

Light axion-like particles and the pseudoscalar mesonic decays $M \rightarrow M' \nu \bar{\nu}$

Guo-Qiang Dai^{1,2}, Chong-Xing Yue^{1,2,*}, Yang-Yang Bu^{1,2} and Yi-Hang Wang^{1,2}

¹Department of physics, Liaoning Normal University, Dalian 116029, China

²Center for Theoretical and Experimental High Energy Physics, Liaoning Normal University, Dalian 116029, China

E-mail: a18340370663@163.com (G-Q Dai) cxyue@lnnu.edu.cn, byy20011020@163.com and wyh15841047016@163.com

Received 6 March 2024, revised 14 May 2024

Accepted for publication 31 May 2024

Published 17 July 2024



CrossMark

Abstract

The axion-like particle (ALP) is one kind of the best-motivated new particles. We consider its production from the pseudoscalar mesonic decays $M \rightarrow M'a$, with M being a pseudoscalar meson B or K . The upper limits on the flavor-conserving ALP–quark coupling parameter g_u are obtained by assuming the ALP to be an invisible particle. We find that the most severe constraint on g_u comes from the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ for $0.05 \text{ GeV} \leq M_a \leq 0.35 \text{ GeV}$, while the decays $B^{+,0} \rightarrow K^{+,0} \nu \bar{\nu}$ and $B^{+,0} \rightarrow \pi^{+,0} \nu \bar{\nu}$ can also generate significant constraints.

Keywords: axion-like particle, pseudoscalar mesons, branching ratios

(Some figures may appear in colour only in the online journal)

1. Introduction

Axion-like particles (ALPs) [1] are generically classified as the pseudo Nambu–Goldstone bosons (PGBs) associated with the spontaneous breaking of global chiral symmetry that arise in many well-motivated models beyond the standard model (SM). ALPs might address several open problems in particle physics, such as the evidence of dark matter [2–4] as well as the flavor [5] and the weak-scale hierarchy [6] problems. Unlike quantum chromodynamics (QCD) axions, introduced to solve the strong charge parity (CP) problem via the Peccei–Quinn mechanism [7, 8], ALPs are unrelated to the solution of the strong CP problem and their mass and coupling are independent to the QCD anomaly. The mass of an ALP may come from the non-perturbative instanton effect in a strongly interacting hidden sector like the QCD axion or from explicit symmetry breaking. Consequently, a generic ALP may interact with various particles and have masses in a wide range [1], whose couplings are not tightly constrained by either cosmological or astrophysical bounds [9–11]. In general, ALPs do not have any specific relation between their masses and decay

constants. Therefore, ALPs can generate rich phenomenology in low-energy and high-energy experiments.

There are a wide range of new physics models that can predict ALPs that can be produced from meson decays. Strict constraints on ALP couplings with SM particles can be derived using the corresponding experimental data. For example, the couplings of ALP to the SM particles can be constrained by the decay $K \rightarrow \pi a$ via the recent data from MicroBooNE [12] and NA62 experiments [13]. In principle, ALPs are produced from mesonic rare decays in two different scenarios. One scenario is induced by flavor-violation (FV) ALP couplings with quarks at tree-level, and the other is induced by the effective ALP couplings that appear due to the renormalization group effects. In this note, we will systematically consider the decays $M \rightarrow M'a$, with $M^{(\prime)}$ being a pseudoscalar meson (B, D, K or π) in the second scenario. In our calculation, the ALP is assumed to be an invisible particle, the latest experimental results for the decays $M \rightarrow M' \nu \bar{\nu}$ are used, and the updated bounds on the ALP–quark couplings for the ALP mass M_a in the sub-GeV range are obtained.

In the next section, we give our calculation framework from the most general effective ALP Lagrangian in the dimension-5 order. By comparing our numerical results for the decays $M \rightarrow M'a$ (with ALP escaping the detector or

* Author to whom any correspondence should be addressed.

decaying into an ‘invisible’ sector) to the corresponding latest data of the decays $M \rightarrow M' \nu \bar{\nu}$, the constraints on the ALP–quark couplings are given in section 3. A discussion and conclusions are presented in section 4.

