Constraining ALPs with Higgs data via SMEFT

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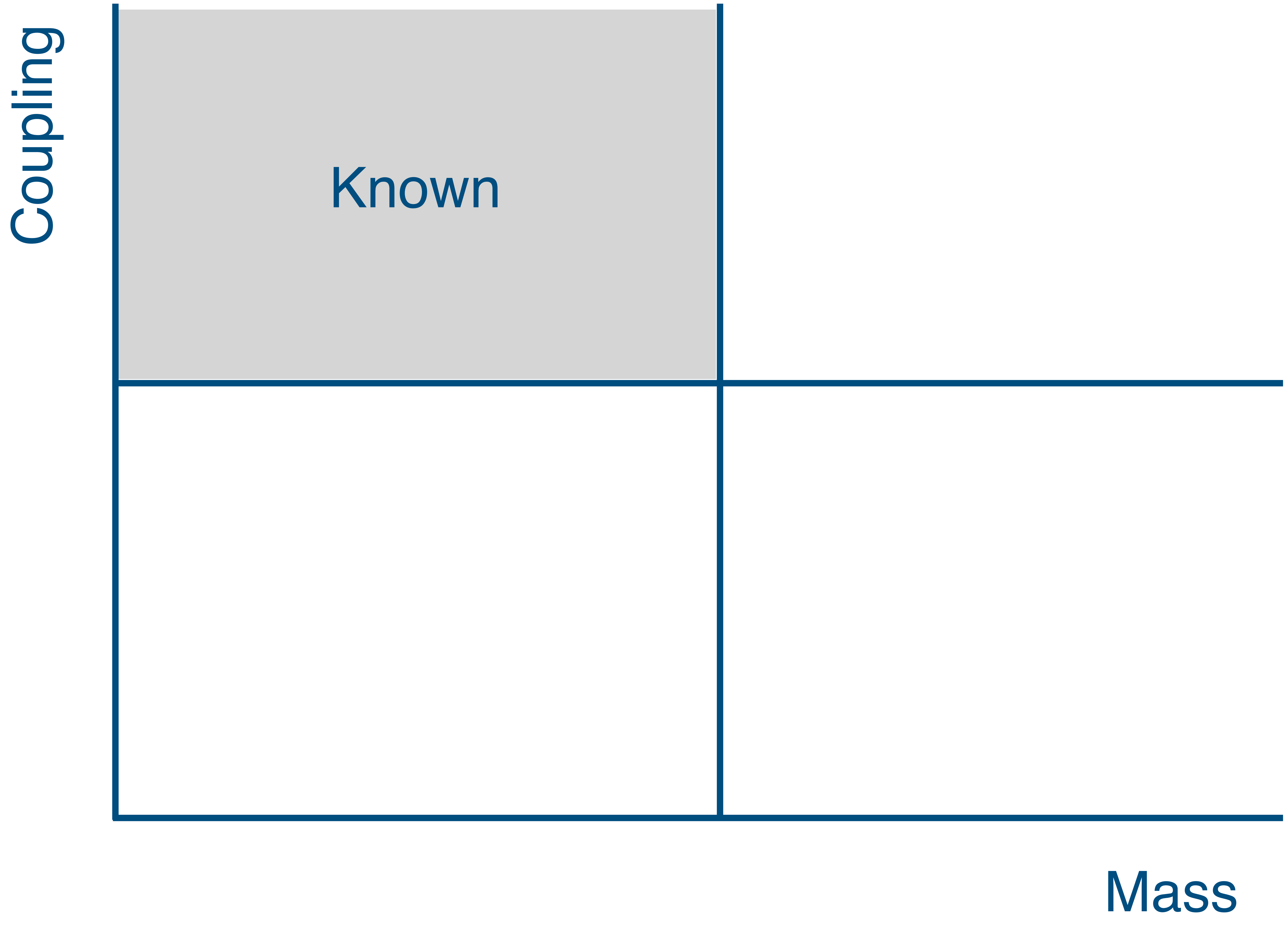
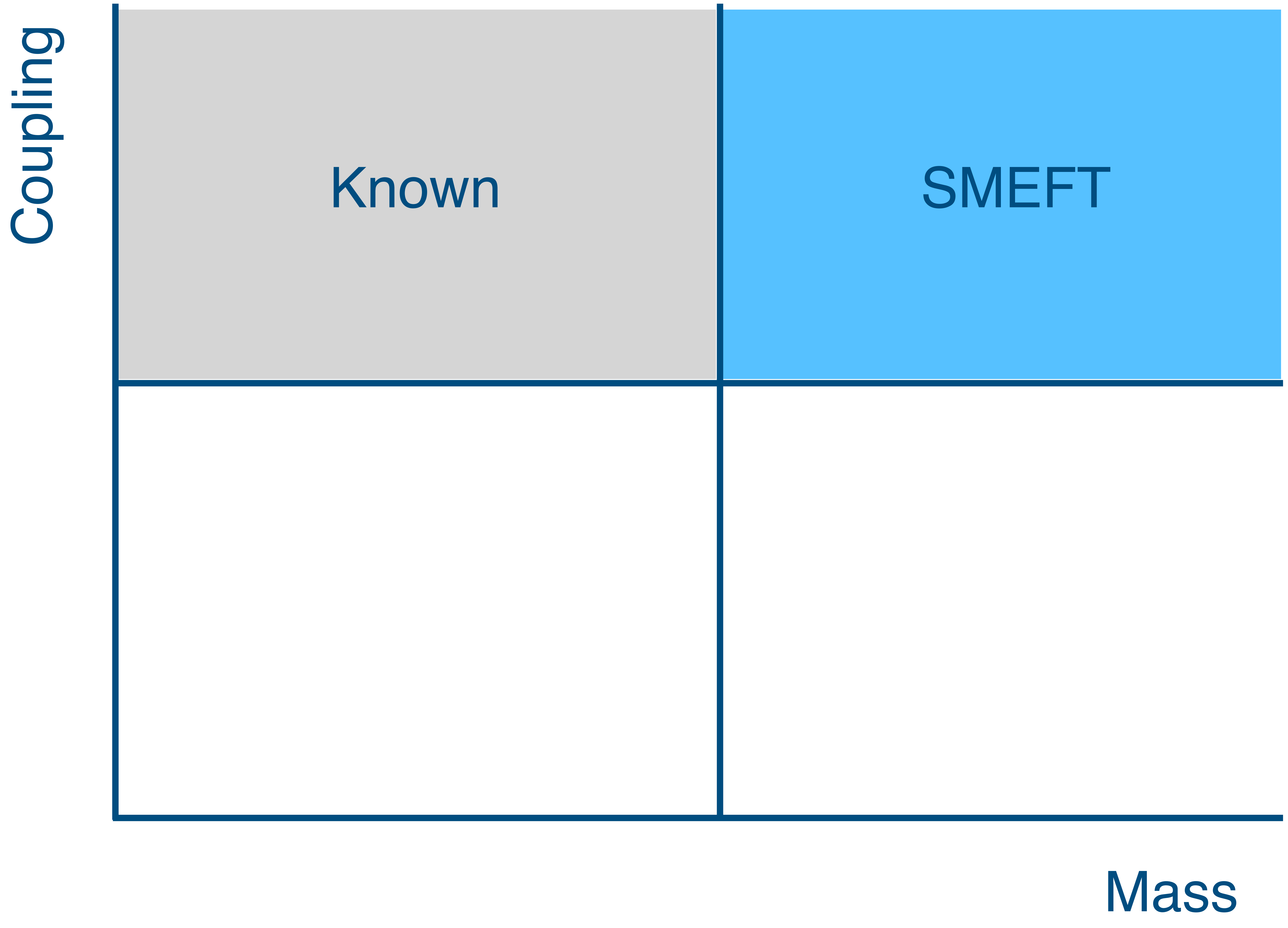
20th Workshop of the LHC Higgs WG - 13 November 2023

The Landscape of (new) physics



New physics has to be…

The Landscape of (new) physics



New physics has to be…

… very heavy

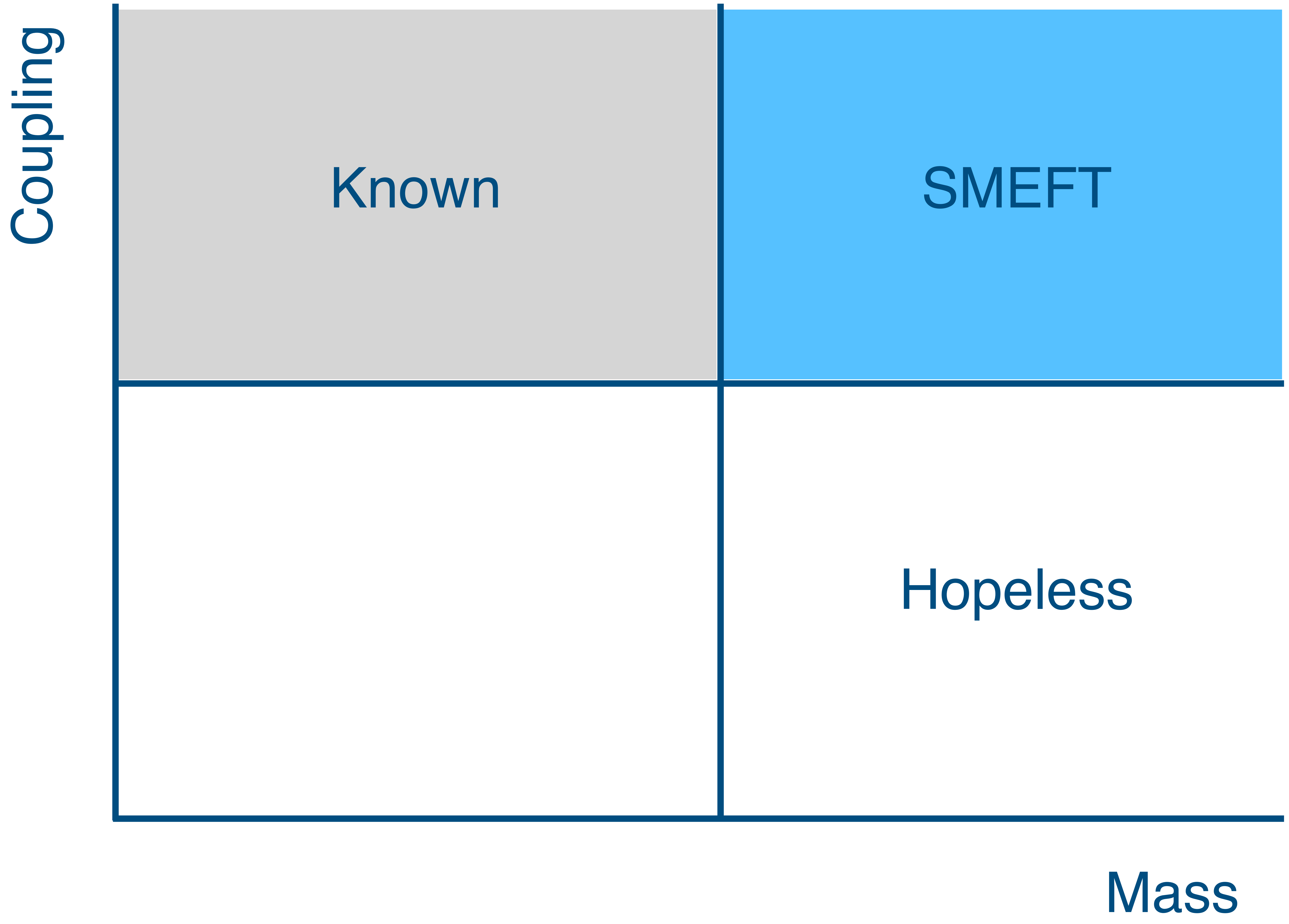
SMEFT

Leptoquarks

Z' bosons

Supersymmetry

The Landscape of (new) physics



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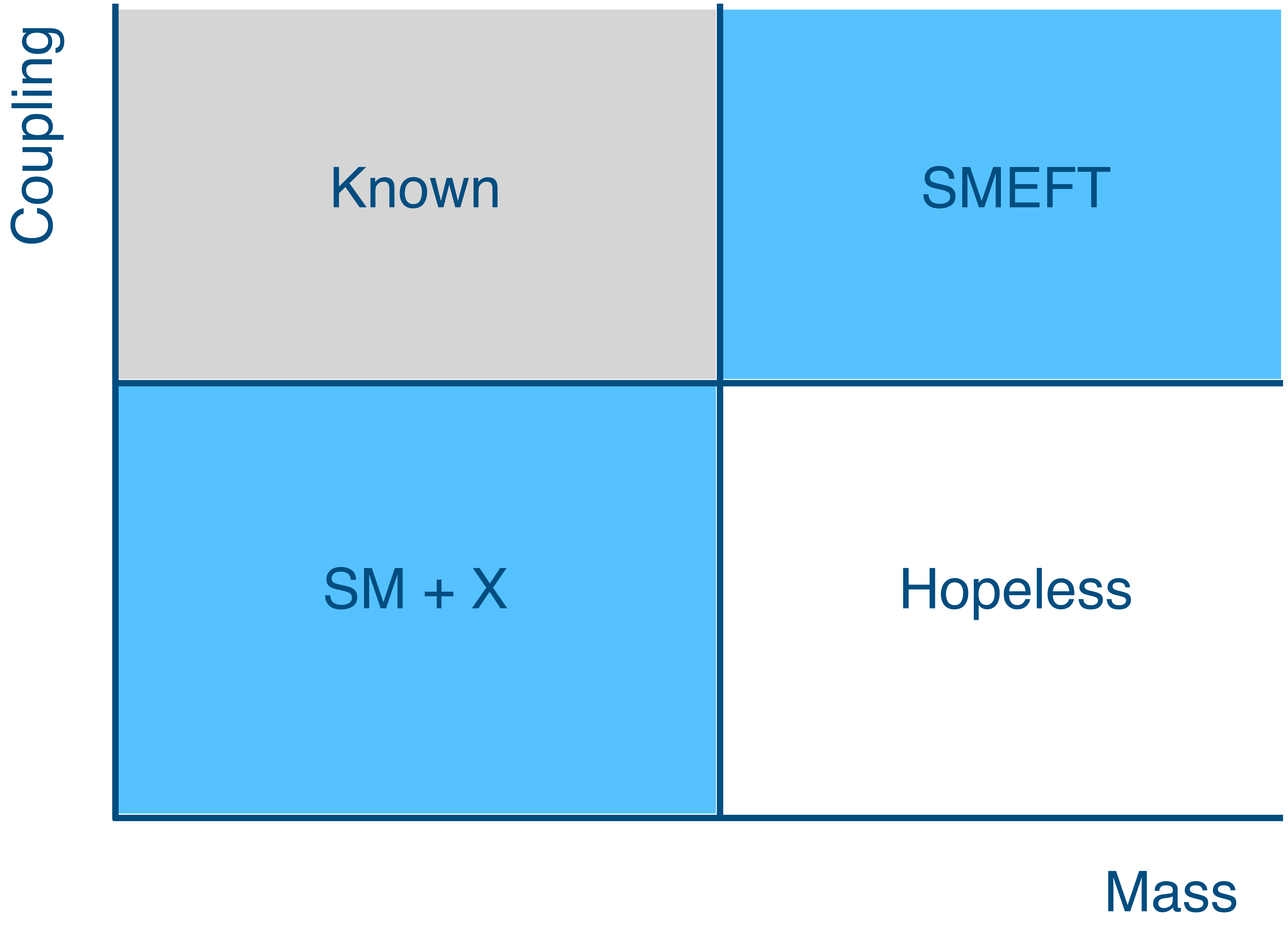

New physics has to be…

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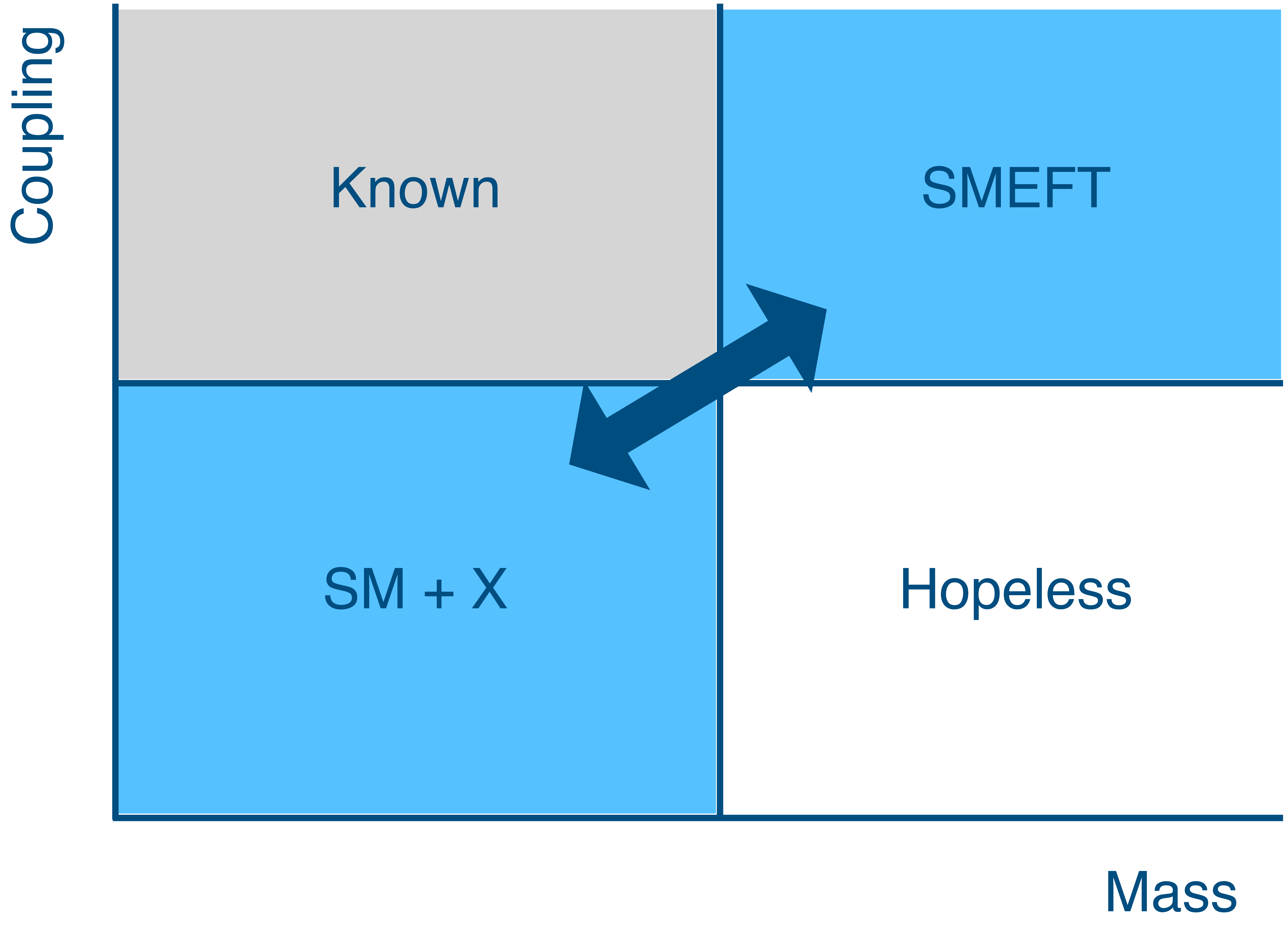
Z' bosons

Supersymmetry

… (light and) very weakly interacting with the SM

Axion-like particles

The Landscape of (new) physics



Can we reuse (Higgs) SMEFT results to constrain light new physics?

Outline

Reuse Recycle Recast

- Axion-like particle (ALP) EFT
- ALP-SMEFT interference [Galda, Neubert, Renner (2105.01078)]
- Global analysis of indirect bounds on ALP couplings from the SMEFT
- Comparison to direct bounds

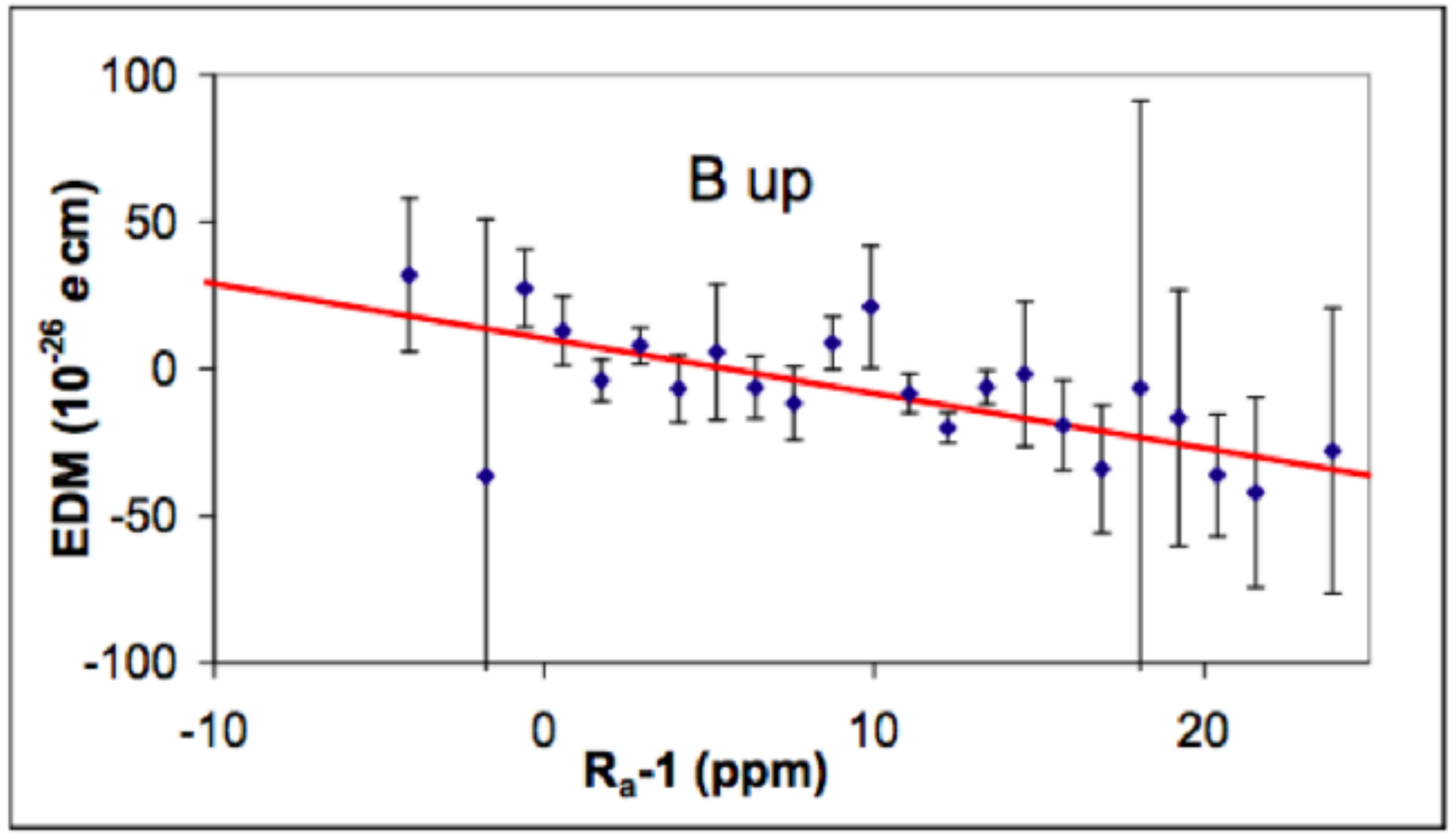
Based on 2307.10372 with
Anne Galda, Javier Fuentes-Martín and Matthias Neubert

Axions

$$\mathcal{L} = \theta \, \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Why is the theta term so small?

