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Searches for hidden sectors using $K^+ \rightarrow \pi^+ X$ decays

The NA62 collaboration

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ABSTRACT: Results from the study of the rare decays $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ and $K^+ \rightarrow \pi^+ \gamma \gamma$ at the NA62 experiment at CERN are interpreted in terms of improved limits for $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ and coupling parameters of hidden-sector models, where X is a mediator. World-leading limits are achieved for dark photon, dark scalar and axion-like particle models.

KEYWORDS: Beyond Standard Model, Fixed Target Experiments

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Contents

1	Introduction	1
2	Searches for $K^+ \rightarrow \pi^+ X$ with invisible X	2
2.1	Interpretation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results	2
2.2	Search for π^0 decays to invisible final states	5
3	Searches for $K^+ \rightarrow \pi^+ X$ with prompt X decays to visible final states	5
3.1	Interpretation of $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ results	5
3.2	Interpretation of $K^+ \rightarrow \pi^+ \gamma \gamma$ results	6
4	Constraints on benchmark hidden-sector models	6
4.1	Massive dark vector	9
4.2	Dark scalar mixing with the Higgs boson	9
4.3	Axion portal with coupling to SM fermions	11
4.4	Axion portal with coupling to SM gluons	13
5	Conclusions	14
	The NA62 collaboration	19

1 Introduction

The NA62 experiment, described in detail in [1], is a fixed-target experiment at the CERN SPS, designed to perform a stringent test of the Standard Model (SM) by measuring the ultra-rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay, which offers sensitivity to physics beyond the SM (BSM) up to a mass scale of $\mathcal{O}(100 \text{ TeV})$. Within the SM, this decay is highly suppressed and precisely calculated. Using tree-level measurements of the CKM matrix elements as external inputs, the SM branching ratio is predicted to be $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ [2], while using only meson mixing processes to eliminate the dependence on $|V_{cb}|$, the branching ratio is predicted to be $(8.60 \pm 0.42) \times 10^{-11}$ [3]. Using a full CKM parameter fit, a value of $(7.86 \pm 0.61) \times 10^{-11}$ is predicted [4]. The NA62 experiment reported the measurement $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$ using data collected in 2016–2022 [5–8]. Additionally, studies of the rare decays $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ [9] and $K^+ \rightarrow \pi^+ \gamma \gamma$ [10] were performed using 2017–2018 data. In this context, BSM contributions, though suppressed by small coupling constants, may still lead to significant enhancement of the decay rate with respect to the SM expectation via the process $K^+ \rightarrow \pi^+ X$, where X is a feebly-interacting BSM particle [11].

In the following, the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ study performed using the 2016–2022 dataset [8] is interpreted as a search for the $K^+ \rightarrow \pi^+ X$ decay. Additionally, the $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay analysis from the 2017–2018 dataset [9] is interpreted as a search for the prompt decay chain $K^+ \rightarrow \pi^+ X$, $X \rightarrow \mu^+ \mu^-$. For completeness, the previously published results related to the

Benchmark	BSM particle (X)	Type	Coupling to SM	Search
BC1	dark photon (A')	vector	ε	$\mu^+\mu^-$
BC2	dark photon (A')	vector	ε	invisible
BC4	dark scalar (S)	scalar	θ	invisible, $\mu^+\mu^-$
BC4-inv	dark scalar (S)	scalar	θ	invisible
BC10	axion-like particle (a)	pseudoscalar	C_{ff} (to fermions)	invisible, $\mu^+\mu^-$
BC10-inv	axion-like particle (a)	pseudoscalar	C_{ff} (to fermions)	invisible
BC11	axion-like particle (a)	pseudoscalar	C_{GG} (to gluons)	invisible, $\gamma\gamma$

Table 1. Summary of new physics benchmark models relevant to NA62 searches for decays of the form $K^+ \rightarrow \pi^+ X$, where X is a vector, scalar or pseudoscalar particle. The last column lists the experimental signature(s) of the X particle considered in each case.

$\pi^0 \rightarrow$ invisible decay search [12] and the study of $K^+ \rightarrow \pi^+ \gamma\gamma$ decays [10] are discussed. Constraints are set on benchmark hidden-sector models as limits of $\mathcal{B}(K^+ \rightarrow \pi^+ X)$, where:

- X is *invisible* (X_{inv}), meaning it is not detected experimentally: it may decay to dark matter particles (or neutrinos), or to visible SM particles but with a sufficiently long lifetime to escape the detector;
- X decays to SM *visible* particles which are detected.

Relevant new physics benchmark models [13] are summarised in table 1, with additional details given in section 4. Constraints are set on the BC2, BC4, BC10 and BC11 models of [13], in which the mediator is a vector, scalar or pseudoscalar particle. In addition, minimally modified BC4-inv and BC10-inv scenarios are considered, which are equivalent to BC4 and BC10 except that the mediator only decays to hidden-sector particles. Other models where the hidden-sector particle is a heavy neutral lepton (N) are investigated at NA62 in dedicated searches for $K^+ \rightarrow \ell^+ N$ ($\ell = \mu, e$) [14, 15] and $\pi^+ \rightarrow e^+ N$ decays [16]. Hidden-sector searches at NA62 with kaon decays are complementary to those performed in beam dump mode [17–19].

2 Searches for $K^+ \rightarrow \pi^+ X$ with invisible X

2.1 Interpretation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results

The measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay rate by the NA62 experiment is described in detail in [8]. It relies on precise momentum and time measurements of the incident K^+ and downstream π^+ , charged particle identification and hermetic veto of other particles produced in abundant K^+ decay modes, using a variety of techniques and detectors specially designed for this purpose [1]. The resulting analysis allows reaching sensitivity to branching ratios as low as 10^{-11} to 10^{-12} .

Because the $\nu \bar{\nu}$ pair is not detected, the signal signature of the SM process is identical to that of the $K^+ \rightarrow \pi^+ X_{\text{inv}}$ decay. A peak search is performed in the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal regions

of the $m_{\text{miss}}^2 = (P_K - P_\pi)^2$ distribution, where P_K (P_π) is the reconstructed four-momentum of the kaon (pion) in the initial (final) state. The SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ background is evaluated using $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 8.4 \times 10^{-11}$. Applying the procedure described in [20], model-independent upper limits for $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ at 90 % confidence level (CL) were established in the mass ranges 0–110 MeV/ c^2 and 150–260 MeV/ c^2 using the 2016–2018 dataset which includes 4.3×10^{12} collected K^+ decays [7].

Here the search is extended to include the 2021–2022 dataset which consists of 2.9×10^{12} collected K^+ decays [8]. The m_{miss}^2 spectrum of expected and observed events satisfying the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal selection in the 2016–2022 dataset is shown in figure 1-a. A scan is performed, searching for peaks in this spectrum, considering m_X hypotheses separated by 1.4 MeV/ c^2 , which is less than the corresponding resolution for any mass hypothesis [20]. For each mass hypothesis a search window is defined, centered on m_X^2 and with a width of $3\sigma_{m_{\text{miss}}^2}$, where $\sigma_{m_{\text{miss}}^2}$ is the m_{miss}^2 resolution (established with simulations) which varies from $1.2 \times 10^{-3} \text{ GeV}^2/c^4$ at $m_X = 0$ to $0.7 \times 10^{-3} \text{ GeV}^2/c^4$ at $m_X = 260 \text{ MeV}/c^2$ [20]. In each search window the expected number of background events is calculated using the m_{miss}^2 spectrum shown in figure 1-a, and the number of observed events is counted. An upper limit for the number of $K^+ \rightarrow \pi^+ X$ events in this search window, $N_{UL}^{\pi X}$, is evaluated using the CLs method [21]. A model-independent limit of $\mathcal{B}(K^+ \rightarrow \pi^+ X) = \mathcal{B}_{\pi X}$, in the scenario where X is invisible, is established according to

$$UL(\mathcal{B}_{\pi X}(m_X)) = N_{UL}^{\pi X}(m_X) \cdot \mathcal{B}_{SES}^{\pi X}(m_X) . \quad (2.1)$$