2. Theoretical framework

It is well known that the ALP a regarded as a CP-odd boson is a singlet under the SM gauge group. The effective interactions of an ALP with the SM particles can be described by the effective Lagrangian. The general effective Lagrangian, including operators of dimension up to five, is given by [14, 15]

$$\begin{aligned} \mathcal{L}_{\text{eff}}^a = & \frac{1}{2} [(\partial_\mu a)^2 - M_a^2 a^2] \\ & - \frac{\partial_\mu a}{2F_a} \sum_{ij} \bar{f}_i \gamma^\mu (V_{ij}^f - a_{ij}^f \gamma_5) f_j \\ & - \frac{\partial_\mu a}{F_a} \sum_\chi C_\chi \chi_{\mu\nu}^a \tilde{\chi}^{\mu\nu\alpha}. \end{aligned} \quad (1)$$

Here, M_a denotes the ALP mass, f stands for three generations of the SM fermions, i and j are flavor indices and F_a is the ALP decay constant. Also, $\chi_{\mu\nu}^a$ indicates any SM gauge boson field strength with $\tilde{\chi}^{\mu\nu a} \equiv \frac{1}{2} \chi_{\alpha\beta}^a \epsilon^{\alpha\beta\mu\nu}$ and C_χ being a coupling coefficient, while V_{ij}^f and a_{ij}^f stand for the vector and axial-vector ALP couplings to SM fermions, respectively.

As carried out in [16–19], the low-energy CP and flavor-conserving (FC) effective Lagrangian for ALP–fermion interactions can be written as

$$\mathcal{L}_{\text{fermion}}^a = -\frac{\partial_\mu a}{2F_a} g_i \bar{f}_i \gamma^\mu \gamma_5 f_i = i \frac{M_i}{F_a} g_i \bar{f}_i \gamma_5 f_i. \quad (2)$$

The index i includes all of the SM fermions, with g_i being real ALP–fermion couplings, and massless neutrinos are implied. According to the idea of the minimal FV hypothesis [20], all FV ALP couplings with SM fermions are loop induced and CKM is suppressed [16].

In general, ALPs with mass in few GeV can be produced from the decays $M \rightarrow M' a$, which are induced at tree-level and one-loop level. It has been shown that the contributions of the one-loop penguin diagram are much larger than those of the tree-level diagram when M and M' are mesons B , D , K or π [16, 21, 22]. Therefore, in this note, we only consider the decays $M \rightarrow M' a$ mediated at the one-loop level. Then, the branching ratio $Br(M \rightarrow M' a)$ can be written as [16–19, 21–25]

$$\begin{aligned} Br(M \rightarrow M' a) = & \frac{M_M^3 |(V_{ij})_{MM'}|^2}{64\pi F_a^2 \Gamma_M} \\ & \times \left(1 - \frac{M_{M'}}{M_M} \right)^2 [f_0^{MM'}(M_a^2)]^2 \lambda_{MM'}^{1/2} \end{aligned} \quad (3)$$

with

$$(V_{ij})_{MM'} = \frac{\alpha_e}{4\pi S_W^2} \sum_f V_{fi} V_{fj}^* g_f \chi_f \ln \frac{F_a^2}{M_f^2} \quad (4)$$

and

$$\begin{aligned} \lambda_{MM'} = & \left[1 - \frac{(M_{M'} + M_a)^2}{M_M^2} \right] \\ & \times \left[1 - \frac{(M_{M'} - M_a)^2}{M_M^2} \right]. \end{aligned} \quad (5)$$

