SMEFT vs HEFT

"Pros and cons"

MBI 2022 Shanghai

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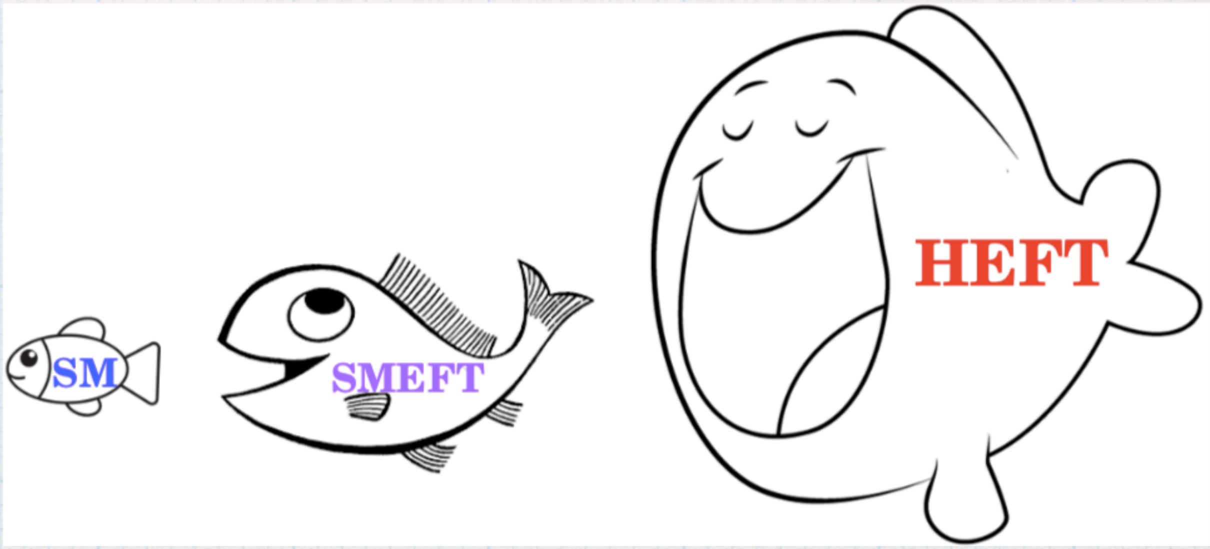
Based largely on 2204.01763 , with F. Llanes-Estrada, A. Salas-Bernardez , and JJ Sanz-Cillero

SMEFT vs HEFT

Similarities

And

Differences



Outline

* The SMEFT: LHC's favourite
* HEFT: the old classic
* Geometrical interpretations
* HEFT in terms of SMEFT

Looking for Physics Beyond the SM

* SMEFT: LHC's favourite

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{n,i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

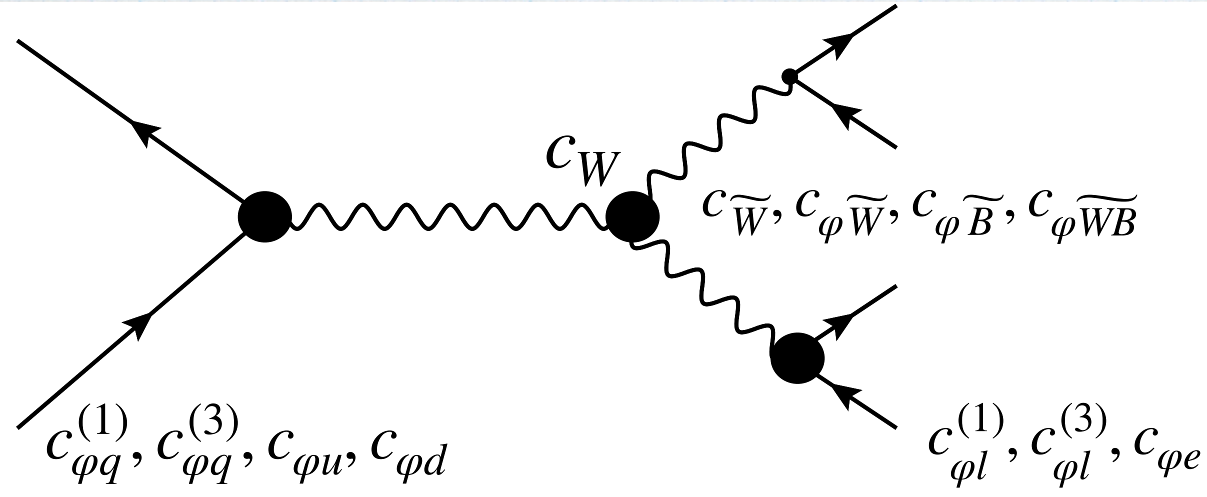
* Assume SM symmetries and fields
* Assume new physics is weakly coupled (clear cut-off scale Lambda)
* Assume traditional EWSB mechanism (H in a doublet)

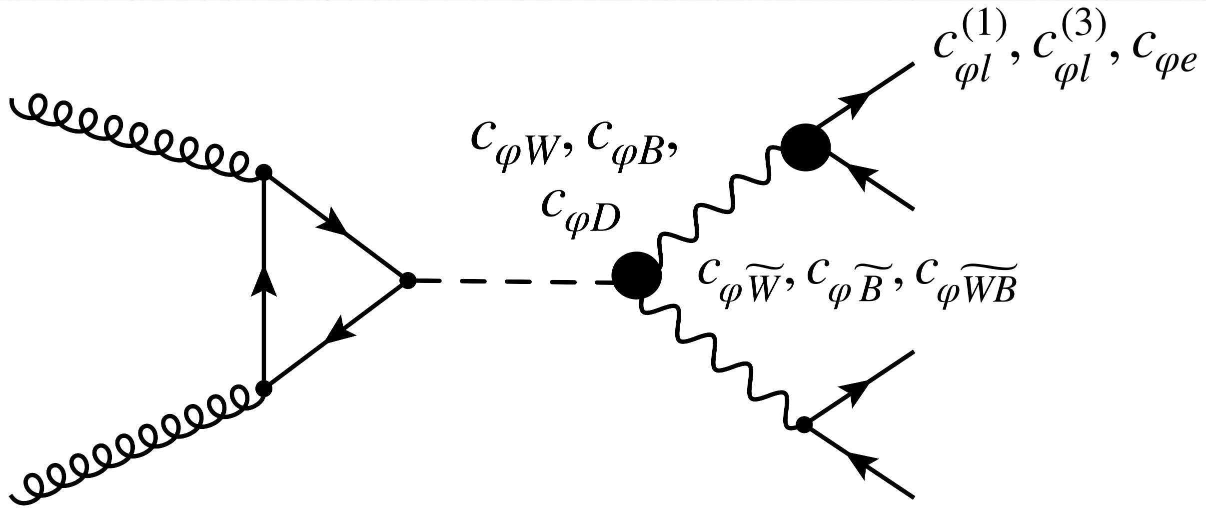
SMEFT in a nutshell

* Pros and cons:
    * A theory of deviations: Natural to parametrise small deviations from the SM (99% of the time!)
    * Couplings get modified as:
        * $V_{EFT} = V_{SM}\left(1 + \frac{g_6}{\Lambda^2}\right)$
        * Similarly for propagators, wave functions, input parameters
    * Not all deviations (ie BSM models) are allowed

SMEFT operators

* Warsaw basis -> 59/2499 operators
* dim 8 basis (Murphy et al) -> 993/44807





$$V_{EFT} = V_{SM}\left(1 + \frac{g_6}{\Lambda^2}\right)$$

Comparing with LHC data

* Amplitude analogous to SM one:

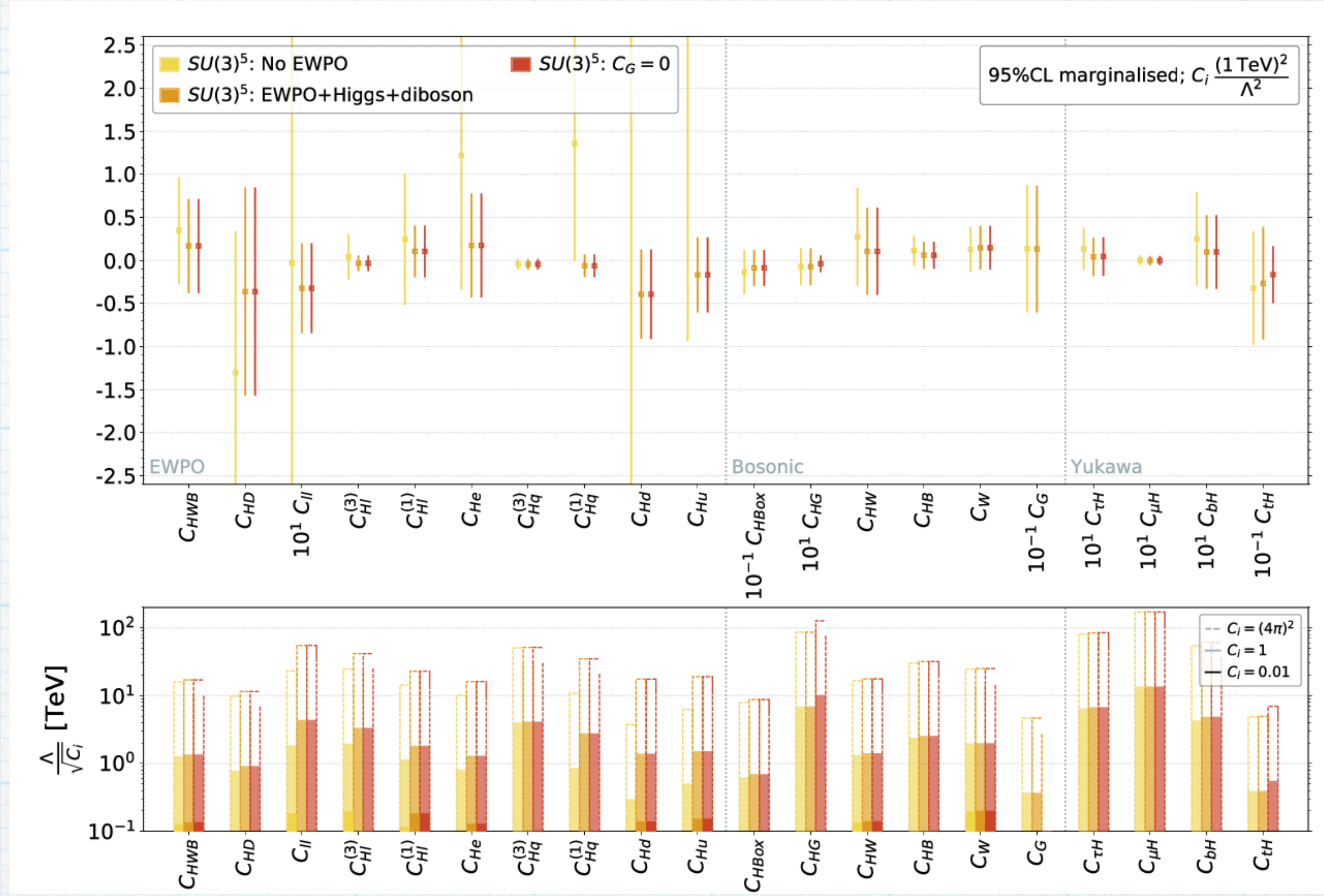
* $$\sigma_{EFT} = \sigma_{SM} + \underbrace{\sigma_{int,6}}_{linear} + \underbrace{\sigma_{pure,6} + \sigma_{int,8}}_{quadratic} + \ldots$$

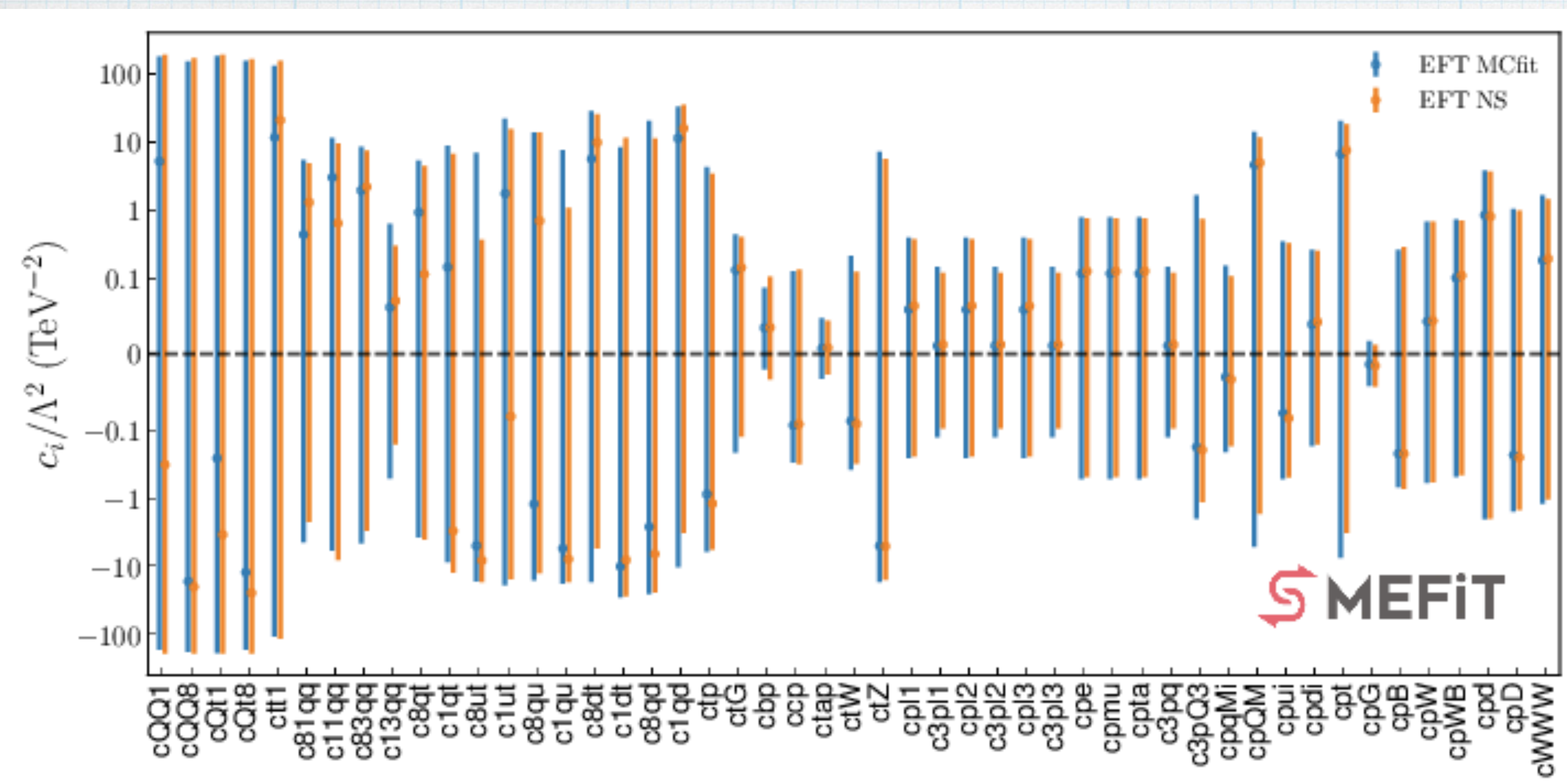
* Not uniquely defined (results are truncation-dependent)

