The axion-down-strange-coupling from ultrarare Kaon decay data

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Based on arXiv:2503.05865 in collaboration with
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Introducing the axion and Axion-Like-Particles

Axions are light pseudo-Goldstone Bosons
suggesting a very high new effective scale f_a

$$m_a = 6\ \mu\text{eV} \times \frac{10^{12}\text{GeV}}{f_a}$$

Motivation

- Elegantly solves the Strong CP problem;
- and the Dark Matter problem

ALPs are a generalization of the axion, where the relation between m_a and f_a is relaxed

Chiral Perturbation Theory + *a*

Meson dynamics is calculable thanks to ChPT, a consistent EFT based on the global chiral symmetries of QCD

Generalization to ChPT + a, by including a dynamical axion [Georgi, Kaplan & Randall, PLB (1986)]

$U \equiv \pi$ field in the CCWZ formalism

$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2 f_a} (\bar{q}\, \gamma^\mu \hat{k}_V\, q + \bar{q}\, \gamma^\mu \gamma_5 \hat{k}_A\, q)$$

$q = (u, d, s)^T$

Fundamental couplings of the axion to light quarks

UV couplings

$$\hat{k}_{V,A} = k_{V,A} + 2\, c_{GG} Q_{V,A}$$

Shift induced by an axion dependent quark field redefinition:

$$q \to e^{-i(Q_V + Q_A \gamma_5) c_{GG} \frac{a}{f_a}}\, q$$

Chiral Perturbation Theory + *a*

About the UV couplings:

$$k_{V,A} = \begin{pmatrix} k_{11} & 0 & 0 \\ 0 & k_{22} & k_{23} \\ 0 & \bar{k}_{23} & k_{33} \end{pmatrix}_{V,A}$$

charge conservation

Axion mediated FCNC (s – d)

Chiral Perturbation Theory + *a*

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Generalization to ChPT + a, by including a dynamical axion [Georgi, Kaplan & Randall, PLB (1986)]

$U \equiv \pi$ field in the CCWZ formalism

$x^b_{V,A} = x^b_{V,A}(\hat{k}_{V,A})$

$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2 f_a} \left(\bar{q}\, \gamma^\mu \hat{k}_V\, q + \bar{q}\, \gamma^\mu \gamma_5 \hat{k}_A\, q \right) \longrightarrow \mathcal{L}_{aU} = \frac{\partial_\mu a}{f_a} \left(x^a_V \mathcal{J}^{b\mu}_V + x^a_A \mathcal{J}^{b\mu}_A \right)$$

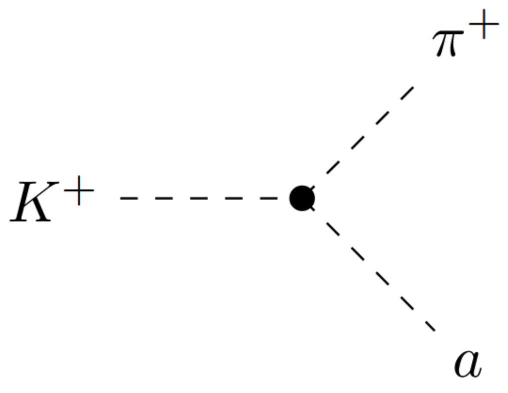
$q = (u, d, s)^T$

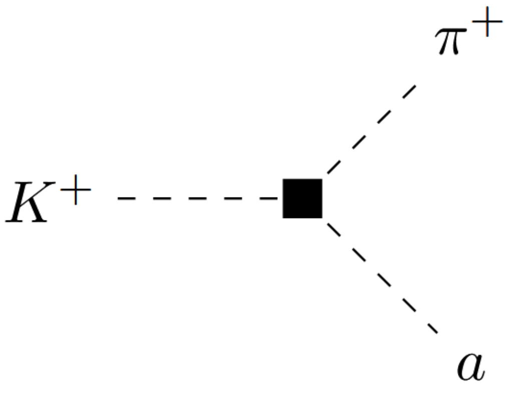
Vectorial and axial currents, functions of the meson fields

