Long live the heavy ALP!

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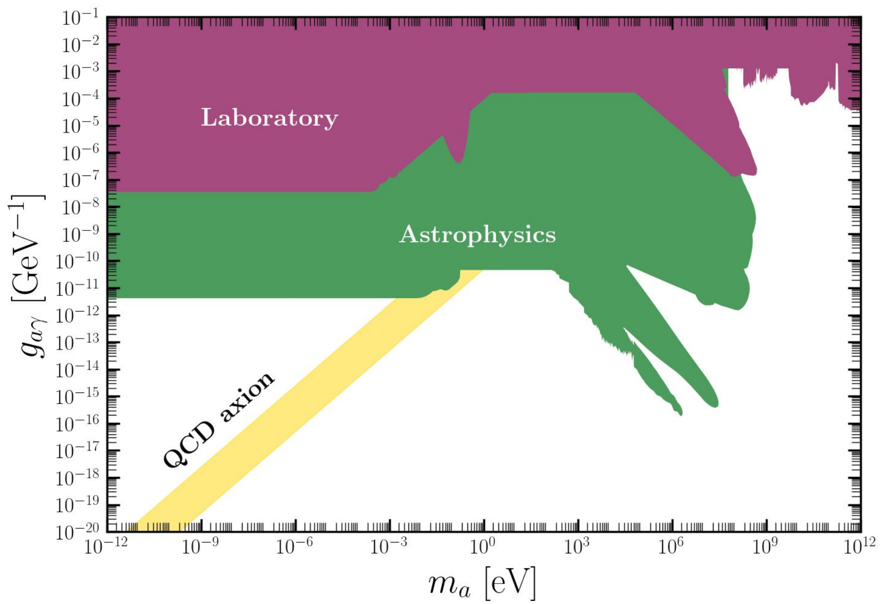
UAM

Motivation

Strong CP problem

Most elegant solution: **QCD axion** [R.D. Peccei, H. R. Quinn, Phys. Rev. D, vol. 16. pp. 1791-1797, 1977]

From SSB of $U(1)_{PQ}$ a pNGB arises with mass generated dynamically from QCD sector, bounded to $m_a f_a \cong m_\pi f_\pi$



In general: $g_{a\gamma} \propto \frac{1}{f_a}$

For $f_a > f_\pi$ is guaranteed $m_a < f_a$ in the band

Outside? Still QCD axion?

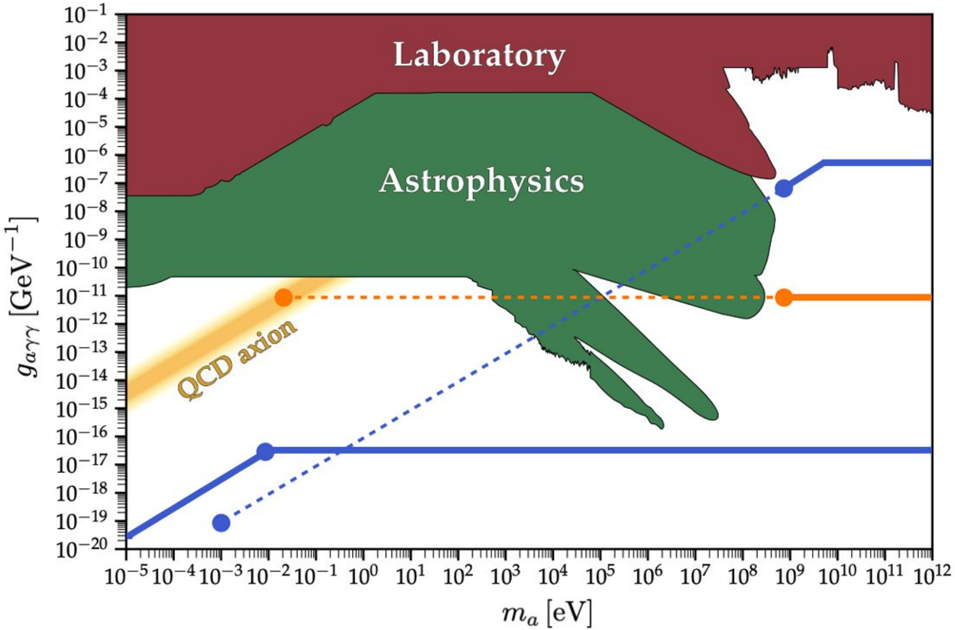
[C. O'Hare, cajohare.github.io/AxionLimits, July 2020]

