New bound on the vectorial axion-down-strange coupling from $K^+ \to \pi^+\nu\bar{\nu}$ data at NA62

Claudio Toni

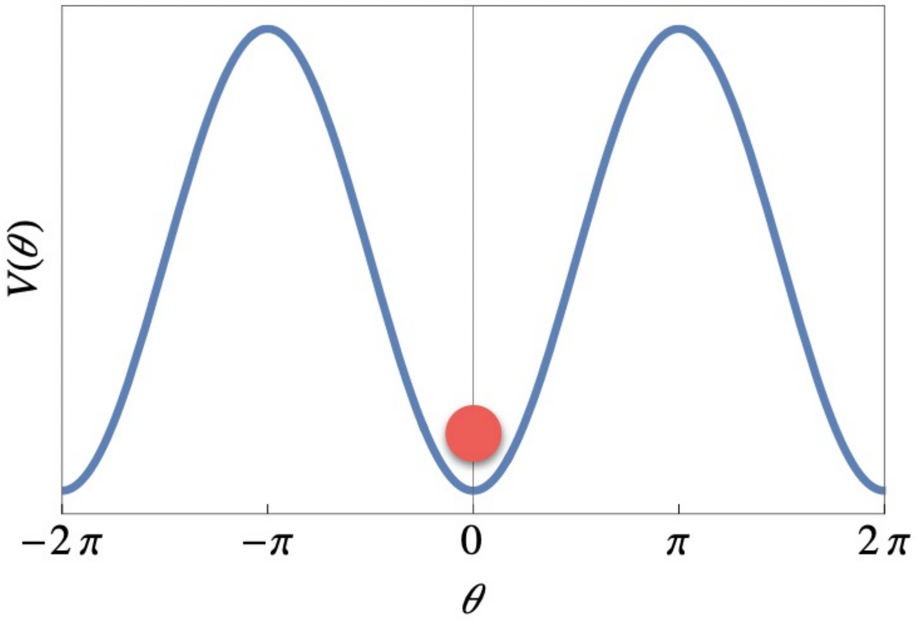
based on arXiv:2503.05865 in collaboration with Diego Guadagnoli, Axel Ionher, Cristina Lazzeroni, Diego Martinez Santos and Joel Swallow

Strong CP problem

- Strong CP problem is a puzzle of the SM: $$\mathcal{L}_\theta = \frac{g^2\theta}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad |\theta| \lesssim 10^{-10}$$

- θ promoted to a dynamical field: $\theta \to \dfrac{a}{f_a}$

- QCD potential relaxed *dynamically* to zero:



QCD Axion and ALPs

- The QCD axion is the pseudo-Goldstone boson of a Peccei-Quinn (PQ) U(1) symmetry anomalously broken by QCD:

$$\mathrm{SU}(3)^2_{\mathrm{QCD}} \times \mathrm{U}(1)_{\mathrm{PQ}} \quad \Longrightarrow \quad \mathscr{L}_a \supset \frac{\alpha_s}{4\pi}\frac{a}{f_a} G\tilde{G}$$

- QCD potential relaxes *dynamically* to zero and induces an axion mass:

$$m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2} \quad \Longrightarrow \quad m_a \simeq 5.7 \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right) \mu\mathrm{eV}$$

Axion-like particles (ALPs) are a generalization of the axion with uncorrelated mass m_a and effective scale f_a, thus not providing any solution to the Strong CP problem.

Axion couplings to quarks

- Axion couplings to quarks are allowed by the SM symmetries:

$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2 f_a} \left(\bar{q}\,\gamma^\mu k_V\, q + \bar{q}\,\gamma^\mu \gamma_5 k_A\, q \right) + c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f_a} G\tilde{G}$$

where at low energies $q = \begin{pmatrix} u & d & s \end{pmatrix}^T$

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

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Axion mediated
$s \rightarrow d$ transitions

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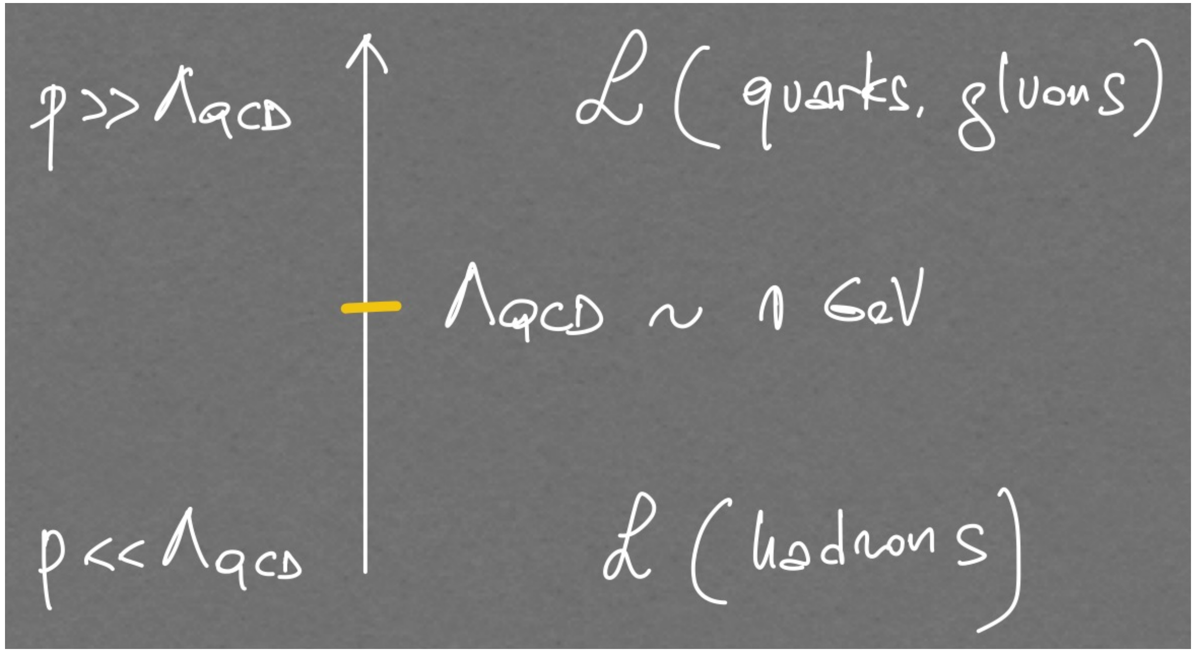

