Physics Beyond the Standard Model with the NA62 experiment at CERN

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(on behalf of NA62 collaboration)

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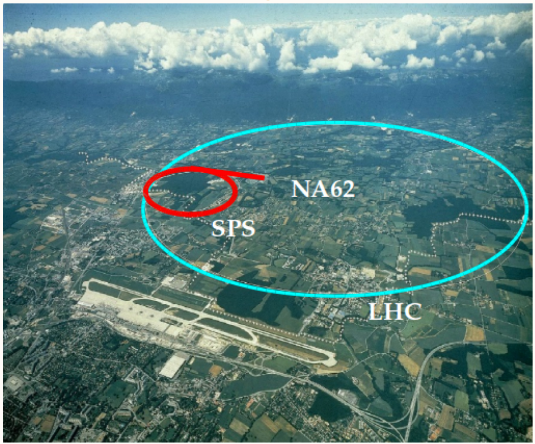
The NA62 experiment at CERN

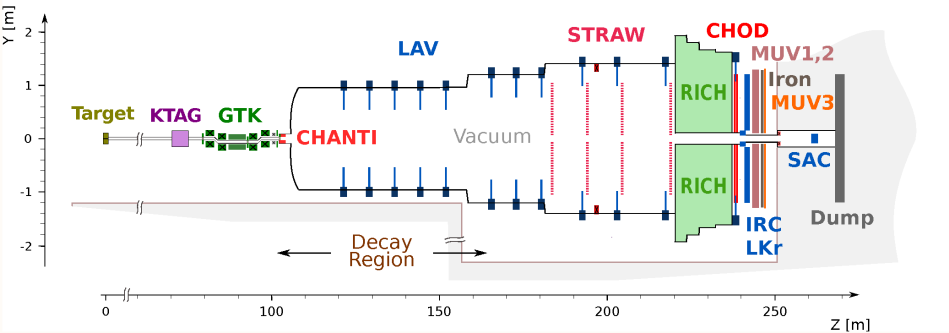
A Kaon factory at CERN



- beam from the SPS: **400 GeV/c protons** on a Be target
- secondary beam of **75 GeV/c** hadrons (70% π, 24% p, **6%** K)
- **decay in flight**: Kaons decay in a $\sim$ 60 m fiducial volume

750 MHz nominal rate of secondary particles $\longrightarrow$ **45 MHz of** K^+

The NA62 experimental setup



Upstream detectors (K^+)

KTAG: differential Cherenkov counter for K^+ ID

GTK: silicon pixel beam tracker

CHANTI: anti-counter against inelastic beam/GTK3 interactions

Downstream detectors

STRAW: track momentum spectrometer

CHOD: plastic scintillators for fast charged trigger

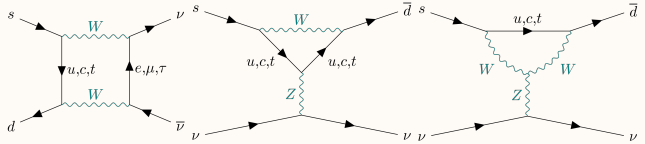
RICH: Cherenkov counter for $\pi/\mu/e$ ID

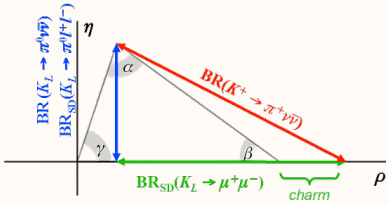
LKr and MUV1-2: calorimetric system

MUV3 muon veto

$K^+ \to \pi^+ \nu \bar{\nu}$

$K^+ \to \pi^+ \nu\bar{\nu}$: theoretical sideview





- ⋆ **FCNC** loop process $s \to d$ coupling with high CKM suppression
- ⋆ **Clean theoretical prediction**: short distance contributions
- ⋆ Hadronic form factors: obtained from $K\ell 3$ measurements and SU(2) isospin symmetry

