A global analysis of axion-like particle interactions using SMEFT fits

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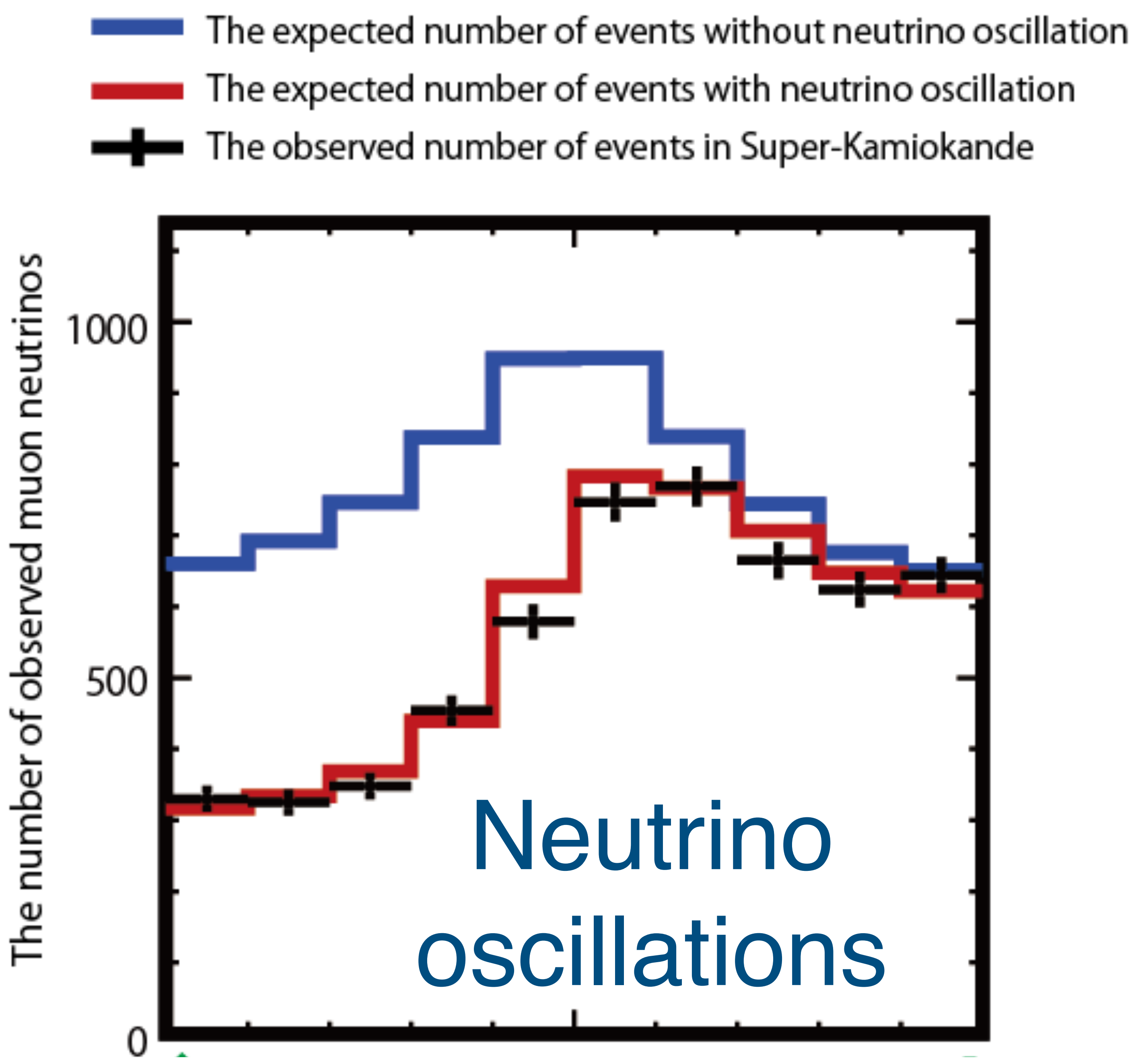
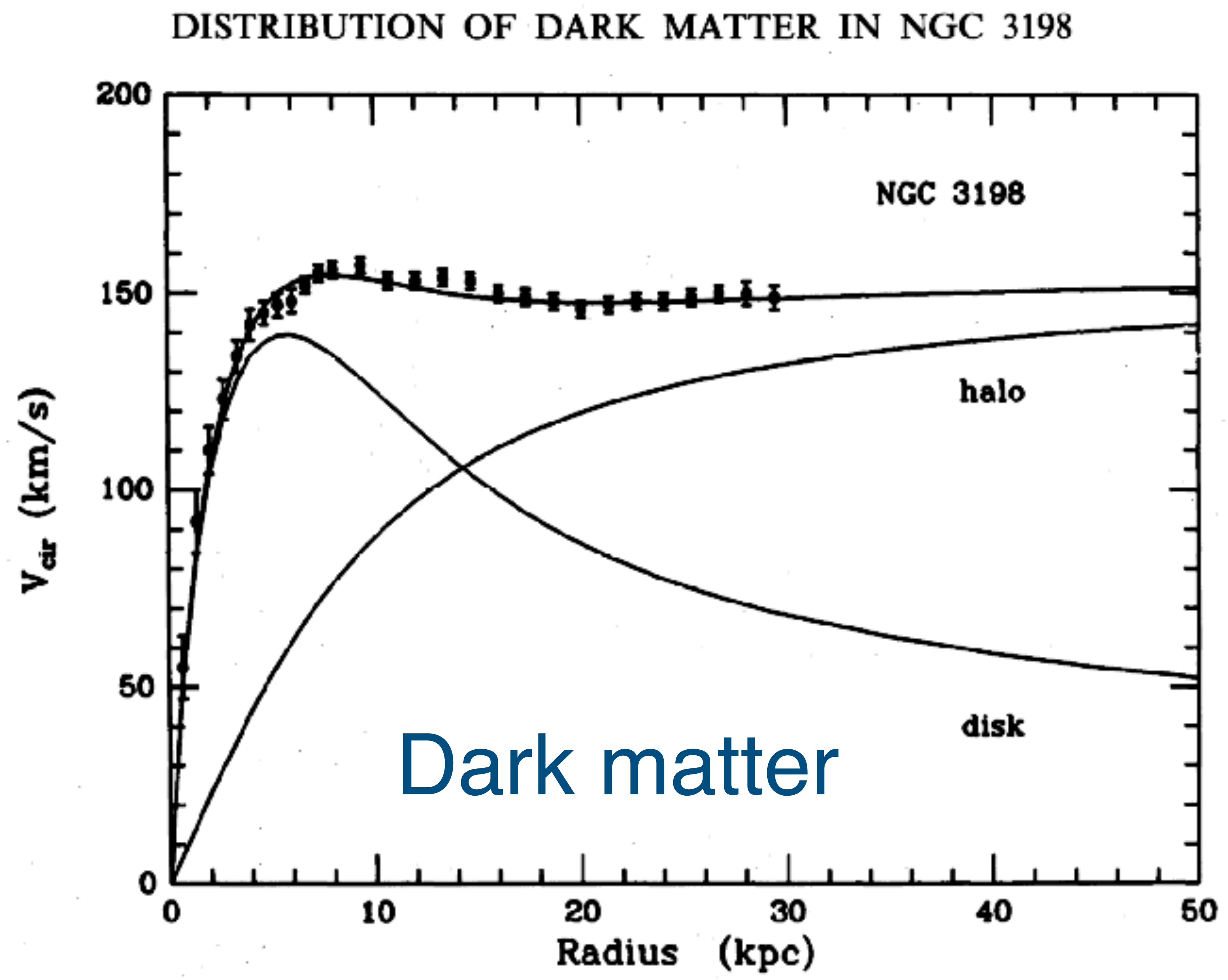
HEP Theory Seminar @Bonn - 16 October 2023

Physics beyond the Standard Model



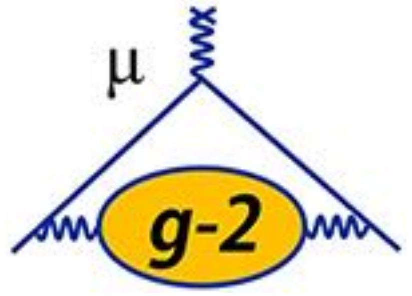
Neutrino oscillations



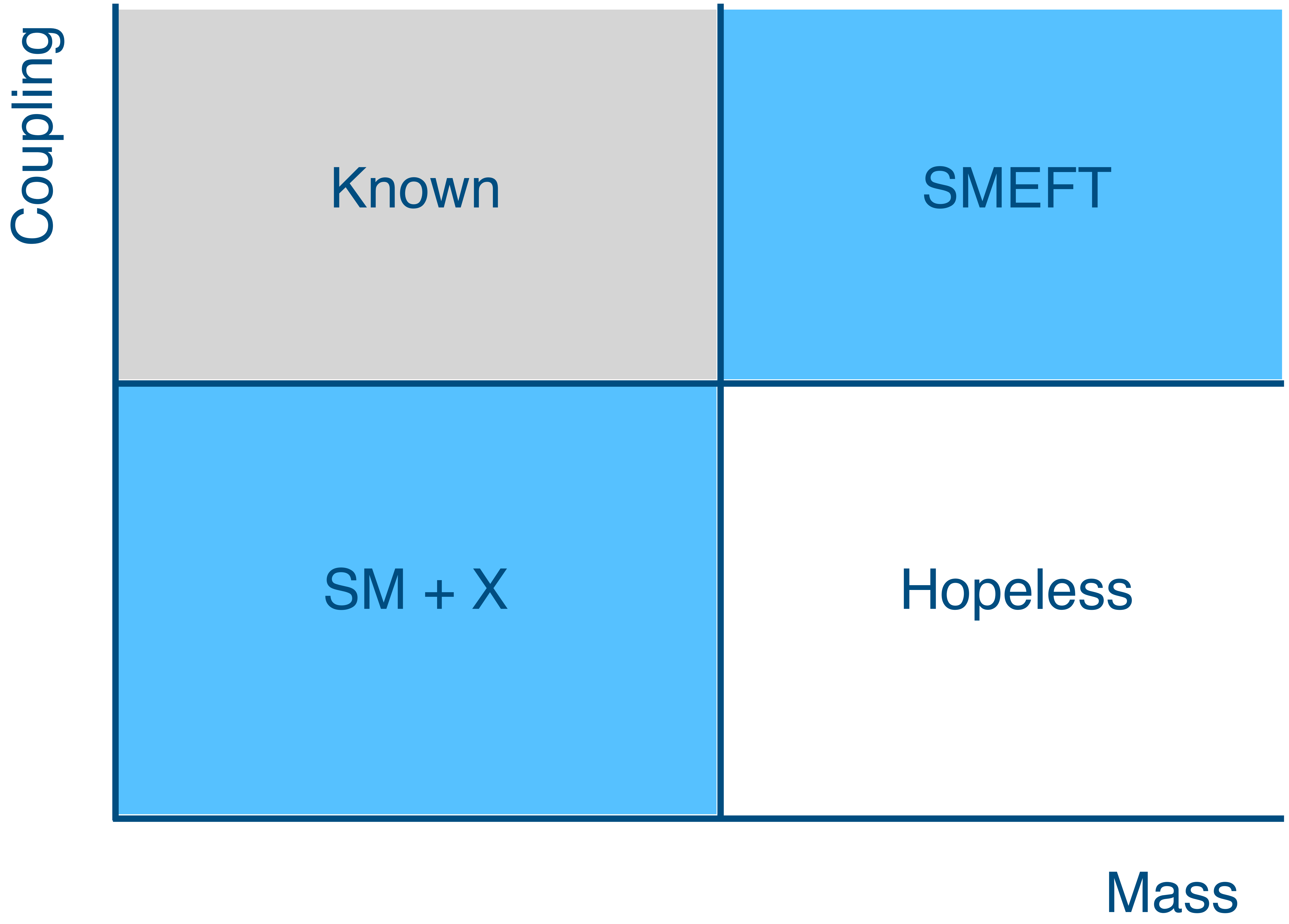
Dark matter

W boson mass (?)

