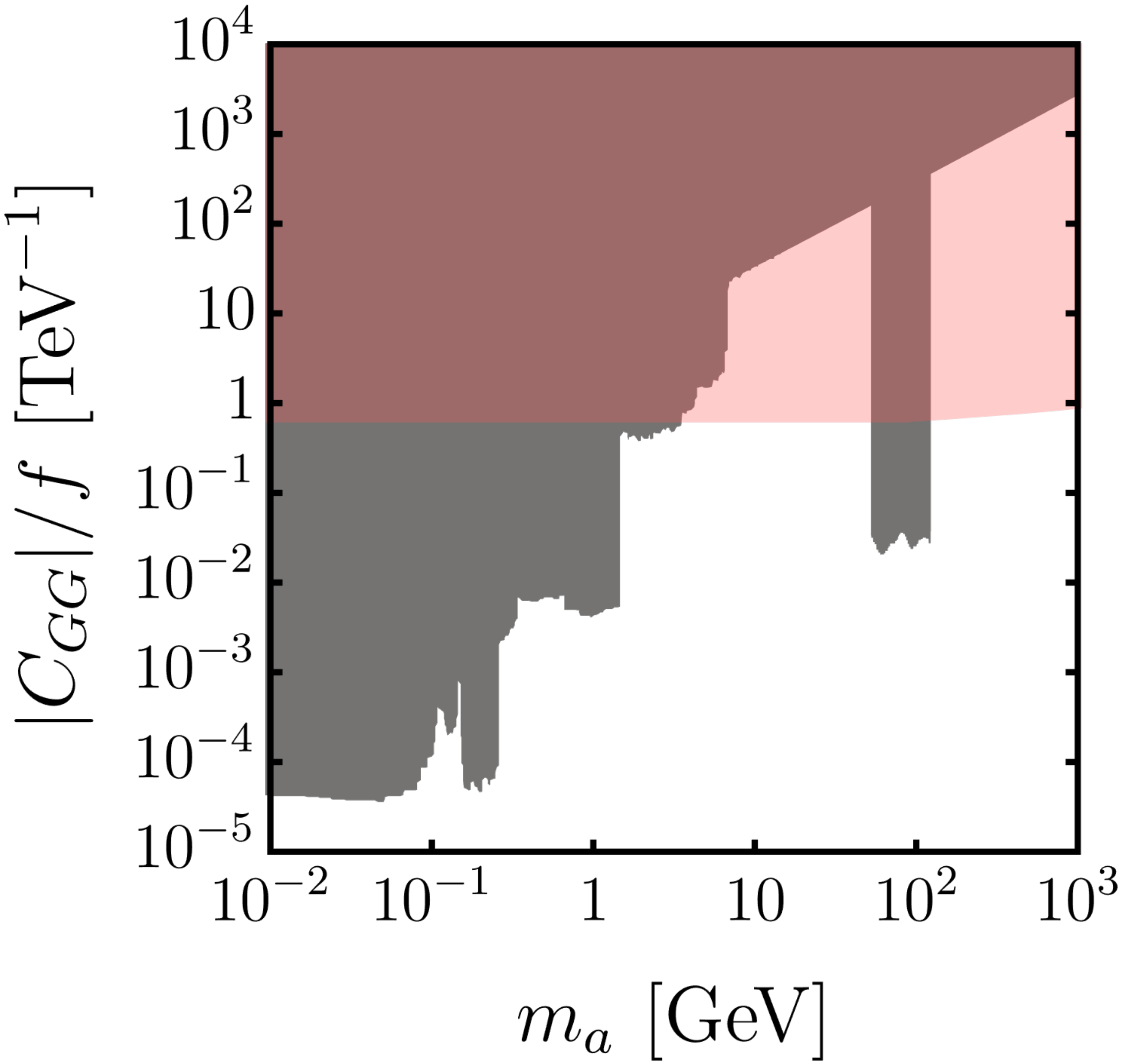
Constraining ALP couplings using SMEFT-interference



Anne Galda

based on

arXiv: 2105.01078

and

arXiv: 2307.10372

In collaboration with

S. Renner and M. Neubert
and
A. Biekötter, J. Fuentes-Martín,
and M. Neubert

PRISMA+

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

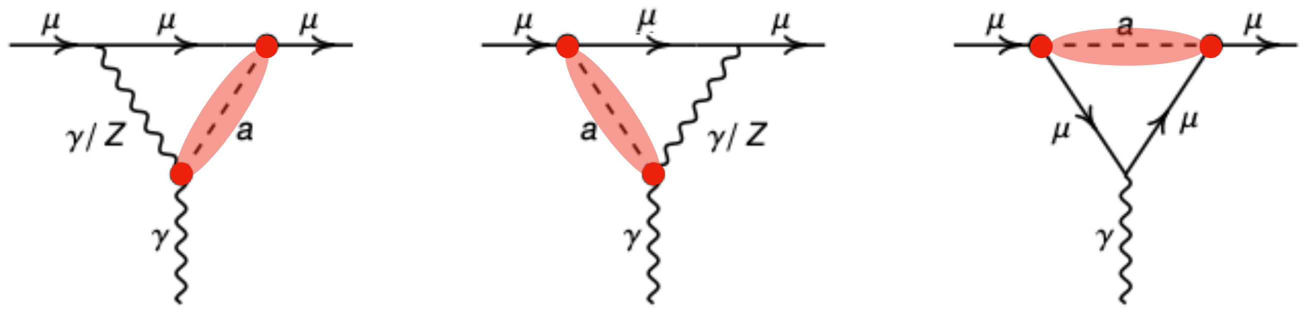
JG|U

Axions and Axion-Like Particles (ALPs)

- **Peccei-Quinn solution to the strong CP-problem** [Peccei, Quinn (1977); Weinberg (1978); Wilczek (1978)]

$$\mathcal{L} = \frac{\theta\alpha_s}{8\pi} G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu} + \frac{a}{f_a}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu} + \ldots$$

- **Potential Dark Matter candidates** [Preskill, Wise, Wilczek (1983)]
- **Give a contribution to** $a_\mu^{\rm exp} - a_\mu^{\rm SM} = 4.2\sigma$ [B. Abi et al. (2021)]



Most general Lagrangian for a classically shift symmetric, gauge singlet, pseudoscalar ALP:

$$\mathcal{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F \boldsymbol{c}_F \gamma_\mu \psi_F$$
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[H. Georgi, D. B. Kaplan, L. Randall (1986)]

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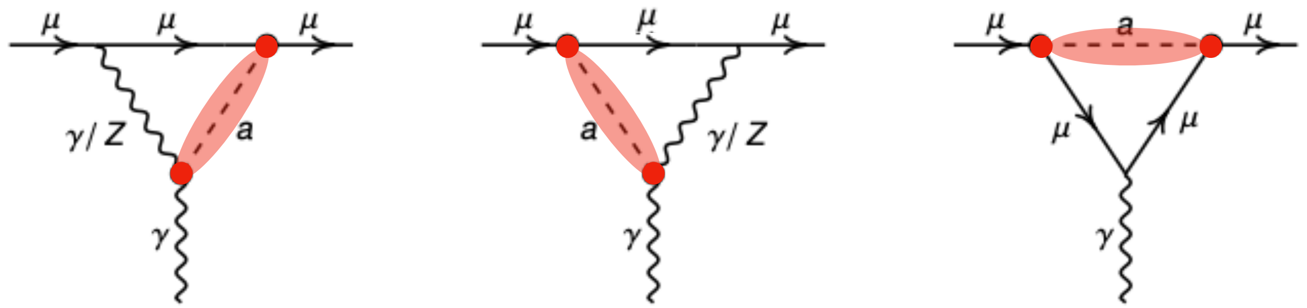

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possible flavor changing interactions ↓

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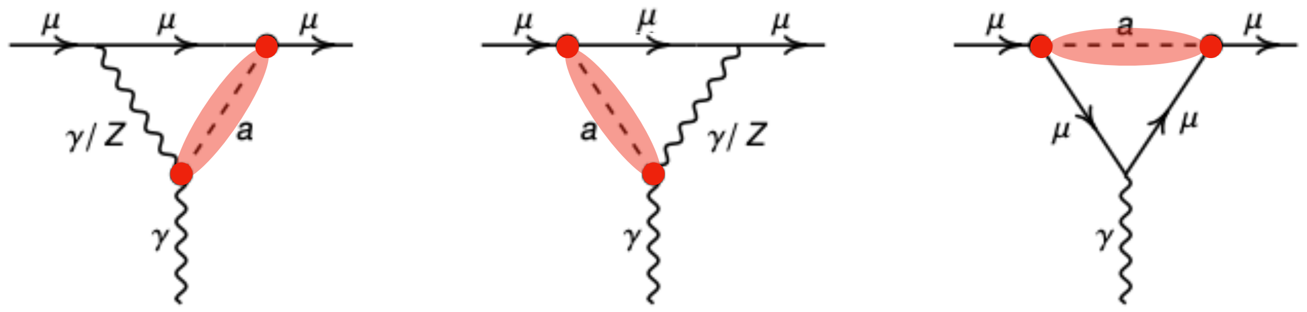

