Flavour Probes of MeV-GeV ALPs

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with Martin Bauer, Matthias Neubert, Sophie Renner and Marvin Schnubel

based on arXiv: 1708.00443, 1808.10323, 1908.00008, 2012.12272, 2102.13112, 2103.?????

THE UNIVERSITY OF MELBOURNE

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KITP PRECISION21

Outline

1. Theory Motivations for ALPs
2. Effective Lagrangian and Operator Evolution
3. Phenomenology of Flavour Changing ALP Couplings to
    - Quarks
    - Leptons

See Marvin Schnubel's talk

4. Conclusions

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Theory Motivation for ALPs

Axion-like particles are pseudo-Nambu Goldstone bosons

Solves $(g-2)_\mu$ anomaly

QCD axion

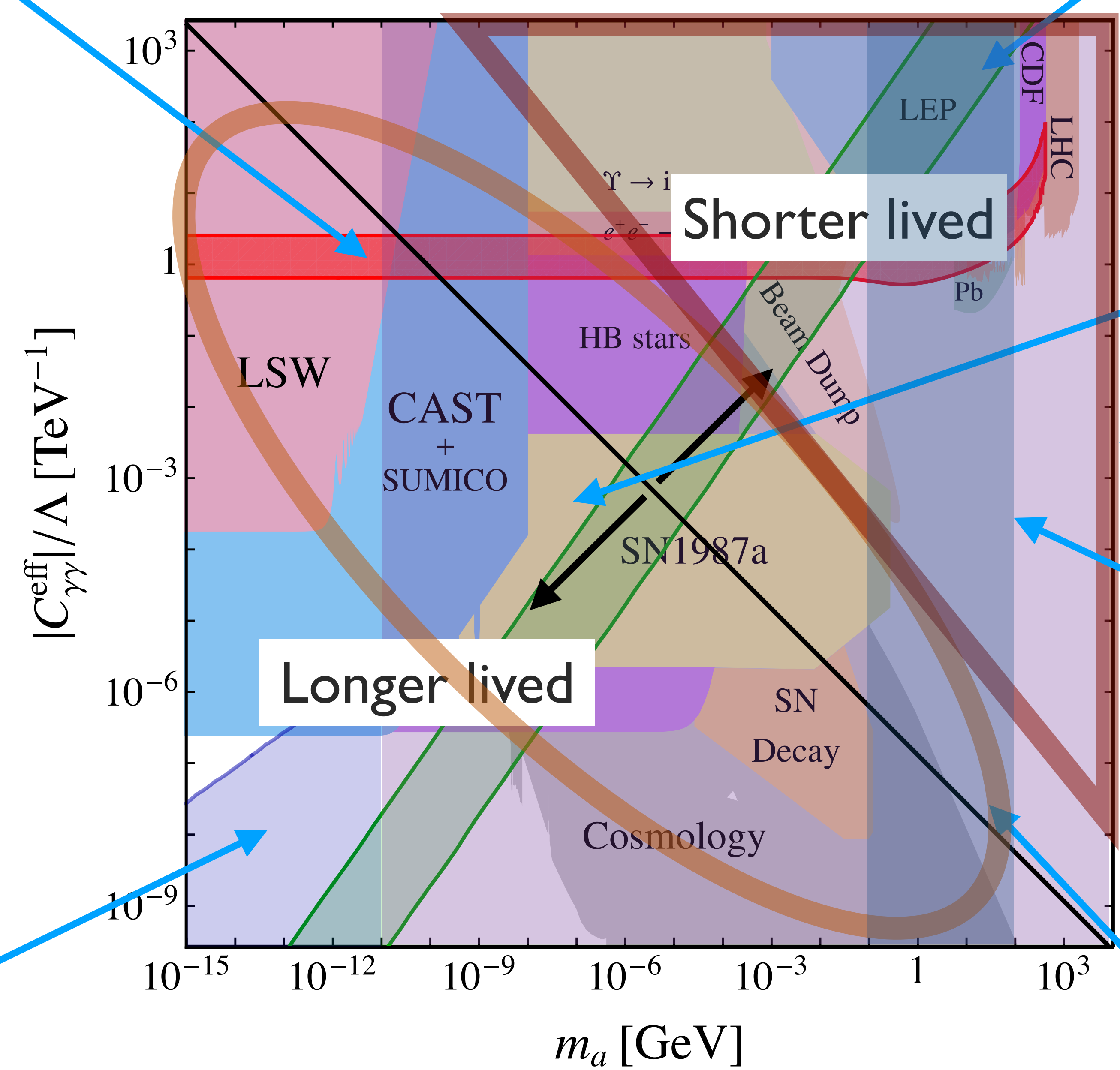
9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

ALPs from sun and stars

ALPs decay within collider

pNGB in supersymmetric or composite models

0902.1483, 1312.5330, 1702.02152



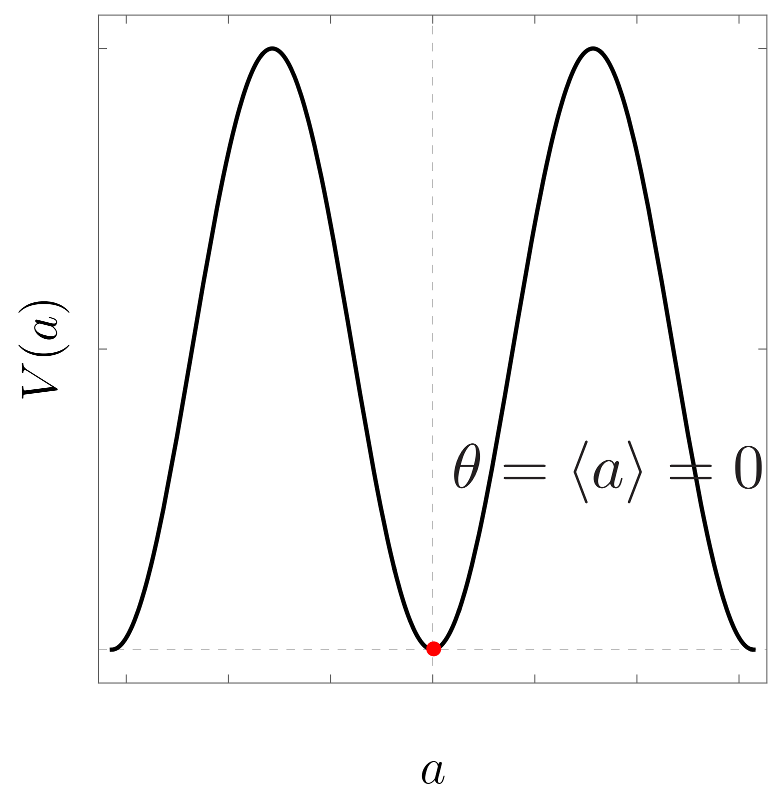
DM candidate

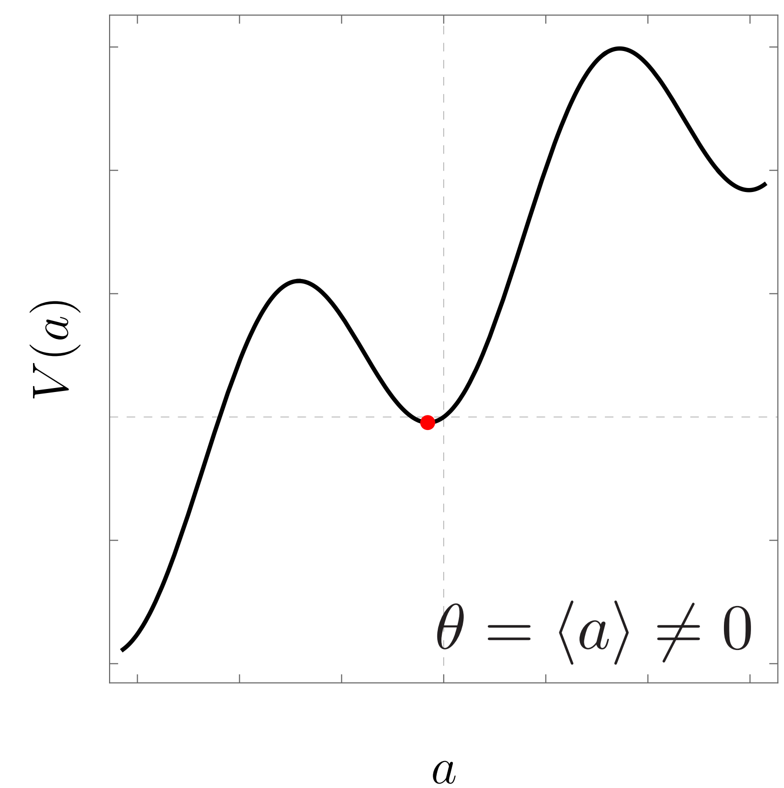
Mediator to the dark sector

Theory Motivation for MeV-GeV ALPs

Axion quality problem

$$V(a) = m_\pi^2 f_\pi^2 \left[1 - \cos\left(\frac{a}{f_a}\right)\right] \qquad + a\,\frac{f_a^{\Delta-1}}{M_{pl}^{\Delta-4}}$$



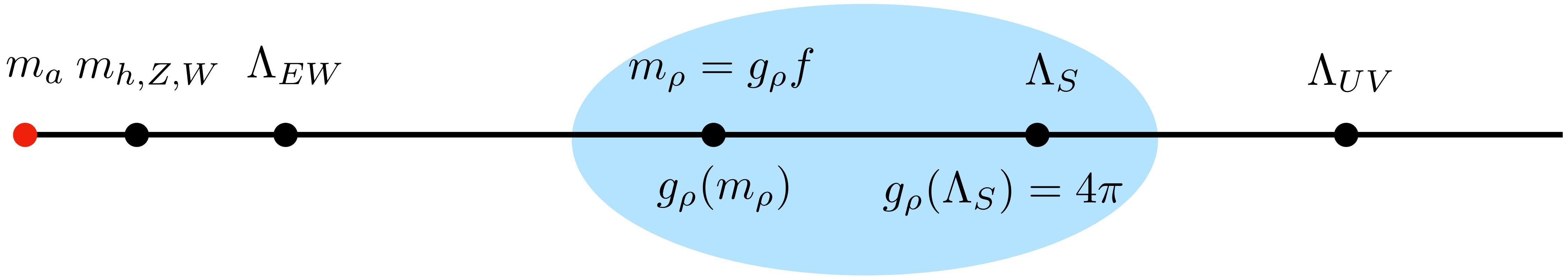


New sector contributes to potential and mass

9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

Theory Motivation for MeV-GeV ALPs

Composite Higgs models



Specify details about heavy sector

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2) \times \mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$

[Agashe, Contino, Pomarol,…]

-

Light pseudo-scalar particles = axion-like particles

[Ferretti 1604.06467]

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Effective Lagrangian

Interactions at dimension-5

[Weinberg: PRL 40 (1978) 223]
[Wilczek: PRL 40 (1978) 279]
[Georgi, Kaplan, Randall: Phys. Lett.169 B (1986)]

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F \boldsymbol{c}_F \gamma_\mu \psi_F$$
$$+ c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

Redundant operator

$$\mathcal{L}_{\text{eff}}^{D\leq 5} \supset c_\phi \frac{\partial^\mu a}{f}\left(\phi^\dagger iD_\mu \phi + \text{h.c.}\right)$$

[Chala, Guedes, Ramos, Santiago: 2012.09017]

Effective Lagrangian

Higgs interactions at dimension-6 and 7

$$\mathcal{L}_{\text{eff}}^{D\geq 6} = \frac{C_{ah}}{\Lambda^2}\,(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C_{Zh}^{(7)}}{\Lambda^3}\,(\partial^\mu a)\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \ldots$$

[Dobrescu, Landsberg, Matchev: 0005308]
[Dobrescu, Matchev: 0008192]

[Bauer, Neubert, Thamm: 1610.00009]
[Bauer, Neubert, Thamm: 1704.08207]
[Bauer, Neubert, Thamm: 1708.004433]

Operator Evolution to the Weak Scale

[Chala, Guedes, Ramos, Santiago: 2012.09017]
[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

ALP couplings to gauge fields

$$\frac{d}{d\ln\mu}\,c_{VV}(\mu) = 0\,; \quad V = G, W, B$$

[Chetyrkin, Kniehl, Steinhauser, Bardeen: 9807241]

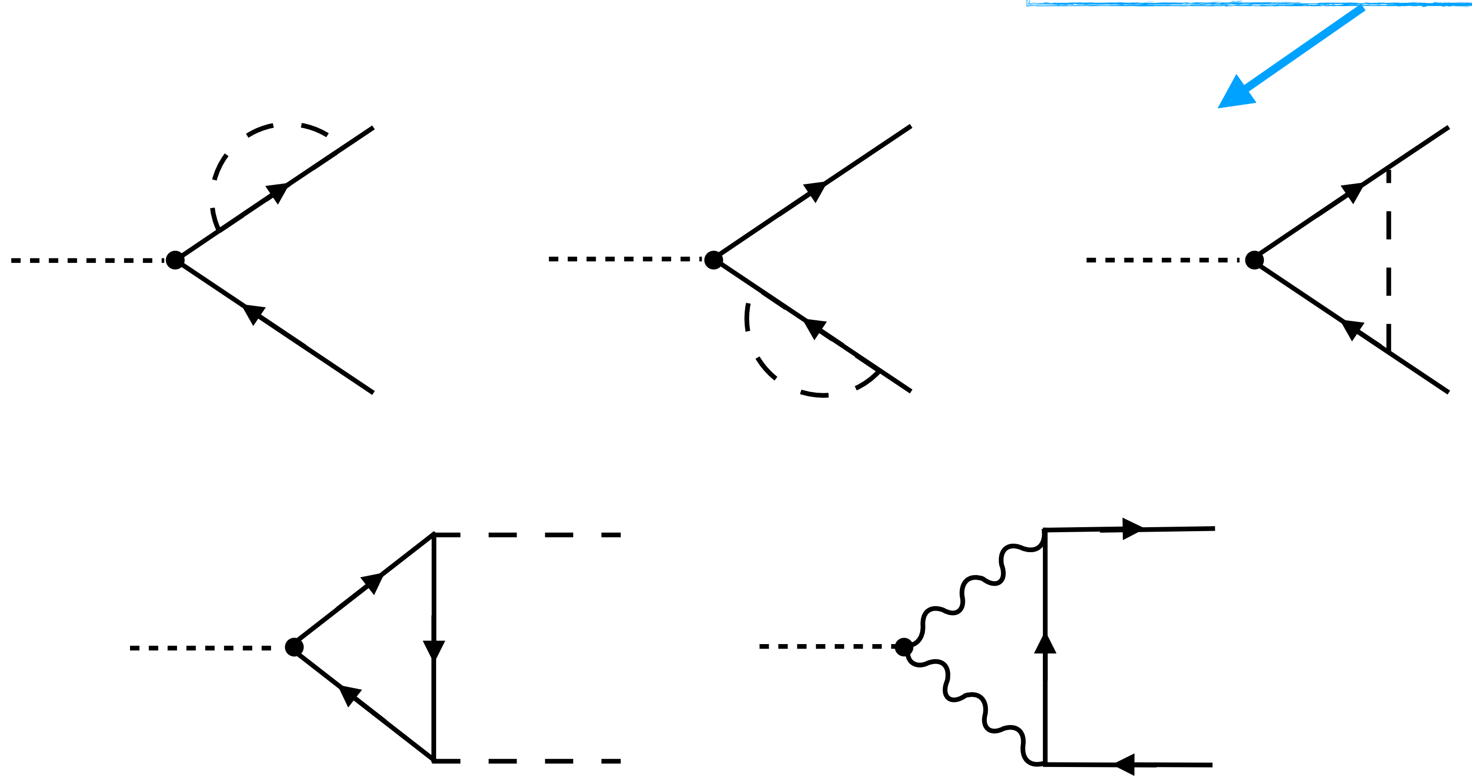
Operator Evolution to the Weak Scale

[Chala, Guedes, Ramos, Santiago: 2012.09017]
[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

ALP couplings to fermions

1708.00021, 2002.04623

Contribution from Yukawas



Require redundant operator as counterterm

$$O_\phi \to \sum_F \beta_F \, O_F$$

1308.2627
2012.09017, 2021.12272

Mixing of ALP-boson operators into ALP-fermions

Operator Evolution to the Weak Scale

[Chala, Guedes, Ramos, Santiago: 2012.09017]
[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

ALP couplings to fermions

1708.00021, 2002.04623   2012.09017, 2021.12272

$$\frac{d}{d\ln\mu}\,\boldsymbol{c}_Q(\mu) = \frac{1}{32\pi^2}\left\{\boldsymbol{Y}_u\boldsymbol{Y}_u^\dagger + \boldsymbol{Y}_d\boldsymbol{Y}_d^\dagger, \boldsymbol{c}_Q\right\} - \frac{1}{16\pi^2}\left(\boldsymbol{Y}_u\,\boldsymbol{c}_u\boldsymbol{Y}_u^\dagger + \boldsymbol{Y}_d\,\boldsymbol{c}_d\boldsymbol{Y}_d^\dagger\right)$$
$$+\left[\frac{\beta_Q}{8\pi^2}\,X - \frac{3\alpha_s^2}{4\pi^2}\,C_F^{(3)}\,\tilde{c}_{GG} - \frac{3\alpha_2^2}{4\pi^2}\,C_F^{(2)}\,\tilde{c}_{WW} - \frac{3\alpha_1^2}{4\pi^2}\,\mathcal{Y}_Q^2\,\tilde{c}_{BB}\right]\mathbb{1}$$

$$\frac{d}{d\ln\mu}\,\boldsymbol{c}_q(\mu) = \frac{1}{16\pi^2}\left\{\boldsymbol{Y}_q^\dagger\boldsymbol{Y}_q, \boldsymbol{c}_q\right\} - \frac{1}{8\pi^2}\,\boldsymbol{Y}_q^\dagger\boldsymbol{c}_Q\boldsymbol{Y}_q + \left[\frac{\beta_q}{8\pi^2}\,X + \frac{3\alpha_s^2}{4\pi^2}\,C_F^{(3)}\,\tilde{c}_{GG} + \frac{3\alpha_1^2}{4\pi^2}\,\mathcal{Y}_q^2\,\tilde{c}_{BB}\right]\mathbb{1}$$

$$\frac{d}{d\ln\mu}\,\boldsymbol{c}_L(\mu) = \frac{1}{32\pi^2}\left\{\boldsymbol{Y}_e\boldsymbol{Y}_e^\dagger, \boldsymbol{c}_L\right\} - \frac{1}{16\pi^2}\,\boldsymbol{Y}_e\,\boldsymbol{c}_e\boldsymbol{Y}_e^\dagger + \left[\frac{\beta_L}{8\pi^2}\,X - \frac{3\alpha_2^2}{4\pi^2}\,C_F^{(2)}\,\tilde{c}_{WW} - \frac{3\alpha_1^2}{4\pi^2}\,\mathcal{Y}_L^2\,\tilde{c}_{BB}\right]\mathbb{1}$$

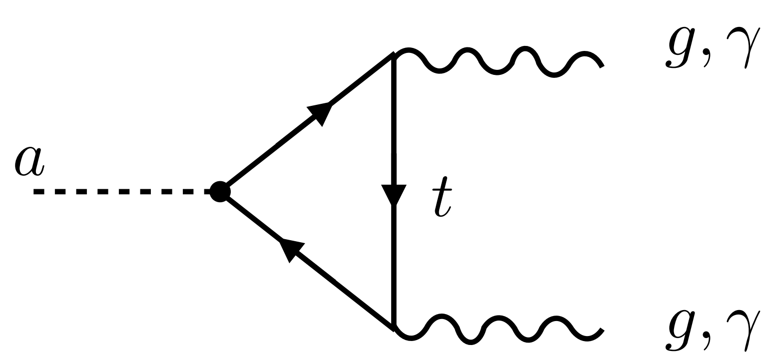
$$\frac{d}{d\ln\mu}\,\boldsymbol{c}_e(\mu) = \frac{1}{16\pi^2}\left\{\boldsymbol{Y}_e^\dagger\boldsymbol{Y}_e, \boldsymbol{c}_e\right\} - \frac{1}{8\pi^2}\,\boldsymbol{Y}_e^\dagger\boldsymbol{c}_L\boldsymbol{Y}_e + \left[\frac{\beta_e}{8\pi^2}\,X + \frac{3\alpha_1^2}{4\pi^2}\,\mathcal{Y}_e^2\,\tilde{c}_{BB}\right]\mathbb{1}$$

$$X = \mathrm{Tr}\left[3\boldsymbol{c}_Q\left(\boldsymbol{Y}_u\boldsymbol{Y}_u^\dagger - \boldsymbol{Y}_d\boldsymbol{Y}_d^\dagger\right) - 3\boldsymbol{c}_u\boldsymbol{Y}_u^\dagger\boldsymbol{Y}_u + 3\boldsymbol{c}_d\boldsymbol{Y}_d^\dagger\boldsymbol{Y}_d - \boldsymbol{c}_L\boldsymbol{Y}_e\boldsymbol{Y}_e^\dagger + \boldsymbol{c}_e\boldsymbol{Y}_e^\dagger\boldsymbol{Y}_e\right]$$

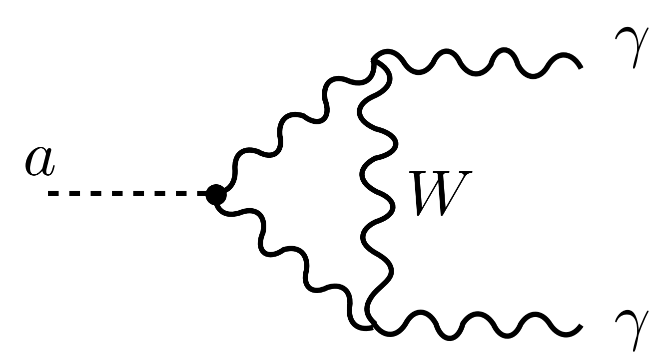
Operator Evolution at the Weak Scale

ALP couplings to gauge bosons

[Bauer, Neubert, Thamm: 1708.00443]



$$\sim \frac{m_a^2}{m_t^2}$$



$$\sim \frac{m_a^2}{m_W^2}$$

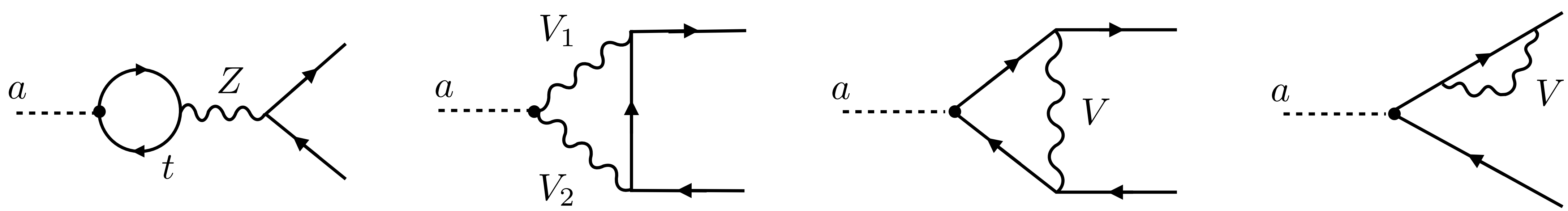
$$\Delta c_{GG}(\mu_w) = 0\,, \qquad \Delta c_{\gamma\gamma}(\mu_w) = 0$$

Operator Evolution at the Weak Scale

[Chala, Guedes, Ramos, Santiago: 2012.09017]
[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

ALP couplings to fermions

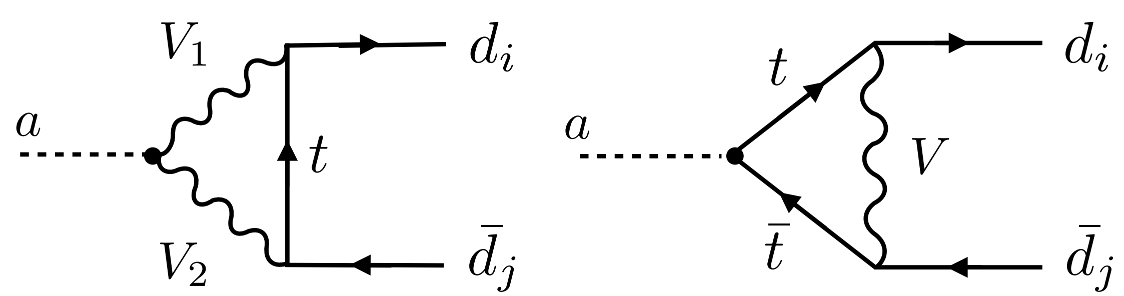
1708.00443



only non-zero for internal t quarks

Non-trivial flavor structure

1412.5174



Operator Evolution at the Weak Scale

[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

Numerical solution for $\Lambda = 4\pi f$ with $f = 1\,\mathrm{TeV}$

- Flavor diagonal couplings

$$\mathcal{L}_{\rm ferm}^{\rm diag}(\mu) = \sum_{f\neq t} \frac{c_{ff}(\mu)}{2}\,\frac{\partial^\mu a}{f}\,\bar f\gamma_\mu\gamma_5 f$$

$$c_{uu,cc}(m_t) \simeq c_{uu,cc}(\Lambda) - 0.116\,c_{tt}(\Lambda) - \Big[6.35\,\tilde c_{GG}(\Lambda) + 0.19\,\tilde c_{WW}(\Lambda) + 0.02\,\tilde c_{BB}(\Lambda)\Big]\cdot 10^{-3}$$

$$c_{dd,ss}(m_t) \simeq c_{dd,ss}(\Lambda) + 0.116\,c_{tt}(\Lambda) - \Big[7.08\,\tilde c_{GG}(\Lambda) + 0.22\,\tilde c_{WW}(\Lambda) + 0.005\,\tilde c_{BB}(\Lambda)\Big]\cdot 10^{-3}$$

$$c_{bb}(m_t) \simeq c_{bb}(\Lambda) + 0.097\,c_{tt}(\Lambda) - \Big[7.02\,\tilde c_{GG}(\Lambda) + 0.19\,\tilde c_{WW}(\Lambda) + 0.005\,\tilde c_{BB}(\Lambda)\Big]\cdot 10^{-3}$$

$$c_{e_ie_i}(m_t) \simeq c_{e_ie_i}(\Lambda) + 0.116\,c_{tt}(\Lambda) - \Big[0.37\,\tilde c_{GG}(\Lambda) + 0.22\,\tilde c_{WW}(\Lambda) + 0.05\,\tilde c_{BB}(\Lambda)\Big]\cdot 10^{-3}$$

