Flavour phenomenology of axion-like particles

Sophie Renner
University of Glasgow

Based on work with M. Bauer, M. Neubert, M. Schnubel and A. Thamm
1908.00008, 2012.12272, 2102.13112, 2110.10698

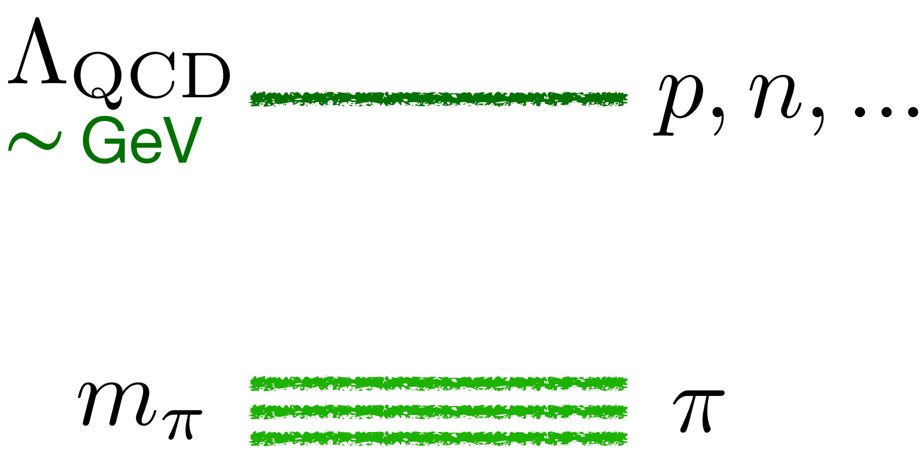
La Thuile 2022

Why axion like particles (ALPs)?

MODEL-BUILDING MOTIVATIONS:

Any dynamics with a spontaneously broken approximate global symmetry will produce light spinless particles

Analogy: QCD pions



Pions are pseudo goldstone bosons of an approximate spontaneously broken symmetry

BSM physics

ALP is a pseudo-goldstone boson

CP-odd gauge singlet

Mass much below scale of BSM physics

<u>Many motivated explicit models:</u> e.g. QCD axion, dark sector models, flavon models, composite Higgs models, ...

(see Adrian Carmona's talk)

Why ALPs? Motivations II

MODEL-INDEPENDENT MOTIVATIONS:

All new particles are heavy ($m \gg v$)? → SM EFT (or similar)

One or more light ($m \lesssim v$) BSM particles?

+ possibly higher spin...

spin 0

ALP
(Goldstone boson explains lightness)

spin 1/2

RH neutrino/heavy neutral lepton

spin 1

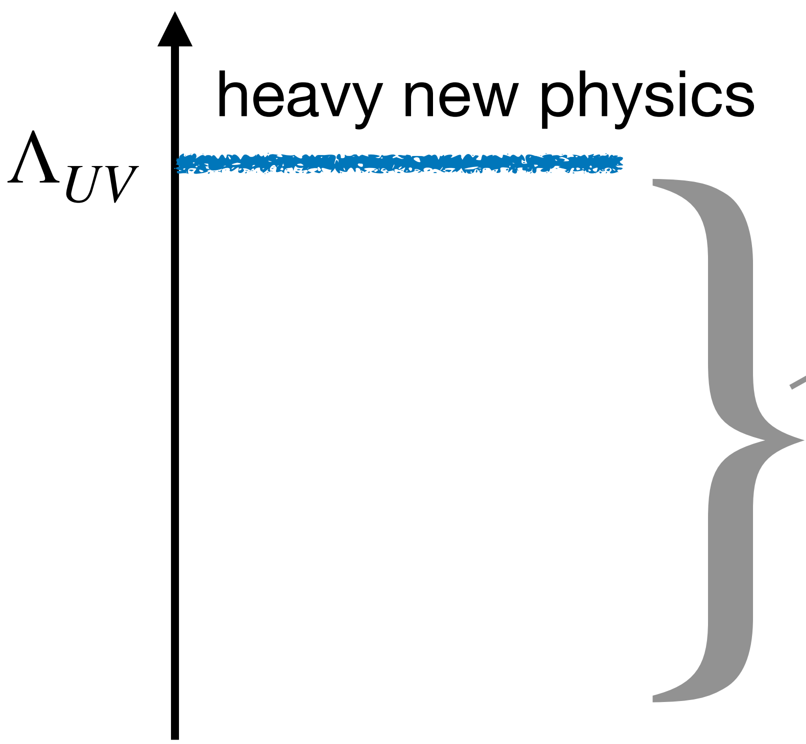
Dark photon/Z'

spin 3/2

e.g. gravitino/composite dark sector resonance

ALP effective Lagrangian

Don't need to know the details of the UV physics to study the ALP



Here particle content is SM+ALP

1) ALP is pseudoscalar under CP, and its interactions preserve CP

2) Invariant under ALP shift symmetry, $a \to a + \sigma$, broken only by ALP mass term

$F = Q, u, d, L, e$

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

$\Lambda_{UV} = 4\pi f$

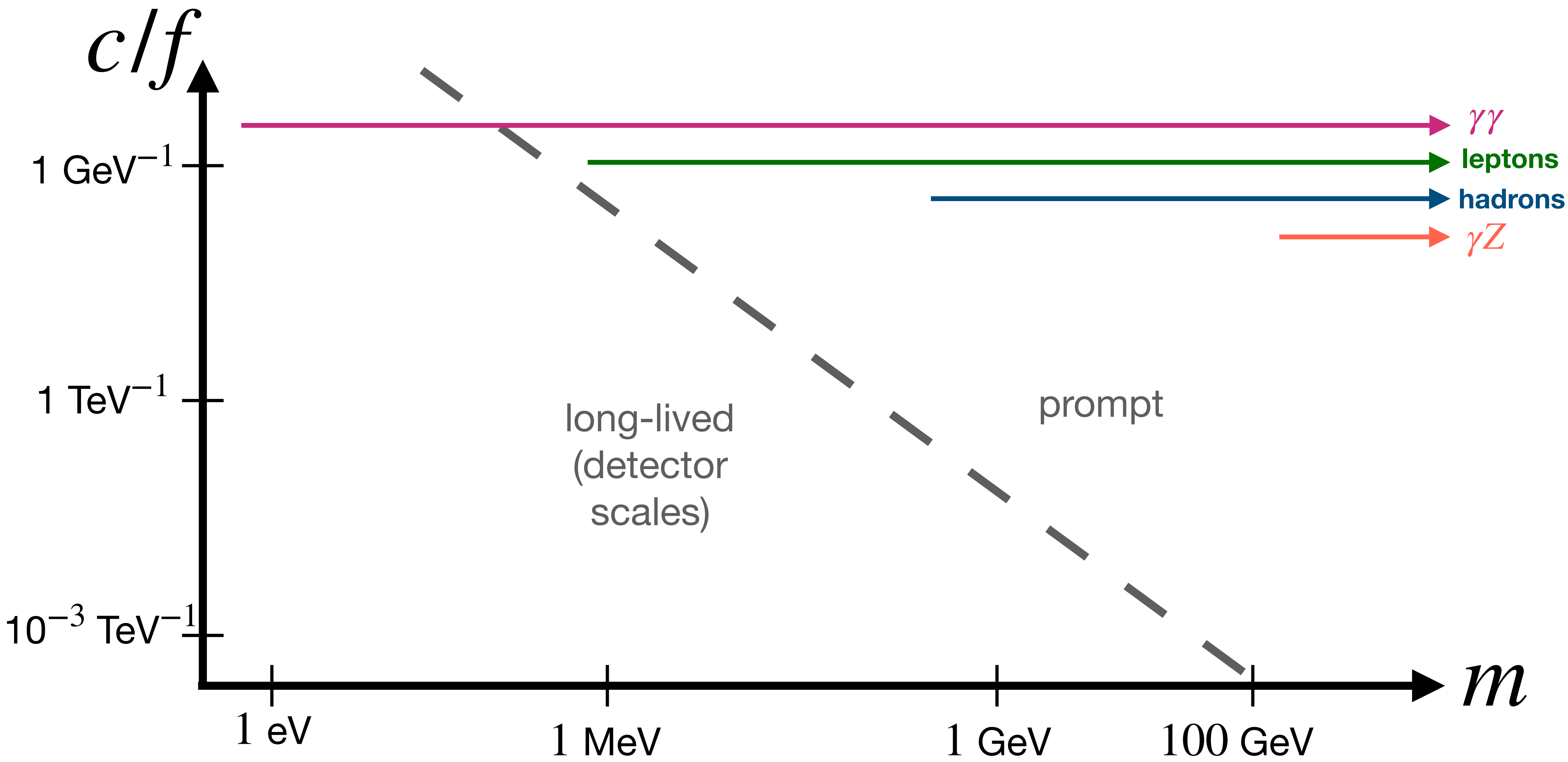
Then the parameter space of the model depends on $m_a, f, \mathbf{c}_F, c_{XX}$

hermitian matrices in flavour space

ALP pheno at a glance

All ALP interactions come with a factor of $1/f$, $\Longrightarrow$ *small couplings, long lifetimes*