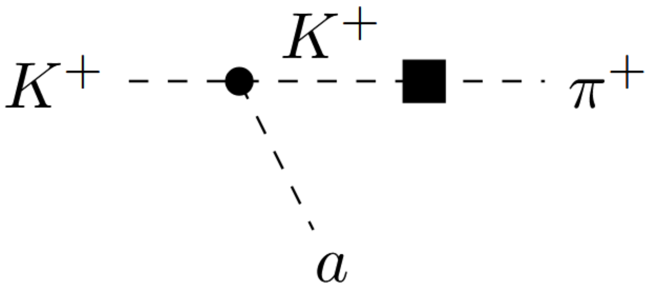
$K^+ \to \pi^+ a$

Strong contribution (●)

- $\propto (k_V)_{23}$
- Dominant in general







Weak contribution (■)

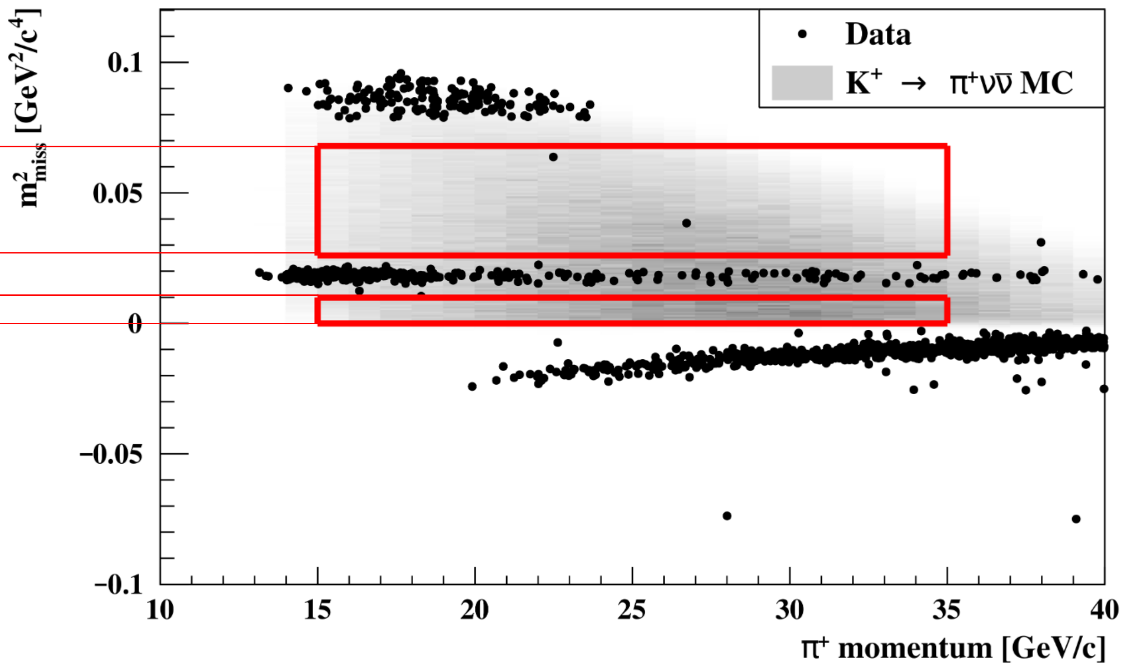
- Parametrically suppressed by $F_0^2 G_F \sim 10^{-7}$
- Hence relevant only if $(k_V)_{23}$ is tiny by assumption

Reinterpretation of NA62 data

NA62 reconstructs the missing invariant mass $m^2_{miss} = (p_K - p_\pi)^2$

Region 2

Region 1



The search focused on 2 regions above and below the $K^+ \rightarrow \pi^+\pi^0$ peak.