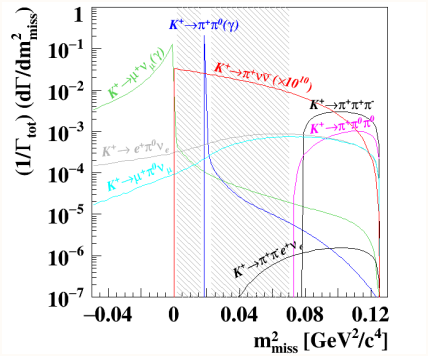
- ⋆ Correlation with the neutral decay $K_L \to \pi^0 \nu\bar{\nu}$
- ⋆ High sensitivity to **New Physics**

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.60 \pm 0.42) \times 10^{-11}$$

Buras and Venturini (2021) arXiv:2109.11032

$K^+ \to \pi^+ \nu\bar{\nu}$: analysis strategy and results

$$m^2_{miss} = (P_K - P_\pi)^2$$



Selection steps

- K^+-π^+ tracks reconstruction and matching
- PID and rejection
- Kinematics requirements

Analysis keystones

- $\mathcal{O}(100$ ps$)$ timing between detectors
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $\mathcal{O}(10^7)$ π^0 rejection
- $\mathcal{O}(10^7)$ μ^+ rejection

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9|_{syst}) \times 10^{-11}$$

(JHEP 06 (2021) 093)

Hidden sector searches in K^+ into $\pi^+ e^+ e^- e^+ e^-$ decays

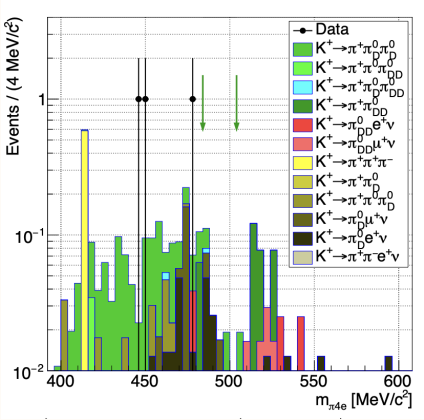
$K^+ \to \pi^+ XX$: motivations

- ⋆ **Two-fold** interest in the context of dark sector:
  - ▷ A **short-lived QCD axion (a)**:
    - ◇ plausible explanation for the *17 MeV anomaly* (Phys. Rev. D105 (2022) 015017)
    - ◇ assuming $m_a = 17$ MeV/c^2, $\mathcal{B}(K^+ \to \pi^+ aa) > 2 \times 10^{-8}$ is predicted (Phys. Rev. D 103(2021)055018), (Eur. Phys. J. C83 (2023) 230)
  - ▷ A scenario involving a **dark scalar (S)**, and a **dark photon (A')** with masses satisfying the condition $m_S \geq 2m_{A'}$ leads to a prompt cascade process $K^+ \to \pi^+ S,\ S \to A'A',\ A' \to e^+e^-$ (Phys. Rev. D105 (2022) 015017)

$K^+ \to \pi^+ XX$: general selection criteria

NEW!

- The **data sample analyzed** is obtained from 8.3×10^5 SPS spills recorded in 2017–2018
- **STRAW information only**, to avoid an order-of-magnitude loss in signal acceptance
- **Invariant mass** $m_{\pi 4e}$ used to distinguish between signal and bkg
- Discriminating kinematic variable and **blind analysis strategy**
  - Signal region (SR) kept masked until the completion and validation of the background evaluation

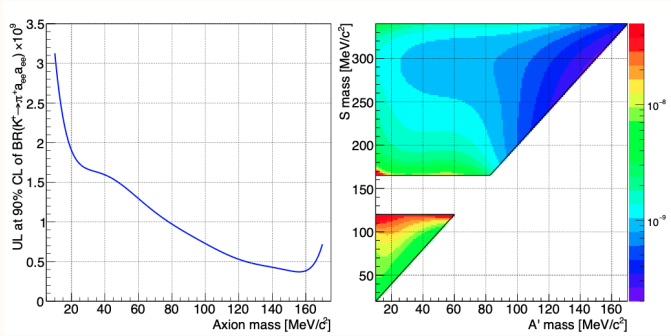


$K^+ \to \pi^+ XX$: additional criteria and results

NEW!