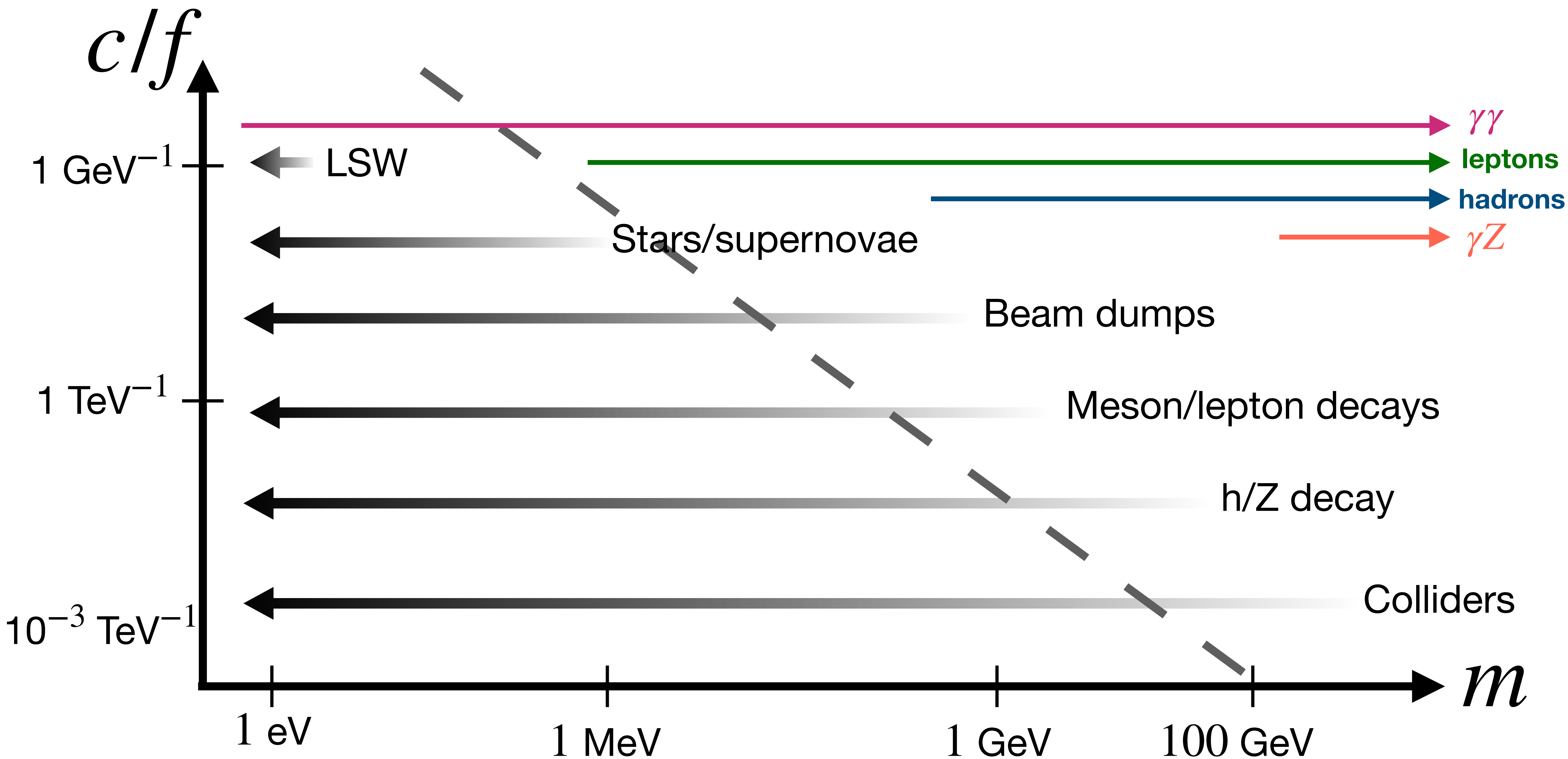
Decay modes & decay length depend on mass and coupling(s)



ALP pheno at a glance

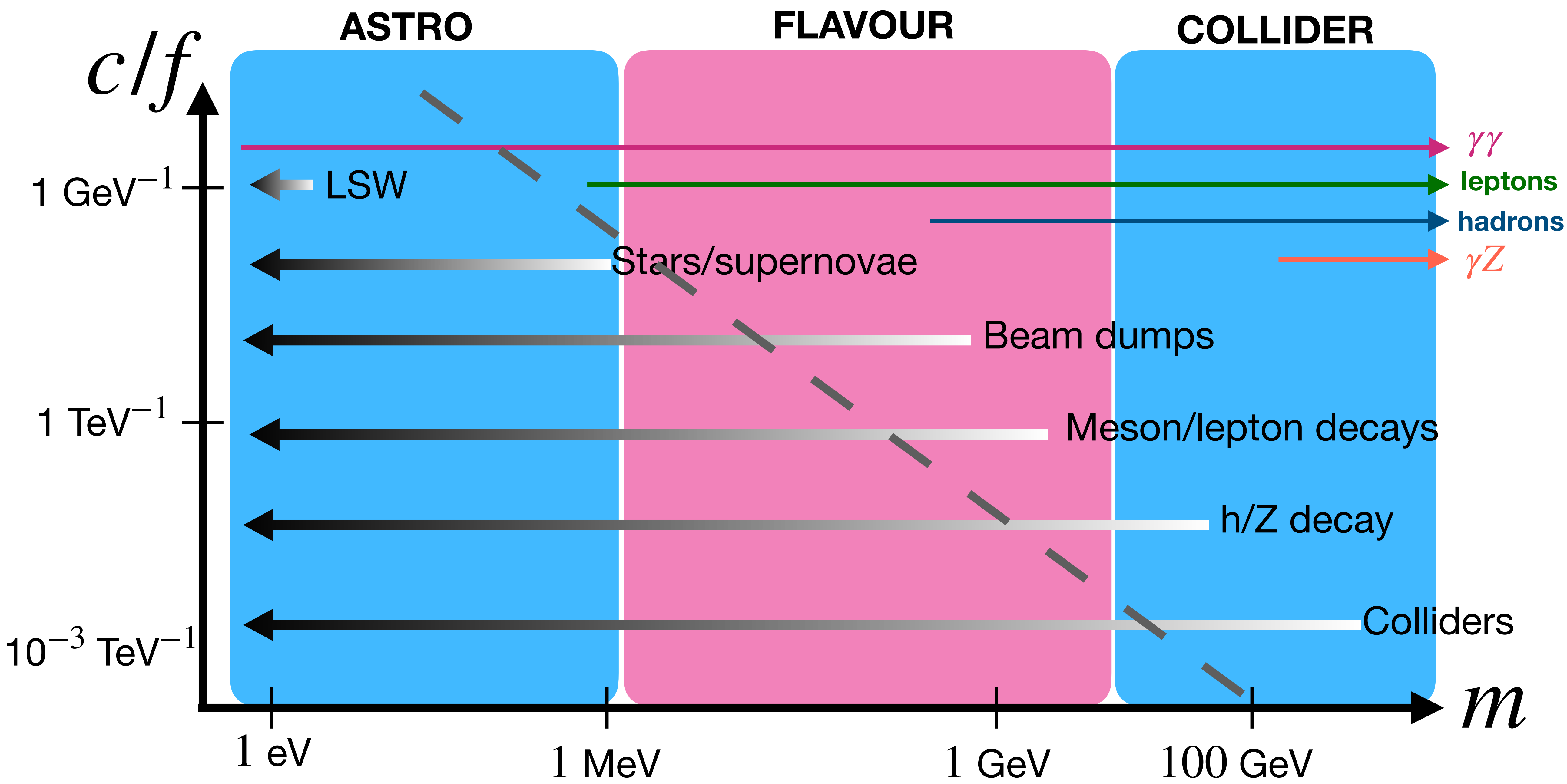
All ALP interactions come with a factor of $1/f$, $\Longrightarrow$ *small couplings, long lifetimes*