[Baker et al. (hep-ex/0602020)]



Electric dipole moment of the neutron

$$\mathcal{L} = \left(\theta - \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Dynamical solution to the strong CP problem

[Peccei, Quinn (ref1, ref2)]
[Weinberg] [Wilczek]

Axion-like particles

- Singlet pseudo-scalars
- QCD axion: $m_a f_a = \text{const.}$, but generally a wide range of masses is possible
- Generic ALP with effective Lagrangian
- Motivation: "Higgs portal" dark matter, composite Higgs models, …
- Shift symmetry $a \to a + a_0$, Lagrangian terms: $\dfrac{\partial_\mu a}{f_a}\,(\text{SM})^\mu$

[Peccei, Quinn (ref1, ref2)]
[Weinberg] [Wilczek]

[Brivio et al. (1701.05379)]
[Bauer et al. (1708.00443)]

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

Dim-5 Lagrangian

ALP Lagrangian

$$\mathcal{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F \, c_F \, \gamma_\mu \psi_F + c_\phi \frac{\partial^\mu a}{f}(\phi^\dagger i \overleftrightarrow{\boldsymbol{D}}_\mu \phi)$$
$$+ c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f} B_{\mu\nu}\tilde{B}^{\mu\nu}\,.$$

$$\psi_F \to \psi_F + i\frac{a}{f}\mathbf{c}_F\,\psi_F$$

$$\mathcal{L}_{\rm SM+ALP}^{D\leq 5} = C_{GG}\frac{a}{f} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + C_{WW}\frac{a}{f} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + C_{BB}\frac{a}{f} B_{\mu\nu}\tilde{B}^{\mu\nu}$$
$$-\frac{a}{f}\left(\bar{Q}\,\tilde{H}\,\tilde{Y}_u\,u_R + \bar{Q}\,H\,\tilde{Y}_d\,d_R + \bar{L}\,H\,\tilde{Y}_e\,e_R + \text{h.c.}\right)$$

$$\tilde{Y}_u = i(Y_u\,c_u - c_Q\,Y_u), \quad \tilde{Y}_d = i(Y_d\,c_d - c_Q\,Y_d), \quad \tilde{Y}_e = i(Y_e\,c_e - c_L\,Y_e)$$

$\tilde{c}_X = c_X \mathbb{1}_3$ Flavor universal

$$\tilde{Y}_u = i(c_u - c_Q)Y_u = -iC_u Y_u, \quad \tilde{Y}_d = i(c_d - c_Q)Y_d = -iC_d Y_d, \quad \tilde{Y}_e = i(c_e - c_L)Y_e = -iC_e Y_e$$

ALP Lagrangian

$\mathcal{L}$ … $\overleftrightarrow{D}_\mu \phi)$

… $_{\mu\nu}\,\tilde{B}^{\mu\nu}\,.$

… $\psi_F \to \psi_F + i\,\frac{a}{f}\,\mathbf{c}_F\,\psi_F$

Six free parameters in the flavor-universal case

$C_{GG},\, C_{WW},\, C_{BB},\, C_u,\, C_d,\, C_e$

$$\mathcal{L}^{D\leq 5}_{\text{SM+ALP}} = C_{GG}\,\frac{a}{f}\,G^a_{\mu\nu}\,\tilde{G}^{\mu\nu,a} + C_{WW}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A} + C_{BB}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}$$
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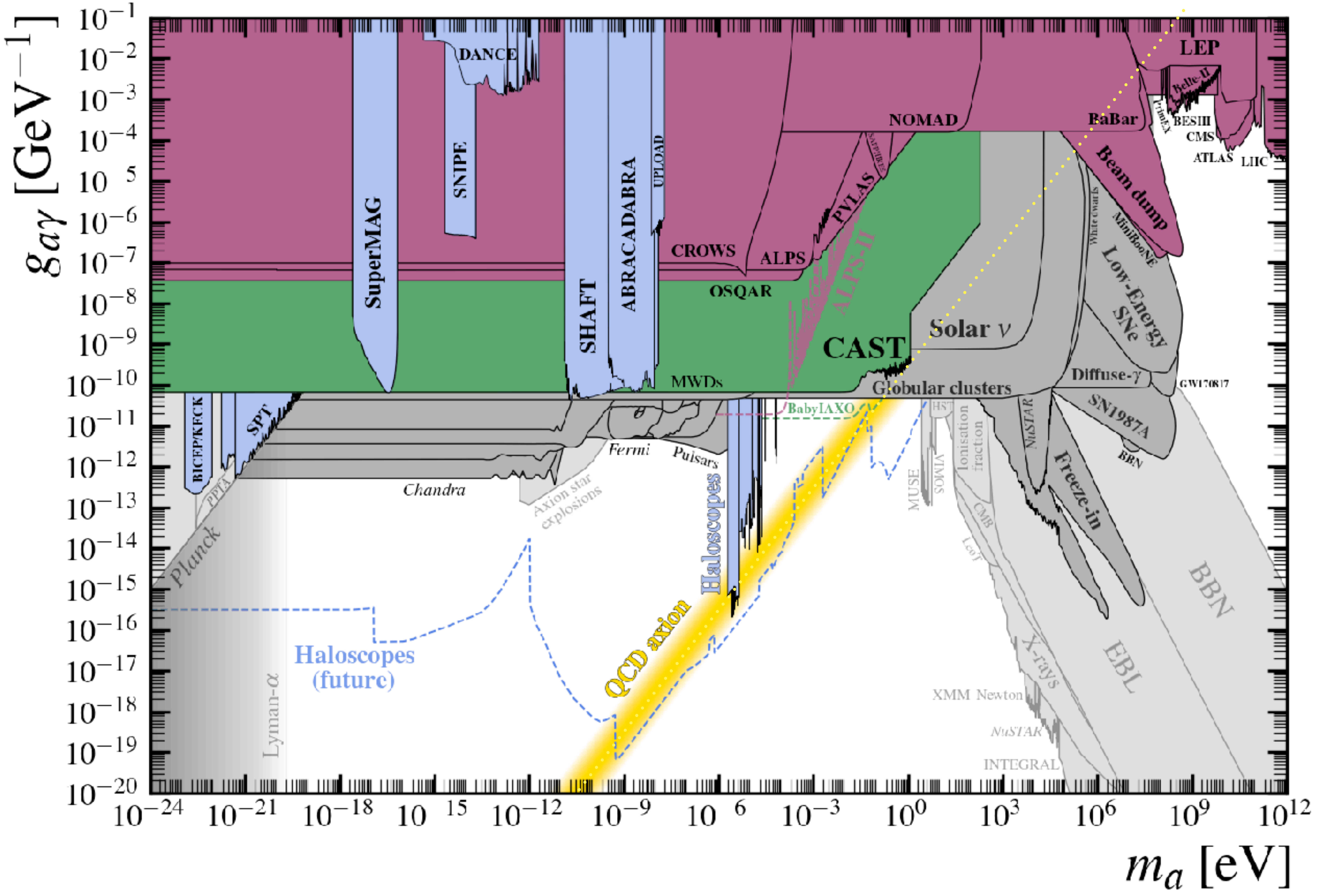
Axion-like particles



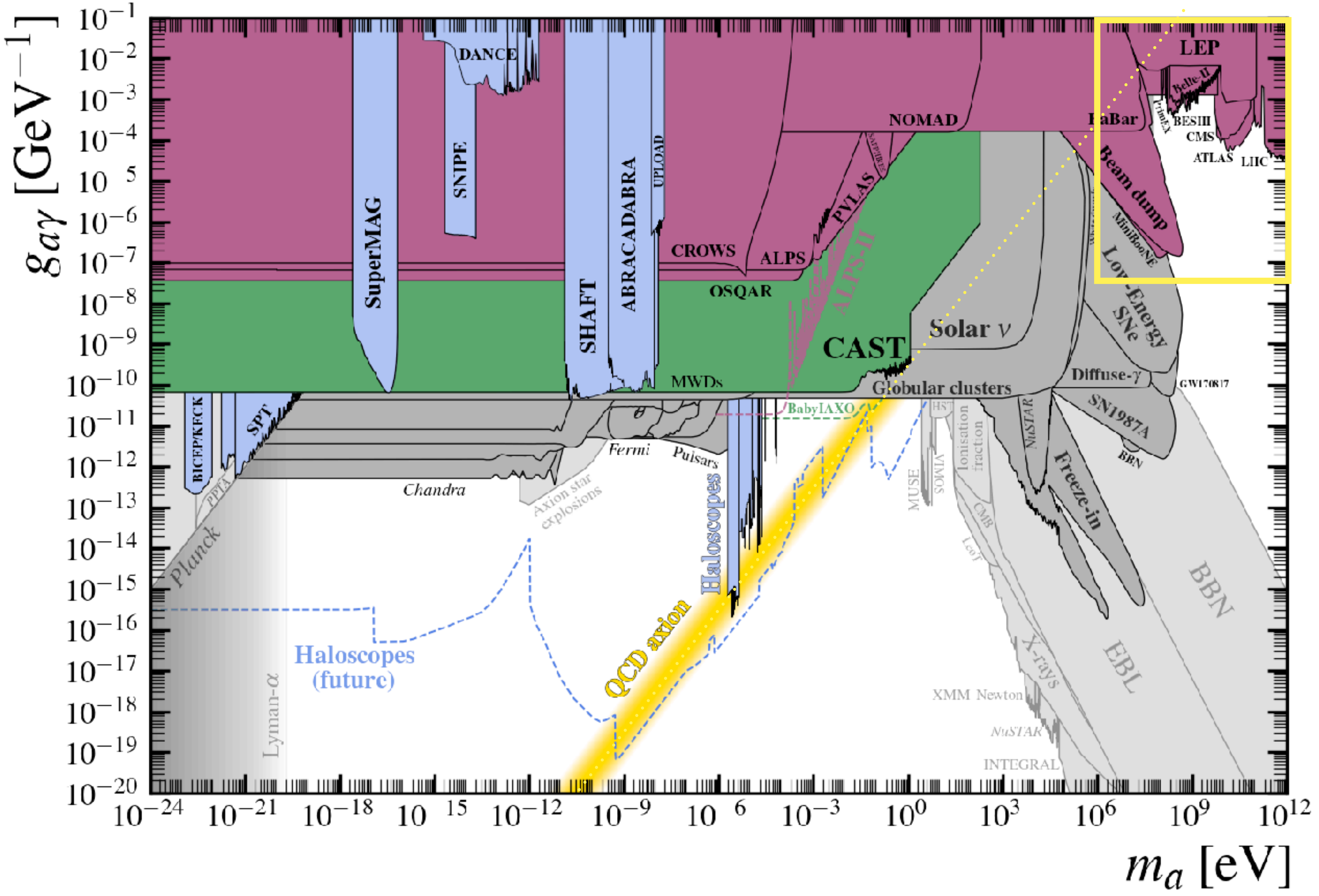
Current status - 2D fits

Assumptions of

- Production mode
- Lifetime
- Branching ratios

[O'Hare (axion limits)]

Axion-like particles



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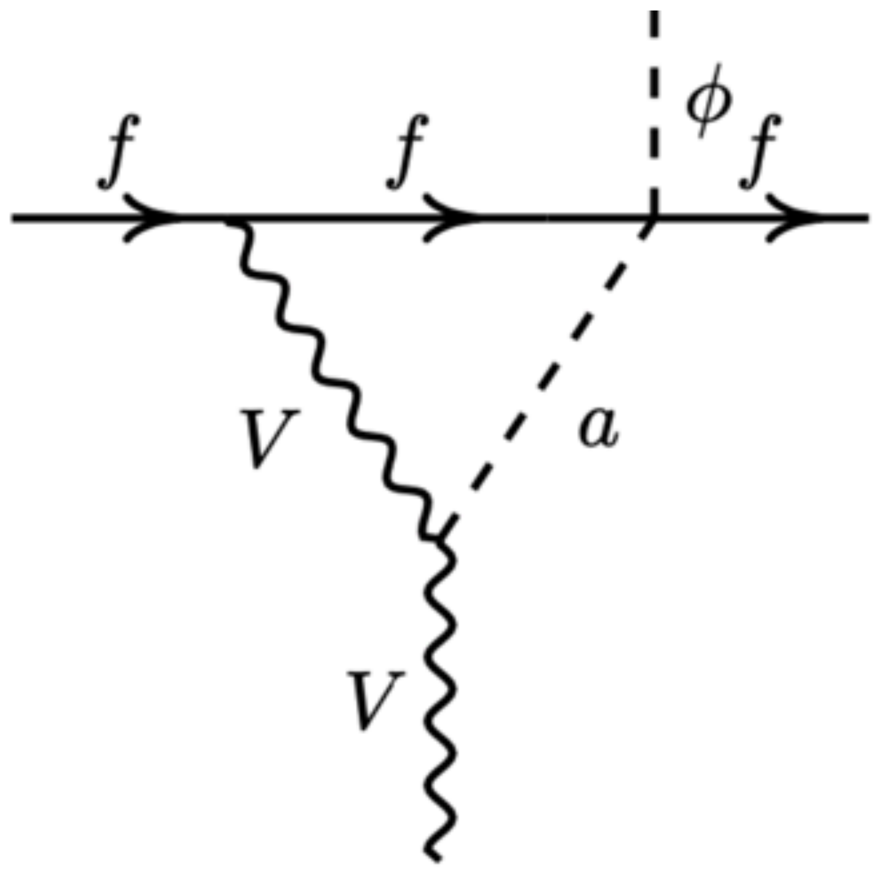
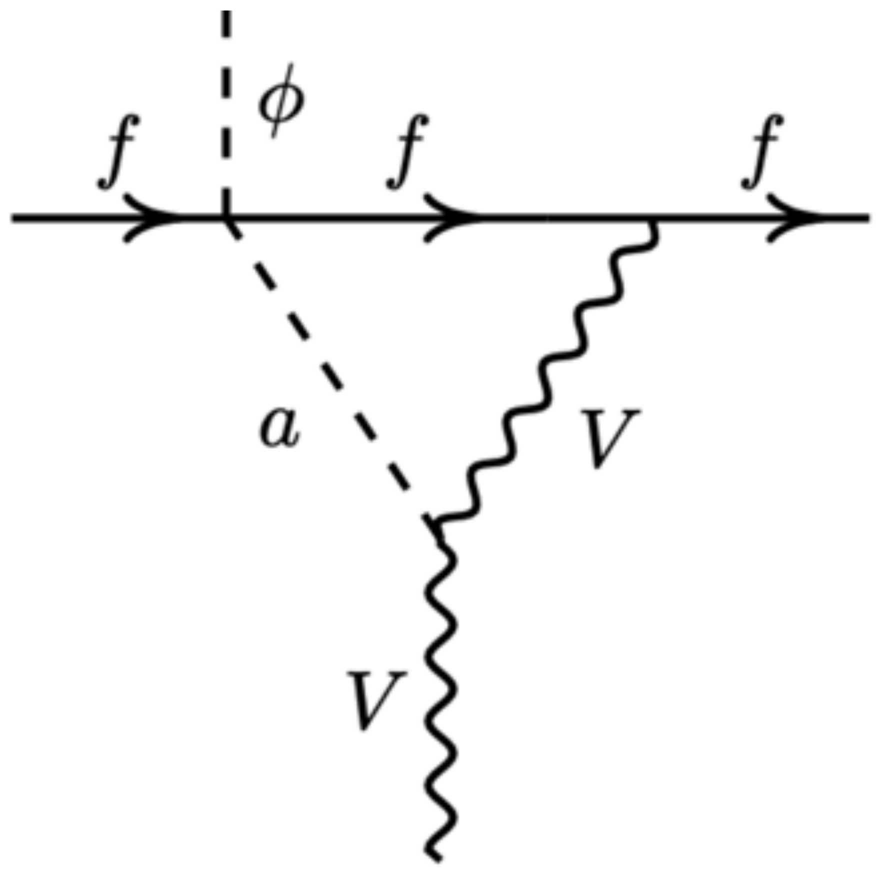
[O'Hare (axion limits)]

ALP-SMEFT interference

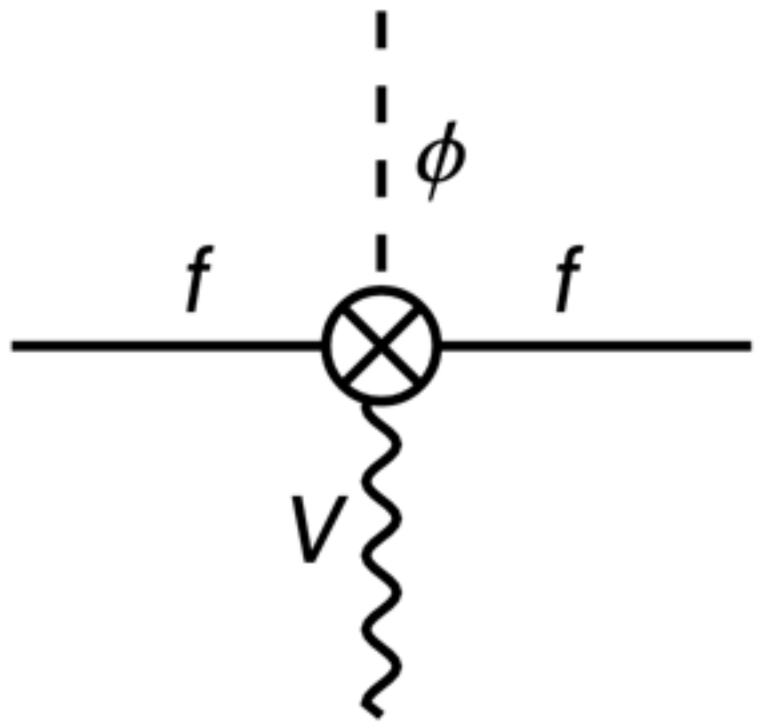
[Marciano, Masiero, Paradisi, Passera (1607.01022)]
[Bauer, Neubert, Thamm (1704.08207)]

- Virtual ALP exchange induces UV-divergent one-loop graphs
- Dimension-6 operators required as counterterms





$\sim 1/\epsilon$



Independent of ALP mass

Renormalisation group running

[Galda, Neubert, Renner (2105.01078)]

- SMEFT RG running

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu} C_i^{\mathrm{SMEFT}} = \gamma_{ji}\, C_j^{\mathrm{SMEFT}}$$

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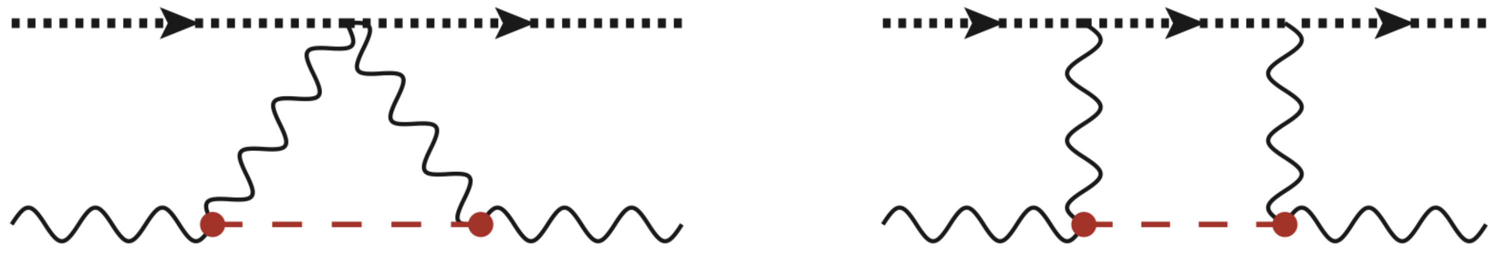

- ALP contributes source terms for D6 SMEFT RG running

Source terms are ALP-mass independent!

