Flavour bounds on axions and hidden photons

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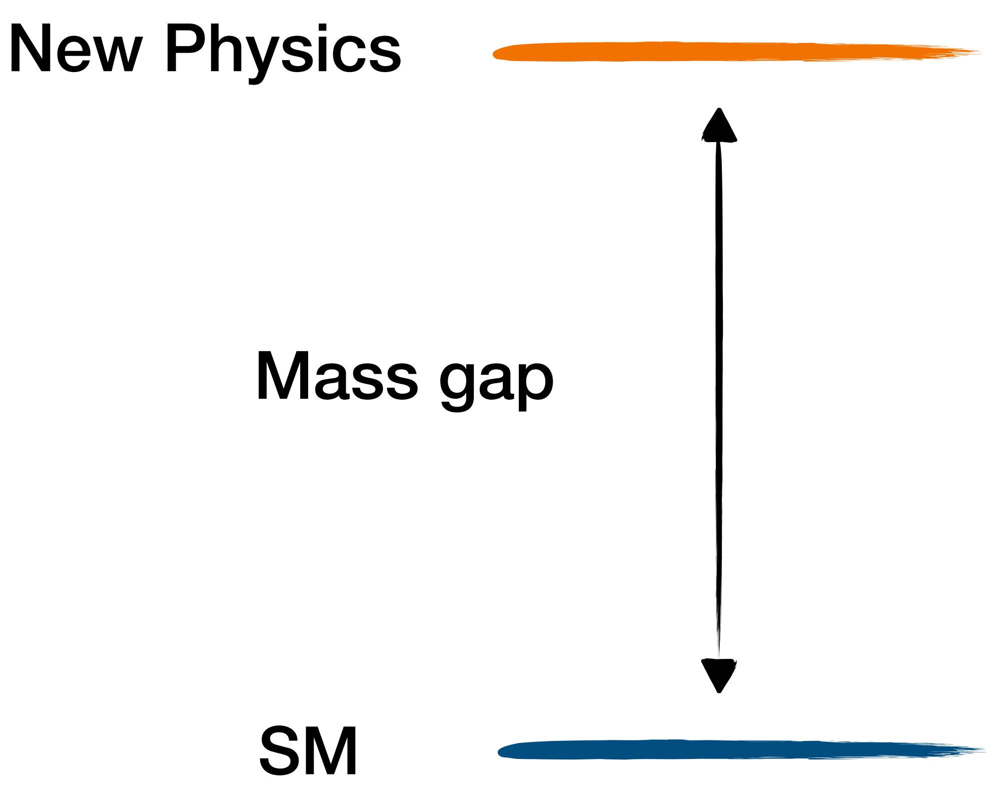
Santiago de Compostela,
Sept 21, 2023

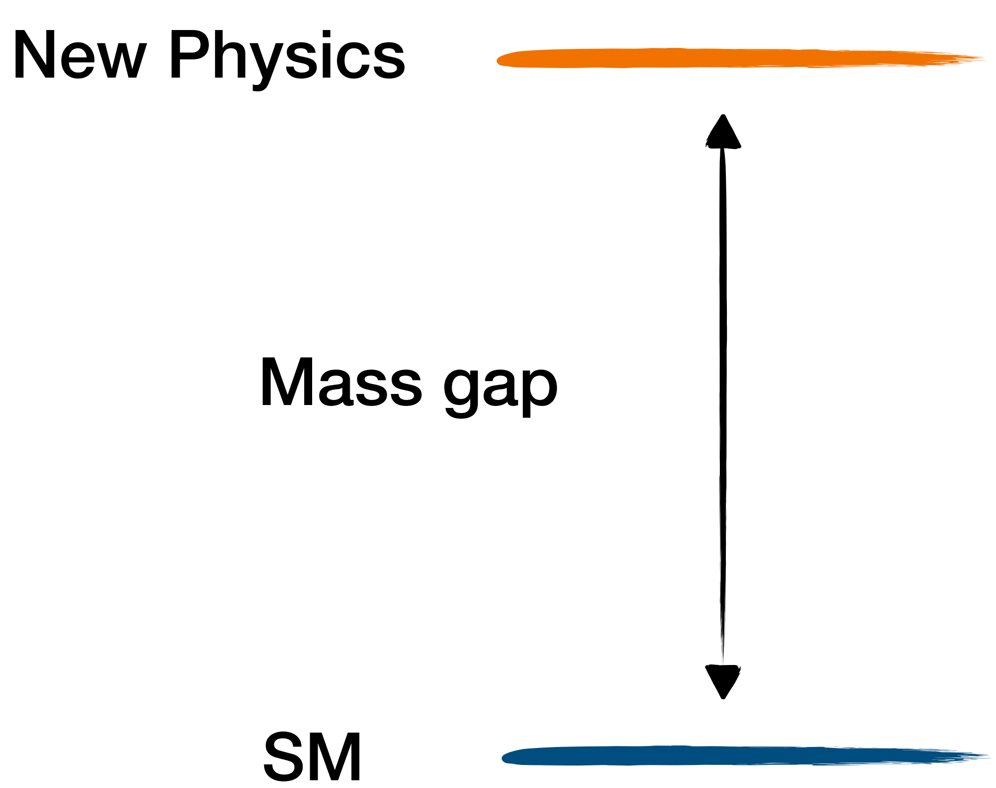
IP3

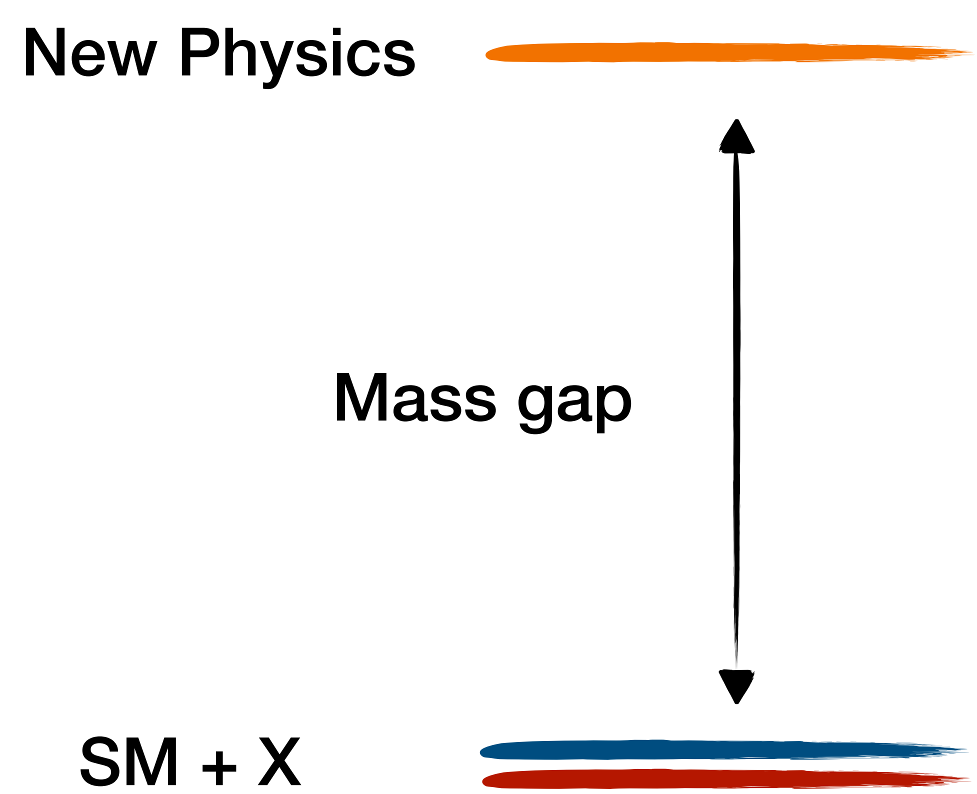
Landscape of new physics



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^5 + \dots$$

Landscape of new physics

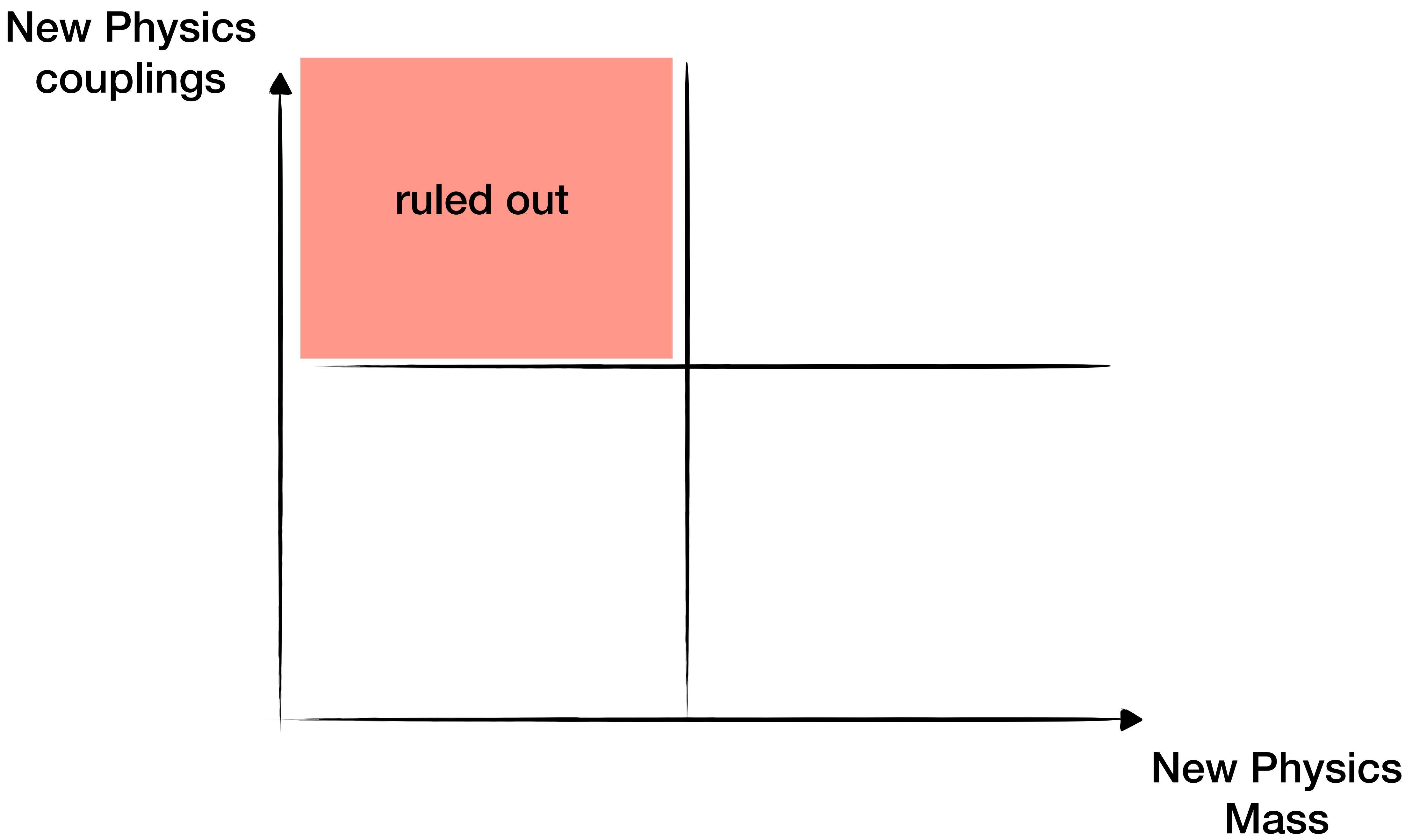




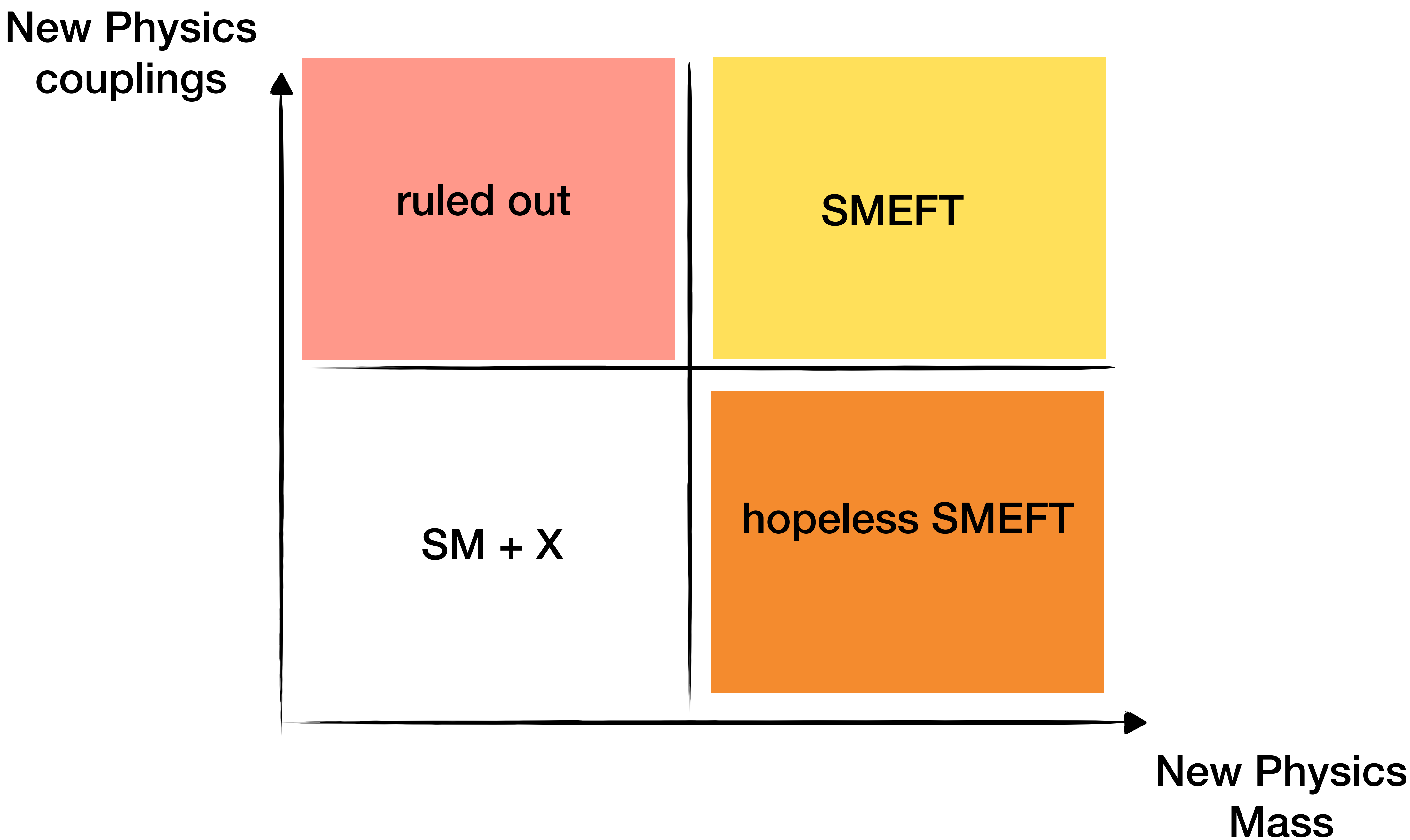
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^5 + \dots$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_X + \dots$$

Landscape of new physics



Landscape of new physics



Why should there be *any* new physics that is light and weakly coupled?