Production modes depend on mass

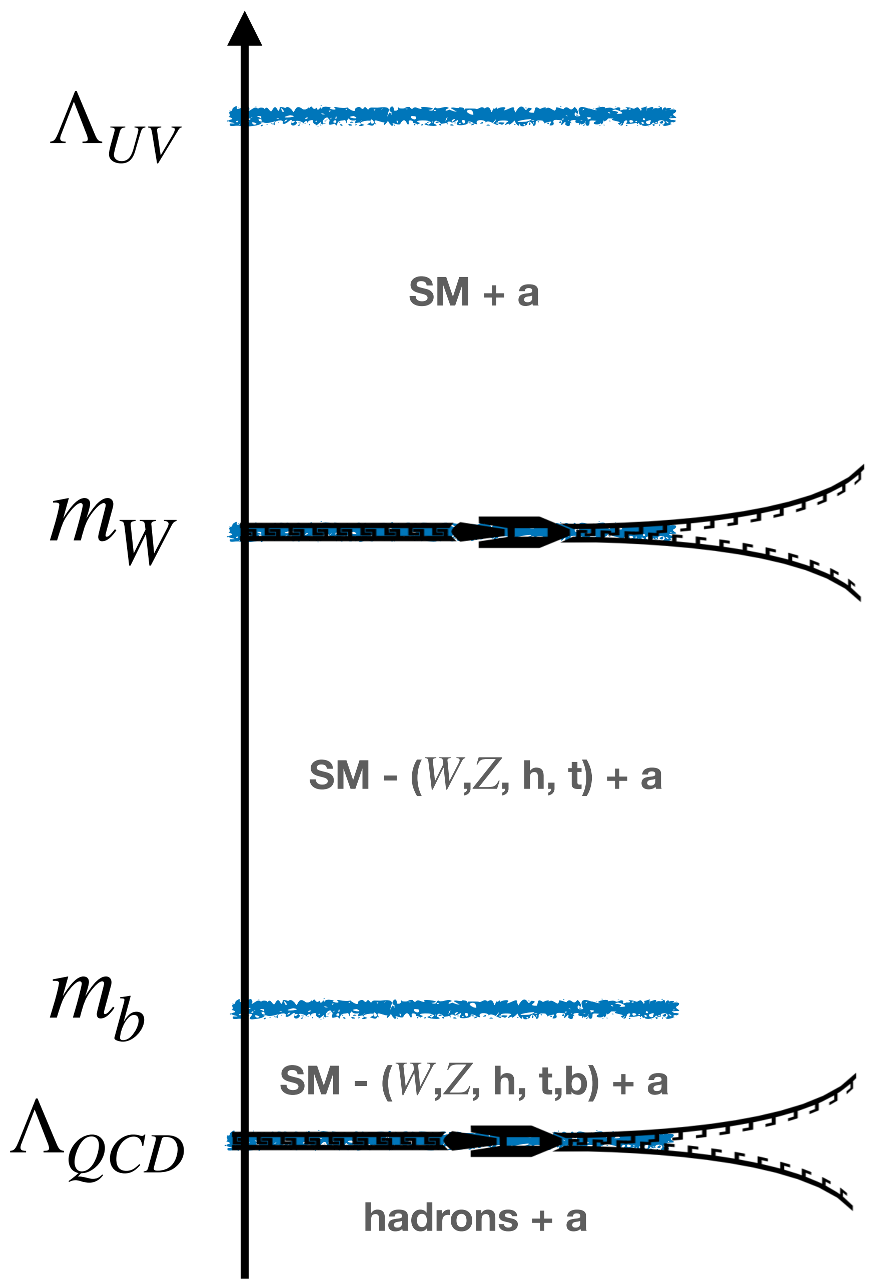


ALP pheno at a glance

Where can measurements of flavour-changing processes play a role?



From the EFT to observables



ALP couplings determined by physics at Λ_{UV}

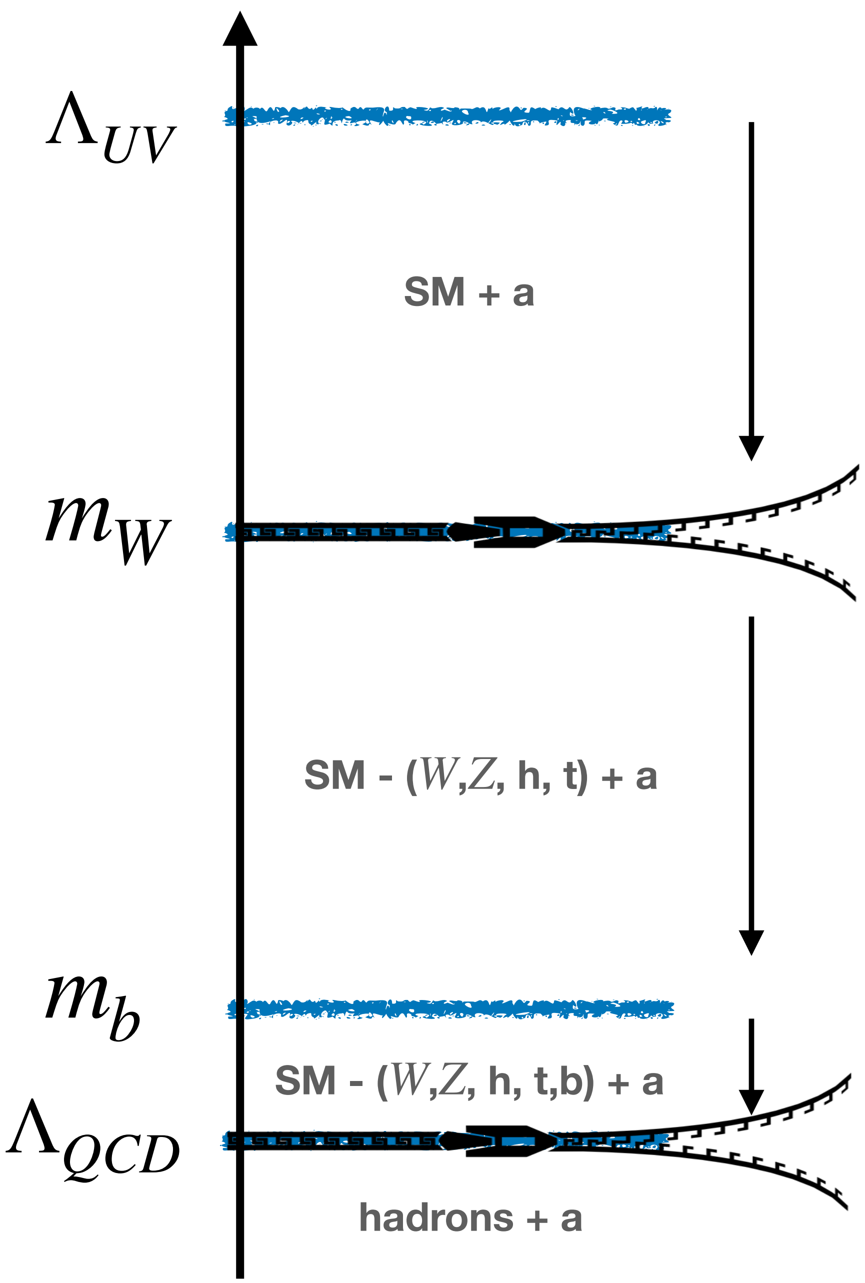
To make connection with observables, need to run and match to scale of measurement