- ⋆ **Additional criteria** wrt $K_{\pi 4e}$ selection
  - ⋆ **consistency** of the two reconstructed e^+e^- mass values
  - ⋆ for each X mass hypothesis (m_X), it is required that $|m_{ee} - m_X| < 0.02 \cdot m_X$
- ⋆ **Uniform** phase space assumed for K^+ decays, **isotropic** decays of dark states
- ⋆ No data observed in the SR

Short-lived QCD axion **Prompt dark cascade**



Upper limits at 90% CL are obtained at the level of 10^{-9} for the branching ratios of two prompt decay chains involving pair-production of hidden-sector mediators. The QCD axion is excluded as a possible explanation of the *17 MeV anomaly*

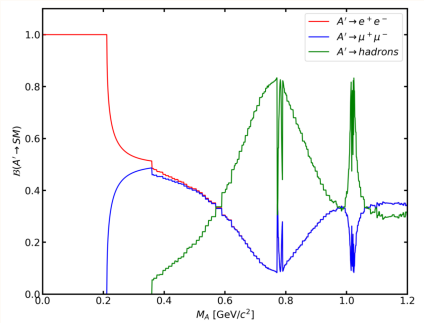
(arXiv:2307.04579 [hep-ex] - submitted to Phys.Lett.B)

$$A' \to \ell^+ \ell^-$$

Search for Dark Photon in NA62

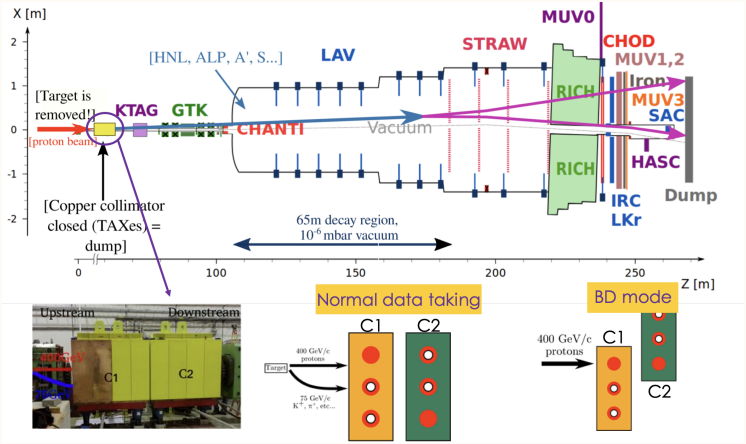
$$\mathcal{L} \propto -\epsilon \frac{1}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

- new **U(1) gauge-simmetry**
- vector mediator field A'
- interaction between A'_μ and the SM hypercharge $B^{\mu\nu}$ via kinetic-mixing



In the mass range < 700 MeV, DP decay width is dominated by lepton-antilepton final states

NA62 in beam dump mode



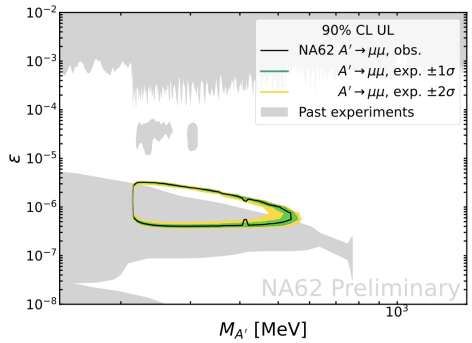
In 2021, NA62 collected $1.40 \pm 0.28 \times 10^{17}$ POT.

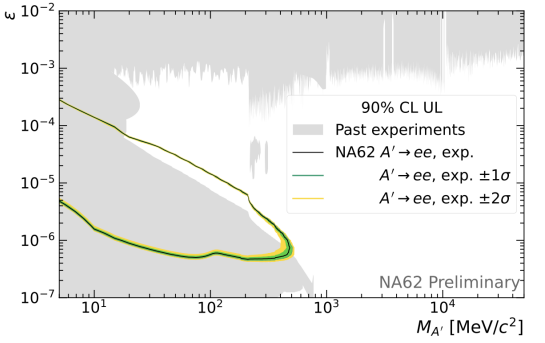
$A' \to \ell^+\ell^-$: analysis strategy

