Higgs EFT coupling constraints

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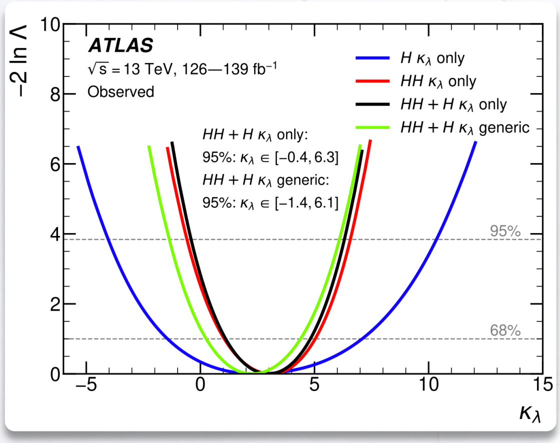
July 10th, 2023

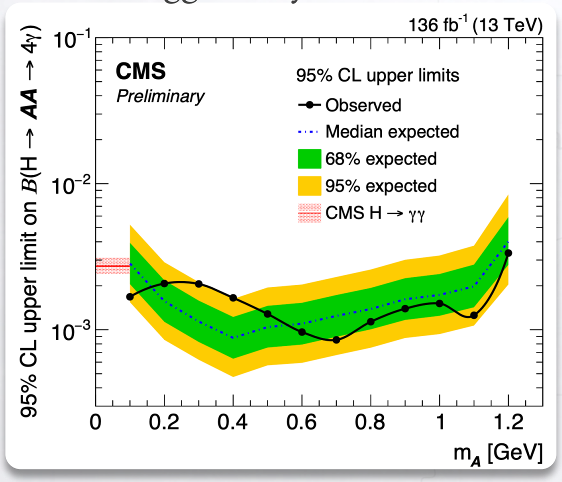
- A scalar boson was seen the LHC in 2012, opening a brave new world: **Higgs physics**

Higgs self-coupling:



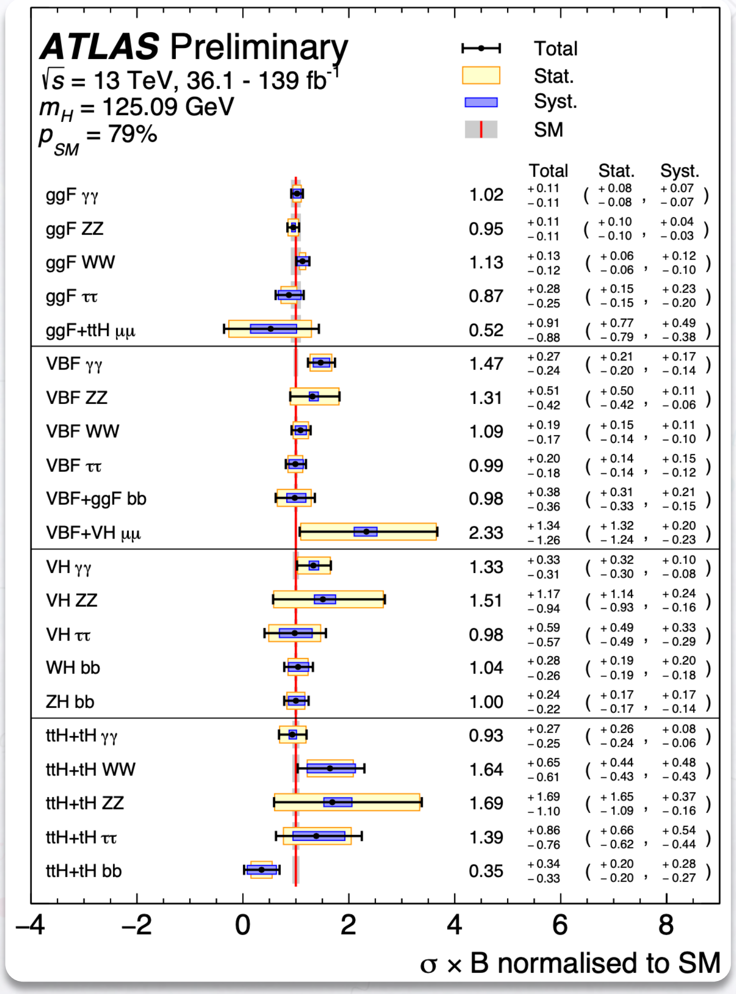
[ATLAS, 2211.01216]

Exotic Higgs decays:



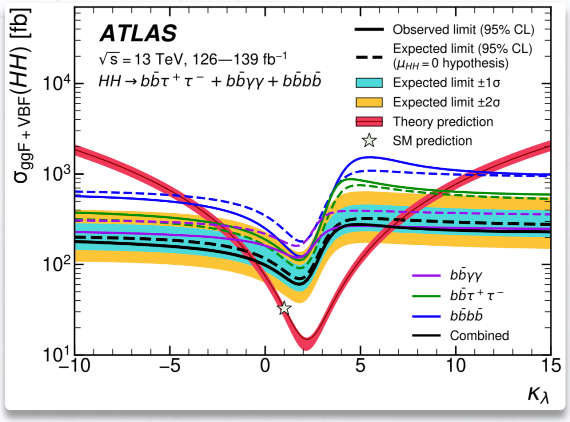
[CMS-PAS-HIG-21-016]

Single Higgs production and decay:



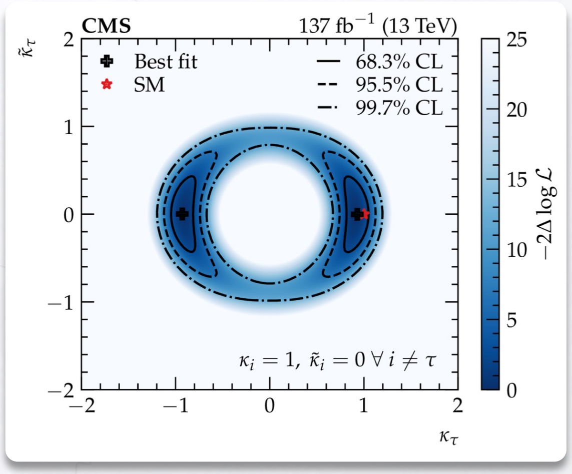
[ATLAS-CONF-2021-053]

Double Higgs production and decay:



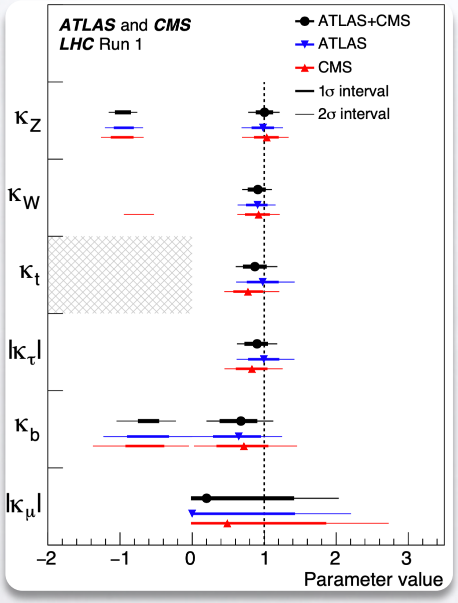
[ATLAS, 2211.01216]

Higgs CP violation:

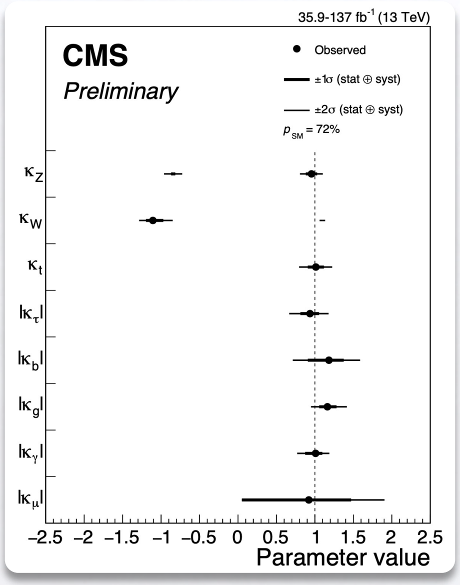


[CMS, 2110.04836]