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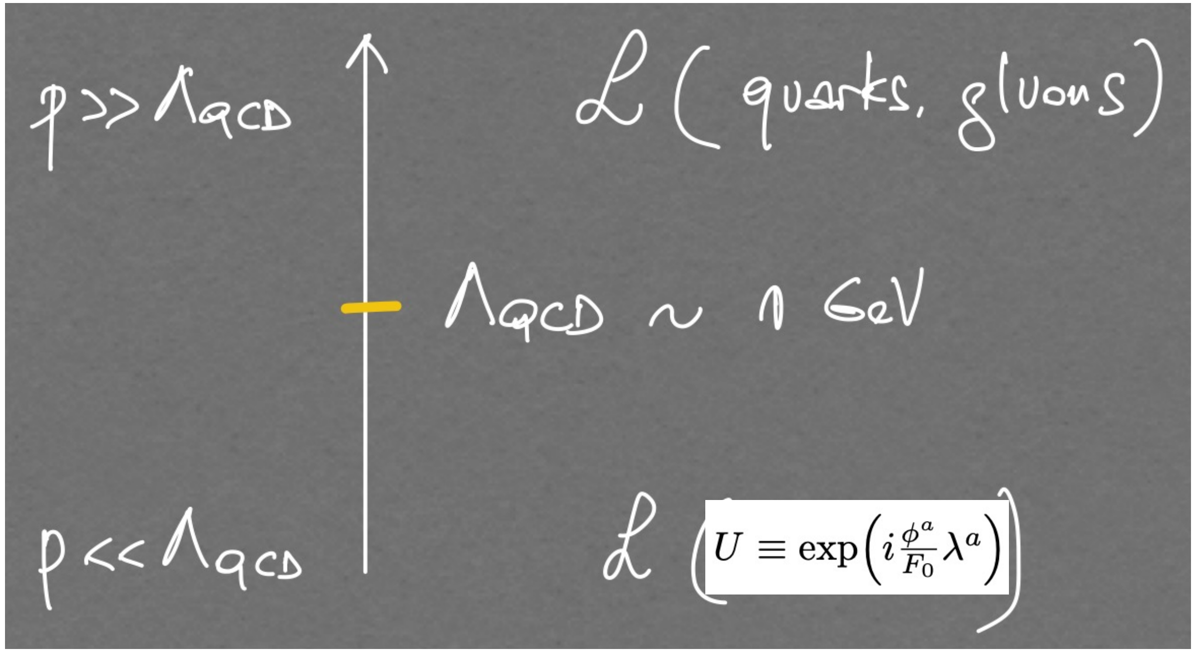

- Chiral perturbation theory (ChPT) is an effective description of hadronic degrees of freedom based solely on the QCD global symmetries:

$$\mathscr{L}_s = \frac{F_0^2}{4}\left(\mathrm{Tr}\, D_\mu U (D^\mu U)^\dagger + 2B_0\, \mathrm{Tr}\left(\hat{M}_q U + U^\dagger \hat{M}_q^\dagger\right)\right)$$

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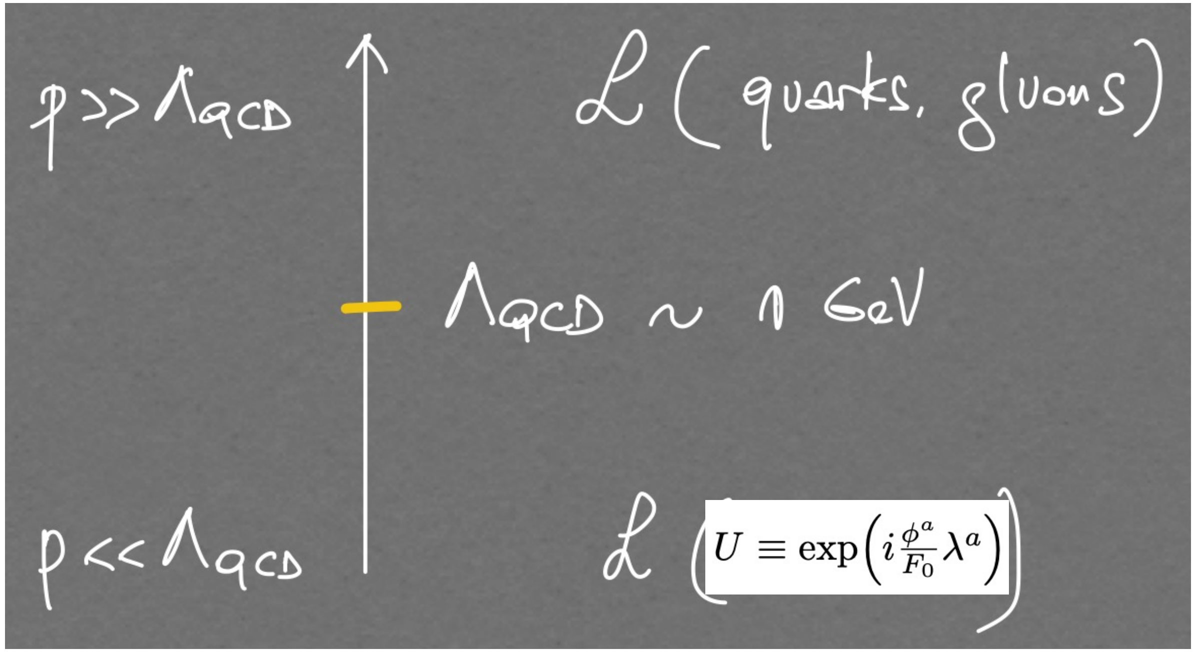

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- Following Georgi, Kaplan & Randall (PLB, 1986):

$$D_\mu U = \partial_\mu U - i\frac{\partial_\mu a}{f_a}\left(\hat{k}_R(a)\, U - U\, \hat{k}_L(a)\right)$$

$$\hat{M}_q = \exp\left(-2ic_{GG}\frac{a}{f_a}\kappa\right) M_q$$

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

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Strong contribution

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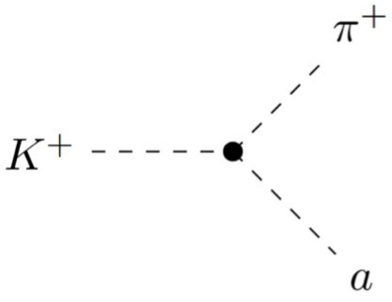

$\propto (k_V)_{23}$

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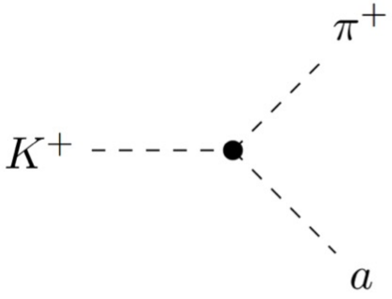

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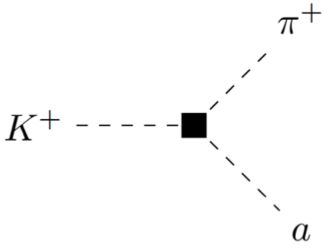
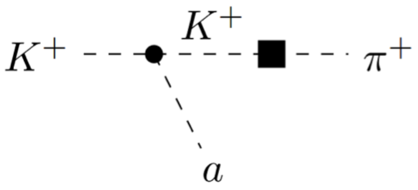
<u>Weak contribution</u>

$$\mathscr{L}_w = -\frac{4G_F}{\sqrt{2}}(V_{\mathrm{CKM}})_{11}^*(V_{\mathrm{CKM}})_{12}\, g_8\, (L_\mu L^\mu)^{32} + \mathrm{h.c.}$$