* Other than that, technically similar to SM-LHC computations

LHC Global fits

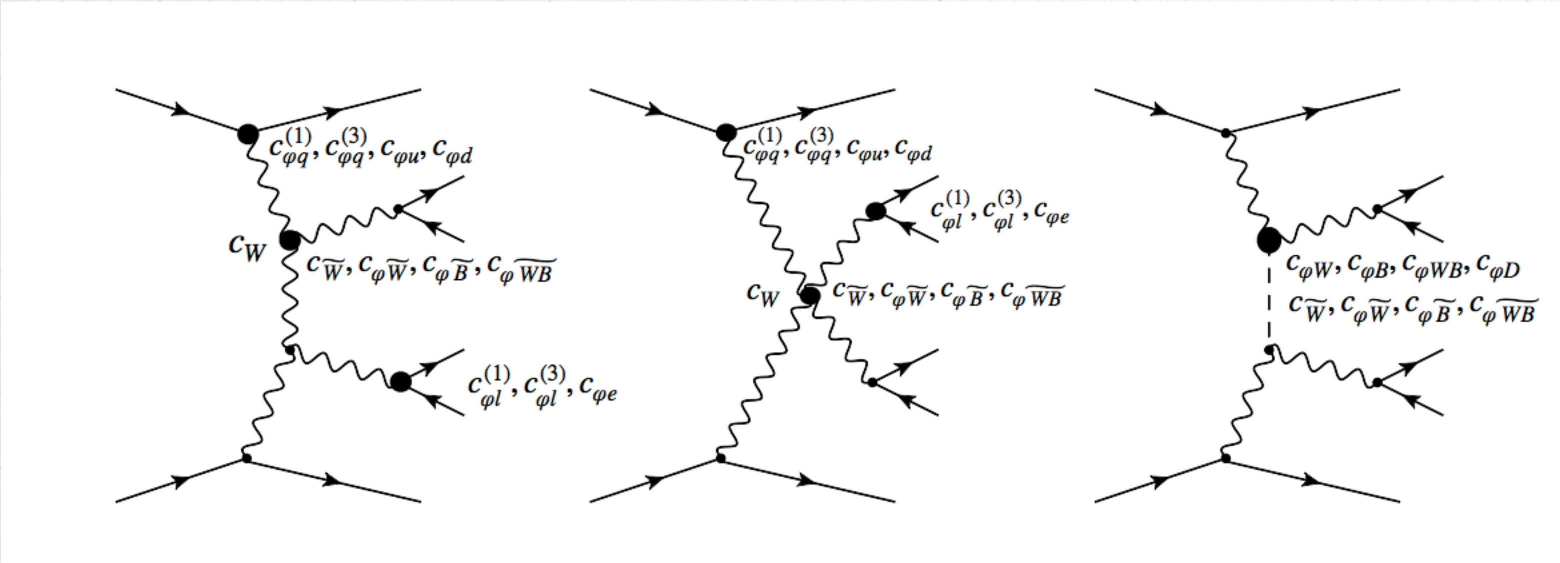
* In the absence of new particles, our main effort goes into constraining SMEFT coefficients