- ⋆ **Signal selection:** $\ell^+\ell^-$ vertex reconstructed within the NA62 decay region and pointing back to the proton beam interaction point at the TAXes
- ⋆ **CR** and **SR** kept masked until the analysis strategy is frozen (new optimized SR for the e^+e^-)
- ⋆ Bkg estimated selecting single tracks in a data sample orthogonal to the one used for the analysis: track pairs are **artificially built** to emulate a random superposition and re-weighted
- ⋆ $A' \to \mu^+\mu^-$ result also interpreted in terms of the emission of **axion-like particles** in a model-independent approach, improving on previous limits for masses below 280 MeV/c^2

$A' \to \ell^+\ell^-$: results

90% CL upper limits have been set, exploring new regions of the parameter space ϵ, $M_{A'}$





$A' \to \mu^+\mu^-$

1 event observed in the SR

counting experiment with 2.4σ global significance

$A' \to e^+e^-$

0 events observed in both CR and SR

arXiv:2303.08666 (2023), submitted to JHEP

Conclusions

- Charged kaon physics successfully pursued at CERN SPS by NA62:
  - ▷ $K^+ \to \pi^+ \nu\bar{\nu}$ RUN1 (2016-18): $BR = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$ (JHEP 06 (2021) 093)
  - ▷ Upper limits at 90% CL are obtained at the level of 10^{-9} for the branching ratios of two prompt decay chains involving pair-production of hidden-sector mediators: $K^+ \to \pi^+ aa$, $a \to e^+e^-$ and $K^+ \to \pi^+ S$, $S \to A'A'$, $A' \to e^+e^-$ (arXiv:2307.04579 [hep-ex] - submitted to Phys.Lett.B)
- $A' \to \ell^+\ell^-$ in beam-dump mode: with $(1.4 \pm 0.28) \times 10^{17}$ POT a 90% CL upper limits have been set, exploring new regions of the parameter space (arXiv:2303.08666 (2023), submitted to JHEP)
- NA62 will take data until LS3 in 2026: **larger data sets** both in kaon and dump mode will be available

Stay tuned, further results will be obtained and new searches developed!

Spares

NA62: a general purpose experiment

Flavor physics

Robustness test of the SM predictions via **FCNC processes**

Main goal

measurement of the BR

$K^+ \to \pi^+ \nu\bar{\nu}$

(JHEP 06 (2021) 093)

Search for **LFV, LNV**, rare and forbidden decays

$K^+ \to \pi^+ e^\mp \mu^\pm$

$K^+ \to \ell_1^+ \nu \ell_2^+ \ell_2^-$

$K^+ \to \pi^- \ell^+ \ell^+$

$K^+ \to \mu^+ \nu\nu\bar{\nu}$

Dark sector

Search for **exotic processes** through direct detection of feebly interacting particles with long lifetime

DP, HNL, DS, ALPs

$A' \to \ell^+ \ell^-$

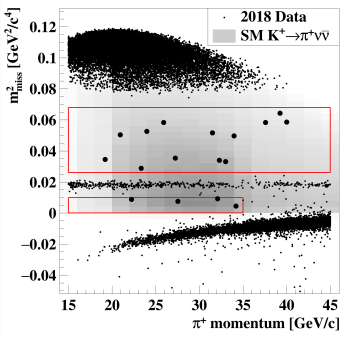
$K^+ \to \ell^+ N$

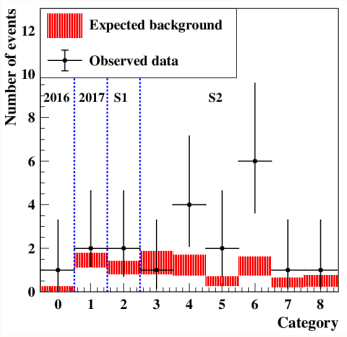
$K^+ \to \mu^+ \nu X$

(Phys.Lett.B 807 (2020) 135599,Phys. Lett. B816 (2021) 136259)
(arXiv:2303.08666 (2023), submitted to JHEP)

$K^+ \to \pi^+ \nu\bar{\nu}$: results

- **Single Event Sensitivity**
  $(0.839 \pm 0.053|_{syst}) \times 10^{-11}$
- Expected **SM signal** events:
  $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- Expected **background** events:
  $7.03^{+1.05}_{-0.82}$
- **Observed** events: 20





$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9|_{syst}) \times 10^{-11}$$

JHEP 06 (2021) 093

Hidden sector searches in K^+ into $\pi^+ e^+ e^- e^+ e^-$ decays

Why is important to study $K^+ \to \pi^+ XX$?

