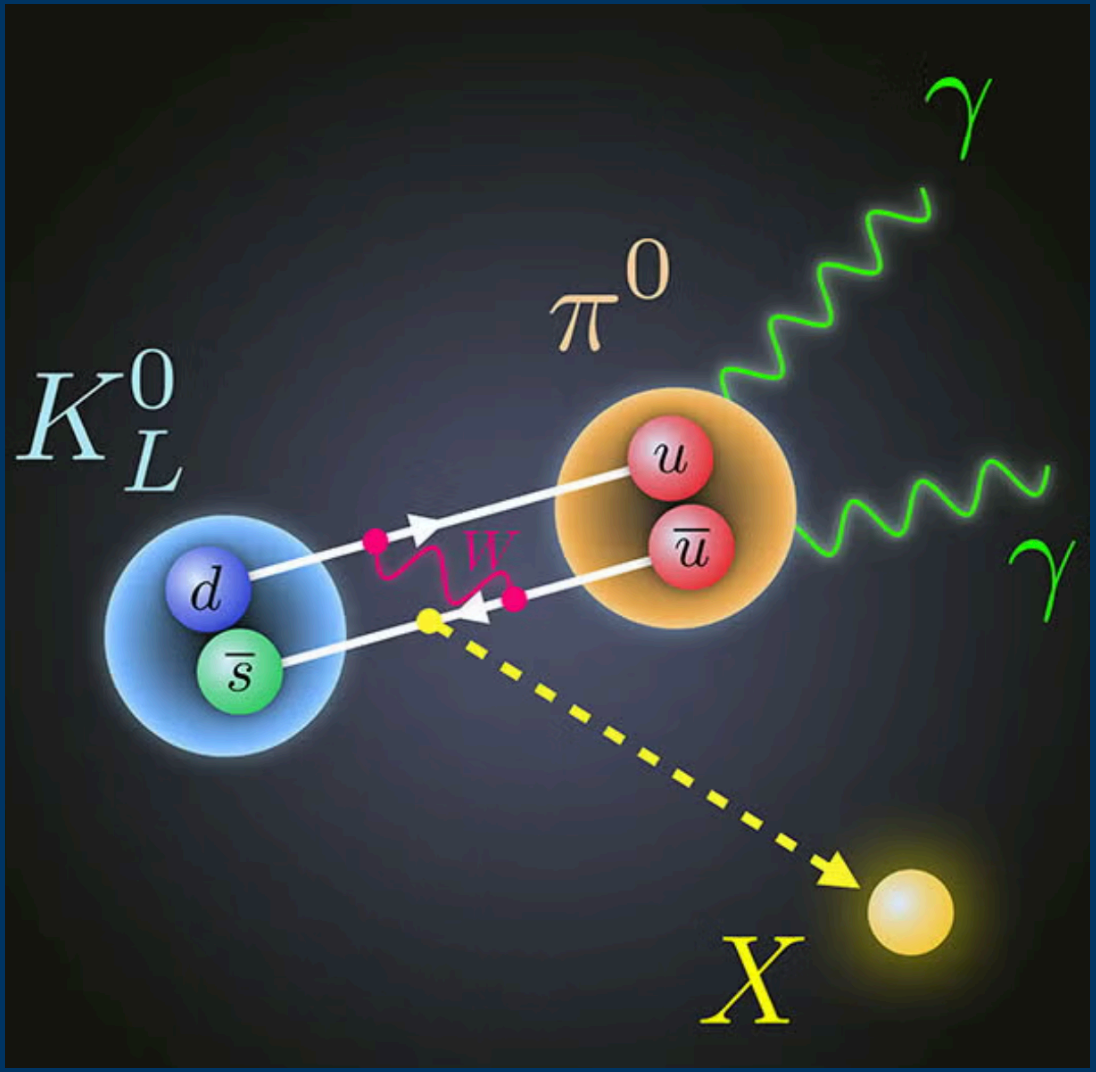
Light new Physics in Kaons

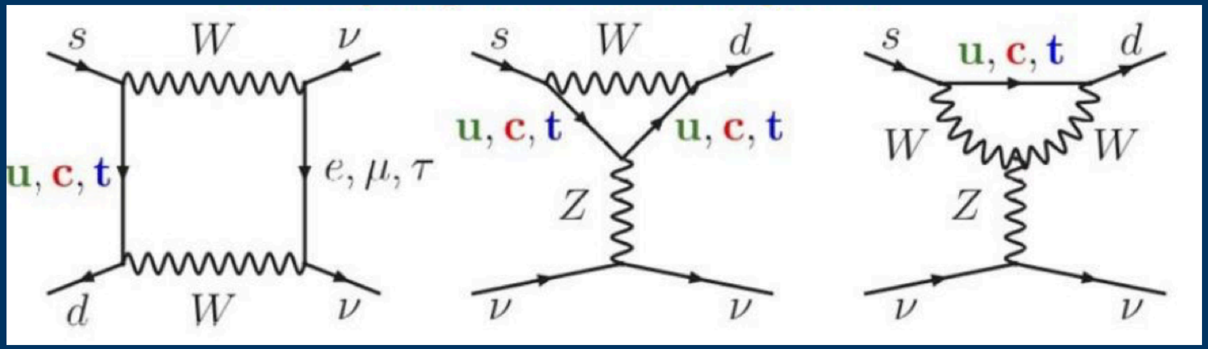


Martin Bauer

Beyond the Flavor Anomalies Rome, 9.4.2025

Light new Physics in Kaons

- Kaons offer a clean laboratory for flavor-violating effects



Light new Physics in Kaons

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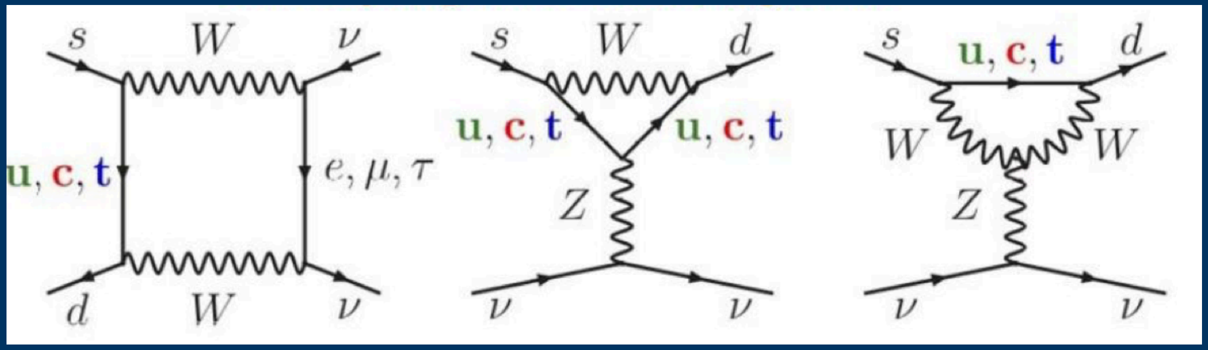
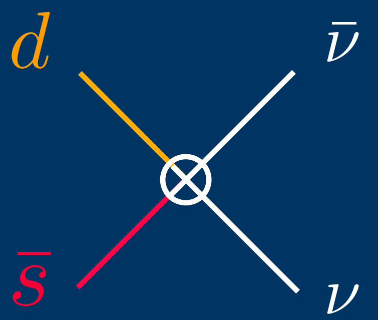


- Kaon decays probe indirect effects from New Physics

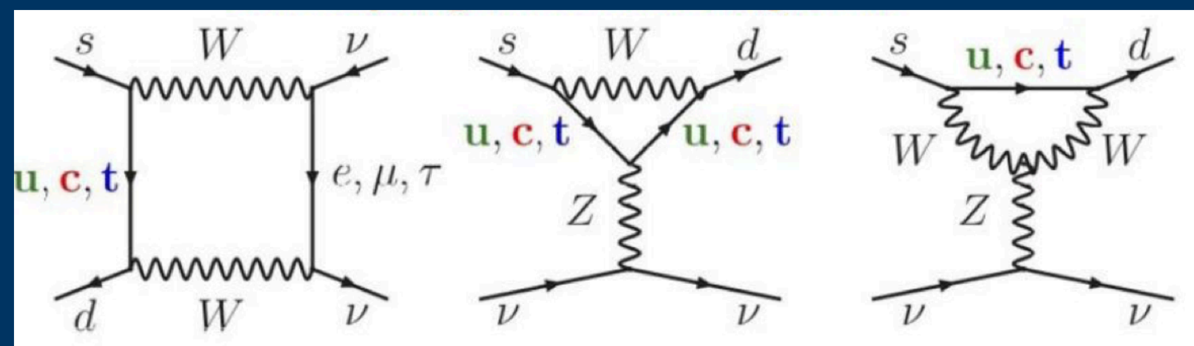
$$\mathcal{H} = \frac{1}{\Lambda^2} \sum_{\ell=e,\mu,\tau} (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{\ell,L} \gamma^\mu \nu_{\ell,L}) + \text{h.c.}$$



$$\Lambda \gtrsim 120\,\text{GeV}$$

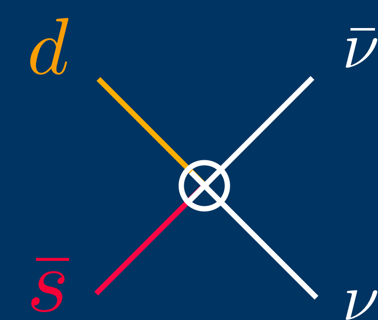
Light new Physics in Kaons

- Kaons offer a clean laboratory for flavor-violating effects



- Kaon decays probe indirect effects from New Physics

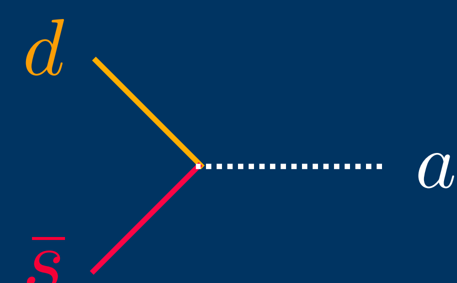
$$\mathcal{H} = \frac{1}{\Lambda^2} \sum_{\ell=e,\mu,\tau} (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{\ell,L} \gamma^\mu \nu_{\ell,L}) + \text{h.c.}$$



$$\Lambda \gtrsim 120\,\text{GeV}$$

- For light new states, Kaon decays are sensitive to scales 10 orders of magnitude higher

