Axion-Like Particles at FCC

Jérémie Quevillon

CERN & LPSC

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Outline of this talk

1. Strong CP Puzzle & QCD axion

A soft introduction

2. Axion couplings to massive gauge bosons

Non-intuitive results in axion DFSZ-like scenario

3. Axion-Like Particle Effective Field Theories

Discussion on scenarios and useful benchmarks

4. ALPs at FCC-ee and FCC-hh

Some prospects

A shift of paradigm

- To solve: the hierarchy problem

concretely: why the gravitational force is so much weaker than the other fundamental interactions?

Main candidate,

Supersymmetry : -enlarges Poincaré algebra (new energy scale)

-needs many new particles

-can preserve SM gauge group

- To solve: the strong CP puzzle

concretely: why matter and not anti-matter in our universe?

Main candidate,

'Peccei-Quinn' theory : -enforces CP-symmetry

-needs a new global 'no symmetry'

(anomalous+spontaneously broken)

(new energy scale)

-entangled with SM gauge group :

(careful!)

$$[SU(3)_c \otimes SU(2)_L \otimes U(1)_Y]_{local} \times [U(1)_{\mathcal{B},\mathcal{L},PQ}]_{global}$$

the **QCD axion**: « new » Goldstone bosons combination $\perp Z_L$

The Strong CP Puzzle in particle physics

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q \underset{\text{CPV}}{e^{i\theta_{EW}}})q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - \theta_{QCD}\frac{\alpha_s}{8\pi}\underset{\text{CPV}}{G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}}$$

4-component Dirac field

$U(1)_A$ chiral transformation: $q \rightarrow e^{i\gamma^5\theta_{EW}}q$ anomalous symmetry

the measure of the path integral is not invariant under this transformation

axial anomaly shifts quark mass phase to QCD vacuum

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q)q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - (\overbrace{\theta_{QCD} - \underset{\neq 0}{\theta_{EW}}}^{\bar{\theta}})\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

Yukawa coupling to the Higgs are complex $\theta_{CKM} \neq 0$

Why is this strong CP-violation term so puzzling? $\mathcal{L}_{\cancel{CP}} = \bar{\theta}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$

this induces a huge electric dipole moment for the neutron:

Theory: $|d_n| \sim |\bar{\theta}|10^{-16}e.cm$ vs Experiment: $|d_n| \lesssim 10^{-26}e.cm$

→ $\bar{\theta} < 10^{-10}$

$$\boxed{\begin{array}{c}\text{The strong CP problem}\\ =\text{Why is } \bar{\theta} \text{ so small?}\end{array}}$$

The strong CP problem is really why the combination of QCD and EW parameters make up should be so small...

The Peccei-Quinn Axion Solution

axial anomaly: $\theta_{EW}^{\text{CPV}} \longleftrightarrow \theta_{QCD}^{\text{CPV}}$

Solution to the strong CP problem of QCD: add fields such that rotate $\bar{\theta}$ to the phase of a complex SM-singlet scalar who gets a VEV and dynamicaly drives $\bar{\theta} \to 0$ Peccei & Quinn

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q e^{i\theta_{EW}})q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - \theta_{QCD}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

1. Introduce a new global axial $U(1)_{PQ}$ symmetry S.B. at high scale
   $\longrightarrow$ the low-energy theory has a **Goldstone boson** (the **axion** field)

2. Design $\mathcal{L}_{axion}$ such that $Q(q_L) \neq Q(q_R)$ $\longrightarrow$ this makes the $U(1)_{PQ}$ **anomalous** :
   net effect: $\mathcal{L}_{axion} = \mathcal{L}_{QCD} + \frac{a}{v}G_{\mu\nu}\tilde{G}^{\mu\nu} + \ldots$ $\qquad \partial_\mu J^\mu \sim G^a_{\mu\nu}\tilde{G}_a^{\mu\nu}$

3. Non-perturbative QCD effects induce:

$$\mathcal{L}_{axion} = \mathcal{L}_{ChPT}(\partial_\mu a, \pi, \eta, \eta', \ldots) + V_{eff}(\bar{\theta} + \frac{a}{v}, \pi, \eta, \ldots)$$

$$\sim -\Lambda^4_{QCD} cos(\bar{\theta} + \frac{a}{v})$$

minimum of the potential: $\bar{\theta} + \frac{<a>}{v} = 0$ CP-violating term cancels!

CP symmetry is dynamically restored!

Two standard axion models

PQWW axion :

Peccei, Quinn '77
Weinberg '78
Wilczek '78

axion identified with a phase in a 2HDM ($f_a \sim v_{ew}$) : **ruled out**

phenomenology calls for $f_a \gg v_{ew}$ (« invisible axion »)

method: mix it with a complex SM singlet with « big » VEV

KSVZ axion :

Kim '79
Shifman, Vainshtein, Zakharov '80

New « heavy » electrically neutral quark, charged under $U(1)_{PQ}$
+ a new complex scalar singlet

$$\mathscr{L}_{KSVZ} = \mathscr{L}_{SM} + \bar{\Psi}_{L,R} \not{D} \Psi_{L,R} + y \bar{\Psi}_L \Psi_R \phi + V(\phi)$$

DFSZ axion :

Zhitnitskii '80
Dine, Fischler, Srednicki '81

2HDM, SM quarks and leptons are charged under $U(1)_{PQ}$
+ a new complex scalar singlet

Axion Like Particles

typical coupling

- QCD axion has couplings correlated to its mass, $m_a \sim \Lambda^2_{QCD} \boxed{\frac{1}{f_a}}$

Non-trivial topology of
the QCD vacuum

Current bounds push the mass well below the eV

-ALP: add an explicit mass term to get a new light pseudo scalar state

$$\mathscr{L}_{ALP} = \frac{1}{2}(\partial_\mu a \partial^\mu a - m_a^2 aa) + \text{couplings to SM particles}$$

No longer solve the strong CP problem

May be a DM candidate

Few might arise from string theory

Mass window spans over sub-eV to few GeV

If the mass is greater than a few GeV: LHC could say something!

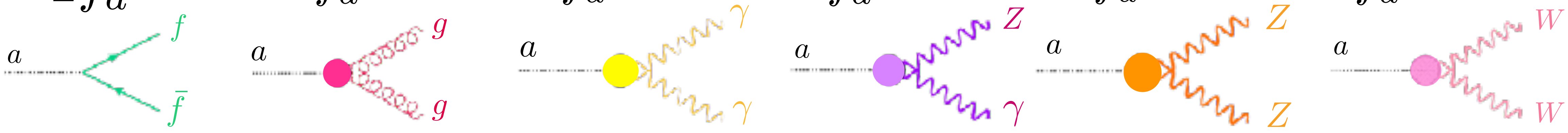
How to tackle ALP-SM couplings?

Axion couplings

Energy

At energies below f_a (SSB):

$$\mathcal{L}_{axion} \supset \frac{\partial_\mu a}{2f_a} j_a^\mu + \#\frac{a}{f_a} G\tilde{G} + \#\frac{a}{f_a} F\tilde{F} + \#\frac{a}{f_a} Z\tilde{F} + \#\frac{a}{f_a} Z\tilde{Z} + \#\frac{a}{f_a} W\tilde{W}$$



LHC regime

free from (complex) low energy QCD effects
probe different couplings than low energy experiments

electroweak couplings recently computed
do not follow the expected pattern
J.Q. and C. Smith, arXiv:1903.12559, 2006.06778, 2010.13683;
J.Q., C. Smith and P.N.H. Vuong , arXiv:2112.00553

At energies below Λ_{QCD} : $a - \eta' - \pi^0 - \eta - \ldots$ mixing

axion mass: $m_a = m_\pi \frac{f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \sim \frac{\Lambda_{QCD}^2}{f_a}$

axion couplings to electrons, nucleons, mesons, photons, ...

(EDMs)

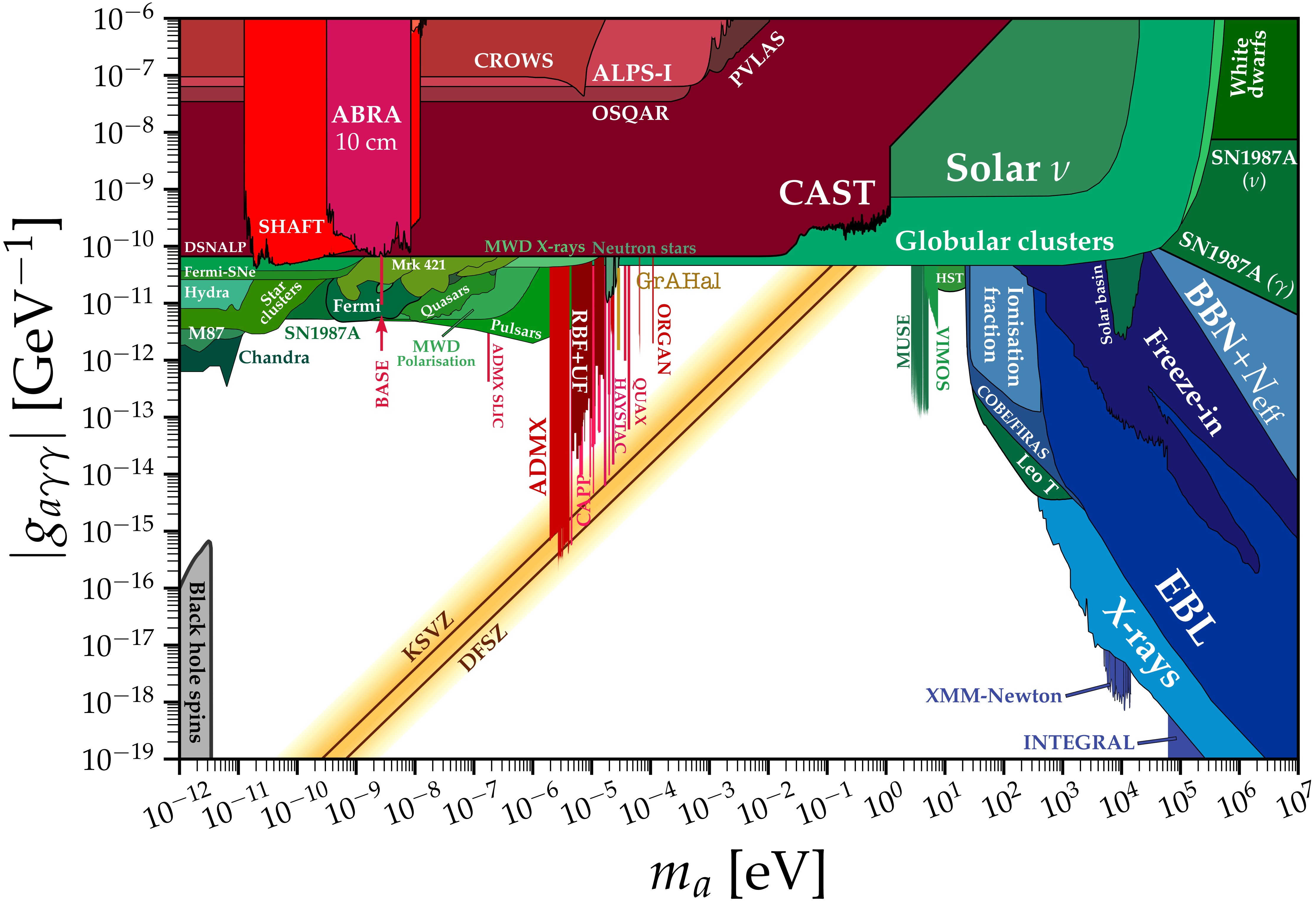
mostly explored:

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\boxed{\frac{E}{N}} - \boxed{1.92}\right)$$

model dep.

model indep.
below confinement

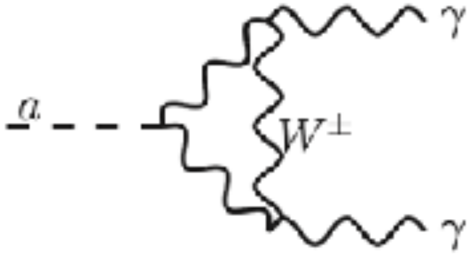
ALP searches from the axion-photon scope



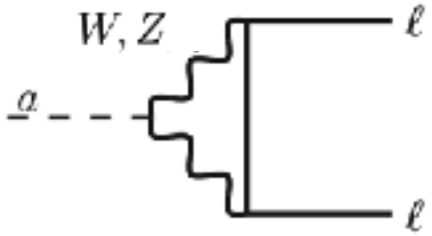
Axion couplings to massive gauge bosons

Axion electroweak couplings

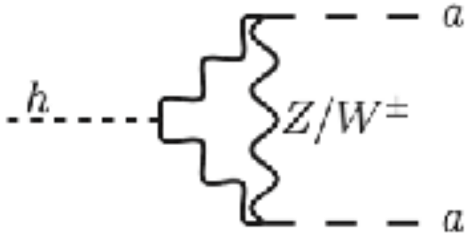
- $a \to \gamma\gamma$:



- $a \to ll$:



- $h \to aa$:

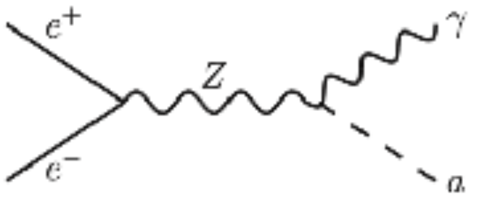


ALP electroweak couplings matters

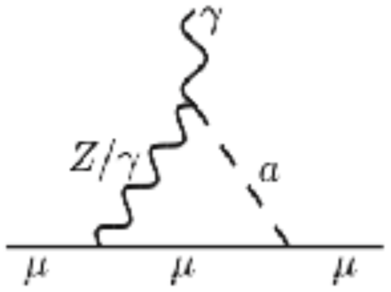
They need to be crucially explored at the LHC and beyond!