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu} C_i^{\mathrm{SMEFT}} - \gamma_{ji}^{\mathrm{SMEFT}} C_j^{\mathrm{SMEFT}} = \frac{S_i}{(4\pi f)^2} \qquad \text{for } \mu < 4\pi f$$

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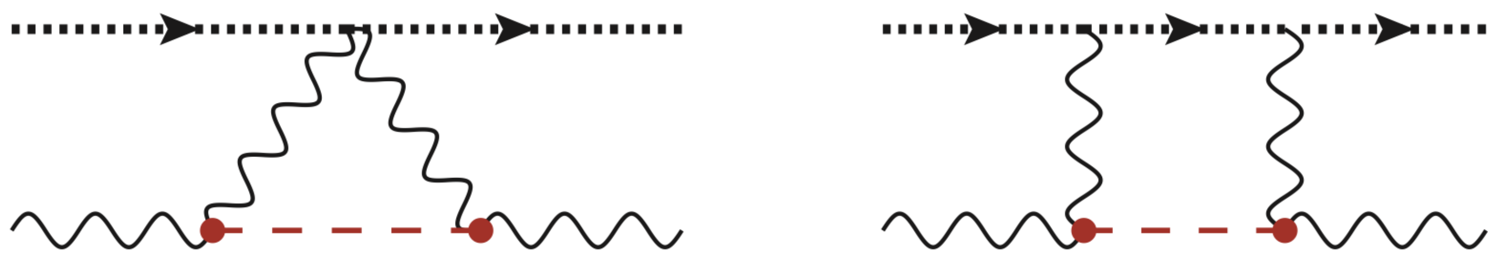

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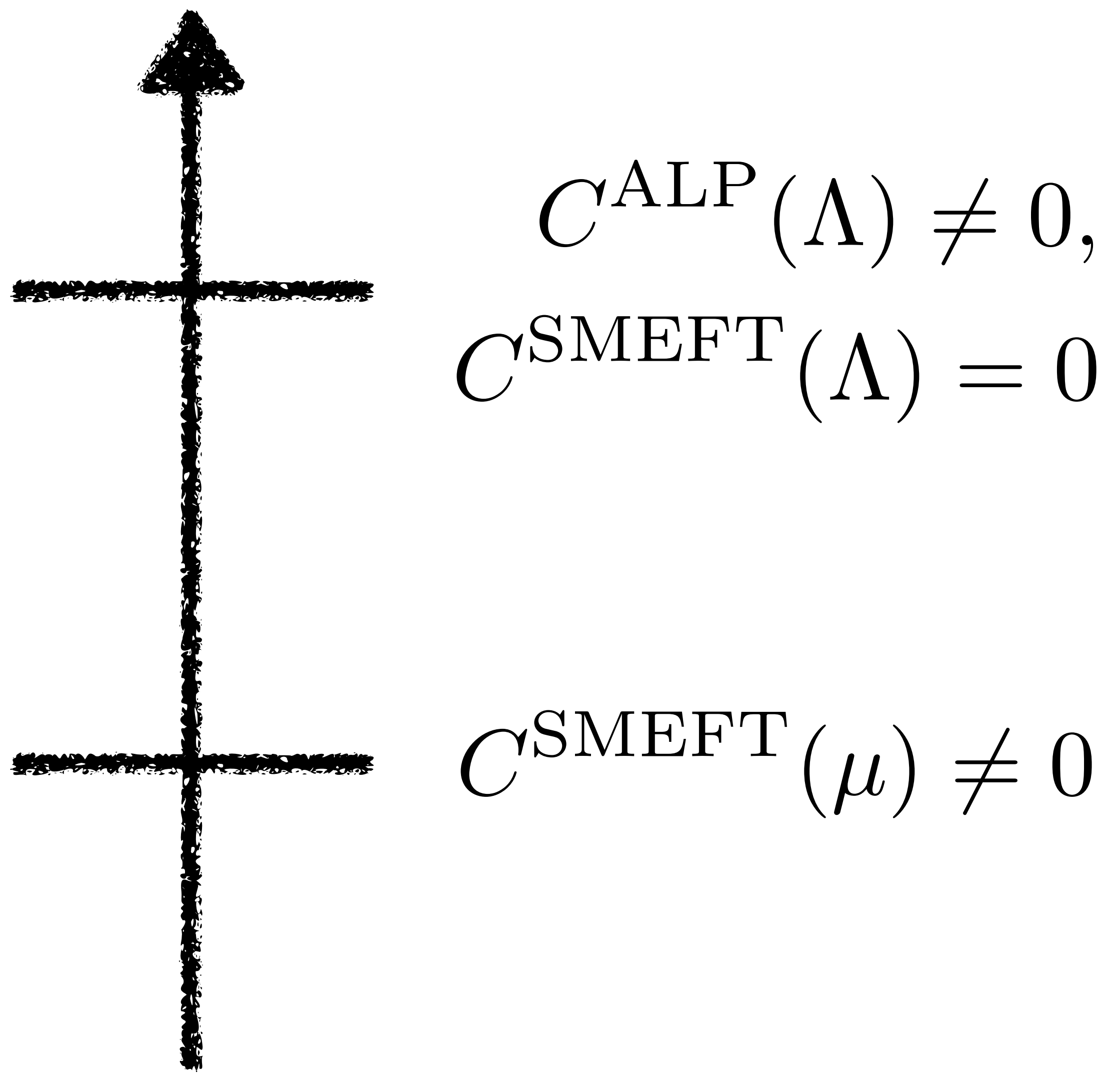
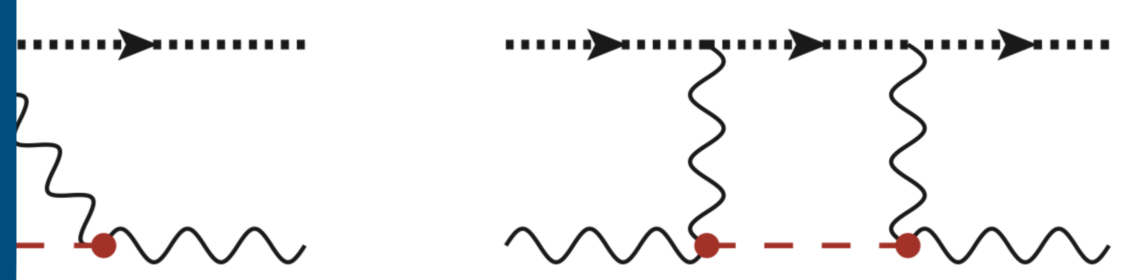


Non-zero ALP couplings at a high scale Λ induce non-zero D6 SMEFT couplings at a lower scale μ

Renormalisation group running

[Galda, Neubert, Renner (2105.01078)]

Can we use SMEFT constraints to obtain mass-independent constraints on the ALP Wilson coefficients?



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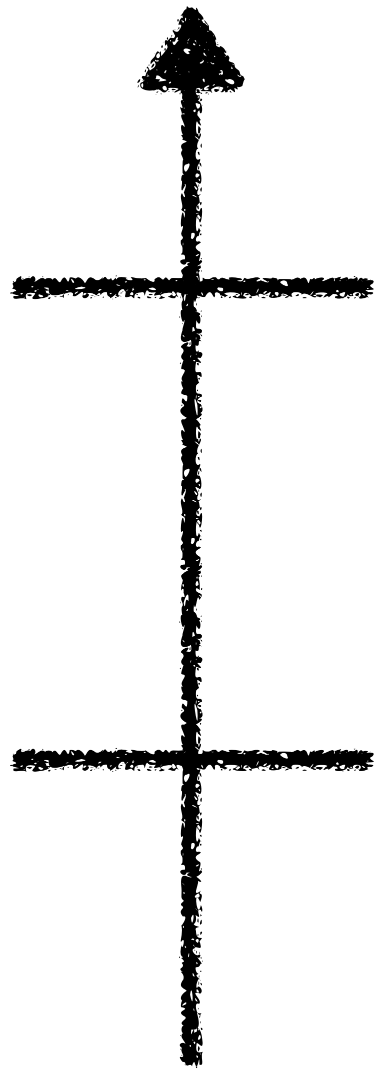


$C^{\mathrm{ALP}}(\Lambda) \neq 0,$

$C^{\mathrm{SMEFT}}(\Lambda) = 0$

$C^{\mathrm{SMEFT}}(\mu) \neq 0$

Non-zero ALP couplings at a high scale Λ induce non-zero D6 SMEFT couplings at a lower scale μ

Exploiting the ALP-SMEFT interference

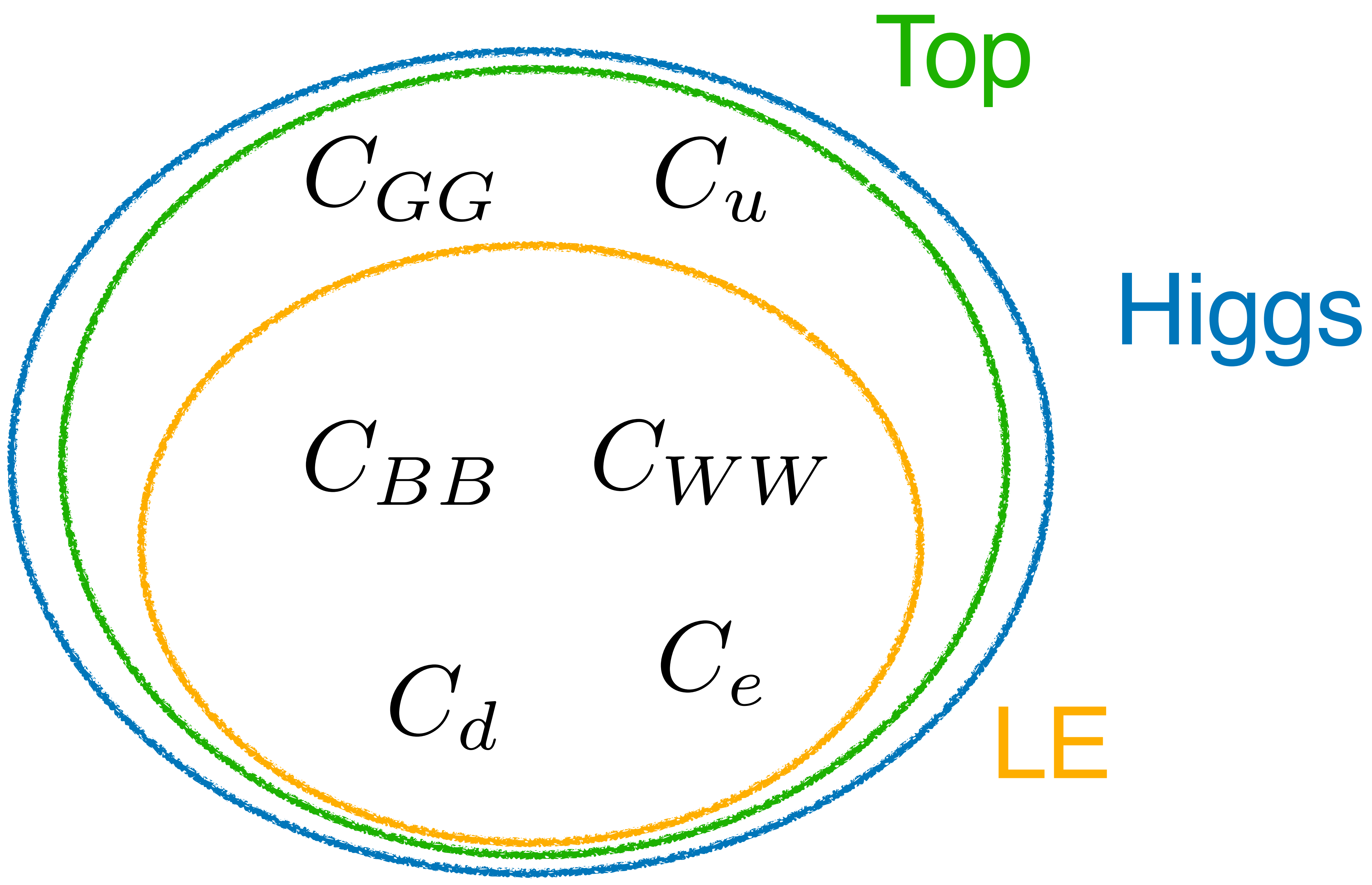
Observables used

- Low-energy observables
- Higgs
- Top

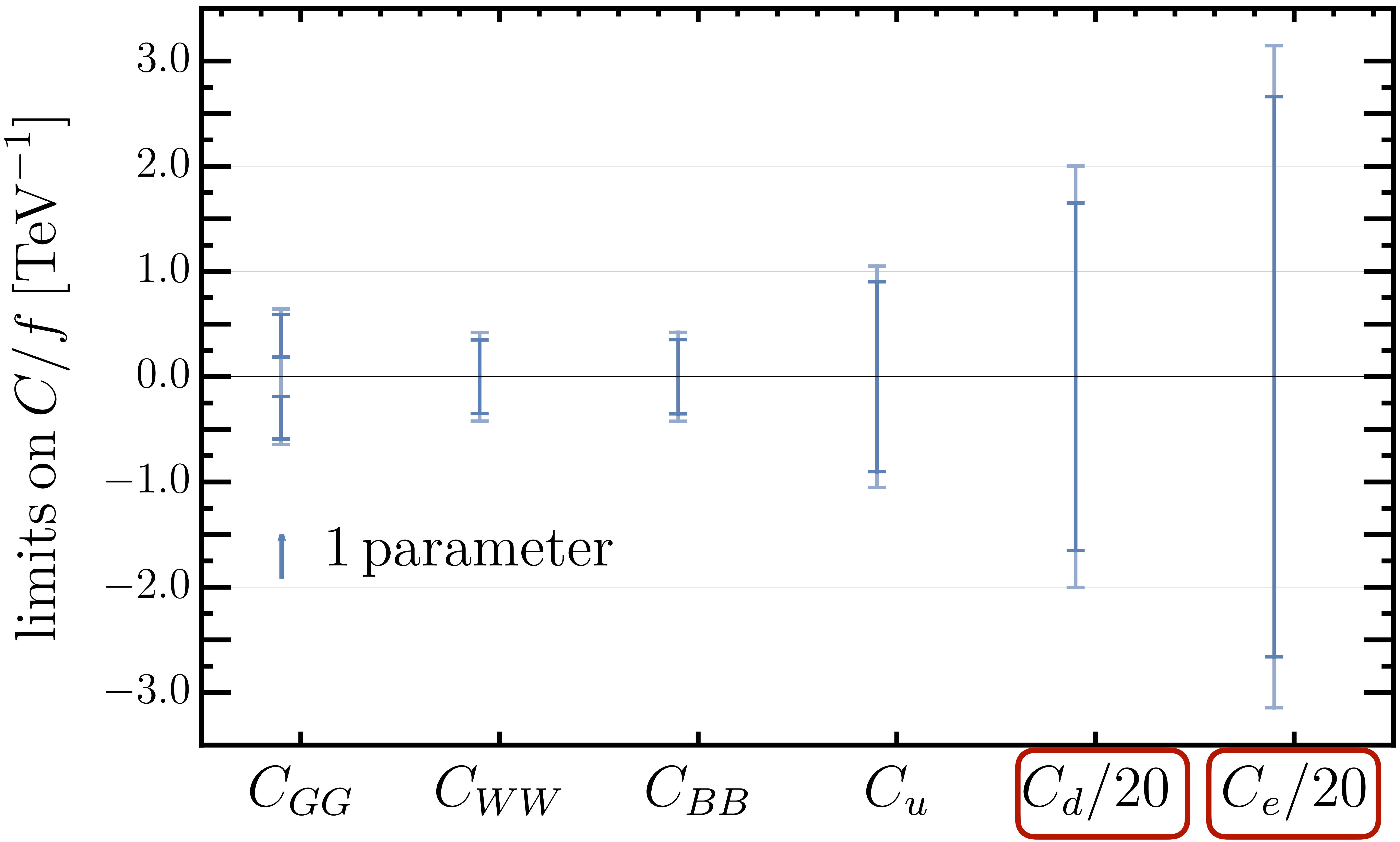
[Falkowski et al. (1706.03783)]
[Ellis et al. (2012.02779)]
[Anisha et al. (2111.05876)]

Six free parameters

$$C_{GG},\, C_{WW},\, C_{BB},\, C_u,\, C_d,\, C_e$$



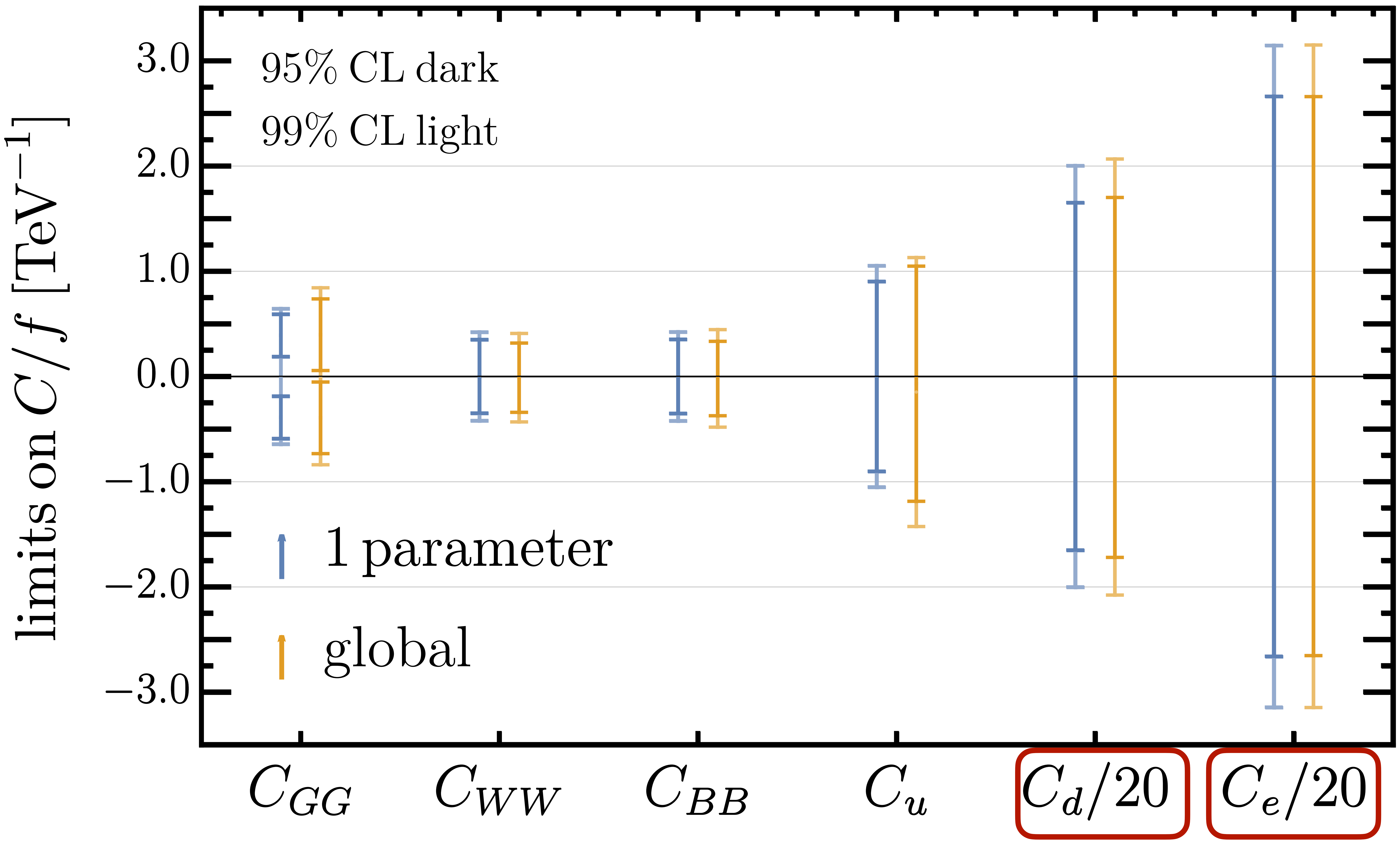
A global analysis



$\Lambda = 4\pi f$

$\mathcal{O}(1)$ limits on ALP couplings for $f = 1$ TeV

A global analysis



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$\mathcal{O}(1)$ limits on ALP couplings for $f = 1$ TeV