- The decay is mediated by weak interactions and it is suppressed by the Fermi constant:





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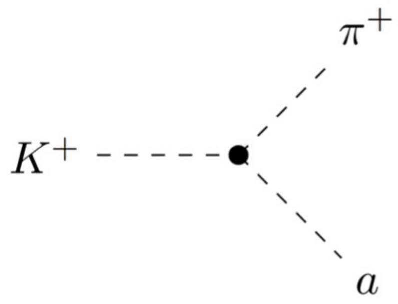

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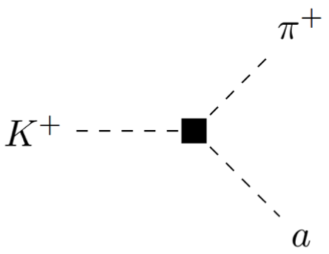
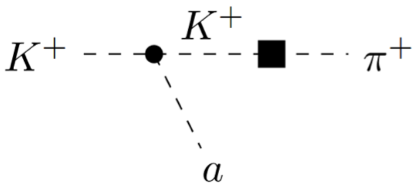
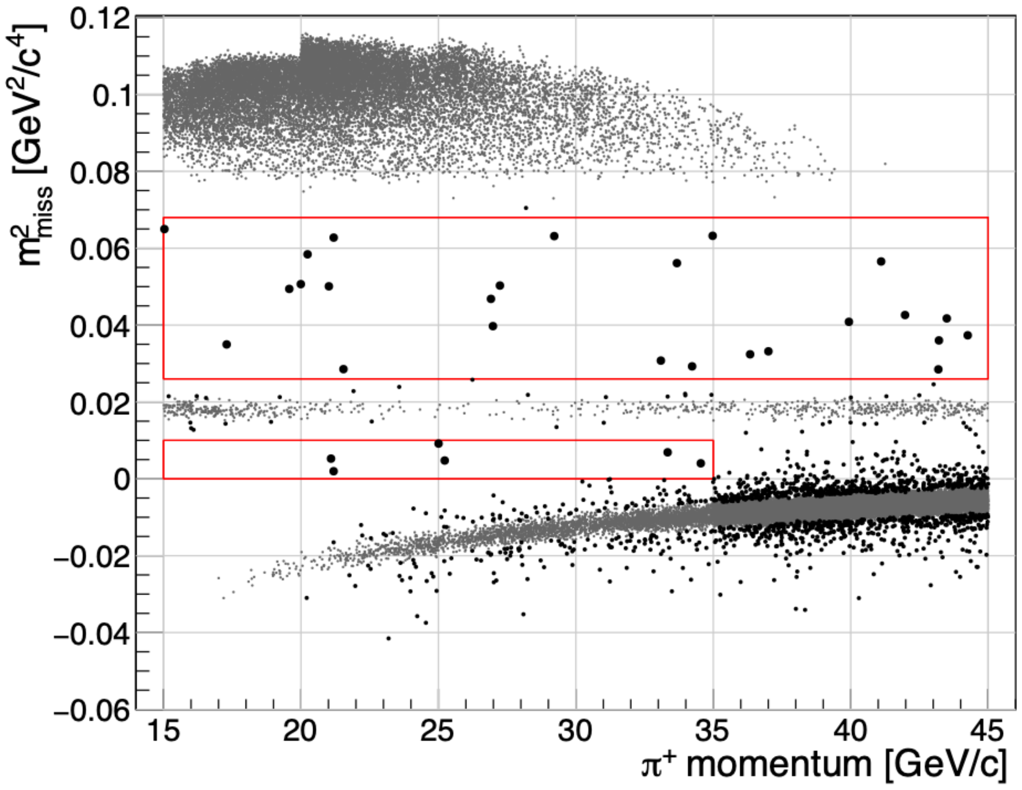


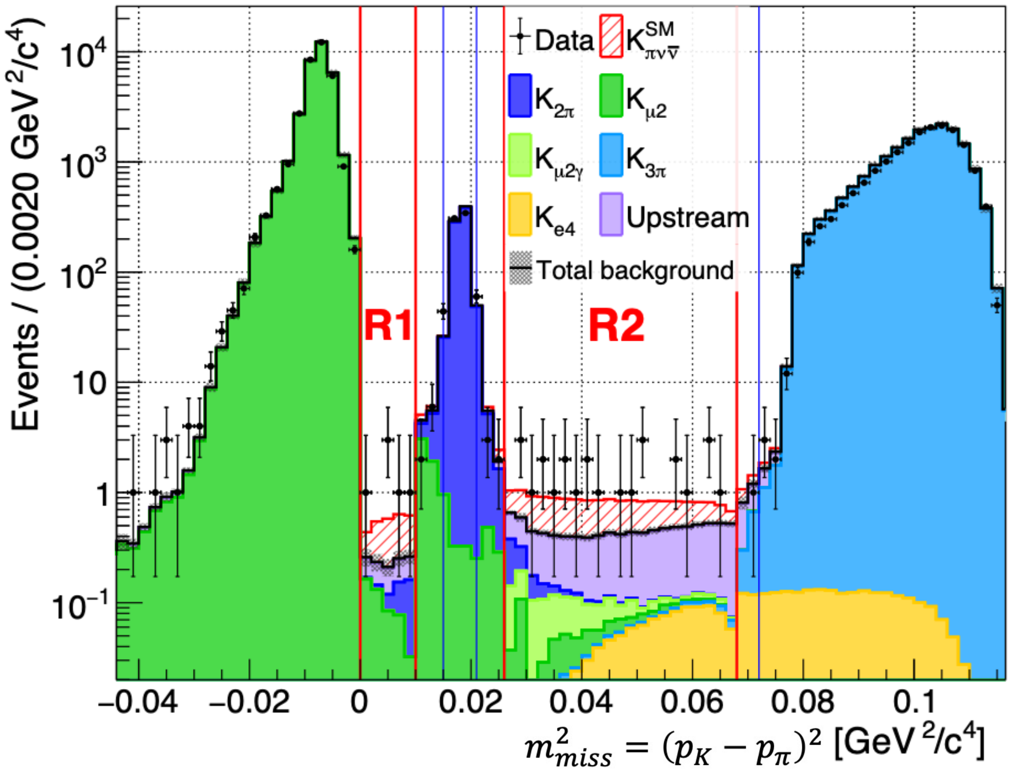


Unless $(k_V)_{23} < O(10^{-7})$, the weak contribution is completely negligible compared to the strong one.

$K^+ \to \pi^+ a$ at NA62

If the axion decays invisible, the experimental signature of such decay is the same of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay whose search is performed at NA62.