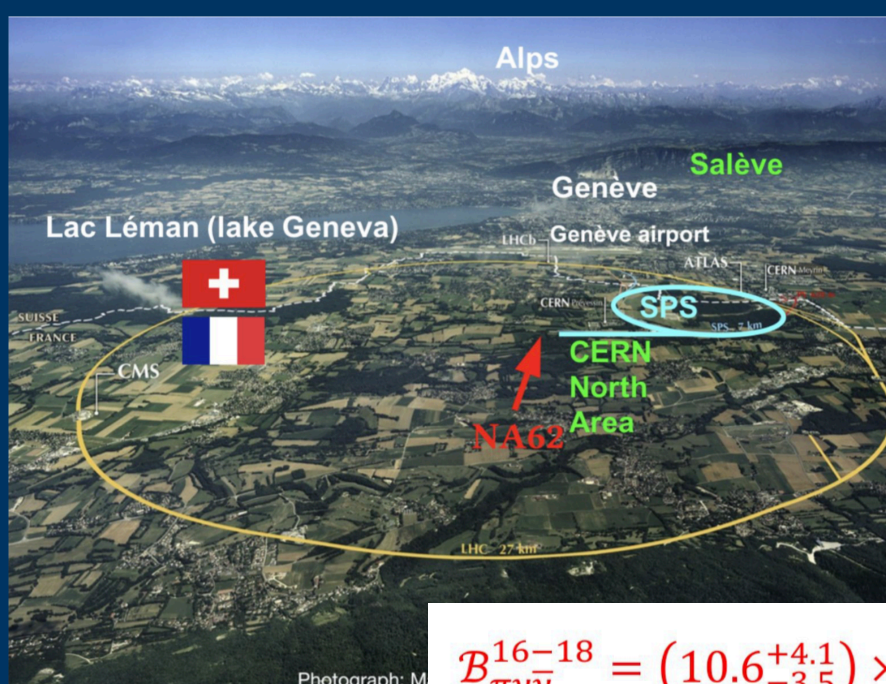
$$\mathcal{L} = \frac{1}{f} \partial_\mu a\, \bar{s} \gamma^\mu d$$



$$f \gtrsim 10^9\,\text{TeV}$$

Experimental status - charged Kaons

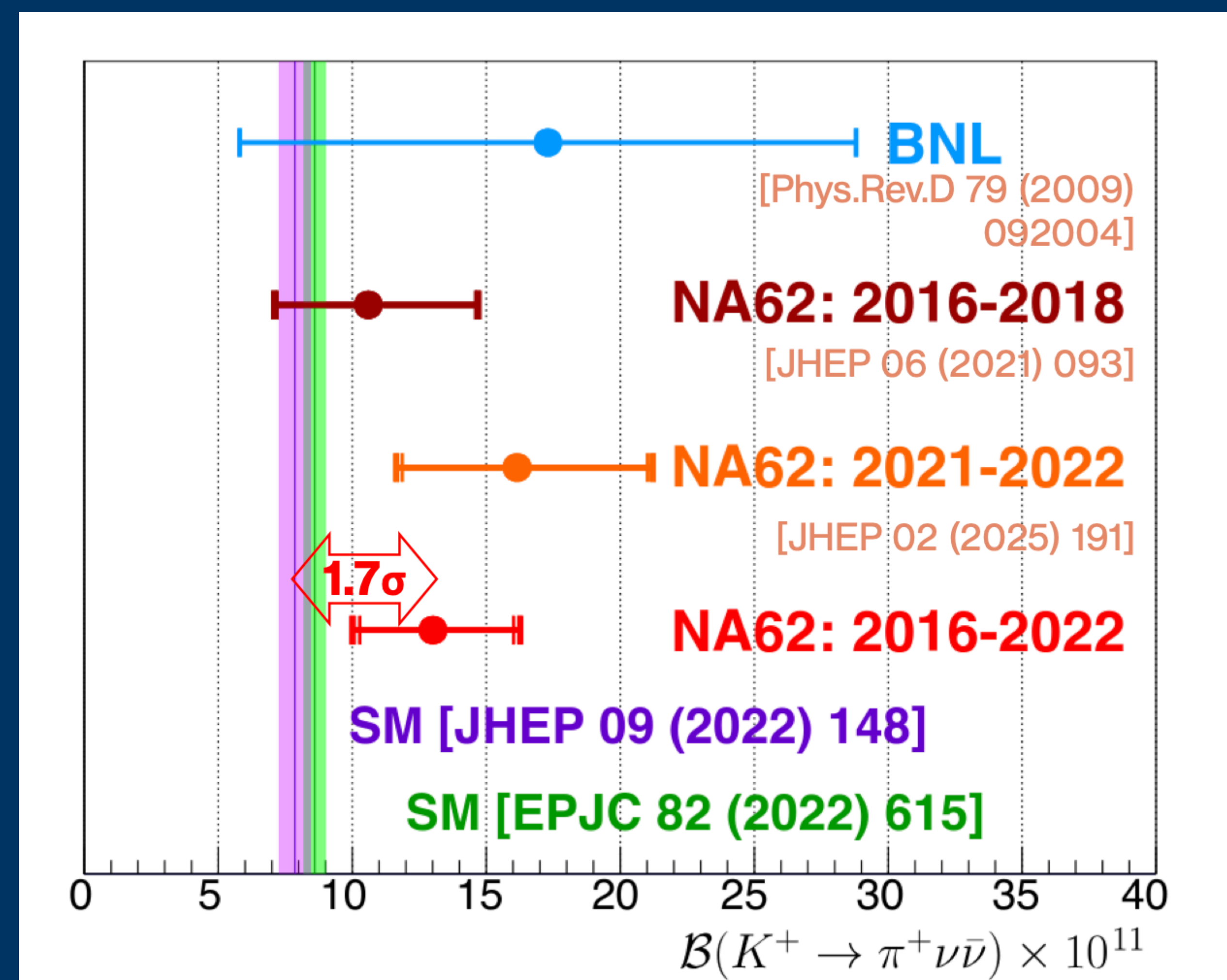
- NA62 observed the 'golden' channel $K^+ \to \pi^+ \nu \bar{\nu}$
- Expected uncertainty ~ 15% with the full data set (until 2026)
- SHiP > HIKE



$\mathcal{B}^{16-18}_{\pi\nu\bar{\nu}} = (10.6^{+4.1}_{-3.5}) \times 10^{-11}$ [JHEP 06 (2021) 093]

$\mathcal{B}^{21-22}_{\pi\nu\bar{\nu}} = (16.0^{+5.0}_{-4.5}) \times 10^{-11}$

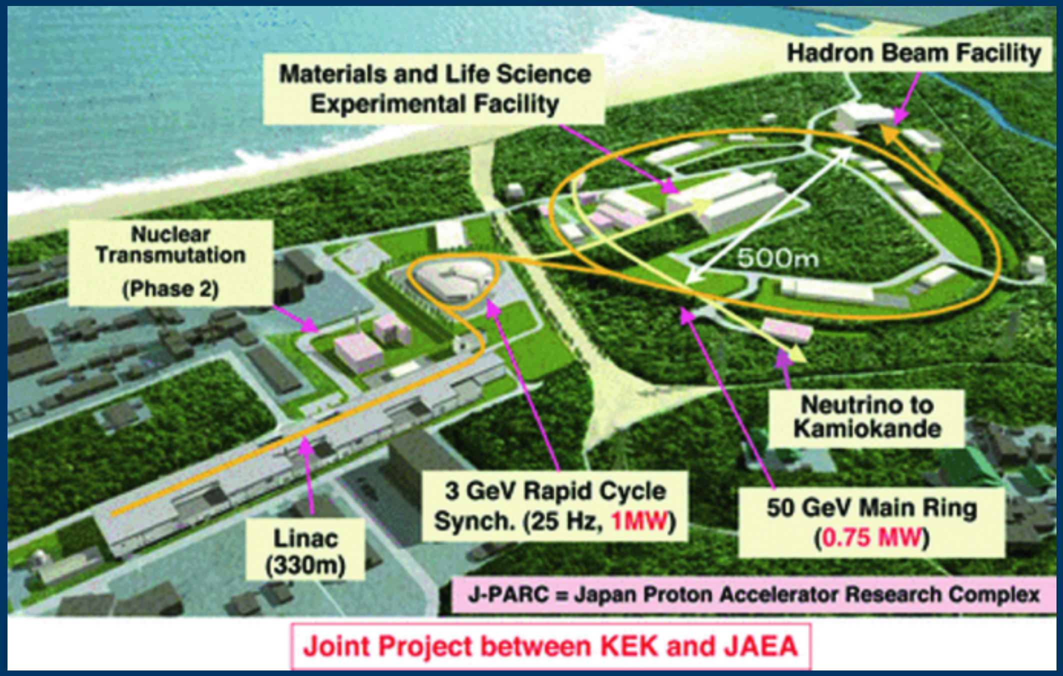
$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = (13.0^{+3.3}_{-2.9}) \times 10^{-11}$

