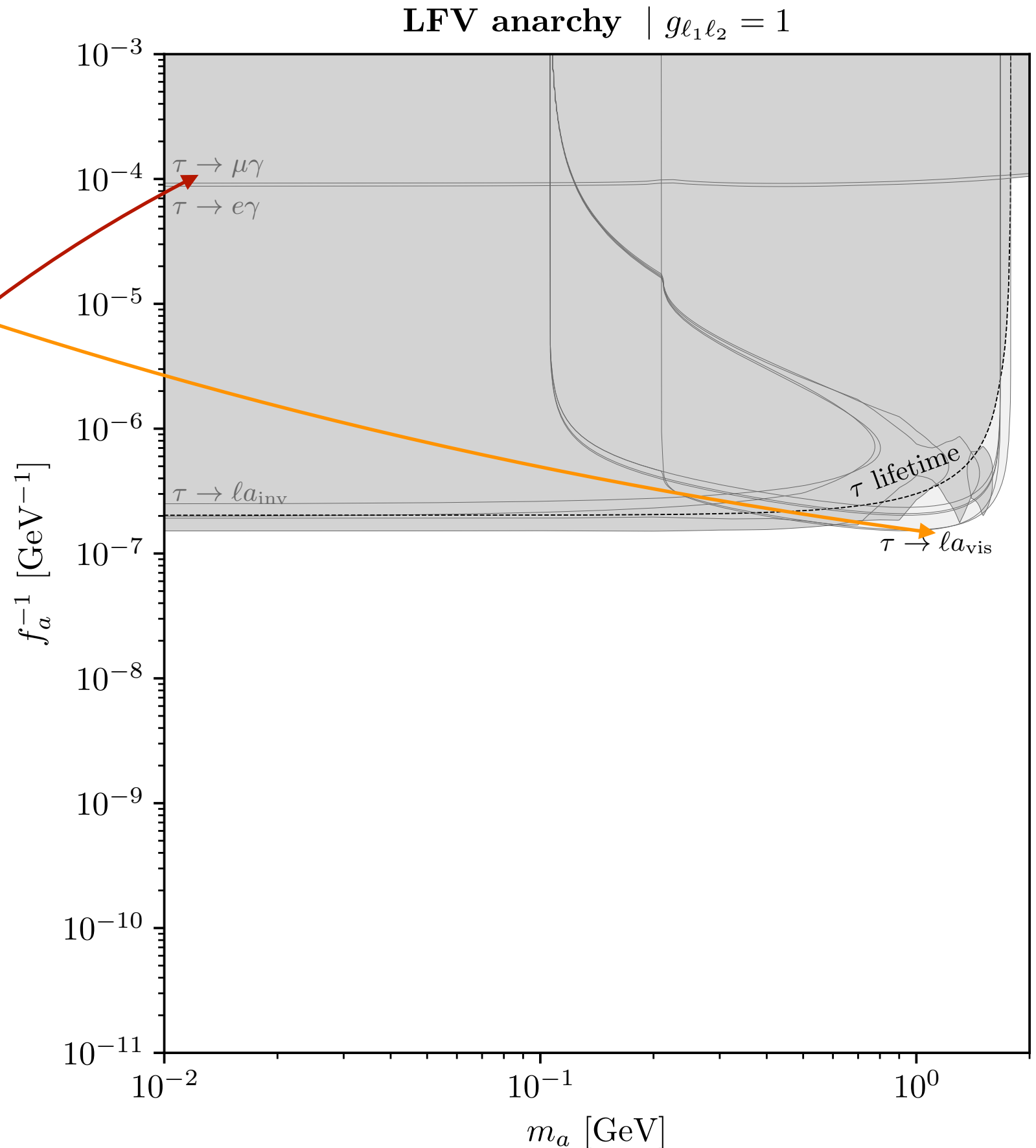
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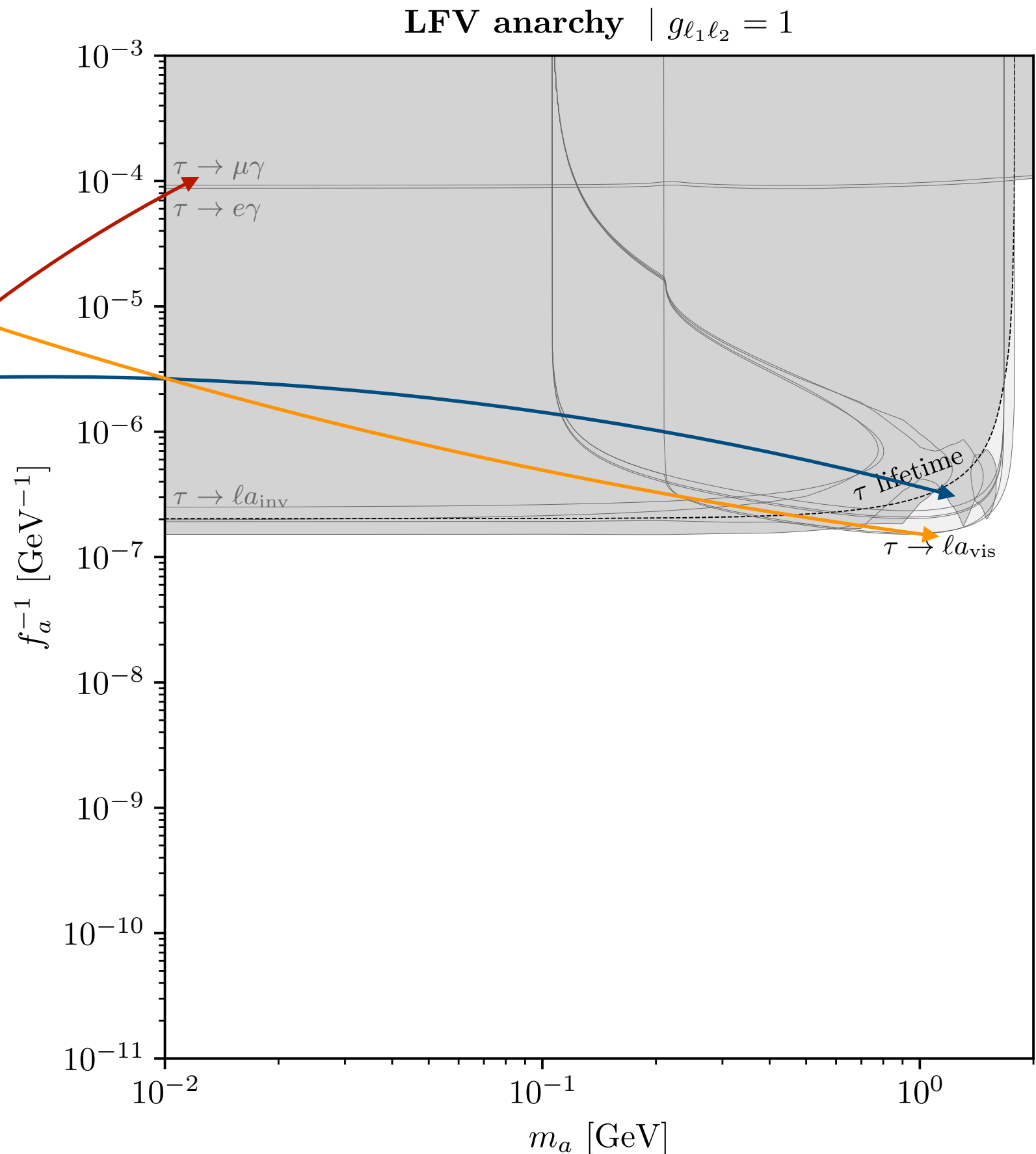
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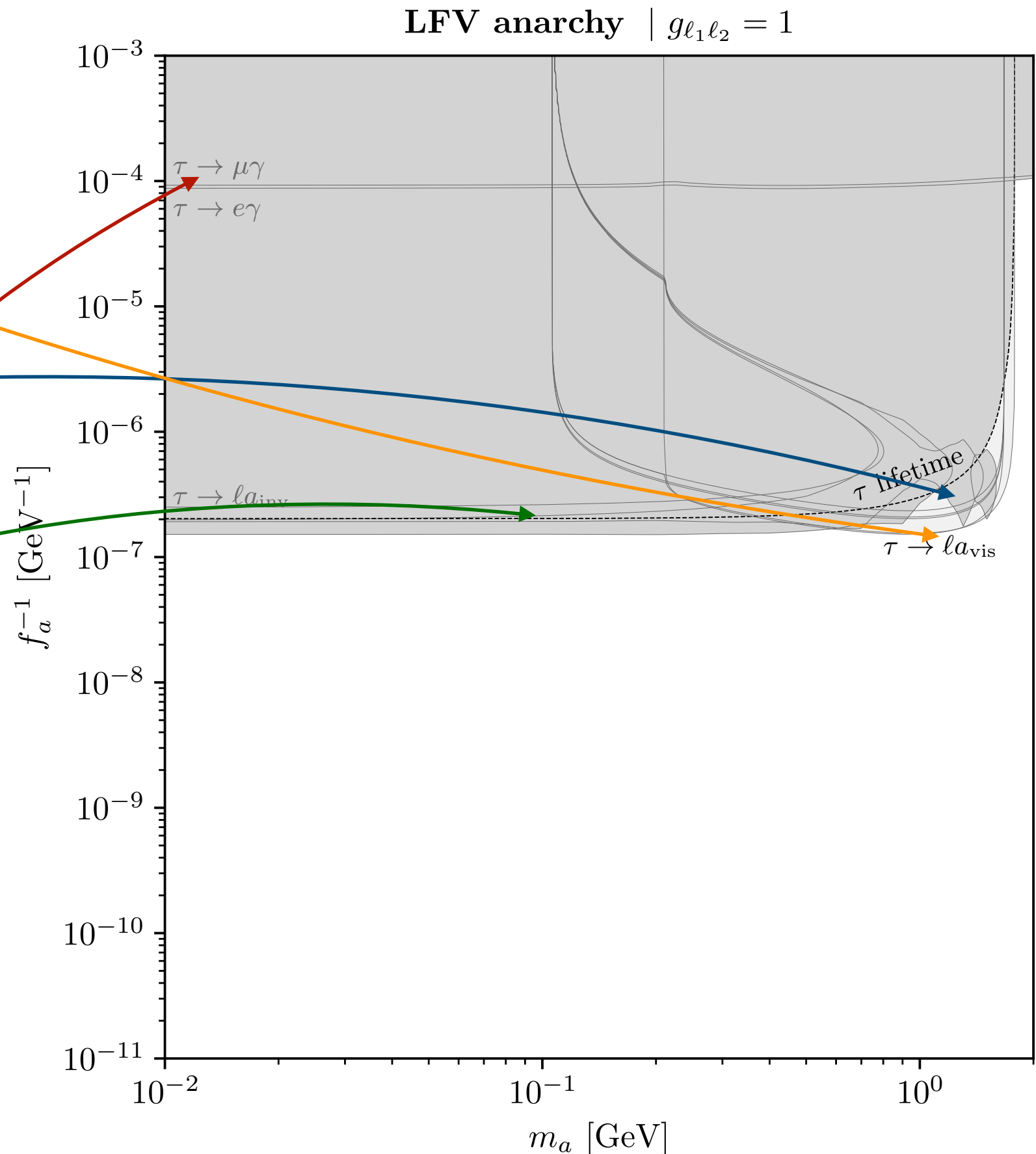
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Existing Limits

Invisible Muon decays

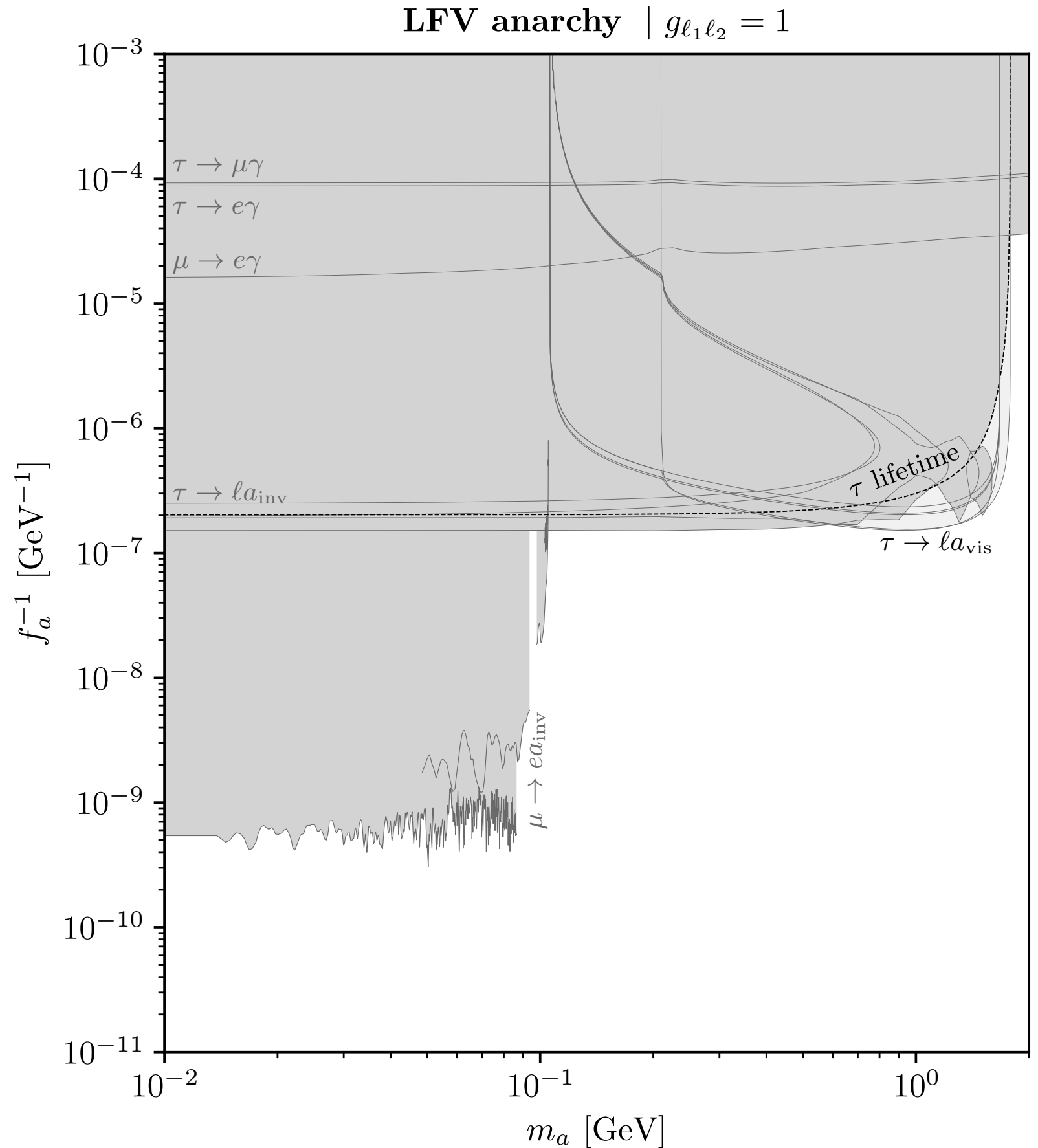
$$\mu \rightarrow e a_{\text{invis.}}$$

[TWIST, PIENU]

Loop decays

$$\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) < 1.5 \times 10^{-13}$$

[MEG-II]



Existing Limits

Invisible Muon decays

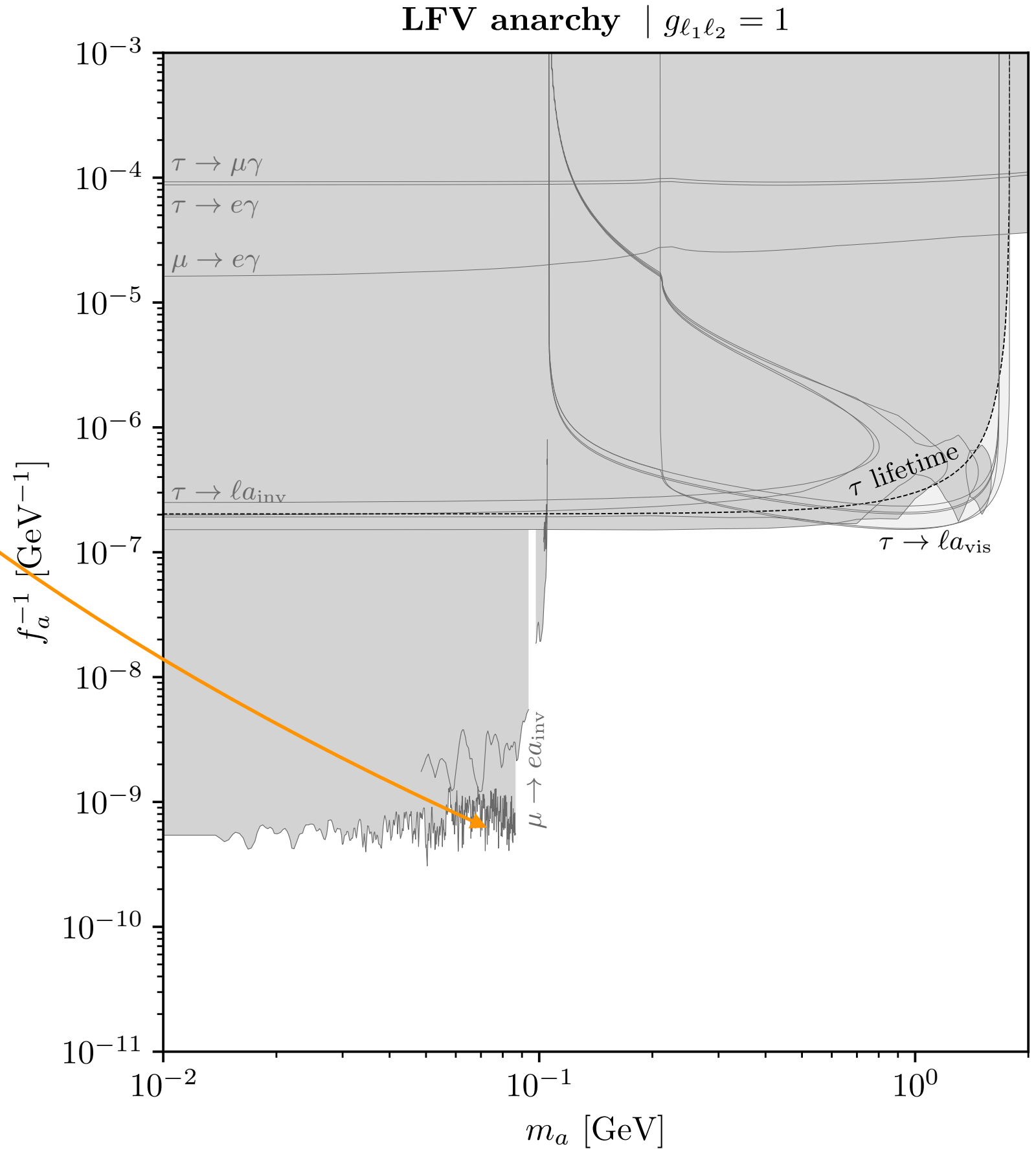
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[TWIST, PIENU]

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[MEG-II]



