Novel multi-lepton signatures in meson decays from MeV QCD axions and dark sectors

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invisibles
neutrinos, dark matter & dark energy physics

- **Several kaon decays with a high multiplicity of leptons have been neglected in the literature. Often no Standard Model prediction exists, and no experimental search has been carried out.**
- **Only KL -> 2(e+e-) channel has been previously discussed as an auxiliary measurement for the long-distance contribution in K -> μ+μ- decay [3]. This channel was measured at KTEV.**
- **Backgrounds to these channels are dominated by pion decay, requiring double-Dalitz or two simultaneous Dalitz decays.**

Kaon decay	predicted BR in SM	measured BR
$K_L \to 2(e^+e^-)$	3.65×10^{-8}	$(3.72 \pm 0.29) \times 10^{-8}$ $(3.67 \pm 0.40) \times 10^{-8}$
$K_L \to \pi^0\, 2(e^+e^-)$	N/A, expected $\mathcal{O}(10^{-10})$	No search
$K_L \to \pi^0\, 2(\nu e^+e^-)$	N/A	No search
$K^+ \to \pi^+\, 2(e^+e^-)$	N/A, expected $\mathcal{O}(10^{-10})$	No search
$K^+ \to \pi^+\, 2(\nu e^+e^-)$	N/A ($\ll 10^{-10}$)	No search

- **We point out that light dark sectors can contribute well above the SM rate and be detectable at NA62, e+e- colliders, and LHCb.**
- **Light dark particle pairs [1,2] appear as double e+e- resonances, arising either from decay cascades in the dark sector or from non-linear interactions (axion).**
- **Minimal model targets for these searches are higgsed U(1)′ dark sectors and an MeV QCD axion.**

TAKE HOME

1) Channels of kaon decays to four or more leptons never searched for.

2) Light dark sectors can dominate these decays, and may be detectable at NA62, KLOE, & LHCb.

3) Kaon decays to four and six lepton channels could robustly exclude a 17 MeV QCD axion.

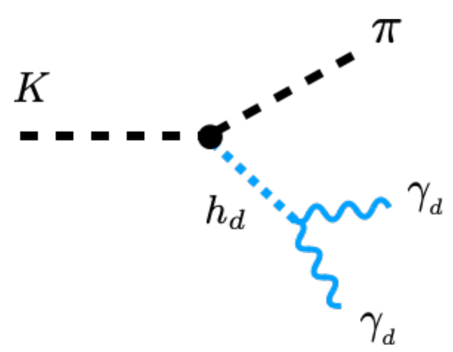
The Dark Higgs of a U(1)$_d$ symmetry

Consider a higgsed dark U(1)$_d$ symmetry with **vector and scalar mixing portals** to the Standard Model:

$$\mathcal{L}_{\rm DS} = |D^\mu \phi|^2 - \frac{1}{4}F_d^{\mu\nu}F_{d\,\mu\nu} - \frac{\varepsilon}{2}F_d^{\mu\nu}F_{\mu\nu} - \mu^2(\Phi^\dagger\Phi) - \lambda(\Phi^\dagger\Phi)^2 - \lambda_d(\Phi^\dagger\Phi)(H^\dagger H)$$

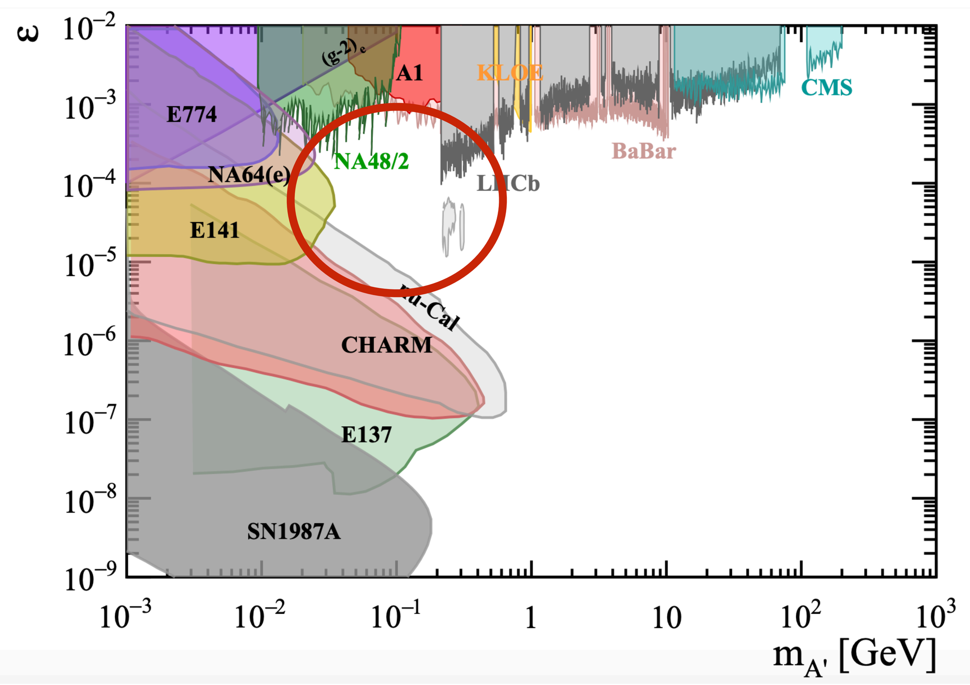
The dark higgs promptly decays to pairs of dark photons, which in turn decay to lepton pairs.

