Axion-like ALPs

Fernando Arias Aragón

Based on 2211.04489 in collaboration
with Jérémie Quevillon and Christopher Smith

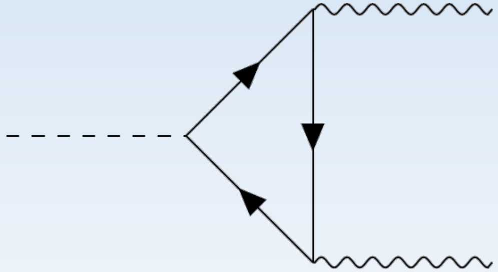
The Strong CP Problem – The Axion Mechanism

- Purely gauge terms proportional to total derivatives can be added to the SM Lagrangian

$$\theta_{QCD}\frac{\alpha_s}{8\pi}G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

$$\frac{\alpha_X}{8\pi}X^{a\mu\nu}\tilde{X}^a_{\mu\nu} = \partial_\mu K^\mu;\ K^\mu = \frac{\alpha_X}{4\pi}\varepsilon^{\mu\nu\alpha\beta}\left(X^a_\nu\partial_\alpha X^a_\beta + \frac{1}{3}f_{abc}X^a_\nu X^b_\alpha X^c_\beta\right)$$

- The $G\tilde{G}$ term is related to quark masses through the chiral anomaly



$$\bar{\theta} = \theta_{QCD} + \mathbf{Arg}\left(\mathbf{Det}\left(M_u M_d\right)\right)$$

- The observable parameter, $\bar{\theta}$ is bound by its relation to the neutron EDM, d_n

Crewther, Di Vecchia, Veneziano & Witten, 1980

Baker et al., 0602020 Afach et al., 1509.04411

$$d_n \sim \bar{\theta} \times 10^{-16} e \cdot cm, \qquad \bar{\theta} \lesssim \mathcal{O}(10^{-10})$$

- Why is a dimensionless parameter so small?

The Strong CP Problem – The Axion Mechanism

Peccei and Quinn, PRL 38 (1977) 1440-1443 and PRD 16 (1977) 1791-1797

- $\bar{\theta}$ becomes dynamical by introducing an axial global symmetry $U(1)_{PQ}$, broken spontaneously

Weinberg, PRL 40 (1978) 223-226
Wilczek, PRL 40 (1978) 279-282

- Its NGB, the axion a, couples to gluons through the chiral anomaly

$$\mathcal{L}_{aGG} = \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{a\mu\nu}\tilde{G}^a_{\mu\nu} \longrightarrow \theta_{eff} = \bar{\theta} + \frac{a}{f_a}$$

- Non-perturbative QCD creates a potential that ensures CP conservation

$$V_{eff} \sim 1 - \sqrt{1 + \cos\left(\bar{\theta} + \frac{a}{f_a}\right)} \longrightarrow \langle a \rangle = -f_a\bar{\theta}$$

- The original model, the PQWW axion broke $U(1)_{PQ}$ with **two Higgs doublets**
- As a consequence, the axion scale was too low and should have been observed already

$$f_a \sim v \approx 246 \text{ GeV}$$

- More elusive axions are required!

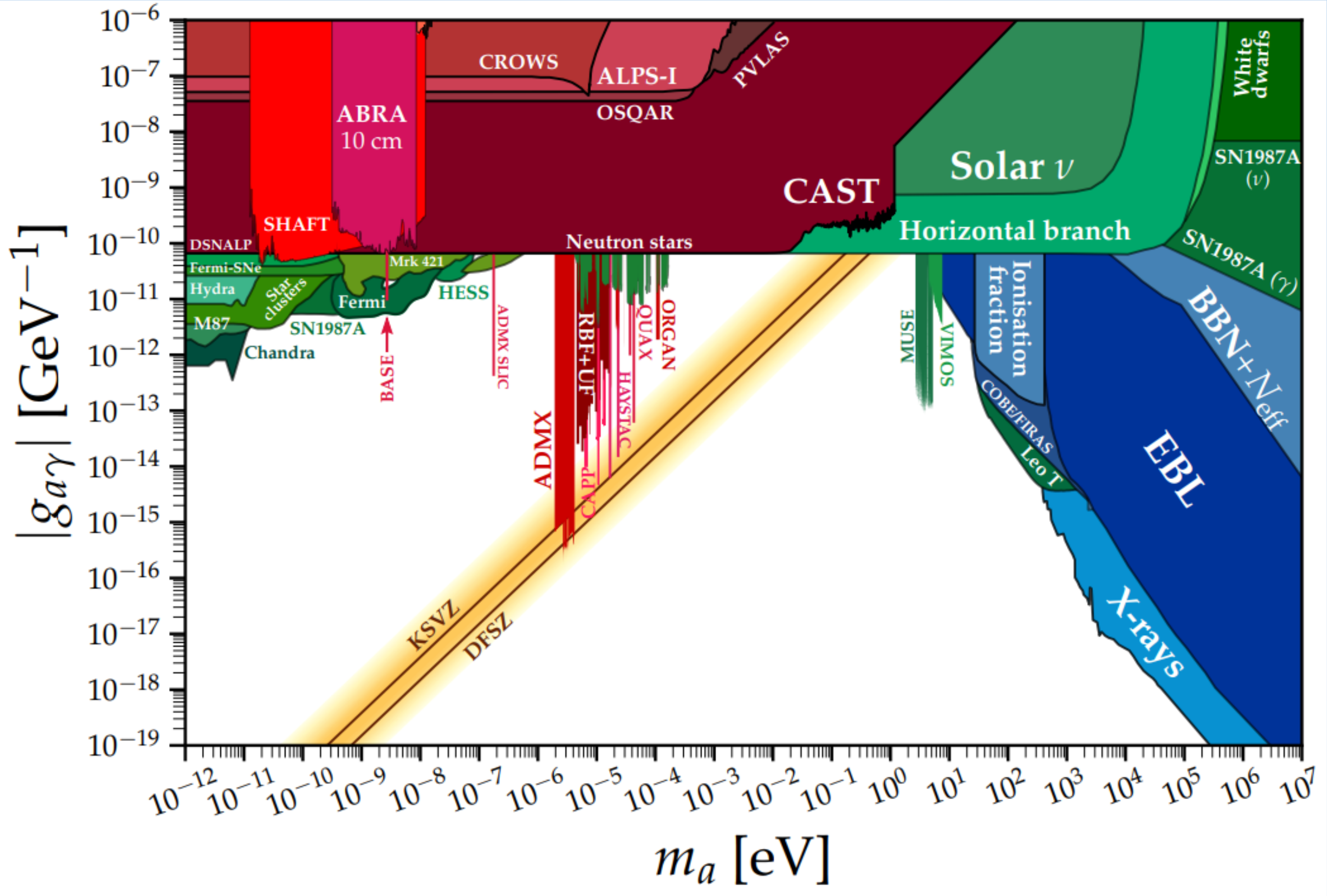
The Strong CP Problem – Invisible Axions

