An axion-like particle explanation of $B \to \pi K$ puzzle and $B^+ \to K^+ \nu\bar{\nu}$ excess

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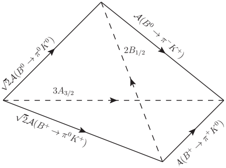
APS DIVISION OF PARTICLES & FIELDS

Outline

- $B \to \pi K$ decays
- $B \to K\nu\bar{\nu}$ decays
- ALP in B decays
- Conclusion

- The four $B \to \pi K$ decay amplitudes are related by isospin,
- $A_{1/2}$, $A_{3/2}$ and $B_{1/2}$ are isospin amplitudes corresponding to $\Delta I = 1$ and $\Delta I = 0$ part of the effective Hamiltonian.

$$
\begin{aligned}
A(B^+ \to \pi^+ K^0) &= B_{1/2} + A_{1/2} + A_{3/2}\,, \\
A(B^+ \to \pi^0 K^+) &= -\frac{1}{\sqrt{2}}\left(B_{1/2} + A_{1/2}\right) + \sqrt{2}A_{3/2} \\
A(B^0 \to \pi^- K^+) &= -B_{1/2} + A_{1/2} + A_{3/2}\,, \\
A(B^0 \to \pi^0 K^0) &= \frac{1}{\sqrt{2}}\left(B_{1/2} - A_{1/2}\right) + \sqrt{2}A_{3/2}\,.
\end{aligned}
$$



- Isospin relation

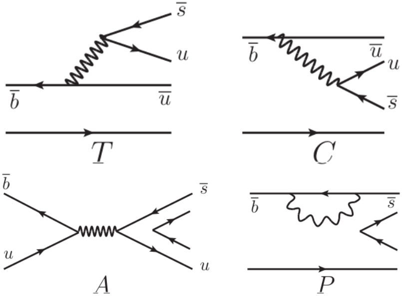
$$
\sqrt{2}\mathcal{A}(B^0 \to \pi^0 K^0) - \sqrt{2}\mathcal{A}(B^+ \to \pi^0 K^+) = \mathcal{A}(B^+ \to \pi^+ K^0) - \mathcal{A}(B^0 \to \pi^- K^+)
$$

- In terms of topological flavor-flow amplitudes:

$$\mathcal{A}^{-+} = -\lambda_u \left(P_{uc} + T\right) - \lambda_t \left(P_{tc} + \frac{2}{3} P^{C}_{EW}\right) ,$$
$$\mathcal{A}^{+0} = \lambda_u \left(P_{uc} + A\right) + \lambda_t \left(P_{tc} - \frac{1}{3} P^{C}_{EW}\right) ,$$
$$\sqrt{2}\mathcal{A}^{00} = \lambda_u \left(P_{uc} - C\right) + \lambda_t \left(P_{tc} - P_{EW} - \frac{1}{3} P^{C}_{EW}\right) ,$$
$$\sqrt{2}\mathcal{A}^{0+} = -\lambda_u \left(P_{uc} + T + C + A\right) - \lambda_t \left(P_{tc} + P_{EW} + \frac{2}{3} P^{C}_{EW}\right) ,$$

Gronau+, PRD '94, Fleischer+ PLB '96, PRD '98, Neubert+ PLB '98, Gronau PLB '05...

- T: Color-allowed tree
- C: Color-suppressed tree
- A: Annihilation
- P: QCD penguin
- P_{EW} & P^{C}_{EW} : Color-allowed and suppressed EW penguin



- In the SM, the relative importance of the flavor flow topologies

$$|\lambda_t P_{tc}| > |\lambda_u T| > |\lambda_u C| > |\lambda_u A| , |\lambda_u P_{uc}| ,$$ *Gronau+, PRD '95*

suppression factor of the order of $\lambda \approx \sin\theta_C = 0.22$, θ_C: Cabibbo angle.