Operator Evolution at the Weak Scale

[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

Numerical solution for $\Lambda = 4\pi f$ with $f = 1\,\text{TeV}$

- Flavor changing couplings

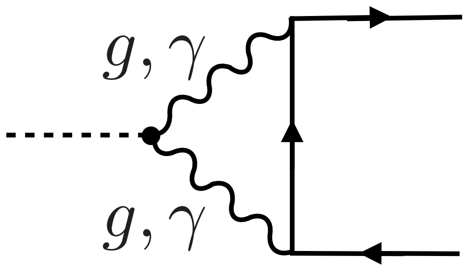
$$\mathcal{L}_{\text{ferm}}^{\text{FCNC}}(\mu) = -\frac{ia}{2f}\sum_f \Big[(m_{f_i} - m_{f_j})\,(k_f + k_F)_{ij}\,\bar{f}_i f_j + (m_{f_i} + m_{f_j})\,(k_f - k_F)_{ij}\,\bar{f}_i \gamma_5 f_j\Big]$$

$$\begin{aligned}
[k_u(\mu_w)]_{ij} &= [k_u(\Lambda)]_{ij}\,; \quad i,j \neq 3 \\
[k_U(\mu_w)]_{ij} &= [k_U(\Lambda)]_{ij}\,; \quad i,j \neq 3 \\
[k_d(\mu_w)]_{ij} &= [k_d(\Lambda)]_{ij} \\
[k_e(\mu_w)]_{ij} &= [k_e(\Lambda)]_{ij} \\
[k_L(\mu_w)]_{ij} &= [k_L(\Lambda)]_{ij} \\
[k_D(m_t)]_{ij} &\simeq [k_D(\Lambda)]_{ij} + 0.019\,V_{ti}^* V_{tj}\Big[c_{tt}(\Lambda) - 0.0032\,\tilde{c}_{GG}(\Lambda) - 0.0057\,\tilde{c}_{WW}(\Lambda)\Big]
\end{aligned}$$

Operator Evolution below the Weak Scale

[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

Only relevant diagram



Small effect at $\mu_0 = 2\,\mathrm{GeV}$

$$c_{qq}(\mu_0) = c_{qq}(m_t) + \Big[3.0\,\tilde{c}_{GG}(\Lambda) - 1.4\,c_{tt}(\Lambda) - 0.6\,c_{bb}(\Lambda)\Big]\cdot 10^{-2}$$
$$+\,Q_q^2\Big[3.9\,\tilde{c}_{\gamma\gamma}(\Lambda) - 4.7\,c_{tt}(\Lambda) - 0.2\,c_{bb}(\Lambda)\Big]\cdot 10^{-5}$$
$$c_{\ell\ell}(\mu_0) = c_{\ell\ell}(m_t) + \Big[3.9\,\tilde{c}_{\gamma\gamma}(\Lambda) - 4.7\,c_{tt}(\Lambda) - 0.2\,c_{bb}(\Lambda)\Big]\cdot 10^{-5}$$

Operator Evolution below the QCD Scale

See Matthias Neubert's talk

Chiral rotation to remove ALP - gluon coupling

$$q \to \exp\left(- i\boldsymbol{\kappa}_q \, c_{GG} \, \frac{a}{f} \, \gamma_5 \right) q \qquad\qquad \mathrm{Tr}\, \boldsymbol{\kappa}_q = \kappa_u + \kappa_d + \kappa_s = 1$$

Match onto chiral Lagrangian

$$\begin{aligned}\mathcal{L}_{\chi PT}^{\mathrm{ALP}} = {} & \frac{1}{2}\, \partial^\mu a \, \partial_\mu a - \frac{m_{a,0}^2}{2}\, a^2 + \frac{f_\pi^2}{8}\, \mathrm{Tr}\big[D^\mu \boldsymbol{\Sigma}\, D_\mu \boldsymbol{\Sigma}^\dagger \big] + \frac{f_\pi^2}{4}\, B_0 \, \mathrm{Tr}\big[\boldsymbol{\Sigma}\, \hat{\boldsymbol{m}}_q^\dagger(a) + \hat{\boldsymbol{m}}_q(a)\, \boldsymbol{\Sigma}^\dagger \big] \\ & + \frac{i f_\pi^2}{4}\, \frac{\partial^\mu a}{2f}\, \mathrm{Tr}\big[\hat{\boldsymbol{c}}_{qq} (\boldsymbol{\Sigma}\, D_\mu \boldsymbol{\Sigma}^\dagger - \boldsymbol{\Sigma}^\dagger D_\mu \boldsymbol{\Sigma}) \big] + \hat{c}_{\gamma\gamma}\, \frac{\alpha}{4\pi}\, \frac{a}{f}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \dots\end{aligned}$$

Operator Evolution below the QCD Scale

QCD axion

ALP mass

$$m_a^2 = m_{a,0}^2 \left[1 + \frac{f_\pi^2}{8f^2} \frac{m_\pi^2\, m_{a,0}^2}{\left(m_\pi^2 - m_{a,0}^2\right)^2} \left(\Delta c_{ud}\right)^2 \right] + c_{GG}^2 \frac{f_\pi^2\, m_\pi^2}{f^2} \frac{2 m_u m_d}{(m_u + m_d)^2} + \mathcal{O}\left(\frac{f_\pi^4}{f^4}\right)$$

Optimal choice for kappa which removes ALP-pion mixing

$$\kappa_u = \frac{m_d}{m_u + m_d} + \frac{m_a^2}{m_\pi^2 - m_a^2} \frac{\Delta c_{ud}}{4 c_{GG}} \qquad \kappa_d = \frac{m_u}{m_u + m_d} - \frac{m_a^2}{m_\pi^2 - m_a^2} \frac{\Delta c_{ud}}{4 c_{GG}}$$

$$\Delta c_{ud} = c_{uu}(\mu_\chi) - c_{dd}(\mu_\chi) + 2 c_{GG} \frac{m_d - m_u}{m_d + m_u}$$

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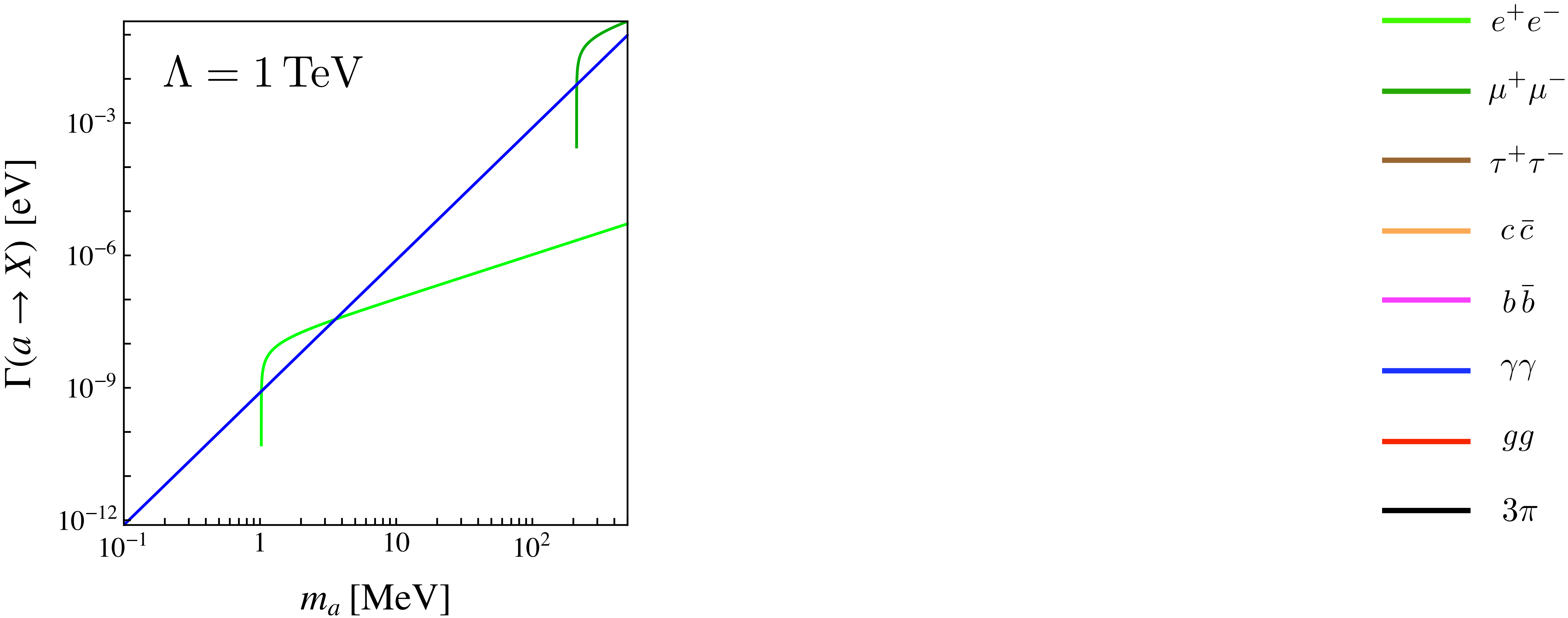
Phenomenology of Flavor Changing ALPs

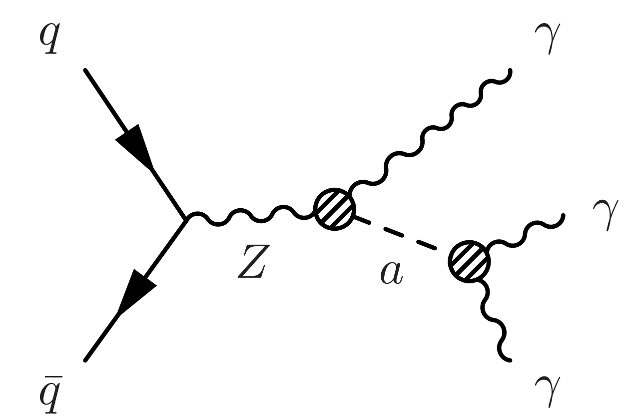
Fermion couplings = 1, Gauge boson couplings = 1 in the plot

More motivated: gauge couplings = $1/(4\pi)^2$

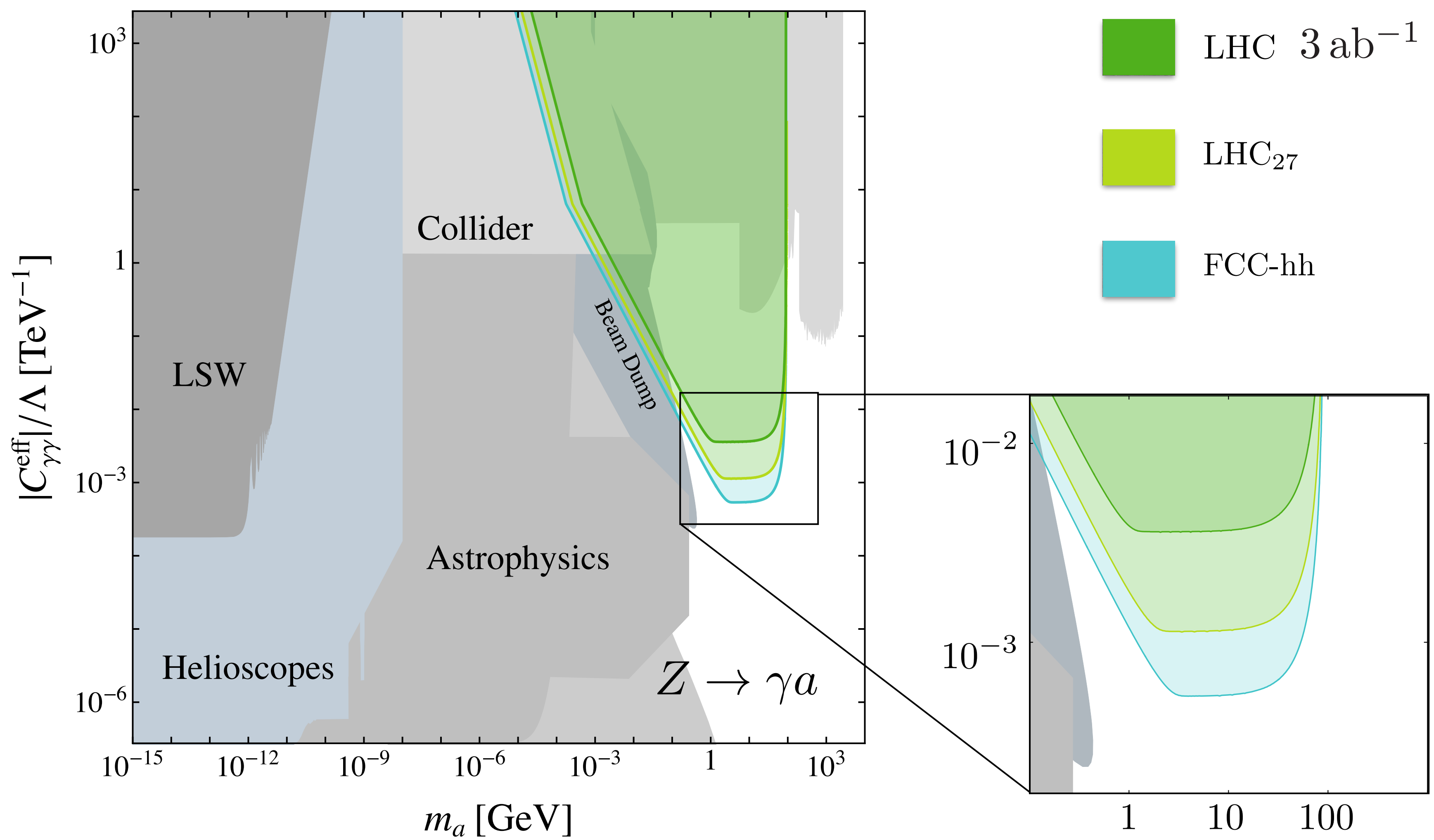


Phenomenology of Flavor Changing ALPs

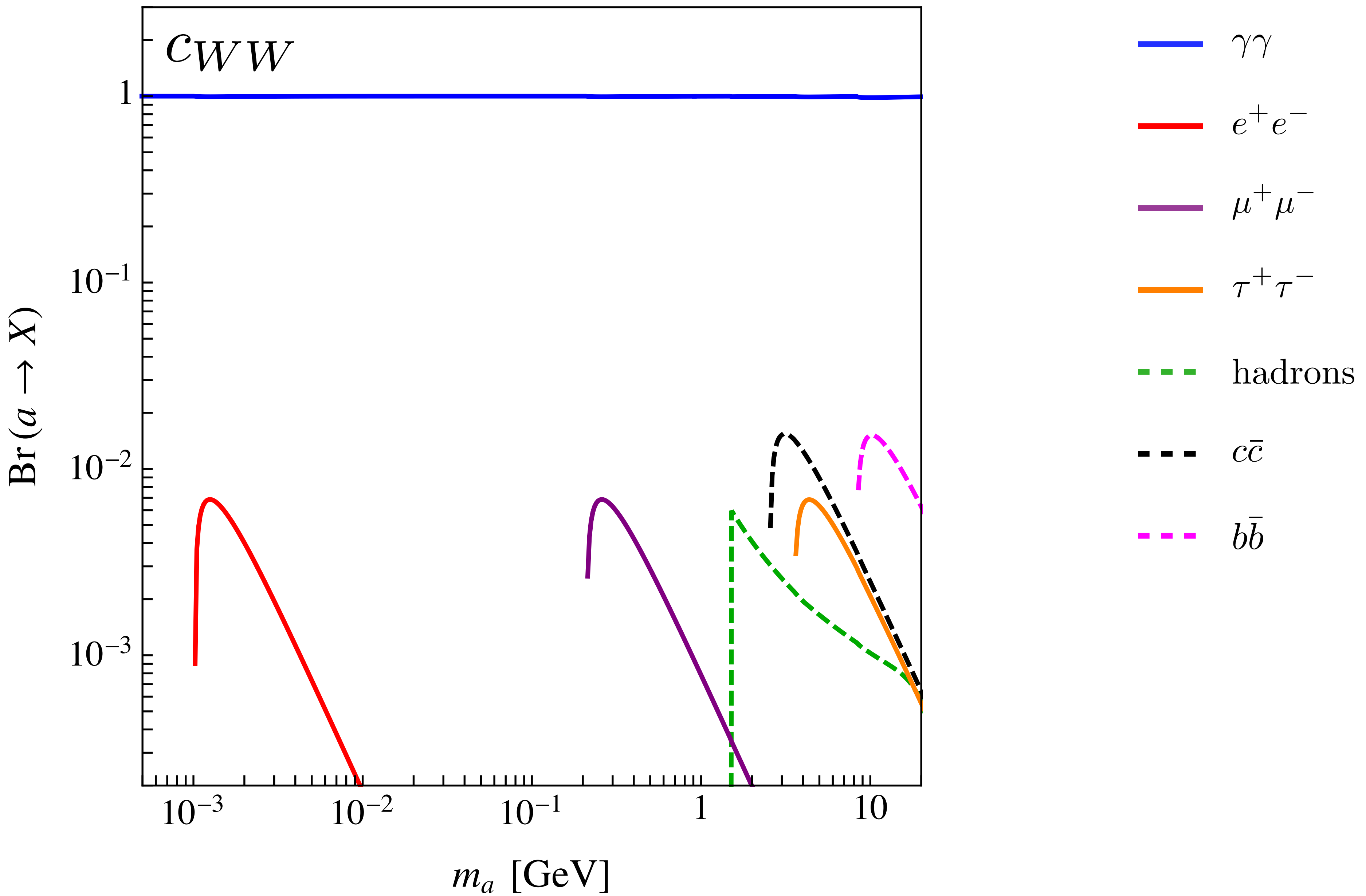
Dominant production mode: exotic Higgs and Z-boson decays



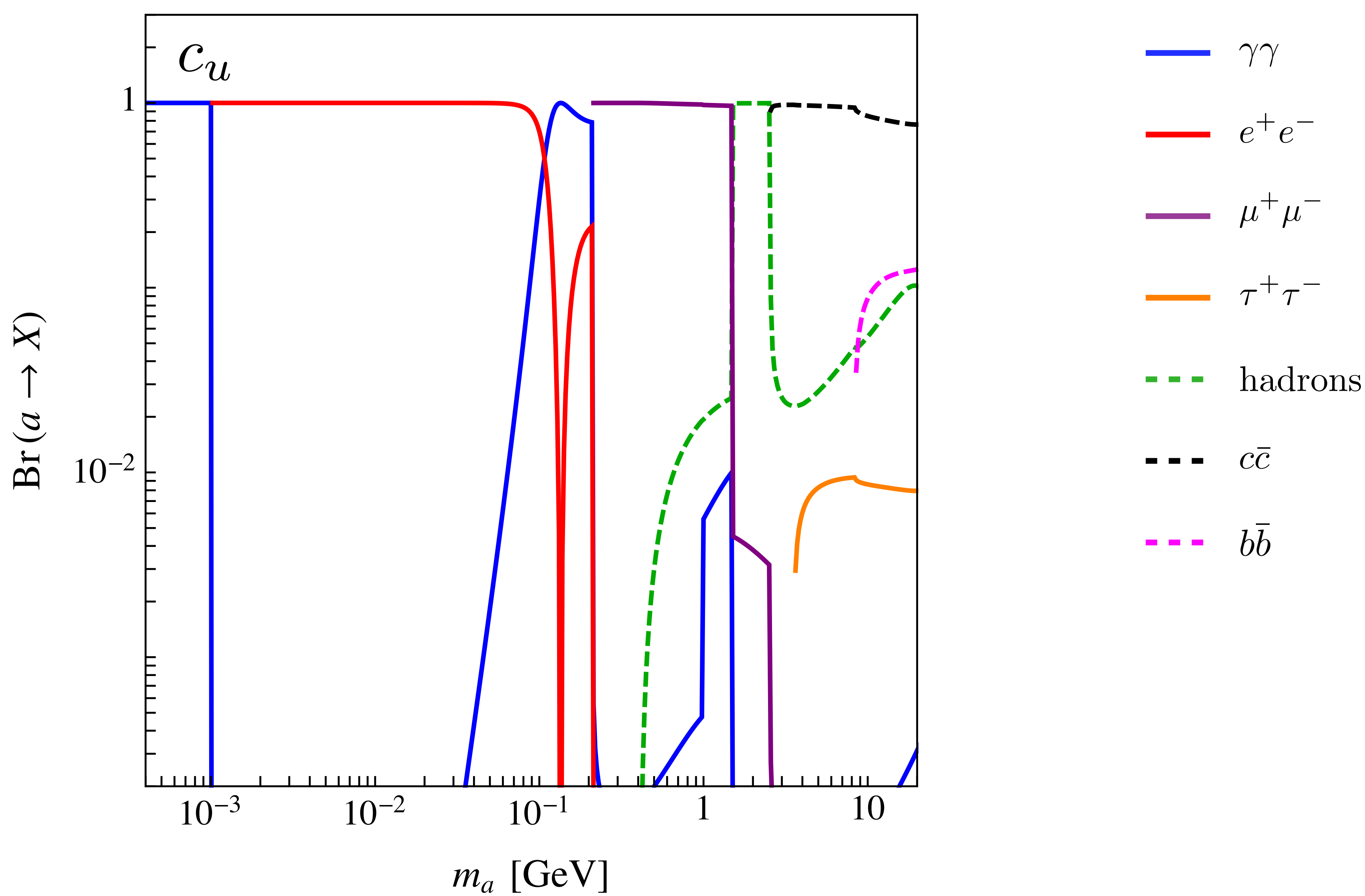
[Bauer, Heiles, Neubert, Thamm: 1808.10323]



