

RGEs & positivity bounds of the SMEFT dim-8 operators

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In collaboration with M. Chala, A Diaz-Carmona, G. Guedes,
arxiv:2205.03301

Dimension-8 operators & where do we find them?

❖ Leading contribution to observables

- Neutral triple gauge couplings, anomalous quartic gauge couplings, angular obs. (Drell-Yan)

arXiv:1308.6323, 2008.04298, 2002.03326, 2003.11615

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❖ When EFT cut-off scale is not very high, dim-8 effects are significant.

- Higgs measurements arXiv:1808.00442, 2205.01561, ...
- Electroweak precision data arXiv:2102.02819
- EFT validity (D6 vs D8 effects) arXiv:1604.06444, 2003.07862

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❖ Dim-8 RGE effects on positivity bounds.

arXiv:2110.01624

SMEFT Dim-8 RGEs

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i c_i^{(6)} O_i^{(6)} + \frac{1}{\Lambda^4} \sum_j c_j^{(8)} O_j^{(8)} + \dots$$

$\mathcal{L}_5, \mathcal{L}_7 \rightarrow \text{B/LNV}$
 $\Lambda = \text{EFT cut-off scale}$

$$\dot{c}_i^{(8)} \equiv 16\pi^2 \tilde{\mu} \frac{dc_i^{(8)}}{d\tilde{\mu}} = \gamma_{ij} c_j^{(8)} + \gamma'_{ijk} c_j^{(6)} c_k^{(6)}$$

At $\mathcal{O}\left(\frac{1}{\Lambda^4}\right)$, assuming no B/LNV.

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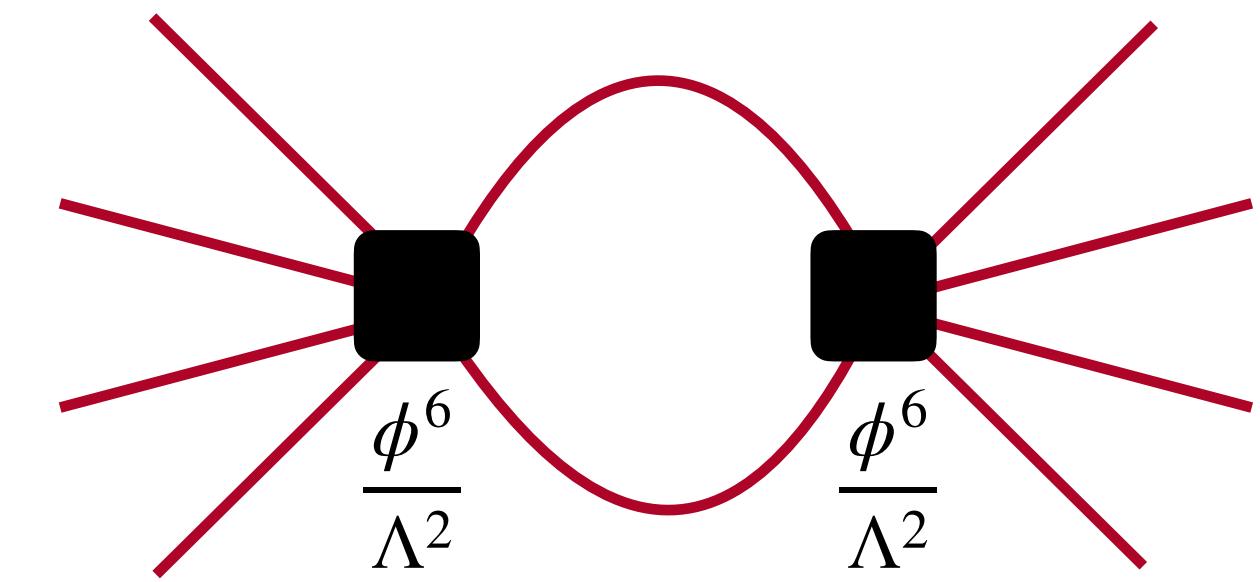
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- ❖ Two dim-6 operator insertions.
[arXiv:2106.05291](https://arxiv.org/abs/2106.05291)

Towards the renormalisation of the Standard Model effective field theory
to dimension eight: Bosonic interactions I
- M Chala, G Guedes, M Ramos, J Santiago

e.g.:



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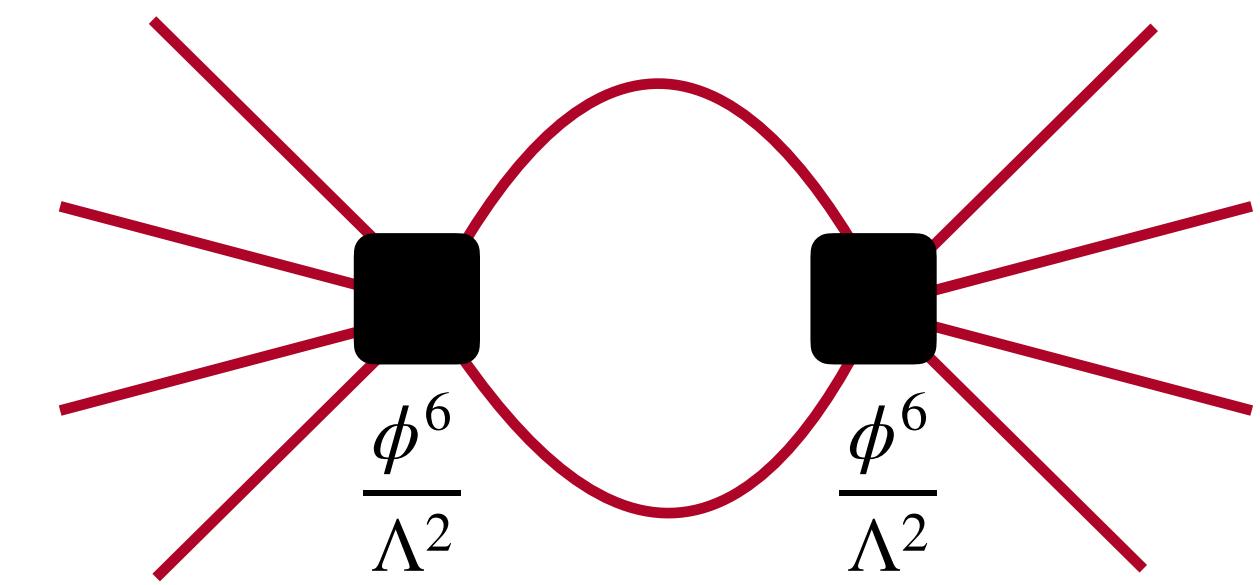
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arXiv:2205.03301