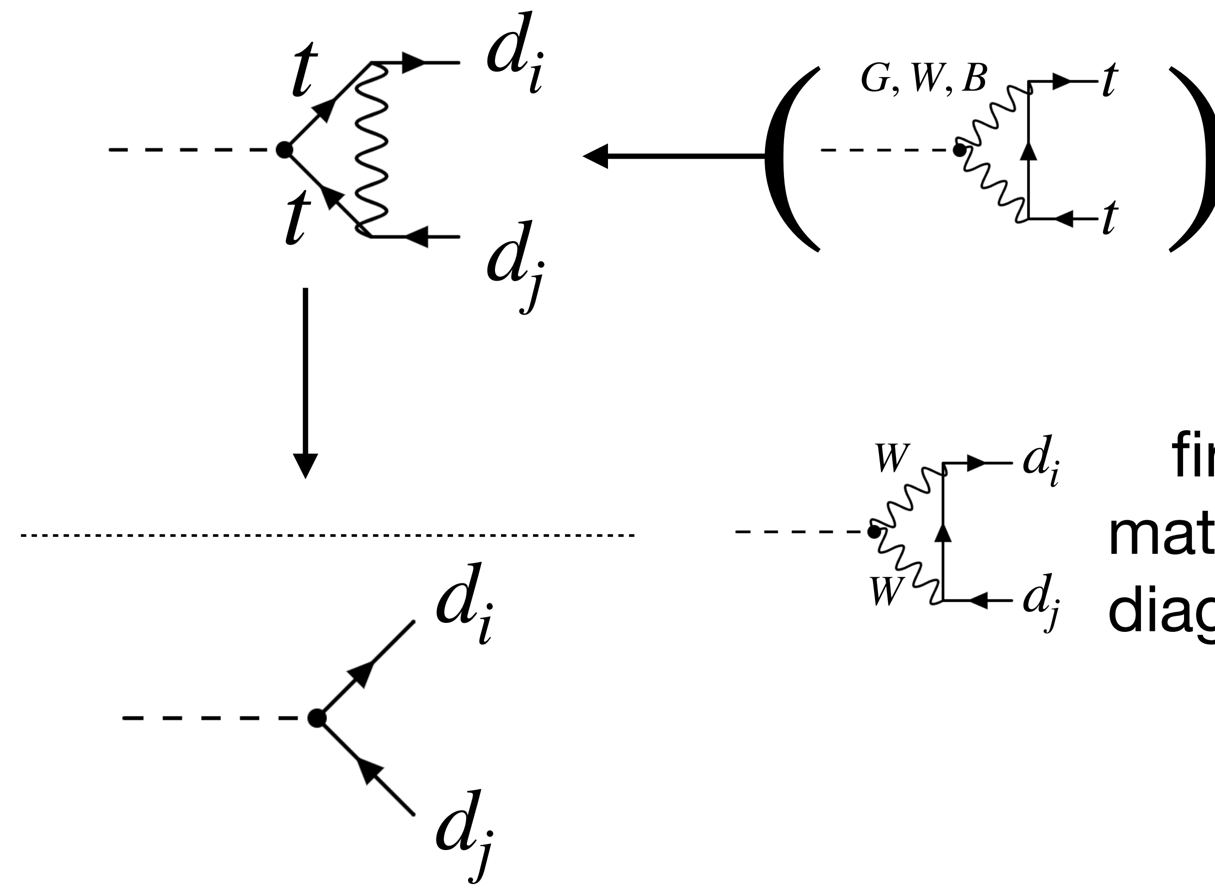
Flavour pheno: focus on ALPs in MeV-GeV mass range
(below an MeV already strongly constrained by astro/cosmology)

Choi, Im, Park, Yun, 1708.00021
Chala, Guedes, Ramos, Santiago 2012.09017
Bauer, Neubert, SR, Schnubel, Thamm, 2012.12272

Flavour effects

Inevitably generate quark flavour changing effects





finite matching diagrams

Starting from flavour universal couplings at $\Lambda = 4\pi$ TeV:

$$\boldsymbol{c}_F \equiv c_F \mathbb{1}$$

$$[k_D(m_t)]^{\rm univ}_{ij} \simeq 10^{-5}\, V^*_{ti}V_{tj}\Big[-6.1\,c_{GG} - 2.8\,c_{WW} - 0.02\,c_{BB} + 1.9\times 10^3\,c_u(\Lambda) - 9.2\,c_d(\Lambda) - 1.9\times 10^3\,c_Q(\Lambda) - 0.05\,c_e(\Lambda) + 4.2\,c_L(\Lambda)\Big]$$

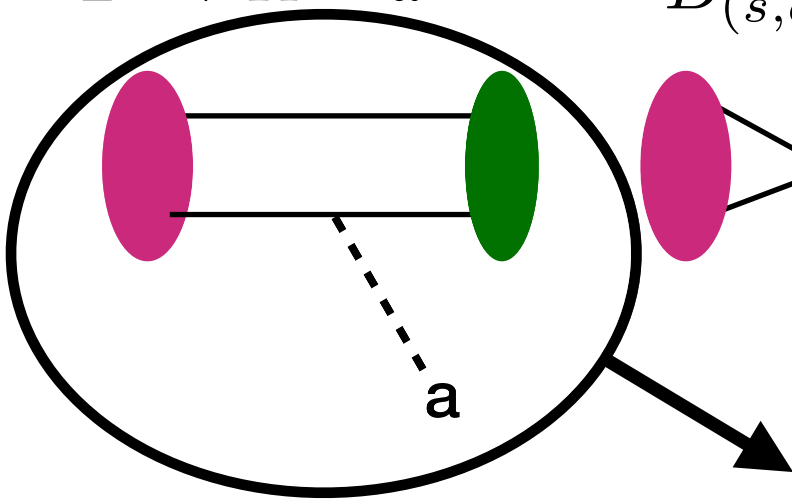
Largest effects for coupling to tops

ALPs in quark flavour processes

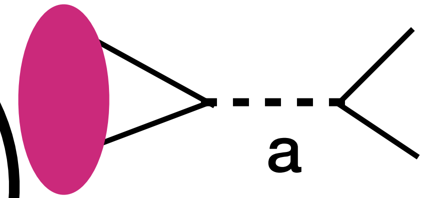
Meson decays

$K \to \pi a$

$B \to K^{(*)} a$

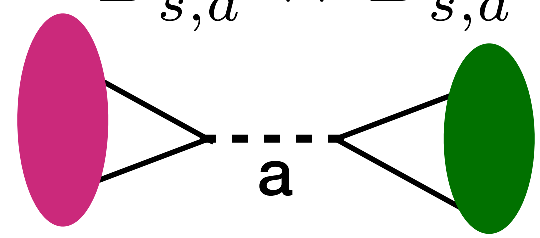


$B_{(s,d)} \to \mu\mu$



Meson mixing

$B^0_{s,d} \leftrightarrow \bar{B}^0_{s,d}$



On-shell signatures:

Long lived ALP: missing energy, monoenergetic final state meson/photon

Decaying ALP: narrow resonance in decay products

RG and matching calculations allow:

> calculate all observables in terms of fundamental lagrangian coeffs at high scale
> plot other constraints & regions of interest in same parameter space

Simplified scenario: coupling to SU(2) gauge bosons

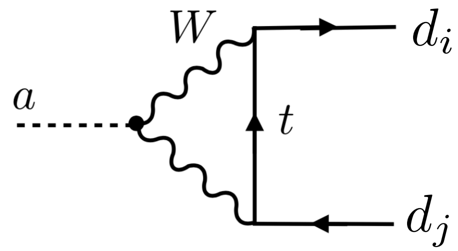
$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

high scale $\Lambda_{UV} = 4\pi$ TeV

Bauer, Neubert, SR, Schnubel, Thamm, 2110.10698

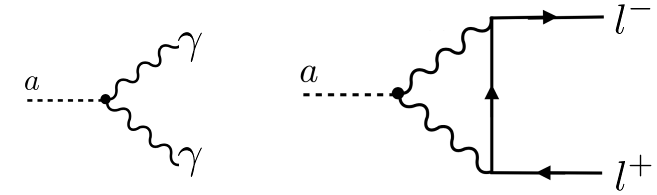
see also: Gavela, Houtz, Quilez, del Rey, Sumensari (2019)
Izaguirre, Lin, Shuve (2016); Gori, Perez, Tobioka (2020)