Interplay between couplings is relatively small

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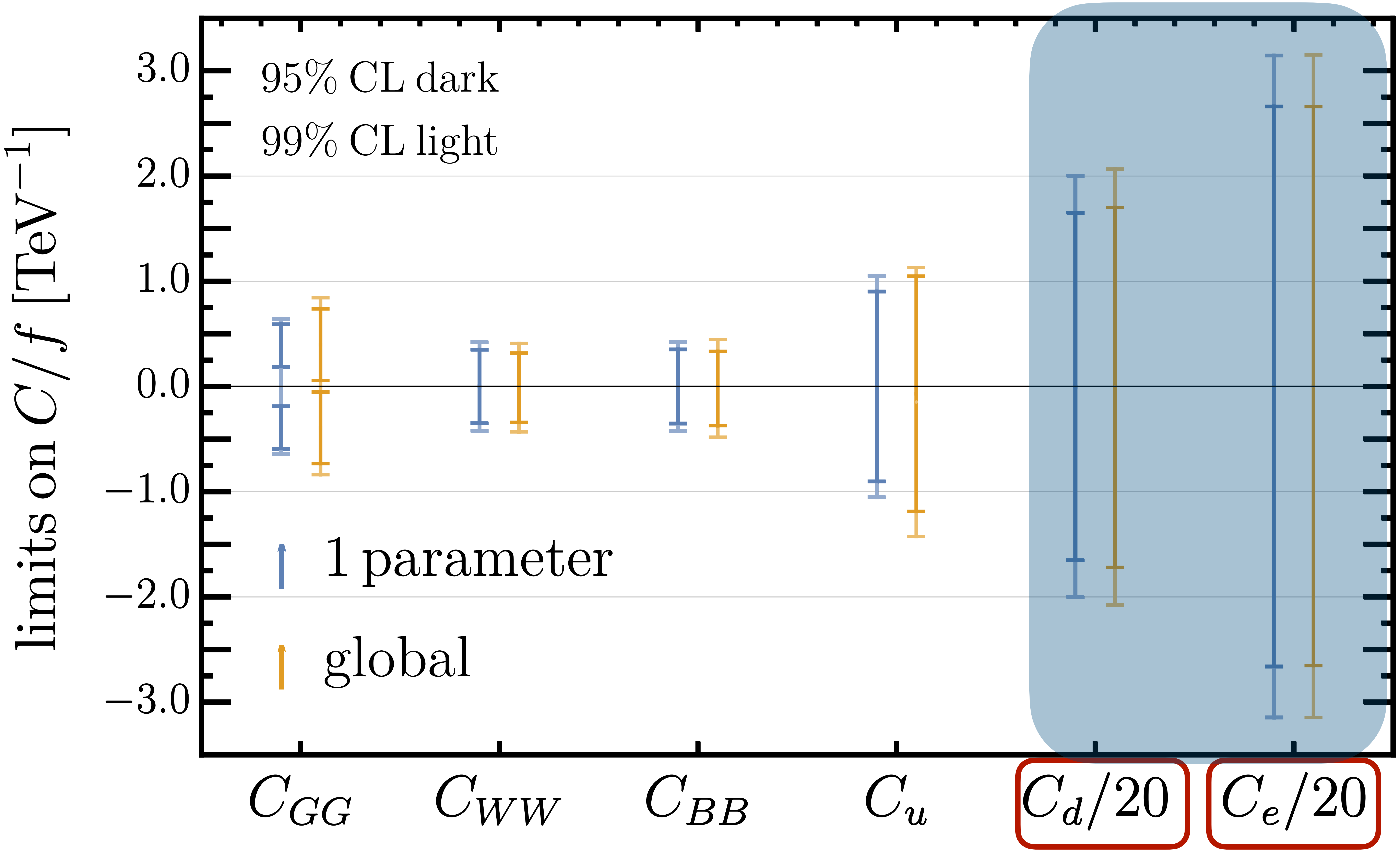


$\Lambda = 4\pi f$

$\mathcal{O}(1)$ limits on ALP couplings for $f = 1$ TeV

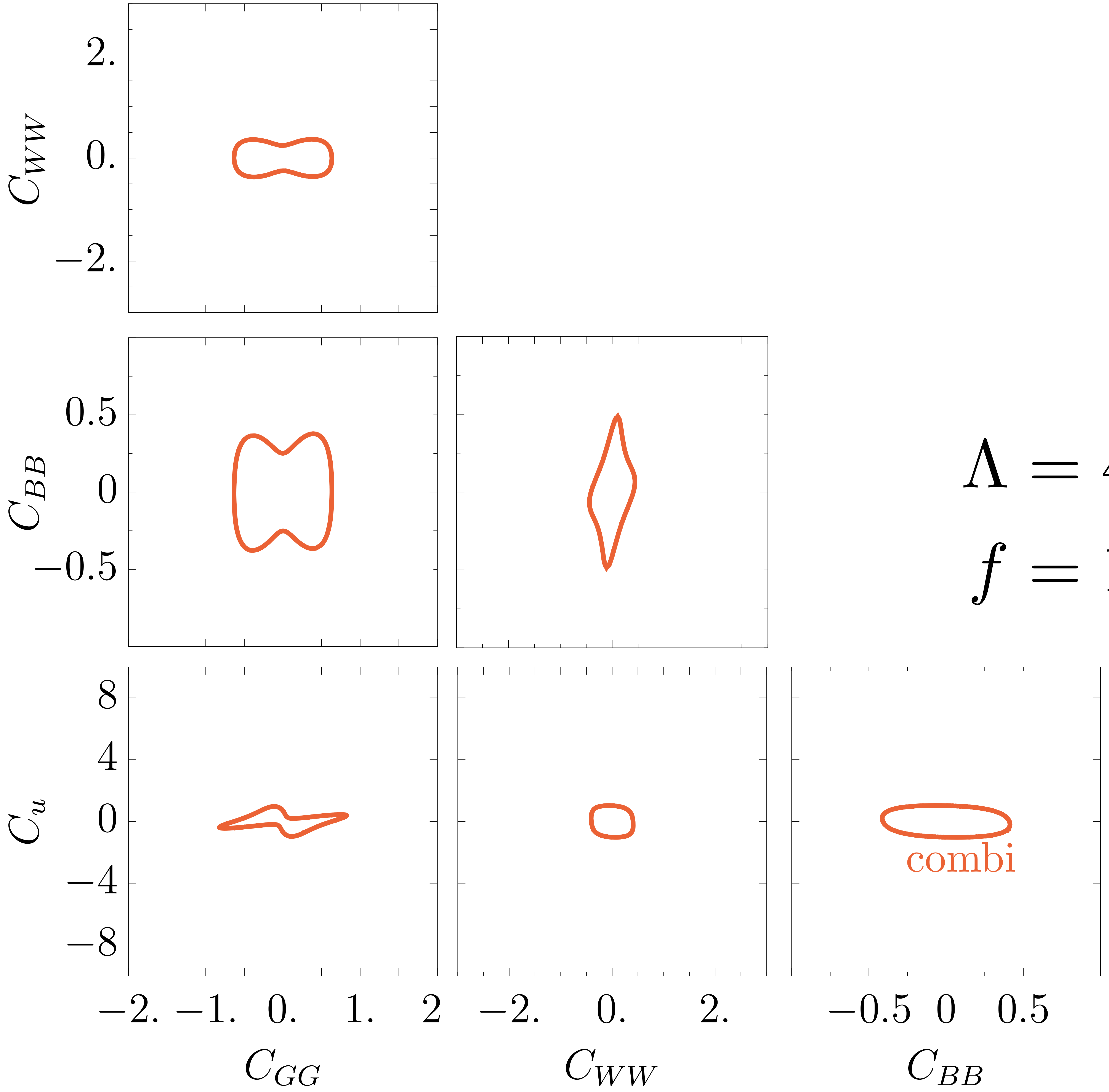
Interplay between couplings is relatively small

Correlations

Dominant constraints

- C_{GG} : Higgs + Top
- C_{WW} : LE + Higgs
- C_{BB} : low energy
- C_u : low energy

- C_d : low energy
- C_e : low energy



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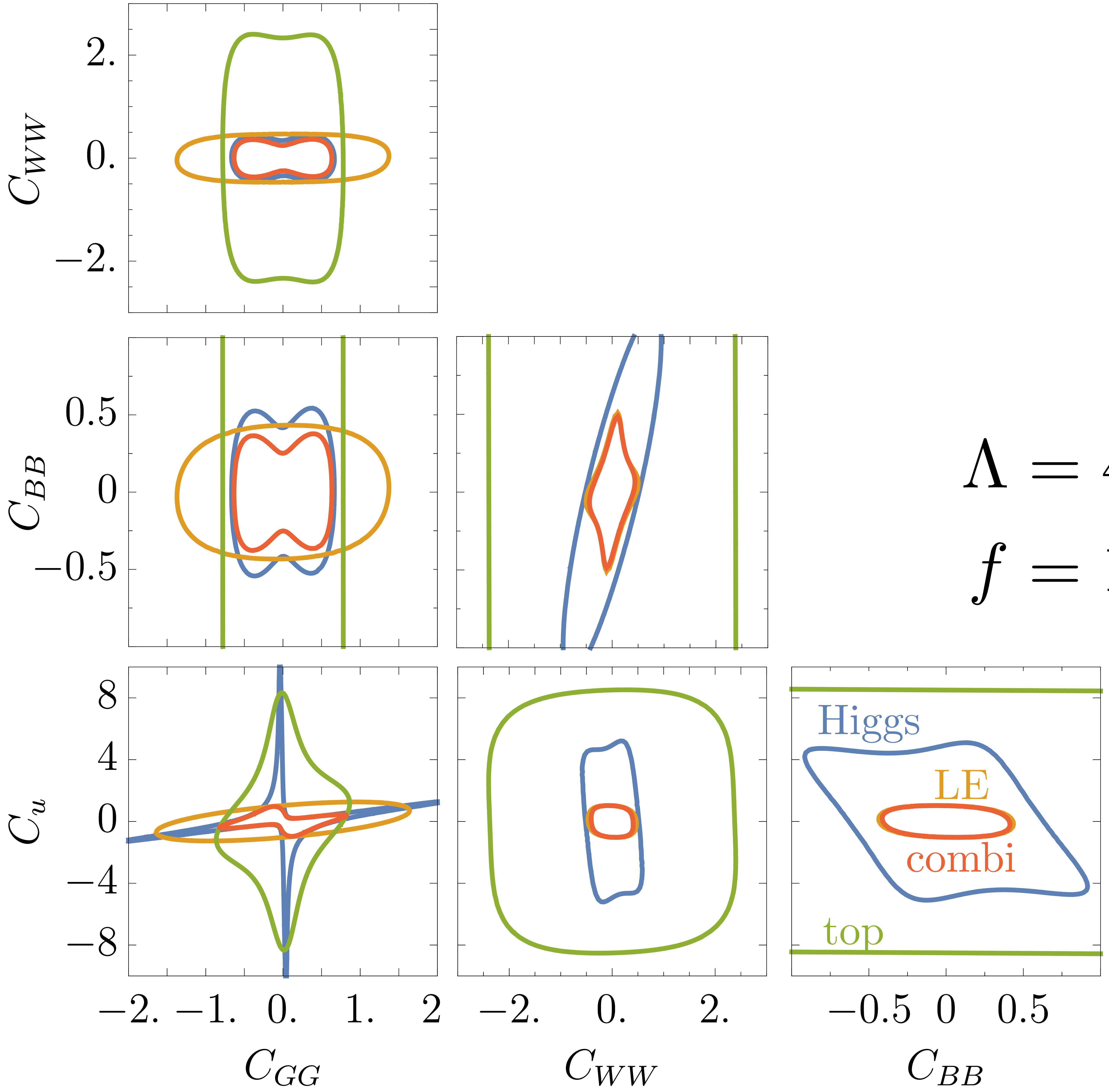

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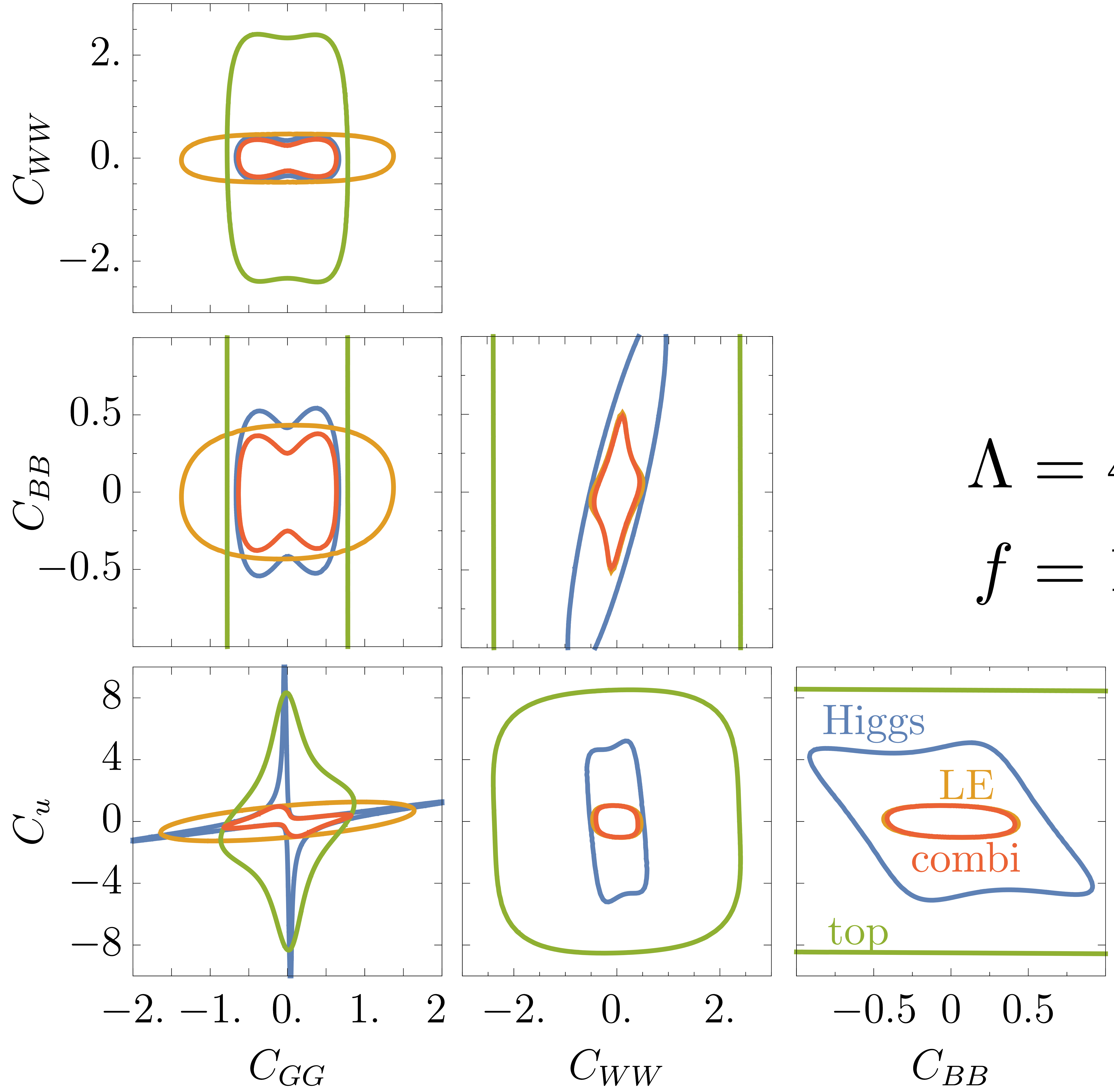
Why?

- C_d : low energy
- C_e : low energy



$\Lambda = 4\pi f$

$f = 1$ TeV

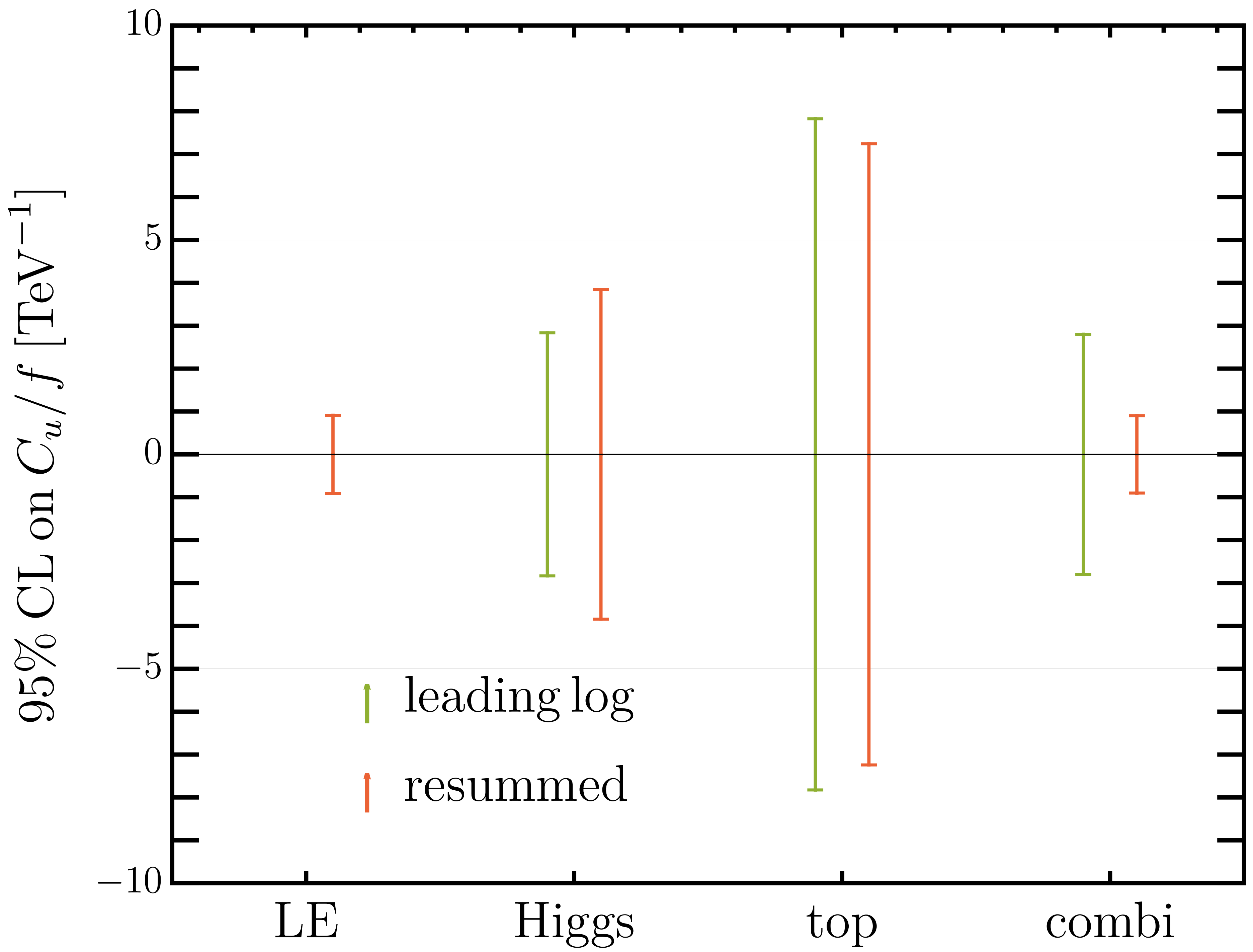
LL approximation - Cu

$$\frac{d}{d\ln\mu} C_{HD} = \left(\frac{3\,\alpha_t}{\pi} + \frac{3\,\lambda}{8\pi^2}\right) C_{HD} + \frac{6\,\alpha_t}{\pi} [C_{Hq}^{(1)}]_{33} - \frac{6\,\alpha_t}{\pi} [C_{Hu}]_{33}$$

$$\frac{d}{d\ln\mu} [C_{Hq}^{(1)}]_{33} = -\pi\,\alpha_t\, C_u^2 + \cdots$$

$$\frac{d}{d\ln\mu} [C_{Hu}]_{33} = 2\pi\,\alpha_t\, C_u^2 + \cdots$$

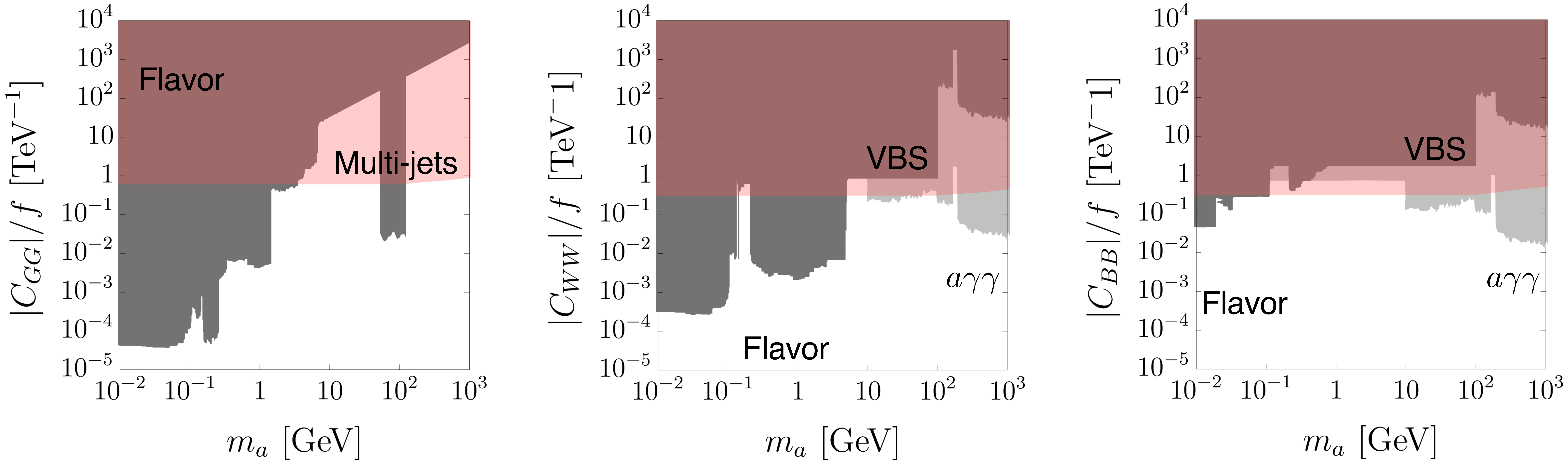
$$C_{HD}(\mu) = -9\,\alpha_t^2\, C_u^2\, \ln^2 \frac{\mu}{\Lambda}$$



CHD strongly constrained from EWPO (measurement of W boson mass)

Comparison with direct bounds

Light gray bounds with additional assumptions



[Mariotti, Redigolo, Sala, Tobiok (1710.01743)]

[Bonilla, Brivio, Machado-Rodríguez, de Trocóniz (2202.03450)]

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[Bauer, Neubert, Renner, Schnubel, Thamm (2110.10698)]