Light new physics ?

Three examples: Goldstone bosons

Hidden Photons

Sterile Neutrinos

Light new physics ?

First example: Goldstone bosons

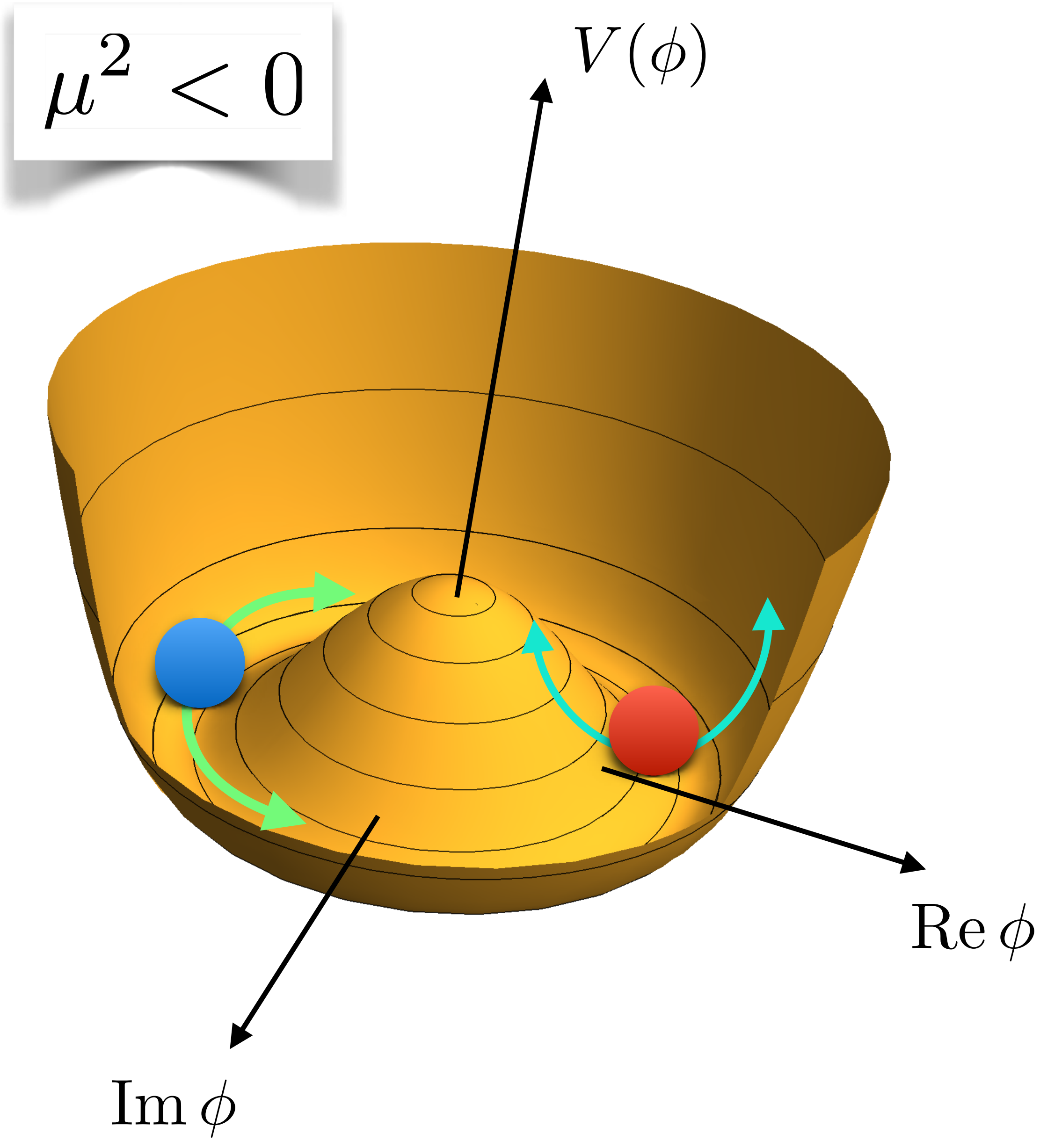
Every spontaneously broken continuous symmetry gives rise to massless spin-0 fields.

$$V(\phi) = \mu^2\phi\phi^\dagger + \lambda\,(\phi\phi^\dagger)^2$$

$$\phi = (f+s)e^{ia/f}$$

$$m_s^2 = 4\lambda f^2 = |\mu^2|$$

$$m_a^2 = 0$$



Goldstone bosons

Since the GB corresponds to the phase of a complex field, it is protected by a shift symmetry

$$\phi = (f + s)e^{ia/f}$$

it is protected by a shift symmetry

$$e^{ia(x)/f} \to e^{i(a(x)+c)/f} = e^{ia(x)/f} e^{ic/f}$$

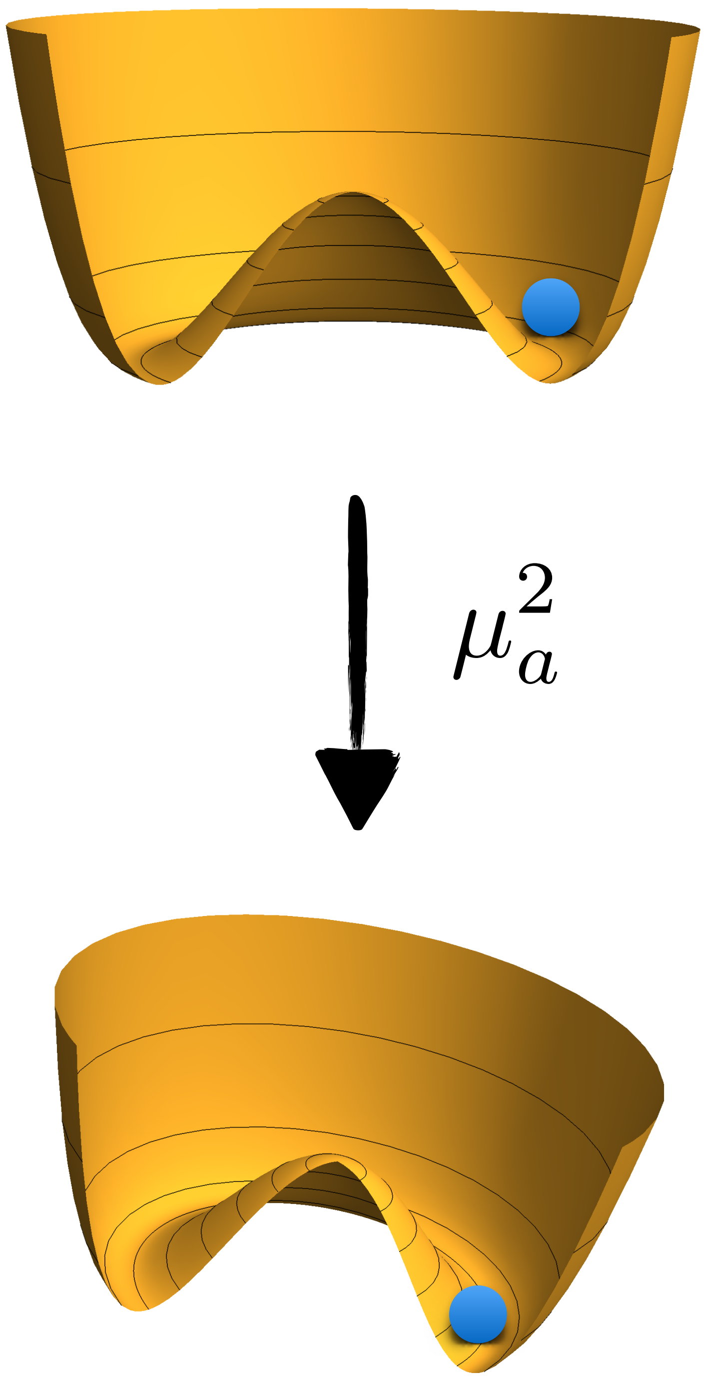
This symmetry forbids a mass term, and all couplings are suppressed by the UV scale

$$\mathcal{L} = \frac{1}{2}\partial_\mu a\, \partial^\mu a + c_\mu \frac{\partial^\nu a}{4\pi f}\, \bar{\mu}\gamma_\nu \mu + \ldots$$

Goldstone bosons

An exactly massless boson is very problematic.

The global symmetry can be broken by
explicit masses or anomalous effects



$$\mathcal{L} = \frac{1}{2}\partial_\mu a\, \partial^\mu a + c_\mu \frac{\partial^\nu a}{4\pi f}\, \bar{\mu}\gamma_\nu \mu + \ldots + \frac{1}{2} m_a^2 a^2$$

$$m_a = \frac{\mu_a^2}{f}$$

Small couplings correspond to small masses and a decoupled NP sector.

Goldstone bosons

The most famous example is the pion

$$\mathcal{L}_{\rm QCD} = \bar{q}_L i \not{D}\, q_L + \bar{q}_R i \not{D}\, q_R + m_q \bar{q}_L q_R$$

$$\langle \bar{q}_L q_R \rangle = \Lambda^3_{\rm QCD} \approx {\rm GeV}^3$$

The pion mass is controlled by the explicit breaking through light quark masses

$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda^3_{\rm QCD} \quad \approx (140\,{\rm MeV})^2$$

Goldstone bosons

NP at f

The most famous example is the pion

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axion

Axionlike particles

Most general dimension five Lagrangian at the UV scale

$$\mathcal{L}_{\text{eff}}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\,\sum_F \bar{\psi}_F\,\boldsymbol{c}_F\,\gamma_\mu\,\psi_F + c_\phi\frac{\partial^\mu a}{f}\,\big(\phi^\dagger iD_\mu\phi + \text{h.c.}\big)$$

$$+ c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde{G}^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde{W}^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}\,.$$

All couplings are suppressed by the UV scale f

Georgi, Kaplan, Randall, Phys. Lett. 169B, 73 (1986)

Axionlike particles

Most general dimension five Lagrangian at the UV scale

explicit mass term

couplings to fermions F=Q,u,d,L,e

coupling to the Higgs current

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{m_{a,0}^2}{2}\, a^2 + \frac{\partial^\mu a}{f} \sum_F \bar{\psi}_F\, \boldsymbol{c}_F\, \gamma_\mu\, \psi_F + c_\phi \frac{\partial^\mu a}{f} \left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right)$$

$$+ c_{GG}\, \frac{\alpha_s}{4\pi}\, \frac{a}{f}\, G_{\mu\nu}^a\, \tilde{G}^{\mu\nu,a} + c_{WW}\, \frac{\alpha_2}{4\pi}\, \frac{a}{f}\, W_{\mu\nu}^A\, \tilde{W}^{\mu\nu,A} + c_{BB}\, \frac{\alpha_1}{4\pi}\, \frac{a}{f}\, B_{\mu\nu}\, \tilde{B}^{\mu\nu}\,.$$

coupling to gluons

coupling to $SU(2)_L$ gauge bosons

coupling to hypercharge

All couplings are suppressed by the UV scale f

Georgi, Kaplan, Randall, Phys. Lett. 169B, 73 (1986)

Axionlike particles

This Lagrangian captures all possible ALP coupling structures up to dimension 5.

It is easy to imagine scenarios in which a single coupling dominates:

For example: A UV theory in which the ALP couples only to $SU(2)_L$ gauge bosons

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}\tilde{W}^{\mu\nu}$$

Georgi, Kaplan, Randall, Phys. Lett. 169B, 73 (1986)

Axionlike particles

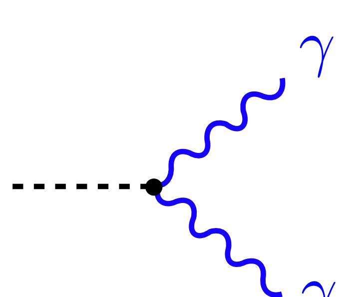
For example: A UV theory in which the ALP couples only to $SU(2)_L$ gauge bosons

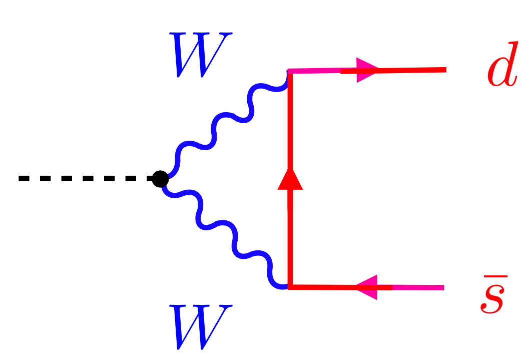
$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}\tilde{W}^{\mu\nu}$$