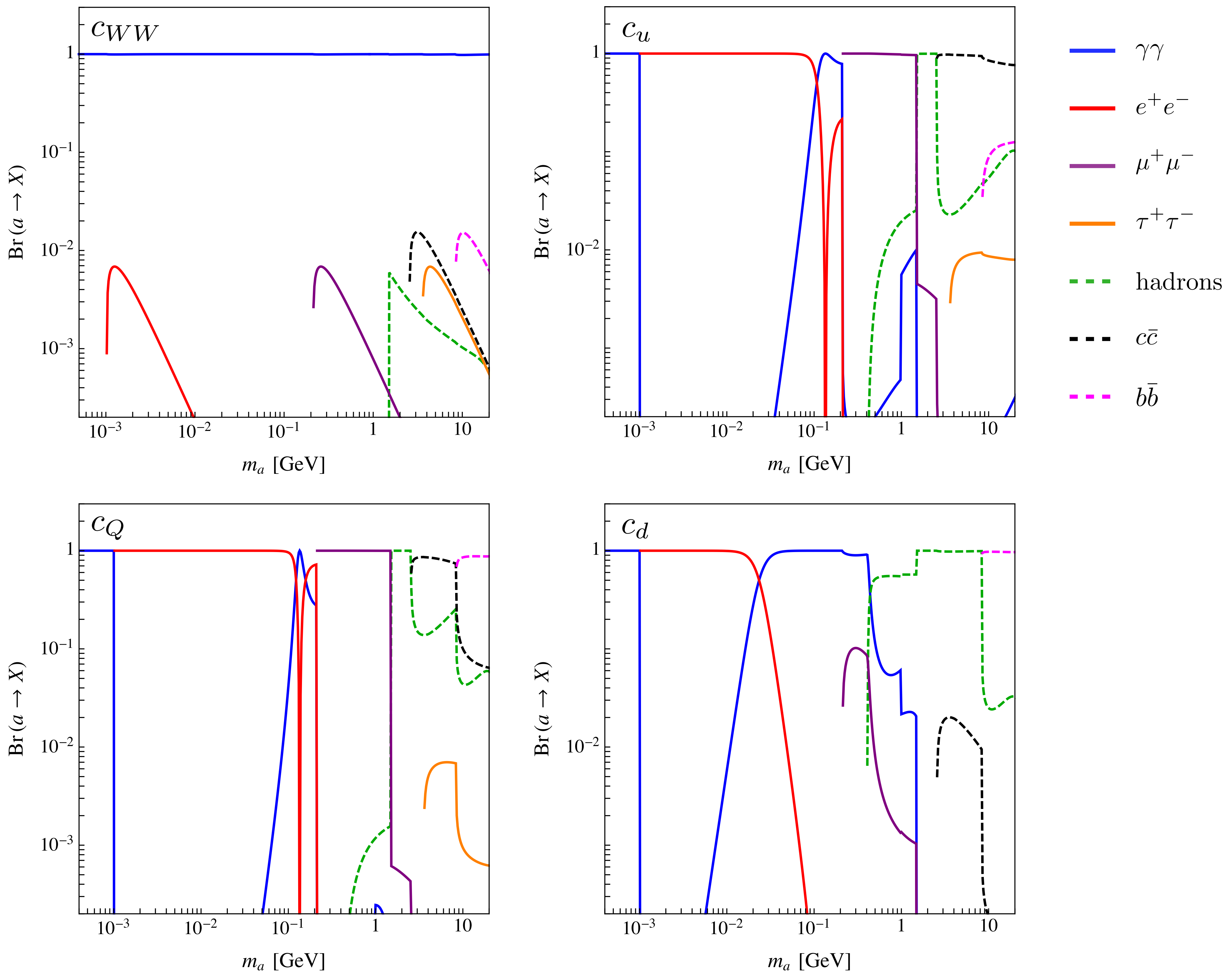
Phenomenology of Flavor Changing ALPs



Phenomenology of Flavor Changing ALPs



Phenomenology of Flavor Changing ALPs



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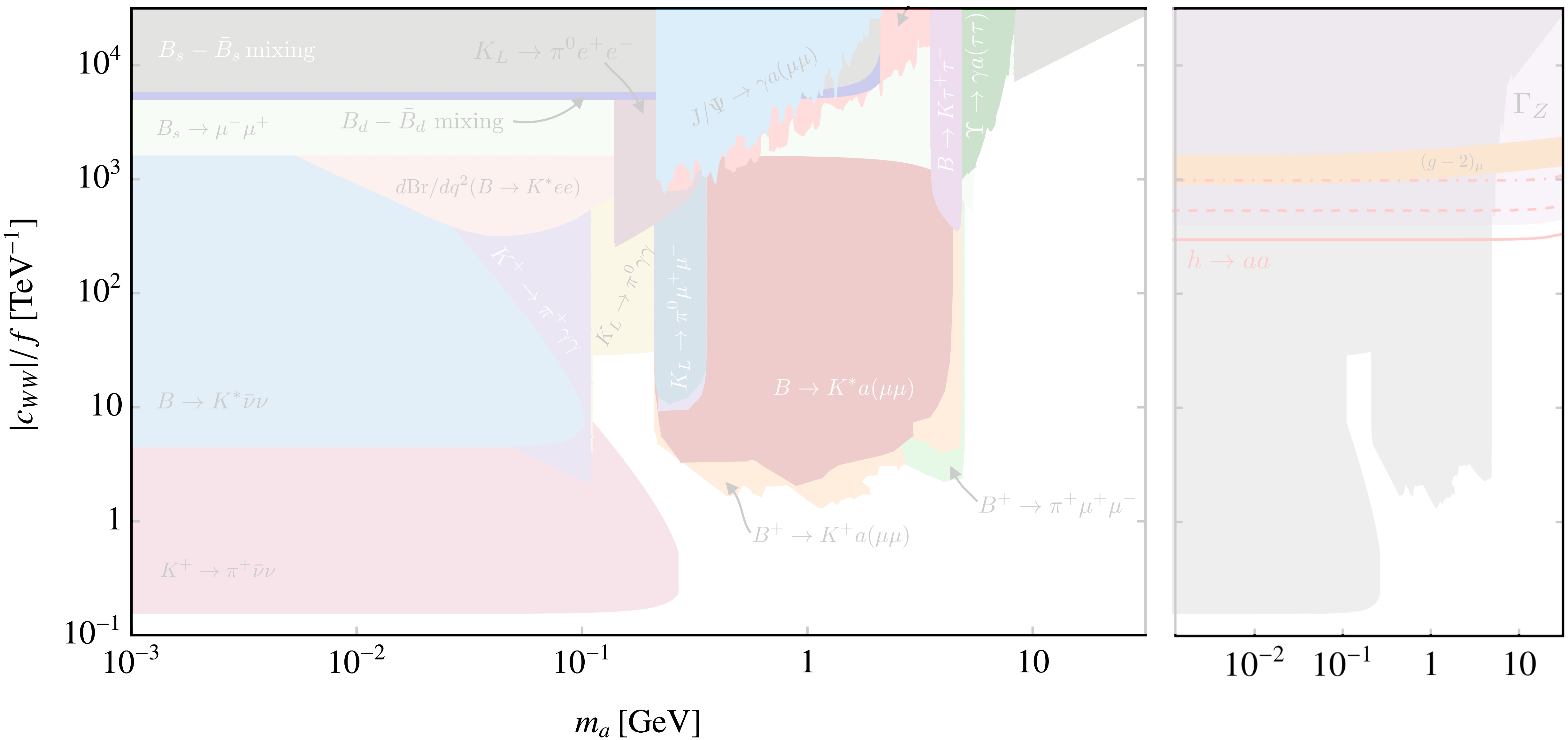
ALPs and Quark Flavour Phenomenology

1412.5174
1708.00021
1806.00660
1810.11336
1901.02031
2002.04623

Phenomenology - Quarks

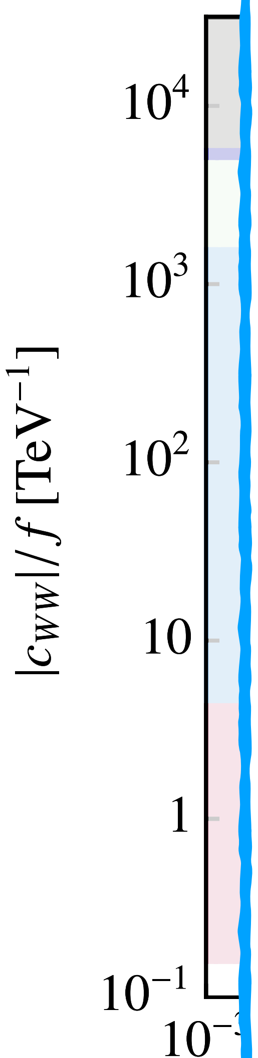
$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

1611.09355, 1901.02031

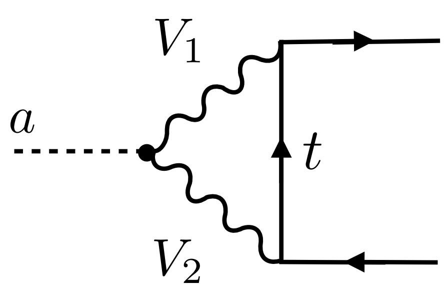


Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

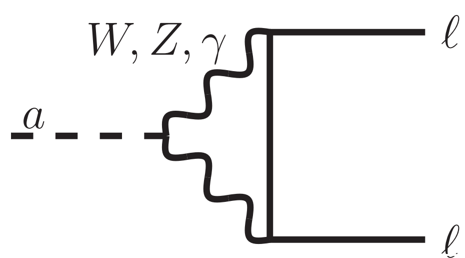


Flavour change



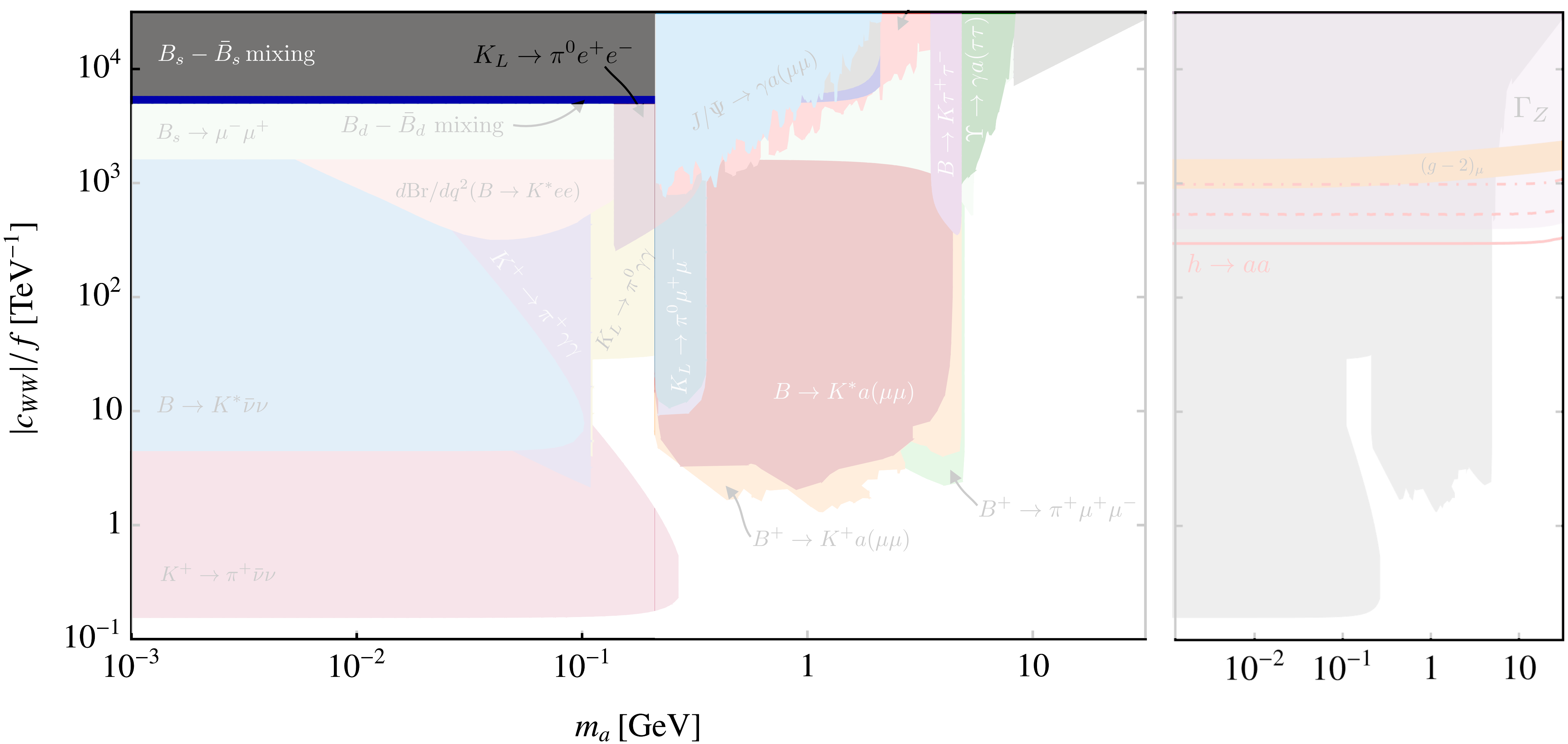
Decay

$$C_{\gamma\gamma} = C_{WW} + C_{BB}$$



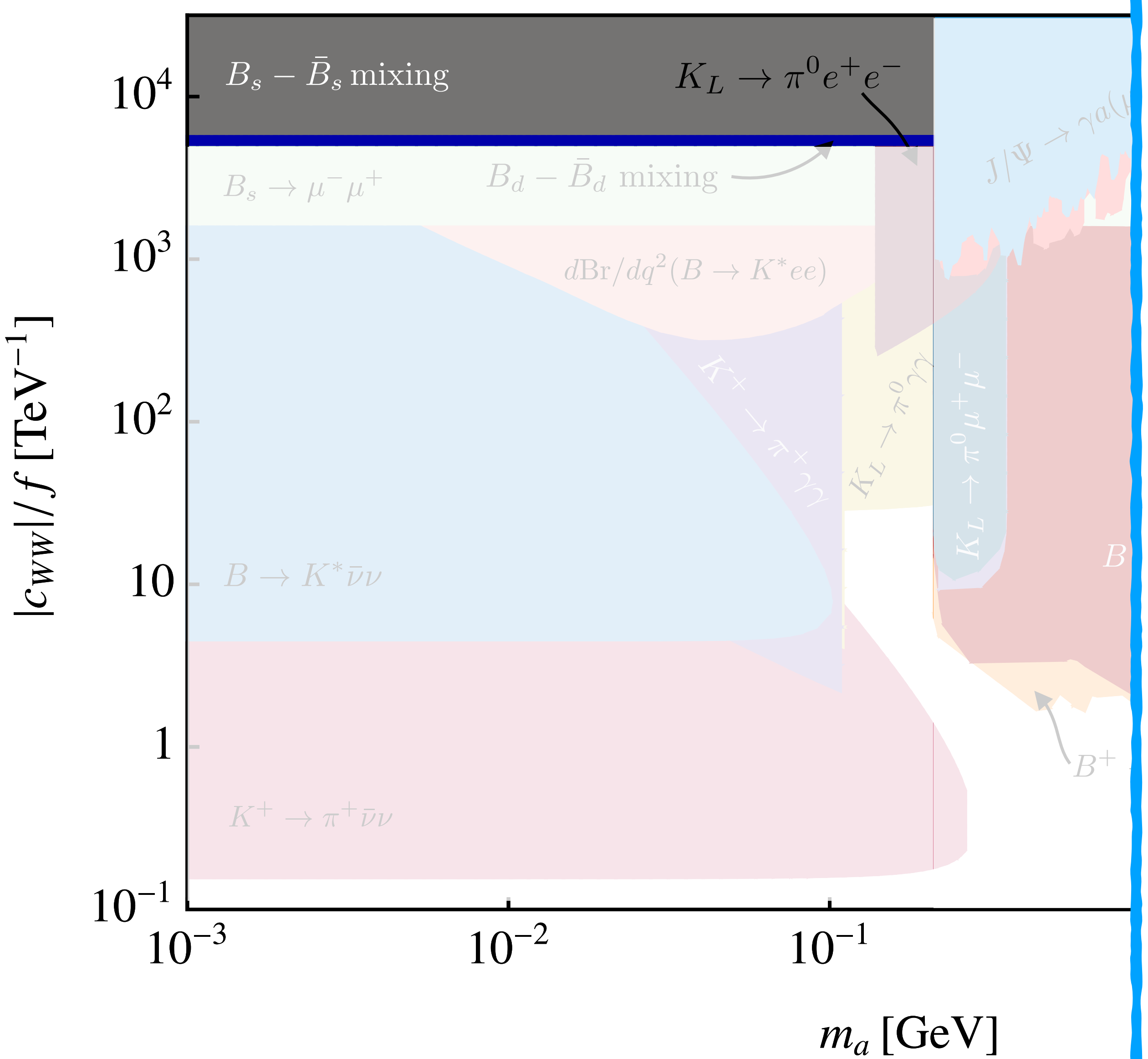
Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

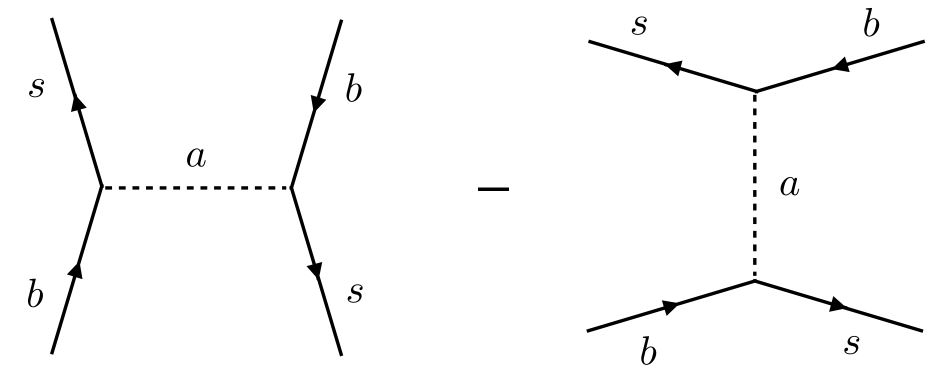


Phenomenology - Quarks

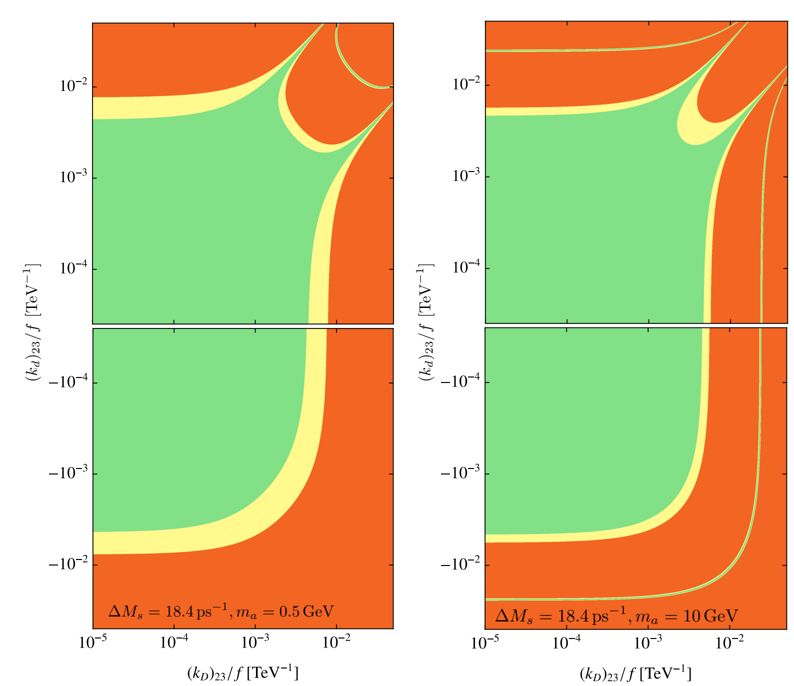
$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$



$B_{d,s} - \bar{B}_{d,s}$ mixing



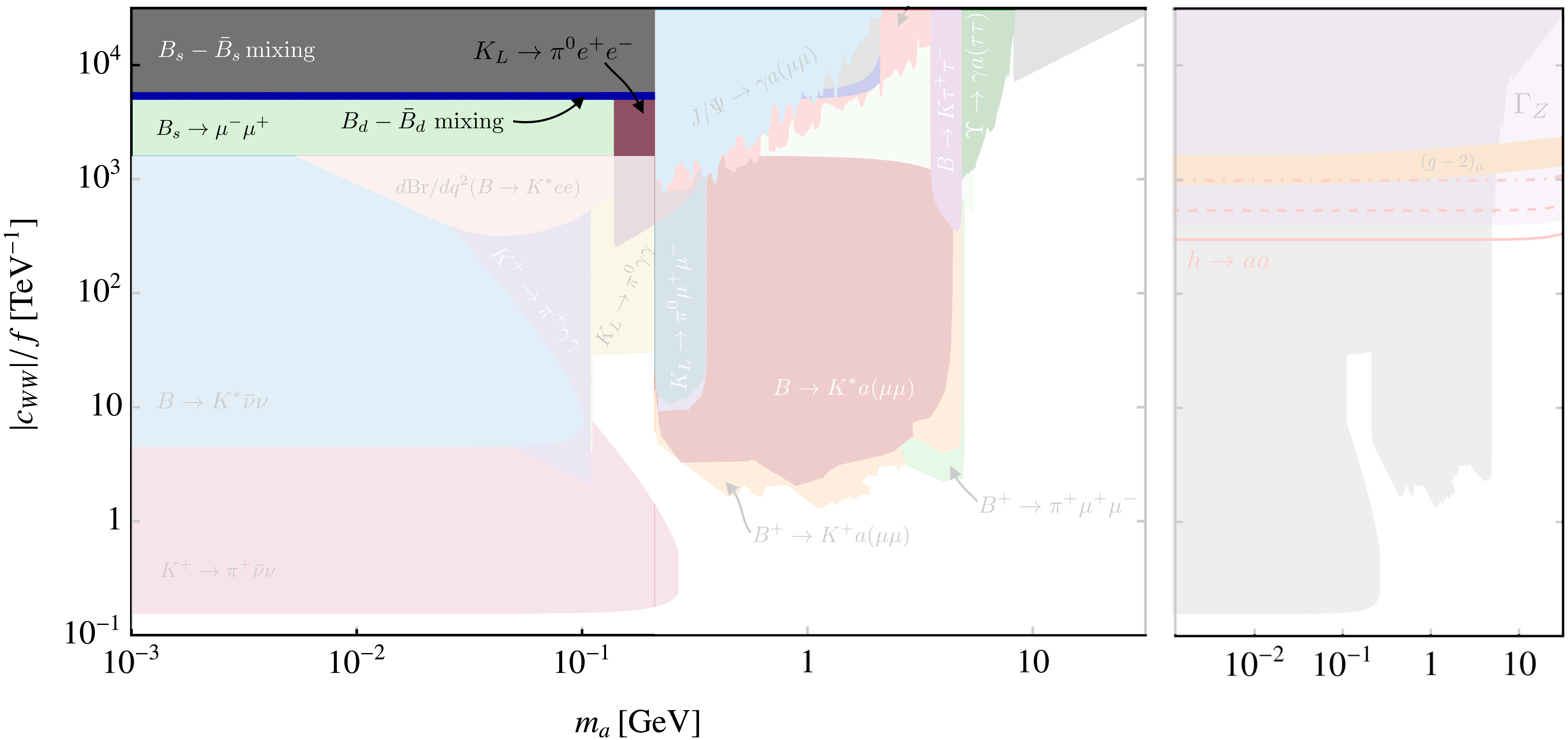
$$\Delta M_d^{\rm exp} = (0.5064 \pm 0.0019)\ \mathrm{ps}^{-1}$$
$$\Delta M_s^{\rm exp} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$$



[HFLAV: 1612.07233]

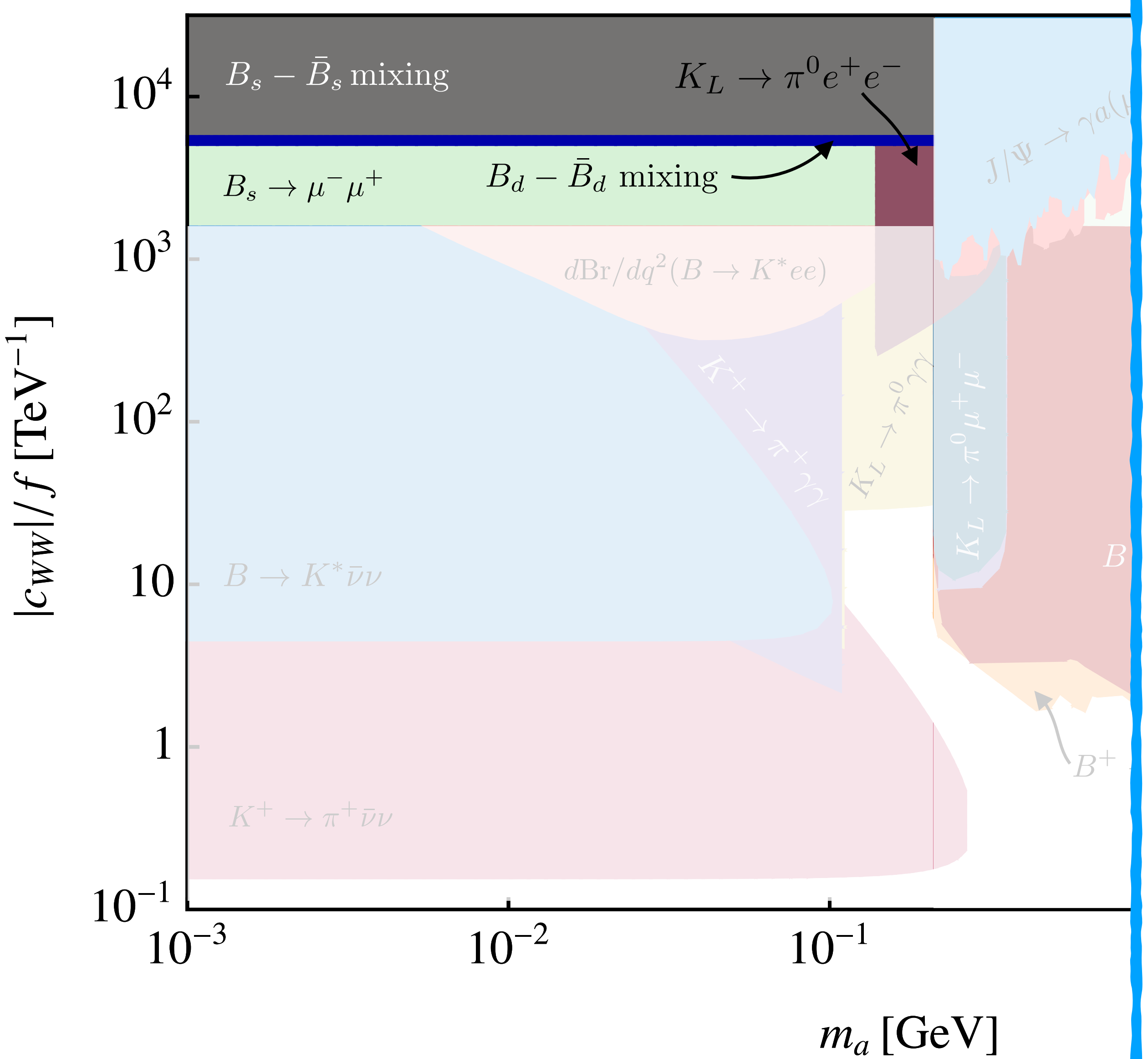
Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