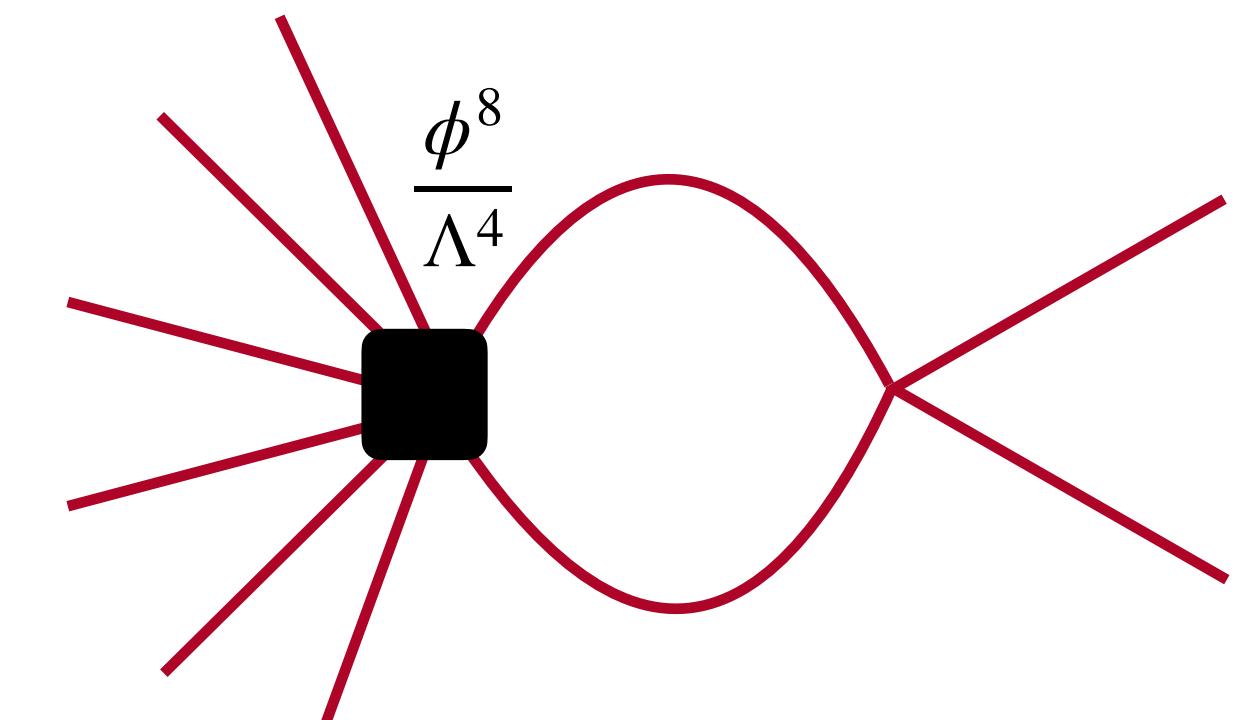
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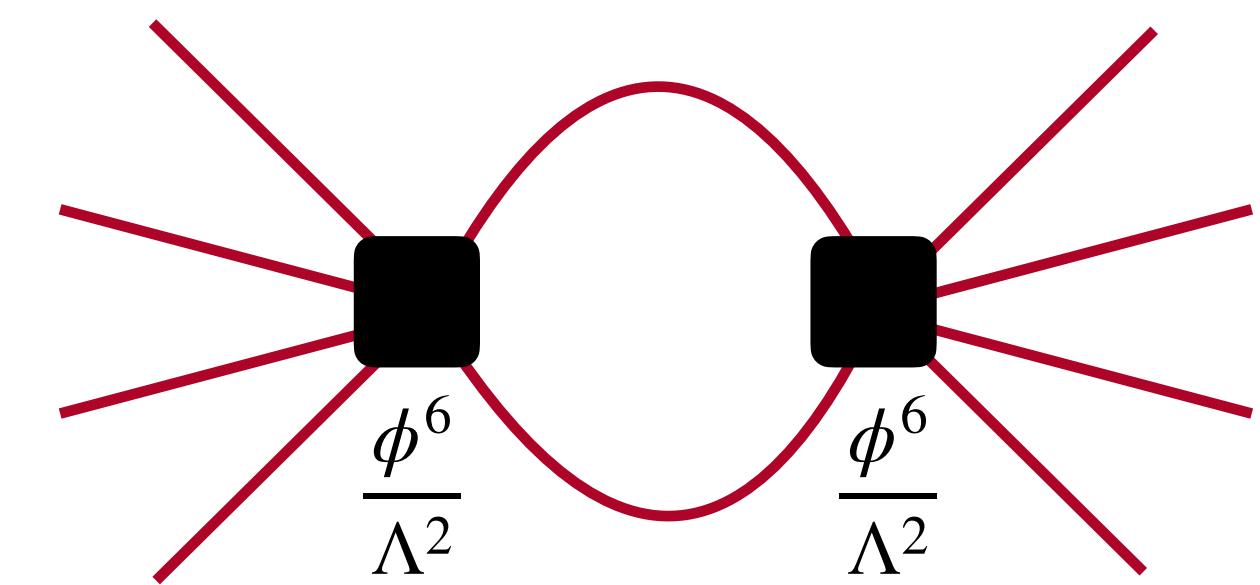
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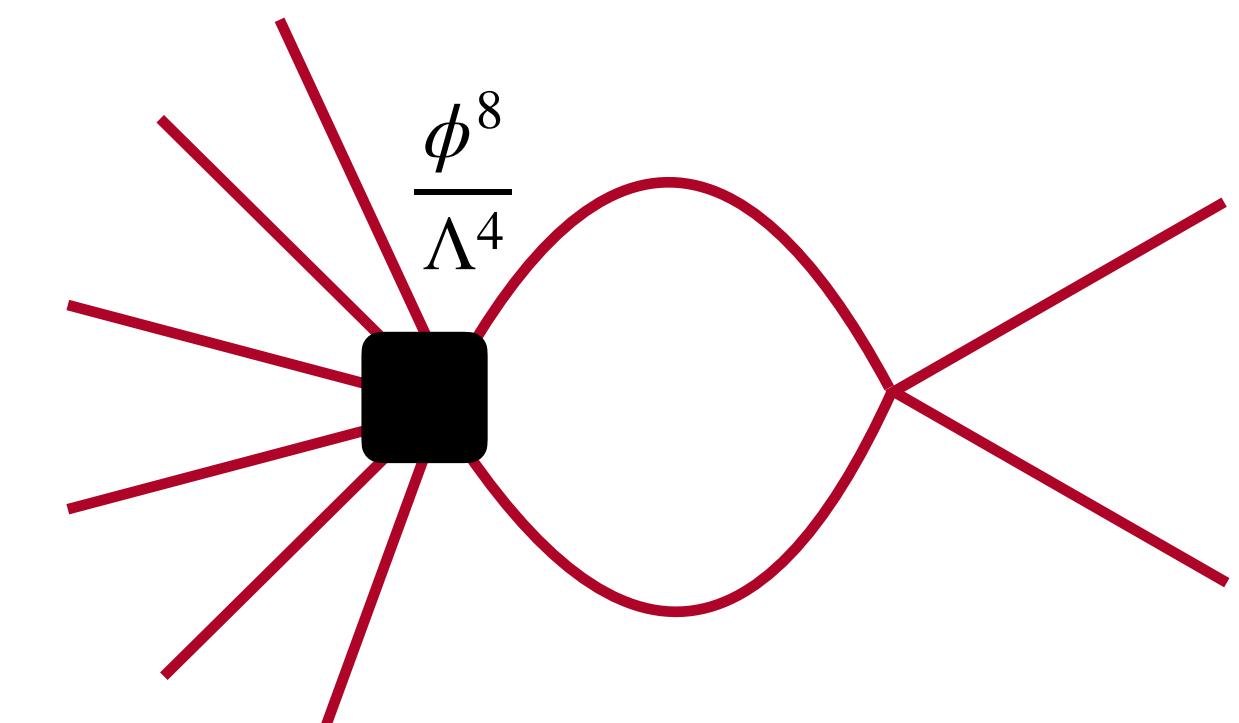
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SMEFT Lagrangian