Here $\mathcal{B}_{SES}^{\pi X}(m_X)$ is the single event sensitivity (SES) for the $K^+ \rightarrow \pi^+ X$ search evaluated at the m_X value, shown in figure 1-b, given by

$$\mathcal{B}_{SES}^{\pi X}(m_X) = \mathcal{B}_{SES}^{\pi \nu \bar{\nu}} \frac{A_{\pi \nu \bar{\nu}}}{A_{\pi X}(m_X)} , \quad (2.2)$$

where $\mathcal{B}_{SES}^{\pi \nu \bar{\nu}}$ and $A_{\pi \nu \bar{\nu}}$ are the SES and acceptance for the SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay [5–8], and $A_{\pi X}(m_X)$ is the acceptance of a $K^+ \rightarrow \pi^+ X$ decay, which depends on m_X . The inclusion of the 2021–2022 data leads to an improvement in the SES by approximately a factor of 2 (figure 1-b). However the background, in particular from the SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay, becomes significant, with up to 2 events expected per search window. This restricts the improvement in the upper limit to a factor of 1–3 depending on the mass hypothesis, as shown in figure 2-a. The effect of the SM $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ value chosen when extracting $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ limits is checked using alternative values in the range $(7.2 - 9.0) \times 10^{-11}$, which covers the uncertainties quoted in [3, 4]. The change in the $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ limits is found to be negligible.

The search for peaks in the m_{miss}^2 distribution uses the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidate events, which pass comprehensive veto criteria rejecting any pair of final state particles in addition to the π^+ . Therefore, if the X particle decays to visible SM particles within the detector, the event is rejected from this search with inefficiency below 10^{-7} [5–8]. As a consequence, the highest sensitivity is obtained for X particles with proper lifetime $\tau_X > 1 \text{ ns}$, or scenarios where X decays invisibly. Model-independent constraints for $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ are also established for decays of X into visible particles and with small τ_X values, as shown in figure 2-b. Simulations of $K^+ \rightarrow \pi^+ X$, $X \rightarrow \ell^+ \ell^-$ prompt decay chains are used to evaluate

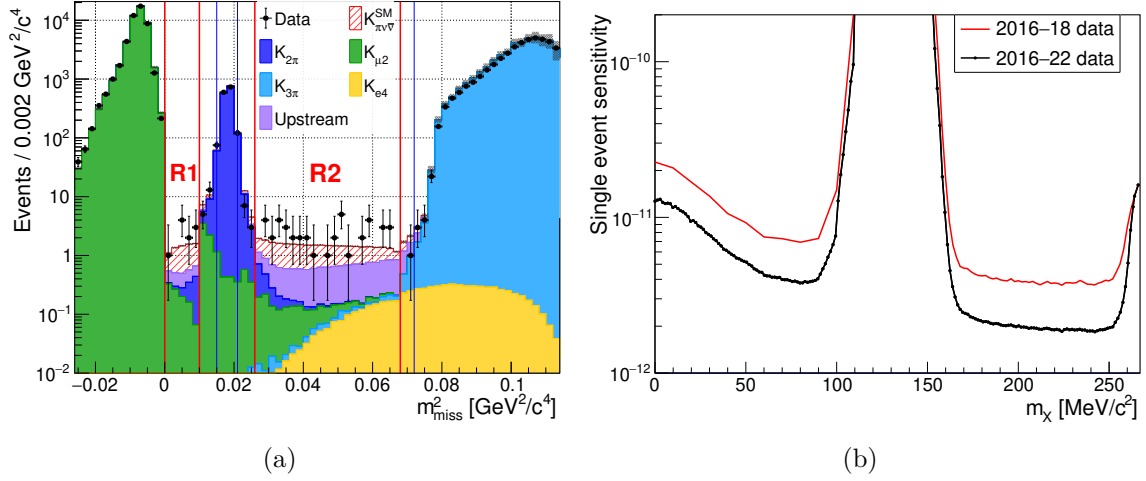


Figure 1. (a): combined m_{miss}^2 distributions for the 2016–2022 dataset, including the SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay using $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 8.4 \times 10^{-11}$ [2], and background expectations. (b): SES of the $K^+ \rightarrow \pi^+ X_{\text{inv}}$ decay search as a function of m_X . The SES obtained with the analysis of the 2016–2018 dataset [7] is also shown for comparison.

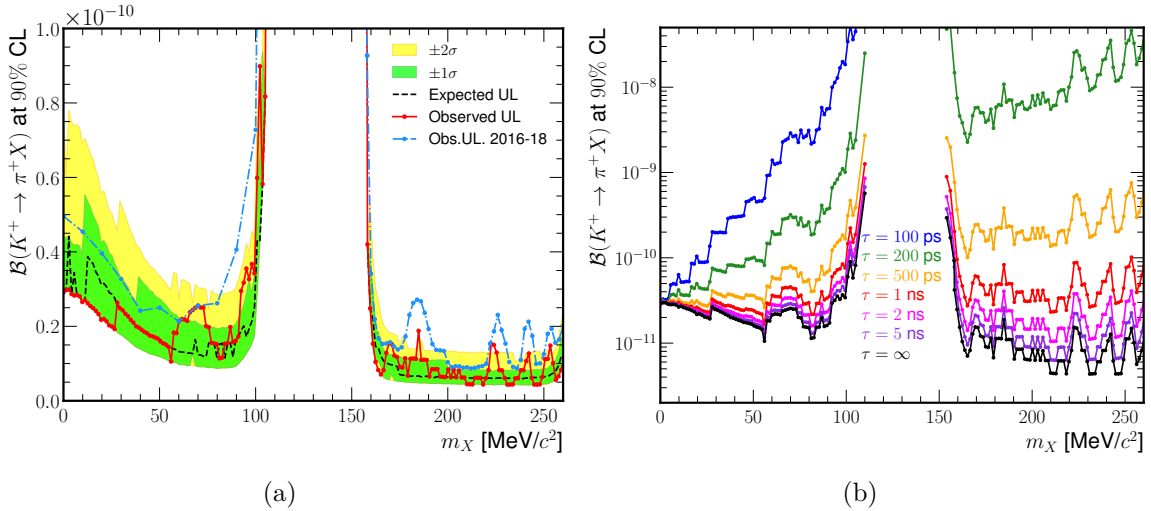


Figure 2. Model-independent constraints on $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ as function of m_X , from interpretation of the 2016–2022 measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay. (a): expected and observed upper limits at 90 % CL for $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ as function of m_X for invisible X , with comparison to observed upper limits from 2016–2018 data [7]. (b): observed upper limits at 90 % CL of $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ as function of m_X , for several τ_X hypotheses, assuming X decays to visible SM particles.

the selection acceptance, and therefore the SES according to equation (2.2), for X particles of mass m_X and lifetime τ_X . Equation (2.1) is used to establish an upper limit for the branching ratio corresponding to each combination of m_X and τ_X . For $\tau_X > \mathcal{O}(10 \text{ ns})$ the X particles become sufficiently long-lived to escape the detector, making them indistinguishable from invisibly decaying X . For $\tau_X < \mathcal{O}(100 \text{ ps})$ the X particles decay in the detector so that this search has negligible sensitivity.