2021-2022 data from [NA62 coll., arXiv:2412.12015]

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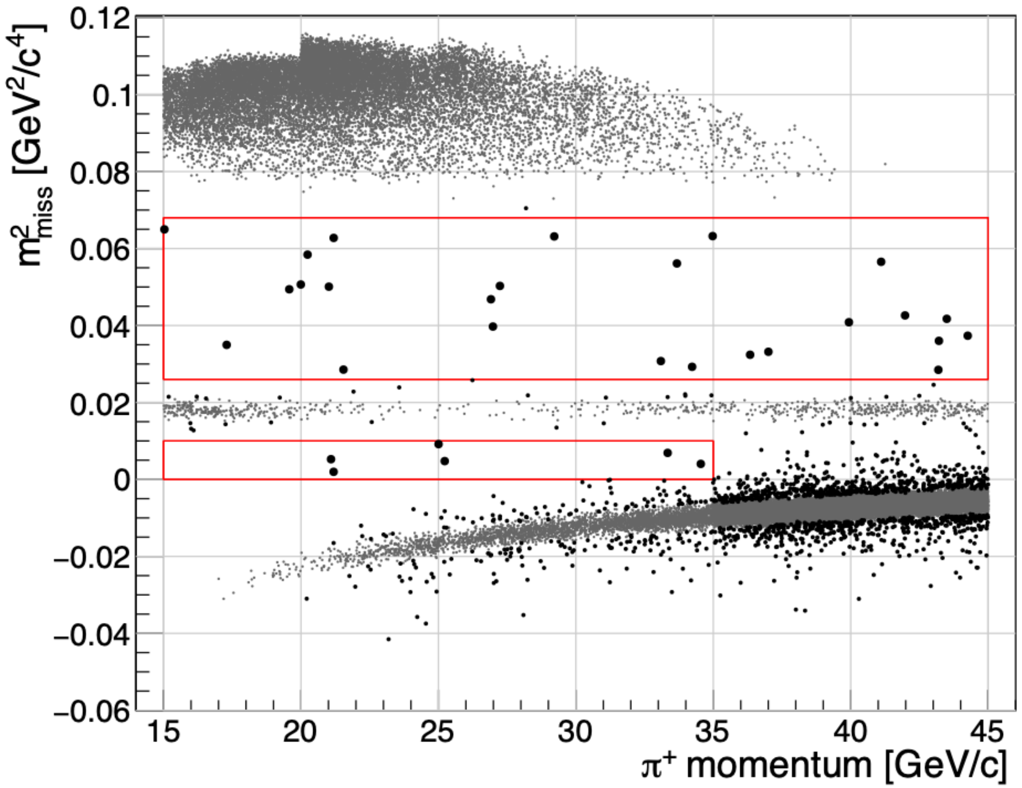

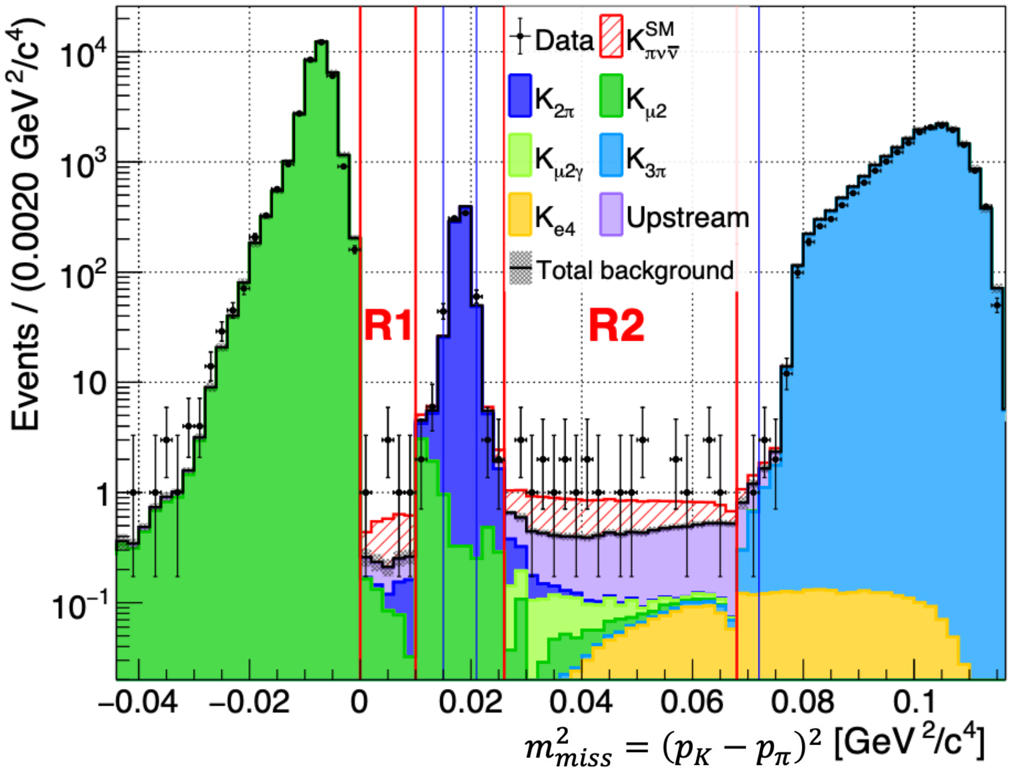

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The question is: can we get a bound on the axion couplings from the NA62 data available to us?

Reinterpretation of NA62 public data

To do so, we perform an unbinned profile likelihood ratio test statistic, based solely on public data, following the same procedure used in the past by the collaboration itself (see [NA62 coll., arXiv:2011.11329]).

$$\mathcal{L} = \frac{(n_{\rm tot})^{n_{\rm obs}}}{n_{\rm obs}!} e^{-n_{\rm tot}} \times \prod_{j=1}^{n_{\rm obs}} \left[\frac{n_b}{n_{\rm tot}} g_b(m^2_{{\rm miss},j}) + \frac{n_a}{n_{\rm tot}} g_a(m^2_{{\rm miss},j}) \right] \times \frac{(\tau n_b)^{n_{\rm off}}}{n_{\rm off}!} e^{-\tau n_b}$$