- Particularly important ratio $|C/T| \sim \lambda$. *Beneke+, Nucl. Phys. B '01*
- A and P_{uc} expected to be subdominant. Can be neglected at $\mathcal{O}(\lambda^2)$.
- The $SU(3)$-flavor symmetry is used to establish a relation between the electroweak penguin amplitudes and tree amplitudes.
- In SM, both P_{EW}/T and P_{EW}^C/C are approximately the same. Given by a common ratio κ,

$$\kappa = -\frac{3}{2}\frac{C_9 + C_{10}}{C_1 + C_2} \simeq -\frac{3}{2}\frac{C_9 - C_{10}}{C_1 - C_2} \simeq 0.0135 \pm 0.0012$$

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- A measurable quantity sensitive to isospin violation encoded in the observable Δ_4:

$$\Delta_4 = A_{CP}(\pi^- K^+) + A_{CP}(\pi^+ K^0)\frac{\mathcal{B}(\pi^+ K^0)\tau_0}{\mathcal{B}(\pi^- K^+)\tau_+} - A_{CP}(\pi^0 K^+)\frac{2\mathcal{B}(\pi^0 K^+)\tau_0}{\mathcal{B}(\pi^- K^+)\tau_+} - A_{CP}(\pi^0 K^0)\frac{2\mathcal{B}(\pi^0 K^0)}{\mathcal{B}(\pi^- K^+)}$$

Gronau+, PLB '05,PRD '06

- $\Delta_4 = 0$ holds up to a few percent in the SM.

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Measurements

$$\Delta_4 = -0.270 \pm 0.132 \pm 0.060$$ *Belle 2012, PRD 2013*

$$\Delta_4 = -0.03 \pm 0.13 \pm 0.04$$ *Belle II 2023, PRD 2024*

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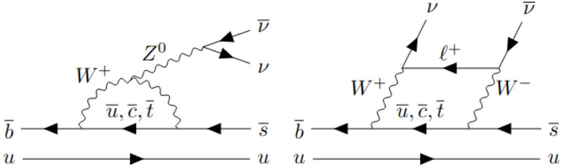
- Also $\Delta A_{CP} = A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+) = 0.108 \pm 0.017$,
LHCb, PRL 21

- Requires large $\frac{C}{T}$ $\Rightarrow$ "Naive $B \to \pi K$ puzzle".

$B^+ \to K^+\nu\bar{\nu}$ decay

- Semileptonic FCNC decay with negligible hadronic uncertainty. Accurate SM prediction for decay rate. *Altmannshofer+ JHEP 09, Buras+, JHEP 15*

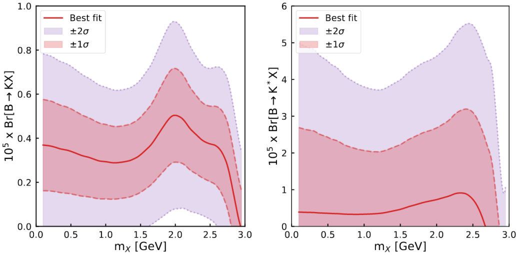


- $Br(B^+ \to K^+\nu\bar{\nu})|_{\mathbf{SM}} = (5.58 \pm 0.37) \times 10^{-6}$ *C. Davies+, PoS LATTICE2022, 421 (2023)*
- Experimentally the final state neutrinos are not reconstructed, signal looks identical to $B^+ \to K^+ \not{E}$.
- The measured branching ratio in Belle II *Belle-II, PRD '24*

$$Br(B^+ \to K^+\nu\bar{\nu})|_{\mathbf{exp}} = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$$

- A deviation of 2.7σ from the SM expectation.
- Several interpretations $\cdots$ *McKeen+ '23, He+ PRD '24, Fridell+ '24, Altmannshofer+ PRD '24 $\cdots$*

$B^+ \to K^+\nu\bar{\nu}$ decay



Altmannshofer+ PRD '24

Fit of $Br(B \to KX)$ from Belle II and BaBar as a function m_X,

- The $B^+ \to K^+\nu\bar{\nu}$ events may contain $B^+ \to K^+ a$ decays, where a is a long-lived axion-like particle.
- Assumption: a decays dominantly to two photons. Agnostic about the origin of $a\gamma\gamma$ coupling.
- Can mimic the signal for $\pi^0 \to \gamma\gamma$, therefore challenging to distinguish from actual π^0 decays if $m_{\pi^0} \simeq m_a$.
- Most of the a decays happen outside the Belle-II detector volume.