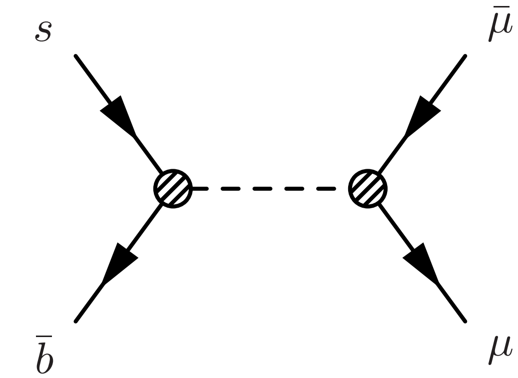


Phenomenology - Quarks

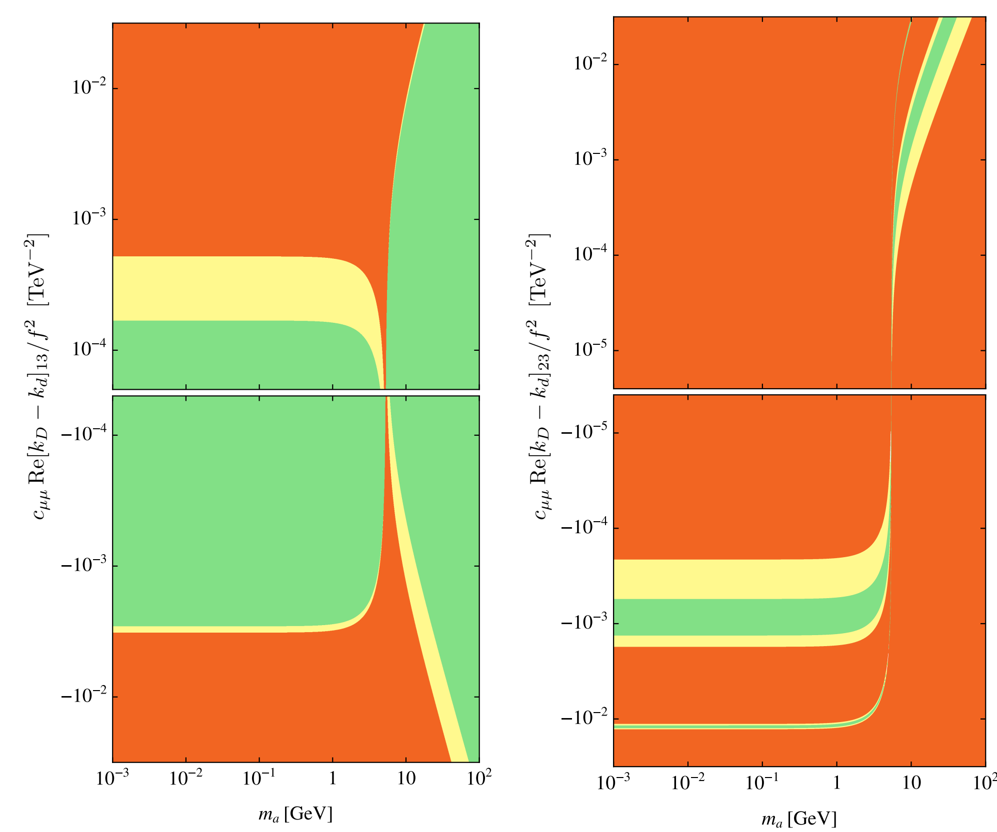
$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$



$B_s \to \mu^+ \mu^-$



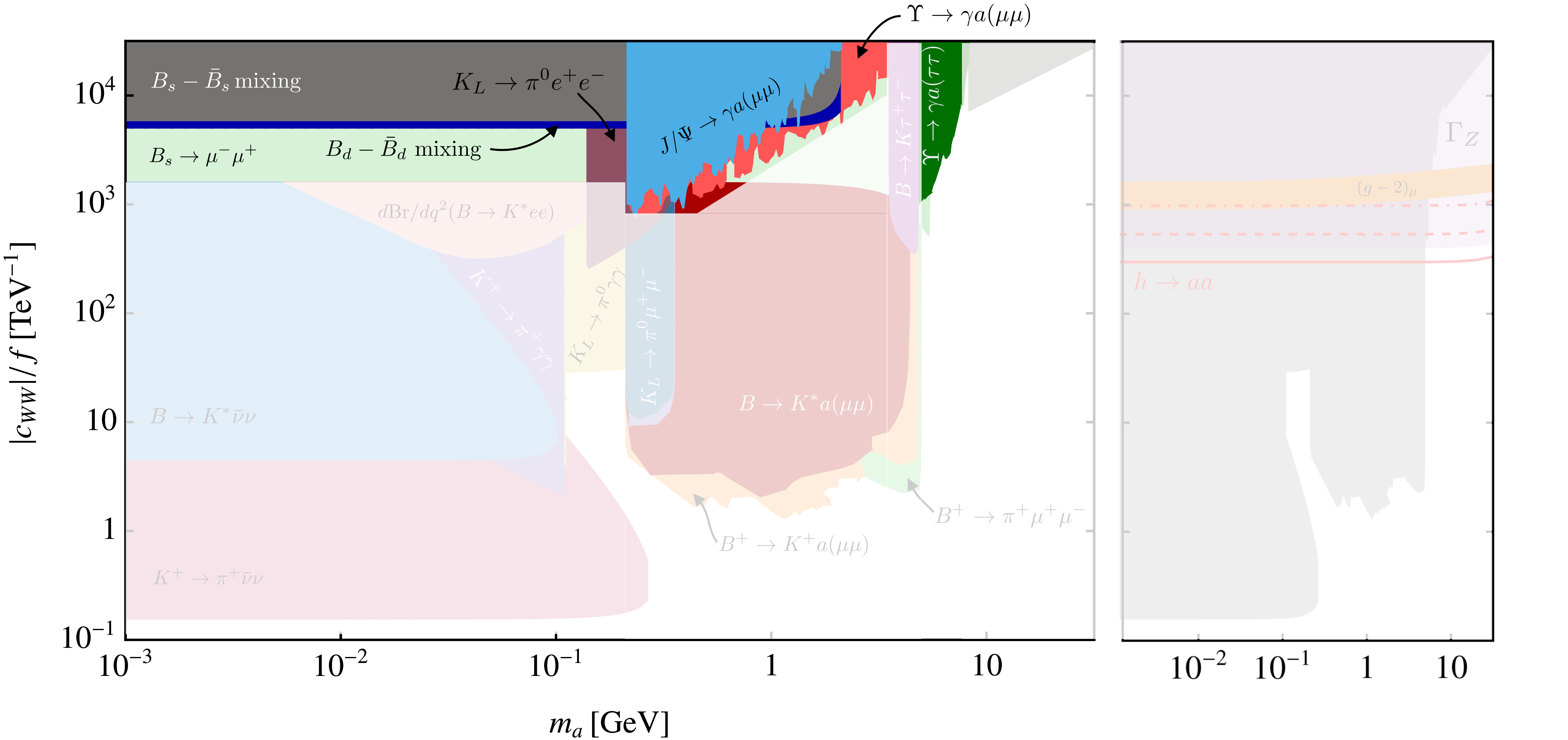
$$\mathrm{Br}_{\mathrm{exp}}(B_d \to \mu^+\mu^-) = (0.6^{+0.7}_{-0.7}) \times 10^{-10}$$
$$\mathrm{Br}_{\mathrm{exp}}(B_s \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$



[ATLAS, CMS, LHCb: ATLAS-CONF-2020-049]

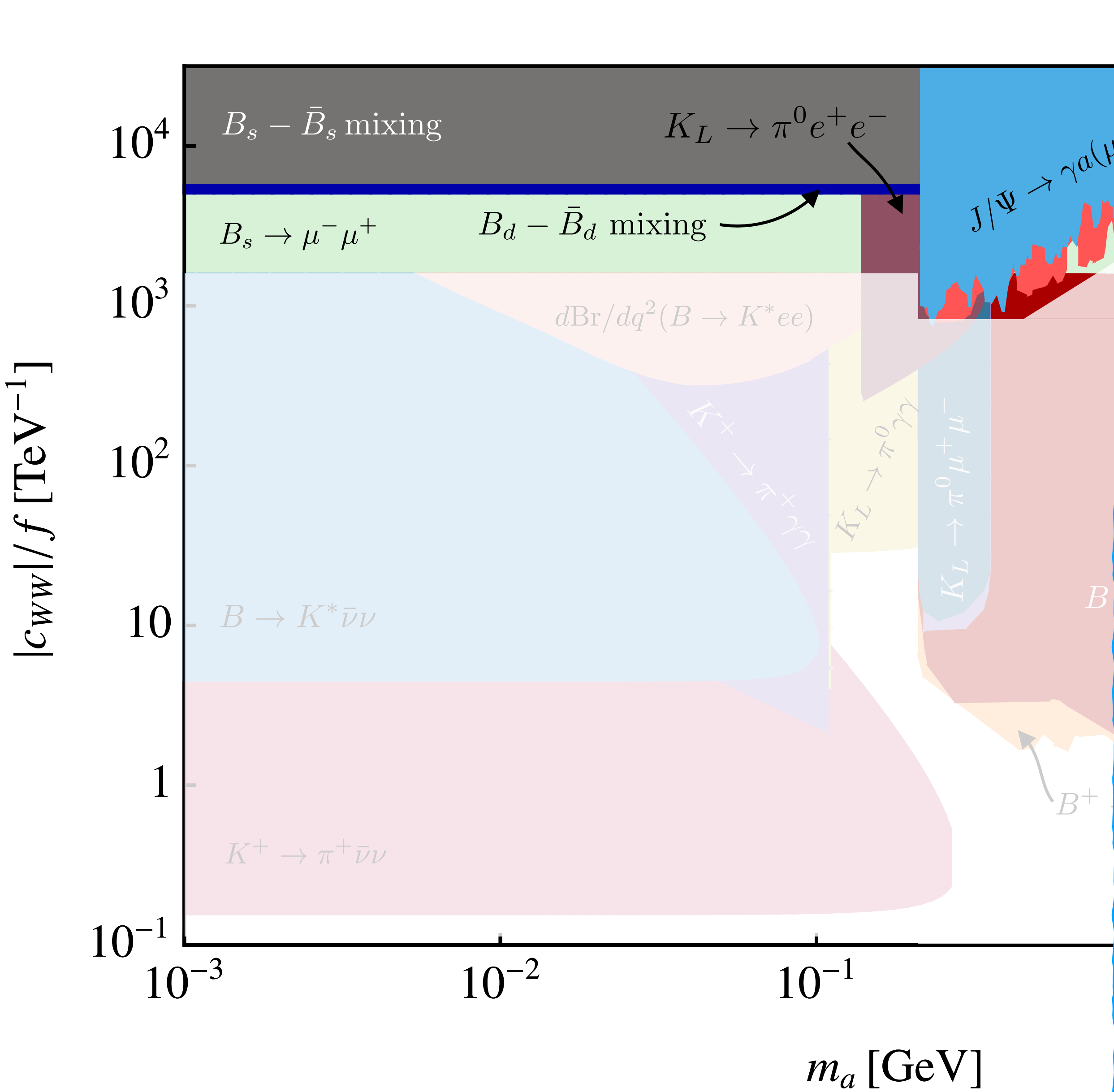
Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

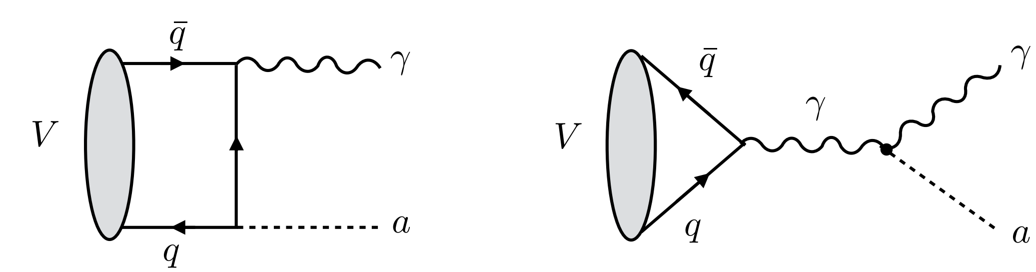


Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$



Radiative Decays



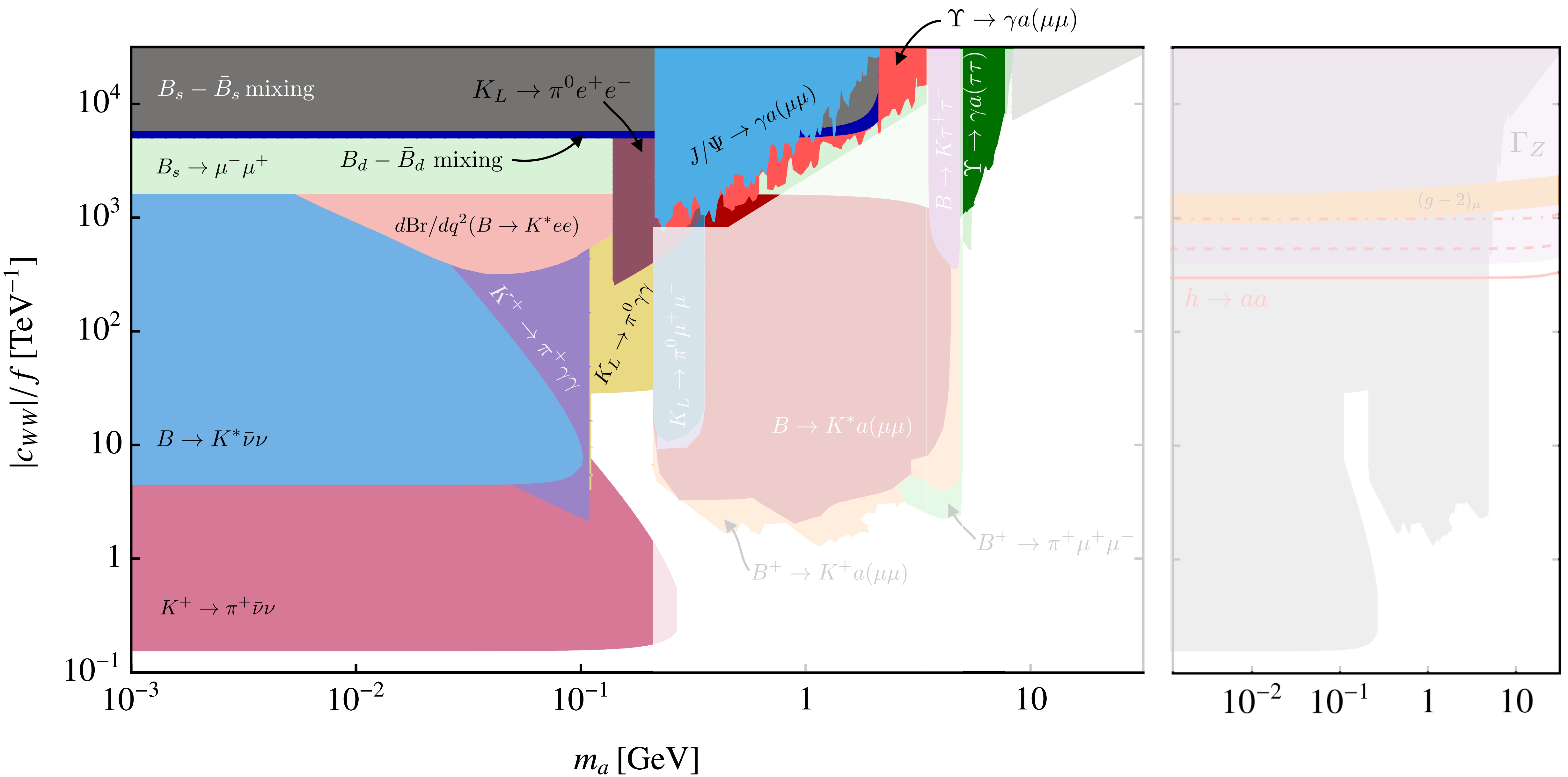
$$\mathrm{BR}(\Upsilon \to \gamma a)\,\mathrm{BR}(a \to \mu^+\mu^-) < 9.7 \times 10^{-6}$$

On-shell ALP

BESIII: 1510.01641, BaBar 1210.0287, BaBar 1210.5669, BaBar 1108.3549

Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^{A}_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$



Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

Observable	Mass range [MeV]	ALP decay mode	Constrained coupling c_{ij}	Limit (95% CL) on $c_{ij}\cdot\left(\frac{\text{TeV}}{f}\right)\cdot\sqrt{\mathcal{B}}$	
$\text{Br}(K^-\to\pi^-\nu\bar{\nu})$	$0<m_a<261^{(*)}$	long-lived	$\lvert k_D+k_d\rvert_{12}$	3.6×10^{-9}	NA62
$\text{Br}(K^-\to\pi^-\gamma\gamma)$	$m_a<108$	$\gamma\gamma$	$\lvert k_D+k_d\rvert_{12}$	2.1×10^{-8}	E949
$\text{Br}(K^-\to\pi^-\gamma\gamma)$	$220<m_a<354$	$\gamma\gamma$	$\lvert k_D+k_d\rvert_{12}$	2.4×10^{-7}	NA62
$\text{Br}(K_L\to\pi^0\gamma\gamma)$	$m_a<110$	$\gamma\gamma$	$\lvert\text{Im}[(k_D+k_d)_{12}]\rvert$	1.4×10^{-8}	NA48
$\text{Br}(K_L\to\pi^0\gamma\gamma)$	$m_a<363$	$\gamma\gamma$	$\lvert\text{Im}[(k_D+k_d)_{12}]\rvert$	1.2×10^{-7}	KTeV
$\text{Br}(K_L\to\pi^0e^+e^-)$	$140<m_a<362$	e^+e^-	$\lvert\text{Im}[(k_D+k_d)_{12}]\rvert$	2.9×10^{-9}	KTeV
$\text{Br}(K_L\to\pi^0\mu^+\mu^-)$	$210<m_a<350$	$\mu^+\mu^-$	$\lvert\text{Im}[(k_D+k_d)_{12}]\rvert$	4.0×10^{-9}	KTeV
$\text{Br}(B^+\to\pi^+e^+e^-)$	$140<m_a<5140$	e^+e^-	$\lvert k_D+k_d\rvert_{13}$	7.0×10^{-7}	Belle
$\text{Br}(B^+\to\pi^+\mu^+\mu^-)$	$211<m_a<5140^{(\ddagger\ddagger)}$	$\mu^+\mu^-$	$\lvert k_D+k_d\rvert_{13}$	1.2×10^{-7}	Belle
$\text{Br}(B^-\to K^-\nu\bar{\nu})$	$0<m_a<4785$	long-lived	$\lvert k_D+k_d\rvert_{23}$	6.9×10^{-6}	BaBar
$\text{Br}(B\to K^*\nu\bar{\nu})$	$0<m_a<4387$	long-lived	$\lvert k_D-k_d\rvert_{23}$	5.1×10^{-6}	BaBar
$d\text{Br}/dq^2(B^0\to K^{*0}e^+e^-)_{[0.0,0.05]}$	$0<m_a<224$	e^+e^-	$\lvert k_D-k_d\rvert_{23}$	6.4×10^{-7}	LHCb
$d\text{Br}/dq^2(B^0\to K^{*0}e^+e^-)_{[0.05,0.15]}$	$224<m_a<387$	e^+e^-	$\lvert k_D-k_d\rvert_{23}$	9.3×10^{-7}	LHCb
$\text{Br}\big(B^-\to K^-a(\mu^+\mu^-)\big)$	$250<m_a<4700^{(\dagger)}$	$\mu^+\mu^-$	$\lvert k_D+k_d\rvert_{23}$	4.4×10^{-8}	LHCb
$\text{Br}\big(B^0\to K^{*0}a(\mu^+\mu^-)\big)$	$214<m_a<4350^{(\dagger)}$	$\mu^+\mu^-$	$\lvert k_D-k_d\rvert_{23}$	5.1×10^{-8}	LHCb
$\text{Br}(B^-\to K^-\tau^+\tau^-)$	$3552<m_a<4785$	$\tau^+\tau^-$	$\lvert k_D+k_d\rvert_{23}$	8.2×10^{-5}	BaBar

1412.5174, 1708.00021, 1806.00660, 2002.04623

On-shell ALPs

Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

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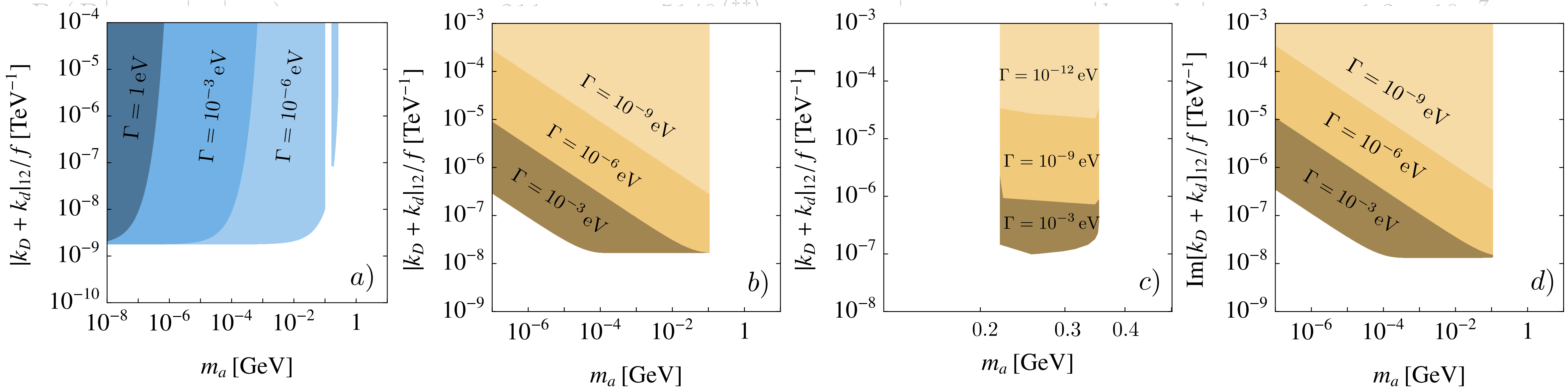
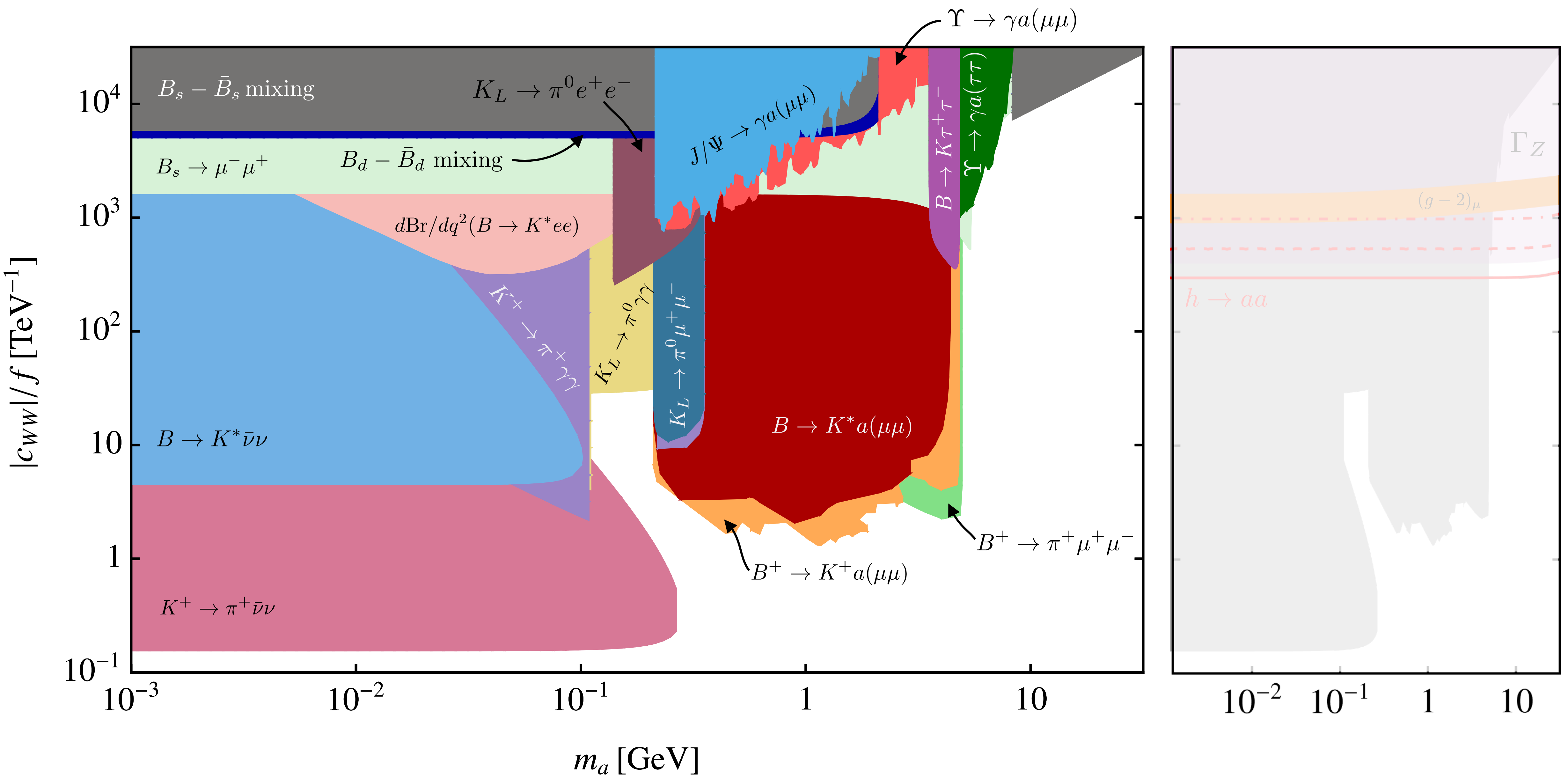