…

- $e^+e^- \to a\gamma$:



- Muon anomalous magnetic moment:



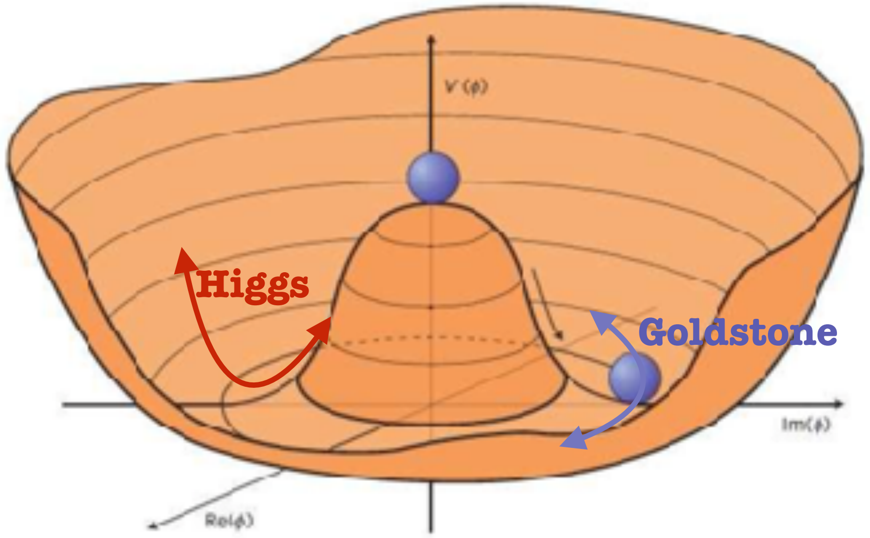
Why axions « have » derivative couplings?

An axionic toy model: simple QED extension

- local $U(1)_{em}$, new scalar field ϕ:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}_L(i\not{D})\psi_L + \bar{\psi}_R(i\not{D})\psi_R + (y\phi\bar{\psi}_L\psi_R + h.c.) + \partial_\mu\phi^\dagger\partial^\mu\phi - V(\phi)$$

→ Goldstone boson (**axion**) remnant of $U(1)_{PQ}$ S.S.B.



Linear representation: $\phi(x) = v + \sigma(x) + i\boxed{a(x)}$

$x + iy$

Polar representation: $\phi(x) = \dfrac{1}{\sqrt{2}}(v + \sigma(x))e^{-i\boxed{a(x)}/v}$

$\rho^{i\theta}$

Linear representation

$$\phi(x) = v + \sigma(x) + i\boxed{a(x)}$$

$$\mathcal{L}_{\text{Linear}} \supset \frac{1}{2}\partial_\mu a^0 \partial^\mu a^0 + \frac{m}{v}\boxed{a\;\bar{\psi}i\gamma_5\psi}$$

(no tree-level couplings
to gauge fields)

→The axion is a usual pseudo-scalar with no derivative couplings to fermions

Polar representation

$$\phi(x) = \rho e^{-i\boxed{a(x)}/v}$$

To remove « a » from the Yukawa terms $(y\phi\bar{\psi}_L\psi_R + h.c.)$

One **reparametrizes** fermion fields:

$$\psi_L(x) \to \exp(i\alpha a^0(x)/v)\psi_L(x)\ ,\ \ \psi_R(x) \to \exp(i(\alpha+1)a^0(x)/v)\psi_R(x)$$

→Fermion kinetic term induce **derivative interactions**

$$\bar{\psi}_L(i\not{D})\psi_L + \bar{\psi}_R(i\not{D})\psi_R$$

$$\boxed{\delta\mathcal{L}_{\rm Der}} = -\frac{\partial_\mu a^0}{v}(\alpha\bar{\psi}_L\gamma^\mu\psi_L + (\alpha+1)\bar{\psi}_R\gamma^\mu\psi_R) = -\frac{\partial_\mu a^0}{2v}((2\alpha+1)\bar{\psi}\gamma^\mu\psi + \bar{\psi}\gamma^\mu\gamma_5\psi)$$

$$\longrightarrow \mathcal{L}_{\rm Polar} \supset \tfrac{1}{2}\partial_\mu a^0\partial^\mu a^0 + \boxed{\delta\mathcal{L}_{\rm Der}} + \boxed{\ ?\ }$$

Polar representation

$$\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma^0(x))e^{-ia^0(x)/v}$$

- Fermionic path integral measure is not invariant under the **fermion reparametrisation**: [Fujikawa]

new local interaction (**anomaly** - Jacobian of the transformation)

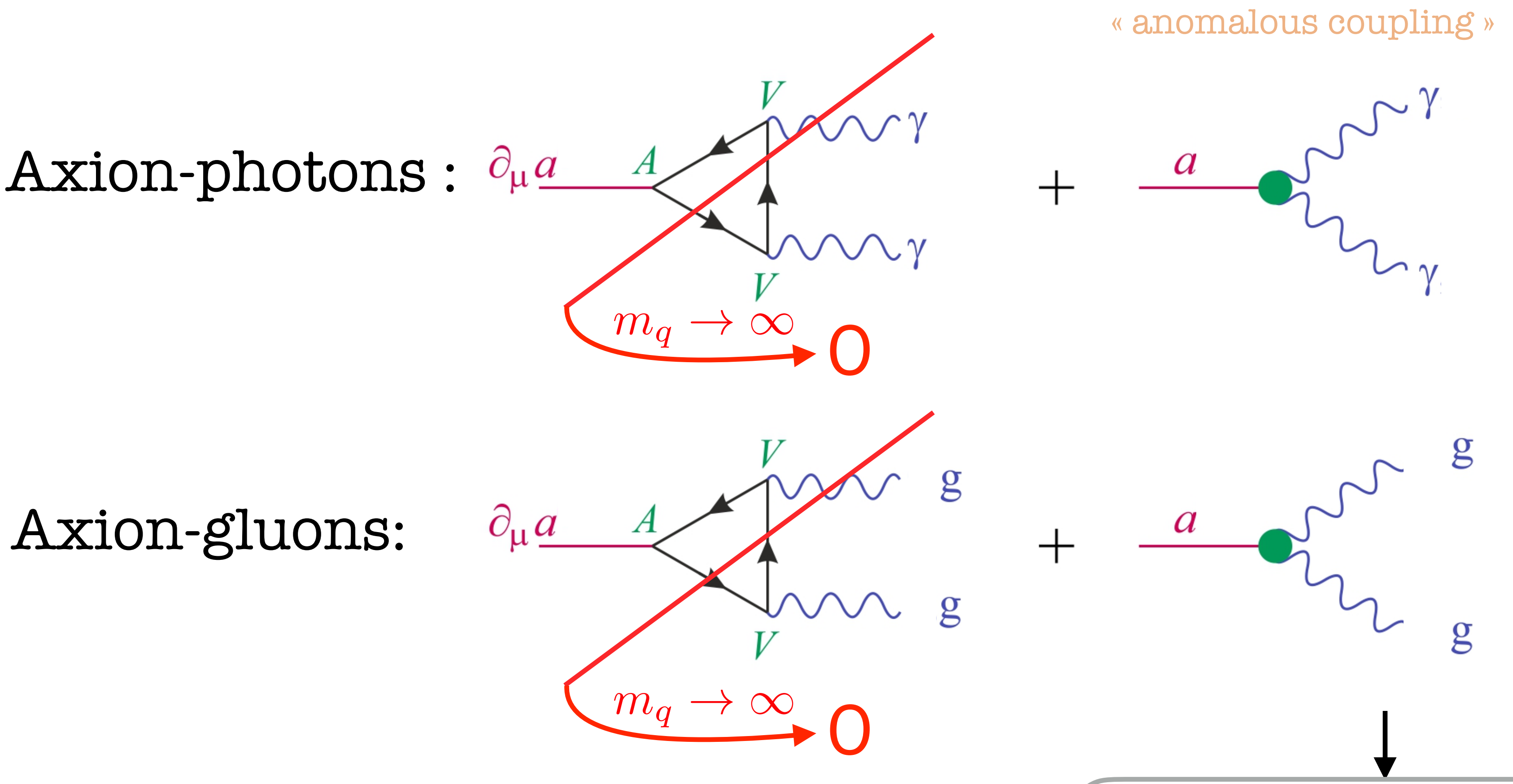
$$\boxed{\delta\mathcal{L}_{\text{Jac}}} = \frac{e^2}{16\pi^2 v} a^0 \underbrace{(\alpha - (\alpha + 1))}_{Q(q_L) \;-\; Q(q_R)} F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{e^2}{16\pi^2 v} a^0 F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\longrightarrow \mathcal{L}_{\text{Polar}} \supset \frac{1}{2}\partial_\mu a^0 \partial^\mu a^0 + \boxed{\delta\mathcal{L}_{\text{Der}}} + \boxed{\delta\mathcal{L}_{\text{Jac}}}$$

DFSZ axion couplings to SM gauge fields

Axion with derivative couplings to fermions

Effective couplings to SM gauge bosons at one loop:



Convenient book-keeping of the effect of heavy fermions

« Polar = Linear »

Polar representation:

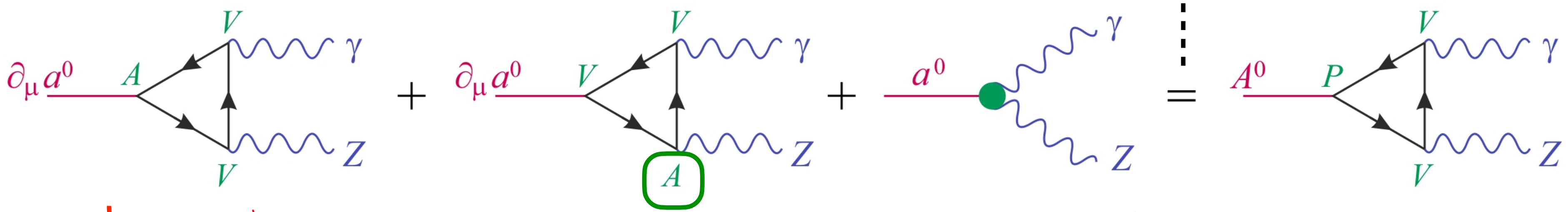
Axial current $A = \bar{\psi}\gamma^\mu\gamma_5\psi$

Vector current $V = \bar{\psi}\gamma^\mu\psi$

Linear representation:

Pseudo-scalar current $P = \bar{\psi}\gamma_5\psi$

- $a \to \gamma Z$:



$m_q \to \infty$ 0

$m_q \to \infty$ $\neq 0$

anomalous interaction

not a reliable **book-keeping** of the effect of heavy fermions

Vector current is not conserved

One has to consider both couplings:

$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma^5\psi$ **and** $\boxed{(\partial_\mu a)\bar{\psi}\gamma^\mu\psi}$

- idem for ZZ and WW

Axion-Like Particle Effective Field Theories

BSM Higgs strategy

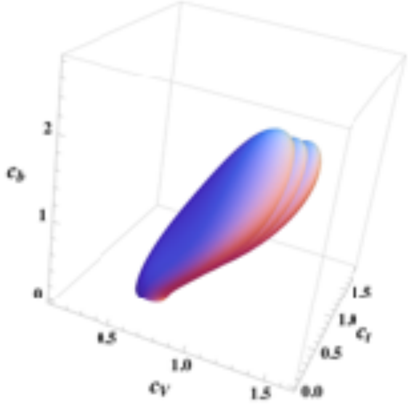
Toy model

(simple, intuitive, model independant, etc.)