Motivation

QCD axion besides $m_a f_a \cong m_\pi f_\pi$

Yes, there are non-canonical QCD axions allowed to not satisfy that relation:

Extra-dimensional Maxions: Axion field maximally mixing with *N* singlet scalars arising from extra dimensions.



Orange line: Canonical QCD axion where all but one modes are decoupled.

Blue line: Extra-dimensional QCD maxion, with no single axion close to canonical band.

[A. de Giorgi, M. Ramos, Phys. Rev. D 111 (2025) 7, 075006]

Motivation

Axion like particles (ALPs)

Yes, ALPs also can solve strong CP problem.

But what is an ALP?

- pNGB arising from the SSB of a **general** global symmetry with an **explicit** mass term.

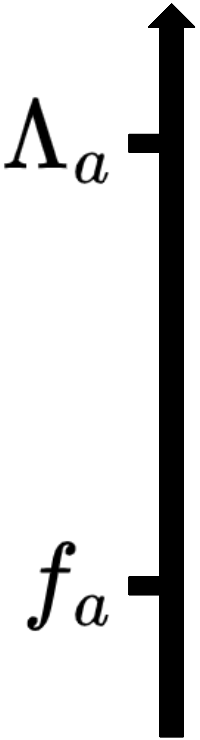
The dynamical contribution like in the QCD axion is **different** to the explicit term.

→ ALPs in general do **not** follow $m_a f_a \cong m_\pi f_\pi$

← Independent relation between m_a and f_a

Motivation

Axion like particles (ALPs)



Validity of the EFT beyond f_a

Effective Lagrangian with explicit mass: [H. Georgi, D. Kaplan, L. Randall, PLB 169B(1986)73]

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \frac{\partial_\mu a}{f_a} \sum_f \bar{f} \gamma^\mu \mathbf{c}_f f - \frac{a}{f_a} \sum_b c_b X^b_{\mu\nu} X^{\mu\nu,b}$$

Naive dimensional analysis: $\Lambda \leq 4\pi f_a$ [A. Manohar, H. Georgi, Nucl. Phys. B 234 (1984) 189-212]

Motivation

General BIAS towards $m_a < f_a$

ALP EFT valid up to $\Lambda_a \leq 4\pi f_a$

$m_a f_a \not\simeq m_\pi f_\pi$

Possible scenario where $f_a \leq m_a \leq \Lambda_a$?

YES

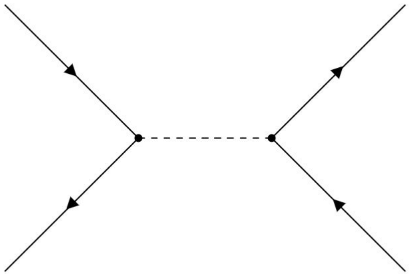
Well-known example: Chiral perturbation theory → $f_\pi < m_\pi < \Lambda_{\chi\mathrm{pt}}$

[S. Weinberg, Physica A96, 327 (1979)]

Procedure

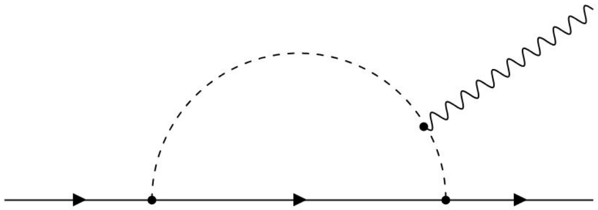
Does it have impact?

