Karlsruhe Institute of Technology

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Discussion about SMEFT and HEFT exemplified for HH production

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INSTITUTE FOR THEORETICAL PHYSICS

Outline

Two bottom-up EFT systematics: SMEFT vs. HEFT

Bottom-up EFT: systematic parameterisation for unknown new physics above energy scale Λ

SMEFT:

- SM fields + symmetries as building blocks of higher order operators
- Light Higgs contained in EW doublet field $\phi(x)$
- Canonical counting ($\Rightarrow$ expansion in $\frac{1}{\Lambda}$):

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{n=1} \sum_{i} \frac{C_i}{\Lambda^{2n}} \mathcal{O}_i^{(4+2n)}$$

- Truncate series at $\frac{1}{\Lambda^2}$, collecting all non-redundant (CP-even) operators (EFT basis)

$$\mathcal{L}_{SMEFT}^{(Warsaw)} \supset \frac{C_{H\Box}}{\Lambda^2} \left(\phi^\dagger \phi\right) \Box \left(\phi^\dagger \phi\right) + \frac{C_{HD}}{\Lambda^2} \left(\phi^\dagger D_\mu \phi\right) \left(\phi^\dagger D^\mu \phi\right) + \frac{C_H}{\Lambda^2} \left(\phi^\dagger \phi\right)^3 + \frac{C_{uH}}{\Lambda^2} \left(\left(\phi^\dagger \phi\right) \bar{q}_L \phi^c t_r + h.c.\right) + \frac{C_{HG}}{\Lambda^2} \left(\phi^\dagger \phi\right) G^a_{\mu\nu} G^{a\,\mu\nu}$$

$\Rightarrow$ Classically non-renormalisable, but consistent if truncations are considered at each step!

Two bottom-up EFT systematics: SMEFT vs. HEFT

HEFT:

- Motivation as analogue to chiral pert. theory
- Chiral dimension of operators $d_\chi(\partial, \bar\psi\psi, g, y) = 1$
- Light Higgs is EW gauge singlet $h(x)$
- Expansion in $\frac{f^2}{\Lambda^2} \sim \frac{1}{16\pi^2}$ ($\Rightarrow$ loop counting)

$$\mathcal{L}_{HEFT} \supset -m_t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right)\bar{t}t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a\,\mu\nu}$$

HEFT	Warsaw
c_{hhh}	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}C_H + 3\frac{v^2}{\Lambda^2}C_{H,\mathrm{kin}}$
c_t	$1 + \frac{v^2}{\Lambda^2}C_{H,\mathrm{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t}C_{uH}$
c_{tt}	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t}C_{uH} + \frac{v^2}{\Lambda^2}C_{H,\mathrm{kin}}$
c_{ggh}	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s(\mu)}C_{HG}$
c_{gghh}	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s(\mu)}C_{HG}$

Naive translation SMEFT $\leftrightarrow$ HEFT after field redefinition up to $\mathcal{O}\left(\frac{1}{\Lambda^2}\right)$ in Lagrangian ($C_{H,kin} = C_{H\Box} - 4C_{HD}$)

However, formally:

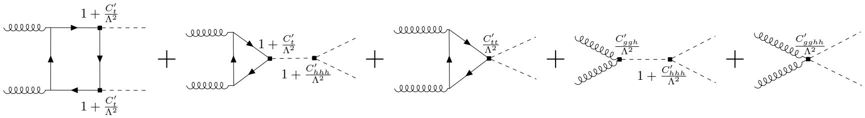
$c_i \sim \mathcal{O}(1)$ possible in contrast to $\frac{E^2}{\Lambda^2}C_i \ll 1$

$\Rightarrow$ Not general applicable in practical calculations (fits, bounds, ...)

SMEFT truncation

Dimension 6 operators in amplitude $\left(\frac{C_i'}{\Lambda^2} = c_i - c_{i,sm}\right)$:

$\mathcal{M} =$



$+ \dots$

$$= \mathcal{M}_{\mathrm{SM}} + \underbrace{\frac{1}{\Lambda^2}\mathcal{M}_{\mathrm{si}}}_{\mathrm{dim6}} \qquad \left(+ \underbrace{\frac{1}{\Lambda^4}\mathcal{M}_{\mathrm{di}}}_{\mathrm{dim6}^2} \right)$$

$\Rightarrow$ Double operator insertion same order as (neglected) dimension 8 operators (and field redefinition)!