Ex: Higgs kappa-framework

$$\mathscr{L}^{BSM}_{Higgs} \supset \kappa_W g^{SM}_{hWW} hW^+W^- + \kappa_Z g^{SM}_{hZZ} hZZ + \kappa_t g^{SM}_{htt} h\bar{t}t + \ldots$$

experimental data ⟶

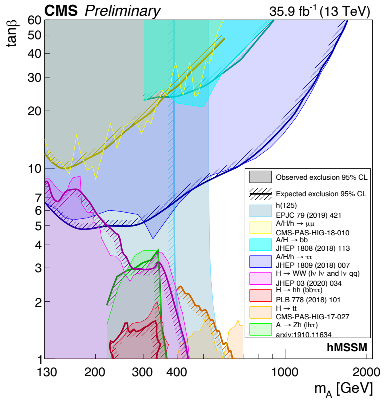


Ultra-Violet model

(solve problems, complicated, many parameters, etc.)

Ex: MSSM

experimental data ⟶



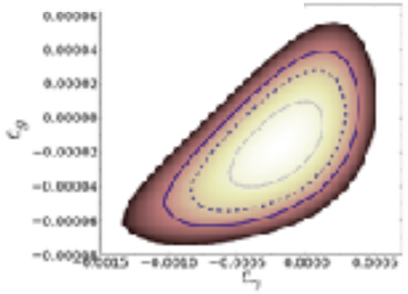
Effective Field Theory

(phenomenological QFT, model independant, etc.)

Ex: SMEFT

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{SM}} + \sum_i c_i \mathcal{O}_i$$

experimental data ⟶



BSM Axion strategy

Ultra-Violet model

Ex: PQWW axion

KSVZ invisible axion

DFSZ invisible axion

$\left.\begin{matrix}\text{PQWW axion}\\ \text{KSVZ invisible axion}\\ \text{DFSZ invisible axion}\end{matrix}\right\}$ QCD axion

ALP models

etc.

On going theoretical effort

ALP Effective Field Theory

$$\mathscr{L}_{SM-ALP-EFT} = \mathscr{L}_{SM} + \mathscr{L}_{a} + \mathscr{L}_{a-SM}$$

Ex:

$$\mathscr{L}^{D=5}_{a-SM} \supset \sum_f C_{ff}\frac{\partial^\mu a}{\Lambda}\bar{f}\gamma_\mu\gamma_5 f + C_{GG}\frac{a}{\Lambda}G_{\mu\nu}\tilde{G}^{\mu\nu} + C_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$+ C_{\gamma Z}\frac{a}{\Lambda}F_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{ZZ}\frac{a}{\Lambda}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{WW}\frac{a}{\Lambda}W_{\mu\nu}\tilde{W}^{\mu\nu}$$

$$\mathscr{L}^{D\geq 6}_{a-SM} \supset \frac{C_{ah}}{\Lambda^2}(\partial_\mu a)(\partial^\mu a)H^\dagger H + \ldots$$

Which basis for ALP-SM couplings?

On going theoretical effort

Useful for model independent searches

Several independent Wilson coefficients :
Is this always reasonable from a UV point of view?

Implication for ALPs searches

How to construct a truly **axion-like** basis?

F. Arias-Aragón, J.Q., C. Smith, arXiv:2211.04489

$$\mathcal{L}^{\rm eff}_{ALP} = \frac{1}{2}(\partial_\mu a^0 \partial^\mu a^0 - m_a^2 a^0 a^0) + \mathcal{L}_{\rm KSVZ-like} + \mathcal{L}_{\rm DFSZ-like}$$

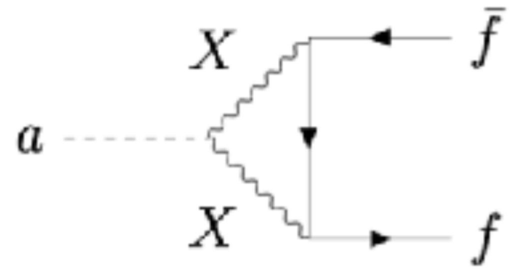
KSVZ like: New, heavy, electrically neutral quark, charged under $U(1)_{\rm PQ}$

$$\mathcal{L}^{\rm eff}_{\text{KSVZ-like}} = \frac{a^0}{16\pi^2 f_a}\left(g_s^2 \mathcal{N}_C G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + g^2 \mathcal{N}_L W_{\mu\nu}\tilde{W}^{\mu\nu} + g'^2 \mathcal{N}_Y B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

$$\begin{aligned} g_{agg} &= \alpha_s \mathcal{N}_C \ , \\ g_{a\gamma\gamma} &= \alpha\left(\mathcal{N}_L + \mathcal{N}_Y\right) \ , \\ g_{a\gamma Z} &= 2\alpha\left(-\mathcal{N}_L/t_W + t_W\mathcal{N}_Y\right) \ , \\ g_{aZZ} &= \alpha\left(\mathcal{N}_L/t_W^2 + t_W^2\mathcal{N}_Y\right) \ , \\ g_{aWW} &= \frac{2\alpha}{s_W^2}\mathcal{N}_L \ . \end{aligned}$$

- Typically assuming some heavy **vector-like** fermions
- Manifestly symmetric under $SU(3)_C \otimes SU(2)_L \otimes U(1)_L$

- No direct coupling to SM fermions, but one loop induced:



$$\mathcal{L}^{eff}_{fermion} = \sum_{f=u,d,e} \frac{m_f}{v_a} c_{af}\, a \bar{f}\gamma_5 f$$

$$\begin{aligned} c_{af} =& 16\left(\alpha^2 Q_f^2\left(\mathcal{N}_L + \mathcal{N}_Y\right) + \alpha_s^2 \frac{4}{3}\mathcal{N}_C\right) I_0 - \frac{\alpha^2(\mathcal{N}_L/t_W^2 + t_W^2\mathcal{N}_Y)}{s_W^2 c_W^2} I_{ZZ} \\ &+ \frac{16\alpha^2 Q_f(T_f^3 - 2Q_f s_W^2)(-\mathcal{N}_L/t_W + t_W\mathcal{N}_Y)}{s_W c_W} I_{\gamma Z} - \frac{4\alpha^2\mathcal{N}_L}{s_W^4}\sum_{f'} V_{ff'} I_{WW} \end{aligned}$$

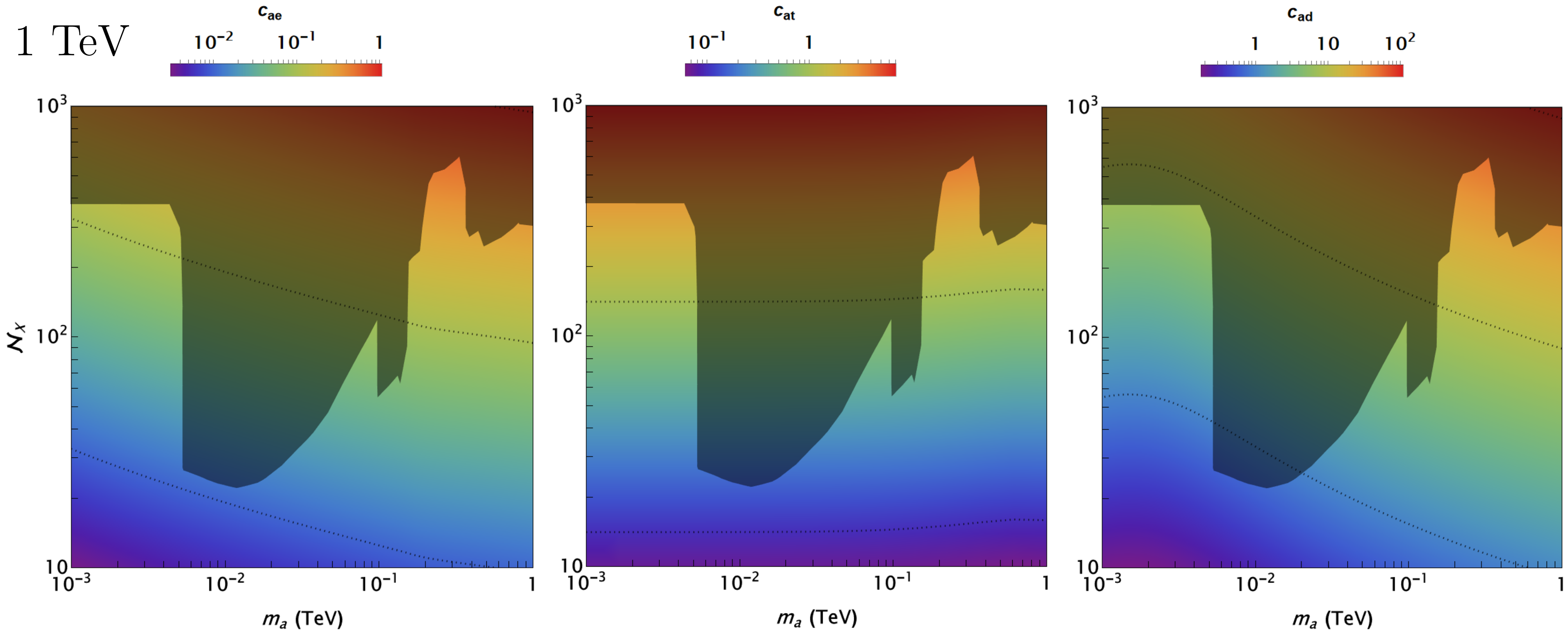
coupling to heavy quarks $\Rightarrow \mathcal{N}_X \Rightarrow c_f \equiv f(\mathcal{N}_X)$

KSZV-like ALPs

- Parameter space easy to bound, with for example, limits on $g_{a\gamma\gamma}$:

$v_a = 1$ TeV

$\mathcal{N}_C = \mathcal{N}_L = \mathcal{N}_Y \equiv \mathcal{N}_X$



F. Arias-Aragón, J.Q., C. Smith, arXiv:2211.04489

Implication for ALPs searches

How to construct a truly **axion-like** basis?

$$\mathcal{L}^{\text{eff}}_{ALP} = \frac{1}{2}(\partial_\mu a^0 \partial^\mu a^0 - m_a^2 a^0 a^0) + \mathcal{L}_{\text{KSVZ}-\text{like}} + \mathcal{L}_{\text{DFSZ}-\text{like}}$$

DFSZ like: 2HDM plus extra scalar, SM quarks and leptons are charged under $U(1)_{\text{PQ}}$

$$\mathcal{L}^{\text{eff}}_{\text{DFSZ-like}} = -\frac{1}{2f_a}\partial_\mu a \sum_{f\,=\,\text{chiral fermions}} \chi_V^f \bar{\psi}_f \gamma^\mu \psi_f + \chi_A^f \bar{\psi}_f \gamma^\mu \gamma^5 \psi_f$$

$$+ \frac{a}{16\pi^2 f_a}\left(g_s^2 \mathcal{N}_C G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + g^2 \mathcal{N}_L W_{\mu\nu}\tilde{W}^{\mu\nu} + g'^2 \mathcal{N}_Y B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

- **Vector currents do contribute** to physical observables
- Spurious $\mathscr{B}$ and $\mathscr{L}$ violation included
- Axion-like ⇒ **need to impose anomaly cancellation**!