Two ways to test:



1) Clean observable in a 2-2 scattering for high energies

$$\frac{c}{f_a}$$



Clean 1-loop observable

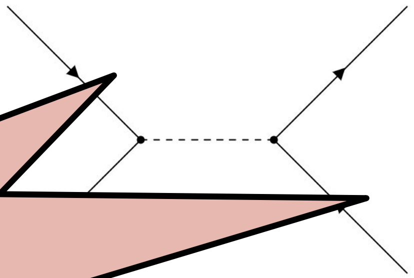
$$m_a$$

Procedure

Does it have impact?

Two ways to test:

1) Clean observa… a 2-2 sca… ies



Not enough precision!

…o obser…

m_a

Procedure

Does it have impact?

Two ways to test:

2) Available parameter space for 5 clean and very precise lepton observables

Obs.	Exp.	SM contribution
$(g-2)_e$	$a_e^{\text{exp}} = 0.00115965218062(12)$ [1]	$a_e^{\text{SM-Rb}} = 0.001159652180252(95)$ [2]
$(g-2)_\mu$	$a_\mu^{\text{exp}} = 0.00116592059(22)$ [3]	$a_\mu^{\text{SM-Lattice}} = 0.00116592033(62)$ [4]
$\mu \to e\gamma$	$Br(\mu \to e\gamma) < 1.5 \cdot 10^{-13}$ (90% C.L) [5]	$< 10^{-54}$
$\mu \to 3e$	$Br(\mu \to 3e) < 1.0 \cdot 10^{-12}$ (90% C.L) [6]	
$\mu\, N \to e\, N$	$Br(\mu^- \text{Au} \to e^- \text{Au}) < 7 \cdot 10^{-13}$ (90% C.L) [7]	

Procedure

ALP-Lepton Lagrangian

$$\mathcal{L}_a \supset \mathcal{L}^l_{\partial a} = \frac{\partial_\mu a}{f_a}\left[\overline{L}'_L \gamma^\mu \mathbf{c}'_L L'_L + \overline{e}'_R \gamma^\mu \mathbf{c}'_e e'_R\right] \supset \mathcal{L}_{c.l} = \frac{\partial_\mu a}{f_a}\sum_{ij}\left[\overline{l_i}\gamma^\mu c_{ij} l_j\right]$$

UV model independent

Only consider the first two generations

$\mathbf{c}'_f$ are 2×2 matrix in flavour space and $c_{ij} = c^L_{ij} P_L + c^R_{ij} P_R$ for *i*, *j* electron and muon

Allowed both LFC and LFV couplings.

We also work in the range $m_a \gg m_\mu$

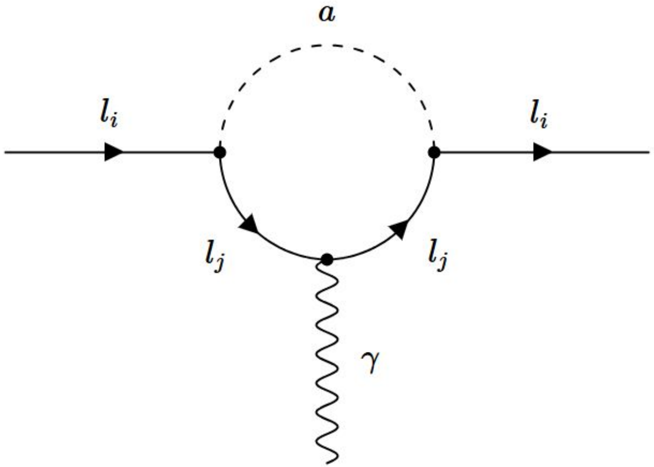
Processes

$(g-2)_i$

Up to one loop

Red: FV Blue: FC

Dependence:



$$a_e^{\mathrm{ALP}} \propto \frac{m_e m_\mu^3}{f_a^2 m_a^2} \mathrm{Re}[c_{e\mu}^L c_{\mu e}^R] \log\left(\frac{m_a^2}{m_\mu^2}\right)$$

$$a_\mu^{\mathrm{ALP}} \propto \frac{m_\mu^4}{f_a^2 m_a^2}\left[-(c_{\mu\mu}^L - c_{\mu\mu}^R)^2 \log\left(\frac{m_a^2}{m_\mu^2}\right) + (|c_{\mu e}^L|^2 + |c_{\mu e}^R|^2)\right]$$