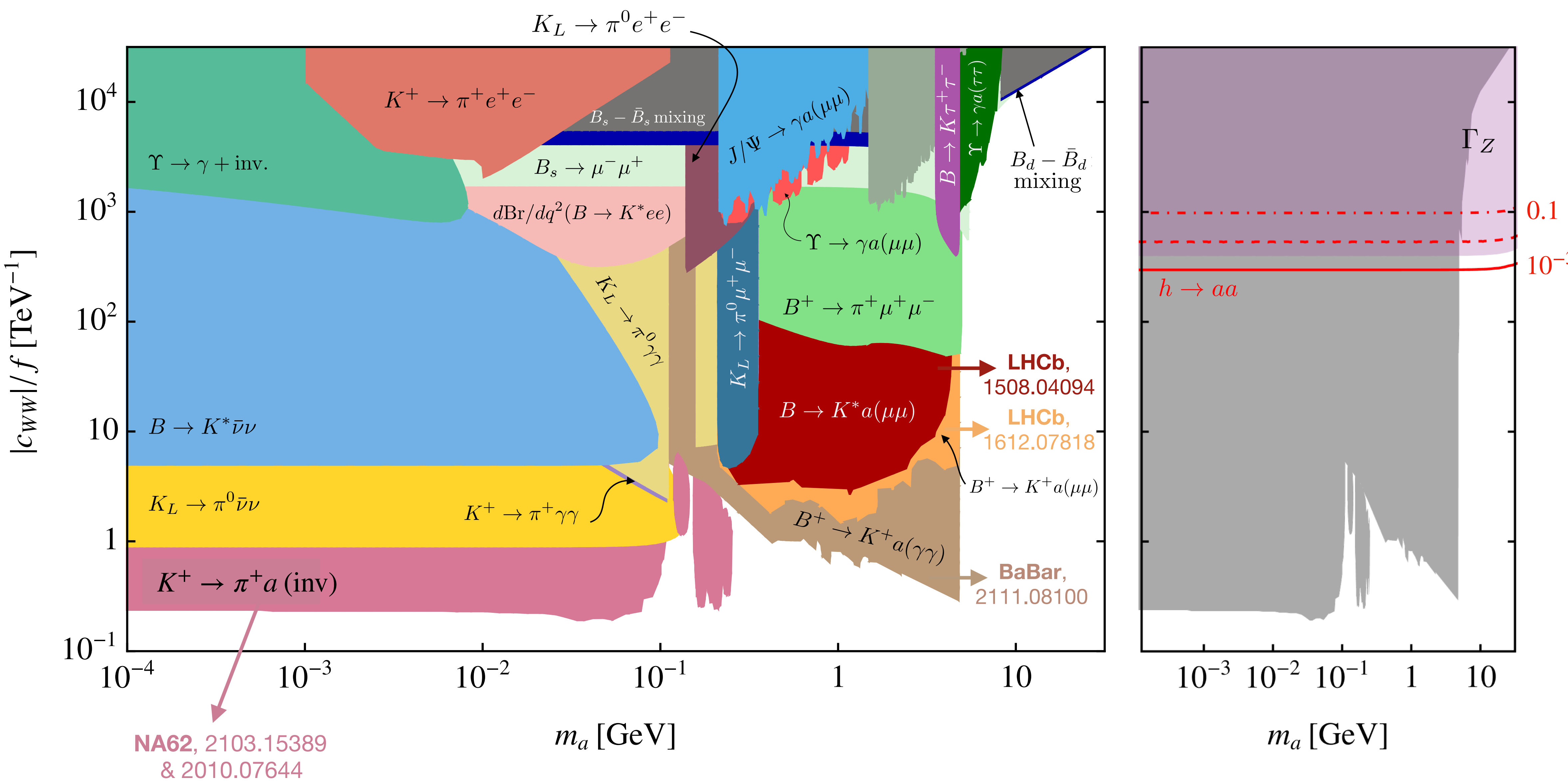
Flavour change:



Decays:

$$c_{\gamma\gamma} = c_{WW} + c_{BB}$$

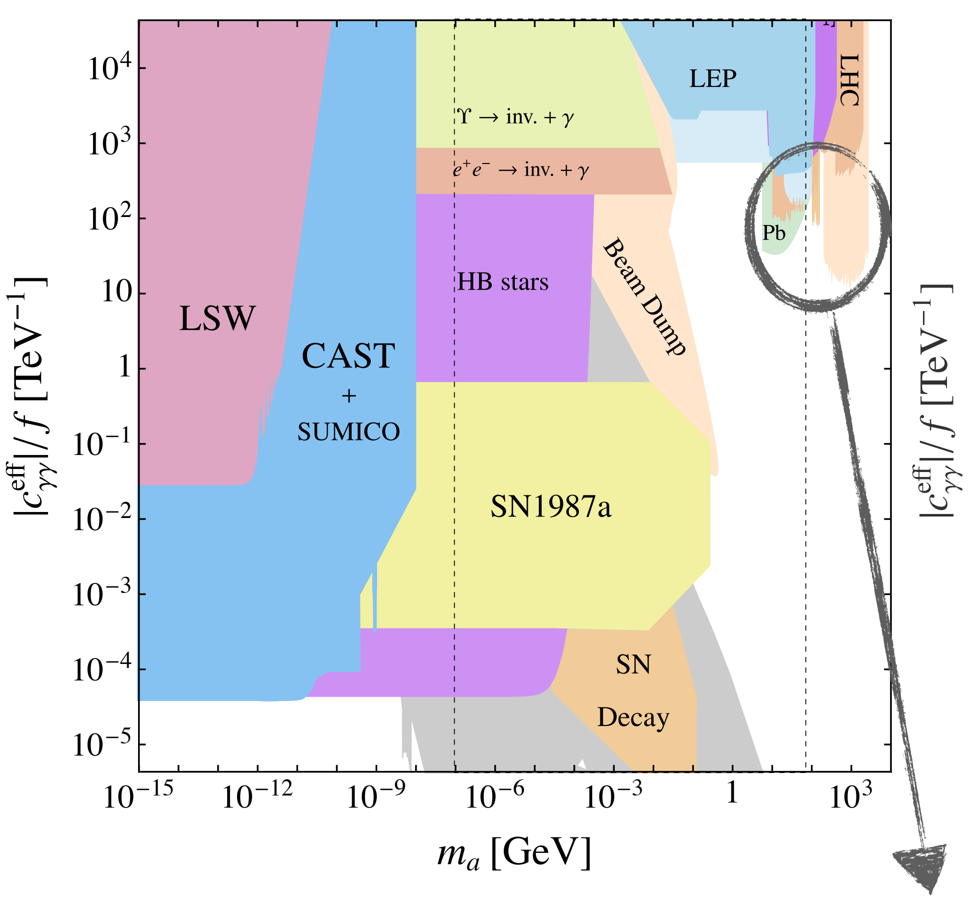




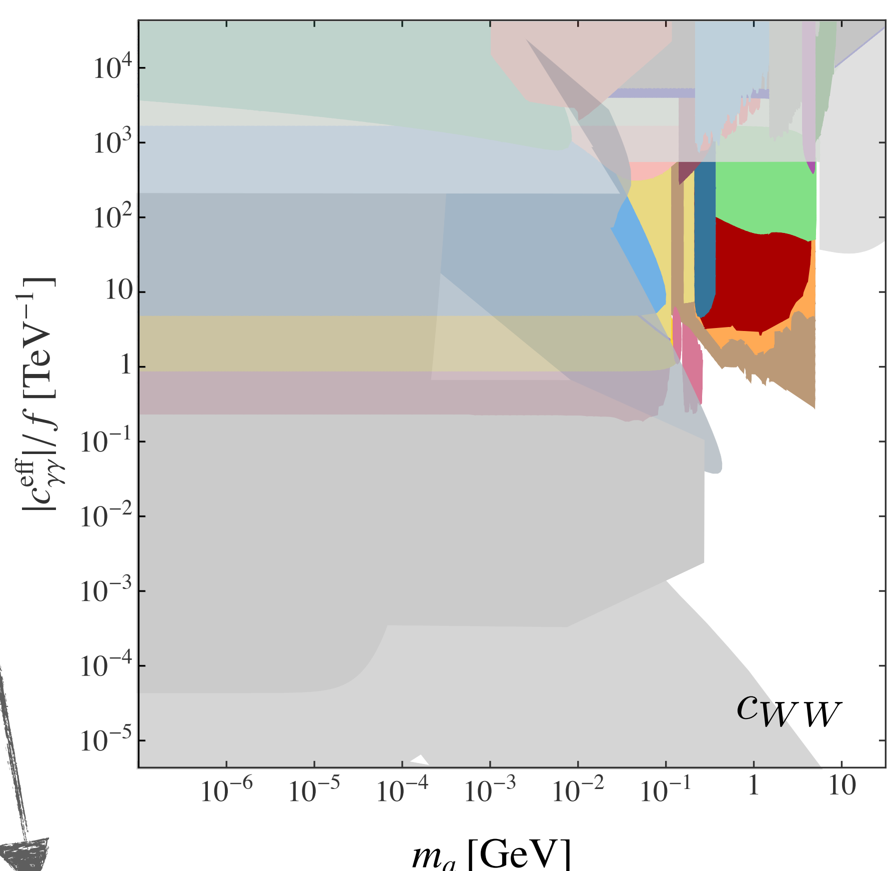
Comparison with photonic constraints

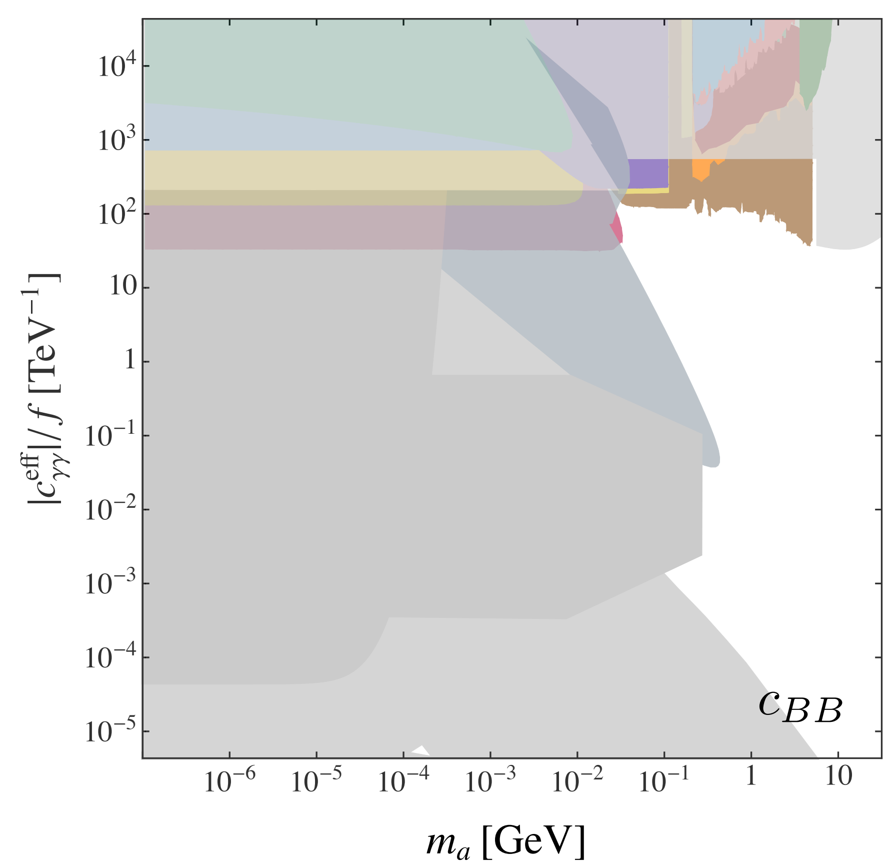
$$c_{\gamma\gamma} = c_{WW} + c_{BB}$$

Bauer, Neubert & Thamm, 1708.00443



Bauer, Neubert, SR, Schnubel, Thamm, 2110.10698





(NB new constraints in this region from ATLAS/CMS! See Mateusz Dyndal's talk)

What about leptons?

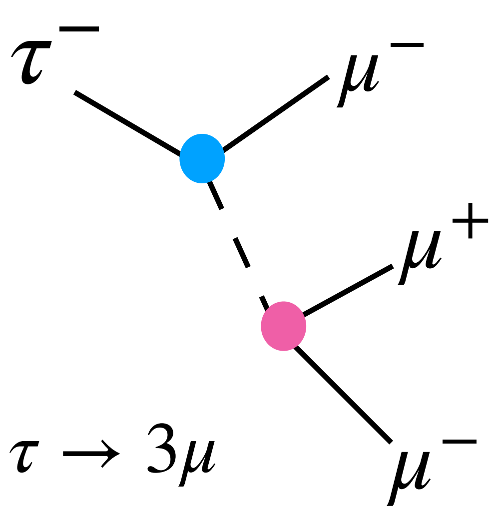
ALPs may also have lepton flavour violating (LFV) couplings

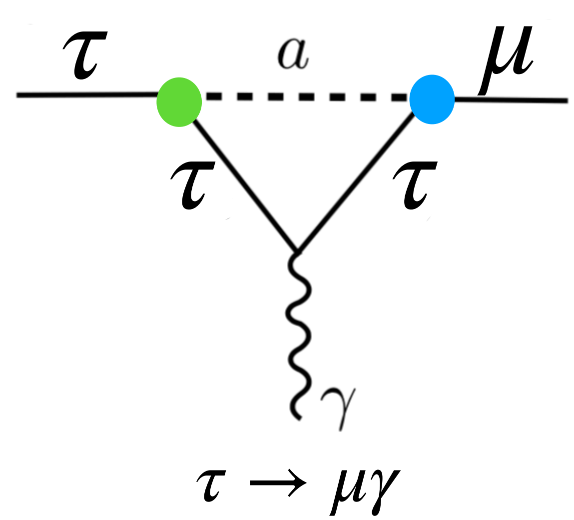
SM is lepton flavour conserving $\Longrightarrow$ unlike quark case, LFV cannot be created from RG alone

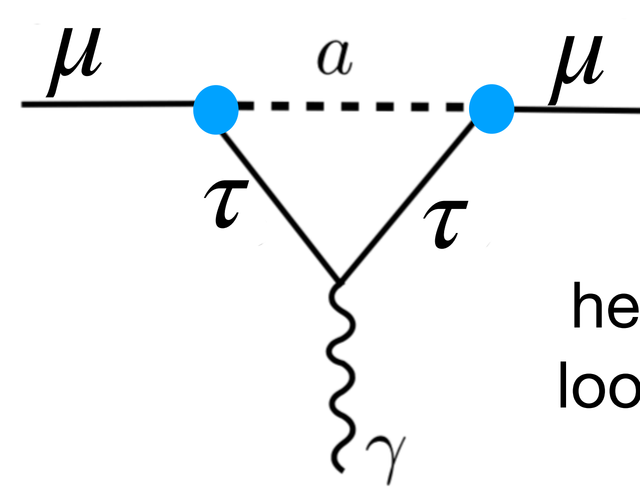
But there can still be *connections* between LFV and flavour conserving processes

e.g.