Existing Limits

Invisible Muon decays

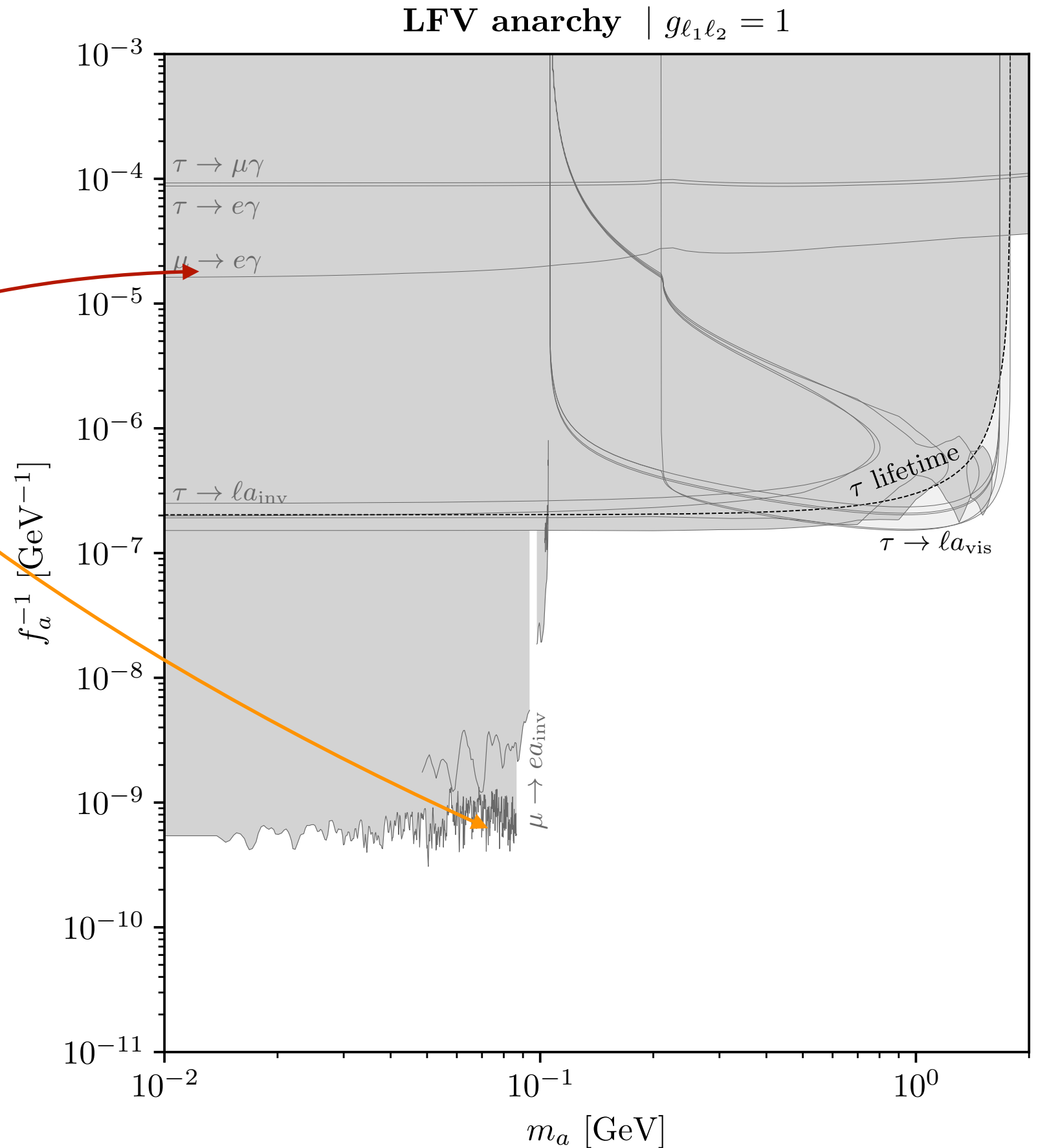
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[TWIST, PIENU]

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$$\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) < 1.5 \times 10^{-13}$$

[MEG-II]



Existing Limits

Supernovae Cooling

“Raffelt criterion”

$$e\gamma \rightarrow ea$$

$$e^+e^- \rightarrow \gamma a$$

[Caputo et al, Fiorollo et al]

Coalescence: $e^+\mu^- \rightarrow a$

[Huang and Liu]

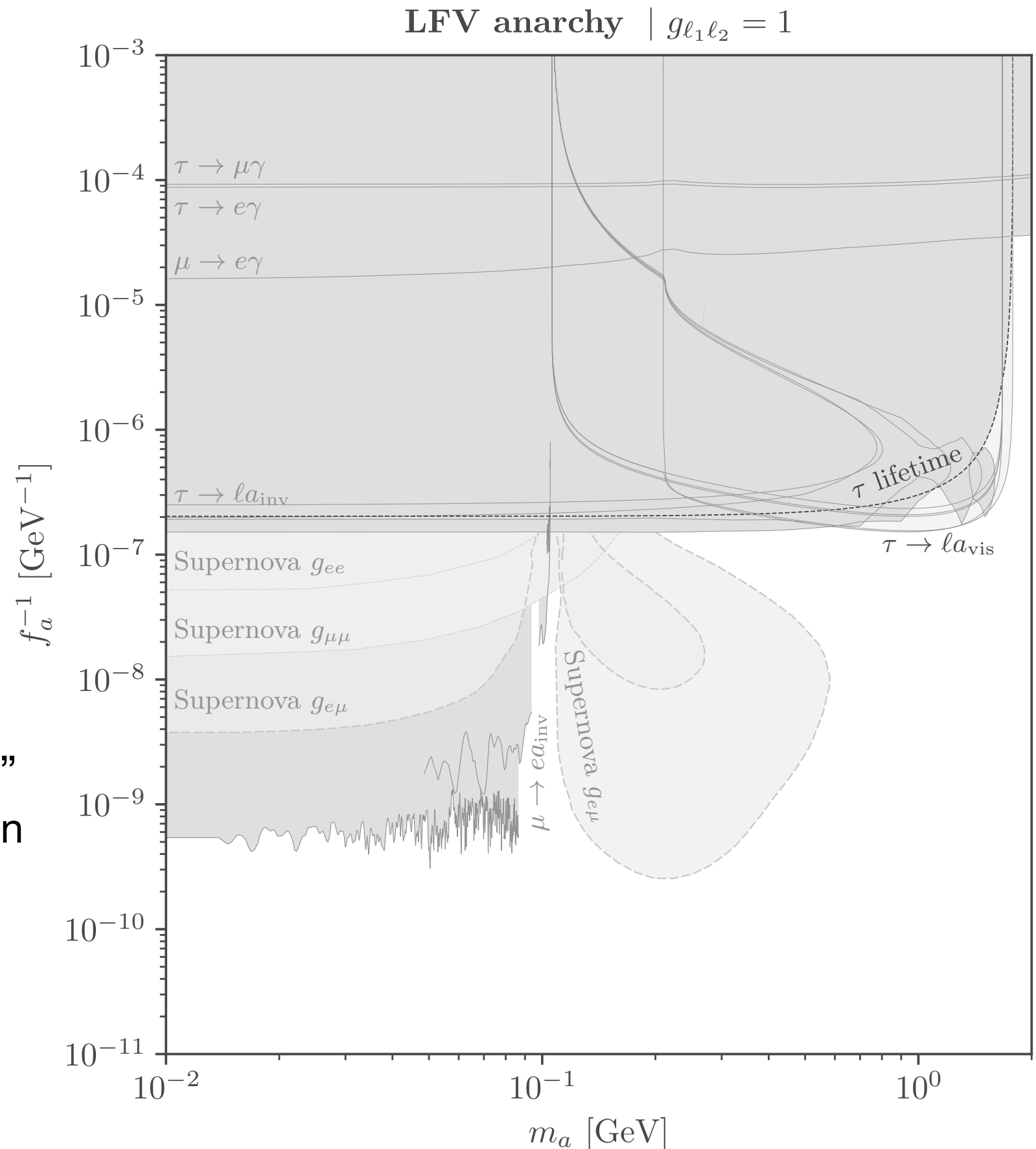
Low energy supernovae

Energy transfer from core to “mantle”

Flavour diagonal (Bremm, annihilation etc) [Fiorollo et al]

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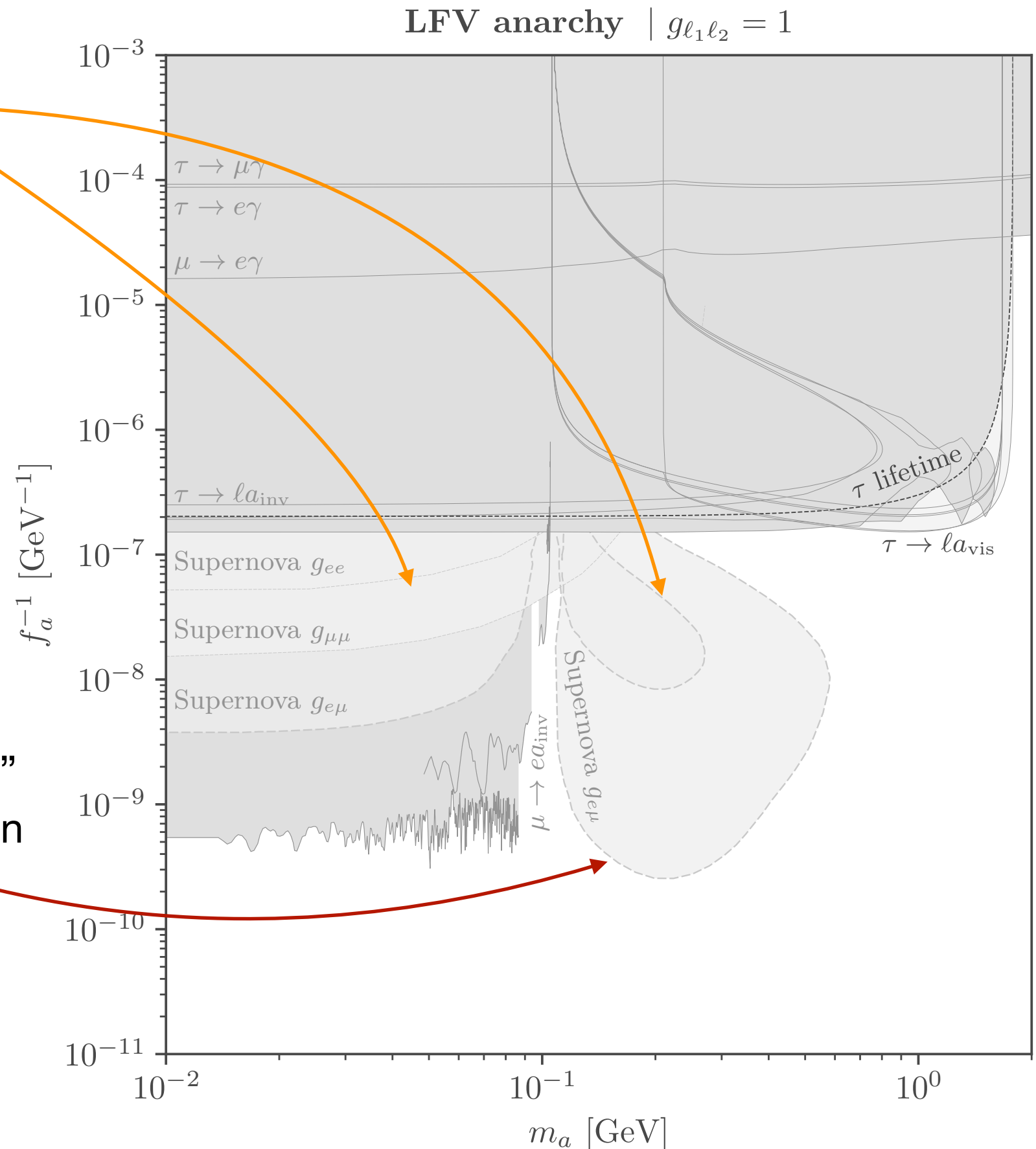
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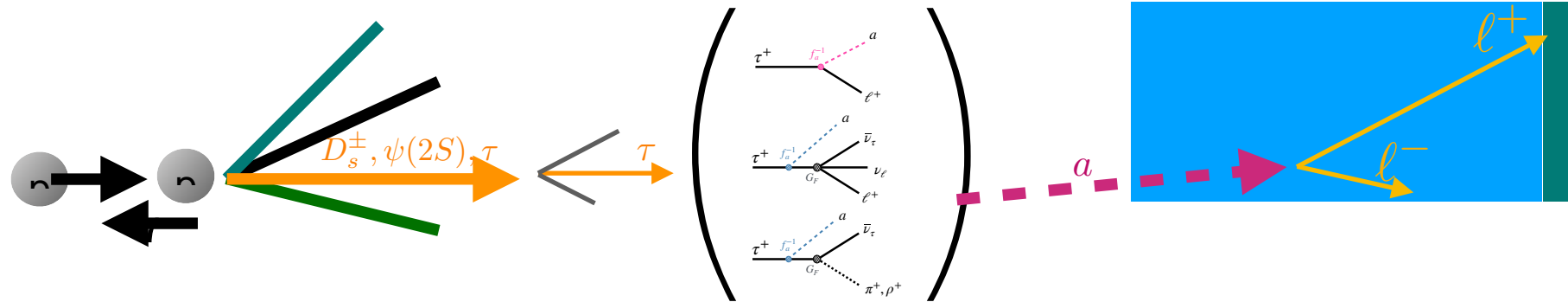
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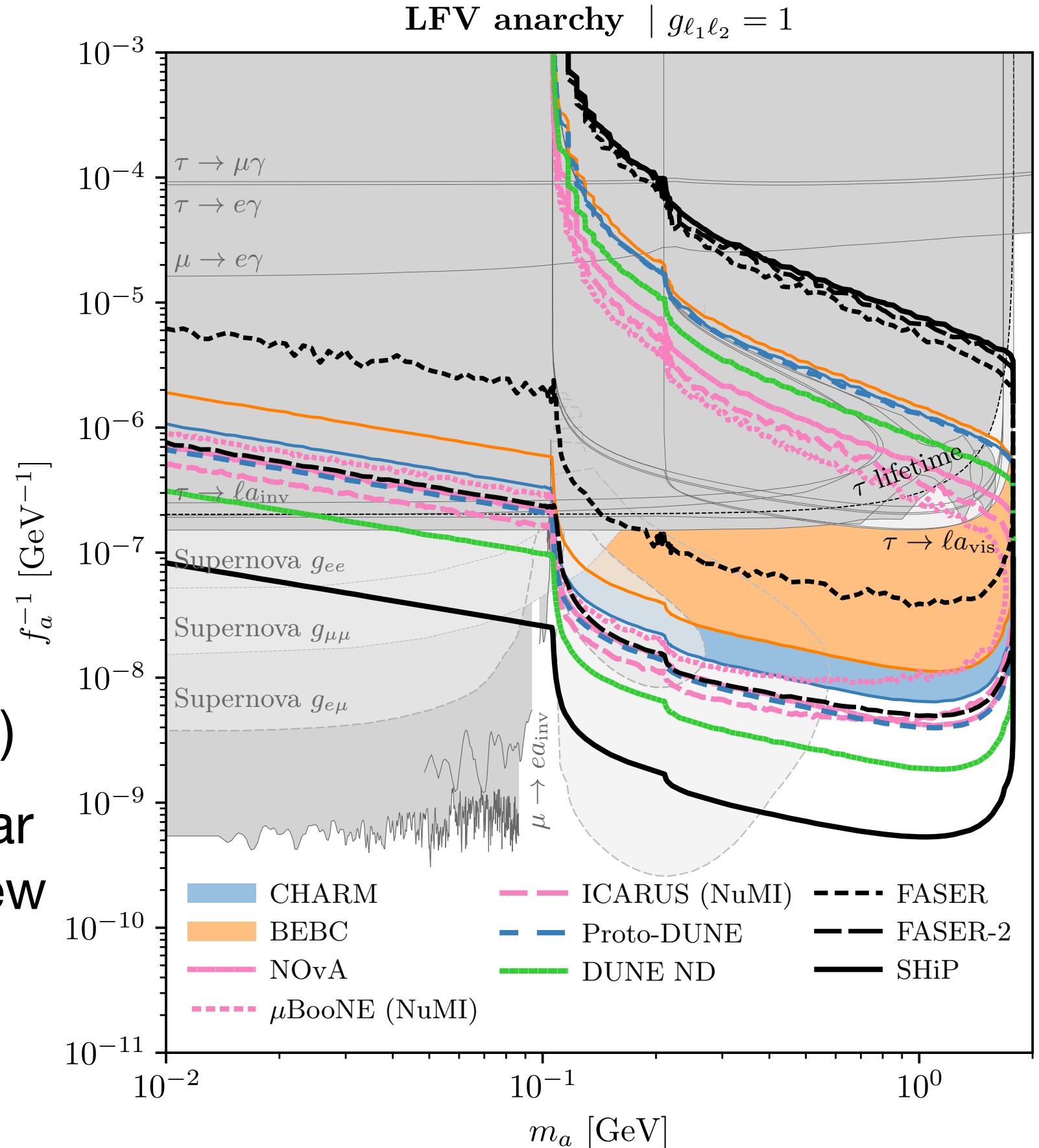
New and Future Sensitivities