- so far searches for the production of dark-sector in meson decays have been focused on the **production of a single particle**, which is either invisible or **decays into lepton or photon pairs** (not on the pair-production of dark states)
- since this process has not been studied experimentally so far, $O(10^{-6})$ sensitivity to its branching ratio is sufficient to **improve existing constraints** on dark-sector models.
- provides a plausible explanation for provides a plausible explanation for the **"17 MeV anomaly"** in the mass spectra of the e^+e pairs produced in the de-excitation of ^{8}Be, ^{4}He and ^{12}C nuclei.

$K^+ \to \pi^+ XX$: more on the selection

- Vertices are reconstructed by **extrapolating STRAW tracks backward**. 5 tracks, $\mathbf{q = +1}$, p_{track} in the **range 5–45 GeV/c**. To suppress photon conversions and fake tracks, each pair of tracks should be **separated by at least 15 mm in each STRAW chamber plane**.
- Three assignments of the π^+ mass to one of the positively charged tracks are considered. The mass assignment corresponding to the minimal value of $|\boldsymbol{m_{\pi 4e}} - \boldsymbol{m_K}|^2$ is chosen.
- In order to suppress the $K_{2\pi DD}$ is required that $|\boldsymbol{m_{\pi 4e}} - \boldsymbol{m_{\pi^0}}|^2 > 10\text{MeV/c}^2$
- $\boldsymbol{p_\pi} > \mathbf{10}$ GeV/c.

$K^+ \to \pi^+ XX$: search for the signal

- $2m_e \leq m_a \leq (m_K - m_\pi)/2$
- $2m_e \leq m_{A'} \leq m_S/2 \leq (m_K - m_\pi)/2$

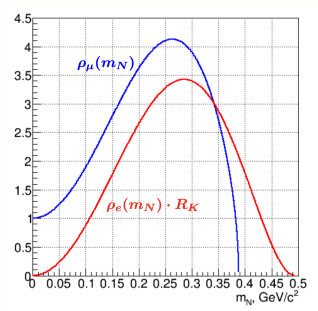
K^+ decays to a lepton and invisible particles

Heavy Neutral leptons production in K^+ decays

- Generic possibility of k sterile neutrinos mass states:

$$\nu_\alpha = \sum_{i=1}^{3+k} U_{\alpha i}\nu_i \qquad (\alpha = e, \mu, \tau)$$

- νMSM: neutrino Minimal Standard Model (Phys. Lett. B620 (2005) 17)
- HNL production is enhanced kinematically wrt SM decays (except near kinematic endpoints)
- Large $f \sim 10^5$ enhancement in the $K^+ \to e^+ N$ case: helicity suppression is relaxed

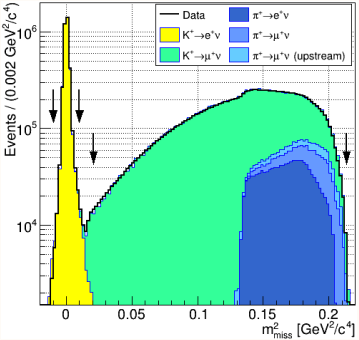


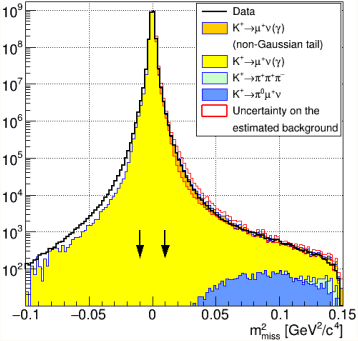
$$\mathcal{B}(K^+ \to \ell^+ N) = \mathcal{B}(K^+ \to \ell^+ \nu) \times \rho_\ell(m_N) \times |U_{\ell 4}|^2$$