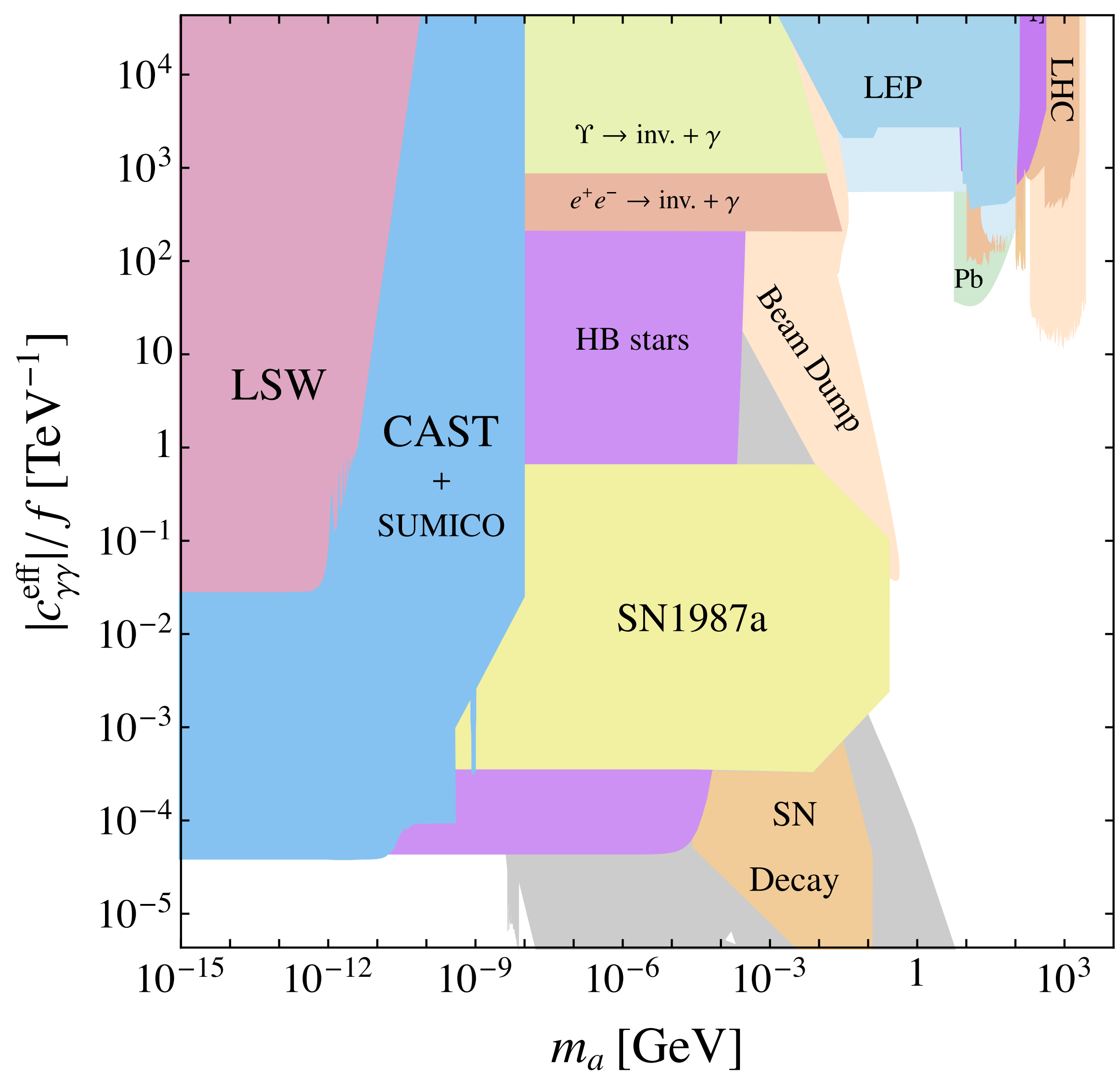
After EW symmetry breaking this ALP couples to photons.

$$W_\mu^3 = s_w A_\mu + c_w Z_\mu$$

But at higher loop order it couples to fermions

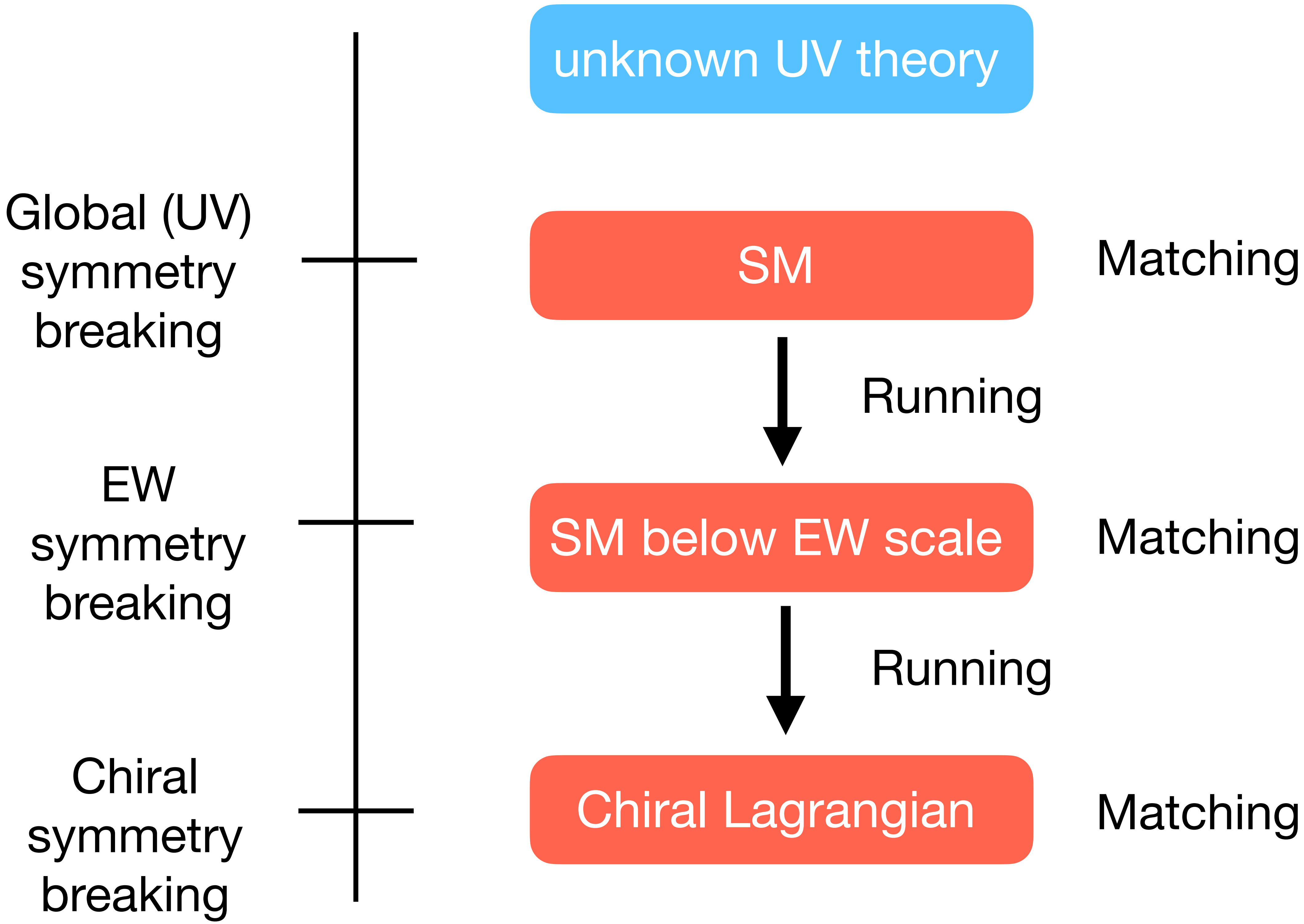






MB, Neubert, Thamm, JHEP 1712 044 (2017)

ALPs at different scales

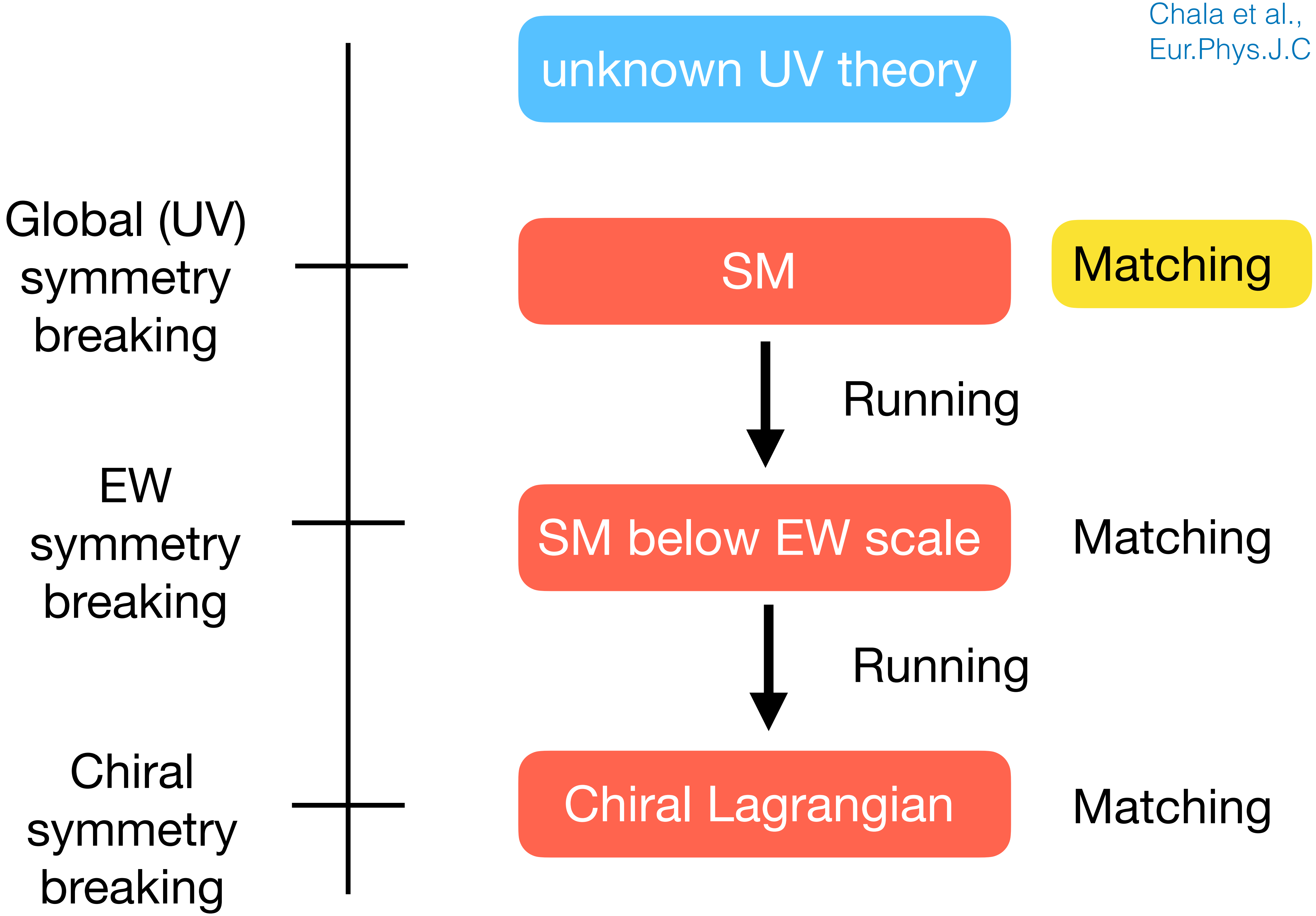


ALPs at different scales

MB, Neubert, Renner, Schnubel, Thamm, *JHEP* 04 (2021) 063

MB, Neubert, Renner, Schnubel, Thamm, 2102.13112, PRL. 127

Chala et al., Eur.Phys.J.C 81 (2021) 2



ALPs at different scales

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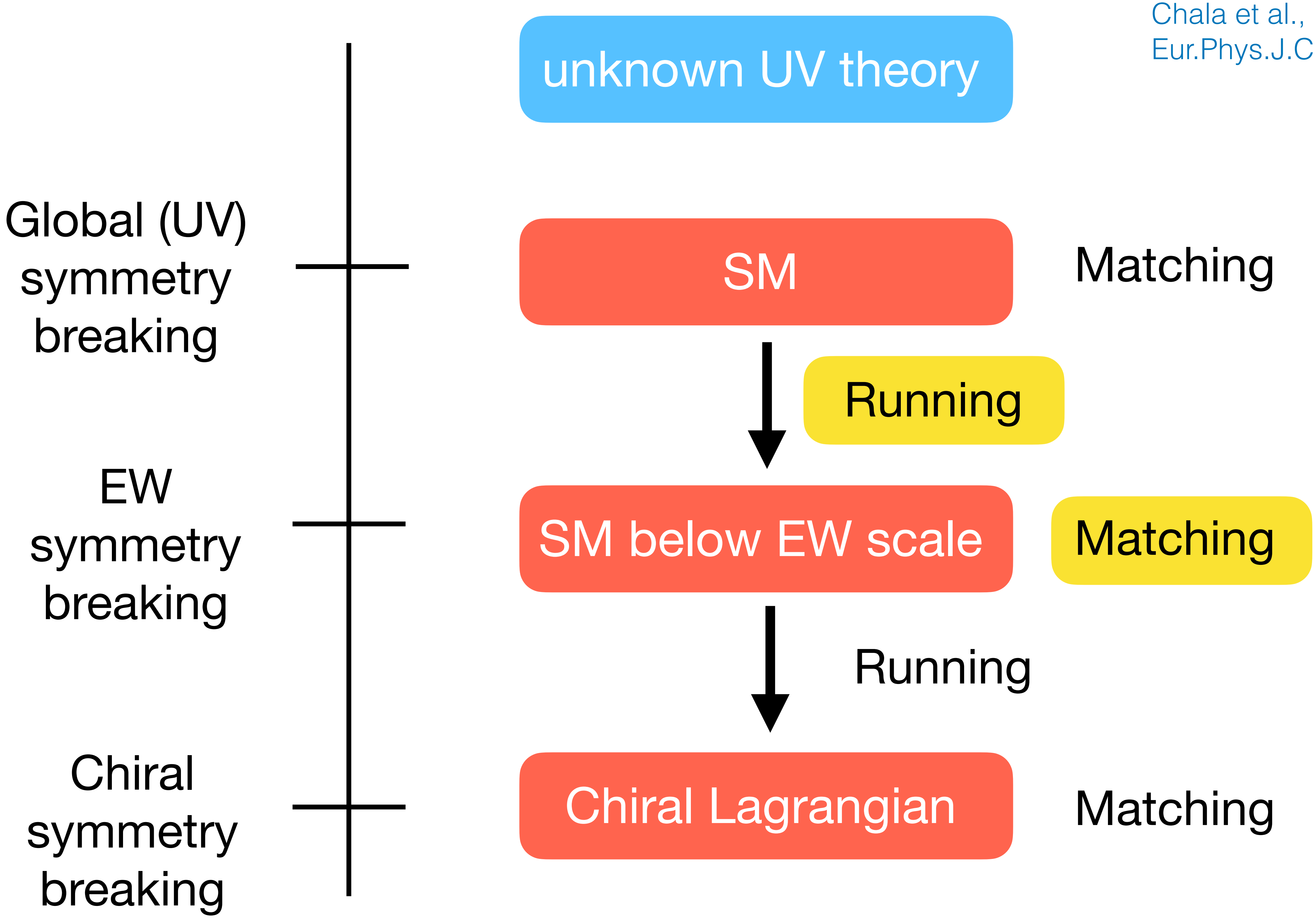
Chala et al., Eur.Phys.J.C 81 (2021) 2