Here, $M_{M^{(\prime)}}$ and Γ_M respectively denote the mass and total decay width of the pseudoscalar meson $M^{(\prime)}$, the sum of quark f for all quarks that run in the loop and f indicates all the quarks in the circle diagram, $\chi_f = M_f^2/M_W^2$, $f_0^{MM'}(m_a^2)$ stands for the $M \rightarrow M'$ scalar form factor from the hadronic matrix element. The values of the CKM matrices V_{ij}^f , the weak mixing angle θ_W and the fine structure constant α_e are taken from the particle data group (PDG) [26]. In this paper, we focus our attention on the constraints on the ALP–fermion coupling g_f from the relevant experimental data; thus we have neglected the contributions for the ALP emitted from the initial/final quarks in equation (4), which are suppressed by at least an extra factor M_f^2/M_W^2 with respect to the penguin contributions.

3. The constraints on the FC ALP–quark couplings from the decays $M \rightarrow M' \nu \bar{\nu}$

The semi-leptonic decays $M \rightarrow M' \nu \bar{\nu}$, with M and M' being B , D , K or π mesons, are the cleanest flavor-changing neutral current processes because of the absence of photonic penguin contributions and strong suppression of light quark contributions, which play an important role when seeking the underlying mechanism of flavor mixing and CP violation. They are frequently considered as a useful tool for probing new physics beyond the SM. Thus, many experimental programs are working for these decays, such as B -factories, including Belle and BaBar, CHARM, BESIII, MicroBooNE and NA62 experiments. The existing experimental measured values for the branching ratios $Br(M \rightarrow M' \nu \bar{\nu})$ are summarized in table 1, and the corresponding SM predictions are also shown for comparison.

From equation (3) one can see that the branching ratios $Br(M \rightarrow M' a)$ depend not only on the ALP free parameters g_f and M_a , but also on the relevant meson parameters $M_{M^{(\prime)}}$, $\Gamma_{M^{(\prime)}}$ and $f_0^{MM'}(M_a^2)$. The masses and total decay widths of the pseudoscalar mesons (B , D , K or π) are given in table 2.

The form factors $f_0^{MM'}(M_a^2)$ parameterize the relevant hadronic matrix elements, which can be obtained from lattice-QCD (LQCD) calculations and are transition specific. For the $B \rightarrow \pi$ transition, we use the combined results made by FLAG [34], and for $B \rightarrow K$ we use the results given in [35, 36]. For $D \rightarrow \pi$, the form factor $f_0^{D\pi}(M_a^2)$ is taken from the LQCD results of [37], while $f_0^{K\pi}(q^2)$ is close to unity for $0 < q^2 \leq (M_K - M_\pi)^2$ [38].

If we assume that the ALP lifetime is sufficiently long to escape the detector or the ALP is mainly decaying into ‘invisible’ particles, then its signature is missing energy/momentum, just as for neutrinos. Based on this hypothesis, we can use