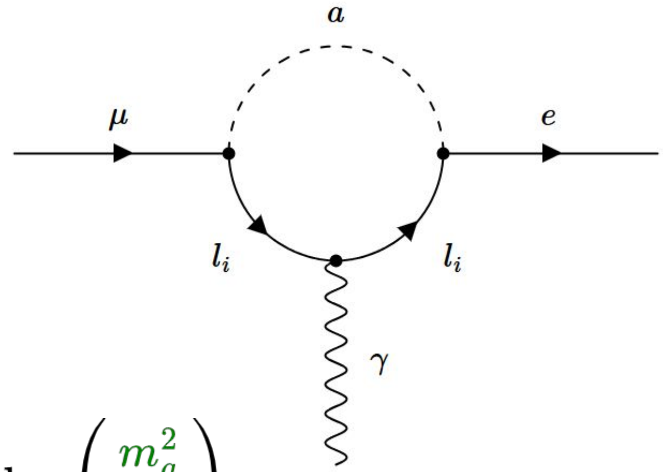
Processes

$\mu \to e\gamma$

Up to one loop

Red: FV Blue: FC

Dependence:



$$Br(\mu \to e\gamma) \propto \frac{\alpha_{\text{em}} m_\mu^2}{G_F^2 f_a^4 m_a^4} (c_{\mu\mu}^L - c_{\mu\mu}^R)^2 (|c_{\mu e}^L|^2 + |c_{\mu e}^R|^2) \log\left(\frac{m_a^2}{m_\mu^2}\right)$$

Processes

$$\mu\, N \to e\, N$$

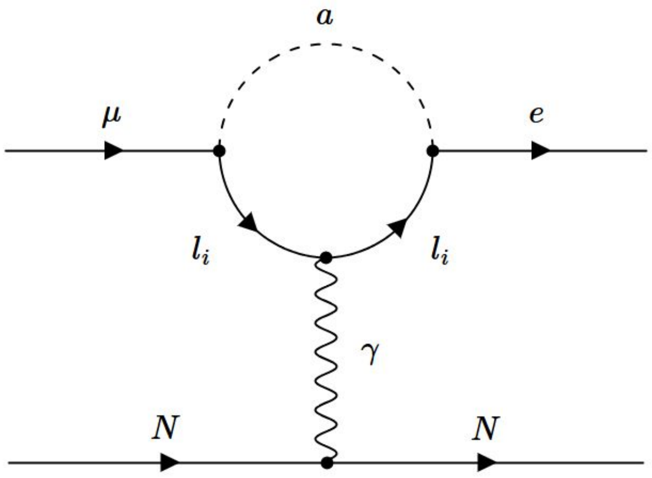
Up to one loop (2 more diagrams)

Red: FV Blue: FC

Dependence:

$$Br(\mu\, N \to e\, N) \propto \frac{m_\mu^8}{f_a^4 m_a^4} (c_{\mu\mu}^L - c_{\mu\mu}^R)^2 \log^2\left(\frac{m_a^2}{m_\mu^2}\right)$$

$$\times \left[a(|c_{\mu e}^L|^2 + |c_{\mu e}^R|^2) - b\,\mathrm{Re}[c_{e\mu}^L c_{\mu e}^R]\right]$$



Besides a prefactor accounting for *N*. Also: $a/b \sim 1$

Processes

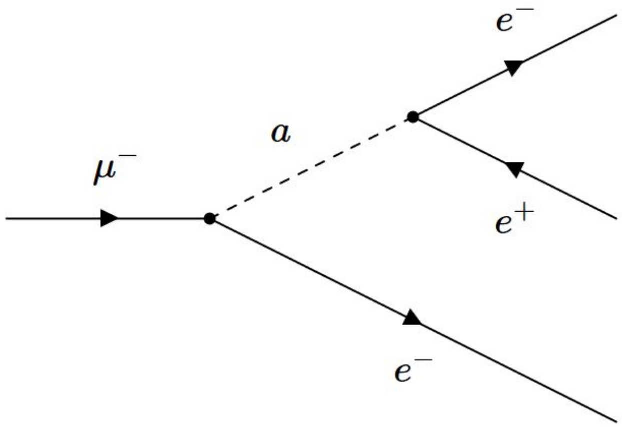
$\mu \to 3e$

Only tree level (1 more diagram)