ALPs mediating $\tau \to \mu$ decays $\Longrightarrow$ **Contribution to $(g-2)_\mu$**







heavy τ in the loop enhances effect

LFV ALP can explain $(g-2)_\mu$ if $m_a > m_\tau$ and flavour *conserving* couplings are not too large

See Julie Pagès's talk for connections between (g-2) and LFV in models of heavy new physics

Summary

- Down-type quark flavour changing effects inevitably generated within ALP EFTs by running and matching

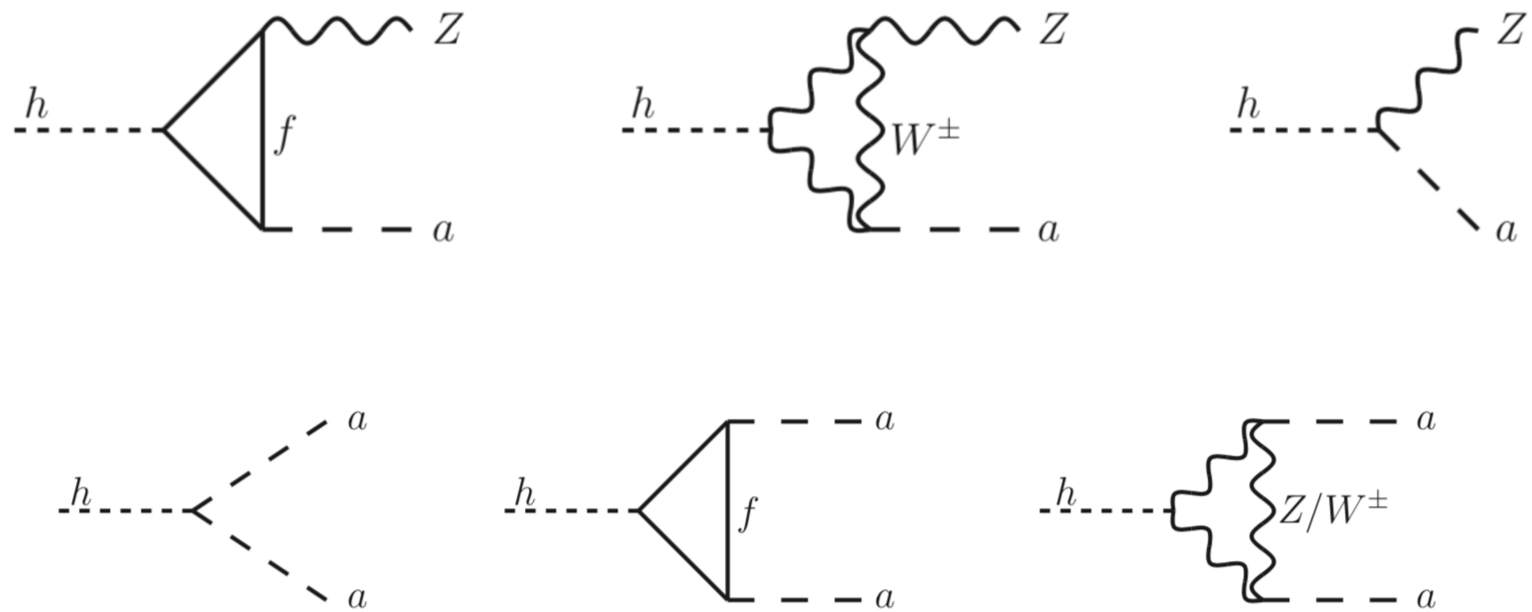
- Main signature: ALPs with mass below m_b can be produced directly in meson decays

- Often best place to look for ALPs in MeV-GeV mass range (between astrophysics and collider)

Backup

Higgs decays to ALPs

Bauer, Neubert & Thamm, 1708.00443



Limits depend strongly on decay modes of the ALP

e.g. for $h \to Za$ can apply limits from a dedicated $h \to \gamma\gamma + \gamma\gamma$ search

From FIPS2020 talk by Maria Cepeda:

Almost model independent BSM width < 0.34

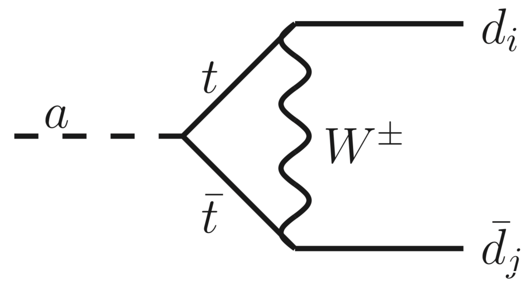
Invisible width < 19%

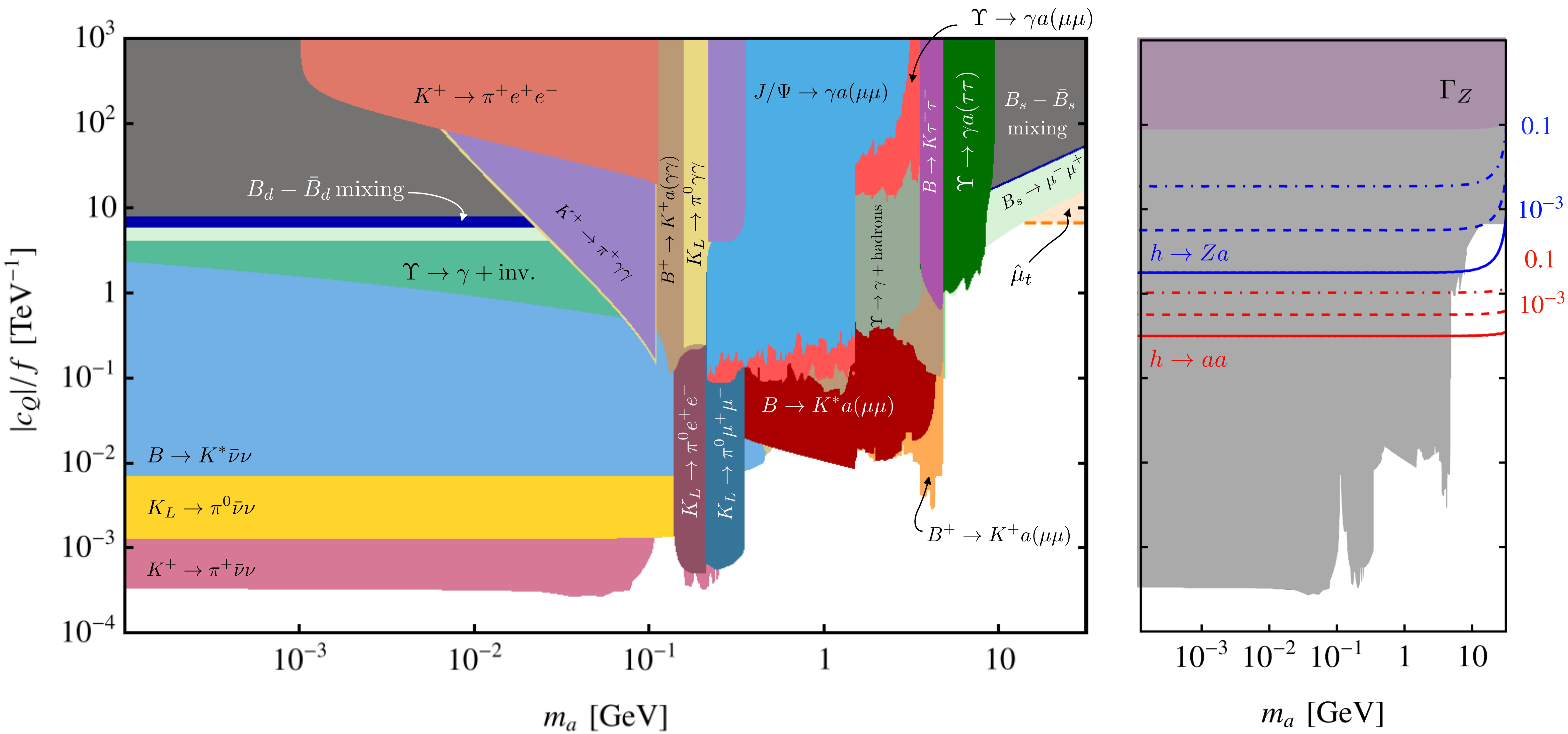
$$\Gamma_H = \frac{\Gamma_H^{SM} \cdot \kappa_H^2}{1 - BR_{BSM}}$$

> Warning: no direct measurement of the width. To probe the BSM BR an additional constrain needs to be imposed. Usually, $\kappa_{W,Z} \leq 1$.