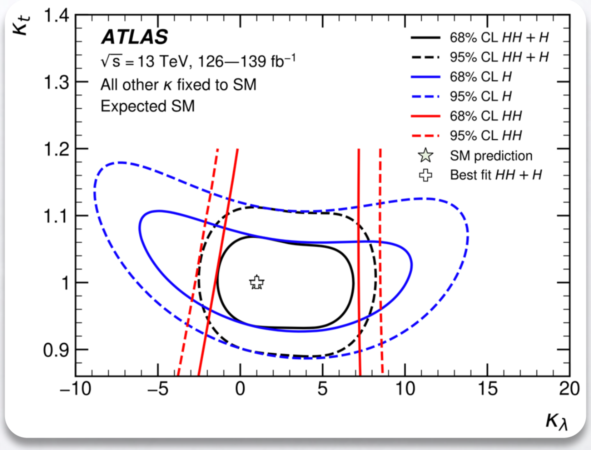
- **How** to search for physics Beyond the Standard Model (BSM) within Higgs physics?
  - The dream: direct detection! But if BSM physics is too heavy to be produced, we resort to indirect methods — ideally, in a model-independent way
  - A usual approach is the kappa formalism: [David et al, 1209.0040] [Heinemeyer et al, 1307.1347]
    - A set of scale factors κ_i are defined, such that all decay channels and production x-section of the SM Higgs are rescaled by a κ_i^2: $\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \kappa_g^2, \quad \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \kappa_\gamma^2, \quad \frac{\Gamma_{ff}}{\Gamma_{ff}^{\mathrm{SM}}} = \kappa_f^2, \quad \ldots$
    - ATLAS and CMS have provided (and still provide) limits on the κ_i parameters:



[Aad et al, 1606.02266]



[CMS, CMS-PAS-HIG-19-005]



[ATLAS, 2211.01216]

- But the kappa formalism was explicitly proposed as an *interim solution*:
  - it deliberately ignores tensorial structures not present in the SM
    (so that it becomes model dependent and cannot be used for kinematic distributions)
  - it does not follow from a consistent Quantum Field Theory
    (so that it does not allow higher order, different scales, etc.)
  - it is not an **Effective Field Theory** (EFT)
    (so that it does not represent an IR limit of an UV sector)

[Brivio, Trott, 1706.08945]

- The theoretical framework that should be used for a model-independent approach is an **EFT**
  - General & consistent for heavy BSM
  - It was not mature at LHC Run 1

Two main **EFT** candidates for Higgs physics:

SMEFT HEFT

- In this talk:
  - What are these two candidates? How are they constrained from Higgs measurements?
  - How to relate them? Which one is preferred?
  - How important are higher orders of the **EFT** expansion?

In both cases, I will resort to the 2HDM

Standard Model Effective Field Theory

- The SMEFT is an **EFT** that takes the SM before SSB and includes higher-order terms:

Wilson coefficients

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)}, \qquad d > 4$$

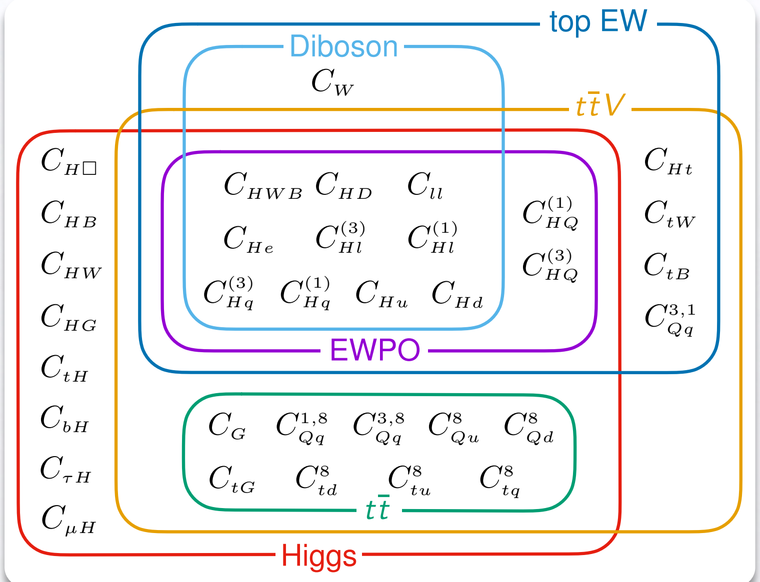
is even if lepton and baryon number are conserved

- dof's and symmetries of the SM
- Higgs belongs to a SU(2) doublet
- clear power-counting in $1/\Lambda$

- The Warsaw basis is a complete basis for dim-6 operators... which can be divided into sectors

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

[Grzadkowski et al, 1008.4884]



[Ellis et al, 2012.02779]

- Combining the Higgs sectors with other sectors is very desirable!

- Generality comes at a cost: at dim-6, there are in general 2499 operators!
- This can be reduced assuming flavor symmetries: e.g. $U(3)^5$ or top specific

The Higgs sector can then be described with ~30 operators

- Ok. Then, how to use Higgs measurements to constrain dim-6 Wilson coefficients?

THEORY

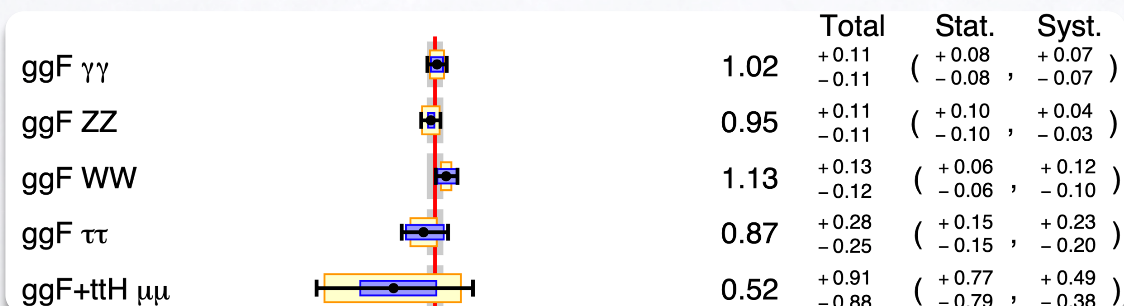
- Calculate all channels of Higgs production and decay in SMEFT at $1/\Lambda^2$
  - prod. modes: ggh, VBF, Wh, Zh, $t\bar{t}h$
  - final states: $\gamma\gamma$, $b\bar{b}$, $\tau^+\tau^-$, W^+W^-, ZZ, $\ldots$
  - Indeed, for an amplitude $\mathcal{A} \propto a_0\, g_{\rm SM} + a_1 \dfrac{C^{(6)}}{\Lambda^2} + a_2 \dfrac{C^{(8)}}{\Lambda^4} + \ldots$, the amplitude square is:

$$|\mathcal{A}|^2 \propto |a_0\, g_{\rm SM}|^2 + \frac{2}{\Lambda^2}\mathrm{Re}[a_0\, a_1\, g_{\rm SM}\, C^{(6)}] + \frac{1}{\Lambda^4}\left\{|a_1\, C^{(6)}|^2 + 2\,\mathrm{Re}[a_0\, a_2\, g_{\rm SM}\, C^{(8)}]\right\} + \ldots$$

  - Tree-level results can be obtained with SMEFTsim, whereas loop ones with SMEFT@NLO [Brivio, 2012.11343] [Degrande et al, 2008.11743]