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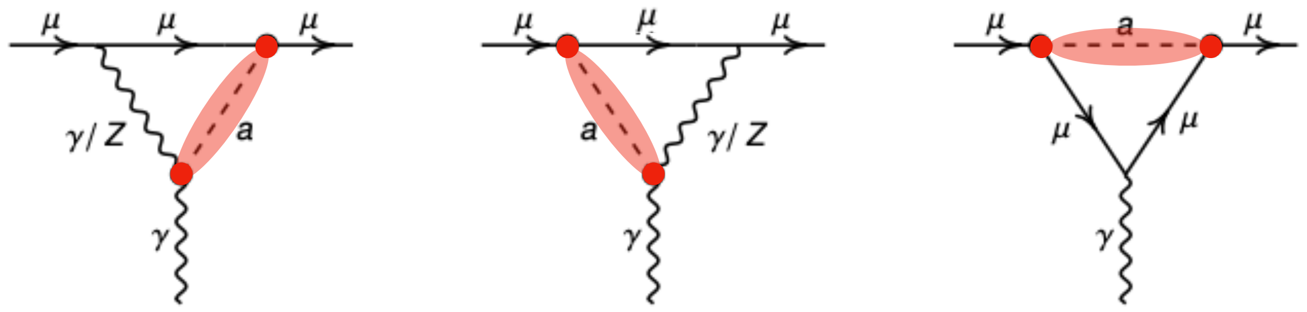

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↪ **Interactions start at dim-5 order!** [H. Georgi, D. B. Kaplan, L. Randall (1986)]

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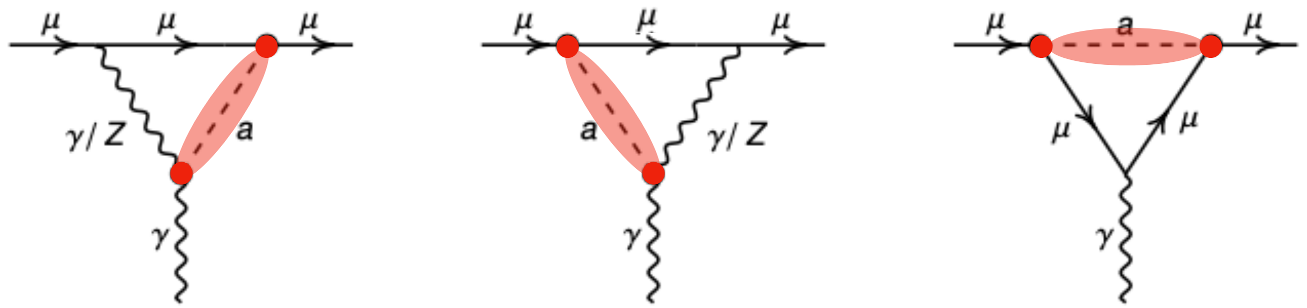

Most general Lagrangian for a classically shift symmetric, gauge singlet, pseudoscalar ALP:

[Bauer, Neubert, Renner, Schnubel, Thamm (2020)]

field redefinition

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

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

flavor universal ALP: $\widetilde{\boldsymbol{Y}}_u \equiv i\, \boldsymbol{Y}_u C_u\,, \quad \widetilde{\boldsymbol{Y}}_d \equiv i\, \boldsymbol{Y}_d C_d\,, \quad \widetilde{\boldsymbol{Y}}_e \equiv i\, \boldsymbol{Y}_e C_e$

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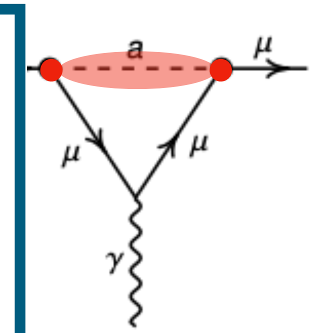
$$C_{GG} = \frac{\alpha_s}{4\pi}\left[c_{GG} + \frac{1}{2}\mathrm{Tr}(\boldsymbol{c}_d + \boldsymbol{c}_u - 2\boldsymbol{c}_Q)\right]$$

$$C_{WW} = \frac{\alpha_2}{4\pi}\left[c_{WW} - \frac{1}{2}\mathrm{Tr}(N_c\,\boldsymbol{c}_Q + \boldsymbol{c}_L)\right]$$

$$C_{BB} = \frac{\alpha_1}{4\pi}\left[c_{BB} + \mathrm{Tr}\left[N_c(\mathcal{Y}_d^2\,\boldsymbol{c}_d + \mathcal{Y}_u^2\,\boldsymbol{c}_u - 2\mathcal{Y}_Q^2\,\boldsymbol{c}_Q) + \mathcal{Y}_e^2\,\boldsymbol{c}_e - 2\mathcal{Y}_L^2\,\boldsymbol{c}_L\right]\right]$$



Most general … **let,**
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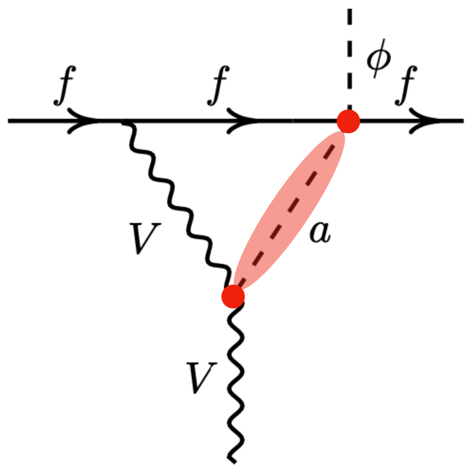
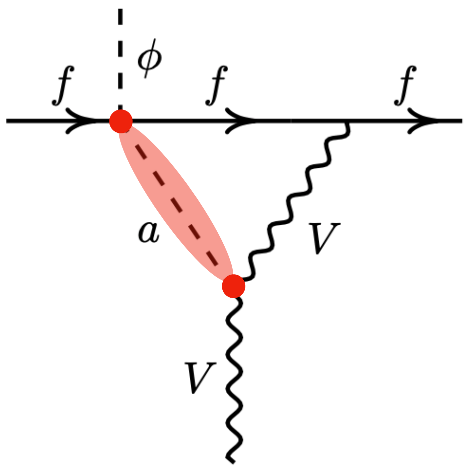
ALP-SMEFT Interference

One-loop diagrams with virtual ALP-exchange and only SM external states, e.g…





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.. are (in general) UV-divergent!

Divergence needs to be absorbed!

here:

C_0^{dipole} x

"bare" UV-divergent quantity

"dipole operator"

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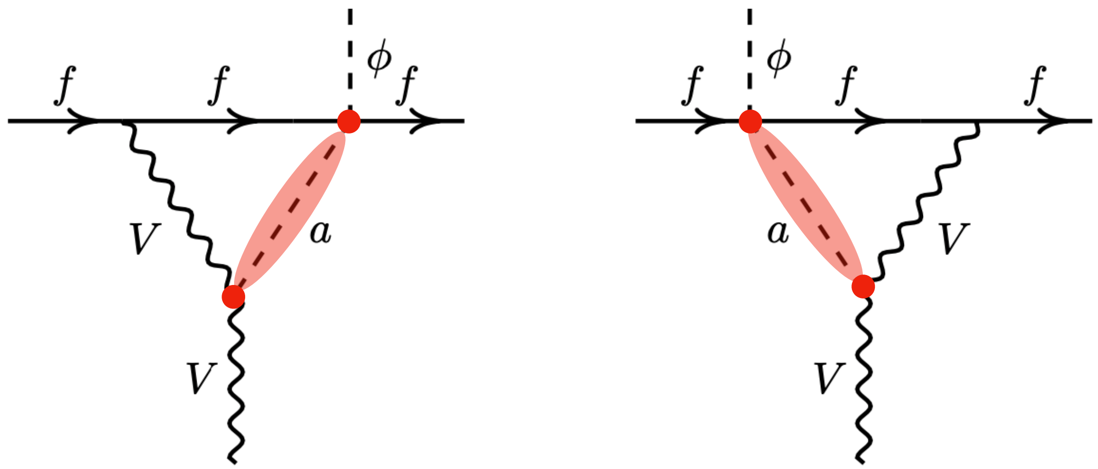

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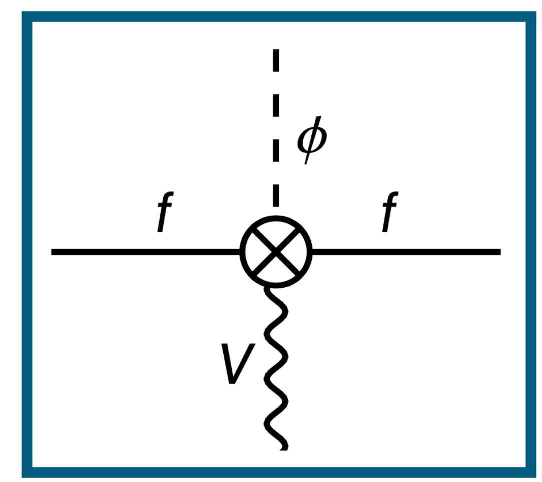

