Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Università degli Studi di Padova
Dipartimento di Fisica e Astronomia "Galileo Galilei"

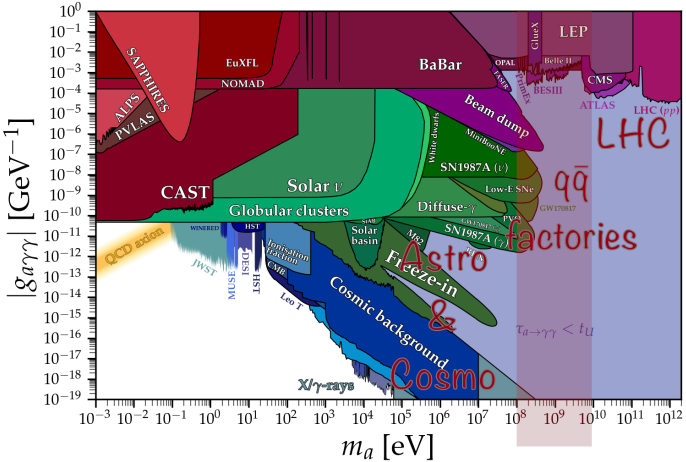
ALP searches in meson decays with ALP-aca

JA, M. Fuentes Zamoro, L. Merlo, X. Ponce Díaz, S. Rigolin 2507.19578 + 2508.08354

Invisibles25, 04-09-2025

Jorge Alda jorge.alda@pd.infn.it
Università degli Studi di Padova & CAPA

GeV scale ALPs

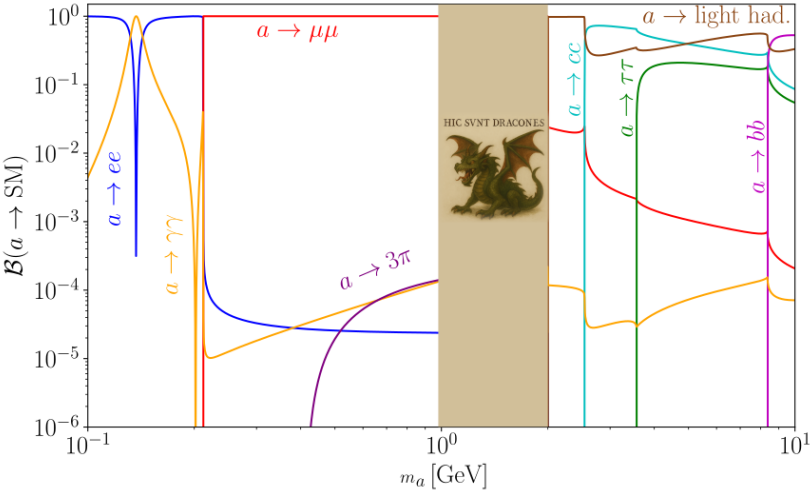


- Ideal range for charm (BESIII) and beauty (BaBar, Belle, Belle II) factories.
- Weaker constraints.
- Flavour.
- Challenges from decays into mesons.

[C. O'Hare, AxionLimits (adapted)]

ALP decays: the *terra incognita*

Example: Universal couplings to fermions $c^{ij}_{q_L} = c^{ij}_{d_R} = c^{ij}_{u_R} = c^{ij}_{\ell_L} = c^{ij}_{e_R} \equiv c_f \delta^{ij}$.



[L. Di Luzio, A. Guerrera, X. Ponce Díaz, S. Rigolin. JHEP 06 (2024) 217 (adapted)]

Matching to chiral perturbation theory

The degrees of freedom are no longer quarks $q = (u, d, s)^T$, but mesons $U = \exp\left(\frac{i}{F_0}\lambda^a \pi^a\right)$.

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,a} + i\bar{q}\not{D}q - \bar{q}(s - i\gamma_5 p)q + \bar{q}\gamma^\mu(r_\mu P_R + l_\mu P_L)q - \frac{\alpha_s}{8\pi}\theta(x) G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} \,.$$

$$\Downarrow \qquad \mu \lesssim 1\,\mathrm{GeV}$$

$$\mathcal{L}^{(p^2)}_{\chi\mathrm{PT}} = \frac{F_0^2}{4}\langle(\partial_\mu U + iUr_\mu - il_\mu U)^2\rangle + \frac{F_0^2 B_0}{2}\langle U^\dagger(s + ip) + \mathrm{h.c.}\rangle \,.$$

[J. Gasser, H. Leutwyler. Annals Phys. 158 (1984) 142 & Nucl.Phys.B 250 (1985) 465-516]

In the ALP case,

$$s = m_q \,, \qquad p = 0 \,, \qquad r_\mu = c_q^R \frac{\partial_\mu a}{f_a} \,, \qquad l_\mu = c_q^L \frac{\partial_\mu a}{f_a} \,, \qquad \theta = -2c_G \frac{a}{f_a} \,.$$

The chiral Lagrangian describes interactions with pseudoscalar mesons: $a \to 3\pi$, $a \to \eta^{(\prime)}\pi\pi$.