- DFSZ Axion (2HDM+ϕ_{PQ}) A. R. Zhitnitsky, Sov. J. Nucl. Phys. 31 (1980); M. Dine, W. Fischler, M. Srednicki, Phys. Lett. B104 (1981)
  - Adds a new scalar SM singlet, ϕ, to the PQWW particle content
  - ϕ is charged under $U(1)_{PQ}$ with $\phi^2 H_u^\dagger H_d$ and has a VEV $v_\phi \gg v \approx 246$ GeV
  - The axion arises as a combination of the different pseudoscalars, with a scale $f_a \simeq \frac{v_\phi}{2} \gg v$
- KSVZ Axion J. E. Kim, PRL 43 (1979); M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, Nucl. Phys. B166 (1980)
  - The SM is neutral under $U(1)_{PQ}$, only vector heavy quark Q and singlet complex scalar σ have PQ charges
  - The axion is the angular part of σ, invisible thanks to the large VEV $v_\sigma \gg v$
  - KSVZ axion couples to SM fermions at a two-loop level
- Axion-gluon coupling implies a scale-mass relation shared by all these axions

$$m_a = 5.691(51)\left(\frac{10^9\ \text{GeV}}{f_a}\right)\ \text{meV}$$

The Strong CP Problem – Invisible Axions

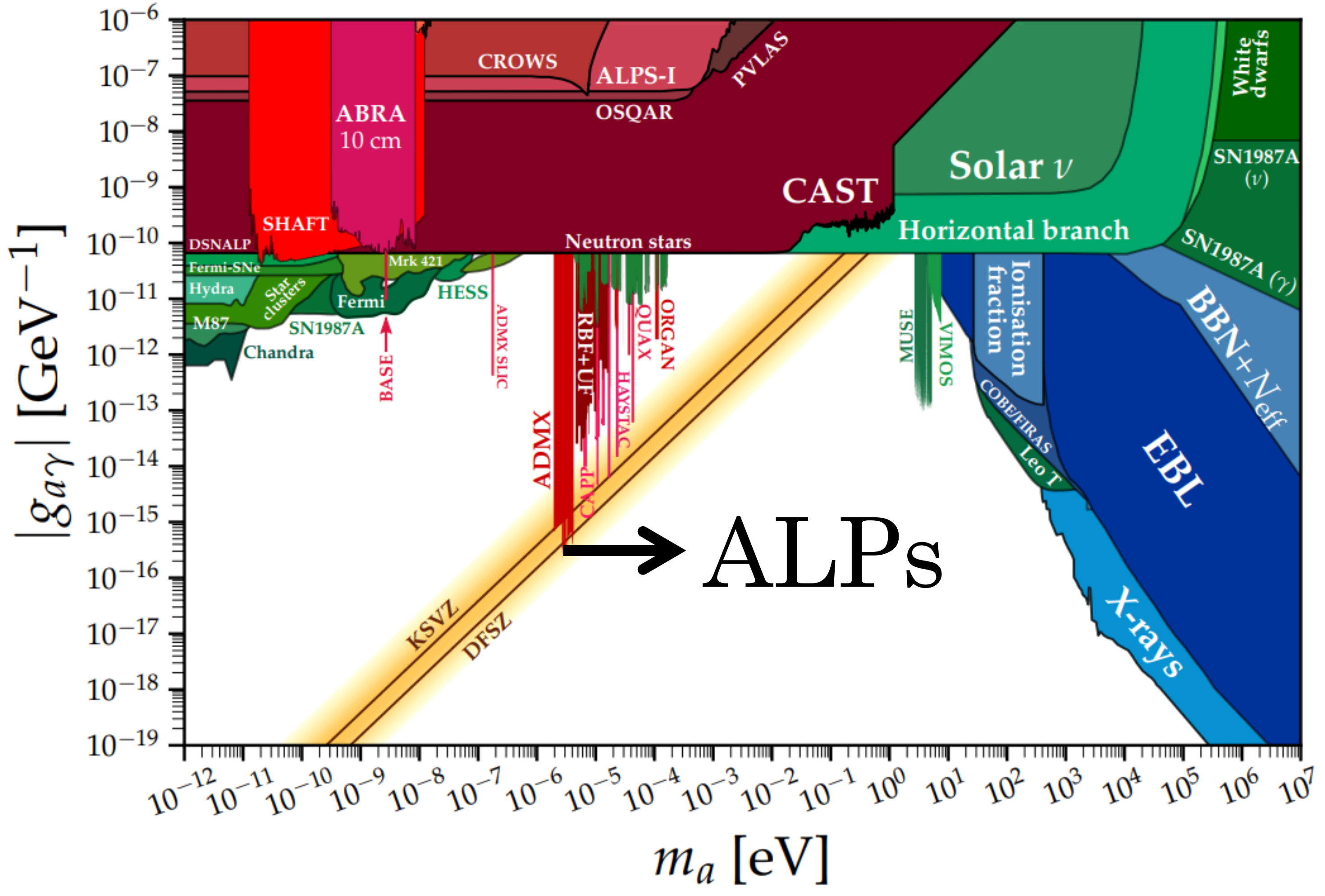
PDG 2022



$$m_a = 5.691(51)\left(\frac{10^9\ \text{GeV}}{f_a}\right)\ \text{meV}$$

The Strong CP Problem – Invisible Axions

PDG 2022



$$m_a \times 5.691(51)\left(\frac{10^9\ \mathrm{GeV}}{f_a}\right)\ \mathrm{meV}$$

ALPs in Effective Field Theories

- EFTs useful for model independent studies
- ALP EFT: derivative fermionic + anomalous bosonic couplings