Simplified scenario: coupling to LH quark doublet

Flavour change:





1 loop RG above EW scale

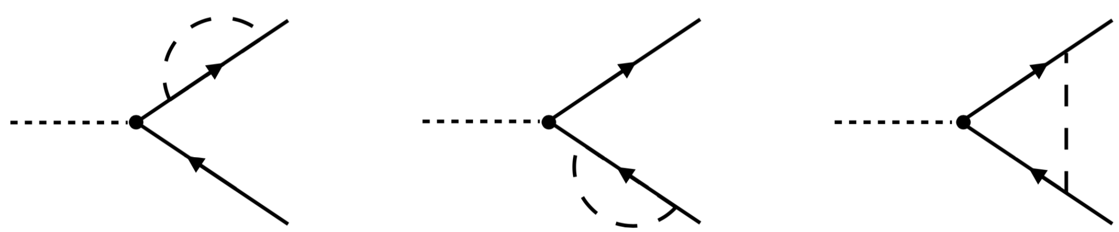
No running for gauge couplings

$$\frac{d}{d\ln\mu}\, c_{VV}(\mu) = 0\,; \quad V = G, W, B$$

Chetyrkin, Kniehl, Steinhauser, Bardeen 1998

Fermion couplings:

Yukawa interactions

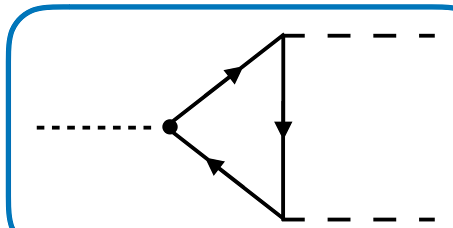


$$\tilde{c}_{GG} = c_{GG} + T_F\, \mathrm{Tr}\,(\boldsymbol{c}_u + \boldsymbol{c}_d - N_L\, \boldsymbol{c}_Q)\,,$$

$$\tilde{c}_{WW} = c_{WW} - T_F\, \mathrm{Tr}\,(N_c\, \boldsymbol{c}_Q + \boldsymbol{c}_L)\,,$$

$$\tilde{c}_{BB} = c_{BB} + \mathrm{Tr}\left[N_c\left(\mathcal{Y}_u^2\, \boldsymbol{c}_u + \mathcal{Y}_d^2\, \boldsymbol{c}_d - N_L\, \mathcal{Y}_Q^2\, \boldsymbol{c}_Q\right) + \mathcal{Y}_e^2\, \boldsymbol{c}_e - N_L\, \mathcal{Y}_L^2\, \boldsymbol{c}_L\right]$$

Gauge interactions



2 loop diagram included because it can be of the same order as the 1 loop diagram

$$c_{GG}\, \frac{\alpha_s}{4\pi}\, \frac{a}{f}\, G^a_{\mu\nu}\, \tilde{G}^{\mu\nu,a}$$

$$\tilde{c}_{GG} = c_{GG} + \frac{1}{2}\, \mathrm{Tr}\,(\boldsymbol{c}_u + \boldsymbol{c}_d - 2\boldsymbol{c}_Q)$$

$$\frac{d}{d\ln\mu}\, \boldsymbol{c}_Q(\mu) = \frac{1}{32\pi^2}\left\{\boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger + \boldsymbol{Y}_d \boldsymbol{Y}_d^\dagger, \boldsymbol{c}_Q\right\} - \frac{1}{16\pi^2}\left(\boldsymbol{Y}_u\, \boldsymbol{c}_u \boldsymbol{Y}_u^\dagger + \boldsymbol{Y}_d\, \boldsymbol{c}_d \boldsymbol{Y}_d^\dagger\right)$$
$$+ \left[\frac{\beta_Q}{8\pi^2}\, X - \frac{3\alpha_s^2}{4\pi^2}\, C_F^{(3)}\, \tilde{c}_{GG} - \frac{3\alpha_2^2}{4\pi^2}\, C_F^{(2)}\, \tilde{c}_{WW} - \frac{3\alpha_1^2}{4\pi^2}\, \mathcal{Y}_Q^2\, \tilde{c}_{BB}\right] \mathbb{1}\,,$$

$q = u, d$

$$\frac{d}{d\ln\mu}\, \boldsymbol{c}_q(\mu) = \frac{1}{16\pi^2}\left\{\boldsymbol{Y}_q^\dagger \boldsymbol{Y}_q, \boldsymbol{c}_q\right\} - \frac{1}{8\pi^2}\, \boldsymbol{Y}_q^\dagger\, \boldsymbol{c}_Q \boldsymbol{Y}_q + \left[\frac{\beta_q}{8\pi^2}\, X + \frac{3\alpha_s^2}{4\pi^2}\, C_F^{(3)}\, \tilde{c}_{GG} + \frac{3\alpha_1^2}{4\pi^2}\, \mathcal{Y}_q^2\, \tilde{c}_{BB}\right] \mathbb{1}$$

$$X = \mathrm{Tr}\left[3\boldsymbol{c}_Q\left(\boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger - \boldsymbol{Y}_d \boldsymbol{Y}_d^\dagger\right) - 3\boldsymbol{c}_u \boldsymbol{Y}_u^\dagger \boldsymbol{Y}_u + 3\boldsymbol{c}_d \boldsymbol{Y}_d^\dagger \boldsymbol{Y}_d - \boldsymbol{c}_L \boldsymbol{Y}_e \boldsymbol{Y}_e^\dagger + \boldsymbol{c}_e \boldsymbol{Y}_e^\dagger \boldsymbol{Y}_e\right]$$

RGEs for the lepton couplings are highly analogous!

$(g\text{-}2)_\ell$ from an ALP: no flavour violation

Lagrangian

$$\mathcal{L}_{\rm eff} = c_{\ell_i\ell_i}\frac{\partial^\mu a}{f}\bar{\ell}_i\gamma_\mu\gamma_5\ell_i + c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

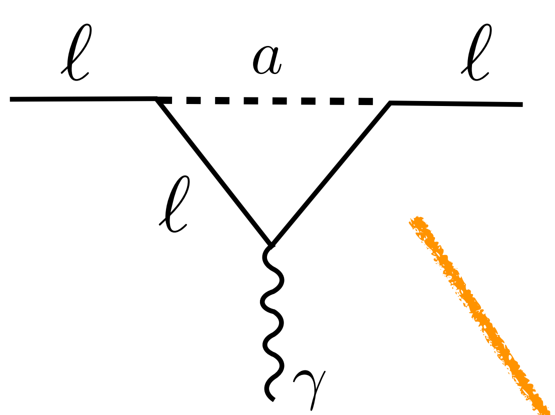
f=ALP decay constant, related to BSM scale ($\Lambda = 4\pi f$)

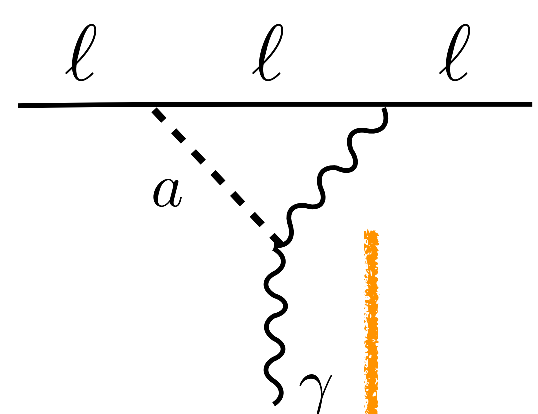
There are loop contributions to the photon coupling from light leptons:

Bauer, Neubert, Thamm JHEP 12 (2017) 044

$$c_{\gamma\gamma}^{\rm eff} = c_{\gamma\gamma} + \sum_i c_{\ell_i\ell_i}B_1(\tau_{\ell_i})$$

$$\tau_{\ell_i} = 4m_{\ell_i}^2/m_a^2 \qquad B_1(0) = 1$$





Marciano, Masiero, Paradisi, Passera PRD 94 (2016) 11
Bauer, Neubert, Thamm JHEP 12 (2017) 044

$$\Delta a_{\ell_i} = -\frac{m_{\ell_i}^2 c_{\ell_i\ell_i}^2}{16\pi^2 f^2}\left[h_1(x_i) + \frac{2\alpha}{\pi}\frac{c_{\gamma\gamma}^{\rm eff}}{c_{\ell_i\ell_i}}\left(\ln\frac{\Lambda^2}{m_{\ell_i}^2} - h_2(x_i)\right)\right] \qquad x_i = m_a^2/m_{\ell_i}^2$$

$$h_{1,2}(x_i) > 0$$

Loop functions are positive

$$\Delta a_\mu > 0 \implies \frac{c_{\gamma\gamma}^{\rm eff}}{c_{\mu\mu}} \ll 0$$

$$\Delta a_e < 0 \implies \frac{c_{\gamma\gamma}^{\rm eff}}{c_{ee}} > 0$$ or first diagram dominates