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  - $g_b(m^2)$ is a normalized pdf digitized from public plot of [NA62 coll., arXiv: 2412.12015].
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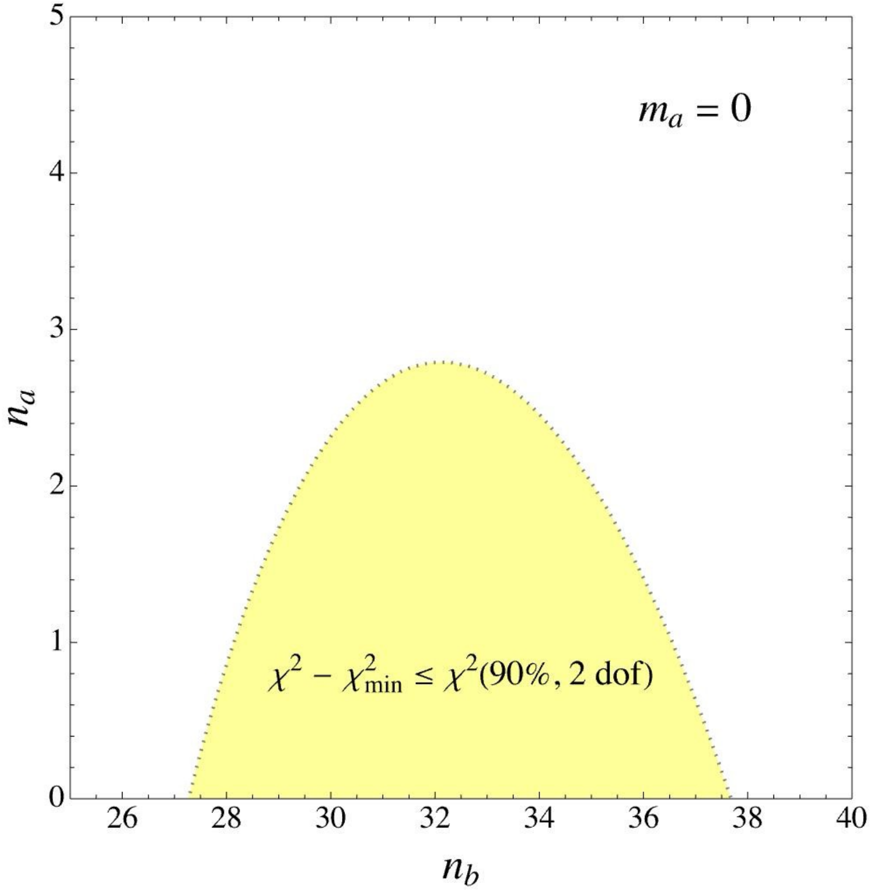
- Third term: Poisson-like distribution constraining the number of backgrounds events from mean value μ_b and uncertainty σ_b estimated from NA62 with:

$$\tau = \mu_b/\sigma_b^2 \text{ and } n_{\rm off} = (\mu_b/\sigma_b)^2$$

Bound on axions from NA62 public data

Minimizing $\chi^2(n_b, n_a) \equiv -2\log\mathcal{L}$, and demanding $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\rm min} = \chi^2(90\%, 2\text{ dof})$ we obtain a limit on $\mathcal{B}(K^+ \to \pi^+ a)$ as a function of m_a.



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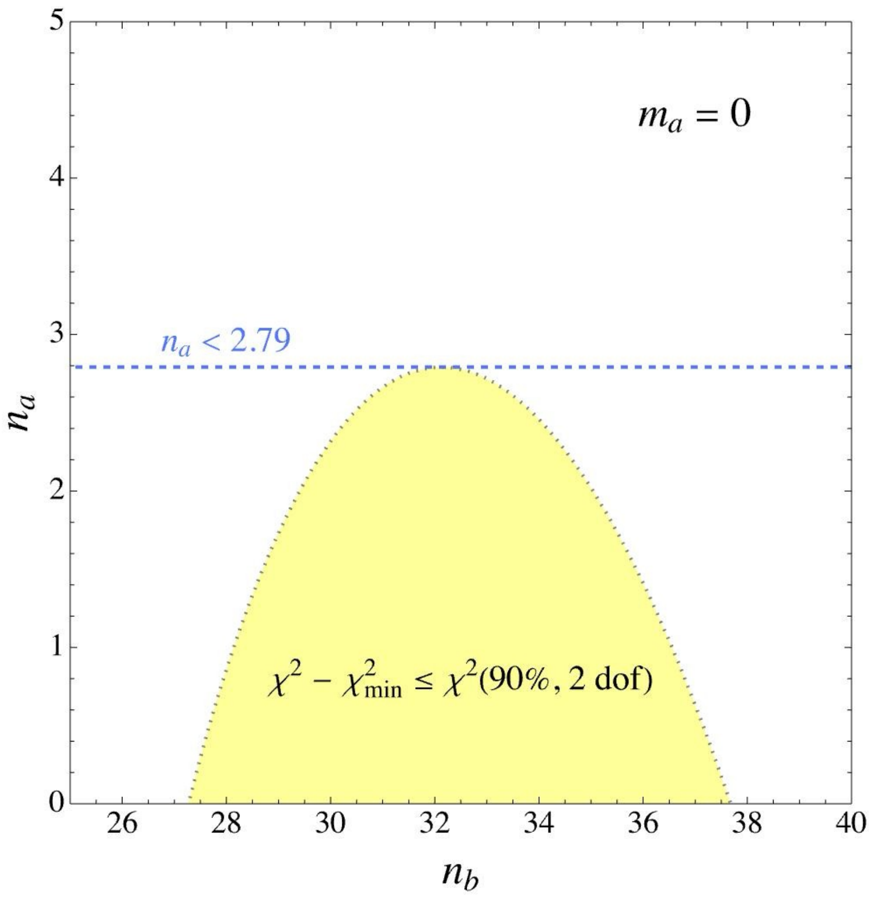

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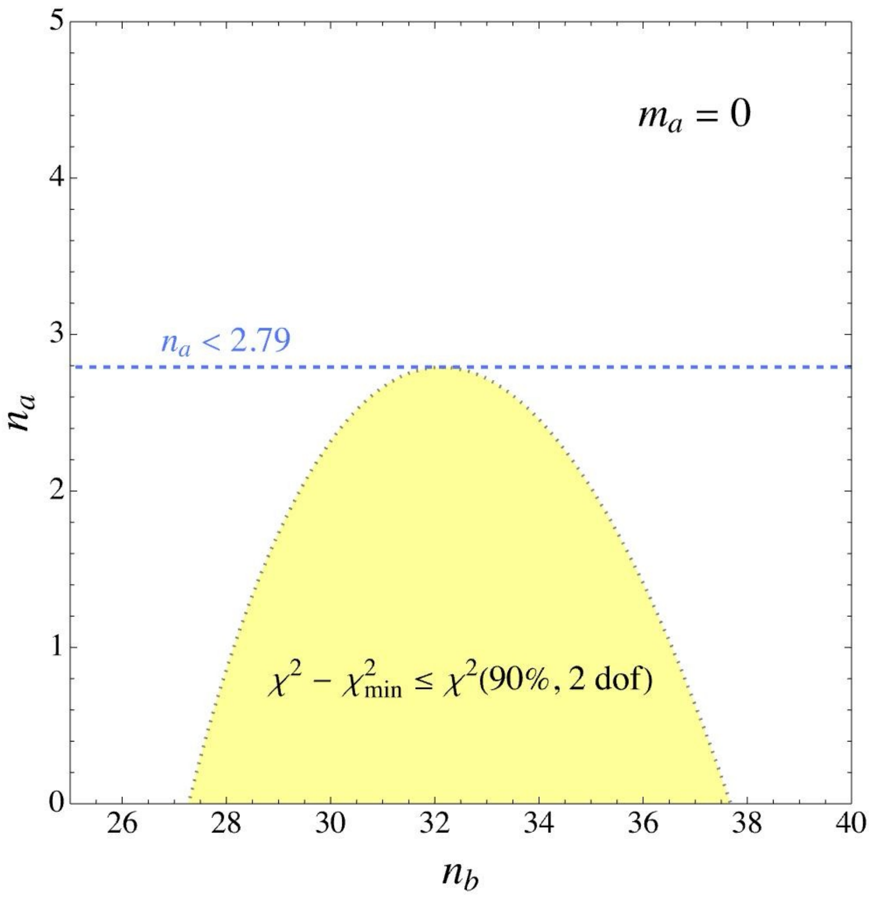
- The number of axion mediated events is related to the $K^+ \to \pi^+ a$ branching ratio (BR) trough the single event sensitivity (SES):

