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New bound on the vectorial axion-down-strange coupling from $K^+ \to \pi^+ \nu\bar{\nu}$ data

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We analyze publicly available $K^+ \to \pi^+ \nu\bar{\nu}$ data collected by NA62 from 2016 to 2022 to constrain the fundamental vectorial coupling of the QCD axion to the down and strange quarks or, equivalently, the Peccei-Quinn scale f_a rescaled by this coupling, obtaining $|(F_V)_{23}| > 1.1 \times 10^{12}$ GeV.

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1. Introduction

Axions are hypothetical but highly plausible particles, as they provide a uniquely elegant resolution to the strong-CP problem, namely the unexplained suppression of a dimension-4 operator violating CP symmetry in strong interactions. A dismissal of this issue as a mere accident of nature is unsatisfactory, given the amount of suppression, of $O(10^{-10})$—and anthropic arguments do not seem viable either [1, 2]. Besides, from a purely observational perspective, axions provide a compelling framework for accounting for the fraction of the universe's total density attributed to Dark Matter [3–5]. Finally, their generally small mass makes axions amenable to being produced, potentially even copiously, in controlled collider environments without the need to push the energy frontier.

Research on axions bifurcates into two major streams. The first focuses on the "invisible" [6–9] QCD axion [10–13], whose mass m_a and decay constant f_a are intrinsically linked: the smaller m_a, the weaker the axion's interactions with known matter, that are parametrically suppressed as $1/f_a$. The second stream is a generalization of the first to so-called axion-like particles (ALPs), where m_a and f_a are treated as independent parameters constrained by an expanding range of laboratory experiments [14–16], astrophysical observations [17–19], cosmological probes [20], and theoretical considerations, see e.g. [21–23].

Among the many experimental approaches to probing the existence of axions, one of the most direct is their potential production in decays recorded at high-intensity facilities such as NA62. This approach is well motivated for several reasons. First, this method has for decades been used to study decays to final-state neutrinos—now-established feebly interacting, uncharged, near-massless particles with properties largely analogous to those of axions. Neutrinos were unambiguously identified in controlled experimental setups thanks precisely to such decay studies [24]. Second, from a theoretical point of view *light* meson decays involving an axion admit a systematic, effective-theory description, known as Chiral Perturbation Theory (ChPT) [25, 26], which ensures reliable predictions with a controlled error. Axion interactions with light mesons can be incorporated in this description by a careful generalization [27] of the very same logic that leads to the construction of ChPT. In this construction, axion couplings to hadrons inherit from the Lagrangian terms

$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2f_a}\left(\bar{q}\,\gamma^\mu k_V\, q + \bar{q}\,\gamma^\mu\gamma_5 k_A\, q\right) - \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G}\,, \tag{1}$$

with $q = (u, d, s)^T$. Once the $k_{V,A}$ coupling matrices are fixed, the ChPT couplings to hadrons are determined accordingly [1]. Third, the fundamental axion-quark couplings themselves are, like Yukawa couplings, free parameters from a theoretical standpoint. Therefore, predicted signals may well be within experimental reach in appropriate channels. In particular, there is no fundamental reason why the (complex) axion-down-strange couplings $(k_{V,A})_{23}$—the only allowed off-diagonal entries in Eq. (1)—should be small. The strongest probe of $|(k_V)_{23}|$ are $K \to \pi a$ decays, whereas $|(k_A)_{23}|$, as well as the diagonal axial couplings $(k_A)_{ii}$ (reals), are best probed by Supernova cooling induced by axions radiated from strange matter in the star core [28, 29] as well as by Neutron Stars [30]. Here we prove that the data used in the most recent measurement of the decay $K^+ \to \pi^+ \nu\bar{\nu}$ [31] can be recast to provide the strongest existing bound on $|(k_V)_{23}|$. We also argue

[1] There is a reparametrization ambiguity [27], but it must cancel in physical observables [41].

that the very same approach, adapted to $K \to \pi\pi a$ data, would lead to the strongest existing bound on the axial counterpart $|(k_A)_{23}|$.

$K^+ \to \pi^+ \nu\bar{\nu}$ is an ultrarare decay, and provides one of the most exquisite precision tests of the Standard Model (SM). The small branching fraction of the K^+ into this decay mode [32–34], which predicts that this process occurs less than once in ten billion K^+ decays, is dominated by short-distance contributions, and the necessary hadronic matrix element can be extracted from *data* using isospin. The decay is thus uniquely rare and uniquely clean theoretically. The NA62 experiment at CERN was designed with the measurement of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \equiv \mathcal{B}_{\nu\bar{\nu}}$ as its primary goal. It relies on the technique of decay-in-flight, and has delivered four measurements of this decay thus far, namely [35–37], based on 2016-2018 data, plus [31], based on 2021-2022 data.