Interplay of $B^+ \to K^+\nu\bar{\nu}$ and $B^+ \to K^+\pi^0$ decays

- The ALP originating in $B^+ \to aK^+$ can get misidentified as a $B^+ \to \pi^0 K^+$ if $a \to \gamma\gamma$ decay happens within the detector.
- Since the signals are indistinguishable,

$$\Gamma(B^+ \to \pi^0 K^+)|_{\text{exp}} = \Gamma(B^+ \to K^+\pi^0) + \Gamma(B^+ \to K^+ a^0)$$
$$\Gamma(B^0 \to \pi^0 K^0)|_{\text{exp}} = \Gamma(B^0 \to K^0\pi^0) + \Gamma(B^0 \to K^0 a^0)$$

- Effective Hamiltonian for $b \to sa$ decay:

$$\mathcal{L}_{\text{FCNC}} \supset \bar{s}(h^S_{sb} + h^P_{sb}\gamma_5) b\, a + \text{h.c.}$$

Dolan+ JHEP '17, Camalich+ PRD '20, Bauer+ JHEP '22

- Decay rate for $B \to aK$: (f^B_0: B-meson decay constant)

$$Br(B \to a\,K) = \tau_B \frac{p_K}{8\pi m_B^2} \frac{(m_B^2 - m_K^2)^2}{(m_b - m_s)^2} |f^B_0|^2 |h^S_{sb}|^2$$

Ferber+ JHEP '23, Bruggisser+ JHEP '24

Estimate of $B \to aK$ decay rate

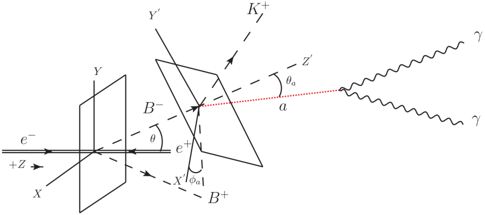
Scenario	p-value	Fit parameter	Fit value
I (SM fit)	0.46	P_{tc}	-0.147 ± 0.001
		κ	0.013 ± 0.007
		$\|T\|$	1.3 ± 0.7
		$\|C\|$	0.36 ± 0.10
		δ_T	0.19 ± 0.12
		δ_C	4.38 ± 0.67
II (SM + ALP)	0.76	P_{tc}	-0.148 ± 0.001
		κ	0.014 ± 0.005
		$\|T\|$	1.21 ± 0.44
		$\|C\|$	0.56 ± 0.14
		δ_T	3.35 ± 0.08
		δ_C	0.66 ± 0.21
		Δ	0.00021 ± 0.00009

$$Br(B^+ \to aK^+) = 1.12^{+1.16}_{-0.75} \times 10^{-7} (\text{fit})$$

Condition on the lifetime of ALP

The photon-ALP effective Lagrangian,

$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$



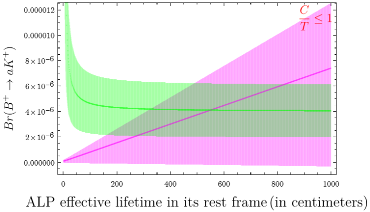
The decay probability,

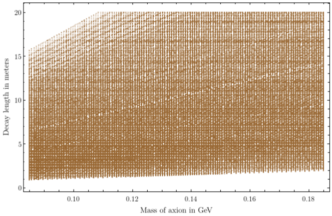
$$f_L(m_B, m_K, m_a = m_{\pi^0}, l_{\max}) = \int_0^{\pi/2} \sin\theta_a d\theta_a \Big(1 - \exp\Big(-\frac{m_a l_{max}}{c\tau_0 |p_L^{\text{lab}}|}\Big)\Big)$$

where $l_{\max}$ is the maximum distance from the primary decay vertex upto which ALP decay products can be resolved.

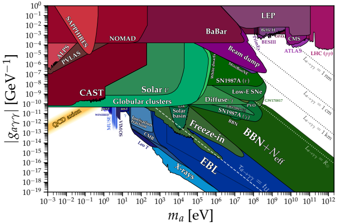
- By assumption, $\Gamma = \frac{1}{\tau_0} = \frac{g_{a\gamma\gamma}^2}{64\pi m_a^3}$
- Allow for a variation of m_a around m_{π^0},