Implication for ALPs searches

How to construct a truly **axion-like** basis?

$$\mathcal{L}^{\rm eff}_{ALP} = \frac{1}{2}(\partial_\mu a^0 \partial^\mu a^0 - m_a^2 a^0 a^0) + \mathcal{L}_{\rm KSVZ-like} + \mathcal{L}_{\rm DFSZ-like}$$

DFSZ like: 2HDM plus extra scalar, SM quarks and leptons are charged under $U(1)_{\rm PQ}$

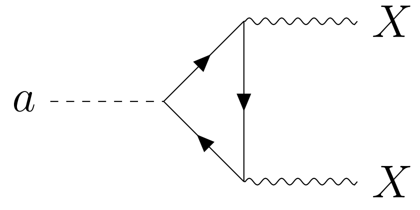
$$\mathcal{L}^{\rm eff}_{\text{DFSZ-like}} = -\frac{i}{f_a} a^0 \sum_{f=u,d,e} m_f \chi_A^f (\bar{\psi}_f \gamma_5 \psi_f)$$

Anomaly cancellation taken into account!

Simple pseudo-scalar couplings

- One should not build EFTs with both **anomalous couplings** and **vectorial-axial fermion couplings** : because of **anomaly cancellations**!
- Effective interactions are not always equal to anomalous interactions!

- One loop induced couplings to gauge fields :



$$\mathscr{L}^{eff}_{gauge} = \frac{a}{4\pi v_a}\left(g_{agg} G^{a\mu\nu}\tilde{G}^a_{\mu\nu} + g_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{aZ\gamma} Z_{\mu\nu}\tilde{F}^{\mu\nu} + g_{aZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu} + g_{aWW} W^{+\mu\nu}\tilde{W}^-_{\mu\nu}\right)$$

$$g_{aV_1V_2} = -2i\pi\sigma \sum_{f=u,d,e} m_f \chi_f \left(g^f_{V_1} g^{f'}_{V_2} \mathcal{T}_{PVV}(m_f) + g^f_{A_1} g^{f'}_{A_2} \mathcal{T}_{PAA}(m_f)\right)$$

$$\mathcal{T}_{PVV}(m) = \frac{-i}{2\pi^2} m C_0(m^2)\ ,$$

$$\mathcal{T}_{PAA}(m) = \frac{-i}{2\pi^2} m (C_0(m^2) + 2C_1(m^2))$$

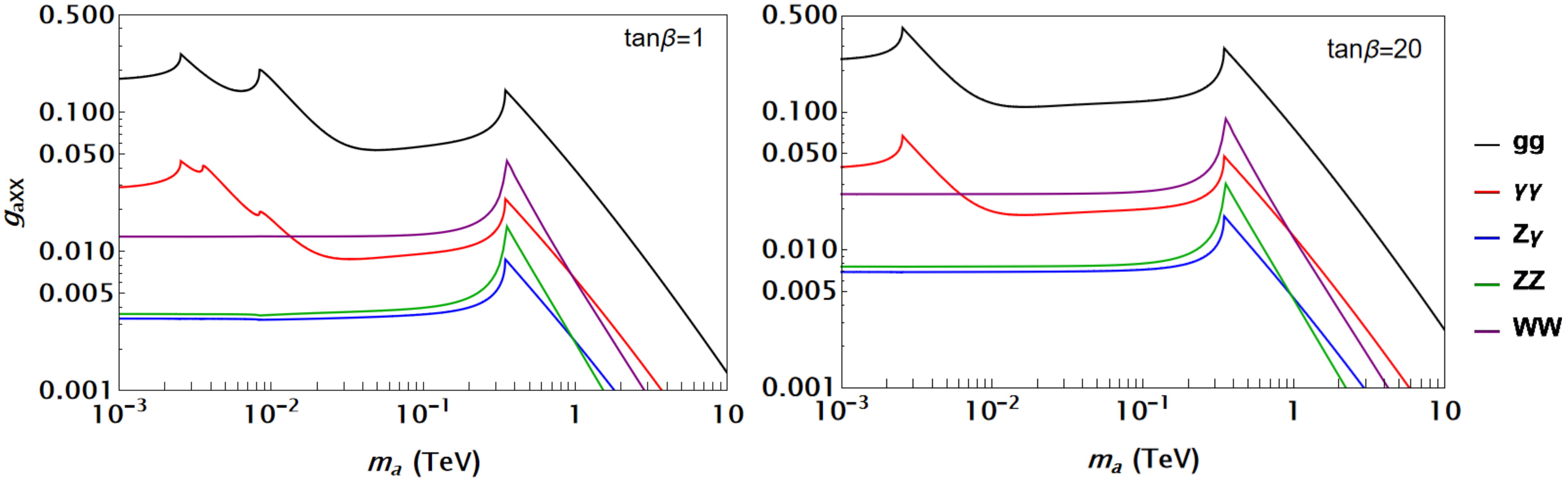
$$g_{aXX} \equiv f(\chi_f)$$

DFSZ-like ALPs

- 4 physical parameters (χ_f/v_a, m_a) as opposed to 7 in the generic ALP EFT

- g_{aXX} is now a function of the ALP mass :

F. Arias-Aragón, J.Q., C. Smith, arXiv:2211.04489



- Non-linear correlations among EW g_{aXX} in the Higgs broken phase

- Ex: measuring g_{agg}, $g_{a\gamma\gamma}$, $g_{aZ\gamma}$ fixes g_{aWW} & g_{aZZ} in the KSVZ-like scenario (generic EFT)

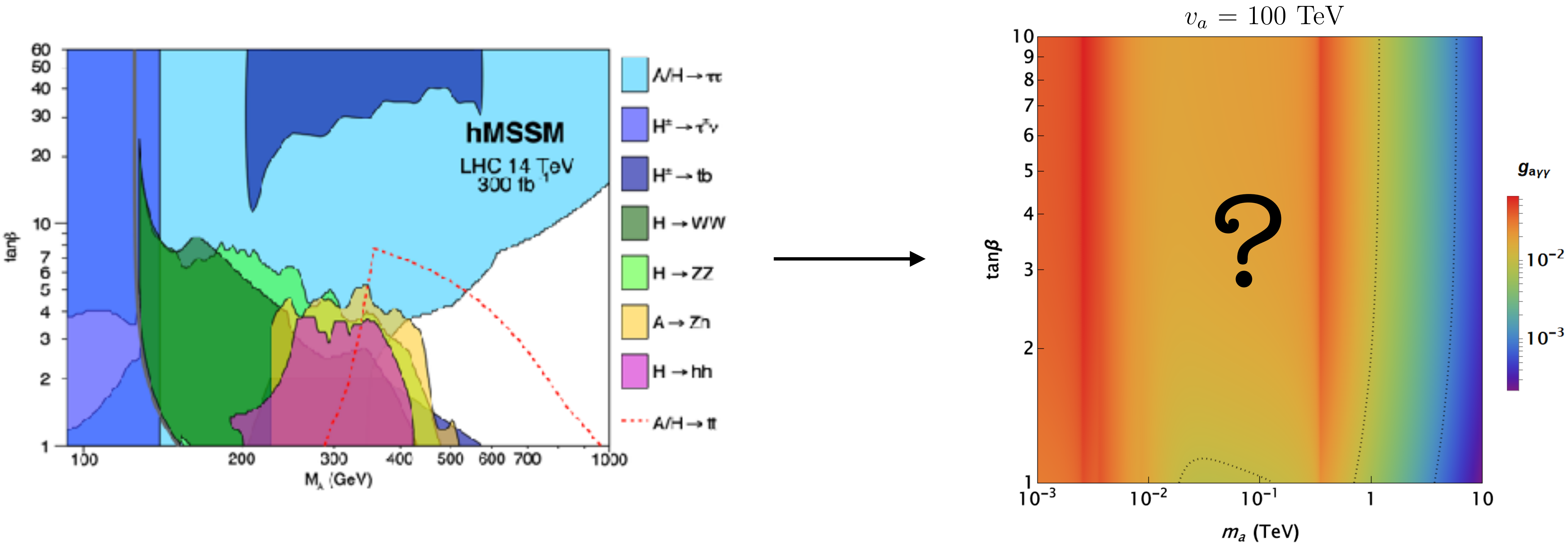
- In DFSZ-like scenario one degree of freedom remains: curve in the g_{aWW} & g_{aZZ} space

DFSZ-like ALPs - a more constrained case

- Mimicking the 2HDM type-II pseudoscalar couplings:

$$\chi_u = \frac{x^2}{1+x^2}, \; \chi_d = \chi_e = \frac{1}{1+x^2} \qquad \text{with} \qquad x = \tan\beta = v_u/v_d$$

- Allows to recast pseudoscalar searches for 2HDM on the DFSZ-like ALP parameter space



For $v_a \gtrsim 100$ GeV the parameter space is completely unconstrained by the ALP-photon coupling

Switch to generic ALP EFT

$$\mathscr{L}_{SM-ALP-EFT} = \mathscr{L}_{SM} + \mathscr{L}_{a} + \mathscr{L}_{a-SM}$$

Ex:

$$\mathscr{L}^{D=5}_{a-SM} \supset \sum_{f} C_{ff} \frac{\partial^{\mu} a}{\Lambda} \bar{f} \gamma_{\mu} \gamma_{5} f + C_{GG} \frac{a}{\Lambda} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

only 2 d.o.f: $+C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + C_{\gamma Z} \frac{a}{\Lambda} F_{\mu\nu} \tilde{Z}^{\mu\nu} + C_{ZZ} \frac{a}{\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + C_{WW} \frac{a}{\Lambda} W_{\mu\nu} \tilde{W}^{\mu\nu}$

$$\mathscr{L}^{D\geq 6}_{a-SM} \supset \frac{C_{ah}}{\Lambda^2} (\partial_{\mu} a)(\partial^{\mu} a) H^{\dagger} H + \frac{C_{Zh}}{\Lambda^2} (\partial^{\mu} a)(H^{\dagger} i D_{\mu} H + h.c.) H^{\dagger} H + \dots$$

