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# GeV-ALP searches with ALP-aca

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# The strong CP problem and axions

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

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

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]

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

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 $U(1)_{\mathrm{PQ}}$ symmetry at scale $\Lambda_{\mathrm{UV}} \sim f_a$.

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.

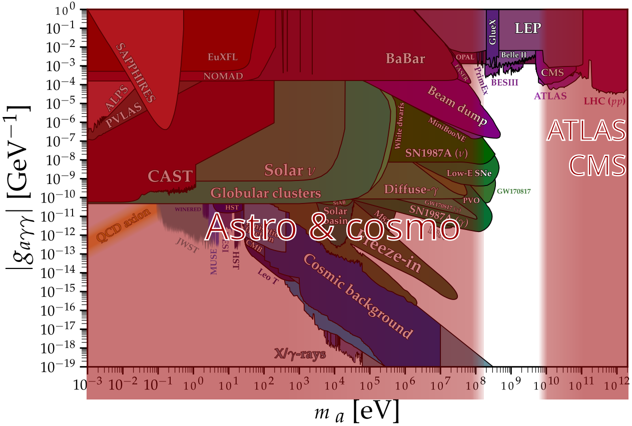
Predicted by many BSM models: string theory (axiverse), flavour (familion, flaxion), neutrino masses (majoron), DM candidates, etc.

Described by dimension-5 ALP-EFT [H. Georgi, D. Kaplan, L. Randall, PLB 169B(1986)73]:

$$\mathcal{L}_a(\Lambda) = \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{m_a^2}{2}a^2 + \sum_{V=G,B,W} c_V(\Lambda)\frac{a}{f_a}\frac{\alpha_V}{4\pi}V_{\mu\nu}\tilde{V}^{\mu\nu} + \sum_{\substack{f=\ell_L,e_R,\\ q_L,u_R,d_R}} \frac{\partial_\mu a}{f_a}\bar{f}_i\gamma^\mu c_f^{ij}(\Lambda) f_j\,.$$

$3 + 5 \times 9 - 4[B, L_e, L_\mu, L_\tau \text{ conservation}] = \mathbf{44}$ independent real coefficients.

# GeV scale ALPs

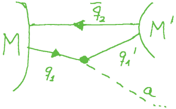



[C. O'Hare, AxionLimits (adapted)]

- Ideal range for LHCb, Belle II, BESIII. Complementary to astrophysics and cosmology (lower masses) and ATLAS and CMS (larger masses).
- Weaker constraints.
- Flavour.
- Challenges from decays into mesons.

# The life of a GeV ALP

## 1- Production

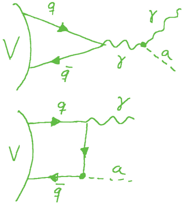



FCNC

$B \to K^{(*)} a$

$K \to \pi a$

$B \to \pi a \ldots$



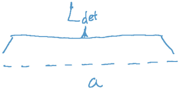

Quarkonia

$J/\psi \to \gamma a$

$\Upsilon(nS) \to \gamma a$


$pp \to a$ (WIP)