$\Rightarrow$ In HEFT the complete anomalous coupling enters at each vertex with no additional truncation

SMEFT truncation of cross section

$$\sigma \simeq \begin{cases} \sigma_{\text{SM}} + \sigma_{\text{SM}\times\text{dim6}} & \text{(a)} \\ \sigma_{(\text{SM}+\text{dim6})\times(\text{SM}+\text{dim6})} & \text{(b)} \\ \sigma_{(\text{SM}+\text{dim6})\times(\text{SM}+\text{dim6})} + \sigma_{\text{SM}\times\text{dim6}^2} & \text{(c)} \\ \sigma_{\left(\text{SM}+\text{dim6}+\text{dim6}^2\right)\times\left(\text{SM}+\text{dim6}+\text{dim6}^2\right)} & \text{(d)} \end{cases}$$

(a) Truncation at leading order of expansion of powers in $1/\Lambda^2$ of cross section
$\Rightarrow$ applicable choice

(b) Truncation at leading order of expansion of powers in $1/\Lambda^2$ of cross section
$\Rightarrow$ applicable choice

(c) Truncate cross section at $\mathcal{O}\left(1/\Lambda^4\right)$ from all dim6 operator insertions (ambiguous definition)

(d) Complete insertion, naive translation SMEFT $\leftrightarrow$ HEFT

- Truncation (a) formally most consistend, however, negative (differential) cross section can appear, since Wilson coefficients not yet restricted close enough to SM

$\Rightarrow$ Perform analysis for truncation (a) and (b) separately!

Naive benchmark translation

Consider HEFT benchmark points with following characteristic m_{hh} shapes

- Benchmark 1^*: enhanced low m_{hh} region
- Benchmark 6^*: close-by double peaks or shoulder left

[Capozi, Heinrich '19]
[Higgs WG HH cross group note to be on cds very soon]

benchmark ($^* =$ modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\mathrm{kin}}$	C_H	C_{uH}	C_{HG}	Λ
SM	1	1	0	0	0	0	0	0	0	1 TeV
1^*	5.105	1.1	0	0	0	4.95	-6.81	3.28	0	1 TeV
6^*	-0.684	0.9	$-\frac{1}{6}$	0.5	0.25	0.561	3.80	2.20	0.0387	1 TeV

$\Rightarrow$ SMEFT expansion based on $E^2 \frac{C_i}{\Lambda^2} \ll 1$ justified?

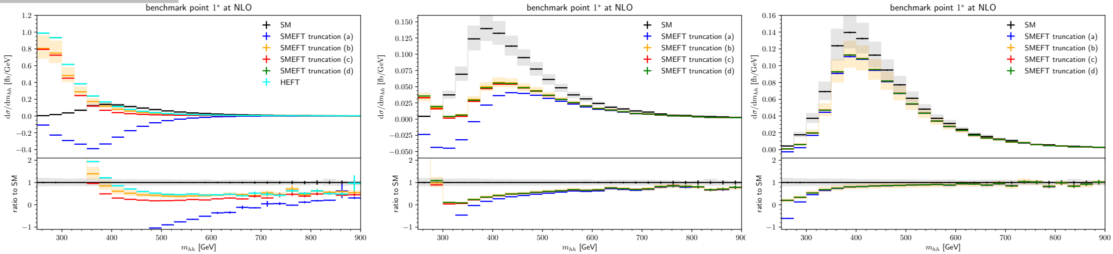
C_{HG} obtained using $\alpha_s(m_Z) = 0.118$

Invariant mass distributions at NLO QCD ($\sqrt{s} = 13$ TeV)

- Benchmark 1*:

Generated with ggHH_SMEFT in POWHEG-BOX-V2

C_{hhh}	C_t	C_{tt}	C_{ggh}	C_{gghh}	$C_{H,\mathrm{kin}}$	C_H	C_{uH}	C_{HG}
5.105	1.1	0	0	0	4.95	-6.81	3.28	0



$\Lambda = 1$ TeV $\Lambda = 2$ TeV $\Lambda = 4$ TeV

- Truncation (a): negative cross sections
- Shape approaches SM for increasing Λ

$\Rightarrow$ Valid HEFT point invalid in SMEFT after direct translation

Invariant mass distributions at NLO QCD ($\sqrt{s} = 13$ TeV)