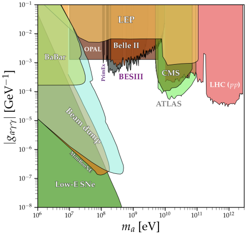
$$N_a(B^+ \to \pi^0 K^+)|_{\text{fake}} = N_B\, Br(B^+ \to aK^+) f_L$$
$$N_a(B^+ \to K^+ \not{E}) = N_B\, Br(B^+ \to aK^+)(1 - f_L)$$





- $c\tau_0 \geq 1.6\, m$
- $Br(B^+ \to aK^+) = 4.13^{+2.09}_{-2.09} \times 10^{-6}$

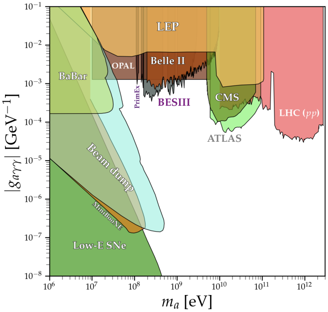




AxionLimits by C O'hare

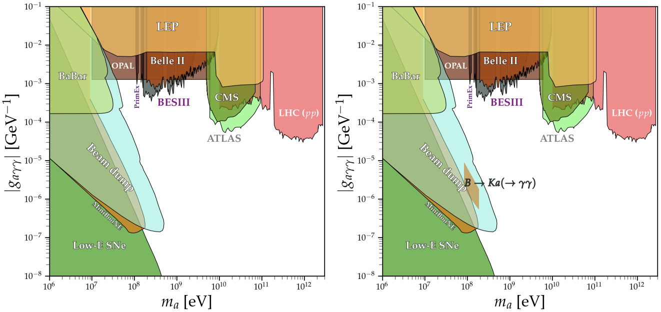
- The relevant $g_{a\gamma\gamma} - m_a$ parameter space to be probed in Beam-dump experiments like SHiP.
- Decay volume of the order of several meters.

$B^+ \to a(\to \gamma\gamma)K^+ \cdots$



- What about Primakoff production of ALPs and its subsequent decay events for allowed values of $g_{a\gamma\gamma}$? $\Rightarrow$ Under Investigation!

$B^+ \to a(\to \gamma\gamma)K^+ \cdots$



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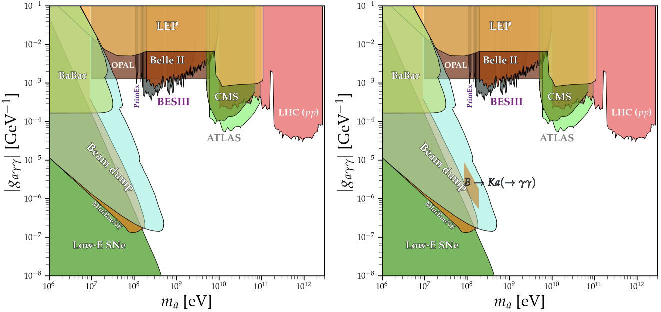

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Summary

- ALPs with MeV-to-GeV scale mass dominantly coupled to photons can be probed in collider experiments.
- Long lived ALPs produced in B-decays contribute to the measured $B \to K\nu\bar{\nu}$ decay rate at Belle-II if the ALPs decay outside the detector.
- Provides a simple solution to the $B \to \pi K$ puzzle if a tiny fraction of the ALPs decay to two photons within the detector.
- The $g_{a\gamma\gamma} - m_a$ parameter space is within the sensitivity reach of the upcoming beam dump experiments.
- An additional invisible decay width of the ALP will move the preferred region to larger values of $g_{a\gamma\gamma}$.
- The inferred bsa coupling is well below the constraints coming from B_s meson mixing.

Thank You

Backup: $B \to \pi K$

- $B \to \pi K$: hadronic weak decays with $|\Delta S| = 1$, ΔS being change in strangeness,
- Underlying quark level transition: $b \to u\bar{u}s$, relevant energy scale $\sim \mathcal{O}(m_b) \ll m_W$
- The decay mediated by dimension-6 effective Hamiltonian consists of tree, QCD penguin and electroweak penguin four-fermion operators,

$$\mathcal{H} = \frac{G_F}{\sqrt{2}}\left[\lambda_u\left(C_1\left(\bar{b}_\alpha u_\beta\right)_{V-A}(\bar{u}_\beta s_\alpha)_{V-A} + C_2\left(\bar{b}_\alpha u_\alpha\right)_{V-A}(\bar{u}_\beta s_\beta)_{V-A}\right) - \lambda_t \sum_{i=3}^{6} C_i Q_i - \lambda_t \sum_{i=7}^{10} C_i Q_i\right]$$