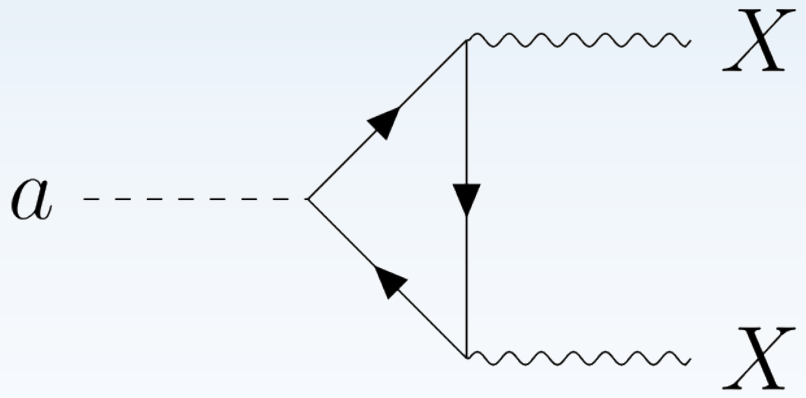
$$\mathscr{L}_{ALP} = \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a a\right) - i \sum_f \frac{\chi_f}{v_a} \partial^\mu a \bar{f} \gamma_\mu f + \frac{a}{16\pi^2 v_a}\left(g_s^2 \mathcal{N}_C G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} + g^2 \mathcal{N}_L W^i_{\mu\nu} \tilde{W}^{i,\mu\nu} + g'^2 \mathcal{N}_Y B_{\mu\nu} \tilde{B}^{\mu\nu}\right)$$

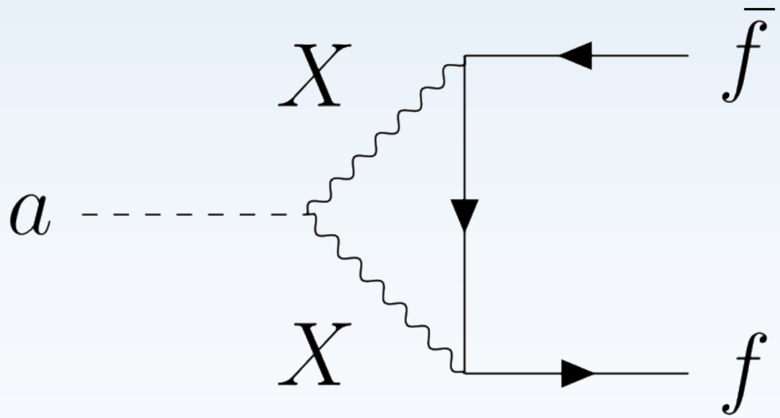
- m_a and v_a no longer correlated
- ALP couplings, χ_f and $\mathcal{N}_X$, independent in this approach
- Is this situation reasonable from a UV point of view?

ALPs in Effective Field Theories

J. Quevillon and C. Smith, 1903.12559

- Anomalous character of $U(1)_{PQ}$ tricky when considering W and Z bosons
- Imposing consistency conditions reduces number of free parameters
- DFSZ-like ALP: pseudoscalar coupling to fermions $\Rightarrow \mathcal{N}_X \equiv f(\chi_f)$
- KSVZ -like ALP: couplings to heavy quarks $\Rightarrow \mathcal{N}_X \Rightarrow \chi_f \equiv f(\mathcal{N}_X)$
- These scenarios represent benchmark for ALP searches

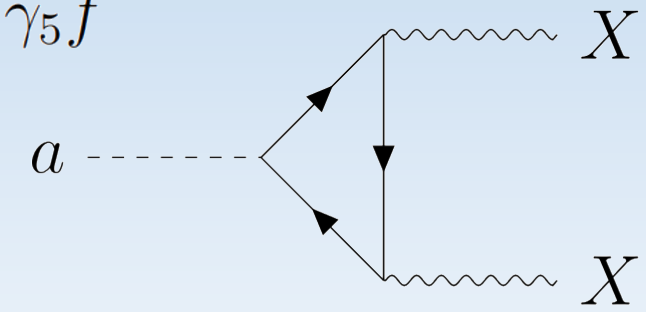




DFSZ-like ALPs

- Original DFSZ: 2HDM plus extra scalar ϕ_{PQ}
- Generalized DFSZ: pseudoscalar coupling to fermions with three independent χ_f

$$\mathscr{L}_{DFSZ} = \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 aa\right) - i \sum_{f=u,d,e} \frac{m_f}{v_a} \chi_f a \bar{f} \gamma_5 f$$