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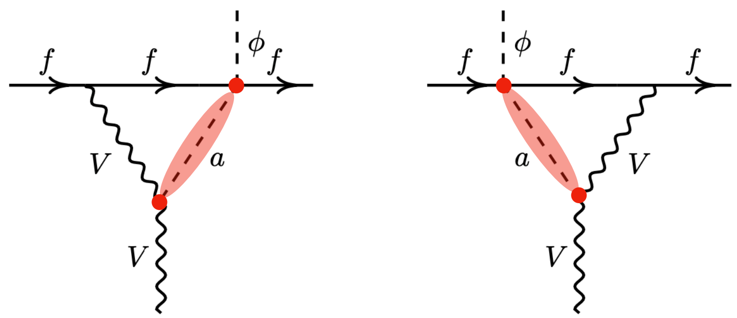
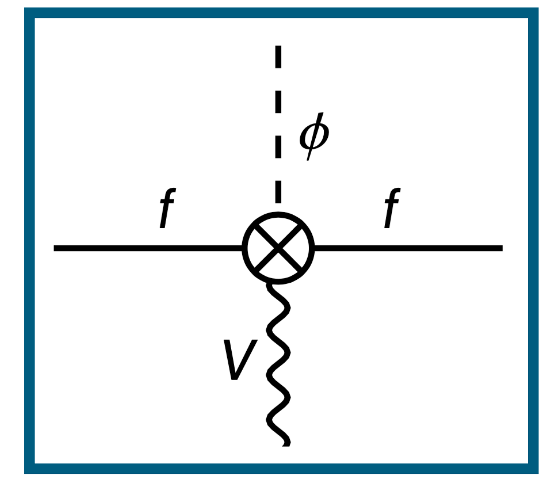


$$C_0^{\text{dipole}}$$ x



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<u>In detail:</u> (still schematically)

$$\mathcal{A}^{\text{dipole}} = \frac{1}{(4\pi f)^2} f(C_\alpha^{\text{ALP}}, C_\beta^{\text{ALP}}) \left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{M^2}\right) + \ldots \right) \langle \mathcal{O}^{\text{dipole}} \rangle$$

ALP-SMEFT Interference

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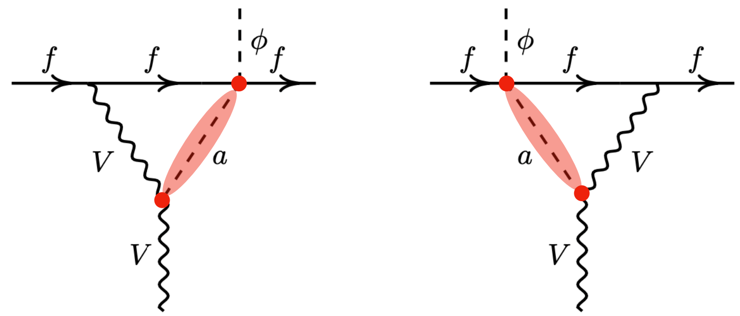
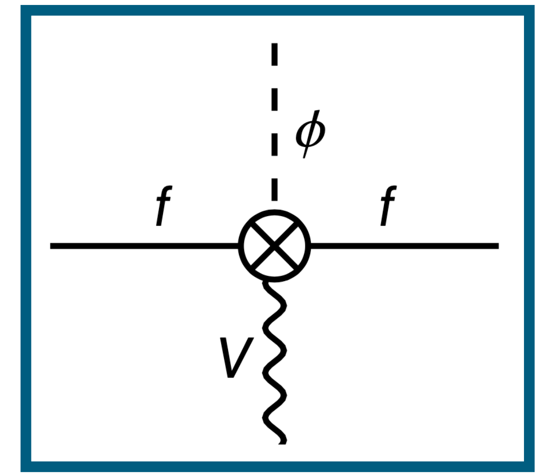


$$C_0^{\text{dipole}} \quad \text{x}$$



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Absorption of the pole in the bare dipole operator Wilson coefficient:

$$C_0^{\text{dipole}} = - \frac{1}{(4\pi f)^2} f(C_\alpha^{\text{ALP}}, C_\beta^{\text{ALP}}) \left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{M^2}\right) + \ldots \right)$$

ALP-SMEFT Interference

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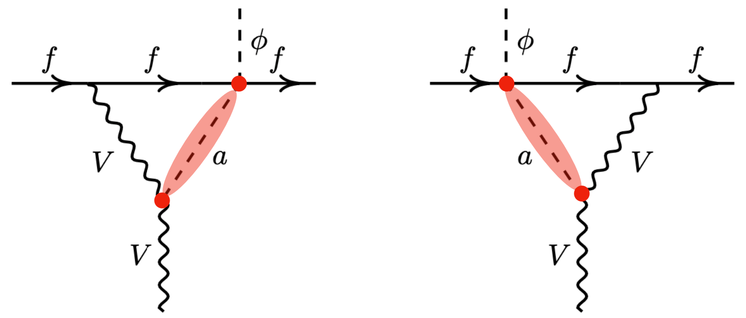
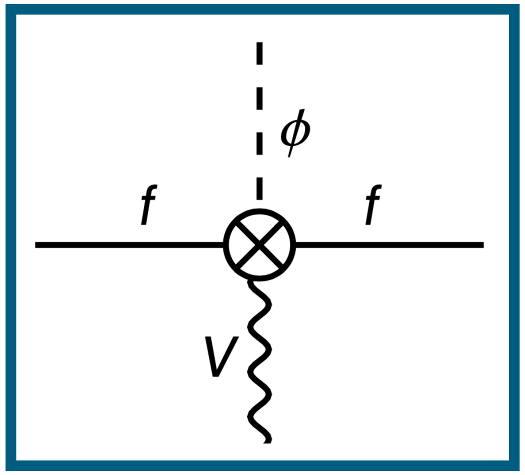


$$C_0^{\text{dipole}} \quad \times$$



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$$C_{\text{ren}}^{\text{dipole}} = - \frac{1}{(4\pi f)^2} f(C_\alpha^{\text{ALP}}, C_\beta^{\text{ALP}}) \left(\cancel{\frac{1}{\epsilon}} + \ln\left(\frac{\mu^2}{M^2}\right) + \dots \right)$$

ALP-SMEFT Interference

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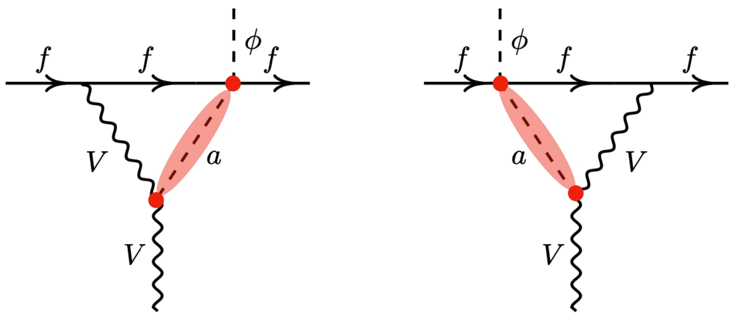

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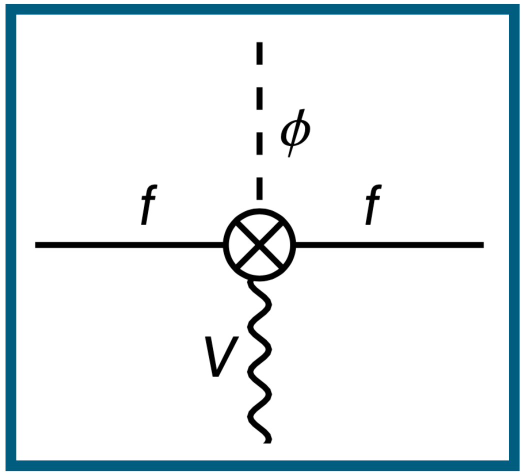

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derivative wrt. scale

$$\frac{d}{d\ln\mu} C_{\text{ren}}^{\text{dipole}} = -\frac{2}{(4\pi f)^2}\, f(C_\alpha^{\text{ALP}}, C_\beta^{\text{ALP}}) \equiv \frac{S^{\text{dipole}}}{(4\pi f)^2}$$

ALP-SMEFT Interference

Main message of this talk:

Dimension-6 SMEFT Wilson coefficients are generated via modification of the Renormalization Group evolution even if the ALP is very light!

