Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

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

Present and future of ALP searches in colliders

JA, G. Levati, P. Paradisi, S. Rigolin, N. Selimović [2407.18296], [2506.xxxxx]

JA, M. Fuentes Zamoro, L. Merlo, X. Ponce Díaz, S. Rigolin [2506.xxxxx]

MITP Workshop, 19-06-2025

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

Contents

1 **Introduction and Motivation**

2 **Leptophilic ALPs**
Tauphilic and LFU ALPs. Direct searches and τ anomalous magnetic moment.

3 **ALPs in the mesonic** ***terra incognita***
The ALPaca toolbox. The $B^+ \to K^+ \nu\bar{\nu}$ anomaly.

4 **Closing remarks**

Introduction and Motivation

The strong CP problem and axions

$$\mathcal{L}_{\text{QCD}} \supset \theta_{\text{QCD}} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} \,.$$

Neutron e.d.m. has not been observed $\Longrightarrow$ $|\bar{\theta}| < 10^{-10}$, with $\bar{\theta} = \theta_{\text{QCD}} + \arg\det(Y_U Y_D)$.

Possible solution: Peccei-Quinn mechanism

[R.D. Peccei, H.R. Quinn, Phys.Rev.Lett. 38 (1977) 1440-1443 & Phys.Rev.D 16 (1977) 1791-1797]

$$\mathcal{L}_{\text{axion}} \supset \frac{a}{f_a} \frac{\alpha_s}{4\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} \,.$$

QCD-induced axion potential: The axion acquires a vev $\langle a \rangle$ such that $\bar{\theta} \to 0$, dynamically solving the strong CP problem.

$$m_a f_a = m_\pi f_\pi \frac{\sqrt{m_u m_d}}{m_u + m_d} \sim m_\pi f_\pi \,.$$

Axion-like particles

Pseudoscalar a arising as pNG boson of spontaneously broken global $U(1)_{\rm PQ}$ symmetry at scale $\Lambda_{\rm UV} \sim f_a$.

ALPs violate the relation $m_a f_a \approx m_\pi f_\pi$ and do not necessarily solve the strong CP problem via Peccei-Quinn mechanism.

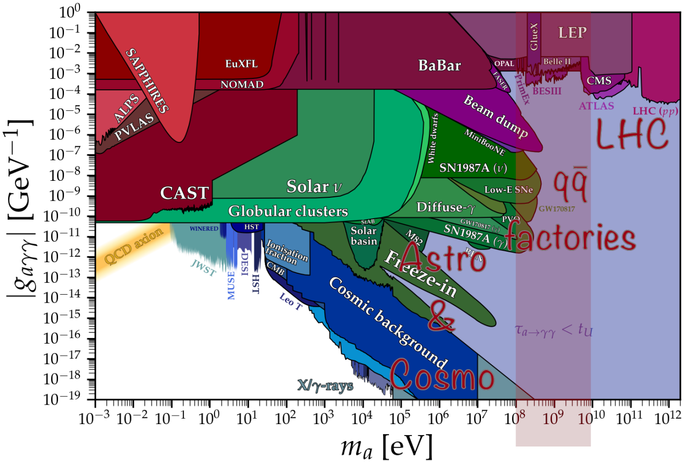
Predicted by many BSM models: string theory (axiverse), flavour (familion, flaxion), neutrino masses (majoron), DM candidate, etc.

Described by dimension-5 ALP-EFT. Schematically,

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{m_a^2}{2}a^2 + c_V\, \frac{a}{f_a}\frac{\alpha_V}{4\pi} V_{\mu\nu}\tilde{V}^{\mu\nu} + \frac{\partial_\mu a}{f_a}\bar{f}_i \gamma^\mu c_f^{ij} f_j\,.$$

[H. Georgi, D. Kaplan, L. Randall, PLB 169B(1986)73]

GeV scale ALPs



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

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

Leptophilic ALPs

Leptophilic ALPs

Pseudoscalar a arising as pNG boson of spontaneously broken global $U(1)_{\mathrm{PQ}}$ symmetry.