- One-loop induced couplings to gauge bosons

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

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

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

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

DFSZ-like ALPs

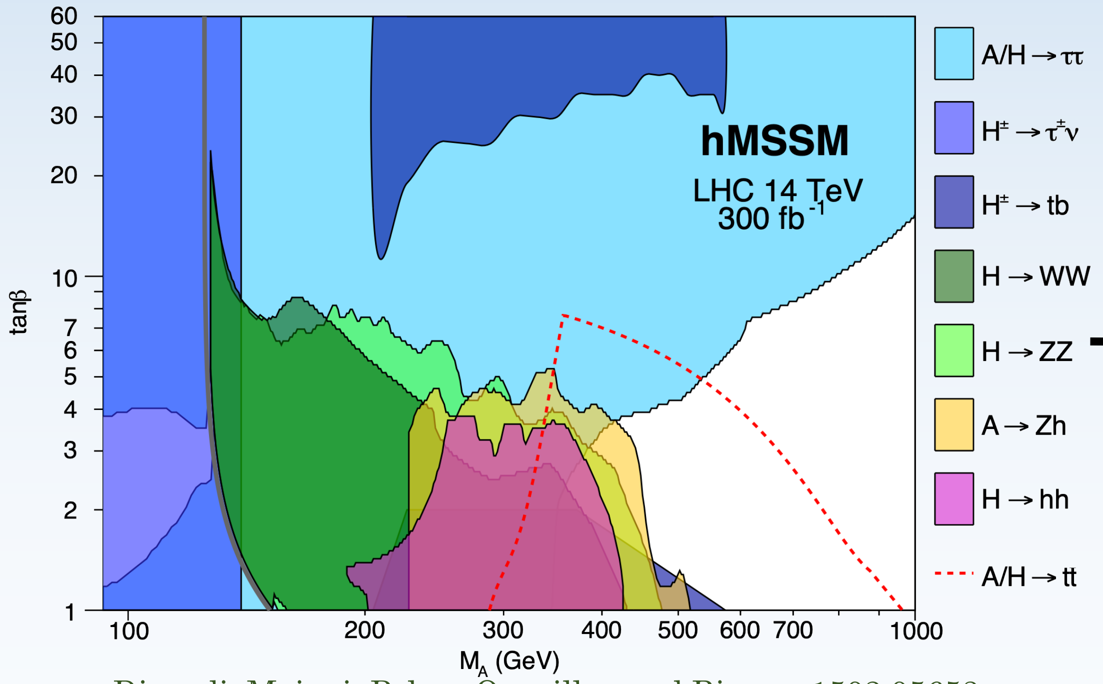
- Four physical parameters, χ_f/v_a and m_a as opposed to seven in the generic EFT
- g_{aXX} now a function of the ALP mass
- Non-linear correlations among EW g_{aXX} in the broken phase
- Measuring g_{agg}, $g_{a\gamma\gamma}$ and $g_{aZ\gamma}$ fixes g_{aWW} and g_{aZZ} in the pure EFT
- In DFSZ-like scenario one degree of freedom remains: curve in the g_{aWW} and g_{aZZ} space

DFSZ-like ALPs – A more constrained case

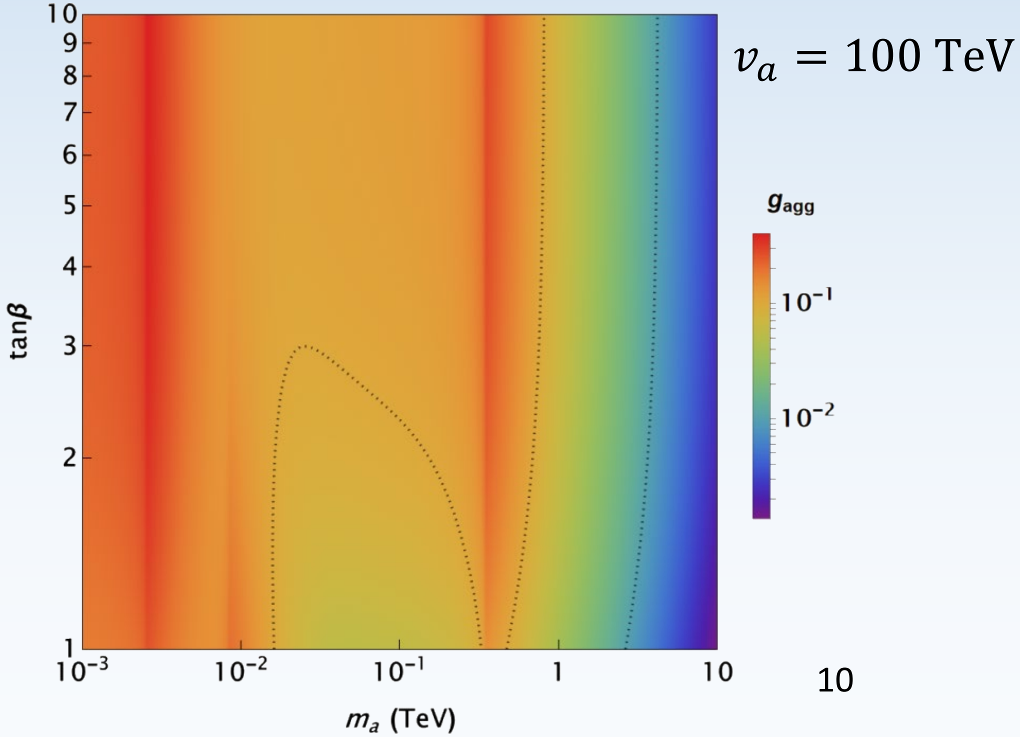
- Micmicking the 2HDM type-II pseudoscalar couplings:

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

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



Djouadi, Maiani, Polosa,Quevillon and Riquer, 1502.05653



KSVZ-like ALPs

- After integrating out heavy quarks, ALP-gauge boson $SU(2)_L \times U(1)_Y$ invariant couplings

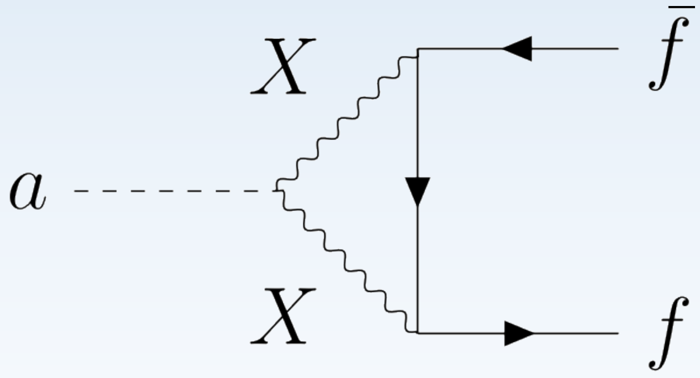
$$\mathcal{L}_{KSVZ} = \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 aa\right) + \frac{a}{16\pi^2 v_a}\left(g_s^2 \mathcal{N}_C G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + g^2 \mathcal{N}_L W^i_{\mu\nu}\tilde{W}^{i,\mu\nu} + g'^2 \mathcal{N}_Y B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

$$g_{agg} = \alpha_s \mathcal{N}_C$$
$$g_{a\gamma\gamma} = \alpha\left(\mathcal{N}_L + \mathcal{N}_Y\right)$$

$$g_{a\gamma Z} = 2\alpha\left(-\mathcal{N}_L/t_W + t_W \mathcal{N}_Y\right)$$
$$g_{aZZ} = \alpha\left(\mathcal{N}_L/t_W^2 + t_W^2 \mathcal{N}_Y\right)$$
$$g_{aWW} = \frac{2\alpha}{s_W^2}\mathcal{N}_L$$

- One-loop coupling to SM fermions

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

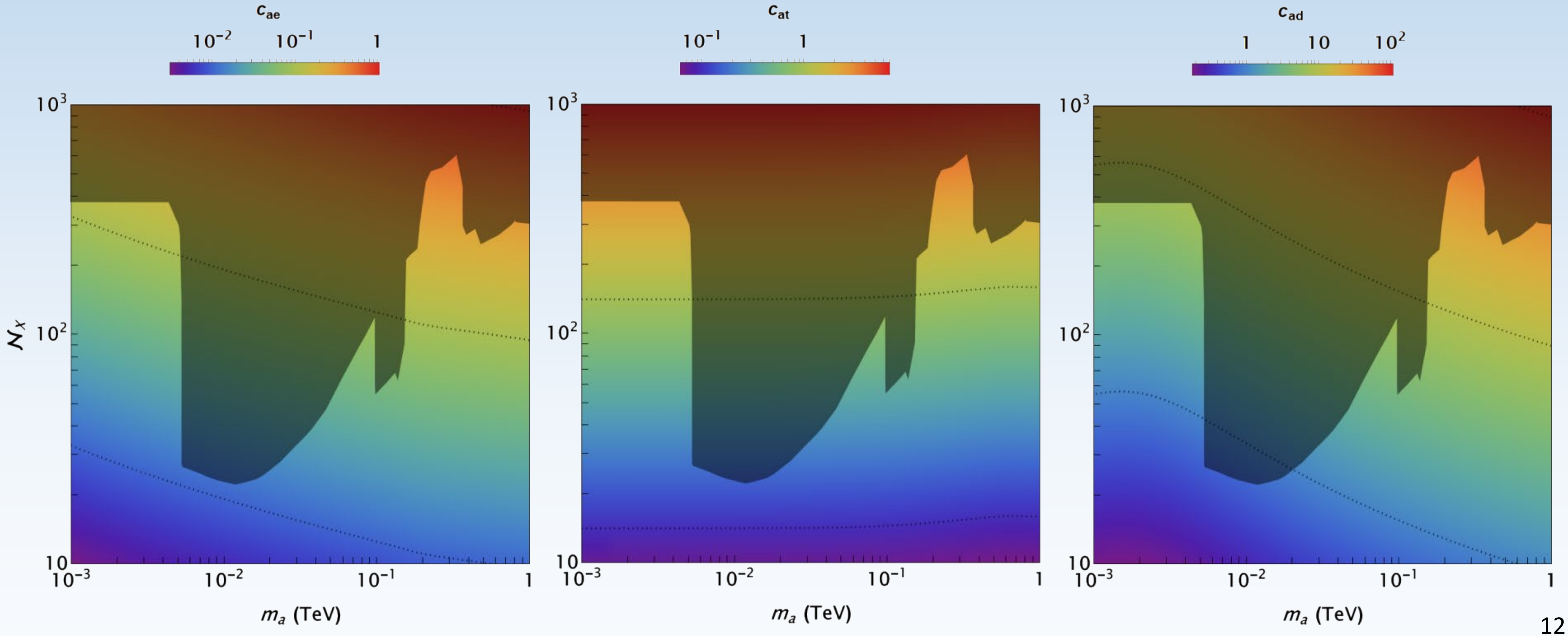


$$c_{af} = 16\left(\alpha^2 Q_f^2\left(\mathcal{N}_L + \mathcal{N}_Y\right) + \alpha_s^2 \frac{4}{3}\mathcal{N}_C\right) I_0 - \frac{\alpha^2(\mathcal{N}_L/t_W^2 + t_W^2 \mathcal{N}_Y)}{s_W^2 c_W^2} I_{ZZ}$$
$$+ \frac{16\alpha^2 Q_f (T_f^3 - 2Q_f s_W^2)(-\mathcal{N}_L/t_W + t_W \mathcal{N}_Y)}{s_W c_W}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