Running and matching at the weak scale

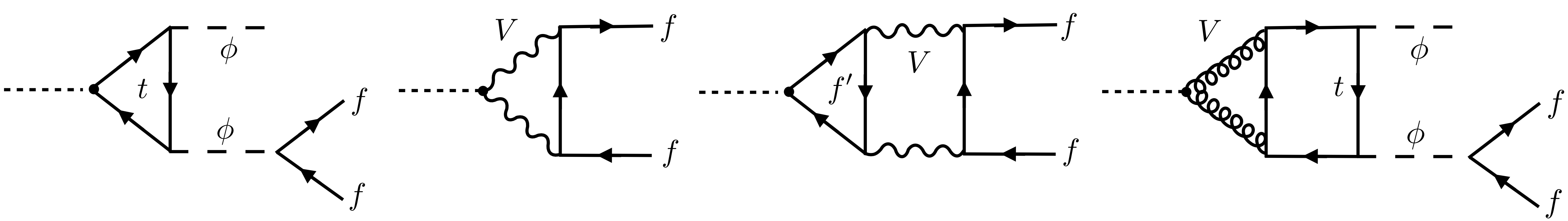
- The gauge boson couplings do not run

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

Bardeen et al. Nucl. Phys. B 535,(1998)

- Neither are there matching contributions at 1-loop

- The running and matching of ALP fermion couplings receives various contributions

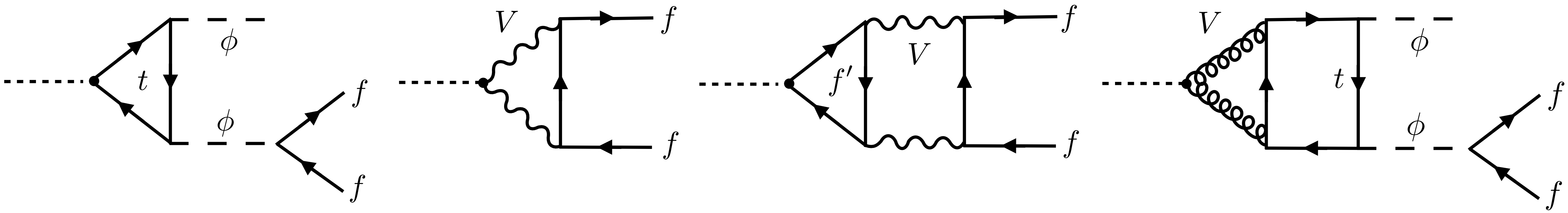


MB, Neubert, Renner, Schnubel, Thamm, *JHEP* 04 (2021) 063

MB, Neubert, Renner, Schnubel, Thamm, 2102.13112

Chala et al., Eur.Phys.J.C 81 (2021) 2

Flavor diagonal ALP-fermion couplings



ALP fermion couplings at the weak scale for $f = 1\,\mathrm{TeV}$

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

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

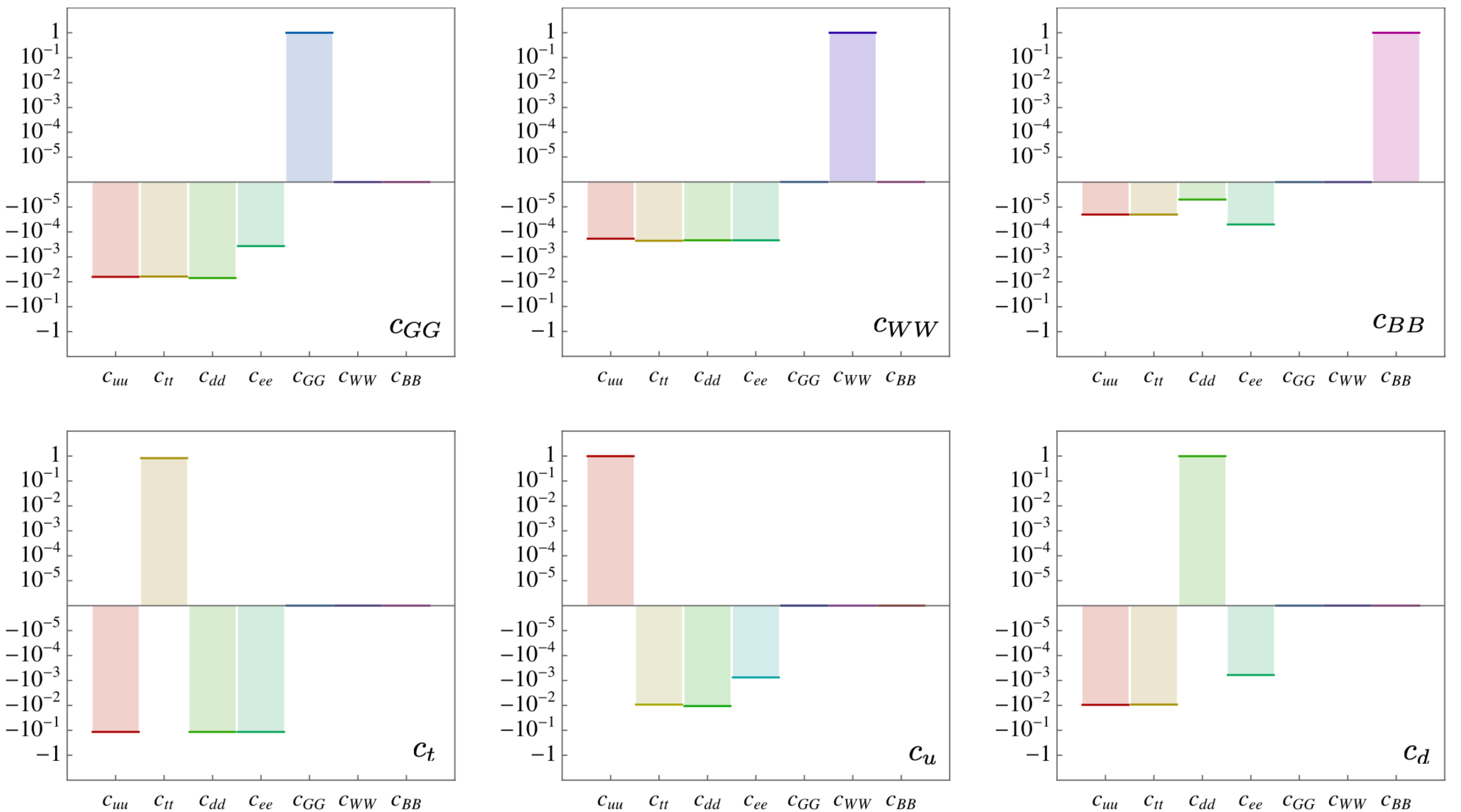
$$c_{bb}(m_t) \simeq c_{bb}(\Lambda) + 0.097\, c_{tt}(\Lambda) - \Big[7.02\, \tilde{c}_{GG}(\Lambda) + 0.19\, \tilde{c}_{WW}(\Lambda) + 0.005\, \tilde{c}_{BB}(\Lambda)\Big] \cdot 10^{-3}\,,$$

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

where we have defined $\mathcal{L} = \frac{c_{ff}}{2} \frac{\partial^\mu a}{\Lambda} \bar{f} \gamma_\mu \gamma_5 f$

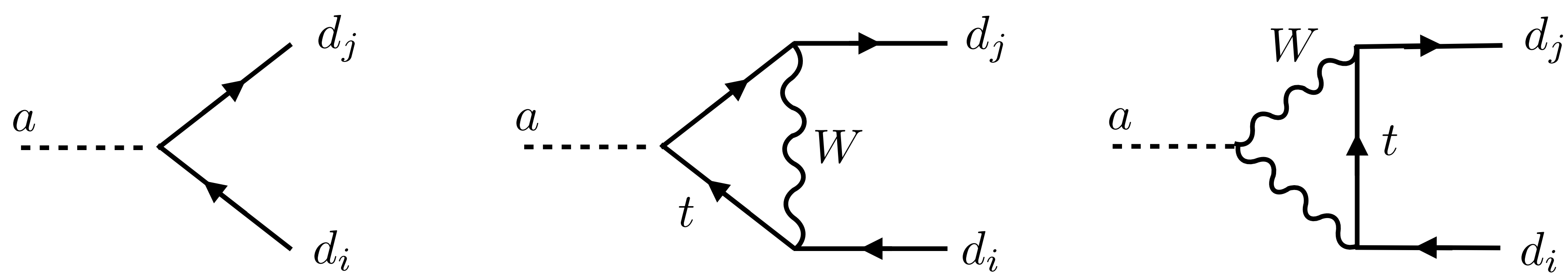
Flavor diagonal ALP-fermion couplings

ALP fermion couplings at the weak scale for $f = 1\,\text{TeV}$



Flavor off-diagonal ALP-fermion couplings

Flavor violation can come from the UV theory or from the SM

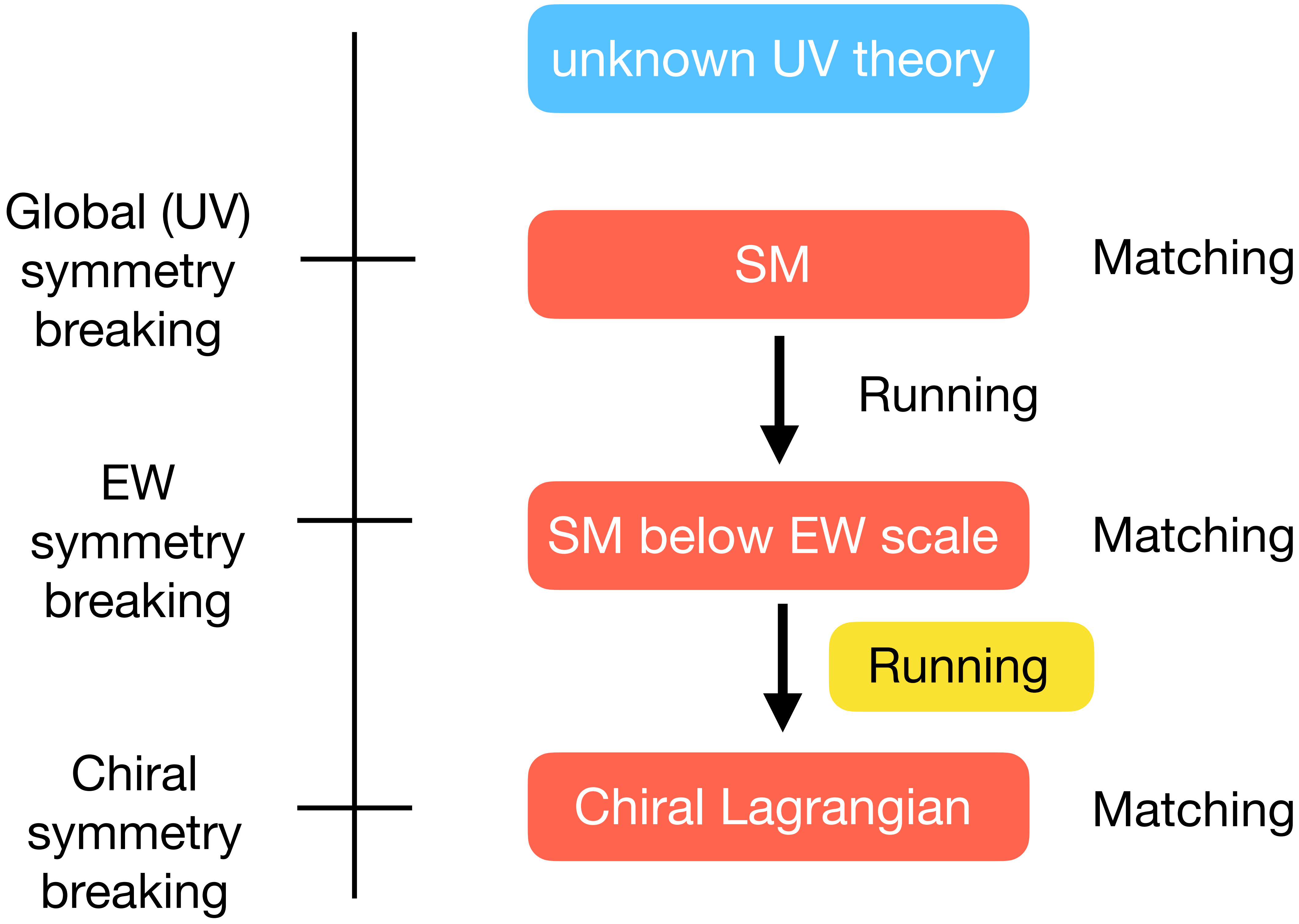


Assuming MFV (only $y_t \neq 0$) for $f = 1\,\mathrm{TeV}$

$$\big[k_U(\mu_w)\big]_{ij} = \big[k_u(\mu_w)\big]_{ij} = \big[k_d(\mu_w)\big]_{ij} = \big[k_E(\mu_w)\big]_{ij} = \big[k_e(\mu_w)\big]_{ij} = 0$$

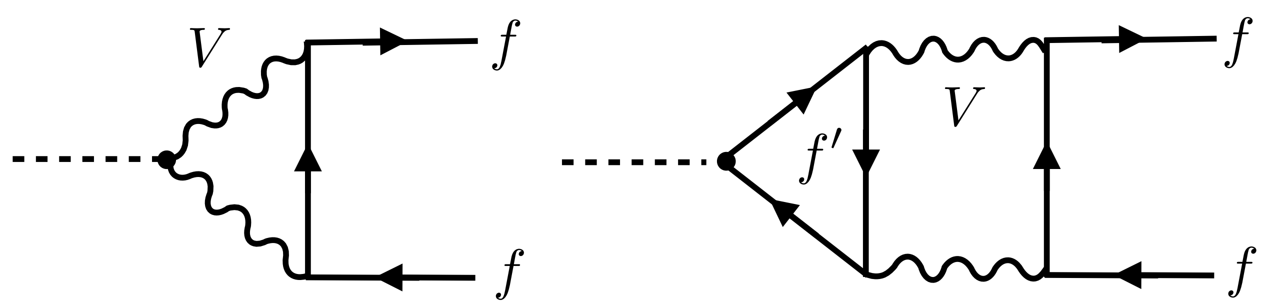
$$[k_D(m_t)]_{ij} \simeq [k_D(\Lambda)]_{ij} + 0.019\, V_{ti}^* V_{tj} \Big[c_{tt}(\Lambda) - 0.0032\,\tilde{c}_{GG}(\Lambda) - 0.0057\,\tilde{c}_{WW}(\Lambda)\Big]$$

