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

Shibasis Roy

In collaboration with Prof. W. Altmannshofer (UC Santa Cruz)

June 3, 2024

In preparation 2406.xxxx

Chennai Mathematical Institute

BEACH 2024

XV International Conference on Beauty, Charm, Hyperons in Hadronic Interactions

3-7 June 2024

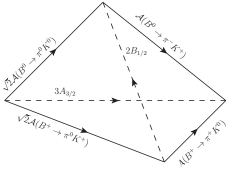
Outline

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

$B \to \pi K$ decays

- 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

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

$B \to \pi K$

- $B \to \pi K$: 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

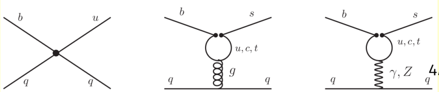
$$Q_{3,5} = (\bar{b}_\alpha s_\alpha)_{V-A} \sum_{q=u,d,s} (\bar{q}_\beta q_\beta)_{V\mp A}$$

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

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

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

	$\Lambda_{\overline{MS}}^{(5)} = 140$ MeV			$\Lambda_{\overline{MS}}^{(5)} = 225$ MeV			$\Lambda_{\overline{MS}}^{(5)} = 310$ 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

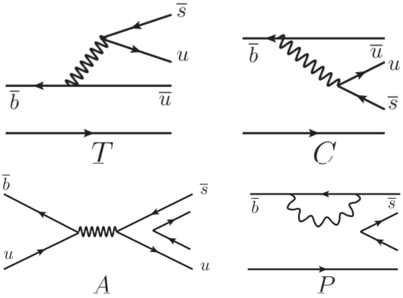


- In terms of topological flavor-flow amplitudes:

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

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^C_{EW}/C are approximately the same. Given by a common ratio κ,

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

- Ignore diagrams of $\mathcal{O}(\lambda^2)$ and beyond. $B \to \pi K$ amplitudes reduce to

$$\mathcal{A}^{-+} = -\lambda_u T - \lambda_t P_{tc} \,,$$
$$\mathcal{A}^{+0} = \lambda_t P_{tc} \,,$$

Buras+, EPJC '03, PRL '04, London+, PRD '05

$$\sqrt{2}\mathcal{A}^{00} = \lambda_t \left(P_{tc} - P_{EW}\right) \,,$$
$$\sqrt{2}\mathcal{A}^{0+} = -\lambda_u T - \lambda_t \left(P_{tc} + P_{EW}\right) \,.$$

- Direct CP asymmetries in $B^0 \to \pi^- K^+$ and $B^+ \to \pi^0 K^+$ due to T–P_{tc} interference,
    - a non-zero relative strong phase,
    - weak phase difference between T and P_{tc}.
- P_{EW} and T carry the same strong phase, related by κ, which is real in SM.
- P_{EW}–T interference for $B^+ \to \pi^0 K^+$ does not contribute to A_{CP}.
- Expect a simplified relation,

$$A_{CP}(B^0 \to \pi^- K^+) = A_{CP}(B^+ \to \pi^0 K^+).$$

Gronau and Rosner, PRD '99

- 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.

- 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.

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*

- 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.

Measurements

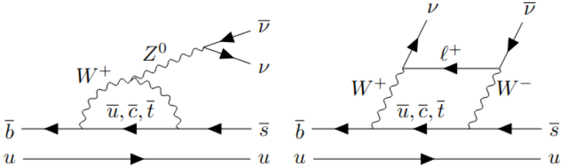
$\Delta_4 = -0.270 \pm 0.132 \pm 0.060$ *Belle 2012, PRD 2013*

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

- 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".

Datta+, JHEP 17, PRDL 21, Fleischer+ PLB 18

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

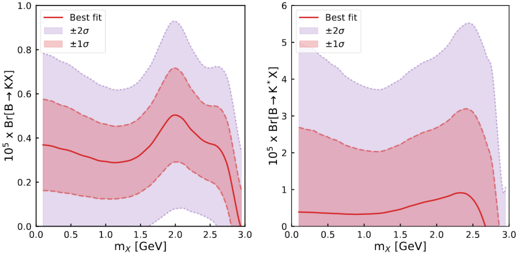


- $Br(B^+ \to K^+\nu\bar{\nu})|_{\text{SM}} = (5.58 \pm 0.37) \times 10^{-6}$ *C. Davies+, PoS LATTICE2022, 421 (2023)*
- Experimentally the final state neutrinos are not reconstructed, signal looks identical to $B^+ \to K^+ \not{E}$.
- The measured branching ratio in Belle II *Belle-II, PRD '24*

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

- 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,

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

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

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

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

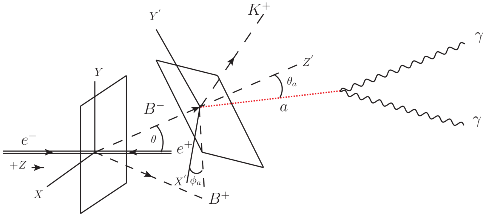
Scenario	p-value	Fit parameter	Fit value
I (SM fit)	0.46	P_{tc}	-0.147 ± 0.001
		κ	0.013 ± 0.007
		$\|T\|$	1.3 ± 0.7
		$\|C\|$	0.36 ± 0.10
		δ_T	0.19 ± 0.12
		δ_C	4.38 ± 0.67
II (SM + ALP)	0.76	P_{tc}	-0.148 ± 0.001
		κ	0.014 ± 0.005
		$\|T\|$	1.21 ± 0.44
		$\|C\|$	0.56 ± 0.14
		δ_T	3.35 ± 0.08
		δ_C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