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- One **tree-level generated dim-8 operator in one-loop.**

arXiv:2001.00017

- Craig, Jiang, Li, Sutherland

Classes of operator that are tree-level generated :

Bosonic : $\{\phi^8, \phi^6 D^2, \phi^4 D^4, X^2 \phi^4, X \phi^4 D^2, X^2 H^2 D^2, X^3 H^2, X^4\}$

Fermionic : $\{\psi^2 X \phi^3, \psi^2 \phi^2 D^3, \psi^2 \phi^5, \psi^2 \phi^4 D, \psi^2 X \phi^2 D, \psi^2 \phi^3 D^2, \psi^2 X^2 \phi, \psi^2 X^2 D, \psi^2 X \phi D^2\}$

SMEFT Dim-8 **on-shell basis** :

arXiv:2005.00059 — C. W. Murphy

SMEFT Dim-8 **Green's/off-shell basis** : arXiv:2112.12724 — M. Chala, Á Díaz-Carmona, G. Guedes

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Divergences to RGEs, some details:

- Compute **1-PI loop diagrams**. Use **FeynRules**, **FeynARTs**, and **FormCalc** packages.
- Divergences are captured by the operators of **off-shell/Green's basis**.

$$16\pi^2\epsilon \mathcal{L}_{\text{DIV}} = \tilde{K}_\phi (D_\mu \phi)^\dagger (D^\mu \phi) + \tilde{\mu}^2 |\phi|^2 - \tilde{\lambda} |\phi|^4 + \tilde{c}_i^{(6)} \frac{\mathcal{O}_i^{(6)}}{\Lambda^2} + \tilde{c}_j^{(8)} \frac{\mathcal{O}_j^{(8)}}{\Lambda^4}$$

[on RHS we have Green's basis]

arXiv:2112.12724
- M Chala, Á Díaz-Carmona, G Guedes

- **Removing redundant operators** using on-shell relations.

arXiv:2106.05291
- M Chala, G Guedes, M Ramos, J Santiago

- **Cross-checks with MatchMakerEFT**. 
H^8 topologies are computed in MM primarily.

arXiv:2112.10787
- A Carmona, A Lazopoulos, P Olgoso, J Santiago

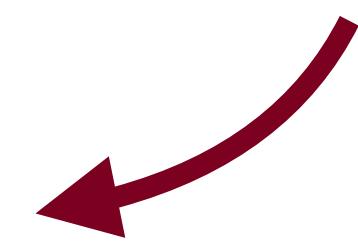
- **Partial cross-checks** with arXiv:2108.03669 (on-shell amplitude methods). 

arXiv:2108.03669
- M A Huber, S De Angelis.

Bosonic-bosonic RGE:

Classes of tree-generated bosonic operators

	$\phi^4 D^4$	$B\phi^4 D^2$	$W\phi^4 D^2$	$B^2\phi^4$	$W^2\phi^4$	$WB\phi^4$	$G^2\phi^4$	$\phi^6 D^2$	ϕ^8
$B^2\phi^2 D^2$	g_1^2	0	0	0	0	0	0	0	0
$W^2\phi^2 D^2$	g_2^2	0	0	0	0	0	0	0	0
$WB\phi^2 D^2$	$g_1 g_2$	0	0	0	0	0	0	0	0
$G^2\phi^2 D^2$	0	0	0	0	0	0	0	0	0
$W^3\phi^2$	0	0	0	0	0	0	0	0	0
$W^2 B\phi^2$	0	0	0	0	0	0	0	0	0
$G^3\phi^2$	0	0	0	0	0	0	0	0	0
$\phi^4 D^4$	g_2^2	0	0	0	0	0	0	0	0
$B\phi^4 D^2$	$g_1 g_2^2$	λ	0	0	0	0	0	0	0
$W\phi^4 D^2$	g_2^3	0	g_2^2	0	0	0	0	0	0
$B^2\phi^4$	$g_1^2 g_2^2$	$g_1 \lambda$	$g_1^2 g_2$	λ	0	$g_1 g_2$	0	0	0
$W^2\phi^4$	g_2^4	$g_1 g_2^2$	g_2^3	0	λ	$g_1 g_2$	0	0	0
$WB\phi^4$	$g_1 g_2^3$	$g_2 \lambda$	$g_1 \lambda$	$g_1 g_2$	$g_1 g_2$	λ	0	0	0
$G^2\phi^4$	0	0	0	0	0	0	g_3^2	0	0
$\phi^6 D^2$	g_2^4	$g_1 \lambda$	$g_2 \lambda$	0	0	0	0	λ	0
ϕ^8	λ^3	$g_1 \lambda^2$	$g_2 \lambda^2$	$g_1^2 \lambda$	$g_2^2 \lambda$	$g_1 g_2 \lambda$	0	λ^2	λ



