

# Hunting ALPs in Meson Decays

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44TH COURSE OF THE INTERNATIONAL SCHOOL OF  
NUCLEAR PHYSICS

Set 22, 2023

# MENU

- Axion-Like Particles
- ALPs in Kaon decays
- ALPS in B meson decays
- Conclusions

# Axion-Like Particles (ALPs)

- Pseudo Goldstone Boson from global symmetries breaking

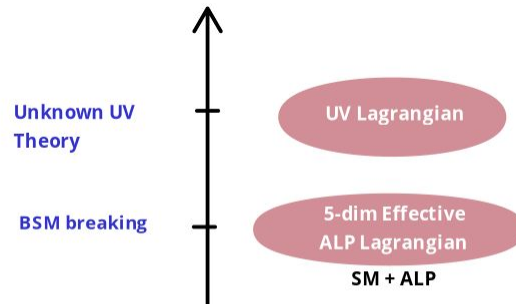
Peccei-Quinn Symmetry  
Lepton Number Symmetry  
Flavor Symmetry

QCD Axion  
Majoron  
Flavon

...

...

- Potential dark matter candidate [Preskill, Wise, Wilczek (1983)]
- Enjoy a shift symmetry.



$$\mathcal{L}_{\text{eff}}^{D \leq 5} = \frac{1}{2} (\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial^\mu a}{f} \sum_F \bar{\psi}_F \mathbf{c}_F \gamma_\mu \psi_F$$

$$+ c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + c_{BB} \frac{\alpha_1}{4\pi} \frac{a}{f} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

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

# Axion-Like Particles (ALPs)

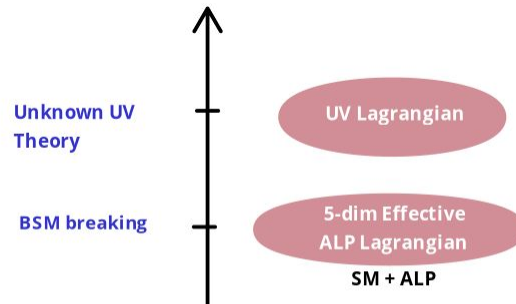
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field redefinition

$$\mathcal{L}_{\text{SM+ALP}}^{D=5'} = C_{GG} \frac{a}{f} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + C_{WW} \frac{a}{f} W_{\mu\nu}^I \tilde{W}^{\mu\nu,I} + C_{BB} \frac{a}{f} B_{\mu\nu} \tilde{B}^{\mu\nu} - \frac{a}{f} \left( \bar{Q} \tilde{H} \tilde{Y}_u u_R + \bar{Q} H \tilde{Y}_d d_R + \bar{L} H \tilde{Y}_e e_R + \text{h.c.} \right)$$

$$\psi_F \rightarrow \psi_F + i \frac{a}{f} \mathbf{c}_F \psi_F$$

$$\text{flavor universal ALP: } \tilde{Y}_u \equiv i \mathbf{Y}_u C_u, \quad \tilde{Y}_d \equiv i \mathbf{Y}_d C_d, \quad \tilde{Y}_e \equiv i \mathbf{Y}_e C_e$$

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# K → pi a phenomenology

- Matching the ALPs into the Chiral Lagrangian
- The degrees of freedom is the hadron

$$\Sigma(x) = \exp \left[ \frac{i\sqrt{2}}{f_\pi} \lambda^a \pi^a(x) \right]$$

- Leading order effective Chiral Lagrangian:

$$\mathcal{L}_{\text{eff}}^\chi = \frac{f_\pi^2}{8} \text{Tr}[\mathbf{D}^\mu \Sigma (\mathbf{D}_\mu \Sigma)^\dagger] + \frac{f_\pi^2}{4} B_0 \text{Tr}[\hat{\mathbf{m}}_q(a) \Sigma^\dagger + \text{h.c.}]$$

$$+ \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{m_{a,0}^2}{2} a^2 + \hat{c}_{\gamma\gamma} \frac{\alpha}{4\pi} \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu},$$

where,

$$i\mathbf{D}_\mu \Sigma = i\partial_\mu \Sigma + eA_\mu [\mathbf{Q}, \Sigma] + \frac{\partial_\mu a}{f} (\hat{\mathbf{k}}_Q \Sigma - \Sigma \hat{\mathbf{k}}_q)$$

$$\hat{\mathbf{m}}_q(a) = \exp \left( -2i\kappa_q c_{GG} \frac{a}{f} \right) \mathbf{m}_q$$