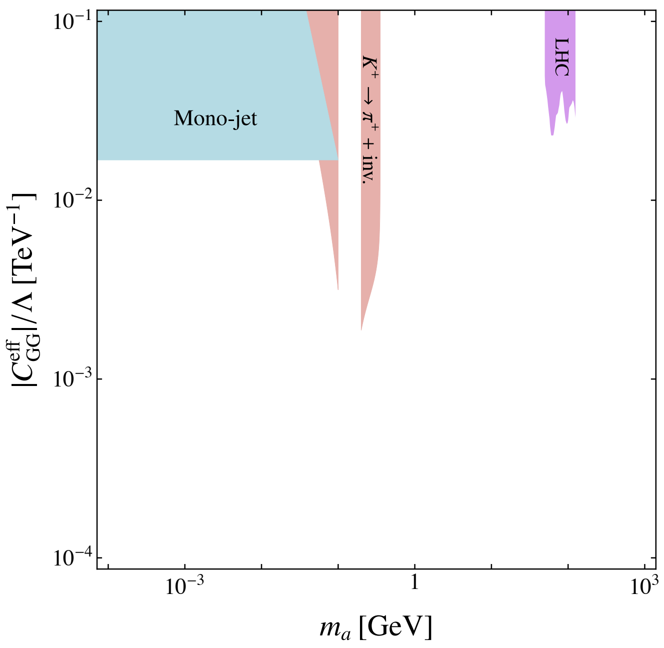
More degrees of freedom

Major difference for analysis: fermionic & gauge sectors are truly secluded here

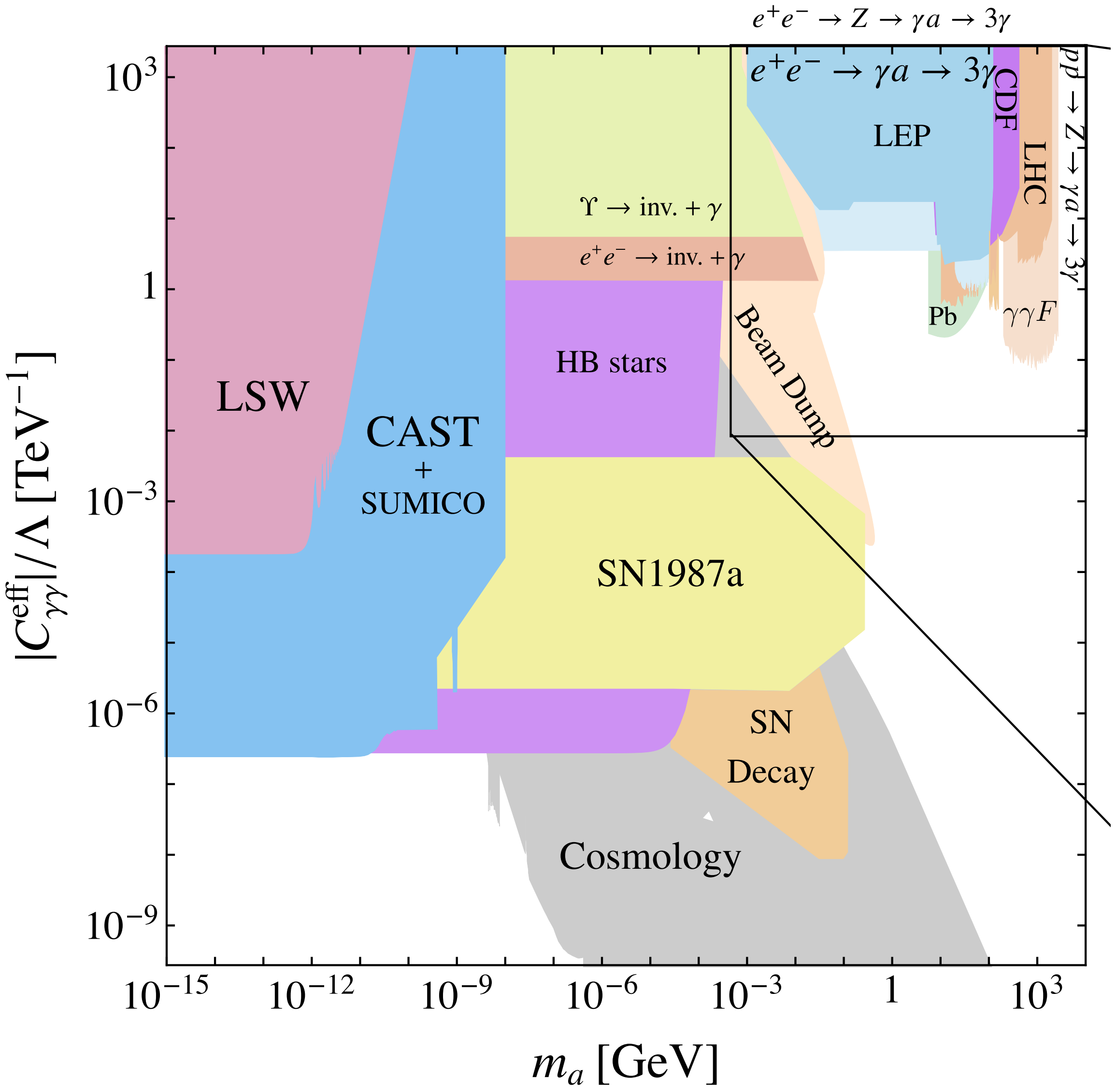
Current constraints on :

M. Bauer, M. Heiles, M. Neubert, A. Thamm, arXiv:1808.10323

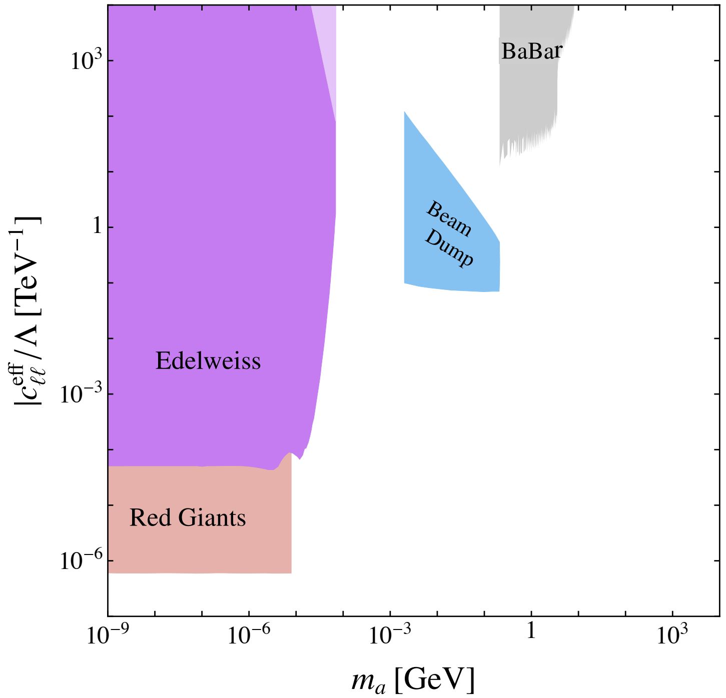
C_{gg}^{eff}



$C_{\gamma\gamma}^{eff}$



C_{ee}^{eff}

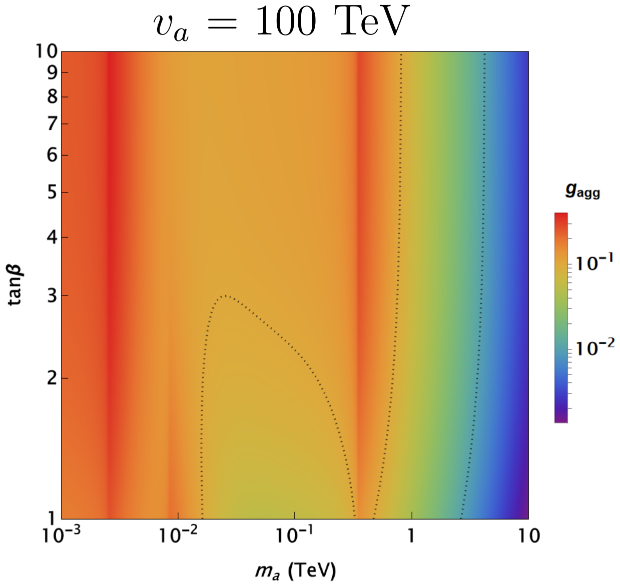


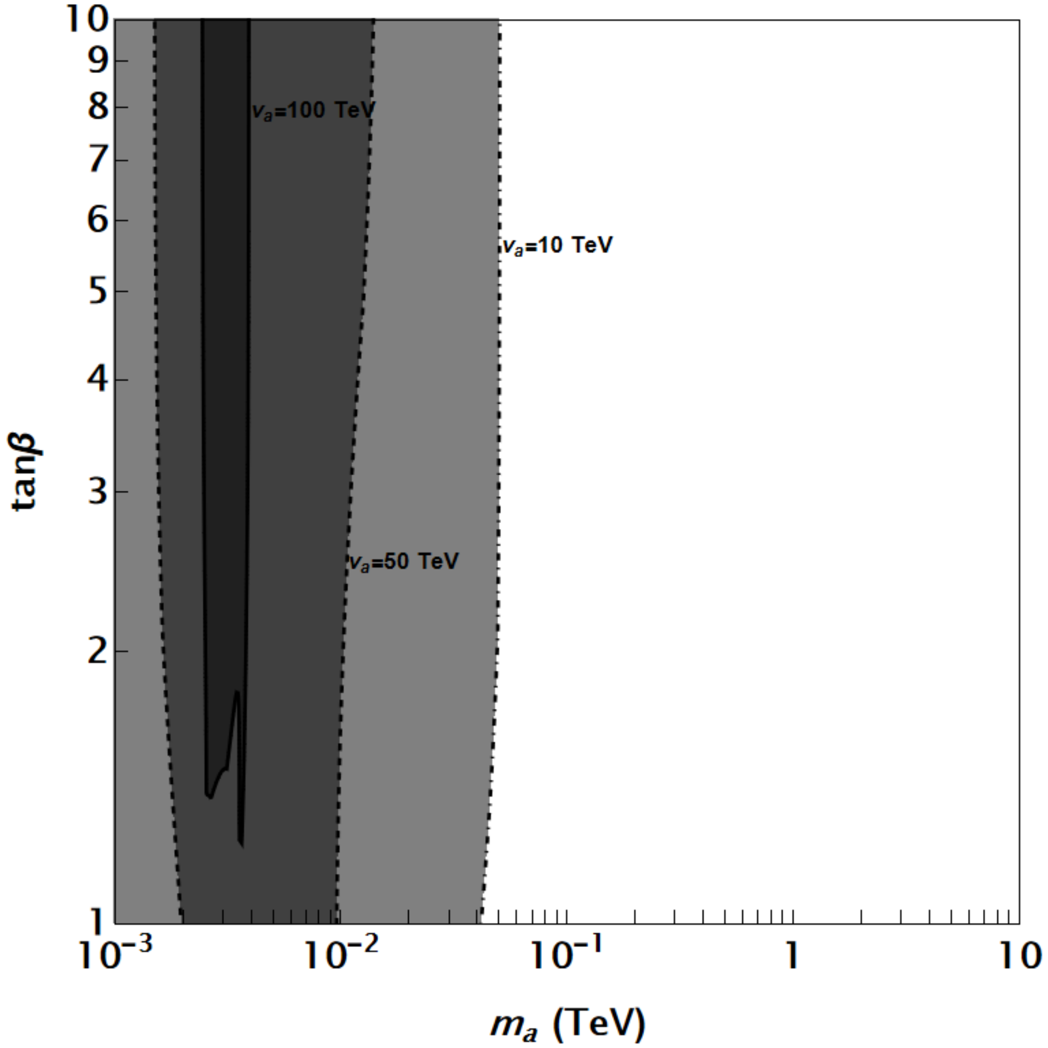
ALPs at FCC

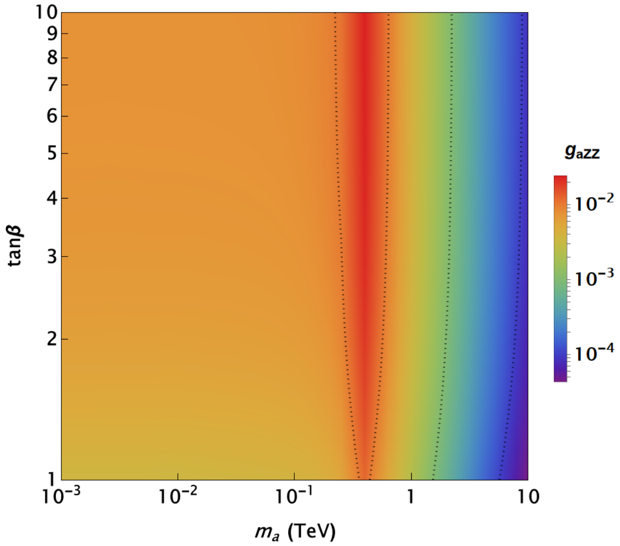
Some prospects

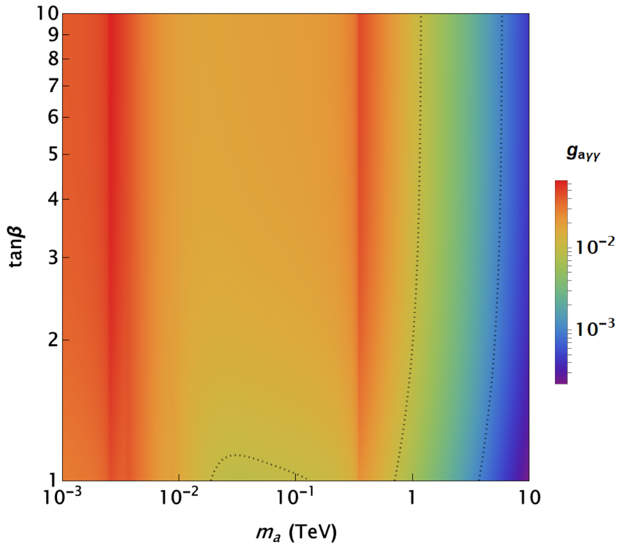
FCC-ee searches for DFSZ-like ALPs

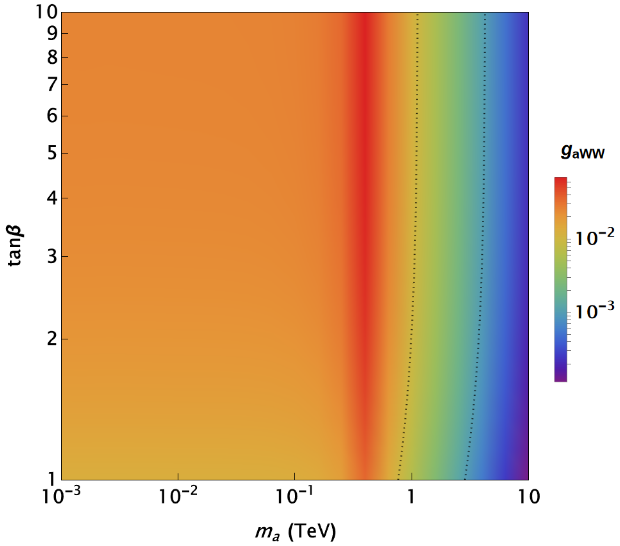
Recast of bounds on $g_{a\gamma\gamma}$ from $e^+e^- \to \gamma a$:

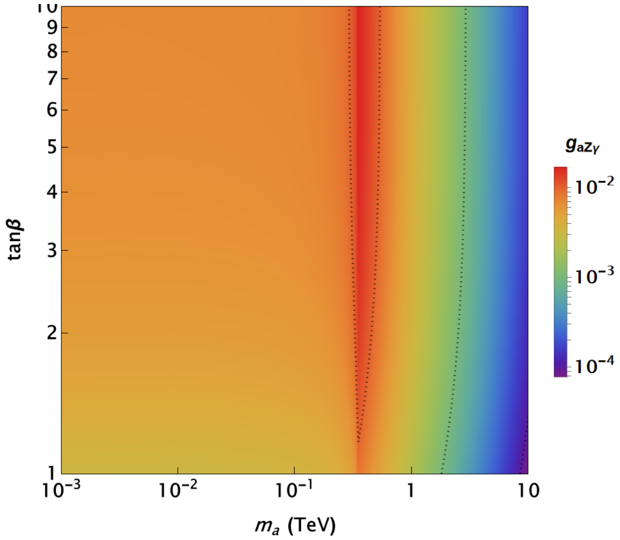










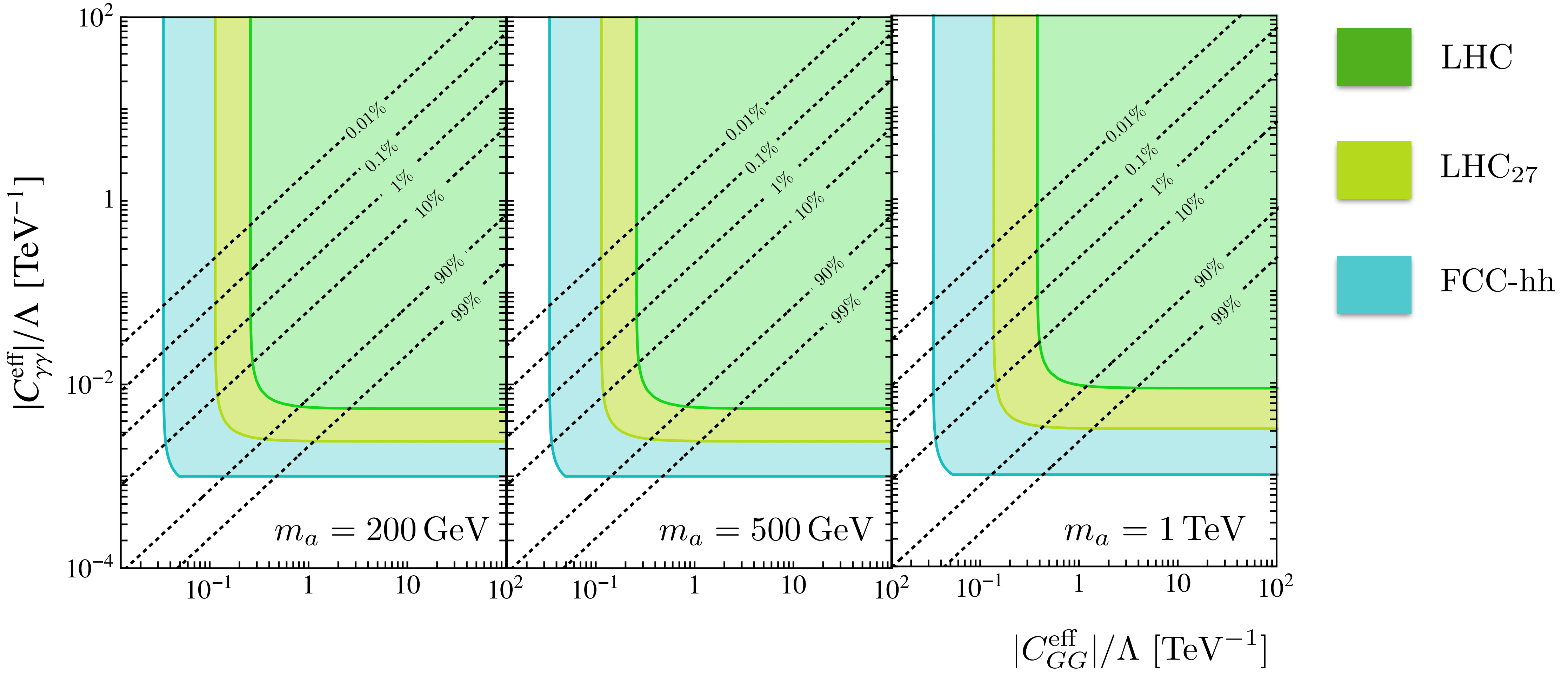


Resonant ALP production - constraints on C_{GG}^{eff}, $C_{\gamma\gamma}^{eff}$

FCC-hh:

$$pp \to a \to \gamma\gamma$$

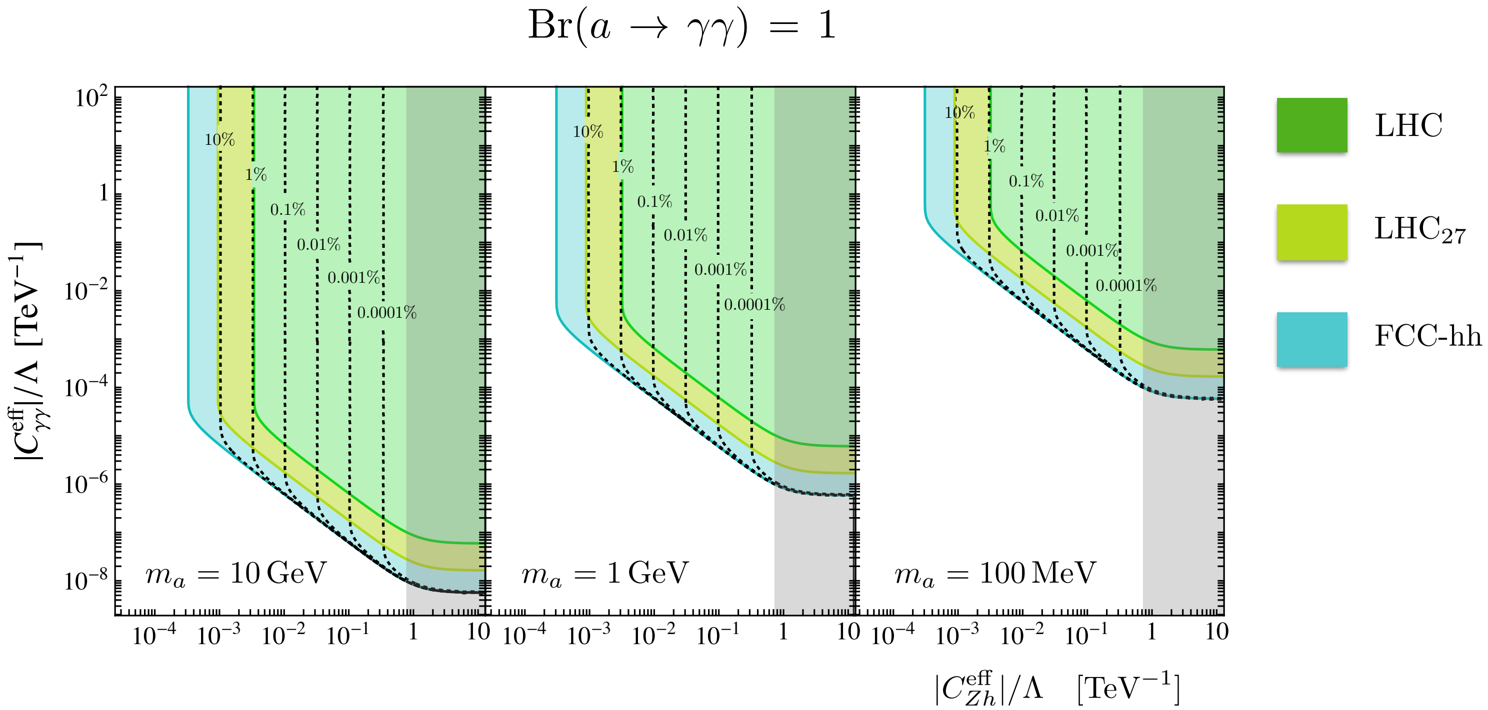
M. Bauer, M. Heiles, M. Neubert, A. Thamm, arXiv:1808.10323



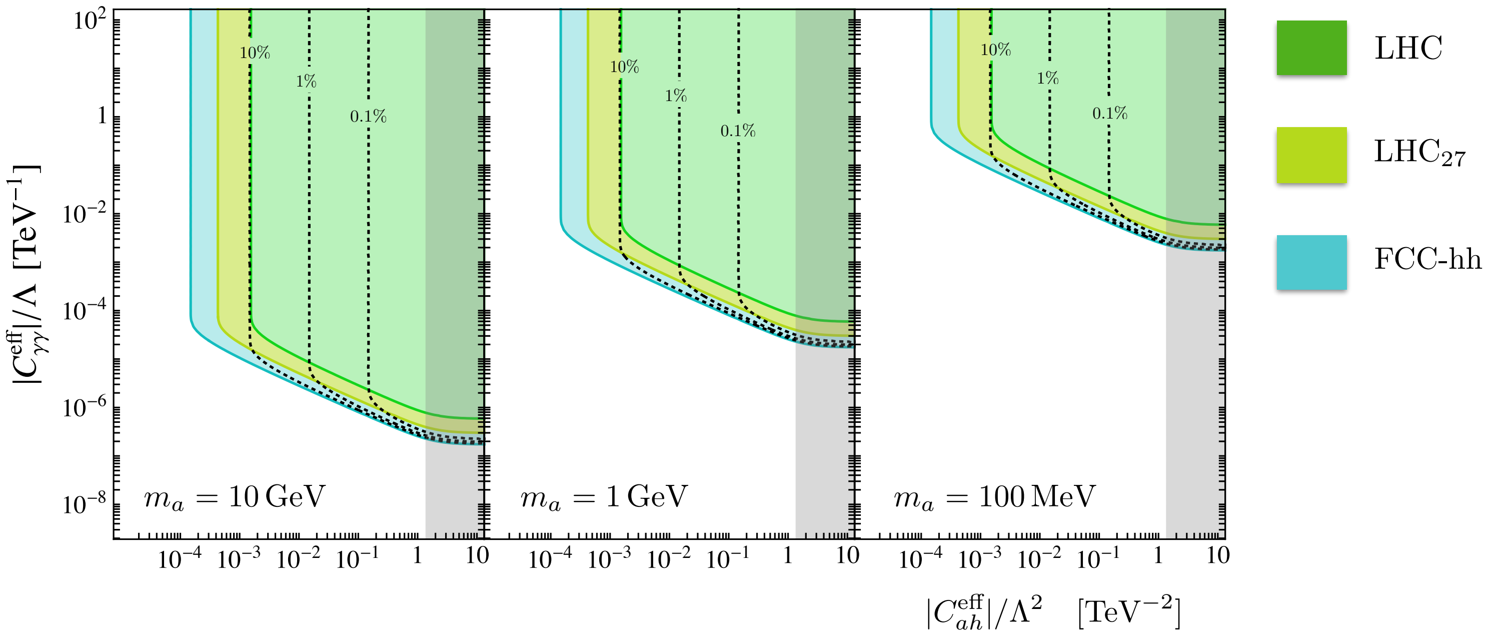
Higgs decays into ALPs $C_{Zh}^{eff}, C_{ah}^{eff}$