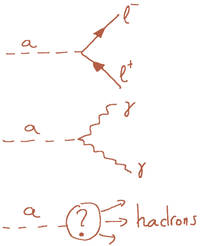
## 2- Propagation




$$\tau_a = \frac{\hbar}{\Gamma_a}$$

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

## 3- Decay

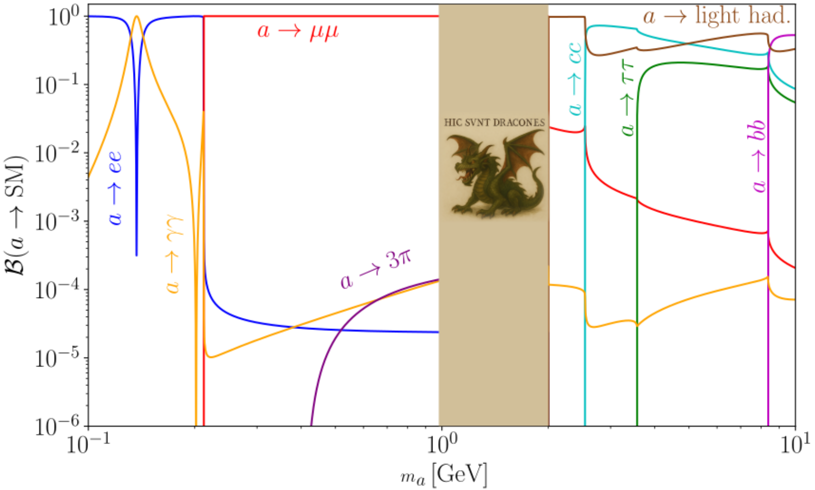



NWA $(\Gamma_a \ll m_a)$

$$\Gamma(X \to YZ) \simeq \Gamma(X \to Ya) BR(a \to Z)$$

# ALP decays: the *terra incognita*

Example: Universal couplings to fermions.




[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**

**–**

**a**utomatic
**c**omputing
**a**lgorithm

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

```
pip3 install alpaca-ALPs
```

# The ALP-aca workflow

1. At the UV scale $\Lambda_{\mathrm{UV}}$ 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 $\chi^2$ analysis with $>$ 100 observables.
5. Plot the exclusion significance.
6. Generate the list of bibliographical references.

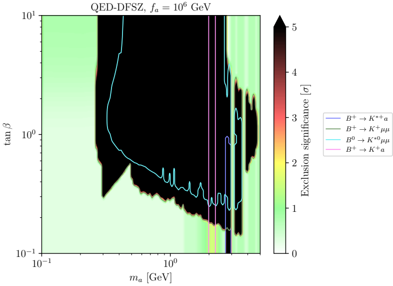
$\}$ NWA approximation

# ALP-aca in action!

```python
from alpaca.uvmodels import QED_DFSZ, beta
from alpaca.scan import Axis, Scan
from alpaca.sectors import default_sectors
from alpaca.plotting.mpl import exclusionplot
import numpy as np

x_ma = Axis(np.logspace(-1, np.log10(5), 100), 'x', r'$m_a\ [GeV]$')
y_tanbeta = Axis(np.logspace(-1, 1, 100), 'y', r'$\tan\beta$')
y_beta = Axis(lambda x: np.arctan(x), 'y_func', r'$\beta$')

scan = Scan(model=QED_DFSZ, ma=x_ma, fa=1e6, lambda_scale=4e6*np.pi,
            mu_scale=5.1, model_pars={beta: y_beta, 'tanbeta': y_tanbeta})

chi2 = scan.get_chi2(default_sectors['bsa_lfu'], integrator='leadinglog')
chi2_obs = chi2.split_observables()
exclusionplot(x_ma, y_tanbeta, chi2_obs, title=r'QED-DFSZ, $f_a = 10^6$ GeV')
```

Written completely in Python
Easy to use, concise syntax

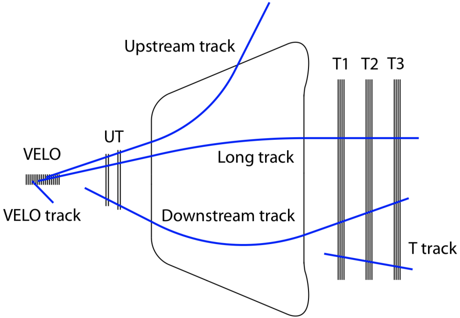
Manual available at 2508.08354




**Interactive version**

# ALP-aca use case: `Downstream` LHCb

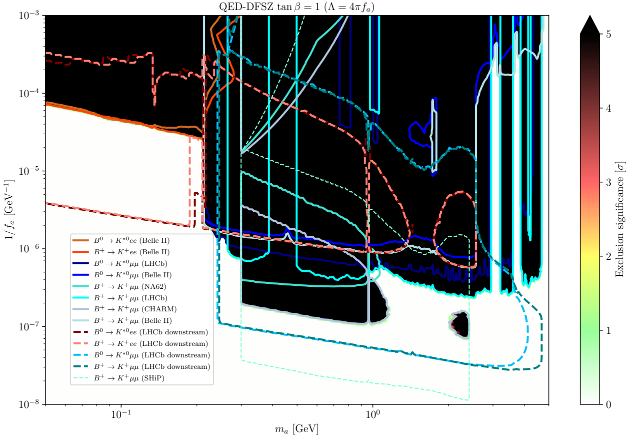
The new `Downstream` algorithm will reconstruct tracks of long-lived particles that do not leave hits on the VELO, only UT and SciFi. [V. Kholoimov, B. K. Jashal, A. Oyanguren, V. Svintozelskyi, J. Zhuo. Comput.Softw.Big Sci. 9 (2025) 1, 10]