$$\mathcal{B}(K^+ \to \pi^+ a) = n_a \times \mathcal{B}_{\rm SES}$$

- $\mathcal{B}_{\rm SES} = \mathcal{B}_{\rm SES}(m_a)$ is taken from [NA62 coll., arXiv:2011.11329] for the 2017 data and rescaled according to by a factor equal to the ratio of the $K^+ \to \pi^+ \nu\bar{\nu}$ SESs



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

Bound on axions from NA62 public data

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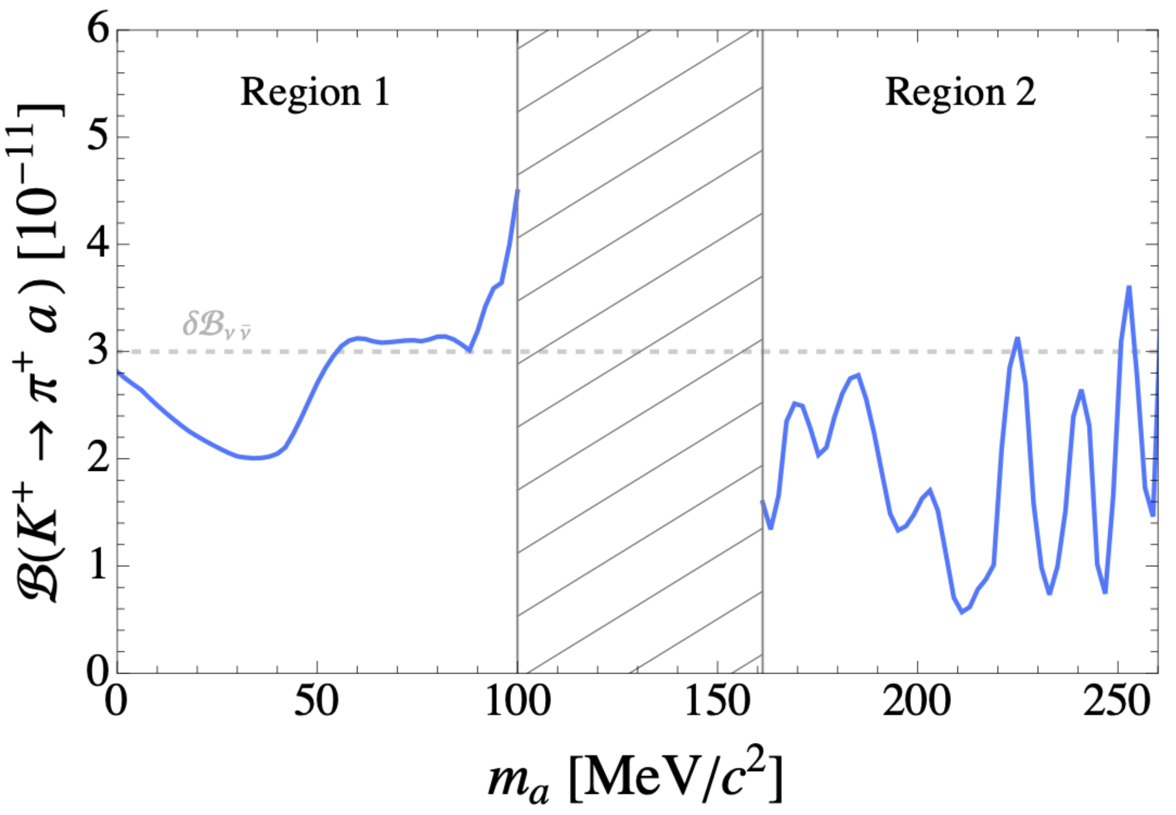


Bound on axion-down-strange coupling

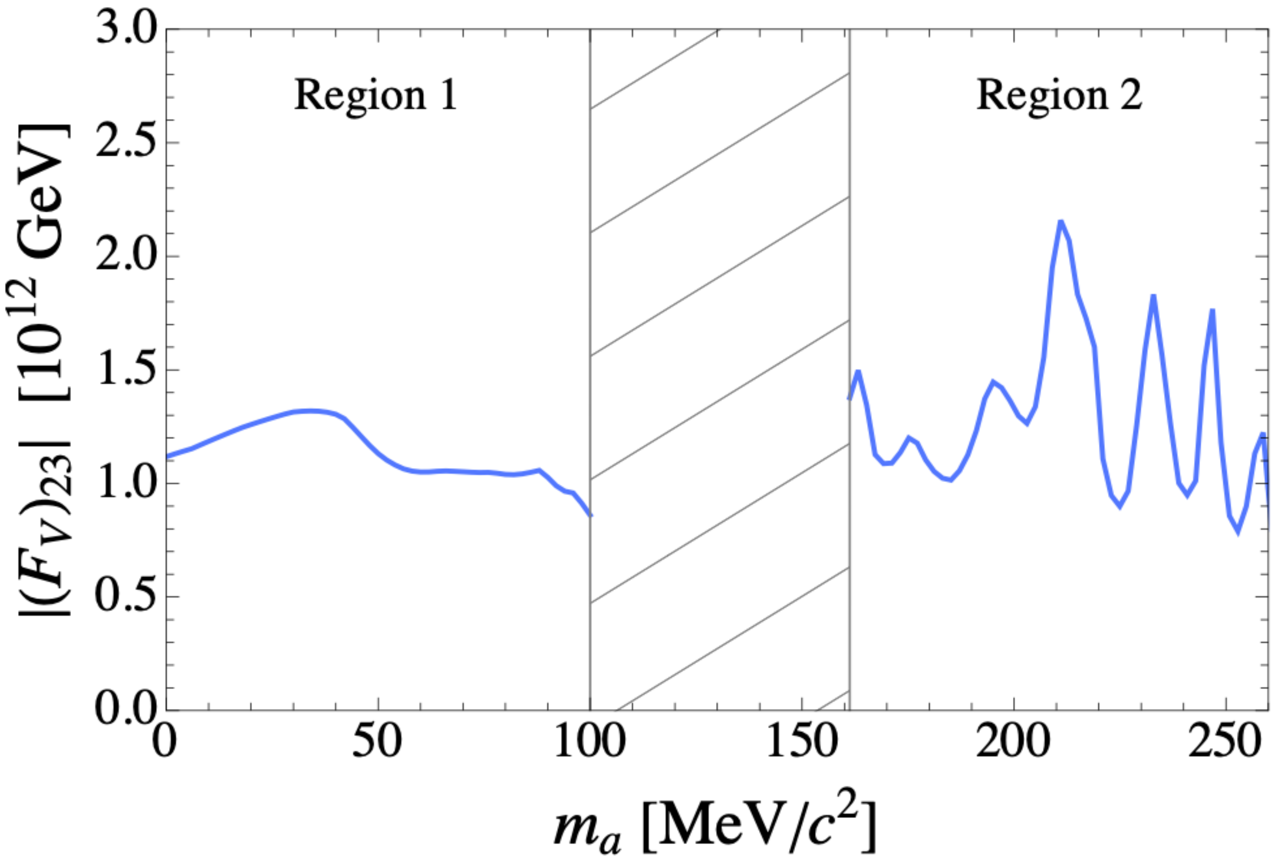
The current bound for a massless axion reads [Camalich et al., arxiv:2002.04623]:

$$(F_V)_{23} \equiv \frac{2f_a}{(k_V)_{23}} > 6.8 \times 10^{11} \text{ GeV at } 90\% \text{ C.L.}$$

At $m_a = 0$ we get

$$(F_V)_{23} > 1.1 \times 10^{12} \text{ GeV at } 90\% \text{ C.L.}$$

A factor of ~2 of improvement!



Conclusions

Meson decays with missing energy are a powerful probe of the QCD axion in a controlled environment.

- In this talk we present a reinterpretation of the $K^+ \to \pi^+ \nu\bar{\nu}$ search at NA62 to constraint the $K^+ \to \pi^+ a$ decay:

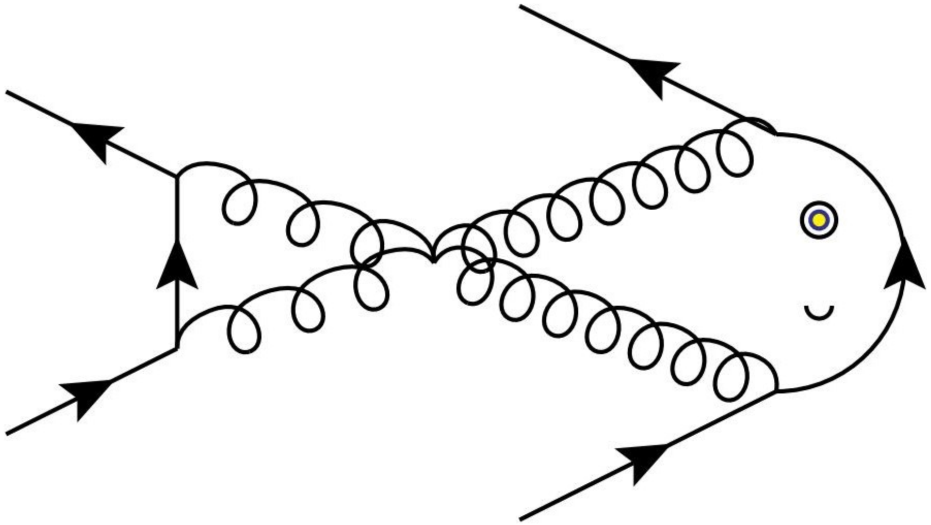
$$\mathcal{B}(K^+ \to \pi^+ a) < 2.8 \times 10^{-11} \text{ at } 90\% \text{ C.L.}$$

- In terms of couplings, we get:

$$(F_V)_{23} > 1.1 \times 10^{12} \text{ GeV at } 90\% \text{ C.L.}$$

- A similar study of $K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$ would allow to constraint also $(k_A)_{23}$ coupling.

The End



THANK YOU FOR THE ATTENTION!

