Revising the phenomenology of axion-like particles coupled to fermions

Giovani Dalla Valle Garcia, Felix Kahlhoefer, Maksym Ovchynnikov, Andrii Zaporozhchenko

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To be submitted on arXiv soon

ALPs coupled to fermions I

– Lagrangian of generic ALPs:

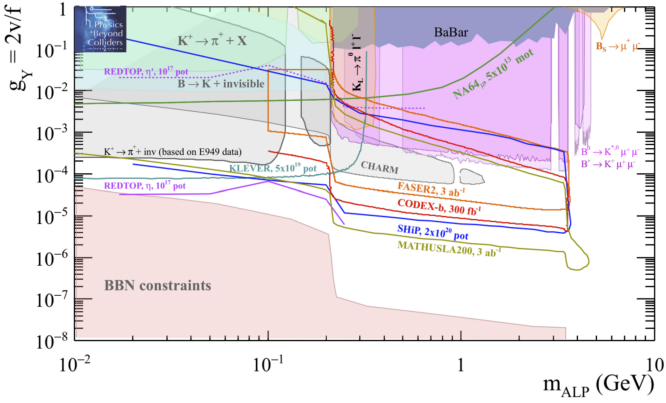
$$\mathcal{L} = \frac{a}{f}\left(c_{GG}\frac{\alpha_s}{4\pi}G^c_{\mu\nu}\tilde{G}^{\mu\nu,c} + c_{WW}\frac{\alpha_W}{4\pi}W^{\mu\nu,c}\tilde{W}^c_{\mu\nu} + c_{BB}\frac{\alpha_B}{4\pi}B_{\mu\nu}\tilde{B}^{\mu\nu}\right) + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\Psi}_F\, C_F\, \gamma_\mu\, \Psi_F \tag{1}$$

– ALPs universally coupled to fermions:

$$\mathcal{L}_{\text{eff}} = \frac{\partial_\mu a}{f}\left(c_\ell \sum_\ell \bar{\ell}\gamma^\mu\gamma_5\ell + c_q\sum_q \bar{q}\gamma^\mu\gamma_5 q\right) \tag{2}$$

ALPs coupled to fermions II

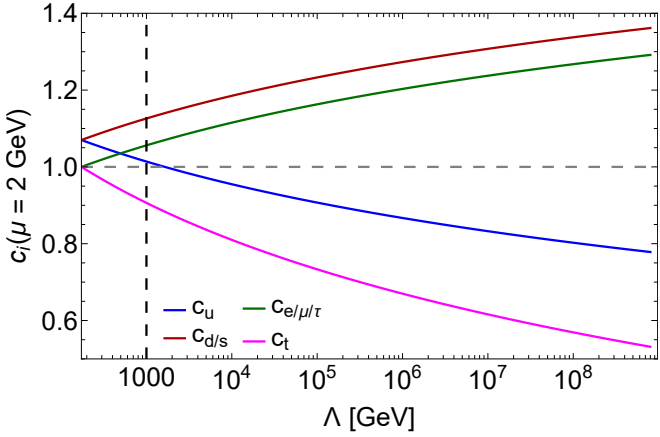
- Commonly adopted phenomenology of GeV-scale ALPs [1901.09966]:
  - missing production channels
  - missing hadronic decays
- These features significantly affect constraints from past experiments and sensitivities of future experiments



The ALP phenomenology has to be revised

RG flow and effective interactions I

- The model (2) is defined at some scale $\Lambda > \Lambda_{\rm EW}$
- To describe the GeV scale ALP phenomenology, one needs to know the RG flow down to the scale $\Lambda \sim m_a$ (see [2110.10698])



Fermions have different weak isospin ⇒ breakdown of the fermion universality

RG flow and effective interactions II

– Effective interactions generated from the Lagrangian (2):
  1. FCNC couplings
     $\mathcal{L} = C_{qq'} a\bar{q}(1+\gamma_5)q' + \text{h.c.}$
  2. The coupling to gluons aGG
  3. The coupling to photons $a\gamma\gamma$