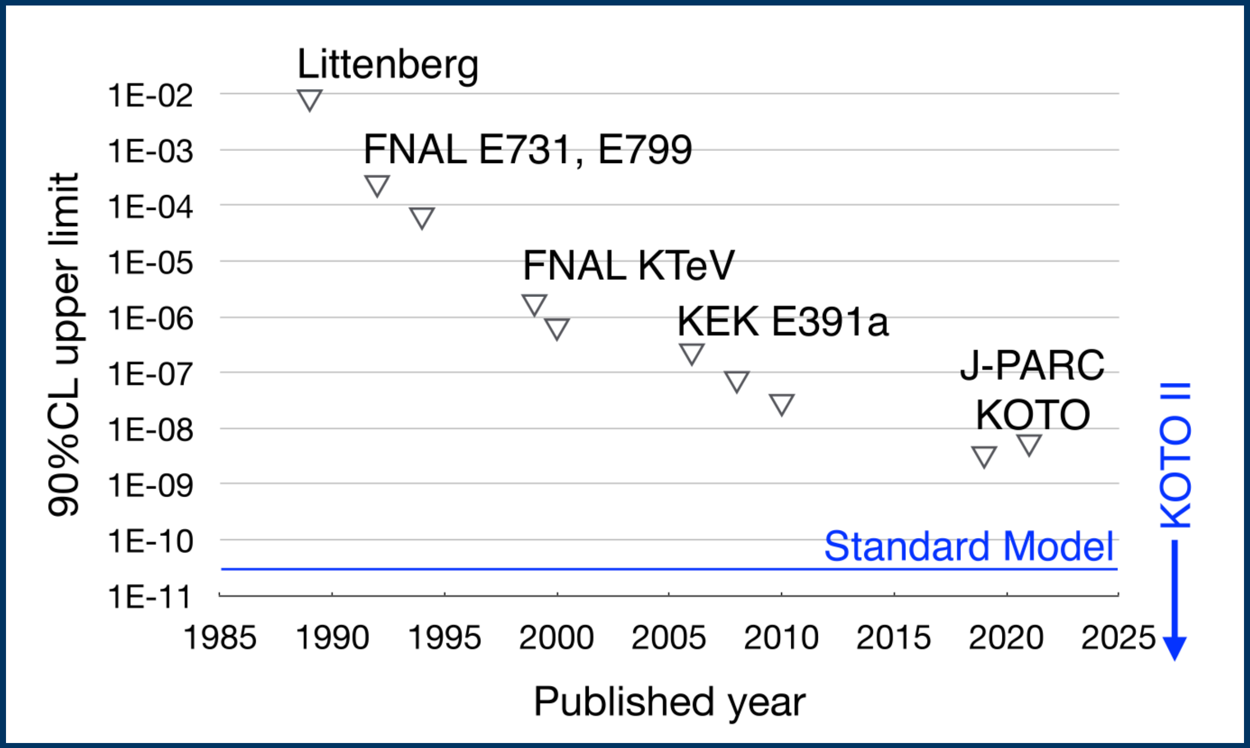


NA62: https://arxiv.org/abs/2412.12015

Experimental status - neutral Kaons

- KOTO at J-PARC $\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) < 2.2 \times 10^{-9}$
- Expected upper limit at 10^{-10} in 2030
- KOTO II plans to reach the SM prediction and measure charged lepton decays



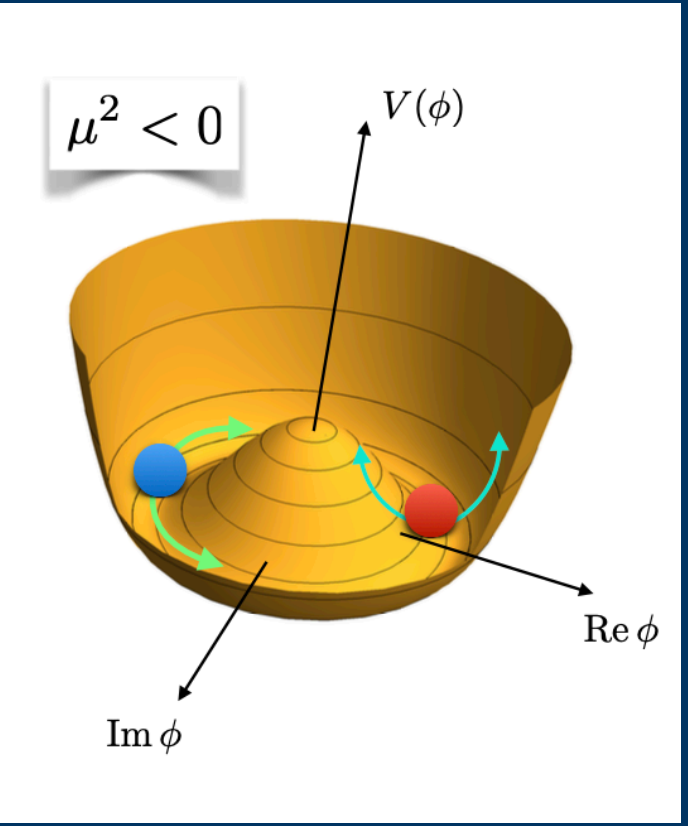


KOTO: https://arxiv.org/abs/2411.11237

New Physics - axions

- Axions and axion-like particles (ALPs) appear in any BSM scenario in which an approximate global symmetry is spontaneously broken

- Axions are phases $\phi = (f + s)e^{ia/f}$



- The axion mass breaks the shift symmetry

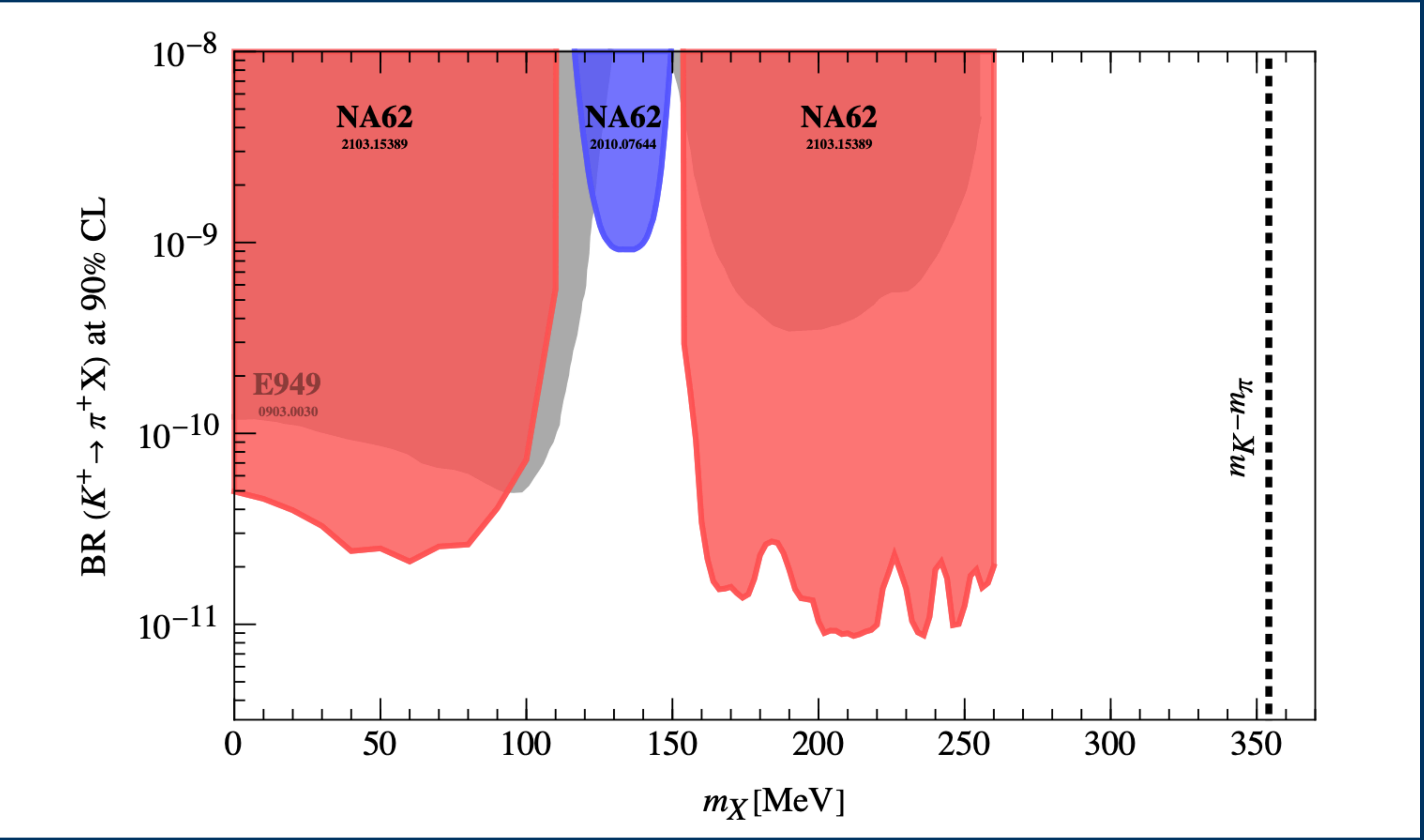
$$m_a = \frac{\mu^2}{f_a}$$

- Axion couplings are derivative couplings

$$\mathcal{L}_{\text{ALP-f}} = \frac{\partial_\mu a}{2 f_a}\, \bar{f}_i \gamma^\mu \left(C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5 \right) f_j$$