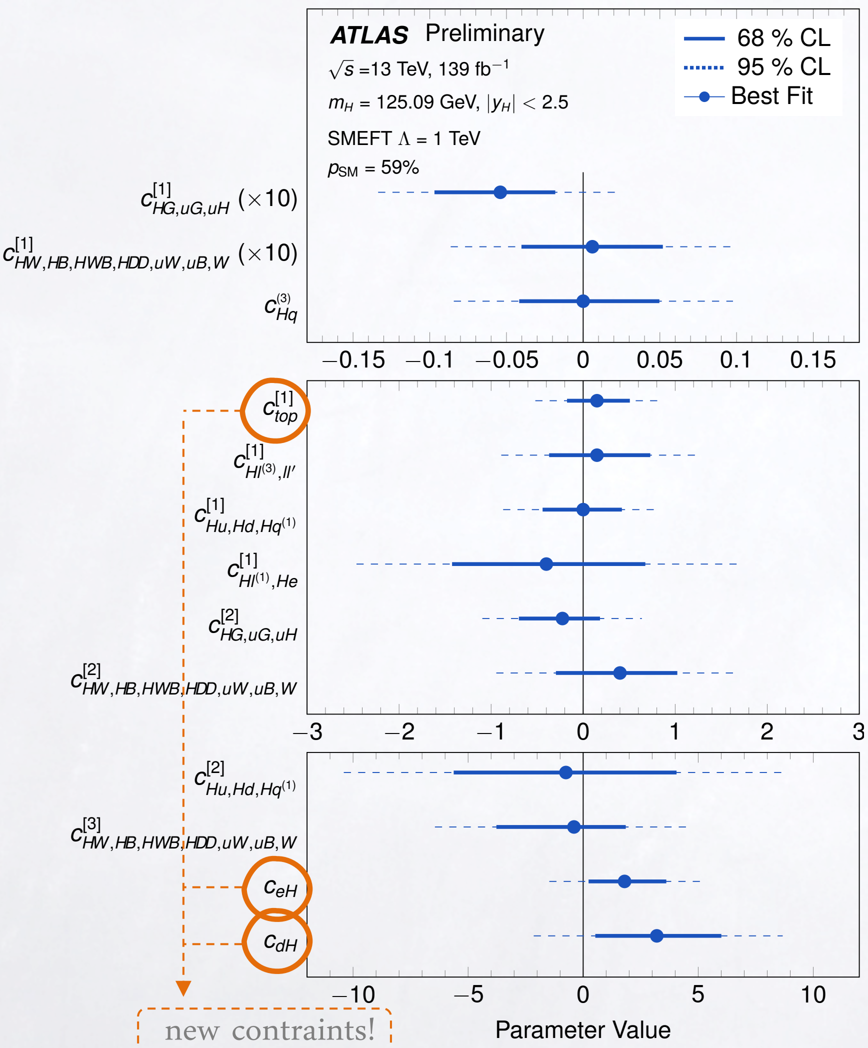
EXPERIMENT

- Compare with experimental Higgs signal strengths: $\mu^P_{pp\to h\to f} = \dfrac{\sigma^P(pp\to h)}{\sigma^P(pp\to h)_{\rm SM}} \times \dfrac{\mathrm{BR}(h\to f)}{\mathrm{BR}(h\to f)_{\rm SM}}$



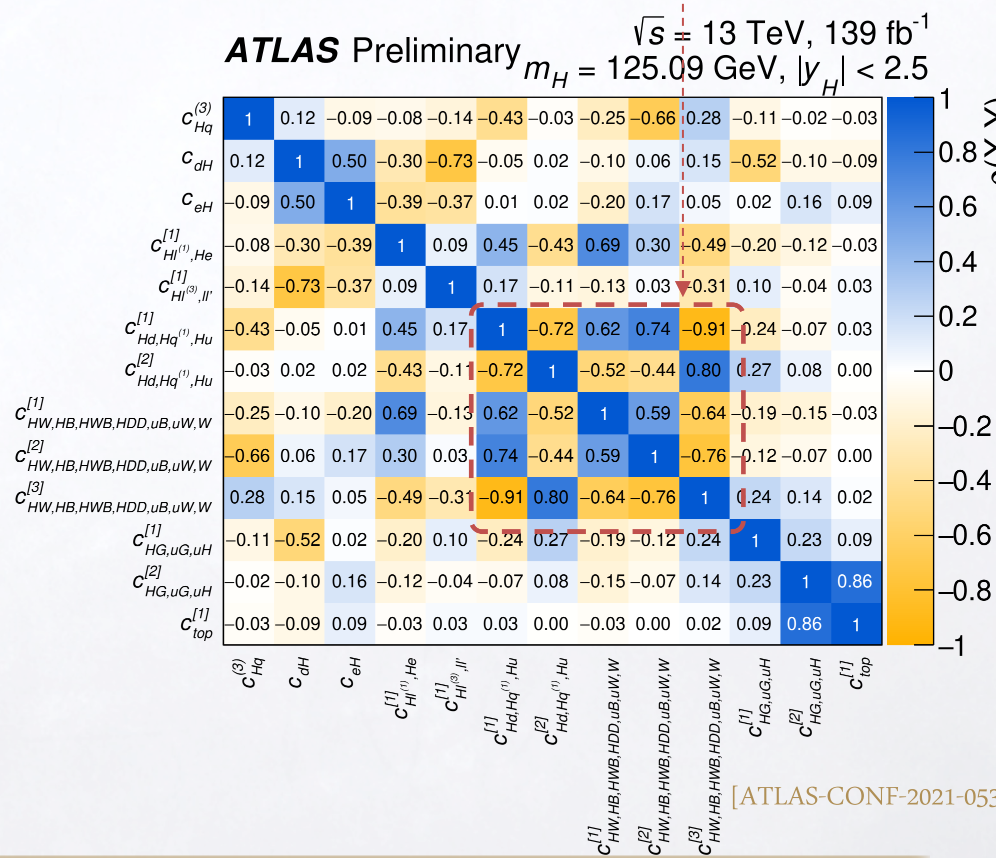
[ATLAS-CONF-2021-053]

- Performing fits, we find:



[ATLAS-CONF-2021-053]

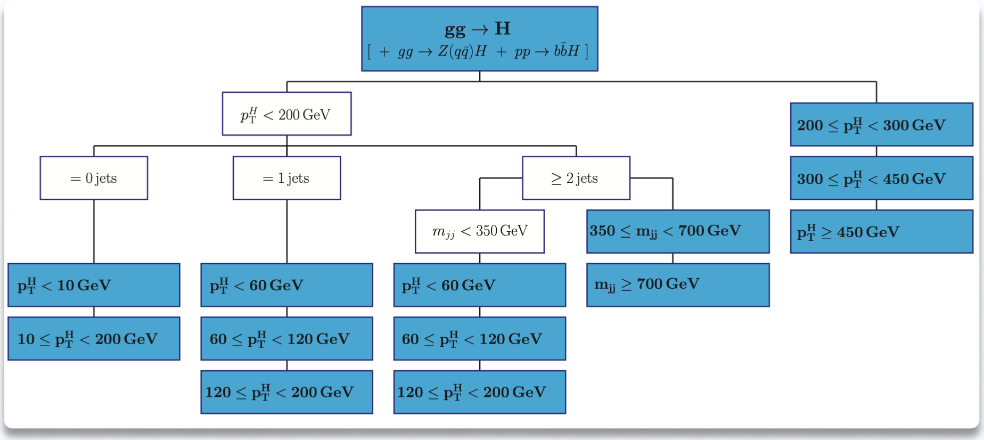
- Additional sensitivity contrains 3 new WCs
- All WCs are compatible with the SM...
- ...but with different hierarchies of errors,
- and with some of them exhibiting strong correlations