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



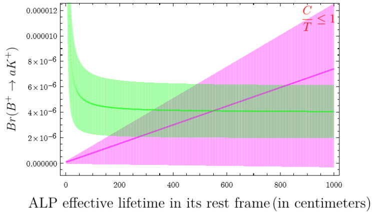
The decay probability,

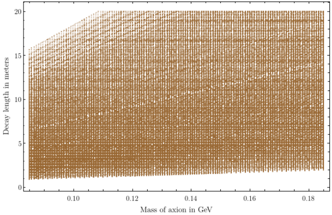
$$f_L(m_B, m_K, m_a = m_{\pi^0}, l_{\max}) = \int_0^{\pi/2} \sin\theta_a d\theta_a \left(1 - \exp\left(-\frac{m_a l_{max}}{c\tau_0 |p_L^{\text{lab}}|}\right)\right)$$

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

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

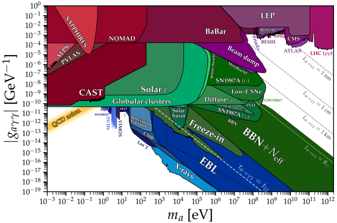
$$N_a(B^+ \to \pi^0 K^+)|_{\text{fake}} = N_B\, Br(B^+ \to aK^+) f_L$$
$$N_a(B^+ \to K^+ \not{E}) = N_B\, Br(B^+ \to aK^+)(1 - f_L)$$

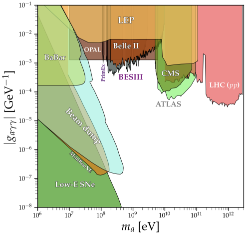




- $c\tau_0 \geq 1.6\, m$
- $Br(B^+ \to aK^+) = 4.13^{+2.09}_{-2.09} \times 10^{-6}$

Existing bounds on $g_{a\gamma\gamma}$

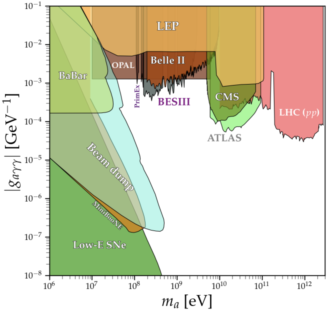




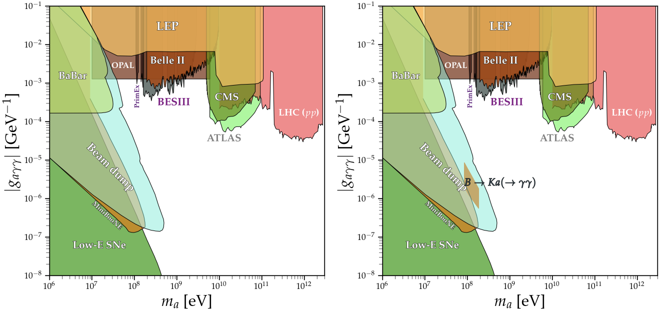
AxionLimits by C O'hare

- 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.

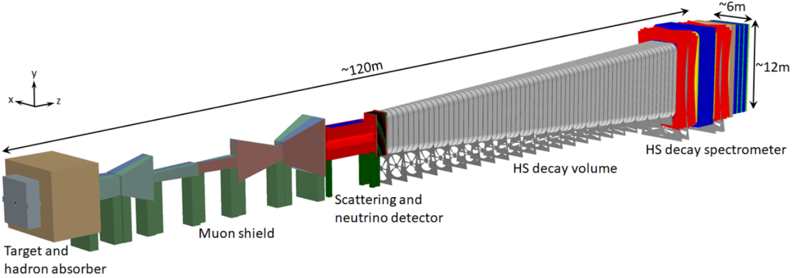
$B^+ \to a(\to \gamma\gamma)K^+ \cdots$



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



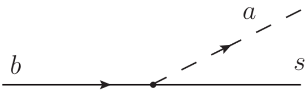
Production at proposed SHiP experiment **(Preliminary!)**



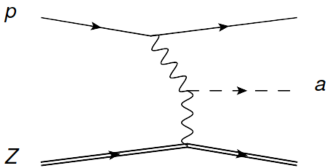
- Indirect production of ALP through $B \to a\,K$ decays,
- Primakoff production of ALP through coherent scattering with target nucleus $p + N \to p + N + a$
- In both cases, a decays to $\gamma\gamma$.

Production at proposed SHiP experiment (Preliminary!)