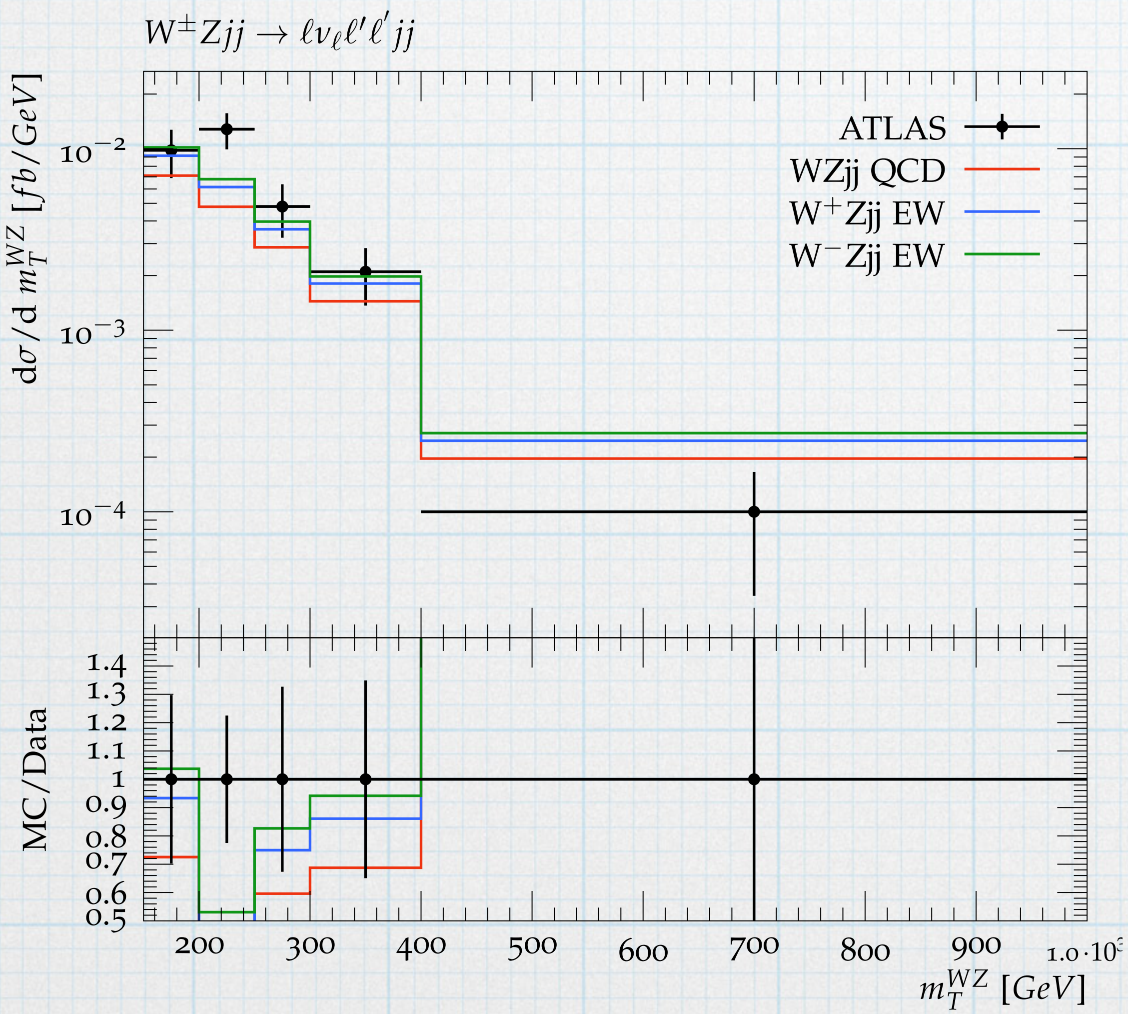


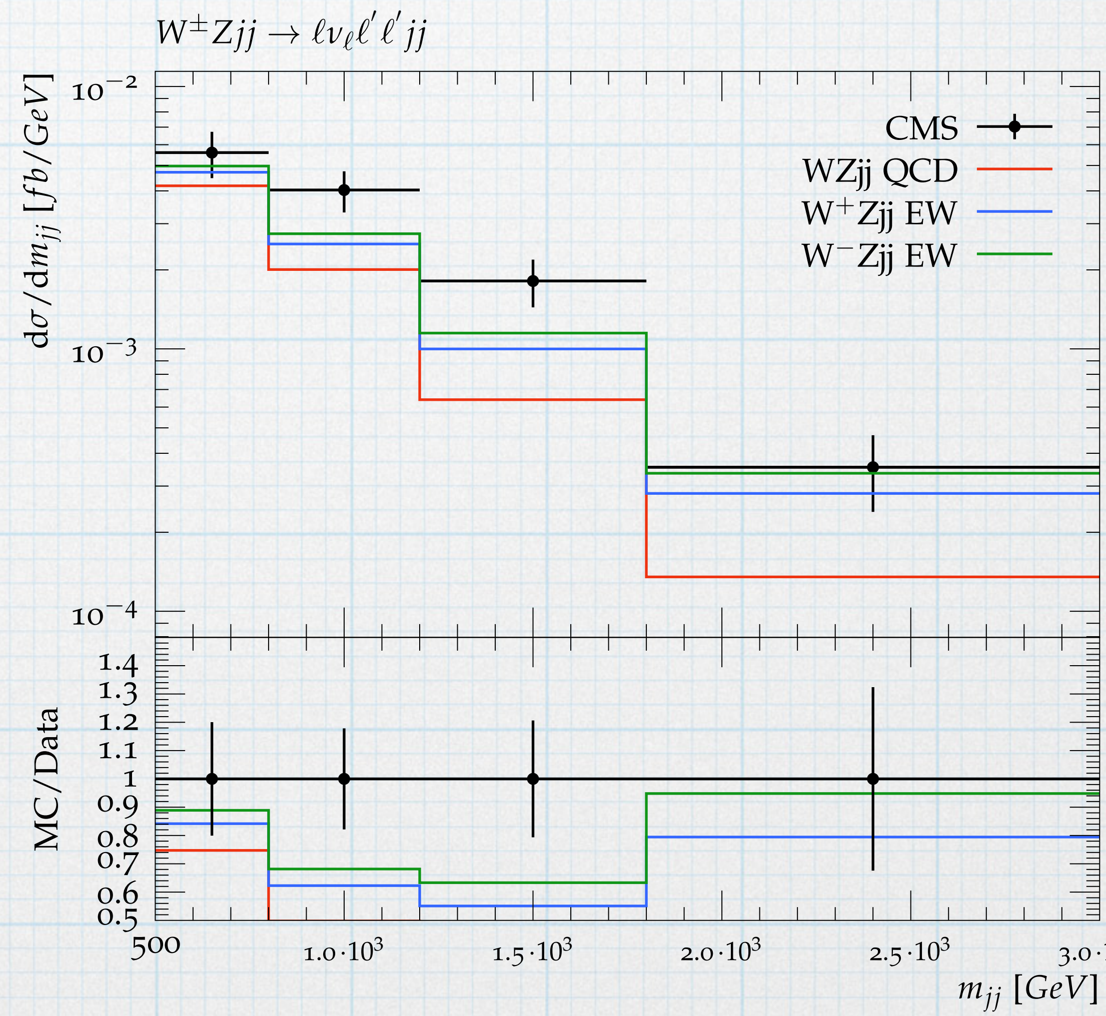


SM-to-SMEFT relatively easy to implement on the technical tools

fitmaker, smefit, et al.







See for example 2101.03180

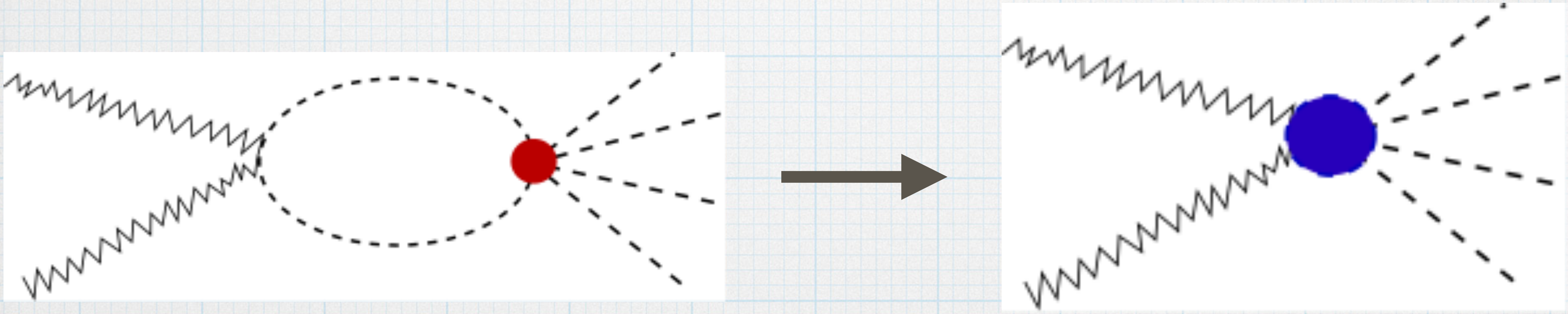
SMEFT mimics the SM structures

* In particular:
* $V^{SM}_{HHH} = v V^{SM}_{HHHH}$ and $V^{SM}_{WWH} = v V^{SM}_{WWHH}$
* (consequence of the EWSB mechanism)

This is the main feature that we can use to falsify smeft

SMEFT@NLO

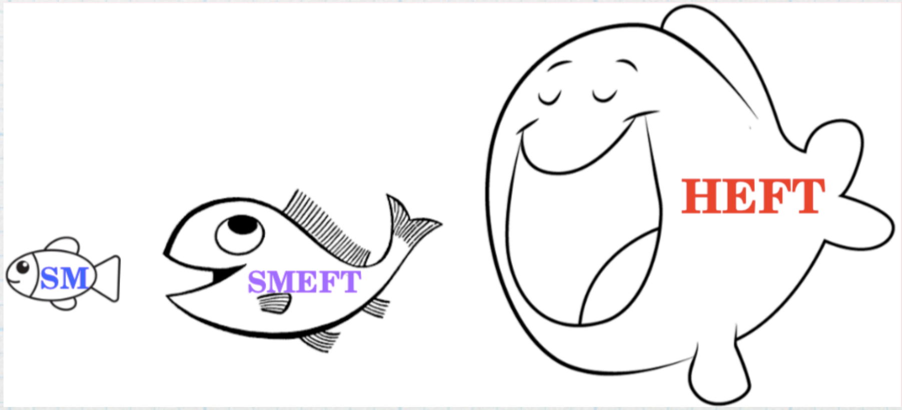
* The SMEFT Lagrangian can be renormalised in the same way as the SM one



See f. ex. 1505.03706. Ghezzi, RGA, Passarino, Uccirati

HEFT: *an old classic*

* Originally the non-linear sigma model (for Pions)
* In principle a QCD Lagrangian -> inspired the EWChL
* Very natural for the study of the Higgs-Goldstone interactions
* I.e: scattering of longitudinal gauge bosons -> Vector boson fusion/scattering
* Natural for strongly coupled new physics