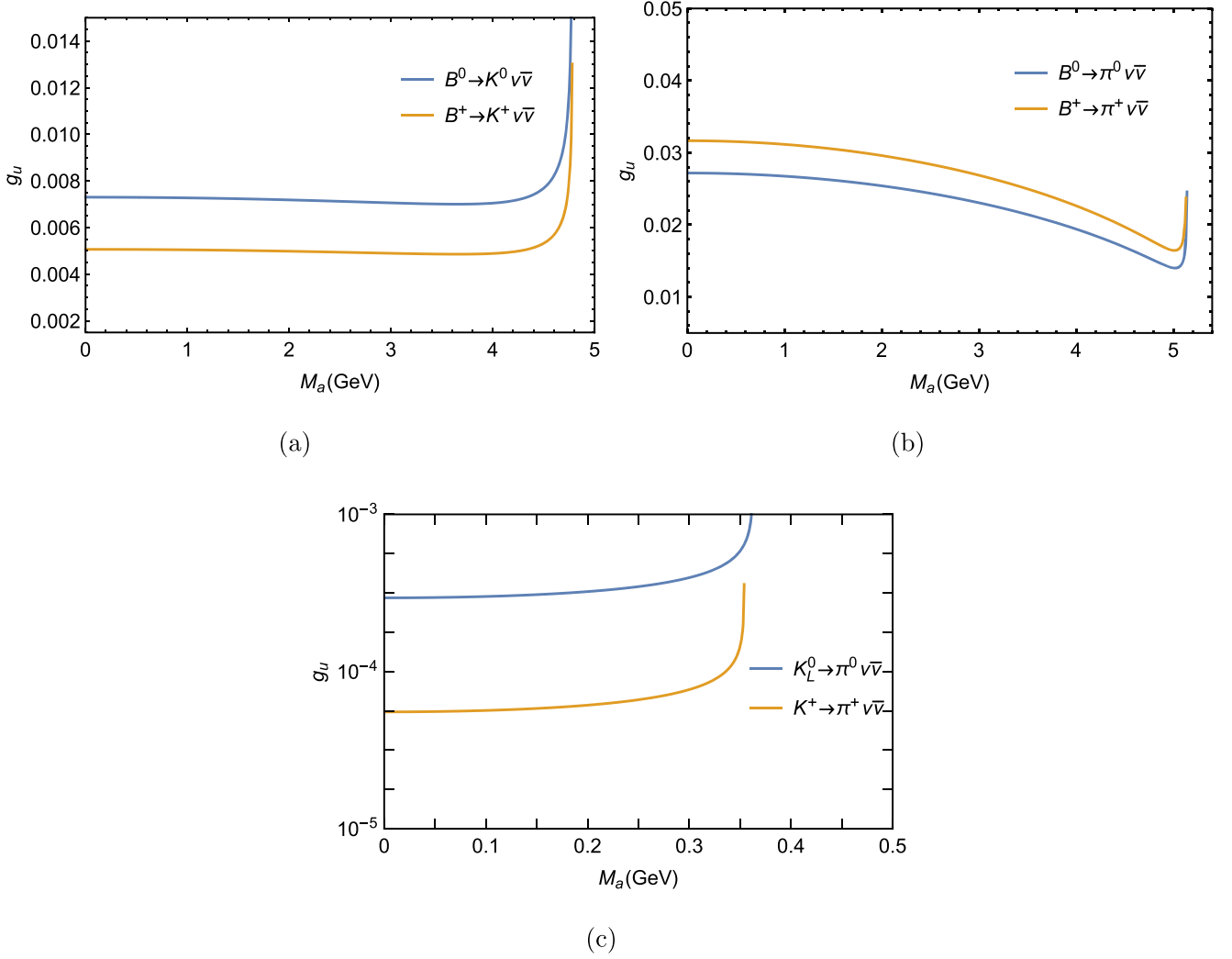


Figure 1. Upper limits on the coupling parameter g_u (u being up-type quarks) from the pseudoscalar meson decay of $B^{+,0} \rightarrow K^{+,0} \nu \bar{\nu}$ (a), $B^{+,0} \rightarrow \pi^{+,0} \nu \bar{\nu}$ (b) and $K^+/K_L^0 \rightarrow \pi^{+,0} \nu \bar{\nu}$ (c) as a function of the mass parameter M_a for $F_a = 1$ TeV.

Table 1. The experimental measurement and SM prediction values for the branching ratios $Br(M \rightarrow M' \nu \bar{\nu})$.