Huge potential to discover long-lived ALPs. [V. Gorkavenko, B. K. Jashal, V. Kholoimov, Y. Kyselov, D. Mendoza, M. Ovchynnikov, A. Oyanguren, V. Svintozelskyi, J. Zhuo. Eur.Phys.J.C 84 (2024) 6, 608]

# Downstream LHCb: $B$ decays

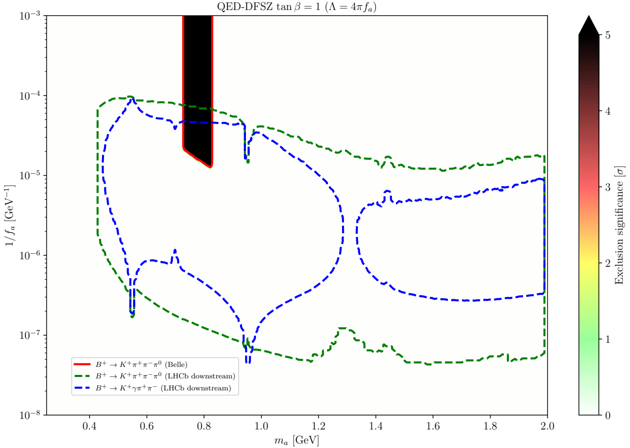
Great improvements in $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$, beating CHARM and competitive with SHiP.




Sensitivity study performed with SensCalc, re-cast with ALP-aca. **Interactive version**

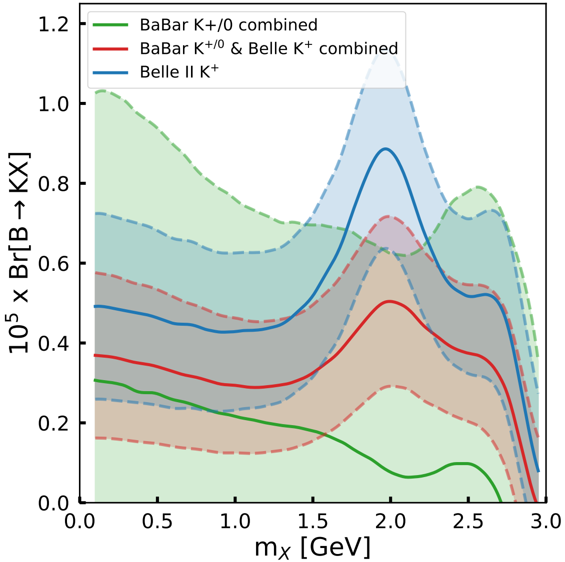
# Downstream LHCb: hadronic ALP decays

$B \to Ka(\to 3\pi)$ and $B \to Ka(\to \gamma\pi^+\pi^-)$ processes could reach sensitivities comparable to $B \to Ka(\to \mu^+\mu^-)$.




Sensitivity study performed with SensCalc, re-cast with ALP-aca. **Interactive version**

# 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][M. Abumusabh, G. Dujany, D. Guadagnoli, A. Iohner, C. Toni. 2510.18953]

Could it be **an ALP**???

Let's find out with ALP-aca!

