Flavor Probes for Axion-Like Particles

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M. Bauer, MN, S. Renner, M. Schnubel, A. Thamm: 2012.12272 (JHEP), 2102.13112 (PRL), 2110.10698 (JHEP)
C. Cornella, A. Galda, MN, D. Wyler: 2308.16903

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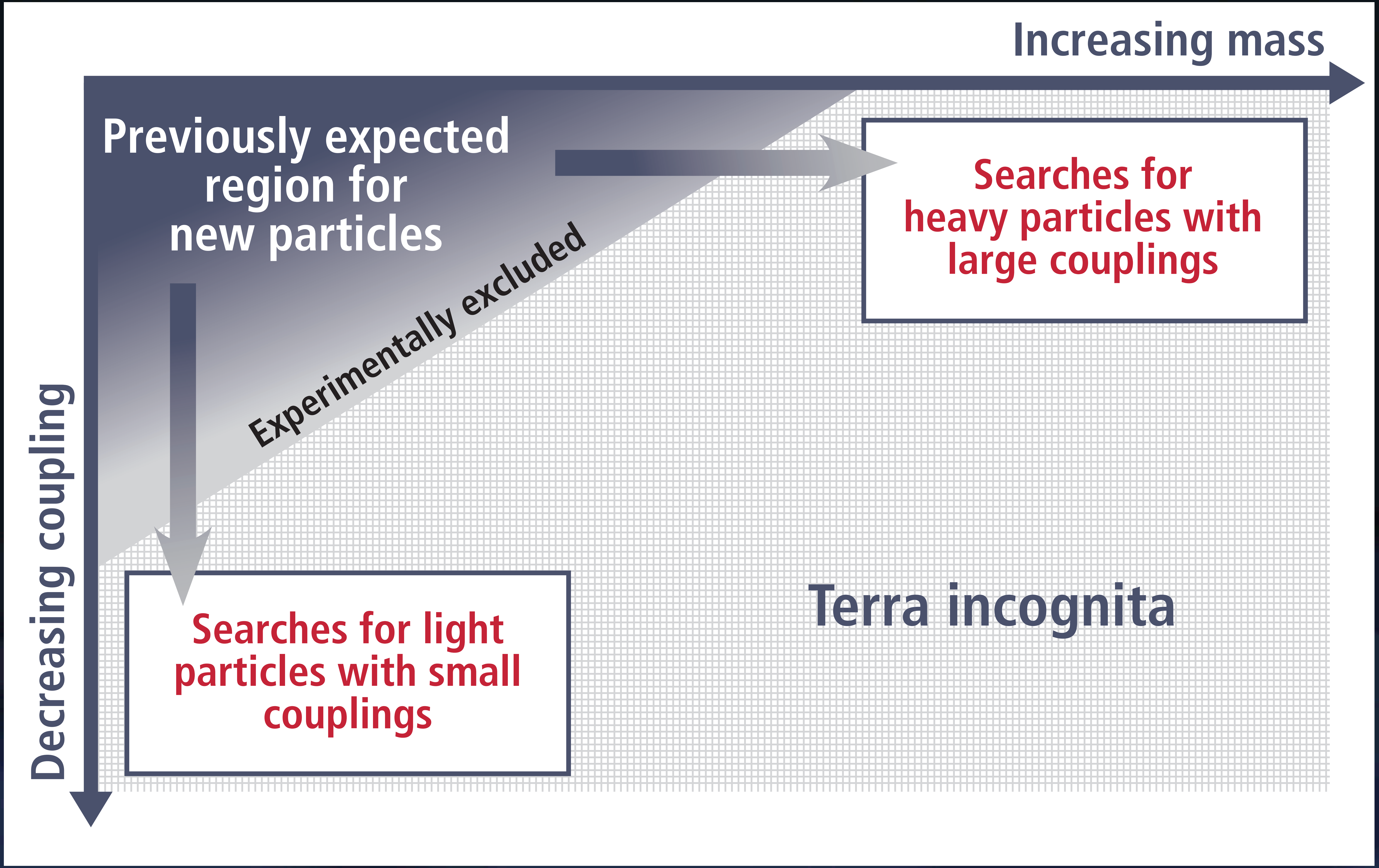
Limits of the Standard Model



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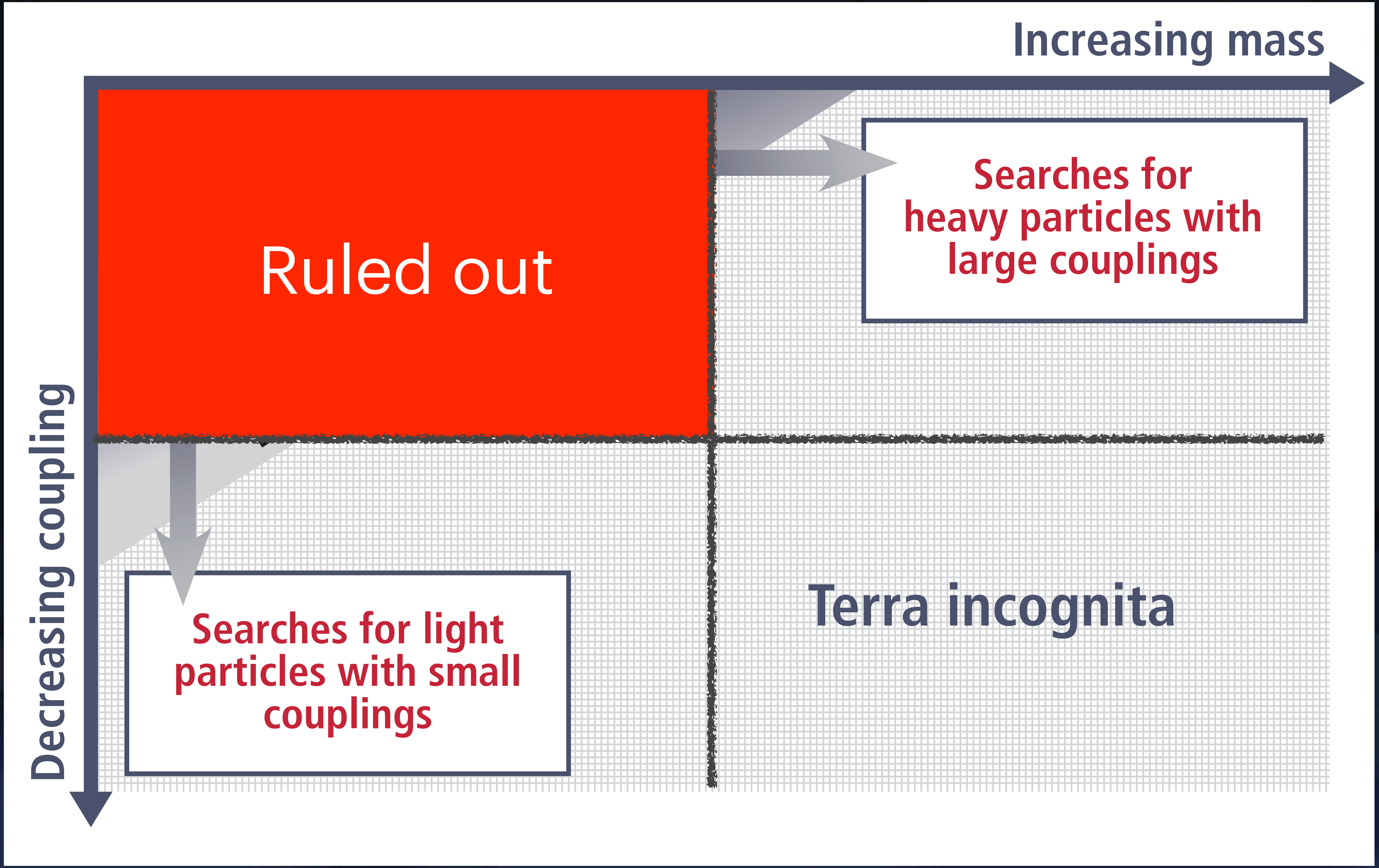
Limits of the Standard Model



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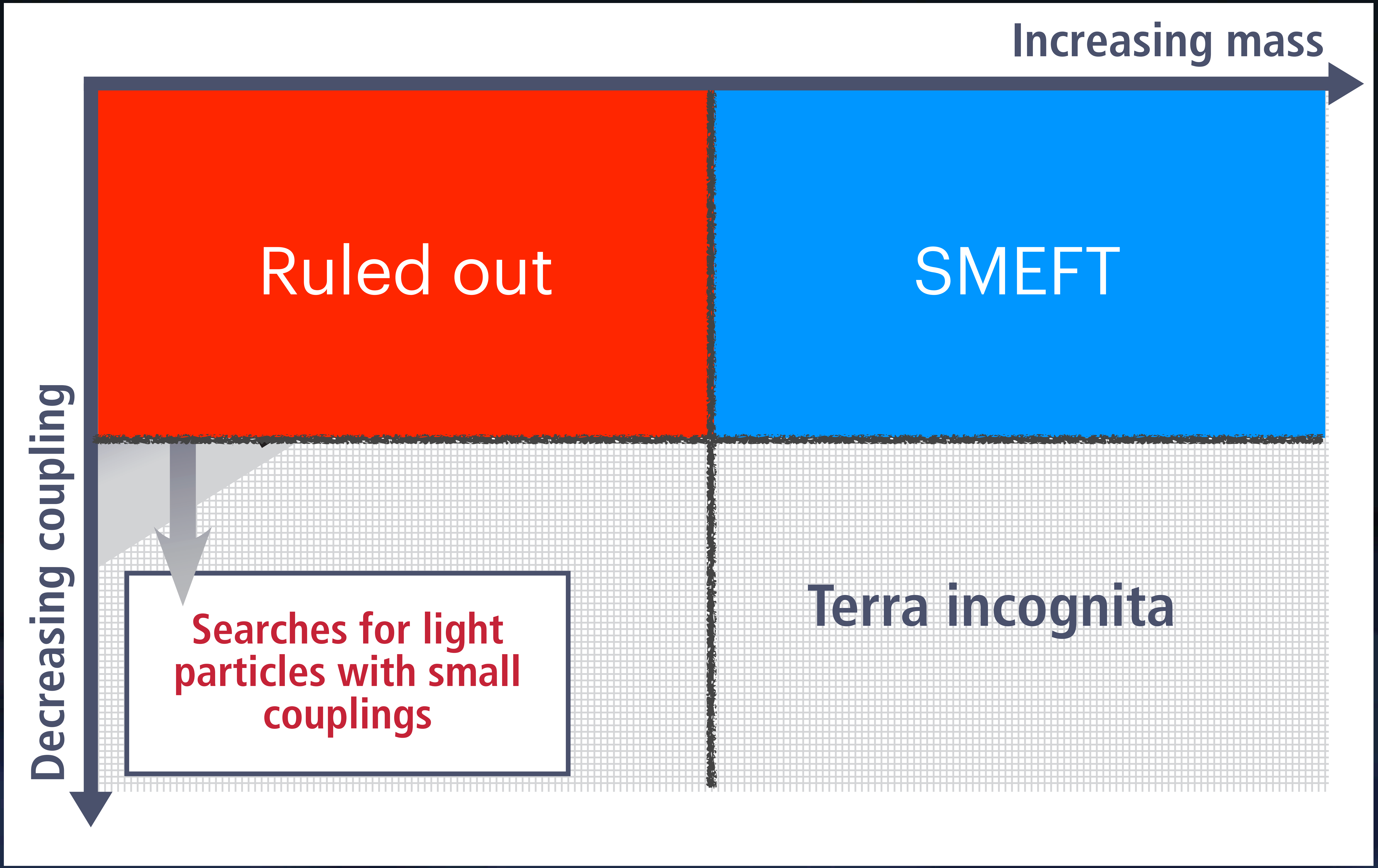
Limits of the Standard Model