Realistic bounds depend on decay length

Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$



Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

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$\text{Br}(K_L \to \pi^0 \gamma\gamma)$	$m_a < 110$	$\gamma\gamma$	$\lvert\text{Im}[(k_D + k_d)_{12}]\rvert$	1.4×10^{-8}	NA48
$\text{Br}(K_L \to \pi^0 \gamma\gamma)$	$m_a < 363$	$\gamma\gamma$	$\lvert\text{Im}[(k_D + k_d)_{12}]\rvert$	1.2×10^{-7}	KTeV
$\text{Br}(K_L \to \pi^0 e^+e^-)$	$140 < m_a < 362$	e^+e^-	$\lvert\text{Im}[(k_D + k_d)_{12}]\rvert$	2.9×10^{-9}	KTeV
$\text{Br}(K_L \to \pi^0 \mu^+\mu^-)$	$210 < m_a < 350$	$\mu^+\mu^-$	$\lvert\text{Im}[(k_D + k_d)_{12}]\rvert$	4.0×10^{-9}	KTeV
$\text{Br}(B^+ \to \pi^+ e^+e^-)$	$140 < m_a < 5140$	e^+e^-	$\lvert k_D + k_d\rvert_{13}$	7.0×10^{-7}	Belle
$\text{Br}(B^+ \to \pi^+ \mu^+\mu^-)$	$211 < m_a < 5140\,^{(\ddagger\ddagger)}$	$\mu^+\mu^-$	$\lvert k_D + k_d\rvert_{13}$	1.2×10^{-7}	Belle
$\text{Br}(B^- \to K^- \nu\bar{\nu})$	$0 < m_a < 4785$	long-lived	$\lvert k_D + k_d\rvert_{23}$	6.9×10^{-6}	BaBar
$\text{Br}(B \to K^* \nu\bar{\nu})$	$0 < m_a < 4387$	long-lived	$\lvert k_D - k_d\rvert_{23}$	5.1×10^{-6}	BaBar
$d\text{Br}/dq^2(B^0 \to K^{*0} e^+e^-)_{[0.0,0.05]}$	$0 < m_a < 224$	e^+e^-	$\lvert k_D - k_d\rvert_{23}$	6.4×10^{-7}	LHCb
$d\text{Br}/dq^2(B^0 \to K^{*0} e^+e^-)_{[0.05,0.15]}$	$224 < m_a < 387$	e^+e^-	$\lvert k_D - k_d\rvert_{23}$	9.3×10^{-7}	LHCb
$\text{Br}\big(B^- \to K^- a(\mu^+\mu^-)\big)$	$250 < m_a < 4700\,^{(\dagger)}$	$\mu^+\mu^-$	$\lvert k_D + k_d\rvert_{23}$	4.4×10^{-8}	LHCb
$\text{Br}\big(B^0 \to K^{*0} a(\mu^+\mu^-)\big)$	$214 < m_a < 4350\,^{(\dagger)}$	$\mu^+\mu^-$	$\lvert k_D - k_d\rvert_{23}$	5.1×10^{-8}	LHCb
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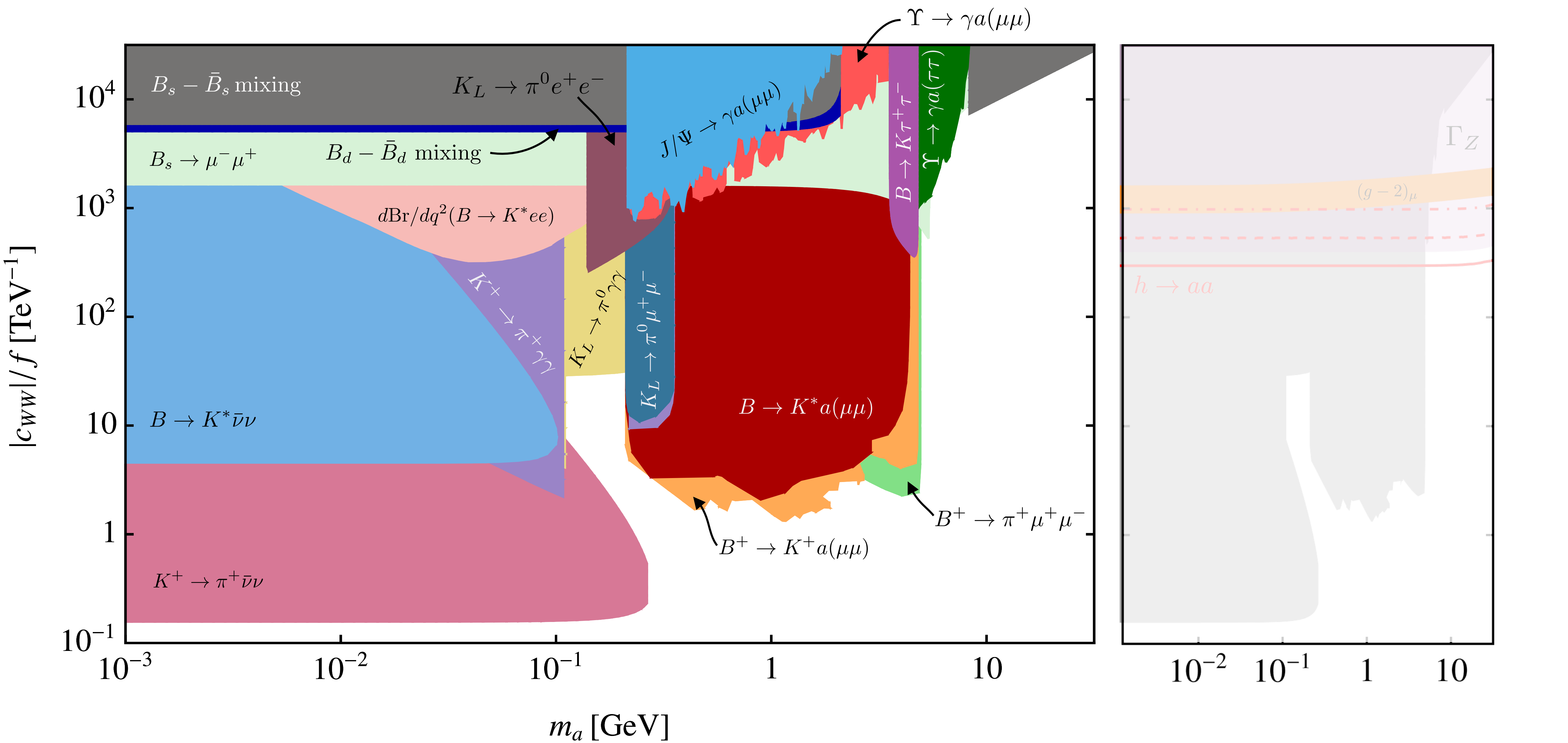
1412.5174, 1708.00021, 1806.00660, 2002.04623

On-shell ALPs

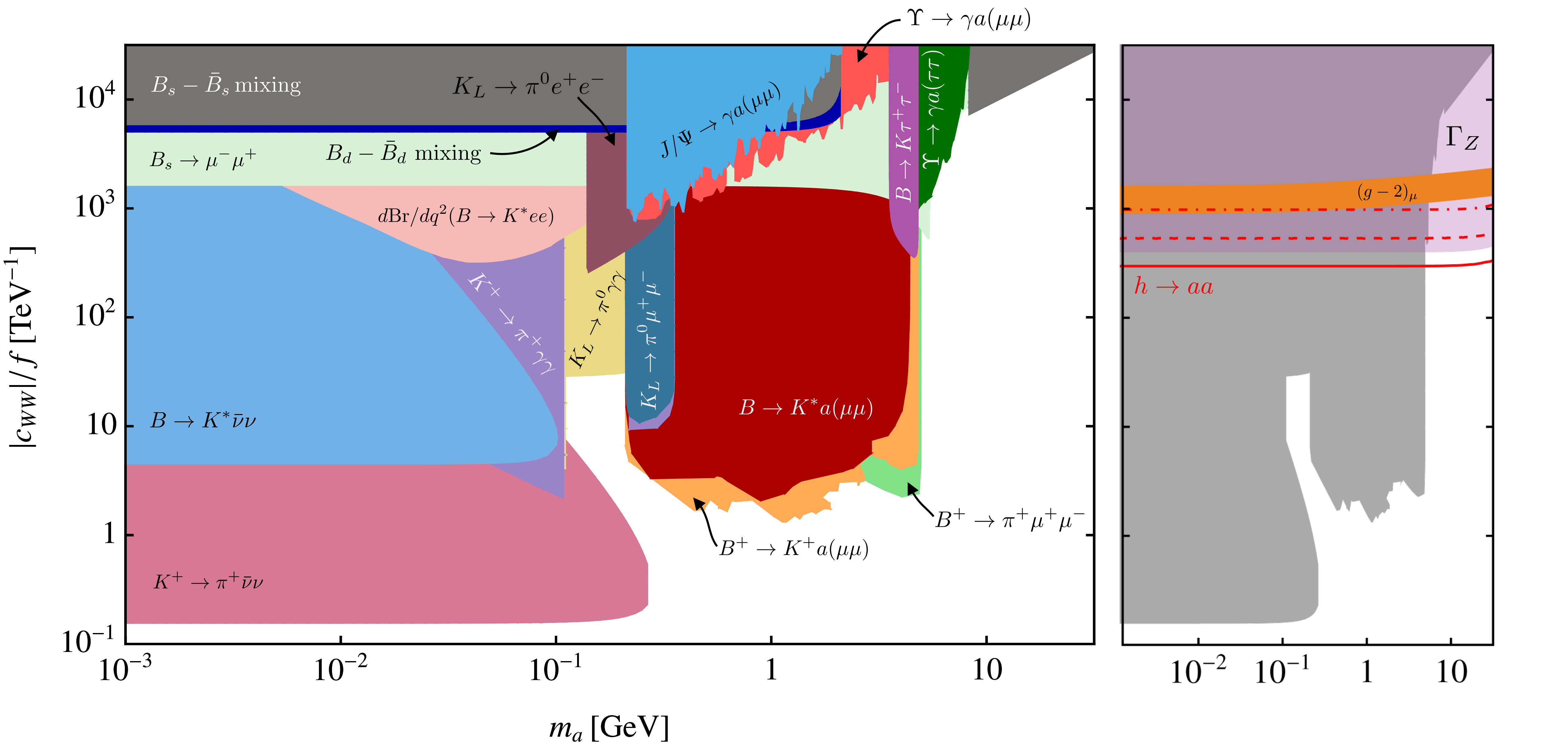
Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$



Phenomenology - Quarks

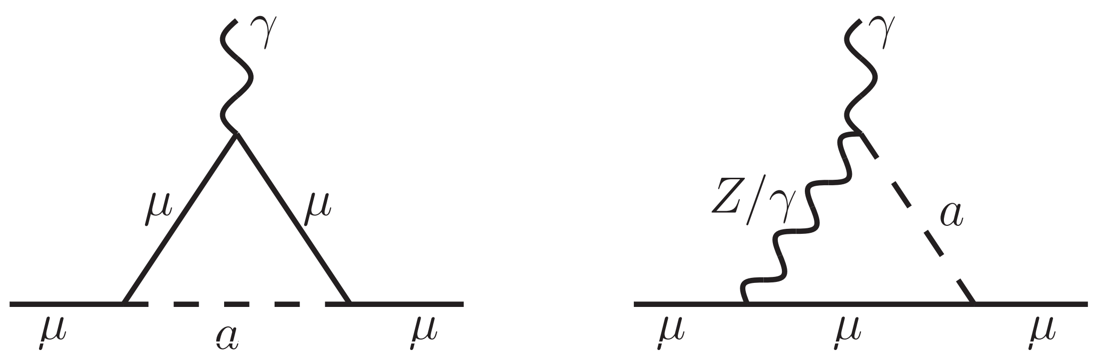
$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$



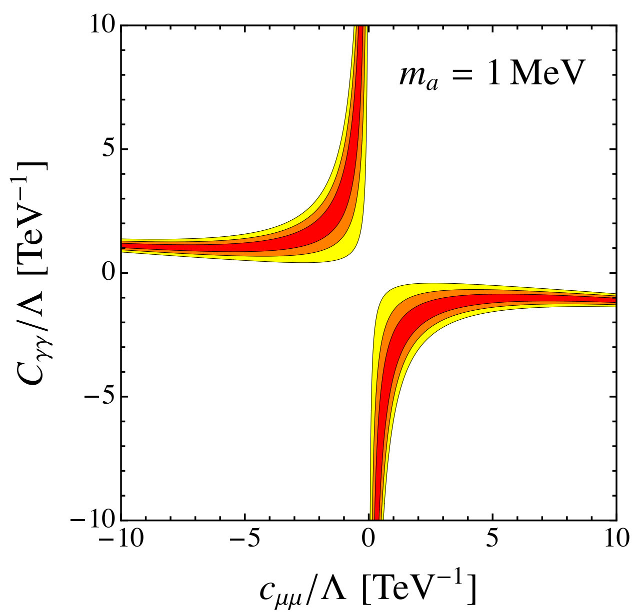
Phenomenology - Quarks

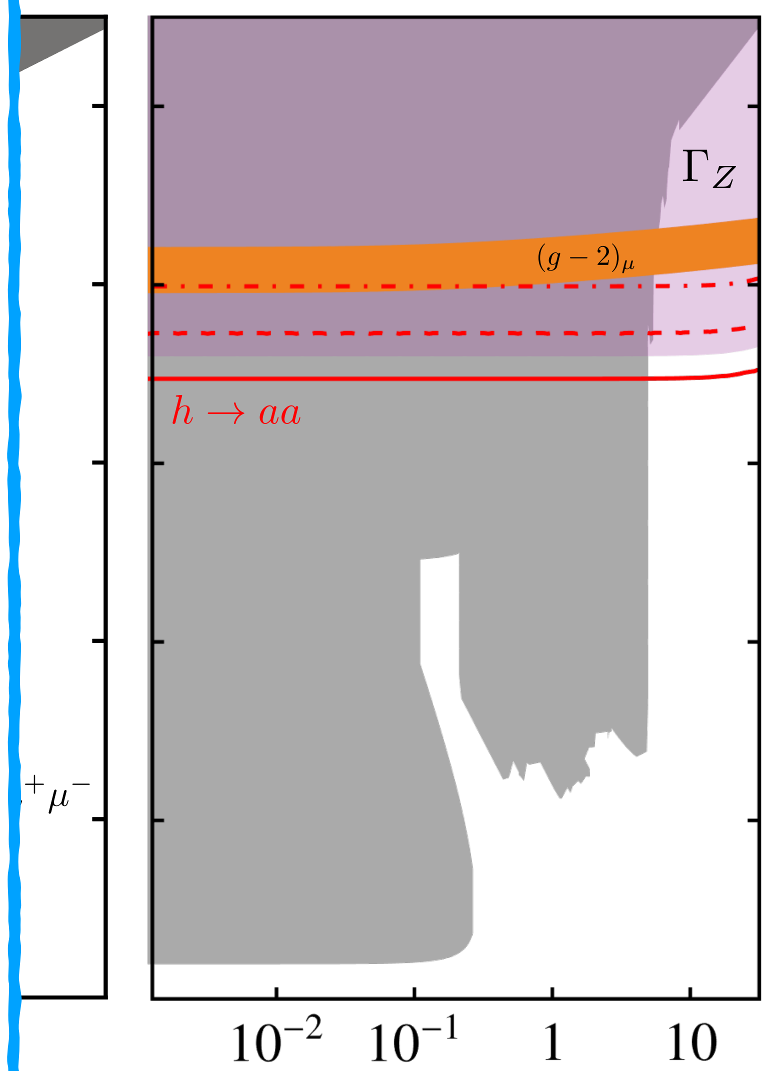
$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

Anomalous magnetic moments



$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (288 \pm 63 \pm 49)\cdot 10^{-11}$$





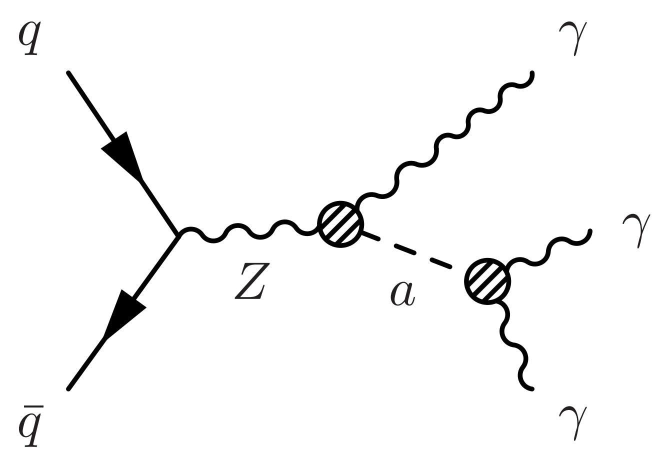
Muon g-2: 0602035, 2006.04822

Haber, Kane, Sterling: Nucl. Phys. B 161 (1979)

Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

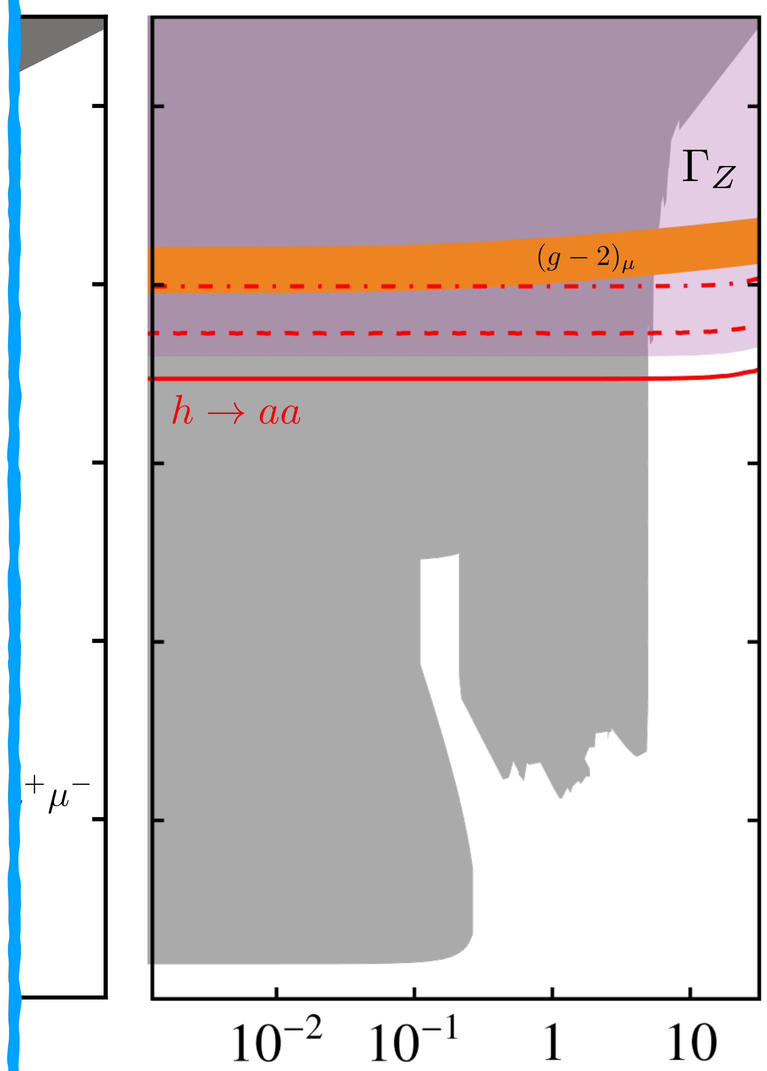
Z widths



$$\Gamma_Z = (2.495 \pm 0.0023)\ \mathrm{GeV}$$

$$\left|C^{\mathrm{eff}}_{\gamma Z}\right| < 1.48\left[\frac{\Lambda}{1\ \mathrm{TeV}}\right]$$

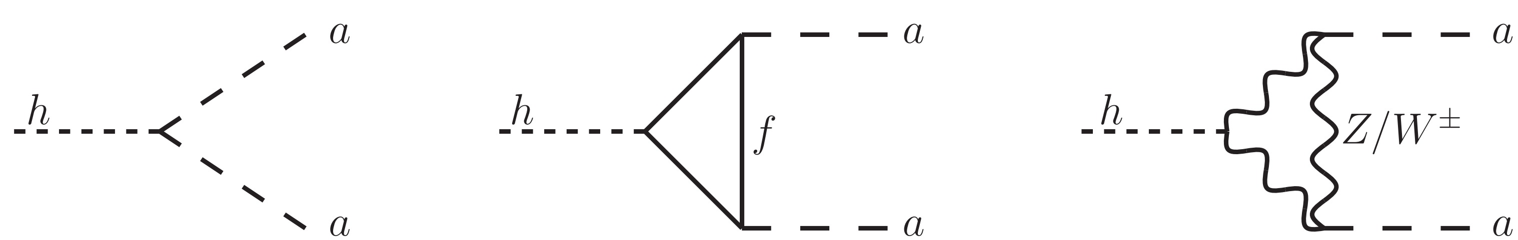
LEP: 0509008



Phenomenology - Quarks

$$c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f} W^A_{\mu\nu} \tilde{W}^{\mu\nu,A}$$

Higgs Branching Ratio

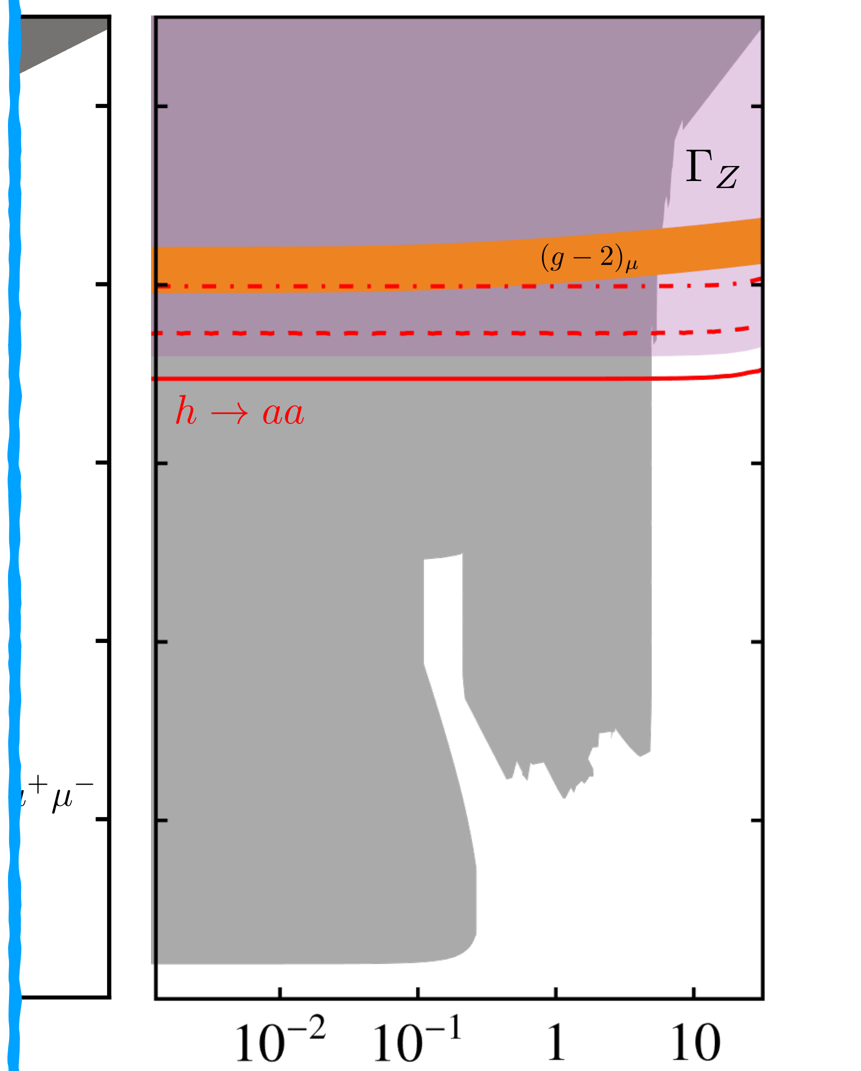


$$\mathrm{Br}(h \to \mathrm{BSM}) < 0.34$$

$$\Longrightarrow \quad \Gamma(h \to \mathrm{BSM}) < 2.1\,\mathrm{MeV}$$

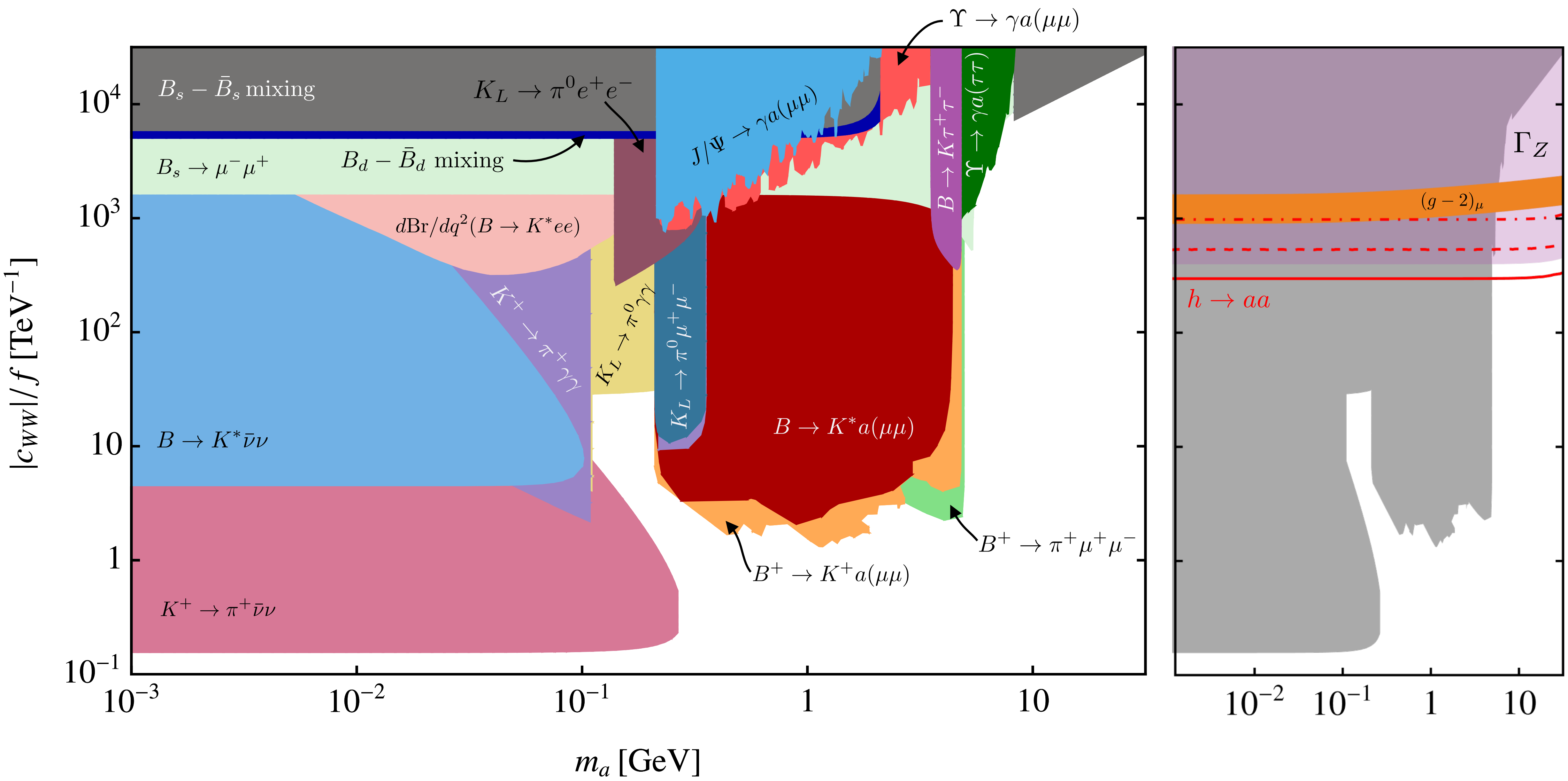
$$\Longrightarrow \quad \left|C_{ah}^{\mathrm{eff}}\right| < 1.34 \left[\frac{\Lambda}{1\,\mathrm{TeV}}\right]^2$$