Br	SM	Exp
$B^0 \rightarrow K^0 \nu \bar{\nu}$	$(3.91 \pm 0.52) \times 10^{-6}$ [27]	$\leq 2.6 \times 10^{-5}$ [26]
$B^+ \rightarrow K^+ \nu \bar{\nu}$	$(4.23 \pm 0.56) \times 10^{-6}$ [27]	$(2.3 \pm 0.7) \times 10^{-5}$ [28]
$B^0 \rightarrow \pi^0 \nu \bar{\nu}$	1.2×10^{-7} [29]	$\leq 9 \times 10^{-6}$ [26]
$B^+ \rightarrow \pi^+ \nu \bar{\nu}$	$(2.49 \pm 0.25) \times 10^{-9}$ [29]	$\leq 1.3 \times 10^{-5}$ [30]
$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$ [31]	$\leq 2.0 \times 10^{-9}$ [32]
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$(8.6 \pm 0.42) \times 10^{-11}$ [33]	$(1.14 \pm 0.4) \times 10^{-10}$ [26]

equations (3)–(5) to calculate the contributions of ALPs to the decays $M \rightarrow M' \nu \bar{\nu}$ and compare our numerical results with the relevant experimental data given in table 1. Then, the constraints on the FC ALP–quark couplings can be obtained, as shown in figure 1 for $F_a = 1$ TeV. The penguin contributions do not dominate anymore over tree-level contributions for the decay $D \rightarrow Ma$ [16]: equation (3) cannot be applied to us. Therefore, we do not show the results for $D \rightarrow \pi(K)a$. For the decays $B^{+,0} \rightarrow K^{+,0} \nu \bar{\nu}$, $B^{+,0} \rightarrow \pi^{+,0} \nu \bar{\nu}$ and $K^+/K_L^0 \rightarrow \pi^{+,0} \nu \bar{\nu}$,

the Cabibbo–Kobayashi–Waskawa (CKM) matrices $(V_{ij})_{MM'} = (V_{bs})_{B^{+,0}K^{+,0}}$, $(V_{bd})_{B^{+,0}\pi^{+,0}}$ and $(V_{sd})_{K^{+,0}\pi^{+,0}}$, respectively. While for all of these decay processes, the upper-type quarks (u , c , and t) of quark f of circle diagram is the dominant. Certainly, the contributions mainly come from the top quark. For convenience, we define a coupling factor g_u for up-type quarks. The differences in each upper-type quark come from its mass, as shown in equation (2). From figure 1 we can see the most severe constraint on the FC ALP coupling factor g_u

Table 2. The masses and total decay widths of the pseudoscalar mesons given by PDG [26].

Meson	Mass (GeV)	Γ_{total} (GeV)
$B^+(B^0)$	5.27934 (5.27966)	$4.01 \times 10^{-13}(4.33 \times 10^{-13})$
$D^+(D^0)$	1.86966 (1.86484)	$6.39 \times 10^{-13}(1.6 \times 10^{-12})$
$K^+(K_L^0)$	0.49368 (0.49761)	$5.31 \times 10^{-17}(1.29 \times 10^{-17})$
$\pi^+(\pi^0)$	0.13957 (0.13498)	$2.53 \times 10^{-17}(7.8 \times 10^{-9})$

given by the decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ for $M_a \leq 0.35$ GeV, which demands $5.57 \times 10^{-5} \leq g_u \leq 3.58 \times 10^{-4}$ for $F_a = 1$ TeV and 0.05 GeV $\leq M_a \leq 0.35$ GeV. While the constraints on g_u come from the decays $B^{+,0} \rightarrow K^{+,0}\nu\bar{\nu}$, which are $5.06 \times 10^{-3} \leq g_u \leq 5.33 \times 10^{-3}$ and $7.30 \times 10^{-3} \leq g_u \leq 7.53 \times 10^{-3}$ for 0.45 GeV $\leq M_a \leq 4.5$ GeV, respectively. For the decays $B^{+,0} \rightarrow \pi^{+,0}\nu\bar{\nu}$, they are $3.16 \times 10^{-2} \leq g_u \leq 2.0 \times 10^{-2}$ and $2.71 \times 10^{-2} \leq g_u \leq 1.69 \times 10^{-2}$ for 0.45 GeV $\leq M_a \leq 4.5$ GeV, respectively.