New Physics - axions

- NA62 provides model-independent constraints



https://arxiv.org/abs/2201.07805

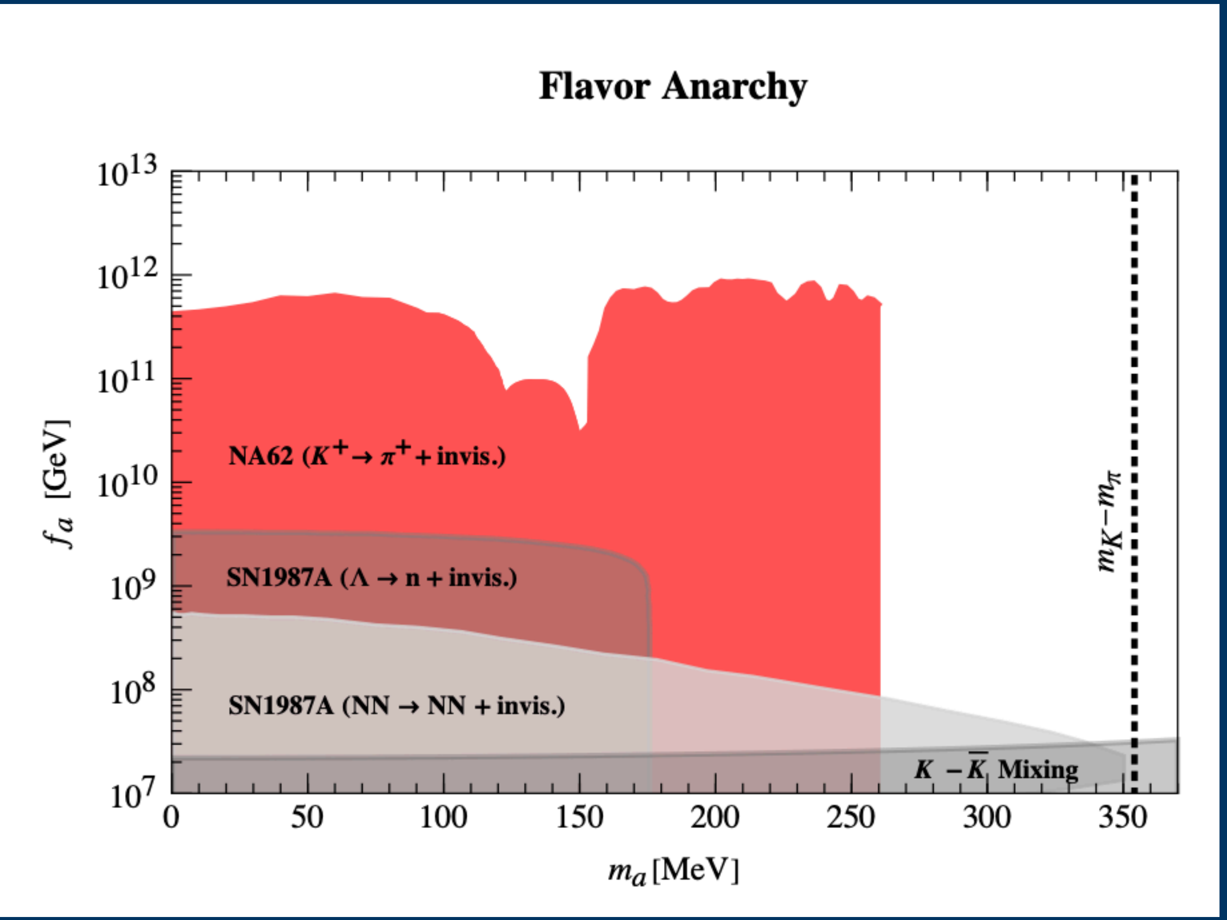
New Physics - axions

For flavor-violating couplings in the UV these translate to very strong constraints

Observable	Mass range [MeV]	ALP decay mode	Constrained coupling c_{ij}	Limit (95% CL) on $c_{ij} \cdot \left(\frac{\text{TeV}}{f}\right) \cdot \sqrt{\mathcal{B}}$
$\text{Br}(K^- \to \pi^- a(\text{inv}))$	$0 < m_a < 261^{(*)}$	long-lived	$\lvert k_D + k_d \rvert_{12}$	1.2×10^{-9}

Here, $C^V_{ds} = 1$

$$\mathcal{L}_{\text{ALP-f}} = \frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu \left(C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5\right) f_j$$

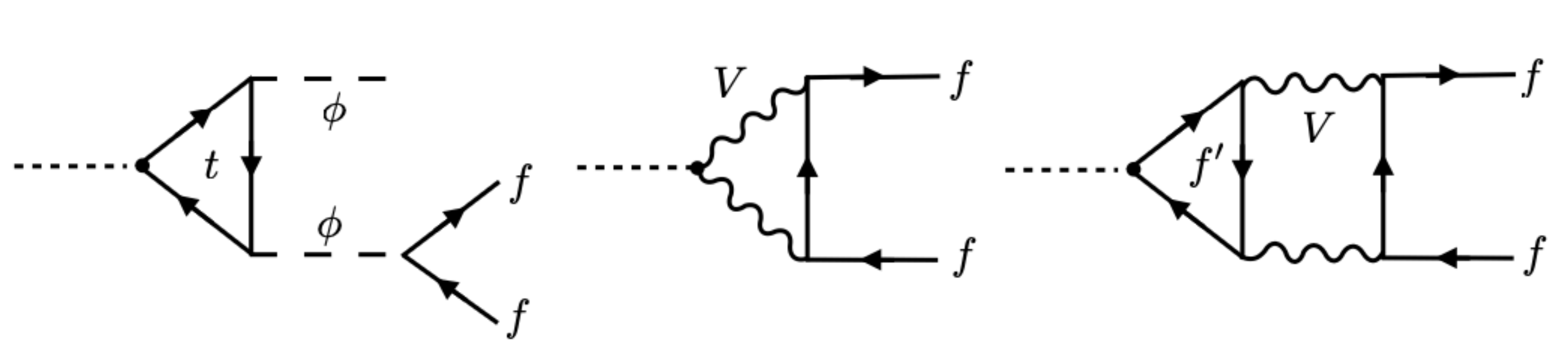


https://arxiv.org/abs/2201.07805

New Physics - axions

But axions have flavor violating couplings even if the UV theory is flavor diagonal : EW loops

$$\mathcal{L} = \frac{\partial_\mu a}{2 f_a} C^A_{FF} \bar{\psi}\gamma^\mu \gamma_5 \psi + c_{BB}\frac{\alpha_1}{8\pi f_a} a B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{WW}\frac{\alpha_2}{8\pi f_a} a W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + c_{GG}\frac{\alpha_s}{8\pi f_a} a G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$



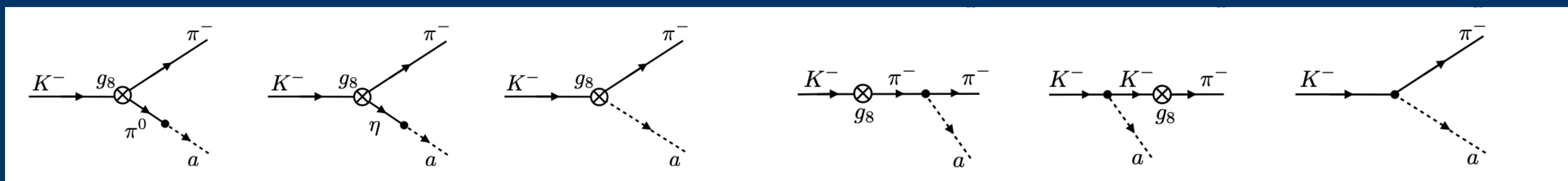
$$C^V_{ds}(\mu_c) = C^V_{ds}(\Lambda_{\rm UV}) + \sum_{F=t,c} \frac{y_F^2 V^*_{Fd} V_{Fs} C^A_{FF}}{16\pi^2}\left(\log\frac{\Lambda_{\rm UV}}{\mu_F} - f_F(x_F)\right) - \frac{g_2^4 N_2}{256\pi^4} V^*_{td} V_{ts} f_W(x_t),$$

$$N_2 = c_{WW}$$

https://arxiv.org/abs/2201.07805

New Physics - axions

But axions have flavor violating couplings even if the UV theory is flavor diagonal : QCD



$$i\mathcal{A}(K^- \to \pi^- a) = \frac{N_8}{4f_a}\Big[8\,N_3\,m^2_{K-\pi}\xi_a + \left(4\,C^A_{ss} + 6\xi_a C^A_{uu+dd-2ss}\right)m_a^2 + C^A_{2uu+dd+ss}\,m^2_{K-\pi-a} + C^V_{dd-ss}\,m^2_{K+\pi-a}\Big] - \frac{m^2_{K-\pi}}{2f_a}C^V_{ds}\,,$$

$$-i\sqrt{2}\mathcal{A}(\bar{K}^0 \to \pi^0 a) = \frac{N_8}{4f_a}\Big[\left(8\,N_3\xi_a + C^A_{3dd+ss}\right)m^2_{K-\pi} + \left(C^A_{2uu-dd-ss} - 2\xi_a C^A_{uu+dd-2ss}\right)m_a^2 - 2C^A_{uu-dd}m_a^2\,\frac{m^2_{K-a}}{m^2_{\pi-a}} + C^V_{dd-ss}m^2_{K+\pi-a}\Big] - \frac{m^2_{K-\pi}}{2f_a}C^V_{ds},$$

For K_L decays the CP conserving part is suppressed

$$K_L = \frac{(1+\epsilon)K^0 + (1-\epsilon)\bar{K}^0}{\sqrt{2(1+|\epsilon|^2)}}$$