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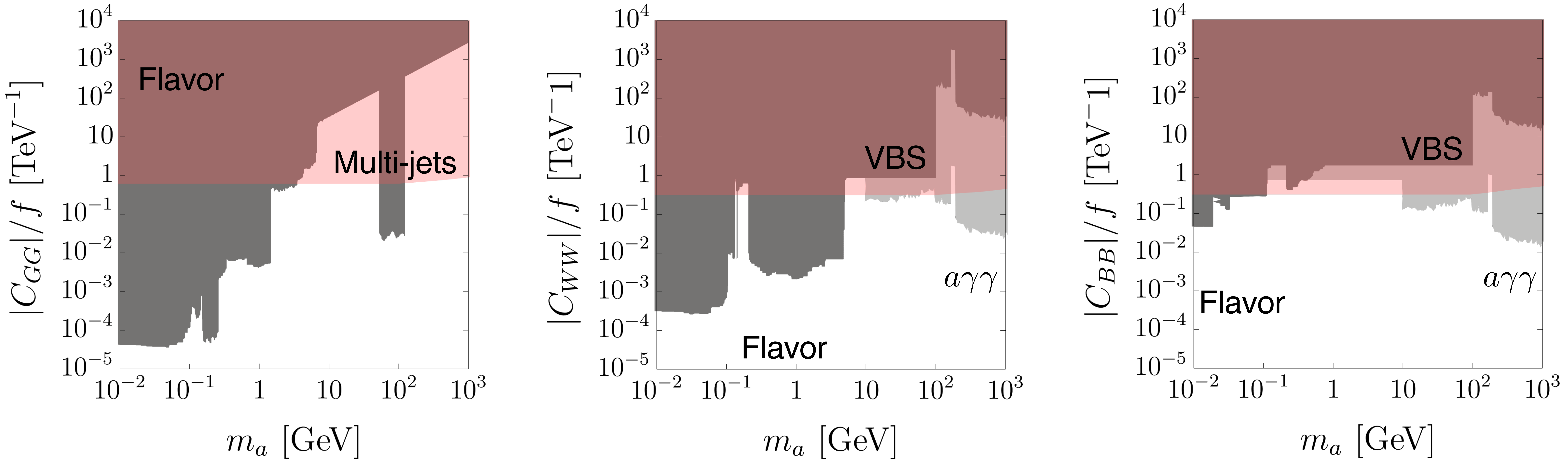

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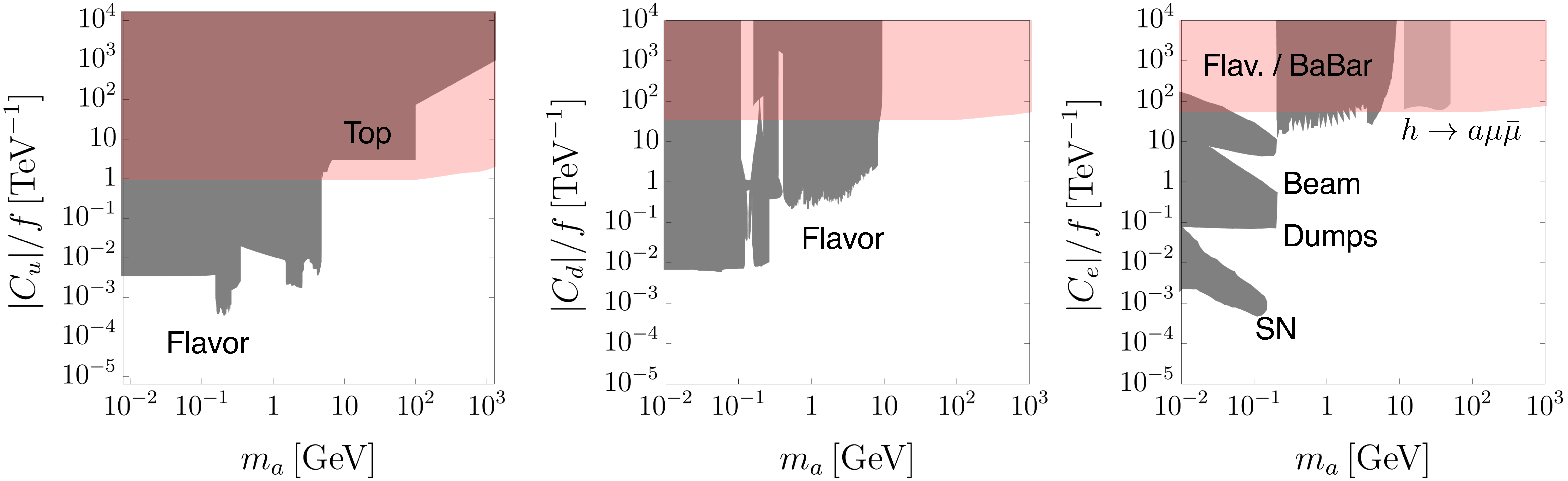
ALP-SMEFT interference tests unconstrained parameter space

Comparison with direct bounds - fermions



[Esser, Madigan, Sanz, Ubiali (2303.17634)]

[Bauer, Neubert, Renner, Schnubel, Thamm (2110.10698)]

[BaBar (1406.2980)]

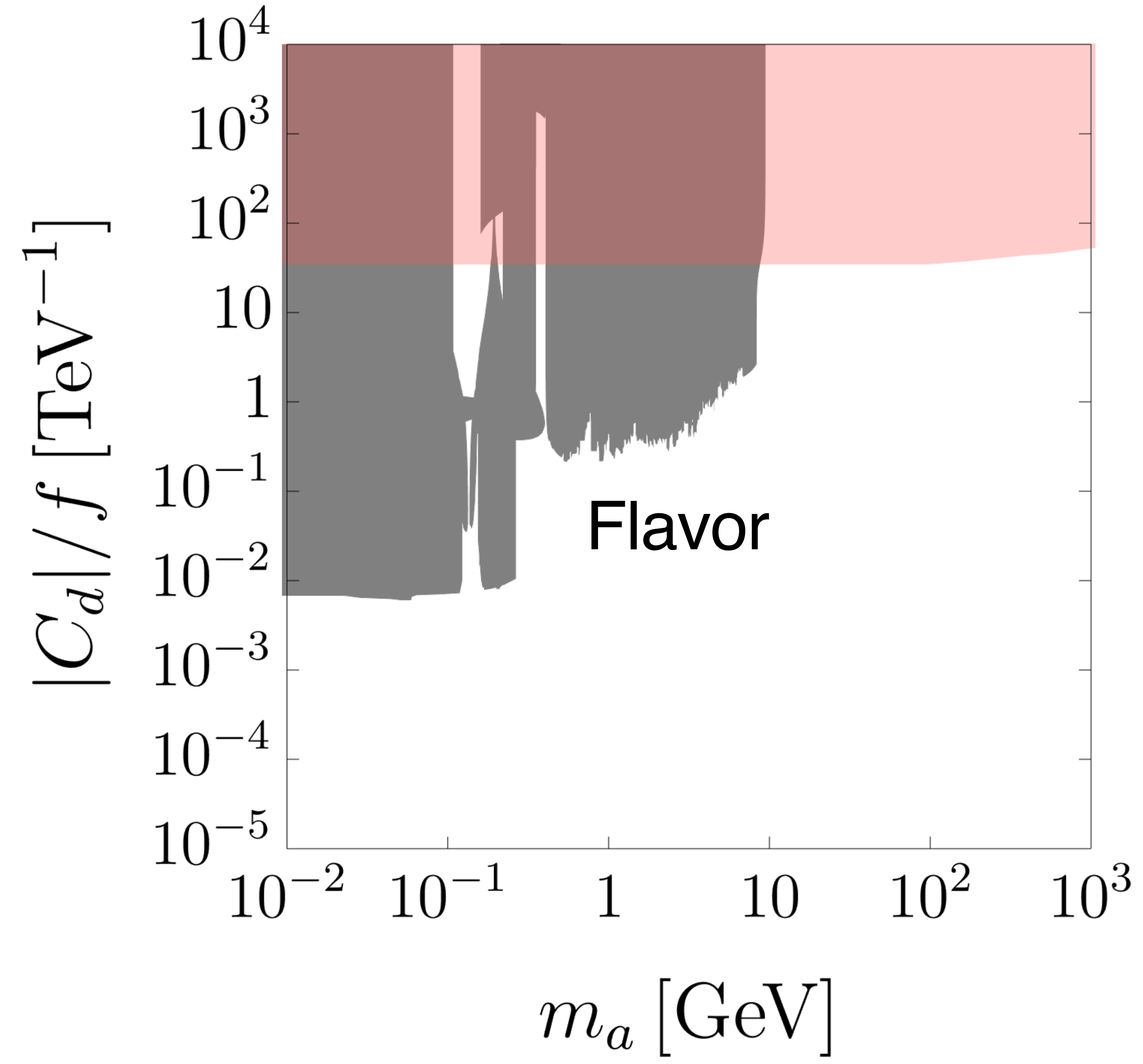
[AB, Chala, Spannowski (2203.14984)]

[Lucente, Carenza (2107.12393)]

[Essig, Harnik, Kaplan, Toro (1008.0636)]

Conclusions

- (Almost) mass-independent bounds on ALP couplings
- Interesting reuse of (Higgs) SMEFT analyses
- Complementary with direct bounds and competitive for high ALP masses
- Backup: interpretation in terms of UV models



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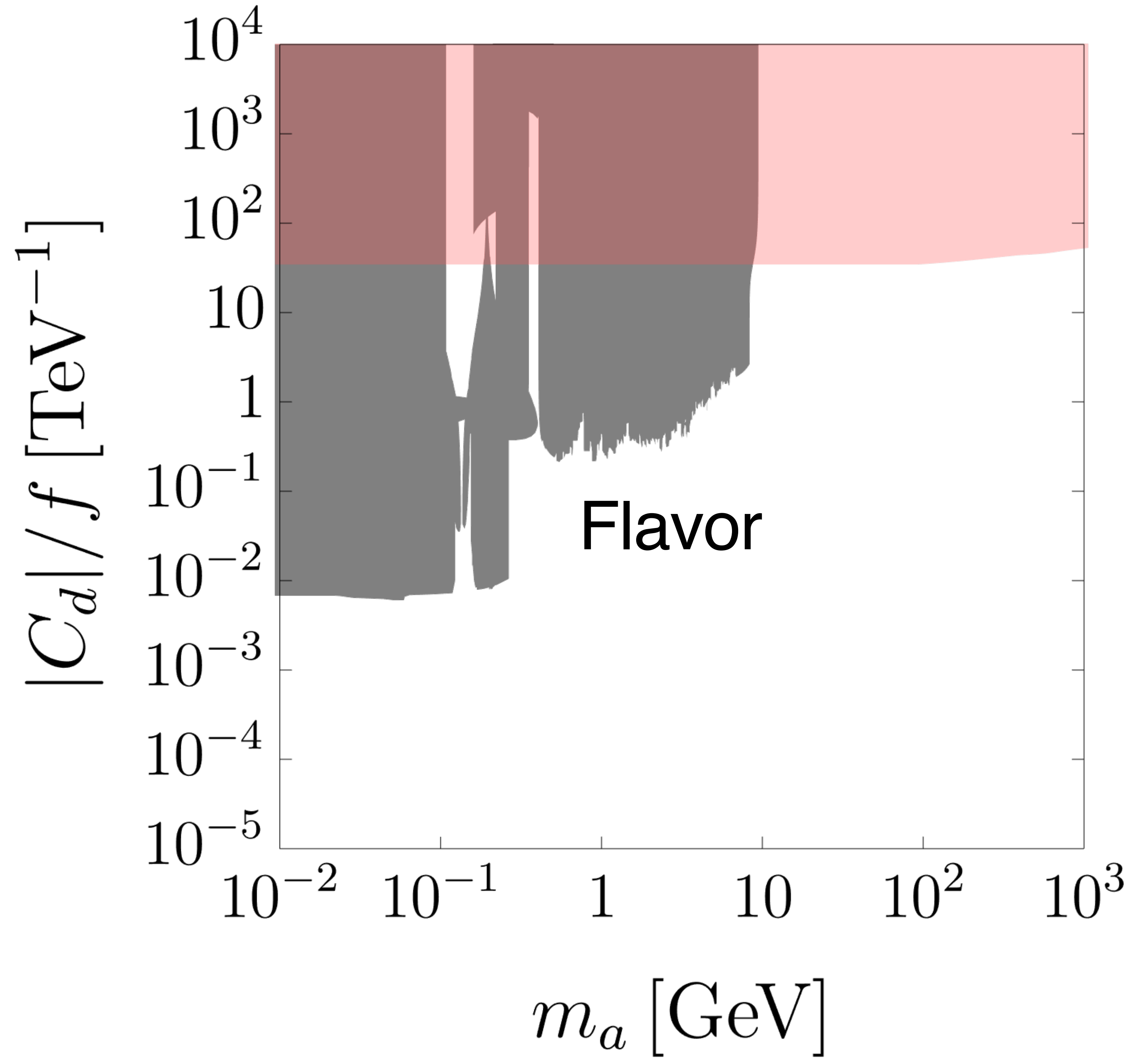
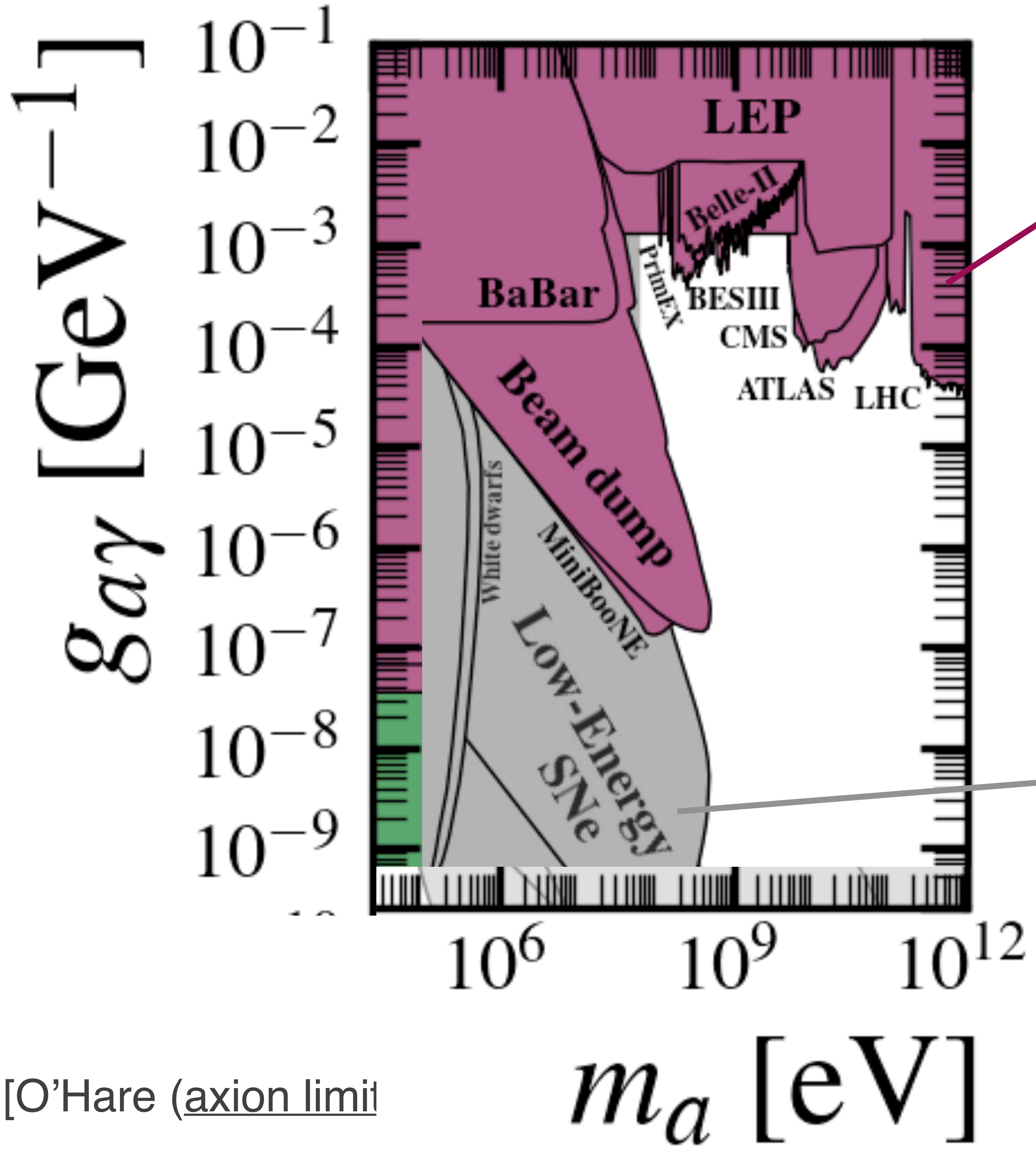


Thank you for your attention!

Backup

2D ALP bounds



[O'Hare (axion limit

LHC limits

$pp \to a \to \gamma\gamma$

Mass-dependent (resonance search)

Assuming $\mathrm{BR}(a \to \gamma\gamma) = 100\,\%$

$\mathrm{BR}(a \to ZZ)$?

$\mathrm{BR}(a \to Z\gamma)$?

Supernova limits

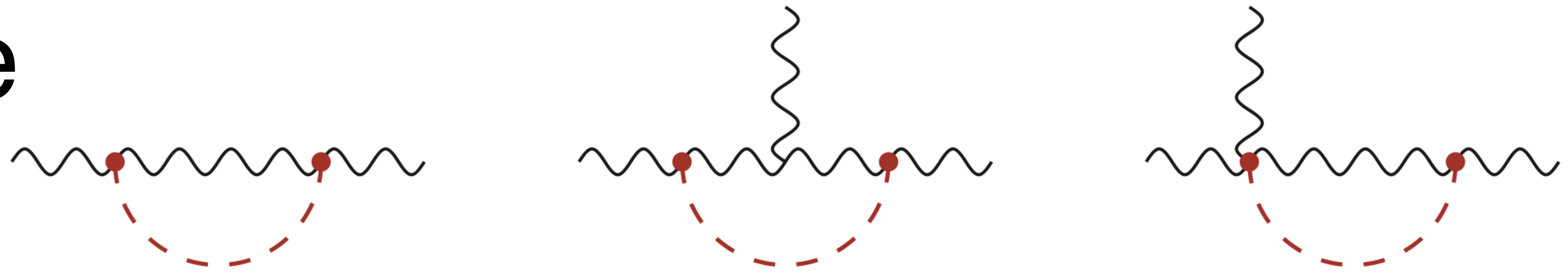
Can be changed (or invalidated) if $a \to e^+e^-$ decay possible

ALP-SMEFT interference

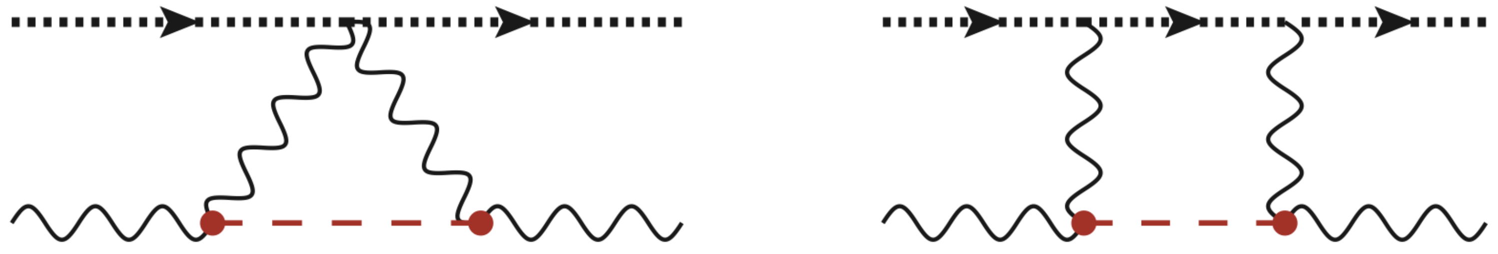
[Galda, Neubert, Renner (2105.01078)]