Muon g-2



The Landscape of (new) physics



New physics has to be…

… very heavy

SMEFT

Leptoquarks

Z' bosons

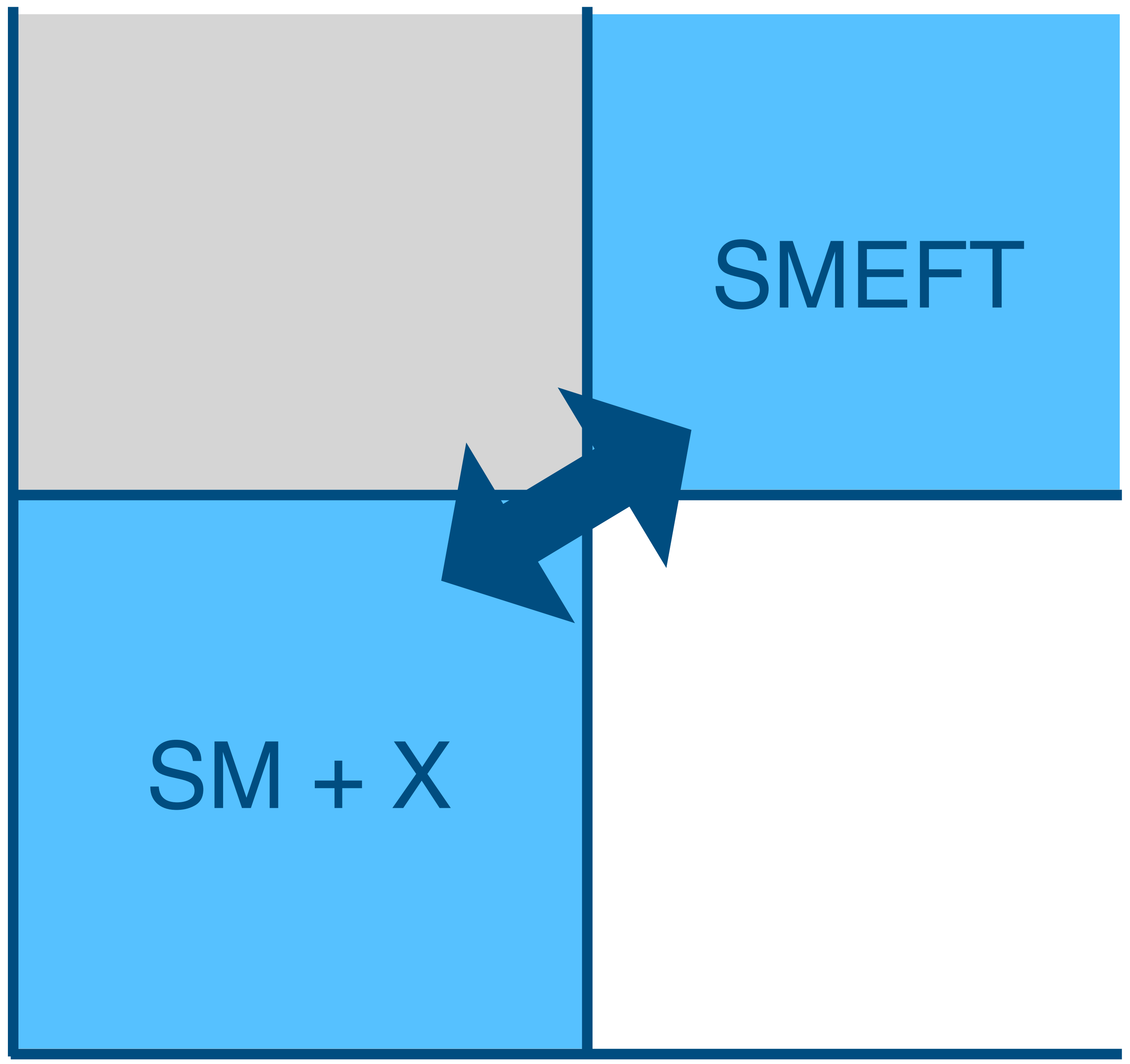
Supersymmetry

… (light and) very weakly interacting with the SM

Axion-like particles

Outline

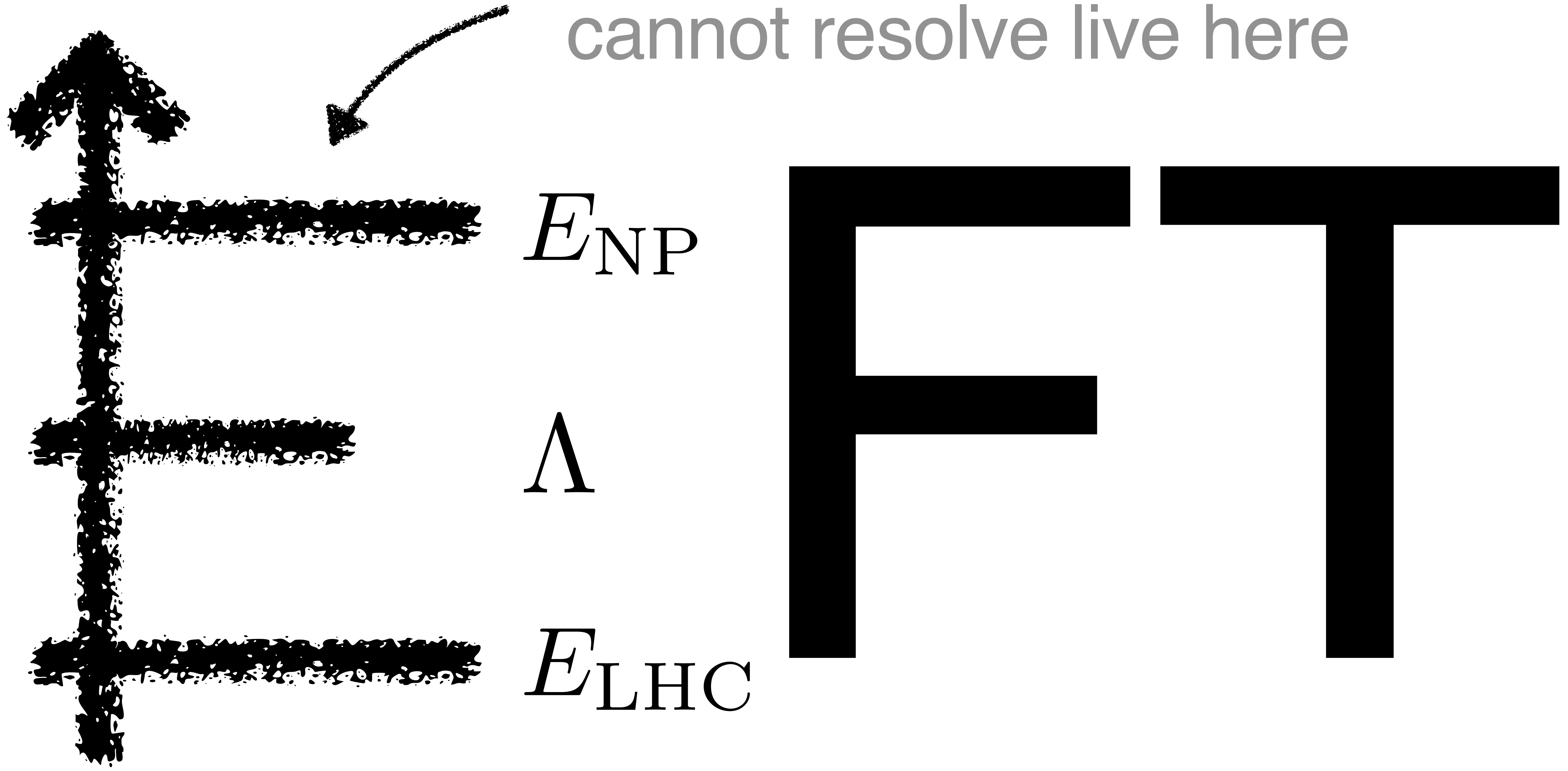
- A (very brief) intro to effective field theory
- Axion-like particle (ALP) EFT
  - ALP-SMEFT interference
  - Indirect bounds on ALP couplings from the SMEFT
  - Global analysis
  - Comparison with direct bounds
  - Interpretation in terms of UV models

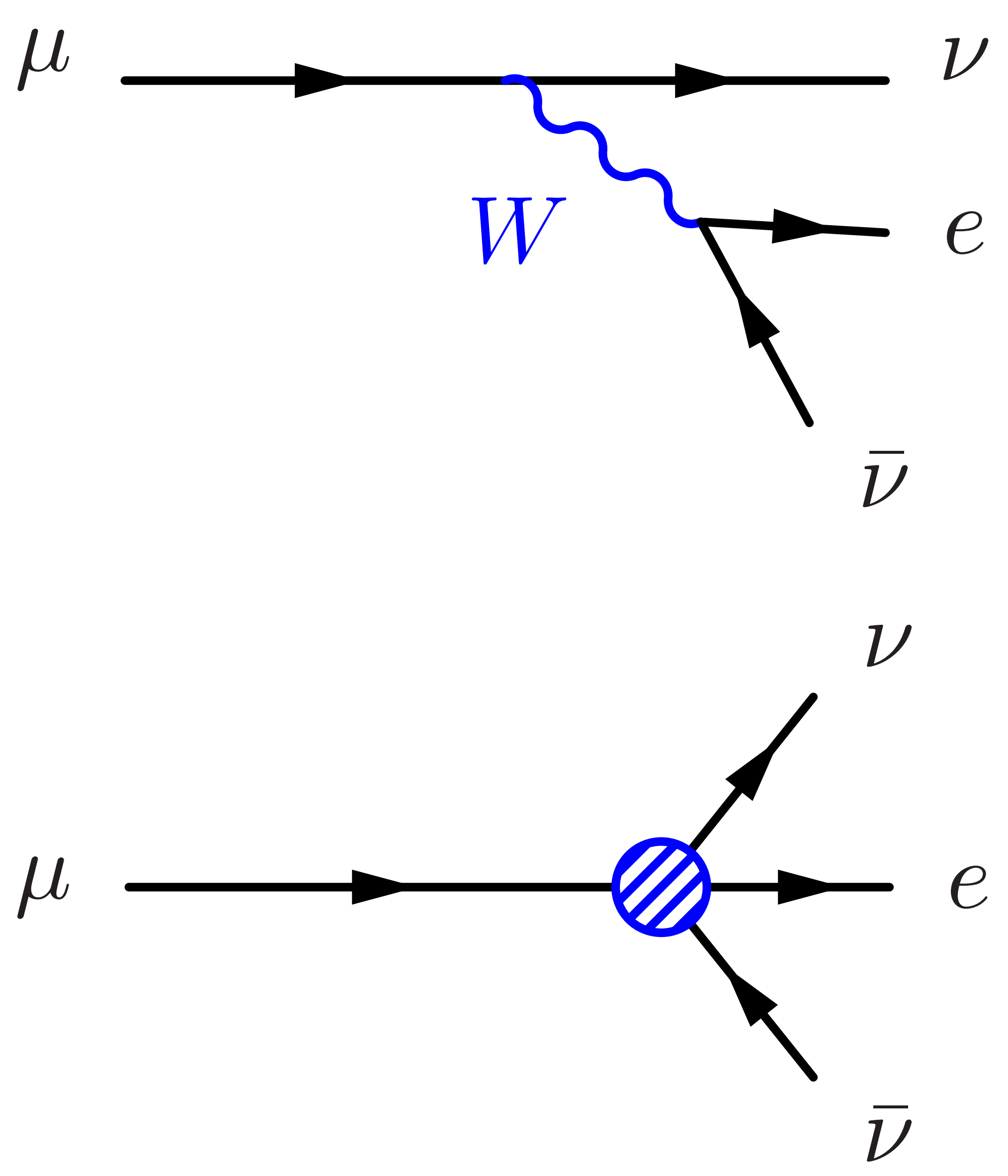


Based on 2307.10372 with
Anne Galda, Javier Fuentes-Martín and Matthias Neubert

Effective field theory - EFT

Heavy particles that we cannot resolve live here



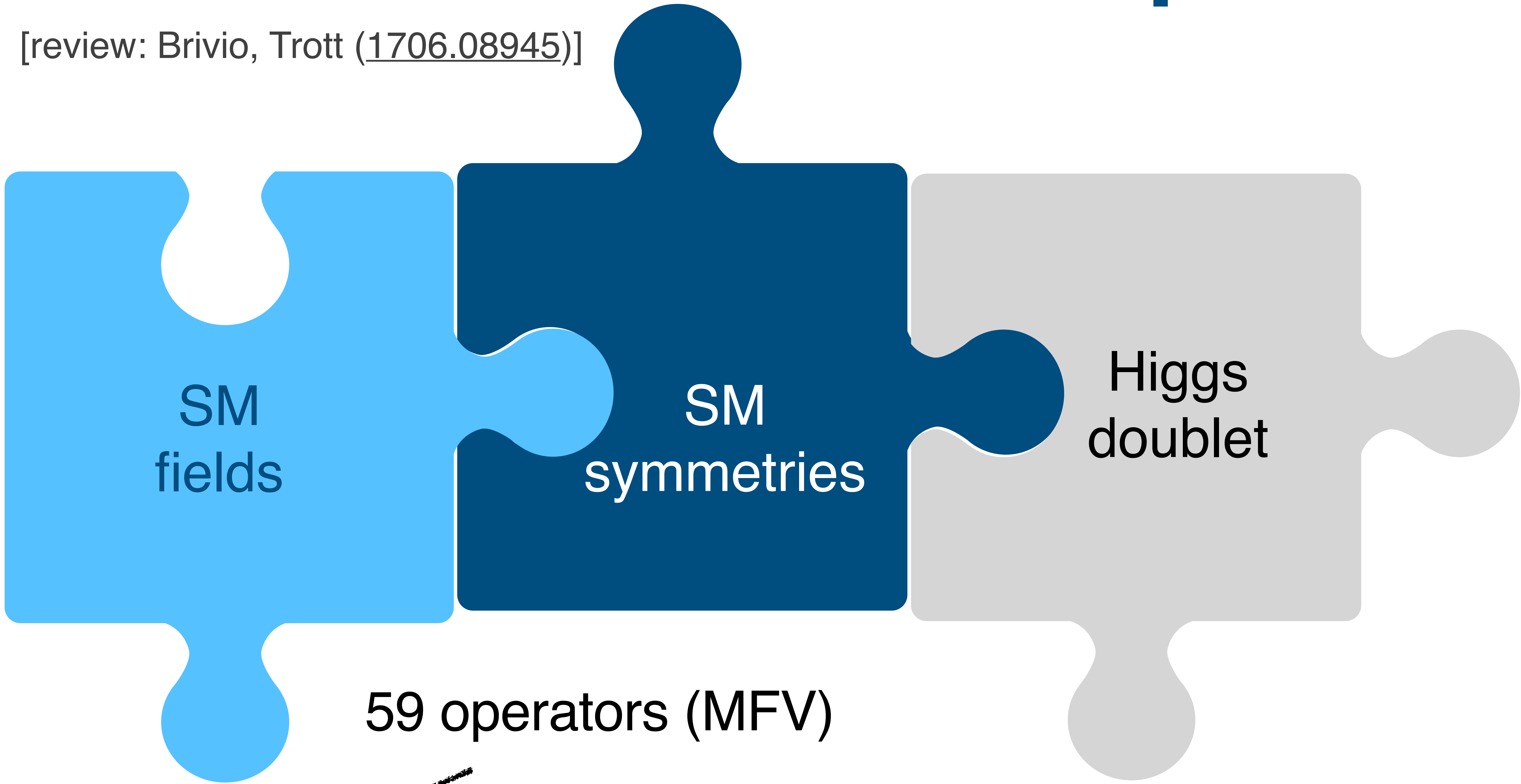


Hierarchy of scales

Describe NP by higher-order interactions of SM fields

EFTs from the bottom-up

[review: Brivio, Trott (1706.08945)]



59 operators (MFV)

- Proper, renormalisable **quantum field theory**
- **Minimal assumptions** on UV completion
- **Universal language** for data interpretation

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \cdots$$

Odd dimensions violate lepton or baryon number

EFTs from the bottom-up

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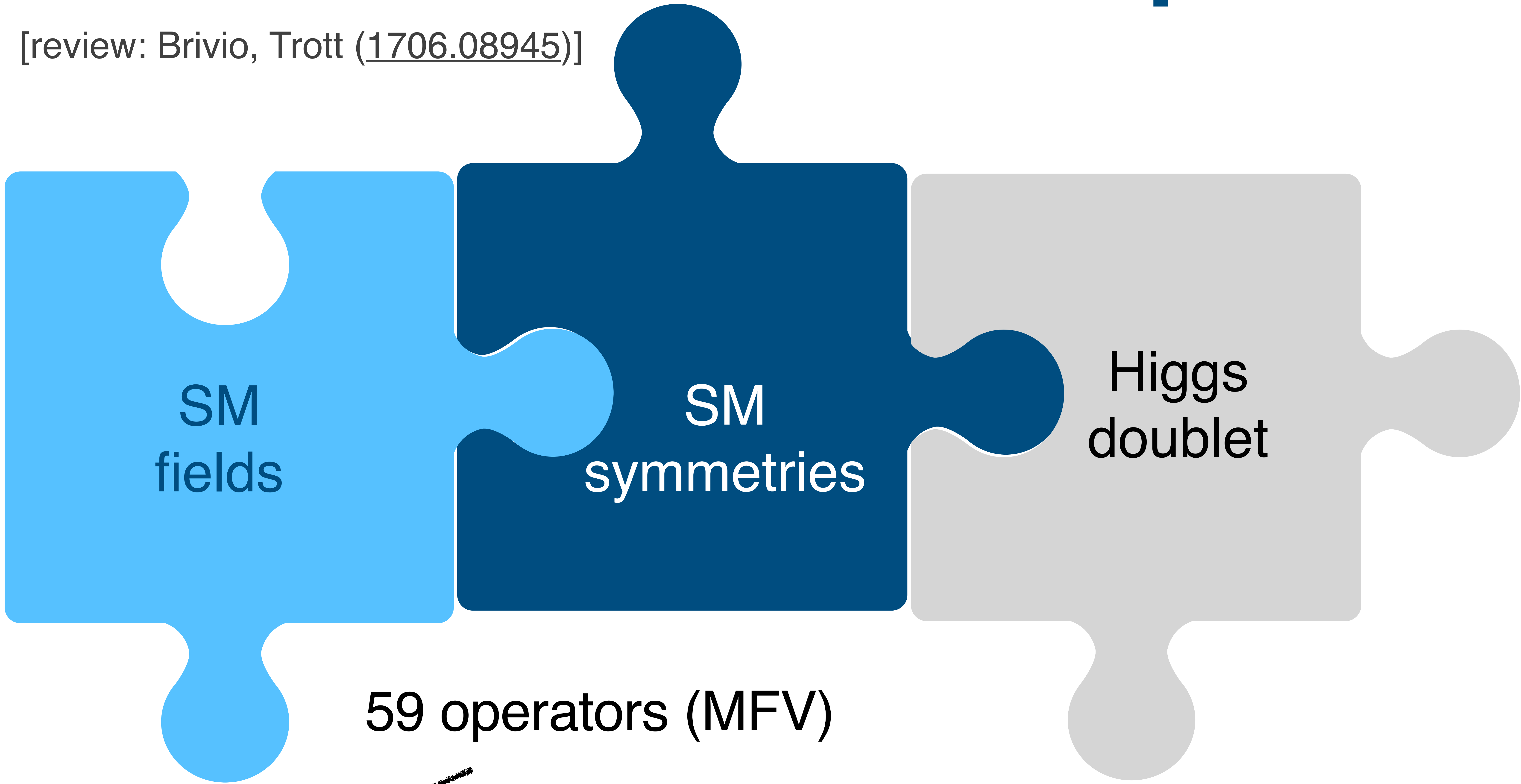

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Odd dimensions violate lepton or baryon number

Warsaw basis

[Grzadkowski et al. (1008.4884)]

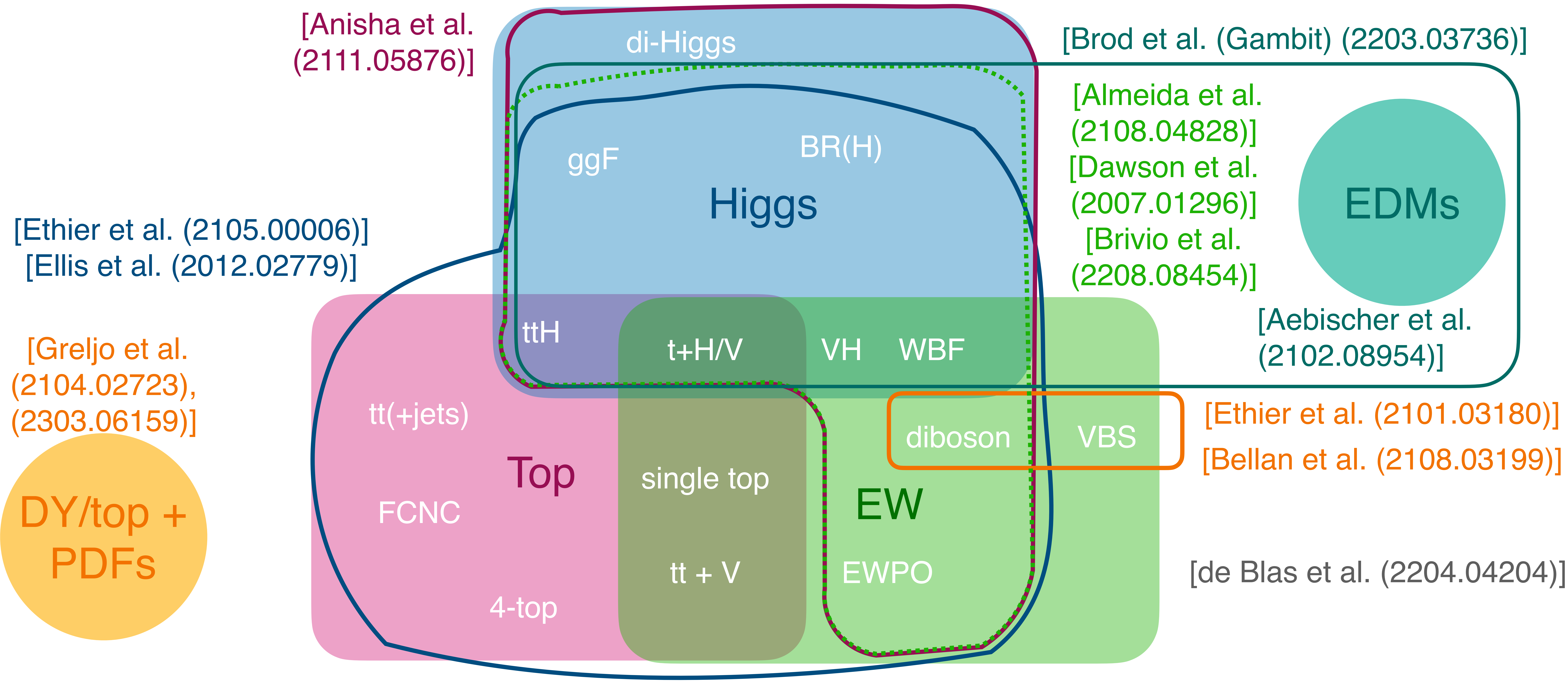
$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2XH + \text{h.c.}$		$7: \psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
Q_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$Q_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