FCC-hh:

$h \to Za$



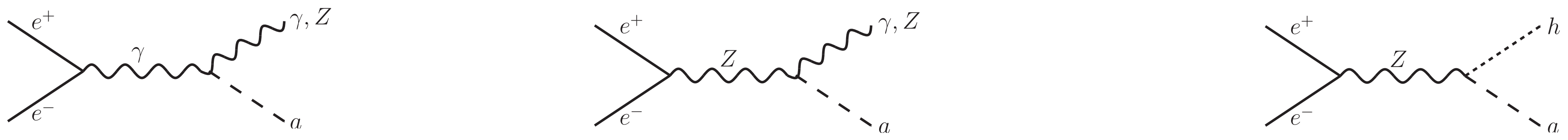
$h \to aa$



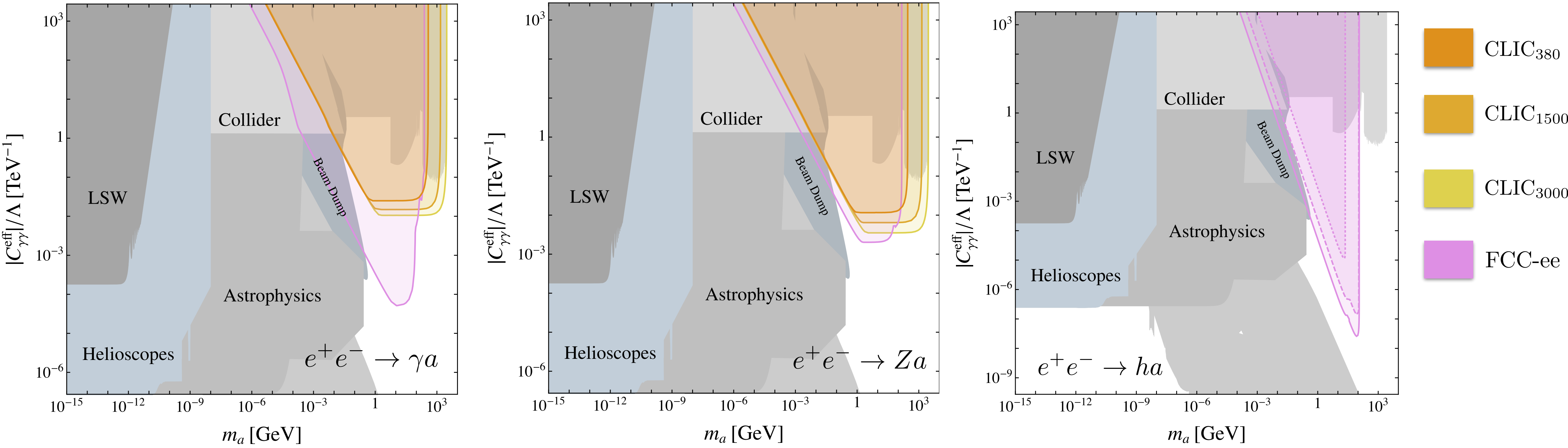
M. Bauer, M. Heiles, M. Neubert, A. Thamm, arXiv:1808.10323

γ, Z, Higgs associated production with an ALPs C_{Zh}^{eff}

FCC-ee:



$\mathrm{Br}(a \to \gamma\gamma) = 1$

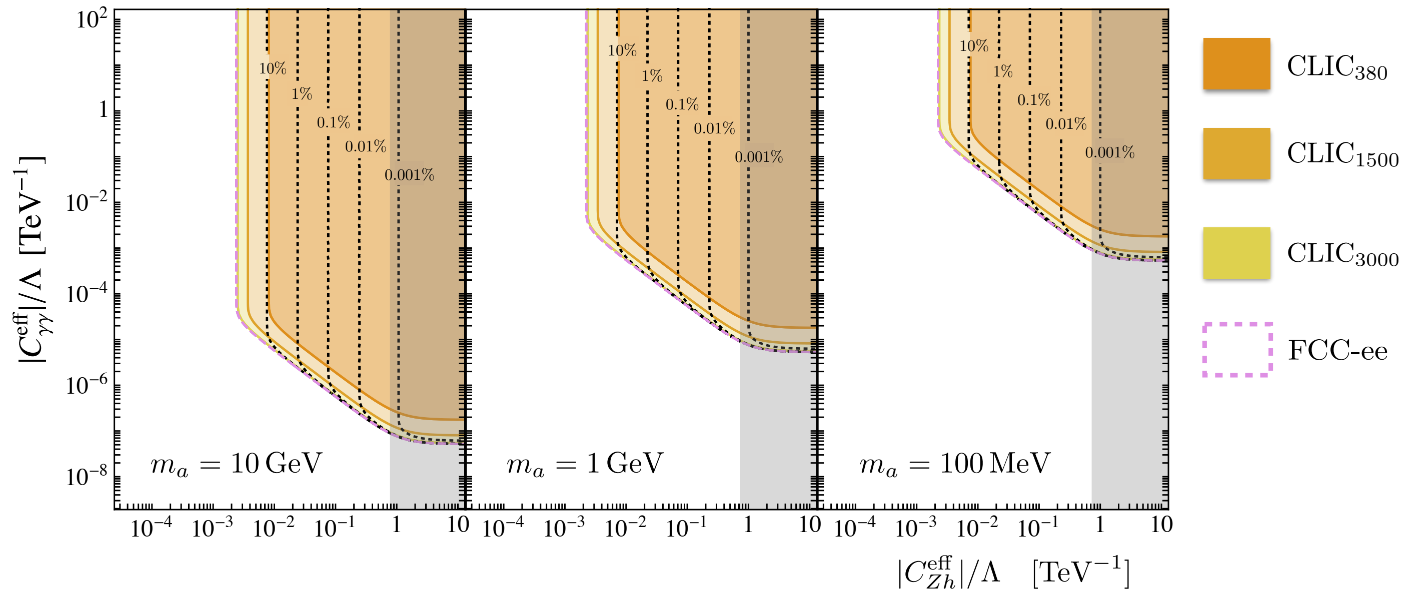


M. Bauer, M. Heiles, M. Neubert, A. Thamm, arXiv:1808.10323

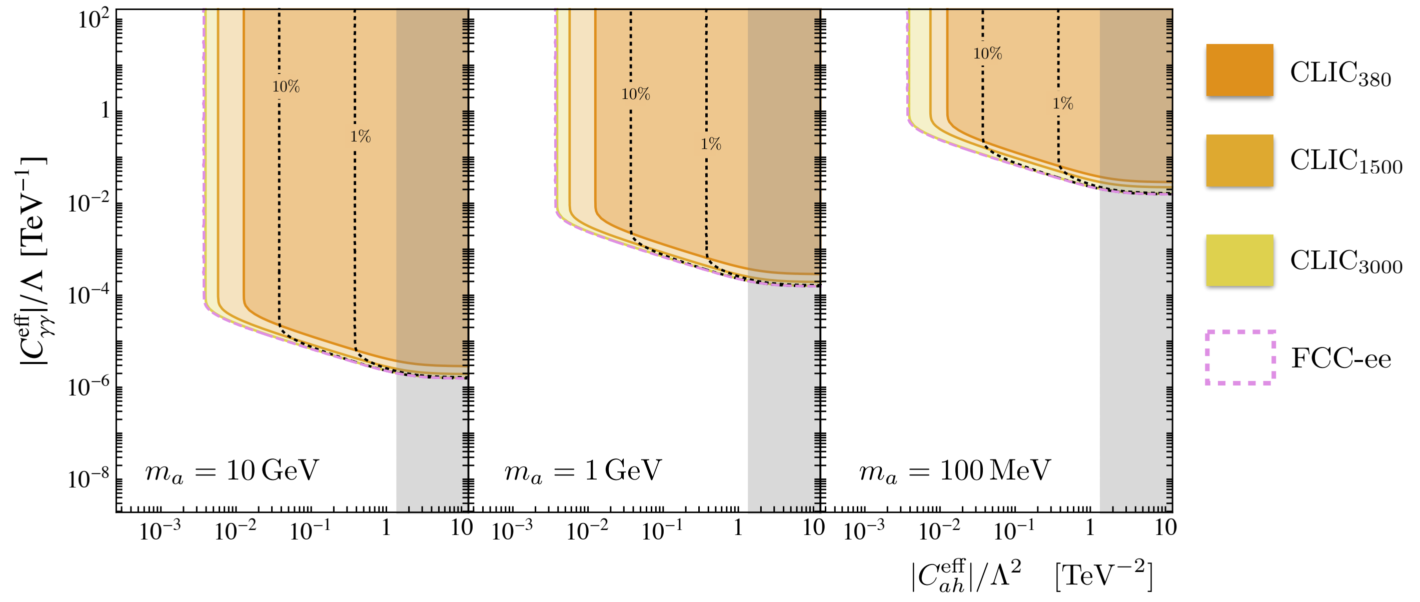
Higgs decays into ALPs $C_{Zh}^{eff}, C_{ah}^{eff}$

FCC-ee:

$h \to Za$



$h \to aa$



M. Bauer, M. Heiles, M. Neubert, A. Thamm, arXiv:1808.10323

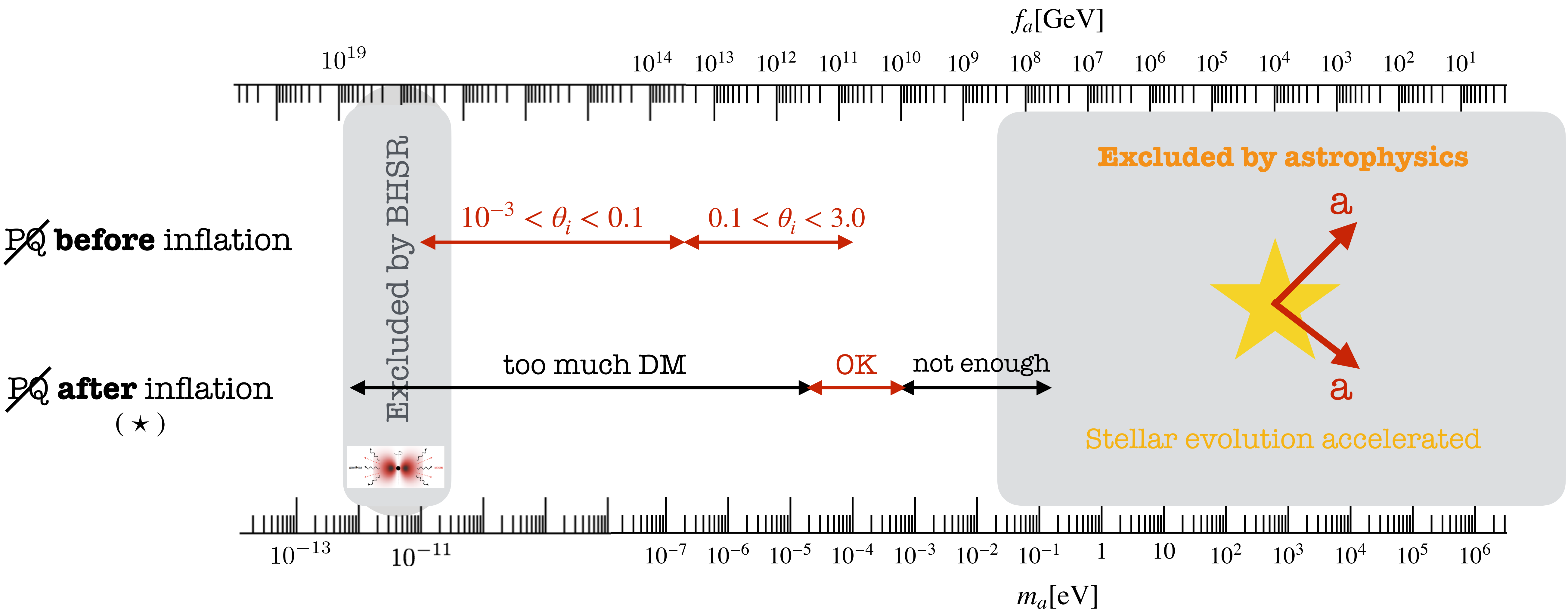
Conclusion

- Axion-electroweak couplings are mostly unexplored yet
- Axion-electroweak couplings do not always follow the expected pattern → must be kept in mind for ALP searches
- Axion with fermion pseudoscalar couplings is safer (no ambiguity)
- DFSZ-like and KSZV-like benchmarks presented
- Different set of parameters identified, reduced with respect to generic ALP EFT with totally different correlations
- Generic ALP EFT does not « incorporate » DFSZ and KSVZ-like benchmarks
- Scenarios easy to constrain, in particular DFSZ-like through 2HDM searches
- Full dedicated analysis with all bounds required for LHC and FCC!