Using *all* these results, a bound can be placed on decays to new particles with the same visible external states: in our case we consider the decay $K^+ \to \pi^+ a$, where a is an undetected axion. This would be seen as an excess above the $K^+ \to \pi^+ \nu\bar{\nu}$ process, which is a background to our signal. Intuitively, the uncertainty $\delta\mathcal{B}_{\nu\bar{\nu}}$ on the measurement of the branching ratio (BR) quantifies the available leeway for the presence of our signal process, and thereby provides an estimate for the typical $\mathcal{B}(K^+ \to \pi^+ a)$ limit achievable with the dataset [38]. The combination of the above NA62 measurements gives approximately $\delta\mathcal{B}_{\nu\bar{\nu}} = 3 \times 10^{-11}$, predominantly of statistical origin. In what follows, we present a procedure based on a rigorous, likelihood-based analysis relying on public data only. Nevertheless, this procedure is found to corroborate the basic argument given above.

2. Reinterpretation Technique

To bound the $K^+ \to \pi^+ a$ decay through the $K^+ \to \pi^+ \nu\bar{\nu}$ measurements at NA62, we follow a variation of the procedure of Ref. [39]. We perform a fully frequentist hypothesis test using a shape analysis on the invisible invariant mass, and an unbinned profile likelihood ratio test statistic, based solely on public data. The likelihood function is constructed as the product of three contributions, *i.e.* $\mathcal{L} = \mathcal{L}_1 \mathcal{L}_2 \mathcal{L}_3$.

The first term is a Poisson distribution for the total number of events n_{tot} with mean value equal to the total number of observed events n_{obs}. The variable n_{tot} can be decomposed as $n_{\text{tot}} = n_b + n_a$, with $n_{b,a}$ being the number of background and axion events, respectively.

The number n_a is related to the BR as $\mathcal{B}(K^+ \to \pi^+ a) = n_a \times \mathcal{B}_{\text{SES}}$, where $\mathcal{B}_{\text{SES}}$ denotes the associated single-event sensitivity (SES). $\mathcal{B}_{\text{SES}} = \mathcal{B}_{\text{SES}}(m_a)$ is provided in e.g. the rightmost panel of Figure 2 of Ref. [39], which pertains to the 2017 data. Limits for any other dataset may then be estimated using a simple rescaling by a factor equal to the ratio of the $K^+ \to \pi^+ \nu\bar{\nu}$ SESs. Note that n_b also includes the $K^+ \to \pi^+ \nu\bar{\nu}$ events, assuming $\mathcal{B}^{\text{SM}}_{\nu\bar{\nu}} = 8.4 \times 10^{-11}$ as in Ref. [31][2].

Given n_{tot}, its two components are distributed as a function of the invisible invariant mass squared m^2_{inv} according to a multinomial likelihood, yielding $\mathcal{L}_2$ as

$$\mathcal{L}_2 = \prod_{j=1}^{n_{\text{obs}}} \left[\frac{n_b}{n_{\text{tot}}} g_b(m_j^2) + \frac{n_a}{n_{\text{tot}}} g_a(m_j^2) \right] , \tag{2}$$

[2] Alternatively, one may treat $K^+ \to \pi^+ \nu\bar{\nu}$ events as a separate component n_ν left as a free parameter. This approach will become viable in experimental analyses as the observed n_ν increases. For a fixed number of degrees of freedom (d.o.f.), we find that allowing n_ν to float strengthens the bounds by approximately 5-10% compared to fixing it to the SM value. However, we adhere to the latter approach to align fully with the procedure outlined in Ref. [39].

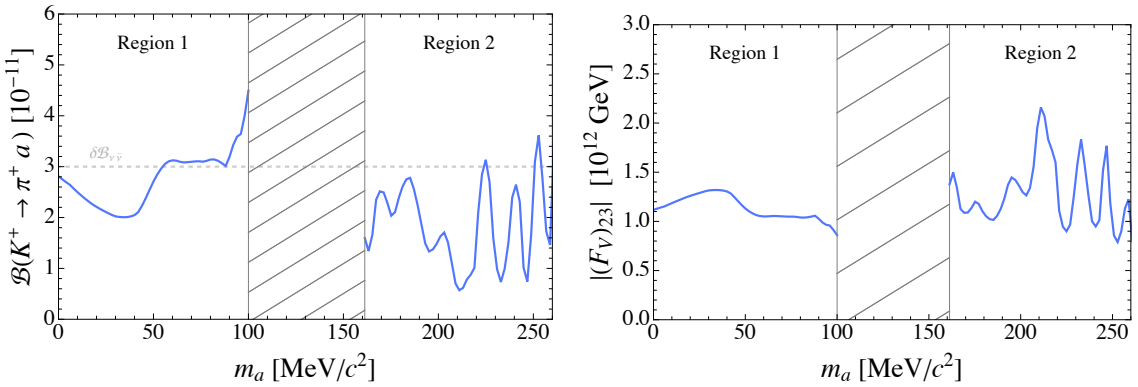

Figure 1: *Left panel:* Upper limit on $\mathcal{B}(K^+ \to \pi^+ a)$ from the full NA62 dataset (2016-2022) on the $K^+ \to \pi^+ \nu\bar{\nu}$ decay. The gray dashed line shows the corresponding value of $\delta\mathcal{B}_{\nu\bar{\nu}}$ for comparison. *Right panel:* Lower limit on the flavour-violating "coupling-rescaled f_a" if the strong amplitude dominates.