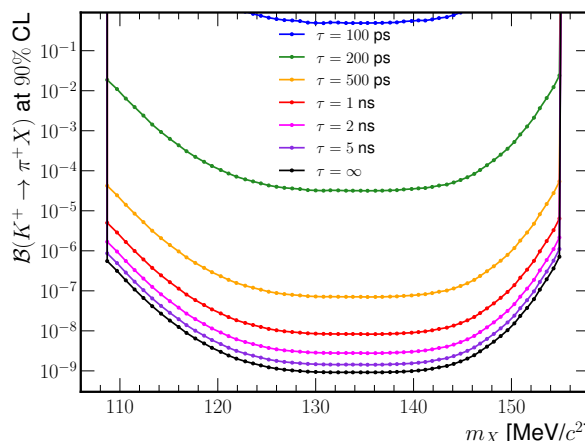


Figure 3. Upper limits at 90 % CL for $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ as a function of m_X for several τ_X hypotheses, from searches for π^0 decays to invisible final states [12].

2.2 Search for π^0 decays to invisible final states

A search for π^0 decays to invisible final states was performed on 2017 data [12], selecting a sample of $K^+ \rightarrow \pi^+ \pi^0$ decays using criteria similar to those used for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ study. This search is interpreted to provide model-independent upper limits for $\mathcal{B}(K^+ \rightarrow \pi^+ X)$, where m_X is close to the π^0 mass in the range 110–155 MeV/ c^2 . Limits are placed for a range of τ_X values, as shown in figure 3.

3 Searches for $K^+ \rightarrow \pi^+ X$ with prompt X decays to visible final states

3.1 Interpretation of $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ results

Based on 2017–2018 data, NA62 conducted a study of the $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay [9]. In scenarios allowing $X \rightarrow \mu^+ \mu^-$ decays, a peak search in the di-muon mass ($m_{\mu\mu}$) spectrum allows constraints to be set on $\mathcal{B}(K^+ \rightarrow \pi^+ X) \times \mathcal{B}(X \rightarrow \mu^+ \mu^-)$, presented in this work for the first time.

In the analysis of [9], 27679 candidate $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ events are selected, with negligible background. The $m_{\mu\mu}$ spectrum observed in the data is shown in figure 4-a. The selection acceptance of the decay chain $K^+ \rightarrow \pi^+ X$, $X \rightarrow \mu^+ \mu^-$ as a function of m_X is evaluated with simulations assuming isotropic $X \rightarrow \mu^+ \mu^-$ decays and several τ_X hypotheses. The acceptance obtained for $\tau_X = 0$ is shown in figure 4-b as a function of m_X , and is found to decrease as a function of τ_X approximately as

$$A(m_X, \tau_X) = A(m_X, \tau_X = 0) \cdot \left(1 - e^{-\tau_0/\tau_X}\right), \quad (3.1)$$

where $\tau_0 = 0.07$ ns. A peak search is performed for 298 di-muon mass hypotheses between 215.3 and 326.7 MeV/ c^2 . This range is determined by the availability of sidebands with sufficient statistics. The distance between adjacent mass hypotheses is equal to the di-muon mass resolution σ_m , shown in figure 5-a. For each hypothesis, a search window of $\pm 1 \sigma_m$ is considered. The background in each window is evaluated from data, using $\pm 9 \sigma_m$ sidebands, and excluding the search window. A linear fit to the sideband data provides the expected

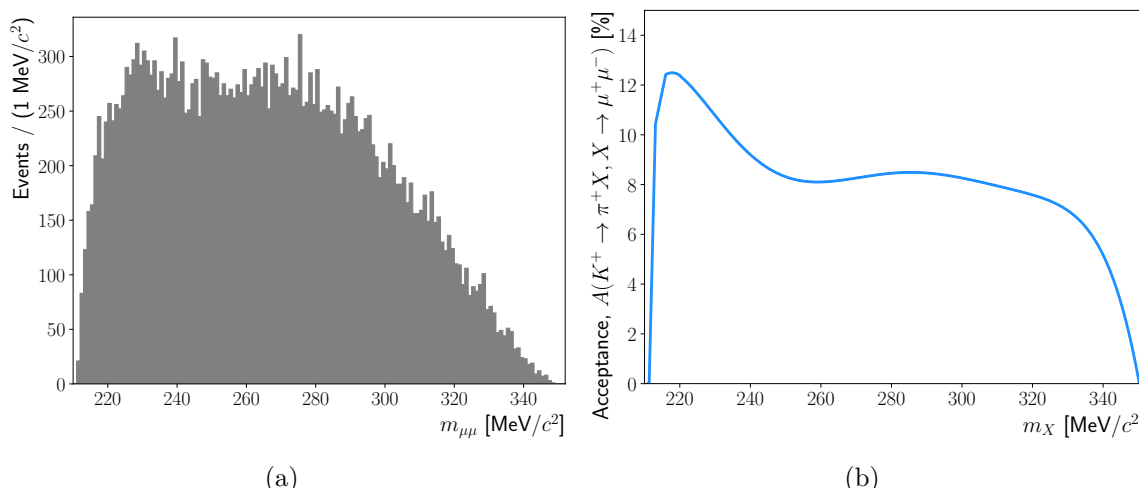


Figure 4. (a): di-muon mass spectrum of selected $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ events from 2017–2018 data. (b): selection acceptance for the decay chain $K^+ \rightarrow \pi^+ X$, $X \rightarrow \mu^+ \mu^-$ from simulations with $\tau_X = 0$.

background in the search window and its statistical uncertainty; the systematic uncertainty is evaluated using alternative quadratic and cubic polynomial fits. The expected and observed numbers of events in each window are shown in figure 5-b.

No significant excess is observed above the background for any mass hypothesis, with a maximum local significance of 3 standard deviations. Upper limits are set on $N_{UL}^{K\pi X, X\mu\mu}$, the number of events of the decay chain $K^+ \rightarrow \pi^+ X$, $X \rightarrow \mu^+ \mu^-$ for each mass hypothesis (figure 5-b), using the CL_s method [21]. These limits are converted to upper limits for the branching ratio product according to

$$UL(\mathcal{B}(K^+ \rightarrow \pi^+ X) \times \mathcal{B}(X \rightarrow \mu^+ \mu^-))(m_X, \tau_X) = \frac{N_{UL}^{K\pi X, X\mu\mu}}{N_K A(m_X, \tau_X)}, \quad (3.2)$$

where $A(m_X, \tau_X)$ is given by equation (3.1) and $N_K = (3.48 \pm 0.09) \times 10^{12}$ is the effective number of K^+ decays in the fiducial decay volume [9]. Figure 6-a displays the expected and observed limits in the scenario $\tau_X = 0$, while figure 6-b shows observed limits for several τ_X values.

3.2 Interpretation of $K^+ \rightarrow \pi^+ \gamma \gamma$ results

Using 2017–2018 data, NA62 performed a measurement of the SM $K^+ \rightarrow \pi^+ \gamma \gamma$ decay [10]. A peak search in the $m_{\gamma\gamma}$ spectrum obtained limits for $\mathcal{B}(K^+ \rightarrow \pi^+ X) \times \mathcal{B}(X \rightarrow \gamma \gamma)$, shown in figure 7-a. These limits become weaker for larger τ_X , as shown in figure 7-b, since the acceptance decreases with a more displaced $X \rightarrow \gamma \gamma$ vertex. The sensitivity of this search is limited to $\tau_X < 3$ ns.