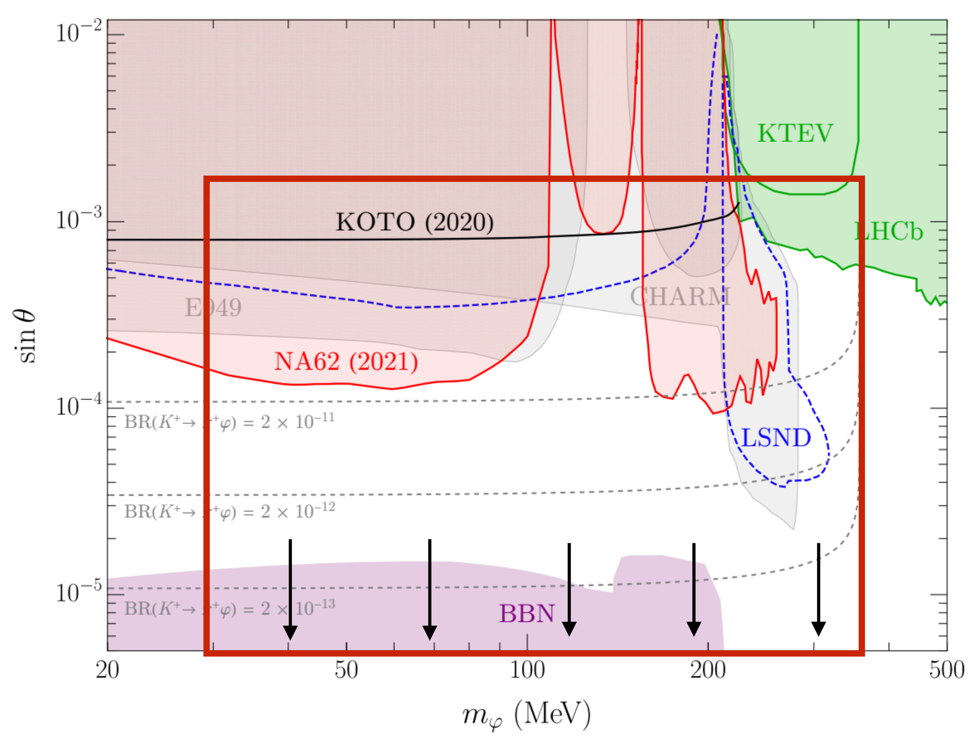
$$c\tau_{A'} \simeq 70\,\mu{\rm m}\left(\frac{2\times 10^{-4}}{\epsilon}\right)^2\left(\frac{30\text{ MeV}}{m_{\gamma_d}}\right)$$



Production is controlled purely by the scalar mixing with the Higgs, and the rate can exceed **Br ~ O(10^{-8} - 10^{-6}).**

$$\mathcal{B}\left(K^+ \to \pi^+ 2(e^+e^-)\right) \simeq 5\times 10^{-8}\left(\frac{s_\theta}{5\times 10^{-3}}\right)^2.$$

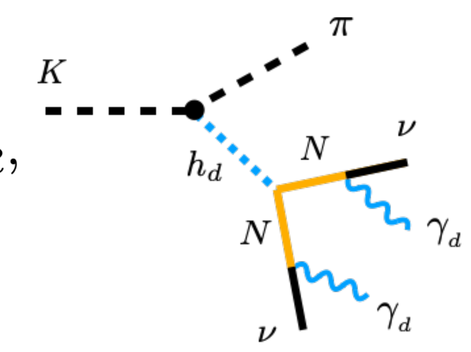




Dark photon and scalar parameter space of interest. Adapted from [4].