- Loop generated operators that are renormalised by tree-generated operators are in gray.
- Largest contribution from each operator class is shown.
- Violet entries contribute larger than what expected from naive dimensional analysis.

$$\tilde{\mu} \frac{dc_{\phi^8}}{d\tilde{\mu}} = \frac{1}{16\pi^2} (192\lambda - 6(g_1^2 + 3g_2^2) + \dots) c_{\phi^8}$$

Fermionic-bosonic RGE:

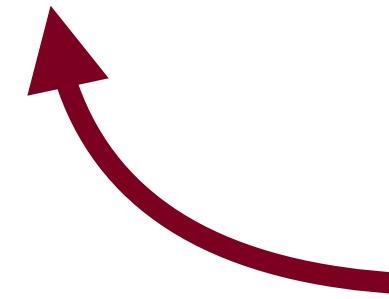
Classes of tree-generated fermionic operators

	$\psi^2 B\phi^3$	$\psi^2 W\phi^3$	$\psi^2 G\phi^3$	$\psi^2 \phi^2 D^3$	$\psi^2 \phi^5$	$\psi^2 \phi^4 D$	$\psi^2 B\phi^2 D$	$\psi^2 W\phi^2 D$	$\psi^2 G\phi^2 D$	$\psi^2 \phi^3 D^2$
$B^2\phi^2 D^2$	0	0	0	g_1^2	0	0	0	0	0	0
$W^2\phi^2 D^2$	0	0	0	g_2^2	0	0	0	0	0	0
$WB\phi^2 D^2$	0	0	0	$g_1 g_2$	0	0	0	0	0	0
$G^2\phi^2 D^2$	0	0	0	g_3^2	0	0	0	0	0	0
$W^3\phi^2$	0	0	0	0	0	0	0	0	0	0
$W^2 B\phi^2$	0	0	0	0	0	0	0	0	0	0
$G^3\phi^2$	0	0	0	0	0	0	0	0	0	0
$\phi^4 D^4$	0	0	0	$ y^t ^2$	0	0	0	0	0	0
$B\phi^4 D^2$	0	0	0	$g_1 y^t ^2$	0	0	$ y^t ^2$	0	0	$g_1 y^t$
$W\phi^4 D^2$	0	0	0	$g_2 y^t ^2$	0	0	0	$ y^t ^2$	0	$g_2 y^t$
$B^2\phi^4$	$g_1 y^t$	0	0	$g_1^2 y^t ^2$	0	0	$g_1 y^t ^2$	0	0	$g_1^2 y^t$
$W^2\phi^4$	0	$g_2 y^t$	0	$g_2^2 y^t ^2$	0	g_2^2	0	$g_2 y^t ^2$	0	$g_2^2 y^t$
$WB\phi^4$	$g_2 y^t$	$g_1 y^t$	0	$g_1 g_2 y^t ^2$	0	$g_1 g_2$	$g_2 y^t ^2$	$g_1 y^t ^2$	0	$g_1 g_2 y^t$
$G^2\phi^4$	0	0	$g_3 y^t$	0	0	0	0	0	0	0
$\phi^6 D^2$	0	0	0	$g_2^2 y^t ^2$	0	$ y^t ^2$	$g_1 y^t ^2$	$g_2 y^t ^2$	0	$y^t y^t ^2$
ϕ^8	0	0	0	$\lambda y^t ^4$	$y^t y^t ^2$	$\lambda y^t ^2$	$g_1 \lambda y^t ^2$	$g_2 \lambda y^t ^2$	0	$\lambda y^t y^t ^2$

RGEs of Dim-6,4,2

- Dim-8 operators also induce running of dim-6, dim-4, dim-2 operators.

	$\phi^4 D^4$	$B\phi^4 D^2$	$W\phi^4 D^2$	$B^2\phi^4$	$W^2\phi^4$	$WB\phi^4$	$G^2\phi^4$	$\phi^6 D^2$	ϕ^8
ϕ^2	μ^6	0	0	0	0	0	0	0	0
ϕ^4	$\lambda\mu^4$	$g_1\mu^4$	$g_2\mu^4$	0	0	0	0	μ^4	0
$B^2\phi^2$	$g_1^2\mu^2$	$g_1\mu^2$	0	μ^2	0	0	0	0	0
$W^2\phi^2$	$g_2^2\mu^2$	0	$g_2\mu^2$	0	μ^2	0	0	0	0
$WB\phi^2$	$g_1g_2\mu^2$	$g_2\mu^2$	$g_1\mu^2$	0	0	μ^2	0	0	0
$G^2\phi^2$	0	0	0	0	0	0	μ^2	0	0
$\phi^4 D^2$	$\lambda\mu^2$	$g_1\mu^2$	$g_2\mu^2$	0	0	0	0	μ^2	0
ϕ^6	$\lambda^2\mu^2$	$\lambda g_1\mu^2$	$\lambda g_2\mu^2$	$g_1^2\mu^2$	$g_2^2\mu^2$	$g_1g_2\mu^2$	0	$\lambda\mu^2$	μ^2



Lower dim. classes renormalised by the bosonic dim-8 operators.
Similar contributions from two-fermionic dim-8 operators are also present.

