Revising the phenomenology of axion-like particles coupled to fermions

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Based on [2310.03524]

LLPs: problems with phenomenology description

- Our understanding of the LLP phenomenology at colliders is far from being complete
- Examples of the unclosed questions:
  1. Proton bremsstrahlung [2306.15800]
  2. Production via mixing with neutral mesons [2201.05170]
  3. Hadronic decay width around Λ_{QCD} and its matching with perturbative width [1806.07759]
  4. ...
- Uncertainties in these processes dominate the total uncertainty in the event rate prediction: orders of magnitude!
- Revisions of these questions are ongoing

ALPs coupled to fermions: prominent example I

Pattern	PBC classification
$C_{BB} \neq 0,\ C_{F,GG,WW} = 0$	BC9
Universal C_F, $C_{BB,GG,WW} = 0$	BC10
$C_{GG} \neq 0,\ C_{F,BB,WW} = 0$	BC11

– Lagrangian of generic ALPs:

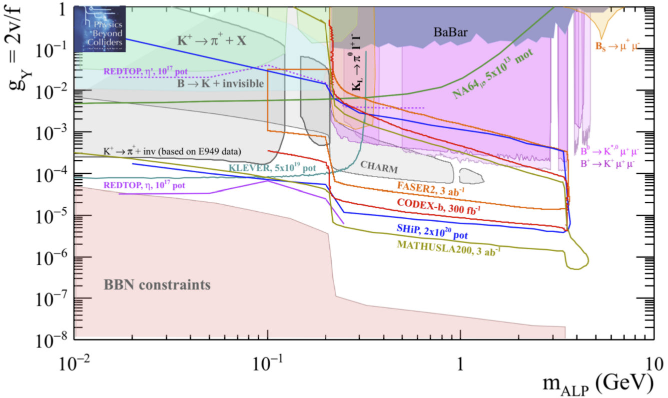
$$\mathcal{L} = \frac{a}{F}\left(C_{GG}\frac{\alpha_s}{4\pi}G^c_{\mu\nu}\tilde{G}^{\mu\nu,c} + C_{WW}\frac{\alpha_W}{4\pi}W^{\mu\nu,c}\tilde{W}^c_{\mu\nu} + C_{BB}\frac{\alpha_B}{4\pi}B_{\mu\nu}\tilde{B}^{\mu\nu}\right) + \frac{\partial^\mu a}{F}\sum_F \bar{\Psi}_F\, C_F\, \gamma_\mu\, \Psi_F \tag{1}$$

– ALPs universally coupled to fermions – **BC10** model:

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

ALPs coupled to fermions: prominent example II

- Commonly adopted BC10 phenomenology [1901.09966]:
  - Missing production channels
  - Missing hadronic decays (at all!)
- These features significantly affect constraints from past experiments and sensitivities of future experiments

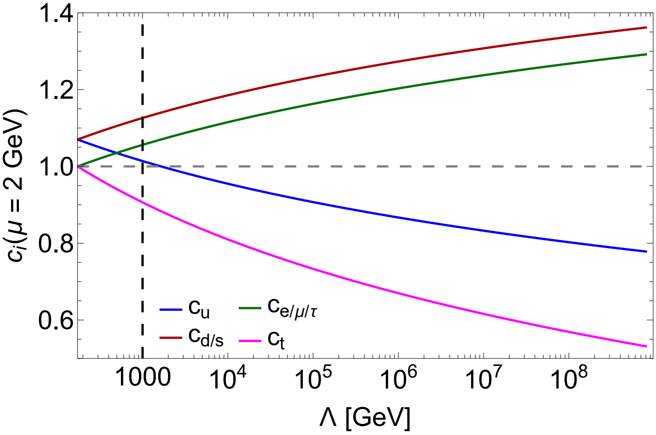


The ALP phenomenology has to be revised

RG flow and effective interactions I

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

$$c_f(\mu) \equiv \frac{C_f(\mu)}{C_f(\Lambda)}, \quad f \equiv \frac{F}{C_F(\Lambda)}$$