Dark fermions charged under the **U(1)$_d$ symmetry,** could also be produced, typically leading to missing energy. Consider, e.g. a dark inverse seesaw model:

$$\mathcal{L}_{{\rm DS}-\nu} = \overline{N_R}i\partial\!\!\!/ N_R + \overline{N_L}i D\!\!\!\!/ N_L + y_d\overline{N_L}\varphi N_R + y_\alpha \overline{L_\alpha}\widetilde{H}N_R,$$



Production via scalar mixing:

$$K \to \pi\, 2(\nu e^+e^-)$$

Production of N via neutrino mixing may be as large as Br~ O(10^{-6}):

$$K^+ \to \ell_\alpha\left(N \to \nu h_d \to \nu\gamma_d\gamma_d \to \nu 2(e^+e^-)\right)$$

A QCD axion at the MeV scale

A QCD axion at the MeV scale is not ruled out if it is "pionphobic" and "muonphobic" [4, 5]. A happy accident in the quark masses can strongly suppress mixing with pions:

$$\frac{Q_u}{Q_d} = 2 \quad \Rightarrow \quad \theta^{(0)}_{a\pi} \approx \frac{4Q_d}{3}\frac{f_\pi}{f_a}\left(\frac{1}{2} - \frac{m_u}{m_d}\right) \approx 0.$$

The MeV axion promptly decays to (e+e-) pairs, and can explain the ATOMKI anomaly if m_a = 17 MeV:

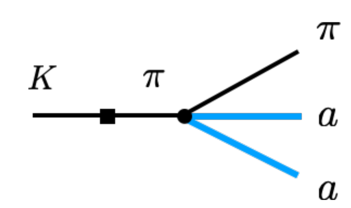
$$c\tau_a^0 \simeq \frac{1.2\,\mu{\rm m}}{(q^e_{PQ})^2}\left(\frac{17\text{ MeV}}{m_a}\right)\left(\frac{f_a}{1.03\text{ GeV}}\right)^2$$

While the pion mixing vanishes, we point out that **higher-order terms in the axion field are sizable.** The coefficients of these terms are fixed:

2nd: $\mathcal{L}_{aa\pi\pi} \supset \frac{m_a^2}{4F_\pi^2}aa\pi^0\pi^0 + \frac{m_a^2}{2F_\pi^2}aa\pi^+\pi^-$ **3rd:** $\mathcal{L}_{aaa\pi} \supset \frac{1}{6}\frac{m_a^2}{F_\pi f_a}a^3\pi^0$

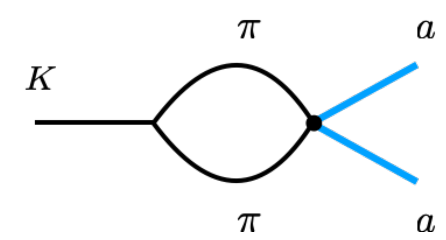
Clear target for NA62. Two peaks in $m_{ee} = m_a$.

$$\mathcal{B}(K^+ \to \pi^+ aa) \simeq 1.7\times 10^{-5}\times\left(\frac{m_a}{17\text{ MeV}}\right)^4$$



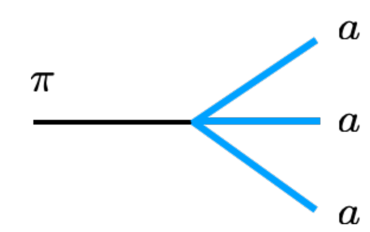
Target for Ks decays at LHCb and KLOE.

$$\mathcal{B}(K_{S,L} \to aa) \gtrsim \left(\frac{m_a}{17\text{ MeV}}\right)^4 \times \begin{cases} 2.6\times 10^{-7} & \text{for } K_S, \\ 7.2\times 10^{-10} & \text{for } K_L. \end{cases}$$



Predicts the **3rd largest BR of the π^0** with six leptons. Never searched for, but BR is even larger than π_{DD}.

$$\mathcal{B}(\pi^0 \to 3a)\big|_{m_a = 17\text{ MeV}} = 1.0\times 10^{-3}$$



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