Crosschecks with NA62

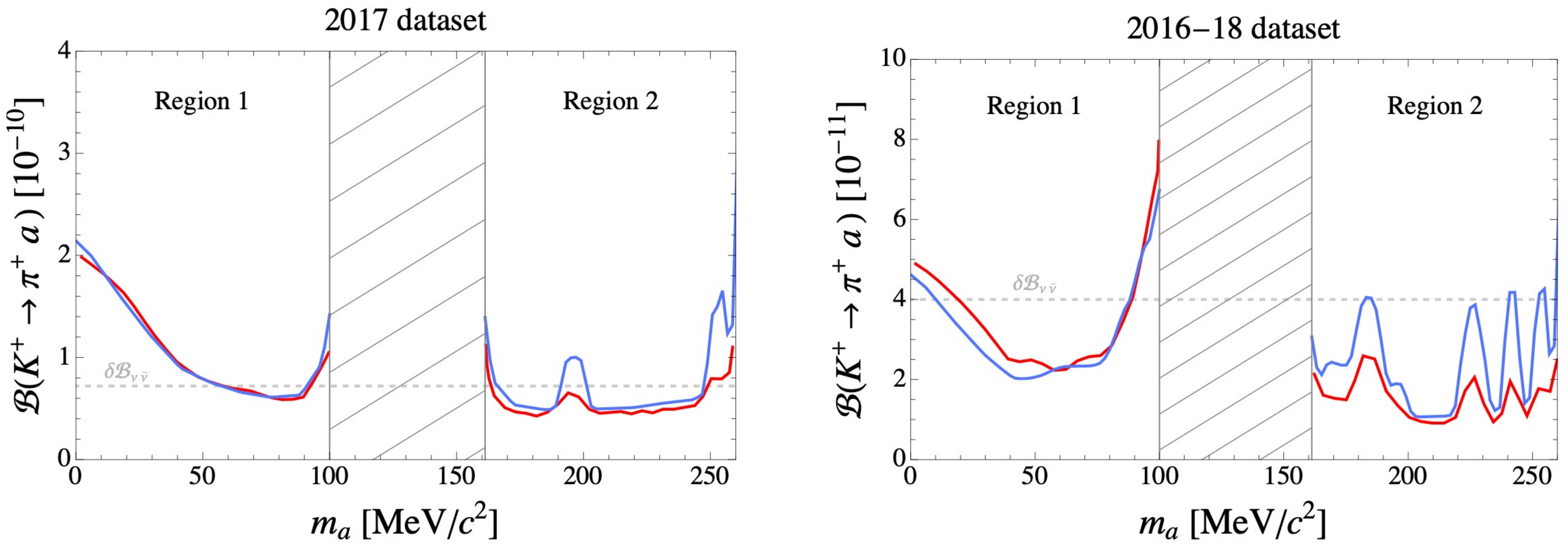
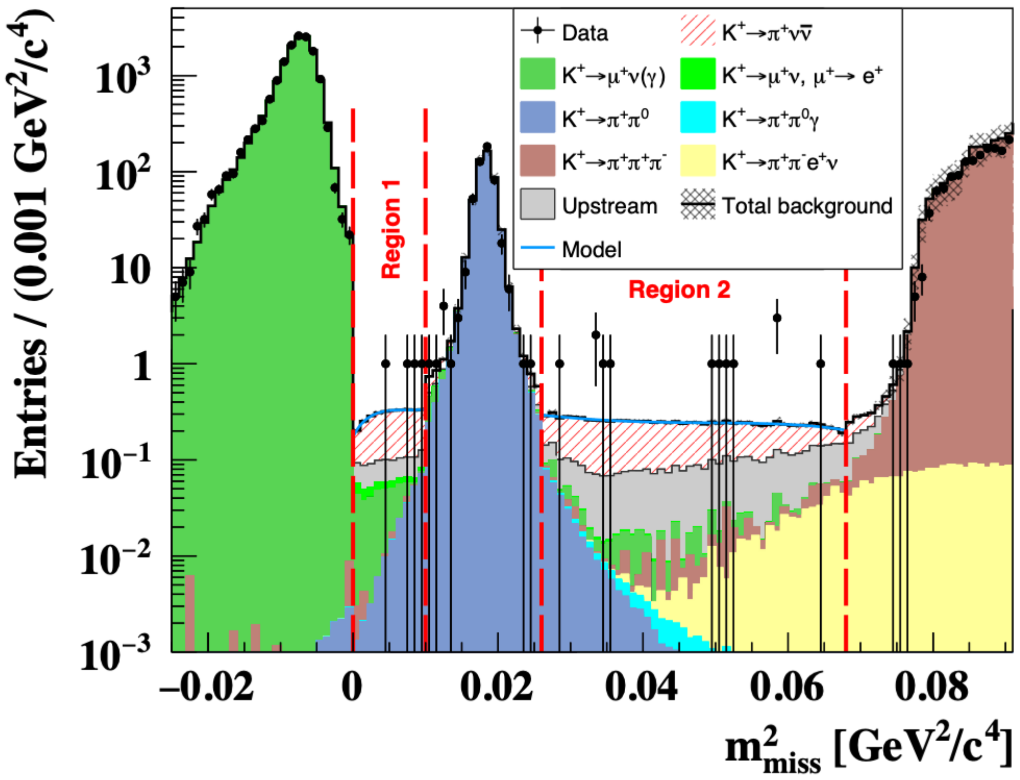


FIG. 3: Upper limit on $\mathcal{B}(K^+ \to \pi^+ a)$ from the 2017 [40] and 2016-18 [38] datasets. The solid red line is the published result of NA62 collaboration. The gray dashed line shows the corresponding value of $\delta\mathcal{B}_{\nu\bar{\nu}}$ for comparison.

[NA62 coll., arXiv:2011.11329]

[NA62 coll., arXiv:2103.15389]

NA62 bound from 2016-18 data



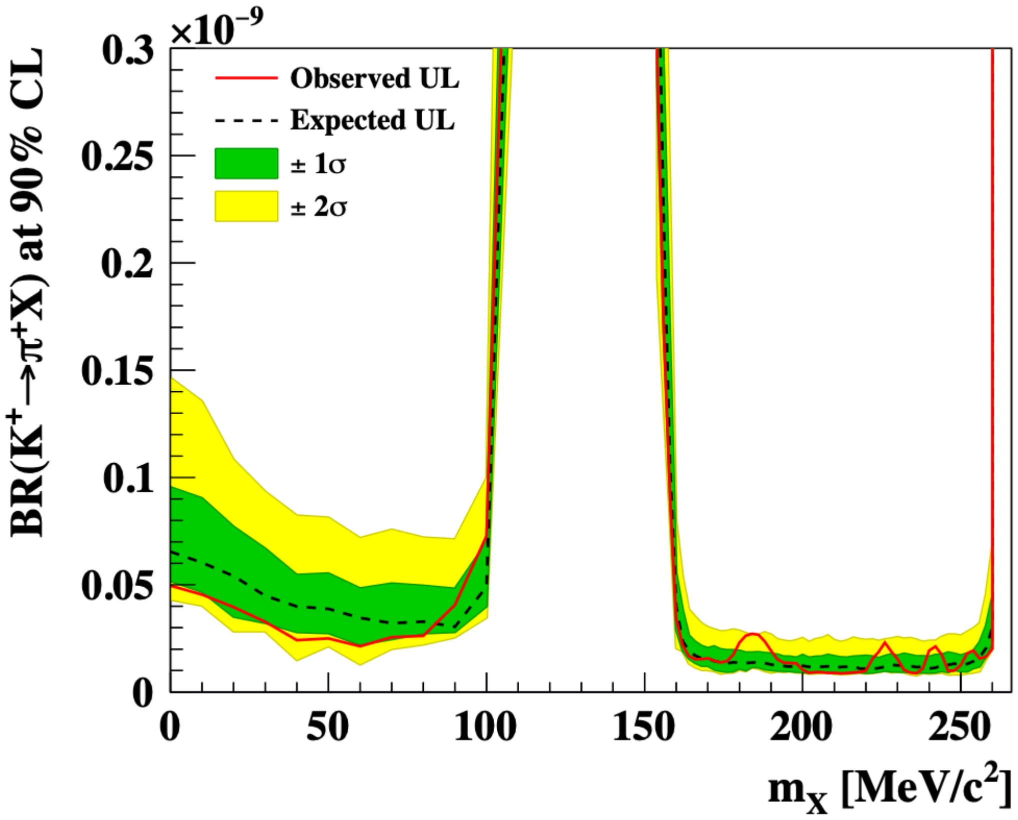


Figure 8: **Left:** Expected and observed number of events as a function of the reconstructed $m^2_{\rm miss}$ for the 2018 data set. **Right:** Upper limits on BR$(K^+ \to \pi^+ X)$ for each tested m_X hypothesis, as obtained for the full 2016–2018 data set.

[NA62 coll., arXiv:2103.15389]

Bound on axion effective scale

Assuming instead no flavour violating axion coupling:

$$\mathcal{M}(K^+ \to \pi^+ a) \approx \frac{iN_8^* m_K^2}{4f_a}\Big(2 + 2(k_A)_{11} + (k_A)_{22} + (k_A)_{33} + (k_V)_{22} - (k_V)_{33}\Big)$$

with $|N_8| \simeq 1.6 \times 10^{-7}.$

At $m_a = 0$ we get

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

data-driven DFSZ KSVZ