Buras+, Rev. Mod. Phys '96

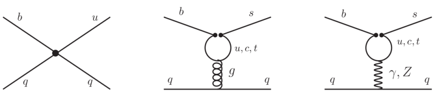
$$Q_{3,5} = (\bar{b}_\alpha s_\alpha)_{V-A} \sum_{q=u,d,s} (\bar{q}_\beta q_\beta)_{V\mp A}$$

$$Q_{4,6} = (\bar{b}_\alpha s_\beta)_{V-A} \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_{V\mp A}$$

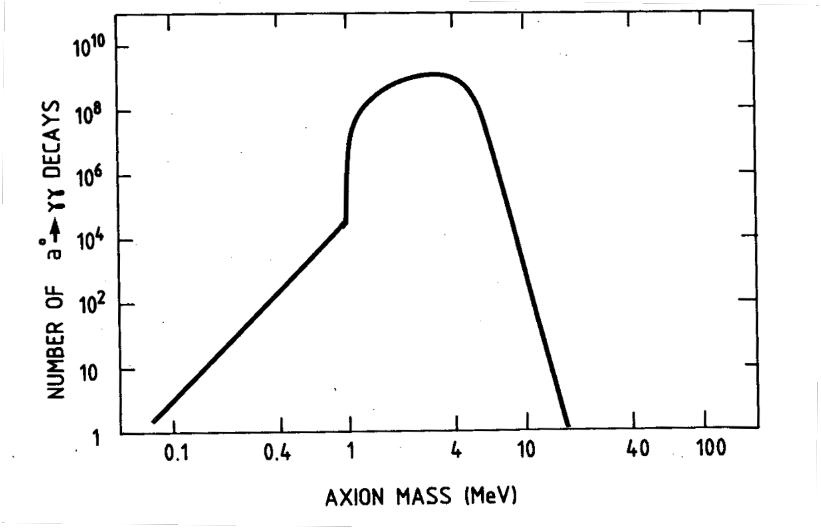
$$Q_{7,9} = \frac{3}{2}(\bar{b}_\alpha s_\alpha)_{V-A} \sum_{q=u,d,s} e_q(\bar{q}_\beta q_\beta)_{V\pm A}$$

$$Q_{8,10} = \frac{3}{2}(\bar{b}_\alpha s_\beta)_{V-A} \sum_{q=u,d,s} e_q(\bar{q}_\beta q_\alpha)_{V\pm A}$$

	$\Lambda^{(5)}_{\overline{MS}} = 140\,\mathrm{MeV}$			$\Lambda^{(5)}_{\overline{MS}} = 225\,\mathrm{MeV}$			$\Lambda^{(5)}_{\overline{MS}} = 310\,\mathrm{MeV}$		
Scheme	LO	NDR	HV	LO	NDR	HV	LO	NDR	HV
C_1	–0.273	–0.165	–0.202	–0.308	–0.185	–0.228	–0.339	–0.203	–0.251
C_2	1.125	1.072	1.091	1.144	1.082	1.105	1.161	1.092	1.117
C_3	0.013	0.013	0.012	0.014	0.014	0.013	0.016	0.016	0.015
C_4	–0.027	–0.031	–0.026	–0.030	–0.035	–0.029	–0.033	–0.039	–0.033
C_5	0.008	0.008	0.008	0.009	0.009	0.009	0.009	0.009	0.010
C_6	–0.033	–0.036	–0.029	–0.038	–0.041	–0.033	–0.043	–0.046	–0.037
C_7/α	0.042	–0.003	0.006	0.045	–0.002	0.005	0.047	–0.001	0.005
C_8/α	0.041	0.047	0.052	0.048	0.054	0.060	0.054	0.061	0.067
C_9/α	–1.264	–1.279	–1.269	–1.280	–1.292	–1.283	–1.294	–1.303	–1.296
C_{10}/α	0.291	0.234	0.237	0.328	0.263	0.266	0.360	0.288	0.291



Number of $a \to \gamma\gamma$ events in CHARM experiment



Reach of NA64 (PRL, 081801 (2020))