4 Constraints on benchmark hidden-sector models

Using the model-independent limits described in sections 2 and 3, constraints are established on benchmark hidden-sector models. Depending on the scenario, the X particle may decay

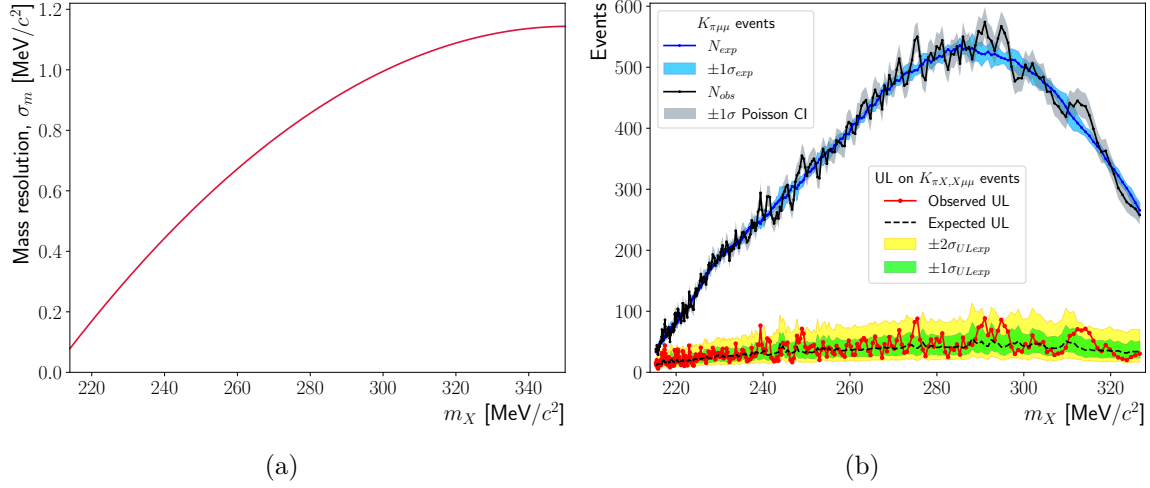


Figure 5. (a): di-muon mass resolution as a function of m_X . (b): numbers of expected (blue) and observed (black) $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ events in each search window, together with the $\pm 1\sigma$ Poisson confidence interval, CI. The corresponding upper limits at 90 % CL for the numbers of expected (dashed line) and observed (red line) $K^+ \rightarrow \pi^+ X$, $X \rightarrow \mu^+ \mu^-$ events are also shown.

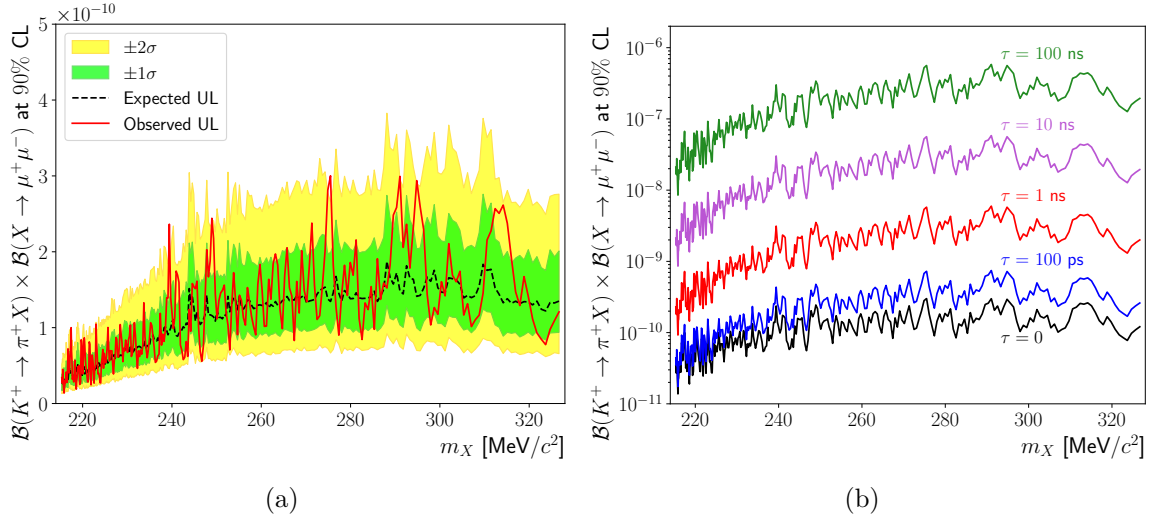


Figure 6. (a): expected and observed upper limits at 90 % CL for $\mathcal{B}(K^+ \rightarrow \pi^+ X) \times \mathcal{B}(X \rightarrow \mu^+ \mu^-)$ as a function of m_X for $\tau_X = 0$. (b): observed upper limits for $\mathcal{B}(K^+ \rightarrow \pi^+ X) \times \mathcal{B}(X \rightarrow \mu^+ \mu^-)$ at 90 % CL as a function of m_X for several τ_X values.

invisibly to dark-sector particles or neutrinos, or visibly to a pair of SM particles. The lifetime expected for a given mass is determined by the coupling strength to SM fields, and the number of available decay channels. Since the model-independent constraints depend on τ_X , a certain range of coupling strengths are excluded for a given m_X . Constraints on $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ from studies of $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ and $K^+ \rightarrow \pi^+ \gamma \gamma$ decays also depend on the model-dependent branching ratios of the $X \rightarrow \mu^+ \mu^-$ and $X \rightarrow \gamma \gamma$ decays.

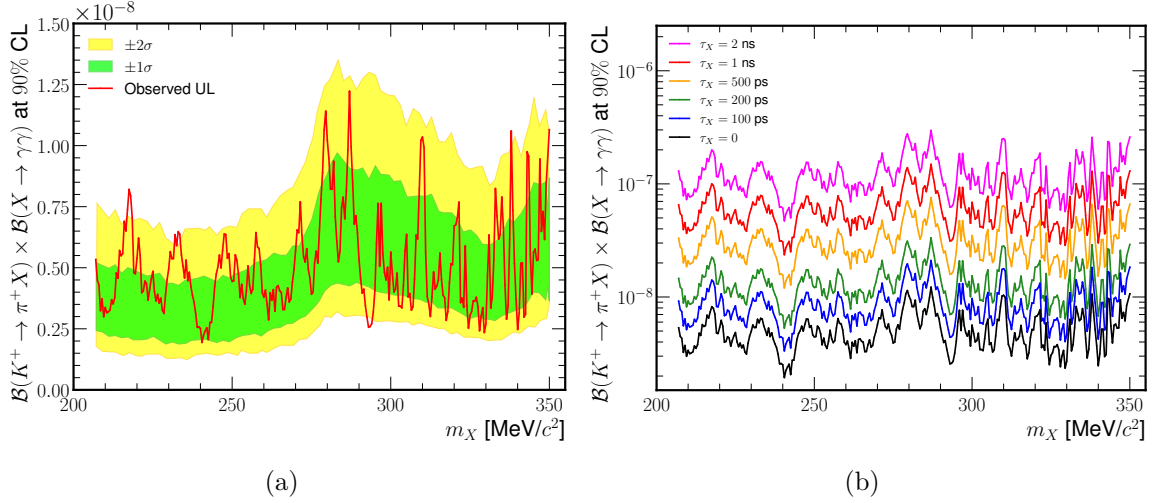


Figure 7. (a): upper limits at 90 % CL for $\mathcal{B}(K^+ \rightarrow \pi^+ X) \times \mathcal{B}(X \rightarrow \gamma\gamma)$ as a function of m_X for $\tau_X = 0$ [10]. (b): upper limits at 90 % CL for $\mathcal{B}(K^+ \rightarrow \pi^+ X) \times \mathcal{B}(X \rightarrow \gamma\gamma)$ for several τ_X values.

The benchmark hidden-sector models considered in this work are portal models where an additional Lagrangian term, $\mathcal{L}_{\text{portal}}$, is introduced to define interactions between hidden-sector and SM fields.