ALPs at different scales



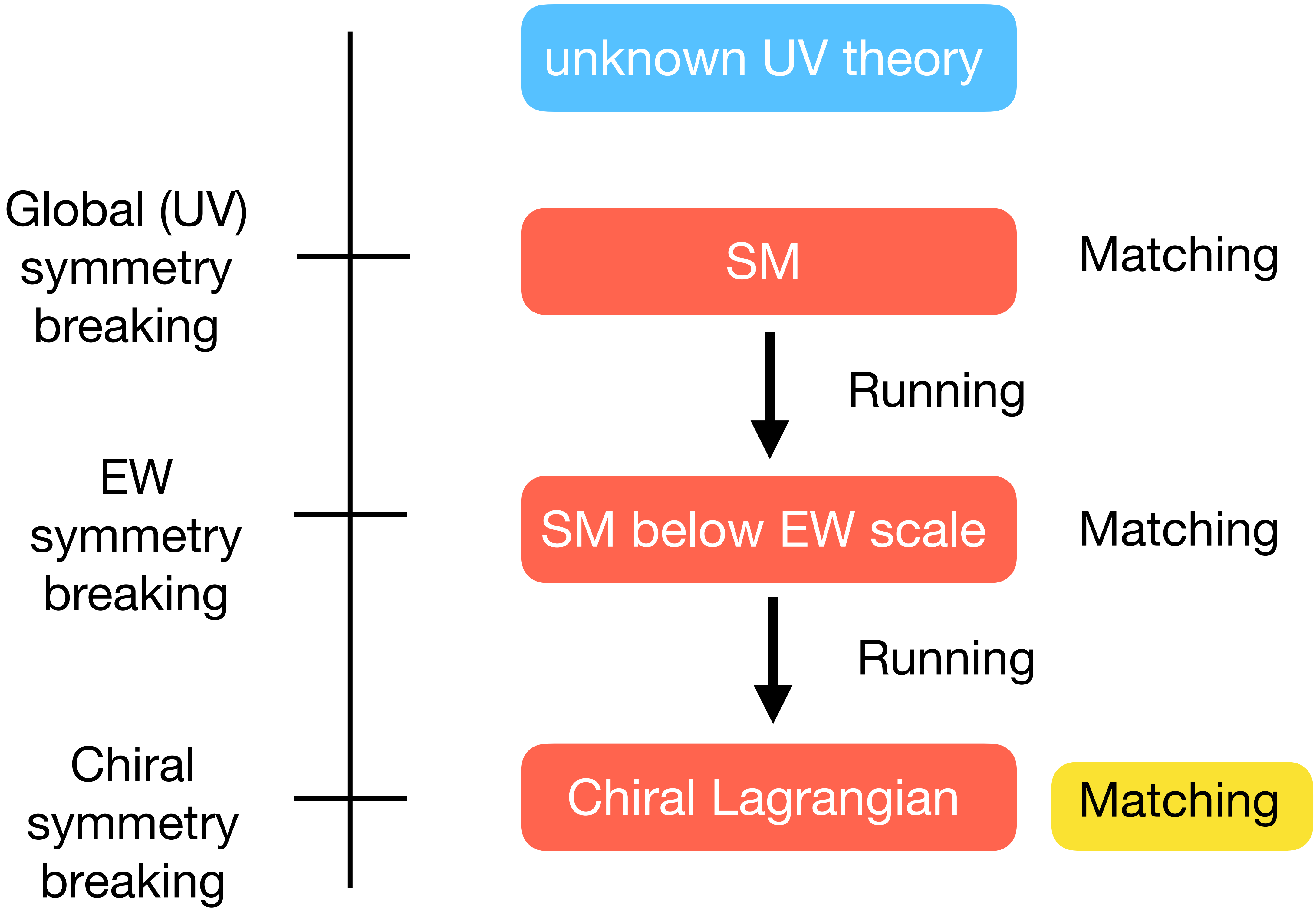
Running below the EW scale

Running below the weak scale affects only flavor-diagonal ALP fermion couplings (running to 2 GeV)



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

ALPs at different scales



Matching to the chiral Lagrangian

The chiral Lagrangian + ALP then reads

$$\mathcal{L}_{\rm eff}^{\chi} = \frac{f_\pi^2}{8}\,\mathrm{Tr}\big[\boldsymbol{D}^\mu\boldsymbol{\Sigma}\,(\boldsymbol{D}_\mu\boldsymbol{\Sigma})^\dagger\big] + \frac{f_\pi^2}{4}\,B_0\,\mathrm{Tr}\big[\hat{\boldsymbol{m}}_q(a)\,\boldsymbol{\Sigma}^\dagger + \text{h.c.}\big] \\ + \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{m_{a,0}^2}{2}\,a^2 + \hat{c}_{\gamma\gamma}\,\frac{\alpha}{4\pi}\,\frac{a}{f}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}\,,$$

where $\boldsymbol{\Sigma} = \exp(i\sqrt{2}\boldsymbol{\Pi}/f_\pi)$

$$\Pi = \lambda_b \pi^b = \begin{pmatrix} \pi_0 + \sqrt{\frac{1}{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi_0 + \sqrt{\frac{1}{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -2\sqrt{\frac{1}{3}}\eta \end{pmatrix}.$$

MB, Neubert, Renner, Schnubel, Thamm, 2102.13112, Phys.Rev.Lett. 127 (2021)

Matching to the chiral Lagrangian

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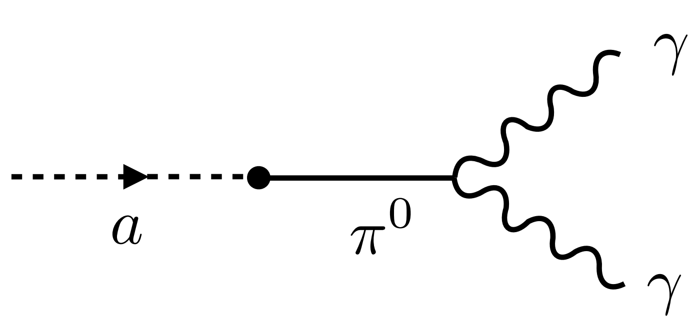
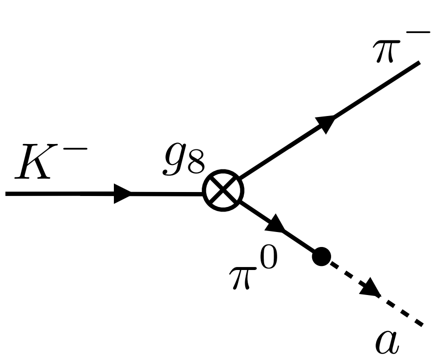
$$+ \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{m_{a,0}^2}{2}\,a^2 + \hat{c}_{\gamma\gamma}\,\frac{\alpha}{4\pi}\,\frac{a}{f}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}\,,$$

Turning on the weak interactions give rise to flavor changing couplings involving the ALP

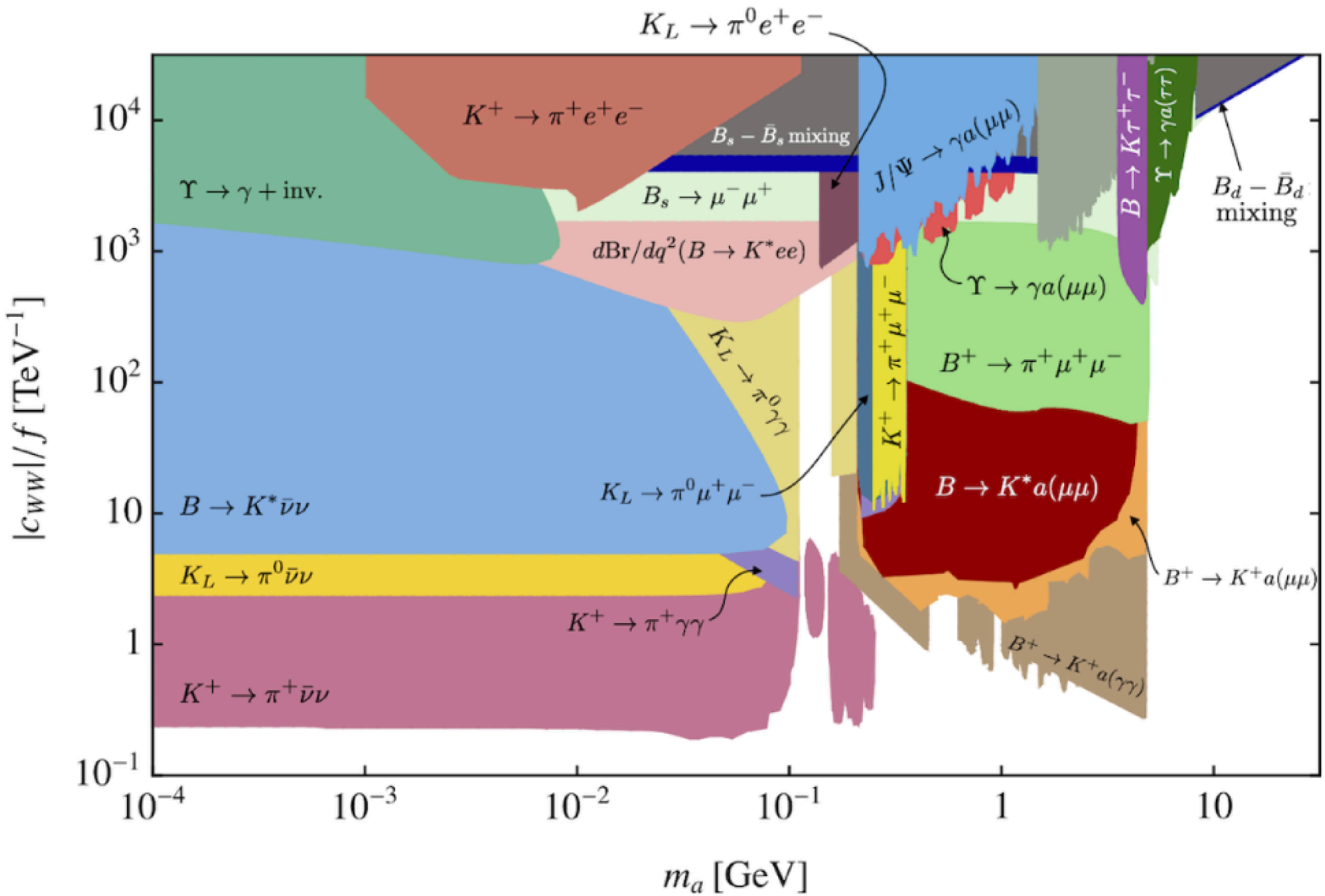
$$\mathcal{L}_{\text{weak}} = -\frac{4G_F}{\sqrt{2}}\,V_{ud}^* V_{us}\,g_8\,[L_\mu\,L^\mu]^{32} \qquad L_\mu \equiv -\frac{i f_\pi^2}{4}\Big[\Sigma \hat{D}_\mu \Sigma^\dagger\Big]$$





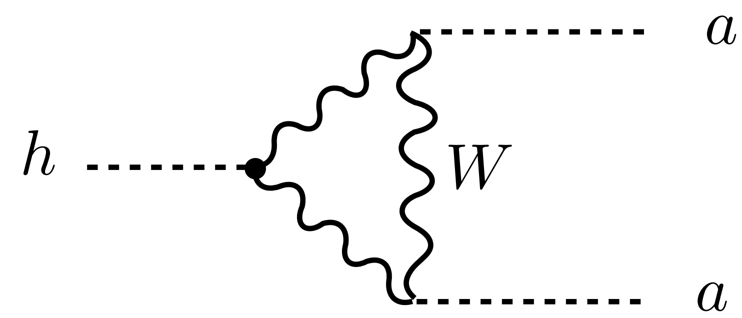
MB, Neubert, Renner, Schnubel, Thamm, PRL 127 (2021)