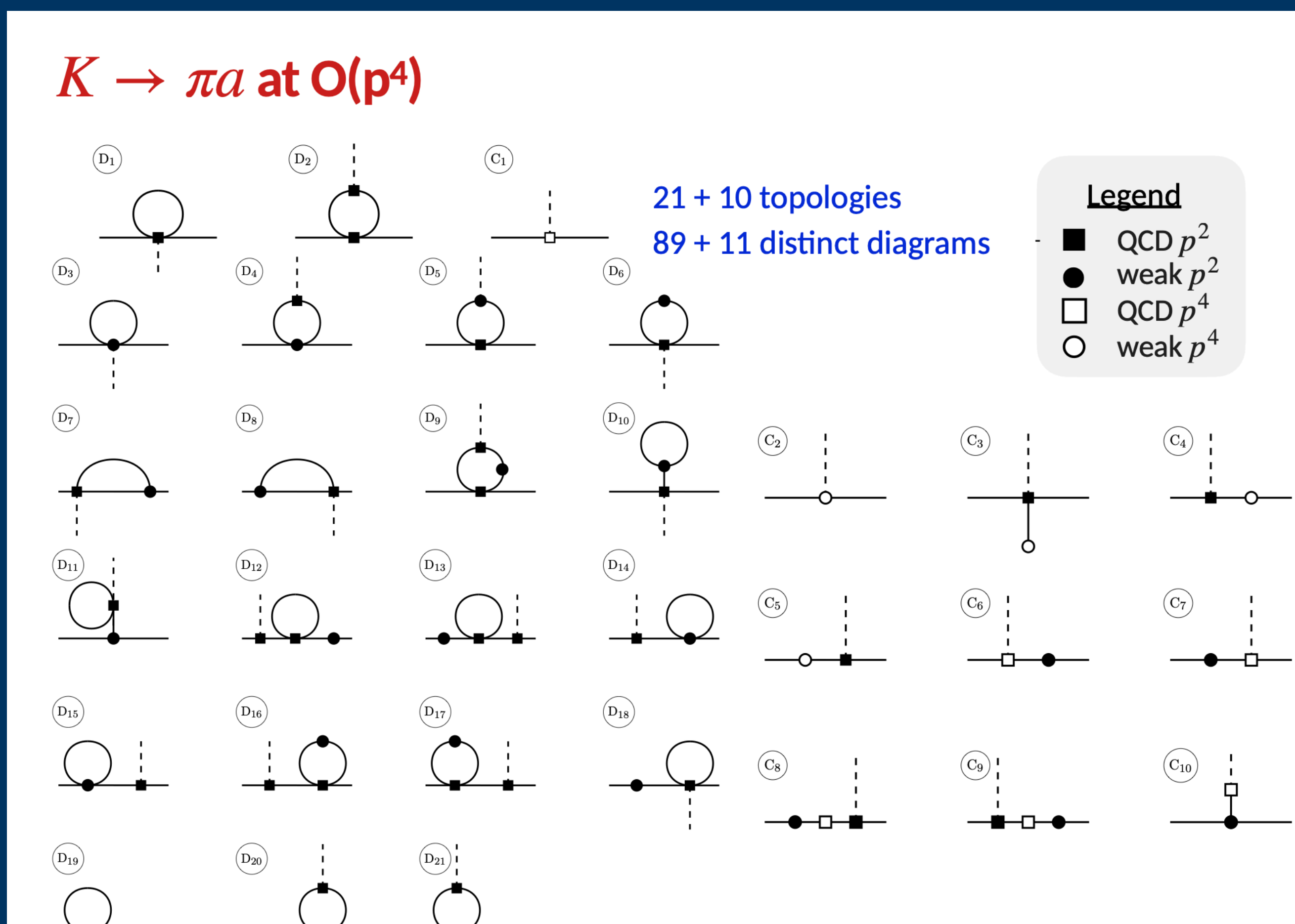
$$|\epsilon| \approx 2\times 10^{-3}$$

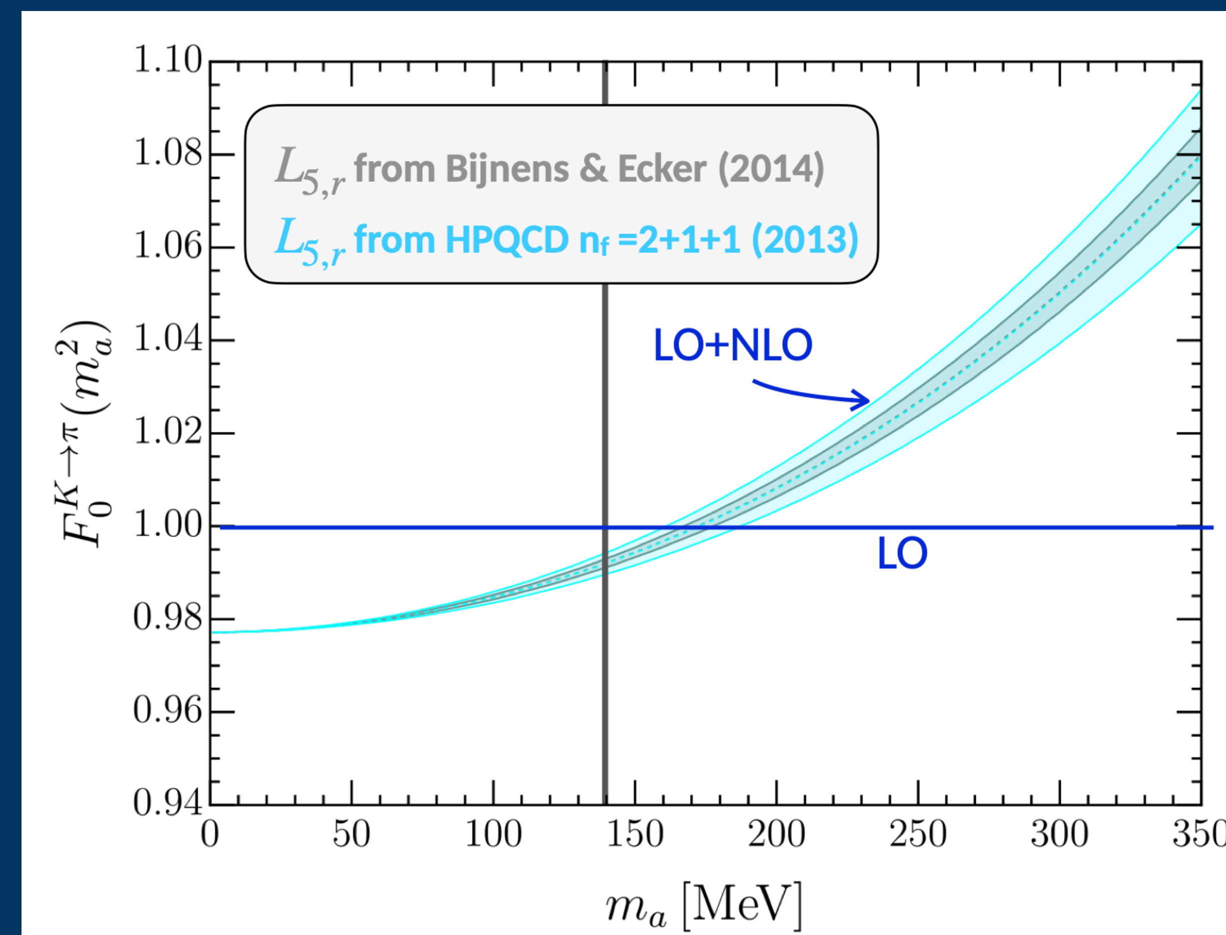
$$N_3 = c_{GG}$$

https://arxiv.org/abs/2102.13112

New Physics - axions

NLO corrections have been calculated





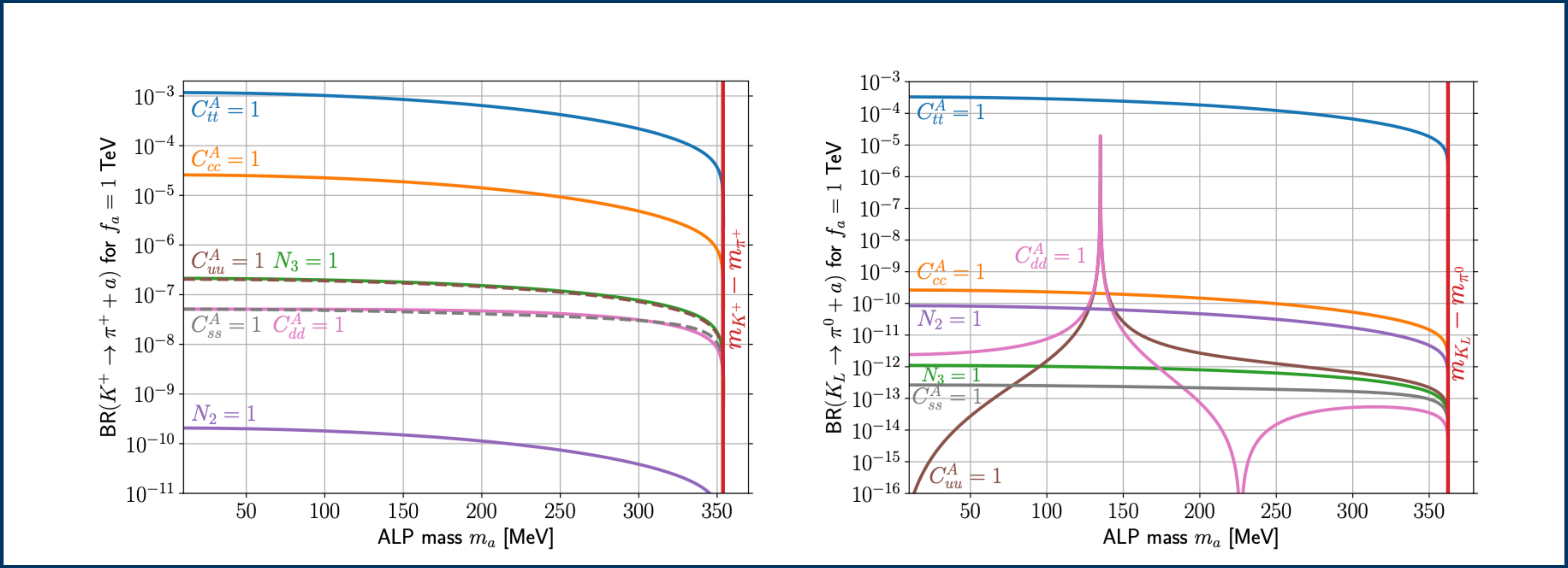
slide from Claudia Cornella, Capri 24

https://arxiv.org/abs/2308.16903

New Physics - axions

Three potential contributions to the amplitude

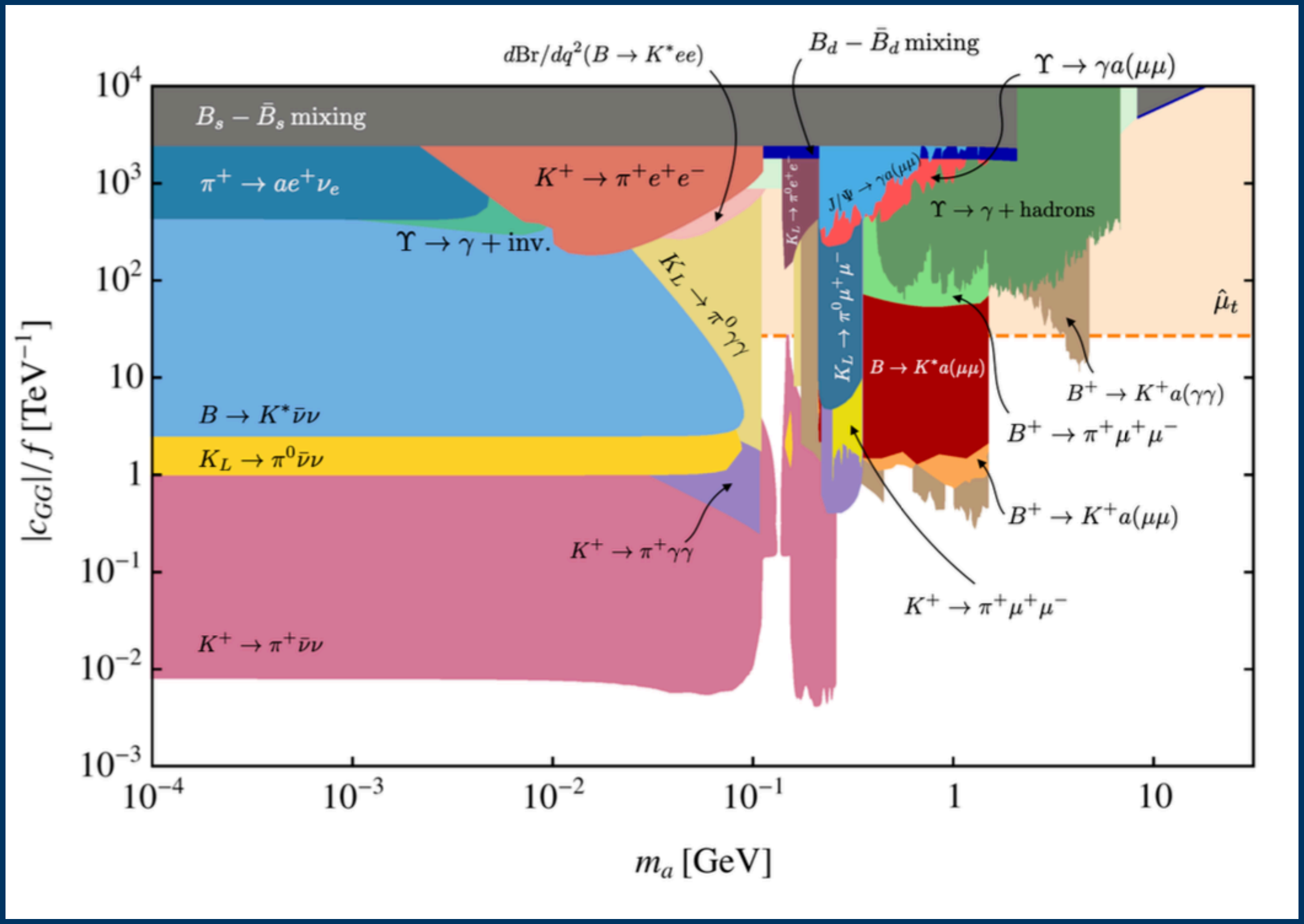
$$\mathcal{A}(K \to \pi + a) = \text{direct flavor violation } (C^V_{ds}) + \text{EW loops } (c_{WW}, c^A_{tt}) + \text{QCD } (c_{GG})$$

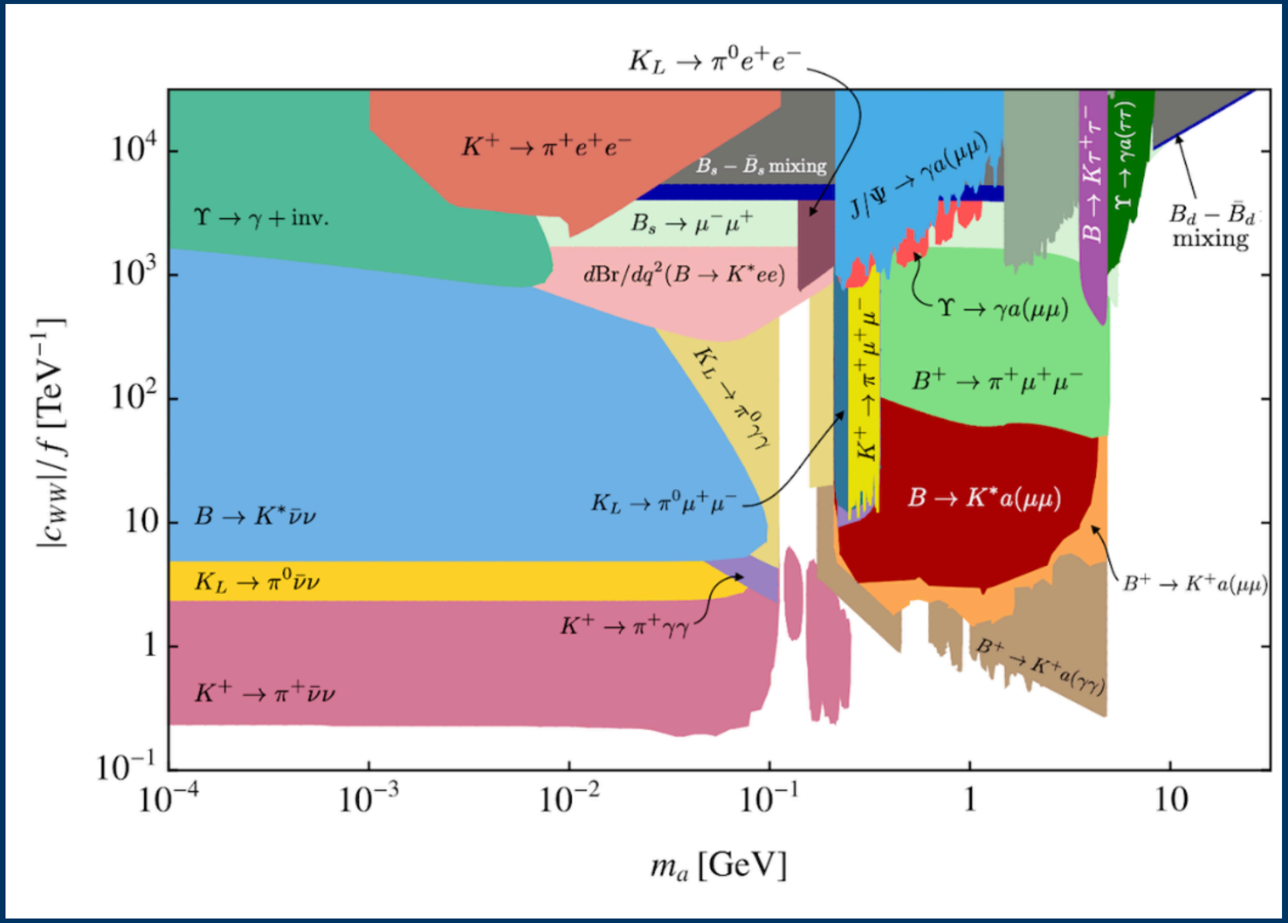


https://arxiv.org/abs/2201.07805

New Physics - axions

Measurements of neutral and charged Kaon decays can determine the UV structure of the theory





https://arxiv.org/abs/2110.10698

New Physics - axions

For B mesons

$$\mathcal{A}(B \to K^{(*)} + a) = \text{direct flavor violation}\,(C_{bs}) + \text{EW loops}\,(c_{WW}, c_{tt}^{A}) + \,?$$

QCD resonances contribute via B → K*π0, B → K* η′, B → K*η_c, etc. and require a consistent embedding of axions using the framework of QCD factorization for non-leptonic B decay

New Physics - axions

Other search channels:

- the three body decay $K \to \pi\pi a$ probes C^A_{ds}

$$\mathcal{B}(K^- \to \pi^-\pi^0 a) < 0.9 \times 10^{-5} \quad \Rightarrow \quad 2f_a/C^A_{sd} > 3.6 \times 10^7\ \text{GeV}$$