Increasing mass

Decreasing coupling

Ruled out

SMEFT

Searches for light particles with small couplings

Terra incognita

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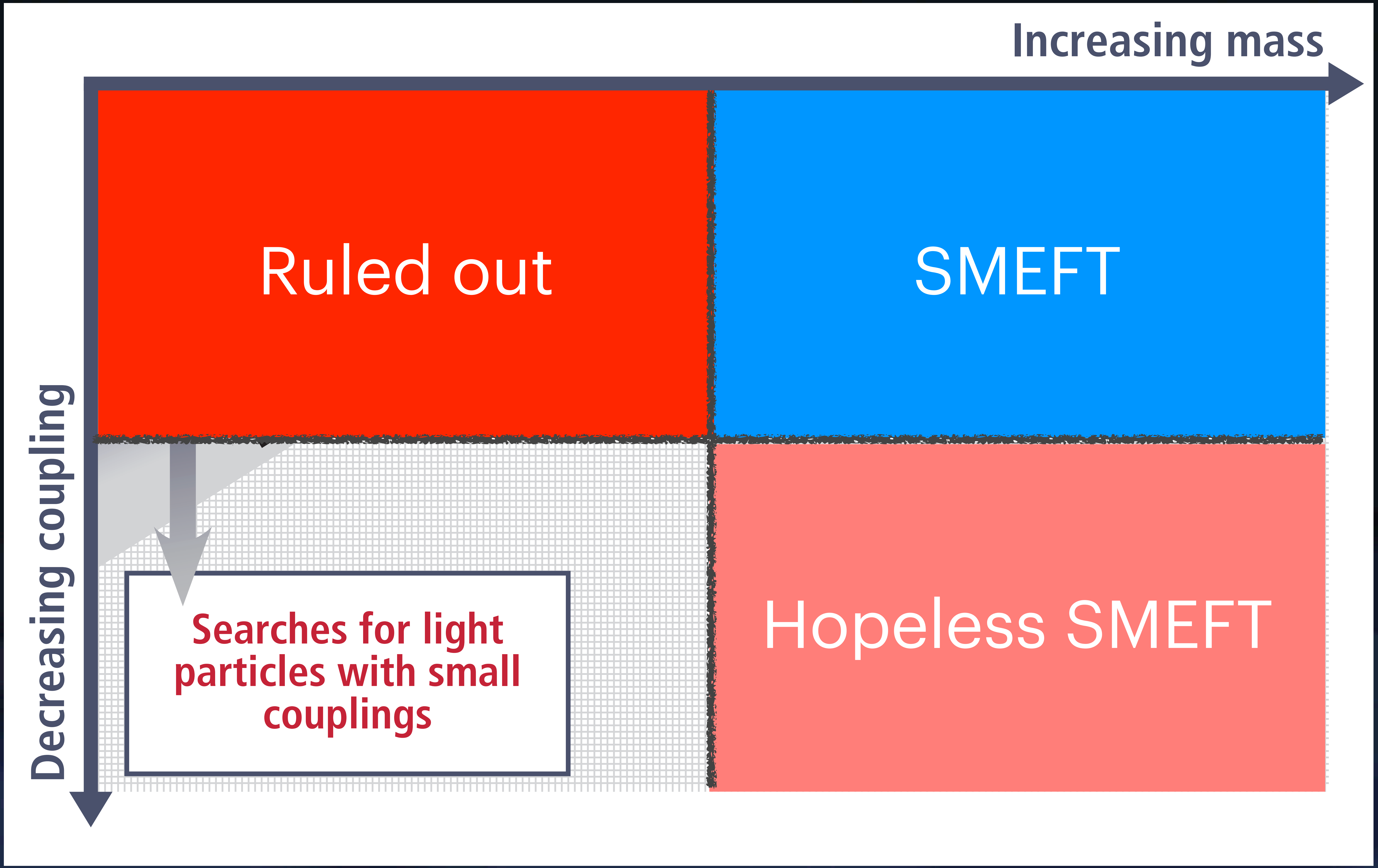
Limits of the Standard Model



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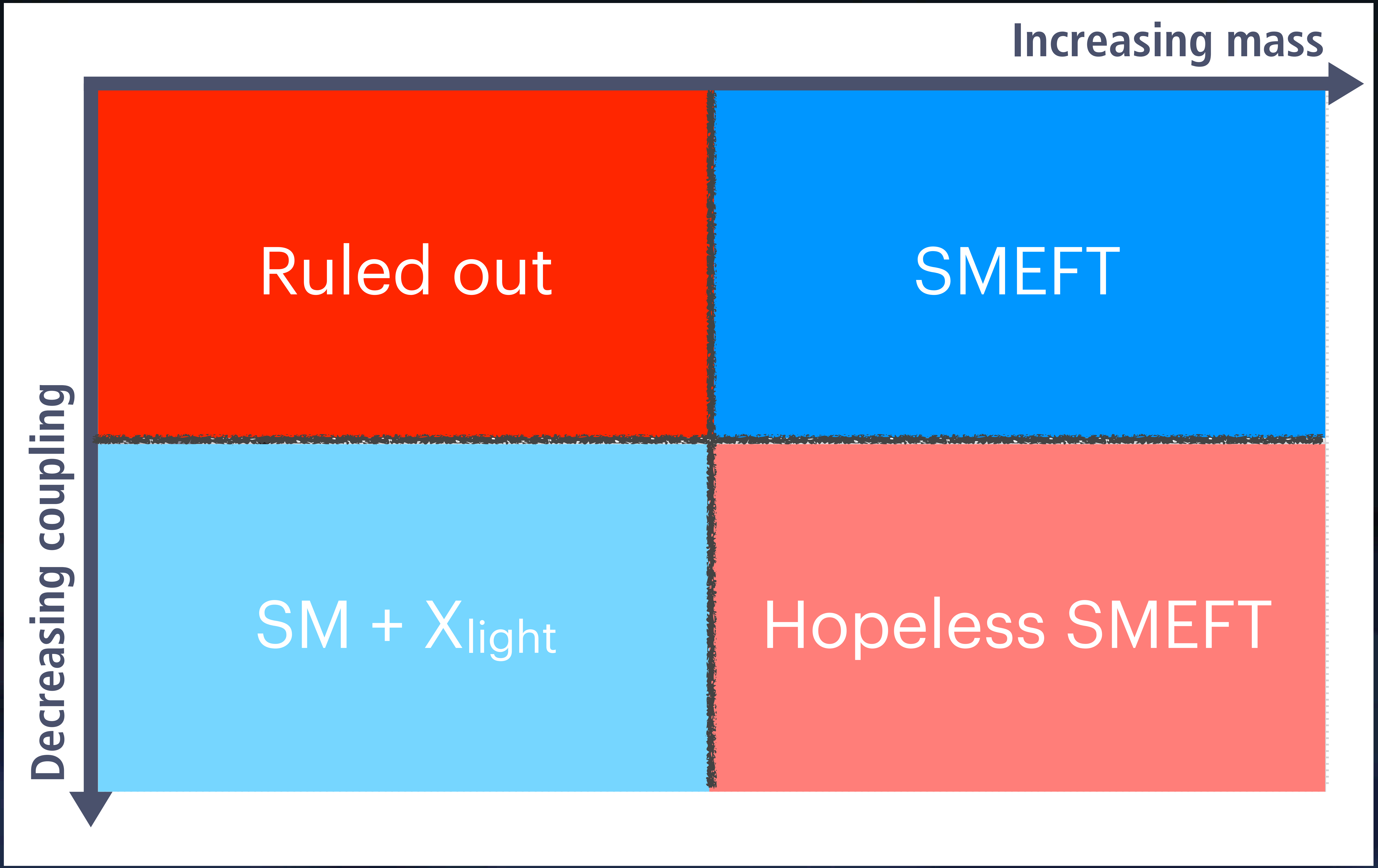
Limits of the Standard Model



Increasing mass

Decreasing coupling

Ruled out

SMEFT

SM + X_{light}

Hopeless SMEFT

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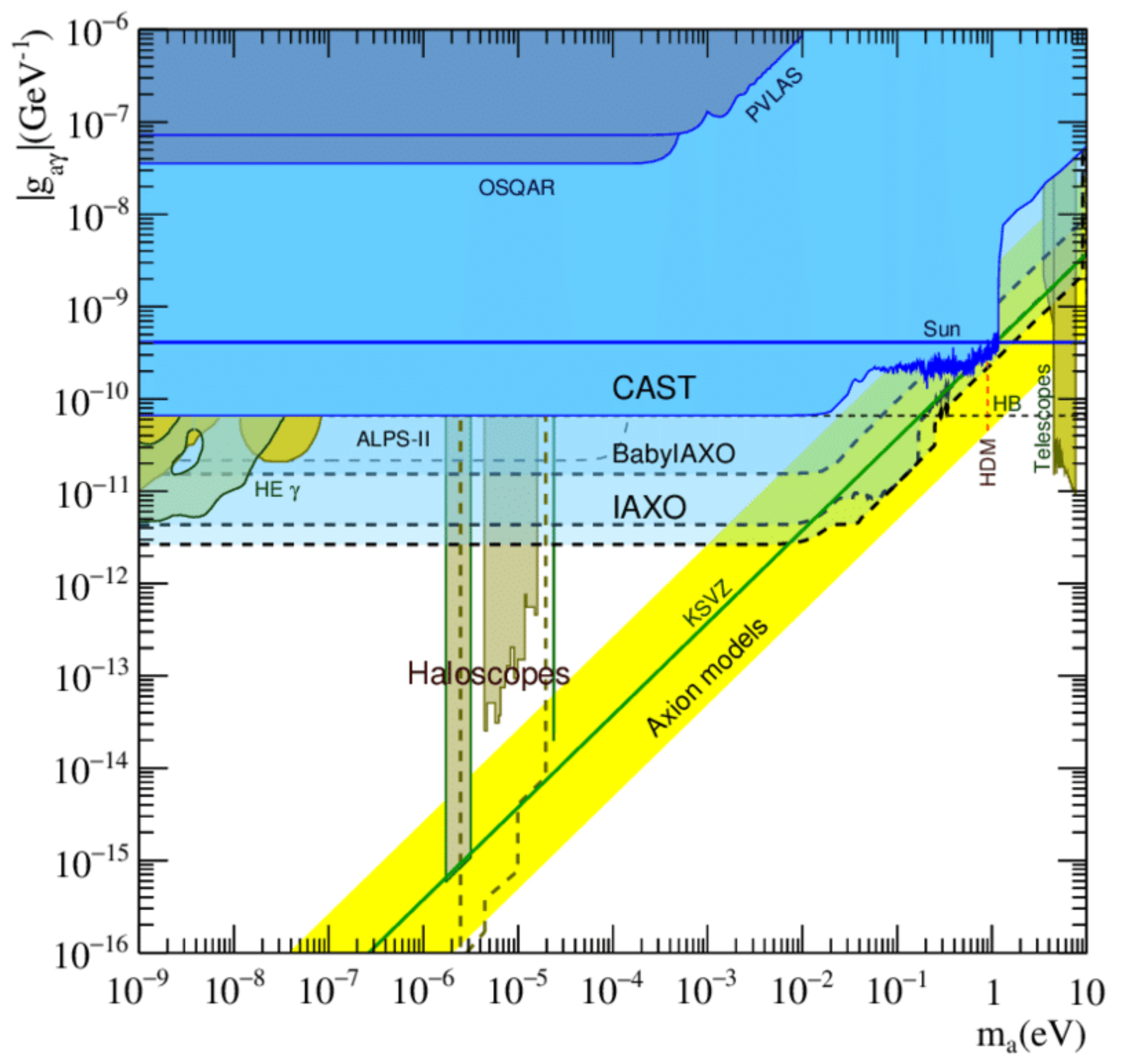
Axions and axion-like particles (ALPs)

Well motivated theoretically: [Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]

- Peccei—Quinn solution to strong CP problem:

$$\mathcal{L}_{\rm QCD} \to \left(\theta + \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi}\, G_{\mu\nu}^a \widetilde{G}^{\mu\nu,a} + \dots$$