μ^2 is the squared
Higgs mass in the SMEFT.

Positivity bounds

arXiv:1908.09845, 2110.01624

- **Restrictions** on Wilson coefficients of dim-8 operators.



Unitarity, analyticity, crossing symmetry

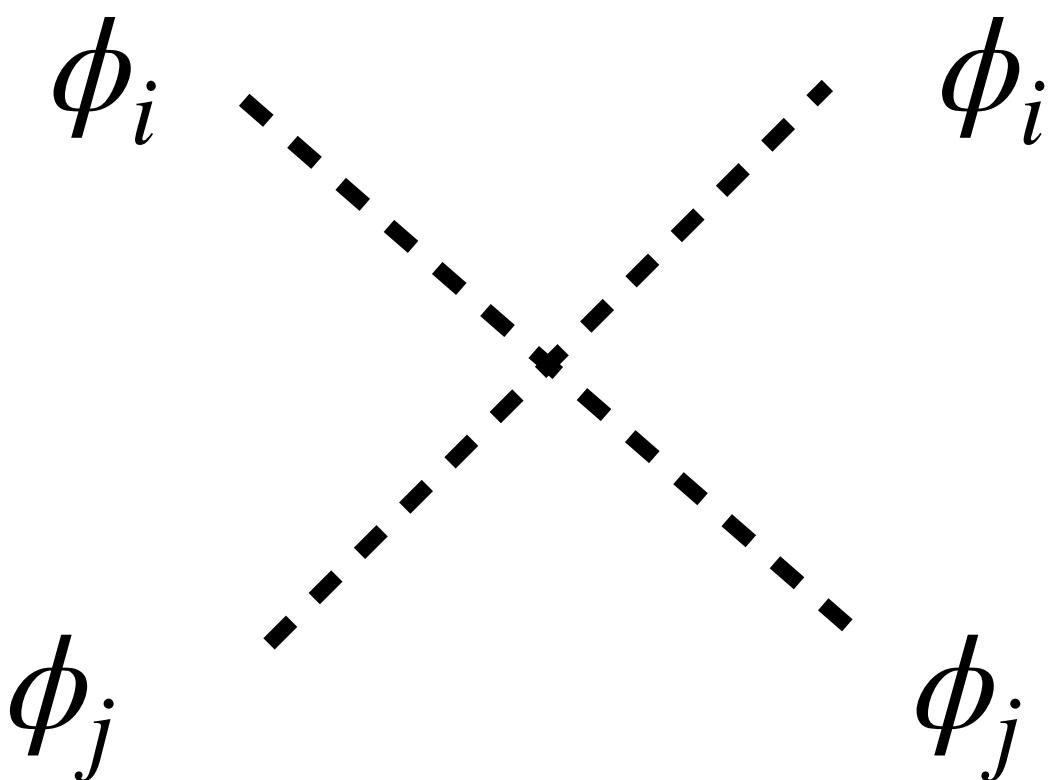
$$\frac{d^2 \mathcal{M}(s, t=0)}{ds^2} \geq 0$$

arXiv:2005.00059

$Q_{H^4}^{(1)}$	$(D_\mu H^\dagger D_\nu H)(D^\nu H^\dagger D^\mu H)$
$Q_{H^4}^{(2)}$	$(D_\mu H^\dagger D_\nu H)(D^\mu H^\dagger D^\nu H)$
$Q_{H^4}^{(3)}$	$(D^\mu H^\dagger D_\mu H)(D^\nu H^\dagger D_\nu H)$

Tree-level scattering :

$2 \rightarrow 2$



$$\mathcal{M}(s)_{1,2 \rightarrow 1,2} = -2\lambda + \frac{c_{H^4}^{(2)}}{\Lambda^4} s^2$$

$$c_{\phi^4 D^4}^{(2)} \geq 0$$

$$c_{\phi^4 D^4}^{(1)} + c_{\phi^4 D^4}^{(2)} \geq 0$$

$$c_{\phi^4 D^4}^{(1)} + c_{\phi^4 D^4}^{(2)} + c_{\phi^4 D^4}^{(3)} \geq 0$$

Dim-8 RGEs effects on positivity

- For $V_1 V_2 \rightarrow V_1 V_2$ process:

arXiv:1902.08977

$$g_1^2 c_{B^2 \phi^2 D^2}^{(1)} + g_2^2 c_{W^2 \phi^2 D^2}^{(1)} + 2g_1 g_2 c_{WB \phi^2 D^2}^{(4)} \leq 0,$$