Spare slides

Landscape

Axions should be very light and feebly interacting



~~PQ~~ **before** inflation

~~PQ~~ **after** inflation
$(\star)$

$(\star)$ for $N_{DW} > 1$, predictions spoiled by topological defects

Axion DM constraints from **laboratory** experiments, from **stars** and **cosmos** observations

QFT Anomalies

Anomalies: classical symmetry broken at the quantum level

Example: « triangle anomalies » in massless QED

$$\mathscr{L}_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi$$

Two invariances: $\xrightarrow{\text{(Noether theorem)}}$ Two classicaly conserved currents:

- $\psi \rightarrow e^{i\theta_V}\psi$
- $\psi \rightarrow e^{-i\theta_A\gamma^5}\psi$

$$V^\mu = \bar{\psi}\gamma^\mu\psi \ , \quad \partial_\mu V^\mu = 0$$

$$A^\mu = \bar{\psi}\gamma^\mu\gamma^5\psi \ , \quad \partial_\mu A^\mu = 0$$

$$\Downarrow$$

At the quantum level:

$$V^\mu = \bar{\psi}\gamma^\mu\psi \ , \quad \partial_\mu V^\mu = 0$$ holds

But axial symmetry is broken :

$$\partial_\mu A^\mu = \frac{1}{8\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Fermionic path integral measure is not invariant: [Fujikawa]

$$Z = \int \mathscr{D}\psi\mathscr{D}\bar{\psi}e^{iS}$$

DFSZ axion summary

$$\begin{aligned}\mathcal{L}^{\text{eff}} = \frac{a^0}{16\pi^2 v}\Bigg(& g_s^2\mathcal{N}^{gg}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + e^2\mathcal{N}^{\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{2e^2}{c_W s_W}\left(\mathcal{N}_1^{\gamma Z} - s_W^2\mathcal{N}_2^{\gamma Z}\right)Z_{\mu\nu}\tilde{F}^{\mu\nu} \\ & + \frac{e^2}{c_W^2 s_W^2}\left(\mathcal{N}_1^{ZZ} - 2s_W^2\mathcal{N}_2^{ZZ} + s_W^4\mathcal{N}_3^{ZZ}\right)Z_{\mu\nu}\tilde{Z}^{\mu\nu} + 2\mathcal{N}^{WW}g^2W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}\Bigg)\end{aligned}$$

in the limit $m_{u,d,e} \to \infty$

J.Gunion et al., PRD 46 (1992) 2907

Linear		Polar		
$a^0\bar{\psi}\gamma_5\psi$	Anomalous interactions	$\partial_\mu a^0\bar{\psi}\gamma^\mu\gamma_5\psi$ AVV	AAA	$\partial_\mu a^0\bar{\psi}\gamma^\mu\psi$ VAV
$\mathcal{N}^{gg} = \frac{1}{2}\left(x + \frac{1}{x}\right)$	$\mathcal{N}^{gg}$	0	$-$	$-$
$\mathcal{N}^{\gamma\gamma} = \frac{4}{3}\left(x + \frac{1}{x}\right)$	$\mathcal{N}^{\gamma\gamma}$	0	$-$	$-$
$\mathcal{N}_1^{\gamma Z} = \frac{1}{2}\left(x + \frac{1}{x}\right)$	$\mathcal{N}_L$	0	$-$	$\mathcal{N}_1^{\gamma Z} - \mathcal{N}_L$
$\mathcal{N}_2^{\gamma Z} = \mathcal{N}^{\gamma\gamma}$	$\mathcal{N}^{\gamma\gamma}$	0	$-$	0
$\mathcal{N}_1^{ZZ} = \frac{1}{4}x + \frac{1}{3x}$	$\mathcal{N}_L$	$\frac{\beta}{16}$	$-\frac{1}{2}\mathcal{N}_1^{ZZ} + \frac{\beta}{16}$	$\frac{3}{2}\mathcal{N}_1^{ZZ} - \mathcal{N}_L - \frac{\beta}{8}$
$\mathcal{N}_2^{ZZ} = \mathcal{N}_1^{\gamma Z}$	$\mathcal{N}_L$	0	0	$\mathcal{N}_2^{ZZ} - \mathcal{N}_L$
$\mathcal{N}_3^{ZZ} = \mathcal{N}^{\gamma\gamma}$	$\mathcal{N}^{\gamma\gamma}$	0	0	0
$\mathcal{N}^{WW} = \frac{x}{4} + \frac{3}{8x}$	$\mathcal{N}_L$	$\frac{3}{2}\mathcal{N}^{WW} - \frac{3}{2}\mathcal{N}_1^{\gamma Z} + \frac{\beta}{16}$	$-\frac{1}{2}\mathcal{N}^{WW} + \frac{\beta}{16}$	$\frac{3}{2}\mathcal{N}_1^{\gamma Z} - \mathcal{N}_L - \frac{\beta}{8}$

$x = v_2/v_1 = 1/\tan\beta$

J.Q. and C. Smith, arXiv:1903.12559

Effective interactions are not always equal to anomalous interactions!

Remember that $\mathcal{N}_L$ is ambiguous

The 2HDM

$$V_{\text{2HDM}} = m_1^2\Phi_1^\dagger + m_2^2\Phi_2^\dagger\Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)$$

After **Spontaneous Symmetry Breaking** :

- two neutral scalar Higgs bosons: **h** and **H**
- a pair of charged Higgs boson $H^\pm$
- a pseudo-scalar **A**

$$\mathscr{L}_{\text{Yukawa}} = -\,\bar{u}_R\mathbf{Y}_u q_L\Phi_1 - \bar{d}_R\mathbf{Y}_d q_L\Phi_2^\dagger - \bar{e}_R\mathbf{Y}_e\ell_L\Phi_2^\dagger + h.c.$$

linear or polar rep. !

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} v_1 + H_1 + iP_1 \\ H_1^- \end{pmatrix}, \qquad \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} H_2^+ \\ v_2 + H_2 + iP_2 \end{pmatrix}$$

with $v_1^2 + v_2^2 = v^2 \sim (246\ \text{GeV})^2$

-neutral CP-even Higges: $\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \# & \# \\ \# & \# \end{pmatrix}\begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$

-charged Higges: $\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \# & \# \\ \# & \# \end{pmatrix}\begin{pmatrix} H_1^\pm \\ H_2^\pm \end{pmatrix}$

-neutral CP-odd Higges: $\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} P_2 \\ P_1 \end{pmatrix}$

DFSZ axion couplings

2. in the polar representation

$$\Phi_1 = \frac{1}{\sqrt{2}} \exp\left\{ i \frac{a}{v} x \right\} \begin{pmatrix} \sqrt{2} H_1^+ \\ v_1 + H_1^0 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \exp\left\{ -i \frac{a}{v} \frac{1}{x} \right\} \begin{pmatrix} \sqrt{2} H_2^+ \\ v_2 + H_2^0 \end{pmatrix}$$

Fermion reparametrization: $\psi \to \exp\left\{ i \frac{PQ(\psi)}{v} a \right\} \psi$

Consequence 1 : non-invariance of the kinetic terms

- Axion **derivative** couplings to fermions :

$$\mathscr{L}_{Der} = -\frac{1}{2f_a} \partial_\mu a \sum_{u,d,e,\nu} \chi_V^f (\bar{\psi}_f \gamma^\mu \psi_f) + \chi_A^f (\bar{\psi}_f \gamma^\mu \gamma^5 \psi_f)$$

Freedom/ambiguity in the PQ charge

	u	d	e	ν
χ_V	$2\alpha + x$	$2\alpha + \frac{1}{x}$	$2\beta + \frac{1}{x}$	β
χ_A	x	$\frac{1}{x}$	$\frac{1}{x}$	$-\beta$

Consequence 2 : non-invariance of the fermionic measure

- Anomalous axion couplings to SM gauge fields at **tree-level** :

(Jacobian of the transformation)

$$\begin{aligned} \delta\mathcal{L}_{Jac} &= \frac{a}{16\pi^2 v} g_s^2 \mathcal{N}_C G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \\ &+ \frac{a}{16\pi^2 v} g^2 \mathcal{N}_L W^i_{\mu\nu} \tilde{W}^{i,\mu\nu} \\ &+ \frac{a}{16\pi^2 v} g'^2 \mathcal{N}_Y B_{\mu\nu} \tilde{B}^{\mu\nu} \end{aligned}$$

$$\mathcal{N}_C = \frac{1}{2}\left(x + \frac{1}{x} \right)$$

$$\mathcal{N}_L = -\frac{1}{2}(3\alpha + \beta)$$

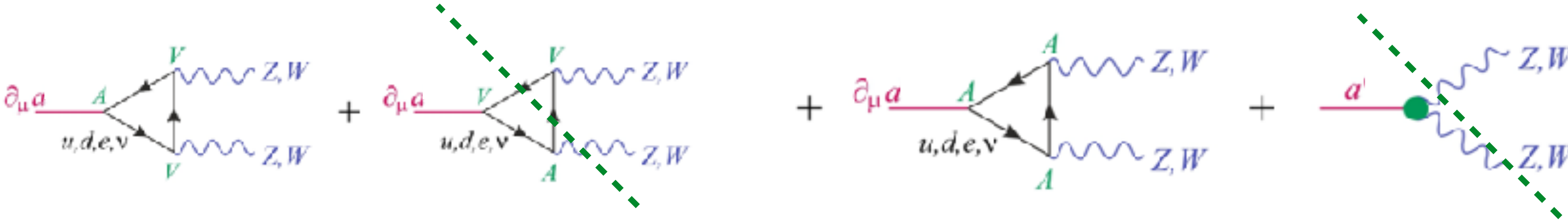
$$\mathcal{N}_Y = \frac{1}{2}(3\alpha + \beta) + \frac{4}{3} x + \frac{1}{3x} + \frac{1}{x}$$

DFSZ axion couplings to SM gauge fields

2. Axion has derivative couplings to fermions

Effective couplings at one loop:

$a \to ZZ, W^+W^-$:



contribute

partially contribute

contribute

does not contribute

Freedom/ambiguity in the PQ charge cancel exactly

2. The anomalous contact int. does cancel out systematically with the anomalous part to the triangle graphs

$$\mathcal{L}_{\text{axion-gauge}} = \underset{\cancel{\text{finite+divergence}}}{\boxed{\delta\mathcal{L}_{\text{Der}}}} + \underset{\cancel{\text{anomaly}}}{\boxed{\delta\mathcal{L}_{\text{Jac}}}}$$

KSZV-like ALPs

- The fermion one-loop coupling arises from an infinite diagram
- Regularizing this diagram may introduce scheme-dependence due to γ_5
- Dependence removed by projecting fermion pair on the $J^{CP} = 0^{-+}$ state
- This yields a result with more physical meaning than the other schemes
- Renormalization scale $\mu = v_a$ identified from two-loop finite process