- More generally, ALPs arise as pseudo Nambu—Golstone bosons of spontaneously broken global U(1) symmetry
- Axion mass and couplings to Standard Model are inversely proportional to f_a
- For heavier ALPs, couplings to particles other than the photon can be probed in particle-physics experiments



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Effective Lagrangian for a light ALP

- Most general effective Lagrangian for a pseudoscalar boson $\boldsymbol{a}$ coupled to the SM via classically shift-invariant interactions (broken softly by a mass term): [Georgi, Kaplan, Randall 1986]

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}\,a^2 + \overset{\text{couplings to fermions}}{\frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F c_F \gamma_\mu \psi_F} + \overset{\text{coupling to Higgs doublet}}{c_\phi\,\frac{\partial^\mu a}{f}\,(\phi^\dagger i \overleftrightarrow{\boldsymbol{D}}_\mu \phi)}$$

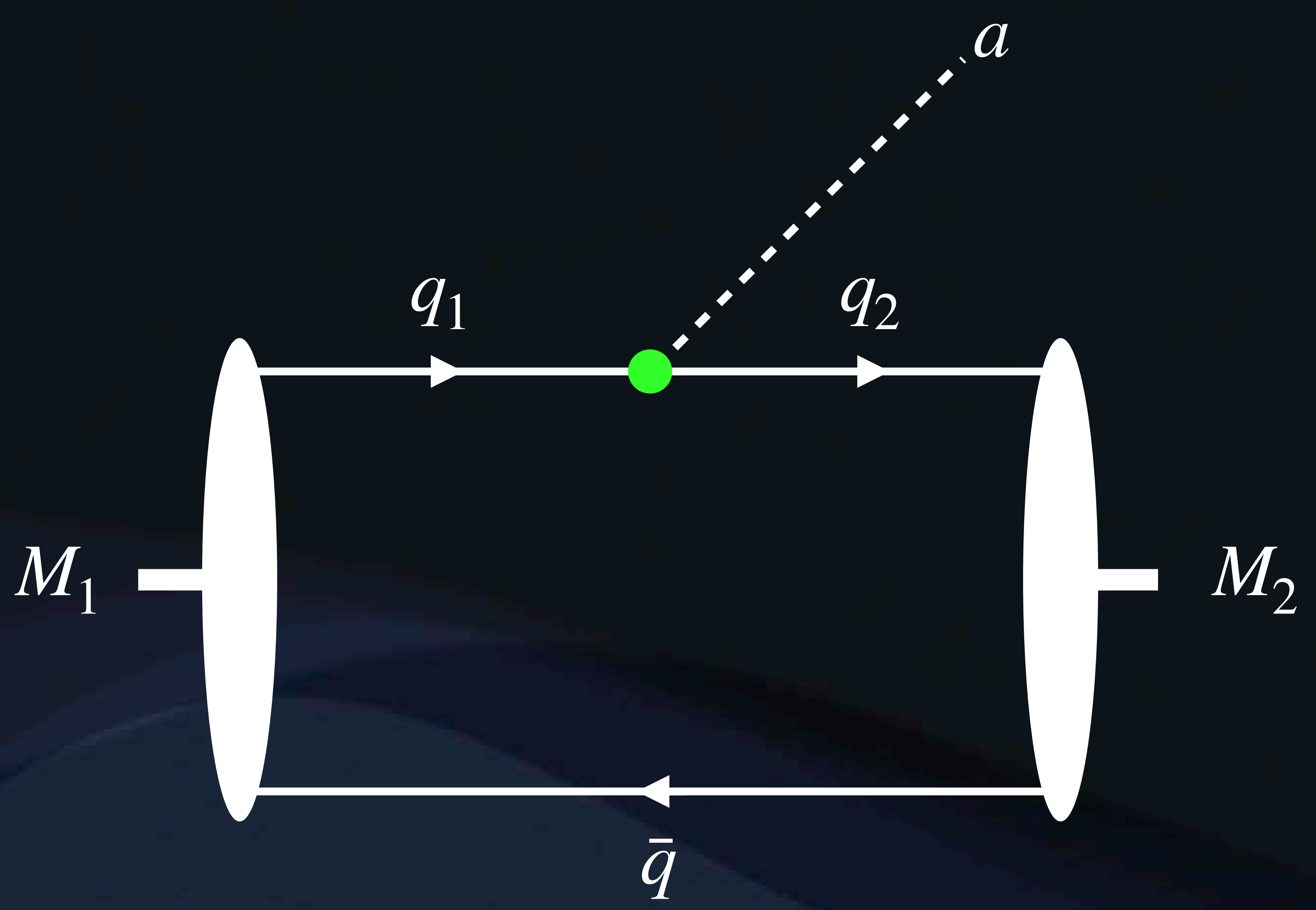
$$+ \overset{\text{coupling to gluons}}{c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde{G}^{\mu\nu,a}} + \overset{\text{coupling to SU(2)}_\text{L}\text{ bosons}}{c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde{W}^{\mu\nu,A}} + \overset{\text{coupling to hypercharge boson}}{c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}}$$

- All interactions are suppressed by inverse powers of f, with $f/|2c_{GG}| = f_a$
- 5 out of the 49 real couplings in this Lagrangian are redundant
- Will always work with physical combinations of coupling parameters

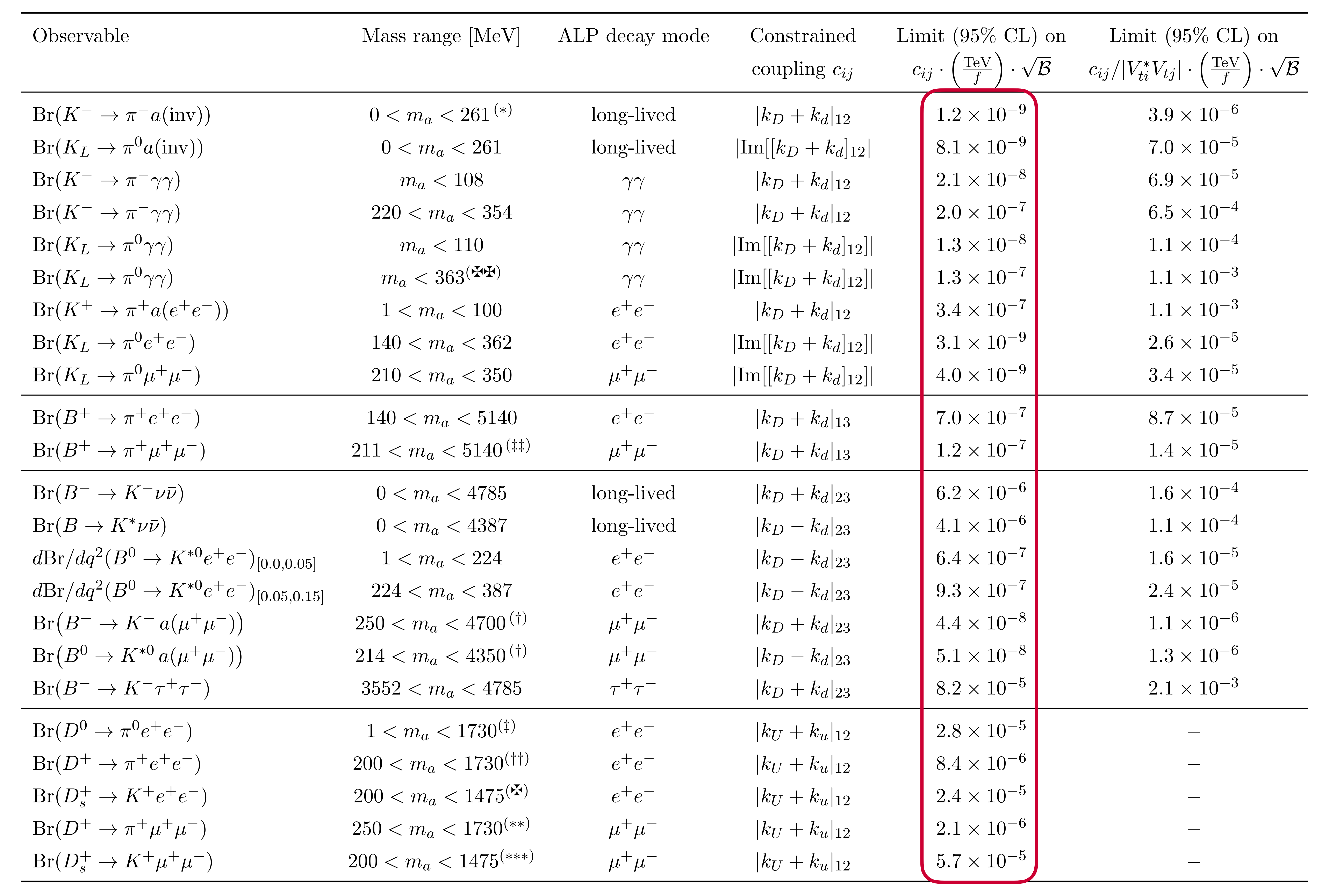
Flavor probes for ALP couplings

Direct probes: ALP production in decays

- FCNC processes analogous to $B \to X_s\gamma$, e.g. $K \to \pi a$ and $B \to Ka$
- Kinematically allowed in certain mass regions only, e.g. $m_a < m_K - m_\pi$
- Phenomenology depends on how the ALP decays ($a \to \gamma\gamma, l^+l^-, \ldots$) and how long it lives