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

[AG, Neubert, Renner (2021)]

→ **Nearly the whole SMEFT Warsaw basis is generated at one-loop order!** [Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)]

(ALP-SMEFT Interference)

ALP source terms: Systematic Study

Consider a (redundant) off-shell (Green's) basis of dim-6 operators

$\hookrightarrow$ compute one-particle irreducible diagrams only

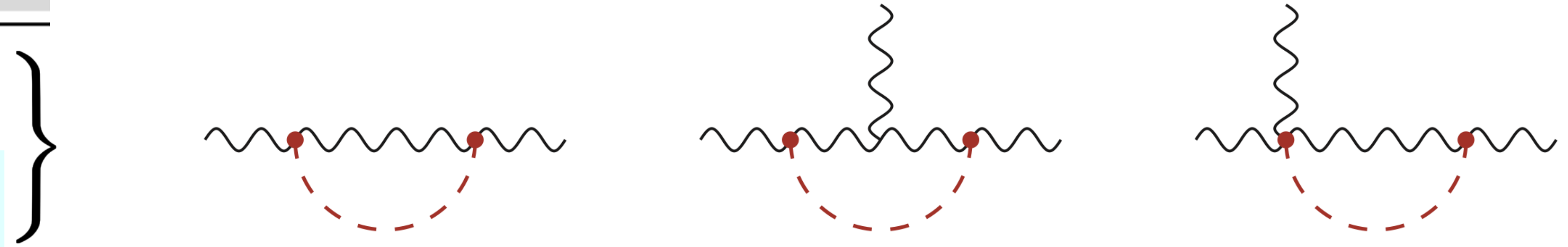
Purely bosonic	Single fermion current	4-fermion operators
X^3	$\psi^2 XD$	$(\bar{L}L)(\bar{L}L)$
X^2D^2	$\psi^2 D^3$	$(\bar{R}R)(\bar{R}R)$
X^2H^2	$\psi^2 XH$	$(\bar{L}L)(\bar{R}R)$
XH^2D^2	$\psi^2 H^3$	$(\bar{L}R)(\bar{R}L)$
H^6	$\psi^2 H^2 D$	$(\bar{L}R)(\bar{L}R)$
H^4D^2	$\psi^2 HD^2$	B-violating
H^2D^4		

blue: operator NOT present in the Warsaw basis

ALP source terms: Systematic Study

Some example diagrams:

Purely bosonic
X^3
$X^2 D^2$
$X^2 H^2$
$X H^2 D^2$
H^6
$H^4 D^2$
$H^2 D^4$



ALP source terms: Systematic Study

Some example diagrams:

Single fermion current
$\psi^2 X D$
$\psi^2 D^3$
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$\psi^2 H^2 D$
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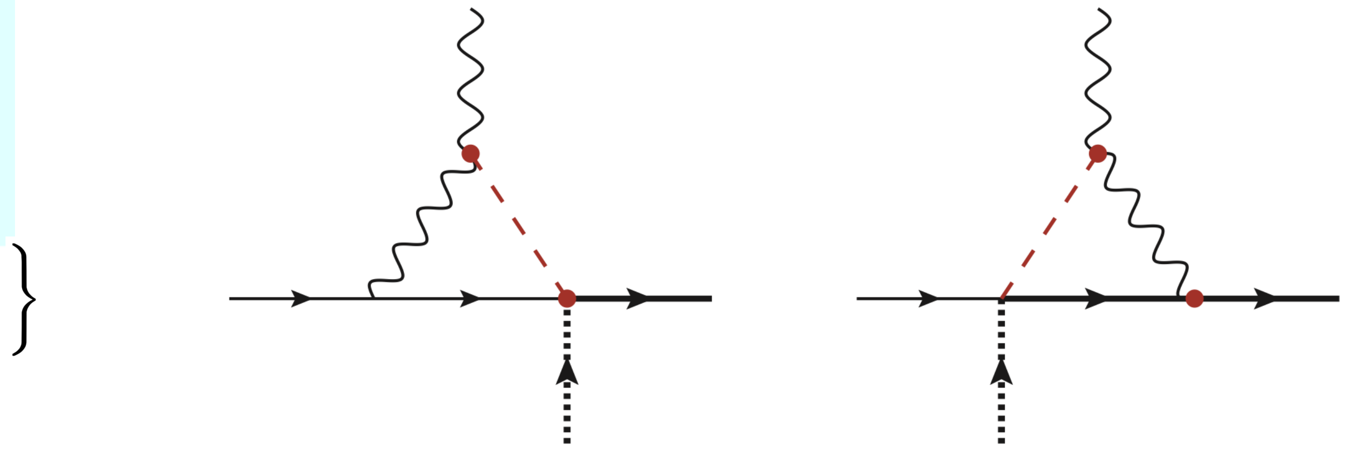

ALP source terms: Systematic Study

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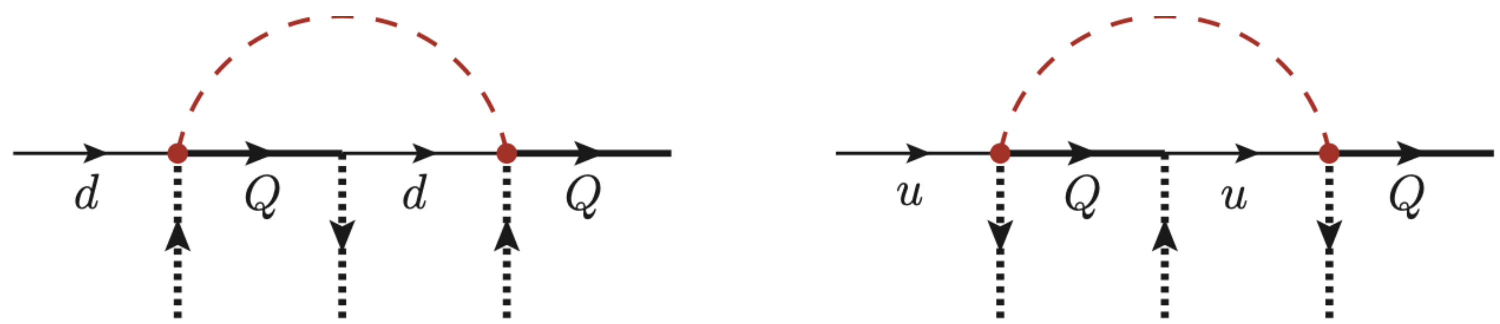

…etc!

ALP source terms: Systematic Study

Some example diagrams:

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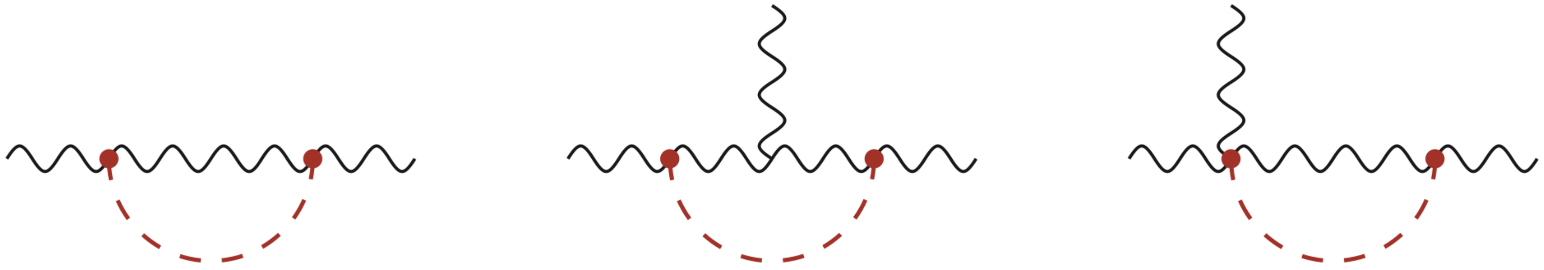

$$\mathcal{A}(gg(g)) = -\frac{C_{GG}^2}{\epsilon}\left[4g_s\,\langle Q_G\rangle + \frac{4}{3}\langle\hat{Q}_{G,2}\rangle - 2m_a^2\langle G^a_{\mu\nu}\,\tilde{G}^{\mu\nu,a}\rangle\right]$$

$$+\text{ finite}$$

where $\hat{Q}_{G,2} = (D^\rho G_{\rho\mu})^a(D_\omega G^{\omega\mu})^a$

ALP source terms: Systematic Study

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$$\widehat{Q}_{G,2} \cong g_s^2\left(\bar{Q}\gamma_\mu T^a Q + \bar{u}\gamma_\mu T^a u + \bar{d}\gamma_\mu T^a d\right)^2$$

$$= g_s^2\left[\frac{1}{4}\left([Q_{qq}^{(1)}]_{prrp} + [Q_{qq}^{(3)}]_{prrp}\right) - \frac{1}{2N_c}[Q_{qq}^{(1)}]_{pprr} + \frac{1}{2}[Q_{uu}]_{prrp} - \frac{1}{2N_c}[Q_{uu}]_{pprr}\right.$$