$$g_1^2 c_{B^2 \phi^2 D^2}^{(1)} + g_2^2 c_{W^2 \phi^2 D^2}^{(1)} - 2g_1 g_2 c_{WB \phi^2 D^2}^{(4)} \leq 0,$$

$$c_{W^2 \phi^2 D^2}^{(1)} \leq 0,$$

$$g_1^2 c_{W^2 \phi^2 D^2}^{(1)} + 2g_1 g_2 c_{WB \phi^2 D^2}^{(4)} + g_2^2 c_{B^2 \phi^2 D^2}^{(1)} \leq 0,$$

$$g_1^2 c_{W^2 \phi^2 D^2}^{(1)} - 2g_1 g_2 c_{WB \phi^2 D^2}^{(4)} + g_2^2 c_{B^2 \phi^2 D^2}^{(1)} \leq 0.$$

$X^2 \phi^2 D^2$ operators are not generated at tree-level matching of weakly coupled UV completion of the SMEFT.

$$Q_{W^2 H^2 D^2}^{(1)}$$

$$Q_{W^2 H^2 D^2}^{(2)}$$

$$Q_{W^2 H^2 D^2}^{(3)}$$

$$Q_{W^2 H^2 D^2}^{(4)}$$

$$(D^\mu H^\dagger D^\nu H) W_{\mu\rho}^I W_\nu^{I\rho}$$

$$(D^\mu H^\dagger D_\mu H) W_{\nu\rho}^I W^{I\nu\rho}$$

$$(D^\mu H^\dagger D_\mu H) W_{\nu\rho}^I \widetilde{W}^{I\nu\rho}$$

$$i\epsilon^{IJK} (D^\mu H^\dagger \tau^I D^\nu H) W_{\mu\rho}^J W_\nu^{K\rho}$$

arXiv:2005.00059

Dim-8 RGEs effects on positivity

- RGE of $X^2\phi^2D^2$ operators:

$$\begin{aligned} c_{W^2\phi^2D^2}^{(1)}(\tilde{\mu}) &= c_{W^2\phi^2D^2}^{(1)}(\Lambda) - \frac{1}{16\pi^2} \dot{c}_{W^2\phi^2D^2}^{(1)}(\Lambda) \log \frac{\Lambda}{\tilde{\mu}} < 0 \\ \Rightarrow \frac{1}{6}g_2^2 \left[&2c_{\phi^4}^{(1)} + 3c_{\phi^4}^{(2)} + c_{\phi^4D^4}^{(3)} \right. \\ &- \frac{16}{3} \left. \left(c_{l^2\phi^2D^3}^{(1)} + c_{l^2\phi^2D^3}^{(2)} + 3c_{q^2\phi^2D^3}^{(1)} + 3c_{q^2\phi^2D^3}^{(2)} \right)_{\alpha_1, \alpha_1} \right] \log \frac{\Lambda}{\tilde{\mu}} > 0, \end{aligned}$$

Sufficient conditions :

- Putting the RGEs of the operators.
- Derive relations among operators of same class.

- Wilson coefficients generated from UV theories matched to SMEFT Dim-8 at tree-level are bounded by these positivity (or negativity) constraints.

$$2c_{\phi^4}^{(1)} + 3c_{\phi^4}^{(2)} + c_{\phi^4}^{(3)} \geq 0,$$

$$c_{\phi^4}^{(1)} + 2c_{\phi^4}^{(2)} + c_{\phi^4}^{(3)} \geq 0,$$

$$c_{\phi^4}^{(1)} + c_{\phi^4}^{(2)} \geq 0,$$

$$\left[c_{\psi_R^2 \phi^2 D^3}^{(1)} + c_{\psi_R^2 \phi^2 D^3}^{(2)} \right]_{\alpha_1, \alpha_1} \leq 0,$$

$$\left[c_{\psi_L^2 \phi^2 D^3}^{(1)} + c_{\psi_L^2 \phi^2 D^3}^{(2)} + c_{\psi_L^2 \phi^2 D^3}^{(3)} + c_{\psi_L^2 \phi^2 D^3}^{(4)} \right]_{\alpha_1, \alpha_1} \leq 0,$$

$$\left[c_{\psi_L^2 \phi^2 D^3}^{(1)} + c_{\psi_L^2 \phi^2 D^3}^{(2)} - c_{\psi_L^2 \phi^2 D^3}^{(3)} - c_{\psi_L^2 \phi^2 D^3}^{(4)} \right]_{\alpha_1, \alpha_1} \leq 0;$$

Summary

- SMEFT Dim-8 operators contribute to observables at leading order.
- Renormalization of bosonic SMEFT Dim-8 operators by tree-level generated operators are computed.
- These operators also contribute to the running of lower dimensional operators.
- We showed the RGE effects on the positivity bounds on dim-8 Wilson coefficients.