Direct probes: ALP production in decays

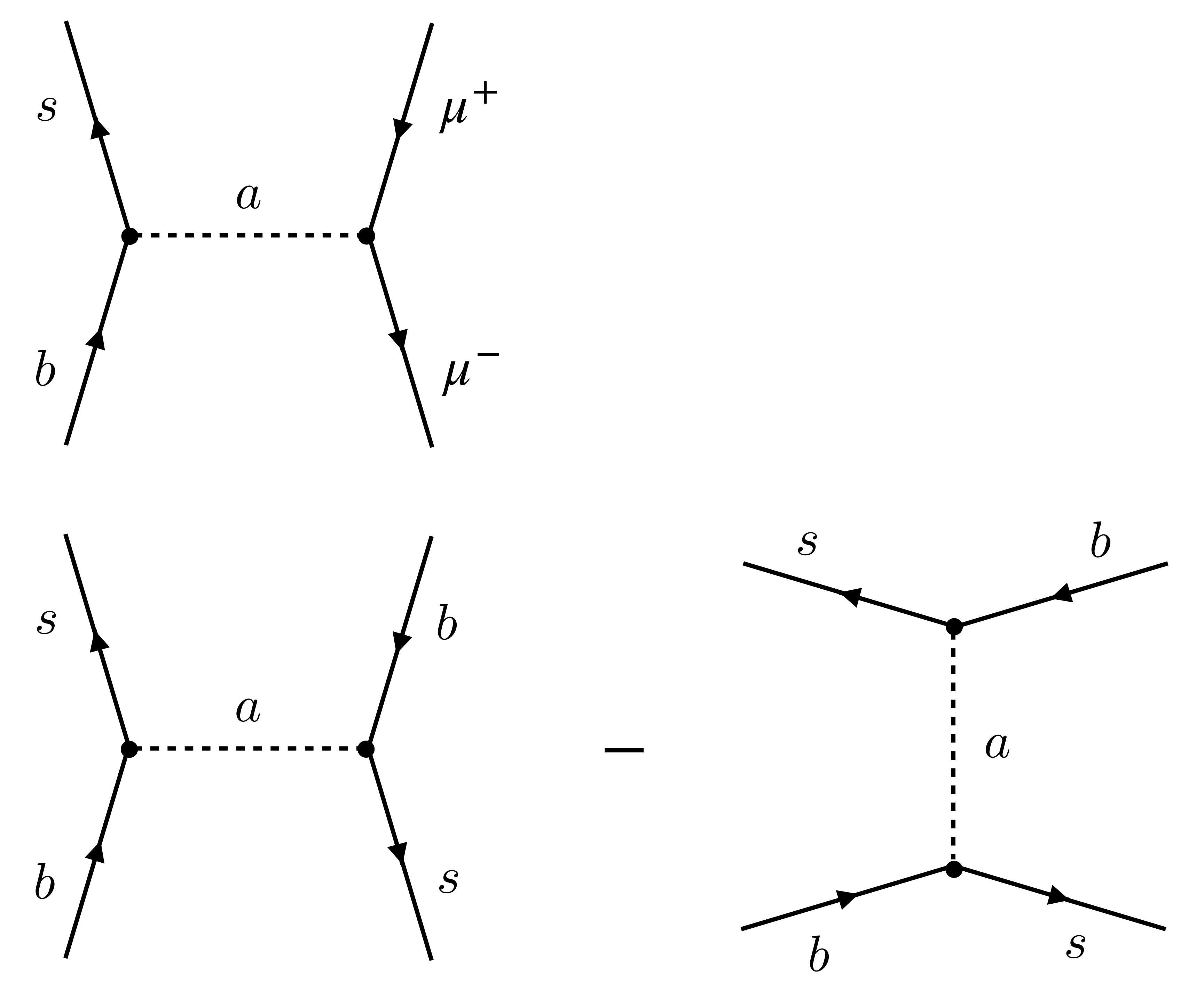


Observable	Mass range [MeV]	ALP decay mode	Constrained coupling c_{ij}	Limit (95% CL) on $c_{ij}\cdot\left(\frac{\text{TeV}}{f}\right)\cdot\sqrt{\mathcal{B}}$	Limit (95% CL) on $c_{ij}/\vert V_{ti}^*V_{tj}\vert\cdot\left(\frac{\text{TeV}}{f}\right)\cdot\sqrt{\mathcal{B}}$
$\text{Br}(K^-\to\pi^-a(\text{inv}))$	$0<m_a<261\,^{(*)}$	long-lived	$\vert k_D+k_d\vert_{12}$	1.2×10^{-9}	3.9×10^{-6}
$\text{Br}(K_L\to\pi^0a(\text{inv}))$	$0<m_a<261$	long-lived	$\vert\text{Im}[[k_D+k_d]_{12}\vert$	8.1×10^{-9}	7.0×10^{-5}
$\text{Br}(K^-\to\pi^-\gamma\gamma)$	$m_a<108$	$\gamma\gamma$	$\vert k_D+k_d\vert_{12}$	2.1×10^{-8}	6.9×10^{-5}
$\text{Br}(K^-\to\pi^-\gamma\gamma)$	$220<m_a<354$	$\gamma\gamma$	$\vert k_D+k_d\vert_{12}$	2.0×10^{-7}	6.5×10^{-4}
$\text{Br}(K_L\to\pi^0\gamma\gamma)$	$m_a<110$	$\gamma\gamma$	$\vert\text{Im}[[k_D+k_d]_{12}]\vert$	1.3×10^{-8}	1.1×10^{-4}
$\text{Br}(K_L\to\pi^0\gamma\gamma)$	$m_a<363^{(\maltese\maltese)}$	$\gamma\gamma$	$\vert\text{Im}[[k_D+k_d]_{12}]\vert$	1.3×10^{-7}	1.1×10^{-3}
$\text{Br}(K^+\to\pi^+a(e^+e^-))$	$1<m_a<100$	e^+e^-	$\vert k_D+k_d\vert_{12}$	3.4×10^{-7}	1.1×10^{-3}
$\text{Br}(K_L\to\pi^0e^+e^-)$	$140<m_a<362$	e^+e^-	$\vert\text{Im}[[k_D+k_d]_{12}]\vert$	3.1×10^{-9}	2.6×10^{-5}
$\text{Br}(K_L\to\pi^0\mu^+\mu^-)$	$210<m_a<350$	$\mu^+\mu^-$	$\vert\text{Im}[[k_D+k_d]_{12}]\vert$	4.0×10^{-9}	3.4×10^{-5}
$\text{Br}(B^+\to\pi^+e^+e^-)$	$140<m_a<5140$	e^+e^-	$\vert k_D+k_d\vert_{13}$	7.0×10^{-7}	8.7×10^{-5}
$\text{Br}(B^+\to\pi^+\mu^+\mu^-)$	$211<m_a<5140\,^{(\ddagger\ddagger)}$	$\mu^+\mu^-$	$\vert k_D+k_d\vert_{13}$	1.2×10^{-7}	1.4×10^{-5}
$\text{Br}(B^-\to K^-\nu\bar\nu)$	$0<m_a<4785$	long-lived	$\vert k_D+k_d\vert_{23}$	6.2×10^{-6}	1.6×10^{-4}
$\text{Br}(B\to K^*\nu\bar\nu)$	$0<m_a<4387$	long-lived	$\vert k_D-k_d\vert_{23}$	4.1×10^{-6}	1.1×10^{-4}
$d\text{Br}/dq^2(B^0\to K^{*0}e^+e^-)_{[0.0,0.05]}$	$1<m_a<224$	e^+e^-	$\vert k_D-k_d\vert_{23}$	6.4×10^{-7}	1.6×10^{-5}
$d\text{Br}/dq^2(B^0\to K^{*0}e^+e^-)_{[0.05,0.15]}$	$224<m_a<387$	e^+e^-	$\vert k_D-k_d\vert_{23}$	9.3×10^{-7}	2.4×10^{-5}
$\text{Br}\big(B^-\to K^-\,a(\mu^+\mu^-)\big)$	$250<m_a<4700\,^{(\dagger)}$	$\mu^+\mu^-$	$\vert k_D+k_d\vert_{23}$	4.4×10^{-8}	1.1×10^{-6}
$\text{Br}\big(B^0\to K^{*0}\,a(\mu^+\mu^-)\big)$	$214<m_a<4350\,^{(\dagger)}$	$\mu^+\mu^-$	$\vert k_D-k_d\vert_{23}$	5.1×10^{-8}	1.3×10^{-6}
$\text{Br}(B^-\to K^-\tau^+\tau^-)$	$3552<m_a<4785$	$\tau^+\tau^-$	$\vert k_D+k_d\vert_{23}$	8.2×10^{-5}	2.1×10^{-3}
$\text{Br}(D^0\to\pi^0e^+e^-)$	$1<m_a<1730^{(\ddagger)}$	e^+e^-	$\vert k_U+k_u\vert_{12}$	2.8×10^{-5}	–
$\text{Br}(D^+\to\pi^+e^+e^-)$	$200<m_a<1730^{(\dagger\dagger)}$	e^+e^-	$\vert k_U+k_u\vert_{12}$	8.4×10^{-6}	–
$\text{Br}(D_s^+\to K^+e^+e^-)$	$200<m_a<1475^{(\maltese)}$	e^+e^-	$\vert k_U+k_u\vert_{12}$	2.4×10^{-5}	–
$\text{Br}(D^+\to\pi^+\mu^+\mu^-)$	$250<m_a<1730^{(**)}$	$\mu^+\mu^-$	$\vert k_U+k_u\vert_{12}$	2.1×10^{-6}	–
$\text{Br}(D_s^+\to K^+\mu^+\mu^-)$	$200<m_a<1475^{(***)}$	$\mu^+\mu^-$	$\vert k_U+k_u\vert_{12}$	5.7×10^{-5}	–

Bauer, MN, Renner, Schnubel, Thamm (2021)

Indirect probes: virtual ALP corrections

- ALP loop corrections to rare processes such as $B_s \to \mu^+\mu^-$ and $B - \bar{B}$ mixing
- Allowed for any value of the ALP mass
- Insensitive to the way in which the ALP decays