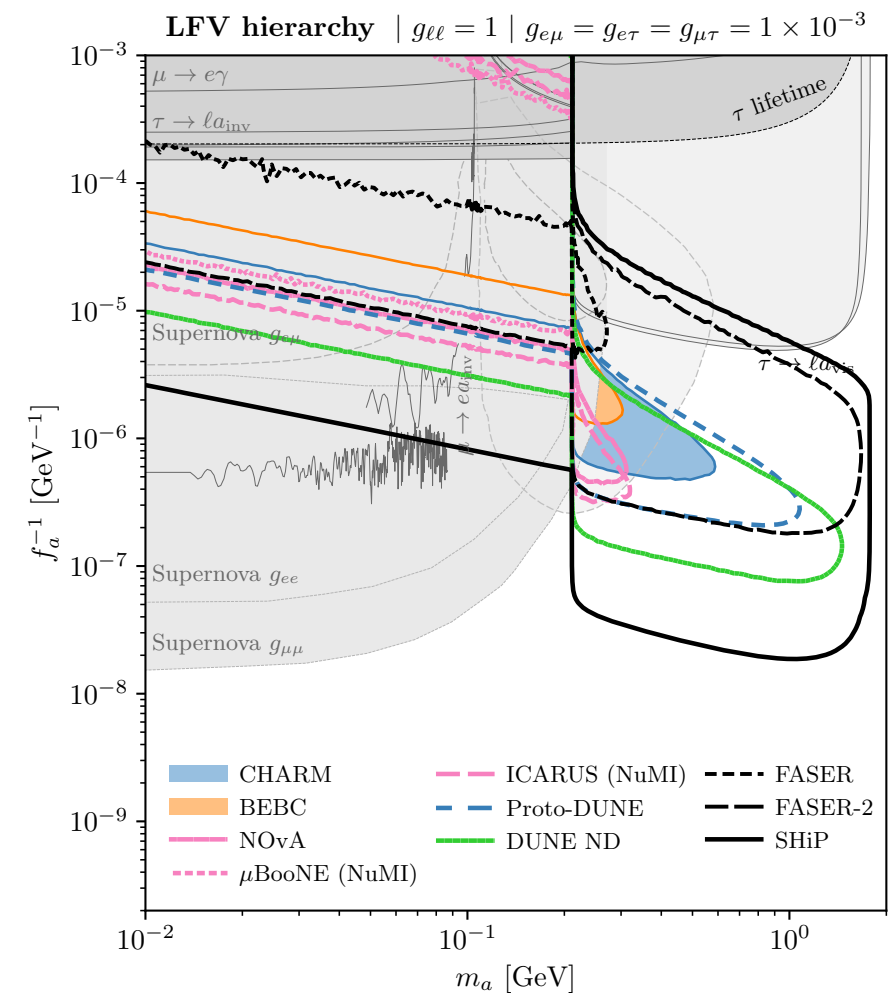
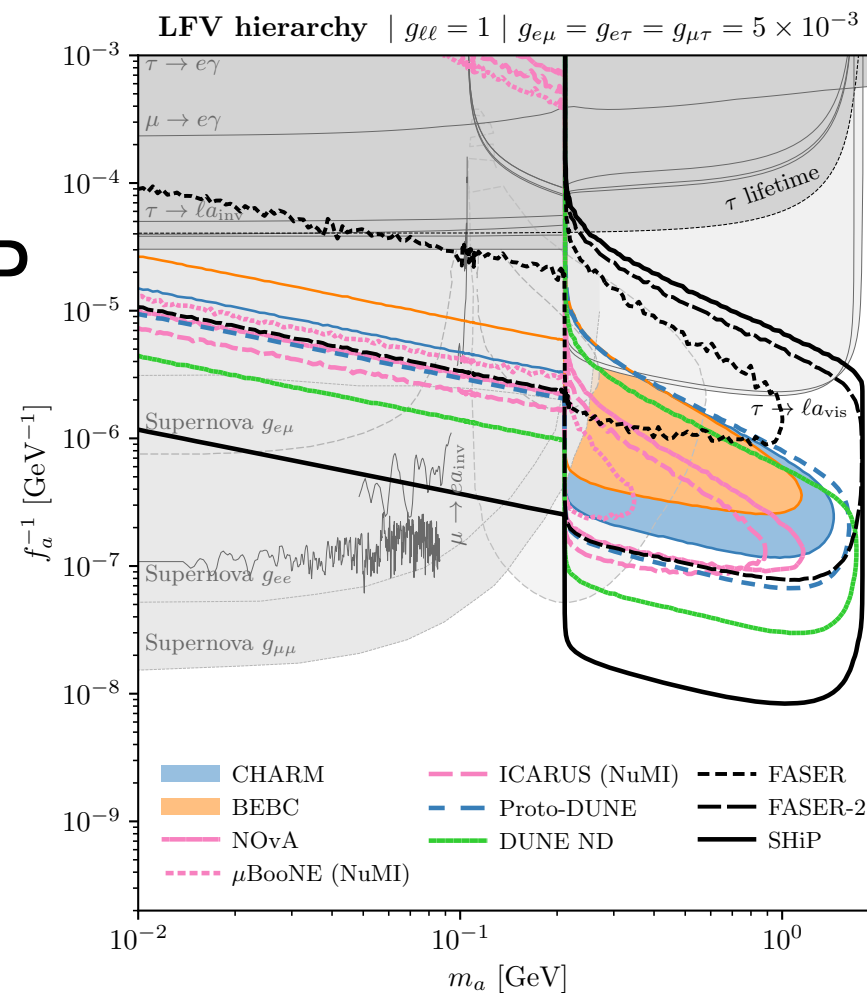
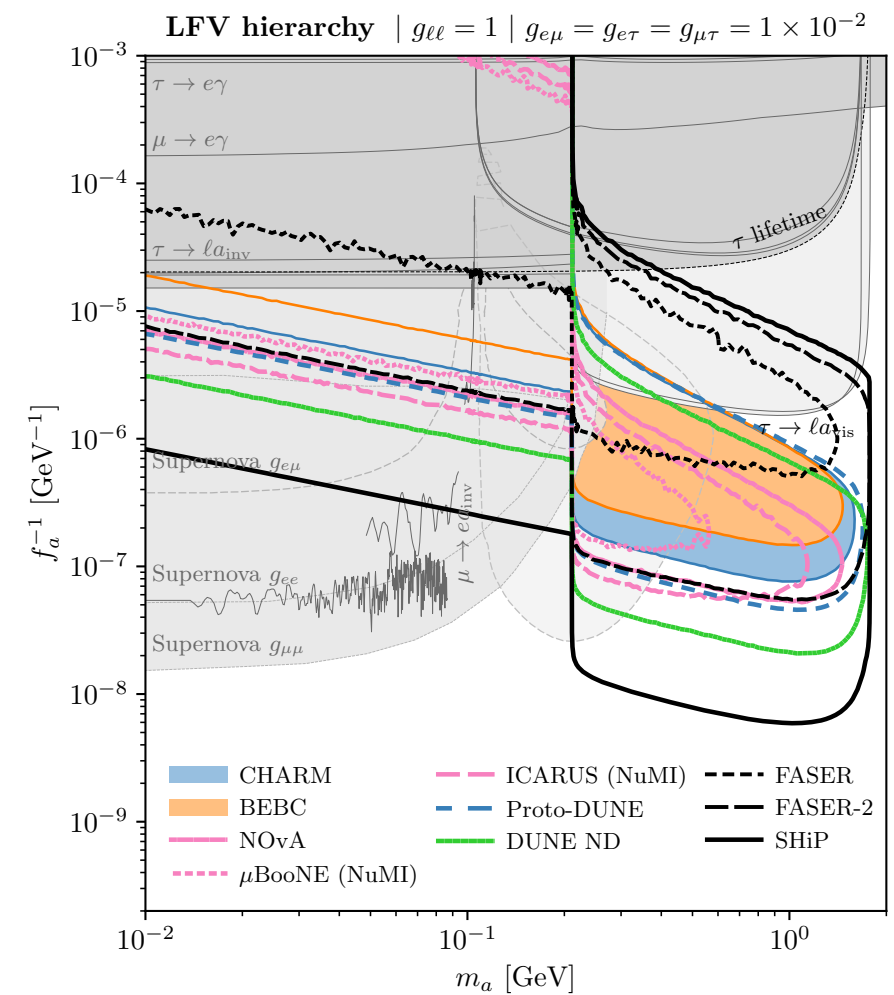
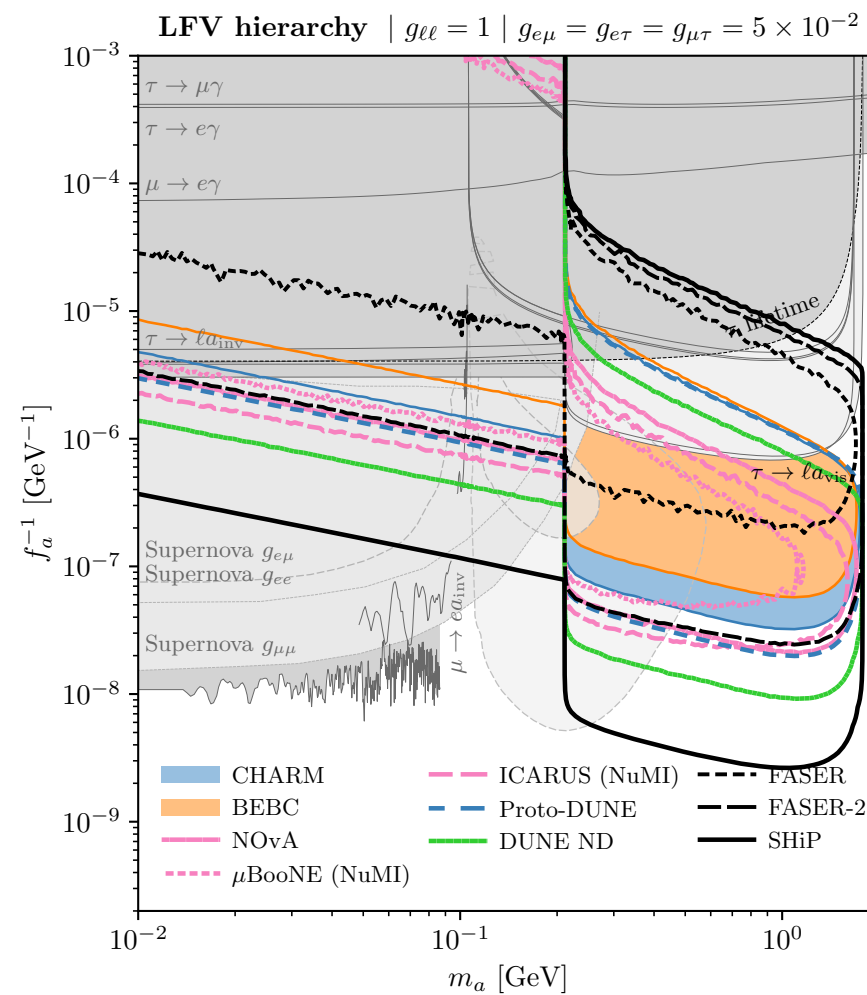
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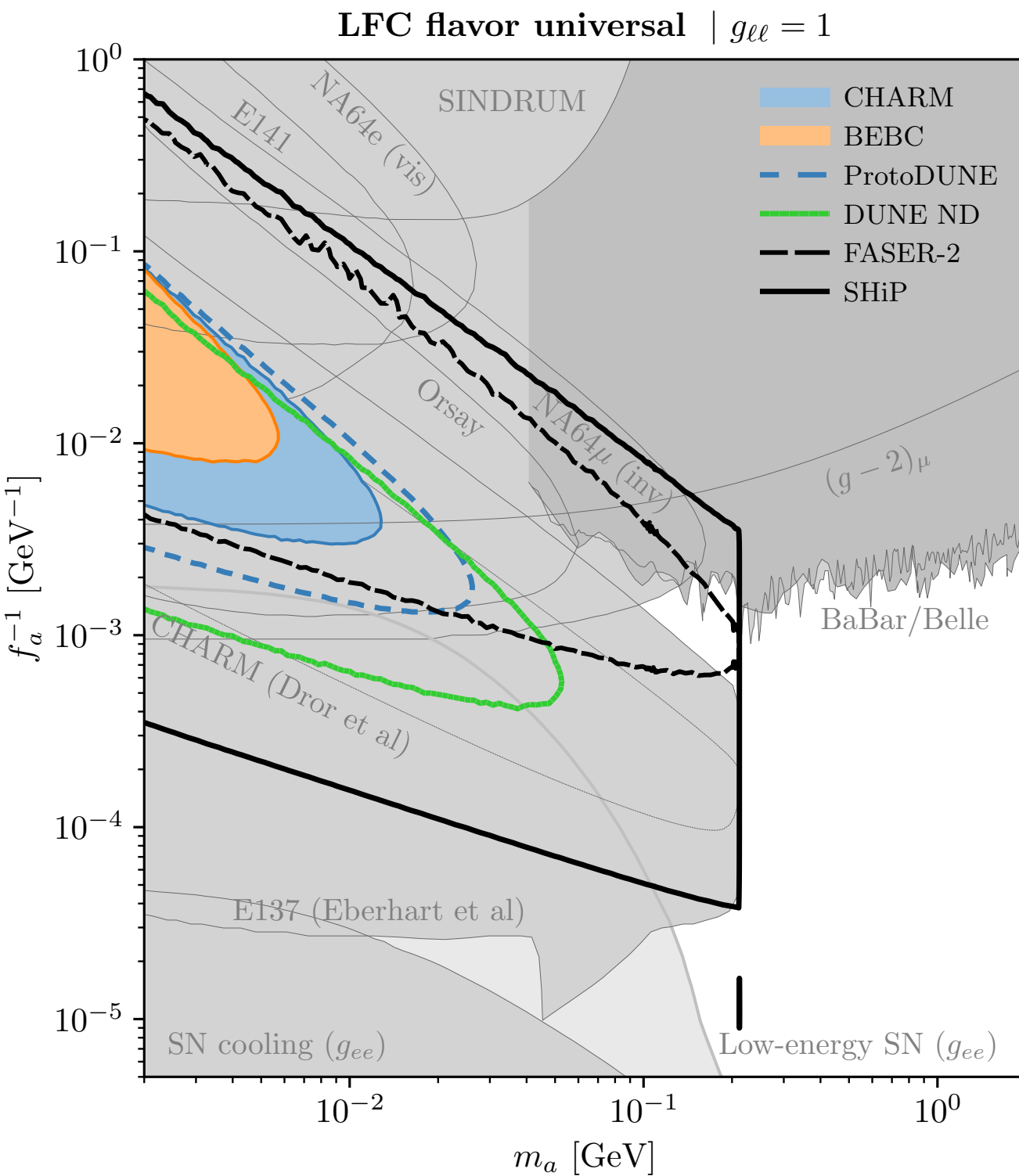
New and Future Sensitivities

- 2.3 signal events
(90% CL for 0 background)
- Existing FNAL neutrino near detectors have reach to new parameter space
- SHiP can reach 10^9 GeV



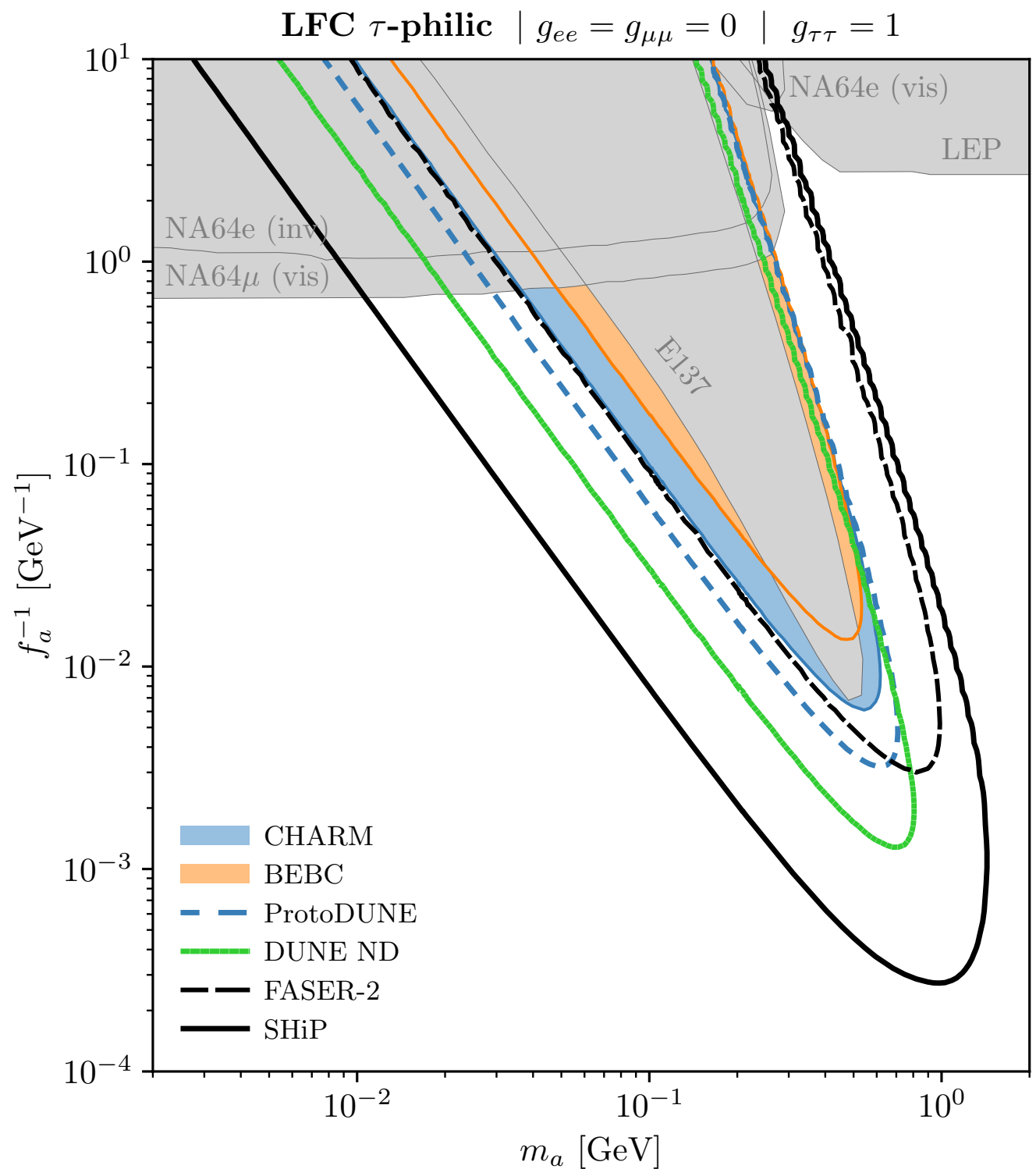
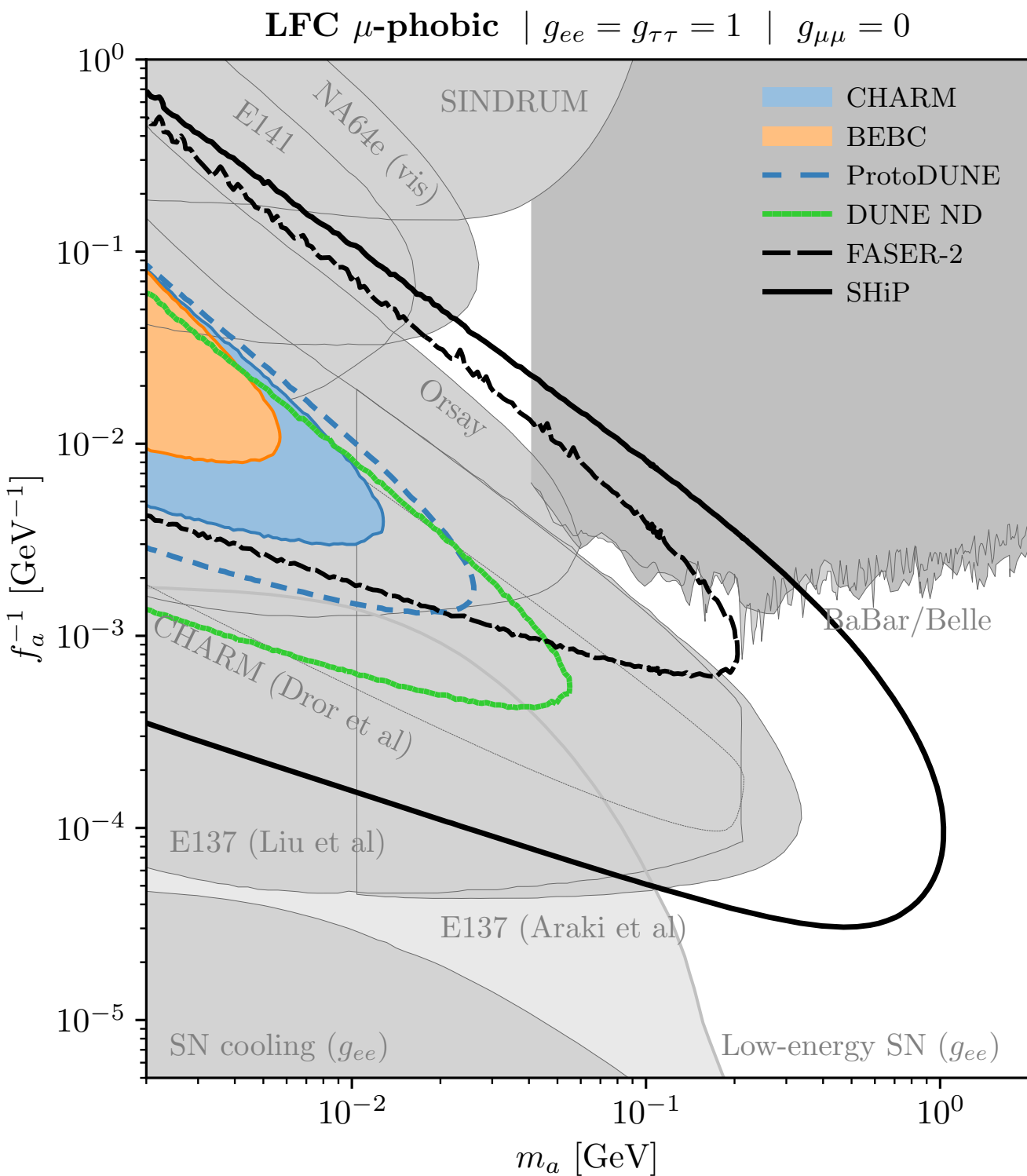
- As FV couplings become smaller other constraints weaken
- Bounds move to smaller f , favouring closer detectors and axions with larger boost i.e. FASER/SHiP