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

Plus another 24 four-fermion operators

Confronting the SMEFT with data

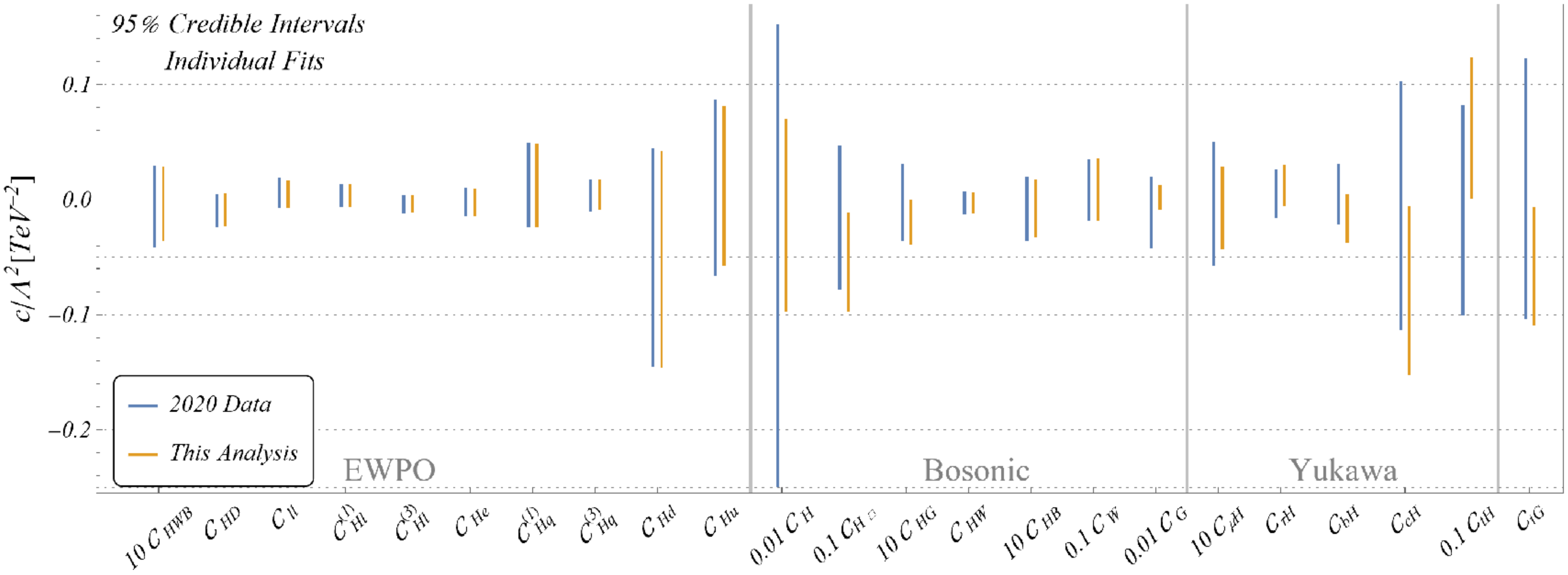


Adapted from Ken Mimasu

Global fits

[Anisha, Bashi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]

See also fits from other collaborations (see previous slide for references)



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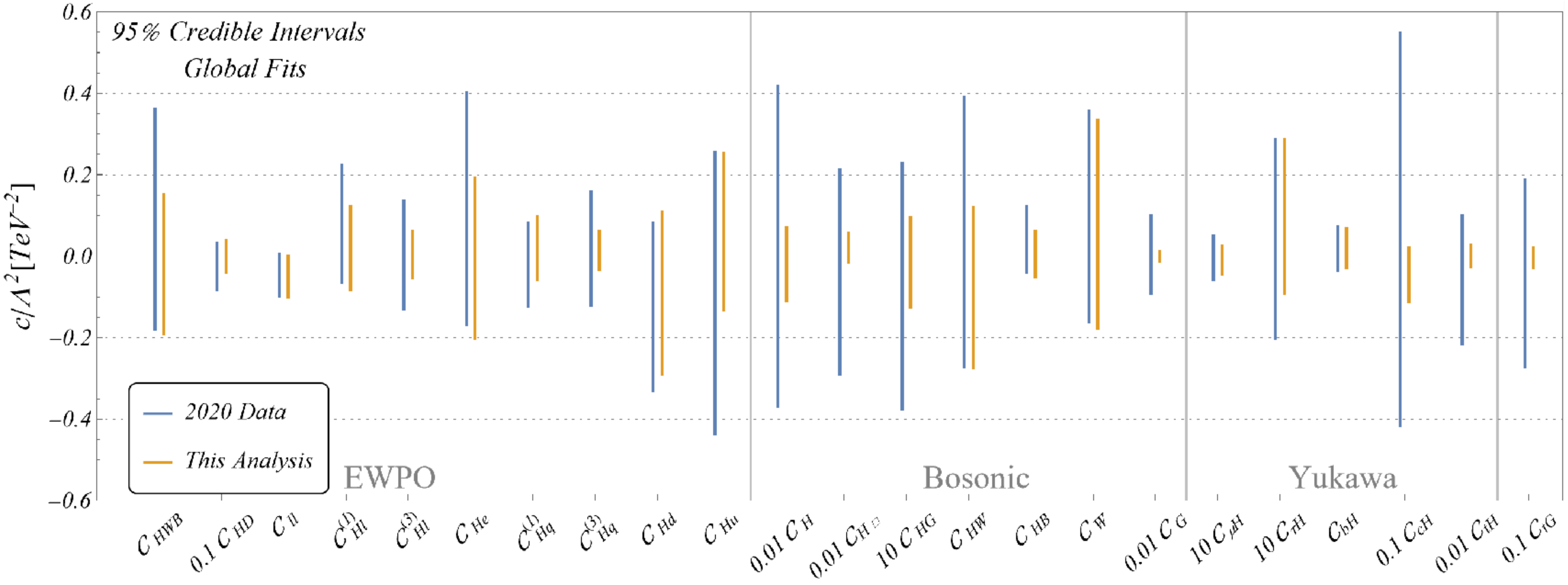


Exploiting the ALP-SMEFT interference

Can we give SMEFT fits a second life for light new physics?

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

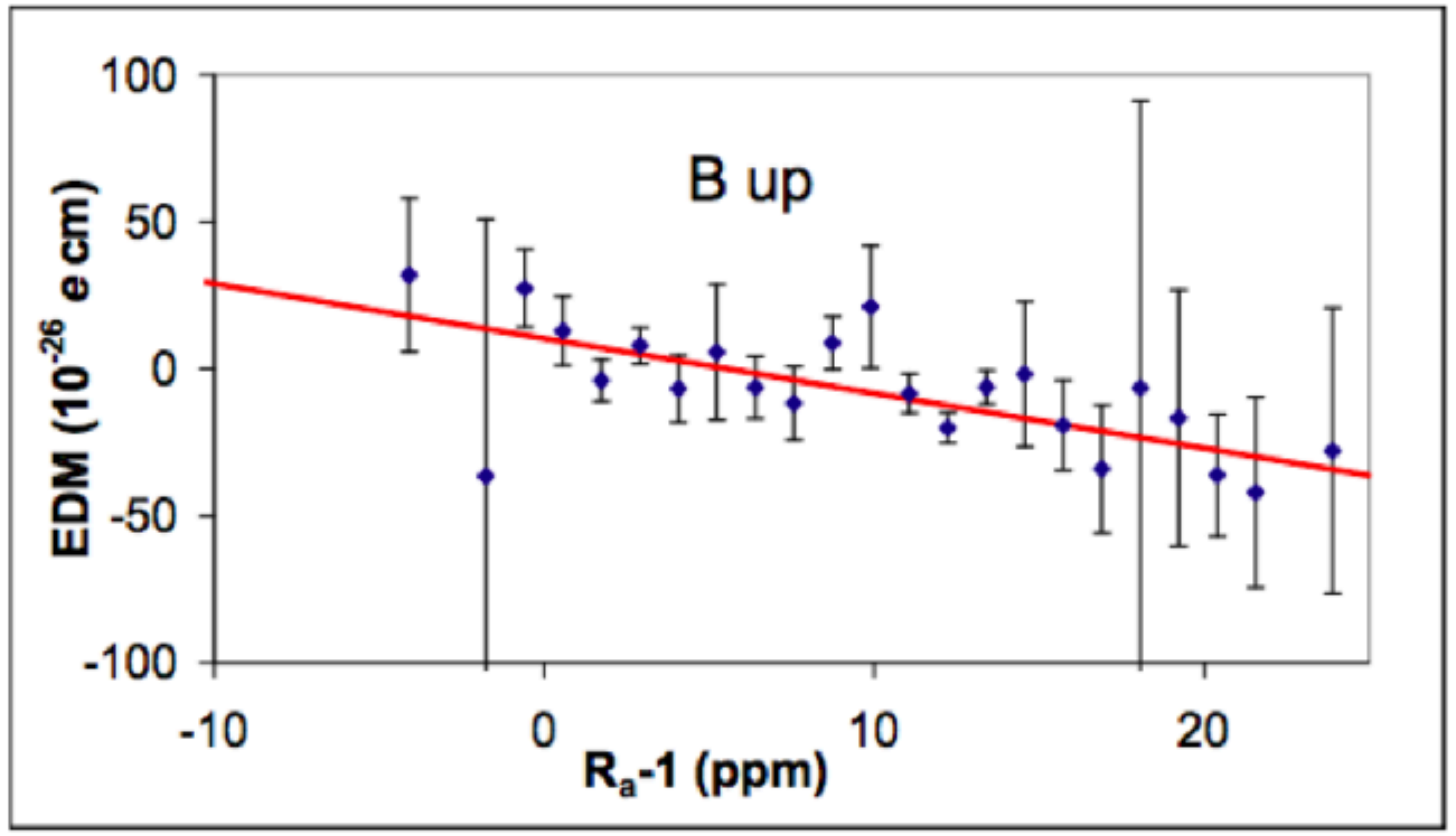


Axions

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

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]

$$m_a f_a = \text{const.}$$

Axion-like particles

EFT with an additional light d.o.f. and at dimension 5

- Featured in many BSM scenarios: “Higgs portal” dark matter, composite Higgs models, …

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

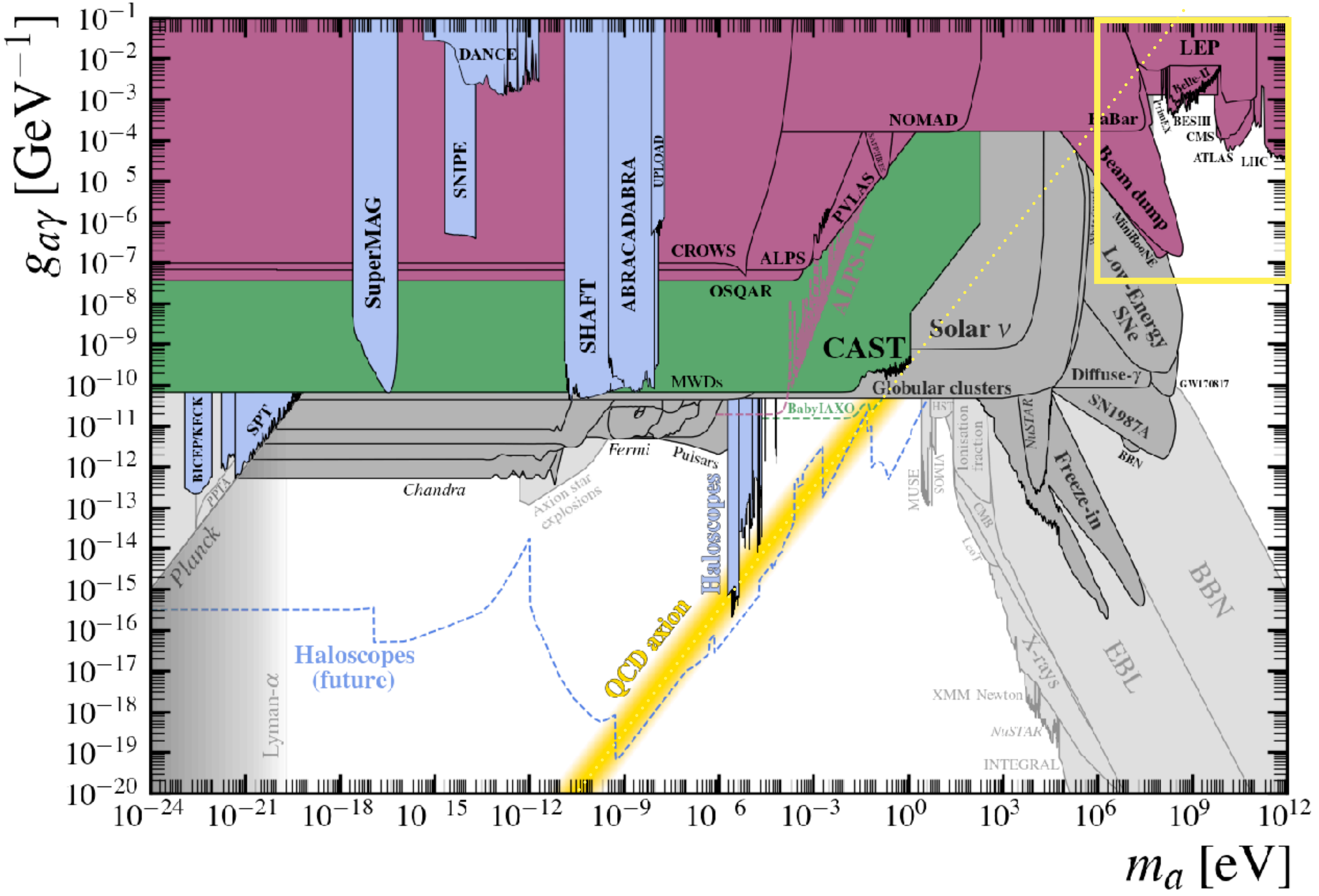
- Consider a generic ALP with effective Lagrangian

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

- Shift symmetry $a \to a + a_0$, Lagrangian terms: $\frac{\partial_\mu a}{f_a}\,(\mathrm{SM})^\mu$