Virtual ALP exchanges contribute to (almost) all D6 SMEFT operators

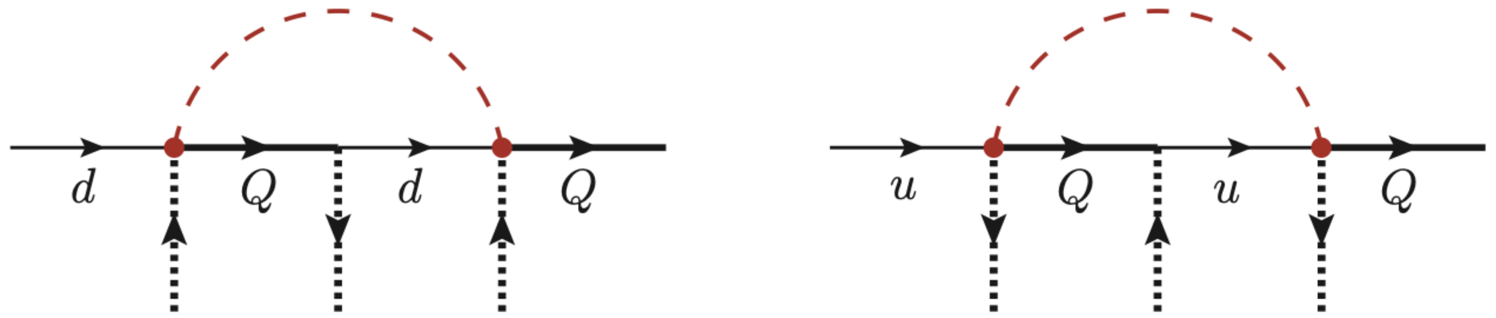
Gauge

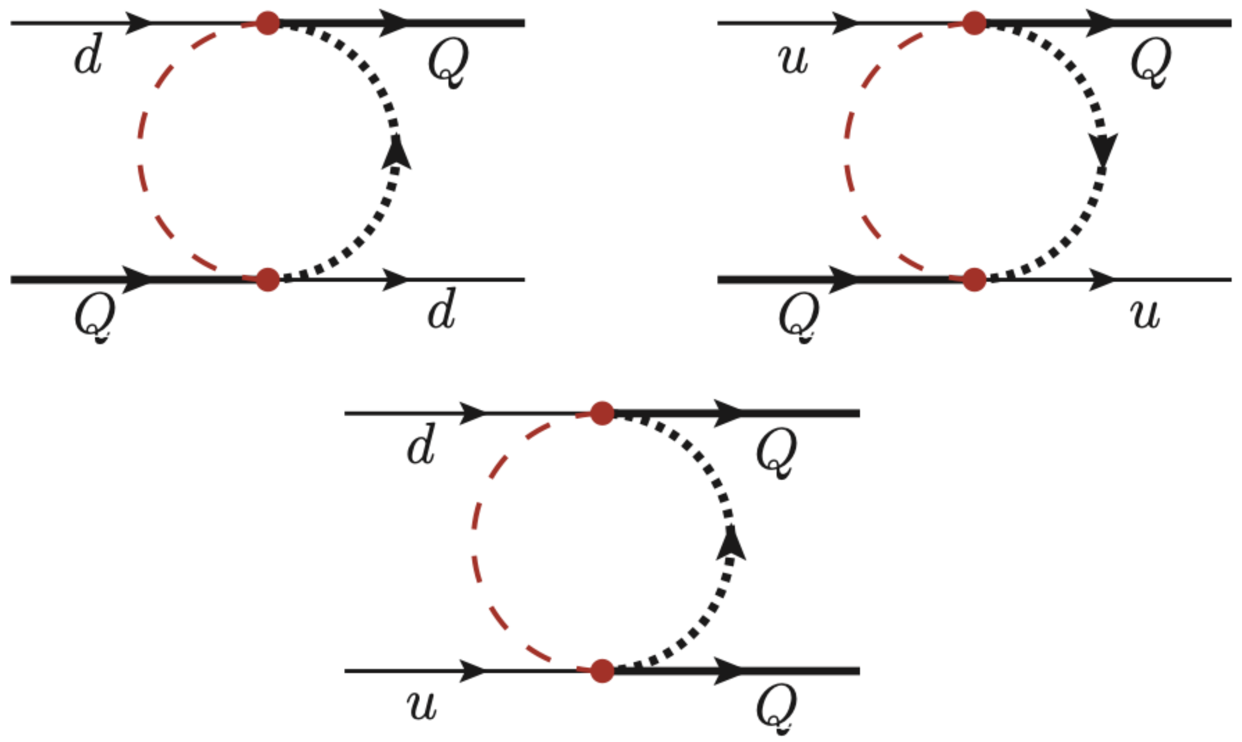


Gauge-Higgs



Fermion-Higgs





Four-fermion

	Operator Q	Source Term D
Q_G	$g_3\, f^{abc}\, G_\mu^{\nu,a} G_\nu^{\rho,b} G_\rho^{\mu,c}$	$8\left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2$
$Q_{\tilde{G}}$	$g_3\, f^{abc}\, \tilde{G}_\mu^{\nu,a} G_\nu^{\rho,b} G_\rho^{\mu,c}$	0
Q_W	$g_2\, \epsilon^{IJK}\, W_\mu^{\nu,I} W_\nu^{\rho,J} W_\rho^{\mu,K}$	$8\left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q_{\tilde{W}}$	$g_2\, \epsilon^{IJK}\, \tilde{W}_\mu^{\nu,I} W_\nu^{\rho,J} W_\rho^{\mu,K}$	0
$Q_{\phi G}$	$g_3^2\, \phi^\dagger \phi\, G^a_{\mu\nu} G^{\mu\nu,a}$	0
$Q_{\phi \tilde{G}}$	$g_3^2\, \phi^\dagger \phi\, \tilde{G}^a_{\mu\nu} G^{\mu\nu,a}$	0
$Q_{\phi W}$	$g_2^2\, \phi^\dagger \phi\, W^I_{\mu\nu} W^{\mu\nu,I}$	$-2\left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q_{\phi \tilde{W}}$	$g_2^2\, \phi^\dagger \phi\, \tilde{W}^I_{\mu\nu} W^{\mu\nu,I}$	0
$Q_{\phi B}$	$g_1^2\, \phi^\dagger \phi\, B_{\mu\nu} B^{\mu\nu}$	$-2\left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\phi \tilde{B}}$	$g_1^2\, \phi^\dagger \phi\, \tilde{B}_{\mu\nu} B^{\mu\nu}$	0
$Q_{\phi WB}$	$g_1 g_2\, \phi^\dagger \sigma^I \phi\, W^I_{\mu\nu} B^{\mu\nu}$	$-4\left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)\left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)$
$Q_{\phi \tilde{W} B}$	$g_1 g_2\, \phi^\dagger \sigma^I \phi\, \tilde{W}^I_{\mu\nu} B^{\mu\nu}$	0
$Q_{\phi \Box}$	$(\phi^\dagger \phi)\Box(\phi^\dagger \phi)$	$g_1^2\, \frac{8}{3}\, \mathcal{Y}_\phi^2 \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2 + 2\, g_2^2 \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q_{\phi D}$	$(\phi^\dagger D_\mu \phi)^*\, (\phi^\dagger D^\mu \phi)$	$g_1^2\, \frac{32}{3}\, \mathcal{Y}_\phi^2 \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$

	Operator Q	Source Term D
$Q_{\underset{ij}{eW}}$	$g_2\, (\bar{L}^i_L\, \sigma^{\mu\nu} e^j_R)\, \tau^I \phi\, W^I_{\mu\nu}$	$-2\, i\, [\hat{\mathbf{Y}}_e]^{ij} \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)$
$Q_{\underset{ij}{eB}}$	$g_1\, (\bar{L}^i_L\, \sigma^{\mu\nu} e^j_R)\, \phi\, B_{\mu\nu}$	$-2\, i\, (\mathcal{Y}_L + \mathcal{Y}_e) [\hat{\mathbf{Y}}_e]^{ij} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)$
$Q_{\underset{ij}{uG}}$	$g_3\, (\bar{Q}^i_L\, \sigma^{\mu\nu}\, t^a u^j_R)\, \tilde{\phi}\, G^a_{\mu\nu}$	$-4\, i\, [\hat{\mathbf{Y}}_u]^{ij} \left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)$
$Q_{\underset{ij}{uW}}$	$g_2\, (\bar{Q}^i_L\, \sigma^{\mu\nu} u^j_R)\, \tau^I \tilde{\phi}\, W^I_{\mu\nu}$	$-2\, i\, [\hat{\mathbf{Y}}_u]^{ij} \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)$
$Q_{\underset{ij}{uB}}$	$g_1\, (\bar{Q}^i_L\, \sigma^{\mu\nu} u^j_R)\, \tilde{\phi}\, B_{\mu\nu}$	$-2\, i\, (\mathcal{Y}_Q + \mathcal{Y}_u)\, [\hat{\mathbf{Y}}_u]^{ij} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)$
$Q_{\underset{ij}{dG}}$	$g_3\, (\bar{Q}^i_L\, \sigma^{\mu\nu}\, t^a d^j_R)\, \phi\, G^a_{\mu\nu}$	$-4\, i\, [\hat{\mathbf{Y}}_d]^{ij} \left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)$
$Q_{\underset{ij}{dW}}$	$g_2\, (\bar{Q}^i_L\, \sigma^{\mu\nu} d^j_R)\, \tau^I \phi\, W^I_{\mu\nu}$	$-2\, i\, [\hat{\mathbf{Y}}_d]^{ij} \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)$
$Q_{\underset{ij}{dB}}$	$g_1\, (\bar{Q}^i_L\, \sigma^{\mu\nu} d^j_R)\, \phi\, B_{\mu\nu}$	$-2\, i\, (\mathcal{Y}_Q + \mathcal{Y}_d)\, [\hat{\mathbf{Y}}_d]^{ij} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)$
$Q_{\underset{ij}{e\phi}}$	$(\phi^\dagger \phi)\, (\bar{L}^i_L e^j_R\, \phi)$	$-2\, [\hat{\mathbf{Y}}_e\, \mathbf{Y}_e^\dagger\, \hat{\mathbf{Y}}_e]^{ij} - \frac{1}{2} [\hat{\mathbf{Y}}_e\, \hat{\mathbf{Y}}_e^\dagger\, \mathbf{Y}_e]^{ij} - \frac{1}{2} [\mathbf{Y}_e\, \hat{\mathbf{Y}}_e^\dagger\, \hat{\mathbf{Y}}_e]^{ij} + \frac{4}{3}\, g_2^2 \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2 [\mathbf{Y}_e]^{ij}$
$Q_{\underset{ij}{u\phi}}$	$(\phi^\dagger \phi)\, (\bar{Q}^i_L u^j_R\, \tilde{\phi})$	$-2\, [\hat{\mathbf{Y}}_u\, \mathbf{Y}_u^\dagger\, \hat{\mathbf{Y}}_u]^{ij} - \frac{1}{2} [\hat{\mathbf{Y}}_u\, \hat{\mathbf{Y}}_u^\dagger\, \mathbf{Y}_u]^{ij} - \frac{1}{2} [\mathbf{Y}_u\, \hat{\mathbf{Y}}_u^\dagger\, \hat{\mathbf{Y}}_u]^{ij} + \frac{4}{3}\, g_2^2 \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2 [\mathbf{Y}_u]^{ij}$
$Q_{\underset{ij}{d\phi}}$	$(\phi^\dagger \phi)\, (\bar{Q}^i_L d^j_R\, \phi)$	$-2\, [\hat{\mathbf{Y}}_d\, \mathbf{Y}_d^\dagger\, \hat{\mathbf{Y}}_d]^{ij} - \frac{1}{2} [\hat{\mathbf{Y}}_d\, \hat{\mathbf{Y}}_d^\dagger\, \mathbf{Y}_d]^{ij} - \frac{1}{2} [\mathbf{Y}_d\, \hat{\mathbf{Y}}_d^\dagger\, \hat{\mathbf{Y}}_d]^{ij} + \frac{4}{3}\, g_2^2 \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2 [\mathbf{Y}_d]^{ij}$
$Q^{(1)}_{\underset{ij}{\phi L}}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)\, (\bar{L}^i_L \gamma^\mu L^j_L)$	$\frac{1}{4} [\hat{\mathbf{Y}}_e\, \hat{\mathbf{Y}}_e^\dagger]^{ij} + \frac{16}{3}\, g_1^2\, \mathcal{Y}_\phi\, \mathcal{Y}_L \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2 \delta_{ij}$
$Q^{(3)}_{\underset{ij}{\phi L}}$	$(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)\, (\bar{L}^i_L \sigma^I \gamma^\mu L^j_L)$	$\frac{1}{4} [\hat{\mathbf{Y}}_e\, \hat{\mathbf{Y}}_e^\dagger]^{ij} + \frac{4}{3}\, g_2^2 \left(\frac{\tilde{c}_{WW}}{4\pi}\right)^2 \delta_{ij}$
$Q_{\underset{ij}{\phi e}}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)\, (\bar{e}^i_R \gamma^\mu e^j_R)$	$-\frac{1}{2} [\hat{\mathbf{Y}}_e^\dagger\, \hat{\mathbf{Y}}_e]^{ij} + \frac{16}{3}\, g_1^2\, \mathcal{Y}_e\, \mathcal{Y}_\phi \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2 \delta_{ij}$
$Q^{(1)}_{\underset{ij}{\phi Q}}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)\, (\bar{Q}^i_L \gamma^\mu Q^j_L)$	$\frac{1}{4} [\hat{\mathbf{Y}}_d\, \hat{\mathbf{Y}}_d^\dagger]^{ij} - \frac{1}{4} [\hat{\mathbf{Y}}_u\, \hat{\mathbf{Y}}_u^\dagger]^{ij} + \frac{16}{3}\, \mathcal{Y}_\phi\, \mathcal{Y}_Q\, g_1^2\, \delta_{ij} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q^{(3)}_{\underset{ij}{\phi Q}}$	$(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)\, (\bar{Q}^i_L \sigma^I \gamma^\mu Q^j_L)$	$\frac{1}{4} [\hat{\mathbf{Y}}_d\, \hat{\mathbf{Y}}_d^\dagger]^{ij} + \frac{1}{4} [\hat{\mathbf{Y}}_u\, \hat{\mathbf{Y}}_u^\dagger]^{ij} + \frac{4}{3}\, g_2^2\, \delta_{ij} \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q_{\underset{ij}{\phi u}}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)\, (\bar{u}^i_R \gamma^\mu u^j_R)$	$\frac{1}{2} [\hat{\mathbf{Y}}_u^\dagger\, \hat{\mathbf{Y}}_u]^{ij} + \frac{16}{3}\, g_1^2\, \mathcal{Y}_\phi\, \mathcal{Y}_u\, \delta_{ij} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\underset{ij}{\phi d}}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)\, (\bar{d}^i_R \gamma^\mu d^j_R)$	$-\frac{1}{2} [\hat{\mathbf{Y}}_d^\dagger\, \hat{\mathbf{Y}}_d]^{ij} + \frac{16}{3}\, g_1^2\, \mathcal{Y}_\phi\, \mathcal{Y}_u\, \delta_{ij} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\underset{ij}{\phi u}} + \text{h.c.}$	$i\, (\tilde{\phi}^\dagger D_\mu \phi)\, (\bar{u}^i_R \gamma^\mu d^j_R)$	$-[\hat{\mathbf{Y}}_u^\dagger\, \hat{\mathbf{Y}}_d]^{ij}$

	Operator Q	Source Term D
$Q_{\underset{ijkl}{LL}}$	$(\bar{L}^i_L\, \gamma_\mu L^j_L)\, (\bar{L}^k_L \gamma^\mu L^l_L)$	$\frac{8}{3}\, g_1^2\, \mathcal{Y}_L^2 \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2 \delta_{ij}\delta_{kl} + \frac{2}{3}\, g_2^2 \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2 (2\, \delta_{il}\delta_{jk} - \delta_{ij}\delta_{kl})$
$Q^{(1)}_{\underset{ijkl}{QQ}}$	$(\bar{Q}^i_L\, \gamma_\mu Q^j_L)\, (\bar{Q}^k_L \gamma^\mu Q^l_L)$	$\frac{8}{3}\, g_1^2\, \mathcal{Y}_Q^2 \left(\frac{\tilde{c}_{BB}}{4\pi}\right)^2 \delta_{ij}\delta_{kl} + \frac{2}{3}\, g_3^2 \left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2 \left(\delta_{il}\delta_{jk} - \frac{2}{N_c}\delta_{ij}\delta_{kl}\right)$
$Q^{(3)}_{\underset{ijkl}{QQ}}$	$(\bar{Q}^i_L\, \gamma_\mu\, \sigma^I\, Q^j_L)\, (\bar{Q}^k_L \gamma^\mu\, \sigma^I\, Q^l_L)$	$\frac{2}{3}\, g_3^2 \left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2 \delta_{il}\delta_{jk} + \frac{2}{3}\, g_2^2\, \delta_{ij}\delta_{kl} \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q^{(1)}_{\underset{ijkl}{LQ}}$	$(\bar{L}^i_L\, \gamma_\mu L^j_L)\, (\bar{Q}^k_L \gamma^\mu Q^l_L)$	$\frac{16}{3}\, g_1^2\, \mathcal{Y}_Q\, \mathcal{Y}_L \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q^{(3)}_{\underset{ijkl}{LQ}}$	$(\bar{L}^i_L\, \gamma_\mu\, \sigma^I\, L^j_L)\, (\bar{Q}^k_L \gamma^\mu\, \sigma^I\, Q^l_L)$	$\frac{4}{3}\, g_2^2\, \delta_{ij}\delta_{kl} \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q_{\underset{ijkl}{ee}}$	$(\bar{e}^i_R\, \gamma_\mu e^j_R)\, (\bar{e}^k_R \gamma^\mu e^l_R)$	$\frac{8}{3}\, g_1^2\, \mathcal{Y}_e^2\, \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\underset{ijkl}{uu}}$	$(\bar{u}^i_R\, \gamma_\mu u^j_R)\, (\bar{u}^k_R \gamma^\mu u^l_R)$	$\frac{8}{3}\, g_1^2\, \mathcal{Y}_u^2\, \delta_{ij}\delta_{kl} \left(\frac{\tilde{c}_{BB}}{4\pi}\right)^2 + \frac{4}{3}\, g_3^2 \left(\delta_{il}\delta_{jk} - \frac{1}{N_c}\, \delta_{ij}\delta_{kl}\right) \left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2$
$Q_{\underset{ijkl}{dd}}$	$(\bar{d}^i_R\, \gamma_\mu d^j_R)\, (\bar{d}^k_R \gamma^\mu d^l_R)$	$\frac{8}{3}\, g_1^2\, \mathcal{Y}_d^2\, \delta_{ij}\delta_{kl} \left(\frac{\tilde{c}_{BB}}{4\pi}\right)^2 + \frac{4}{3}\, g_3^2 \left(\delta_{il}\delta_{jk} - \frac{1}{N_c}\, \delta_{ij}\delta_{kl}\right) \left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2$
$Q_{\underset{ijkl}{eu}}$	$(\bar{e}^i_R\, \gamma_\mu e^j_R)\, (\bar{u}^k_R \gamma^\mu u^l_R)$	$\frac{16}{3}\, g_1^2\, \mathcal{Y}_e\, \mathcal{Y}_u\, \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\underset{ijkl}{ed}}$	$(\bar{e}^i_R\, \gamma_\mu e^j_R)\, (\bar{d}^k_R \gamma^\mu d^l_R)$	$\frac{16}{3}\, g_1^2\, \mathcal{Y}_e\, \mathcal{Y}_d\, \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q^{(1)}_{\underset{ijkl}{ud}}$	$(\bar{u}^i_R\, \gamma_\mu u^j_R)\, (\bar{d}^k_R \gamma^\mu d^l_R)$	$\frac{16}{3}\, g_1^2\, \mathcal{Y}_u\, \mathcal{Y}_d\, \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q^{(8)}_{\underset{ijkl}{ud}}$	$(\bar{u}^i_R\, \gamma_\mu\, t^a u^j_R)\, (\bar{d}^k_R \gamma^\mu\, t^a\, d^l_R)$	$\frac{16}{3}\, g_3^2\, \delta_{ij}\delta_{kl} \left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2$
$Q_{\underset{ijkl}{Le}}$	$(\bar{L}^i_L\, \gamma_\mu L^j_L)\, (\bar{e}^k_R \gamma^\mu e^l_R)$	$[\hat{\mathbf{Y}}_e]^{il}\, [\hat{\mathbf{Y}}_e^\dagger]^{kj} + \frac{16}{3}\, g_1^2\, \mathcal{Y}_L\, \mathcal{Y}_e\, \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\underset{ijkl}{Lu}}$	$(\bar{L}^i_L\, \gamma_\mu L^j_L)\, (\bar{u}^k_R \gamma^\mu u^l_R)$	$\frac{16}{3}\, g_1^2\, \mathcal{Y}_L\, \mathcal{Y}_u\, \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\underset{ijkl}{Ld}}$	$(\bar{L}^i_L\, \gamma_\mu L^j_L)\, (\bar{d}^k_R \gamma^\mu d^l_R)$	$\frac{16}{3}\, g_1^2\, \mathcal{Y}_L\, \mathcal{Y}_d\, \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\underset{ijkl}{Qe}}$	$(\bar{Q}^i_L\, \gamma_\mu Q^j_L)\, (\bar{e}^k_R \gamma^\mu e^l_R)$	$\frac{16}{3}\, g_1^2\, \mathcal{Y}_Q\, \mathcal{Y}_e\, \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q^{(1)}_{\underset{ijkl}{Qu}}$	$(\bar{Q}^i_L\, \gamma_\mu Q^j_L)\, (\bar{u}^k_R \gamma^\mu u^l_R)$	$\frac{1}{N_c}\, [\hat{\mathbf{Y}}_u]^{il}\, [\hat{\mathbf{Y}}_u^\dagger]^{kj} + \frac{16}{3}\, g_1^2\, \mathcal{Y}_u\, \mathcal{Y}_Q\, \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q^{(8)}_{\underset{ijkl}{Qu}}$	$(\bar{Q}^i_L\, \gamma_\mu\, t^a\, Q^j_L)\, (\bar{u}^k_R \gamma^\mu\, t^a\, u^l_R)$	$2\, [\hat{\mathbf{Y}}_u]^{il}\, [\hat{\mathbf{Y}}_u^\dagger]^{kj} + \frac{16}{3}\, g_3^2\, \delta_{ij}\delta_{kl} \left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2$
$Q^{(1)}_{\underset{ijkl}{Qd}}$	$(\bar{Q}^i_L\, \gamma_\mu Q^j_L)\, (\bar{d}^k_R \gamma^\mu d^l_R)$	$\frac{1}{N_c}\, [$
$Q^{(8)}_{\underset{ijkl}{Qu}}$	$(\bar{Q}^i_L\, \gamma_\mu\, t^a\, Q^j_L)\, (\bar{d}^k_R \gamma^\mu\, t^a\, d^l_R)$	

	Operator Q	Source Te
$Q_{\underset{ijkl}{LedQ}}$	$(\bar{L}^i_L\, e^j_R)\, (\bar{d}^k_R\, Q^l_L)$	$-2\, [\hat{\mathbf{Y}}_e]^{ij}\, [$
$Q^{(1)}_{\underset{ijkl}{QuQd}}$	$(\bar{Q}^{i,m}_L\, u^j_R)\, \epsilon_{mn} (\bar{Q}^{k,n}_L\, d^l_R)$	$-2\, [\hat{\mathbf{Y}}_u]^{ij}\, [$
$Q^{(8)}_{\underset{ijkl}{QuQd}}$	$(\bar{Q}^{i,m}_L\, t^a\, u^j_R)\, \epsilon_{mn}\, (\bar{Q}^{k,n}_L\, t^a\, d^l_R)$	0
$Q^{(1)}_{\underset{ijkl}{LeQu}}$	$(\bar{L}^{i,m}_L\, e^j_R)\, \epsilon_{mn}\, (\bar{Q}^{k,n}_L\, u^l_R)$	$2\, [\hat{\mathbf{Y}}_e]^{ij}\, [\hat{\mathbf{Y}}$
$Q^{(3)}_{\underset{ijkl}{LeQu}}$	$(\bar{L}^{i,m}_L \sigma_{\mu\nu}\, e^j_R)\, \epsilon_{mn}\, (\bar{Q}^{k,n}_L \sigma^{\mu\nu}\, u^l_R)$	0

Nearly the whole Warsaw basis is sourced by the ALP at one-loop order!