EWChL HEFT *natural to study* VBF/VBS

* Madrid UCM and UAM
  * Strongly coupled theories beyond the Standard Model. Antonio Dobado, Domènec Espriu. Prog.Part.Nucl.Phys. 115 (2020) 103813
  * Unitarity, analyticity, dispersion relations, and resonances in strongly interacting WL WL, ZL ZL, , and hh scattering. R.Delgado , A Dobado, F Llanes-Estrada. Phys.Rev.D 91 (2015) 7, 075017
  * Production of vector resonances at the LHC via WZ-scattering: a unitarized EChL analysis. R.L. Delgado, A. Dobado, D. Espriu, C. Garcia-Garcia, M.J. Herrero et al. JHEP 11 (2017) 098
  * One-loop $\gamma\gamma \to$ WL WL and $\gamma\gamma \to$ ZL ZL from the Electroweak Chiral Lagrangian with a light Higgs-like scalar. R.L. Delgado, A. Dobado, M.J. Herrero, J.J. Sanz-Cillero. JHEP 07 (2014) 149

And refs therein…

SMEFT

$$\vec{\phi} = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix}$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_4 + i\phi_3 \end{pmatrix}$$

HEFT

$$h \quad \text{and} \quad \vec{n} = \begin{pmatrix} n_1 = \pi_1/v \\ n_2 = \pi_2/v \\ n_3 = \pi_3/v \\ n_4 = \sqrt{1 - n_1^2 - n_2^2 - n_3^2} \end{pmatrix}$$

* SMEFT scalar sector —> Linear sigma model
* HEFT —> Non-linear sigma model

Strongly interacting Higgs bosons

Thomas Appelquist and Claude Bernard
Phys. Rev. D **22**, 200 – Published 1 July 1980

HEFT: *an old classic*

* First differences: Power counting

LO

$$\mathcal{L}_{\text{NLO HEFT}} = \frac{1}{2}\left[1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2\right]\partial_\mu\omega^i\partial^\mu\omega^j\left(\delta_{ij} + \frac{\omega^i\omega^j}{v^2 - \boldsymbol{\omega}^2}\right) + \frac{1}{2}\partial_\mu h\partial^\mu h$$

$$+ \frac{4\alpha_4}{v^4}\partial_\mu\omega^i\partial_\nu\omega^i\partial^\mu\omega^j\partial^\nu\omega^j + \frac{4\alpha_5}{v^4}\partial_\mu\omega^i\partial^\mu\omega^i\partial_\nu\omega^j\partial^\nu\omega^j + \frac{g}{v^4}(\partial_\mu h\partial^\mu h)^2$$

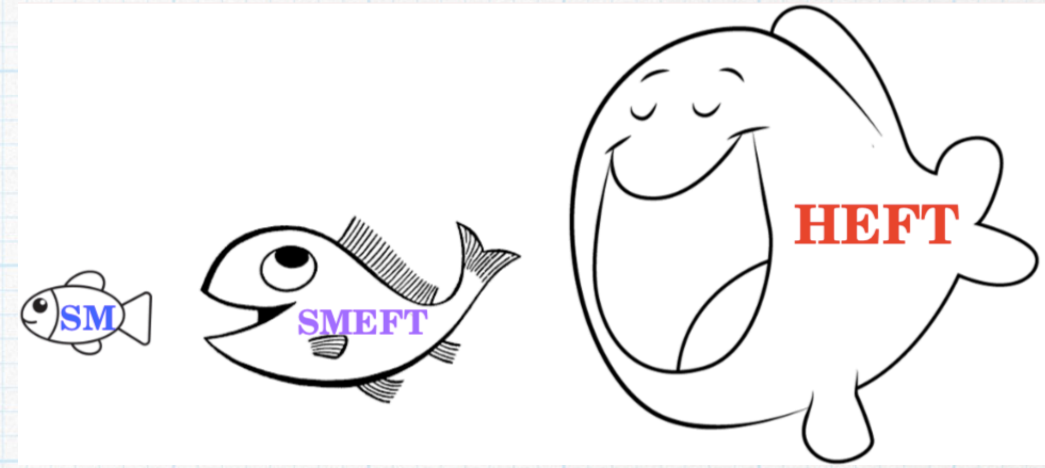
$$+ \frac{2d}{v^4}\partial_\mu h\partial^\mu h\partial_\nu\omega^i\partial^\nu\omega^i + \frac{2e}{v^4}\partial_\mu h\partial^\nu h\partial^\mu\omega^i\partial_\nu\omega^i\ ,$$

NLO

HEFT: caveats

* The correspondence between SM/SMEFT goldstones and the HEFT goldstones is not one-to-one:
* $w^+ w^- \to n \times h \quad \neq \quad \phi^+ \phi^- \to n \times h$
* One of the handicaps to implement UFO models and to compare with Monte Carlo

HEFT: "cons"



* Not widely implemented in Montecarlo
* Difficult to measure/interpret longitudinal gauge bosons in experiment

Testing anomalous $H - W$ couplings and Higgs self-couplings via double and triple Higgs production at e^+e^- colliders

M. Gonzalez-Lopez (Madrid, Autonoma U. and Madrid, IFT), M.J. Herrero (Madrid, Autonoma U. and Madrid, IFT), P. Martinez-Suarez (Madrid, Autonoma U. and Madrid, IFT and Barcelona, IFAE)
Nov 27, 2020

Comparing mesons and $W_L W_L$ TeV-resonances #1

Antonio Dobado (Madrid U. and ICC, Barcelona U.), Rafael L. Delgado (Madrid U. and ICC, Barcelona U.), Felipe J. Llanes-Estrada (Madrid U. and ICC, Barcelona U.), Domenec Espriu (Madrid U. and ICC, Barcelona U.) (Oct 13, 2015)

A new look to the SMEFT-HEFT duality

Recent works highlighting the EFT geometry

* R. Alonso, E. E. Jenkins, and A. V. Manohar,
    * "A Geometric Formulation of Higgs Effective Field Theory: Measuring the Curvature of Scalar Field Space," Phys. Lett. B754 (2016) 335–342, arXiv:1511.00724 [hep-ph].
    * "Sigma Models with Negative Curvature," Phys.Lett.B756,358(2016),arXiv:1602.00706 [hep-ph].
    * "Geometry of the Scalar Sector," JHEP 08 (2016) 101, arXiv:1605.03602 [hep-ph]." (Cohen et al., 2021, p. 95)
* T. Cohen, N. Craig, X. Lu, and D. Sutherland:
    * "Is SMEFT Enough?", JHEP 03, 237, arXiv:2008.08597 [hep-ph].
    * "Unitarity Violation and the Geometry of Higgs EFTs", (2021), arXiv:2108.03240 [hep- ph].

we now know that HEFT and SMEFT can be understood geometrically

And refs therein…

- These works show us that SMEFT vs HEFT is more than linear vs nonlinear realisations…
  - SMEFT exists if: $\exists h^* \rightarrow \mathscr{F}(h) = 0$
  - And $\mathscr{F}(h)$ is analytic in a certain region
- Consequences:
  - $\exists F(h) \implies \mathscr{F}(h) = F(h)^2$
  - Double 0 of $\mathscr{F}(h)$
  - Odd derivatives vanish (even derivatives of $F(h)$)

HEFT *after* 2010

* Take EwChL, enhanced by a flare function:

$$\mathscr{L}_{HEFT} = \frac{1}{2}\partial_\mu h \partial_\mu h - V(h) + \frac{1}{2}\mathscr{F}(h)\ \partial_\mu w^i \partial^\mu w^j \left(\delta_{ij} + \frac{w_i w_j}{v^2 - \mathrm{w}^2}\right)$$

$$\mathscr{F}(h) = 1 + \sum a_n \left(\frac{h}{v}\right)^n$$

In HEFT, h and w's are independent

The flair of the Higgsflare: motivation

flair

noun

UK /fleəʳ/ **US** /fler/

C1 [S]

natural ability to do something well:

- *He has a flair **for** languages.*

$$\mathcal{F}(h) = \left(1 + a_1\frac{h}{v} + a_2\frac{h^2}{v^2} + a_3\frac{h^3}{v^3} + \ldots + a_n\frac{h^n}{v^n}\right)$$

See 2204.01763

Looking for Physics Beyond the SM

* Recast SMEFT in the HEFT language

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{n,i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

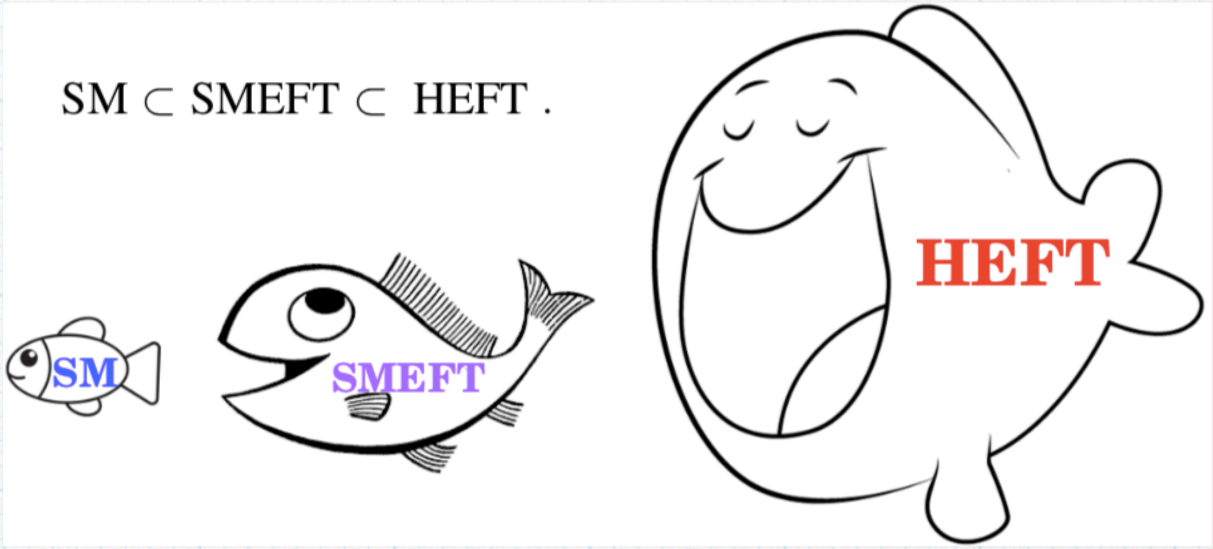
$$\mathcal{L}_{SMEFT} = A(|H|^2)|\partial H|^2 + \frac{1}{2}B(|H|^2)(\partial |H|^2)^2 - V(|H|^2) + \mathcal{O}(\partial^4)$$

$$|H|^2 = (h+v)^2$$

See 2008.08597

Here is where HEFT kicks in

Write SMEFT
in HEFT form:

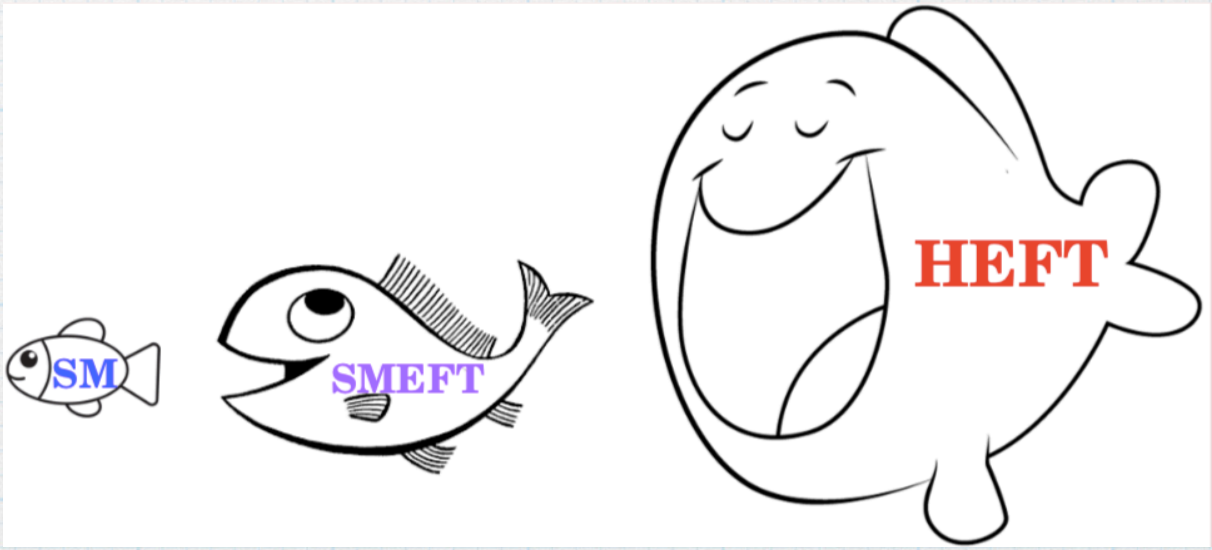


$$|\partial H|^2 + \frac{1}{2}B(|H|)^2(\partial(|H|^2))^2 \;\rightarrow\; \frac{v^2}{4}\mathcal{F}(h)\langle D_\mu U^\dagger D^\mu U\rangle + \frac{1}{2}(\partial h_{HEFT})^2$$

$$dh_{HEFT} = \sqrt{1 + (v + h_{SMEFT})^2 B(h_{SMEFT})} \;\; dh_{SMEFT}$$

The Flare Function

* In HEFT: $\mathcal{F}(h)_{HEFT} = 1 + a_1 \frac{h}{v} + a_2 \left(\frac{h}{v}\right)^2 + a_3 \left(\frac{h}{v}\right)^3 + \ldots$
* In the SM: $\mathcal{F}(h)_{SM} = \left(1 + \frac{h}{v}\right)^2$
* In SMEFT?



Falsifying SMEFT

* Relevant SMEFT operators for the Higgs sector (dim 6):

* $$\mathcal{O}_H = (H^\dagger H)^3 \,, \qquad \mathcal{O}_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H) \,,$$
  $$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H) \,.$$