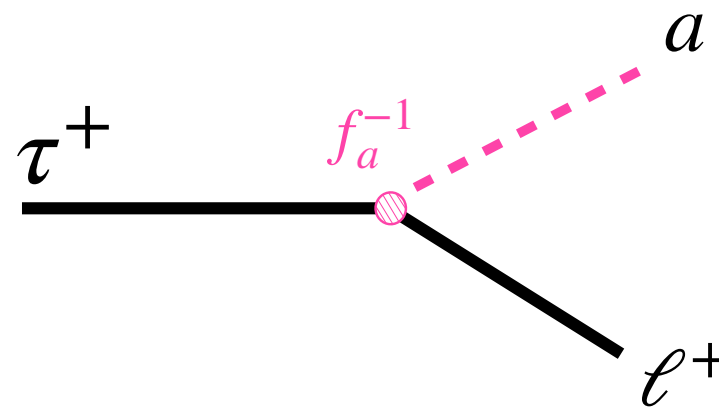
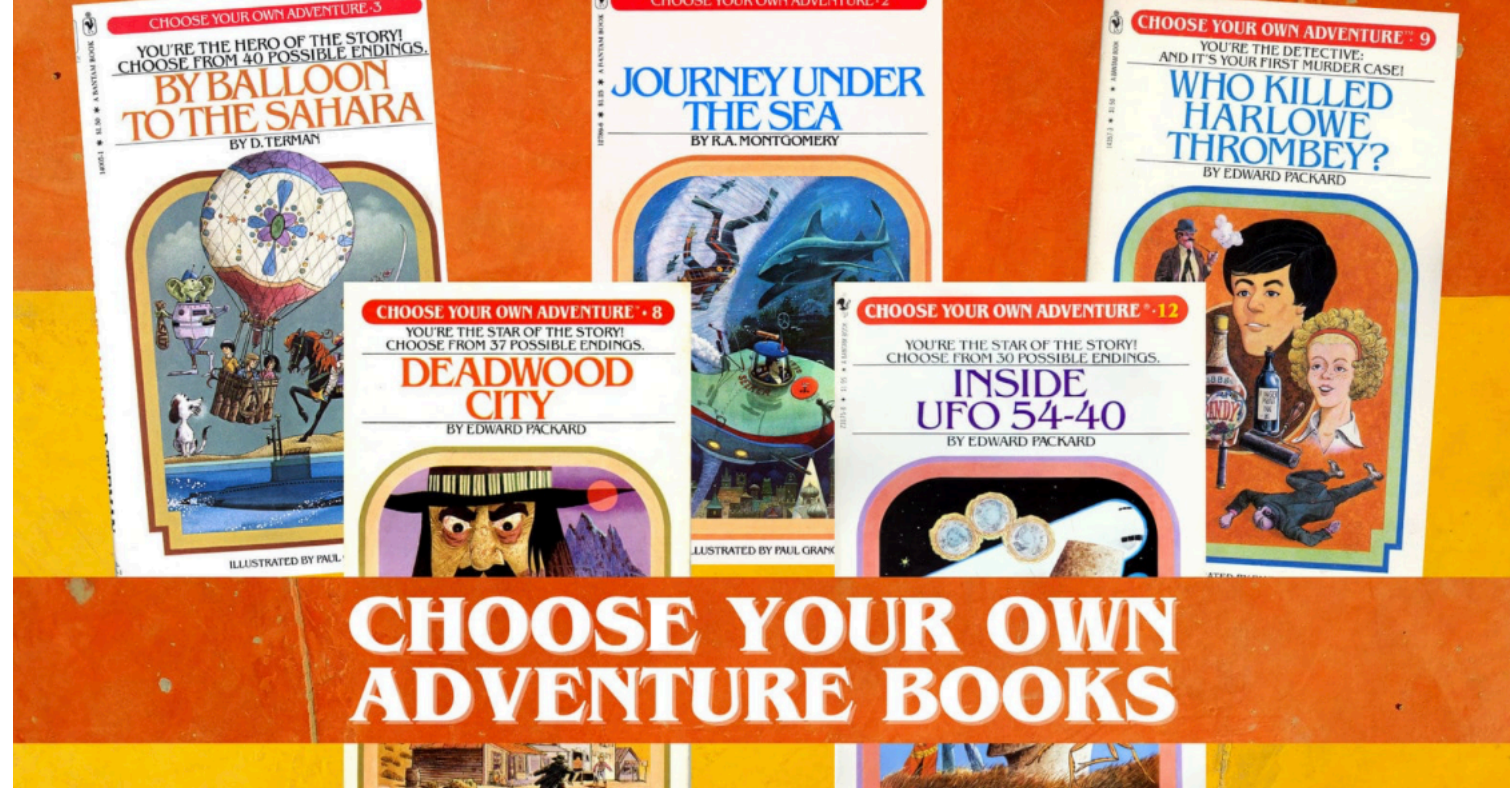
- Coupling to muon important (muon-phobic vs universal)
- Steep dependence on axion mass in tau-philic case.

$$\Gamma(a \rightarrow \gamma\gamma) = \frac{\alpha^2 g_{\ell\ell}^2}{96^2 \pi^3} \frac{m_a^7}{m_\ell^4 f_a^2}$$



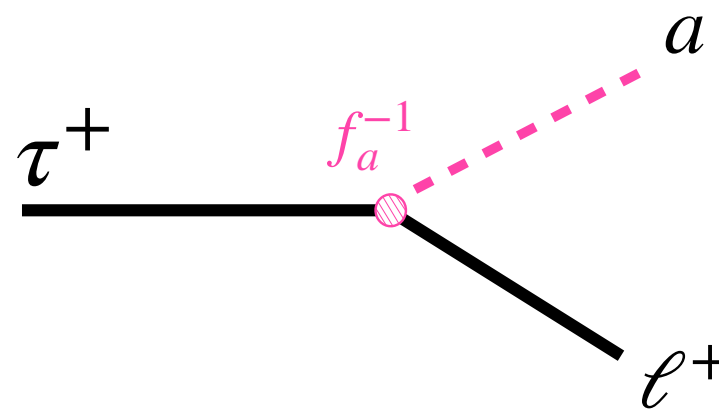
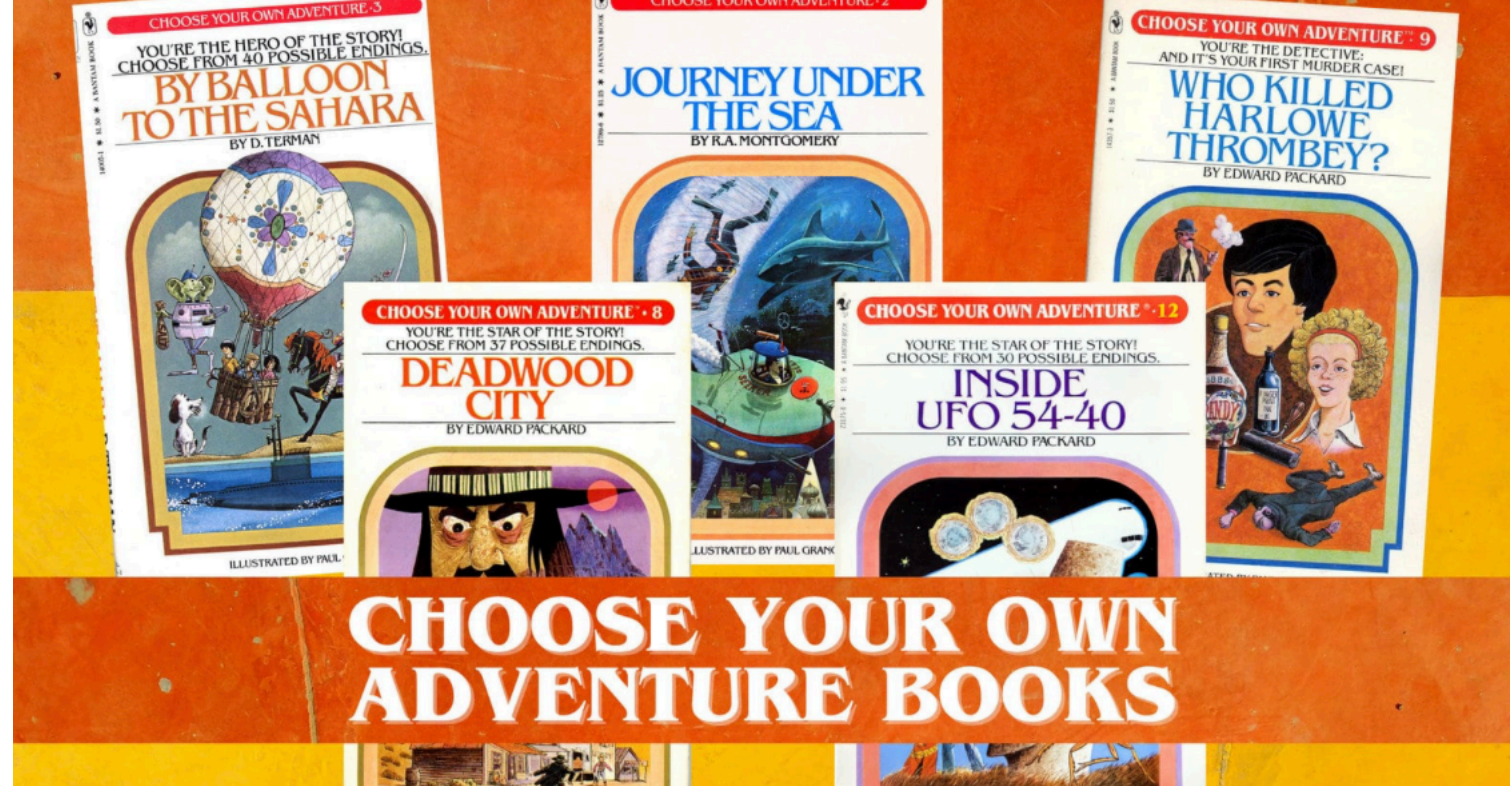
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a is long lived

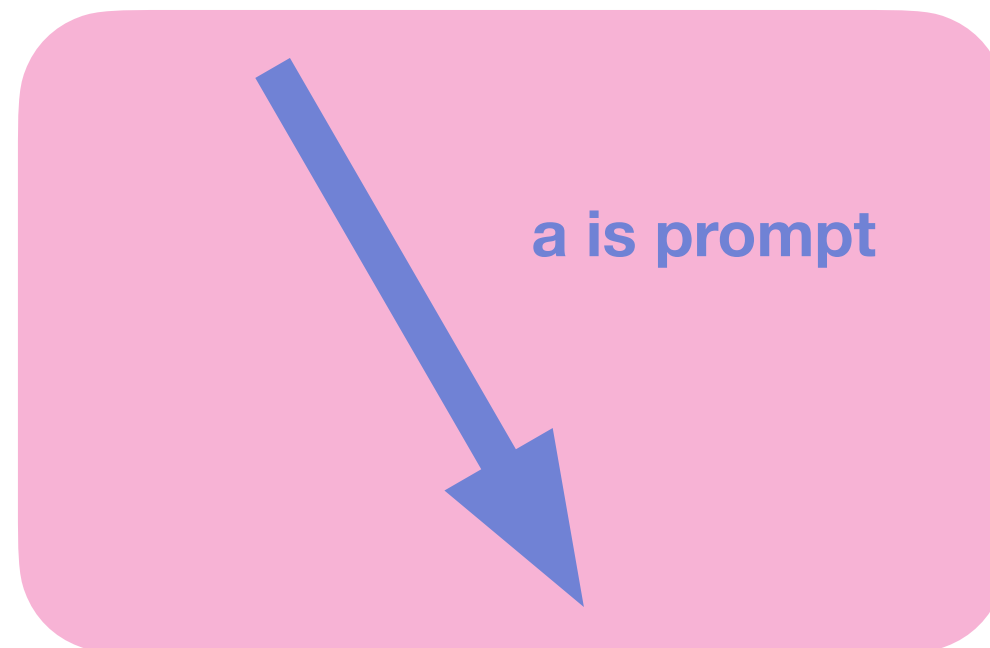
a is prompt



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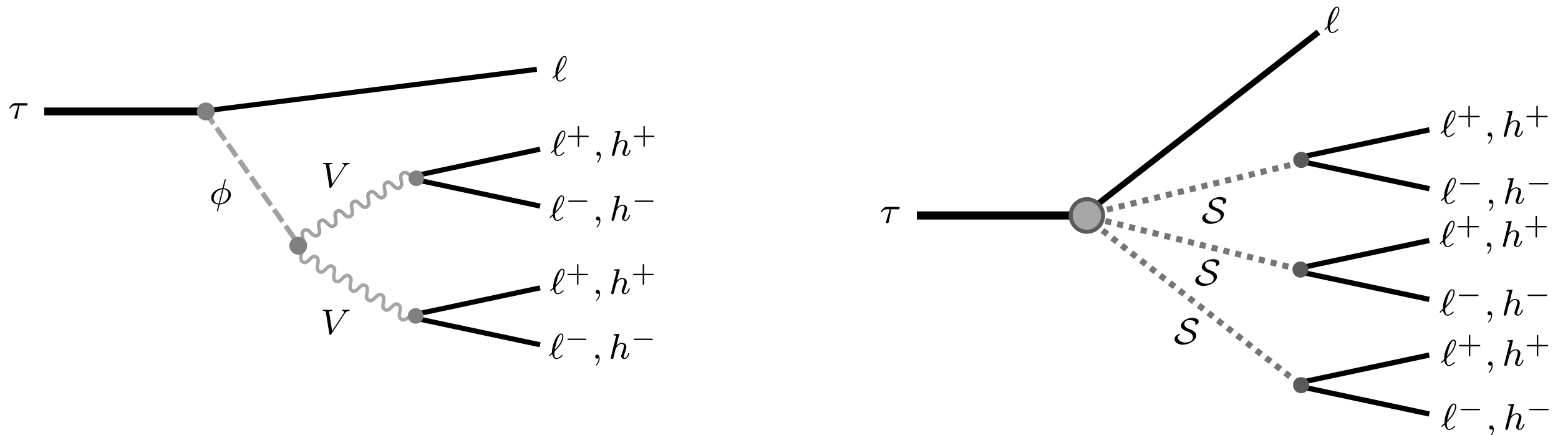


a is prompt



Prompt mulilepton tau decays

- Dark sector showers leading to SM-rich final states
- Tau mass allows many more final states than for other leptons
- Many candidate models — lepton “fingerprints”



Low energy description: flavour violating scalar coupled to a dark vector, “flavour protected scalar”, ...

$$\mathcal{L}_{\text{eff}} \supset g_V V_\mu J^\mu + \mu_V \phi V_\mu V^\mu + (c_{ij} \phi \bar{\ell}_{L,i} \ell_{R,j} + \text{h.c.})$$

$$J^\mu \equiv \bar{\psi}_L \gamma^\mu Q_L \psi_L + \bar{\psi} \gamma^\mu Q_R \psi_R$$

Kinetic mixing

U(1)', kinetic mixing, no SM states charged

$$\mathcal{L}_{U(1)'} = -\frac{1}{4}F_{\mu\nu}'^2 - \frac{\varepsilon}{2}F_{\mu\nu}'\hat{F}^{\mu\nu} + |D_\mu\Phi|^2 - V(\Phi)$$

Higher (dim-6) operator gives off-diagonal scalar coupling

$$-\mathcal{L}_{\text{LFV,I}} = \frac{\kappa_{ij}}{\Lambda^2}|\Phi|^2\bar{L}_i H \ell_{Rj} + \text{h.c.}$$

Leads to $5\mu, \mu 4e, 3\mu 2e, 3\mu 2\pi^\pm$ etc final states, eg

$$\begin{aligned}\mathcal{B}(\tau \rightarrow 5\ell) &\sim \mathcal{B}(\tau \rightarrow \phi\ell) \times \mathcal{B}^2(A' \rightarrow \ell\ell) \\ &\sim 10^{-8} \kappa_{\ell\tau}^2 \left(\frac{10^6 \text{ GeV}}{\Lambda} \right)^4 \left(\frac{v'}{10 \text{ GeV}} \right)^2 \times \sim (0.5)^2\end{aligned}$$

Gauged lepton flavour

Gauge L_{mu}-L_{tau}, or some other (anomaly free) combination

Higher (dim-5) operator gives off-diagonal scalar coupling

$$-\mathcal{L}_{\text{LFV,II}} = \frac{\tilde{k}_{ij}}{\Lambda} \Phi \bar{L}_i H \ell_j + \frac{\tilde{k}'_{ji}}{\Lambda} \Phi^* \bar{L}_j H \ell_i + \text{h.c.}$$

Charge of scalar dictates decay mode: $\overset{Q_\phi = 1}{\tau \rightarrow e\phi} \quad \overset{Q_\phi = 2}{\tau \rightarrow \mu\phi}$

Vector now has invisible decays, but no hadronic modes

Vector also has FV couplings, opening up 3-body decays

$$R_{\phi Z'}^\ell \equiv \frac{\Gamma(\tau \rightarrow \phi \ell)}{\Gamma(\tau \rightarrow Z' \ell)} \simeq 1$$

Belle II: $\mathcal{B} \lesssim 10^{-8}$

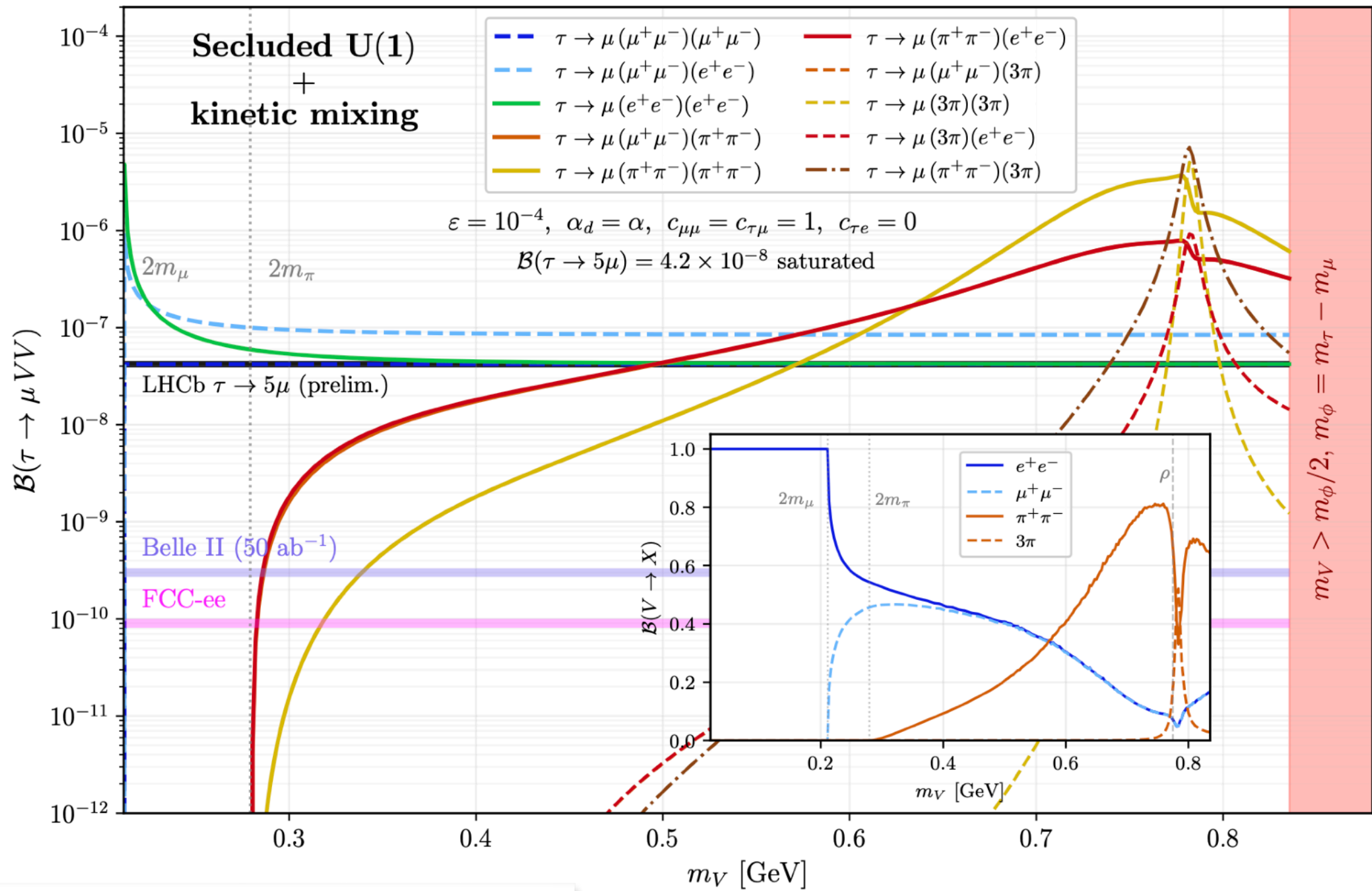
Belle II: $\mathcal{B} \lesssim 10^{-3}$