	Operator Q	Source Term D
Q_G	$g_3 f^{abc} G_\mu^{\nu,a} G_\nu^{\rho,b} G_\rho^{\mu,c}$	$8\left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2$
$Q_{\tilde{G}}$	$g_3 f^{abc} \tilde{G}_\mu^{\nu,a} G_\nu^{\rho,b} G_\rho^{\mu,c}$	0
Q_W	$g_2 \epsilon^{IJK} W_\mu^{\nu,I} W_\nu^{\rho,J} W_\rho^{\mu,K}$	$8\left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q_{\tilde{W}}$	$g_2 \epsilon^{IJK} \tilde{W}_\mu^{\nu,I} W_\nu^{\rho,J} W_\rho^{\mu,K}$	0
$Q_{\phi G}$	$g_3^2 \phi^\dagger\phi\, G^a_{\mu\nu} G^{\mu\nu,a}$	0
$Q_{\phi\tilde{G}}$	$g_3^2 \phi^\dagger\phi\, \tilde{G}^a_{\mu\nu} G^{\mu\nu,a}$	0
$Q_{\phi W}$	$g_2^2 \phi^\dagger\phi\, W^I_{\mu\nu} W^{\mu\nu,I}$	$-2\left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q_{\phi\tilde{W}}$	$g_2^2 \phi^\dagger\phi\, \tilde{W}^I_{\mu\nu} W^{\mu\nu,I}$	0
$Q_{\phi B}$	$g_1^2 \phi^\dagger\phi\, B_{\mu\nu} B^{\mu\nu}$	$-2\left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\phi\tilde{B}}$	$g_1^2 \phi^\dagger\phi\, \tilde{B}_{\mu\nu} B^{\mu\nu}$	0
$Q_{\phi WB}$	$g_1 g_2\, \phi^\dagger\sigma^I\phi\, W^I_{\mu\nu} B^{\mu\nu}$	$-4\left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)\left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)$
$Q_{\phi\tilde{W}B}$	$g_1 g_2\, \phi^\dagger\sigma^I\phi\, \tilde{W}^I_{\mu\nu} B^{\mu\nu}$	0
$Q_{\phi\Box}$	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$g_1^2 \frac{8}{3} \mathcal{Y}^2 \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2 + 2 g_2^2 \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q_{\phi D}$	$(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi)$	

	Operator Q	Source Term D
$Q_{\substack{LL\\ijkl}}$	$(\bar{L}^i_L \gamma_\mu L^j_L)(\bar{L}^k_L \gamma^\mu L^l_L)$	$\frac{8}{3} g_1^2 \mathcal{Y}_L^2 \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2 \delta_{ij}\delta_{kl} + \frac{2}{3} g_2^2 \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2 (2\,\delta_{il}\delta_{jk} - \delta_{ij}\delta_{kl})$
$Q^{(1)}_{\substack{QQ\\ijkl}}$	$(\bar{Q}^i_L \gamma_\mu Q^j_L)(\bar{Q}^k_L \gamma^\mu Q^l_L)$	$\frac{8}{3} g_1^2 \mathcal{Y}_Q^2 \left(\frac{\tilde{c}_{BB}}{4\pi}\right)^2 \delta_{ij}\delta_{kl} + \frac{2}{3} g_3^2 \left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2 \left(\delta_{il}\delta_{jk} - \frac{2}{N_c}\delta_{ij}\delta_{kl}\right)$
$Q^{(3)}_{\substack{QQ\\ijkl}}$	$(\bar{Q}^i_L \gamma_\mu \sigma^I Q^j_L)(\bar{Q}^k_L \gamma^\mu \sigma^I Q^l_L)$	$\frac{2}{3} g_3^2 \left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2 \delta_{il}\delta_{jk} + \frac{2}{3} g_2^2 \delta_{ij}\delta_{kl} \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q^{(1)}_{\substack{LQ\\ijkl}}$	$(\bar{L}^i_L \gamma_\mu L^j_L)(\bar{Q}^k_L \gamma^\mu Q^l_L)$	$\frac{16}{3} g_1^2 \mathcal{Y}_Q \mathcal{Y}_L \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q^{(3)}_{\substack{LQ\\ijkl}}$	$(\bar{L}^i_L \gamma_\mu \sigma^I L^j_L)(\bar{Q}^k_L \gamma^\mu \sigma^I Q^l_L)$	$\frac{4}{3} g_2^2 \delta_{ij}\delta_{kl} \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q_{\substack{ee\\ijkl}}$	$(\bar{e}^i_R \gamma_\mu e^j_R)(\bar{e}^k_R \gamma^\mu e^l_R)$	$\frac{8}{3} g_1^2 \mathcal{Y}_e^2 \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\substack{uu\\ijkl}}$	$(\bar{u}^i_R \gamma_\mu u^j_R)(\bar{u}^k_R \gamma^\mu u^l_R)$	$\frac{8}{3} g_1^2 \mathcal{Y}_u^2 \delta_{ij}\delta_{kl} \left(\frac{\tilde{c}_{BB}}{4\pi}\right)^2 + \frac{4}{3} g_3^2 \left(\delta_{il}\delta_{jk} - \frac{1}{N_c}\delta_{ij}\delta_{kl}\right)\left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2$
$Q_{\substack{dd\\ijkl}}$	$(\bar{d}^i_R \gamma_\mu d^j_R)(\bar{d}^k_R \gamma^\mu d^l_R)$	$\frac{8}{3} g_1^2 \mathcal{Y}_d^2 \delta_{ij}\delta_{kl} \left(\frac{\tilde{c}_{BB}}{4\pi}\right)^2 + \frac{4}{3} g_3^2 \left(\delta_{il}\delta_{jk} - \frac{1}{N_c}\delta_{ij}\delta_{kl}\right)\left(\alpha_s \frac{\tilde{c}_{GG}}{4\pi}\right)^2$
$Q_{\substack{eu\\ijkl}}$	$(\bar{e}^i_R \gamma_\mu e^j_R)(\bar{u}^k_R \gamma^\mu u^l_R)$	$\frac{16}{3} g_1^2 \mathcal{Y}_e \mathcal{Y}_u \delta_{ij}\delta_{kl} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q^{(1)}_{\substack{Qd\\ijkl}}$	$(\bar{Q}^i_L \gamma_\mu Q^j_L)(\bar{d}^k_R \gamma^\mu d^l_R)$	$\frac{1}{N_c}$ [
$Q^{(8)}_{\substack{Qu\\ijkl}}$	$(\bar{Q}^i_L \gamma_\mu t^a Q^j_L)(\bar{d}^k_R \gamma^\mu t^a d^l_R)$	

	Operator Q	Source Term D
$Q_{\substack{eW\\ij}}$	$g_2 (\bar{L}^i_L \sigma^{\mu\nu} e^j_R)\, \tau^I \phi\, W^I_{\mu\nu}$	
$Q_{\substack{eB\\ij}}$	$g_1 (\bar{L}^i_L \sigma^{\mu\nu} e^j_R)\, \phi\, B_{\mu\nu}$	
$Q_{\substack{uG\\ij}}$	$g_3 (\bar{Q}^i_L \sigma^{\mu\nu} t^a u^j_R)\, \tilde{\phi}\, G^a_{\mu\nu}$	
$Q_{\substack{uW\\ij}}$	$g_2 (\bar{Q}^i_L \sigma^{\mu\nu} u^j_R)\, \tau^I \tilde{\phi}\, W^I_{\mu\nu}$	
$Q_{\substack{uB\\ij}}$	$g_1 (\bar{Q}^i_L \sigma^{\mu\nu} u^j_R)\, \tilde{\phi}\, B_{\mu\nu}$	
$Q_{\substack{dG\\ij}}$	$g_3 (\bar{Q}^i_L \sigma^{\mu\nu} t^a d^j_R)\, \phi\, G^a_{\mu\nu}$	
$Q_{\substack{dW\\ij}}$	$g_2 (\bar{Q}^i_L \sigma^{\mu\nu} d^j_R)\, \tau^I \phi\, W^I_{\mu\nu}$	
$Q_{\substack{dB\\ij}}$	$g_1 (\bar{Q}^i_L \sigma^{\mu\nu} d^j_R)\, \phi\, B_{\mu\nu}$	
$Q_{\substack{e\phi\\ij}}$	$(\phi^\dagger\phi)(\bar{L}^i_L e^j_R \phi)$	$-2[\hat{\mathbf{Y}}_e \mathbf{Y}_e^\dagger \hat{\mathbf{Y}}_e]^{ij} - \frac{1}{2}[\hat{\mathbf{Y}}_e \hat{\mathbf{Y}}_e^\dagger \mathbf{Y}_e]^{ij} - \frac{1}{2}[\mathbf{Y}_e \hat{\mathbf{Y}}_e^\dagger \hat{\mathbf{Y}}_e]^{ij} + \frac{4}{3} g_2^2 \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2 [\mathbf{Y}_e]^{ij}$
$Q_{\substack{u\phi\\ij}}$	$(\phi^\dagger\phi)(\bar{Q}^i_L u^j_R \tilde{\phi})$	$-2[\hat{\mathbf{Y}}_u \mathbf{Y}_u^\dagger \hat{\mathbf{Y}}_u]^{ij} - \frac{1}{2}[\hat{\mathbf{Y}}_u \hat{\mathbf{Y}}_u^\dagger \mathbf{Y}_u]^{ij} - \frac{1}{2}[\mathbf{Y}_u \hat{\mathbf{Y}}_u^\dagger \hat{\mathbf{Y}}_u]^{ij} + \frac{4}{3} g_2^2 \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2 [\mathbf{Y}_u]^{ij}$
$Q_{\substack{d\phi\\ij}}$	$(\phi^\dagger\phi)(\bar{Q}^i_L d^j_R \phi)$	$-2[\hat{\mathbf{Y}}_d \mathbf{Y}_d^\dagger \hat{\mathbf{Y}}_d]^{ij} - \frac{1}{2}[\hat{\mathbf{Y}}_d \hat{\mathbf{Y}}_d^\dagger \mathbf{Y}_d]^{ij} - \frac{1}{2}[\mathbf{Y}_d \hat{\mathbf{Y}}_d^\dagger \hat{\mathbf{Y}}_d]^{ij} + \frac{4}{3} g_2^2 \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2 [\mathbf{Y}_d]^{ij}$
$Q^{(1)}_{\substack{\phi L\\ij}}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{L}^i_L \gamma^\mu L^j_L)$	$\frac{1}{4}[\hat{\mathbf{Y}}_e \hat{\mathbf{Y}}_e^\dagger]^{ij} + \frac{16}{3} g_1^2 \mathcal{Y}_\phi \mathcal{Y}_L \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2 \delta_{ij}$
$Q^{(3)}_{\substack{\phi L\\ij}}$	$(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi)(\bar{L}^i_L \sigma^I \gamma^\mu L^j_L)$	$\frac{1}{4}[\hat{\mathbf{Y}}_e \hat{\mathbf{Y}}_e^\dagger]^{ij} + \frac{4}{3} g_2^2 \left(\frac{\tilde{c}_{WW}}{4\pi}\right)^2 \delta_{ij}$
$Q_{\substack{\phi e\\ij}}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}^i_R \gamma^\mu e^j_R)$	$-\frac{1}{2}[\hat{\mathbf{Y}}_e^\dagger \hat{\mathbf{Y}}_e]^{ij} + \frac{16}{3} g_1^2 \mathcal{Y}_e \mathcal{Y}_\phi \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2 \delta_{ij}$
$Q^{(1)}_{\substack{\phi Q\\ij}}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{Q}^i_L \gamma^\mu Q^j_L)$	$\frac{1}{4}[\hat{\mathbf{Y}}_d \hat{\mathbf{Y}}_d^\dagger]^{ij} - \frac{1}{4}[\hat{\mathbf{Y}}_u \hat{\mathbf{Y}}_u^\dagger]^{ij} + \frac{16}{3} \mathcal{Y}_\phi \mathcal{Y}_Q g_1^2 \delta_{ij} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q^{(3)}_{\substack{\phi Q\\ij}}$	$(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi)(\bar{Q}^i_L \sigma^I \gamma^\mu Q^j_L)$	$\frac{1}{4}[\hat{\mathbf{Y}}_d \hat{\mathbf{Y}}_d^\dagger]^{ij} + \frac{1}{4}[\hat{\mathbf{Y}}_u \hat{\mathbf{Y}}_u^\dagger]^{ij} + \frac{4}{3} g_2^2 \delta_{ij} \left(\alpha_2 \frac{\tilde{c}_{WW}}{4\pi}\right)^2$
$Q_{\substack{\phi u\\ij}}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}^i_R \gamma^\mu u^j_R)$	$\frac{1}{2}[\hat{\mathbf{Y}}_u^\dagger \hat{\mathbf{Y}}_u]^{ij} + \frac{16}{3} g_1^2 \mathcal{Y}_\phi \mathcal{Y}_u \delta_{ij} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\substack{\phi d\\ij}}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}^i_R \gamma^\mu d^j_R)$	$-\frac{1}{2}[\hat{\mathbf{Y}}_d^\dagger \hat{\mathbf{Y}}_d]^{ij} + \frac{16}{3} g_1^2 \mathcal{Y}_\phi \mathcal{Y}_u \delta_{ij} \left(\alpha_1 \frac{\tilde{c}_{BB}}{4\pi}\right)^2$
$Q_{\substack{\phi u\\ij}} + \text{h.c.}$	$i(\tilde{\phi}^\dagger D_\mu\phi)(\bar{u}^i_R \gamma^\mu d^j_R)$	$-[\hat{\mathbf{Y}}_u^\dagger \hat{\mathbf{Y}}_d]^{ij}$

	Operator Q	Source Te
$Q_{\substack{LedQ\\ijkl}}$	$(\bar{L}^i_L e^j_R)(\bar{d}^k_R Q^l_L)$	$-2[\hat{\mathbf{Y}}_e]^{ij}$ [
$Q^{(1)}_{\substack{QuQd\\ijkl}}$	$(\bar{Q}^{i,m}_L u^j_R)\,\epsilon_{mn}(\bar{Q}^{k,n}_L d^l_R)$	$-2[\hat{\mathbf{Y}}_u]^{ij}$ [
$Q^{(8)}_{\substack{QuQd\\ijkl}}$	$(\bar{Q}^{i,m}_L t^a u^j_R)\,\epsilon_{mn}(\bar{Q}^{k,n}_L t^a d^l_R)$	0
$Q^{(1)}_{\substack{LeQu\\ijkl}}$	$(\bar{L}^{i,m}_L e^j_R)\,\epsilon_{mn}(\bar{Q}^{k,n}_L u^l_R)$	$2[\hat{\mathbf{Y}}_e]^{ij}$ [
$Q^{(3)}_{\substack{LeQu\\ijkl}}$	$(\bar{L}^{i,m}_L \sigma_{\mu\nu} e^j_R)\,\epsilon_{mn}(\bar{Q}^{k,n}_L \sigma^{\mu\nu} u^l_R)$	0

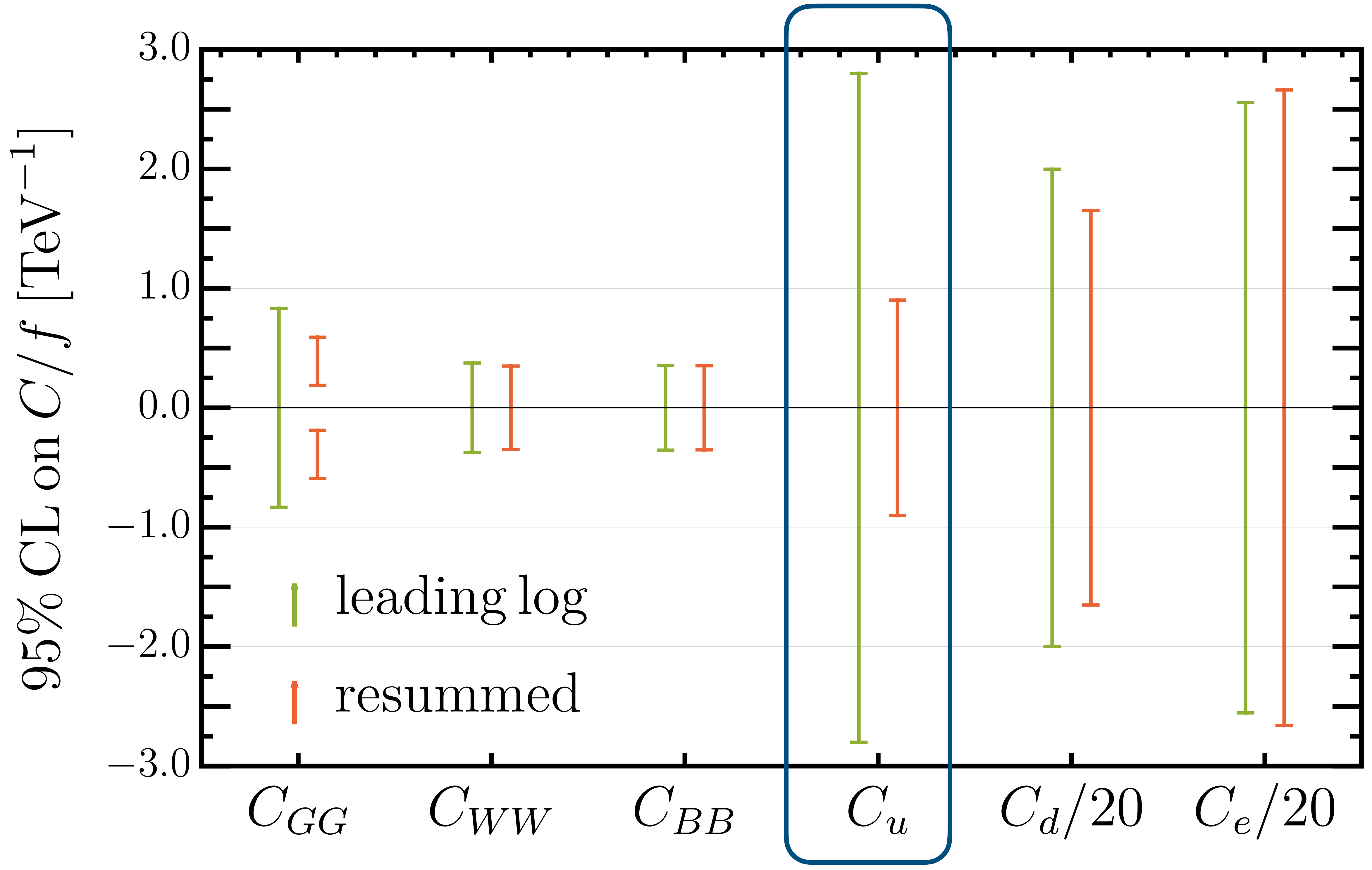
Can we use SMEFT constraints to obtain mass-independent constraints on the ALP Wilson coefficients?

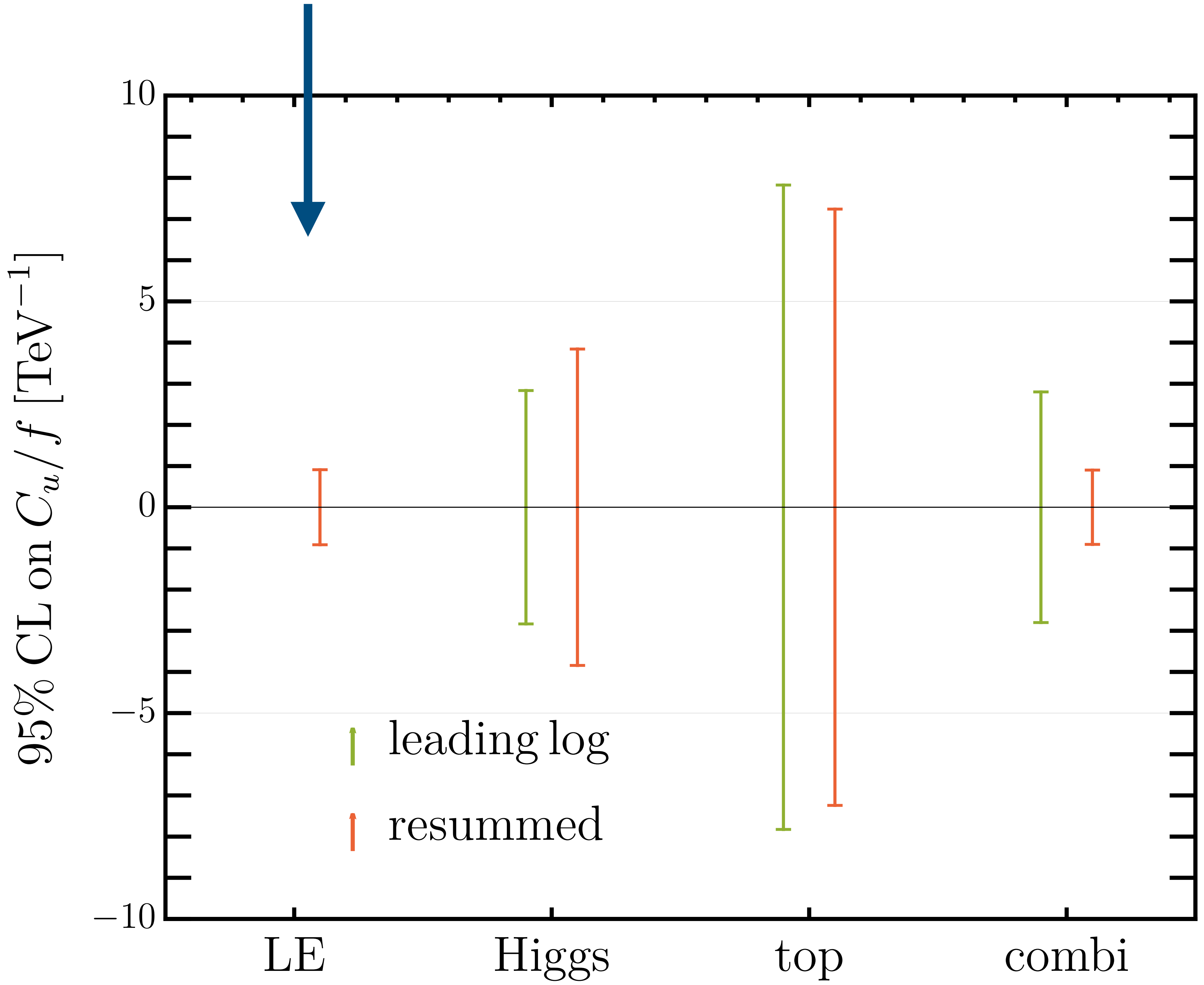
Nearly the whole Warsaw basis is sourced by the ALP at one-loop order!