ATLAS and CMS:1606.02266



Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

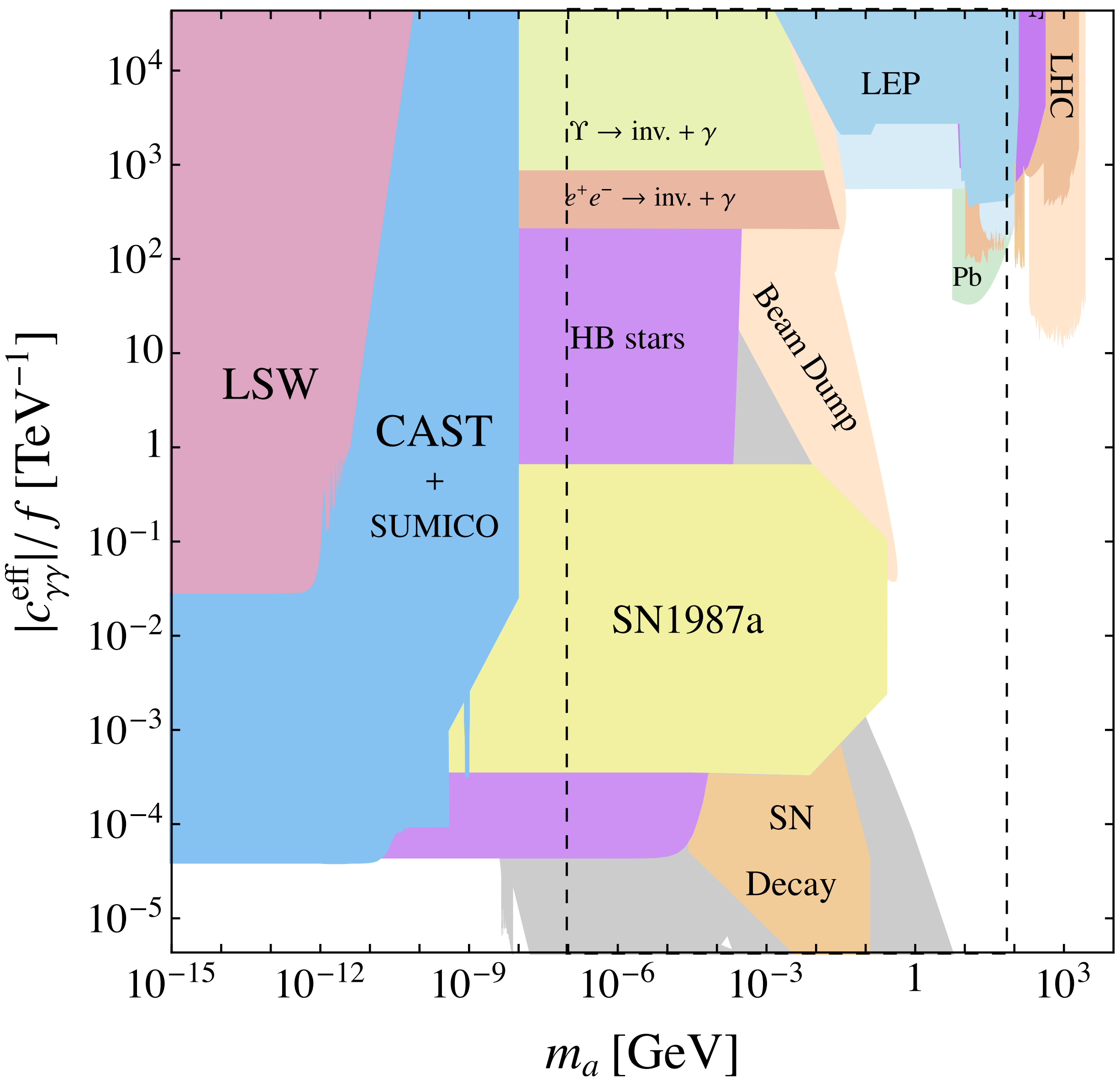


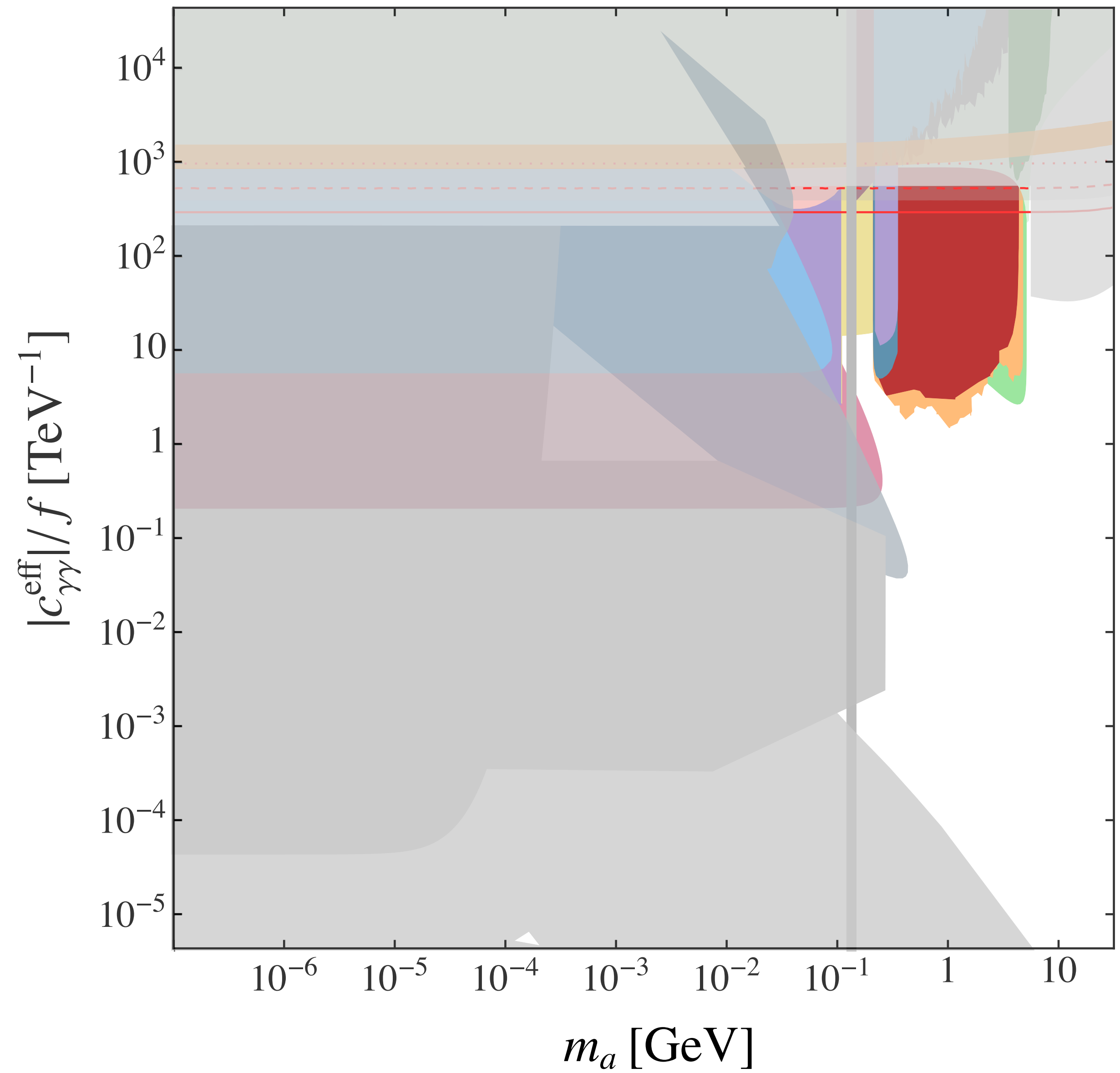
Flavour bounds are complementary to other collider bounds

Phenomenology - Quarks

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^{A}_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

[Jaeckel, Jankowiak, Spannowsky: 1212.3620]
[ATLAS High mass di-photon final states: 1707.04147]

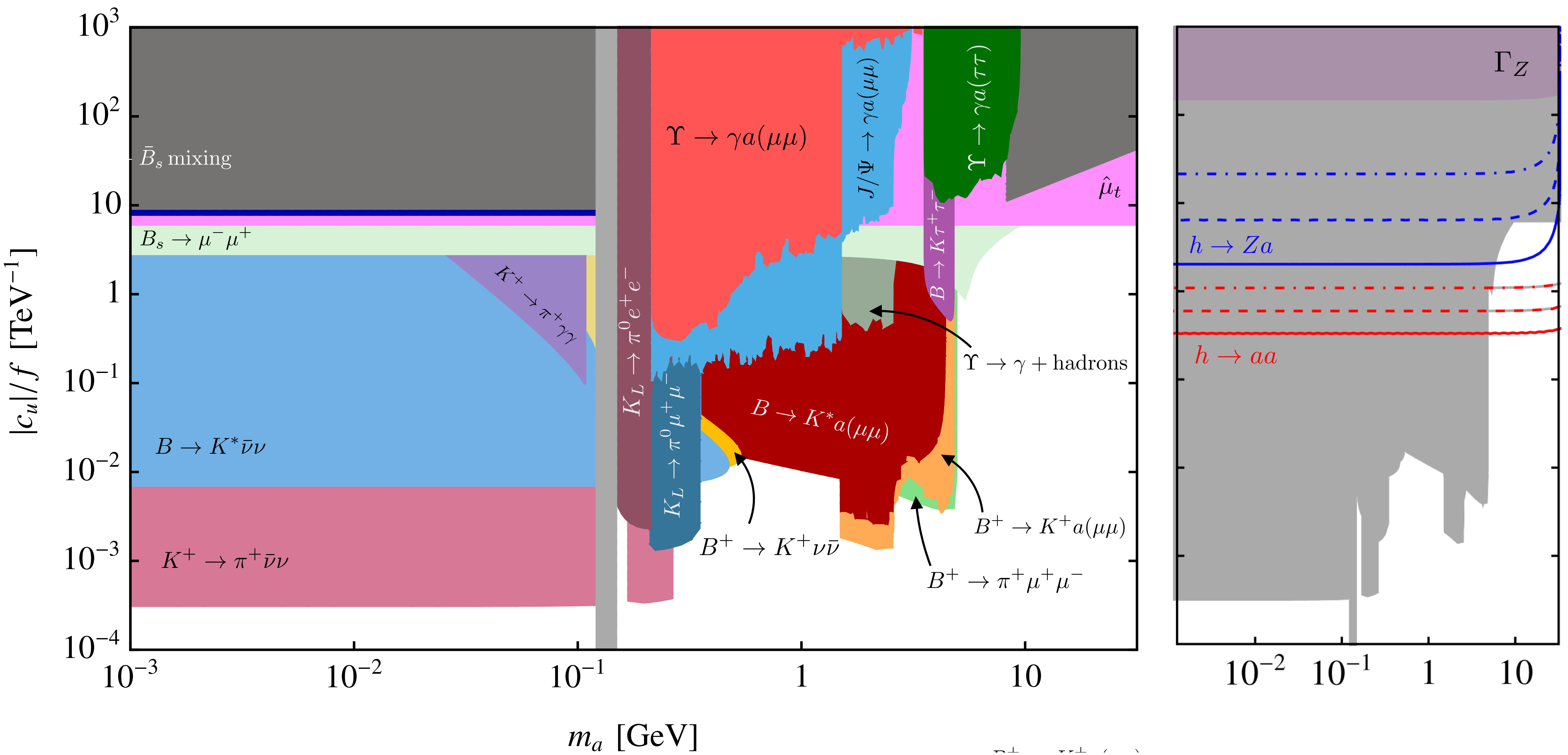




Flavour bounds are complementary to other collider bounds

Phenomenology - Quarks

$$c_u \frac{\partial^\mu a}{f} \sum_i \bar{u}_i \gamma_\mu u_i$$



Phenomenology - Quarks

$$c_u \frac{\partial^\mu a}{f} \sum_i \bar{u}_i \gamma_\mu u_i$$

10^3

10^2

10

1

10^{-1}

10^{-2}

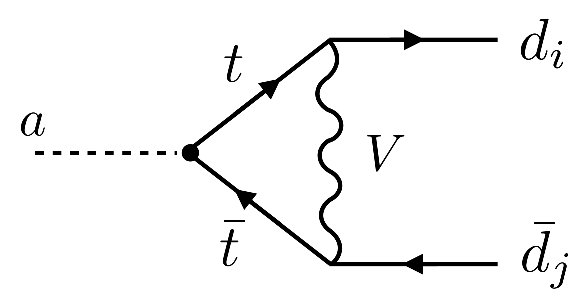
10^{-3}

10^{-4}

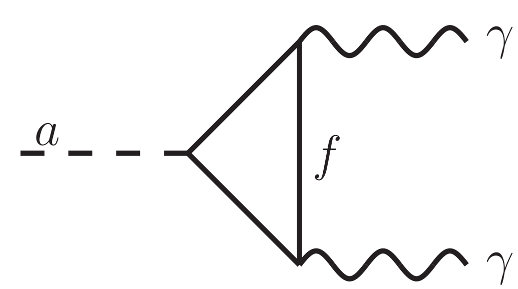
10^{-3}

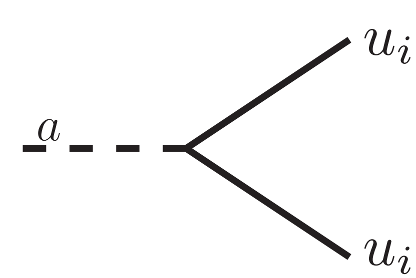
$|c_u|/f$ [TeV^{-1}]

Flavour change



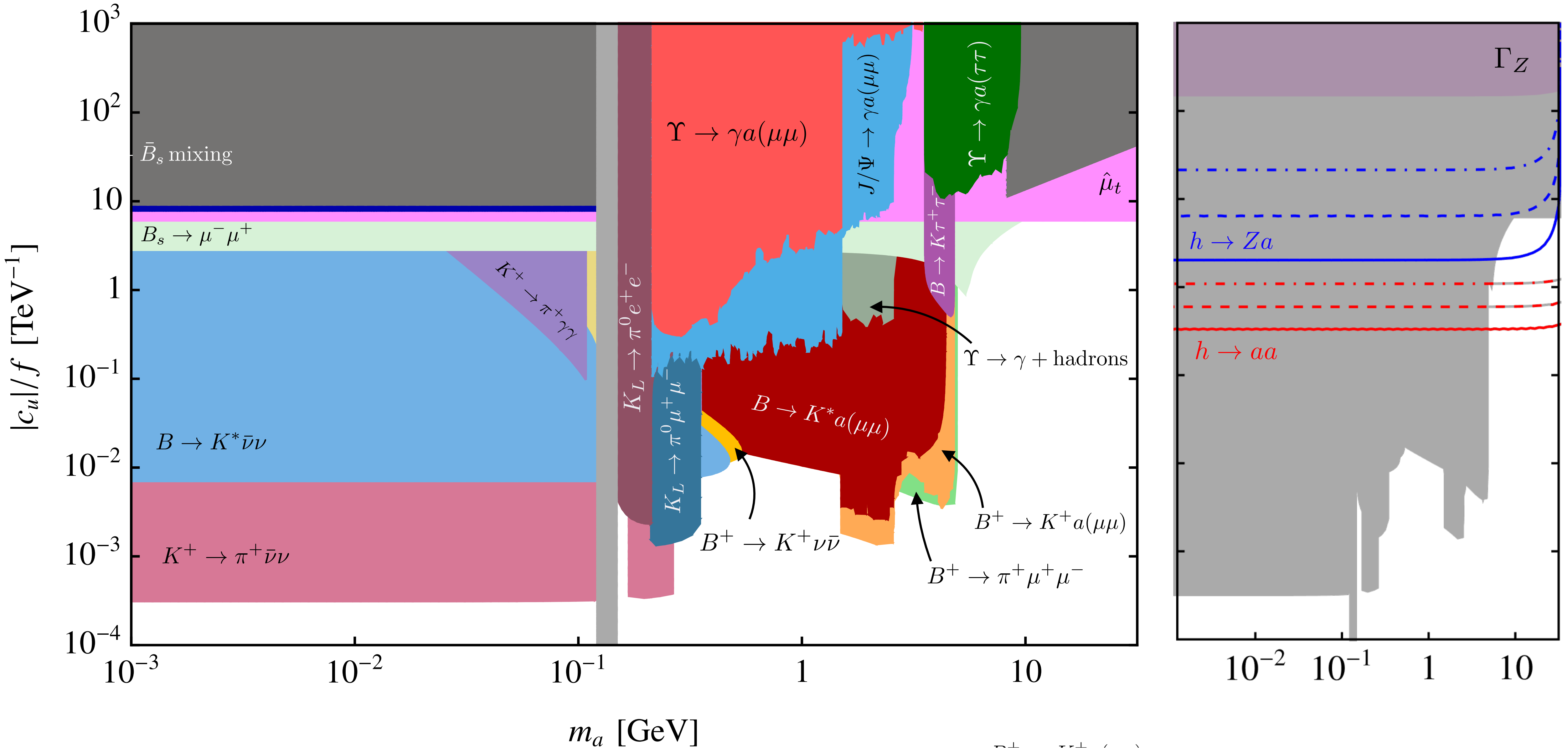
Decay





Phenomenology - Quarks

$$c_u \frac{\partial^\mu a}{f} \sum_i \bar{u}_i \gamma_\mu u_i$$

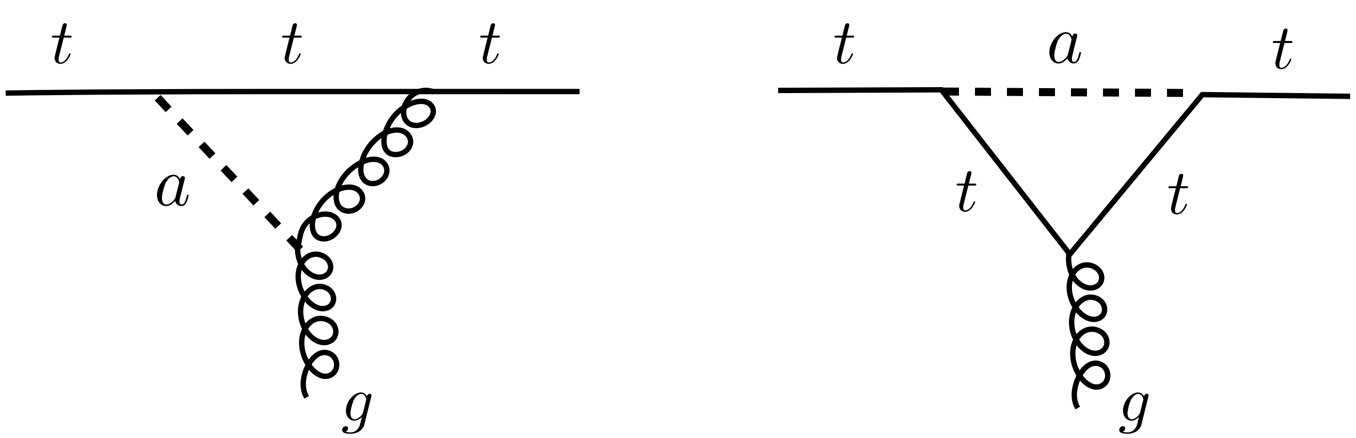


Phenomenology - Quarks

$$c_u \frac{\partial^\mu a}{f} \sum_i \bar{u}_i \gamma_\mu u_i$$

Chromomagnetic moment of the top

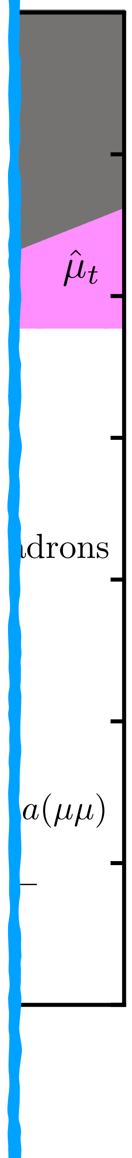
$$\mathcal{L} = \hat{\mu}_t \frac{g_s}{2m_t} \bar{t} \sigma^{\mu\nu} T^a t \, G^a_{\mu\nu}$$