Red: FV Blue: FC

Penguin diagram suppressed by α_{em}

Dependence:

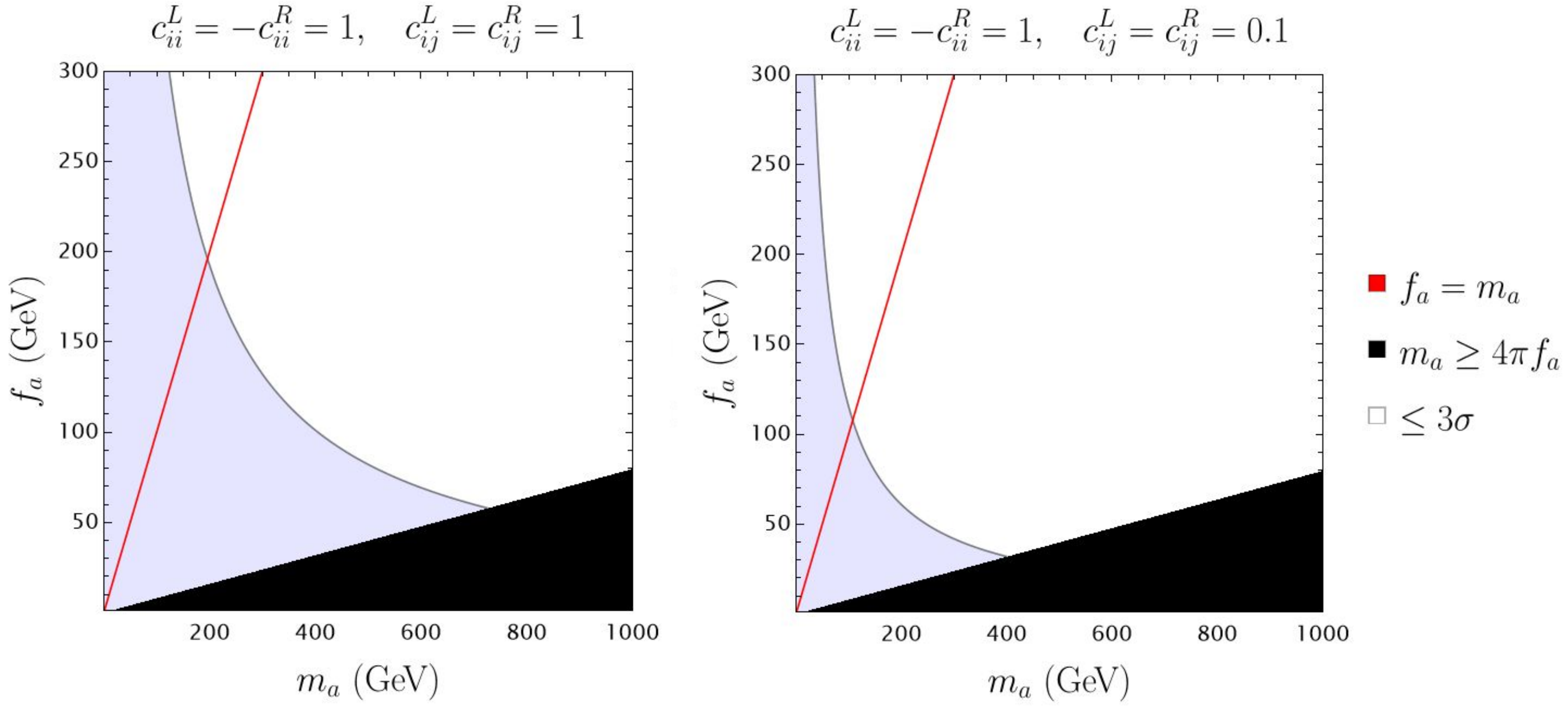


$$Br(\mu \to 3e) \propto \frac{m_e^2 m_\mu^2}{G_F^2 f_a^4 m_a^4} (c_{ee}^L - c_{ee}^R)^2 (|c_{\mu e}^L|^2 + |c_{\mu e}^R|^2)$$