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2\, a^2 - \frac{c_\ell^{ij}}{2f_a}(\partial_\mu a)\left(\chi_L\, \bar{\ell}_L^i \gamma^\mu \ell_L^j + \chi_R\, \bar{e}_R^i \gamma^\mu e_R^j\right) + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f_a}B\tilde{B} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f_a}W\tilde{W}\,.$$

We consider 2 scenarios: **LFU** $c_\ell^{ij} = c_\ell \delta^{ij}$ and **tauphilic** $c_\ell^{33} = c_\tau,\ c^{ij} \approx 0$.
After applying integration by parts and equations of motion

$$\mathcal{L}_{\mathrm{int}} = i\frac{c_\ell \chi_A}{f_a} a \sum_\ell m_\ell \bar{\ell}\gamma_5 \ell - \frac{\alpha_{\mathrm{em}}}{4\pi}\frac{a}{f_a} c_{XY}^{\mathrm{eff}} X_{\mu\nu}\tilde{Y}^{\mu\mu}\,,$$

where $\chi_{V,A} = (\chi_R \pm \chi_L)/2$ and $XY = \gamma\gamma,\ \gamma Z,\ W^+W^-,\ ZZ$.

Motivation: Example of UV completion

SM extended by vector-like lepton doublet $L \sim (\mathbf{1},\mathbf{2})_{-1/2}$ with L_L charged under global $U(1)_{\rm PQ}$, and complex scalar $\Phi \sim (\mathbf{1},\mathbf{1})_0$ whose vev breaks PQ.

$$\mathcal{L}_{\rm UV} = (\partial_\mu \Phi)^\dagger \partial^\mu \Phi + i\bar{L}\not{D}L - y\Phi \bar{L}_L L_R - m_3 \bar{\ell}^3_L L_R + \text{h.c.}$$

In the broken phase $\Phi \to \frac{1}{\sqrt{2}}(f_a + \rho)e^{ia/f_a}$. We can move the pNG to the kinetic term after a chiral rotation $L_L \to e^{ia/f_a} L_L$:

$$\mathcal{L}_{\rm UV} \supset -\left(\frac{y f_a}{\sqrt{2}} \bar{L}_L L_R + m_3\, \bar{\ell}^3_L L_R + \text{h.c.}\right) + \frac{1}{f_a}(\partial_\mu a)\, \bar{L}_L \gamma^\mu L_L + \frac{\alpha_1}{8\pi}\frac{a}{f_a} B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\alpha_2}{8\pi}\frac{a}{f_a} W^I_{\mu\nu}\tilde{W}^{I\,\mu\nu}\,.$$

Finally, after diagonalizing the mass terms

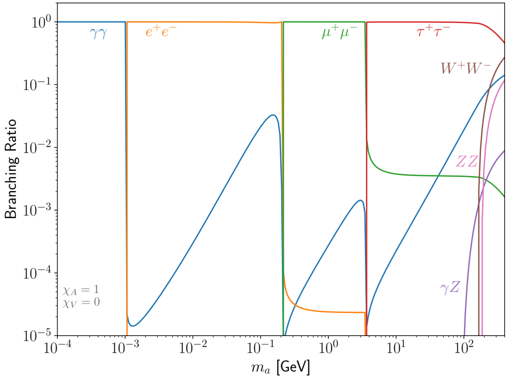
$$\mathcal{L} \supset \frac{\sin^2\theta}{f_a}(\partial_\mu a)(\bar{\ell}^3_L \gamma^\mu \ell^3_L), \qquad \tan\theta = \frac{\sqrt{2} m_3}{y f_a}\,,$$

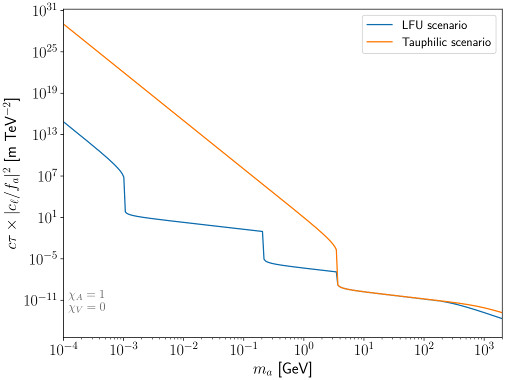
which corresponds to a tauphilic ALP with

$$c_\tau = -2\sin^2\theta, \quad \chi_L = 1, \quad \chi_R = 0, \quad c_{BB} = c_{WW} = \frac{1}{2}\,.$$

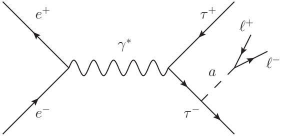
ALP decays

LFU ALPs with $m_a < 2m_e$ (tauphilic with $m_a < 2m_\tau$) will decay into $\gamma\gamma$ typically outside the detector; heavier ALPs will decay mostly into a pair of the heaviest leptons available, typically inside the detector.