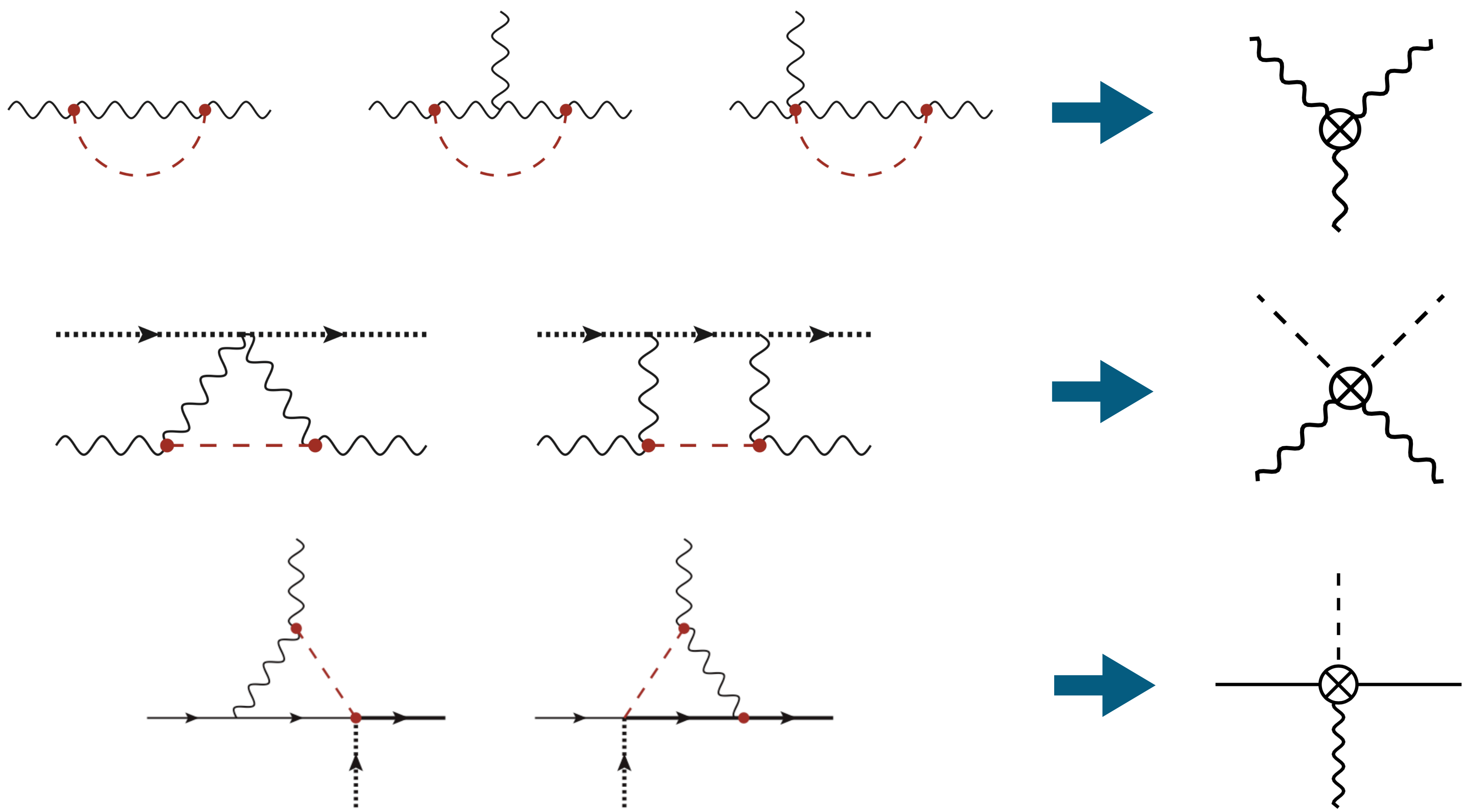
$$\left. + \frac{1}{2}[Q_{dd}]_{prrp} - \frac{1}{2N_c}[Q_{dd}]_{pprr} + 2[Q_{qu}^{(8)}]_{pprr} + 2[Q_{qd}^{(8)}]_{pprr} + 2[Q_{ud}^{(8)}]_{pprr}\right]$$

→ **Contribution to <u>fermionic operators</u> from pure gluon amplitude!**

ALP source terms: Systematic Study

A consistent effective theory **necessarily** includes the **dimension-6 SMEFT Lagrangian**!

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{SM+ALP}} + \mathcal{L}_{\text{SMEFT}}$$



$$S_G = 8\, g_s\, C_{GG}^2$$
$$S_W = 8\, g_2\, C_{WW}^2$$

$$S_{HW} = -2\, g_2^2\, C_{WW}^2$$
$$S_{HB} = -2\, g_1^2\, C_{BB}^2$$
$$S_{HWB} = -4\, g_1\, g_2\, C_{BB}\, C_{WW}$$

e.g. leptonic:

$$\boldsymbol{S}_{eB} = -2ig_1\,(\mathcal{Y}_L + \mathcal{Y}_e)\,\widetilde{\boldsymbol{Y}}_e\, C_{BB}$$
$$\boldsymbol{S}_{eW} = -2ig_2\,\widetilde{\boldsymbol{Y}}_e\, C_{WW}$$

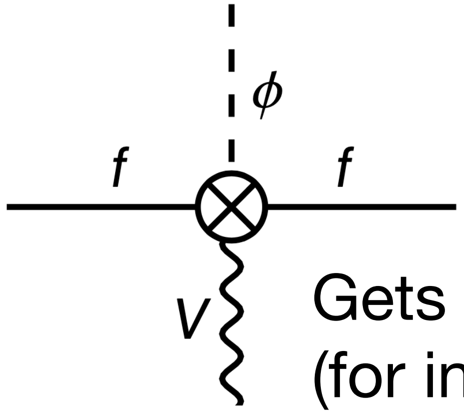
[AG, Neubert, Renner (2021)]

...etc!

ALP constraints from SMEFT fits

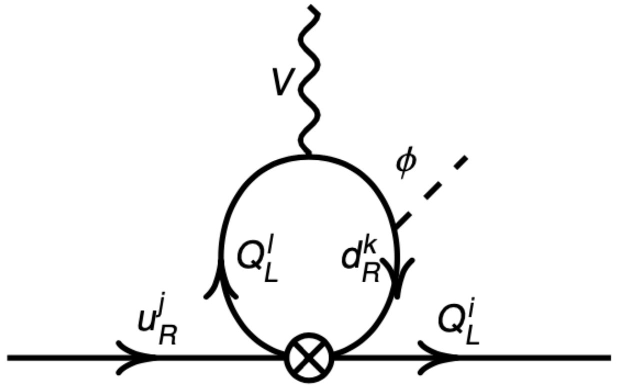
$$\frac{d}{d\ln\mu}C_i^{\text{SMEFT}} - \gamma_{ji}^{\text{SMEFT}} C_j^{\text{SMEFT}} = \frac{S_i}{(4\pi f)^2} \qquad (\text{for } \mu < 4\pi f)$$

- **Mixing: Large set of coupled differential equations!**

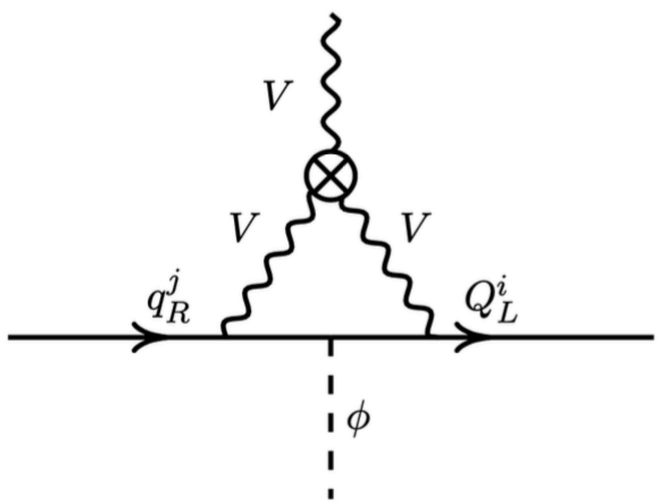


Gets contributions from (for instance)

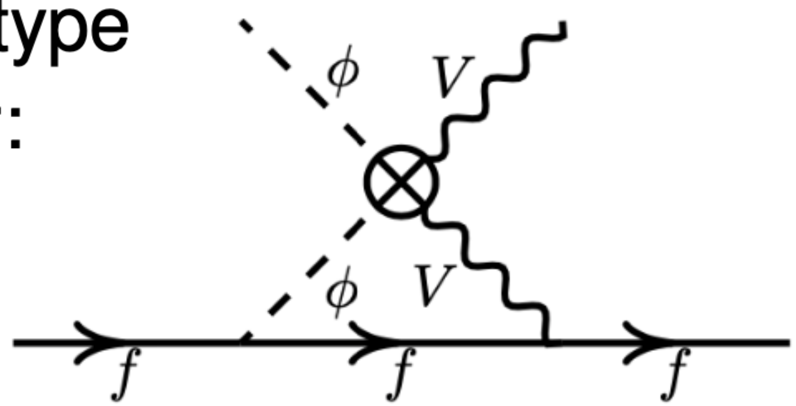
four-fermion operator:



Weinberg operator:



$Q_{HV(V')}$-type operator:



ALP constraints from SMEFT fits

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- **Mixing: Large set of coupled differential equations!**
- **Solved numerically using a modified version of** `DsixTools` [Celis, Fuentes-Martín, Vicente, Virto (2017), Fuentes-Martín, Ruiz-Femenia, Vicente, Virto (2020)]

Result: **SMEFT Wilson coefficients at a low scale μ in terms of ALP-couplings at the scale Λ.**

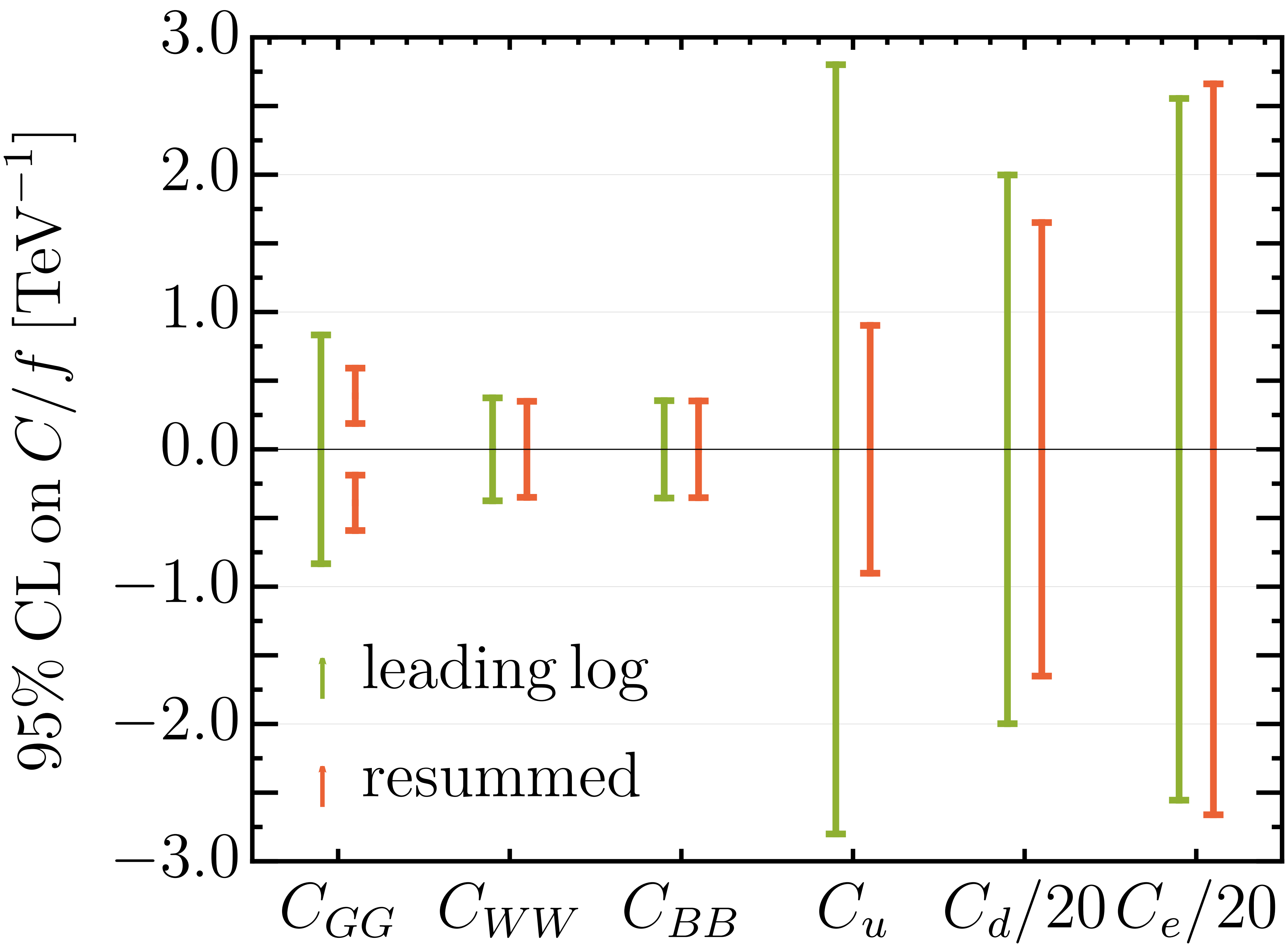
We use SMEFT constraints from low-energy, Higgs and top data in a χ^2 fit to constrain the ALP-coefficients.

$$\chi^2(C_i) = \left[\vec{d} - \vec{p}(C_i)\right]^T \boldsymbol{V}^{-1} \left[\vec{d} - \vec{p}(C_i)\right]$$

from e.g. [Ellis, Madigan, Mimasu, Sanz, You (2021)]

Leading-Logarithmic vs. Resumed Fit

$$C_{i,\mathrm{LL}}^{\mathrm{SMEFT}}(\mu) = \frac{S_i(\Lambda)}{(4\pi f)^2}\ \ln\frac{\mu}{\Lambda}$$



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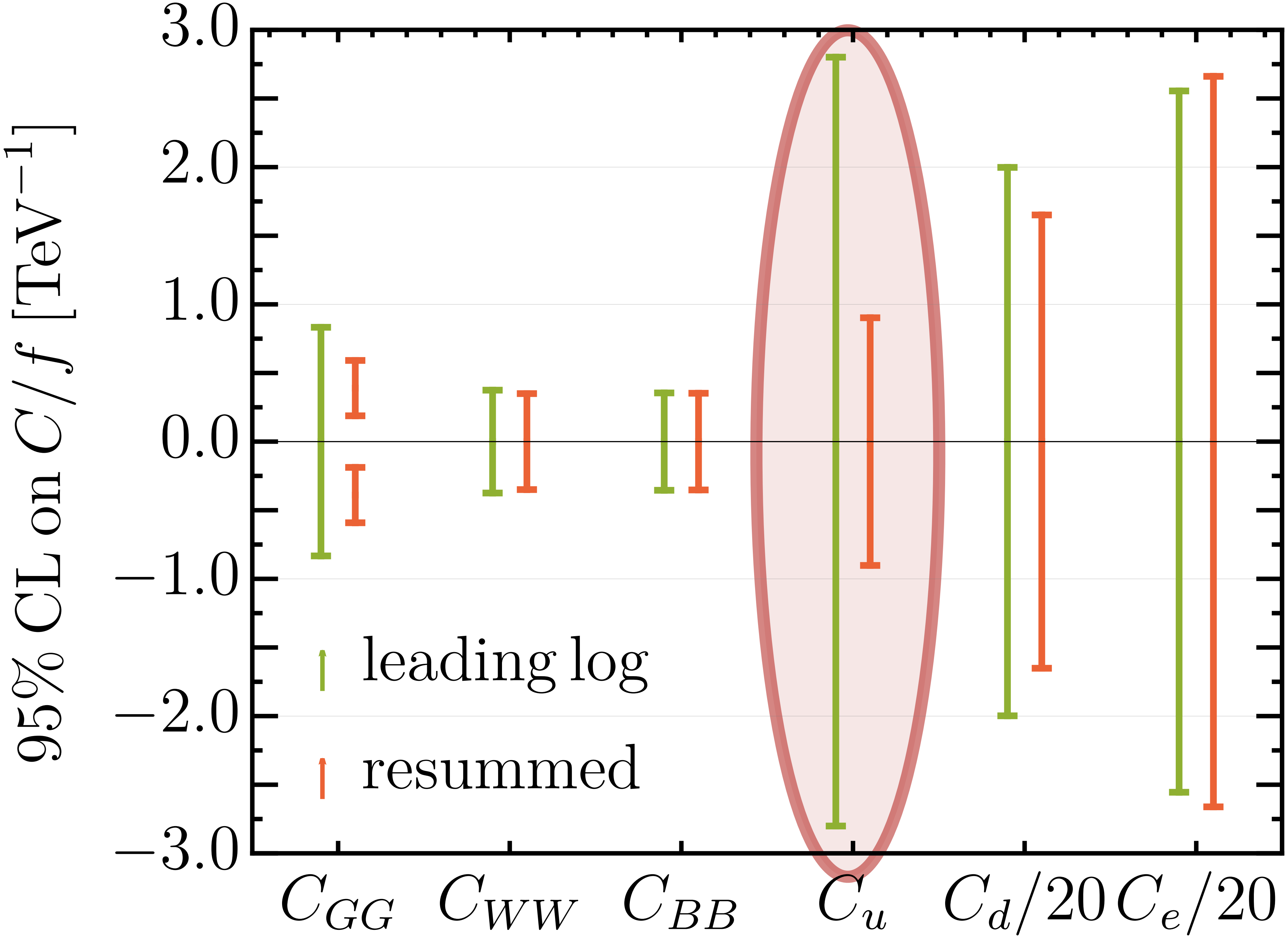