LHCb (prelim): $\mathcal{B} \lesssim 10^{-8}$

CLEO: $\mathcal{B} \lesssim 10^{-5}$

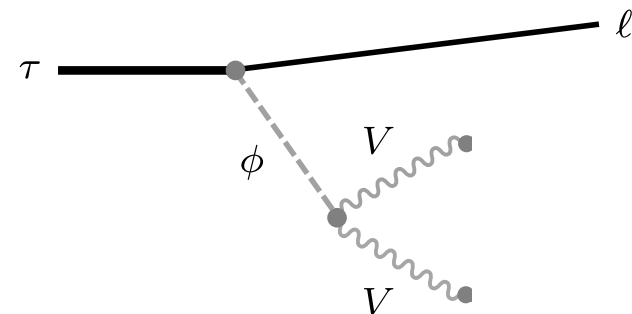
Model			I	IIa	IIb	III	IVa	IVb	V
			Seclud. $U(1)$	$U(1)_{L_\mu-L_\tau}$	$U(1)_{L_\mu-L_\tau}$	$U(1)_{L_\mu+L_e-2L_\tau}$	Chiral	Chiral	Flav. prot.
$\not{E}$	τ decay	Search	Kinetic mix.	$Q_\Phi = +1$	$Q_\Phi = +2$	$Q_\Phi = -3$	$U(1)_\mu$	$U(1)_e$	scalar
$\not{E} = 0$ 3 leptons	$\tau \rightarrow 3\mu$	[45]	(✓)		✓	✓	✓		(✓)
	$\tau \rightarrow 2\mu e$	[40]	(✓)	✓		✓			
	$\tau \rightarrow \mu 2e$	[40]	(✓)			✓			(✓)
	$\tau \rightarrow 3e$	[40]	(✓)			✓		✓	
$\not{E} > 0$ 3 leptons	$\tau \rightarrow \mu 2\nu$	[38, 55]			✓	✓	✓		
	$\tau \rightarrow e 2\nu$	[38, 55]		✓		✓		✓	
$\not{E} = 0$ 5 leptons	$\tau \rightarrow 5\mu$	[56]*	✓		✓	✓	✓		(✓)
	$\tau \rightarrow 4\mu e$	✗	✓	✓		✓			(✓)
	$\tau \rightarrow 3\mu 2e$	✗	✓			✓			(✓)
	$\tau \rightarrow 2\mu 3e$	✗	✓			✓			(✓)
	$\tau \rightarrow \mu 4e$	✗	✓			✓			(✓)
	$\tau \rightarrow 5e$	✗	✓			✓		✓	(✓)
$\not{E} = 0$ hadrons	$\tau \rightarrow 3\mu 2\pi$	✗	✓						
	$\tau \rightarrow 2\mu e 2\pi$	✗	✓						
	$\tau \rightarrow \mu 2e 2\pi$	✗	✓						
	$\tau \rightarrow \mu 4\pi$	✗	✓						
	$\tau \rightarrow 3e 2\pi$	✗	✓						
	$\tau \rightarrow e 4\pi$	✗	✓						
$\not{E} > 0$ 5 leptons	$\tau \rightarrow 3\mu 2\nu$	✗			✓	✓	(✓)		
	$\tau \rightarrow 2\mu e 2\nu$	[57]		✓		✓			
	$\tau \rightarrow \mu 2e 2\nu$	✗				✓			
	$\tau \rightarrow \mu 4\nu$	✗			✓	✓	(✓)		
	$\tau \rightarrow 3e 2\nu$	[57]				✓		(✓)	
	$\tau \rightarrow e 4\nu$	✗		✓		✓		(✓)	
$\not{E} = 0$ 7 leptons	$\tau \rightarrow 7\mu$	✗							✓
	$\tau \rightarrow 6\mu e$	✗							✓
	$\tau \rightarrow 5\mu 2e$	✗							✓
	$\tau \rightarrow 4\mu 3e$	✗							✓
	$\tau \rightarrow 3\mu 4e$	✗							✓
	$\tau \rightarrow 2\mu 5e$	✗							✓
	$\tau \rightarrow \mu 6e$	✗							✓
	$\tau \rightarrow 7e$	✗							✓

Kinetic mixing



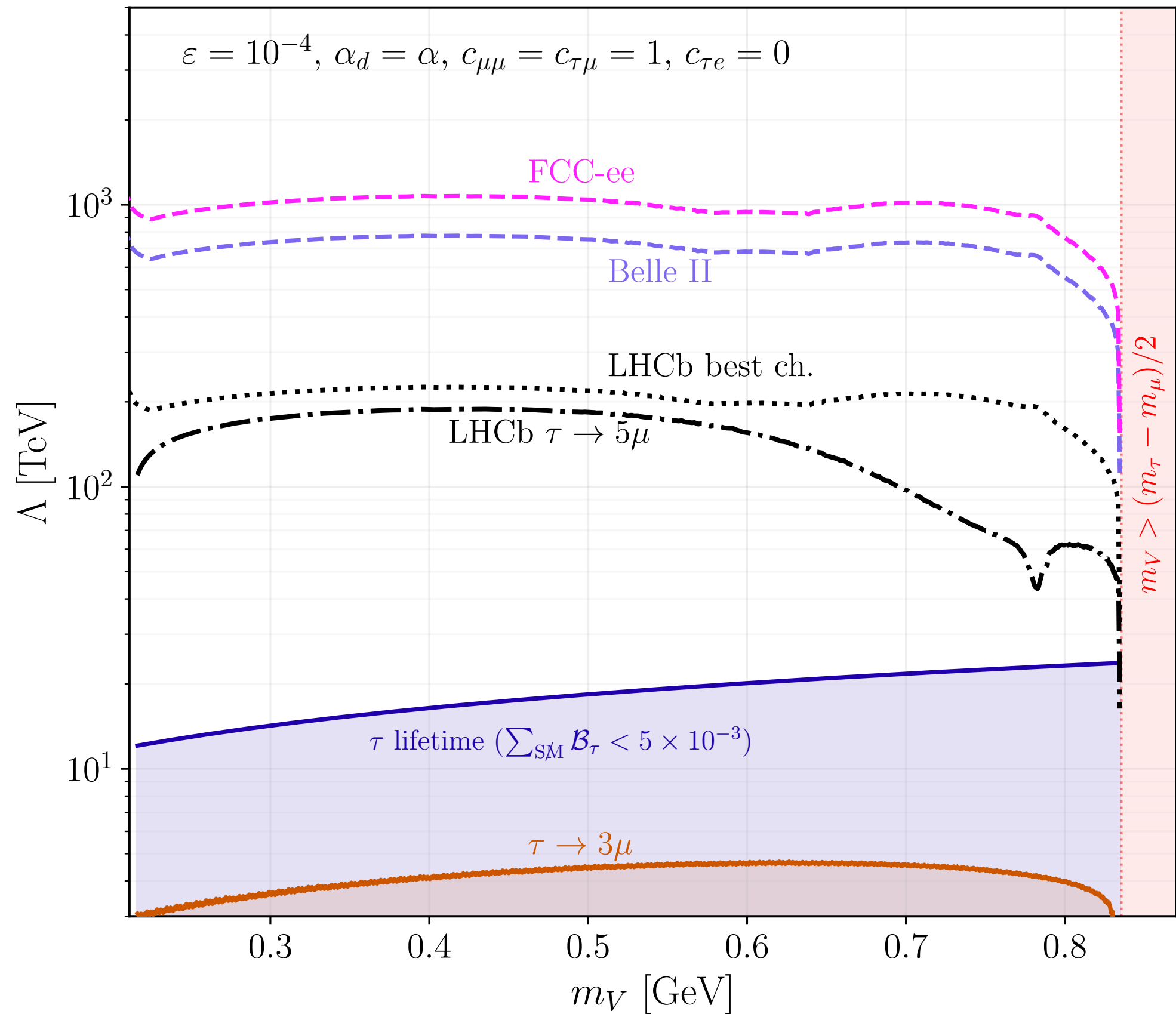
$$m_\phi = m_\tau - m_\mu \approx 1.67 \text{ GeV}$$

$$-\mathcal{L}_{\text{LFV,I}} = \frac{\kappa_{ij}}{\Lambda^2} |\Phi|^2 \bar{L}_i H \ell_{Rj} + \text{h.c.},$$