Matching to chiral perturbation theory

Extension to $\mu \sim 3\,\mathrm{GeV}$:
Data-driven hadronic form factors $\mathcal{F}(\mu)$ that interpolate to the perturbative regime.
[D. Aloni, Y. Soreq, M. Williams. Phys.Rev.Lett. 123 (2019) 3, 031803] [R. Balkin, T. Coren, Y. Soreq, M. Williams. 2506.15637]

Adding other mesons: **Recent theoretical developments!**

- Vector and axial-vector: $a \to \gamma\pi\pi$, $a \to \gamma\omega$, $a \to \omega\omega$,...
  Hidden Local Symmetry [M. Ovchynnikov, A. Zaporozhchenko. 2501.04525],
  Wess-Zumino-Witten [Y. Bai, T.-K. Chen, J. Liu, X. Ma. 2505.24822].
- Scalar and tensor: Resonant contributions to $a \to 3\pi$, $a \to \eta^{(\prime)}\pi\pi$ above $1\,\mathrm{GeV}$.
  Phenomenological Lagrangians. [M. Ovchynnikov, A. Zaporozhchenko. 2501.04525]
  [R. Balkin, T. Coren, Y. Soreq, M. Williams. 2506.15637]

Venturing into the mesonic *terra incognita*

ALP
automatic
computing
algorithm

https://github.com/alp-aca/alp-aca

```
pip3 install alpaca-ALPs
```

The ALP-aca workflow

1. At the UV scale $\Lambda_{\rm UV}$ define the ALP-EFT couplings or match one of the benchmark models: DFSZ, KSVZ, flaxion...
2. Run the RGEs and integrate out heavy particles.
   [M. Bauer, M. Neubert, S. Renner, M. Schnubel, A. Thamm. JHEP 04 (2021) 063]
3. ALP production: $M_1 \to M_2 a$, $V \to \gamma a$.
   ALP decays (including mesons).
   Probability of decaying in/outside the detector.
   [T. Ferber, A. Filimonova, R. Schäfer, S. Westhoff. JHEP 04 (2023) 131]
4. Statistical χ^2 analysis with $>$ 100 observables.
5. Plot the exclusion significance.
6. Generate the list of bibliographical references.

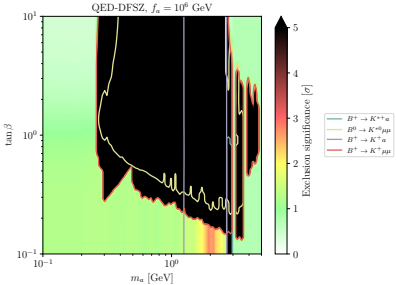
$\Big\}$ NWA approximation

ALP-aca in action!

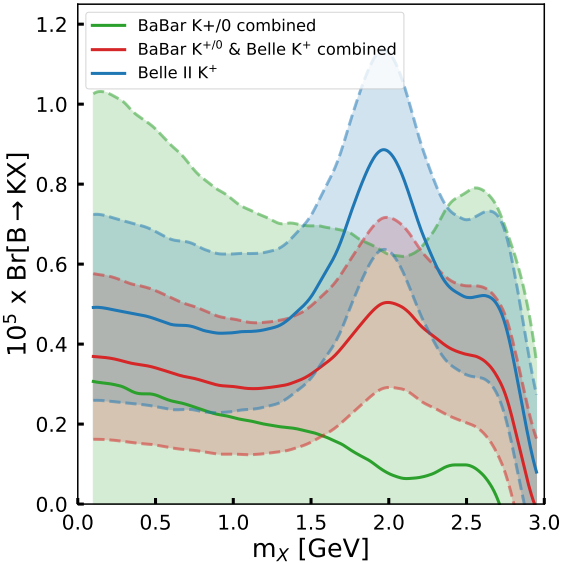
```python
from alpaca.models import QED_DFSZ, beta
from alpaca.statistics import get_chi2
from alpaca.sectors import default_sectors
from alpaca.plotting.mpl import exclusionplot
import numpy as np

fa = 1e6 #GeV
tanbeta = np.logspace(-1, 1, 100)
ma = np.logspace(-1, np.log10(5), 100) #GeV
x_ma, y_tanbeta = np.meshgrid(ma, tanbeta)
couplings = [QED_DFSZ.get_couplings({beta: np.arctan(tb)}, 4*np.pi*fa).match_run(10, 'VA_below') for tb in
x_ma, y_couplings = np.meshgrid(ma, couplings)

chi2 = get_chi2(default_sectors['bsa_lfu'], x_ma, y_couplings, fa, 0, integrator='leadinglog')
chi2_obs = chi2[0].split_observables()

exclusionplot(x_ma, y_tanbeta, chi2_obs, r'$m_a$ [GeV]', r'$\tan\beta$', r'QED-DFSZ, $f_a = 10^6$ GeV')
```