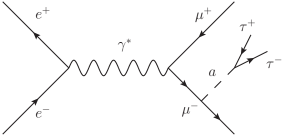




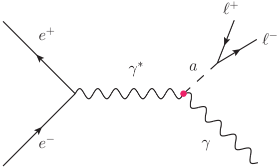
Search at B factories: LFU scenario



Studied by BaBar and Belle in the context of dark photon searches. Loses sensitivity for $m_a \geq 2m_\tau$.



New at Belle II. Reaches higher m_a, but is suppressed by a factor m_μ^2/m_τ^2 and experimental signature is less clear.



Proposed search: for $m_a < 2m_\tau$. Both photon and di-lepton have fixed energy. Belle II could resolve the displaced vertex of the $a \to \ell^+\ell^-$ decay. Sensitive to effective coupling to photons.

Quarkonia decays

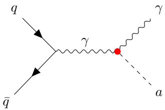
In BaBar and Belle, $e^+e^- \to \Upsilon(nS) \to \gamma a$; also $e^+e^- \to J/\psi \to \gamma a$ at BES-III.

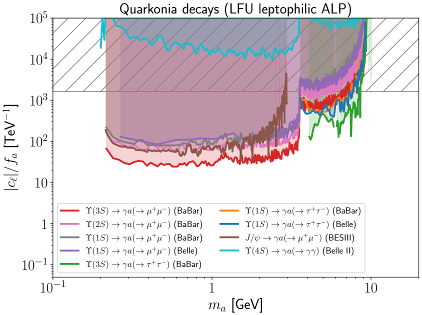
- LFU ALP: $a \to \mu^+\mu^-$ below $m_a > 2m_\tau$, $a \to \tau^+\tau^-$ above $m_a > 2m_\tau$.
- Tauphilic ALPs $a \to \gamma\gamma$ below $m_a > 2m_\tau$, $a \to \tau^+\tau^-$ above $m_a > 2m_\tau$.

Affected by UV contributions to photon coupling.

Depending on experimental setup, there is an interplay between resonant and non-resonant decays.

[L. Merlo, F. Pobbe, S. Rigolin, O. Sumensari. JHEP 1906 (2019) 091]

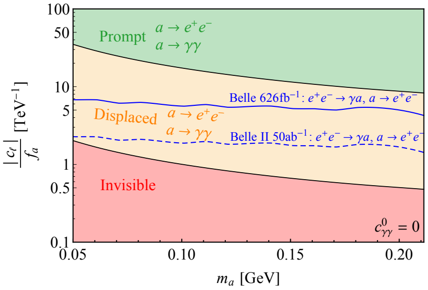




Belle II operates exclusively at $\sqrt{s} = m_{\Upsilon(4S)}$, but the resonance is much wider than the energy spread of the beam: always non-resonant process.

New Search at Belle II: LFU scenario

Non-resonant $e^+e^- \to \gamma a$ at Belle II:



FeynRules $\to$ UFO model $\to$ MadGraph_5AMC@NLO to simulate signal and background events.

Search for events with $m^2_{\ell\ell} = m^2_a$ and $E_\gamma = \frac{s - m_a^2}{2\sqrt{s}}$.

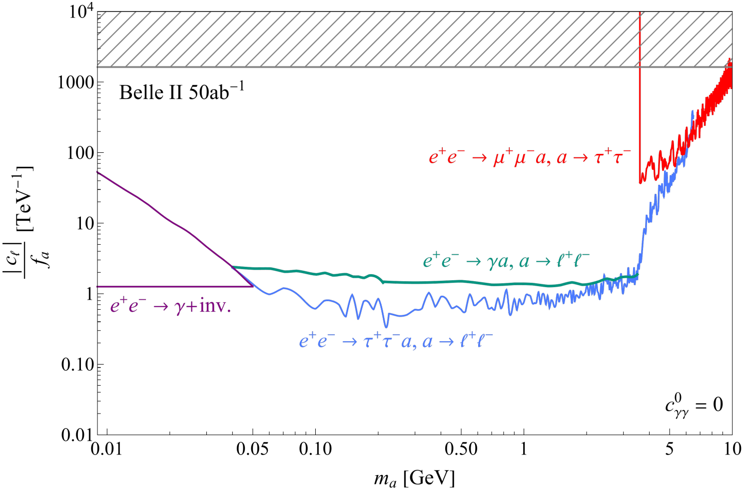
Belle II electromagnetic calorimeter coverage: $12.4° < \theta < 155.1°$.