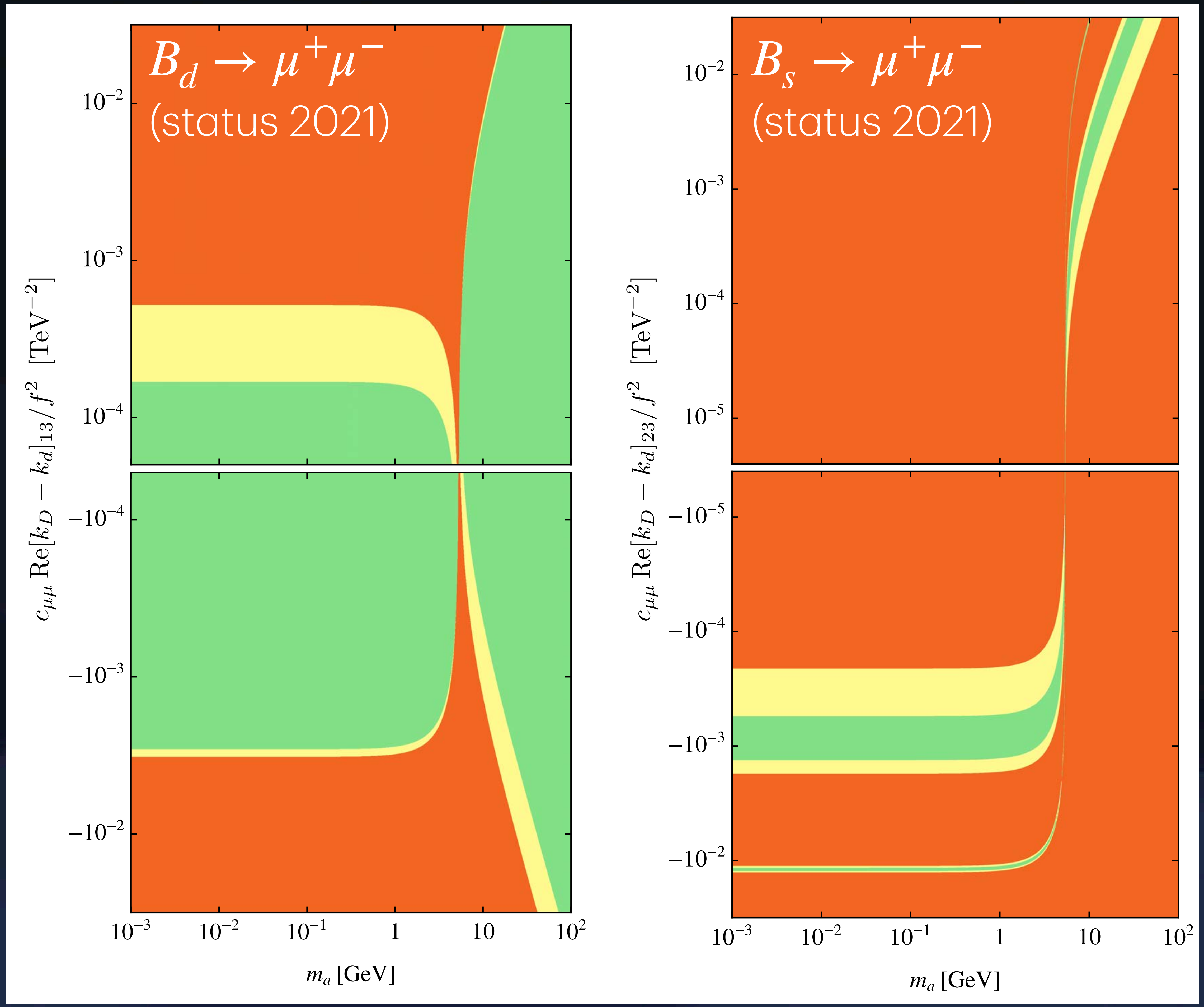


Indirect probes: virtual ALP corrections

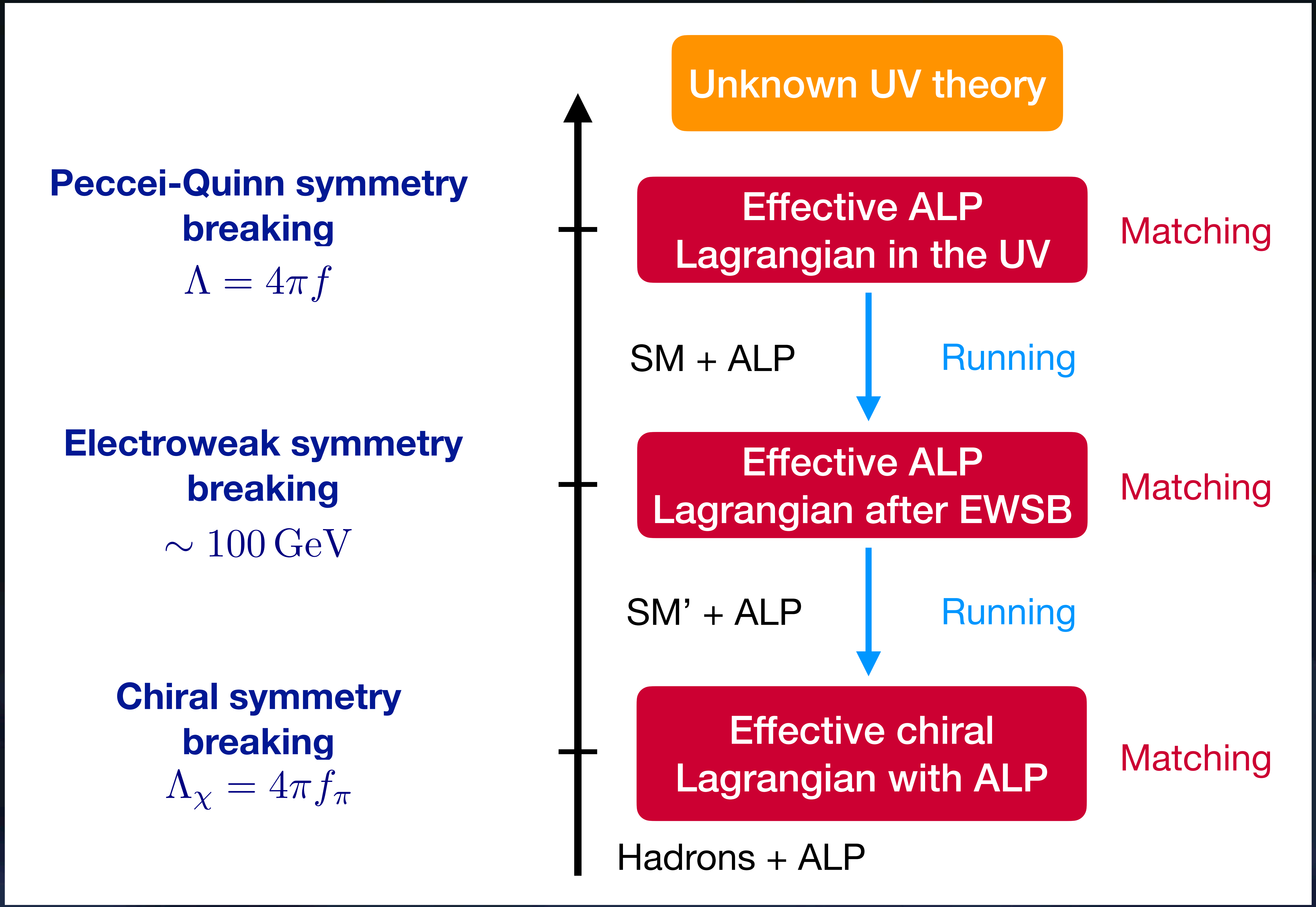
- ALP loop corrections to rare processes such as $B_s \to \mu^+\mu^-$ and $B - \bar{B}$ mixing
- Allowed for any value of the ALP mass
- Insensitive to the way in which the ALP decays
- Simple example:

$$\frac{\mathrm{Br}(B_s \to \mu^+\mu^-)}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} = \left| 1 - \frac{c_{\mu\mu}(\mu_b)}{C_{10}^{\mathrm{SM}}(\mu_b)} \, \frac{\pi}{\alpha(\mu_b)} \, \frac{v^2}{f^2} \, \frac{1}{1 - m_a^2/m_{B_s}^2} \, \frac{[k_D - k_d]_{23}}{V_{ts}^* V_{tb}} \right|^2$$

Bauer, MN, Renner, Schnubel, Thamm (2021)



RG evolution from the UV to lower scales



Unknown UV theory

Peccei-Quinn symmetry breaking

$\Lambda = 4\pi f$

Effective ALP Lagrangian in the UV

Matching

SM + ALP

Running

Electroweak symmetry breaking

$\sim 100\,\text{GeV}$

Effective ALP Lagrangian after EWSB

Matching

SM’ + ALP

Running

Chiral symmetry breaking

$\Lambda_\chi = 4\pi f_\pi$

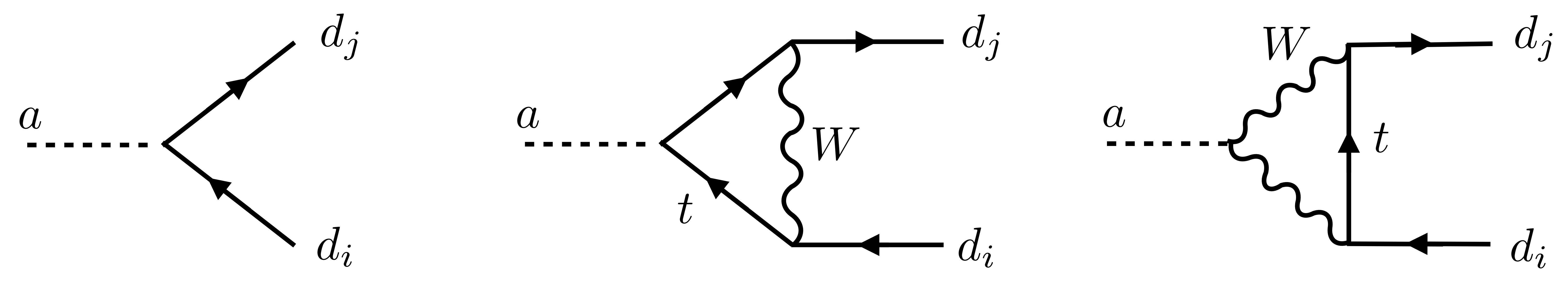
Effective chiral Lagrangian with ALP

Matching

Hadrons + ALP

Bauer, MN, Renner, Schnubel, Thamm (2020); Chala, Guedes, Ramos, Santiago (2020)

Flavor-changing ALP couplings



Bauer, MN, Renner, Schnubel, Thamm (2021)

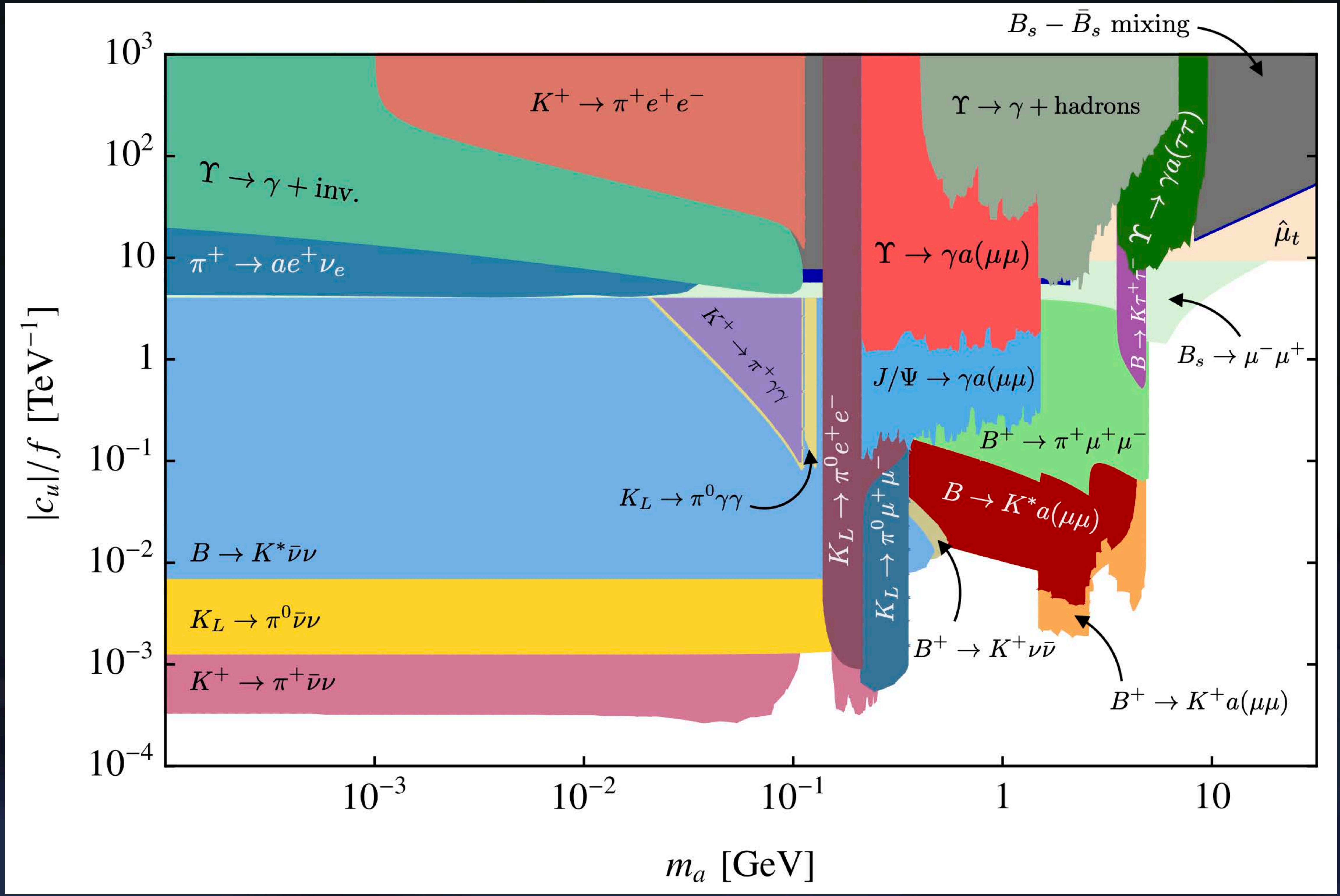
- Can be avoided at UV scale using flavor symmetries, but are unavoidably generated during RG evolution

- Assuming **flavor universality** in the UV yields for $f = 1$ TeV ($\Lambda = 4\pi f$):