Results

f_a vs m_a

Relevant process: $\mu \to e\gamma$



Results

f_a vs m_a

Future prospects for $\mu \to e\gamma$ and

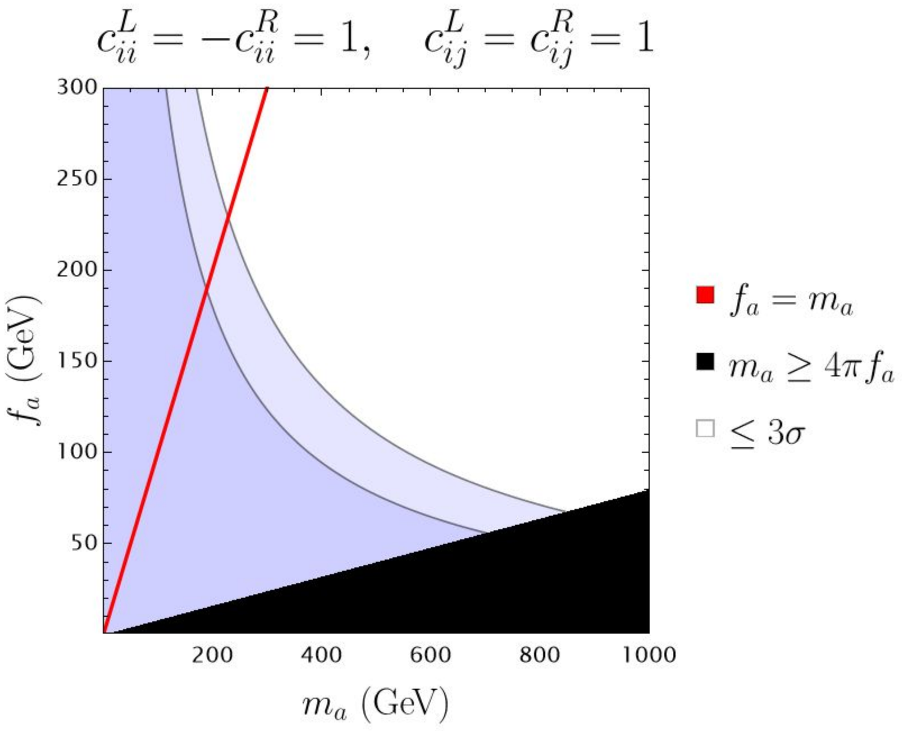
$\mu^- \mathrm{Al} \to e^- \mathrm{Al}$

$$Br(\mu \to e\gamma) < 6 \cdot 10^{-14} \text{ (90\% C.L)}$$

[K. Afanaciev et al., arXiv: 2504.15711]