	$c^{(3)}_{Hq}$	c_{dH}	c_{eH}	$c^{[1]}_{Hl^{(1)},He}$	$c^{[1]}_{Hl^{(3)},ll'}$	$c^{[1]}_{Hd,Hq^{(1)},Hu}$	$c^{[2]}_{Hd,Hq^{(1)},Hu}$	$c^{[1]}_{HW,HB,HWB,HDD,uB,uW,W}$	$c^{[2]}_{HW,HB,HWB,HDD,uB,uW,W}$	$c^{[3]}_{HW,HB,HWB,HDD,uB,uW,W}$	$c^{[1]}_{HG,uG,uH}$	$c^{[2]}_{HG,uG,uH}$	$c^{[1]}_{top}$
$c^{(3)}_{Hq}$	1	0.12	−0.09	−0.08	−0.14	−0.43	−0.03	−0.25	−0.66	0.28	−0.11	−0.02	−0.03
c_{dH}	0.12	1	0.50	−0.30	−0.73	−0.05	0.02	−0.10	0.06	0.15	−0.52	−0.10	−0.09
c_{eH}	−0.09	0.50	1	−0.39	−0.37	0.01	0.02	−0.20	0.17	0.05	0.02	0.16	0.09
$c^{[1]}_{Hl^{(1)},He}$	−0.08	−0.30	−0.39	1	0.09	0.45	−0.43	0.69	0.30	−0.49	−0.20	−0.12	−0.03
$c^{[1]}_{Hl^{(3)},ll'}$	−0.14	−0.73	−0.37	0.09	1	0.17	−0.11	−0.13	0.03	−0.31	0.10	−0.04	0.03
$c^{[1]}_{Hd,Hq^{(1)},Hu}$	−0.43	−0.05	0.01	0.45	0.17	1	−0.72	0.62	0.74	−0.91	−0.24	−0.07	0.03
$c^{[2]}_{Hd,Hq^{(1)},Hu}$	−0.03	0.02	0.02	−0.43	−0.11	−0.72	1	−0.52	−0.44	0.80	0.27	0.08	0.00
$c^{[1]}_{HW,HB,HWB,HDD,uB,uW,W}$	−0.25	−0.10	−0.20	0.69	−0.13	0.62	−0.52	1	0.59	−0.64	−0.19	−0.15	−0.03
$c^{[2]}_{HW,HB,HWB,HDD,uB,uW,W}$	−0.66	0.06	0.17	0.30	0.03	0.74	−0.44	0.59	1	−0.76	−0.12	−0.07	0.00
$c^{[3]}_{HW,HB,HWB,HDD,uB,uW,W}$	0.28	0.15	0.05	−0.49	−0.31	−0.91	0.80	−0.64	−0.76	1	0.24	0.14	0.02
$c^{[1]}_{HG,uG,uH}$	−0.11	−0.52	0.02	−0.20	0.10	−0.24	0.27	−0.19	−0.12	0.24	1	0.23	0.09
$c^{[2]}_{HG,uG,uH}$	−0.02	−0.10	0.16	−0.12	−0.04	−0.07	0.08	−0.15	−0.07	0.14	0.23	1	0.86
$c^{[1]}_{top}$	−0.03	−0.09	0.09	−0.03	0.03	0.03	0.00	−0.03	0.00	0.02	0.09	0.86	1

[ATLAS-CONF-2021-053]

- Besides with signal strengths, one can also compare with Simplified Template X-Sections (STXS), which are kinematically richer [Andersen et al, 1605.04692] [Berger et al, 1906.02754]
  - Example: gluon fusion Higgs production
    - Without STXS, one would be restricted to the '0-jet' entry
    - In that case, there would be a degeneracy of the 4 relevant WCs
    - The use of STXS, by introducing jets, allows to break that degeneracy, and thus better constrain the different WCs



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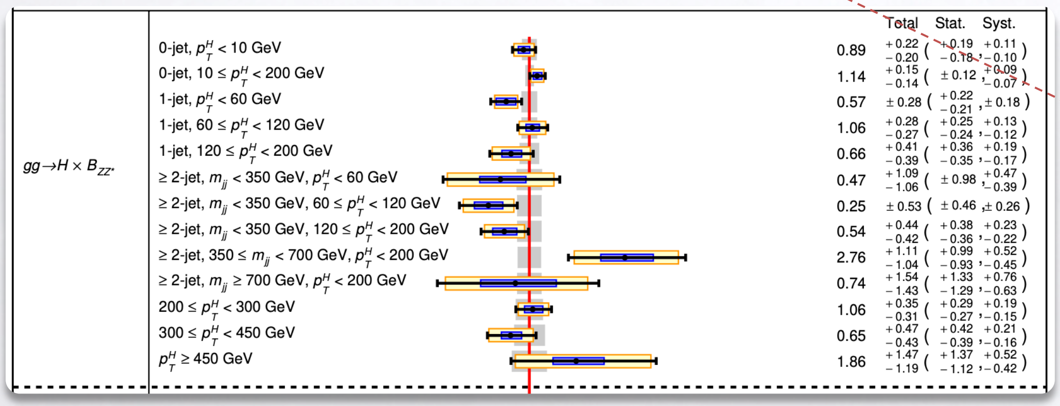

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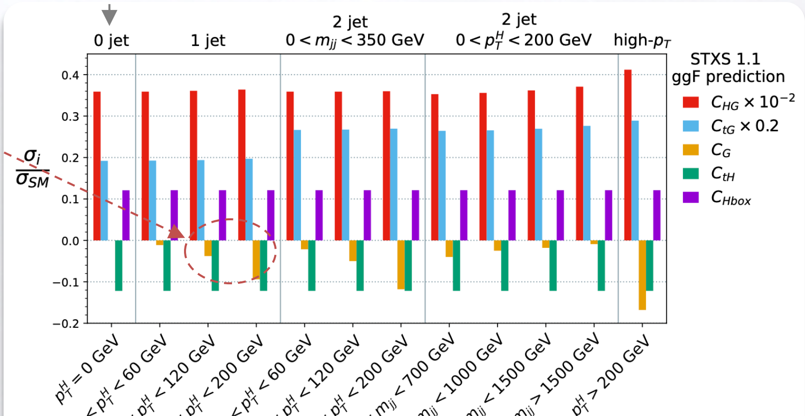
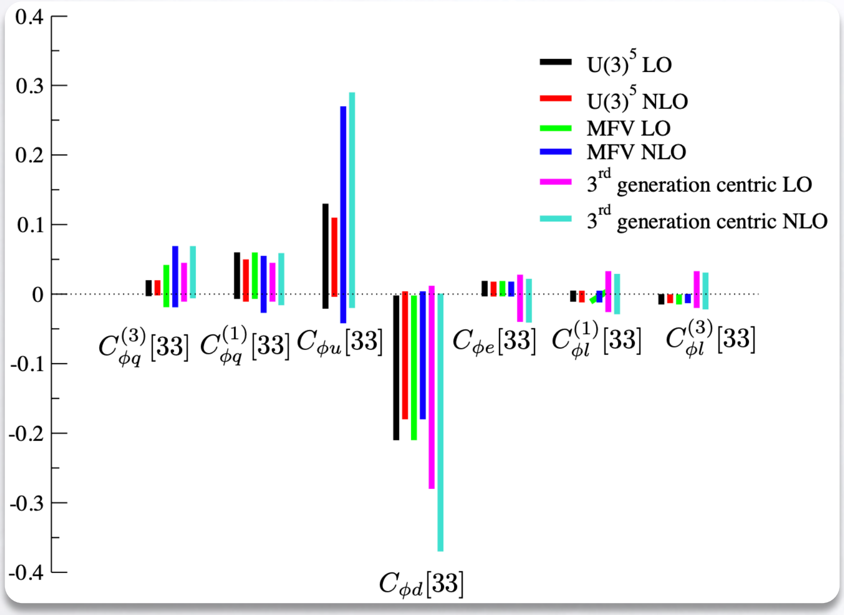
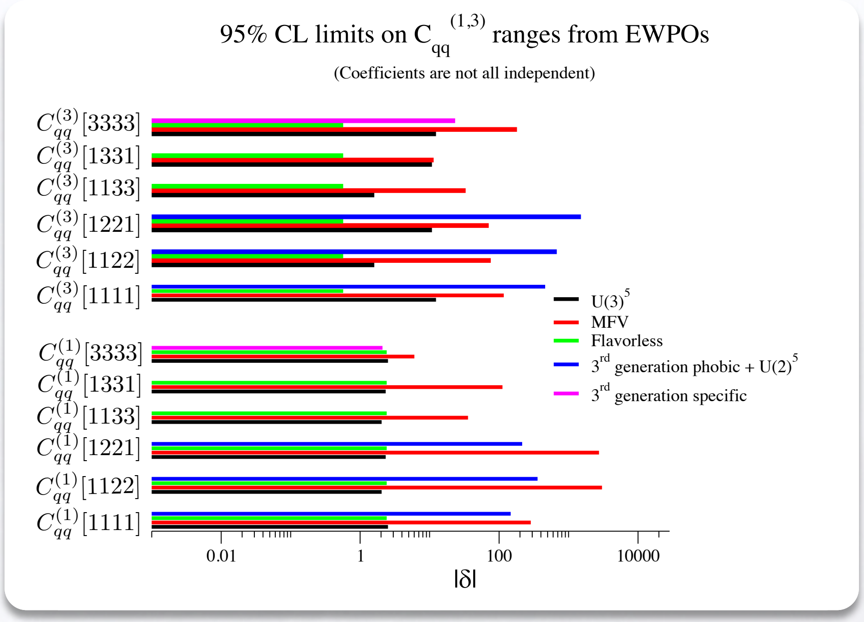