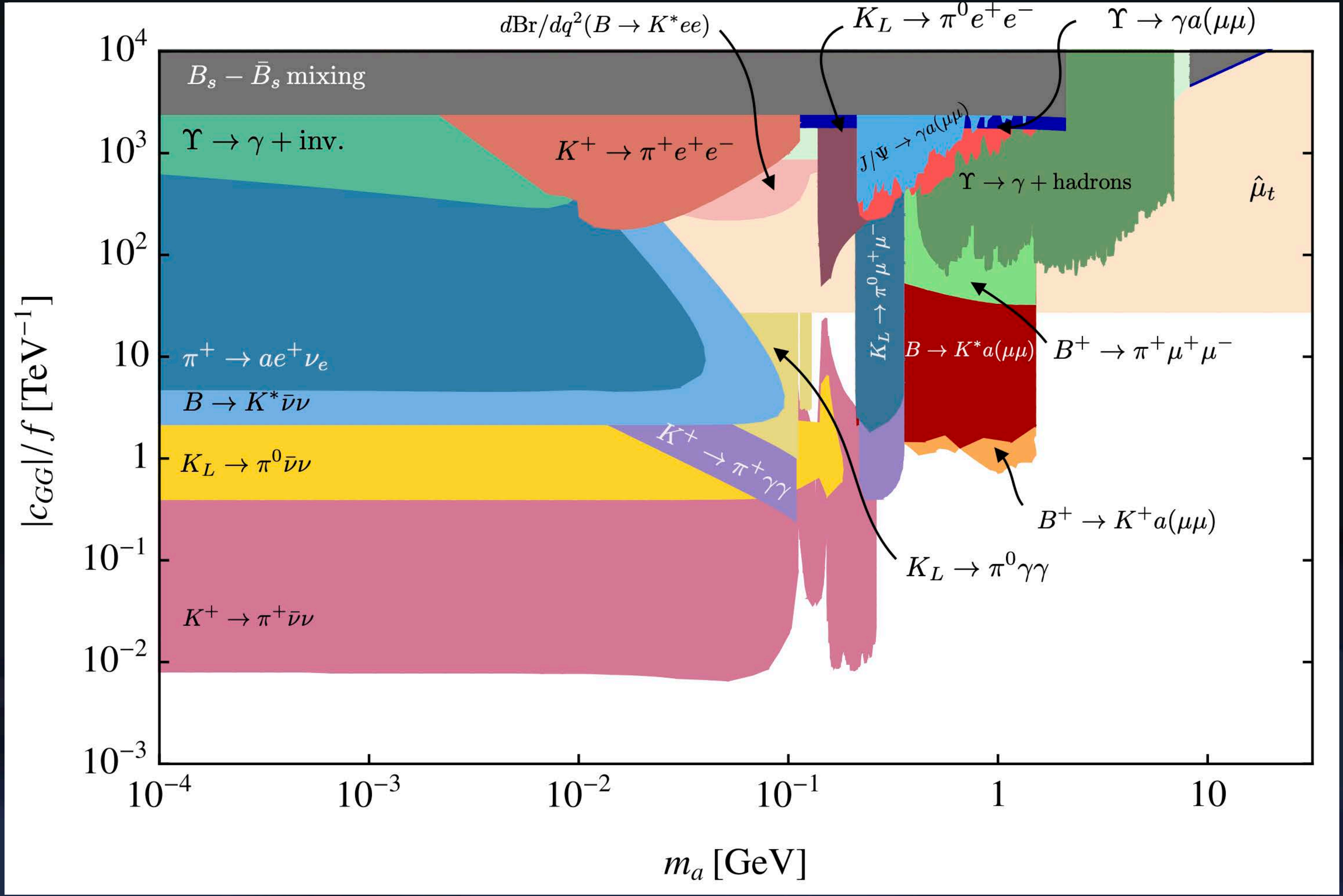
$$[k_{U,E}(m_t)]_{ij} = [k_{u,d,e}(m_t)]_{ij} = 0$$

$$[k_D(m_t)]_{ij} \simeq 0.019\, V_{ti}^* V_{tj} \left[c_{tt}(\Lambda) - 0.0032\, \tilde{c}_{GG}(\Lambda) - 0.0057\, \tilde{c}_{WW}(\Lambda) \right]$$

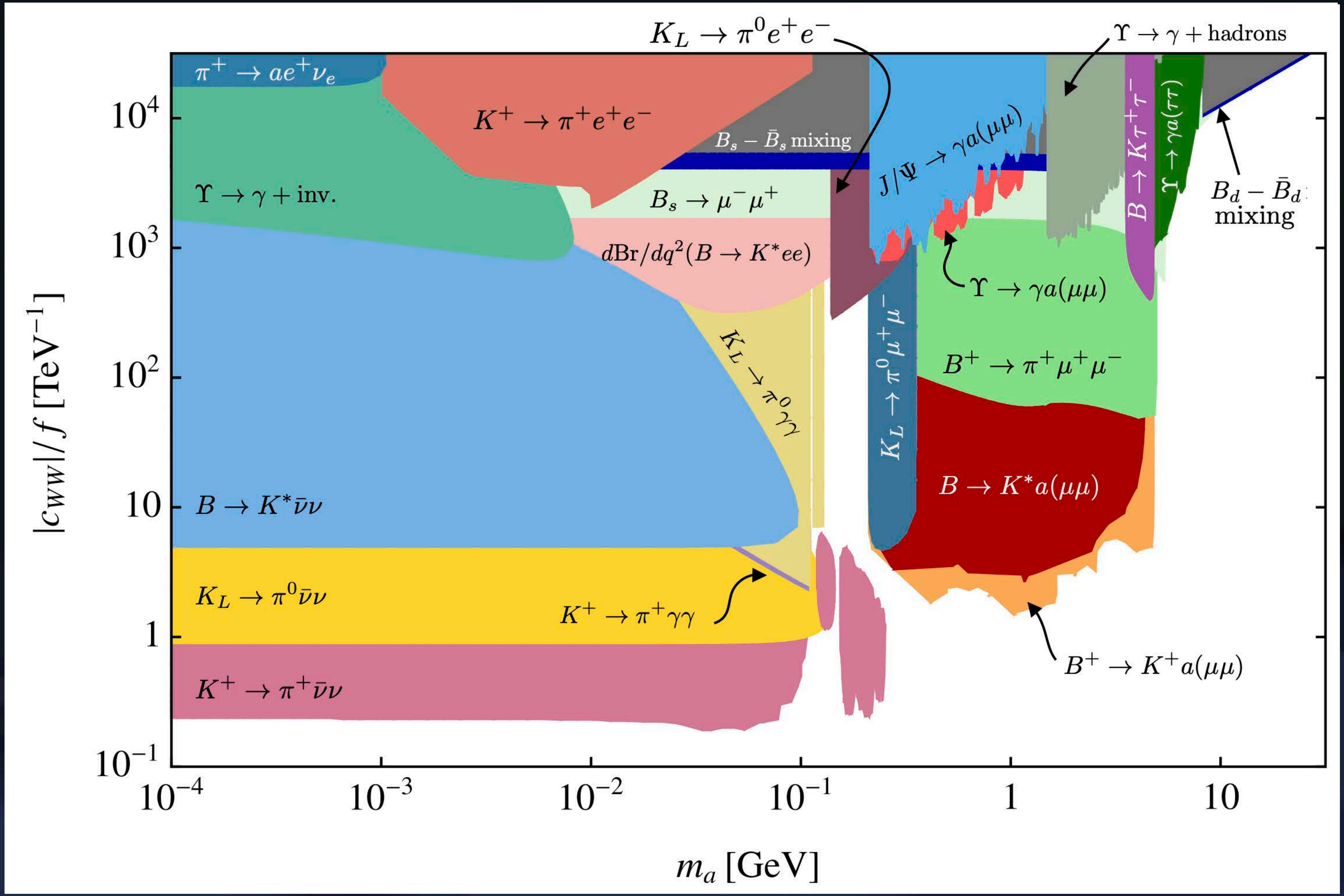
Constraints on ALP-top coupling in UV



Constraints on ALP-gluon coupling in UV



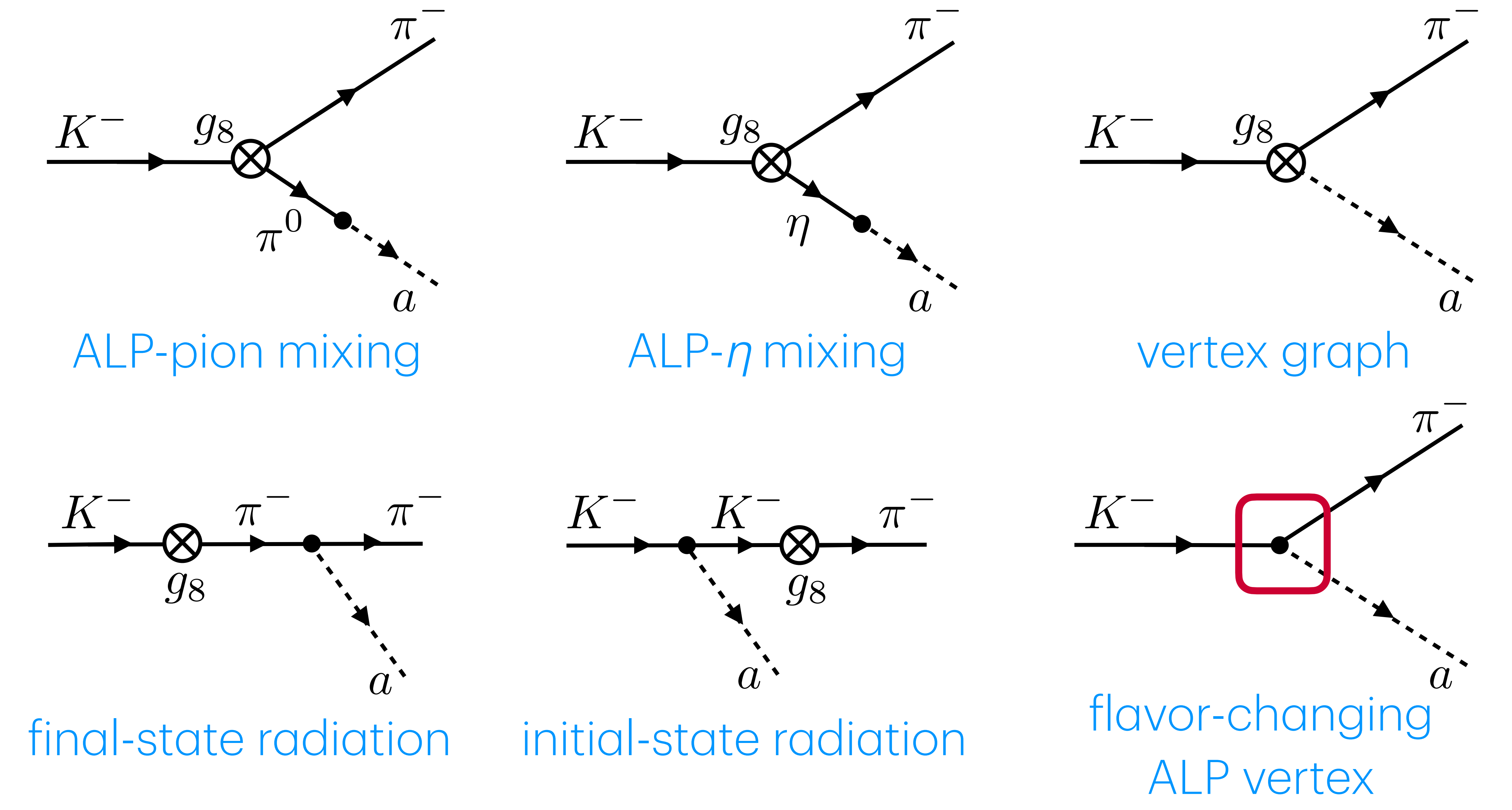
Constraints on ALP-*W* coupling in UV



ALP production in rare kaon decays

Interesting search channel $K^- \to \pi^- a$

- Model-independent analysis using chiral perturbation theory
- Previous calculations used an incorrect implementation of the chiral currents; as a result, the BR gets enhanced by factor 37
- Strong constraints on flavor-violating and flavor-conserving ALP couplings



Bauer, MN, Renner, Schnubel, Thamm (2021)

ALP production in rare kaon decays

Subtlety: a new SU(3) octet operator arises in the LO weak chiral Lagrangian

Cornella, Galda, MN, Wyler (2023)

$$\mathcal{L}_{\text{QCD}}^{(p^2)} = \frac{F^2}{8}\langle(D_\mu\Sigma)\,(D^\mu\Sigma^\dagger) + \chi\Sigma^\dagger + \Sigma\chi^\dagger\rangle + \frac{F^2}{8}\,H_0\,(D_\mu\theta)(D^\mu\theta)$$

$$\mathcal{L}_{\text{weak}}^{(p^2)} = \frac{F^4}{4}\Big[G_8\langle\lambda_6 L_\mu L^\mu\rangle + G_8^\theta\,\underline{(D_\mu\theta)\langle\lambda_6 L^\mu\rangle}\Big] + \text{h.c.}$$

$$L_\mu = \Sigma\, i\,(D_\mu\Sigma^\dagger)$$

$$D_\mu\theta = -2\tilde{c}_{GG}(\partial_\mu a)/f$$

Whereas G_8 is known from $K \to \pi\pi$ decays, G_8^θ is still unknown

ALP production in rare kaon decays

Interesting search channel $K^- \to \pi^- a$

- At NLO in chiral perturbation theory the calculation is far more involved
- NLO QCD and weak chiral Lagrangians need to be supplemented by 3 resp. 9 operators involving $D_\mu \theta$
- Sensitivity to several poorly known low-energy constants
- Modest NLO corrections with sizable uncertainties