We cover two mass ranges: $[0,\ 100]$ MeV and $[160,\ 260]$ MeV

Image taken from arXiv:2007.08218

Reinterpretation of NA62 data

An intuitive estimate of the achievable limit can be obtained as the uncertainty on the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

$$\delta\mathcal{B}_{\nu\bar{\nu}} = 3 \times 10^{-11}$$

Procedure presented in « Probing QCD Axions or ALPs in tree-body K Decays » – M. Cavan-Piton, D. Guadagnoli, A. Iohner, D. Martínez Santos, L. Vittorio

More rigorously: we construct an unbinned profile Likelihood test with $K^+ \rightarrow \pi^+ a$ as the signal over a background including $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

The Likelihood terms

$$\mathcal{L} = \mathcal{P}(n_{tot}, n_{obs}) \times \prod_{j=1}^{n_{obs}} \left(\frac{n_b}{n_{tot}} g_b(m_j^2) + \frac{n_a}{n_{tot}} g_a(m_j^2) \right) \times \mathcal{L}_3$$

First term: Poisson distribution for the total number of events

Second term: distribution for background and signal events numbers

- Background includes $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
  - Polynomial function
- Gaussian for signal

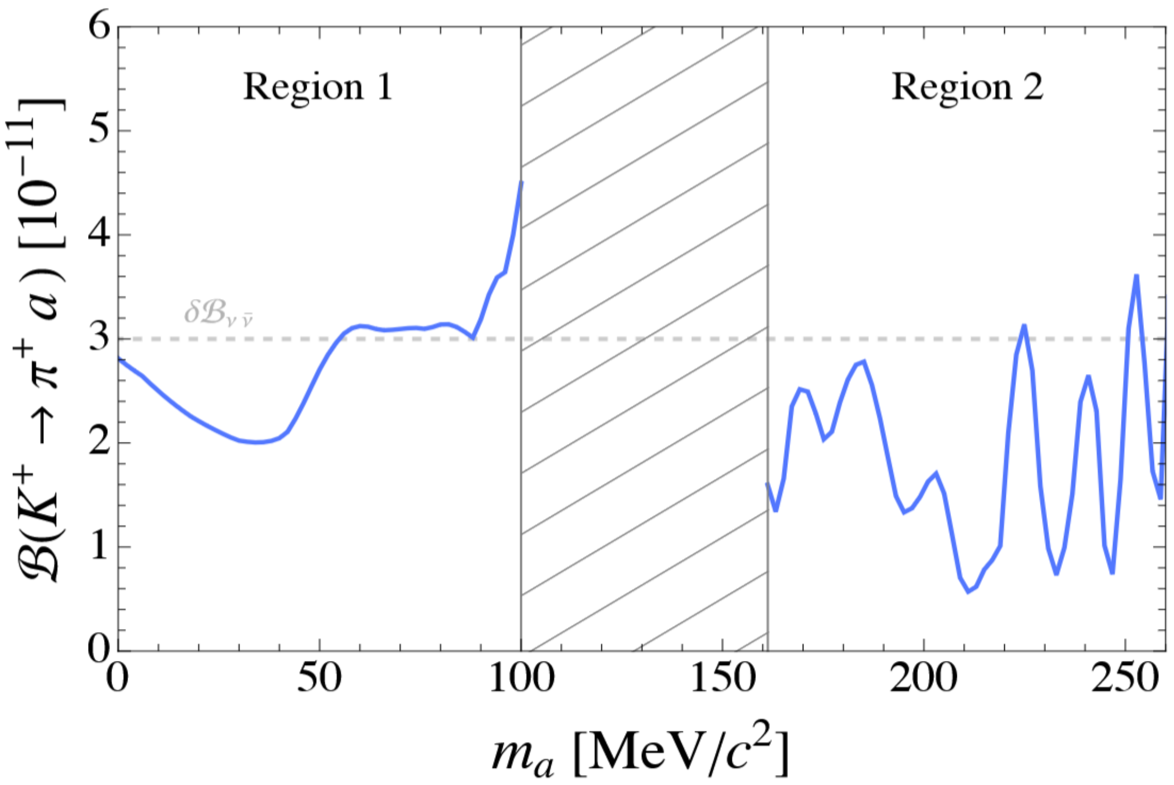
Third term: binomial distribution obtained from n_{tot} with known average