[Ellis et al, 2012.02779]

- Are flavor assumptions really justified?
  - Without flavor assumptions, there are simply too many operators...
  - Still, a recent study suggests that flavor matters:
    [Bellafronte, Dawson, Giardino, 2304.00029]





  - The study focused on Electroweak Precision Observables (EWPO)
  - The impact of flavor on Higgs measurements is still to be investigated

Higgs Effective Field Theory

- The HEFT is a fusion of chiral perturbation theory (χPT) (in the scalar sector) with SMEFT (in the fermion and gauge sector). Just as in χPT:
  - The $\underbrace{\text{3 Goldstone}}_{\pi^I\text{, imbedded into } U = \exp\left(i\tau^I\pi^I/v\right)}$ bosons are independent of the $\underbrace{\text{Higgs}}_{h}$, which is a **gauge singlet** (instead of part of an SU(2) doublet)
  - There is an expansion in the number of (covariant) derivatives. At LO:

$$\mathcal{L}_{\text{HEFT}} \supset \frac{v^2}{4}\mathcal{F}(h)\text{Tr}\left\{D_\mu U^\dagger D_\mu U\right\} + \frac{1}{2}(\partial_\mu h)^2 - V(h)$$

with:

HEFT coefficients

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots, \qquad V(h) = \frac{1}{2}m_h^2 h^2\left(1 + d_3\frac{h}{v} + \frac{d_4}{4}\frac{h^2}{v^2} + \ldots\right)$$

(such that the SM corresponds to $a = b = d_3 = d_4 = 1$)

- Because the Higgs is a **gauge singlet**, it has arbitrary couplings: e.g. d_3 and d_4 are independent (whereas in the SMEFT they are related, since h is contained in a doublet)

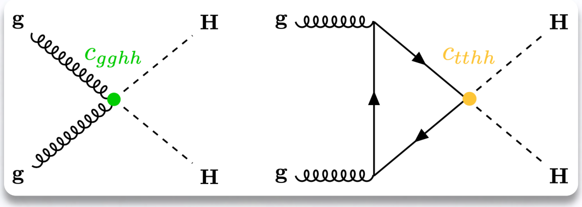
- The organization of HEFT is subtle, since χPT and SMEFT have different organizations
  - One sometimes includes the NLO term, since the LO one has a poor structure
  - But there is no agreement in the literature on what is LO and what is NLO [Brivio et al, 1604.06801] [Buchalla, Cata, Krause, 1307,5017]

- Does the LHC use Higgs measurements to constrain HEFT couplings?
- **Recently, yes**: in searches for Higgs pair production [ATL-PHYS-PUB-2022-019]

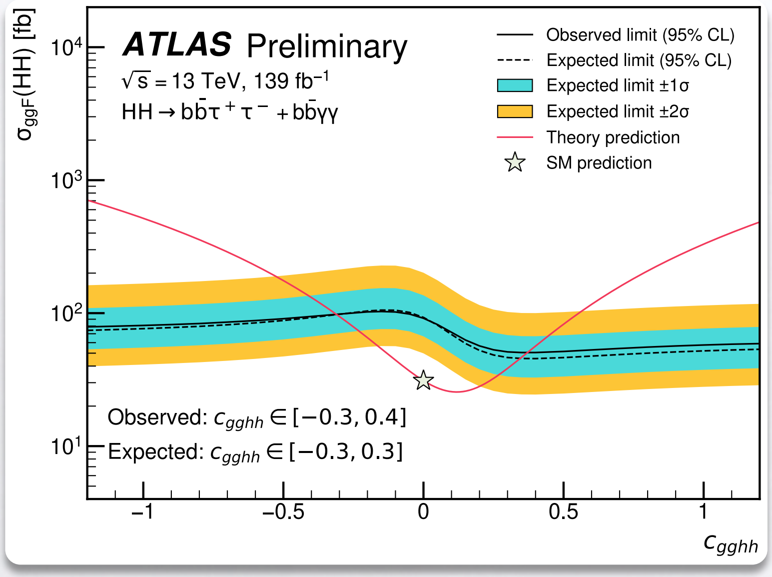
The LHC was recently able to put bounds on this channel

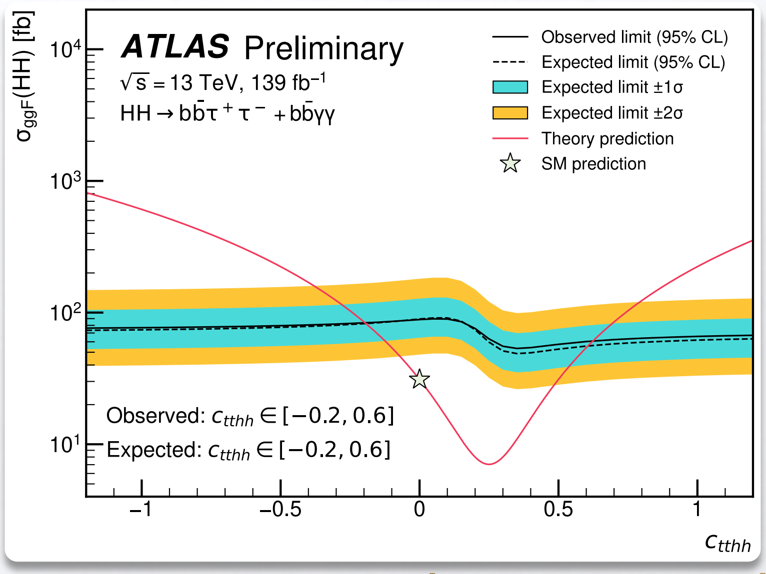
albeit in a primitive form, with no reference to basis, Lagrangian or EFT order

  - It thus exploits the fact that, in the HEFT, couplings to 1 or 2 Higgs are treated separately
  - Examples of diagrams considered:



  - In the end, then, the 'HEFT' parameters c_{tthh} and c_{gghh} are constrained:





[ATL-PHYS-PUB-2022-019]

- We may then ask: given SMEFT and HEFT, which one should be used?
- This question has been addressed several times (from a rather theoretical perspective)

[Brivio et al, 1311.1823] [Brivio, PhD thesis, 2016] [Cohen et al, 2008.08597] [Banta et al, 2110.02967] [Ambrosio et al, 2204.01763]
[Alonso et al, 1409.1589] [Brivio, Trott, 1706.08945] [Cohen et al, 2108.03240] [Kanemura, Nagai, 2111.12585] [Ambrosio et al, 2207.09848]
[Brivio et al, 1604.06801] [Falkowski, Rattazzi, 1902.05936] [Alonso, West, 2109.13290] [Banta, 2202.04608] [Gráf et al, 2211.06275]

- As an intro:

	SMEFT	HEFT
Higgs couplings	polynomial dependence in $(v+h)^n$, determined by the $\mathrm{SU_L}(2)$ doublet	totally arbitrary functions $\mathcal{F}(h)$
Power counting	simple: canonical mass dimensions	complex!
Number of terms (flavor blind)	76 at dim-6	148 at NLO

[Brivio, PhD thesis, 2016]

- It seems clear that, by allowing the Higgs to have arbitrary couplings, the HEFT is more general
- The distinction SMEFT vs. HEFT is usually: linear vs. nonlinear realization of the symmetry

[Brivio et al, 1311.1823] [Alonso et al, 1409.1589] [Brivio et al, 1604.06801]

- But more physical descriptions are preferred: analytic vs. non-analytic, or geometrical descriptions
  [Falkowski, Rattazzi, 1902.05936] [Alonso, Jenkins, Manohar, 1511.00724]

- Very interesting... but also quite theoretical. Is there a more phenomenological answer to the question 'Which **EFT**?'? Specifically:
  The LHC Higgs measurements should constrain the couplings of an **EFT**. Which one?