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

Axion-like particles



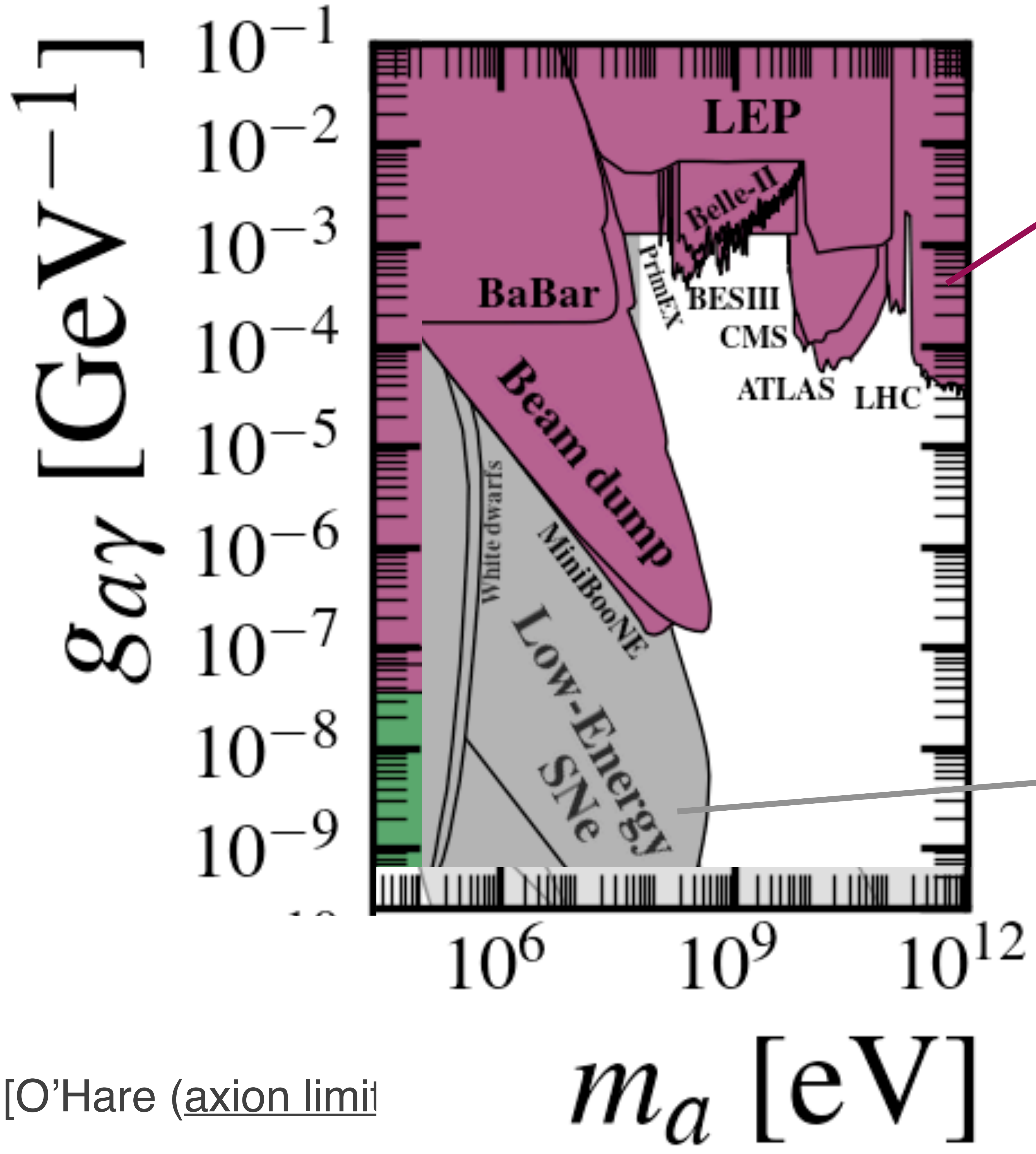
Current status - 2D fits

Assumptions of

- Production mode
- Lifetime
- Branching ratios

[O'Hare (axion limits)]

2D axion-like bounds



[O'Hare (axion limi

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 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

$$\tilde Y_u = i(c_u - c_Q)Y_u = -iC_uY_u, \quad \tilde Y_d = i(c_d - c_Q)Y_d = -iC_dY_d, \quad \tilde Y_e = i(c_e - c_L)Y_e = -iC_eY_e$$

ALP Lagrangian

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

Six free parameters in the flavor-universal case

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

… $_{\mu\nu}\, \tilde{B}^{\mu\nu}\,.$

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

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

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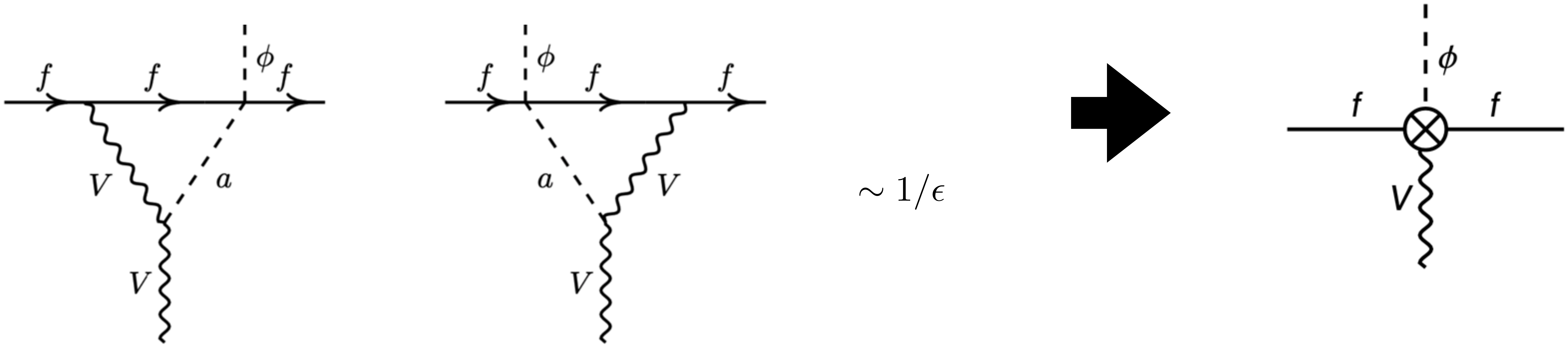
Virtual ALP exchanges

[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



Renormalisation Group Evolution

Physics does not rely on an arbitrary energy scale μ

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\log\mu} = \frac{\mathrm{d}}{\mathrm{d}\log\mu}\sum_i C_i(\mu)\mathcal{O}_i(\mu) = 0$$

RGE for SMEFT + ALP

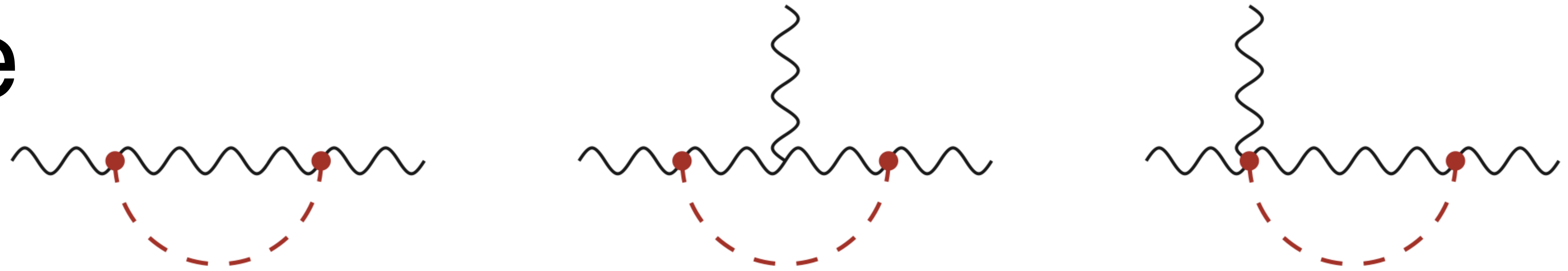
$$\frac{\mathrm{d}}{\mathrm{d}\log\mu} C_i^{\mathrm{SMEFT}} - \gamma_{ji}^{\mathrm{SMEFT}} C_j^{\mathrm{SMEFT}} = \frac{S_i}{(4\pi f)^2}$$

ALP-SMEFT interference

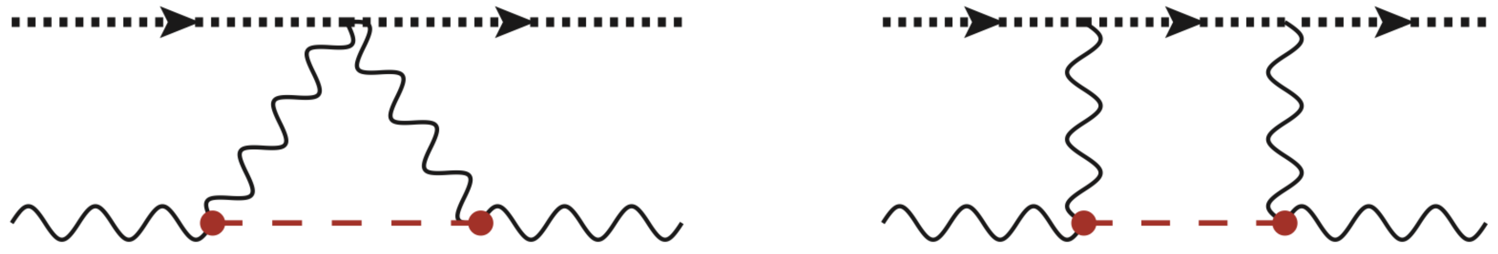
[Galda, Neubert, Renner (2105.01078)]

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

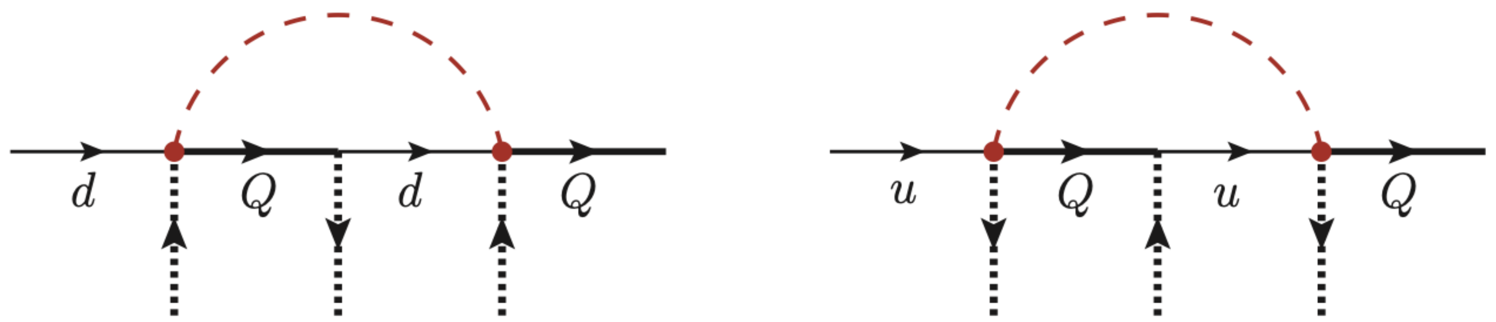
Gauge

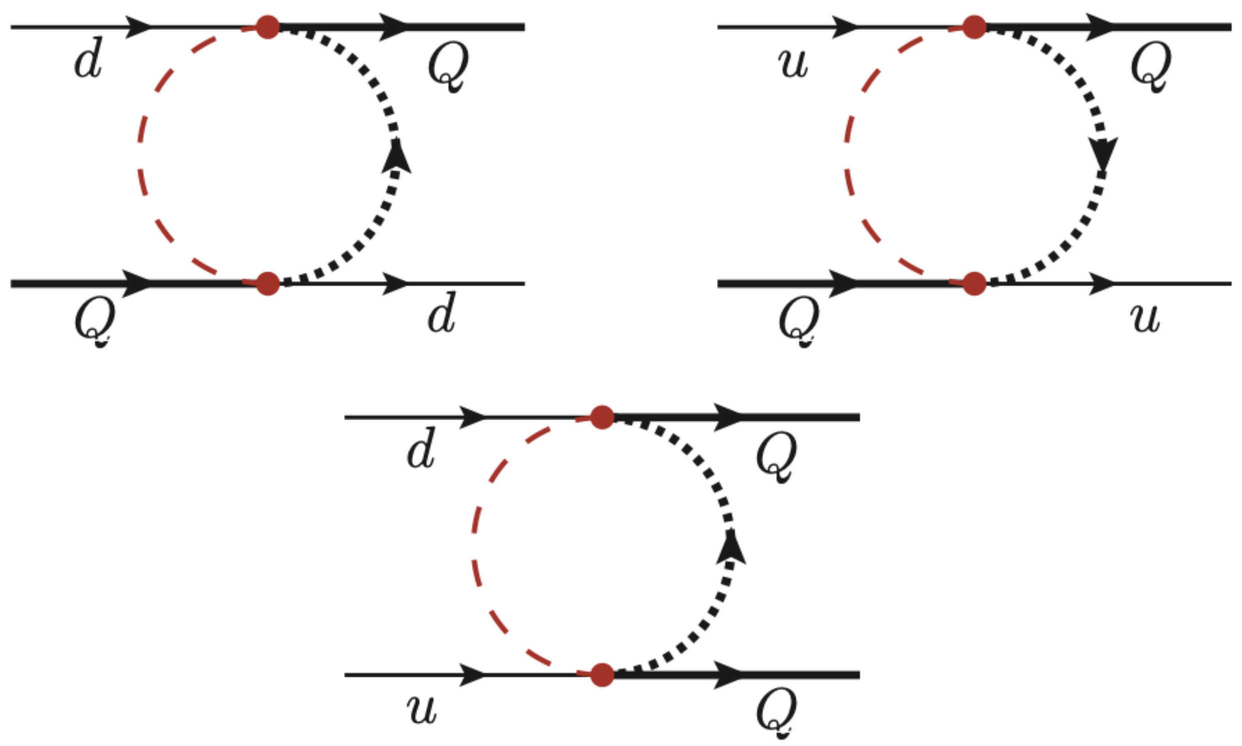


Gauge-Higgs



Fermion-Higgs





Four-fermion

Source terms

[Galda, Neubert, Renner (2105.01078)]

- ALP contributes source terms for D6 SMEFT Wilson coefficients

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

ALP extension of DsixTool coming soon!

$$\begin{aligned}
S_{HG} &= 0\,, & S_{H\tilde{G}} &= 0\,,\\
S_{HW} &= -2g_2^2\, C_{WW}^2\,, & S_{H\widetilde{W}} &= 0\,,\\
S_{HB} &= -2g_1^2\, C_{BB}^2\,, & S_{H\tilde{B}} &= 0\,,\\
S_{HWB} &= -4g_1 g_2\, C_{WW} C_{BB}\,, & S_{H\widetilde{W}B} &= 0\,.
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{S}_{Hl}^{(1)} &= \frac{1}{4}\tilde{\boldsymbol{Y}}_e\tilde{\boldsymbol{Y}}_e^\dagger + \frac{16}{3}g_1^2\,\mathcal{Y}_H\mathcal{Y}_L\,C_{BB}^2\,\mathbf{1}\,,\\
\boldsymbol{S}_{Hl}^{(3)} &= \frac{1}{4}\tilde{\boldsymbol{Y}}_e\tilde{\boldsymbol{Y}}_e^\dagger + \frac{4}{3}g_2^2\,C_{WW}^2\,\mathbf{1}\,,\\
\boldsymbol{S}_{He} &= -\frac{1}{2}\tilde{\boldsymbol{Y}}_e^\dagger\tilde{\boldsymbol{Y}}_e + \frac{16}{3}g_1^2\,\mathcal{Y}_H\mathcal{Y}_e\,C_{BB}^2\,\mathbf{1}\,,\\
\boldsymbol{S}_{Hq}^{(1)} &= \frac{1}{4}\left(\tilde{\boldsymbol{Y}}_d\tilde{\boldsymbol{Y}}_d^\dagger - \tilde{\boldsymbol{Y}}_u\tilde{\boldsymbol{Y}}_u^\dagger\right) + \frac{16}{3}g_1^2\,\mathcal{Y}_H\mathcal{Y}_Q\,C_{BB}^2\,\mathbf{1}\,,\\
\boldsymbol{S}_{Hq}^{(3)} &= \frac{1}{4}\left(\tilde{\boldsymbol{Y}}_d\tilde{\boldsymbol{Y}}_d^\dagger + \tilde{\boldsymbol{Y}}_u\tilde{\boldsymbol{Y}}_u^\dagger\right) + \frac{4}{3}g_2^2\,C_{WW}^2\,\mathbf{1}\,,\\
\boldsymbol{S}_{Hu} &= \frac{1}{2}\tilde{\boldsymbol{Y}}_u^\dagger\tilde{\boldsymbol{Y}}_u + \frac{16}{3}g_1^2\,\mathcal{Y}_H\mathcal{Y}_u\,C_{BB}^2\,\mathbf{1}\,,\\
\boldsymbol{S}_{Hd} &= -\frac{1}{2}\tilde{\boldsymbol{Y}}_d^\dagger\tilde{\boldsymbol{Y}}_d + \frac{16}{3}g_1^2\,\mathcal{Y}_H\mathcal{Y}_d\,C_{BB}^2\,\mathbf{1}\,,
\end{aligned}$$

Independent of ALP mass

[Bakshi, Machado-Rodríguez, Ramos (2306.08036)]

Source terms

[Galda, Neubert, Renner (2105.01078)]