(Phys. Rev. D24 (1981) 1232)

$K^+ \to \ell^+ N$: selection and final sample

- **Triggers**: the main $K_{\pi\nu\nu}$ for $K^+ \to e^+ N$, Control/400 for $K \to \mu^+ N$
- **Peak search** in the missing mass distribution $(P_K - P_\ell)^2$

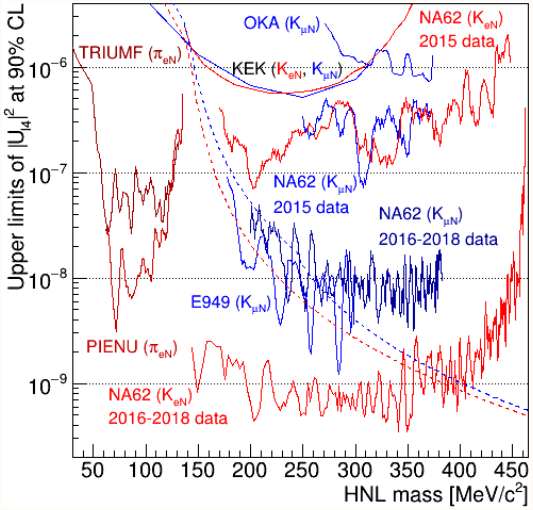




Electron $N_K = (3.52 \pm 0.02) \times 10^{12}$

Muon $N_K = (1.14 \pm 0.02) \times 10^{10}$

$K^+ \to \ell^+ N$: results

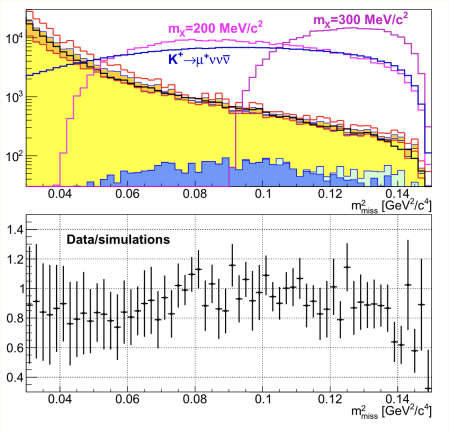


- **No signal observed**
- Full **2016-18** (Run1) data set is analyzed
- Improvement over earlier production searches by up to two orders of magnitude in terms of $|U_{\ell 4}|^2$
- For $|U_{e4}|^2$, the **BBN-allowed range** is excluded up to 340 MeV/c^2
- For $|U_{\mu 4}|^2$, **sensitivity** approaches the one of BNL-E949 in the range 200–300 MeV/c^2. The search extends to 383 MeV/c^2

(Phys.Lett.B 807 (2020) 135599)

(Phys.Lett.B 816 (2021) 136259)

$K^+ \to \mu^+\nu\nu\bar{\nu}$ and $K^+ \to \mu^+\nu X$



$K^+ \to \mu^+\nu\nu\nu$

- Very rare in the Standard Model, $BR : 1.62 \times 10^{-16}$ (J. High Energ. Phys. 2016, 39 (2016))
- The current experimental limit: $< 2.4 \times 10^{-6}$ (E949) (Phys. Rev. D 94, 032012)
- Search region $m^2_{miss} > 0.1\text{GeV}^2/\text{c}^4$ (optimized to extract stronger limit): U.L. 1.0×10^{-6} at 90% CL in the SM framework