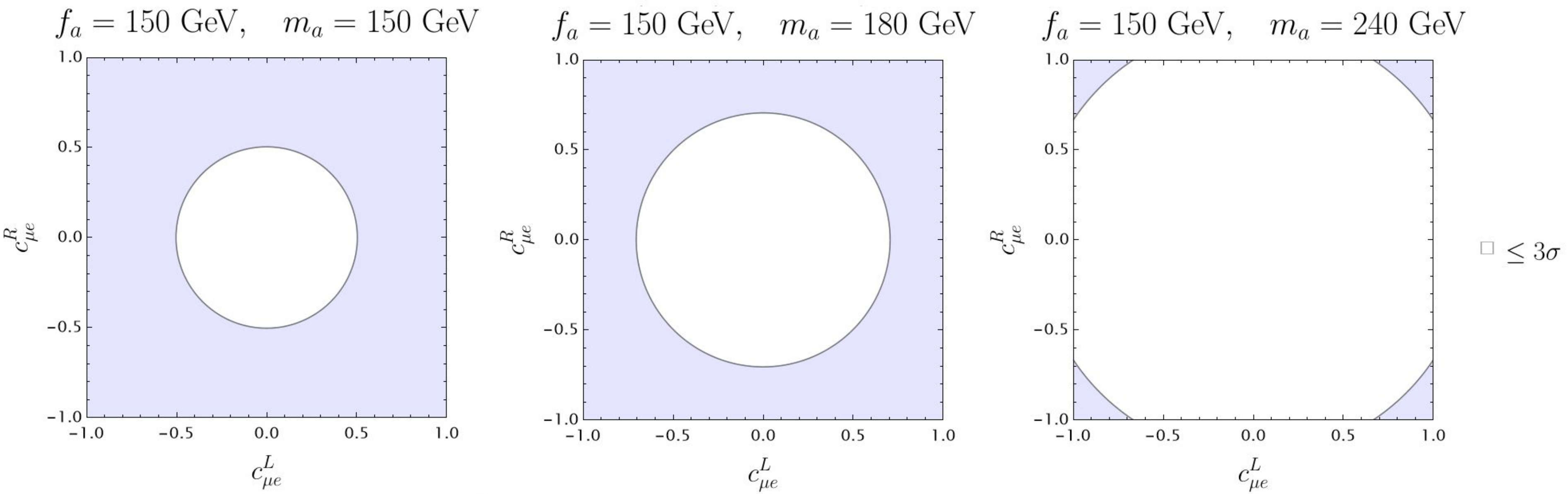
$$Br(\mu^- \mathrm{Al} \to e^- \mathrm{Al}) < 8 \cdot 10^{-17} \text{ (90\% C.L)}$$

[R. H. Bernstein, Front. in Phys. 7 (2019) 1]



Results

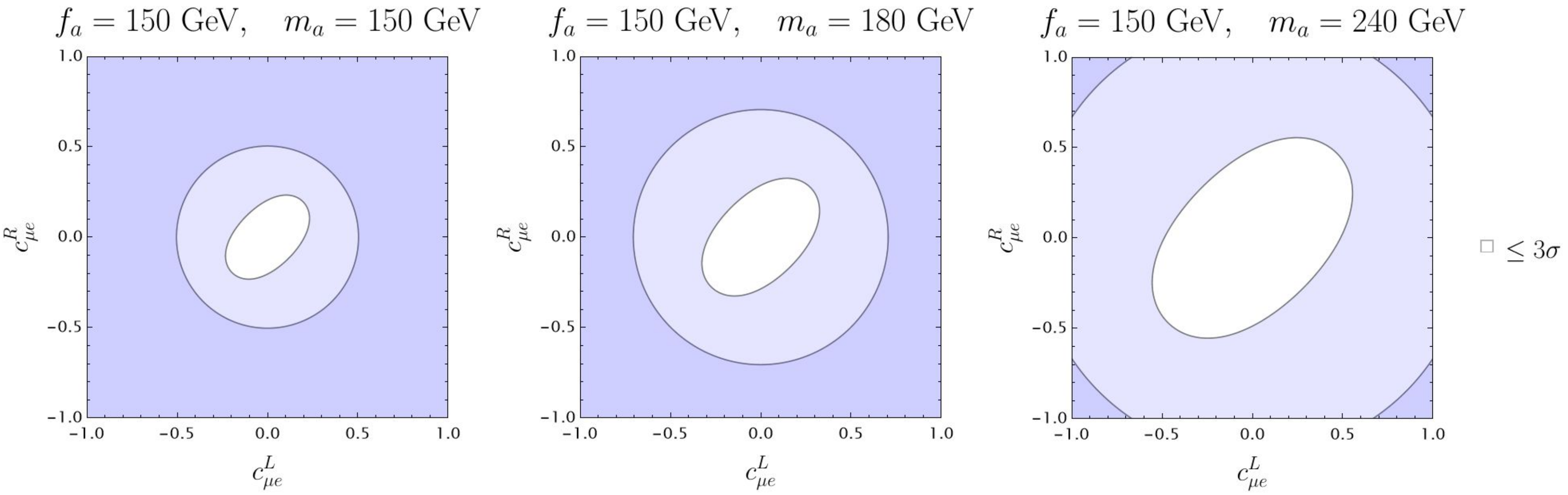
$$c^R_{\mu e} \text{ vs } c^L_{\mu e} \ , \quad c^L_{ii} = -c^R_{ii} = 1$$



Results

$$c^R_{\mu e} \text{ vs } c^L_{\mu e} \;, \quad c^L_{ii} = -c^R_{ii} = 1$$

For the previous future prospects:



Conclusions

- No reason to not consider $f_a \leq m_a \leq \Lambda_a$

- Maybe answers are hidden within that regime.