- ALP contributes source terms for D6 SMEFT Wilson coefficients

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

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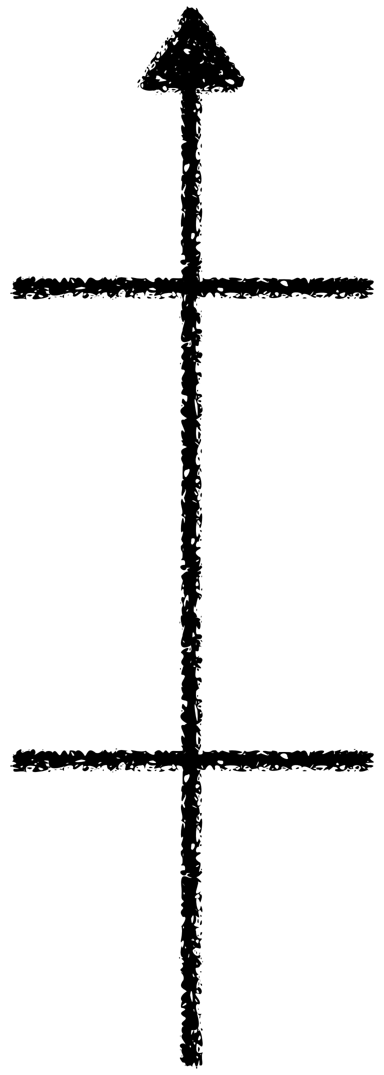

$C^{\mathrm{ALP}}(\Lambda) \neq 0,$

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

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

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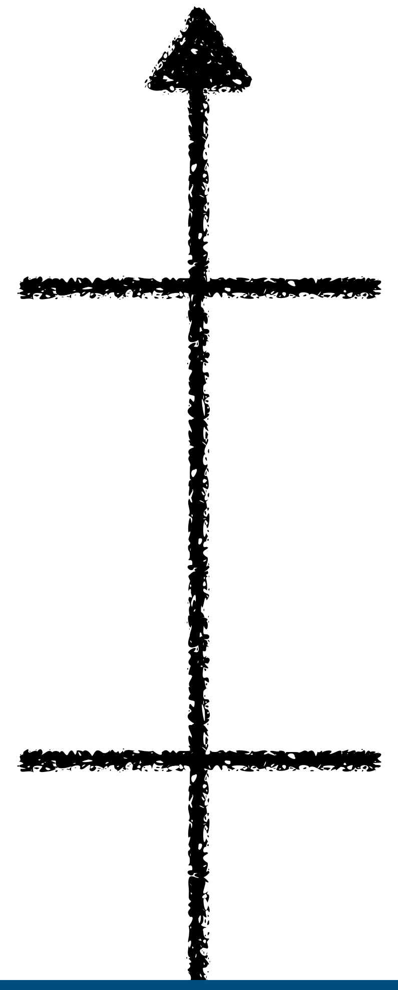
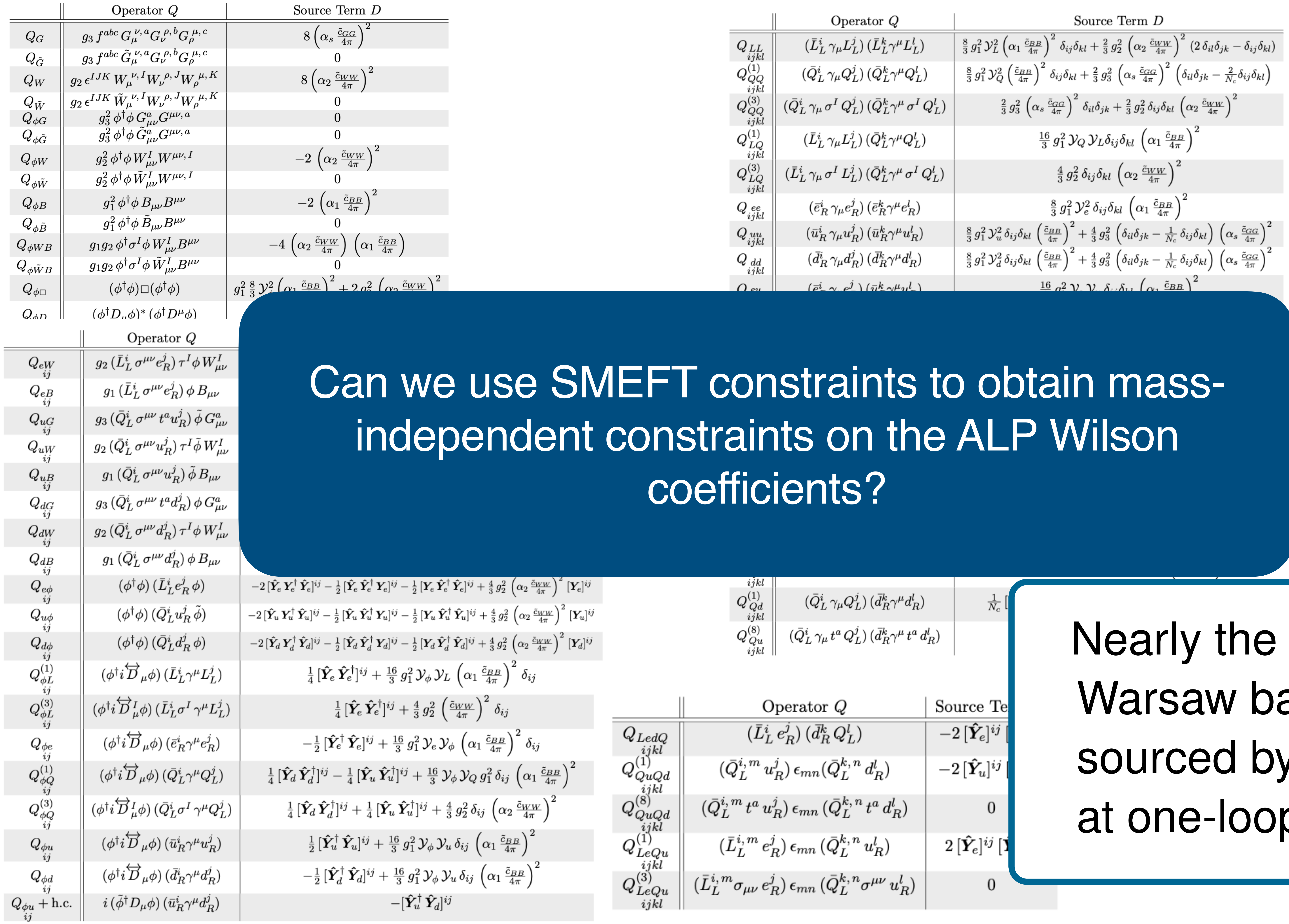


ALP running induces non-zero SMEFT coefficients!

[Bakshi, Machado-Rodríguez, Ramos (2306.08036)]



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!

Exploiting the ALP-SMEFT interference

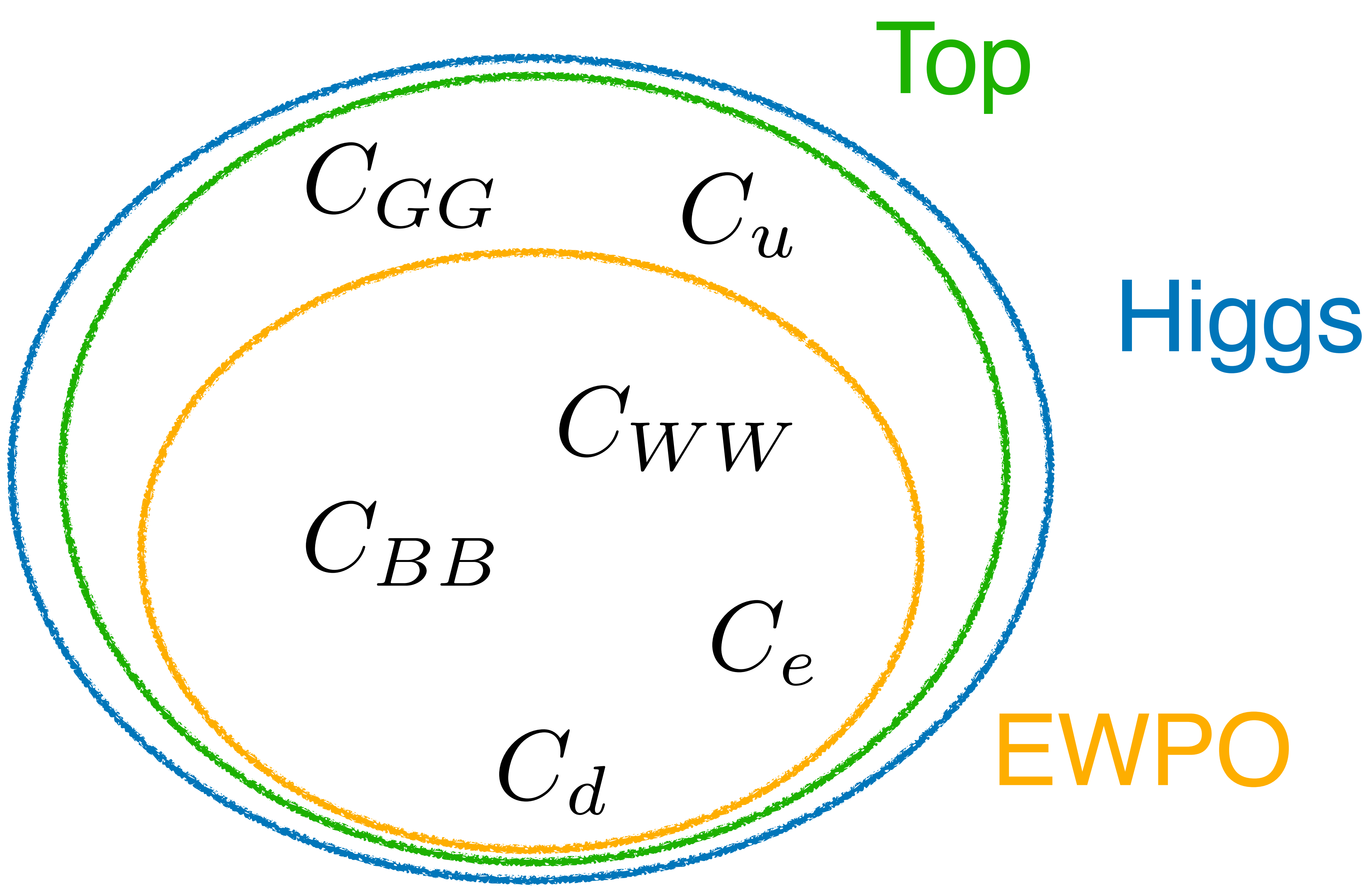
Observables used

- Low energy:
  - Electroweak precision observables (EWPO)
  - Parity violation experiments
  - Lepton scattering

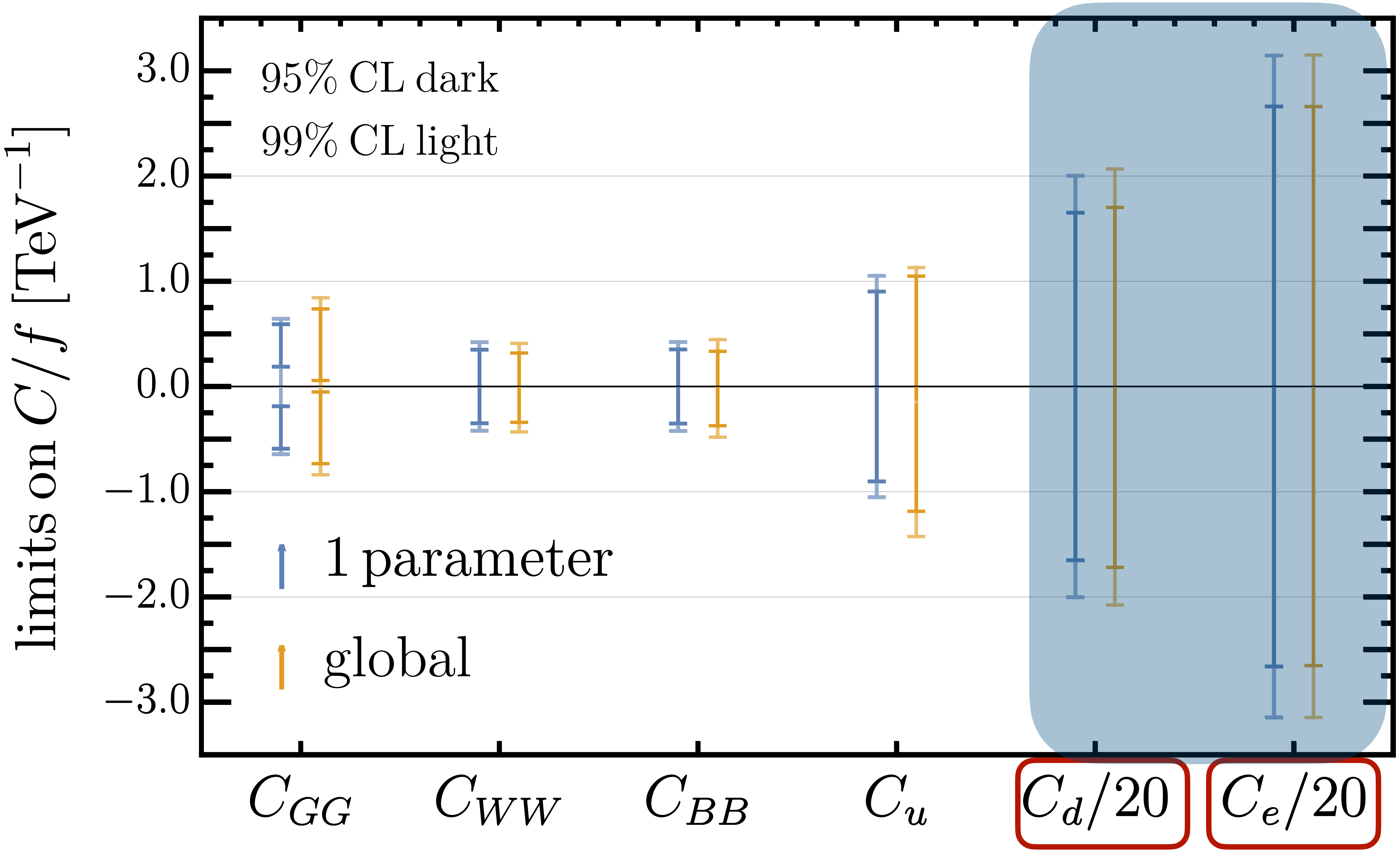
  [Falkowski et al. (1706.03783)]
- Higgs
- Top [Ellis et al. (2012.02779)]

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

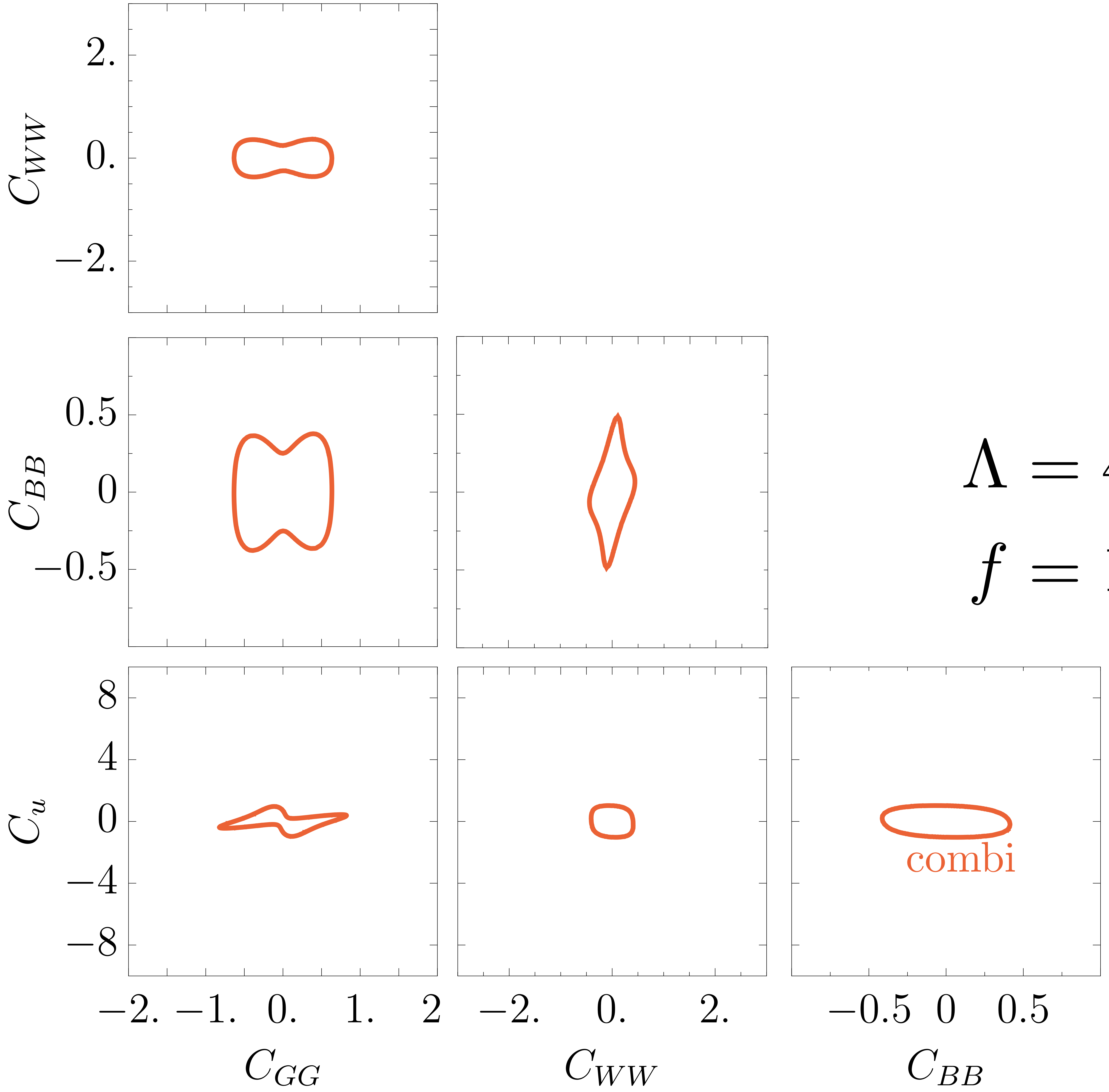
Interplay between couplings is relatively small