- In **BC1** and **BC2** a new U(1) symmetry gauge boson A' , called the dark photon, interacts with the SM fields through kinetic mixing: $\mathcal{L}_{\text{portal}} = -(\varepsilon/(2 \cos \theta_W)) F'_{\mu\nu} B^{\mu\nu}$, where $F'_{\mu\nu}$ and $B_{\mu\nu}$ are the field strength tensors of the dark photon and SM hypercharge gauge boson, respectively; θ_W is the Weinberg angle; and the mixing parameter ε defines the interaction strength.
- In **BC4** a new scalar singlet S , called the dark scalar, interacts with the SM Higgs doublet H : $\mathcal{L}_{\text{portal}} = -\mu S H^\dagger H$, where μ is a coupling constant. Below the electroweak symmetry breaking scale, S mixes with the SM Higgs boson h in proportion to the parameter $\theta \simeq \mu v / (m_h^2 - m_S^2)$, where v is the vacuum expectation value of the Higgs field.
- **BC10** and **BC11** belong to a class of models where an axion-like particle, a , couples to SM fermions, f , and gauge bosons, V : $\mathcal{L}_{\text{portal},f} = (C_{ff}/(2\Lambda)) \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$ and $\mathcal{L}_{\text{portal},V} = g^2 (C_{VV}/\Lambda) a V_{\mu\nu} \tilde{V}^{\mu\nu}$, where g is the corresponding SM gauge boson coupling constant, Λ is the new physics energy scale (assumed to be 1 TeV) and C_{ff} and C_{VV} are the coupling constants.

In all the scenarios considered, the branching ratio of the $K^+ \rightarrow \pi^+ X$ decay is given by

$$\mathcal{B}(K^+ \rightarrow \pi^+ X) = \frac{p_X}{8\pi\Gamma_K m_K^2} |\mathcal{M}|^2, \quad (4.1)$$

where $\Gamma_K = 5.32 \times 10^{-14}$ MeV is the K^+ decay width, p_X is the momentum of X in the kaon rest frame, and m_K is the K^+ mass [22]. The matrix element $\mathcal{M}$ depends on the hidden-sector scenario and is proportional to the coupling strength.

4.1 Massive dark vector

In QED-like theories [23], a new vector particle (the dark photon A') is introduced, which couples to the electromagnetic current. This particle with mass $m_{A'}$ mediates interactions both with the SM fields, through a kinetic mixing coupling $\varepsilon \ll 1$, and with the hidden-sector fields, through a coupling constant α_D of $\mathcal{O}(1)$.

In the minimal vector portal implementation, the BC1 model [13], A' is the only light BSM particle, and is forced to decay exclusively to SM particles. In this case $K^+ \rightarrow \pi^+ X_{\text{inv}}$ searches have no sensitivity because A' is short-lived and $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ searches, which provide limits of ε of $\mathcal{O}(10^{-3})$, are not competitive [24, 25]. In contrast, in the BC2 model a dark fermion χ with mass $m_\chi < m_{A'}/2$ is introduced, and therefore A' decays predominantly to invisible particles, $A' \rightarrow \chi \bar{\chi}$. The dark fermion is considered to be stable or extremely long-lived and can contribute to the dark matter abundance. Results from $K^+ \rightarrow \pi^+ A'$ searches are independent of α_D and m_χ , and are therefore presented in the $(m_{A'}, \varepsilon)$ plane.

The radiative decay $K^+ \rightarrow \pi^+ \gamma$ violates angular momentum conservation because the photon is massless. However, the $K^+ \rightarrow \pi^+ A'$ decay is allowed if $m_{A'} > 0$, although the decay rate is suppressed for small values of $m_{A'}$. In this scenario, the branching ratio of the $K^+ \rightarrow \pi^+ A'$ decay is given by equation (4.1) with a matrix element [26, 27]

$$|\mathcal{M}| = \frac{e\varepsilon|W(z)|m_{A'}}{16\pi^2 m_K^2} \sqrt{\lambda(m_K^2, m_\pi^2, m_{A'}^2)}, \quad (4.2)$$

where e is the elementary charge, λ is the triangle function, m_π is the charged pion mass, and $|W(z)|$, introduced in [28], is evaluated at $z = (m_{A'}/m_K)^2$ using the model derived from the NA62 study of the $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay [9]. Figure 8-a displays values of $\mathcal{B}(K^+ \rightarrow \pi^+ A')/\varepsilon^2$ as a function of $m_{A'}$.

Using upper limits for $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ described in section 2 and equations (4.1) and (4.2), new regions are excluded at 90 % CL in the $(m_{A'}, \varepsilon)$ plane. For $m_X < m_{\pi^0}$ and $m_X \approx m_{\pi^0}$ limits have also been established in this scenario by the NA62 searches for $\pi^0 \rightarrow \gamma A'$ [29] and $\pi^0 \rightarrow \text{invisible}$ (section 2.2), respectively. The results are displayed in figure 8-b, together with limits from other experiments, and provide the strongest limits of the A' invisible decays in the $m_{A'}$ range 160–230 MeV/ c^2 .

4.2 Dark scalar mixing with the Higgs boson

In the minimal scalar portal model BC4 [13, 35], hidden-sector particles are coupled to the SM Higgs field. A massive scalar particle S , with mass m_S , mixes with the SM Higgs boson, and both its production and decay (to SM particles) are driven by the mixing parameter $\sin^2 \theta$. The $K^+ \rightarrow \pi^+ S$ branching ratio is given by equation (4.1), with a matrix element [36, 37]

$$|\mathcal{M}| = \frac{1}{2} \left(\frac{m_K^2 - m_\pi^2}{m_s - m_d} \right) \left(\frac{m_S}{v} \frac{3\sqrt{2}G_F}{16\pi^2} m_t^2 |V_{ts}^* V_{td}| \right) \sin \theta = \sqrt{(8\pi\Gamma_K m_K) C} \sin \theta, \quad (4.3)$$

where G_F is the Fermi constant, $m_{d,s,t}$ are the masses of the down, strange and top quarks, respectively, and V_{ij} are elements of the CKM matrix. For this analysis $C = 3 \times 10^{-3}$ is used [35], while similar values are used elsewhere [37–39]. The resulting values of $\mathcal{B}(K^+ \rightarrow \pi^+ S)/\sin^2 \theta$ as a function of m_S are shown in figure 9-a.

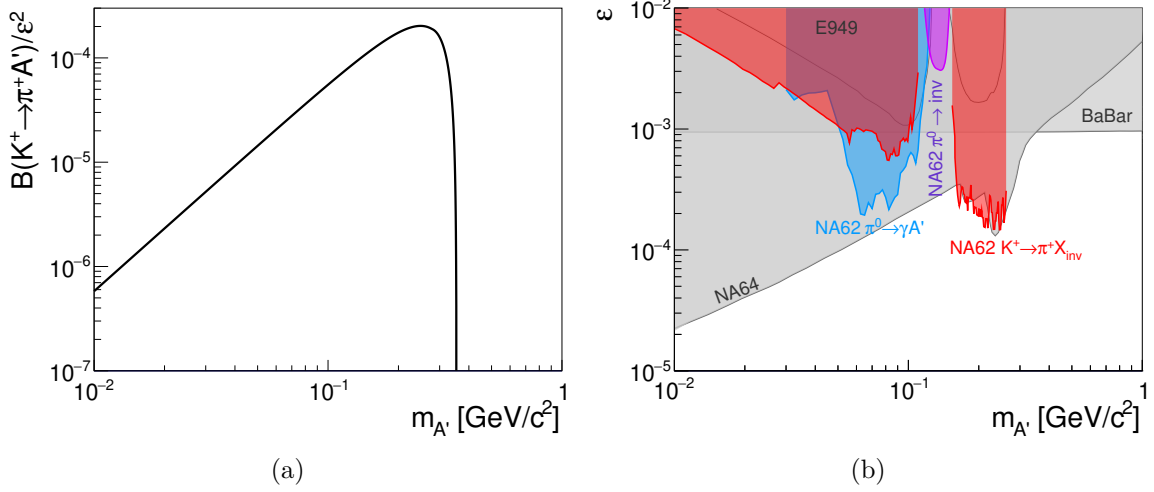


Figure 8. (a): branching ratio of the $K^+ \rightarrow \pi^+ A'$ decay divided by the kinetic mixing coupling squared, ε^2 , as a function of $m_{A'}$ [26], according to equation (4.2). (b): excluded regions, at 90 % CL, of the parameter space $(m_{A'}, \varepsilon)$ for a dark photon A' , decaying invisibly, in the BC2 model [30]. Excluded regions from NA62 searches for $K^+ \rightarrow \pi^+ X_{\text{inv}}$ (figure 2), $\pi^0 \rightarrow \text{inv}$ [12] and $\pi^0 \rightarrow \gamma A'$ [29] are shown in red, purple and blue, respectively. Other bounds, shown in grey, are from the experiments E949 [26, 31], NA64 [32, 33], and BaBar [34].