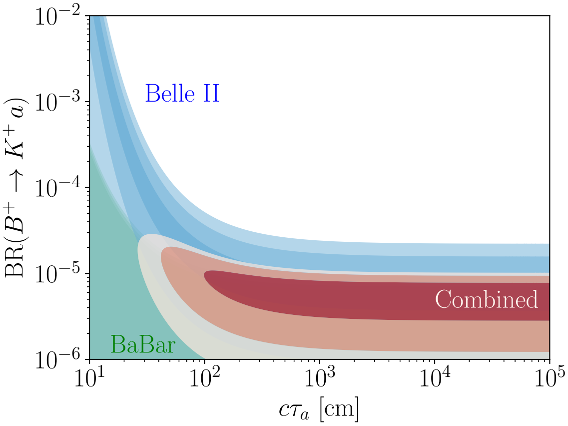
# Re-(re)-analysis of BaBar and Belle II

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

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

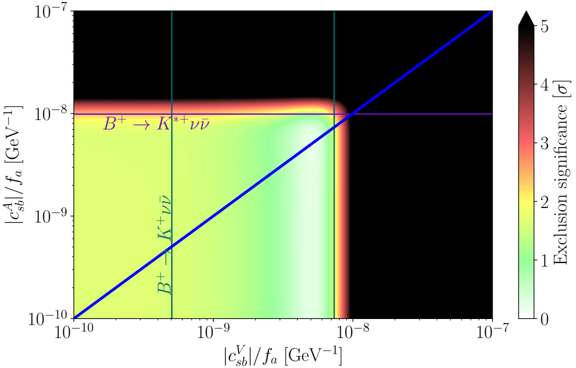
The difference in detector size and boost between BaBar and Belle II allows us to disentangle $\mathrm{BR}(B^+ \to K^+ a)$ and $P_{\mathrm{out}}$.

For $m_a = 2\,\mathrm{GeV}$, preference for longer-lived ALP and $\mathrm{BR}(B^+ \to K^+ a) \sim 5 \times 10^{-6}$.




**Interactive version**

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




**Interactive version**

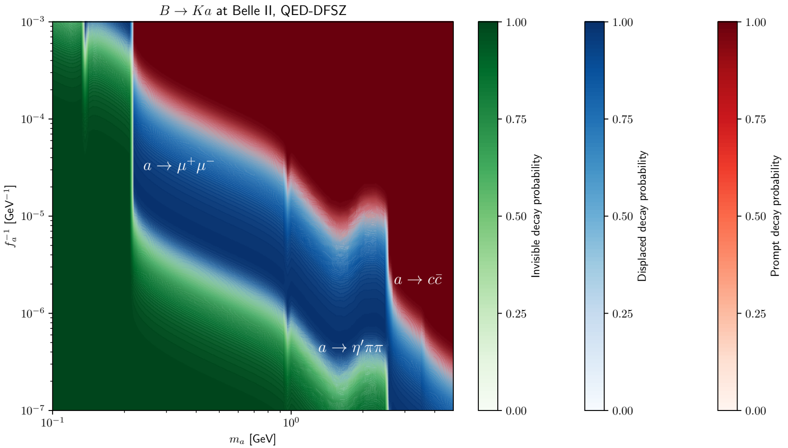
Effective Lagrangian at $\mu = m_a = 2\,\mathrm{GeV}$:

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

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

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

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



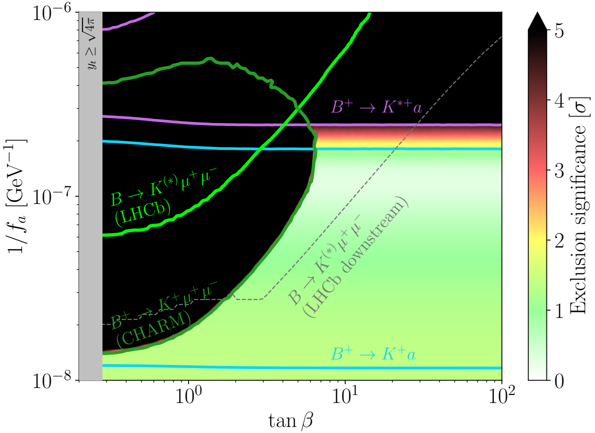
# Possible solution: Flavour violation at tree level

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]




**Interactive version**

# ALP-aca to the future

There is still much to be included in future versions of ALP-aca:

- Heavy ALPs: $pp$ production, light-by-light scattering
- Intermediate ALPs: Beam dump and forward experiments (FASER, SHiP, MATHUSLA)
- Indirect probes: Anomalous magnetic moments and chromomagnetic moments
- Light ALPs: Astrophysics, cosmology, ...