Fermions have different weak isospin ⇒ breakdown of the fermion universality

RG flow and effective interactions II

Effective interactions generated from the Lagrangian (2):

- FCNC couplings
  $\mathcal{L} = C_{qq'} a\bar{q}(1+\gamma_5)q' + \text{h.c.}$
- With gluons: $\mathcal{L} \propto aG_{\mu\nu}\tilde{G}^{\mu\mu}$
- With photons: $\mathcal{L} \propto aF_{\mu\nu}\tilde{F}^{\mu\mu}$

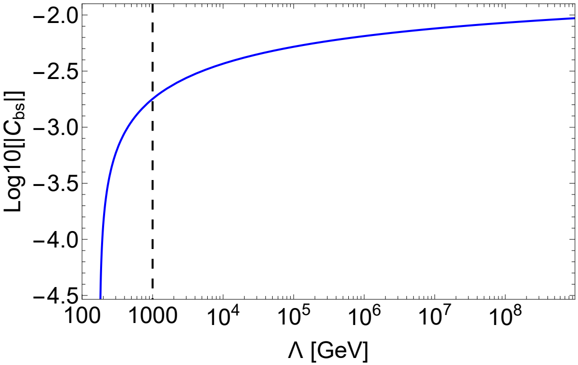


Figure: $C_{bs}(\mu = 2\text{ GeV})$. $f = 1$ TeV in the plot.

- The FCNC couplings strongly depend on Λ, the other interactions are much less sensitive

ALP production I

- **Production channel 1**: mixing with light mesons $m^0 = \pi^0, \eta, \eta'$
- Estimate of the 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
  Poor approximation but follow common description
- Mixing with π^0 strongly depends on the scale Λ, since $\theta_{\pi^0 a} \propto c_u - c_d$

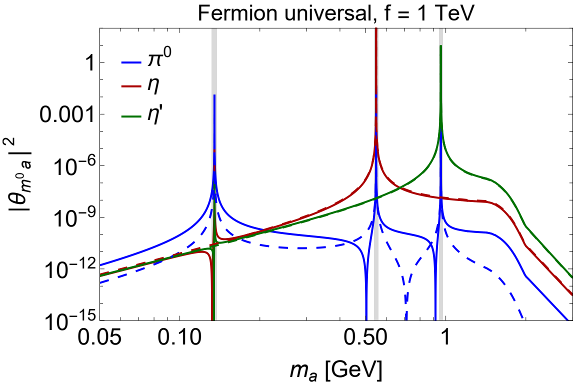
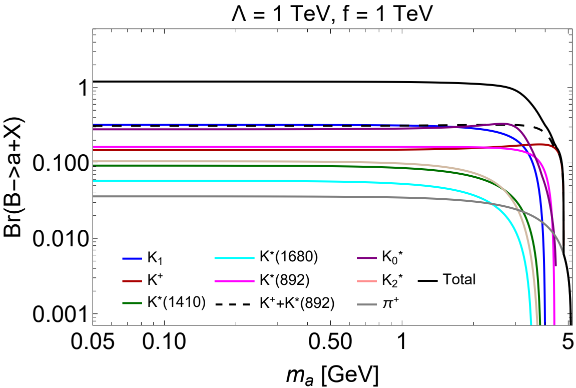