  * At high energies they decouple and only one survives: $\mathcal{O}_{H\Box}$

Alonso & West 2109.13290

The Flare function in SMEFT

$$\mathcal{L}_{\rm SMEFT} = \frac{v^2}{4}\left(1+\frac{h_1}{v}\right)^2 \langle D_\mu U^\dagger D^\mu U\rangle + \frac{1}{2}\left(1-\frac{2c_{H\Box}(h_1+v)^2}{\Lambda^2}\right)(\partial_\mu h_1)^2 \;-\; V(h_1)$$

$$= \frac{v^2}{4}\mathcal{F}(h_1)\langle D_\mu U^\dagger D^\mu U\rangle + \frac{1}{2}(\partial_\mu h_1)^2 - V(h) - \frac{c_{H\Box}\left[(v+h_1)^3 - v^3\right]}{3\Lambda^2}V'(h_1)\,.$$

$$\mathcal{F}(h_1) = \left(1+\frac{h_1}{v}\right)^2 + \frac{2v^3 c_{H\Box}}{\Lambda^2}\left(1+\frac{h_1}{v}\right)\left(\frac{h_1^3}{3v^3}+\frac{h_1^2}{v^2}+\frac{h_1}{v}\right) + \mathcal{O}\left(\frac{c_{H\Box}^2}{\Lambda^4}\right) =$$

$$= 1 + \left(\frac{h_1}{v}\right)\left(2+2\frac{c_{H\Box}v^2}{\Lambda^2}\right) + \left(\frac{h_1}{v}\right)^2\left(1+4\frac{c_{H\Box}v^2}{\Lambda^2}\right) +$$

$$+ \left(\frac{h_1}{v}\right)^3\left(8\frac{c_{H\Box}v^2}{3\Lambda^2}\right) + \left(\frac{h_1}{v}\right)^4\left(2\frac{c_{H\Box}v^2}{3\Lambda^2}\right),$$

$$a_1 = 2a = 2\left(1+v^2\frac{c_{H\Box}}{\Lambda^2}\right), \quad a_2 = b = 1+4v^2\frac{c_{H\Box}}{\Lambda^2}, \quad a_3 = \frac{8v^2}{3}\frac{c_{H\Box}}{\Lambda^2}, \quad a_4 = \frac{2v^2}{3}\frac{c_{H\Box}}{\Lambda^2}.$$

The Flare function in SMEFT

$$\mathcal{F}(h_1) = 1 + \left(\frac{h_1}{v}\right)\left(2 + 2\frac{c^{(6)}_{H\Box}v^2}{\Lambda^2} + 3\frac{(c^{(6)}_{H\Box})^2 v^4}{\Lambda^4} + 2\frac{c^{(8)}_{H\Box}v^4}{\Lambda^4}\right) +$$

$$+ \left(\frac{h_1}{v}\right)^2\left(1 + 4\frac{c^{(6)}_{H\Box}v^2}{\Lambda^2} + 12\frac{(c^{(6)}_{H\Box})^2 v^4}{\Lambda^4} + 6\frac{c^{(8)}_{H\Box}v^4}{\Lambda^4}\right) +$$

$$+ \left(\frac{h_1}{v}\right)^3\left(8\frac{c^{(6)}_{H\Box}v^2}{3\Lambda^2} + 56\frac{(c^{(6)}_{H\Box})^2 v^4}{3\Lambda^4} + 8\frac{c^{(8)}_{H\Box}v^4}{\Lambda^4}\right) +$$

Naturally extend to dim8 and further, and to quadratic terms

$$+ \left(\frac{h_1}{v}\right)^4\left(2\frac{c^{(6)}_{H\Box}v^2}{3\Lambda^2} + 44\frac{(c^{(6)}_{H\Box})^2 v^4}{3\Lambda^4} + 6\frac{c^{(8)}_{H\Box}v^4}{\Lambda^4}\right) +$$

$$+ \left(\frac{h_1}{v}\right)^5\left(88\frac{(c^{(6)}_{H\Box})^2 v^4}{15\Lambda^4} + 12\frac{c^{(8)}_{H\Box}v^4}{5\Lambda^4}\right) +$$

$$+ \left(\frac{h_1}{v}\right)^6\left(44\frac{(c^{(6)}_{H\Box})^2 v^4}{45\Lambda^4} + 2\frac{c^{(8)}_{H\Box}v^4}{5\Lambda^4}\right) + \mathcal{O}(\Lambda^{-6})\,.$$

The SM is falsified by finding a nonzero Wilson coefficient

How is the SMEFT falsified?

SMEFT vs HEFT

* A deviation from the SM, if small enough, can always be parametrised by the Warsaw basis

SMEFT vs HEFT

* A deviation from the SM, if small enough, can always be parametrised by the Warsaw basis

NOT STRICTLY TRUE

The role of cHBox in SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \frac{1}{2}\left(1 - \frac{2c_{H\Box}v^2}{\Lambda^2}\right)\partial_\mu h \partial^\mu h + \ldots$$

$$\frac{\sigma_{H,\,\text{SMEFT}}}{\sigma_{H,\,\text{SM}}} \propto \frac{\Gamma_{H,\,\text{SMEFT}}}{\Gamma_{H,\,\text{SM}}} \propto 1 + 2\frac{c_{H\Box}v^2}{\Lambda^2} = 1 + 0.12 c_{H\Box}\,,$$

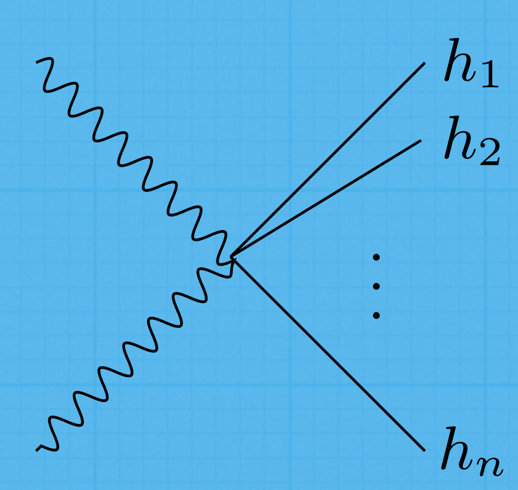
Current Bounds
(SMEFiT and Fitmaker)

$$c_{H\Box} \simeq -0.3 \pm 0.7 \ \ \text{(individual)}$$
$$c_{H\Box} \simeq -1 \pm 2 \ \ \text{(marginalized)}\,.$$

Multihiggs production

* At high energies ($\approx 1\text{TeV}$) we can rely on the equivalence theorem

$$T_{\omega\omega\to n\times h} = \frac{s}{v^n}\sum_{i=1}^{p(n)}\left(\psi_i(q_1,q_2,\{p_k\})\prod_{j=1}^{|\mathrm{IP}[n]_i|} a_{\mathrm{IP}[n]_i^j}\right)$$



$$= -\frac{n!a_n}{2v^n}\,s$$

Falsifying SMEFT

* Two approaches

1. Ratios of total cross sections of $w_L w_L \to nh$

2. Correlations between flare coefficients

Tabulated amplitudes for ww -> nh available on request

Falsifying SMEFT: Ratios of XSECS

In HEFT:

$$T_{\omega\omega\to nh} = f(a_1, \ldots, a_n)$$

$$T_{\omega\omega\to h} = -\frac{a_1 s}{2v}$$

$$T_{\omega\omega\to hh} = \frac{s}{v^2}(a^2 - b) = \frac{s}{v^2}\left(\frac{a_1^2}{4} - a_2\right)$$

$$T_{\omega\omega\to nh} \propto \left(\frac{s}{v^{n-2}\Lambda^2}\right) c_{H\Box} \quad \text{in SMEFT up to } \mathcal{O}\left(\Lambda^{-2}\right)$$

$$\frac{\sigma(\omega\omega \to nh)}{\sigma(\omega\omega \to mh)} = \text{independent of } c_{H\Box}$$