- A model-independent strategy was proposed by Alonso et al and perfected by Brivio et al
  [Alonso et al, 1212.3305] [Brivio et al, 1311.1823]

- But can we look at particular UV models? [*Check Samuel Homiller's talk on Thursday*]
  - **EFTs** are generic, model-independent $\dashrightarrow$ (bottom-up approach)
  - Still, by matching to $\underbrace{\text{particular UV models}}_{\text{(top-down approach)}}$, one may gain insight about the generic approach

2 Higgs Doublet Model

- Let us take the 2HDM to compare SMEFT and HEFT. The 2HDM in (very) short:
[Dawson et al, 2305.07689]
  - Start with the SM and add an extra scalar doublet. The potential reads:

$$
\begin{aligned}
V \;=\;& Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + \left(Y_3 H_1^\dagger H_2 + \text{h.c.}\right) + \frac{Z_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{Z_2}{2}\left(H_2^\dagger H_2\right)^2 + Z_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) \\
& + Z_4\left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \left\{\frac{Z_5}{2}\left(H_1^\dagger H_2\right)^2 + Z_6\left(H_1^\dagger H_1\right)\left(H_1^\dagger H_2\right) + Z_7\left(H_2^\dagger H_2\right)\left(H_1^\dagger H_2\right) + \text{h.c.}\right\}
\end{aligned}
$$

  - To diagonalize the states in H_1 and H_2 , introduce two mixing angles: β and $\beta-\alpha$
  - In the end, 4 scalars: h is the (SM) scalar found at the LHC, and H, A, H^+ are BSM scalars

- In order to build an **EFT** from the 2HDM, this model needs separated scales: $\Lambda \gg v = 246$ GeV
  - We thus assume that the BSM scalars decouple: $m_H \simeq m_A \simeq m_{H^+} \gg m_h \simeq v$
  - But we do not want the couplings constants too large: we want perturbativity

$$
m_h^2 = \frac{c_{\beta-\alpha}^2}{2\,c_{\beta-\alpha}^2 - 1} Y_2 + \frac{2\,(c_{\beta-\alpha}^2 - 1) Z_1 + c_{\beta-\alpha}^2 Z_{345}}{4\,c_{\beta-\alpha}^2 - 2} v^2, \qquad m_A^2 = Y_2 + \frac{Z_{345} - 2 Z_5}{2} v^2,
$$

$$
m_H^2 = \frac{(c_{\beta-\alpha}^2 - 1)}{2\,c_{\beta-\alpha}^2 - 1} Y_2 + \frac{c_{\beta-\alpha}^2 (2 Z_1 + Z_{345}) - Z_{345}}{4\,c_{\beta-\alpha}^2 - 2} v^2 \qquad m_{H^+}^2 = Y_2 + \frac{Z_3}{2} v^2
$$

with $Z_{345} \equiv Z_3 + Z_4 + Z_5$

  - Keeping the Z's fixed, we have decoupling if Y_2 is large and $c_{\beta-\alpha}$ is small

- Then, the decoupling limit $m_H \simeq m_A \simeq m_{H^+} \gg m_h$ can be obtained in a way consistent with perturbativity if, for a small ξ, we have: $v^2/Y_2 \sim \mathcal{O}(\xi), \quad c_{\beta-\alpha} \sim \mathcal{O}(\xi)$
  - We can use this to perform an **EFT** expansion!
  - Both the SMEFT and the HEFT matchings to the 2HDM will follow this expansion
  - So, even if they are structurally different...

integrate out the physical states H, A, H^+

integrate out the doublet H_2

SMEFT/HEFT matching to the 2HDM:
integrate out the heavy dof's before/after SSB

...they end up being very similar!

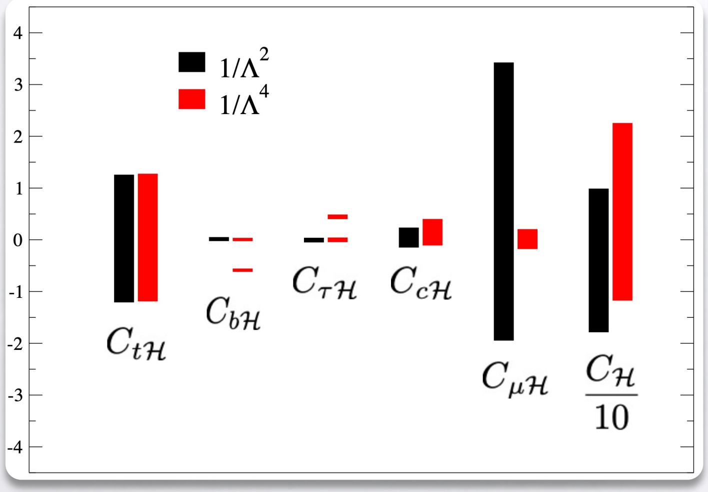
  - In fact, for tree-level at $\mathcal{O}(\xi^2)$, for both single/double Higgs production/decay, they are *identical*!

- In sum: assuming decoupling and perturbativity in the 2HDM, we find *no differences* between the SMEFT and the HEFT matchings [Dawson et al, 2305.07689]
- Open questions:
  - How general is this identity between SMEFT and HEFT matchings in the UV models?
  - And what are the consequences for a model-independent comparison between the two?
  - Is it possible to have an **EFT** without decoupling? How much room for that?

- Back to a model-independent approach. In an EFT like the SMEFT, there are several types of theory uncertainties:
  - from dependence on SM quantities (input schemes, PDFs, scales)
  - from higher orders in the loop expansion (both QCD and QED)
  - from running and mixing of the EFT coefficients
  - from higher orders in the EFT expansion:

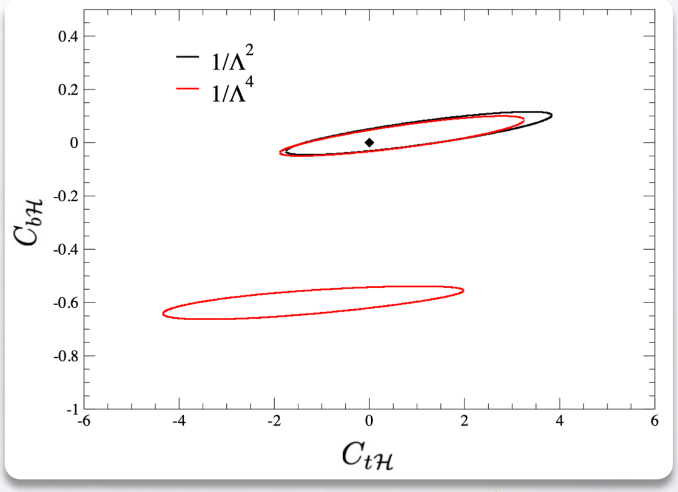
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{n_6} \frac{C_i^{(6)}}{\Lambda^2} Q_i^{(6)} + \sum_{i=1}^{n_8} \frac{C_i^{(8)}}{\Lambda^4} Q_i^{(8)} + \dots$$

- When using Higgs measurements to constrain SMEFT coefficients, is $1/\Lambda^2$ **enough**?



[Dawson et al, 2205.01561]

- even if we stick to dim-6 terms, the $1/\Lambda^4$ corrections can be very relevant!
- then, and for consistency, we need to consider dim-8 operators as well



[Dawson et al, 2205.01561]

SMEFT

beyond $1/\Lambda^2$:

Bases

[Harlander, Kempkens, Schaaf, 2305.06832]
[Ren, Yu, 2211.01420]
[Li et al, 2201.04639]
[Chala, Díaz-Carmona, Guedes, 2112.12724]
[Liao, Ma, 2007.08125]
[Li et al, 2007.07899]
[Liao, Ma, Wang, 2005.08013]
[Murphy, 2005.00059]
[Li et al, 2005.00008]
[Lehman, 1410.4193]
...

RGE's and positivity

[Assi et al, 2307.03187]
[Zhang, 2306.03008]
[Chala, 2301.09995]
[Bakshi, Díaz-Carmona, 2301.07151]
[Helset, Jenkins, Manohar, 2212.03253]
[Bakshi et al, 2205.03301]
[Chala et al, 2106.05291]
...

[*Check Mikael Chala's talk on Wednesday*]

geoSMEFT

[Corbett, Martin, 2306.00053]
[Kim, Martin, 2203.11976]
[Martin, Trott, 2109.05595]
[Corbett et al, 2102.02819]
[Hays et al, 2007.00565]
[Helset, Martin, Trott, 2001.01453]
...