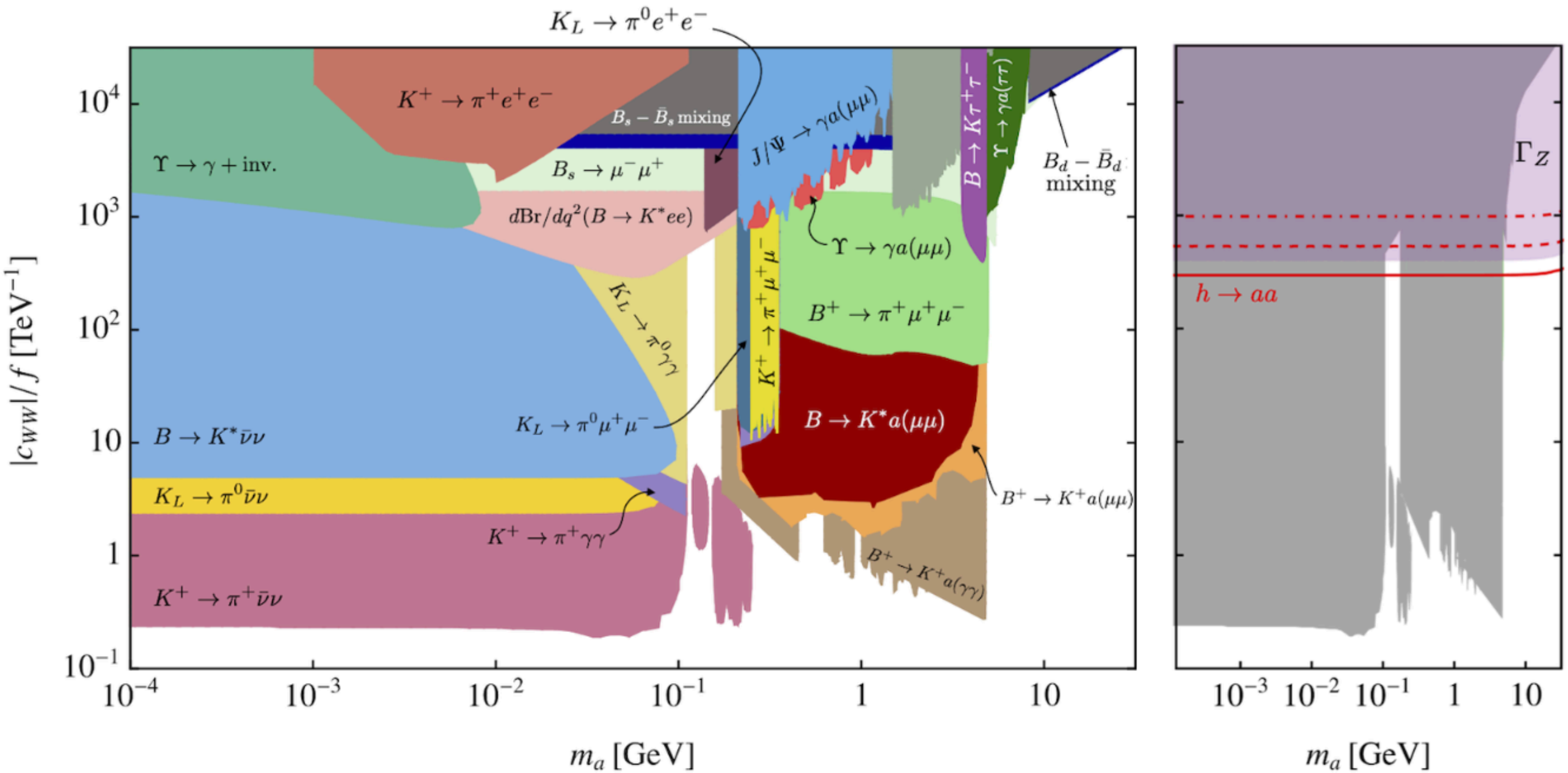
Flavor bounds on ALPs



MB, Neubert, Renner, Schnubel, Thamm, *JHEP* 09 (2022) 056

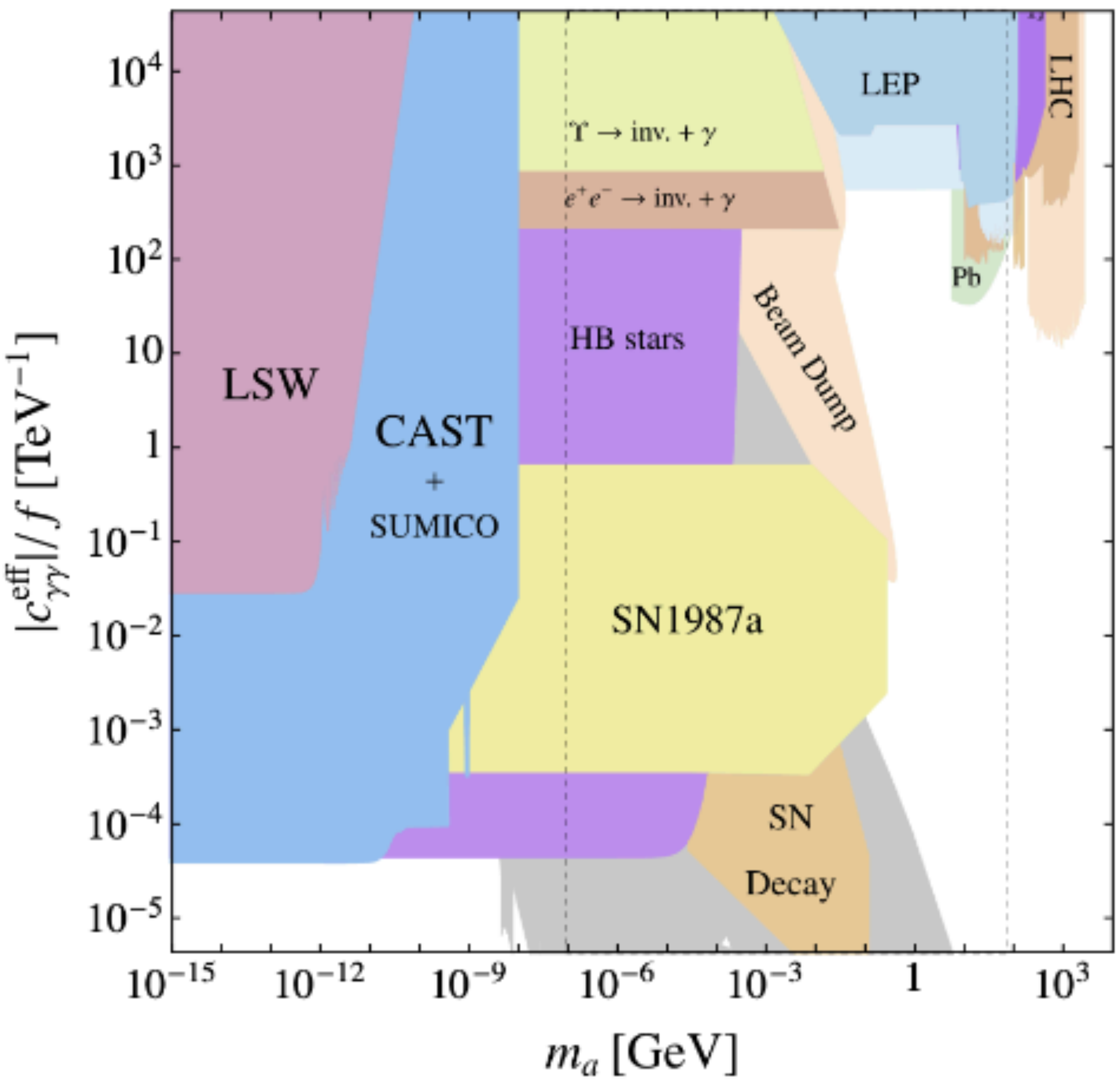
Flavor bounds on ALPs

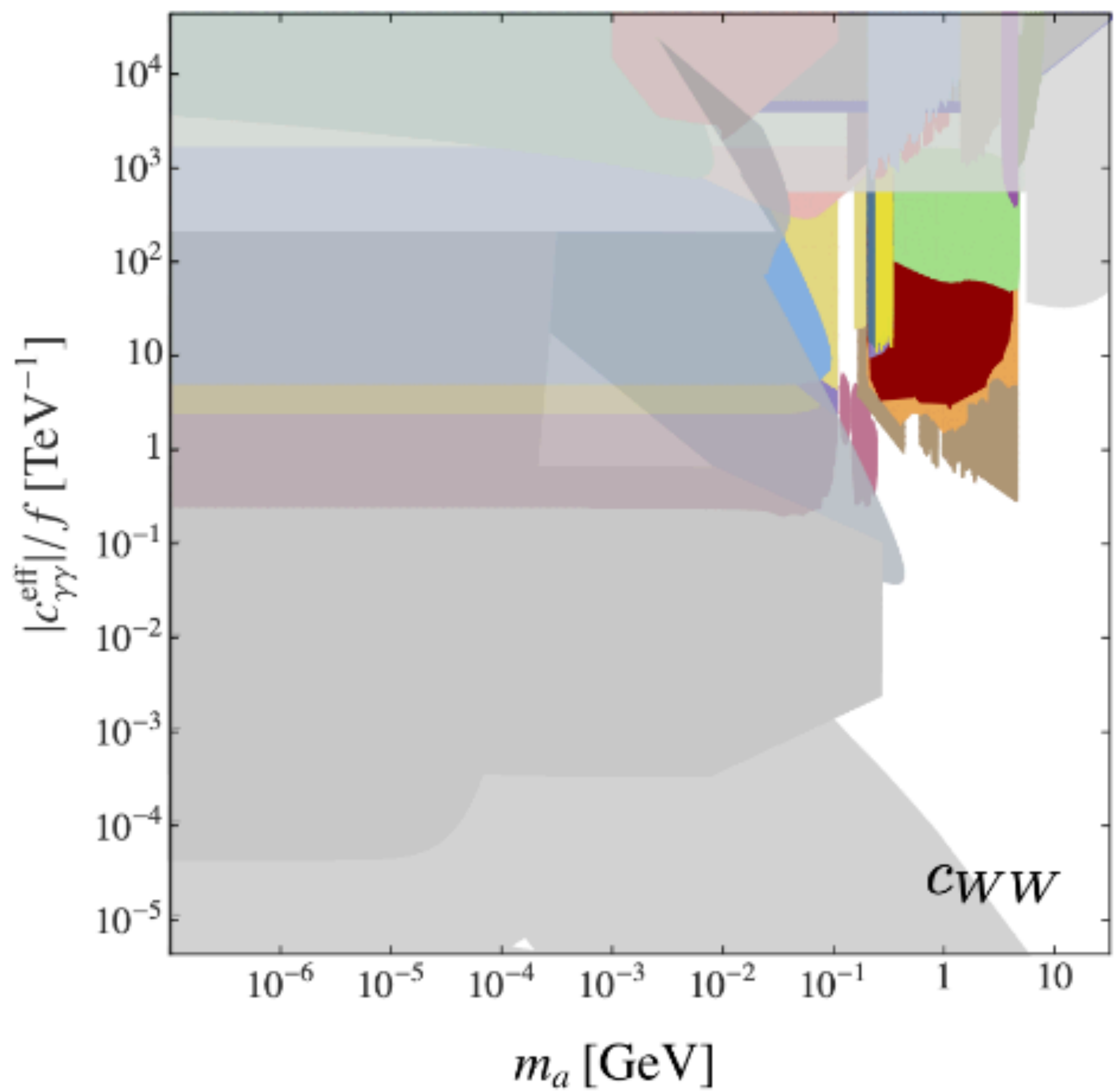




MB, Neubert, Renner, Schnubel, Thamm, *JHEP* 09 (2022) 056

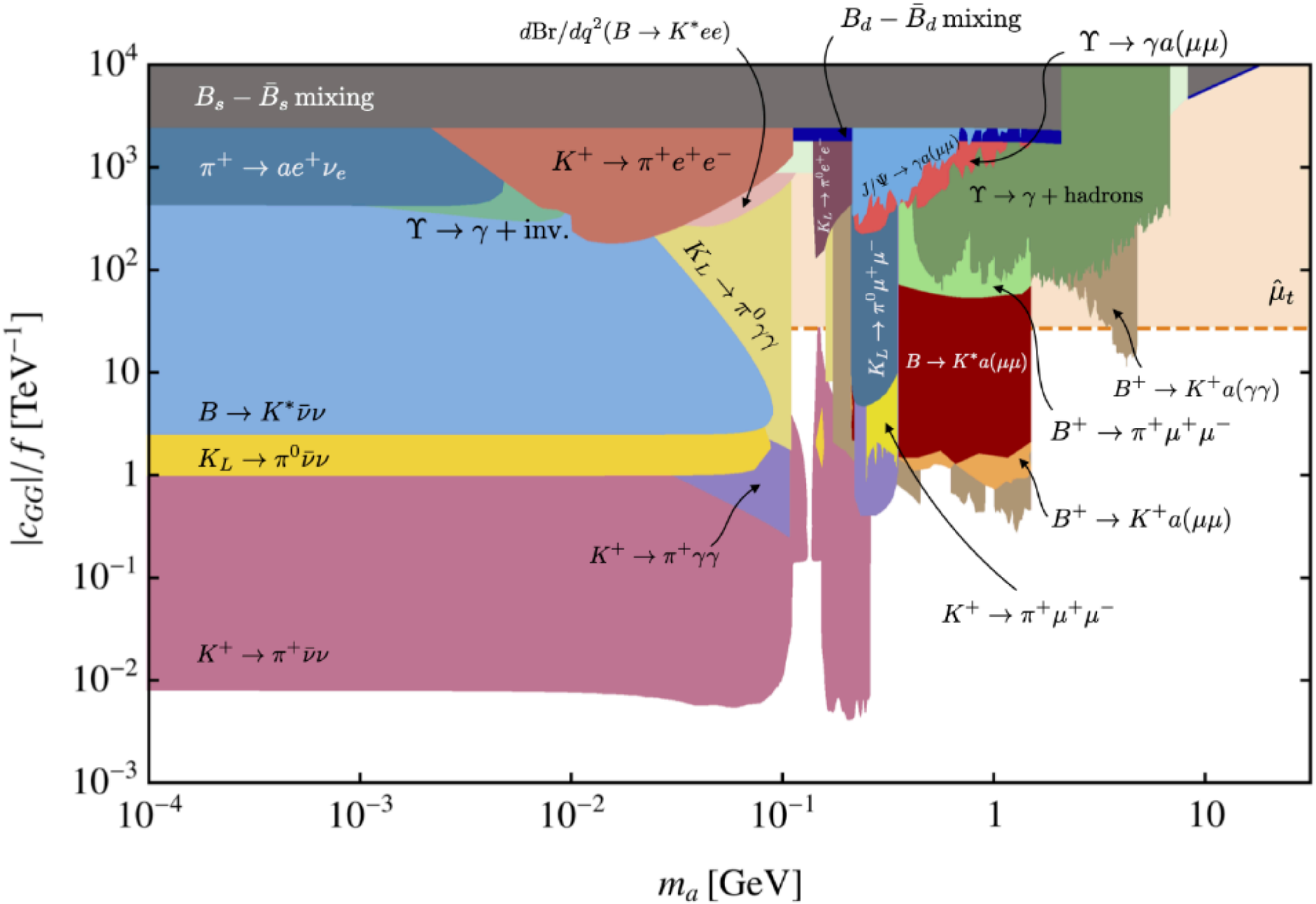
Flavor bounds vs other bounds





MB, Neubert, Renner, Schnubel, Thamm, *JHEP* 09 (2022) 056

Flavor bounds vs other bounds



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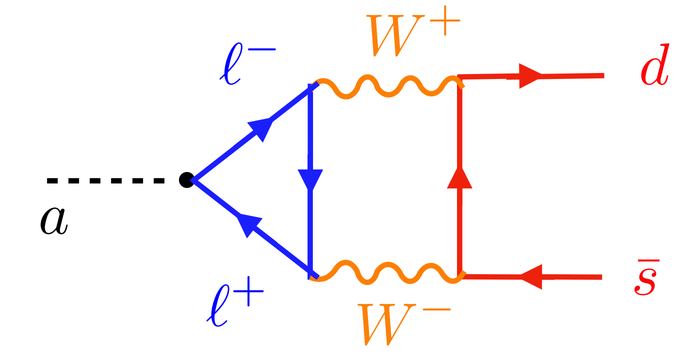
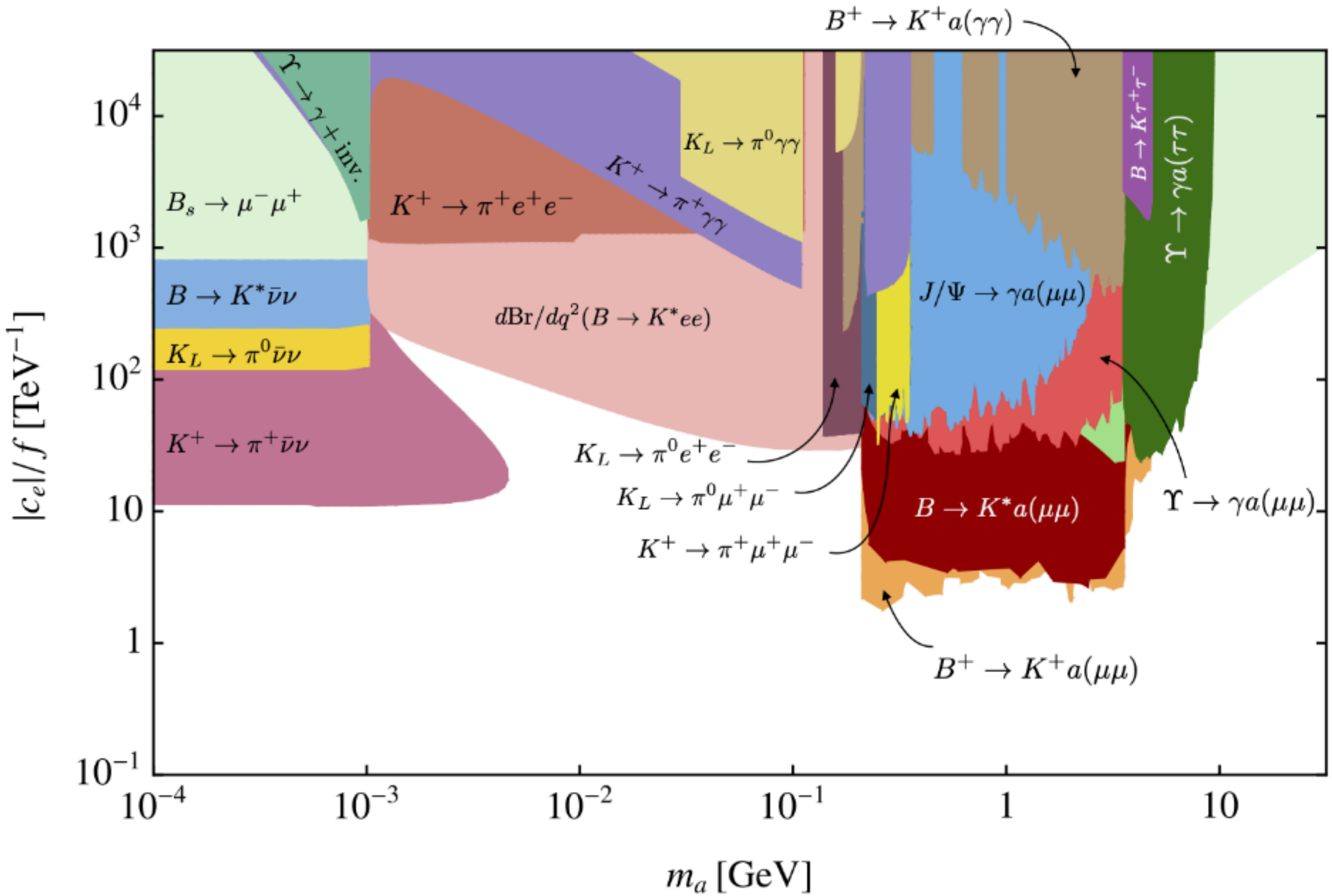
Flavor bounds vs other bounds





MB, Neubert, Renner, Schnubel, Thamm, *JHEP* 09 (2022) 056

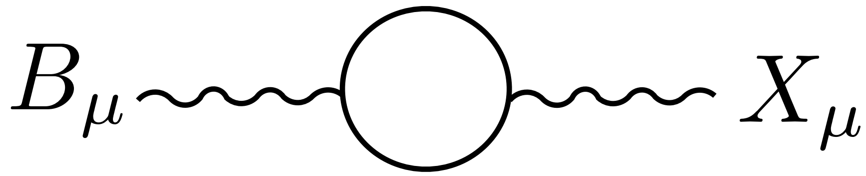
Light new physics ?

Second example: gauge bosons (local symmetry breaking)

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

$$\phi = (f+s)e^{ia/f} \longrightarrow m_X = g_X f$$

Interactions with the SM are either directly set by the gauge coupling or through kinetic mixing

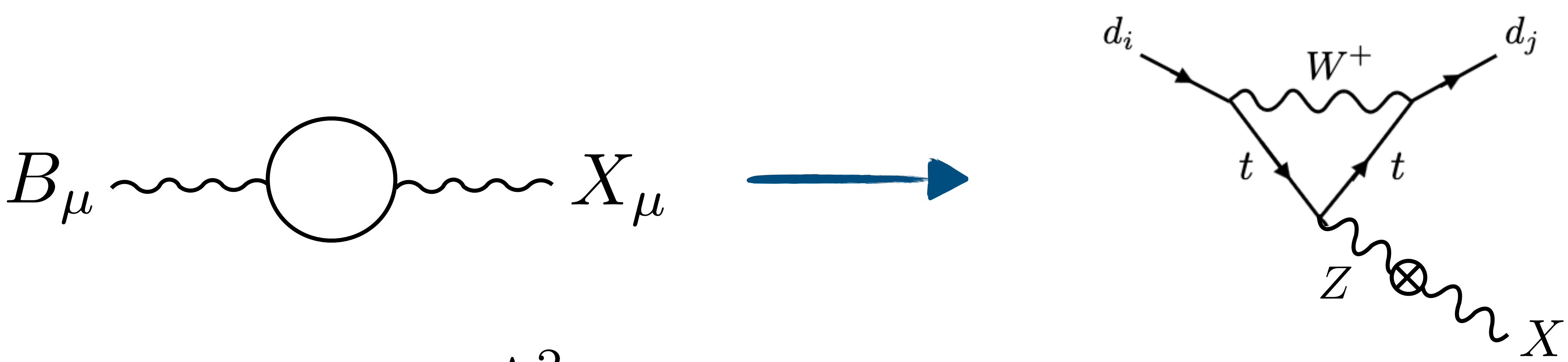


$$\epsilon \propto \frac{g_X e}{8\pi^2}\log\frac{\Lambda^2}{m^2}$$

Small gauge couplings imply small masses

Light new physics ?