In the BC4-inv model, the dark scalar production phenomenology is identical to BC4 (figure 9-a), however the dark scalar is stable or decays invisibly to a pair of hidden-sector particles. Upper limits for $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ (section 2) are converted to upper limits for $\sin^2 \theta$ according to equations (4.1) and (4.3). Results are shown in figure 9-b.

In the BC4 model, where the dark scalar decays to SM particles only and has a mass below the di-pion mass threshold, S decays to lepton pairs $\ell^+ \ell^-$ with a proper lifetime τ_S , shown in figure 9-c and given by

$$\tau_S(m_S, \sin^2 \theta) = \frac{\hbar}{\Gamma_S} , \quad (4.4)$$

where the decay width is

$$\Gamma_S = \begin{cases} \Gamma(S \rightarrow e^+ e^-) & 2m_e \leq m_S < 2m_\mu \\ \Gamma(S \rightarrow e^+ e^-) + \Gamma(S \rightarrow \mu^+ \mu^-) & m_S \geq 2m_\mu \end{cases} , \quad (4.5)$$

and

$$\Gamma(S \rightarrow \ell^+ \ell^-) = \frac{m_\ell^2 m_S}{8\pi v^2} \left(1 - \frac{4m_\ell^2}{m_S^2} \right)^{3/2} \sin^2 \theta . \quad (4.6)$$

For a given m_S value the excluded range of $\sin^2 \theta$ values depends on τ_S . Excluded regions from NA62 searches for $K^+ \rightarrow \pi^+ X_{\text{inv}}$ (figure 2), $\pi^0 \rightarrow \text{inv}$ [12] and $K^+ \rightarrow \pi^+ S$, $S \rightarrow \mu^+ \mu^-$ (figure 6) are displayed in figure 9-d. As discussed in section 3, the sensitivity of NA62 searches is limited by lifetime effects. For $m_S > 2m_\mu$ the decay width is dominated by the di-muon decay, therefore the lifetime decreases significantly and the excluded region of the parameter space $(m_S, \sin^2 \theta)$ is correspondingly reduced (figure 9-d).

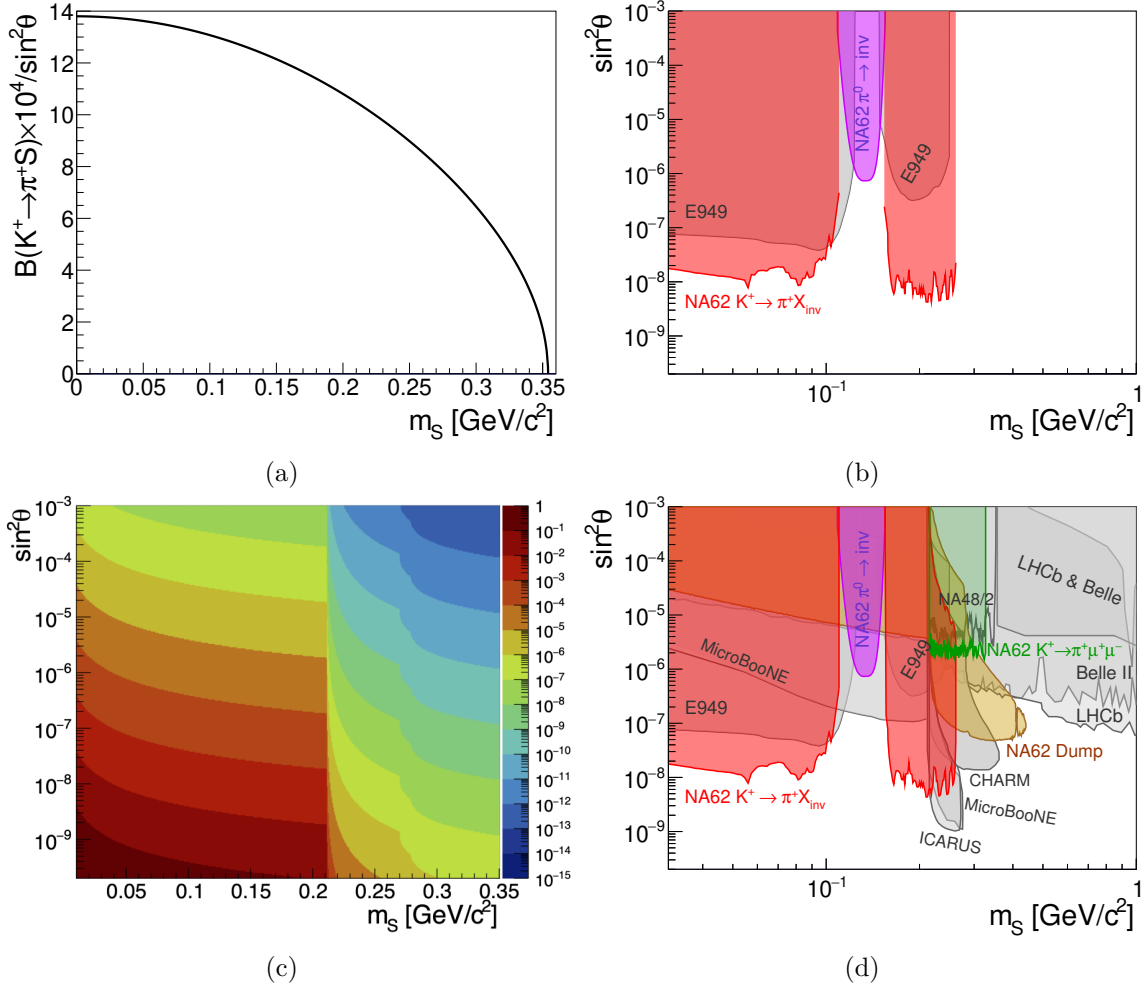


Figure 9. (a): branching ratio of the $K^+ \rightarrow \pi^+ S$ decay divided by $\sin^2 \theta$, as a function of m_S (equation (4.3)). (b): excluded regions, at 90 % CL, of the parameter space $(m_S, \sin^2 \theta)$ for a dark scalar S , in the BC4-inv model. (c): lifetime (colour scale, τ_S in s) of a dark scalar S , in the BC4 model [13]. (d): excluded regions, at 90 % CL, of the parameter space $(m_S, \sin^2 \theta)$ for a dark scalar S , in the BC4 model [13]. Excluded regions from NA62 searches for $K^+ \rightarrow \pi^+ X_{\text{inv}}$ (figure 2), $\pi^0 \rightarrow \text{inv}$ [12], $K^+ \rightarrow \pi^+ S$, $S \rightarrow \mu^+ \mu^-$ (figure 6), and in beam dump mode [19] are shown in red, purple, green and brown, respectively. Other bounds, shown in grey, are derived from the experiments E949 [31], CHARM [35], NA48/2 [40], LHCb [41, 42], Belle [30], Belle II [43], MicroBooNE [44, 45], and ICARUS [46].