Unknown UV  
Theory

BSM breaking

Chiral Symmetry  
breaking

UV Lagrangian

5-dim Effective  
ALP Lagrangian

SM + ALP

Effctv Chiral Lagrangian  
coupled to ALP

Hadrons + ALP

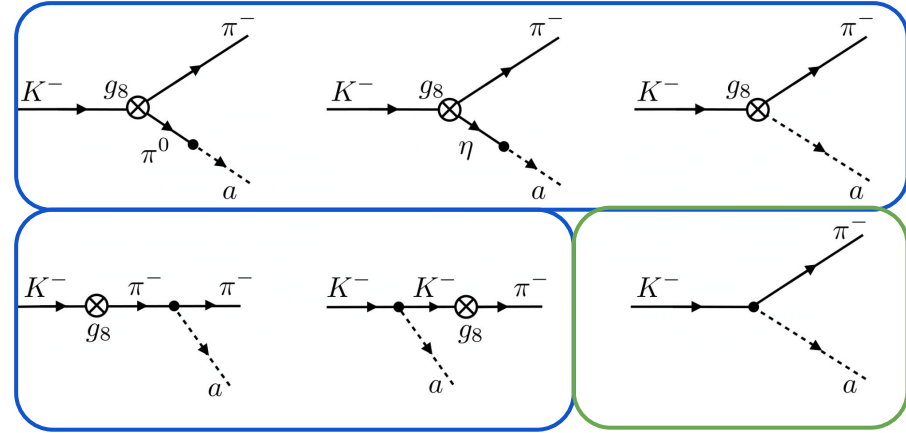
# K → pi a phenomenology

M. Bauer, M. Neubert, et al, [arXiv:2102.13112](https://arxiv.org/abs/2102.13112)

- Flavor changing  $s \rightarrow d$

$$K^- \longrightarrow \pi^- + \text{ALP}$$

$$m_a \leq m(K^-) - m(\pi^-) \approx 350 \text{ MeV}$$



- The amplitude is

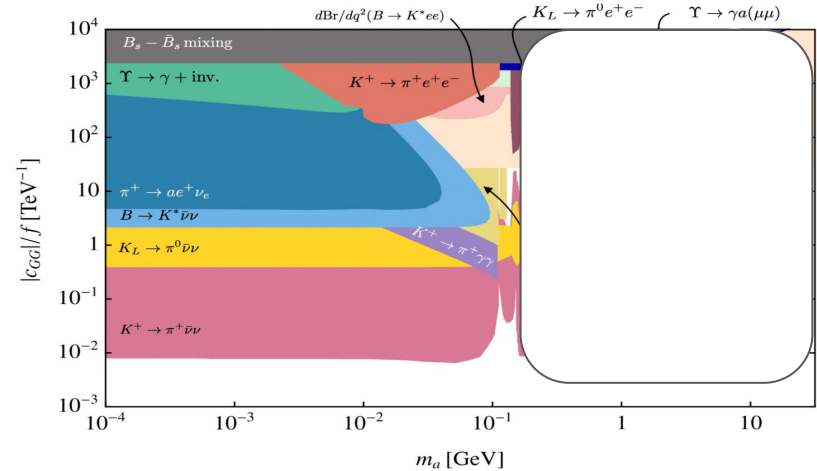
$$i\mathcal{A}(K^- \longrightarrow \pi^- + a) \approx -1.12 \times 10^{-4} \text{ GeV} \left[ \frac{1 \text{ TeV}}{f} [k_d + k_D]_{12} \right] + 10^{-11} \text{ GeV} \left[ \frac{1 \text{ TeV}}{f} [3.50 C_{GG} + 0.86 (2c_{uu} + c_{dd} + c_{ss}) + 1.01 ([k_d + k_D]_{11} - [k_d + k_D]_{22})] \right]$$

# K → pi a phenomenology

- Expressing the ALPs in terms of the coupling at the UV scale

$$|\mathcal{A}(K^- \rightarrow \pi^- + a)| \approx 10^{-11} \text{GeV} \left[ \frac{1 \text{TeV}}{f} \right] \cdot [(3.58 C_{GG} + 1.79 C_{uu}(\Lambda) + 1.81 C_{dd}(\Lambda)) + (-65.8 C_{uu}(\Lambda) + 0.32 C_{dd}(\Lambda) + 0.21 C_{GG} + 0.38 C_{WW}) - 1.12 \cdot 10^7 \kappa_D^{12}(\Lambda)]$$

M. Bauer, M. Neubert, et al, [arXiv:2102.13112](https://arxiv.org/abs/2102.13112)



- Using the NA62 upper limit  $\text{Br}(K \rightarrow \pi X) < 2.0 \cdot 10^{-10}$  (90% CL)