LL approximation

Strongest bound from low energy

Absent at LL order





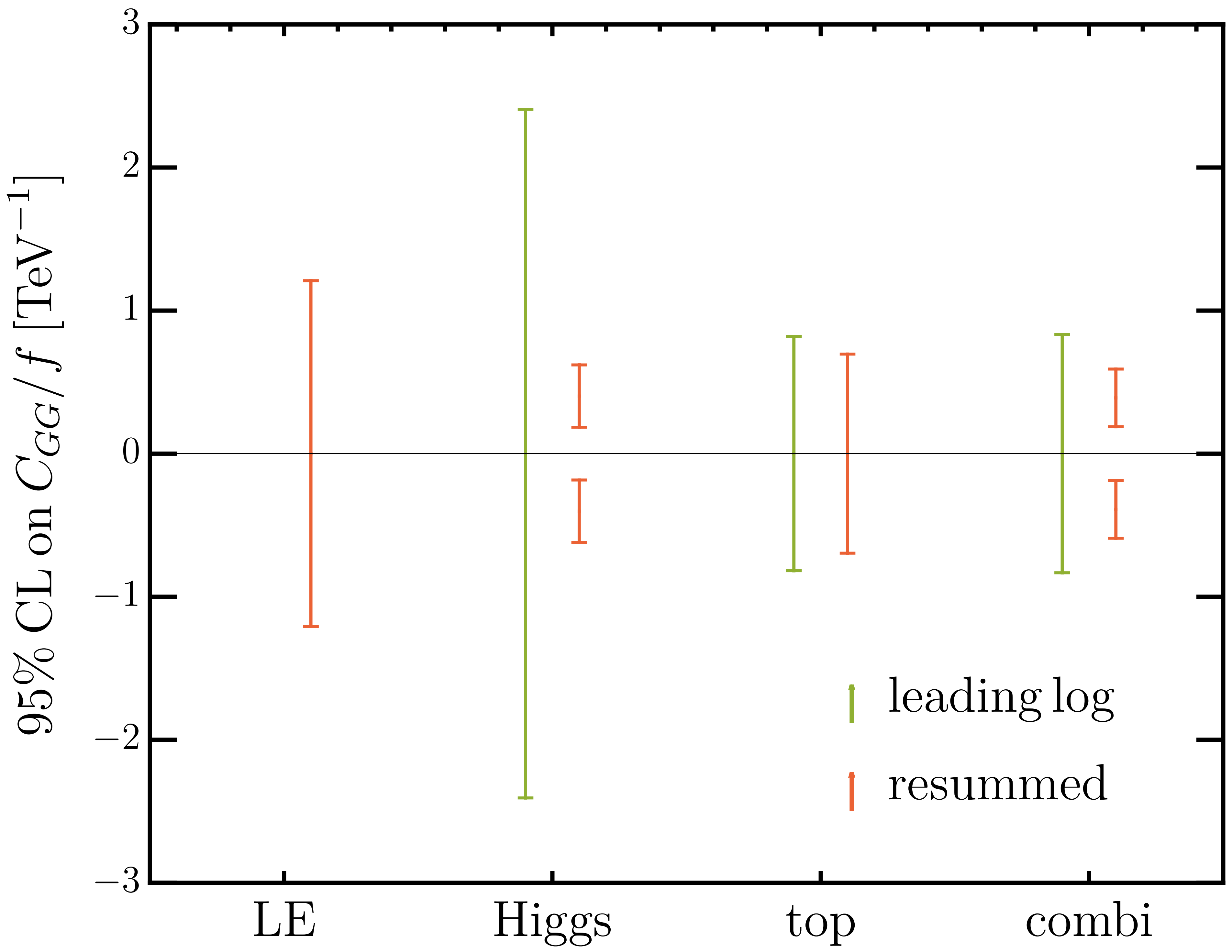
$$C_i^{\text{SMEFT}}(\mu) \approx \frac{S_i}{(4\pi f)^2} \log\left(\frac{\mu}{\Lambda}\right)$$

LL approximation - CGG

(Small) experimental anomaly in CMS Higgs STXS causes deviation at 95% CL

$$[C_{uG}]_{33}(\mu) \supset -\frac{25\, g_s\, y_t\, \alpha_s}{\pi}\, C_{GG}^2\, \ln^2 \frac{\mu}{\Lambda}$$

$$C_{HG}(\mu) \supset \frac{100\, \alpha_s^2\, \alpha_t}{3}\, C_{GG}^2\, \ln^3 \frac{\mu}{\Lambda}$$



CHG (Higgs-gluon coupling) and CuG (top-gluon coupling) strongly constrained through gluon-fusion Higgs production

Can I translate these limits for UV axion models?

Matching a UV model onto an EFT would lead to additional SMEFT operators. What is the influence of those?

[Arias-Aragón, Quevillon, Smith (2211.04489)]

KSVZ

[Kim-Shifman-Vainshtein-Zakharov (1979, 1980)]

Vector-like quark + Scalar singlet

Boson-philic

DFSZ

[Dine-Fischler-Srednicki-Zhitnitsky (1980, 1981)]

2HDM + Scalar singlet

Fermion-philic

KSVZ model

[Kim-Shifman-Vainshtein-Zakharov (1979, 1980)]

$$\mathcal{L}_{Qq} = -y_q^p \, \bar{q}_L^p H Q_R + \text{h.c.}$$

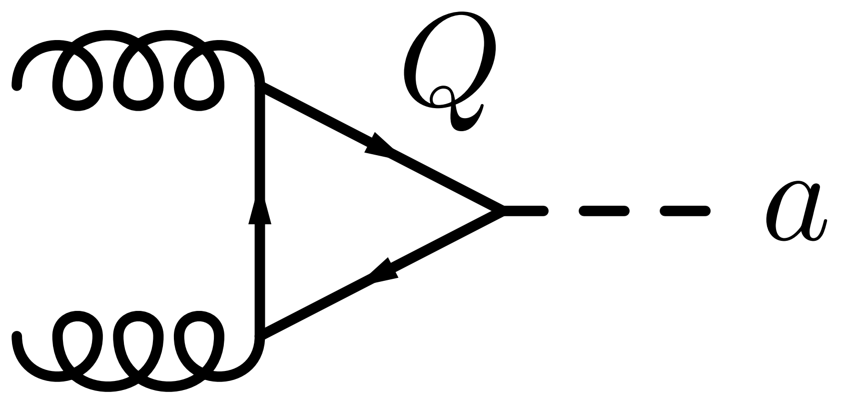
$$Q_{L,R} \sim (\mathbf{3}, \mathbf{1})_{-1/3}$$

$$\mathcal{L}_{\text{KSVZ}} = \mathcal{L}_{\text{SM}} + |\partial_\mu S|^2 + \bar{Q}\, i \not{D}\, Q - y_Q \left(S\, \bar{Q}_L Q_R + \text{h.c.}\right)$$
$$+ \mu_S |S|^2 - \frac{\lambda_S}{2}|S|^2 - \lambda_{SH}|S|^2 (H^\dagger H) + \mathcal{L}_{Qq}$$

VLQ decay

Vector-like quark Q

Singlet scalar S $\quad S(x) = \frac{1}{\sqrt{2}}\left[f + \rho(x)\right] e^{\frac{i a(x)}{f}},$



Heavy particles Q and ρ

$M_Q = y_Q\, f/\sqrt{2},\ M_\rho^2 = \lambda_S f^2$

Integrate out

KSVZ model - EFT

$$\mathcal{L}_{Qq} = -y_q^p \, \bar{q}_L^p H Q_R + \text{h.c.}$$

$$\mathcal{L}_{\text{EFT}} \supset +\frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 \, a^2 - \frac{\alpha_s}{8\pi} \frac{a}{f} \, G_{\mu\nu}^A \widetilde{G}^{\mu\nu \, A} - \frac{1}{3} \frac{\alpha_Y}{4\pi} \frac{a}{f} \, B_{\mu\nu} \widetilde{B}^{\mu\nu}$$
$$- \frac{\lambda_{SH}^2 f^2}{2 M_\rho^4} Q_{H\Box} + \frac{y_q^p y_q^{r\,*}}{2 M_Q^2} \left(\boldsymbol{Y}_d^{rs} \, [Q_{dH}]^{ps} - \frac{1}{2} \, [Q_{Hq}^{(1)}]^{pr} - \frac{1}{2} \, [Q_{Hq}^{(3)}]^{pr} + \text{h.c.} \right)$$

At scale Λ: ALP couplings and SMEFT contributions

→ Limits on f can be obtained for fixed CGG and CBB from one-parameter ALP fit

Additional Limits on scalar parameters and portal

$$\lambda_S^2 \, f / \lambda_{SH} > 2.8 \, \text{TeV}$$
$$|y_q / M_Q| < 0.1 \text{TeV}^{-1}$$

DFSZ model

Two-Higgs doublet model + scalar singlet

$$S(x) = \frac{1}{\sqrt{2}}\left[f + \rho(x)\right] e^{\frac{i a(x)}{f}} \,,$$

Two options for relation to SM Yukawas

$$\begin{aligned}\mathcal{L}_{\text{DFSZ}} \supset\; & |D_\mu H_1|^2 + |D_\mu H_2|^2 + |\partial_\mu S|^2 - (\bar{q}\,\tilde{H}_1\,\mathbf{\Gamma}_u\,u_R + \bar{q}\,H_2\,\mathbf{\Gamma}_d\,d_R + \boxed{\bar{\ell}\,H_i\,\mathbf{\Gamma}_e\,e_R} + \text{h.c.}) \\ & - m_1^2\,|H_1|^2 - m_2^2\,|H_2|^2 - \frac{\lambda_1}{2}\,|H_1|^4 - \frac{\lambda_2}{2}\,|H_2|^4 - \lambda_3\,|H_1|^2|H_2|^2 - \lambda_4\,|H_1^\dagger H_2|^2 \\ & + \mu_S\,|S|^2 - \frac{\lambda_S}{2}\,|S|^4 - \lambda_{SH_1}\,|S|^2|H_1|^2 - \lambda_{SH_2}\,|S|^2|H_2|^2 - \lambda_{SH_{12}}\left[(H_1^\dagger H_2)S^2 + \text{h.c.}\right]\end{aligned}$$

Heavy particles Φ and ρ

DFSZ model - EFT

$|C_u|/f < 1/\text{TeV}$

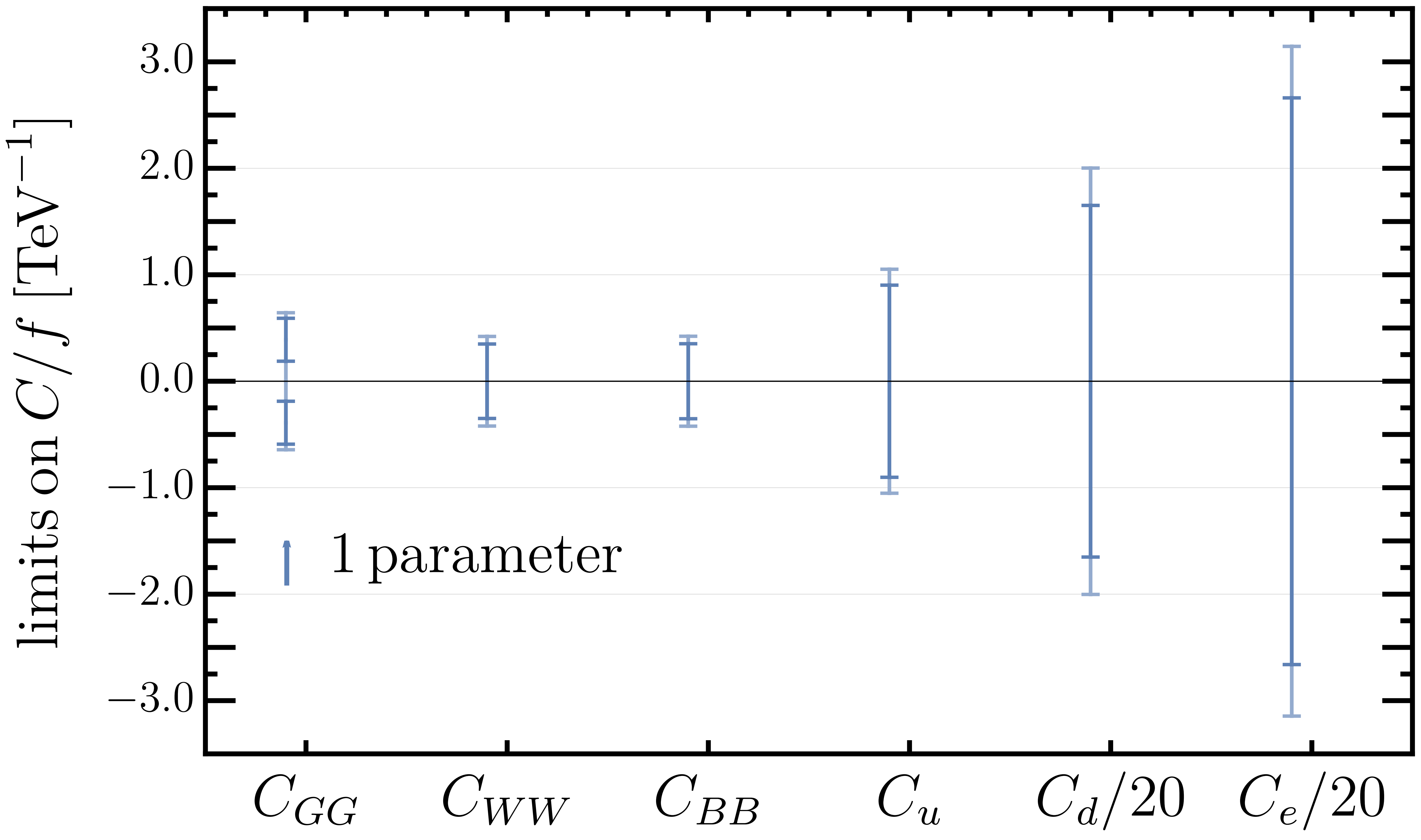
$C_u = -2s_\alpha^2$ $\quad$ $C_d = -2c_\alpha^2$

DFSZ I $\quad C_e = -2s_\alpha^2$

DFSZ II $\quad C_e = -2c_\alpha^2$

Mixing angle α

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ \Phi \end{pmatrix}$$



DFSZ model - EFT

Mixing angle α

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ \Phi \end{pmatrix}$$

$|C_u|/f < 1/\text{TeV}$

$C_u = -2s_\alpha^2$ $\quad C_d = -2c_\alpha^2$

DFSZ I $\quad C_e = -2s_\alpha^2$

DFSZ II $\quad C_e = -2c_\alpha^2$

$$\mathcal{L}_{\text{EFT}} \supset -\frac{C_{\psi H}}{M_\Phi^2}\Big(t_\alpha [\boldsymbol{Y}_u]^{pr} [Q_{uH}]^{pr} - t_\alpha^{-1} [\boldsymbol{Y}_d]^{pr} [Q_{dH}]^{pr} - \eta_\alpha [\boldsymbol{Y}_e]^{pr} [Q_{eH}]^{pr} + \text{h.c.}\Big)$$
$$- \frac{[\boldsymbol{Y}_u^*]^{sr} [\boldsymbol{Y}_u]^{pt}\, t_\alpha^2}{M_\Phi^2}\left(\frac{1}{6}[Q_{qu}^{(1)}]^{prst} + [Q_{qu}^{(8)}]^{prst}\right) - \frac{[\boldsymbol{Y}_d^*]^{sr} [\boldsymbol{Y}_d]^{pt}\, t_\alpha^{-2}}{M_\Phi^2}\left(\frac{1}{6}[Q_{qd}^{(1)}]^{prst} + [Q_{qd}^{(8)}]^{prst}\right)$$
$$- \frac{[\boldsymbol{Y}_e^*]^{sr} [\boldsymbol{Y}_e]^{pt}\, \eta_\alpha^2}{2M_\Phi^2}[Q_{le}]^{prst} - \frac{1}{M_\Phi^2}\Big([\boldsymbol{Y}_u]^{pr} [\boldsymbol{Y}_d]^{st} [Q_{quqd}^{(1)}]^{prst} - [\boldsymbol{Y}_u]^{st} [\boldsymbol{Y}_e]^{pr}\, t_\alpha \eta_\alpha [Q_{lequ}^{(1)}]^{prst}$$
$$- [\boldsymbol{Y}_d^*]^{st} [\boldsymbol{Y}_e]^{pr}\, t_\alpha^{-1}\eta_\alpha [Q_{ledq}]^{prst} + \text{h.c.}\Big) + \frac{C_H}{M_\Phi^2} Q_H - \frac{\lambda_{SH}^2 f^2}{2M_\rho^4} Q_{H\Box}\,,$$

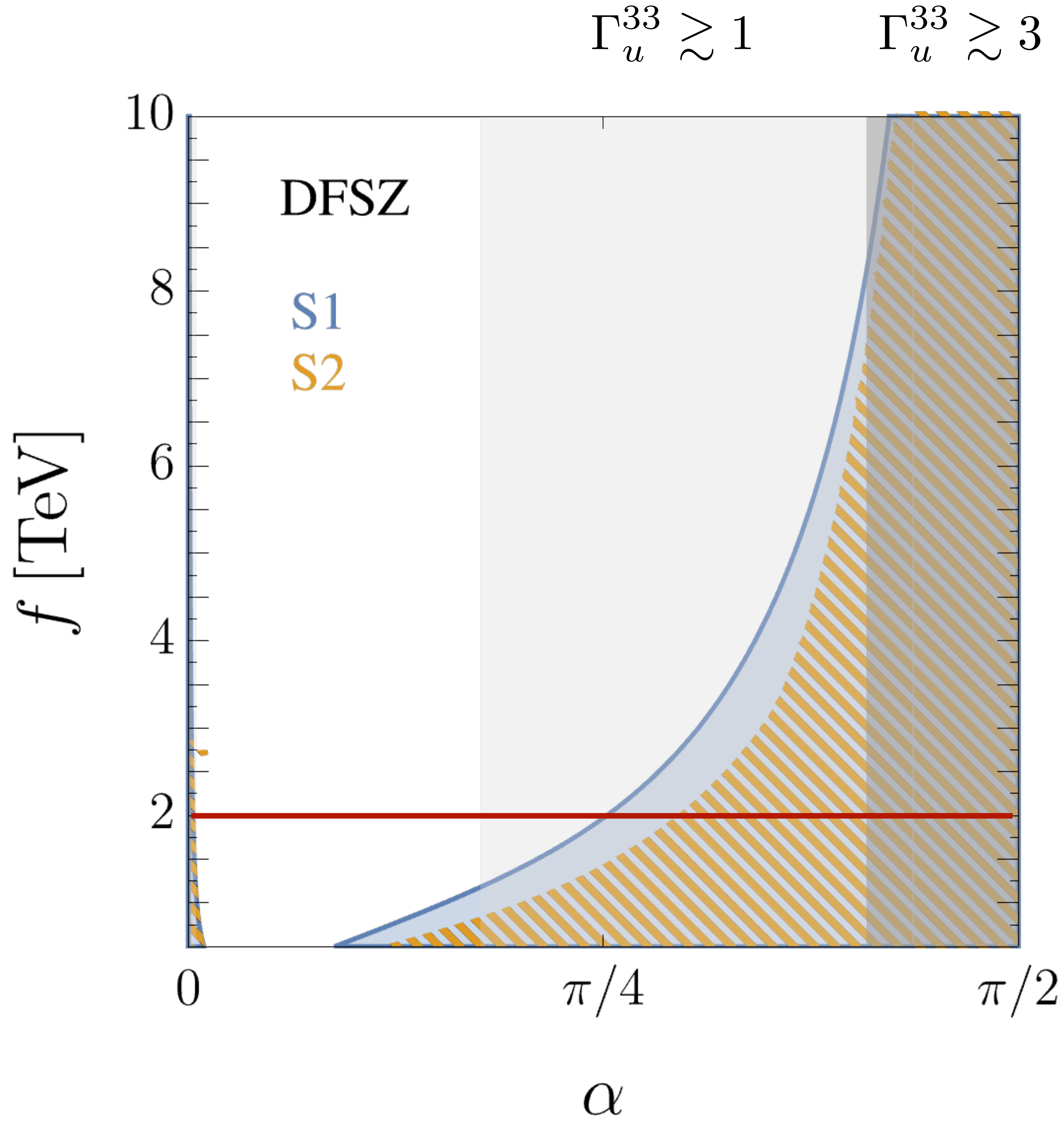
Yukawa suppressed

ALP couplings and SMEFT operators depend on same parameters α and f

DFSZ models - results

$C_u = -2 s_\alpha^2$

$|C_u|/f < 1/\text{TeV}$



S1: negligible scalar parameters

S2: profiling of scalar parameters

Limits on f dominated by SMEFT contributions

Warsaw basis

[Grzadkowski et al. (1008.4884)]

$1: X^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$

$6: \psi^2XH + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$

$7: \psi^2H^2D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$

Plus another 24 four-fermion operators