4.3 Axion portal with coupling to SM fermions

In the axion portal scenario, a is a light pseudoscalar axion-like particle (ALP) which acts as a mediator between the SM and the hidden sector. A scenario with universal coupling to charged fermions [13], parameterized by C_{ff} , is considered. In this case, unlike the benchmark vector and scalar portal models discussed above, UV completion is required below a certain mass scale, and the renormalization group evolution can introduce additional couplings [13, 52, 53]. The branching ratio divided by $(C_{ff}/\Lambda)^2$ as a function of the ALP mass assuming $\Lambda = 1$ TeV, based on [54] and evaluated using the ALPINIST framework [47], is displayed in figure 10-a.

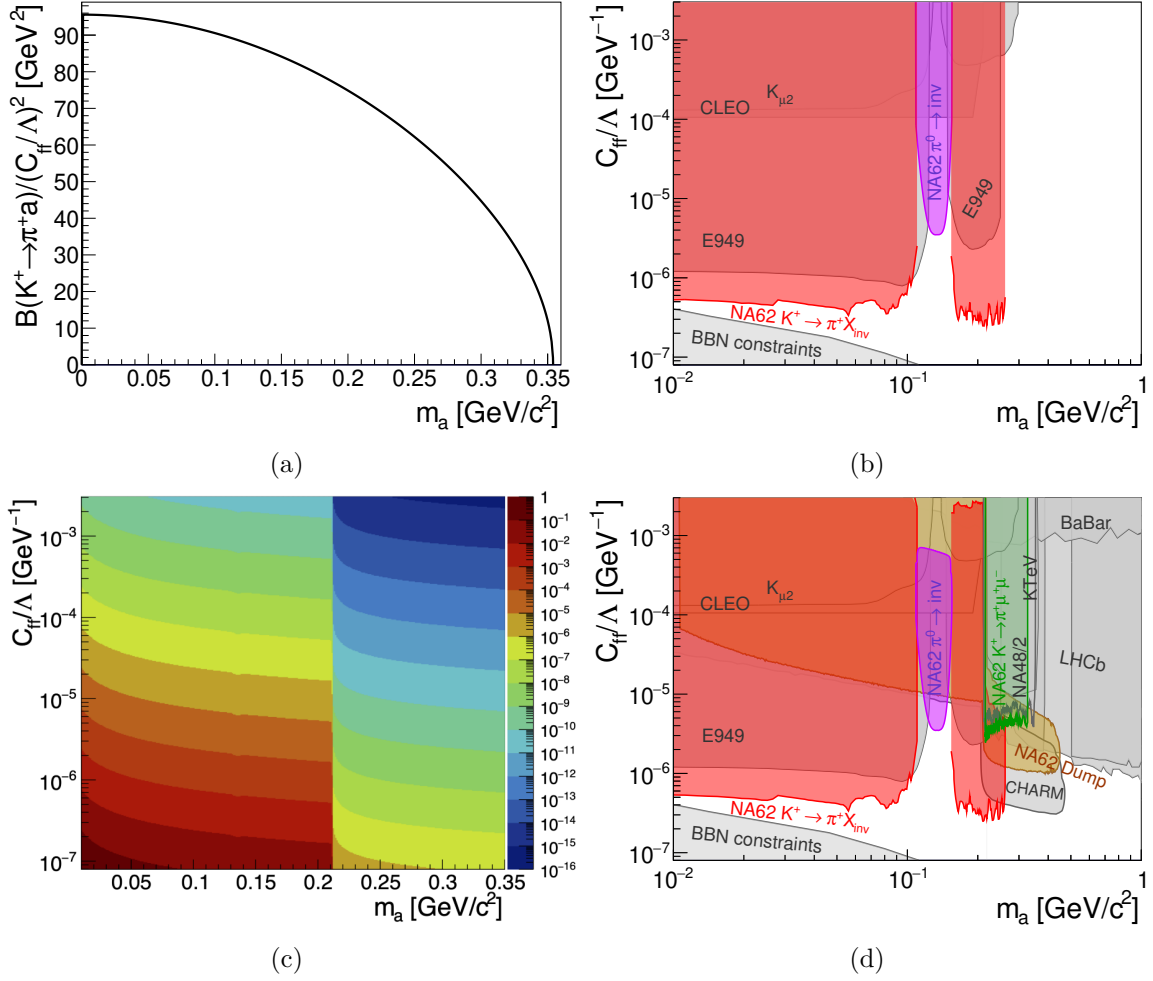


Figure 10. (a): branching ratio of the $K^+ \rightarrow \pi^+ a$ decay divided by $(C_{ff}/\Lambda)^2$, as a function of m_a , assuming $\Lambda = 1$ TeV [47]. (b): excluded regions, at 90% CL, of the parameter space $(m_a, C_{ff}/\Lambda)$ for an ALP a , in the BC10-inv model, evaluated assuming $\Lambda = 1$ TeV. (c): lifetime (colour scale, τ_a in s) of an ALP a , in the BC10 model [13], as a function of mass and coupling strength [47]. (d): excluded regions, at 90% CL, of the parameter space $(m_a, C_{ff}/\Lambda)$ for an ALP a , in the BC10 model [13], evaluated assuming $\Lambda = 1$ TeV. Excluded regions from NA62 searches for $K^+ \rightarrow \pi^+ X_{\text{inv}}$ (figure 2), $\pi^0 \rightarrow \text{inv}$ [12] and $K^+ \rightarrow \pi^+ a, a \rightarrow \mu^+ \mu^-$ (figure 6), and in beam dump mode [19] are shown in red, purple, green and brown, respectively. Other bounds, shown in grey, are derived from the experiments E949 [31], $K\mu 2$ [48], CLEO [49], CHARM [50], KTeV [51], NA48/2 [40], LHCb [41, 42] and from Big Bang nucleosynthesis (BBN) [13].

If the ALP is stable or decays invisibly (to a pair of hidden-sector particles, BC10-inv), upper limits for C_{ff} are established according to ALPINIST from the model-independent $\mathcal{B}(K^+ \rightarrow \pi^+ X)$ limits discussed in section 2, as shown in figure 10-b. Alternatively, if the ALP decays to SM particles only (BC10 model) and is light ($m_a < 2m_\pi$), the a lifetime is

$$\tau_a(m_a, C_{ff}) = \frac{\hbar}{\Gamma_{\ell\ell} + \Gamma(a \rightarrow \gamma\gamma)} \, , \quad (4.7)$$

as shown in figure 10-c. The total $a \rightarrow \ell^+ \ell^-$ decay width is given by

$$\Gamma_{\ell\ell} = \begin{cases} \Gamma(a \rightarrow e^+ e^-) & 2m_e \leq m_a < 2m_\mu \\ \Gamma(a \rightarrow e^+ e^-) + \Gamma(a \rightarrow \mu^+ \mu^-) & m_a \geq 2m_\mu \end{cases}, \quad (4.8)$$

where

$$\Gamma(a \rightarrow \ell^+ \ell^-) = \left(\frac{C_{ff}}{\Lambda} \right)^2 \frac{m_\ell^2 m_a}{8\pi} \beta_\ell, \quad (4.9)$$

m_ℓ is the lepton mass and $\beta_\ell = \sqrt{1 - 4m_\ell^2/m_a^2}$. The width of the decay to a photon pair is given by

$$\Gamma(a \rightarrow \gamma\gamma) = \left(\frac{C_{ff}}{\Lambda} \right)^2 \frac{\alpha^2 m_a^3}{64\pi^3} \left| \sum_{f=e,\mu,u,d,s} N_C Q_f^2 C_{ff} F_A(\beta_f^2) \right|^2, \quad (4.10)$$

where: f labels a fermion; α is the fine-structure constant; $N_C = 1(3)$ for leptons (quarks); Q_f is the fermion charge; $\beta_u^2 = \beta_d^2 = (1 - 4m_\pi^2/m_a^2)$ and $\beta_s^2 = (1 - 4m_K^2/m_a^2)$; and

$$F_A = \beta_f^2 \begin{cases} \arcsin^2 \left(\frac{1}{\sqrt{1-\beta_f^2}} \right) & \beta_f^2 \leq 0 \\ -\frac{1}{4} \left[\log \left(\frac{1+\beta_f}{1-\beta_f} \right) - i\pi \right]^2 & \beta_f^2 > 0 \end{cases}. \quad (4.11)$$