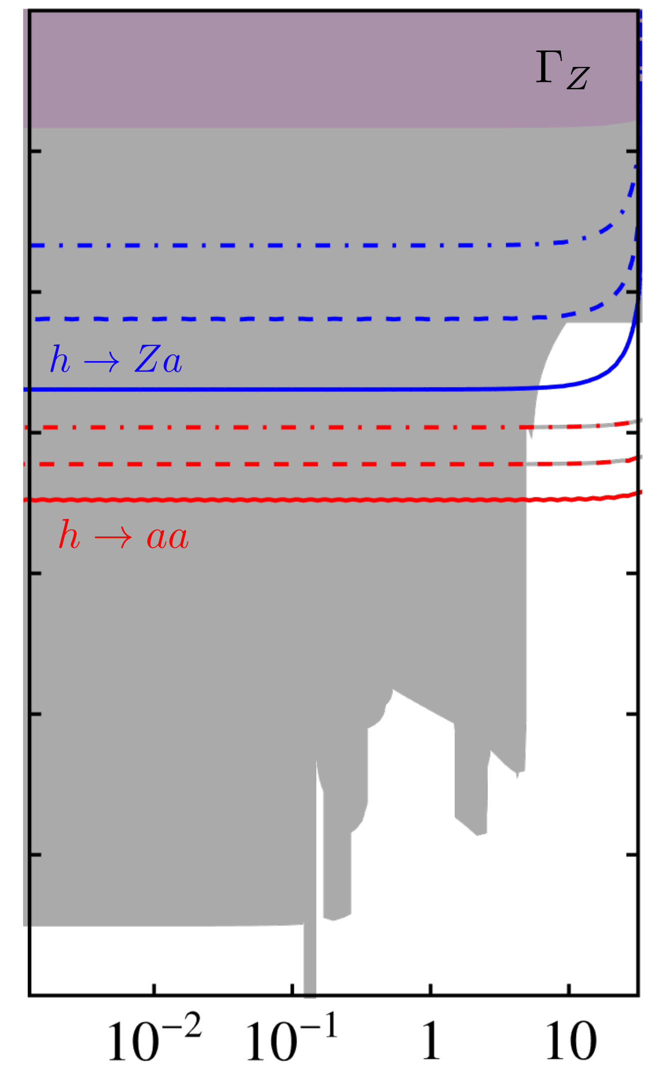


$$\hat{\mu}_t = \frac{m_t^2}{f^2} \frac{c_{tt}}{32\pi^2} \left\{ c_{tt} \, h_1(0, m_t, m_a) + \frac{2\alpha_s}{\pi} c_{GG} \left[\log \frac{\mu^2}{m_t^2} - h_2(0, m_t, m_a) \right] \right\}$$

$$-0.014 \leq \mathrm{Re}(\hat{\mu}_t) < 0.004$$

CMS: 1907.03729

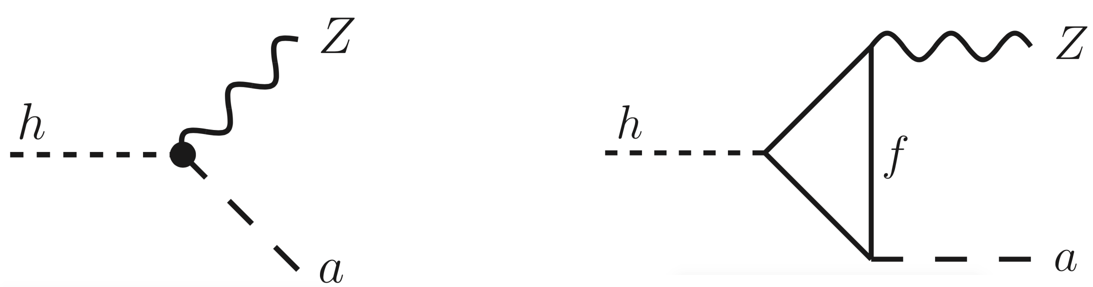




Phenomenology - Quarks

$$c_u \frac{\partial^\mu a}{f} \sum_i \bar{u}_i \gamma_\mu u_i$$

Higgs Branching Ratio

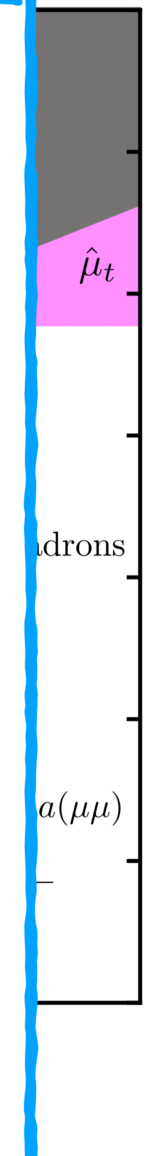


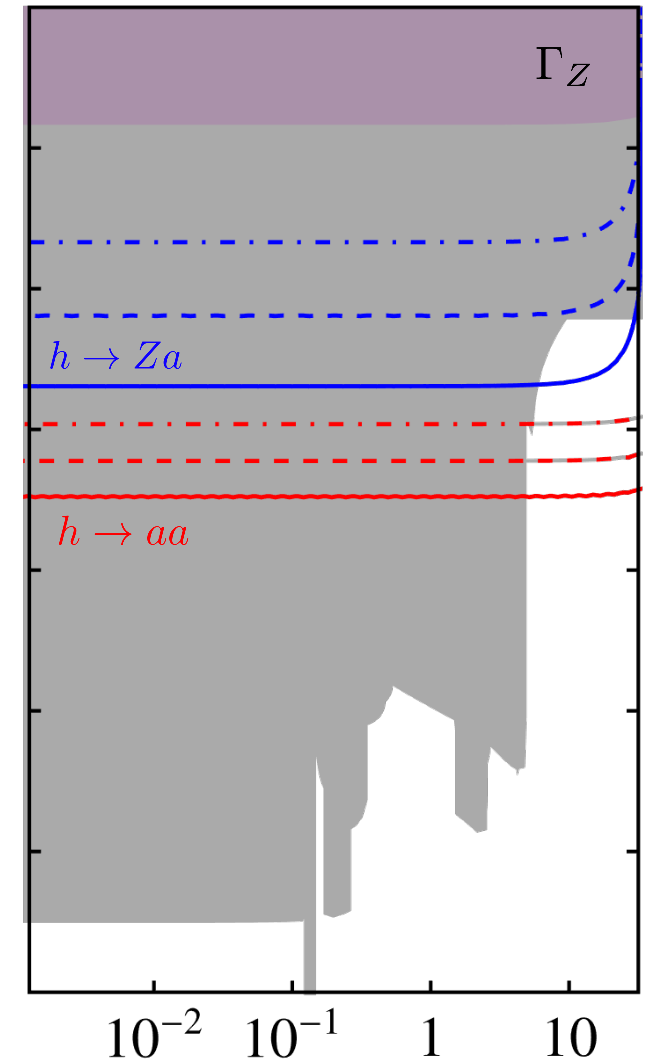
$$\mathrm{Br}(h \to \mathrm{BSM}) < 0.34$$

$$\implies \quad \Gamma(h \to \mathrm{BSM}) < 2.1\,\mathrm{MeV}$$

$$\implies \quad \frac{|C_{Zh}^{\mathrm{eff}}|}{\Lambda} < 0.72\,\mathrm{TeV}^{-1}$$

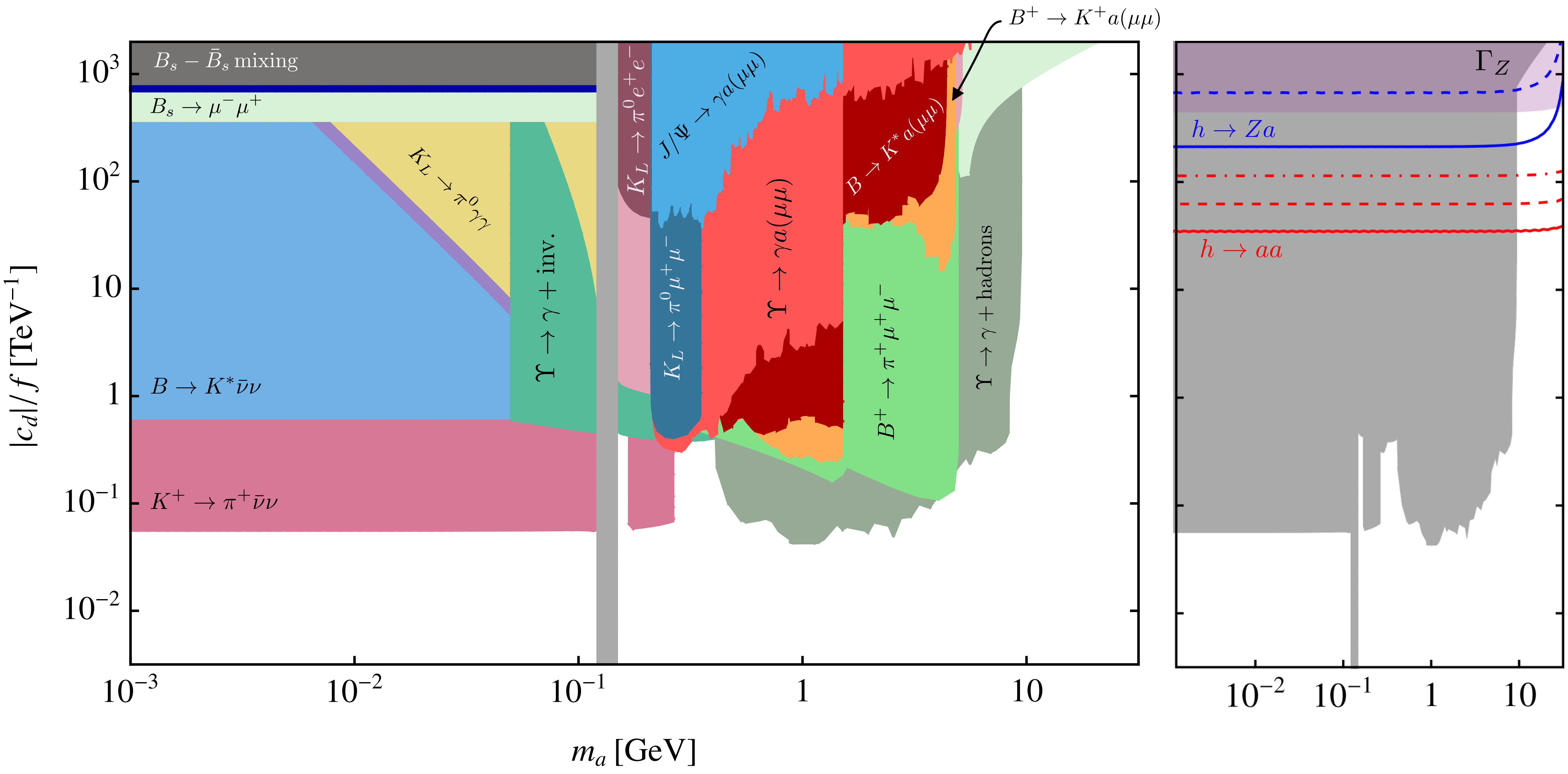
ATLAS and CMS:1606.02266





Phenomenology - Quarks

$$c_d \frac{\partial^\mu a}{f} \sum_i \bar{d}_i \gamma_\mu d_i$$



Phenomenology - Quarks

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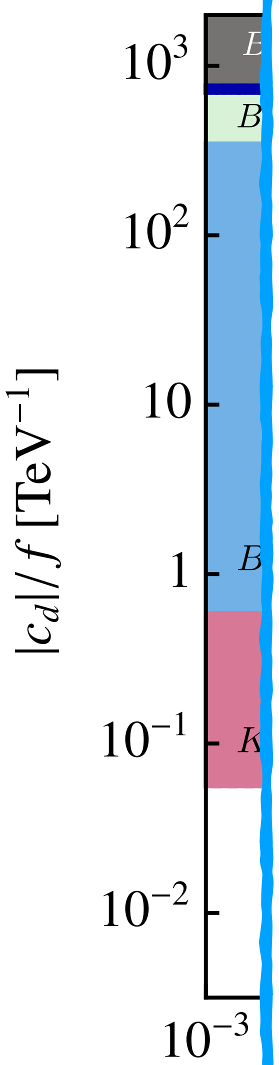
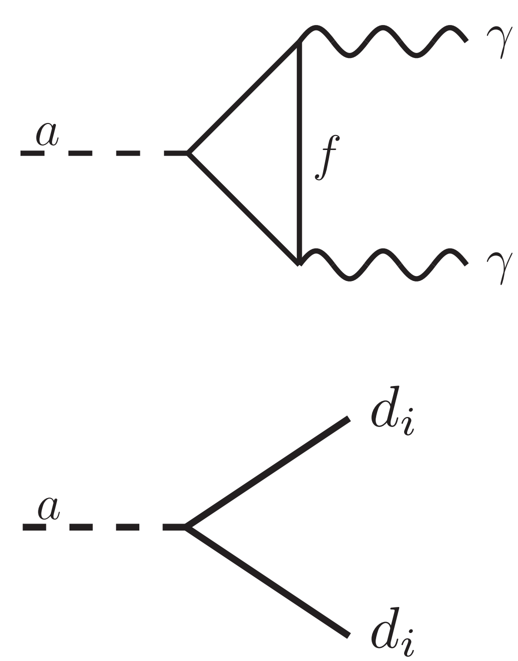


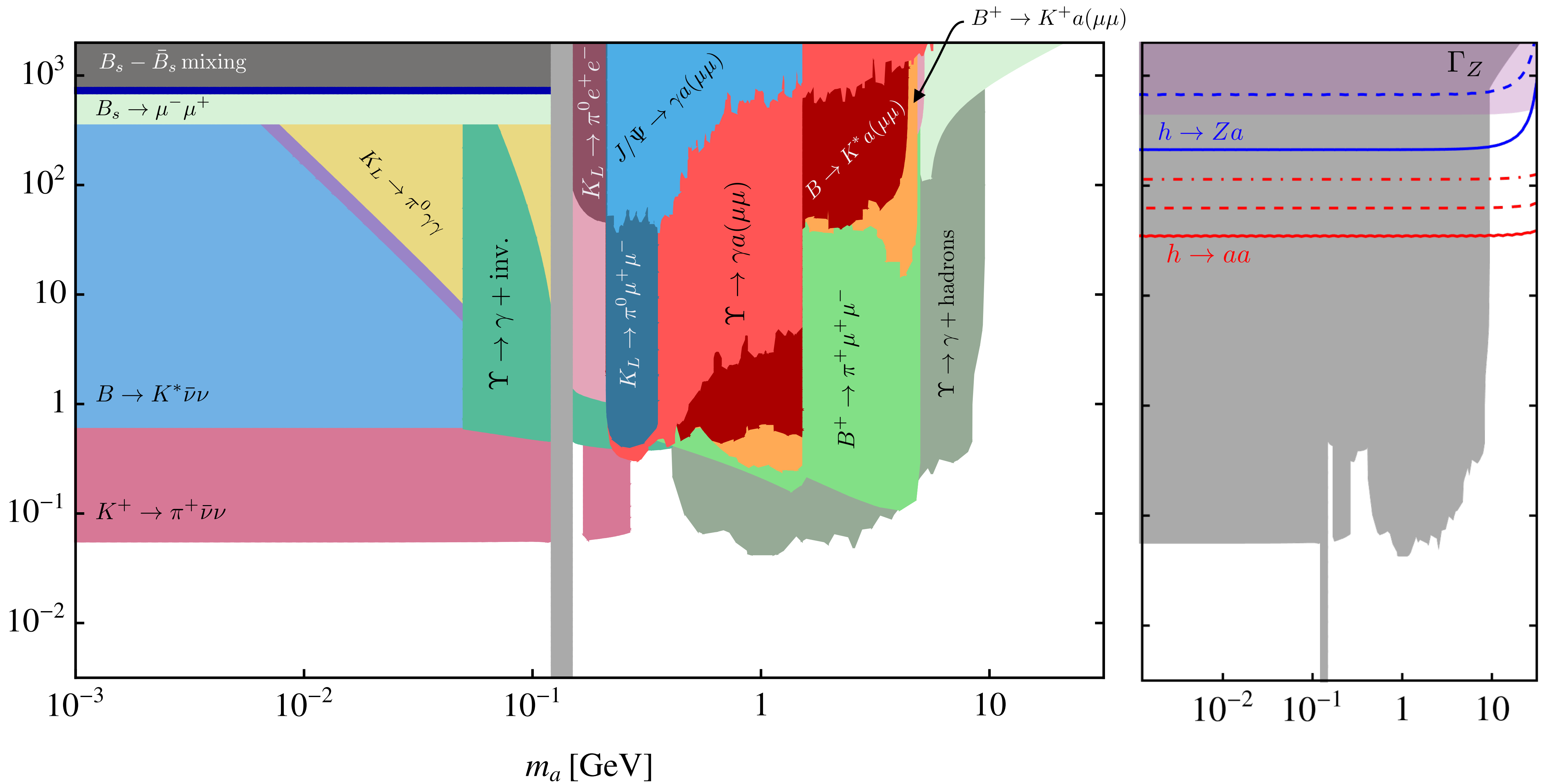
Flavour change | none

Decay



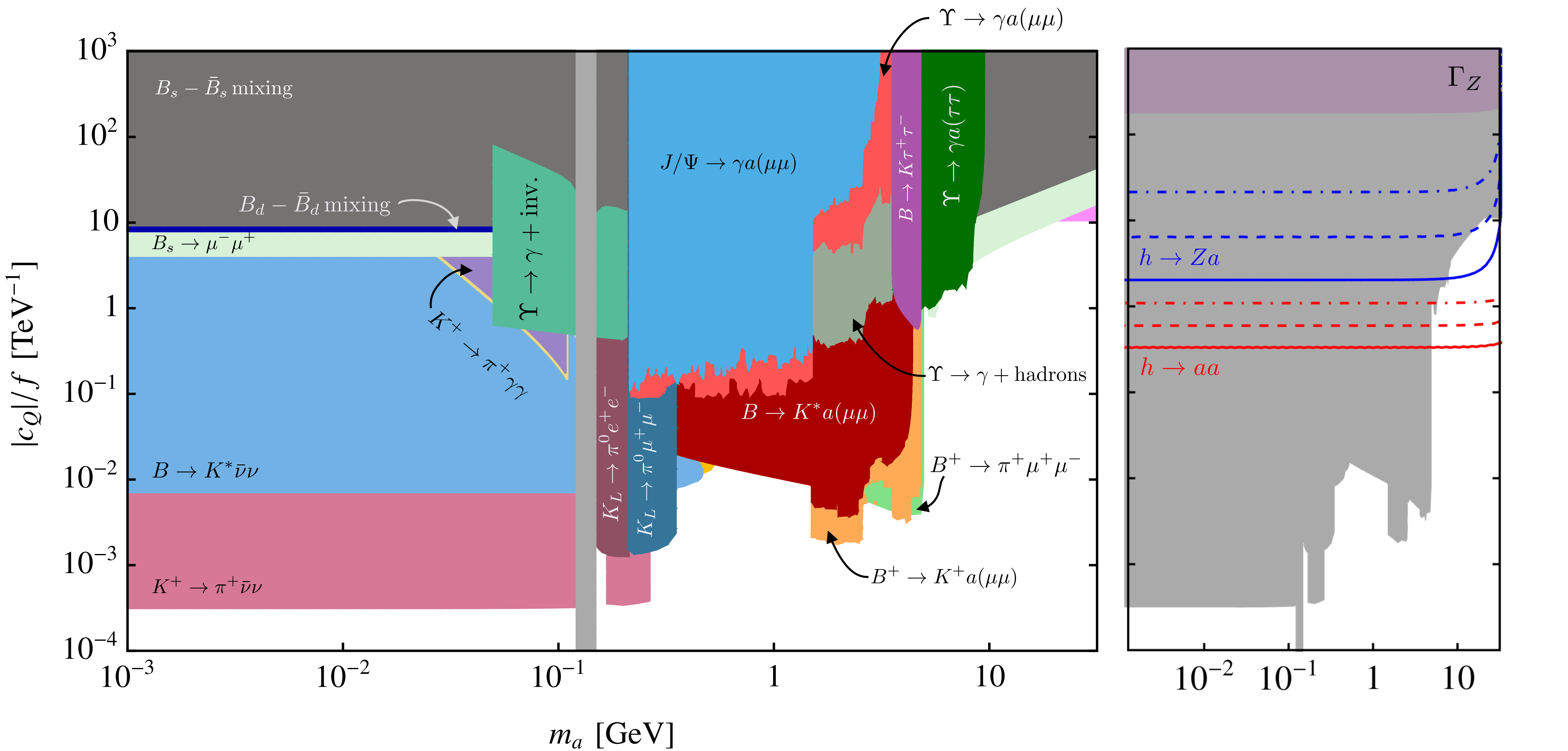
Phenomenology - Quarks

$$c_d \frac{\partial^\mu a}{f} \sum_i \bar{d}_i \gamma_\mu d_i$$



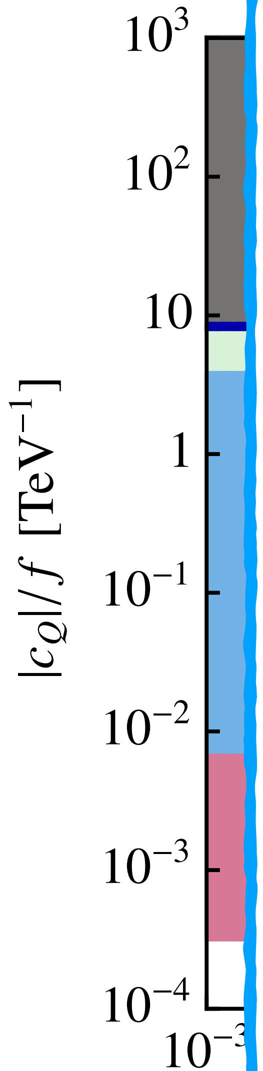
Phenomenology - Quarks

$$c_Q \frac{\partial^\mu a}{f} \sum_i \bar{Q}_i \gamma_\mu Q_i$$

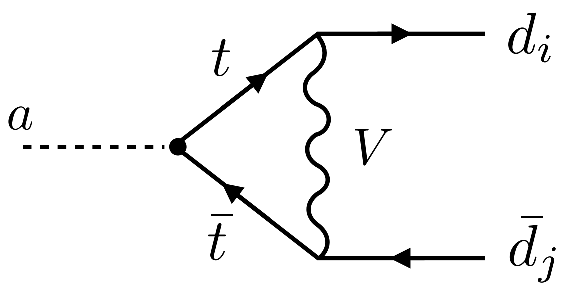


Phenomenology - Quarks

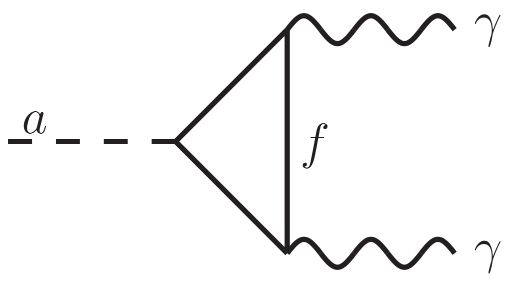
$$c_Q \frac{\partial^\mu a}{f} \sum_i \bar{Q}_i \gamma_\mu Q_i$$

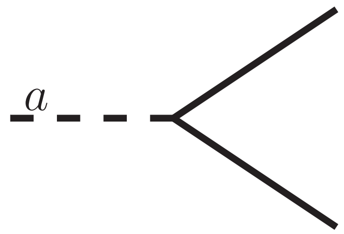


Flavour change



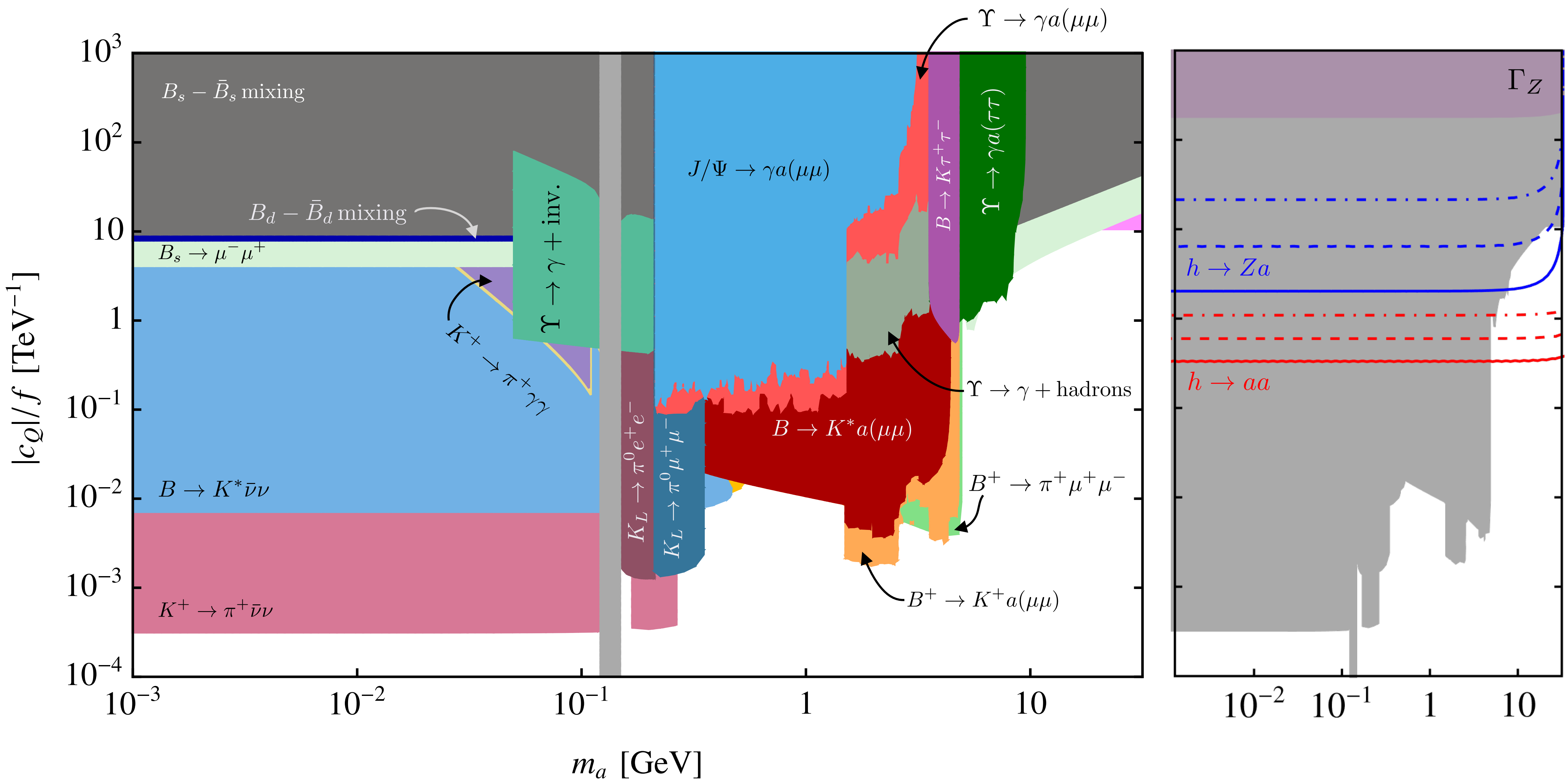
Decay





Phenomenology - Quarks

$$c_Q \frac{\partial^\mu a}{f} \sum_i \bar{Q}_i \gamma_\mu Q_i$$



Outline

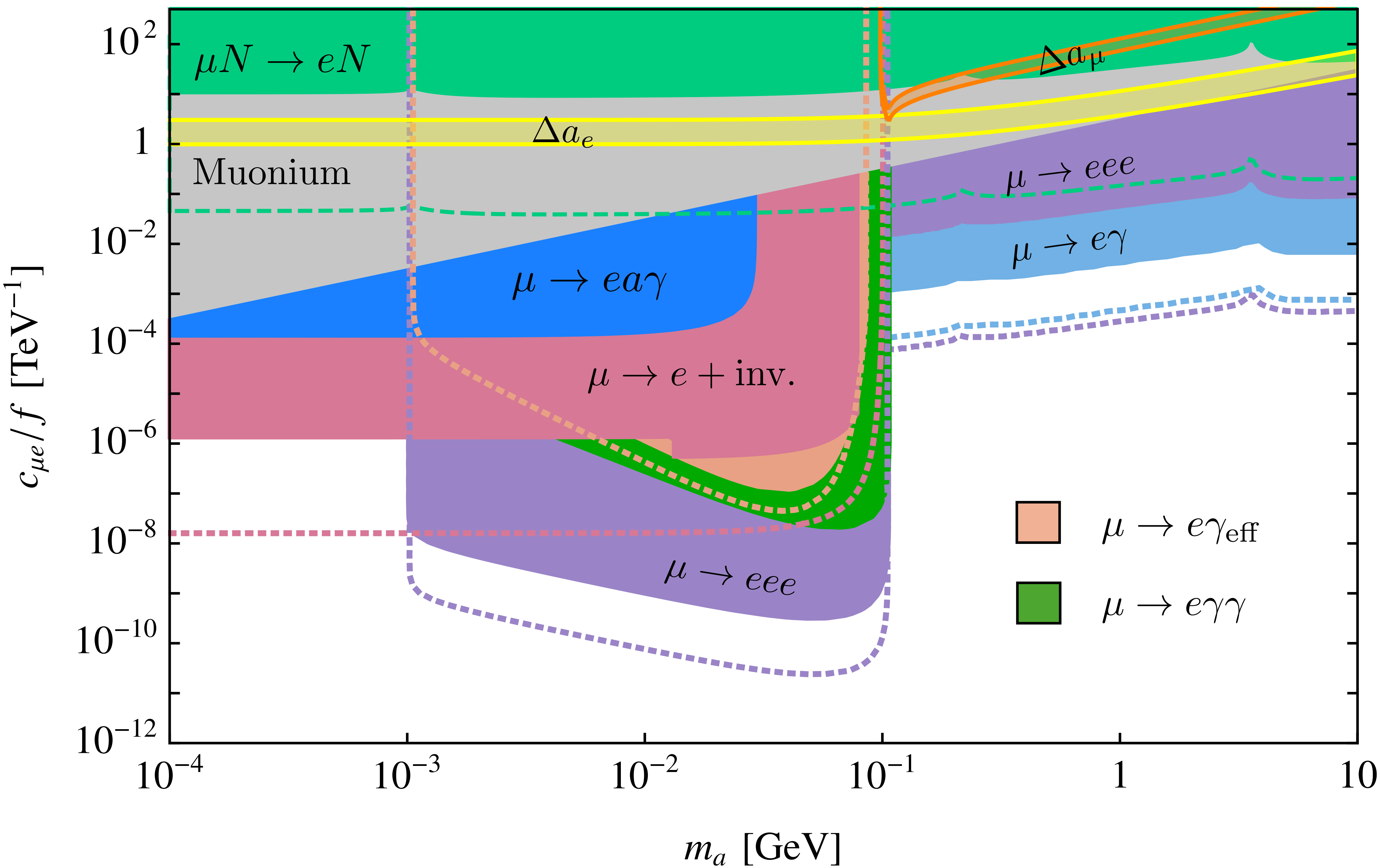
1. Theory Motivations for ALPs
2. Effective Lagrangian and Operator Evolution
3. Phenomenology of Flavour Changing ALP Couplings to
    - Quarks
    - Leptons
4. Conclusions