Branching ratio limit

Likelihood function constructed solely with public data + assumptions inferred from public information

At $m_a = 0$ (QCD axion), we find

$$\mathrm{BR}(K^+ \to \pi^+ a)_{m_a=0} < 2.8 \times 10^{-11}$$



Strong amplitude: Constraint on $|k_V|_{23}$

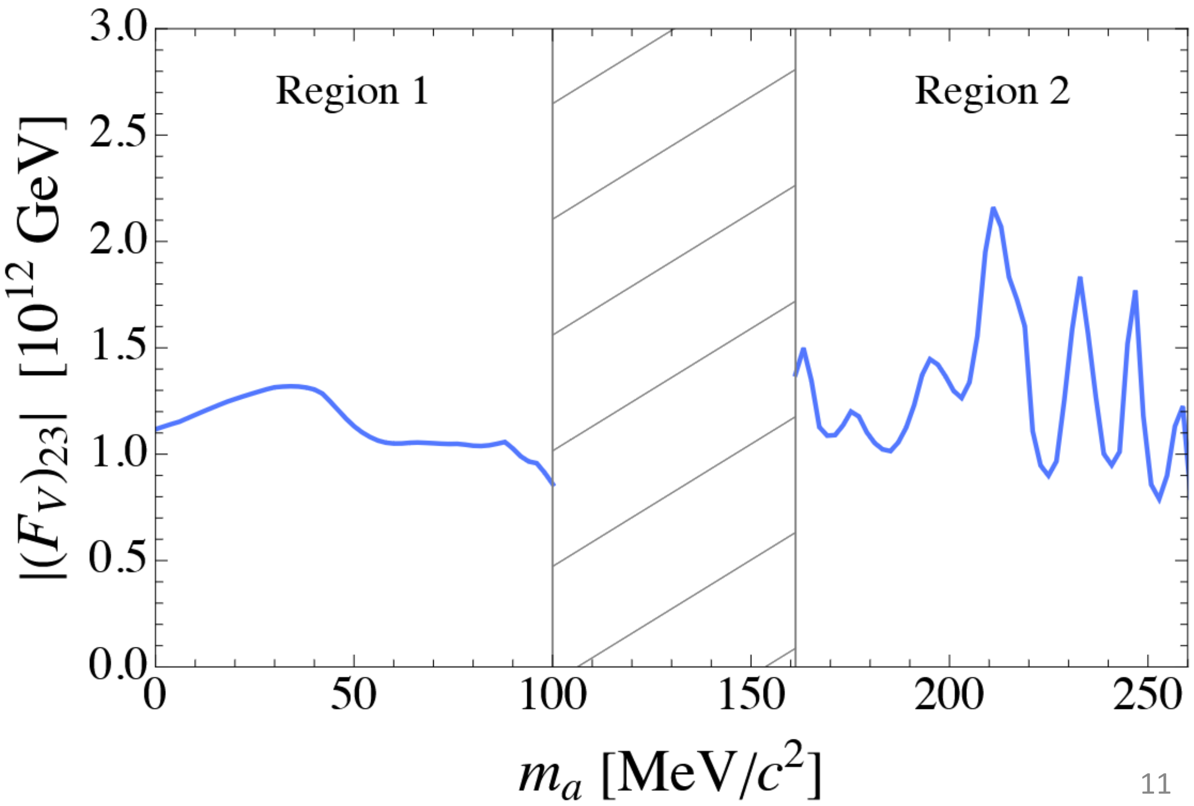
$$(F_V)_{23} = 2\frac{f_a}{(k_V)_{23}}$$

(Camalich et al. arXiv:2002.04623)

In terms of the coupling-rescaled f_a,
The limit reads ($m_a = 0$)

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

(Current bound: $|(F_V)_{23}| > 6.8 \times 10^{11}$ GeV)