https://arxiv.org/abs/hep-ex/0308061
https://arxiv.org/abs/2411.04170

- axion decays

Observable	Experimental reference	Mass range [MeV]	ALP decay mode	Constrained coupling c_{ij}	Limit (95% CL) on $c_{ij} \cdot \left(\frac{\text{TeV}}{f}\right) \cdot \sqrt{\mathcal{B}}$	Limit (95% CL) on $c_{ij}/\lvert V^*_{ti}V_{tj}\rvert \cdot \left(\frac{\text{TeV}}{f}\right) \cdot \sqrt{\mathcal{B}}$
$\text{Br}(K^+ \to \pi^+ a(\text{inv}))$	NA62 2021 [125]	$0 < m_a < 261^{(*)}$	long-lived	$\lvert k_D + k_d\rvert_{12}$	1.2×10^{-9}	3.9×10^{-6}
$\text{Br}(K_L \to \pi^0 a(\text{inv}))$	KOTO 2018 [126]	$0 < m_a < 261$	long-lived	$\lvert\text{Im}[[k_D + k_d]_{12}\rvert$	8.1×10^{-9}	7.0×10^{-5}
$\text{Br}(K^+ \to \pi^+\gamma\gamma)$	E949 2005 [127]	$m_a < 108$	$\gamma\gamma$	$\lvert k_D + k_d\rvert_{12}$	2.1×10^{-8}	6.9×10^{-5}
$\text{Br}(K^+ \to \pi^+\gamma\gamma)$	NA62 2014 [128]	$220 < m_a < 354$	$\gamma\gamma$	$\lvert k_D + k_d\rvert_{12}$	2.0×10^{-7}	6.5×10^{-4}
$\text{Br}(K_L \to \pi^0\gamma\gamma)$	NA48 2002 [129]	$30 < m_a < 110$	$\gamma\gamma$	$\lvert\text{Im}[[k_D + k_d]_{12}]\rvert$	1.3×10^{-8}	1.1×10^{-4}
$\text{Br}(K_L \to \pi^0\gamma\gamma)$	KTeV 2008 [130]	$m_a < 363^{(\maltese\maltese)}$	$\gamma\gamma$	$\lvert\text{Im}[[k_D + k_d]_{12}]\rvert$	1.3×10^{-7}	1.1×10^{-3}
$\text{Br}(K^+ \to \pi^+ a(e^+e^-))$	BNL 1987 [131]	$1 < m_a < 100$	e^+e^-	$\lvert k_D + k_d\rvert_{12}$	3.4×10^{-7}	1.1×10^{-3}
$\text{Br}(K^+ \to \pi^+e^+e^-)$	E865 1999 [132]	$150 < m_{ee} < 350$	e^+e^-	$\lvert k_D + k_d\rvert_{12}$	1.7×10^{-7}	5.5×10^{-4}
$\text{Br}(K^+ \to \pi^+e^+e^-)$	NA48/2 2009 [133]	$140 < m_a < 350$	e^+e^-	$\lvert k_D + k_d\rvert_{12}$	1.8×10^{-7}	5.7×10^{-4}
$\text{Br}(K_L \to \pi^0e^+e^-)$	KTeV 2004 [134]	$140 < m_a < 362$	e^+e^-	$\lvert\text{Im}[[k_D + k_d]_{12}]\rvert$	3.1×10^{-9}	2.6×10^{-5}
$\text{Br}(K_L \to \pi^0\mu^+\mu^-)$	KTeV 2000 [135]	$210 < m_a < 350$	$\mu^+\mu^-$	$\lvert\text{Im}[[k_D + k_d]_{12}]\rvert$	4.0×10^{-9}	3.4×10^{-5}
$\text{Br}(K^+ \to \pi^+ a(\mu^+\mu^-))$	NA48/2 2016 [136]	$211 < m_a < 350$	$\mu^+\mu^-$	$\lvert k_D + k_d\rvert_{12}$	3.2×10^{-9}	1.0×10^{-5}

https://arxiv.org/abs/2110.10698

Kaons at LHCb

- K_S decays: $\mathcal{B}(K_S^0 \to \mu^+\mu^-)_{SM} = (5.18 \pm 1.50_{LD} \pm 0.02_{SD}) \times 10^{-12}$ $\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$

https://arxiv.org/abs/2001.10354

- semi-leptonic K_S decays:

$$\mathcal{B}(K_S^0 \to \pi^0\mu^+\mu^-) \propto 0.07 - 4.52a_S - 1.5b_S + 98.7a_S^2 + 57.7a_S b_S + 8.95b_S^2$$

uncertainty Δa_S ~ 15% (NA48) to 2% (LHCb, q^2 dependence)

https://arxiv.org/pdf/1808.03477

- lepton violation, e.g.

$$\mathcal{B}(K_L \to e^\pm\mu^\mp) < 4.7 \times 10^{-12}$$
$$\mathcal{B}(K^+ \to \pi^+e^-\mu^+) < 1.3 \times 10^{-11}$$

- K_L - K_S interference: CP asymmetries

Decay	Upgrade-Ia	Upgrade-Ib	Upgrade-II
$K^0 \to \mu^+\mu^-$	$30\% - 80\%$	$20\% - 55\%$	$8.5\% - 25\%$
$K^0 \to \pi^0\mu^+\mu^-$	$\approx 26\%$	$\approx 18\%$	$\approx 7.5\%$
$K^0 \to \mu^+\mu^-e^+e^-$	$23\% - 33\%$	$15\% - 22\%$	$6.5\% - 9.6\%$
$K^0 \to \pi^+\pi^-e^+e^-$	$\approx 4.3\%$	$1.8\% - 2.9\%$	$0.05\% - 1.2\%$

https://arxiv.org/pdf/2503.22256

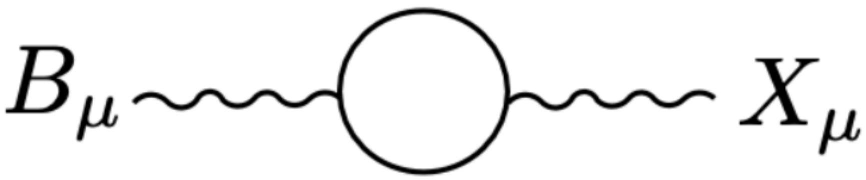
New Physics - hidden photons

A new spin-1 boson

$$\mathcal{L} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}D_\mu\phi D^\mu\phi - V(\phi) + g_X\bar{\psi}\gamma_\mu\psi X^\mu$$

interacts with the SM either though direct couplings or via kinetic mixing

$$\epsilon F_{\mu\nu}X^{\mu\nu}$$

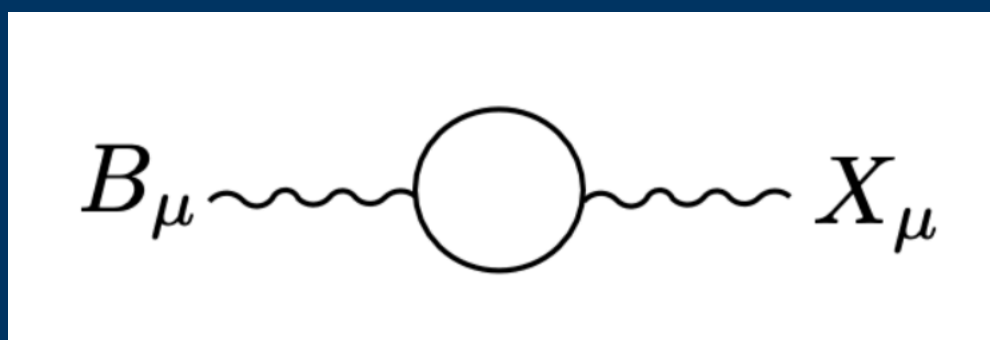


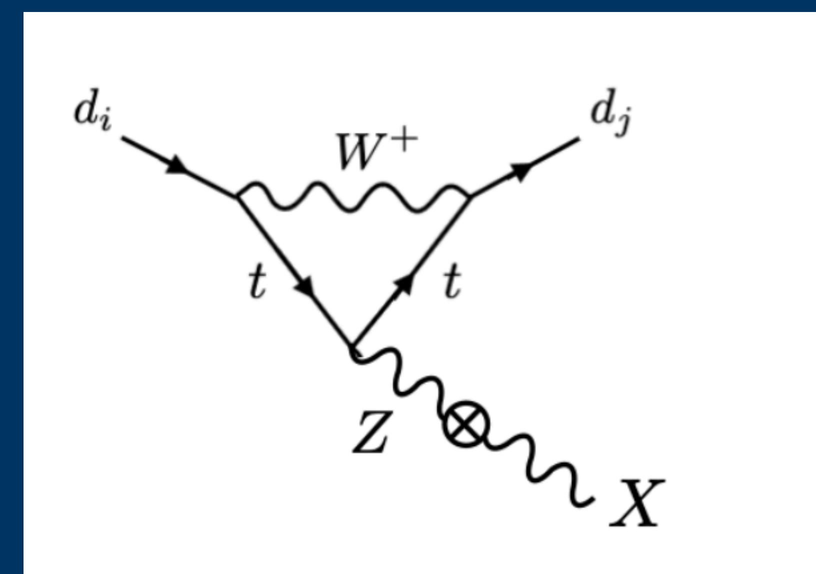
$$\epsilon \propto \frac{g_X e}{8\pi^2}\log\frac{\Lambda^2}{m^2}$$

https://arxiv.org/abs/2011.12973

New Physics - hidden photons

Flavor changing couplings via Z-kinetic mixing inherit the SM GIM suppression and are very small





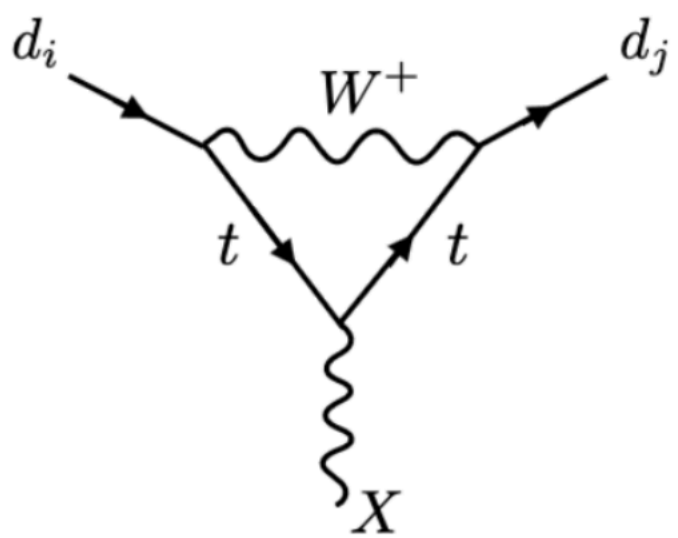
$$\epsilon \propto \frac{g_X e}{8\pi^2} \log \frac{\Lambda^2}{m^2}$$

https://arxiv.org/abs/2011.12973

New Physics - hidden photons

What about direct couplings to SM fermions? Maybe a global SM symmetry is gauged

Gauge anomaly cancellation and constraints from the CKM matrix force the couplings to be flavor diagonal



$$\mathcal{L} = g^L_{ij} \frac{M_X^2}{M_W^2} \bar{d}_j \gamma_\mu P_L d_i X^\mu + \frac{1}{2} g^\sigma_{ij} \bar{d}_j \sigma^{\mu\nu} \left(\frac{m_{d_j}}{M_W^2} P_L + \frac{m_{d_i}}{M_W^2} P_R \right) d_i X_{\mu\nu}$$