Computational tools

[Dedes et al, 2302.01353]
[Fuentes-Martin et al, 2212.04510]
[Allwicher et al, 2207.10756]
[Carmona et al, 2112.10787]
[Fuentes-Martin et al, 2012.08506]
[Criado, 1901.03501]
...

Specific processes

[Corbett et al, 2304.03305]
[Degrande, Li, 2303.10493]
[Asteriadis, Dawson, DF, 2212.03258]
[Aoude et al, 2208.04962]
[Allwicher et al, 2207.10714]
[Boughezal, Huang, Petriello, 2207.01703]
[Ellis, He, Xiao, 2206.11676]
[Boughezal, Mereghetti, Petriello, 2106.05337]
[Hays et al, 1808.00442]
...

Matching to UV models

[Banerjee et al, 2303.05224]
[Dawson et al, 2305.07689]
[Ellis, Mimasu, Zampedri, 2304.06663]
[Banerjee et al, 2210.14761]
[Liao, Ma, 2210.04270]
[Dawson et al, 2205.01561]
[Dawson, Homiller, Sullivan, 2110.06929]
...

Other theoretical analyses

[Banerjee, 2306.09103]
[Banta et al, 2304.09884]
[Naskar, Prakash, Rahaman, 2205.00910]
[Li et al, 2204.03660]
[Fonseca, 1907.12584]
[Henning et al, 1706.08520]
[Henning, et al, 1512.03433]
[Lehman, Martin, 1510.00372]
[Lehman, Martin, 1503.07537]
...

- Again, the cost of generality: *44807 operators* at dim-8!
  - Even if imposing assumptions, and even focusing on Higgs measurements, we still have several dozens of operators

$Q^{(1)}_{l^2H^4D}$	$i(l_p\gamma^\mu l_r)(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$
$Q^{(2)}_{l^2H^4D}$	$i(l_p\gamma^\mu\tau^I l_r)[(H^\dagger \overleftrightarrow{D}^I_\mu H)(H^\dagger H)+(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger\tau^I H)]$
$Q^{(3)}_{l^2H^4D}$	$i\epsilon^{IJK}(l_p\gamma^\mu\tau^I l_r)(H^\dagger \overleftrightarrow{D}^J_\mu H)(H^\dagger\tau^K H)$
$Q^{(4)}_{l^2H^4D}$	$\epsilon^{IJK}(l_p\gamma^\mu\tau^I l_r)(H^\dagger\tau^J H)D_\mu(H^\dagger\tau^K H)$
$Q_{e^2H^4D}$	$i(e_p\gamma^\mu e_r)(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$
$Q^{(1)}_{q^2H^4D}$	$i(q_p\gamma^\mu q_r)(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$
$Q^{(2)}_{q^2H^4D}$	$i(q_p\gamma^\mu\tau^I q_r)[(H^\dagger \overleftrightarrow{D}^I_\mu H)(H^\dagger H)+(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger\tau^I H)]$
$Q^{(3)}_{q^2H^4D}$	$i\epsilon^{IJK}(q_p\gamma^\mu\tau^I q_r)(H^\dagger \overleftrightarrow{D}^J_\mu H)(H^\dagger\tau^K H)$
$Q^{(4)}_{q^2H^4D}$	$\epsilon^{IJK}(q_p\gamma^\mu\tau^I q_r)(H^\dagger\tau^J H)D_\mu(H^\dagger\tau^K H)$
$Q_{u^2H^4D}$	$i(u_p\gamma^\mu u_r)(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$
$Q_{d^2H^4D}$	$i(d_p\gamma^\mu d_r)(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$
Q_{udH^4D} + h.c.	$i(u_p\gamma^\mu d_r)(\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$

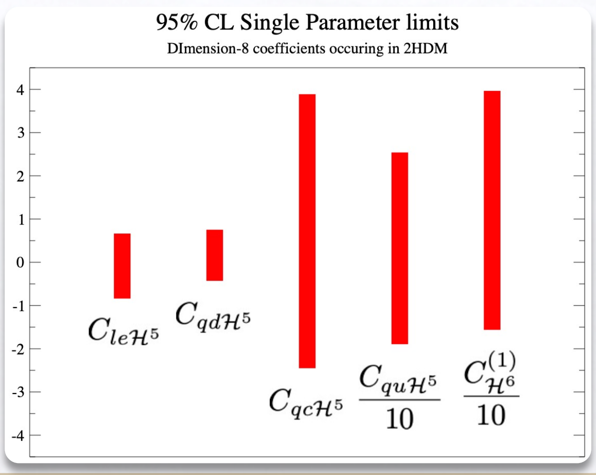
$Q^{(1)}_{l^2H^2D^3}$	$i(\bar{l}_p\gamma^\mu D^\nu l_r)(D_{(\mu}D_{\nu)}H^\dagger H)$
$Q^{(2)}_{l^2H^2D^3}$	$i(\bar{l}_p\gamma^\mu D^\nu l_r)(H^\dagger D_{(\mu}D_{\nu)}H)$
$Q^{(3)}_{l^2H^2D^3}$	$i(\bar{l}_p\gamma^\mu\tau^I D^\nu l_r)(D_{(\mu}D_{\nu)}H^\dagger\tau^I H)$
$Q^{(4)}_{l^2H^2D^3}$	$i(\bar{l}_p\gamma^\mu\tau^I D^\nu l_r)(H^\dagger\tau^I D_{(\mu}D_{\nu)}H)$
$Q^{(1)}_{e^2H^2D^3}$	$i(\bar{e}_p\gamma^\mu D^\nu e_r)(D_{(\mu}D_{\nu)}H^\dagger H)$
$Q^{(2)}_{e^2H^2D^3}$	$i(\bar{e}_p\gamma^\mu D^\nu e_r)(H^\dagger D_{(\mu}D_{\nu)}H)$
$Q^{(1)}_{q^2H^2D^3}$	$i(\bar{q}_p\gamma^\mu D^\nu q_r)(D_{(\mu}D_{\nu)}H^\dagger H)$
$Q^{(2)}_{q^2H^2D^3}$	$i(\bar{q}_p\gamma^\mu D^\nu q_r)(H^\dagger D_{(\mu}D_{\nu)}H)$
$Q^{(3)}_{q^2H^2D^3}$	$i(\bar{q}_p\gamma^\mu\tau^I D^\nu q_r)(D_{(\mu}D_{\nu)}H^\dagger\tau^I H)$
$Q^{(4)}_{q^2H^2D^2}$	$i(\bar{q}_p\gamma^\mu\tau^I D^\nu q_r)(H^\dagger\tau^I D_{(\mu}D_{\nu)}H)$
$Q^{(1)}_{u^2H^2D^3}$	$i(\bar{u}_p\gamma^\mu D^\nu u_r)(D_{(\mu}D_{\nu)}H^\dagger H)$
$Q^{(2)}_{u^2H^2D^3}$	$i(\bar{u}_p\gamma^\mu D^\nu u_r)(H^\dagger D_{(\mu}D_{\nu)}H)$
$Q^{(1)}_{d^2H^2D^3}$	$i(\bar{d}_p\gamma^\mu D^\nu d_r)(D_{(\mu}D_{\nu)}H^\dagger H)$
$Q^{(2)}_{d^2H^2D^3}$	$i(\bar{d}_p\gamma^\mu D^\nu d_r)(H^\dagger D_{(\mu}D_{\nu)}H)$
$Q_{udH^2D^3}$ + h.c.	$i(\bar{u}_p\gamma^\mu D^\nu d_r)(\widetilde{H}^\dagger D_{(\mu}D_{\nu)}H)$