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



$$\Lambda = 4\pi f$$

$$f = 1 \text{ TeV}$$

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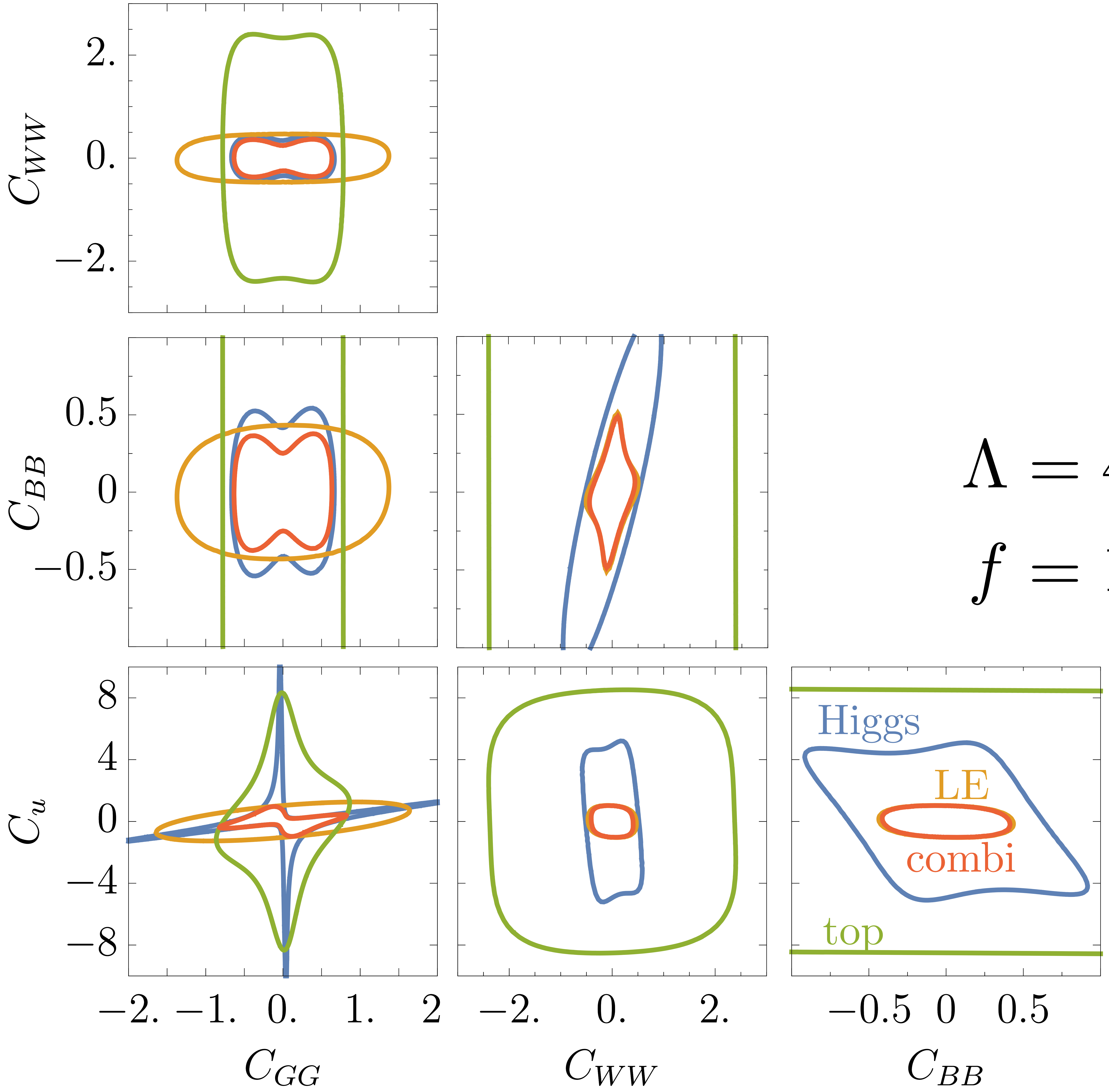


$\Lambda = 4\pi f$

$f = 1$ TeV

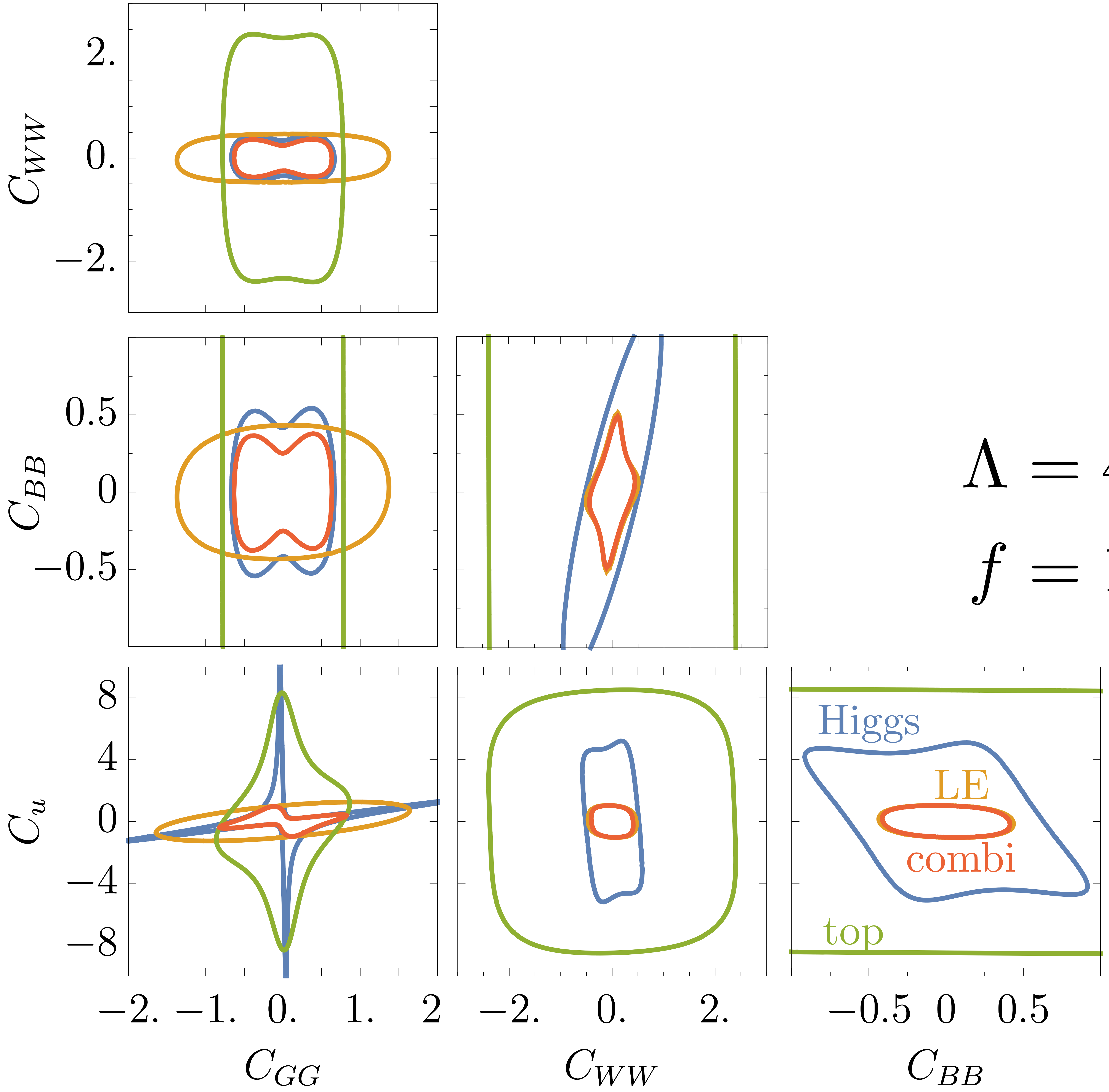
Correlations

Dominant constraints

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

Why?

- C_d : low energy
- C_e : low energy

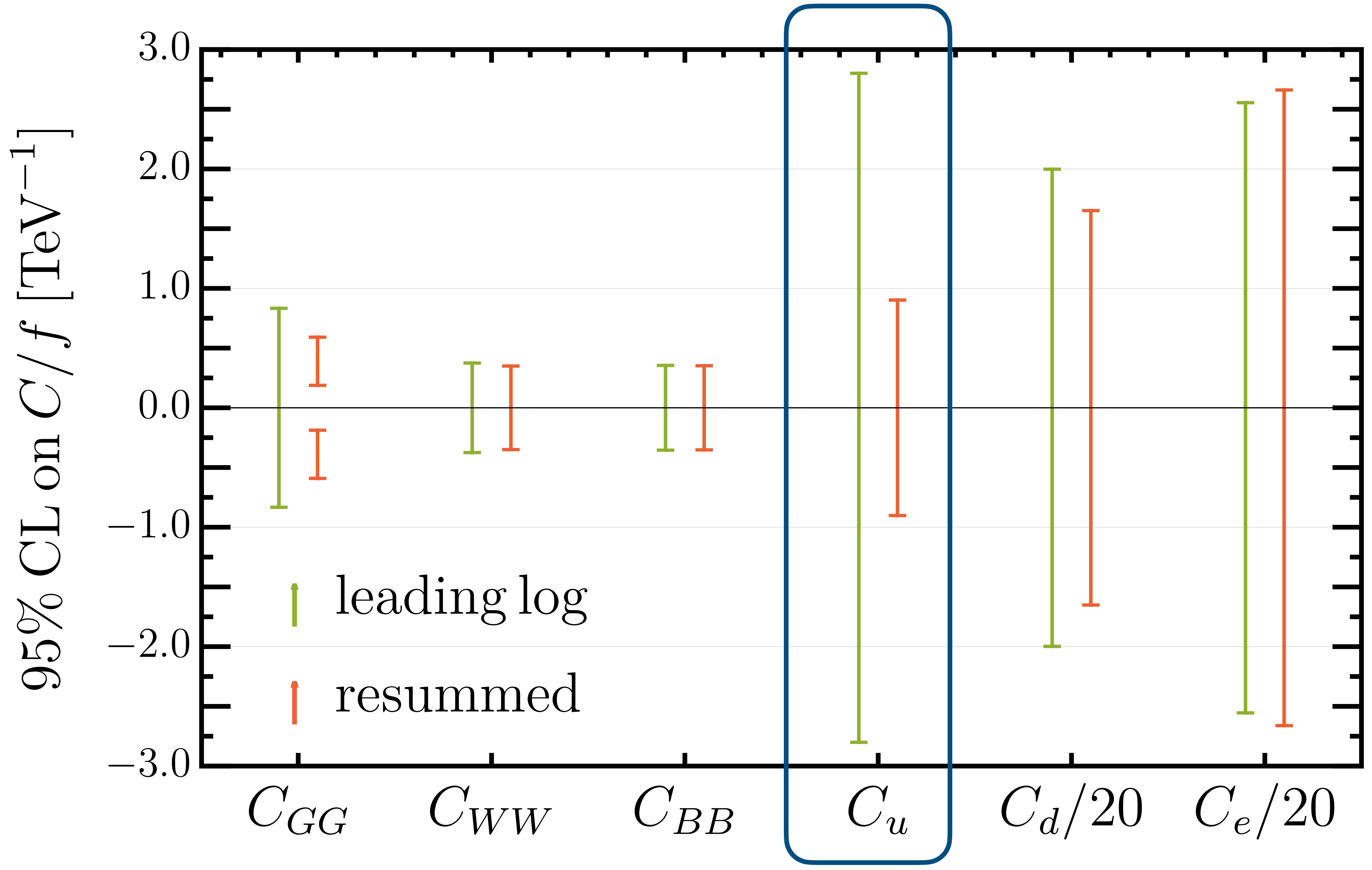


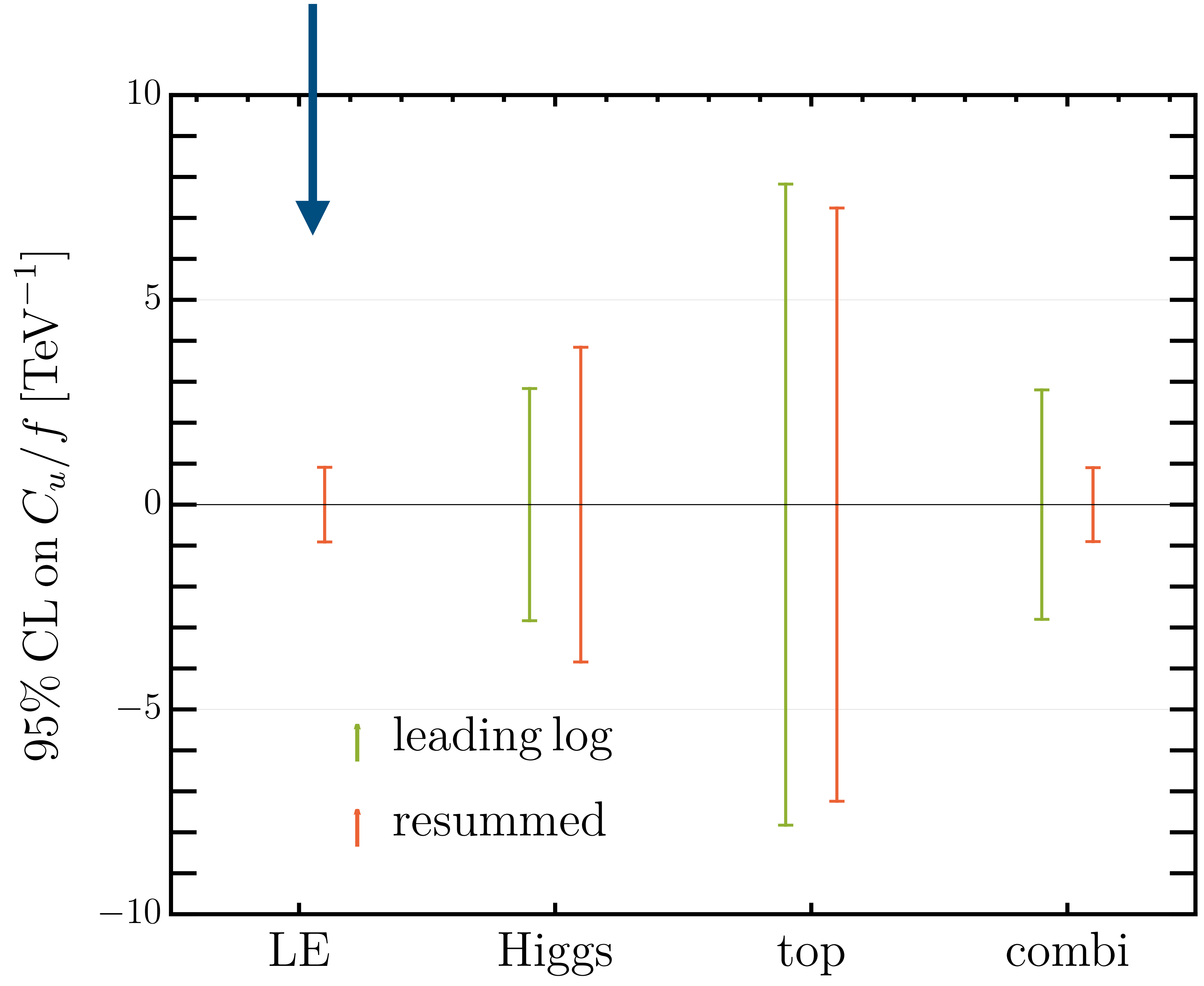
$$\Lambda = 4\pi f$$
$$f = 1 \text{ TeV}$$