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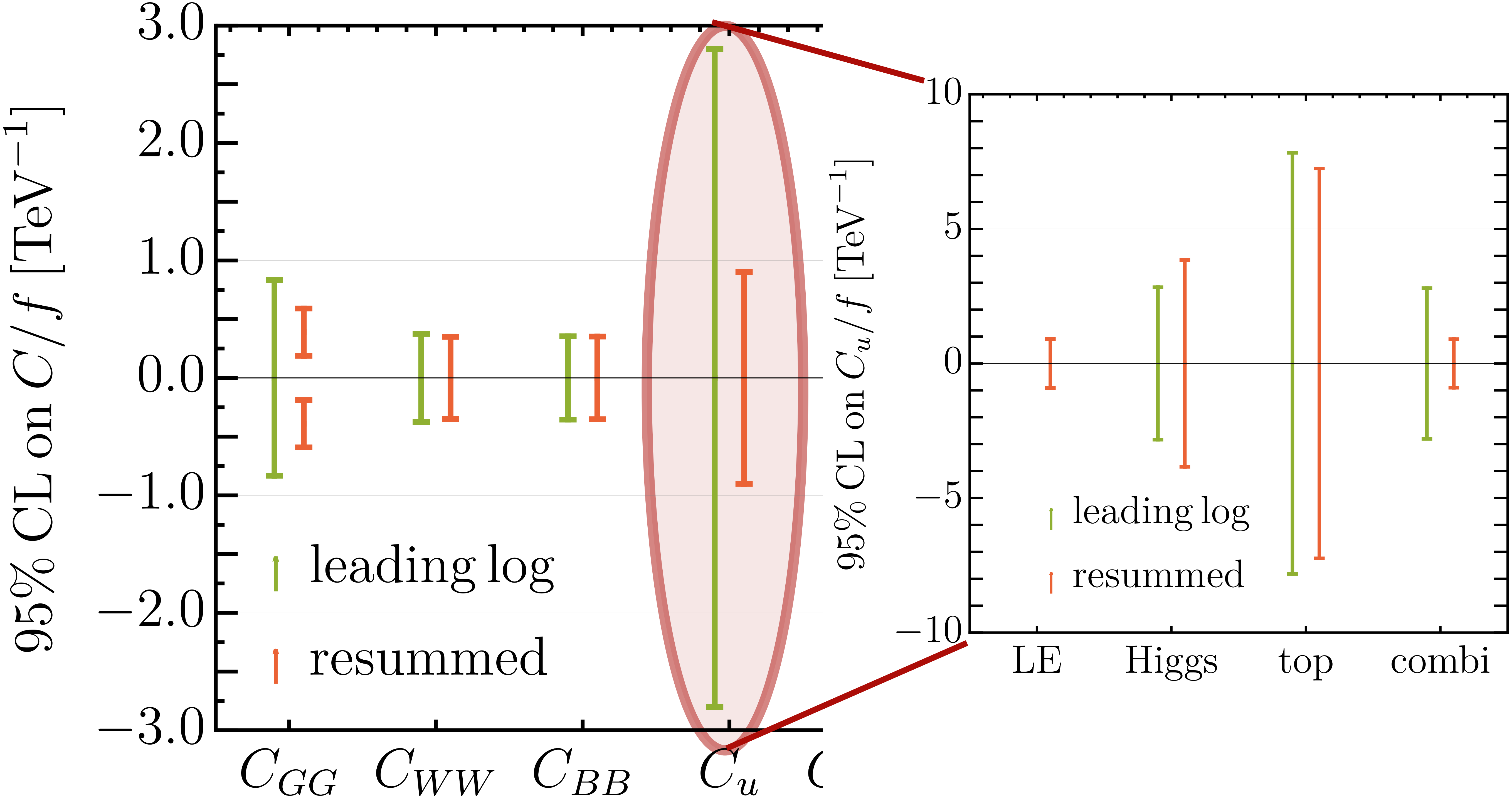

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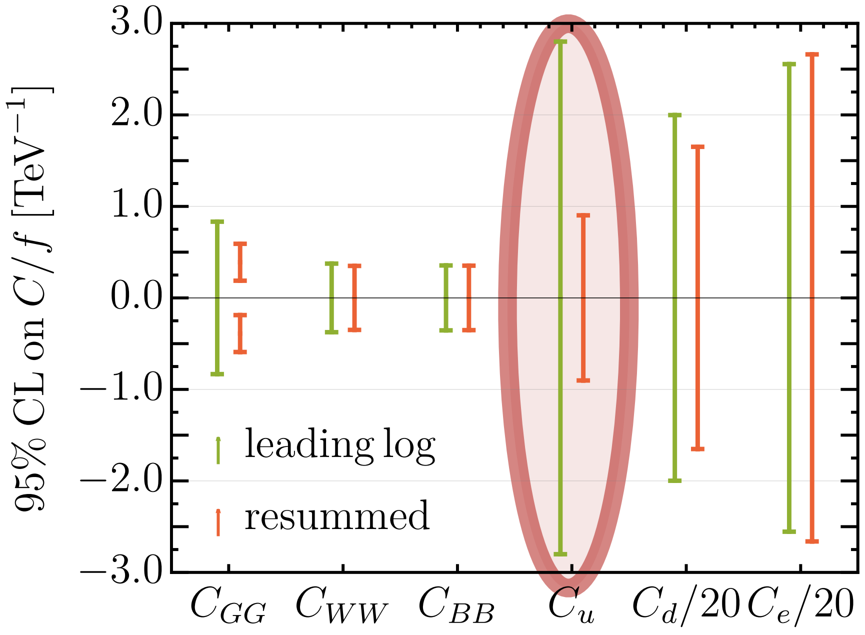


RG Evolution Equation for C_{HD} :

$$\alpha_t \equiv \frac{y_t^2}{4\pi}$$

neglecting $\alpha_i \neq \alpha_s$ and all Yukawa couplings except y_t

[Jenkins, Manohar, Trott (2013)
Alonso, Jenkins, Manohar, Trott (2014)]

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

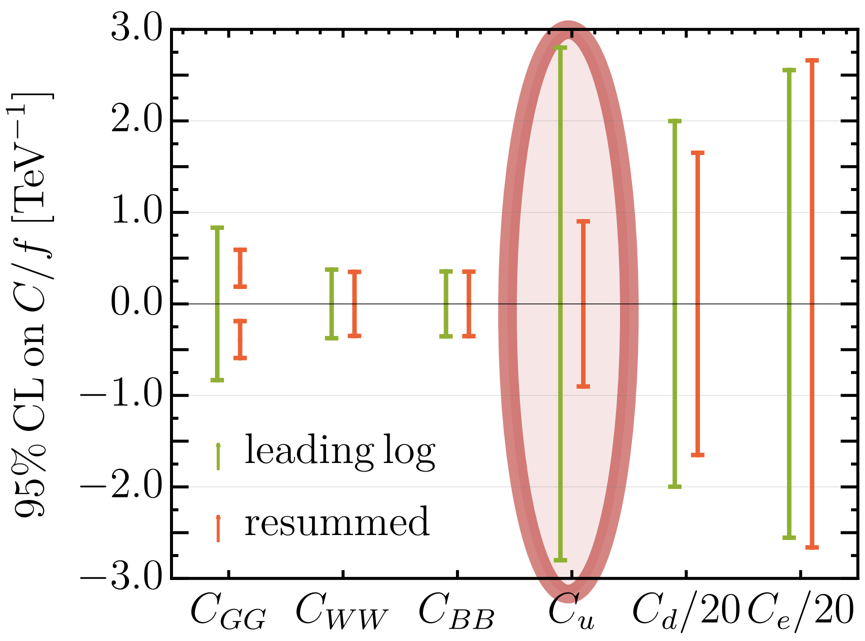
where

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

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

$$Q_{HD} = (H^\dagger D^\mu H)^\star\,(H^\dagger D_\mu H)$$
$$Q_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)\,(\bar{Q}_p \gamma^\mu Q_r)$$
$$Q_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)\,(\bar{u}_p \gamma^\mu u_r)$$