Written completely in Python
Easy to use, concise syntax

Manual available at 2508.08354



ALP-aca use case: the $B^+ \to K^+\nu\bar{\nu}$ excess



Belle II has found a $\sim 2.7\,\sigma$ excess in $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$.

[Belle II collaboration. Phys.Rev.D 109 (2024) 11, 112006]

Compatible with two-body decay with a $\sim 2\,\mathrm{GeV}$ invisible particle.

[W. Altmannshofer, A. Crivellin, H. Haigh, G. Inguglia, J. Martín Camalich. Phys.Rev.D 109 (2024) 7, 075008]

Could it be **an ALP**???
Let's find out with ALP-aca!

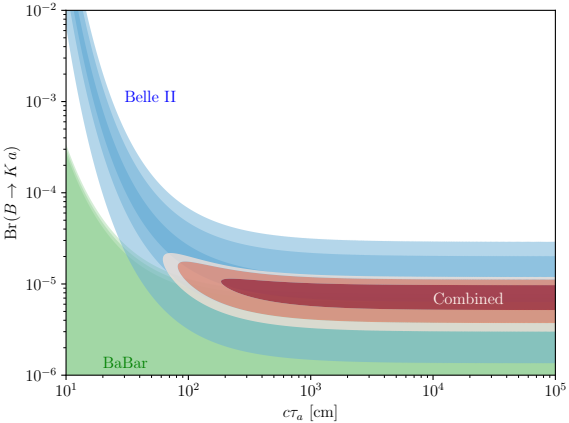
Re-(re)-analysis of BaBar and Belle II

Invisible decay
$\mathcal{B}(B^+ \to K^+ + \text{inv}) = \mathcal{B}(B^+ \to K^+ a) \times P_{\text{out}}$.

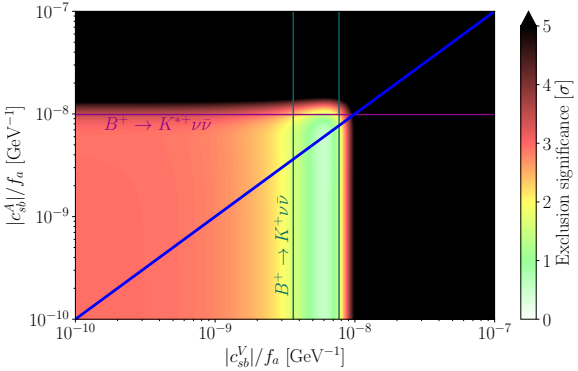
$$P_{\text{out}} = \exp\left(-\frac{L_{\text{det}}}{c\tau_a\,\beta_a\gamma_a}\right).$$

The difference in detector size and boost between BaBar and Belle II allows us to disentangle $\mathcal{B}(B^+ \to K^+ a)$ and P_{out}.

For $m_a = 2\,\text{GeV}$, preference for longer-lived ALP and $\mathcal{B}(B^+ \to K^+ a) \sim 10^{-5}$.



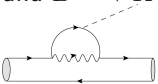
ALP-EFT analysis of $B \to K^{(*)}a$

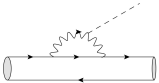


Effective Lagrangian at $\mu = m_a = 2\,\mathrm{GeV}$:

$$\mathcal{L}_{\text{eff}} \supset \frac{\partial_\mu a}{f_a}\left(c^V_{sb}\bar{s}\gamma^\mu b + c^A_{sb}\bar{s}\gamma^\mu\gamma_5 b\right) + \text{h.c.}$$