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 - Cu

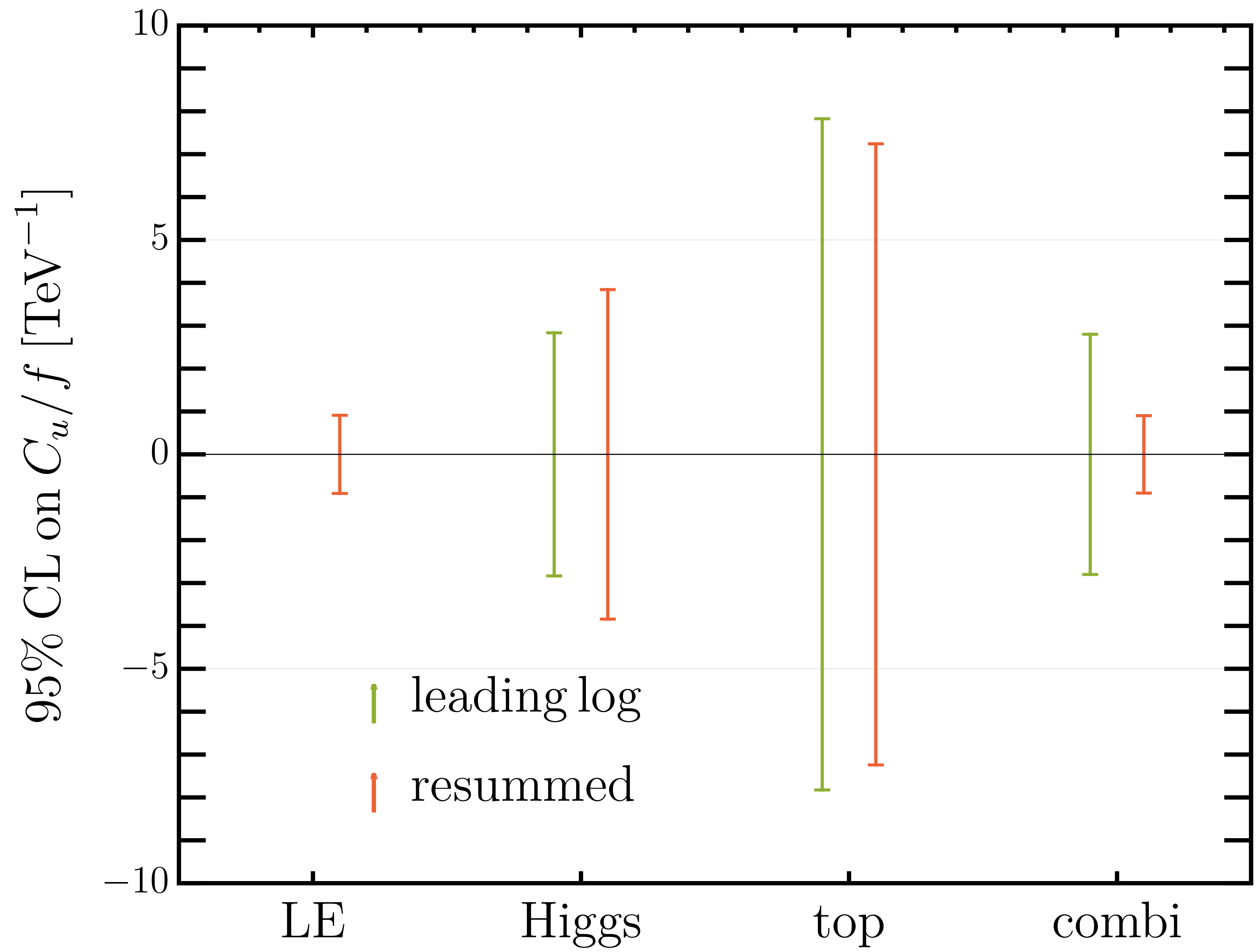
$$\frac{d}{d\ln\mu} C_{HD} = \left(\frac{3\,\alpha_t}{\pi} + \frac{3\,\lambda}{8\pi^2}\right) C_{HD} + \frac{6\,\alpha_t}{\pi}[C^{(1)}_{Hq}]_{33} - \frac{6\,\alpha_t}{\pi}[C_{Hu}]_{33}$$

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

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

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

CHD strongly constrained from measurement of W boson mass

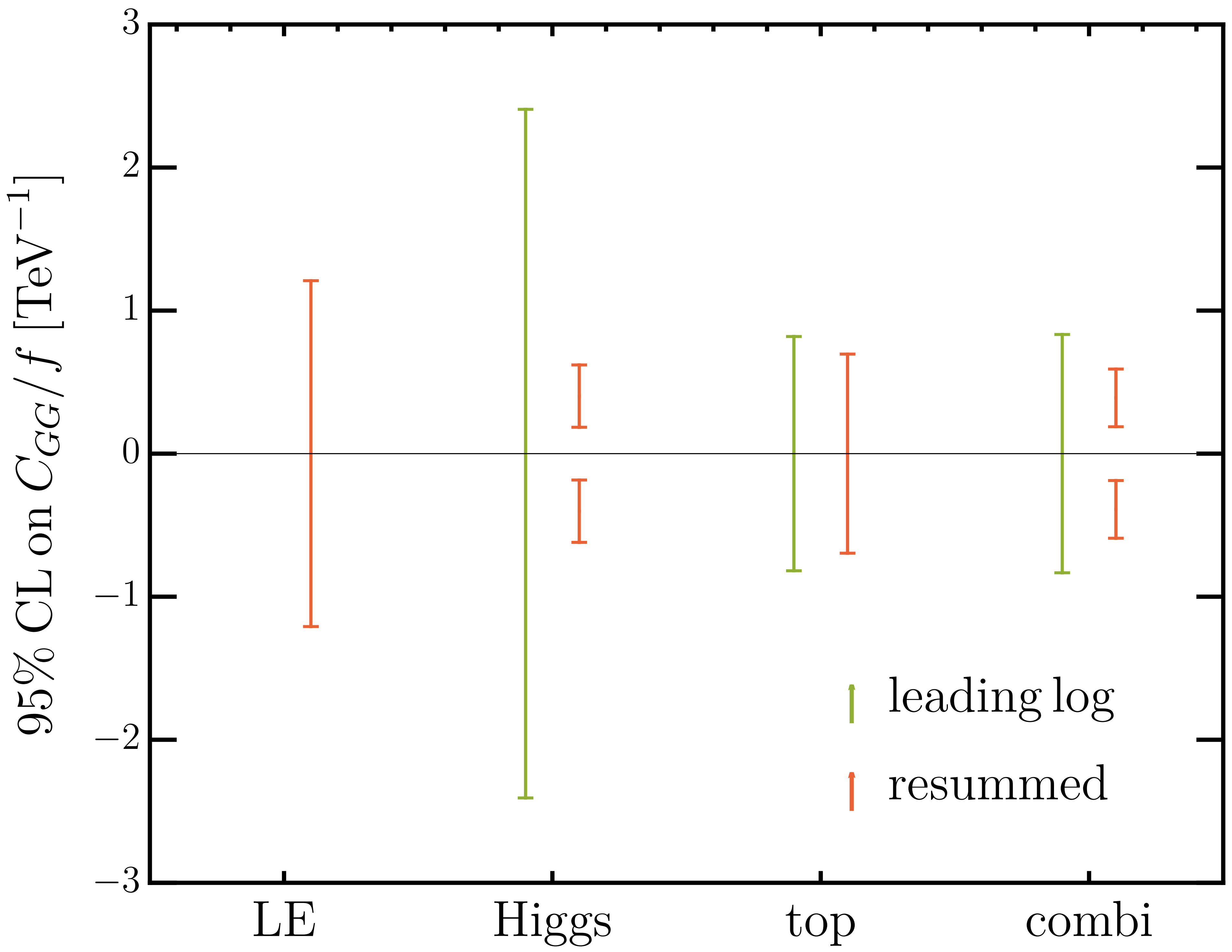


LL approximation - CGG

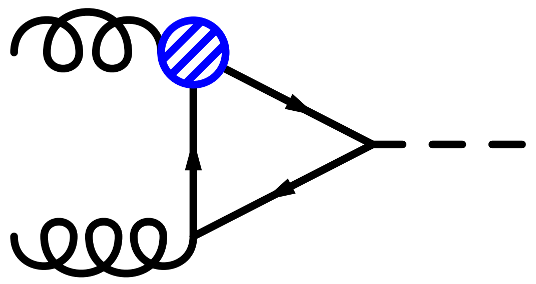
(Small) experimental anomaly in CMS Higgs STXS causes deviation at 95% CL

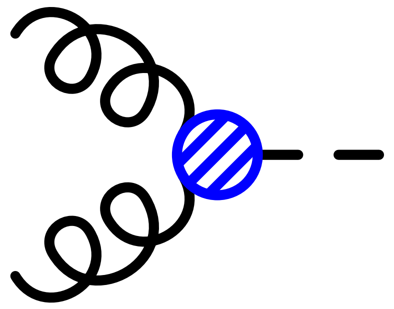
$$[C_{uG}]_{33}(\mu) \supset -\frac{25\, g_s\, y_t\, \alpha_s}{\pi}\, C_{GG}^2\, \ln^2 \frac{\mu}{\Lambda}$$

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



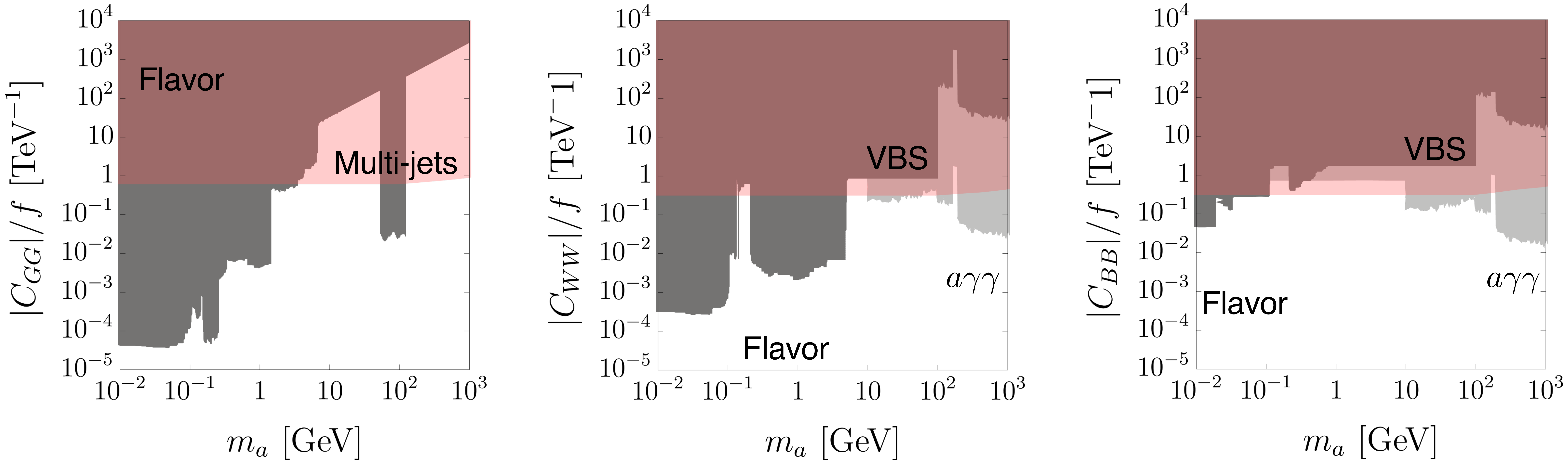
CHG (Higgs-gluon coupling) and CuG (top-gluon coupling) strongly constrained through gluon-fusion Higgs production





Comparison with direct bounds

Light gray bounds with additional assumptions



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

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

[Bauer, Neubert, Thamm (1708.00443)]

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Comparison with direct bounds

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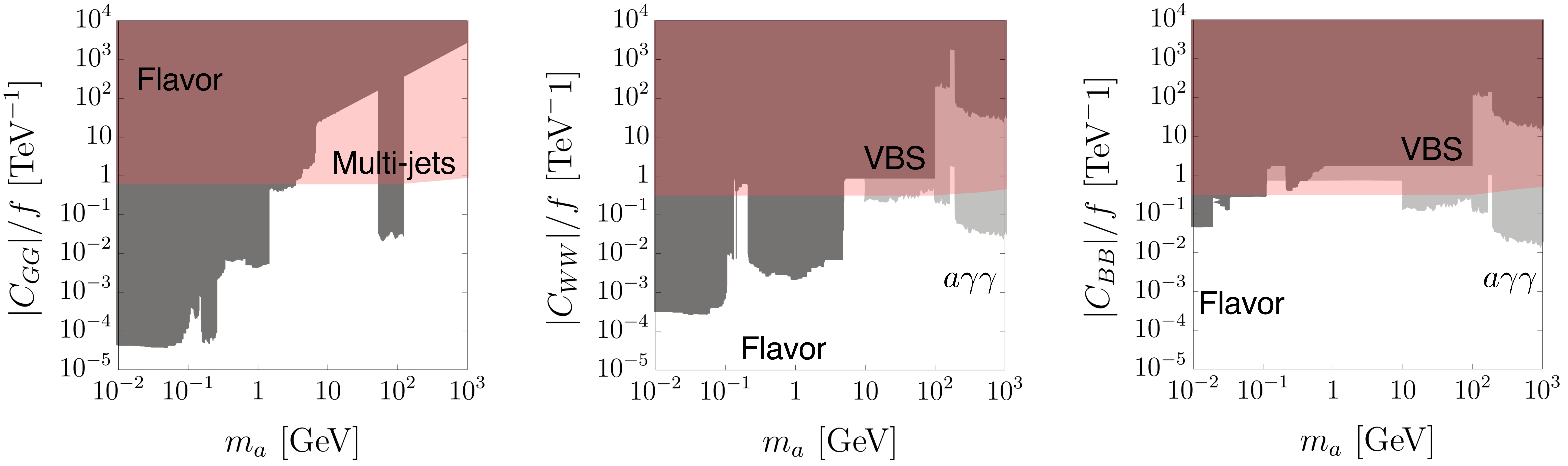

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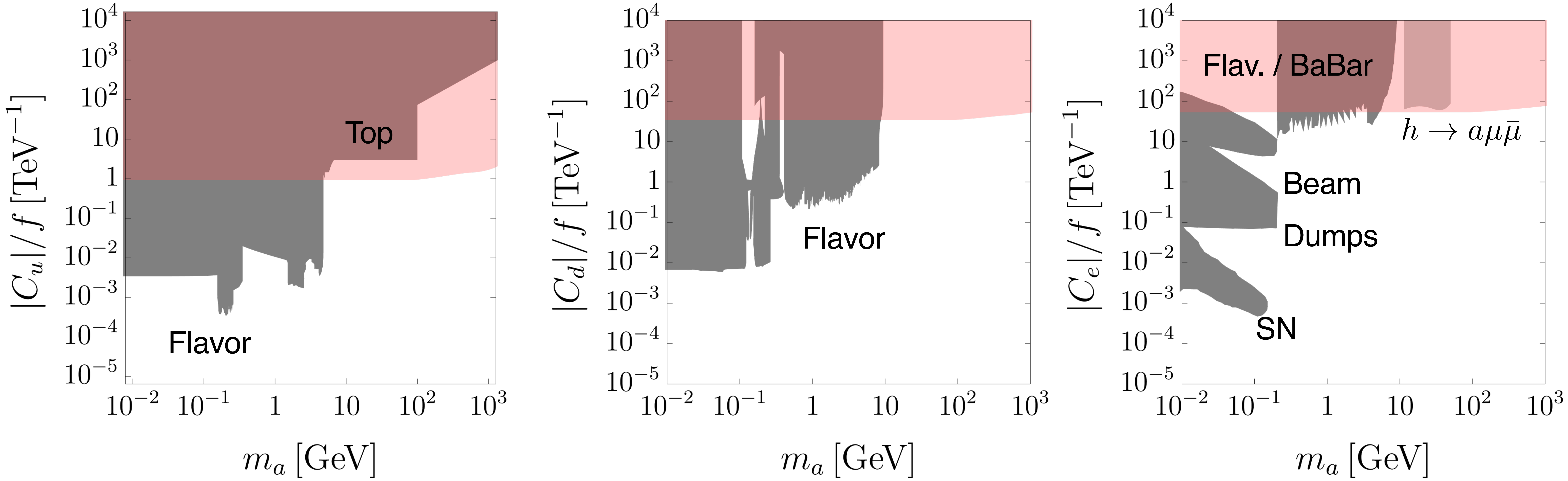
ALP-SMEFT interference tests unconstrained parameter space

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)]

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)]

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

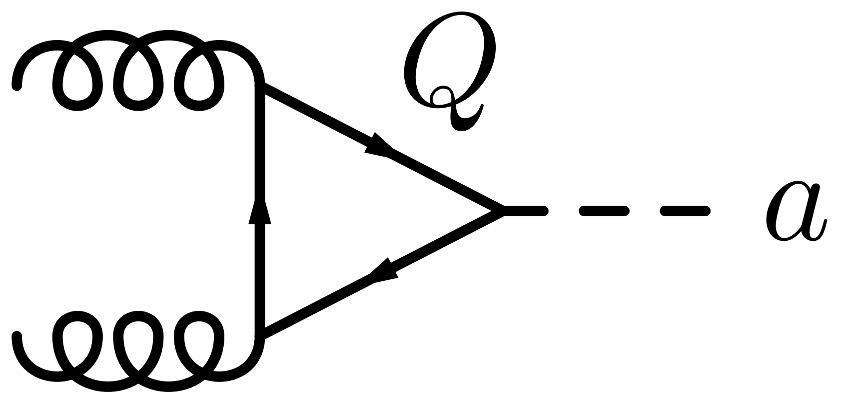
$$Q_{L,R} \sim (\mathbf{3},\mathbf{1})_{-1/3}$$