Cornella, Galda, MN, Wyler (2023)

ALP production in rare kaon decays

Contributions proportional to G_8 (for $m_a = 0$):

$$i\mathcal{A}_{\text{LO}}^{G_8} = \frac{G_8 F_\pi^2\, m_K^2}{2f} \Big[1.88\, \tilde{c}_{GG} - 0.02\, c_{uu}^a - 0.48\, (c_{dd}^a + c_{ss}^a) \Big]$$

$$\begin{aligned} i\mathcal{A}_{\text{NLO}}^{G_8} = \frac{G_8 F_\pi^2\, m_K^2}{2f} \Big[& (-0.25 \pm 0.43 \pm 0.61)\, \tilde{c}_{GG} + (5.21 \pm 1.03 \pm 6.52) \cdot 10^{-3}\, c_{uu}^a \\ & + (0.06 \pm 0.11 \pm 0.16)\, (c_{dd}^a + c_{ss}^a) \Big] \end{aligned}$$

Contribution proportional to $G_8{}^\theta$ (for $m_a = 0$):

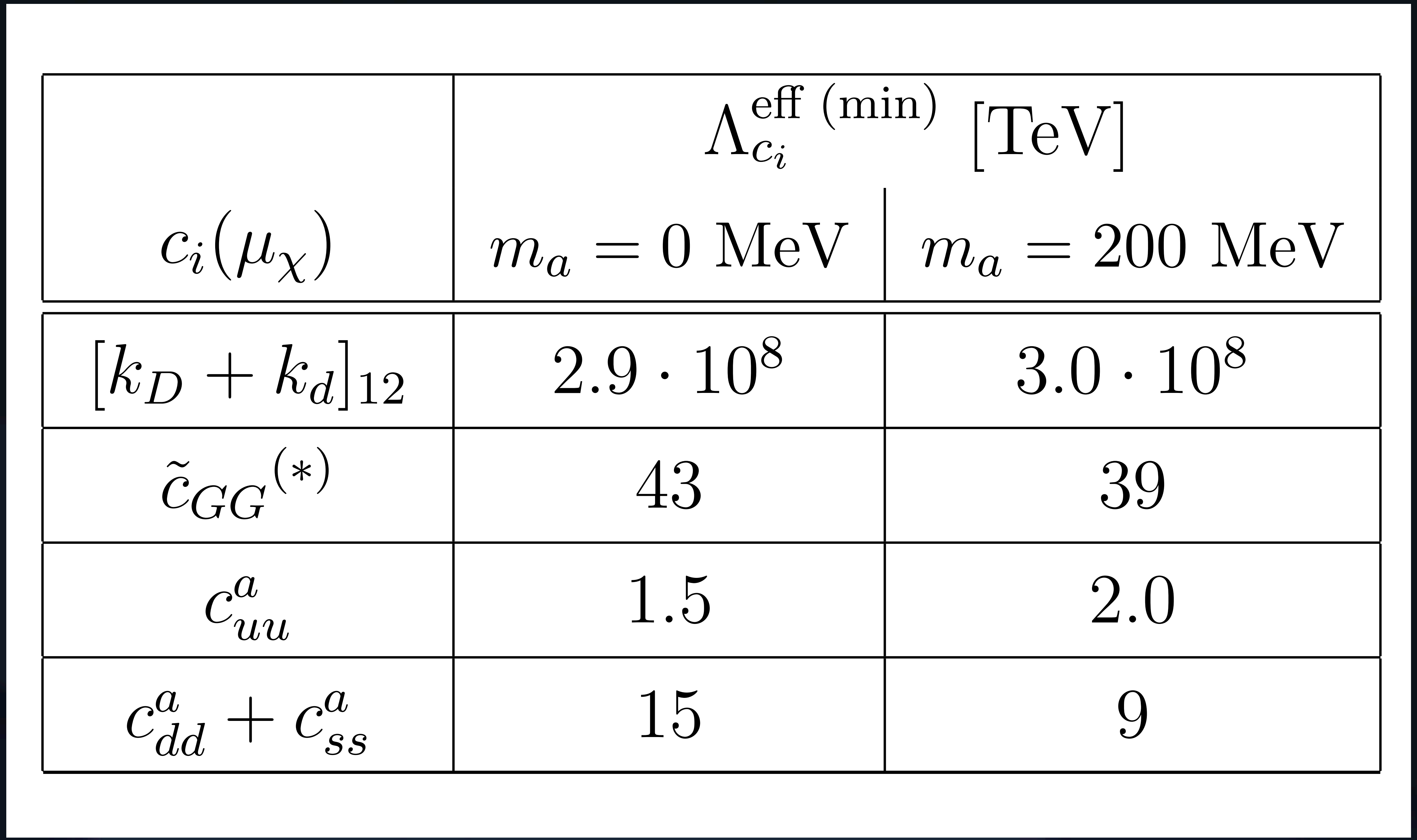
$$i\mathcal{A}_{\text{LO+NLO}}^{G_8^\theta} = \frac{G_8^\theta\, F_\pi^2\, m_K^2}{2f} \; \big[-1.84_{\text{LO}} + (0.25 \pm 0.43 \pm 0.60)_{\text{NLO}} \big]\, \tilde{c}_{GG}$$

Bounds on ALP couplings

Interesting search channel $K^- \to \pi^- a$

- NA62 experimental limits on $K^- \to \pi^- X$ imply bounds on ALP couplings (one at a time), which we express in the form of parameters $\Lambda^{\rm eff}_{c_i} = f/|c_i|$ [NA62: 2103.15389]

- New-physics scales probed range from few to tens of TeV



$c_i(\mu_\chi)$	$\Lambda^{\rm eff\,(min)}_{c_i}$ [TeV] $m_a = 0$ MeV	$m_a = 200$ MeV
$[k_D + k_d]_{12}$	$2.9 \cdot 10^8$	$3.0 \cdot 10^8$
$\tilde{c}_{GG}{}^{(*)}$	43	39
c^a_{uu}	1.5	2.0
$c^a_{dd} + c^a_{ss}$	15	9

Cornella, Galda, MN, Wyler (2023)

$^{(*)}$ assuming $G_8^\theta = 0$

Bounds on ALP couplings

Interesting search channel $K^- \to \pi^- a$

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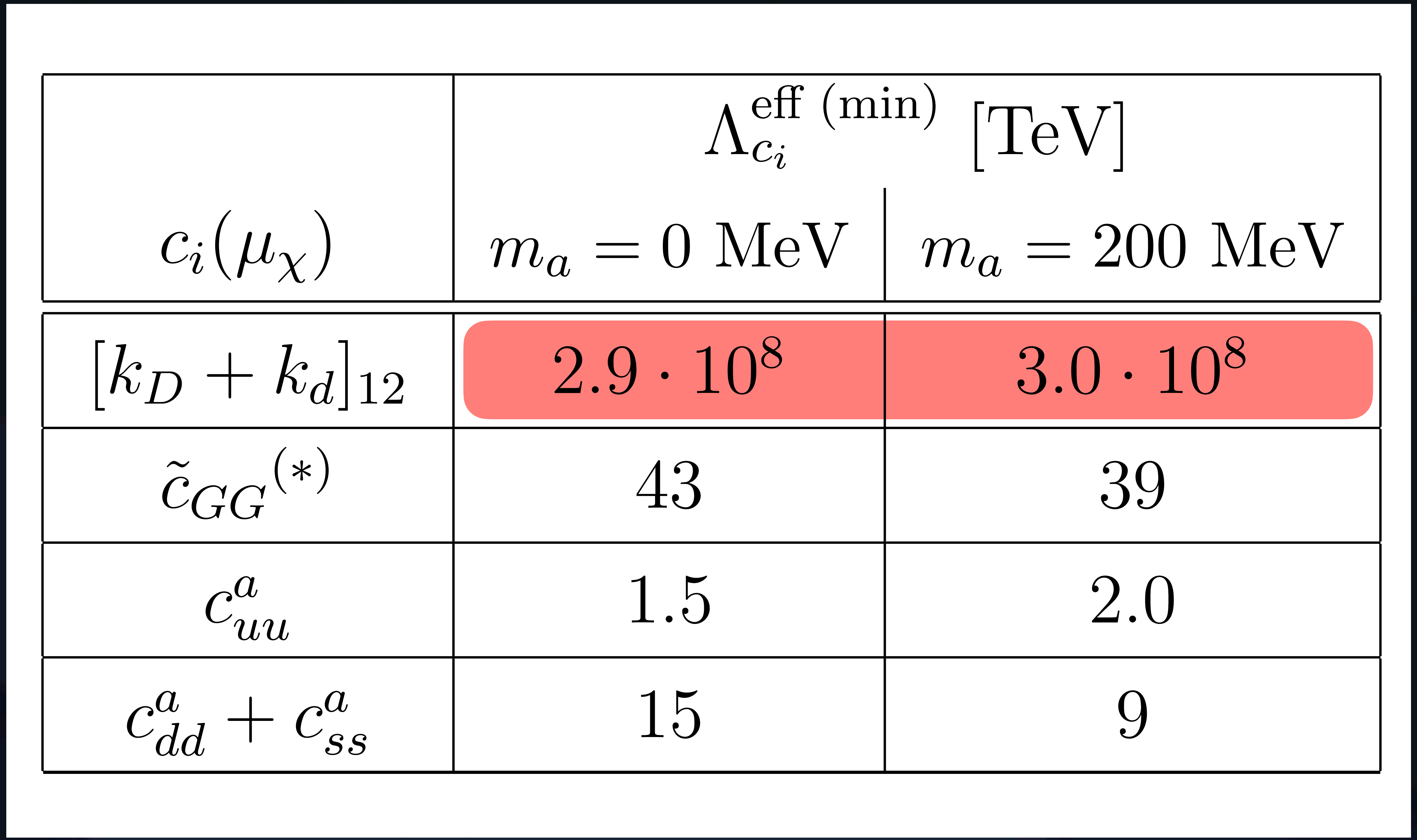
- New-physics scales probed range from few to tens of TeV

- Strong bounds on flavor-changing ALP couplings call for a flavor symmetry, else:

$$f_a \sim f > 30 \cdot 10^{10}\ \text{GeV}$$



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$\tilde{c}_{GG}{}^{(*)}$	43	39
c_{uu}^a	1.5	2.0
$c_{dd}^a + c_{ss}^a$	15	9