$C_{ii}$	$C_{GG}$	$C_{WW}$	$C_{uu}$	$C_{dd}$	$\kappa_D^{12}$
$(\text{upper limit [TeV]})^{-1}$	61.3	6.5	1126	31.0	$1.9 \cdot 10^8$

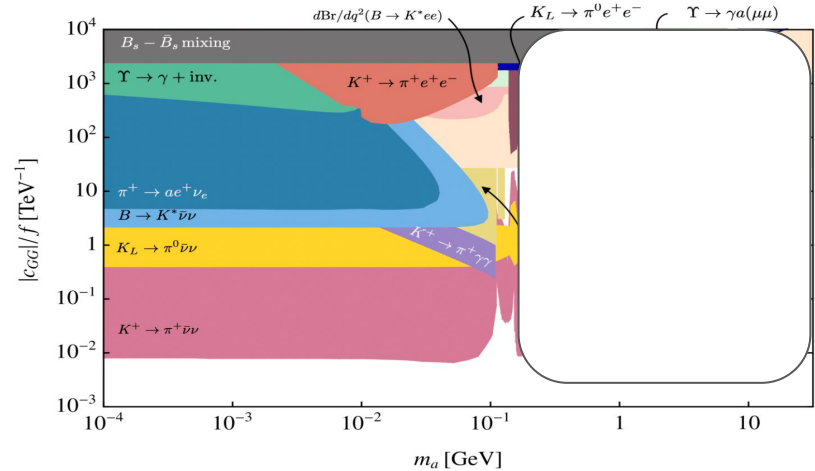


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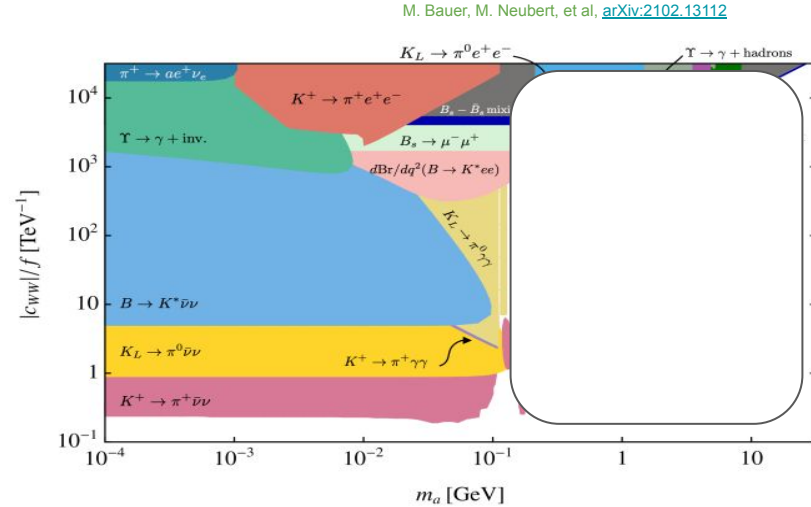
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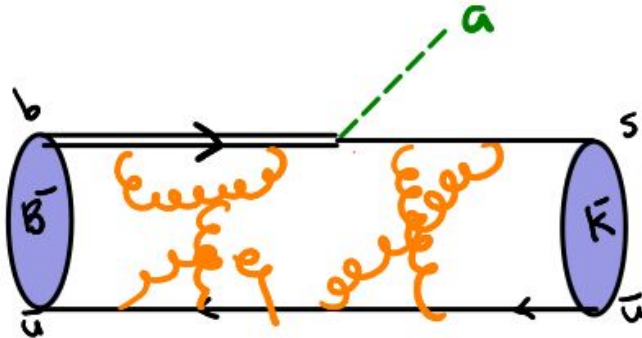
# B → K a phenomenology

- Flavor changing  $b \rightarrow s$

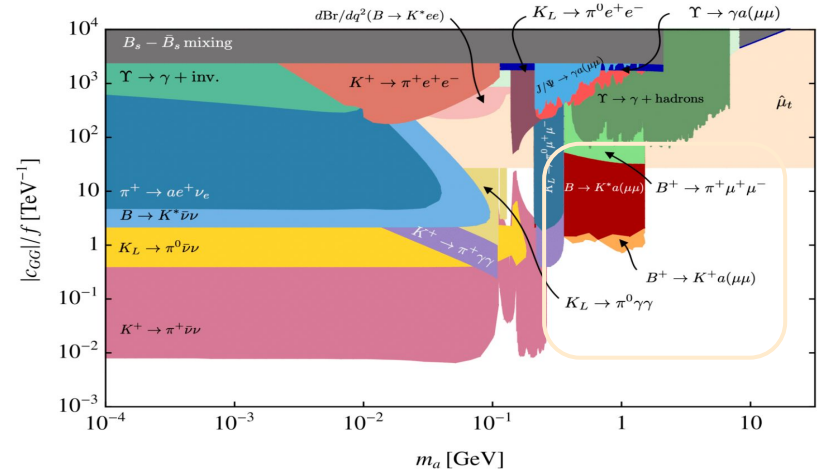
$$B^- \longrightarrow K^- + \text{ALP}$$

$$m_a \leq m(B^-) - m(K^-) \approx 4.8 \text{ GeV}$$

- ALP Flavor Changing:



M. Bauer, M. Neubert, et al, [arXiv:2102.13112](https://arxiv.org/abs/2102.13112)



$$\Gamma(B^- \rightarrow \pi^- a) = \frac{m_B^3}{64\pi f^2} |[k_D + k_d]_{13}|^2 |F_0^{B \rightarrow \pi}(m_a^2)|^2 \left(1 - \frac{m_\pi^2}{m_B^2}\right)^2 \lambda^{1/2} \left(\frac{m_\pi^2}{m_B^2}, \frac{m_a^2}{m_B^2}\right),$$

$$\Gamma(\bar{B}^0 \rightarrow \pi^0 a) = \frac{1}{2} \Gamma(B^- \rightarrow \pi^- a),$$

$$\Gamma(B^- \rightarrow K^- a) = \frac{m_B^3}{64\pi f^2} |[k_D + k_d]_{23}|^2 |F_0^{B \rightarrow K}(m_a^2)|^2 \left(1 - \frac{m_K^2}{m_B^2}\right)^2 \lambda^{1/2} \left(\frac{m_K^2}{m_B^2}, \frac{m_a^2}{m_B^2}\right),$$

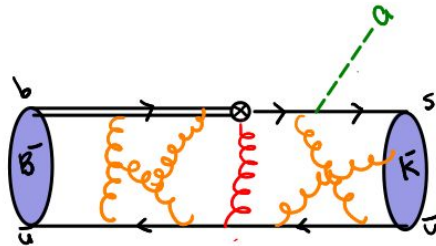
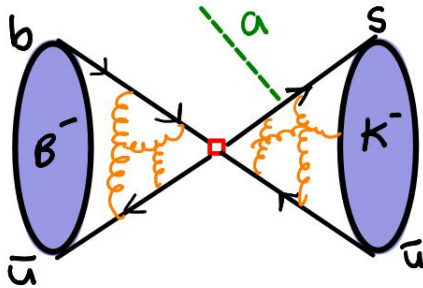
$$\Gamma(B^- \rightarrow K^{*+} a) = \frac{m_B^3}{64\pi f^2} |[k_D - k_d]_{23}|^2 |A_0^{B \rightarrow K^*}(m_a^2)|^2 \lambda^{3/2} \left(\frac{m_K^{*2}}{m_B^2}, \frac{m_a^2}{m_B^2}\right),$$

# B → K a phenomenology

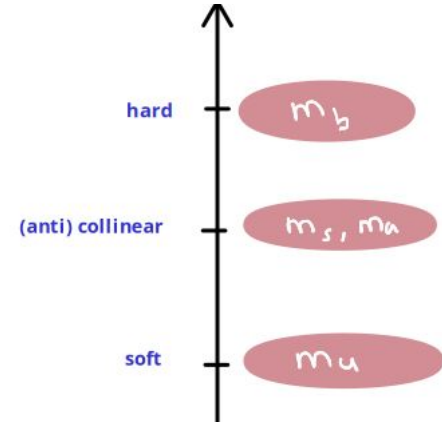
- Flavor-changing by the Weak Interaction and ALP-flavor conserving

$$\mathcal{H}_{\text{eff}}(b \rightarrow s) = \sum_j C_j \text{[diagram]} + C_8 \text{[diagram]}$$

The equation shows the effective Hamiltonian for the  $b \rightarrow s$  transition. The first term is a sum over operators  $C_j$  with a diagram showing a  $b_L$  quark and a  $s_L$  quark connected by a  $q$  quark loop. The second term is  $C_8$  with a diagram showing a  $b_R$  quark and a  $s_L$  quark connected by a  $G_3$  gluon loop.



- Multi-scale problem



# Conclusions

- ALPs can be constrained by meson decays: Kaon and B meson.
- Kaon decays are more sensitive to ALP flavor-changing than flavor-conserving decays
- Flavor-changing in B meson decays given by EW effective interaction are bigger or smaller?

**STAY IN TUNE**