$Q^{(1)}_{G^2H^4}$	$(H^\dagger H)^2 G^A_{\mu\nu}G^{A\mu\nu}$
$Q^{(2)}_{G^2H^4}$	$(H^\dagger H)^2 \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$
$Q^{(1)}_{W^2H^4}$	$(H^\dagger H)^2 W^I_{\mu\nu}W^{I\mu\nu}$
$Q^{(2)}_{W^2H^4}$	$(H^\dagger H)^2 \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$
$Q^{(3)}_{W^2H^4}$	$(H^\dagger\tau^I H)(H^\dagger\tau^J H)W^I_{\mu\nu}W^{J\mu\nu}$
$Q^{(4)}_{W^2H^4}$	$(H^\dagger\tau^I H)(H^\dagger\tau^J H)\widetilde{W}^I_{\mu\nu}W^{J\mu\nu}$
$Q^{(1)}_{WBH^4}$	$(H^\dagger H)(H^\dagger\tau^I H)W^I_{\mu\nu}B^{\mu\nu}$
$Q^{(2)}_{WBH^4}$	$(H^\dagger H)(H^\dagger\tau^I H)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$
$Q^{(1)}_{B^2H^4}$	$(H^\dagger H)^2 B_{\mu\nu}B^{\mu\nu}$
$Q^{(2)}_{B^2H^4}$	$(H^\dagger H)^2 \widetilde{B}_{\mu\nu}B^{\mu\nu}$

$Q^{(1)}_{H^6}$	$(H^\dagger H)^2(D_\mu H^\dagger D^\mu H)$
$Q^{(2)}_{H^6}$	$(H^\dagger H)(H^\dagger\tau^I H)(D_\mu H^\dagger\tau^I D^\mu H)$

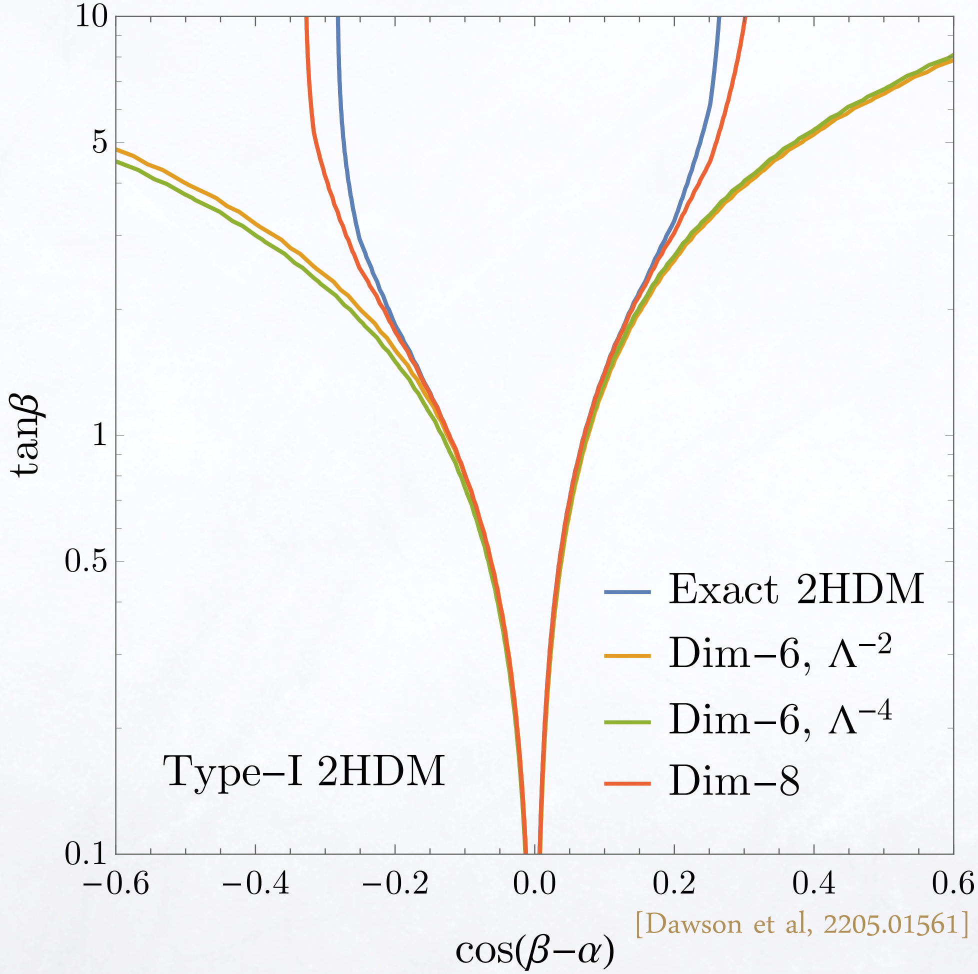
[Murphy, 2005.00059]

  - Fitting them all seems too daring!
    - Is an EFT the best strategy?
  - One can always focus on a subset:



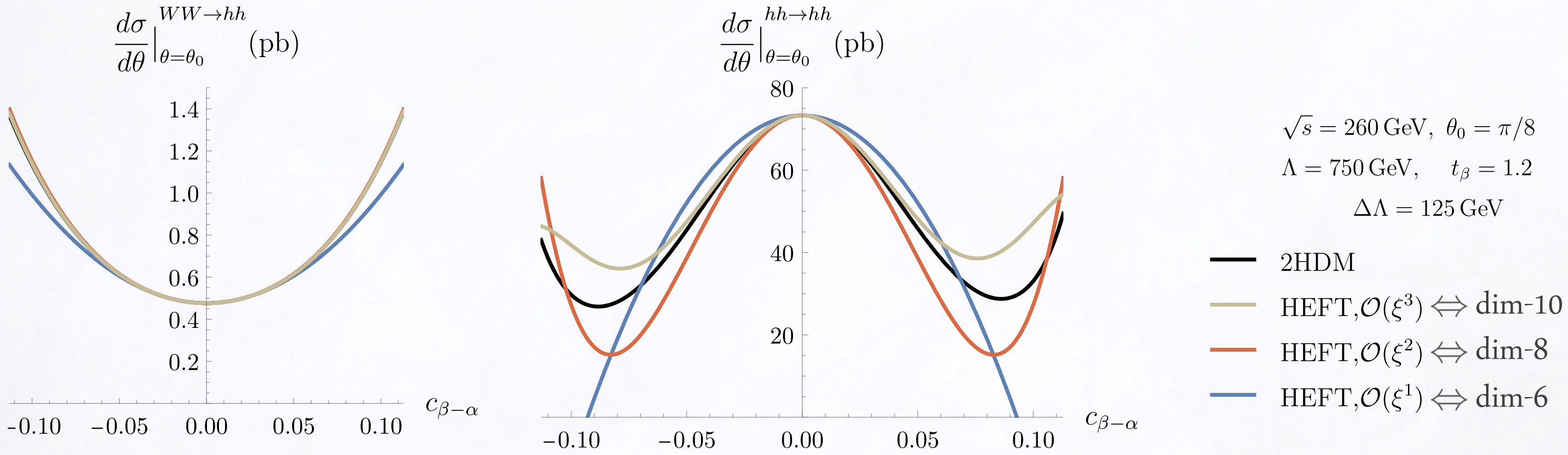
[Dawson et al, 2205.01561]

- In the case of the SMEFT matched to the 2HDM, there are regions where dim-8 really matters!



[Dawson et al, 2205.01561]

- But is it possible that even dim-8 operators are not enough?
  - Using again the 2HDM as probe, Higgs pair production can give some clues:



[Dawson et al, 2305.07689]

  - In $WW \to hh$, dim-8 operators properly replicate the full model
  - In $hh \to hh$, however, there are regions where dim-8 operators are not enough
    - Is an EFT the best strategy?

- Higgs measurements were inaugurated in 2012 and have been spectacularly improved ever since
- If they are to be used in a model-independent way, an **EFT** should be used
- The SMEFT has the Higgs as part of the SU(2) doublet, with a simple power-counting. It is the preferred **EFT** at the LHC, and immense progress has been done to contrain its couplings
- The HEFT has the Higgs as a gauge singlet, with a not-so-simple power-counting. Only recently have its couplings been constrained at the LHC via Higgs measurements
- Which **EFT** should be used, given the Higgs measurements?
  - One way to address this question is by looking at particular UV models
  - In the 2HDM with decoupling, there seems to be *no difference* between the two approaches
- And is the leading order of the **EFT** expansion enough, given the Higgs measurements?
  - Not really. A huge progress has been done into dim-8 SMEFT operators
  - But the amount of operators is also huge... and in some cases even dim-8 is not enough!
- All in all, is an **EFT** the best strategy?

Thank you