Hidden photons mixing with the SM photon or Z boson inherit the SM GIM mechanism and are strongly suppressed



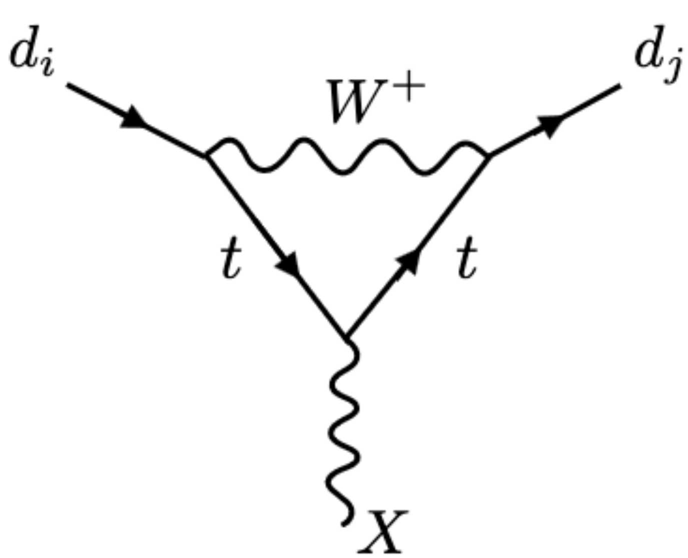
$$\epsilon \propto \frac{g_X e}{8\pi^2} \log \frac{\Lambda^2}{m^2}$$

MB, Foldenauer, Mosny, *Phys.Rev.D* 103 (2021) 7

Light new physics ?

Hidden photons can also interact directly with SM fermions if baryon number or lepton numbers are charged

Gauge anomaly cancellation and constraints from the CKM matrix force all couplings to SM fermions to be diagonal couplings at tree-level (apart from neutrinos)



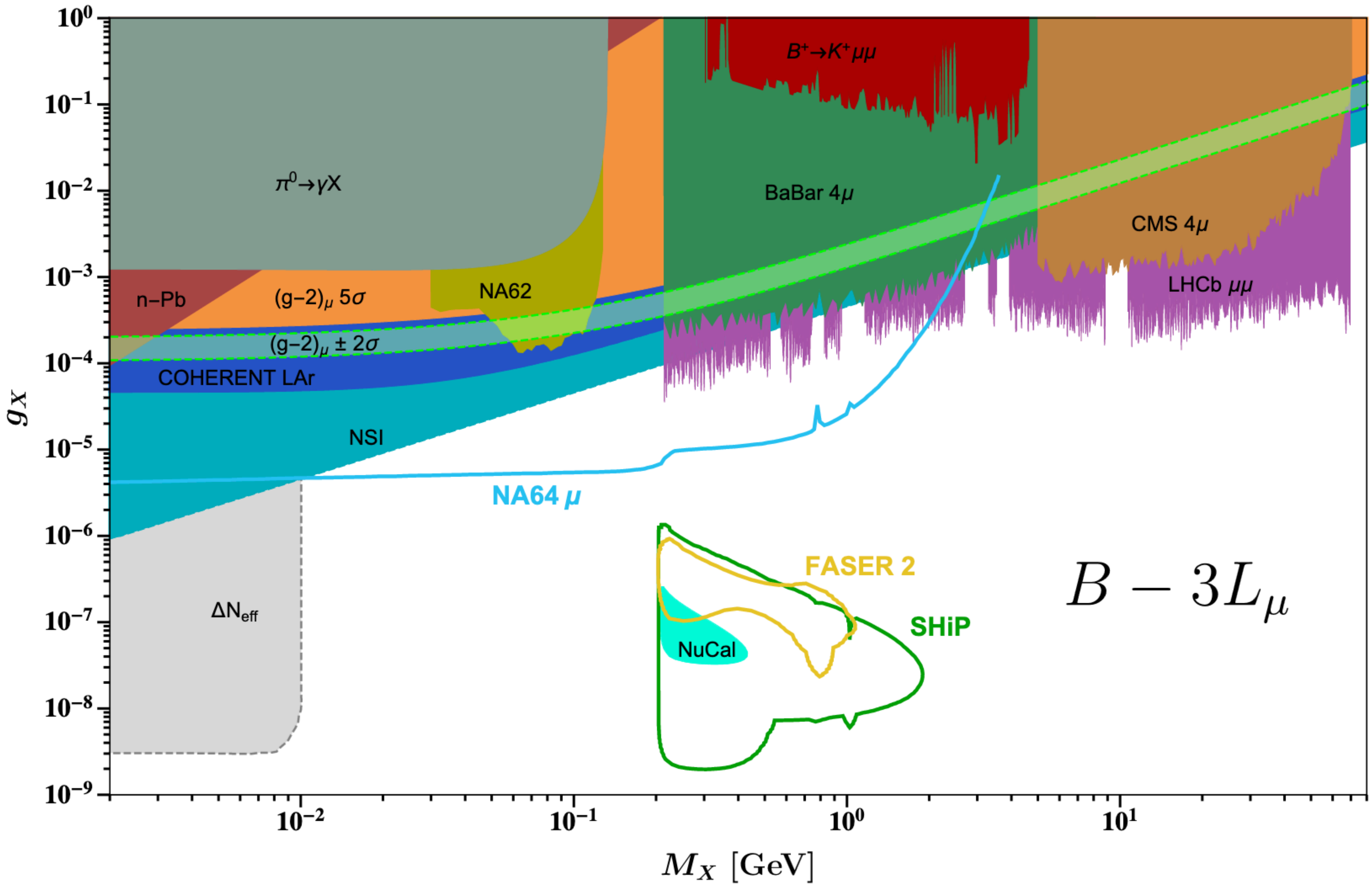
$$\mathcal{L} = g_{ij}^L \frac{M_X^2}{M_W^2} \bar{d}_j \gamma_\mu P_L d_i X^\mu + \frac{1}{2} g_{ij}^\sigma \bar{d}_j \sigma^{\mu\nu} \left(\frac{m_{d_j}}{M_W^2} P_L + \frac{m_{d_i}}{M_W^2} P_R \right) d_i X_{\mu\nu}$$

$$g_{ij}^L = g_X q_q \frac{\alpha}{8\pi s_w^2} V_{ti} V_{tj}^* f_1(x_t) \qquad g_{ij}^\sigma = g_X q_q \frac{\alpha}{8\pi s_w^2} V_{ti} V_{tj}^* f_2(x_t)$$

B decays are suppressed $\quad \Gamma(B \to K X) \approx \frac{1}{256\pi} \frac{M_B^3 M_X^2}{M_W^4} \left(g_{32}^L f_+\right)^2$

MB, Foldenauer, Mosny, *Phys.Rev.D* 103 (2021) 7

Flavor bounds on hidden photons



MB, Foldenauer, Mosny, *Phys.Rev.D* 103 (2021) 7

Light new physics ?