Figure: Solid: $\Lambda = \Lambda_{\text{EW}}$. Dashed: $\Lambda = 1$ TeV

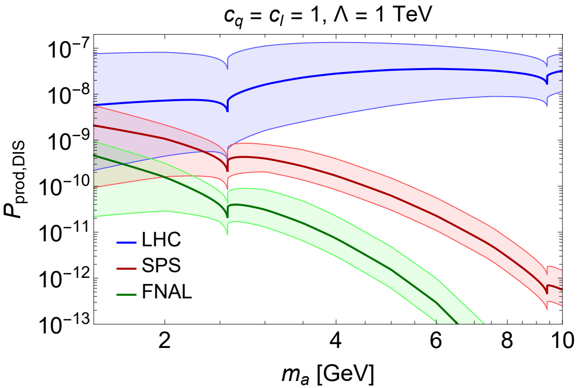
ALP production II

- **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

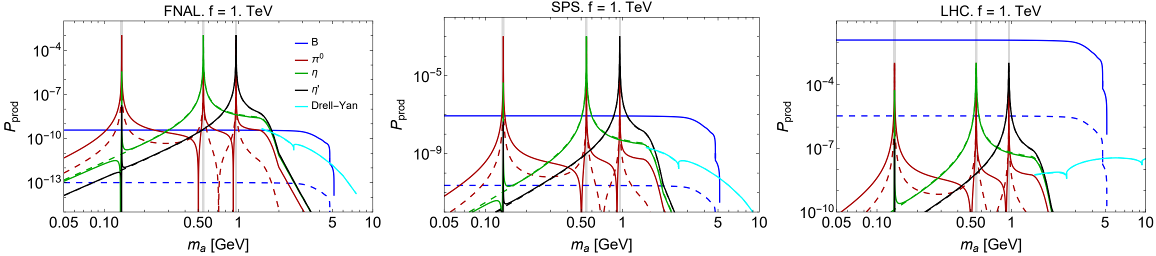


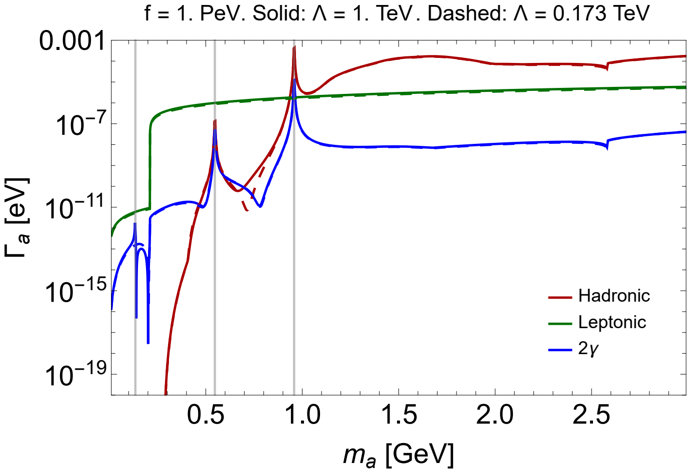
Figure: Solid: $\Lambda = 1$ TeV. Dashed: $\Lambda = \Lambda_{\text{EW}}$

– 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 decays I

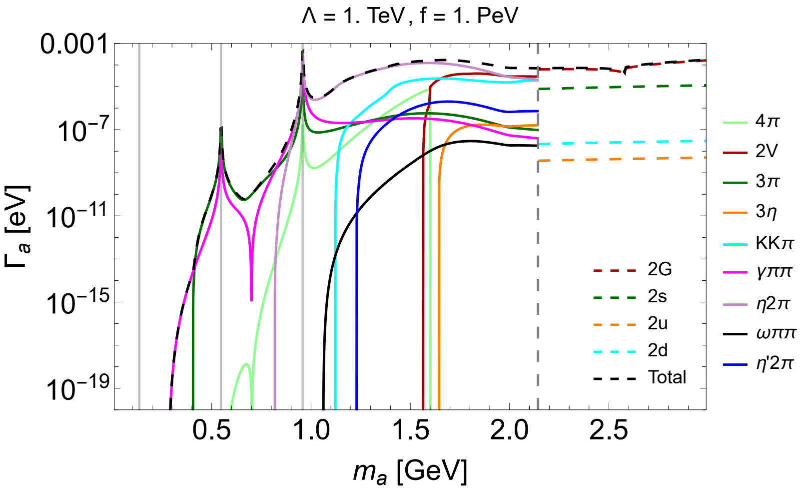
- Non-hadronic decays: into a pair of leptons/photons
- Hadronic ALP decays: for $m_a \gg \Lambda_{\text{QCD}}$ – perturbative QCD description, for $m_a \lesssim 1-2$ GeV – description in terms exclusive decays into mesons