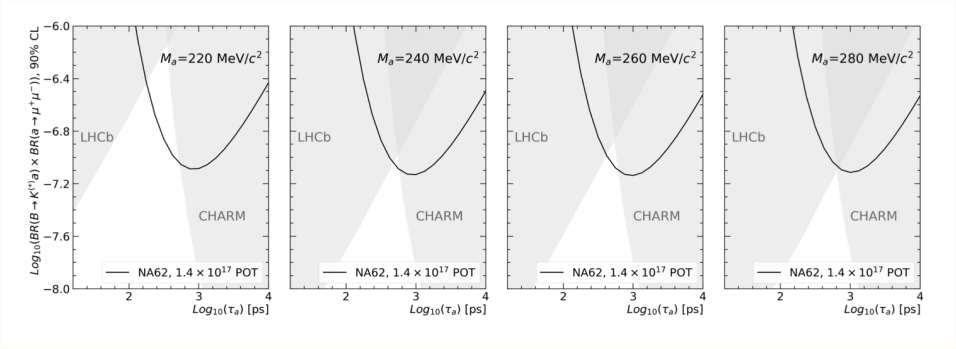
$K^+ \to \mu^+\nu X$, X is a scalar or vector

- X is a scalar or vector hidden sector mediator in the mass range 10–370 MeV/c
- Upper limits obtained at 90% CL on the decay branching fraction range from $\mathcal{O}(10^5)$ for low m_X values to $\mathcal{O}(10^7)$ for high m_X values

$$A' \to \ell^+ \ell^-$$

Model-independent limits on $a \to \mu^+\mu^-$ process

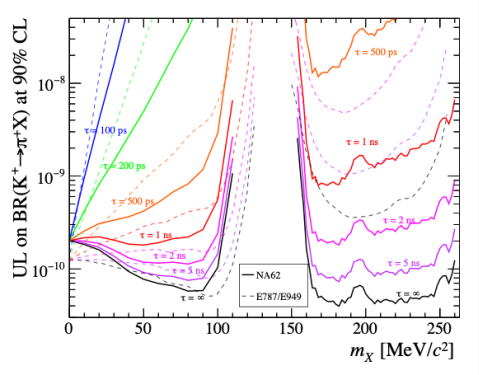
- Assume that a is a pseudoscalar(scalar) particle [Phys. Lett. B 790 (2019) 537]
- Assume mass M_a,lifetime τ_a and coupling to be independent parameters
- ◇ Set limits in $Br(B \to K^* a) \times Br(a \to \mu^+\mu^-)$ vs τ_a parameter space for each mass separately



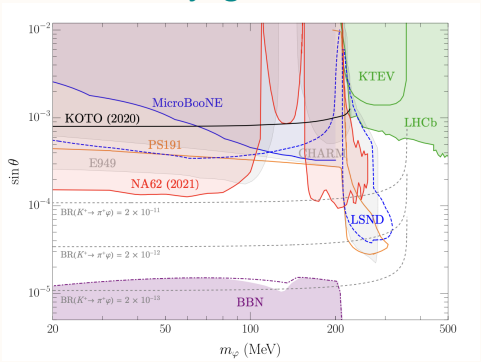
$K^+ \to \pi^+ X$ (Run1)

Search for $K^+ \to \pi^+ X$ (RUN1)

Upper Limits at 90% CL vs m_X for different lifetimes (τ)



Searches for long-lived dark scalar decaying into SM



(J. High Energ. Phys. 2021, 58 (2021))

Not only dark sector

- HNL production ($K^+ \to \ell^+ N$) with the 2016-18 data set:
  - ◇ Set limits on $|U_{e4}|^2$, at the level of 10^{-9} in the 144−462 MeV/c^2 mass range
  - ◇ Set limits on $|U_{\mu 4}|^2$, at the level of 10^{-8} in the 200−384 MeV/c^2 mass range

  (Phys.Lett.B 807 (2020) 135599 ,Phys.Lett.B 816 (2021) 136259)
- BR ULs at 90% C.L. of $O(10^{-11})$ for a variety of **LFV** and **LNV** processes were established (PLB 797 (2019) 134794, PRL 127 (2021) 131802, PLB 830 (2022) 137172, PLB 838 (2023) 137679)
- Precision measurements of rare K+ decays with the world's largest samples: $K^+ \to \pi^+\mu^+\mu^-$, $K^+\pi^0 e^+\nu\gamma$, $K^+ \to \pi^+\gamma\gamma$. (JHEP 11 (2022) 11), (arXiv:2304.12271)
- **HIKE** project (future kaon program at CERN SPS) is under discussion at CERN