The photon energy resolution averaged over the entire calorimeter is 1.7% for $E_\gamma > 5\,\mathrm{GeV}$. Di-lepton invariant mass resolution $\sigma_{m_{\ell\ell}}/m_{\ell\ell}$ reported by Belle II.

We analyze 2D bins in $E_\gamma \otimes m^2_{\ell\ell}$ assuming Posisson statistics and require $S/\sqrt{B} = 2$.

Below $m_a < 0.04\,\mathrm{GeV}$, the decay length exceeds the detector size, and the signal is mono-γ. Existing sensitivity studies for Belle II.

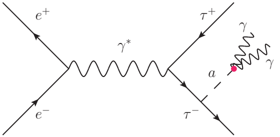
Belle II at $50\,\mathrm{ab}^{-1}$: LFU scenario



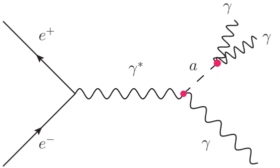
The proposed Belle II searches will

- Improve constraints in $e^+e^- \to \gamma\ell^+\ell^-$ by one order of magnitude, complementary to $e^+e^- \to \tau^+\tau^-\ell^+\ell^-$.
- Extend the constraints to $m_a < 0.05\,\mathrm{GeV}$.

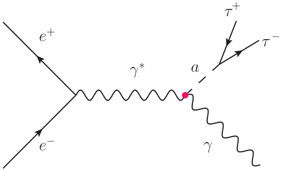
Search at B factories: tauphilic scenario



Proposed search at Belle II for $m_a < 2m_\tau$. Narrow signal at $m_{\gamma\gamma}^2 = m_a^2$ superimposed over continuous QED background.



Studied at Belle II and BESIII. Below $m_a < 0.5\,\mathrm{GeV}$, the ALP is long-lived, and the signature is $e^+e^- \to \gamma$ instead(BESIII).
Proposed search: In the region $0.5\,\mathrm{GeV} < m_a < 1.0\,\mathrm{GeV}$ Belle II could search for displaced vertices.



Studied at BaBar ($e^+e^- \to \Upsilon(1S, 3S) \to \gamma\tau^+\tau^-$) and Belle ($e^+e^- \to \Upsilon(1S) \to \gamma\tau^+\tau^-$).
Proposed search at Belle II, in non-resonant process.

New searches at Belle II: tauphilic scenario

$e^+e^- \to \tau^+\tau^- a, a \to \gamma\gamma$

FeynRules $\to$ UFO model $\to$ MadGraph_5AMC@NLO to simulate signal and background events.

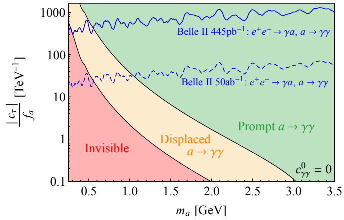
Search for events with $m_{\gamma\gamma}^2 = m_a^2$
We assume the same resolution for $m_{\gamma\gamma}^2$ as in $e^+e^- \to \gamma a, a \to \gamma\gamma$.

Belle II electromagnetic calorimeter coverage: $37.3° < \theta_\gamma < 123.7°$; separation between photons of $\Delta\theta_{\gamma\gamma} > 0.014$ rad and $\Delta\phi_{\gamma\gamma} > 0.400$ rad to reduce background from photon conversions outside of the tracking detectors.

At least one τ decays leptonically.

We analyze bins in $m_{\gamma\gamma}^2$ assuming Posisson statistics and require $S/\sqrt{B} = 2$.

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

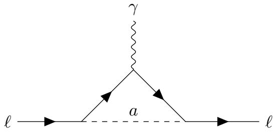


$e^+e^- \to \gamma a, a \to \tau^+\tau^-$

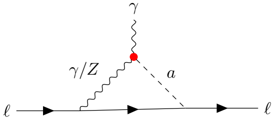
FeynRules $\to$ UFO model $\to$ MadGraph_5AMC@NLO to simulate signal and background events.