KSVZ-like ALPs

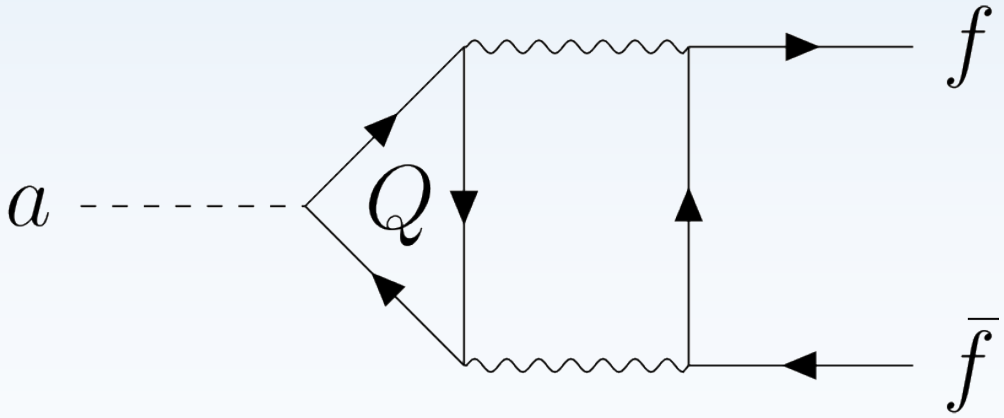
- Parameter space easy to bound with, for example, limits on $g_{a\gamma\gamma}$

$$\mathcal{N}_C = \mathcal{N}_L = \mathcal{N}_Y \equiv \mathcal{N}_X \qquad v_a = 1\ \text{TeV}$$



KSVZ-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 other schemes
- Renormalziation scale $\mu = v_a$ identified from two-loop finite process



Conclusions

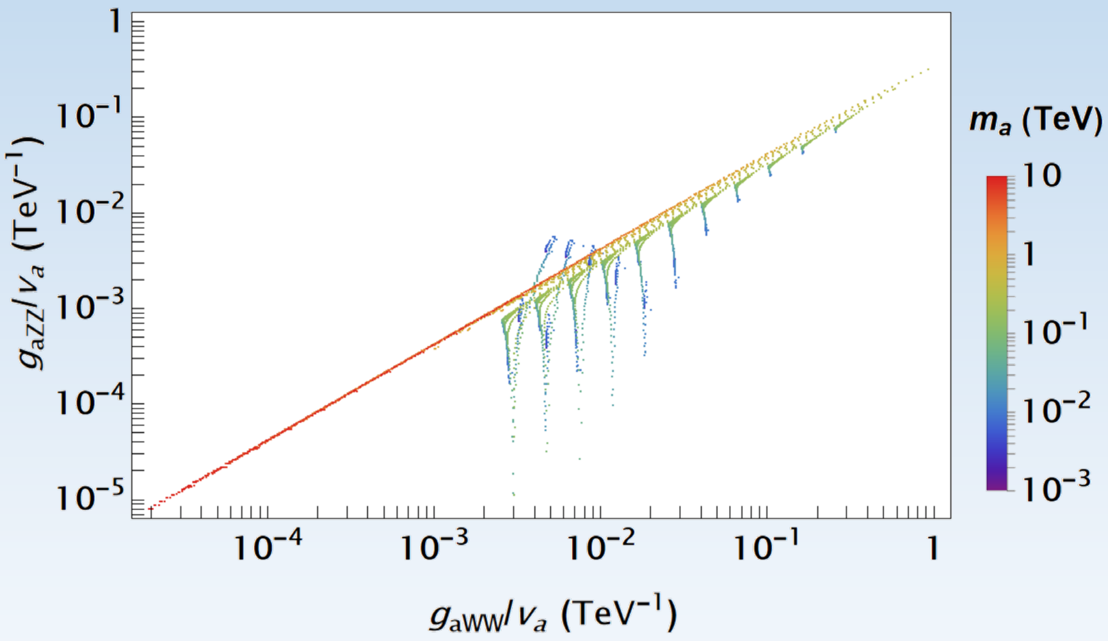
- DFSZ-like and KSVZ-like benchmarks presented
- Inconsistencies and scheme dependences avoided
- Different set of parameters identified, reduced with respect to pure EFT
- Scenarios easy to constrain, in particular DFSZ-like through 2HDM searches
- Full dedicated analysis with all bounds required!