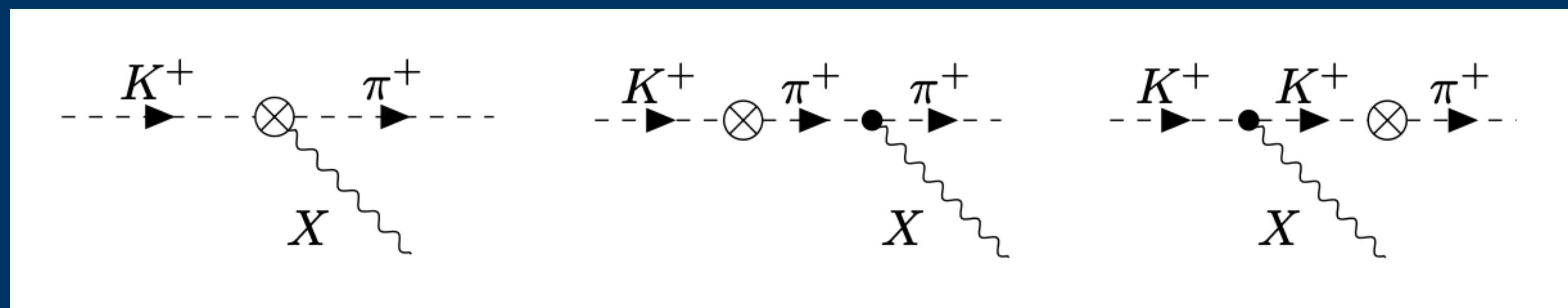
$$g^L_{ij} = g_X q_q \frac{\alpha}{8\pi s_w^2} V_{ti} V^*_{tj} f_1(x_t) \qquad g^\sigma_{ij} = g_X q_q \frac{\alpha}{8\pi s_w^2} V_{ti} V^*_{tj} f_2(x_t)$$

$$\Gamma(B \to K X) \approx \frac{1}{256\pi} \frac{M_B^3 M_X^2}{M_W^4} \left(g^L_{32} f_+ \right)^2$$

https://arxiv.org/abs/2011.12973

New Physics - hidden photons

How about the QCD contribution



Vanishes for $x^q_A=0$ and $x^d_V=x^s_V$:

$$
\begin{aligned}
|\overline{\mathcal{M}}|^2 = \frac{g_x^2}{m_X^2\,(m_K^2-m_\pi^2)^2}\big[(m_K-m_\pi)^2-m_X^2\big]\big[(m_K+m_\pi)^2-m_X^2\big]\Big[x_V^{32}(m_K^2-m_\pi^2) \\
-2g_{\mathrm{ew}}e^2 f^4 G g_8(x_V^s-x_V^d)-f^2 G\Big(g_8^S(m_K^2-m_\pi^2)(x_A^u+x_A^d+x_A^s) \\
+\frac{2}{3}g_{27}m_K^2(x_V^s-x_V^d+2x_A^d+2x_A^s-4x_A^u)+g_8 m_\pi^2(x_V^s-x_V^d+x_A^d+x_A^s+2x_A^u) \\
-\frac{2}{3}g_{27}m_\pi^2(x_V^s-x_V^d-2x_A^d-2x_A^s+4x_A^u)-g_8 m_K^2(x_V^s-x_V^d-x_A^d-x_A^s-2x_A^u)\Big)\Big]^2
\end{aligned}
$$

https://arxiv.org/abs/2308.05215

New Physics - hidden photons

Broken gauge symmetries with SM matter content

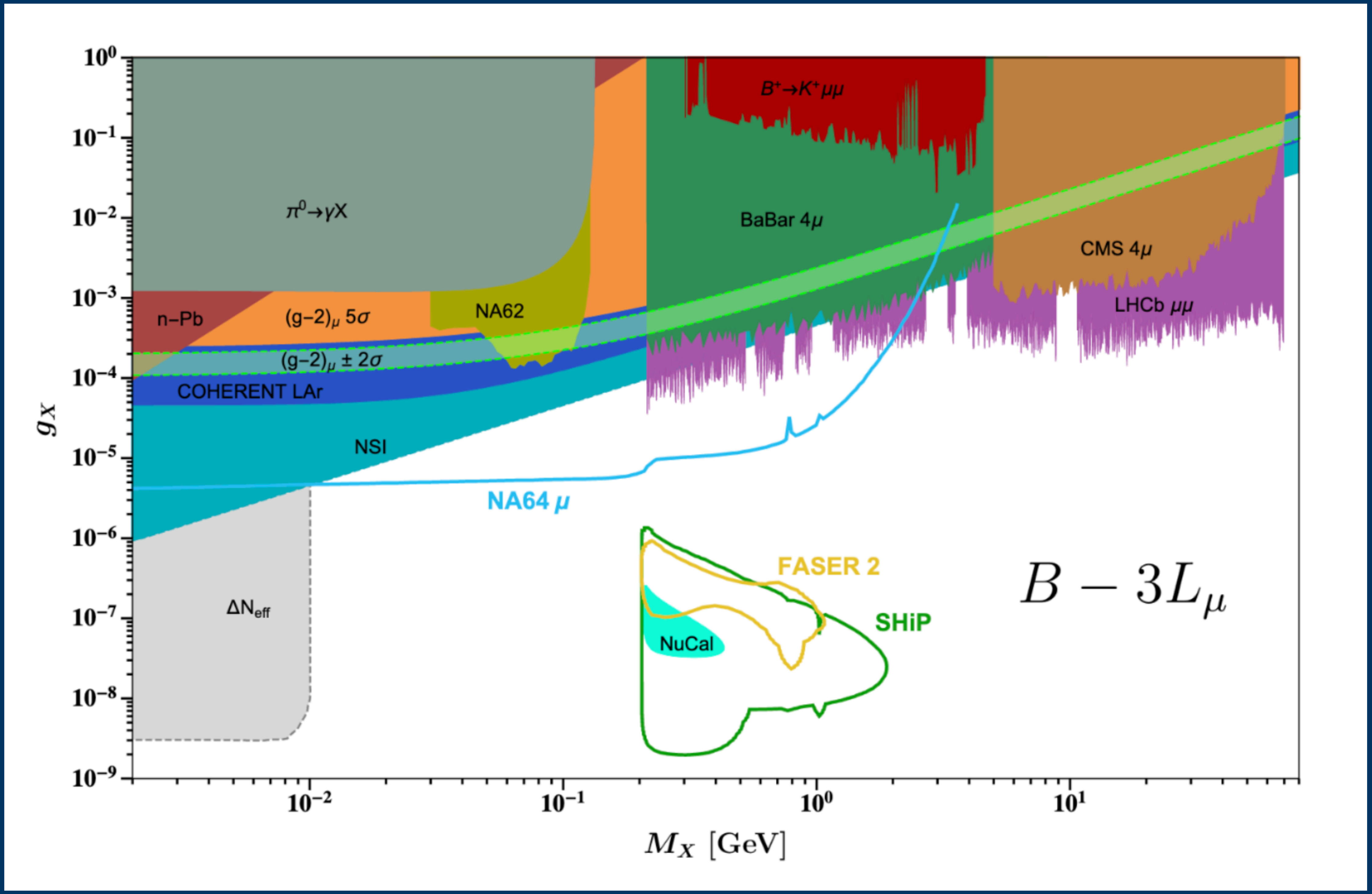
$$\mathcal{A}(K \to \pi + X) =$$ direct flavor violation (~0) $+$ EW loops (heavily suppressed) $+$ QCD (~0)

Extended models

- Currents aren't conserved https://arxiv.org/abs/1707.01503
- Two Higgs doublet models with additional fermions

https://arxiv.org/pdf/1609.09072

New Physics - hidden photons



https://arxiv.org/abs/2011.12973

Conclusions

Rare kaon decays are an excellent tool to search for new physics - both heavy and light

Flavor-violating transitions are strongly suppressed for (minimal) hidden photon models, but can be large for axions

Different Kaon decays can pin down the UV structure and potentially identify the global symmetry

History

In 1961, an experiment in Dubna to looked for the decay

$K_L \rightarrow \pi^+\pi^-$ 597 events, no signal

AN EXPERIMENTAL INVESTIGATION OF SOME CONSEQUENCES OF CP INVARIANCE IN K_2^0-MESON DECAYS

M. Kh. ANIKINA, D. V. NEAGU, É. O. OKONOV, N. I. PETROV, A. M. ROZANOVA, and V. A. RUSAKOV

Joint Institute for Nuclear Research

Submitted to JETP editor September 2, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **42**, 130-134 (January, 1962)

In the analysis of 597 K_2^0 decays recorded in a cloud chamber no events corresponding to the decay into two charged pions were found. This result favors the hypothesis that the decay interaction of neutral K mesons is CP-invariant, and the equality (within experimental errors) of the probabilities of leptonic K_2^0 decays with the emission of a π^+ or π^- does not contradict this assumption. Previously obtained data, indicating a large probability for the decays $K_2^0 \rightarrow 3\pi$, are also in agreement with this conclusion. Among the 597 K_2^0 decays no decays into two charged leptons were found.

History

In 1964 the search was repeated with 40 times the statistics

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

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(Received 10 July 1964)

The relative efficiency for detection of the three-body K_2^0 decays compared to that for decay to two pions is 0.23. We obtain 45 ± 9 events in the forward peak after subtraction of background out of a total corrected sample of 22 700 K_2^0 decays.

$$\mathrm{Br}(K_L \to \pi^+\pi^-) = 1.9 \times 10^{-3} \times 600 \approx 1$$

History

Late 1950s, early 60s: Is CP symmetry a good symmetry of nature ?

One way of testing that assumption was looking for Kaon decays:

$$K_1 = \tfrac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right) \qquad K_2 = \tfrac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right)$$

$$\mathrm{CP}\left|K_1\right\rangle = +\left|K_1\right\rangle \qquad \mathrm{CP}\left|K_2\right\rangle = -\left|K_2\right\rangle$$

2 states can be easily distinguished via lifetime measurements

$$K_s\ (K_1, \mathrm{CP} = +1) \rightarrow \pi^+\pi^-, \pi^0\pi^0\ (\mathrm{CP} = +1)$$

$$K_l\ (K_2, \mathrm{CP} = -1) \rightarrow \pi^{+,0}\pi^{-,0}\pi^0\ (\mathrm{CP} = -1)$$

If CP is violated the can decay into $K_L \rightarrow \pi^+\pi^-$