Peak in $m_{\tau\tau}^2 = s - 2\sqrt{s}E_\gamma$.
Both τ required to decay leptonically.

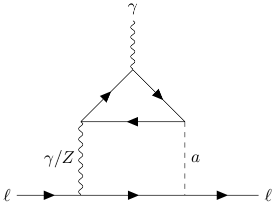
τ Anomalous magnetic moment



Negative contribution.
Dominant term for small m_a.



The contribution from the effective coupling is negative, and dominant for large m_a. UV contributions may have either sign.



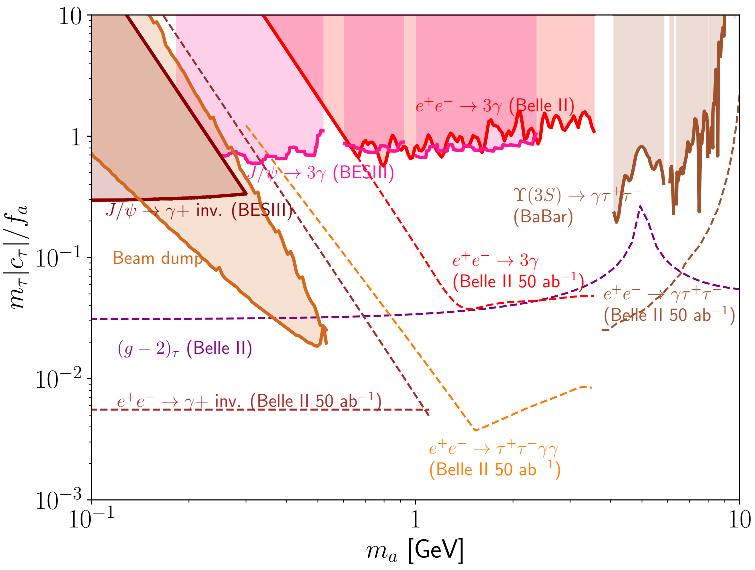
Barr-Zee term:
Additional suppression m_f^2/m_a^2.

Belle II will be sensitive to the $\tau^+\tau^-\gamma^*$ form factor $F_2(s)$, with experimental resolution $\mathcal{O}(10^{-6})$.

Search at B factories: tauphilic scenario

Belle II will significantly improve all the bounds.

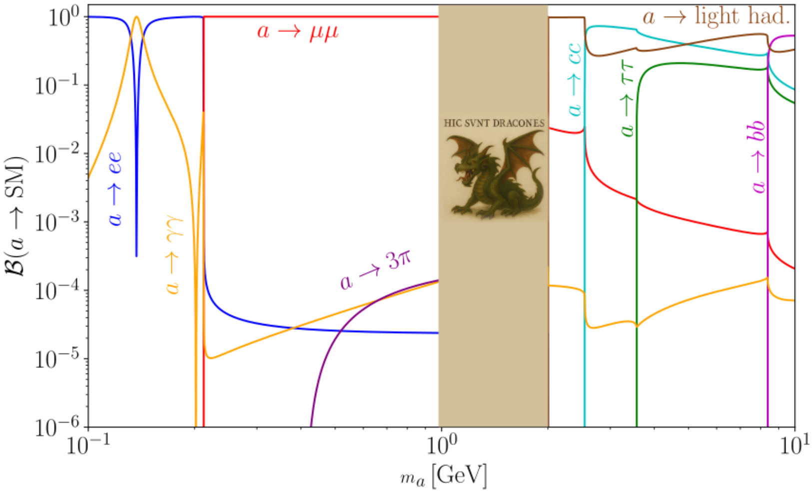
Complementarity between direct searches and anomalous magnetic moment.



ALPs in the mesonic *terra incognita*

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 $U = \exp\left(\frac{i}{F_0}\lambda^a\pi^a\right)$.