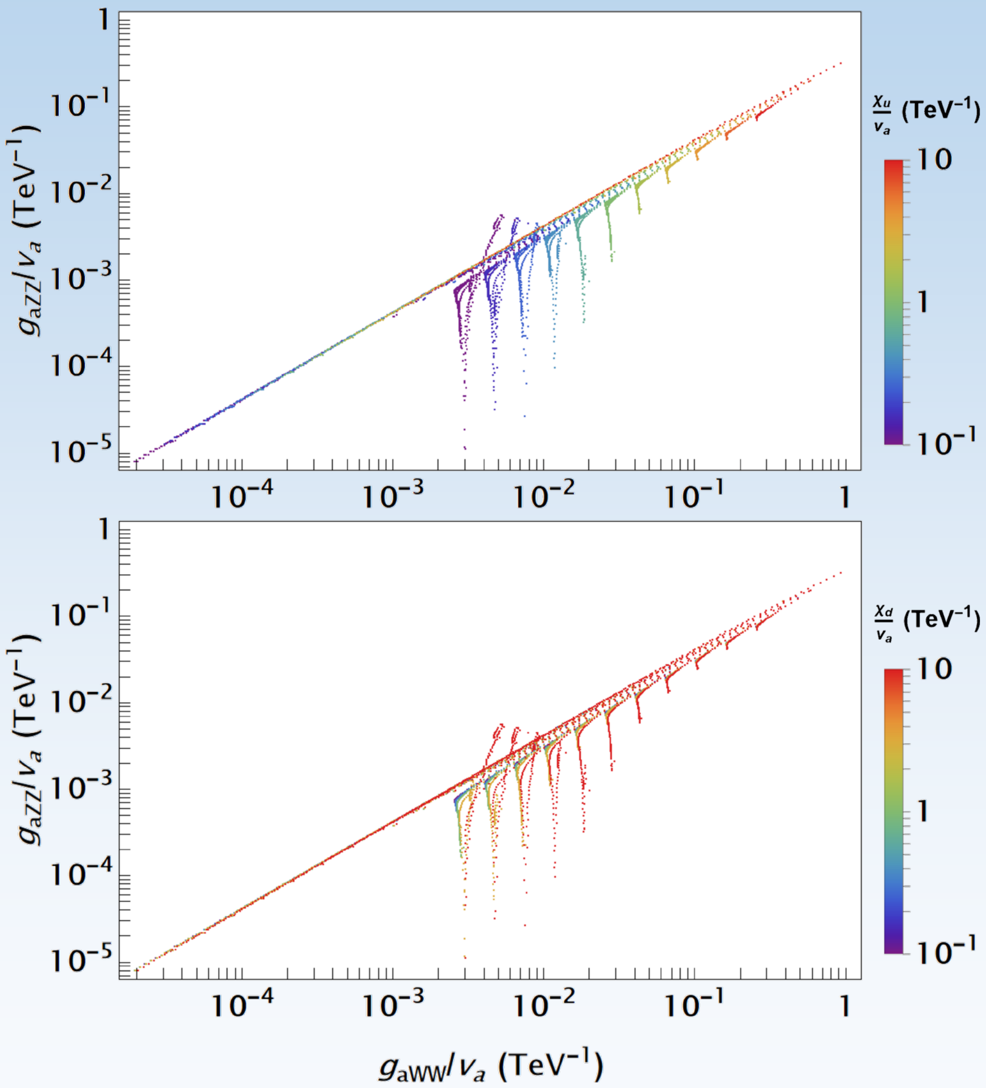
Thank you for your attention

DFSZ-like ALPs

$g_{a\gamma\gamma}/v_a = 0$

$v_a = 1$ TeV

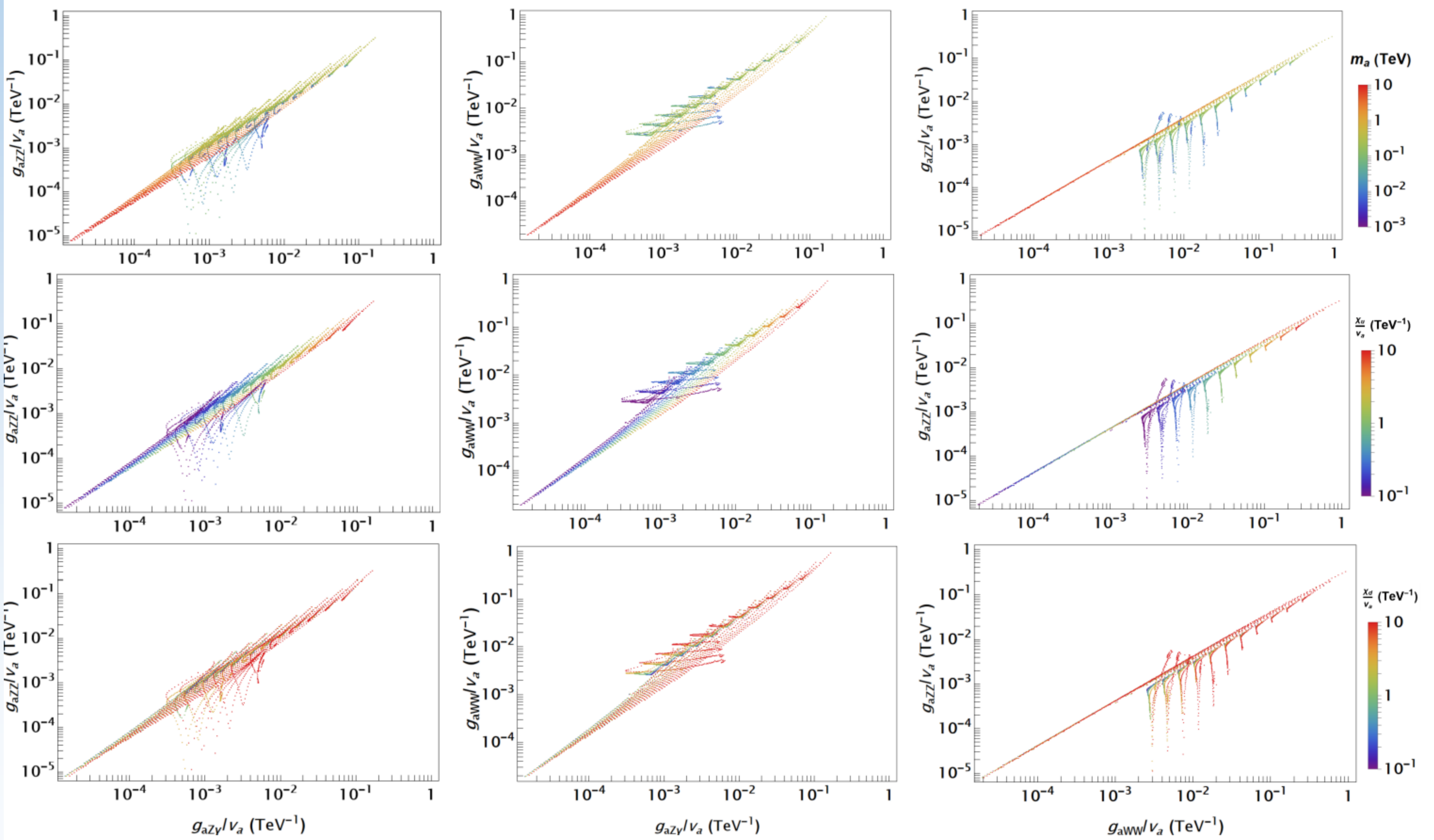




$g_{a\gamma\gamma}/v_a = 0$

DFSZ-like ALPs

$v_a = 1$ TeV



KSVZ-like ALPs

$$I_0 = \int \frac{d^d k}{(2\pi)^d} \frac{k^2 - (k \cdot p)^2/m_a^2}{k^2(p-k)^2\left((p_1-k)^2 - m_f^2\right)}$$

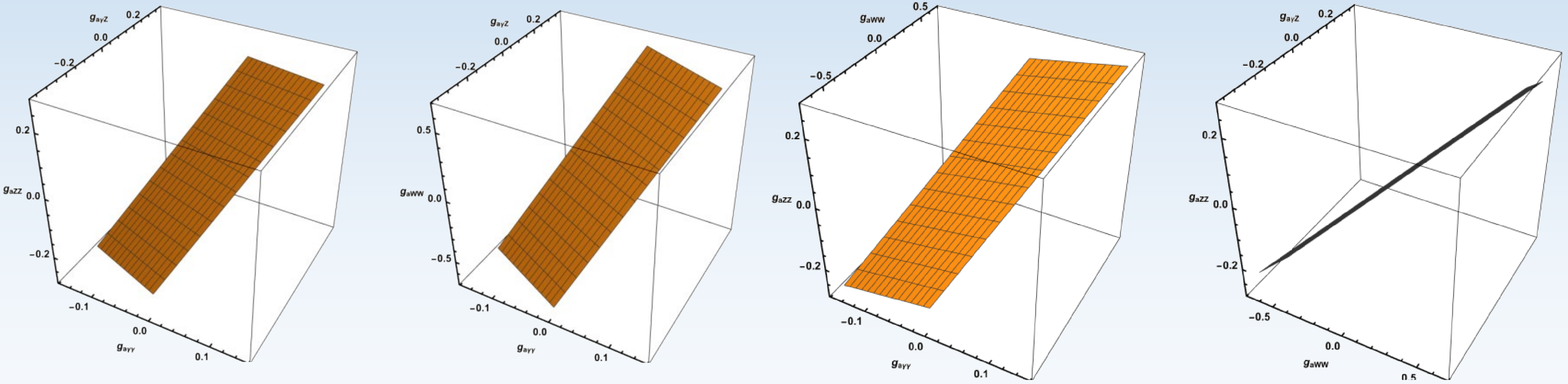
$$I_{\gamma Z} = \int \frac{d^d k}{(2\pi)^d} \frac{k^2 - (k \cdot p)^2/m_a^2}{(k^2 - M_Z^2)(p-k)^2\left((p_1-k)^2 - m_f^2\right)}$$

$$I_{ZZ} = \int \frac{d^d k}{(2\pi)^d} \frac{((k \cdot p) - 2(k \cdot p_1) + 2F_f k^2) - 2F_f (k \cdot p)^2/m_a^2}{\left((p_1-k)^2 - m_f^2\right)(k^2 - M_Z^2)\left((p-k)^2 - M_Z^2\right)}$$

$$I_{WW} = \int \frac{d^d k}{(2\pi)^d} \frac{((k \cdot p) - 2(k \cdot p_1) + 2k^2) - 2(k \cdot p)^2/m_a^2}{\left((p_1-k)^2 - m_{f'}^2\right)(k^2 - M_W^2)\left((p-k)^2 - M_W^2\right)}$$

KSVZ-like ALPs

- ALP-gauge boson couplings independent of the ALP mass