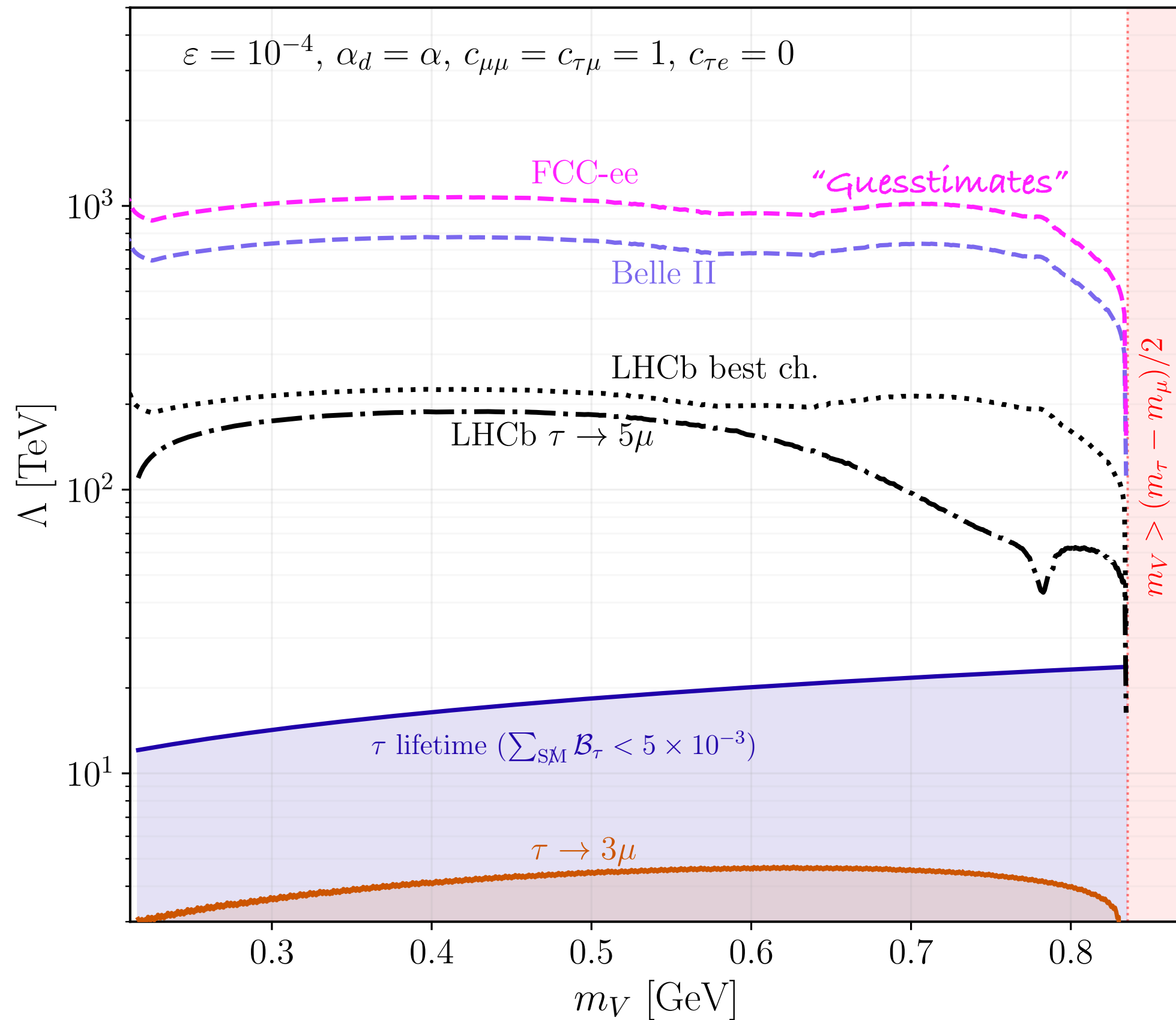
Kinetic mixing

Secluded U(1) + kinetic mixing



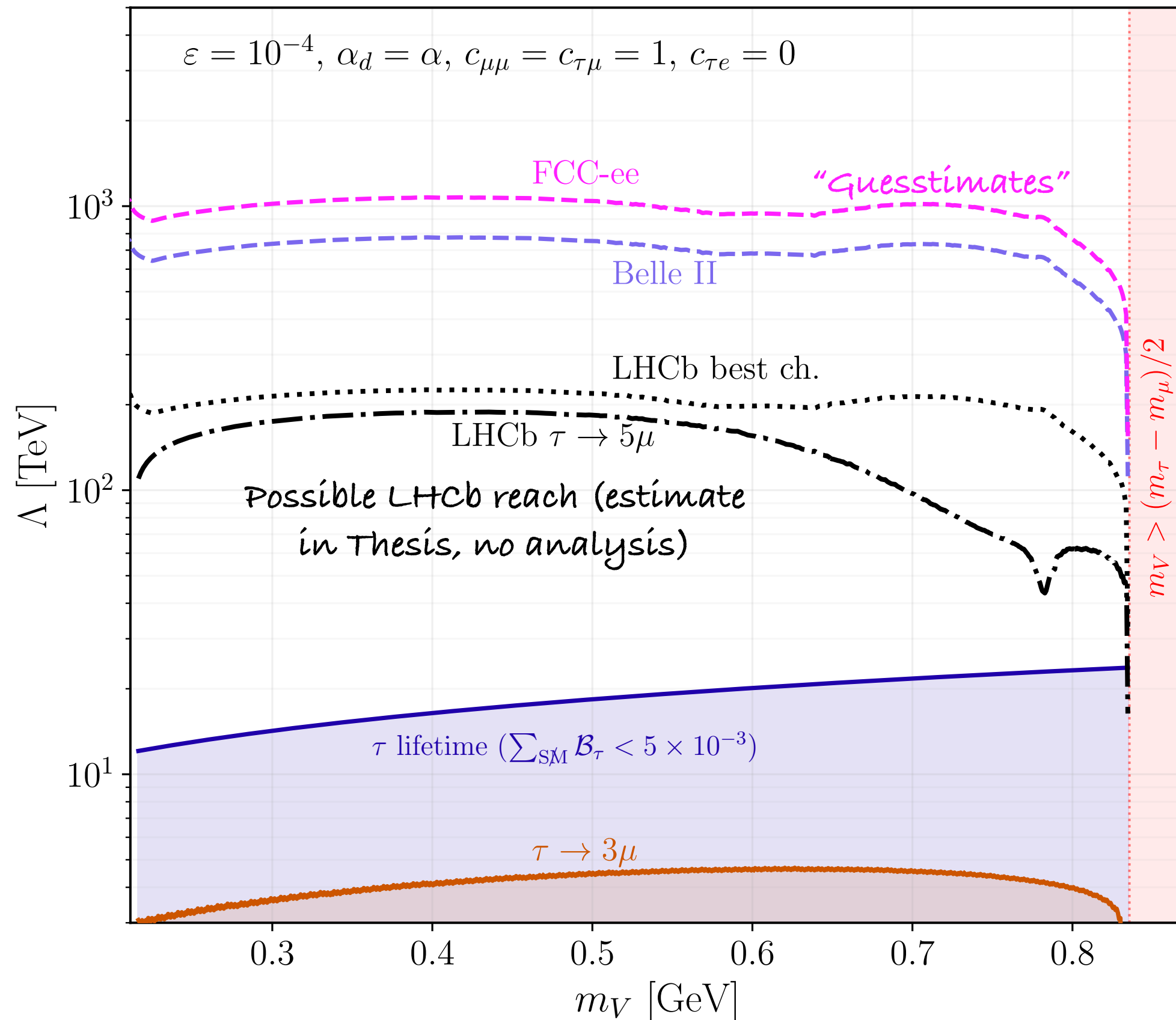
Kinetic mixing

Secluded U(1) + kinetic mixing



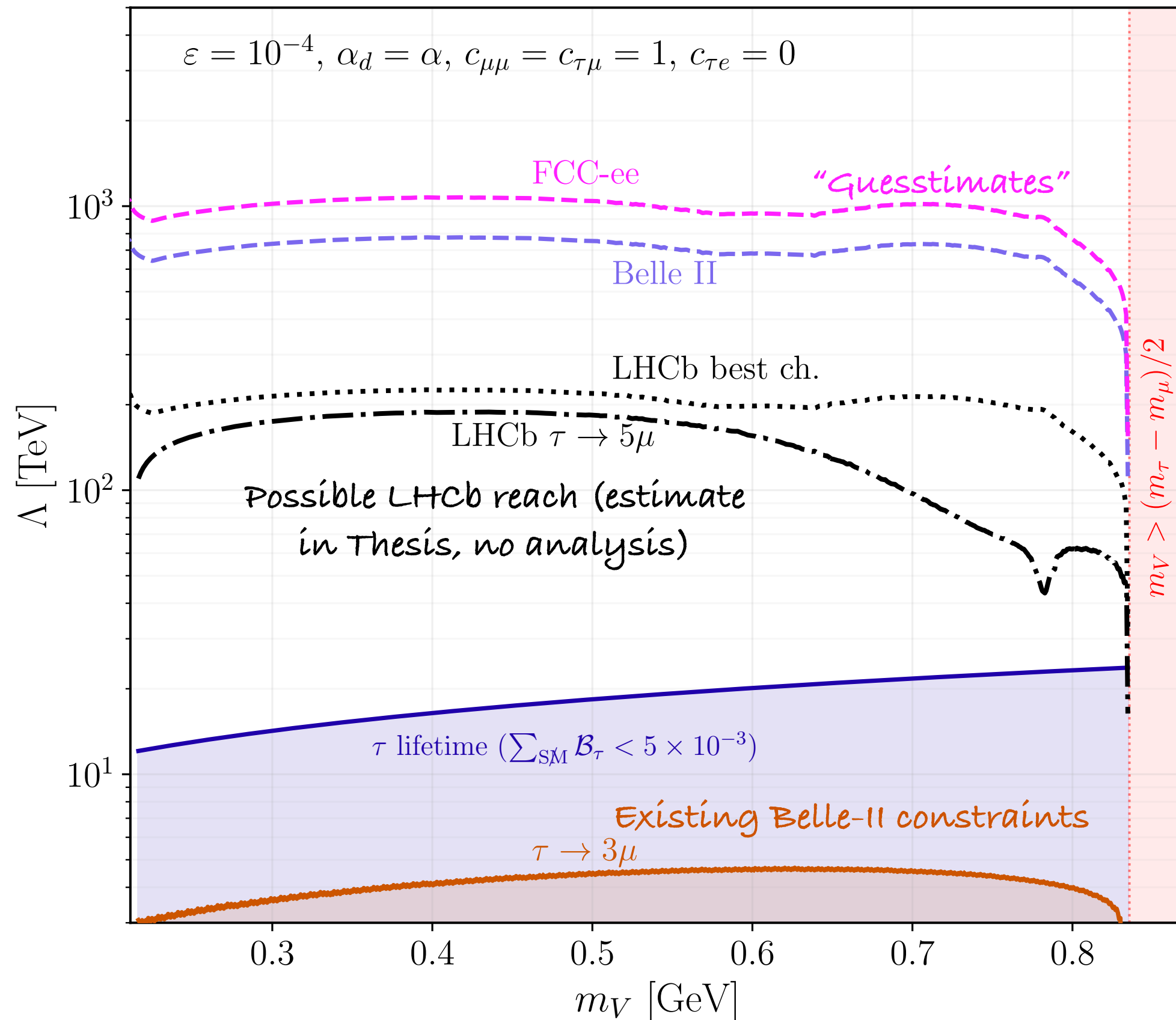
Kinetic mixing

Secluded U(1) + kinetic mixing



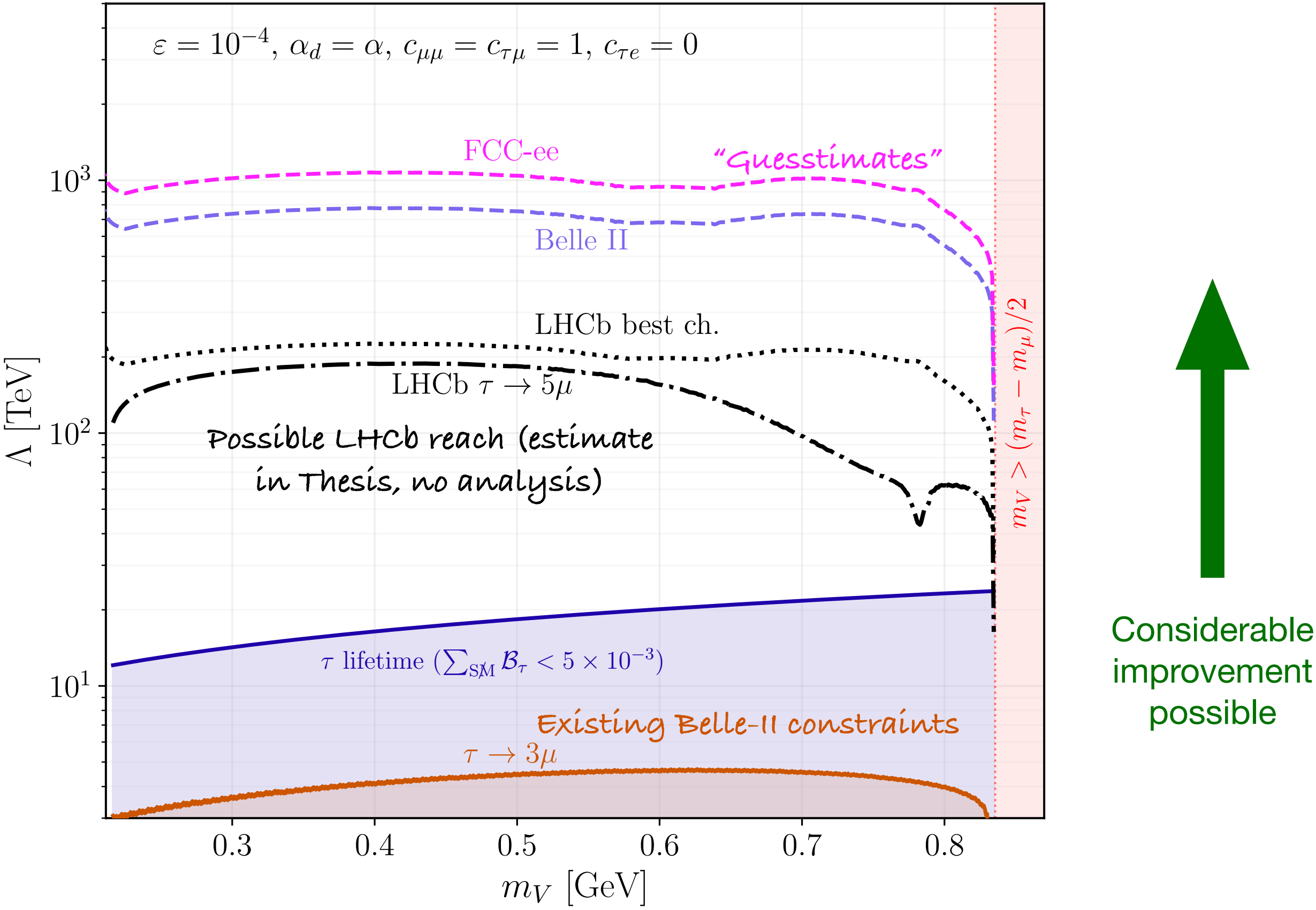
Kinetic mixing

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Kinetic mixing

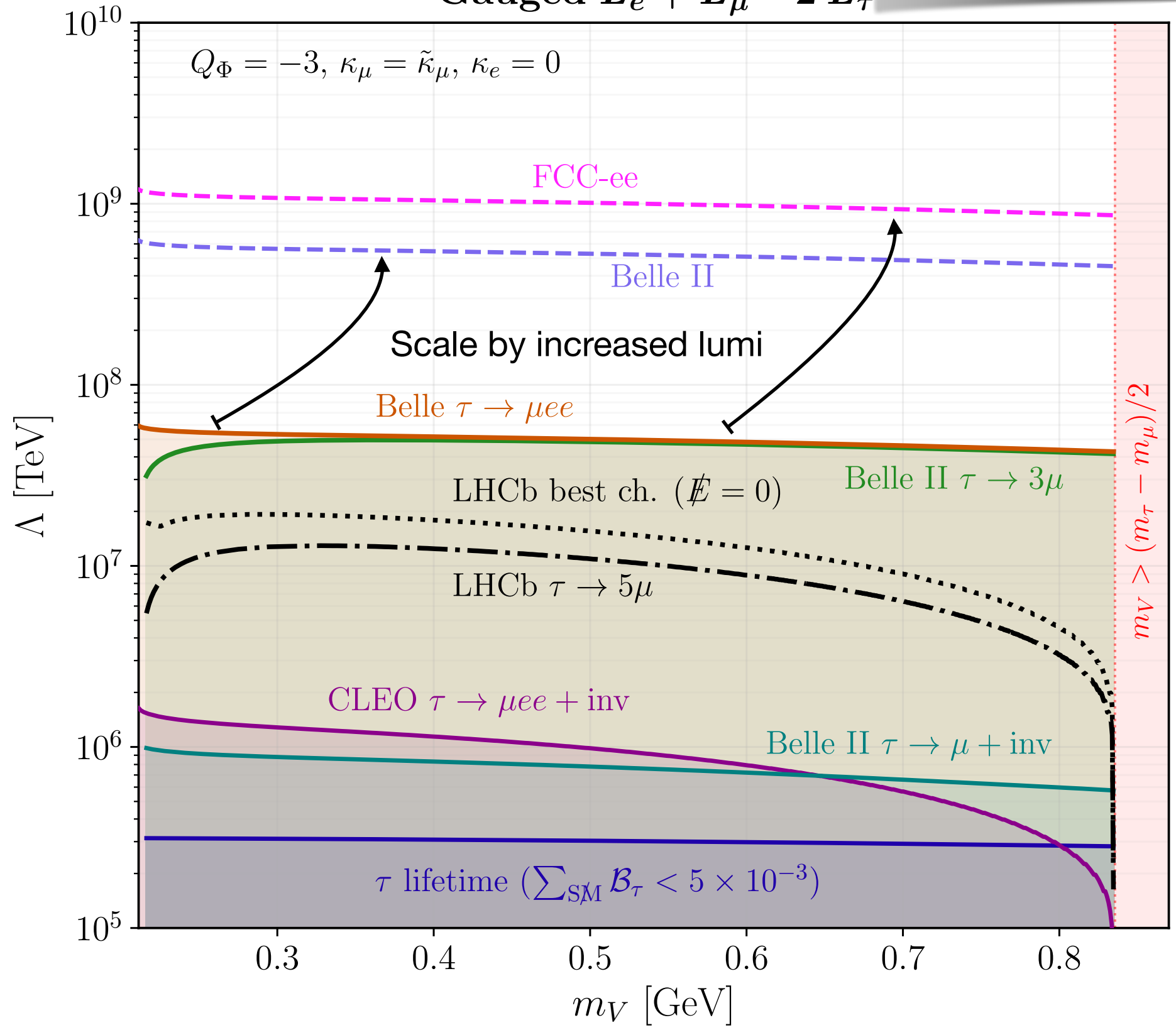
Secluded U(1) + kinetic mixing



Gauged lepton flavour

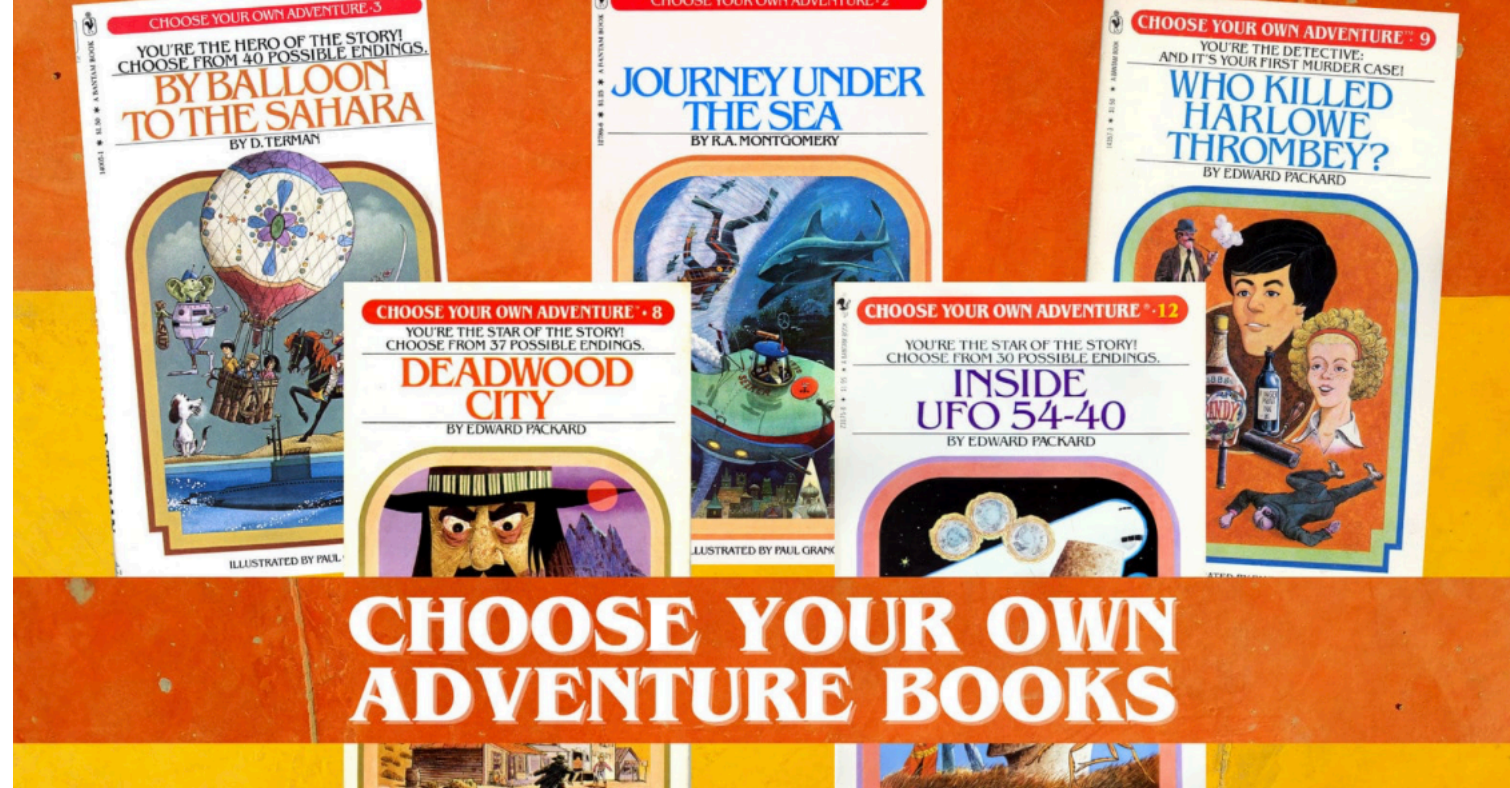
$$\begin{aligned}
 -\mathcal{L} \supset & \frac{\kappa_e}{\Lambda} \Phi \bar{L}_\tau H e_R + \frac{\tilde{\kappa}_e}{\Lambda} \Phi^* \bar{L}_e H \tau_R \\
 & + \frac{\kappa_\mu}{\Lambda} \Phi \bar{L}_\tau H \mu_R + \frac{\tilde{\kappa}_\mu}{\Lambda} \Phi^* \bar{L}_\mu H \tau_R + \text{h.c.}
 \end{aligned}$$

Gauged $L_e + L_\mu - 2 L_\tau$

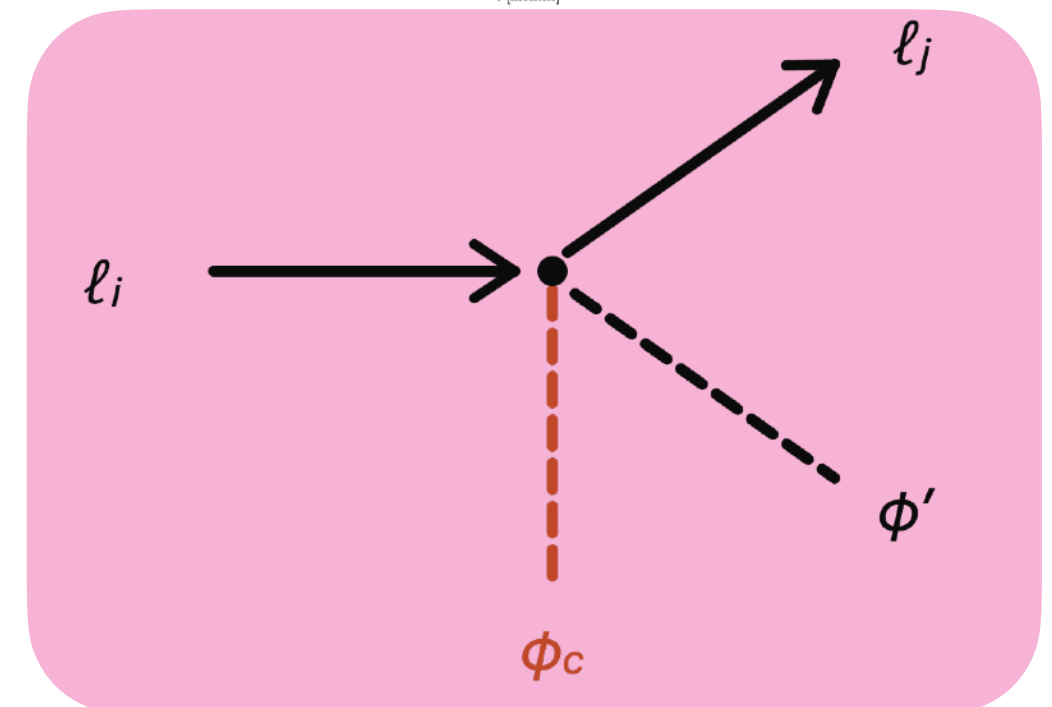
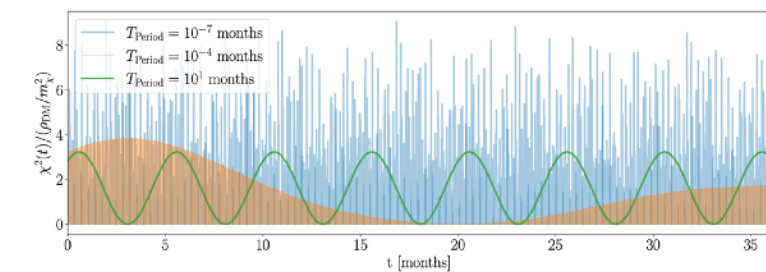
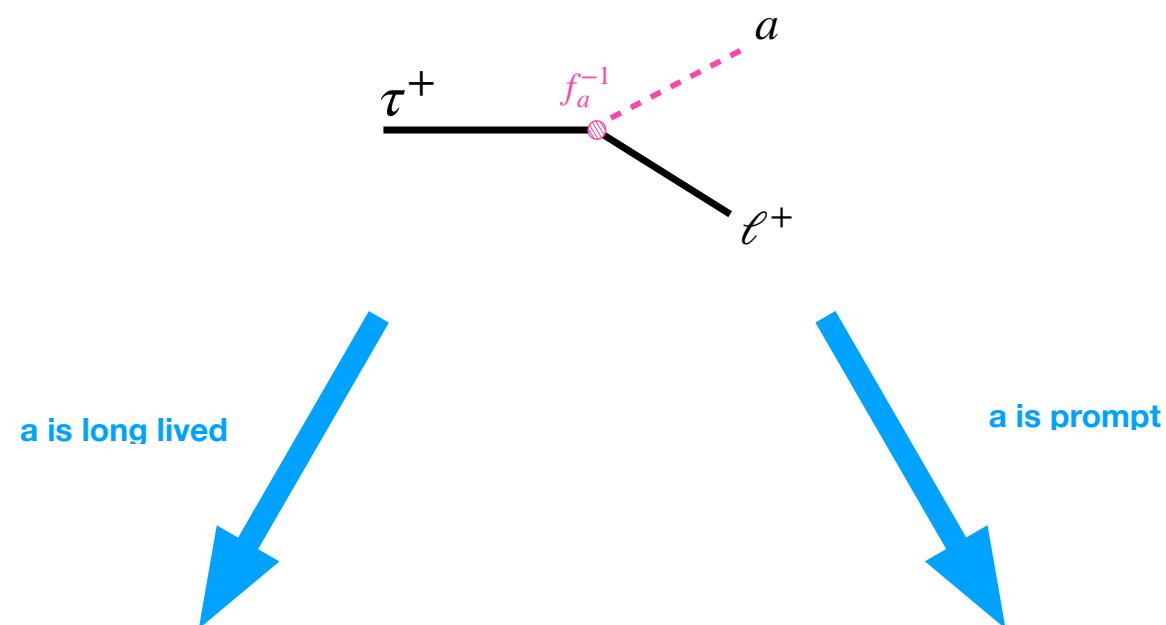


Both scalar and
vector flavour
violating
couplings

$$R_{\phi Z'}^\ell = \frac{\Gamma(\tau \rightarrow \phi \ell)}{\Gamma(\tau \rightarrow Z' \ell)} \simeq 1$$