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

$$\Downarrow \qquad \mu \lesssim 1.6\,\mathrm{GeV}$$

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

[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

How to deal with the $\theta(x)$ term? Two equivalent approaches:

1. Eliminate via chiral rotation $q(x) \to \exp(i\theta(x)\kappa_q\gamma_5/2)q(x)$.
   [D. Aloni, Y. Soreq, M. Williams. Phys.Rev.Lett. 123 (2019) 3, 031803]
2. Promote the meson matrix to $U(3)$
   $\det U_\theta = \exp(-i\theta(x)) \implies U_\theta = \exp(-i\theta(x)\kappa_q/2)U\exp(-i\theta(x)\kappa_q/2)$.
   [C. Cornella, A. M. Galda, M. Neubert, D. Wyler. JHEP 06 (2024) 029]

with $\langle\kappa_q\rangle = 1$. Physical observables must be independent of the components of κ_q.

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

- Vector and axial-vector: $a \to \gamma\pi\pi$, $a \to \gamma\omega$, $a \to \omega\omega$,...
  VMD [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 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

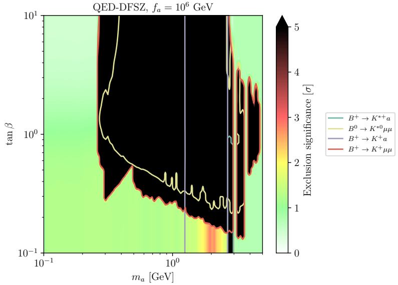
The ALPaca workflow

1. At the UV scale Λ_{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]
   } NWA approximation
4. Statistical χ^2 analysis with > 100 observables.
5. Plot the exclusion significance.
6. Generate the list of bibliographical references.