Third example: sterile neutrinos

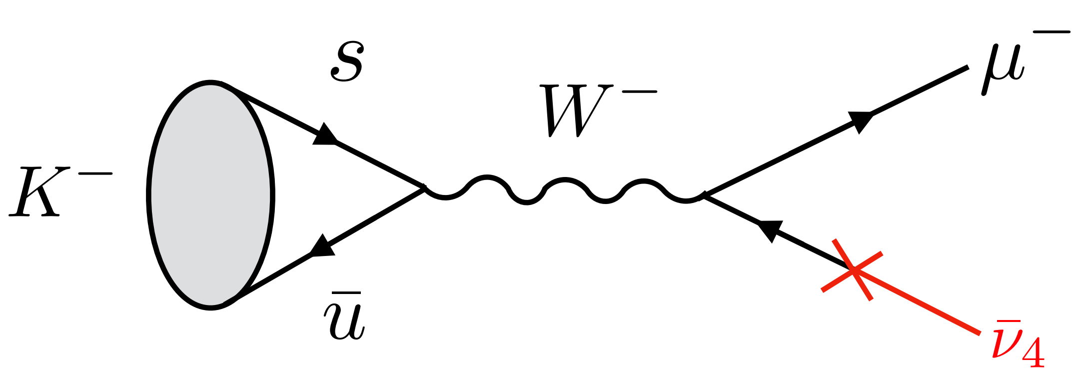
$$\mathcal{L}_{\text{mass}} \supset -\frac{1}{2} n^T M n \equiv -\frac{1}{2} n^T \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} n + h.c. \, .$$

Active masses: $m_\nu \sim \frac{M_D^2}{M_R}$

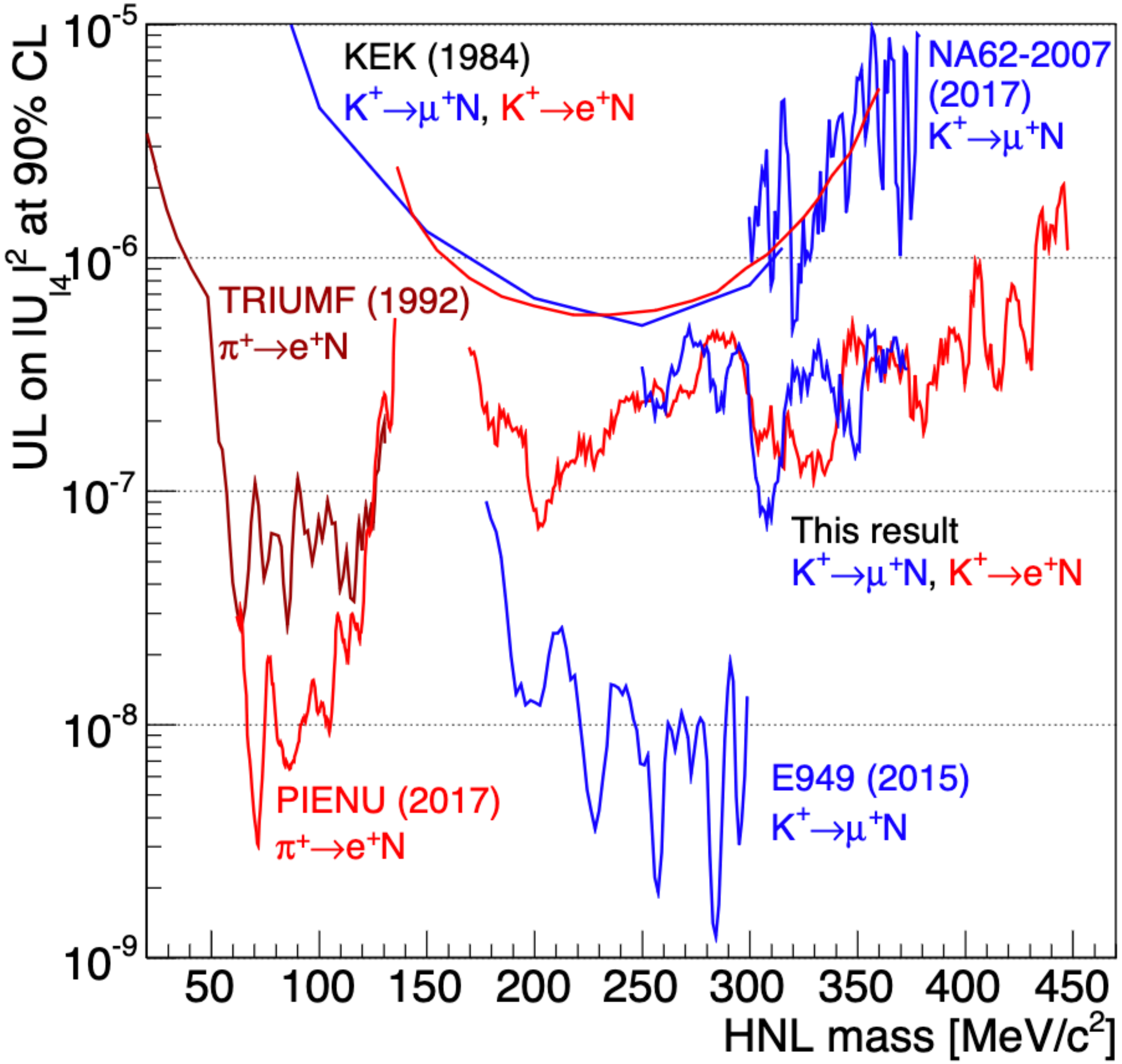
Sterile masses: $m_4 \sim M_R$

Mixing angles: $|U_{\ell 4}|^2 \sim \left| \frac{M_D^2}{M_R^2} \right|^2 \sim \frac{m_\nu^2}{m_4^2}$

Couplings suppressed my neutrino masses

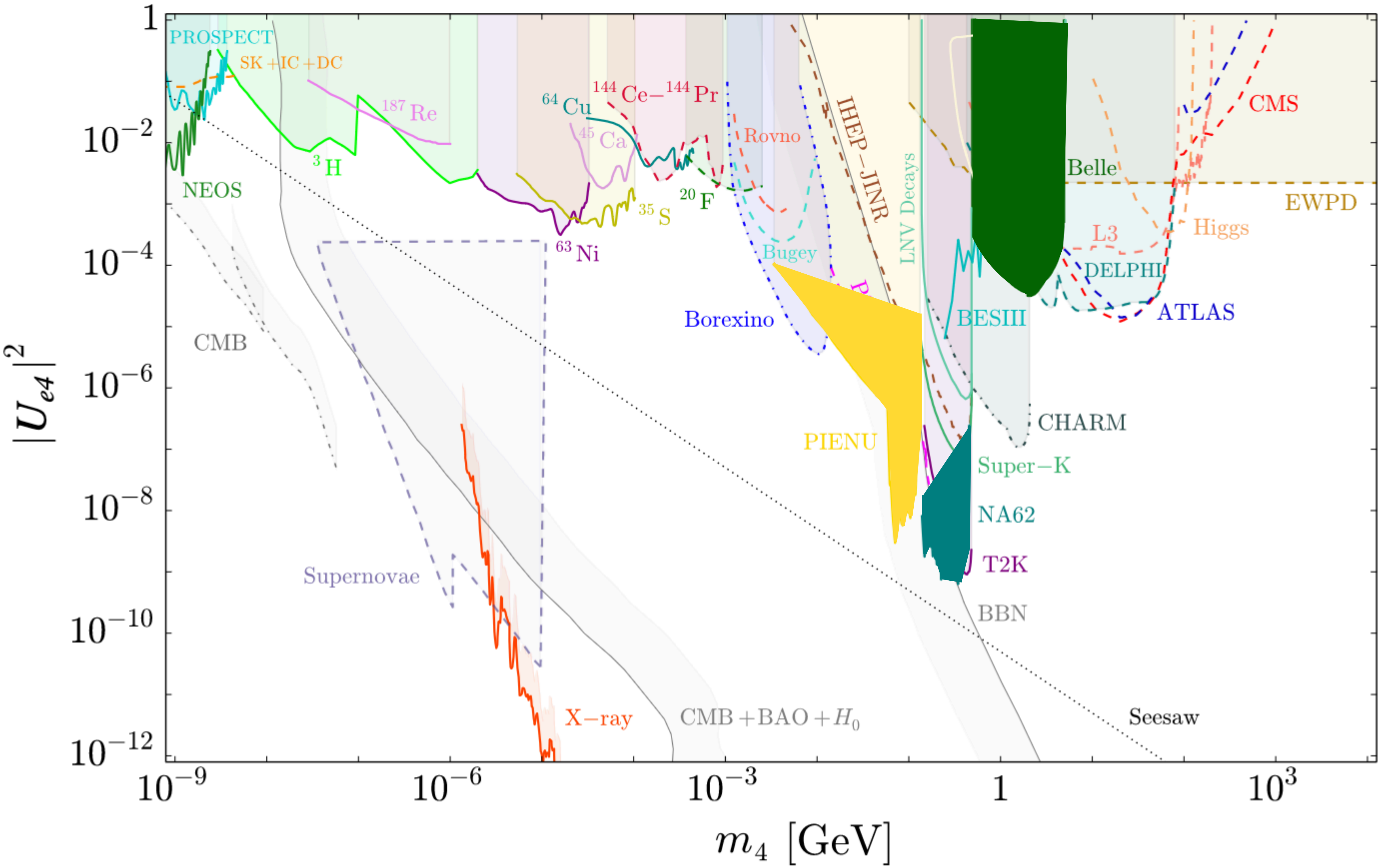


Flavor bounds on sterile neutrinos



NA62, 1712.00297

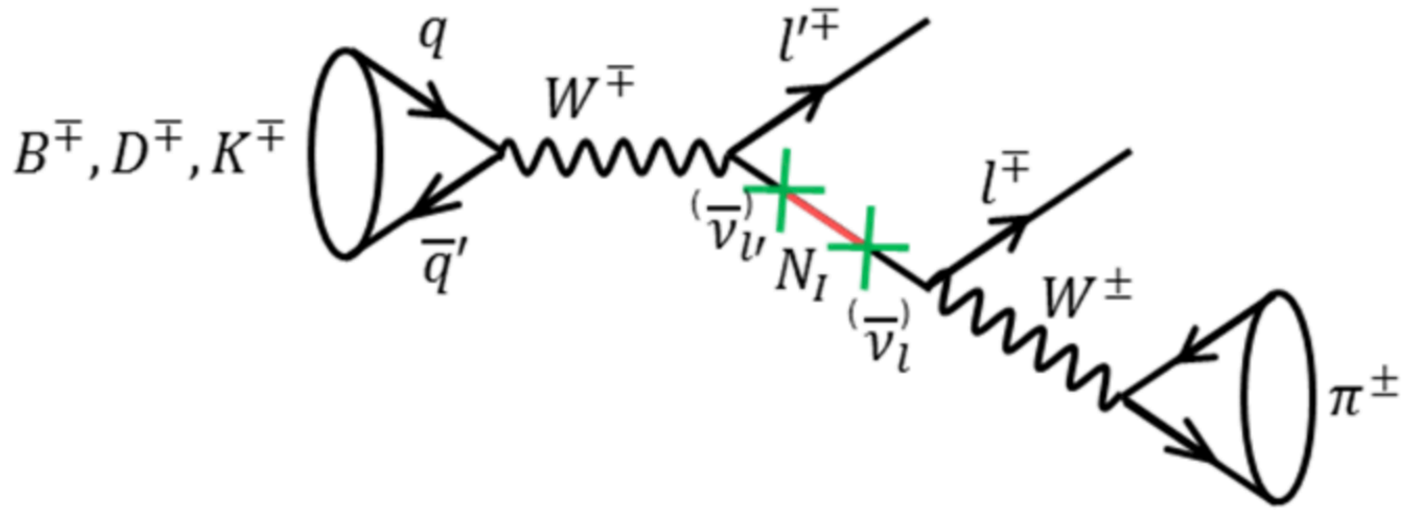
Flavor bounds on sterile neutrinos



Dasgupta, Kopp, 2106.05913

Flavor bounds on sterile neutrinos

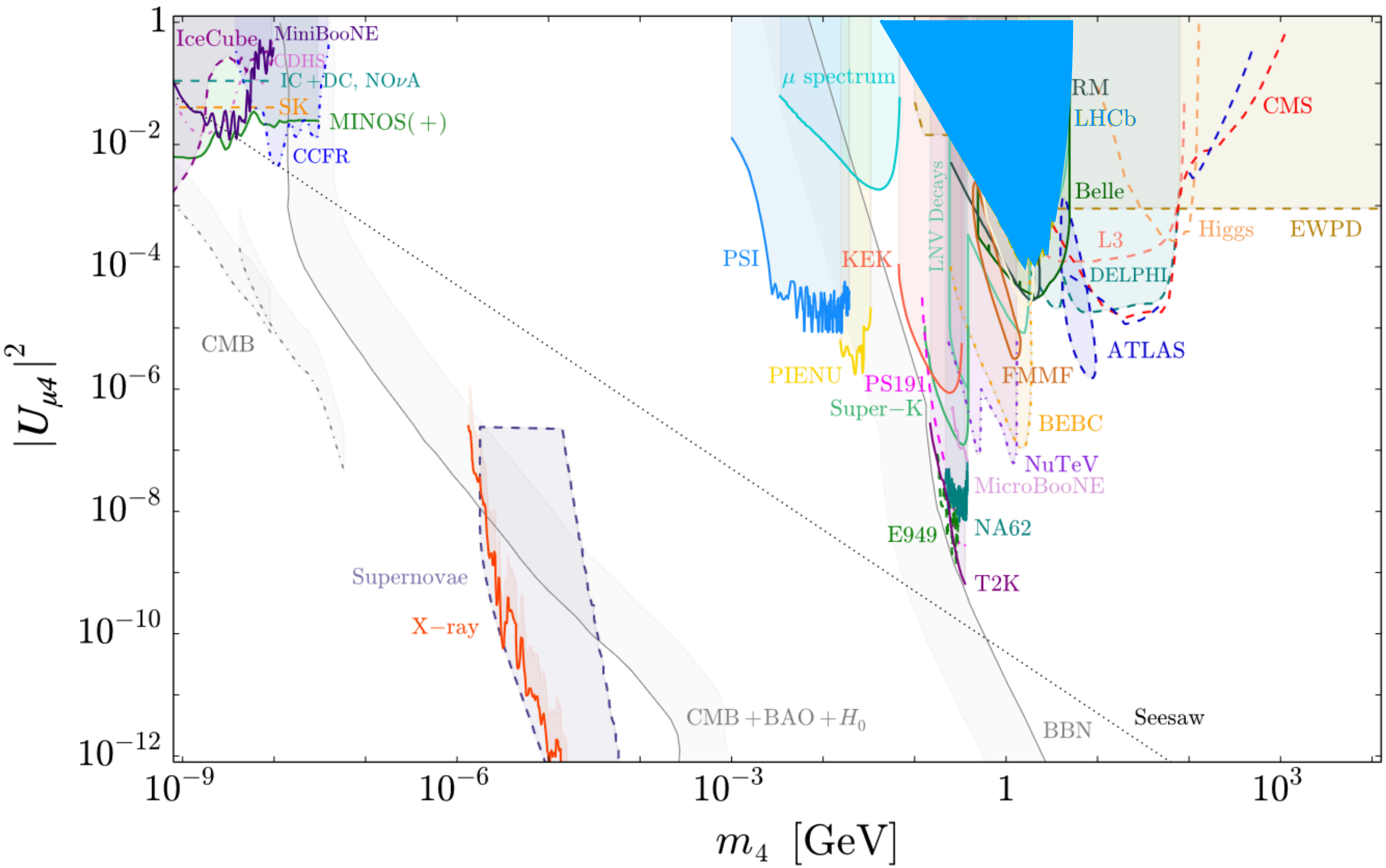
If neutrinos are Majorana they can mediate meson decays with lepton number violation



Atre, Han, Pascoli, and Zhang, JHEP 05 (2009) 030, [0901.3589].

Flavor bounds on sterile neutrinos

$B^- \to \mu^- \mu^- \pi^+$ LHCb 1401.5361



Conclusions

An axion or hidden photon could be the only light remnant of a heavy new physics sector out of reach of the LHC

Flavor bounds uniquely constrain axionlike particles with masses between 100 MeV and 10 GeV

Flavor transitions for hidden photons are very strongly suppressed and can't compete with flavor conserving observables

Sterile Neutrinos can induce lepton number violating decays which would signal Majorana nature of neutrinos