ALPs and Lepton Flavour Phenomenology

1806.00660
1908.00008
1911.06279
2006.04795

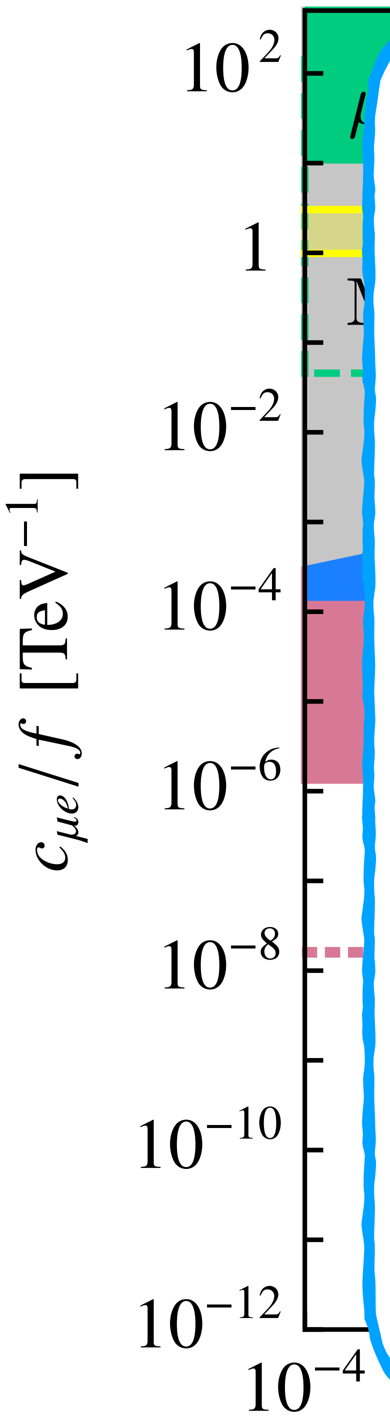
Phenomenology - Leptons

$\frac{c_{ee}}{f} = \frac{c_{\mu\mu}}{f} = \frac{c_{\tau\tau}}{f} = 1\,\text{TeV}^{-1}$



Phenomenology - Leptons

$$\frac{c_{ee}}{f} = \frac{c_{\mu\mu}}{f} = \frac{c_{\tau\tau}}{f} = 1\,\mathrm{TeV}^{-1}$$



Flavour change can't be generated from loops

Some observables generated only at loop-level

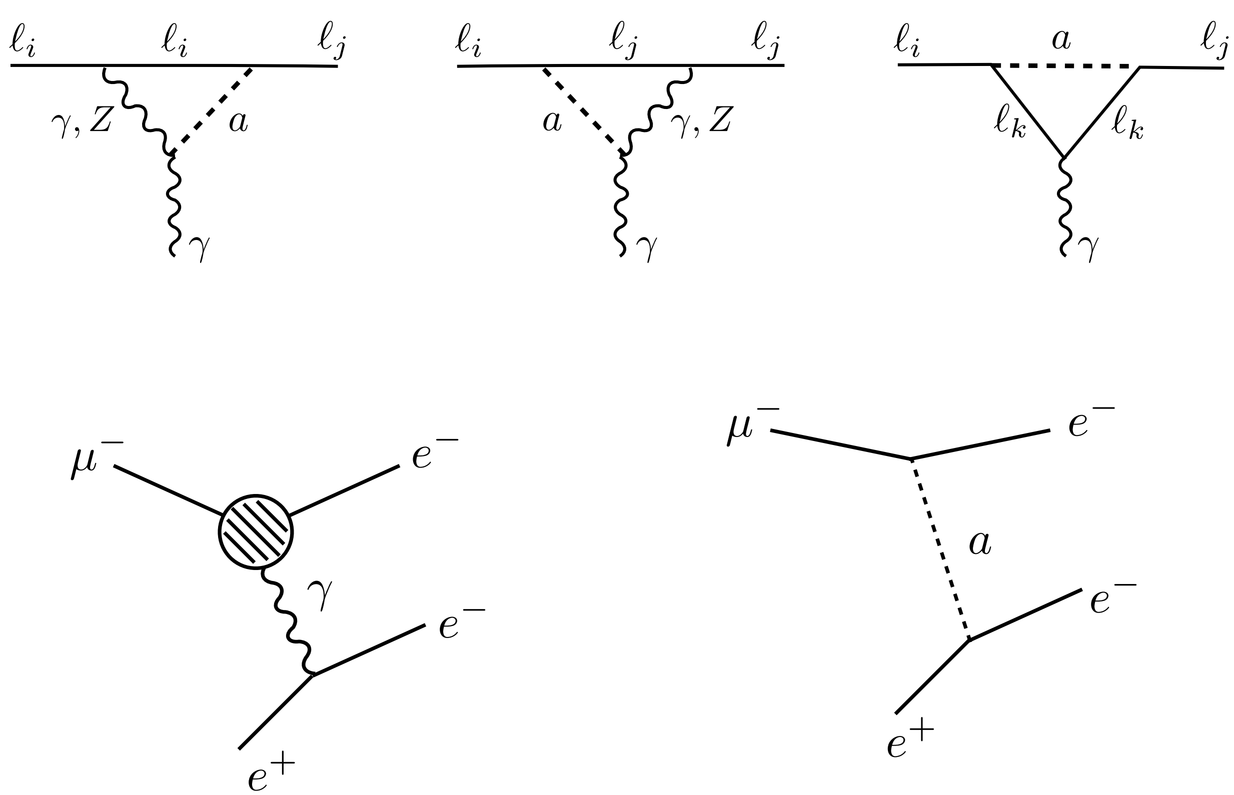
Heavy leptons in the loop can magnify ALP effects

m_a [GeV]

Phenomenology - Leptons

$$\frac{c_{ee}}{f} = \frac{c_{\mu\mu}}{f} = \frac{c_{\tau\tau}}{f} = 1\,\text{TeV}^{-1}$$

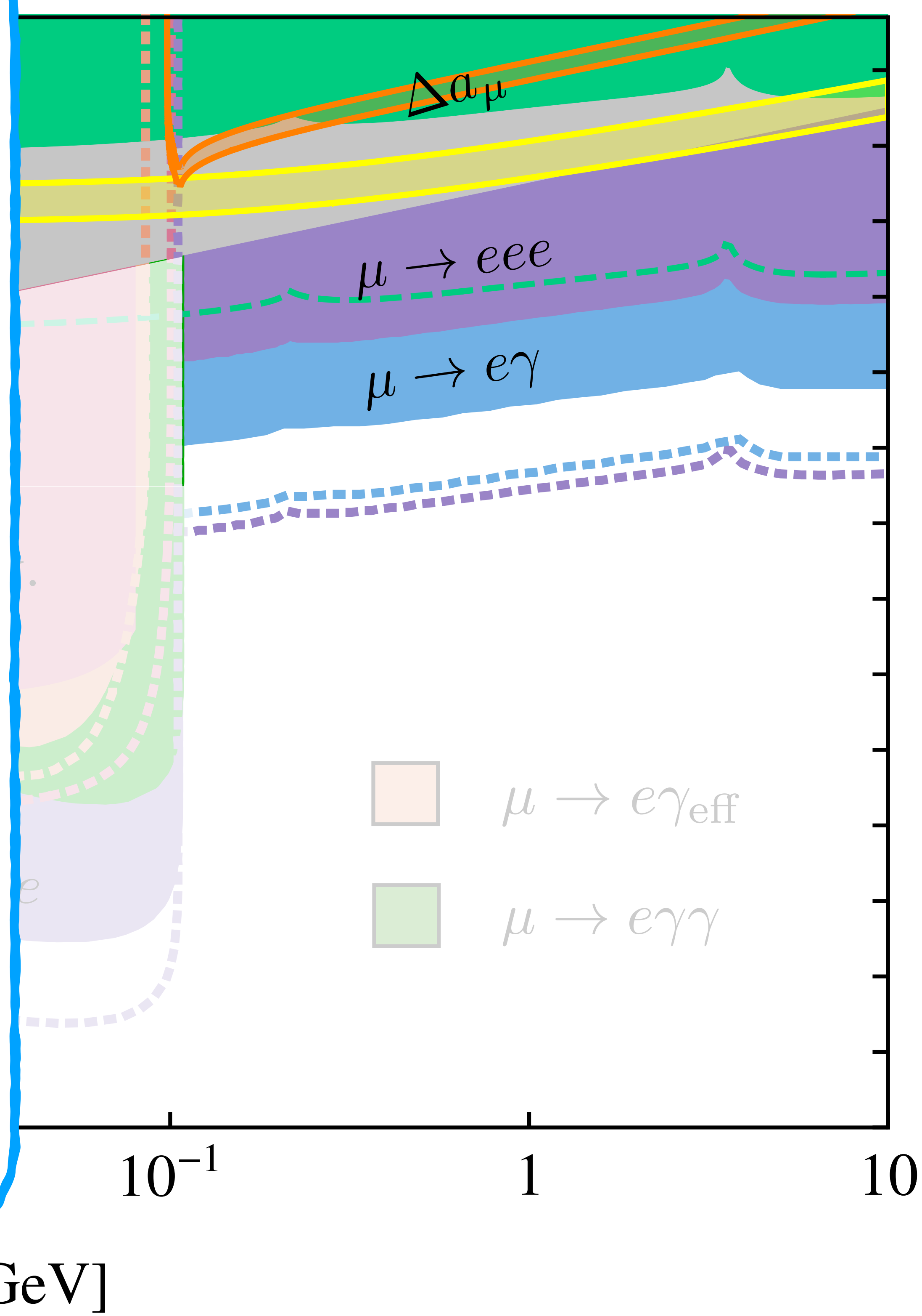
Lepton decays



Off-shell ALP

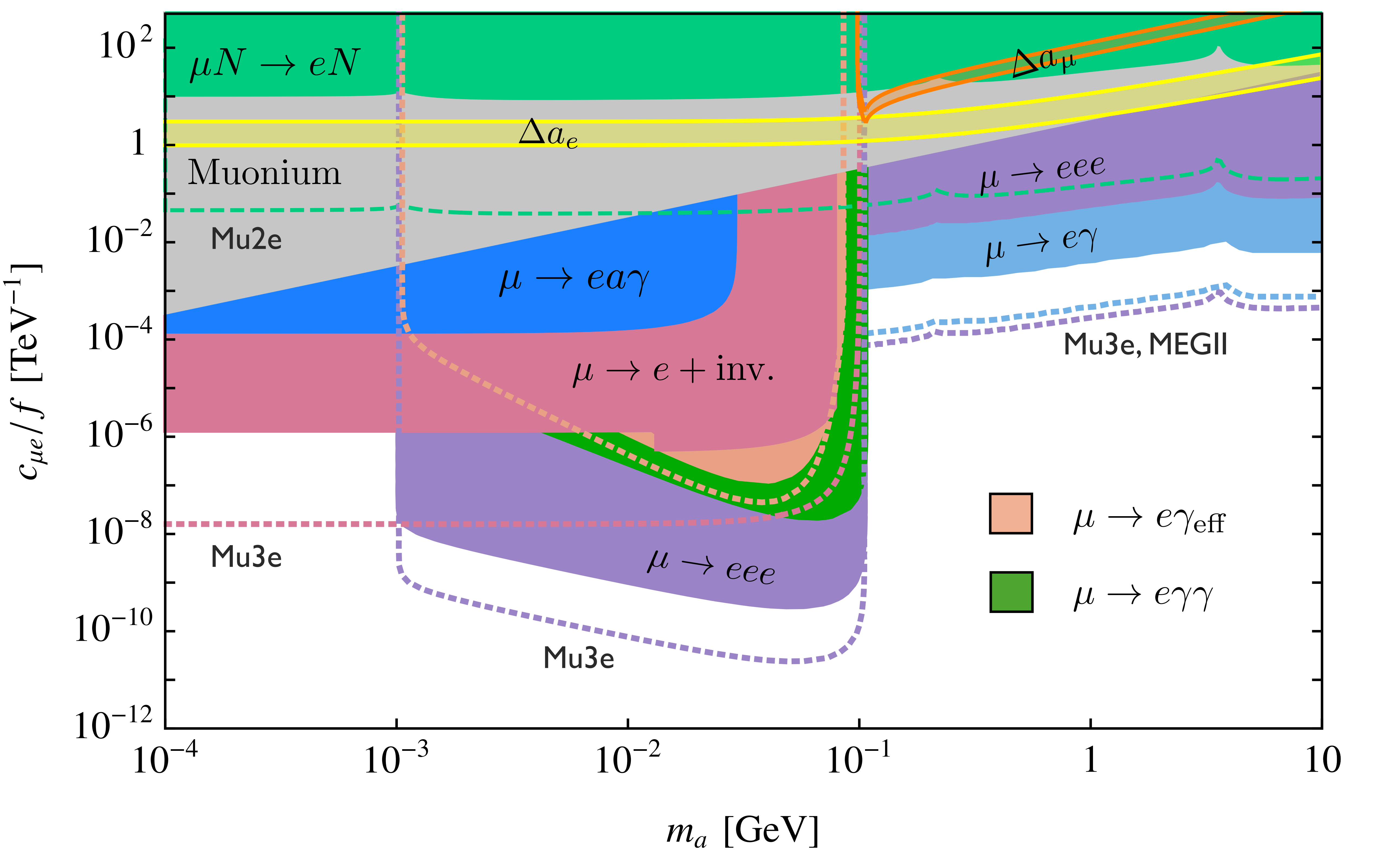
Strongest limits for on-shell ALP

LAMPF: Phys.Rev.D 38 (1988) 2077
Sindrum: Nucl.Phys.B 299 (1988) 1-6



Phenomenology - Leptons

$$\frac{c_{ee}}{f} = \frac{c_{\mu\mu}}{f} = \frac{c_{\tau\tau}}{f} = 1\,\mathrm{TeV}^{-1}$$



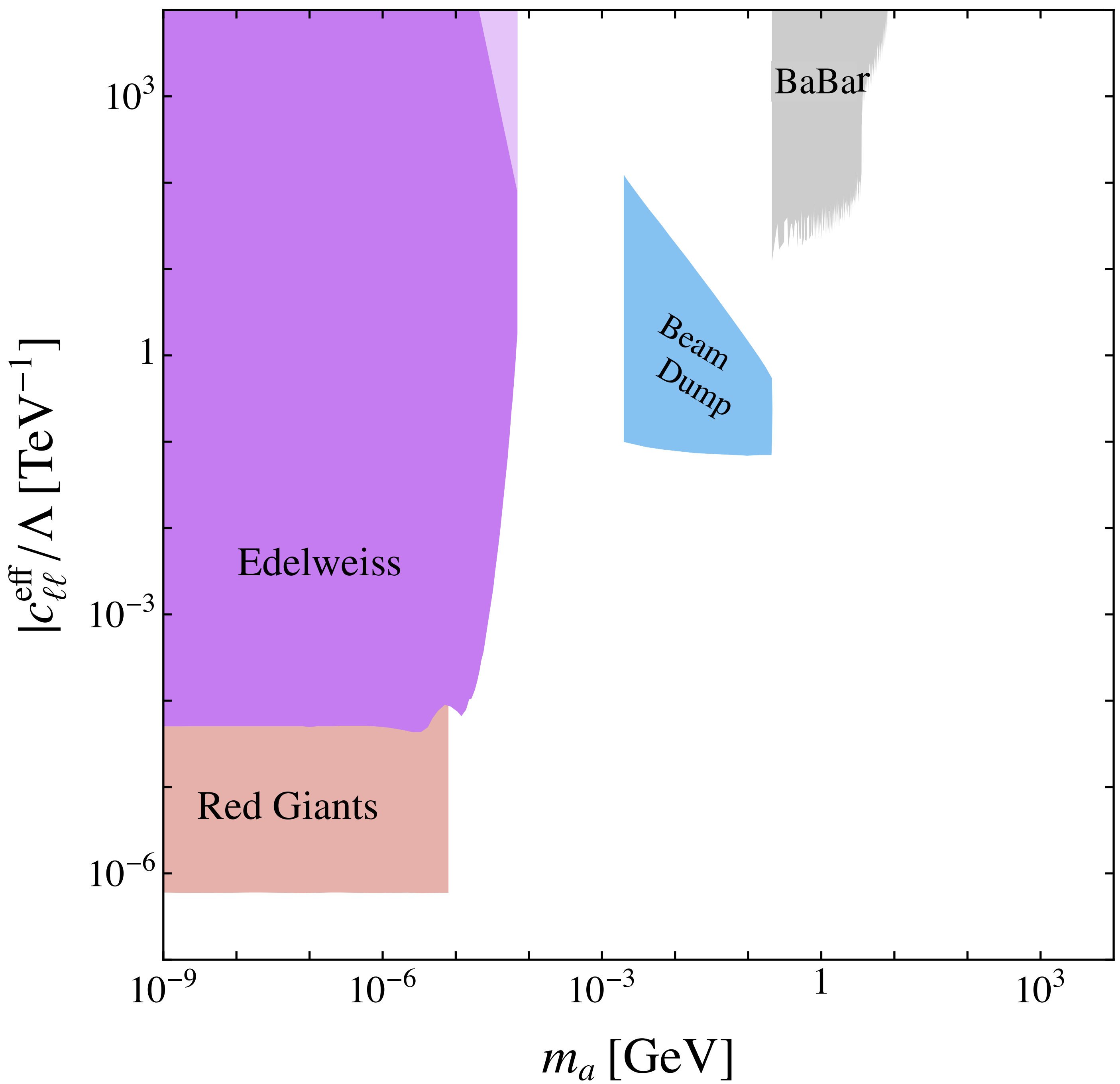
Conclusions

- MeV-GeV ALPs and Axions well motivated
- Significant impact of RG evolution on phenomenology
- Collider probes complementary to flavor probes

Thank you!

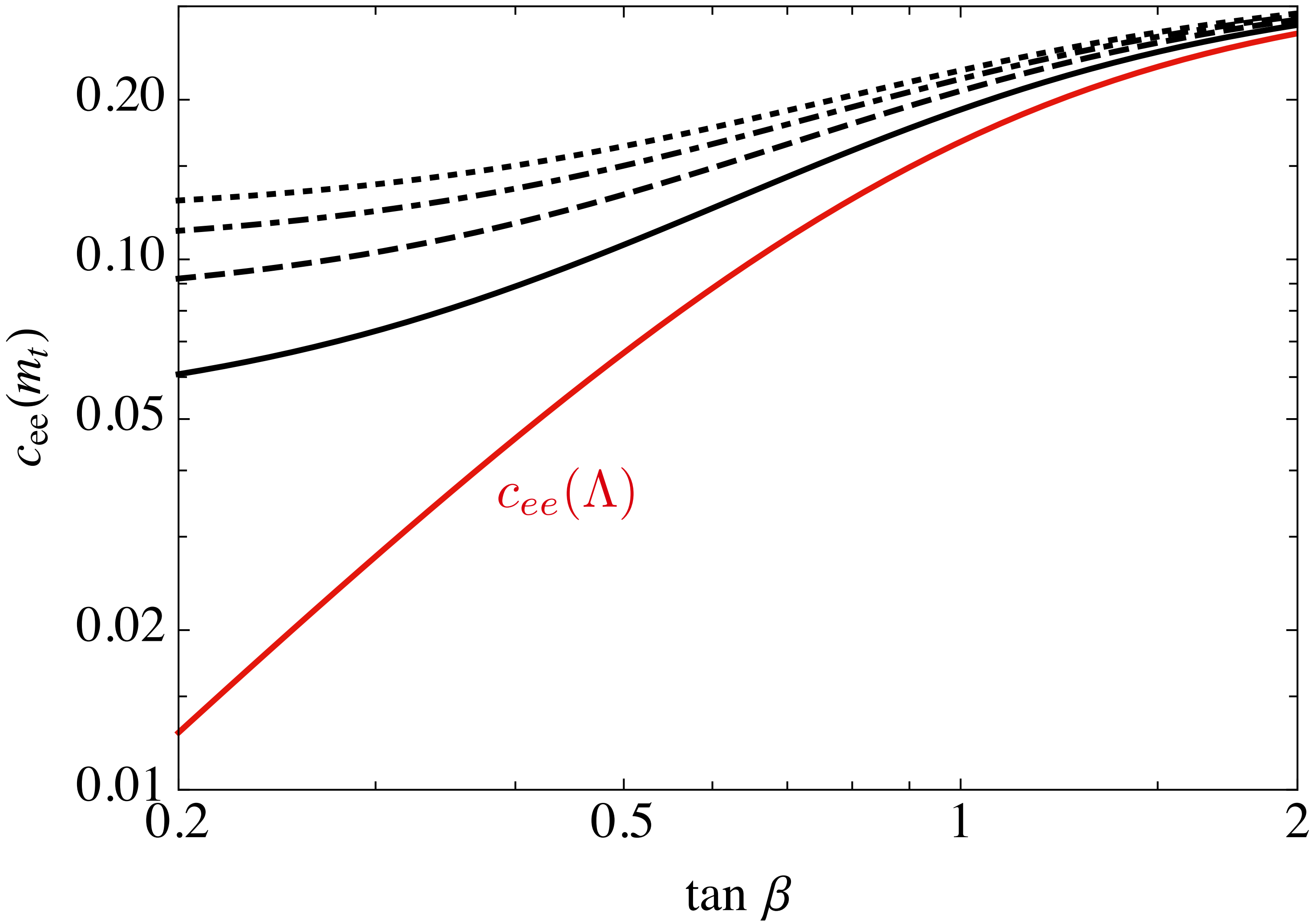
Backup

Lepton coupling only



Operator Evolution at the Weak Scale

Example: DFSZ QCD axions



$$c_{u_i u_i}(\Lambda) = \frac{1}{3}\cos^2\beta\,, \qquad c_{d_i d_i}(\Lambda) = c_{e_i e_i}(\Lambda) = \frac{1}{3}\sin^2\beta\,, \qquad c_{GG} = -\frac{1}{2}$$