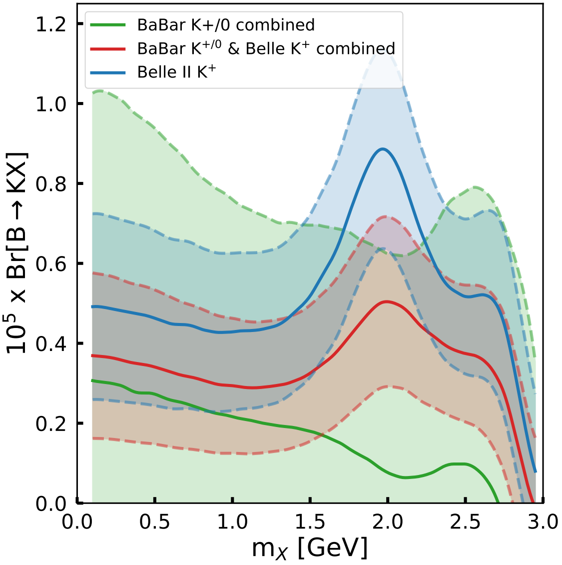
ALPaca in action!

```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 i
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



ALPaca 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 ALPaca!

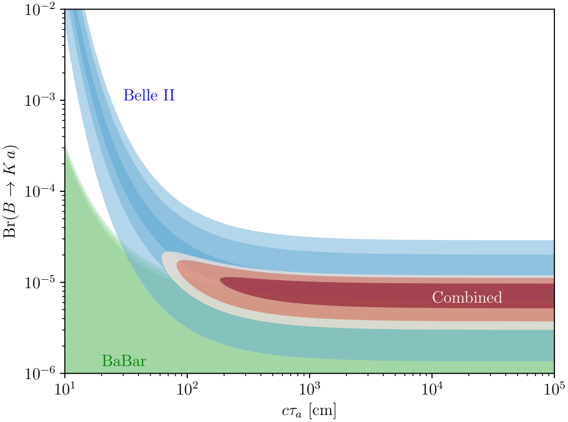
Re-(re)-analysis of BaBar and Belle II

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

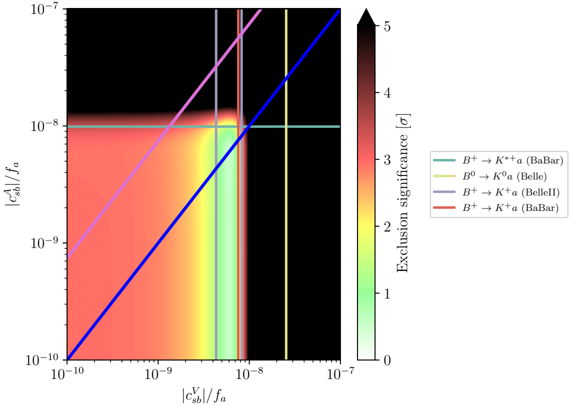
$$P_{\text{out}} = \exp\left(-\frac{L_{\text{det}}}{c\tau_a\,\beta_a\gamma_a}\right).$$

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

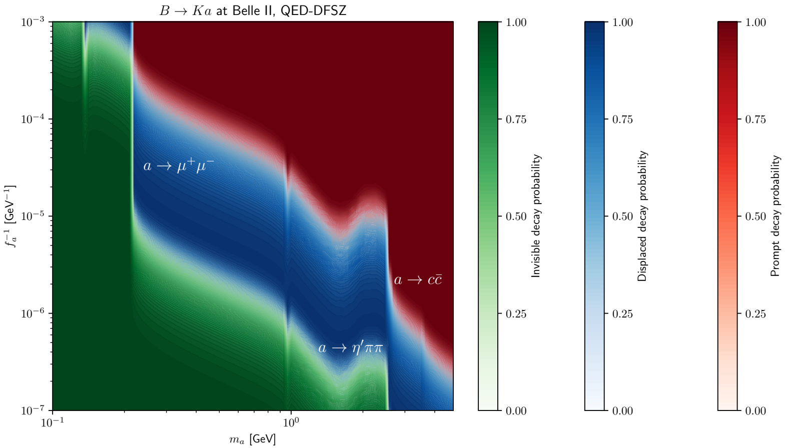
$$\mathcal{L}_{\text{eff}} \supset \frac{\partial_\mu a}{f_a} \left(c_{sb}^V \bar{s}\gamma^\mu b + c_{sb}^A \bar{s}\gamma^\mu \gamma_5 b \right) + \text{h.c.}$$

If flavour violation is induced by top loops, $c_{sb}^V = -c_{sb}^A$, compatible with $B^+ \to K^+ \nu\bar{\nu}$ and $B^+ \to K^{*+}\nu\bar{\nu}$. See Xiyuan Gao's talk

Models with tree-level flavour violation (e.g. flaxion) populate all the c_{sb}^V — c_{sb}^A plane.
[Y. Ema, K. Hamaguchi, T. Moroi, and K. Nakayama, JHEP 01 (2017) 096]

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

The previous ALP-EFT analysis fails because $c_{sb}^{V,A}$ do not generate ALP decays.
In more complete scenarios, a 2 GeV ALP will have large Γ to muons and/or mesons.
The ALP will, in general, decay very promptly.

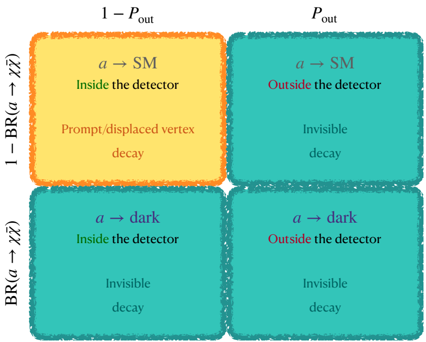


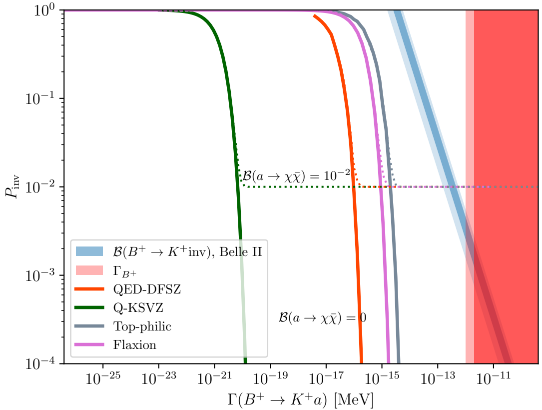
Solution 1: ALP portal to dark sector

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_{inv} and $\mathcal{B}(B^+ \to K^+ a)$ at the same time.





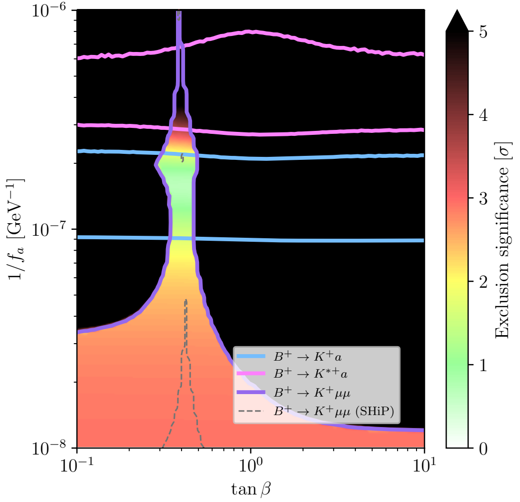