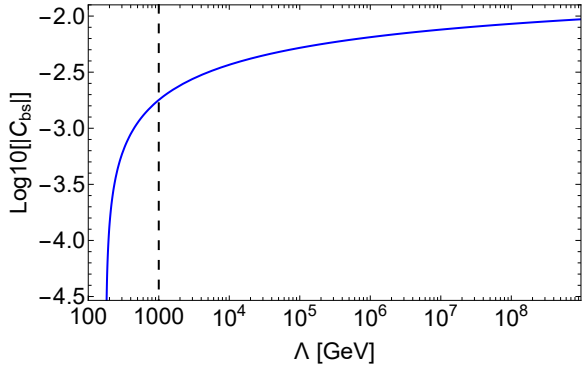


Figure: $C_{bs} \propto f^{-2}$. $f = 1$ TeV in the plot.

– The FCNC couplings strongly depend on Λ, the other interactions are weakly sensitive to it

ALP production I

- **Production channel 1**: mixing with light mesons $m^0 = \pi^0, \eta, \eta'$
- Production cross-section:

$$\sigma_{a,\text{mixing}} \approx |\theta_{m^0 a}|^2 \sigma_{m_0}, \qquad (3)$$

where $\theta_{m^0 a}$ is the mixing angle

- Mixing with π^0 strongly depends on the scale Λ since includes $c_u - c_d$

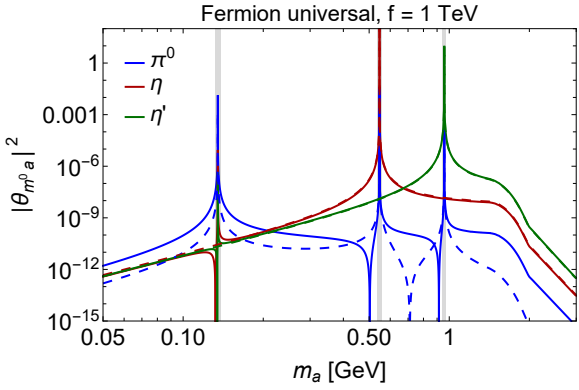
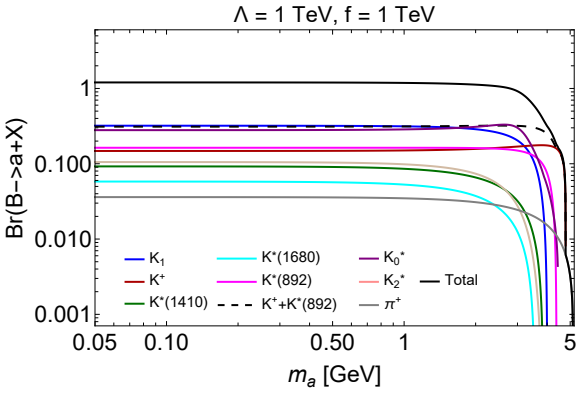


Figure: Solid: $\Lambda = \Lambda_{\text{EW}}$. Dashed: $\Lambda = 1$ TeV

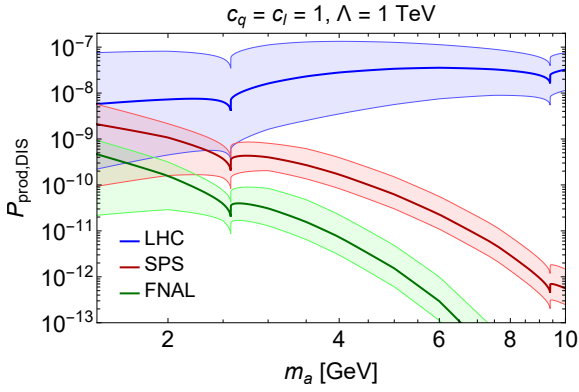
ALP production II

- **Production channel 2**: decays $B \to a + X_{s/d}$, $K \to a + \pi$
- Originates from the FCNC couplings
- Previously unaccounted channels $B \to a + K_1/K_0^*/K_2^*/K^*(1410)$ increase the total production rate by a factor of 4