Weak amplitude: model-independent constraint on f_a

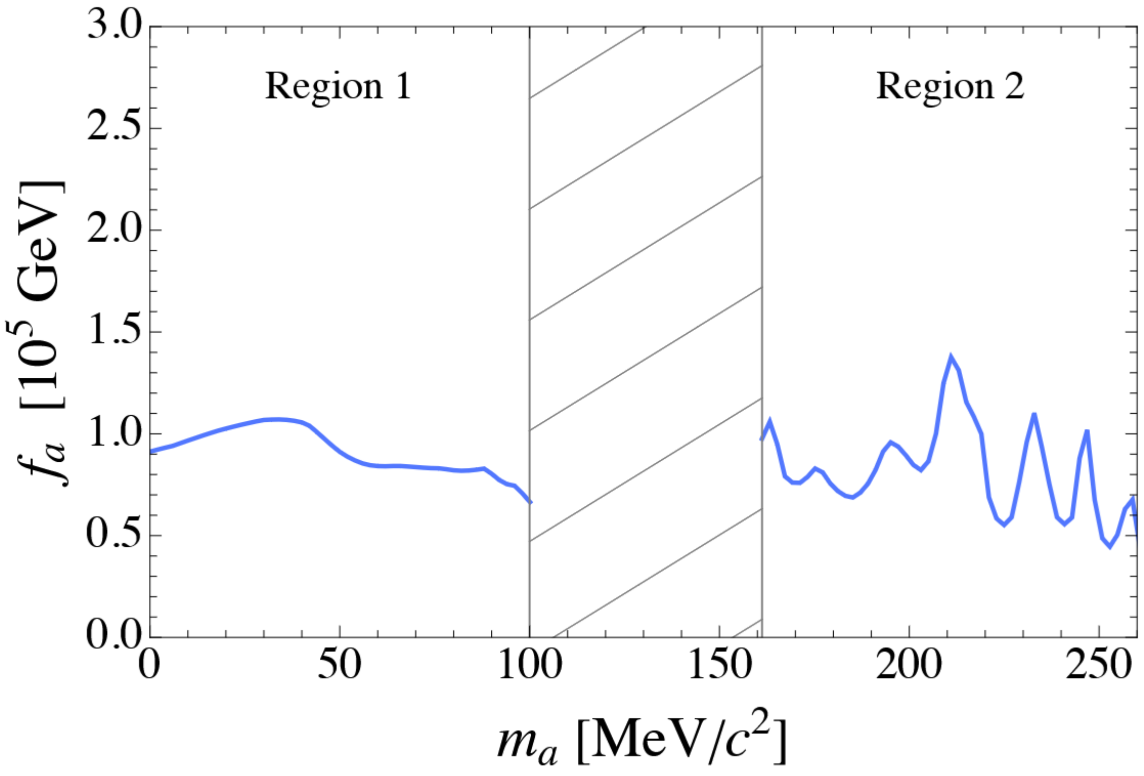
If the strong amplitude is negligible by assumption, signal dominated by weak amplitude

$$A_{weak} \propto 4c_{GG} + \sum_{i=1}^{3}(C_{V_i}(k_V)_{ii} + C_{A_i}(k_A)_{ii})$$

The s-to-d transition is a SM penguin, so we infer a model-independent bound on f_a

$$f_a \text{ (GeV)} > \{1.4, 1.2, 1.0\} \cdot 10^5$$

1.4: data-driven; 1.2: DFSZ; 1.0: KSVZ



Conclusion and outlook

Kaon decays to pions + invisible at NA62 represent a strong test of the QCD axion, in a controlled environment

- From $K^+ \rightarrow \pi^+\nu\bar{\nu}$ interpreted as $K^+ \rightarrow \pi^+ a$, we find:

$$|(F_V)_{23}| > 1.1 \times 10^{12} \text{ GeV} ; f_a > 10^5 \text{ GeV}$$

- Adding a pion (namely $K^+ \rightarrow \pi^+\pi^0 a$) allows access to the $(k_A)_{23}$ coupling

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

Thank you for your attention!