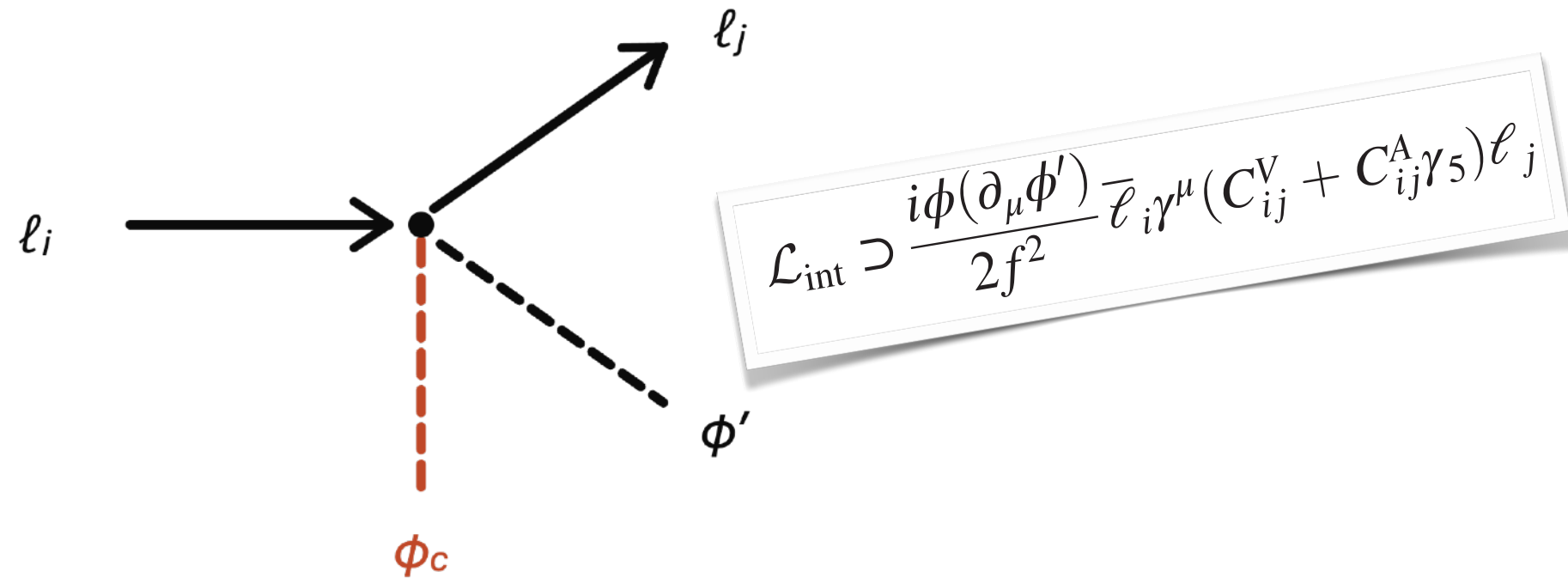
Modulation



DM and time-variation in lepton decays

Assume coupling of DM to SM is quadratic in dark sector

DM-background dependent processes eg



$$\phi_c(t) = \phi_0 \cos(m_\phi t + \delta)$$

$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi} \simeq 2.5 \text{ TeV} \left(\frac{10^{-15} \text{ eV}}{m_\phi} \right)$$

Leads to large time variation

$$\tau_\phi = \frac{2\pi}{m_\phi} \simeq 4 \text{ s} \left(\frac{10^{-15} \text{ eV}}{m_\phi} \right)$$

Allows removal of static systematic backgrounds

Model Building (some) details

Non-abelian pseudo-Nambu Goldstone bosons (npNGBs) $G \rightarrow H$

$$\mathcal{L}_{\text{int}} \supset \text{Tr} (QU^\dagger i\partial_\mu U) \bar{\ell}_i \gamma^\mu (\tilde{C}_{\ell_i \ell_j}^V + \tilde{C}_{\ell_i \ell_j}^A \gamma_5) \ell_j + \text{h.c.},$$

Generated by integrating out a mediator, SM leptons charged

$$U = e^{i\Pi^a T^a / f} \quad \text{with} \quad U \rightarrow V_L^\dagger U V_R \quad \text{and} \quad Q \rightarrow V_R^\dagger U V_R$$

Shift symmetry preserved, so light DM protected

$$\mathcal{L}_{\text{int}} \supset \left(\frac{\phi_1}{f} \frac{i\partial_\mu \phi_2}{2f} - \frac{\phi_2}{f} \frac{i\partial_\mu \phi_1}{2f} \right) \bar{\ell}_i \gamma^\mu (C_{\ell_i \ell_j}^V + C_{\ell_i \ell_j}^A \gamma_5) \ell_j + \text{h.c.} + \dots$$

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DM and time-variation in muon decays

$$\mathcal{B}(\ell_i \rightarrow \ell_j \phi') = \frac{C_{ij}^2 \phi_0^2}{64\pi f^4} \frac{m_{\ell_i}^3}{\Gamma_{\ell_i}} \cos^2(m_\phi t + \delta)$$

Mu3e collected $\sim 1\text{E}15$ decays, $1\text{E}13$ in “endpoint” bin $E_e = m_\mu/2$

$$\sigma_{\text{stat}} = \sqrt{N_{\text{bg}}/n_{\text{bin}}}, \quad \sigma_{\text{sys}} = \alpha N_{\text{bg}}/n_{\text{bin}}$$

Systematics limited

**Time-variation allows measurement of backgrounds *in situ*,
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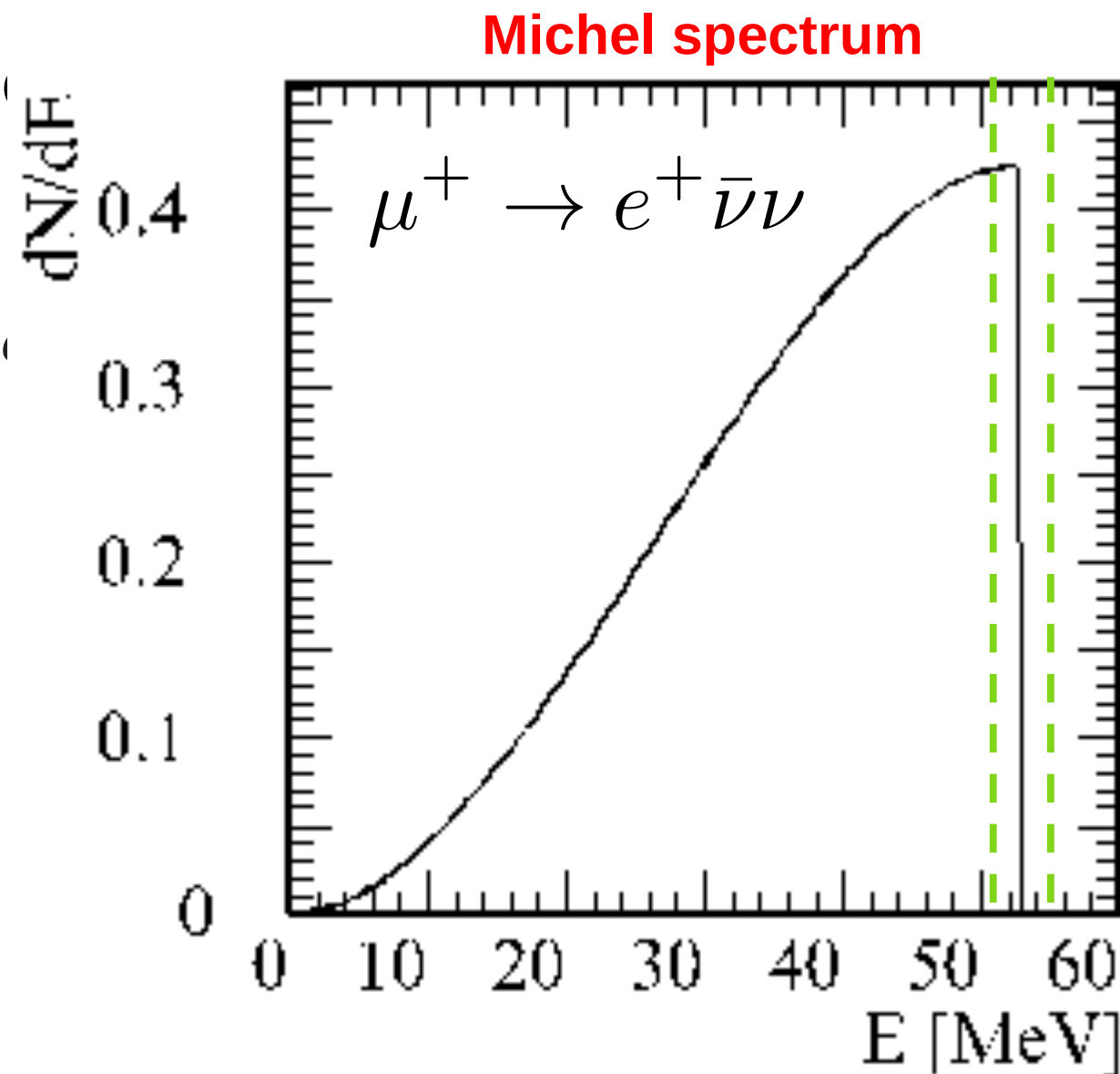
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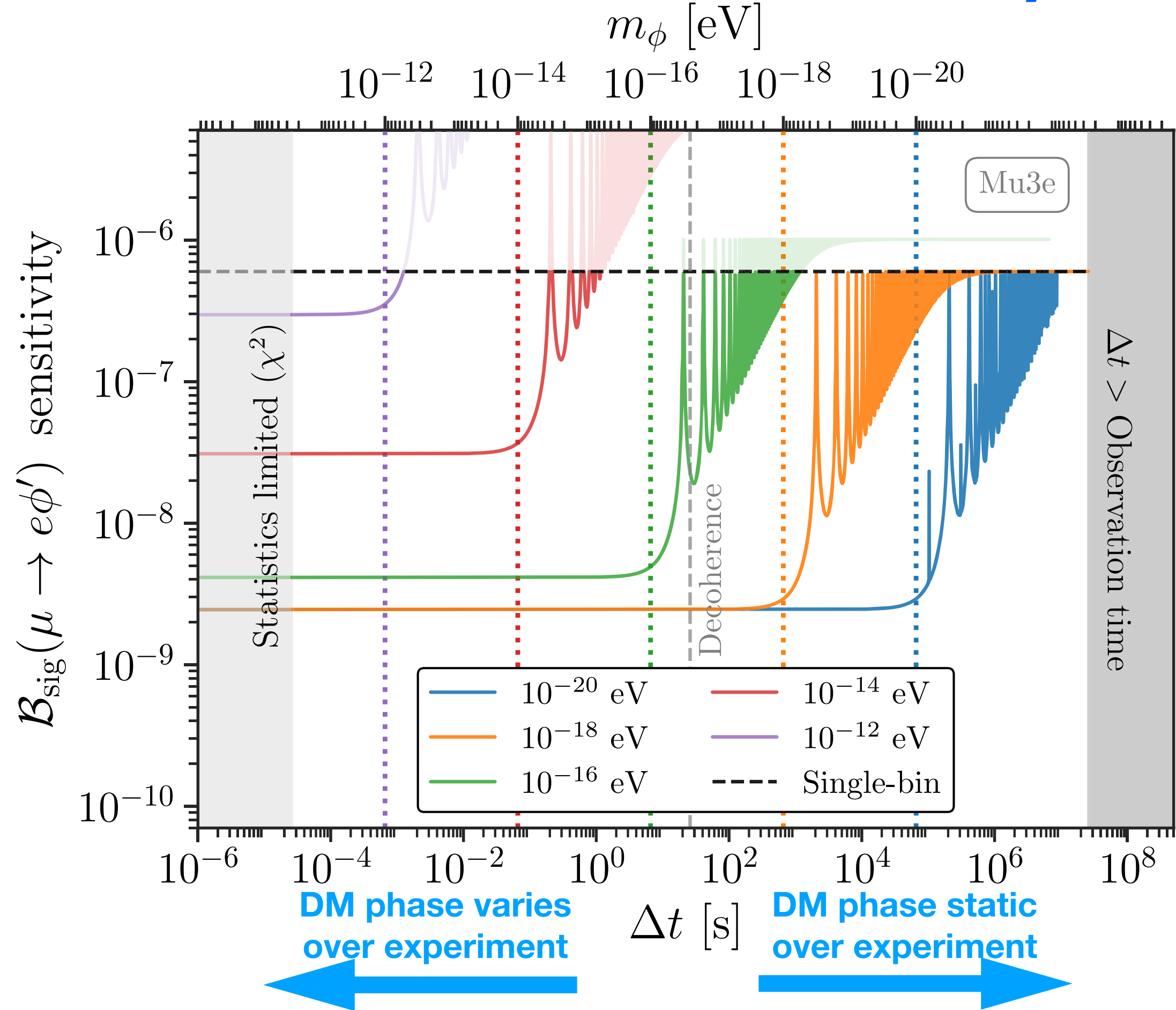
Systematics limited

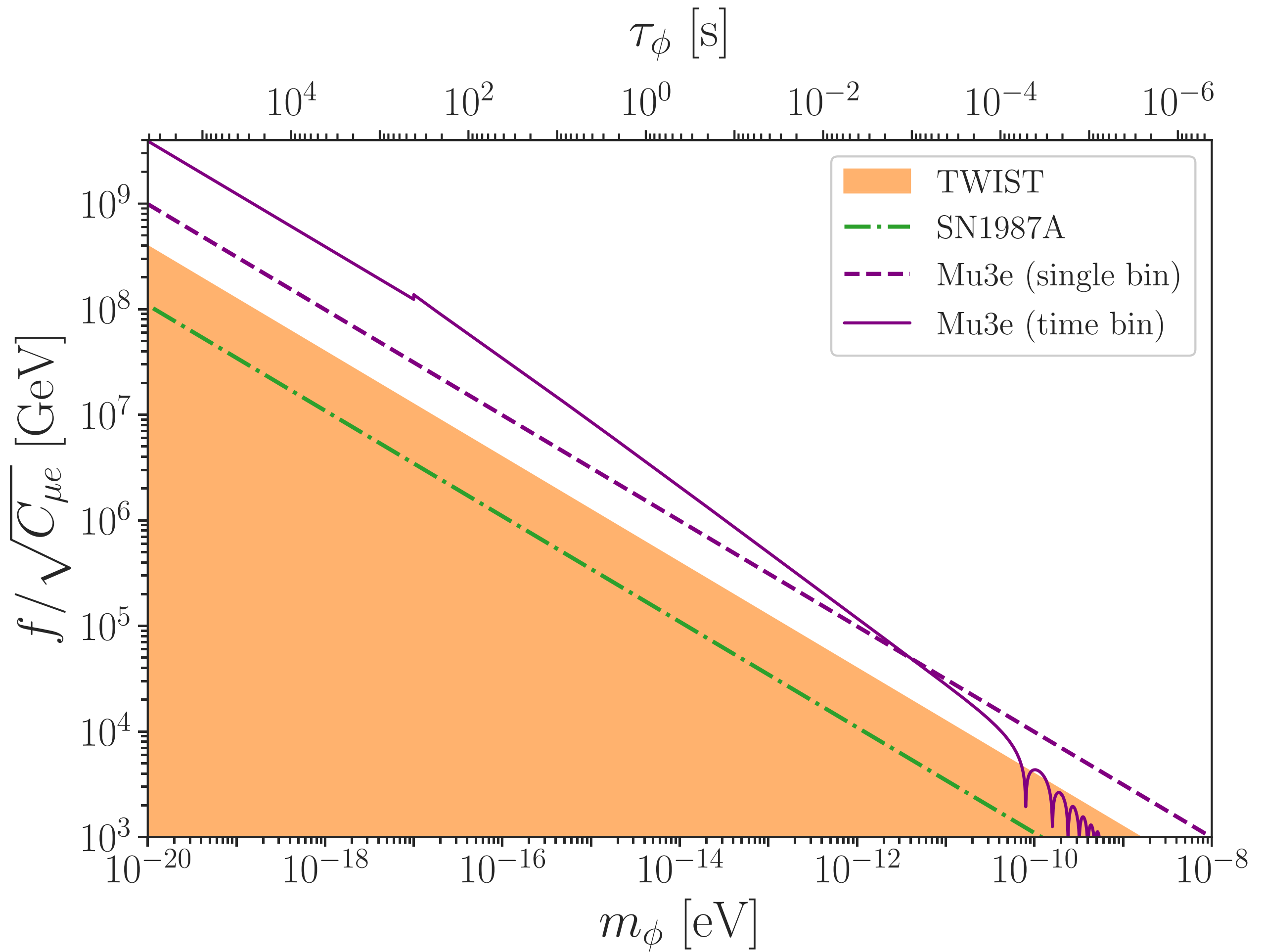
Time-variation all
removed

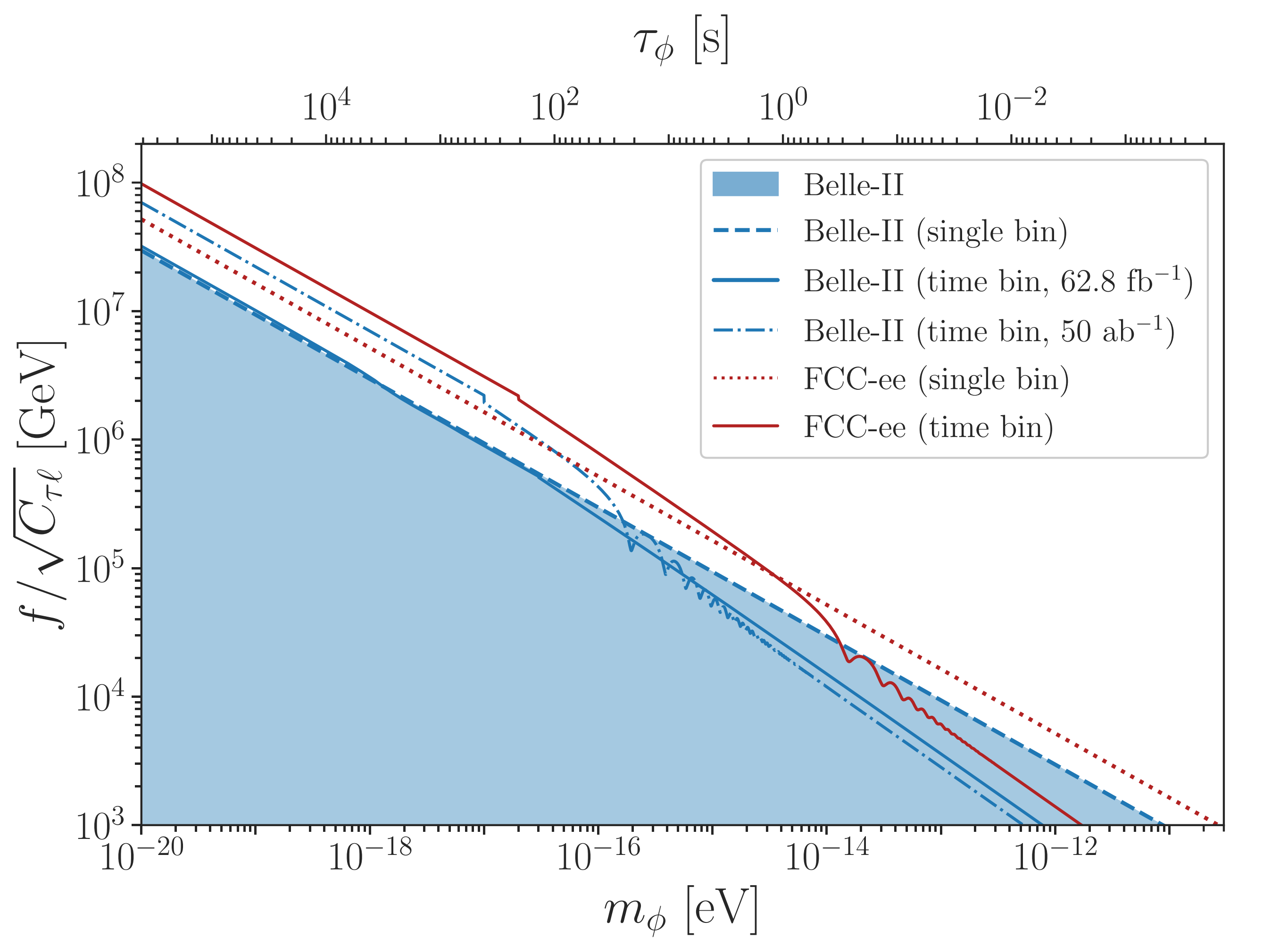
$$\chi_{\text{fb}}^2 = \frac{3}{2} \left[1 + \frac{n_{\text{bin}}}{3} \left(\frac{\sigma_{\text{sys}}}{\sigma_{\text{stat}}} \right)^2 \right] \chi_{\text{const}}^2$$

backgrounds *in situ*,
monitors

DM and time-variation in MUON decays







Conclusions

- ALPs — “standard” BSM, coupling to taus somewhat overlooked
- Broad array of possible couplings to leptons (anarchy, hierarchy, FV, FC)
- Beam dumps are rich source of taus and provide strong constraints for long-lived ALPs
 - Old data at CHARM, BEBC provide new constraints
 - New parameter space can be probed by NOvA, Icarus, MicroBooNE
 - DUNE and SHiP will have greatest reach
- Prompt exotic tau decays can be searched for at LHCb, Belle-II, FCC-ee.
 - With reach to 10^3 - 10^9 TeV scale.
 - Many possible final states, high charge multiplicity
- Quadratic couplings can be leading effect in some models
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Thank you!