Excluded regions in the $(m_a, C_{ff}/\Lambda)$ plane from NA62 searches for $K^+ \rightarrow \pi^+ X_{\text{inv}}$ (figure 2), $\pi^0 \rightarrow \text{inv}$ [12] and $K^+ \rightarrow \pi^+ S$, $S \rightarrow \mu^+ \mu^-$ (figure 6) are displayed in figure 10-d.

4.4 Axion portal with coupling to SM gluons

In the BC11 model [13] a is an ALP with gluon coupling C_{GG} . For $m_a < 3m_\pi$, the ALP decays almost exclusively to photon pairs due to the assumption of vanishing lepton coupling. The branching ratio divided by $(C_{GG}/\Lambda)^2$ as a function of the ALP mass, assuming $\Lambda = 1$ TeV, based on [54] and evaluated using the ALPINIST framework [47], is displayed in figure 11-a.

Figure 11-b shows the ALP lifetime as a function of mass and coupling. Excluded regions established in the $(m_a, C_{GG}/\Lambda)$ parameter space from the searches for $K^+ \rightarrow \pi^+ X_{\text{inv}}$ (figure 2), $\pi^0 \rightarrow \text{inv}$ [12] and $K^+ \rightarrow \pi^+ a$, $a \rightarrow \gamma\gamma$ [10] are displayed in figure 11-c.

Within a more specific QCD axion model, constraints on the vectorial axion-down-strange coupling were established [55], using an independent analysis procedure of the public NA62 data [56] from the search for the $K^+ \rightarrow \pi^+ X$ decay with $m_X = 0$.

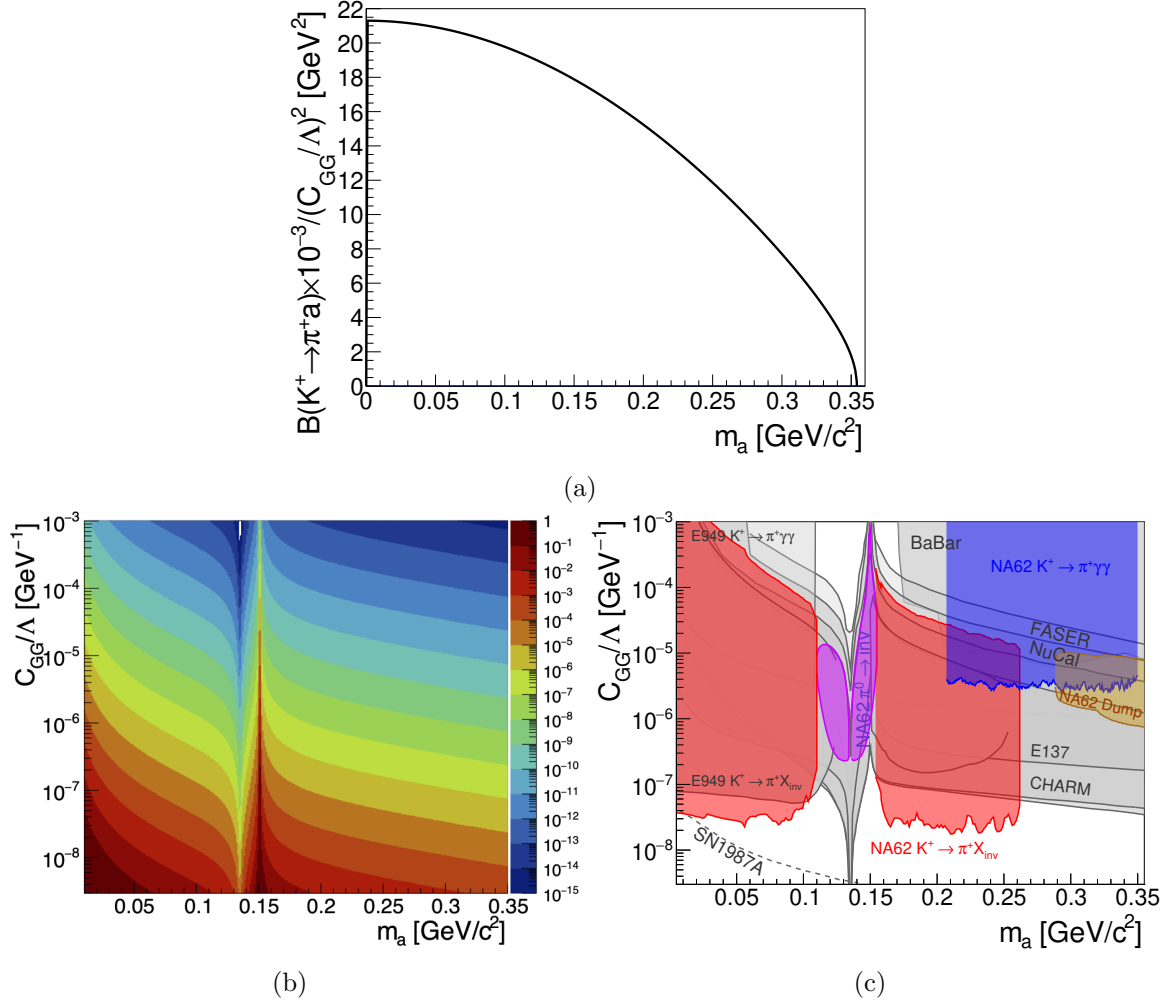


Figure 11. (a): branching ratio of the $K^+ \rightarrow \pi^+ a$ decay divided by $(C_{GG}/\Lambda)^2$, as a function of m_a , assuming $\Lambda = 1$ TeV [47]. (b): lifetime (colour scale, τ_a in s) of an ALP a , in the BC11 model [13] as a function of mass and coupling strength [47]. (c): excluded regions, at 90 % CL, of the parameter space $(m_a, C_{GG}/\Lambda)$ for an ALP a , of the BC11 model [13], evaluated assuming $\Lambda = 1$ TeV. Excluded regions from NA62 searches for $K^+ \rightarrow \pi^+ X_{\text{inv}}$ (figure 2), $\pi^0 \rightarrow \text{inv}$ [12], $K^+ \rightarrow \pi^+ a$, $a \rightarrow \gamma\gamma$ [10], and in beam dump mode [19] are shown in red, purple, blue and brown, respectively. Other experimental limits [46, 57, 58] are shown in grey.

5 Conclusions

Constraints on the production of a hidden-sector particle X are derived from studies of the rare kaon decays $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ and $K^+ \rightarrow \pi^+ \gamma\gamma$. The scenarios where X is invisible or visible (decaying to a pair of SM particles) are considered. New limits are obtained for a vector particle decaying to invisible final states, as well as for scalar and axion-like particles. Interpretation of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ measurement to search for $K^+ \rightarrow \pi^+ X_{\text{inv}}$, now extended to the 2016–2022 dataset, provides world-leading constraints in the m_X ranges 0–100 MeV/c^2 and 150–260 MeV/c^2 .

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