Future directions?

arxiv:2205.03301

	d_5	d_5^2	d_6	d_5^3	$d_5 \times d_6$	d_7	d_5^4	$d_5^2 \times d_6$	d_6^2	$d_5 \times d_7$	d_8
$d_{\leq 4}$ (bosonic)				✓					✓		This work
$d_{\leq 4}$ (fermionic)				✓					✗		✗
d_5	✓				✓	✓					
d_6 (bosonic)		✓	✓					✗	✓	✗	This work
d_6 (fermionic)	✓	✓						✗	✗	✗	✗
d_7			✓		✓	✓					
d_8 (bosonic)							✗	✗	✓	✗	This work
d_8 (fermionic)							✗	✗	✗	✗	✓

Blank entries vanish; a tick ✓ represents that the complete contribution is known; the ✓ implies that only (but substantial) partial results have been already obtained; the ✗ indicates that nothing, or very little, is known. The contribution made in this paper is marked by ■.

Future directions?

arxiv:2205.03301

	d_5	d_5^2	d_6	d_5^3	$d_5 \times d_6$	d_7	d_5^4	$d_5^2 \times d_6$	d_6^2	$d_5 \times d_7$	d_8
$d_{\leq 4}$ (bosonic)					✓				✓		This work
$d_{\leq 4}$ (fermionic)					✓				✗		✗
d_5	✓					✓	✓				
d_6 (bosonic)		✓	✓					✗	✓	✗	This work
d_6 (fermionic)	✓	✓						✗	✗	✗	✗
d_7			✓		✓	✓					
d_8 (bosonic)							✗	✗	✓	✗	This work
d_8 (fermionic)							✗	✗	✗	✗	✓

Blank entries vanish; a tick ✓ represents that the complete contribution is known; the ✓ implies that only (but substantial) partial results have been already obtained; the ✗ indicates that nothing, or very little, is known. The contribution made in this paper is marked by ■.



Compute dim-5, 6, 7 contributions to dim-8 bosonic operators' RGEs.

Thanks for your attention !

RGE comparison

Standard Model EFTs via On-shell Methods. JHEP 11 (2011) 221. arXiv:2108.03669

Manuel Accettulli Huber, Stefano De Angelis.

- RGEs of order $\mathcal{O}(g^2, \lambda)$ are computed using on-shell amplitude methods.
- But, dim-8 bases are not identical. Basis transformation necessary to compare.

$$\mathcal{P}^{-1} \tilde{\gamma} \mathcal{P} = \gamma$$

\mathcal{P} → basis rotation matrix

γ → RGE matrix in our basis

$\tilde{\gamma}$ → RGE matrix in their basis

$$\mathcal{P} = \begin{pmatrix} 1 & & & & \\ & P_{\phi^6 D^2} & & & \\ & & P_{\phi^4 D^4} & & \\ & & & P_{X^2 \phi^4} & \\ & & & & P_{X \phi^4 D^2} \end{pmatrix}$$

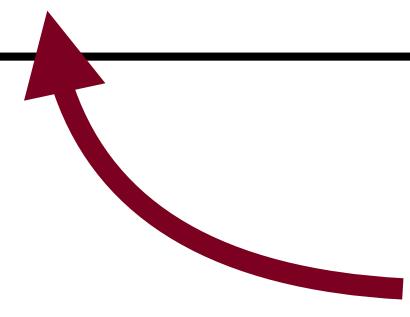
Only one op. in ϕ^8 class,
so no rotation needed!

Operator blocks → $\{\phi^8, \phi^6 D^2, \phi^4 D^4, X^2 \phi^4, X \phi^4 D^2\}$

RGEs of Dim-6,4,2

- Fermionic dim-8 operators also induce running of dim-6, dim-4, dim-2 operators.

	$\psi^2 B\phi^3$	$\psi^2 W\phi^3$	$\psi^2 G\phi^3$	$\psi^2 \phi^2 D^3$	$\psi^2 \phi^5$	$\psi^2 \phi^4 D$	$\psi^2 B\phi^2 D$	$\psi^2 W\phi^2 D$	$\psi^2 G\phi^2 D$	$\psi^2 \phi^3 D^2$
ϕ^2	0	0	0	0	0	0	0	0	0	0
ϕ^4	0	0	0	$\mu^4 y^t ^2$	0	0	0	0	0	$\mu^4 y^t$
$B^2 \phi^2$	0	0	0	0	0	0	0	0	0	0
$W^2 \phi^2$	0	0	0	0	0	0	0	0	0	0
$WB\phi^2$	0	0	0	0	0	0	0	0	0	0
$G^2 \phi^2$	0	0	0	0	0	0	0	0	0	0
$\phi^4 D^2$	0	0	0	$\mu^2 y^t ^2$	0	0	0	0	0	$\mu^2 y^t$
ϕ^6	0	0	0	$\lambda \mu^2 y^t ^2$	$\mu^2 y^t$	$\mu^2 y^t ^2$	$\mu^2 y^t ^2$	$\mu^2 y^t ^2$	0	$\mu^2 y^t y^t ^2$



 Lower dim. classes renormalised by the fermionic dim-8 operators.