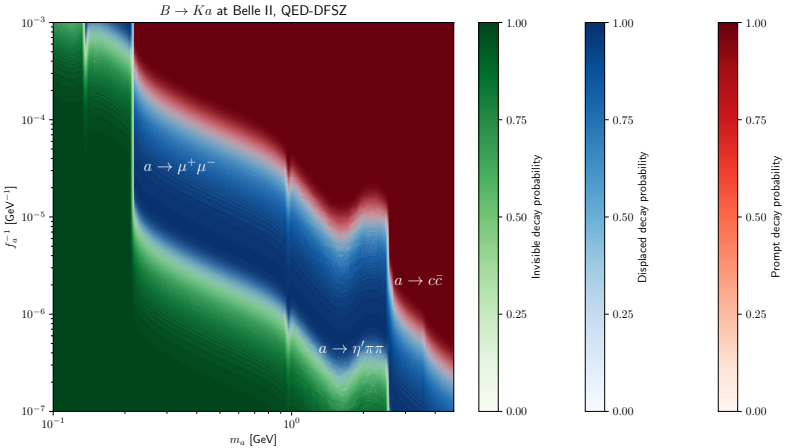
If flavour violation is induced by top loops, $c^V_{sb} = -c^A_{sb}$, compatible with $B^+ \to K^+\nu\bar{\nu}$ and $B^+ \to K^{*+}\nu\bar{\nu}$.





$B \to Ka$: is the ALP invisible?

The ALP decay length is controlled by flavour-conserving couplings to fermions.
A 2 GeV ALP will have large BR to muons and/or mesons, and will, in general, decay very promptly.

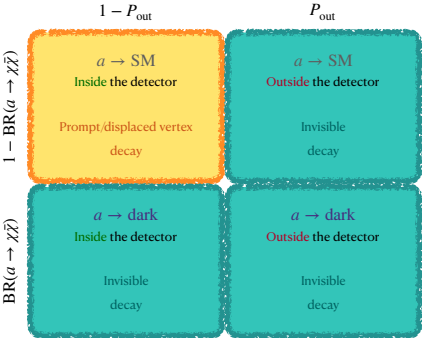


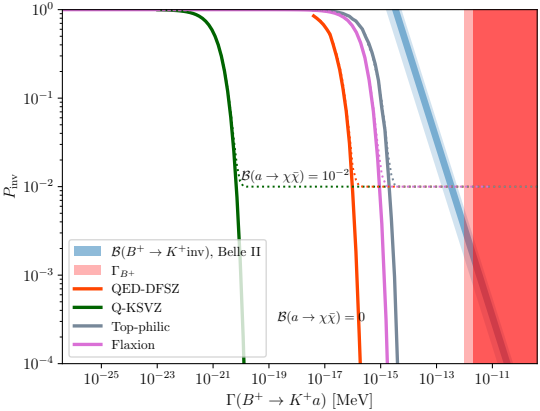
Solution 1: ALP portal to dark sector

If the ALP can decay into a dark particle, e.g.

$$\mathcal{L}_\chi \supset c_\chi \frac{\partial_\mu a}{f_a} \bar{\chi}\gamma^\mu\gamma_5\chi \,,$$

it is possible to achieve large $P_{\rm inv}$ and $\mathcal{B}(B^+ \to K^+ a)$ at the same time.





Solution 2: Flavour violation at tree level

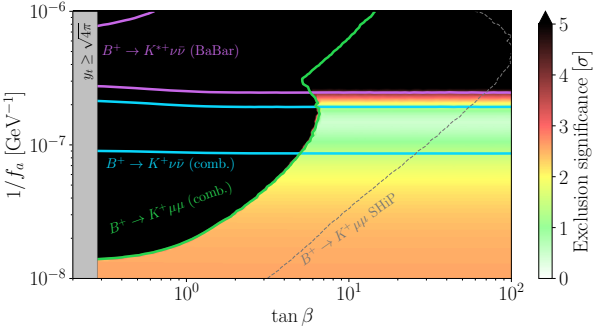
Is it possible to find a model with sizeable c_{sb}^V while suppressing decays to muons and mesons?

Yes!, but fine-tuning is required...

Example:

Non-universal PQ-2HDM with

$$\mathcal{X}_{q_L} = \mathrm{diag}(0,0,1)\,,$$
$$\mathcal{X}_{\ell_L} = -\mathcal{X}_{q_L}\,,$$
$$\mathcal{X}_{u_R} = \sin^2\beta\ \mathbb{1}\,,$$
$$\mathcal{X}_{d_R} = \cos^2\beta\ \mathbb{1}\,,$$
$$\mathcal{X}_{e_R} = -\mathcal{X}_{u_R}\,.$$



[L. Di Luzio, F. Mescia, E. Nardi, P. Panci, R. Ziegler. Phys.Rev.Lett. 120 (2018) 26, 261803]