4. Conclusions

The absence of evidence for new physics at the TeV scale so far has led to renewed attention to lighter new particles. In this work, we have considered the production of light ALPs from the decays $M \rightarrow M'a$ for the ALP mass in the sub-GeV range. After assuming the ALP to be an invisible particle, we compare our numerical results with the corresponding experimental measurements for the decays $B^{+,0} \rightarrow K^{+,0}\nu\bar{\nu}$, $B^{+,0} \rightarrow \pi^{+,0}\nu\bar{\nu}$ and $K^+/K_L^0 \rightarrow \pi^{+,0}\nu\bar{\nu}$, and the upper limits on the FC ALP–quark coupling parameter g_u are obtained. We find that the most severe constraint on the coupling g_u comes from the decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ for 0.05 GeV $\leq M_a \leq 0.35$ GeV, while the decays $B^{+,0} \rightarrow K^{+,0}\nu\bar{\nu}$ and $B^{+,0} \rightarrow \pi^{+,0}\nu\bar{\nu}$ can also generate significant constraints on g_u . We hope that our results will be helpful for the discovery of ALPs in future experiments.

Acknowledgments

This work was partially supported by the National Natural Science Foundation of China under Grant Nos. 11875157 and 12147214. G Q Dai would like to thank Xing-Yang Li and Han-Wang for the very useful guidance.

References

- [1] Jaeckel J and Ringwald A 2010 The low-energy frontier of particle physics *Ann. Rev. Nucl. Part. Sci.* **60** 405–37
- [2] Preskill J, Wise M B and Wilczek F 1983 Cosmology of the invisible axion *Phys. Lett. B* **120** 127–32
- [3] Abbott L F and Sikivie P 1983 A cosmological bound on the invisible axion *Phys. Lett. B* **120** 133–6
- [4] Dine M and Fischler W 1983 The not so harmless axion *Phys. Lett. B* **120** 137–41
- [5] Wilczek F 1982 Axions and family symmetry breaking *Phys. Rev. Lett.* **49** 1549–52
- [6] Graham P W, Kaplan D E and Rajendran S 2015 Cosmological relaxation of the electroweak scale *Phys. Rev. Lett.* **115** 221801
- [7] Peccei R D and Quinn H R 1977 CP conservation in the presence of instantons *Phys. Rev. Lett.* **38** 1440–3
- [8] Weinberg S and New Light Boson A 1978 *Phys. Rev. Lett.* **40** 223–6
- [9] Marsh D J E 2016 Axion cosmology *Phys. Rept.* **643** 1–79
- [10] Irastorza I G and Redondo J 2018 New experimental approaches in the search for axion-like particles *Prog. Part. Nucl. Phys.* **102** 89–159
- [11] Di Luzio L, Giannotti M, Nardi E and Visinelli L 2020 The landscape of QCD axion models *Phys. Rept.* **870** 1–117
- [12] Erbin H and Fırat A H 2023 Open string stub as an auxiliary string field arXiv:2308.08587
- [13] Cortina Gil E (NA62) et al 2024 Measurement of the $K^+ \rightarrow \pi^+\gamma\gamma$ decay *Phys. Lett. B* **850** 138513
- [14] Georgi H, Kaplan D B and Randall L 1986 Manifesting the invisible axion at low-energies *Phys. Lett. B* **169** 73–8
- [15] Brivio I, Gavela M B, Merlo L, Mimasu K, No J M, del Rey R and Sanz V 2017 ALPs effective field theory and collider signatures *Eur. Phys. J. C* **77** 572
- [16] Guerrero A W M and Rigolin S 2023 ALP production in weak mesonic decays *Fortsch. Phys.* **71** 2200192
- [17] Merlo L, Pobbe F, Rigolin S and Sumensari O 2019 Revisiting the production of ALPs at B-factories *J. High Energy Phys. JHEP06(2019)091*
- [18] Martin Camalich J, Pospelov M, Vuong P N H, Ziegler R and Zupan J 2020 Quark flavor phenomenology of the QCD axion *Phys. Rev. D* **102** 015023
- [19] Gallo J A, Guerrero A W M, Peñaranda S and Rigolin S 2022 Leptonic meson decays into invisible ALP *Nucl. Phys. B* **979** 115791
- [20] D’Ambrosio G, Giudice G F, Isidori G and Strumia A 2002 Minimal flavor violation: an effective field theory approach *Nucl. Phys. B* **645** 155–87
- [21] Izaguirre E, Lin T and Shuve B 2017 Searching for axionlike particles in flavor-changing neutral current processes *Phys. Rev. Lett.* **118** 111802
- [22] Guerrero A W M and Rigolin S 2022 Revisiting $K \rightarrow \pi a$ decays *Eur. Phys. J. C* **82** 192
- [23] Gavela M B, Houtz R, Quilez P, Del Rey R and Sumensari O 2019 Flavor constraints on electroweak ALP couplings *Eur. Phys. J. C* **79** 369
- [24] Carmona A, Scherb C and Schwaller P 2021 Charming ALPs *J. High Energy Phys. JHEP08(2021)121*
- [25] Bauer M, Neubert M, Renner S, Schnubel M and Thamm A 2022 Flavor probes of axion-like particles *J. High Energy Phys. JHEP09(2022)056*
- [26] Workman R L et al 2022 Review of particle physics *PTEP* **2022** 083C01
- [27] Bause R, Gisbert H, Golz M and Hiller G 2021 Interplay of dineutrino modes with semileptonic rare B-decays *J. High Energy Phys. JHEP12(2021)061*
- [28] Adachi I(Belle-II) et al 2024 Evidence for $B^+ \rightarrow K^+\nu\bar{\nu}$ decays *Phys. Rev. D* **109** 112006
- [29] Hambrock C, Khodjamirian A and Rusov A 2015 Hadronic effects and observables in $B \rightarrow \pi\ell^+\ell^-$ decay at large recoil *Phys. Rev. D* **92** 074020
- [30] Grygier J et al 2017 Search for $B \rightarrow h\nu\bar{\nu}$ decays with semileptonic tagging at Belle *Phys. Rev. D* **96** 091101
- [31] Buras A J 2023 Standard model predictions for rare k and b decays without new physics infection *Eur. Phys. J. C* **83** 66
- [32] Ahn J K et al (KOTO) 2019 Search for the $K_L \rightarrow \pi^0\nu\bar{\nu}$ and $K_L \rightarrow \pi^0X^0$ decays at the J-PARC KOTO experiment *Phys. Rev. Lett.* **122** 021802