# 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.
- 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 have created ALP-aca to facilitate the full analysis of ALP models, with special emphasis on mesonic processes.
- LHCb provides some of the most stringent bounds in $B \to K^{(*)}\mu^+\mu^-$. Very exciting prospects for `Downstream` tracks!
- 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.
- Many more observables will be implemented soon$^{\mathrm{TM}}$!

**Thank you for your attention!**

# Backup slides

# ALP benchmarks

Benchmarks from Physics Beyond Colliders at CERN BSM WG report [J.Phys.G 47 (2020) 1, 010501]:

- $\mathcal{L}_{\mathrm{BC9}}(\Lambda = 1\,\mathrm{TeV}) = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\quad c_B(\Lambda) \approx \frac{\pi f_a}{\alpha_{\mathrm{em}}} g_{a\gamma\gamma}$
- $\mathcal{L}_{\mathrm{BC10}}(\Lambda = 1\,\mathrm{TeV}) = \frac{g_Y}{2v}\partial_\mu a \sum_f \bar{f}\gamma^\mu\gamma_5 f$, $\quad c_{f_R}^{ij}(\Lambda) = -c_{f_L}^{ij}(\Lambda) = \frac{g_Y}{2}\frac{f_a}{v}\delta^{ij}$
- $\mathcal{L}_{\mathrm{BC11}}(\Lambda = 1\,\mathrm{TeV}) = \frac{1}{4 f_G} a G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\quad c_G(\Lambda) = \frac{\pi}{\alpha_s}\frac{f_a}{f_G}$

UV-inspired benchmarks:

- KSVZ-like models: Heavy vector-like fermions charged under $U(1)_{\mathrm{PQ}}$: ALP couplings to gauge bosons.
- DFSZ-like models: SM fermions charged under $U(1)_{\mathrm{PQ}}$: flavour-universal couplings to fermions + gauge bosons.
- Flaxion models: Froggatt-Nielsen mechanism providing Yukawa interactions for SM fermions: non-universal couplings to fermions + gauge bosons.

# 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:** $-\mathcal{L} \supset \bar{q}_L Y_u \tilde{H}_q u_R + \bar{q}_L Y_d H_q d_R + \bar{\ell}_L Y_e \tilde{H}_e e_R + \lambda_{H\phi} H_e^\dagger H_q \phi^2$.

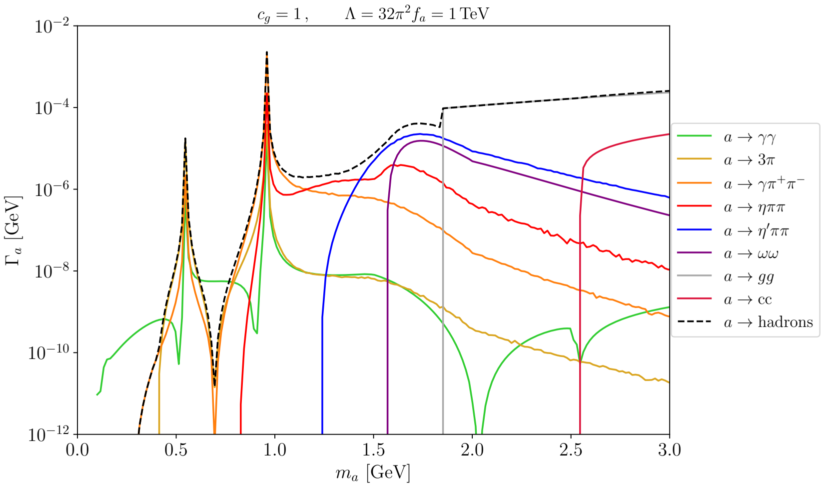
$$a = \frac{1}{f_a} \sum_{i=q,e,\phi} \mathcal{X}_{H_i} v_i a_i \,, \quad \text{with} \quad f_a^2 = \sum_i \mathcal{X}_{H_i}^2 v_i^2 \,,$$

  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

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

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

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



# Other possible solution: 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 $P_{\mathrm{inv}}$ and $\mathrm{BR}(B^+ \to K^+ a)$ at the same time.