where $g_b(m^2_{\text{inv}})$ is a polynomial function. Its integral over the signal regions is normalised to unity, and is required to reproduce the distribution of the background events, taken from published data, i.e. from the right panel of Fig. 10 in Ref. [31]. Conversely, $g_a(m^2_{\text{inv}})$ is a normal distribution centered at the axion mass value with uncertainty given by the invariant mass resolution at fixed m_a, $\sigma_{m_a^2}$, taken from the left panel of Figure 2 of Ref. [39]. Finally, the last likelihood factor, $\mathcal{L}_3$, is a Poisson-distributed constraint term for the number of background events

$$\mathcal{L}_3 = \frac{(\tau n_b)^{n_{\text{off}}}}{n_{\text{off}}!} e^{-\tau n_b} \,, \tag{3}$$

with $\tau = \mu_b/\sigma_b^2$ and $n_{\text{off}} = (\mu_b/\sigma_b)^2$ [40] obtained from the estimated mean value μ_b and uncertainty σ_b of the number of background events. We neglect the uncertainty on the rest of the nuisance parameters considered in Ref. [39], namely the SES uncertainty, as well as the error on the parameters of the axion mass probability density function. By inspection, these uncertainties are subleading with respect to those discussed, and are expected to affect our results in a minor way.

Minimizing $\chi^2(n_b, n_a) \equiv -2 \log \mathcal{L}$, and demanding $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\text{min}} = \chi^2(90\%, 2\text{ dof})$ we obtain a limit on $\mathcal{B}(K^+ \to \pi^+ a)$ as a function of m_a. We tested this procedure by comparing our obtained limit with the NA62 results based on 2016-2018 [37] and 2017 data [39], respectively, finding very good agreement. If we apply this procedure to the full NA62 dataset available, encompassing data from 2016 to 2022, we obtain the limit shown in Fig. 1 (left). At $m_a = 0$, it reads

$$\mathcal{B}(K^+ \to \pi^+ a) < 2.8 \times 10^{-11} \text{ at } 90\% \text{ C.L.} \tag{4}$$

Compared to the theoretical prediction, this limit sets unprecedented bounds on the relevant axion coupling or, alternatively, on the axion scale, as detailed following our discussion of axion-meson interactions.

3. Theory Prediction

The axion, as the near-Goldstone boson of a global $U(1)$ Peccei-Quinn symmetry, can be incorporated into ChPT as elucidated in Ref. [27]. A generalization of this procedure allows to also

include the effect of strangeness (S) changing weak interactions, see Refs. [41, 42]. The amplitude $\mathcal{M}$ for the $K^+ \to \pi^+ a$ decay is thus given by

$$i\mathcal{M} = \frac{m_K^2 (k_V)_{32}}{2 f_a} \Big(1 - x_{\pi K}\Big) + \dots \,, \tag{5}$$

$$\mathcal{B}(K^+ \to \pi^+ a) = \frac{\tau_{K^+} |\mathcal{M}|^2}{16\pi m_K} \sqrt{x_{aK}^2 + (1 - x_{\pi K})^2 - 2x_{aK}(1 + x_{\pi K})} \,, \tag{6}$$

with $x_{ij} \equiv (m_i/m_j)^2$. The above amplitudes agree with the results in Ref. [41]. The dots in Eq. (5) refer to the contribution from $|\Delta S| = 1$ terms which are collectively suppressed by $G_F F_\pi^2 \sim 10^{-7}$ and thus are negligible unless $(k_V)_{32}$ turns out to be extremely small or vanishing.

4. Results

Equating the theory BR with the limit in Eq. (4), we can infer a bound on the flavour-violating axion coupling $(k_V)_{23}$. In terms of the useful "coupling-rescaled f_a", defined as $(F_{V,A})_{ij} \equiv 2 f_a / (k_{V,A})_{ij}$ [43], Eq. (4) thus implies, for $m_a = 0$,

$$|(F_V)_{23}| > 1.1 \times 10^{12} \text{ GeV} \,, \tag{7}$$

namely about a factor-of-2 increase w.r.t. the latest data-driven bound [43] on the effective scale of the underlying interaction. In Fig. 1 (right) we show a generalization of Eq. (7) for any m_a in the range of values probed by NA62.

The result in Eq. (7) is of great interest, because of its strength, and because, at variance with limits inferred from astrophysical systems, they arise from a controlled experimental setup.

Disclaimer— Months after our work [44], the NA62 collaboration published an analysis of $K^+ \to \pi^+ X$ with X an ALP, using the same datasets [45]. At $m_X = 0$, their limit coincides exactly with our result in Eq. (4). This agreement strongly validates our approach: it confirms our treatment of the leading uncertainties, the possibility of retrieving them from public data alone, and the negligible impact of those we did not include. While our method cannot substitute for a full NA62 search—which remains the benchmark—the above comparison shows that it provides an excellent and fully reproducible approximation.

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