- Indirect production of ALP through $B \to a\,K$ decays,



- Primakoff production of ALP through coherent scattering with target nucleus $p + N \to p + N + a$

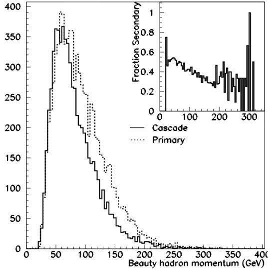


- In both cases, a decays to $\gamma\gamma$.

$B \to a\,K$ production **(Preliminary!)**

- 400 GeV proton beam on Molybdenum target, $E_{\rm CM} \sim 27.4$ GeV
- $N_{\rm PoT} = 2 \times 10^{20}$, $\sigma_{pN} \simeq 10.7\,$mbarn
- $\sigma_{bb} = 1.7\,$nanobarn
- $N(B \to aK) = N_{\rm PoT} \times \frac{\sigma_{bb}}{\sigma_{pN}} \times Br(B \to a\,K) = 3.9 \times 10^8$

$$N_{\rm det} = N_{B\to aK}\,\epsilon_{\rm det} \times \left(\exp\left[-\frac{l_1}{\gamma\beta c\tau_0}\right] - \exp\left[-\frac{l_2}{\gamma\beta c\tau_0}\right]\right)$$



SHiP-NOTE, T Ruf+ 15, Mangano+ Nucl.Phys.B 93

- $l_1 = 70\,$m, $l_2 = 120\,$m

$$N_{det} \sim \mathcal{O}(110 - 330)$$ Preliminary!

Primakoff production (Preliminary!)

Döbrich+ JHEP 16

- Calculated using the Weizsäcker-Williams approximation
- Coherent scattering $\propto Z^2 F(|t|^2)$, Z: atomic number of the target, $F(t)$: charge form factor
- ALPs produced typically have a small transverse momentum
- Production strongly peaked in the forward direction, $\theta_a^{\max} = \frac{m_a^2}{2E_\gamma^2}$
- $E_\gamma \simeq E_a$
- Momentum transfer $t = (p_\gamma - p_a)^2 = -\frac{m_a^4}{4E_a^2} - p_t^2 + 2E_a p_t \theta_a - E_a^2 \theta_a^2$
- Only those AlPs captured by the detector which has $\theta_a^{\max} \lesssim \frac{r}{L}$, $\theta_a^{\min} > \frac{2L}{d_{\min}} = 5\,\text{mrad}$
- Opening angle of ALP decay products $\theta_\gamma = \frac{2}{\gamma}$

$$\frac{d\sigma(\gamma N \to aN)}{d\cos\theta_a} = \frac{\alpha g_{\alpha\gamma\gamma}^2 Z^2 F(|t|^2)}{16}\left[-\frac{(t-m_a^2)^2 + 4E_\gamma^2 t}{t^2} + \frac{2E_\gamma(m_a^2 - t)}{tm_N} - \frac{2E_\gamma((t-m_a^2)^2 + 4E_\gamma t)}{2tm_N}\right]$$

- Total number of detectable events,

$$N_{\text{det}} = \frac{N_{\text{PoT}}}{\sigma_{pN}} \frac{1}{2\pi E_{\text{beam}}} \int d\cos\theta_a dE_a dp_t^2 \gamma_p(E_a/E_{\text{beam}}, p_t^2) \frac{d\sigma(\gamma N \to aN)}{d\cos\theta_a}, \quad \theta_a \in [0, \min[\frac{m_a^2}{2E_a^2}, \theta_{\text{det}}]]$$
$$\left(\exp\left[- \frac{l_1}{\gamma(E_a)\beta(E_a)c\tau_0} \right] - \exp\left[- \frac{l_2}{\gamma(E_a)\beta(E_a)c\tau_0} \right] \right) \epsilon_{det}$$

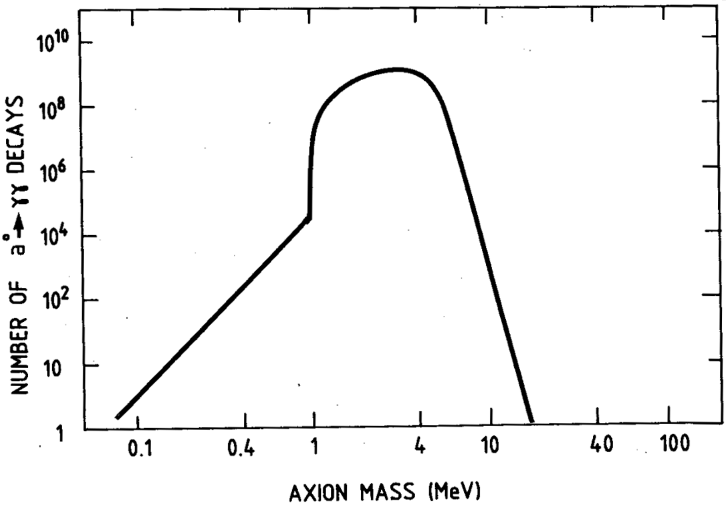
- $N_{\text{det}}^{\text{Primakoff}} \simeq 5$ (Preliminary!)
- Use more realistic angular acceptance (ϵ_{det}) for improved prediction (In progress)

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

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



Reach of NA64 (PRL, 081801 (2020))