Leading-Logarithmic vs. Resumed Fit



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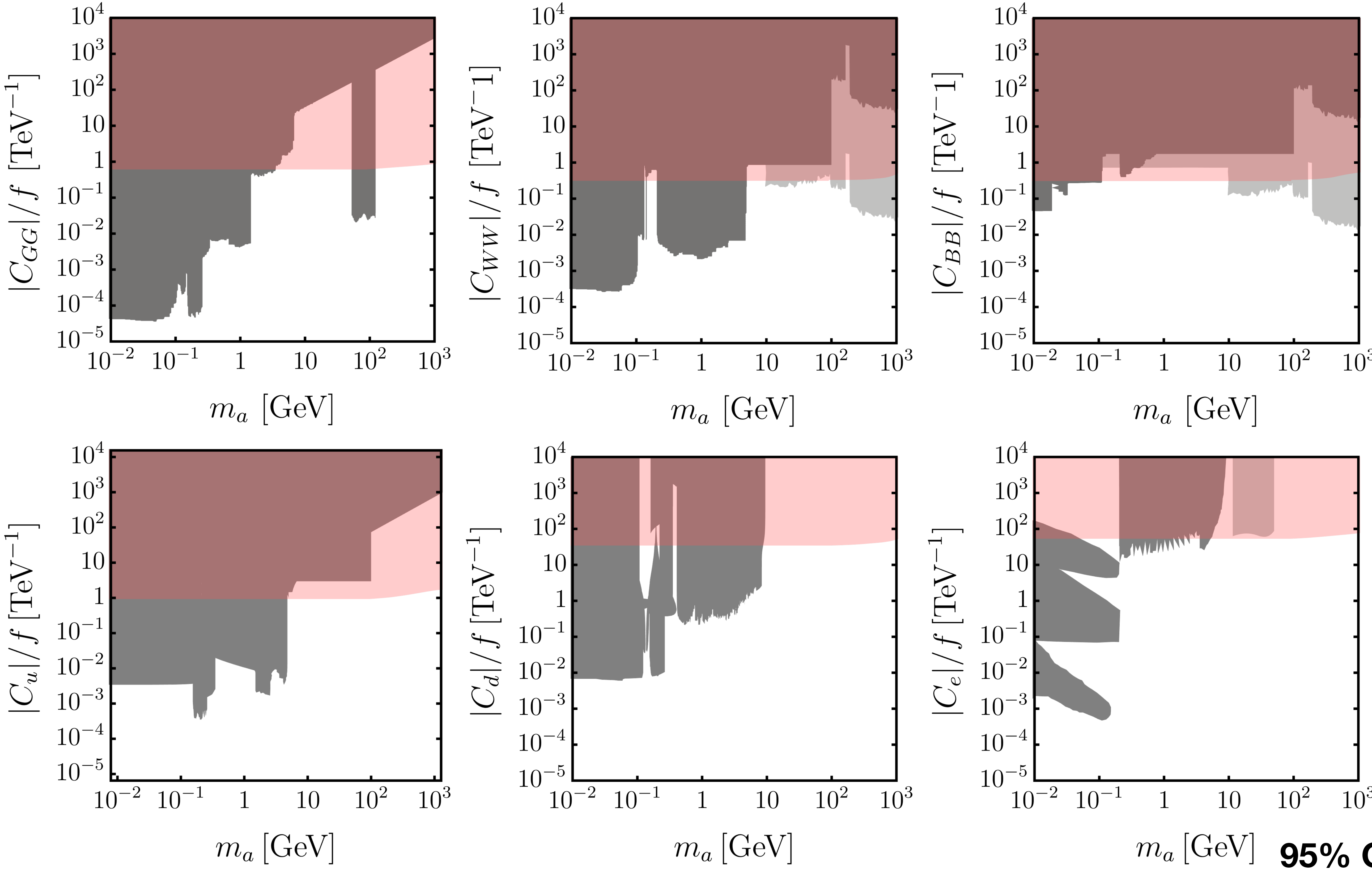
$$C_{HD}(\mu) = -9\,\alpha_t^2\, C_u^2\, \ln^2\frac{\mu}{\Lambda}$$

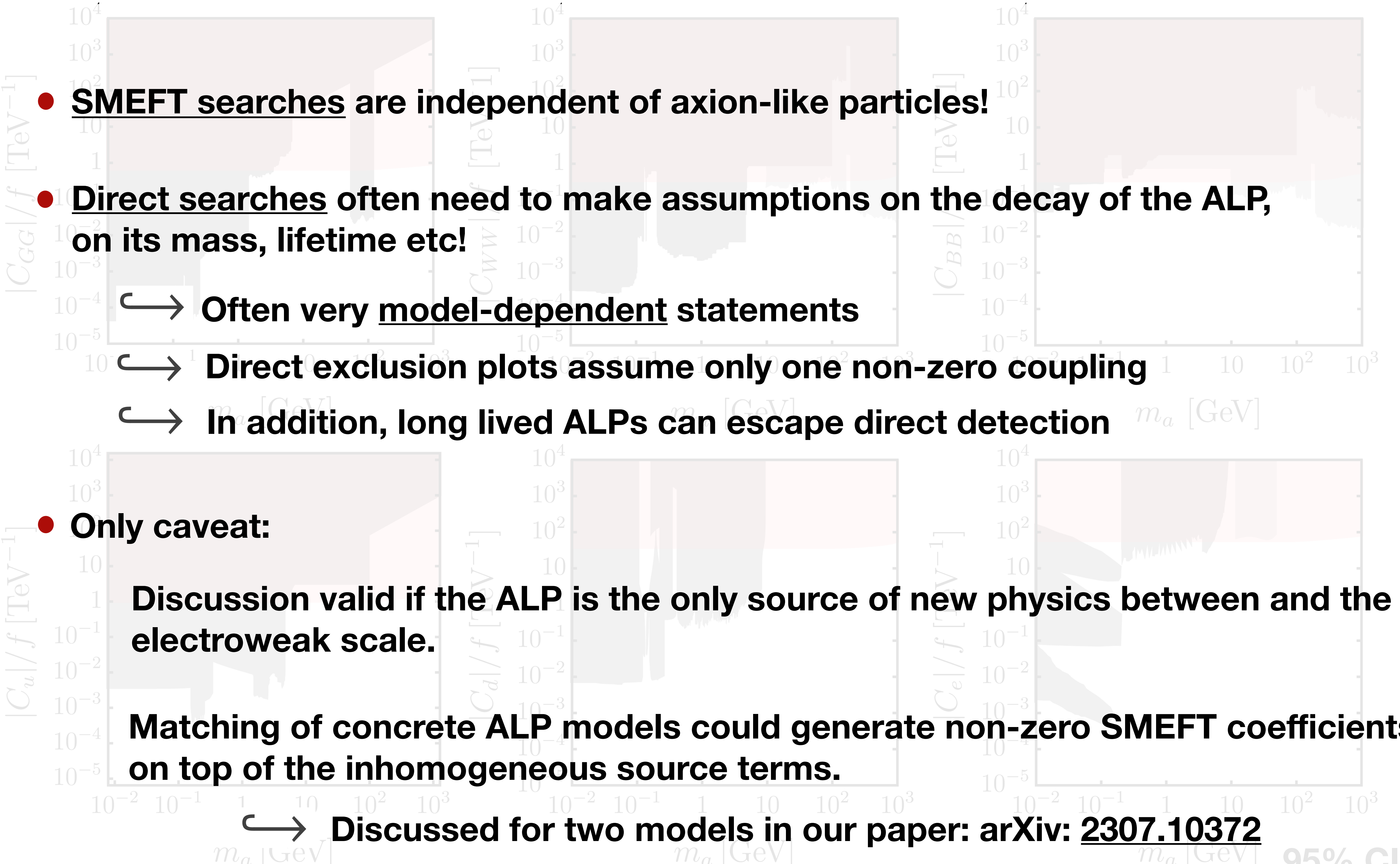
Model-Independent Bounds on Axion-Like Particles



95% CL

red: our new model-independent bounds gray: direct, model-dependent bounds

Model-Independent Bounds on Axion-Like Particles



- **<u>SMEFT searches</u> are independent of axion-like particles!**
- **<u>Direct searches</u> often need to make assumptions on the decay of the ALP, on its mass, lifetime etc!**

  ↪ **Often very <u>model-dependent</u> statements**

  ↪ **Direct exclusion plots assume only one non-zero coupling**

  ↪ **In addition, long lived ALPs can escape direct detection**

- **Only caveat:**

  Discussion valid if the ALP is the only source of new physics between and the electroweak scale.

  Matching of concrete ALP models could generate non-zero SMEFT coefficients on top of the inhomogeneous source terms.

  ↪ **Discussed for two models in our paper: arXiv: <u>2307.10372</u>**

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red: our new model-independent bounds gray: direct, model-dependent bounds

Summary

In this talk we have seen..

- ✓ **that divergences from one-loop virtual ALP exchange with external SM particles are absorbed in SMEFT Wilson coefficients by modifying the RG equations.**
- ✓ **that the ALP thus generates nearly the whole dim-6 SMEFT basis at one-loop order.**
- ✓ **how RG running and ALP-independent SMEFT bounds can be used to obtain model-independent bounds on ALP coefficients.**

→ **Indirect bounds from global fits are a model-independent way to constrain ALPs and the results are competitive to or even exceed current constraints!**


$|C_{GG}|/f$ [TeV^{-1}]
$|C_{WW}|/f$ [TeV^{-1}]
$|C_{BB}|/f$ [TeV^{-1}]
$|C_u|/f$ [TeV^{-1}]
$|C_d|/f$ [TeV^{-1}]
$|C_e|/f$ [TeV^{-1}]
m_a [GeV]

Thank you!