- The proof of concept depicted here can be translated to general EFT scenarios.

Thank you for your attention

References not shown:

[1] - [PDG]
[2] - [L. Morel et al., Nature 588 (2020) 7836, 61-65]
[3] - [D. P. Aguillard et al., Phys. Rev. D 110 (2024) 3, 032009]
[4] - [R. Aliberti et al., arXiv: 2002.12347]
[5] - [K. Afanaciev et al., arXiv: 2504.15711]
[6] - [U. Bellgardt et al., Nucl. Phys. B 299 (1988) 1-6]
[7] - [W. H. Bertl et al., Eur. Phys. J. C 47 (2006) 337-346]

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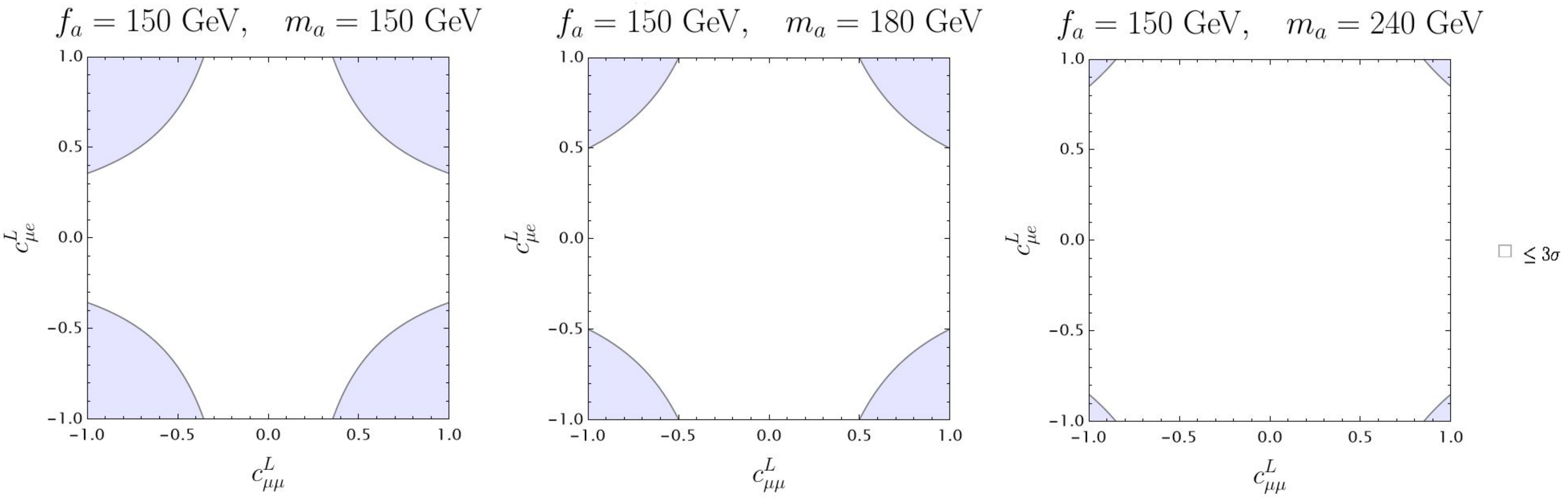
Parameter scan and fit

$c^L_{\mu e}$ vs $c^L_{\mu\mu}$



Parameter scan and fit

$$c^R_{\mu\mu} \text{ vs } c^L_{\mu\mu}\,, \quad c^L_{\mu e} = c^R_{\mu e} = 1$$