- Linearly dependent on only two free parameters, $\mathcal{N}_L$ and $\mathcal{N}_Y$



KSVZ-like ALPs

$$P_{S=0} = \frac{1}{2\sqrt{2p^2}}\left(-\frac{1}{2}\varepsilon_{\rho\sigma\mu\nu}(p_1^\rho p_2^\sigma - p_1^\sigma p_2^\rho)\sigma^{\mu\nu} + (p^2 - 2m_f(\not{p}_1 + \not{p}_2))\gamma_5\right)$$

$$\mathcal{M}(a \to f\bar{f}) = \bar{u}(p_1)T(a \to f\bar{f})v(p_2) = \bar{u}(p_1)\gamma_5 v(p_2)F(a \to f\bar{f})$$

$$F(a \to f\bar{f}) = \frac{1}{\sqrt{2p^2}}\mathrm{Tr}(P_{S=0}T(a \to f\bar{f}))$$

KSVZ-like ALPs

- Photon contribution to ALP-fermion coupling in Larin's scheme

$$c_{af}^{\gamma\gamma} = c\left(D_\epsilon + \ln \frac{\mu^2}{m_f^2} - \frac{4}{3} \right) + \ldots$$

- Our computation

$$c_{af}^{\gamma\gamma} = c\left(D_\epsilon + \ln \frac{\mu^2}{m_f^2} + \frac{5}{3} \right) + \ldots$$

- Full two-loop computation

$$c_{af}^{\gamma\gamma} = c\left(0 + \ln \frac{m_Q^2}{m_f^2} + \frac{17}{6} + \frac{5}{27} \frac{m_f^2}{m_Q^2} \ln \frac{m_Q^2}{m_f^2} + \frac{11}{54} \frac{m_f^2}{m_Q^2} + \ldots \right)$$