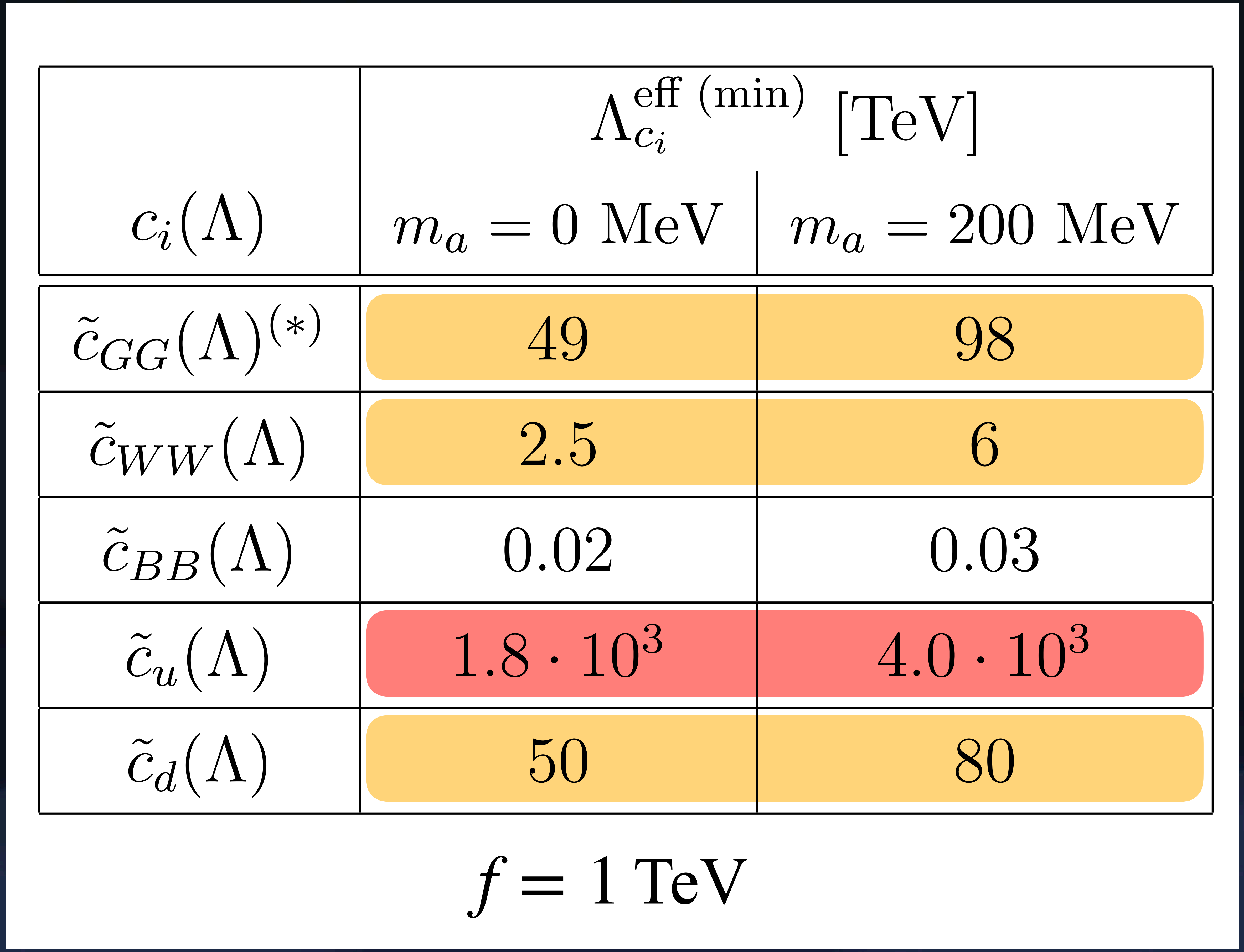
Cosmological upper bound:

$$f_a \lesssim 10^{10}\ \text{GeV} \quad (\text{KSVZ})$$
$$2 \cdot 10^9\ \text{GeV} \quad (\text{DFSZ})$$

Gorghetto, Hardy, Villadoro (2021)

Bounds on ALP couplings

- Large flavor-changing ALP couplings can be avoided by assuming a **flavor-universal ALP** at the UV scale $\Lambda = 4\pi f$
- Still, at low energies flavor-changing couplings are generated by RG effects
- Obtained strong bounds on the ALP couplings to gluons, *W*-bosons and quarks are the best particle-physics bounds in the mass range below 340 MeV



$c_i(\Lambda)$	$\Lambda^{\text{eff (min)}}_{c_i}$ [TeV]	
	$m_a = 0$ MeV	$m_a = 200$ MeV
$\tilde{c}_{GG}(\Lambda)^{(*)}$	49	98
$\tilde{c}_{WW}(\Lambda)$	2.5	6
$\tilde{c}_{BB}(\Lambda)$	0.02	0.03
$\tilde{c}_{u}(\Lambda)$	$1.8 \cdot 10^3$	$4.0 \cdot 10^3$
$\tilde{c}_{d}(\Lambda)$	50	80

$f = 1$ TeV

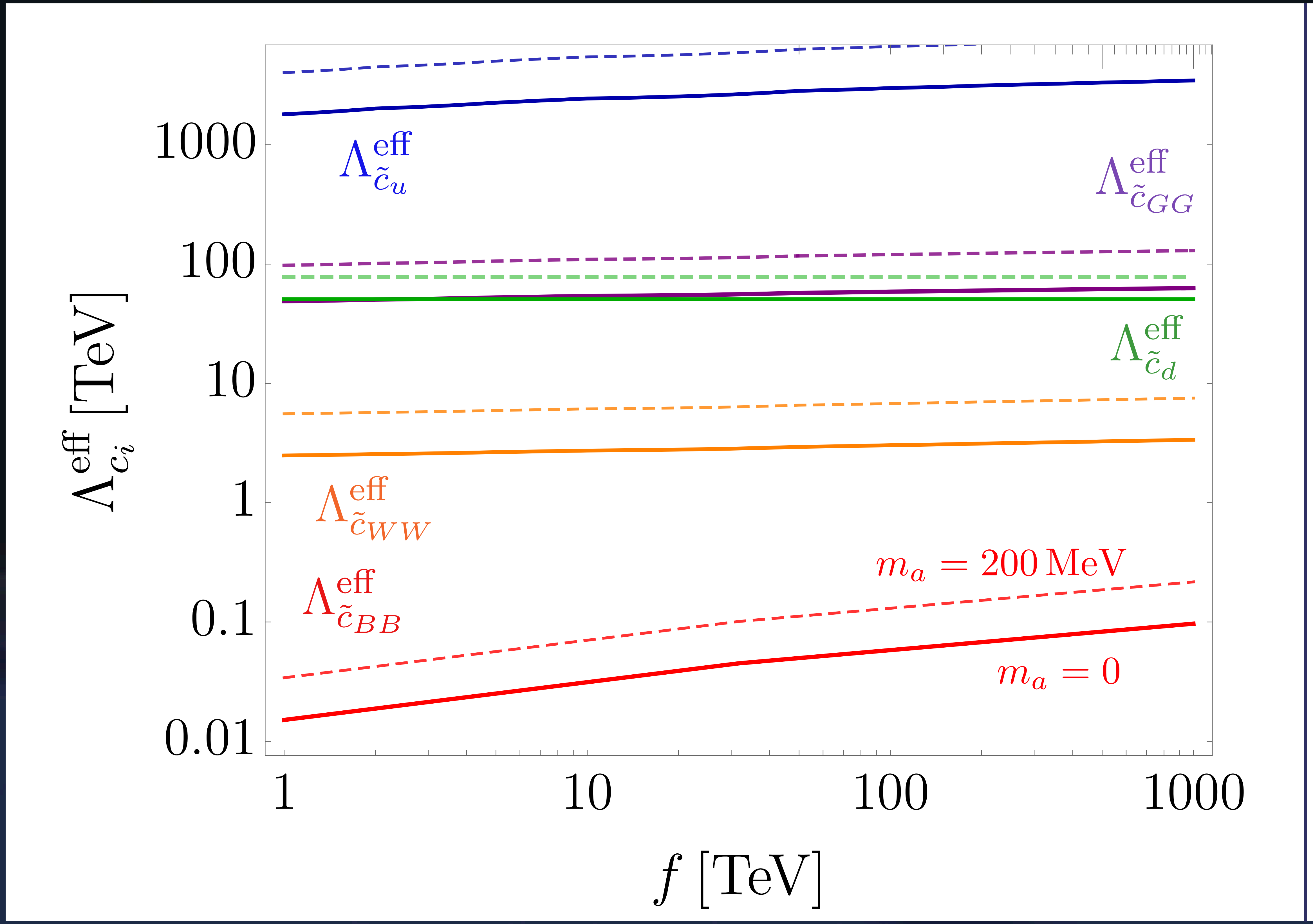
Cornella, Galda, MN, Wyler (2023)

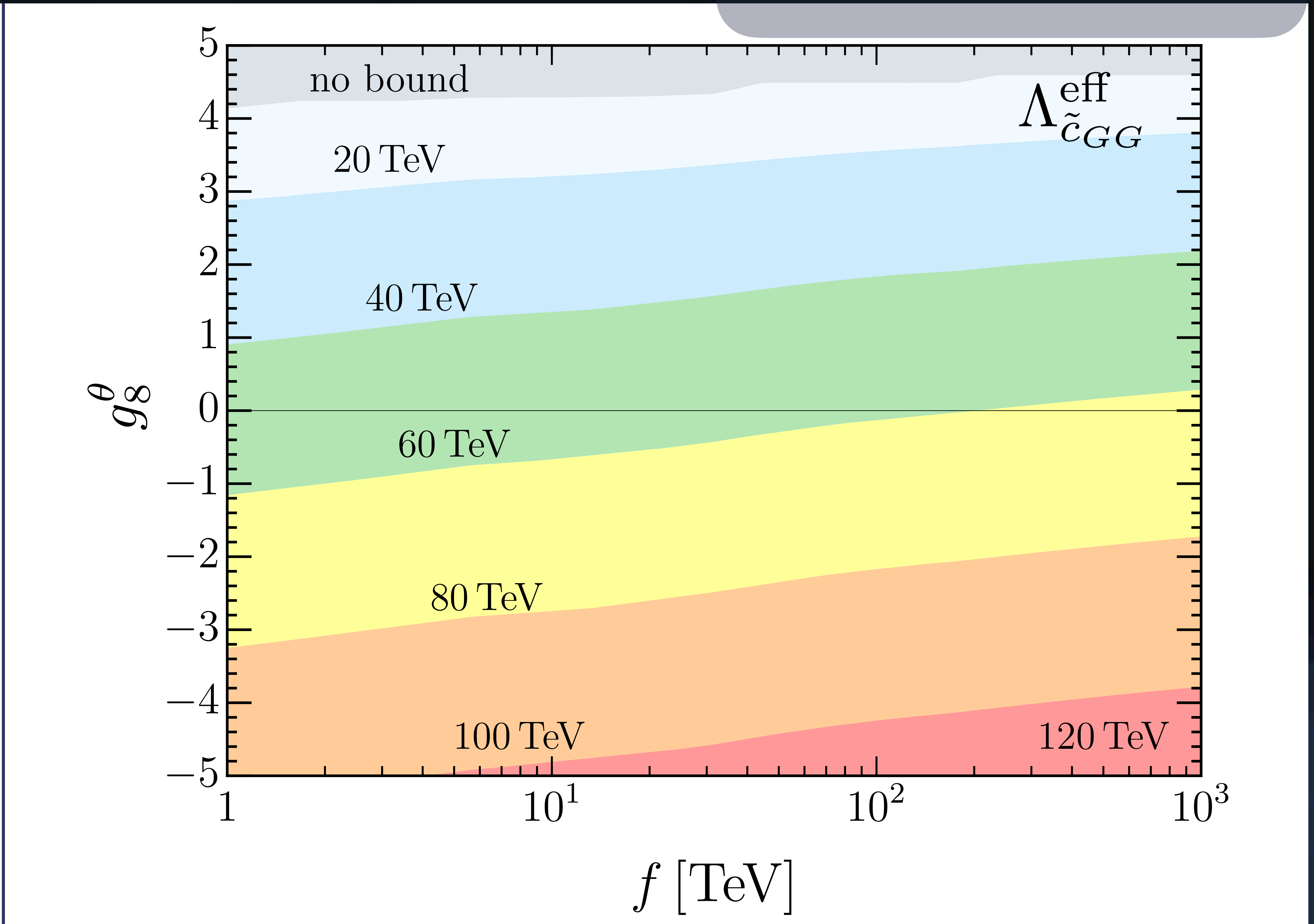
Bounds on ALP couplings

Logarithmic dependence of the effective new-physics scales on f:

Dependence of $\Lambda^{\text{eff}}_{\tilde{c}_{GG}}$ on the low-energy constant G_8^θ:

$$G_8^\theta = -\frac{G_F}{\sqrt{2}} V_{ud}^* V_{us}\, g_8^\theta$$





Conclusions

- Axions and axion-like particles belong to a class of well-motivated light BSM particles with weak couplings to the Standard Model
- They are interesting targets for searches in high-energy physics, using collider, flavor, and precision probes
- Rare meson decays have been discussed in detail, with the process $K^- \to \pi^- a$ provides the strongest particle-physics bounds (for $m_a < 340$ MeV) on almost all ALP couplings to the SM

Thank you!