Solution 2: Flavour violation at tree level

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

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

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



Closing remarks

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.
- Belle II will significantly improve the constraints for ALP couplings with τ leptons.
- We have created ALPaca to facilitate the full analysis of ALP models, with special emphasis on mesonic processes.
- We showcased the capabilities of ALPaca 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

Leptophilic ALPs: effective photon couplings

Two on-shell photons:

$$c_{\gamma\gamma}^{\mathrm{eff},0} = c_{\gamma\gamma}^{0} + c_\ell \sum B_1\left(\frac{4m_\ell^2}{m_a^2}\right) .$$

One on-shell and one off-shell photon

$$c_{\gamma\gamma}^{\mathrm{eff}}(s) = c_{\gamma\gamma}^{0} + c_\ell \sum B_3\left(\frac{4m_\ell^2}{m_a^2}, \frac{4m_\ell^2}{s}\right) .$$

with loop functions

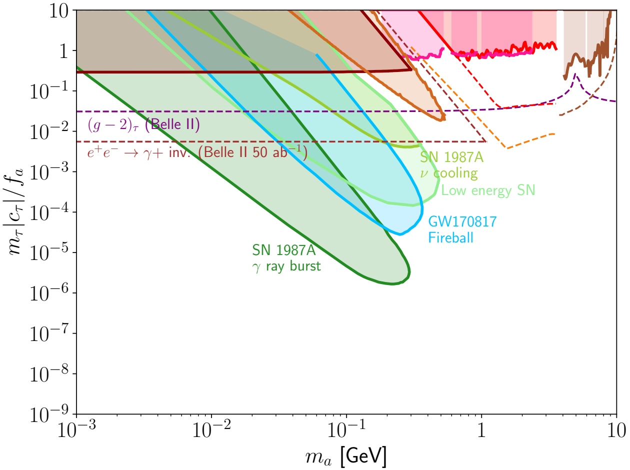
$$B_3(x,y) = 1 + \frac{xy}{x-y}\left[f^2(x) - f^2(y)\right] ,$$

$$f(x) = \begin{cases} \arcsin\left(\frac{1}{\sqrt{x}}\right) & x \geq 1 \\ \frac{\pi}{2} + \frac{i}{2}\log\frac{1+\sqrt{1-x}}{1-\sqrt{1-x}} & x < 1 \end{cases}$$

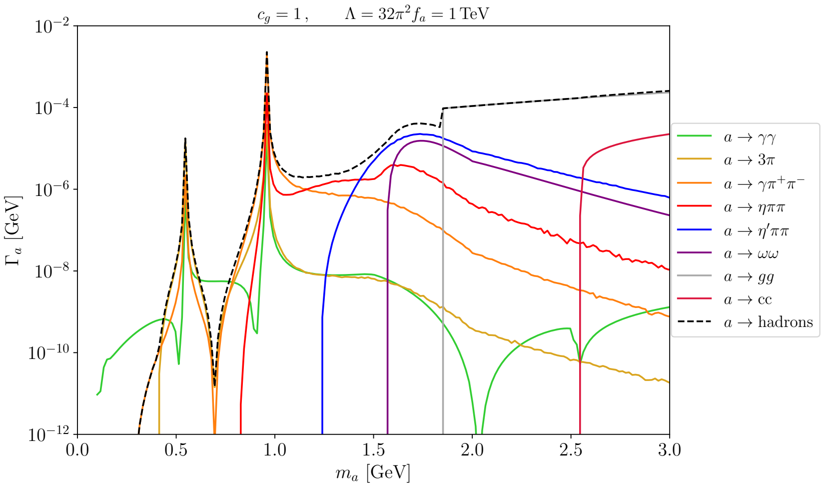
$$B_1(x) = B_3(x, y \gg 1) \simeq 1 - x f^2(x) .$$

Tauphilic ALP: Astrophysical bounds

For $m_a \lesssim 0.4\,\mathrm{GeV}$, supernovae and neutron star mergers impose strong bounds to tauphilic ALPs via $c_{\gamma\gamma}^{\mathrm{eff}}$.



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

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

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