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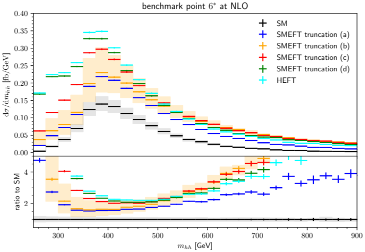
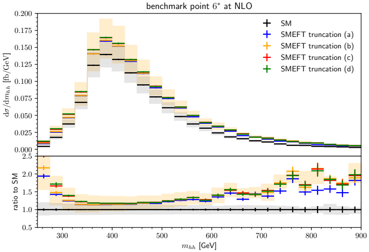
- Benchmark 6^*:

Generated with ggHH_SMEFT in POWHEG-BOX-V2

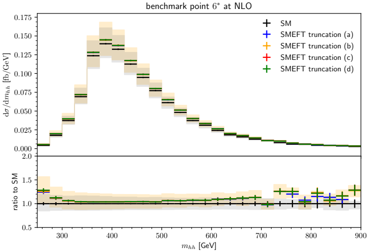
C_{hhh}	C_t	C_{tt}	C_{ggh}	C_{gghh}	$C_{H,\mathrm{kin}}$	C_H	C_{uH}	C_{HG}
-0.684	0.9	$-\frac{1}{6}$	0.5	0.25	0.561	3.80	2.20	0.0387



$\Lambda = 1$ TeV



$\Lambda = 2$ TeV



$\Lambda = 4$ TeV

- No negative cross section
- No shoulder left (except for (d))
- Shape indistinguishable from SM for $\Lambda = 4$ TeV within scale uncertainties
- Difference between HEFT and (d) only due to α_s scale dependence

Summary

- SMEFT and HEFT both valid EFT approaches based on different assumptions

$\Rightarrow$ Treatment in calculations very different

- Benchmark study: Naive translation from HEFT $\rightarrow$ SMEFT can lead out of validity of $\frac{1}{\Lambda^2}$ expansion

$\Rightarrow$ Study both EFT representations separately

- Comparison of truncation options, (a) (linear dim-6) and (b) (linear+quadratic dim-6), could be used as qualitative proxy for truncation uncertainties

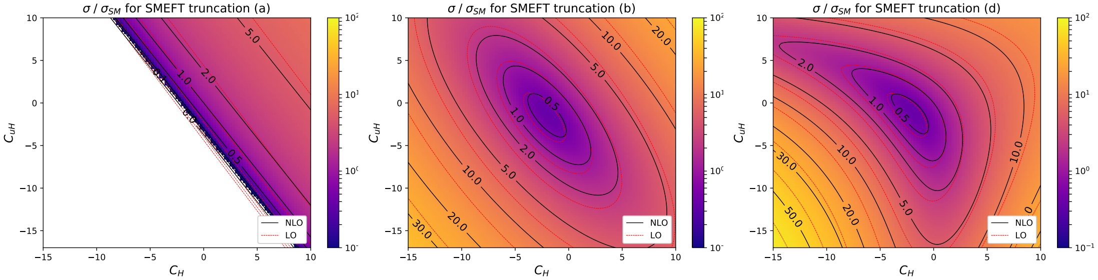
NLO total cross section

Generated at $\sqrt{s} = 13$ TeV

benchmark	σ_{NLO}[fb] option (b)	K-factor option (b)	ratio to SM option (b)	σ_{NLO}[fb] option (a)	σ_{NLO}[fb] HEFT
SM	$27.94^{+13.7\%}_{-12.8\%}$	1.67	1	-	-
$\Lambda = 1$ TeV					
1^*	$74.29^{+19.8\%}_{-15.6\%}$	2.13	2.66	-61.17	94.32
6^*	$72.51^{+20.6\%}_{-16.4\%}$	1.90	2.60	52.89	91.40
$\Lambda = 2$ TeV					
1^*	$14.03^{+12.0\%}_{-11.9\%}$	1.56	0.502	5.58	-
6^*	$35.39^{+17.5\%}_{-15.2\%}$	1.76	1.27	34.18	-

NLO total cross section

Generated at $\sqrt{s} = 13$ TeV with $\Lambda = 1$ TeV



- Large area of negative cross section for truncation (a)
- Non-trivial shape for HEFT-like option (d)
- Flat directions differ substantially