- [33] Cortina Gil E *et al* (NA62) 2021 Measurement of the very rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay *J. High Energy Phys.* JHEP06(2021)093
- [34] Aoki Y *et al* (FLAG) 2022 FLAG review 2021 *Eur. Phys. J. C* **82** 869
- [35] Parrott W G *et al* (HPQCD) 2023 Standard Model predictions for $B \rightarrow K \ell^+ \ell^-$, $B \rightarrow K \ell^+ \ell^{2+}$ and $B \rightarrow K \nu \bar{\nu}$ using form factors from $N_f=2+1+1$ lattice QCD *Phys. Rev. D* **107** 014511
erratum: 2023 *Phys. Rev. D* **107** 119903
- [36] Bečirević D, Piazza G and Sumensari O 2023 Revisiting $B \rightarrow K^{(*)} \nu \bar{\nu}$ decays in the Standard Model and beyond *Eur. Phys. J. C* **83** 252
- [37] Bazavov A *et al* (Fermilab Lattice and MILC) 2023 D-meson semileptonic decays to pseudoscalars from four-flavor lattice QCD *Phys. Rev. D* **107** 094516
- [38] Carrasco N, Lami P, Lubiez V, Riggio L, Simula S and Tarantino C 2016 $K \rightarrow \pi$ semileptonic form factors with $N_f=2+1+1$ twisted mass fermions *Phys. Rev. D* **93** 114512