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

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

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

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

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

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

Heavy particles Φ and ρ

DFSZ model - EFT

Mixing angle α

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

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

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

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

DFSZ model - EFT

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

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

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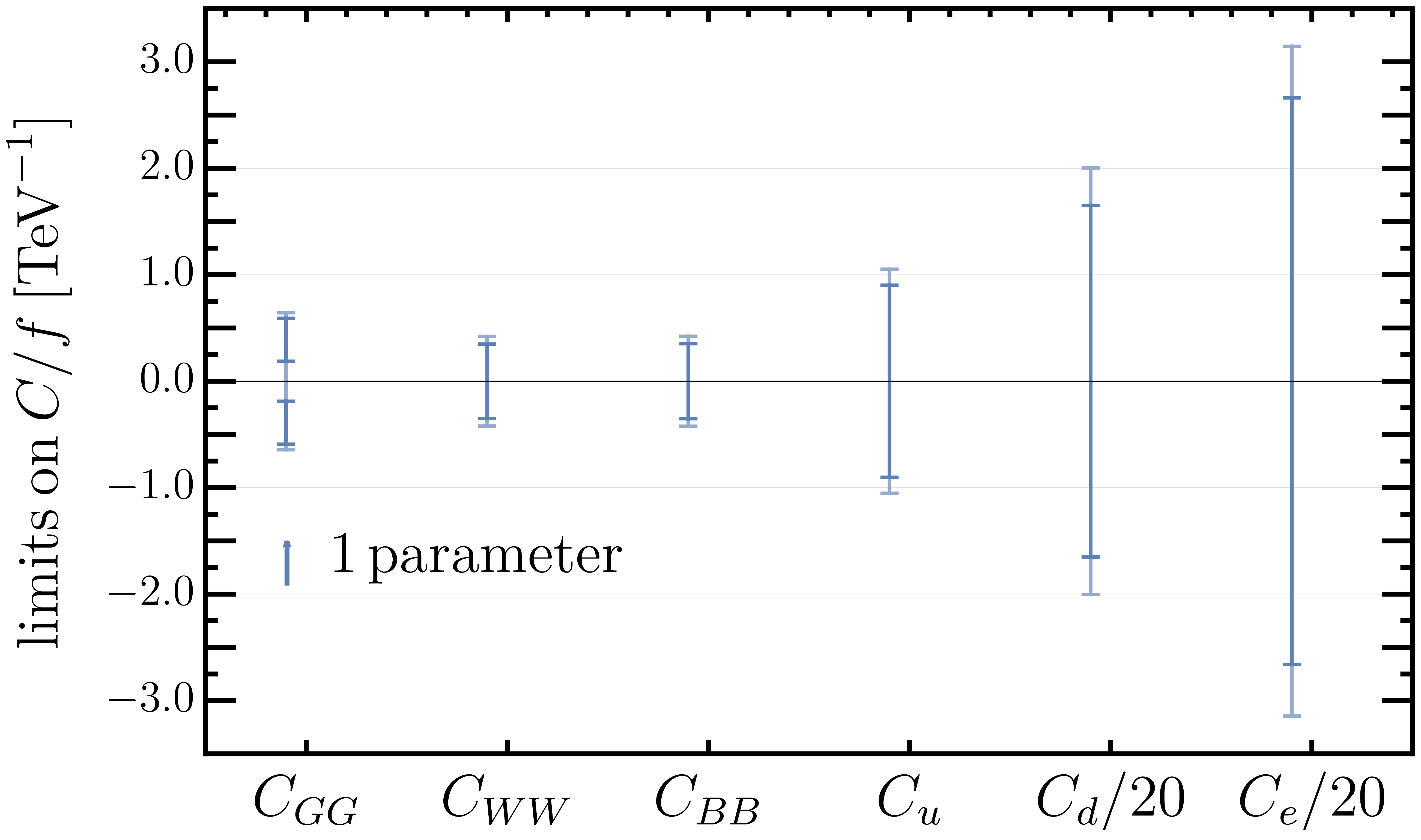

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DFSZ I $\quad C_e = -2s_\alpha^2$

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

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

Yukawa suppressed

DFSZ model - EFT

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

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

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

Mixing angle α

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

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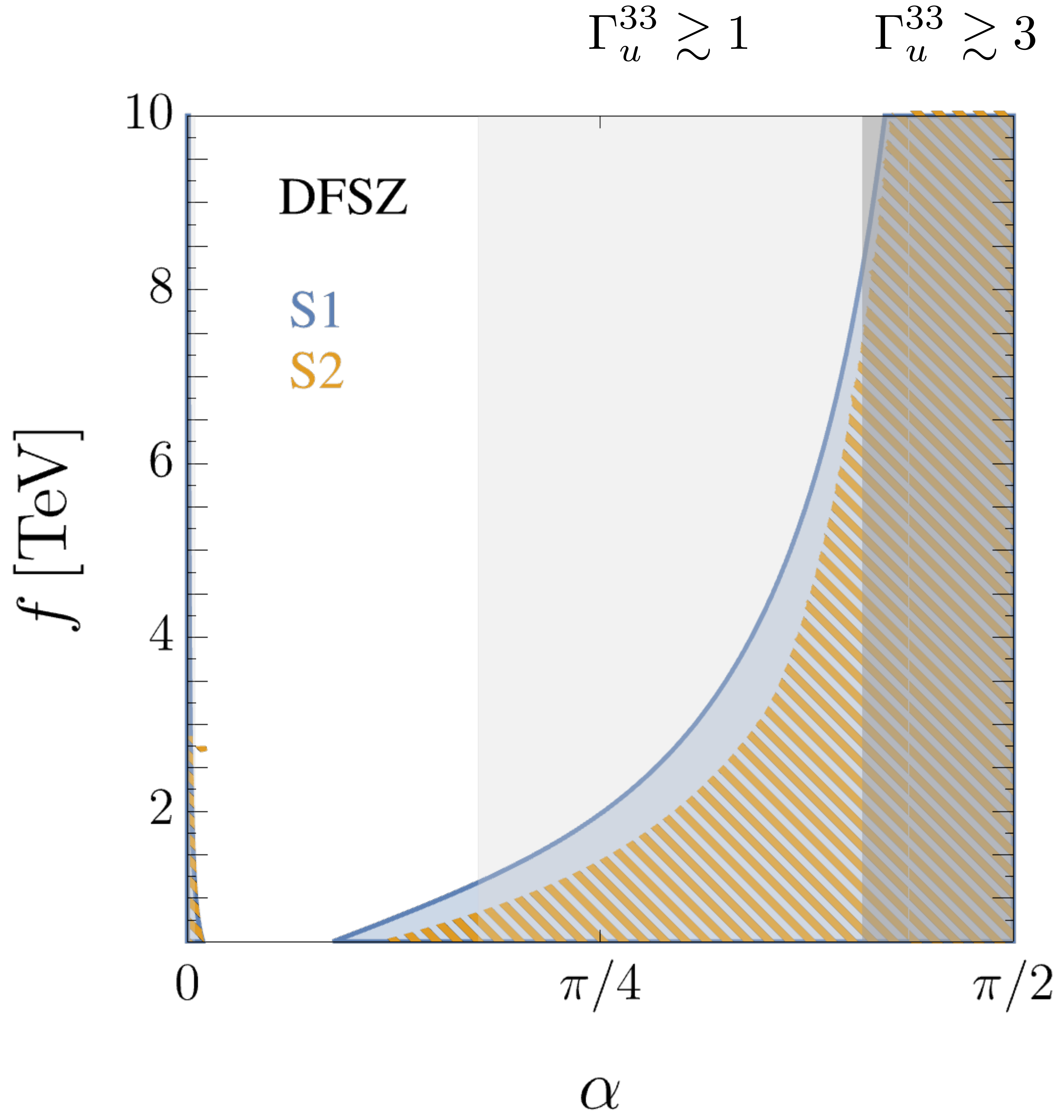
& - \frac{[\mathbf{Y}_e^*]^{sr} [\mathbf{Y}_e]^{pt}\, \eta_\alpha^2}{2M_\Phi^2}[Q_{le}]^{prst} - \frac{1}{M_\Phi^2}\left([\mathbf{Y}_u]^{pr} [\mathbf{Y}_d]^{st} [Q_{quqd}^{(1)}]^{prst} - [\mathbf{Y}_u]^{st} [\mathbf{Y}_e]^{pr}\, t_\alpha \eta_\alpha [Q_{lequ}^{(1)}]^{prst}\right. \\
& \left. - [\mathbf{Y}_d^*]^{st}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

Yukawa suppressed

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

DFSZ models - results



S1: negligible scalar parameters

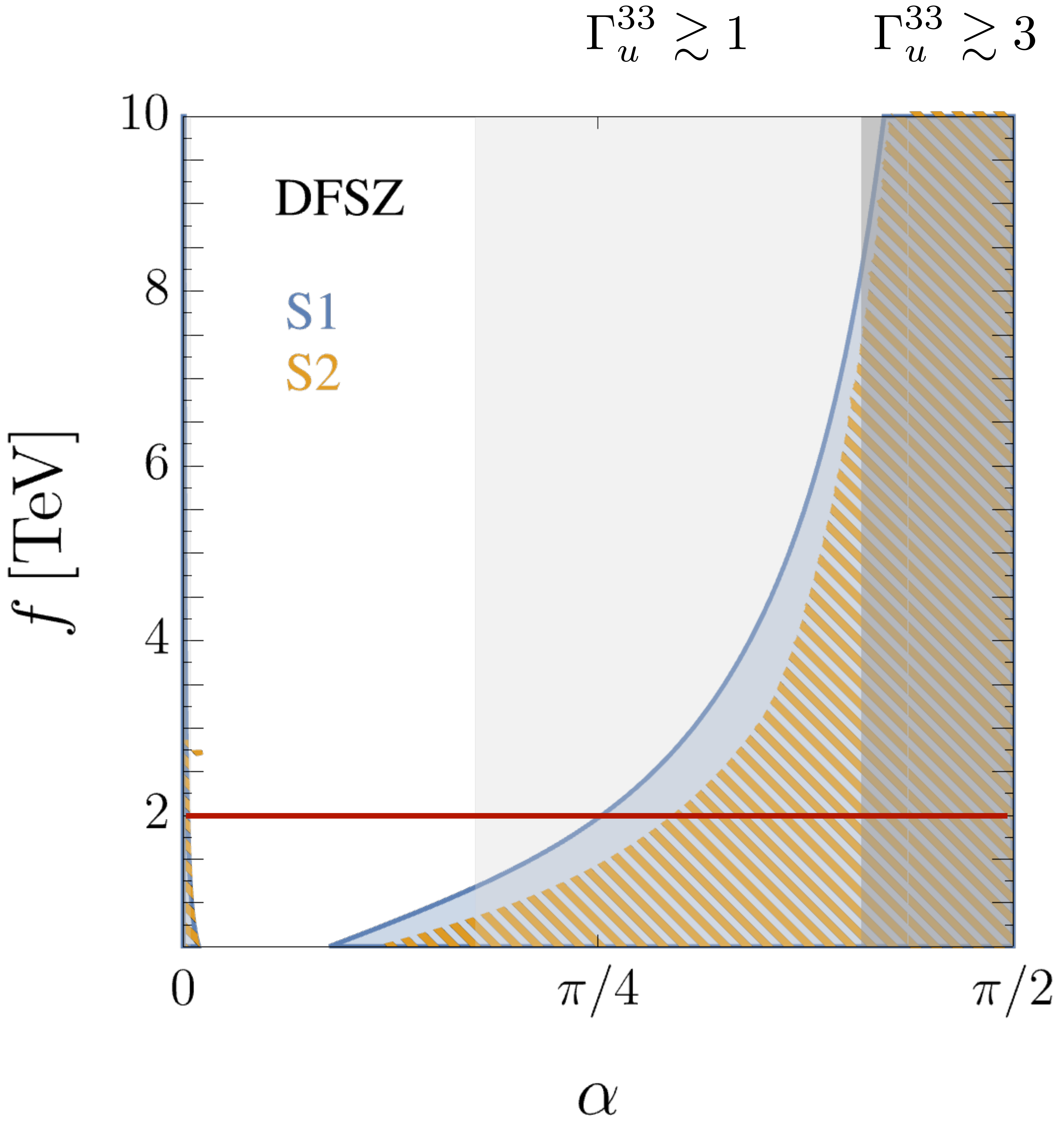
S2: profiling of scalar parameters

Limits on f dominated by SMEFT contributions

DFSZ models - results

$C_u = -2s_\alpha^2$

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



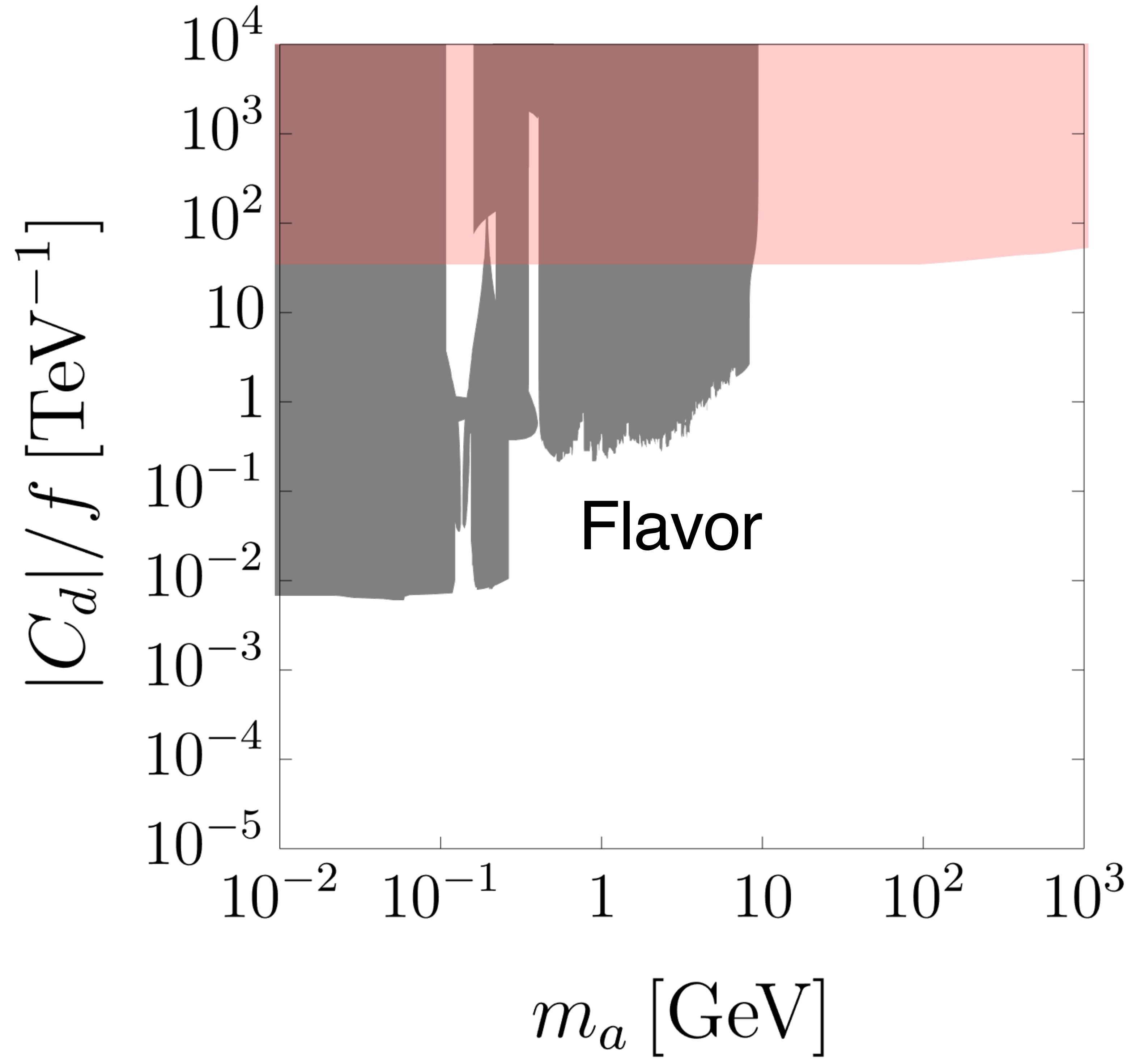
S1: negligible scalar parameters

S2: profiling of scalar parameters

Limits on f dominated by SMEFT contributions

Conclusions

- (Almost) mass-independent bounds on ALP couplings
- Interesting reuse of SMEFT analyses
- Complementary to direct bounds and competitive for high ALP masses
- Interpretation in terms of UV models works



Thank you for your attention!