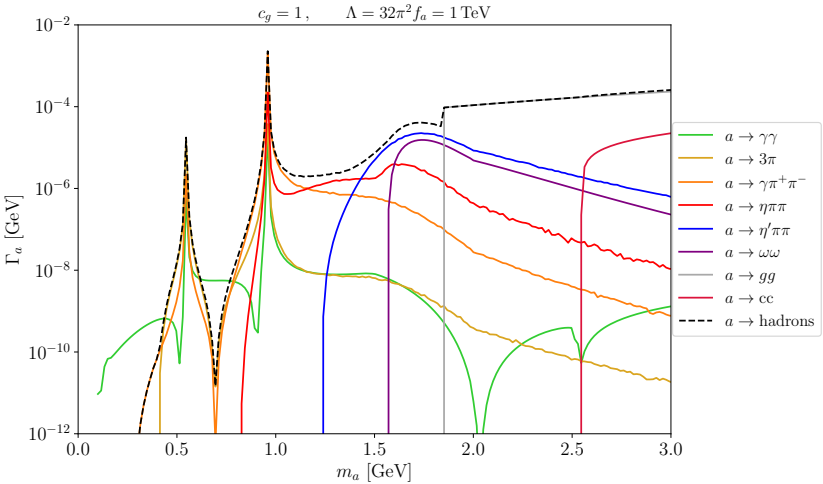
Conclusions

- ALPs with $m_a \sim \mathcal{O}(\mathrm{GeV})$ display a rich phenomenology.
- ALP-EFT allows for a systematic study of all possible observables.
- We have created ALP-aca to facilitate the full analysis of ALP models, with special emphasis on mesonic processes.
- For $m_a \sim 1 - 3\,\mathrm{GeV}$, mesonic decays must be under control in order to determine if the ALP decays inside/outside the detector.
- We showcased the capabilities of ALP-aca with the study of the excess in $B^+ \to K^+ \nu \bar{\nu}$ found by Belle II.
  It could be explained by a $m_a = 2\,\mathrm{GeV}$ ALP, albeit requiring additional hypothesis or fine-tuning.

Thank you for your attention!

Backup slides

ALP hadronic (and $\gamma\gamma$) decays



Benchmark models

- **Q-KSVZ:** Heavy VLF charged under PQ, $Q \sim (\mathbf{3}, \mathbf{1}, 0, \pm 1/2)$:
  At the matching scale $c_G = -1/2$.
- **QED-DFSZ:** $-\mathcal{L} \supset \bar{q}_L Y_u \tilde{H}_q u_R + \bar{q}_L Y_d H_q d_R + \bar{\ell}_L Y_e \tilde{H}_e e_R + \lambda_{H\phi} H_e^\dagger H_q \phi^2$.

$$a = \frac{1}{f_a} \sum_{i=q,e,\phi} \mathcal{X}_{H_i} v_i a_i \,, \quad \text{with} \quad f_a^2 = \sum_i \mathcal{X}_{H_i}^2 v_i^2 \,,$$

  At the matching scale
  $c_u^A = -c_d^A = 2\sin^2\beta\,\mathbb{1}\,, \qquad c_e^A = 2\cos^2\beta\,\mathbb{1}\,, \qquad c_\gamma = 6\,, \qquad c_G = 0\,.$
- **Flaxion:** Froggatt-Nielsen model

$$\mathcal{L}_{\rm FN} = \bar{q}_{Li}\, y_{u,ij} \tilde{H}\, u_{Rj} \left(\frac{\phi}{\Lambda}\right)^{\mathcal{X}^i_{q_L} - \mathcal{X}^j_{u_R}} + \bar{q}_{Li}\, y_{d,ij} H\, d_{Rj} \left(\frac{\phi}{\Lambda}\right)^{\mathcal{X}^i_{q_L} - \mathcal{X}^i_{d_R}} + \bar{\ell}_{Li}\, y_{e,ij} H\, e_{Rj} \left(\frac{\phi}{\Lambda}\right)^{\mathcal{X}_{\ell^i_L} - \mathcal{X}^j_{e_R}} \,,$$

$$\mathcal{X}_{q_L} = \begin{pmatrix} 3 & 2 & 0 \end{pmatrix}, \; \mathcal{X}_{u_R} = \begin{pmatrix} -5 & -1 & 0 \end{pmatrix}, \; \mathcal{X}_{d_R} = \begin{pmatrix} -4 & -3 & -3 \end{pmatrix},$$
$$\mathcal{X}_{\ell_L} = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix}, \; \mathcal{X}_{e_R} = \begin{pmatrix} -8 & -5 & -3 \end{pmatrix}.$$