ALP production III

- **Production channel 3**: gluon fusion
- Hard process: $g + g \to a$
- Huge theoretical uncertainties:
  1. $\sigma_{\text{fusion,hard}} \propto \alpha_s^2(m_a) \Rightarrow$ large dependence on scale variations
  2. The production of the ALP is forward $\Rightarrow$ needs to know PDFs at very small x



ALP production IV

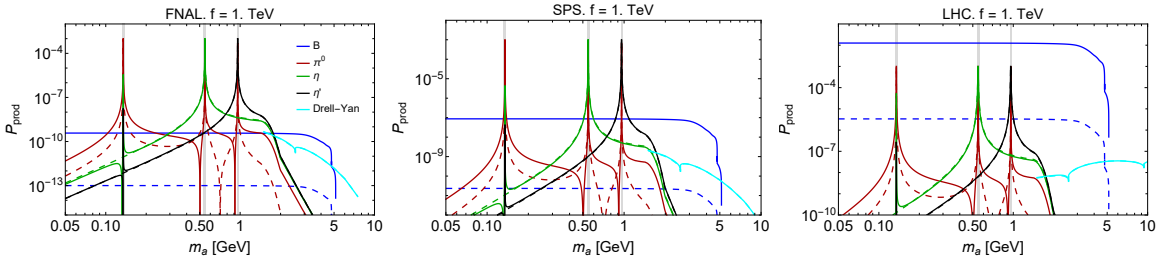


Figure: Solid: $\Lambda = 1$ TeV. Dashed: $\Lambda = \Lambda_{\rm EW}$

– Consider three facilities where ALPs may be produced: FNAL, SPS, LHC

Different yields of B mesons + Λ dependence $\Rightarrow$ various production channels may dominate at various facilities

ALP production V

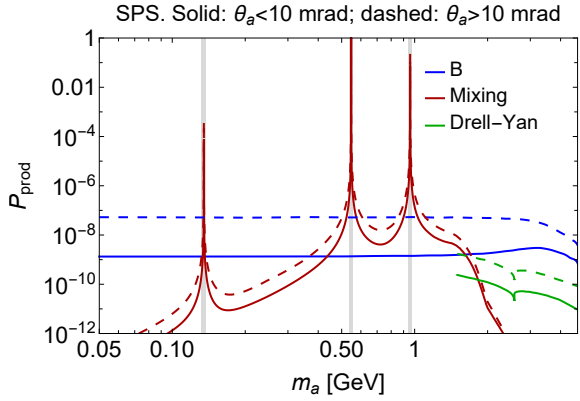
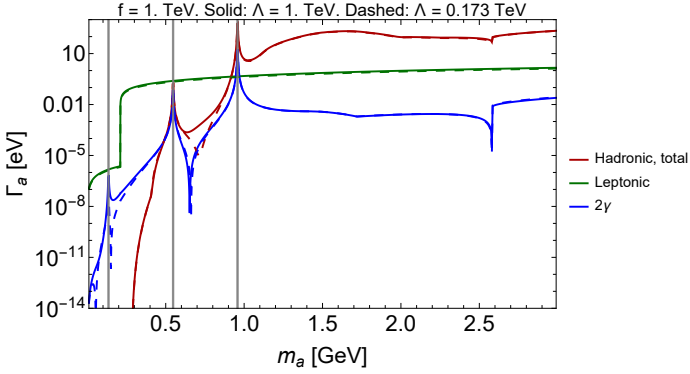


Figure: $\Lambda = 0.3$ TeV

– The dominant production channel also depends on the angular coverage of the experiment