Backup

Model Building details — example

$$SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$$

Dark QCD-like theory, but with different quark masses etc

$$\mathcal{L} = \frac{f_{UV}^2}{8} \text{Tr} (D_\mu U D^\mu U^\dagger) + \frac{f_{UV}^2}{8} \text{Tr} (\chi^\dagger U + U^\dagger \chi) + \dots$$

$$D_\mu U = \partial_\mu U + ig' A'_\mu Q U$$

$$Q = q_U \lambda_3$$

$$\chi \propto (m_u^{\text{hid}}, m_d^{\text{hid}}, m_s^{\text{hid}})$$

$$U = \exp (i\sqrt{2}\Pi_D/f_{UV}) \quad \text{and} \quad \Pi_d = \begin{pmatrix} \frac{\pi_D^0}{\sqrt{2}} + \frac{\eta_{D8}}{\sqrt{6}} & \pi_D^+ & K_D^+ \\ \pi_D^- & -\frac{\pi_D^0}{\sqrt{2}} + \frac{\eta_{D8}}{\sqrt{6}} & K_D^0 \\ K_D^- & \bar{K}_D^0 & -\sqrt{\frac{2}{3}}\eta_{D8} \end{pmatrix}$$

Expand...

$$\begin{aligned} \frac{f_{UV}^2}{8} \text{Tr} (D_\mu U D^\mu U^\dagger) &\supset \frac{f_{UV}^2}{8} g' A'_\mu \text{Tr} (QU i\partial_\mu U^\dagger - i\partial_\mu U U^\dagger Q) + \dots \\ &= \frac{f_{UV} g' q_u}{2\sqrt{2}} A'_\mu \partial_\mu \pi_D^0 + \frac{g' q_U}{4} A'_\mu (\bar{K}_D^0 i\partial^\mu K_D^0 - K_D^0 i\partial^\mu \bar{K}_D^0) + \dots \end{aligned}$$

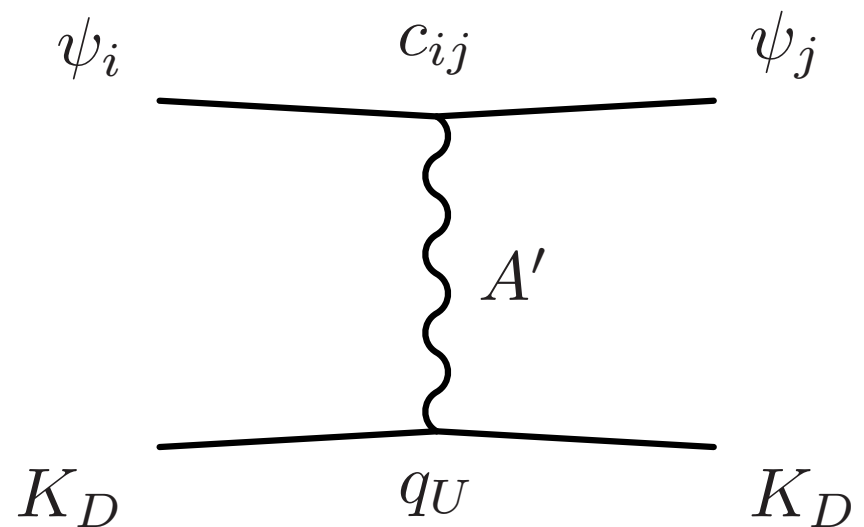
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Work in limit: $m_u \gg m_{d,s}$ “Kaons” are DM, coupling quadratic

SM side: charge some leptons $\mathcal{L}_{\text{int}} = i g' c_{ij} \bar{\psi}_i A' \psi_j + \text{h.c.}$



$$\Rightarrow \frac{c_{ij} q_U g'^2}{4m_{A'}^2} (\bar{\psi}_i \gamma^\mu \psi_j) (\bar{K}_D^0 i \partial_\mu K_D^0 + \text{h.c.})$$

$$\frac{f}{\sqrt{C_{ij}}} \sim \frac{2m_{A'}}{g' \sqrt{c_{ij} q_U}} = \frac{2 \cdot 10^9 \text{ GeV}}{\sqrt{c_{ij} q_U}} \left(\frac{m_{A'}}{10^6 \text{ GeV}} \right) \left(\frac{10^{-3}}{g'} \right)$$

Axions

QCD Lagrangian is “simple”

$$\mathcal{L}_{QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} - \frac{\theta}{64\pi^2}\epsilon^{\mu\nu\alpha\beta}G_{\mu\nu}^a G_a^{\alpha\beta}$$

Neutron electric dipole moment $d_n \sim 10^{-16}\theta$ ecm

Experimental bound: $|d_n| < 2 \times 10^{-26}$ ecm

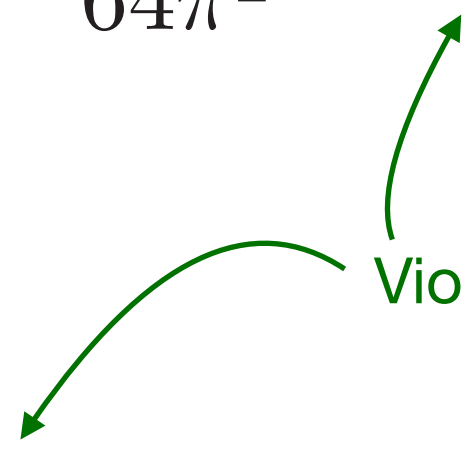
What is reason for smallness of θ ?

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Violates CP



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PQ Symmetry

Elevate θ to a dynamical variable

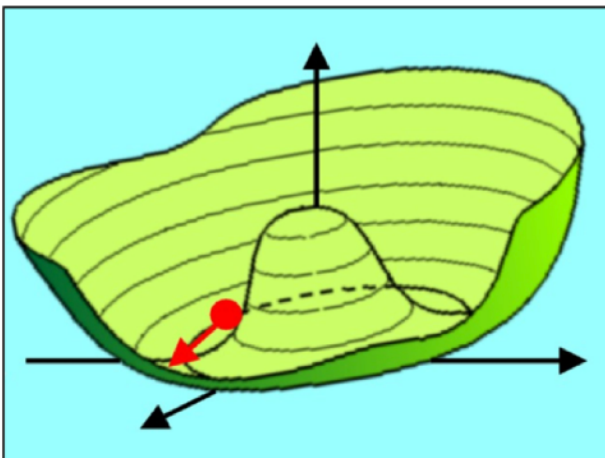
Introduce a spontaneously broken global chiral U(1) symmetry, charge a coloured field

$$\Phi \rightarrow f e^{i a(x)/f}$$

The QCD-U(1) anomaly means that theta term becomes dynamical

$$\frac{1}{64\pi^2} \left(\theta + \mathcal{A} \frac{a}{f} \right) \epsilon^{\mu\nu\alpha\beta} G_{\mu\nu}^a G_a^{\alpha\beta}$$

QCD instantons (topological susceptibility) give a potential



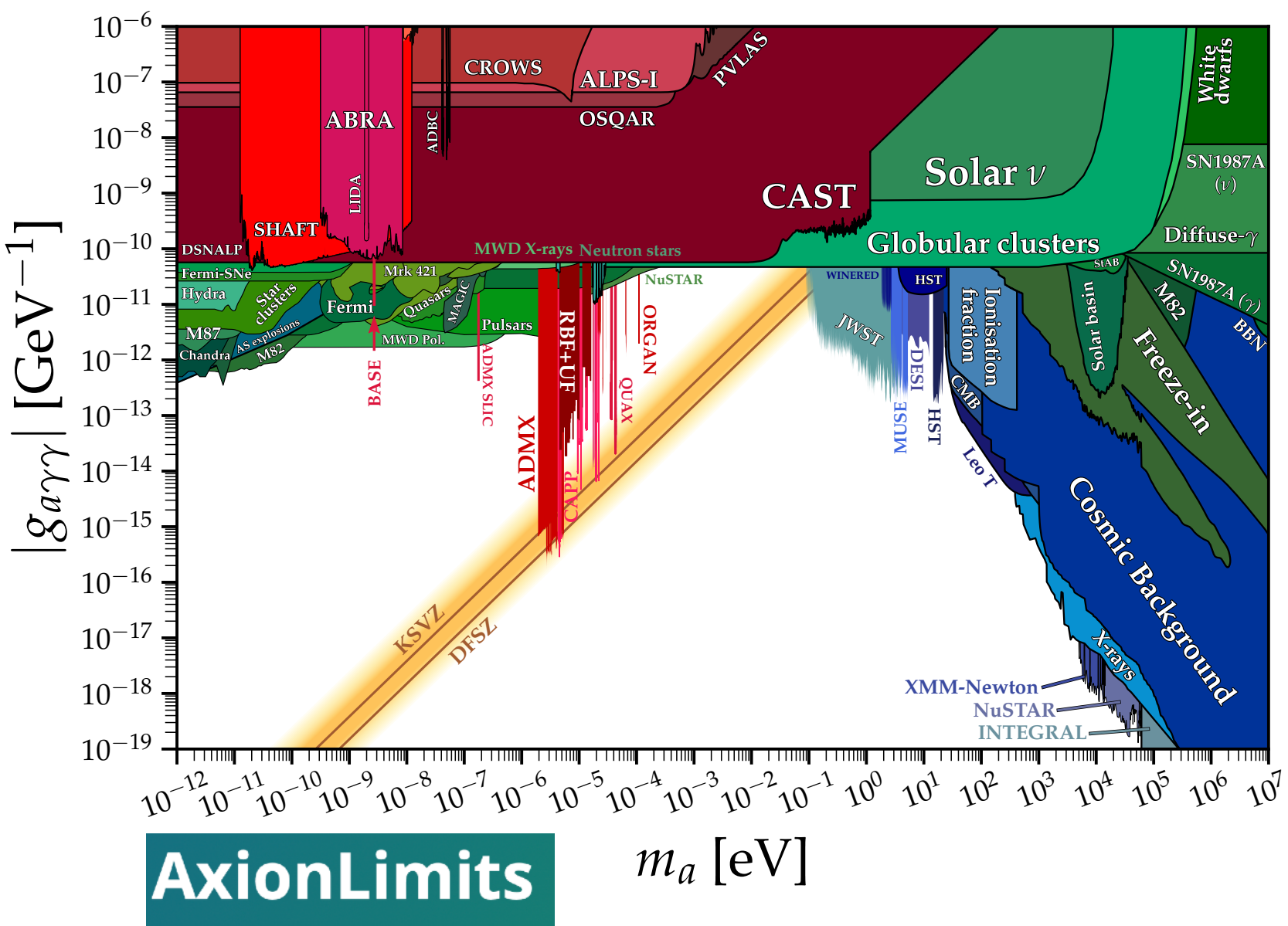
$$V(a) \sim -\Lambda^4 \left[1 - \kappa \sin^2 \left(\theta + \mathcal{A} \frac{a}{f} \right) \right]^{1/2}$$

$$m_\pi f_\pi = m_a f_a$$

Models and other couplings

KSVZ (Kim-Shifman-Vainshtein-Zakharov): introduce heavy quarks with PQ charge

DFSZ (Dine-Fischler-Srednicki-Zhitnitsky): give SM quarks (and 2HDM) PQ charge



$$\frac{\alpha_s}{8\pi} \frac{a}{f} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

$$c_{a\gamma\gamma} \frac{\alpha}{8\pi} \frac{a}{f} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$\frac{\partial_\mu a}{2f} J_{PQ}^\mu$$

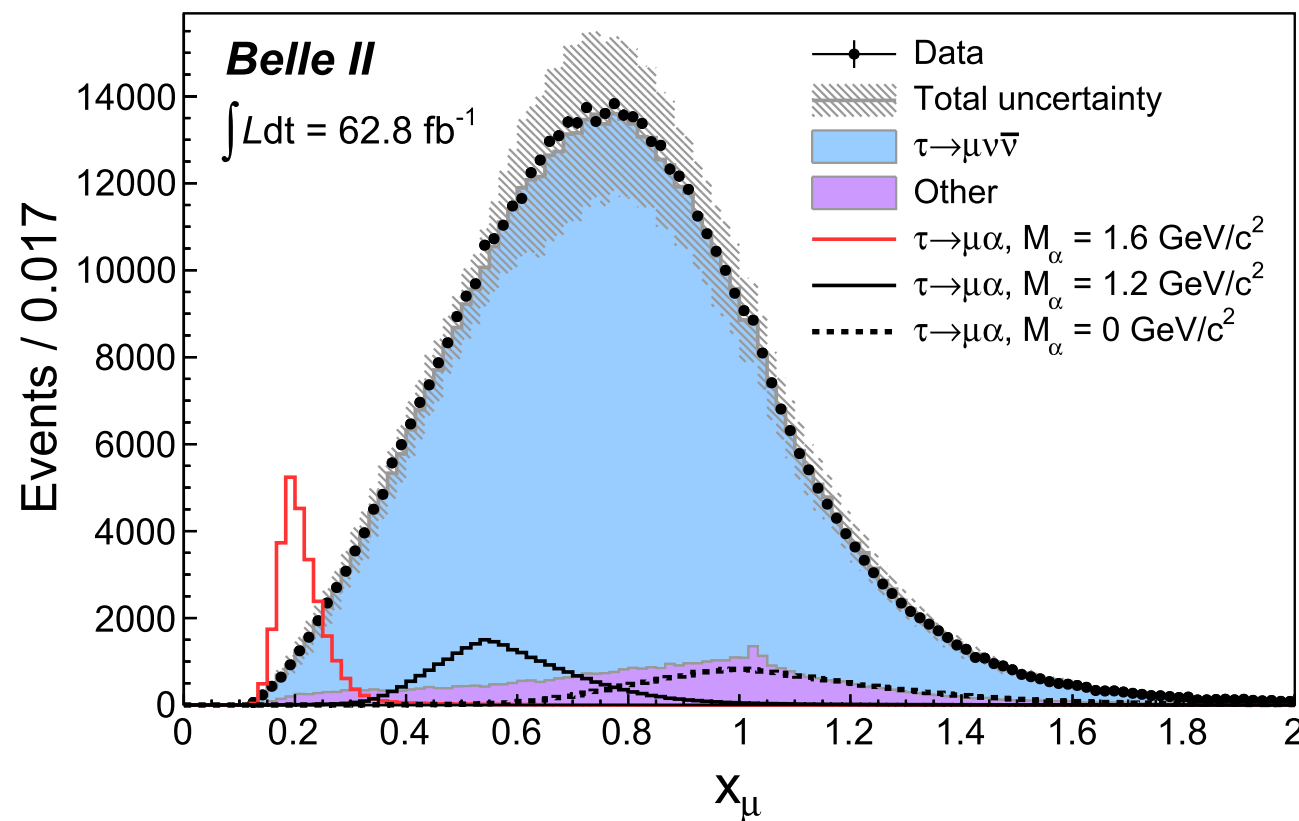
DM and time-variation in TAU decays

$$\mathcal{B}(\ell_i \rightarrow \ell_j \phi') = \frac{C_{ij}^2 \phi_0^2}{64\pi f^4} \frac{m_{\ell_i}^3}{\Gamma_{\ell_i}} \cos^2(m_\phi t + \delta)$$

Belle II collected ~60M tau pairs, systematics limited

$$\sigma_{\text{stat}} = \sqrt{N_{\text{bg}}/n_{\text{bin}}}, \quad \sigma_{\text{sys}} = \alpha N_{\text{bg}}/n_{\text{bin}}$$

$$\tau \rightarrow \ell X_{\text{invis}}$$



Due to neutrinos need
to construct tau's
pseudo rest frame

$$x_\ell = \frac{E_\ell^*}{m_\tau/2}$$

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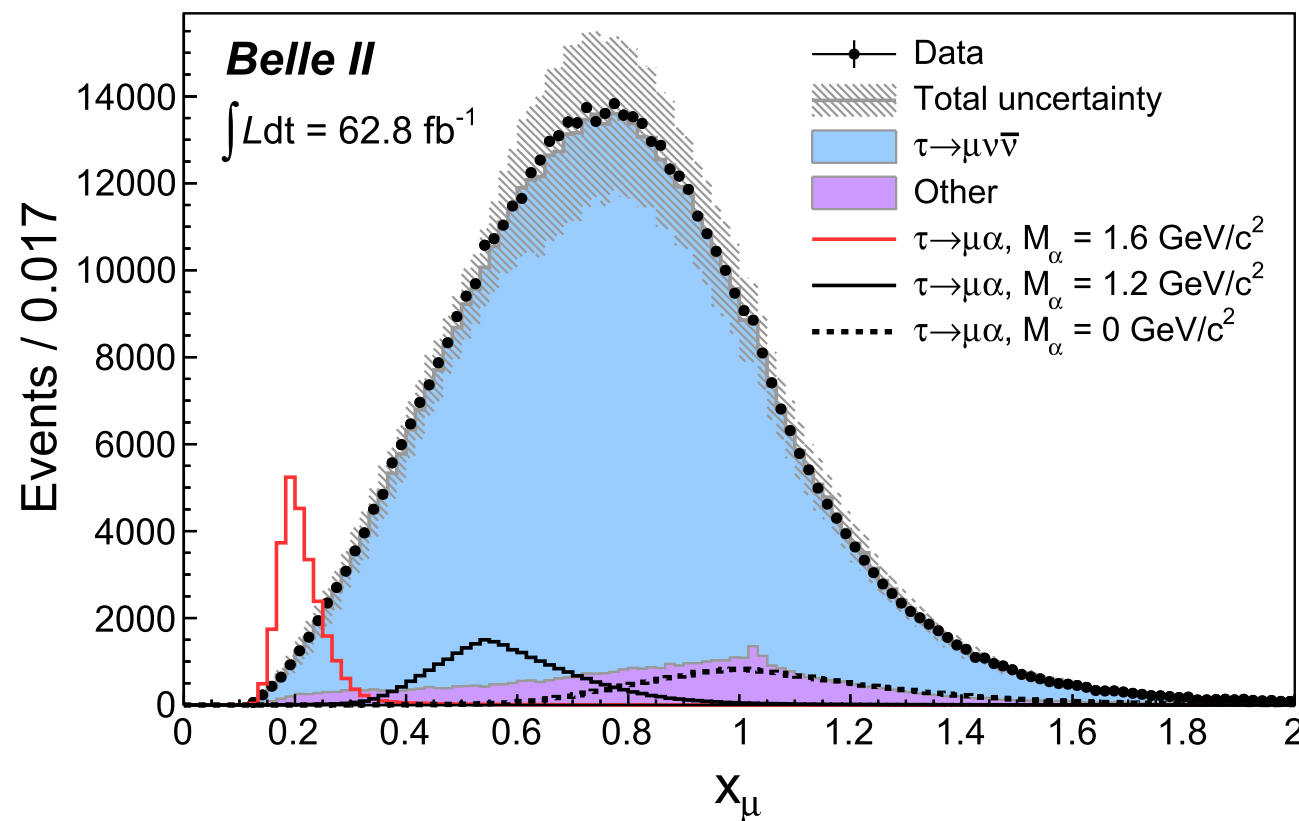
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~2-3%



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