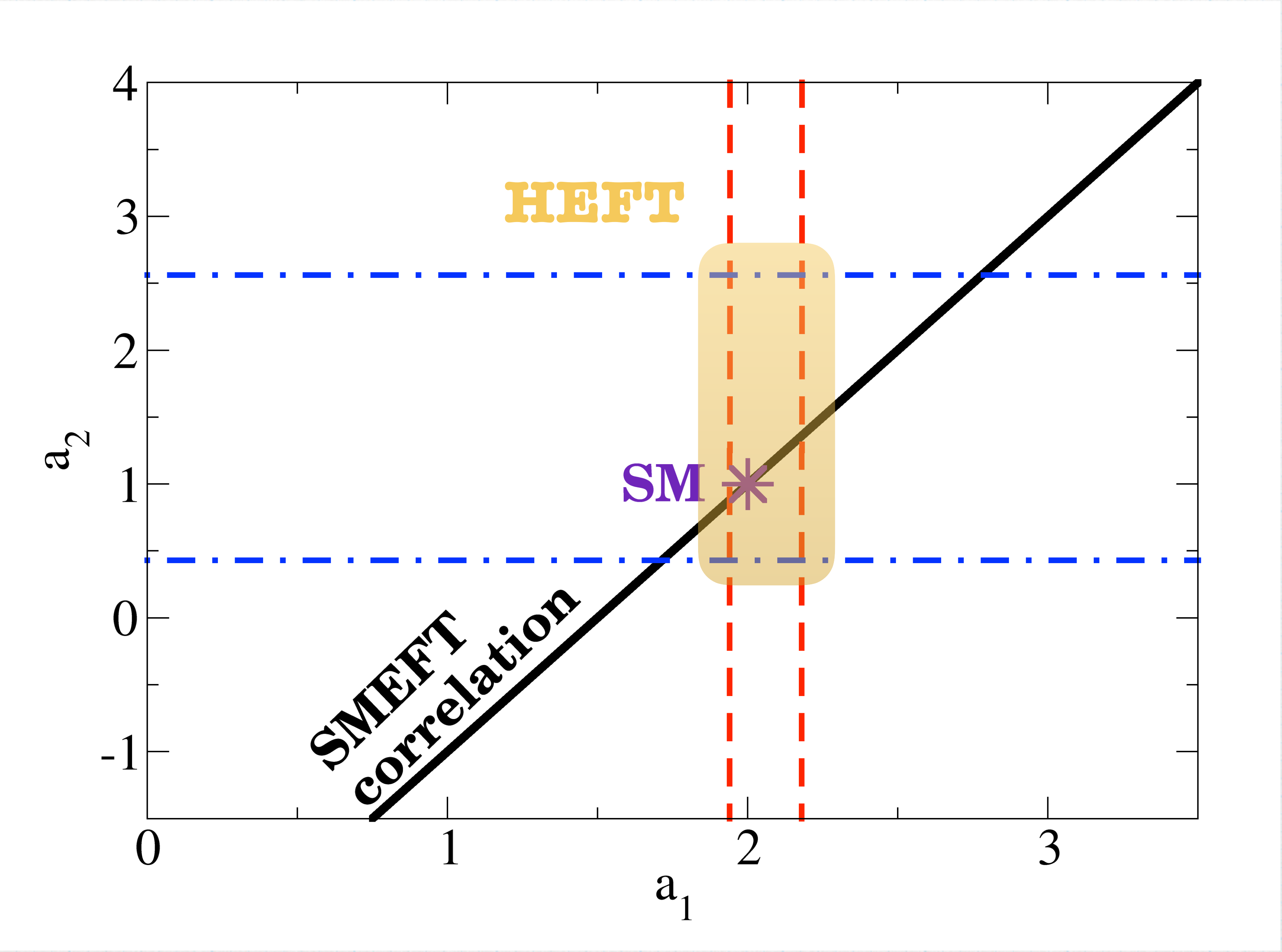
Work in progress....

Falsifying SMEFT: correlations

Correlations accurate at order Λ^{-2}	**Correlations accurate at order Λ^{-4}**	**Λ^{-4} Assuming SMEFT perturbativity**
$\Delta a_2 = 2\Delta a_1$		$\lvert\Delta a_2\rvert \leq 5\lvert\Delta a_1\rvert$
$a_3 = \frac{4}{3}\Delta a_1$	$\left(a_3 - \frac{4}{3}\Delta a_1\right) = \frac{8}{3}(\Delta a_2 - 2\Delta a_1) - \frac{1}{3}\left(\Delta a_1\right)^2$	
$a_4 = \frac{1}{3}\Delta a_1$	$\left(a_4 - \frac{1}{3}\Delta a_1\right) = \frac{5}{3}\Delta a_1 - 2\Delta a_2 + \frac{7}{4}a_3 = \frac{8}{3}(\Delta a_2 - 2\Delta a_1) - \frac{7}{12}\left(\Delta a_1\right)^2$	those for a_3, a_4, a_5, a_6
$a_5 = 0$	$a_5 = \frac{8}{5}\Delta a_1 - \frac{22}{15}\Delta a_2 + a_3 = \frac{6}{5}(\Delta a_2 - 2\Delta a_1) - \frac{1}{3}\left(\Delta a_1\right)^2$	all the same
$a_6 = 0$	$a_6 = \frac{1}{6}a_5$	

$$a_1 = \left(2 + 2\frac{c^{(6)}_{H\Box}v^2}{\Lambda^2} + 3\frac{(c^{(6)}_{H\Box})^2 v^4}{\Lambda^4} + 2\frac{c^{(8)}_{H\Box}v^4}{\Lambda^4}\right) \qquad a_2 = \left(1 + 4\frac{c^{(6)}_{H\Box}v^2}{\Lambda^2} + 12\frac{(c^{(6)}_{H\Box})^2 v^4}{\Lambda^4} + 6\frac{c^{(8)}_{H\Box}v^4}{\Lambda^4}\right).$$

Falsifying SMEFT



Blue and red:
Best available bounds

Experimental application

* Ideally future colliders will be able to measure multihiggs production at a good enough accuracy to test these correlations.
* Already a measurement of double H production at HL-LHC would provide greater insight on the a1/a2 values.

Experimental application: state of the art

* Measurements by ATLAS and CMS have produced bounds on a1 and a2:

$a_1/2 = a \in [0.97, 1.09]$

$a_2 \in [-0.43, 2.56] (AT)$

$\in [-0.1, 2.2] (CMS)$

Consistent SMEFT range at order Λ^{-2}	**Consistent SMEFT range at order Λ^{-4}**	**Perturbativity of Λ^{-4} SMEFT**
$\Delta a_2 \in [-0.12, 0.36]$	ATLAS	ATLAS
$a_3 \in [-0.08, 0.24]$	$a_3 \in [-4.1, 4.0]$	$a_3 \in [-3.1, 1.7]$
$a_4 \in [-0.02, 0.06]$	$a_4 \in [-4.2, 3.9]$	$a_4 \in [-3.3, 1.5]$
$a_5 = 0$	$a_5 \in [-1.9, 1.8]$	$a_5 \in [-1.5, 0.6]$
$a_6 = 0$	$a_6 = a_5$	$a_6 = a_5$
	CMS	CMS
	$a_3 \in [-3.2, 3.0]$	$a_3 \in [-3.1, 1.7]$
	$a_4 \in [-3.3, 3.0]$	$a_4 \in [-3.3, 1.5]$
	$a_5 \in [-1.5, 1.3]$	$a_5 \in [-1.5, 0.6]$
	$a_6 = a_5$	$a_6 = a_5$

Conclusions and outlook

* The Higgs potential is a big open question at LHC
* We have shown here a procedure to rule out the SMEFT, independent of the finding of new particles
* A first clue might be accessible at HL-LHC (through double H production)
* We can use properties of the flare function to extract further insights on low energy physics (see paper)
* We can associate the flare function being HEFT-like or SMEFT-like with concrete BSM scenarios

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Cariplo and **Regione Lombardia**, grant 20

Backup - References

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* Dim 8 basis:
  * C. W. Murphy, Dimension-8 operators in the Standard Model Eective Field Theory, JHEP 10, 174, arXiv:2005.00059 [hep-ph].
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Measurements of a1/a2

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