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 S, V, and T mesons determined by symmetry arguments and to fit data (see, e.g., 2110.10691)

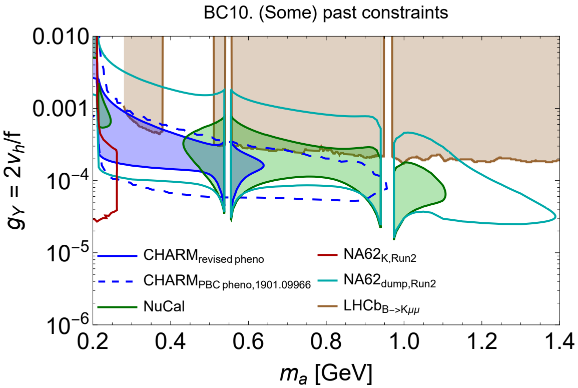


– Matching mass between perturbative QCD and ChPT: $m_a \approx 2.2$ GeV

(Some) past experiments (in preparation) I

Fix the model: $\Lambda = 1$ TeV

- Exclusions from CHARM: surprisingly, became worse than computed previously using PBC phenomenology
  Reasons: wrong setup?
- NuCal: covers masses $0.4 < m_a < 1$ GeV
- NA62 with LS3 data: may cover larger parameter space

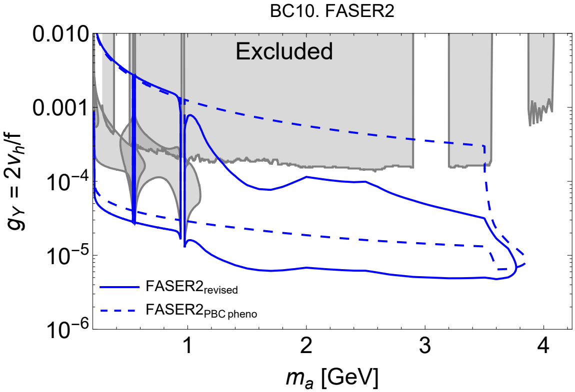


- Domain of large couplings: covered by searches for $B \to K\mu\mu$ at LHCb

Sensitivity of BD experiments computed using SensCalc

ALPs at future experiments (in preparation) I

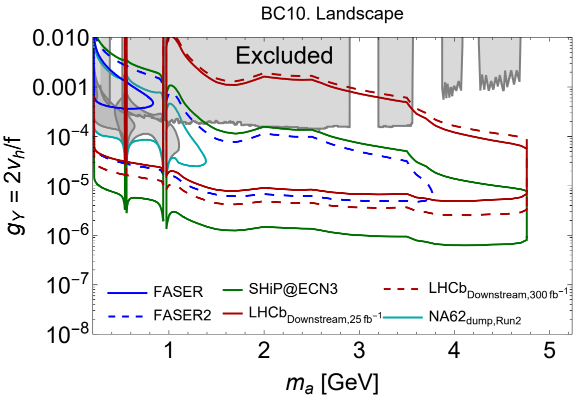
- What is the impact of the revised phenomenology on the sensitivity of FASER?
- New production channels, Γ_{decay} gets larger at 1 GeV $\Rightarrow$ better sensitivity to small couplings and worse to large couplings
- Difference in N_{events} would be orders in magnitude



- Domain of masses up to the threshold $m_B - m_\pi$: inaccessible due to parametric smallness of $c\tau_a$

ALPs at future experiments (in preparation) II

- Upper bound of the sensitivity $g_{Y,\text{upper bound}} \propto \sqrt{p_{a,\max}/z_{\text{to decay volume}}}$
- Experiments having larger ratio $p_a/z_{\text{to decay volume}}$: SHiP, LHCb-Downstream, FACET



Summary

- PBC description of ALPs universally coupled to fermions: missing important production channels and 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
- We release `Mathematica` notebook allowing to produce tabulated widths/production probabilities/matrix elements. The phenomenology has been implemented in `SensCalc`
- This is a small step ahead to revise the commonly used descriptions of LLPs' phenomenology