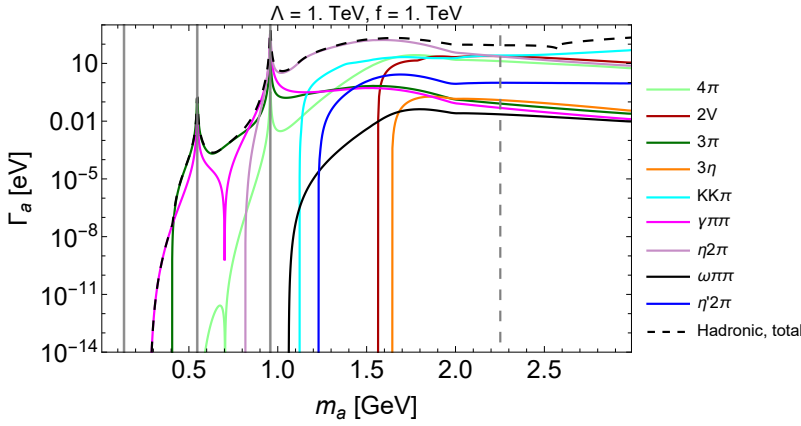
ALP decays I

- Non-hadronic decays: into a pair of leptons/photons
- Hadronic ALP decays: for $m_a \gg \Lambda_{\rm QCD}$ – perturbative QCD description, for $m_a \lesssim 1-2$ GeV – description in terms of mesons



Leptonic decays dominate below 1 GeV, hadronic decays - for higher masses

ALP decays II



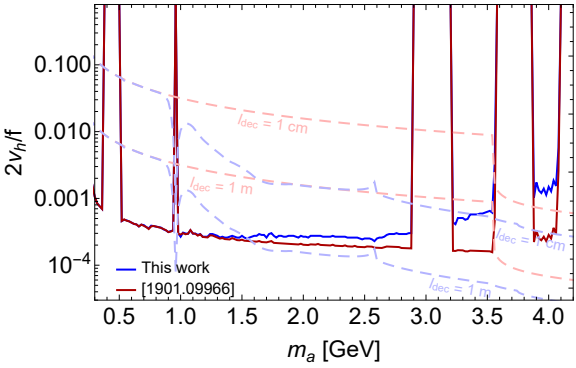
– Hadronic width below $m_a \approx 2$ GeV: ChPT + phenomenological interactions with scalar, vector, and tensor mesons determined by symmetry arguments and to fit data (see, e.g., 2110.10691)

– Matching mass between perturbative QCD and ChPT: $m_a \approx 2.2$ GeV

How constraints and sensitivities are affected (in preparation) I

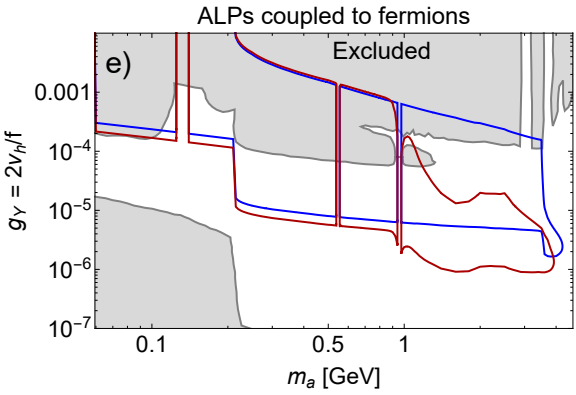
Fix the model: $\Lambda = 1$ TeV

- **Case 1**: LHCb constraints
- Searches $B \to K(a \to)\mu\mu$, no peaks in $m_{\mu\mu}$ seen over background
- Revised phenomenology: $\mathrm{Br}(a \to \mu\mu)$ and lifetime $c\tau$ are much shorter $\Rightarrow$ weaker constraints



How constraints and sensitivities are affected (in preparation) II

- **Case 2**: sensitivities of future experiments
- MATHUSLA as an example
- Computed using `SensCalc`
  See also Jean-Loup's talk tomorrow



Above 1 GeV, entirely different probed parameter space: $c\tau$ becomes parametrically much shorter

Summary

- The phenomenology of ALPs universally coupled to fermions has been revised: **new production channels**, **hadronic decays**
- The revised phenomenology leads to a huge change in the parameter space of the model constrained by past experiments/accessible by future experiments
- Together with the preprint (to be submitted soon), we release a `Mathematica` notebook allowing to produce tabulated widths/production probabilities
- The phenomenology has been implemented in `SensCalc` – to compute the changes of the sensitivities of future experiments at FNAL, SPS, LHC, FCC-hh

Backup slides