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TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

# Effective Field Theory descriptions of Higgs boson pair production

The 19th Workshop of the LHC Higgs Working Group

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based on WG note (to be published on CDS **very** soon) | November 28, 2022

INSTITUTE FOR THEORETICAL PHYSICS

# Outline

# Why study EFT phenomenology in *hh* production?

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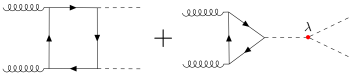
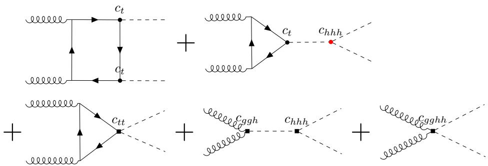
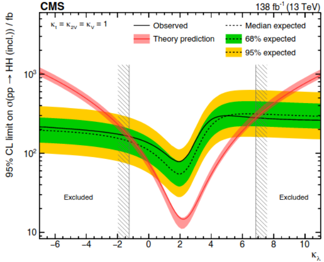
- Is Higgs potential SM-like? $V_{\text{SM}} \sim \frac{m_h^2}{2} h^2 + \lambda v\, h^3 + \frac{\lambda}{4} h^4$

$\Rightarrow$ Trilinear Higgs coupling accessible in *hh* production




- However, to maintain some generality BSM deviations should enter in systematic way!

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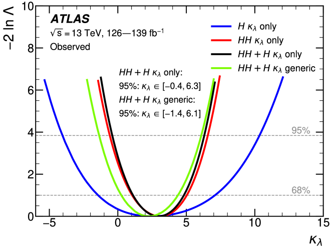


[2211.01216]

# Two bottom-up EFT systematics: SMEFT vs. HEFT

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**Bottom-up** EFT: systematic parameterisation for unknown new physics above energy scale $\Lambda$

**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)

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

$$\mathcal{L}_{SMEFT}^{(SILH)} \supset \frac{\bar{c}_H}{2v^2} \partial_\mu \left(\phi^\dagger \phi\right) \partial^\mu \left(\phi^\dagger \phi\right) - \frac{\bar{c}_6}{2v^2} \frac{m_h^2}{v^2} \left(\phi^\dagger \phi\right)^3$$
$$+ \frac{\bar{c}_u}{v^2} y_t \left(\left(\phi^\dagger \phi\right) \bar{q}_L \tilde{\phi} t_R + \mathrm{h.c.}\right) + \frac{4\bar{c}_g}{v^2} g_s^2 \left(\phi^\dagger \phi\right) G^a_{\mu\nu} G^{a\mu\nu} + \frac{\bar{c}_{ug}}{v^2} g_s \left(\bar{q}_L \sigma^{\mu\nu} T^a G^a_{\mu\nu} \tilde{\phi} t_R + \mathrm{h.c.}\right)$$

# Two bottom-up EFT systematics: SMEFT vs. HEFT

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**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)

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

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 $\quad \leftrightarrow \quad \frac{E^2}{\Lambda^2} C_i \ll 1$

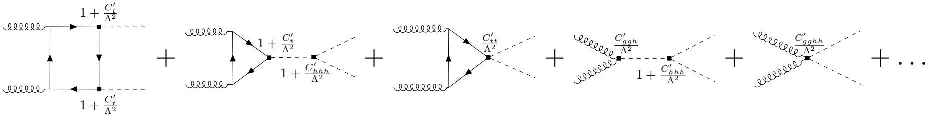
$\Rightarrow$ Not generally applicable in practical calculations (fits, bounds, ...)

| HEFT | SILH | Warsaw |
|---|---|---|
| $c_{hhh}$ | $1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$ | $1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2} C_H + 3\frac{v^2}{\Lambda^2} C_{H,\mathrm{kin}}$ |
| $c_t$ | $1 - \frac{\bar{c}_H}{2} - \bar{c}_u$ | $1 + \frac{v^2}{\Lambda^2} C_{H,\mathrm{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t} C_{uH}$ |
| $c_{tt}$ | $-\frac{\bar{c}_H + 3\bar{c}_u}{4}$ | $-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t} C_{uH} + \frac{v^2}{\Lambda^2} C_{H,\mathrm{kin}}$ |
| $c_{ggh}$ | $128\pi^2 \bar{c}_g$ | $\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s(\mu)} C_{HG}$ |
| $c_{gghh}$ | $64\pi^2 \bar{c}_g$ | $\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s(\mu)} C_{HG}$ |

# SMEFT truncation

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

$\mathcal{M} =$




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

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

⇒ In HEFT the complete anomalous coupling enters at each vertex with no additional truncation

# SMEFT truncation of cross section

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

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

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

(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) theoretically best suited for central value fit, 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!

# Public implementations

HTL = Heavy top limit ($m_t \to \infty$)

## HEFT

- LO and NLO QCD HTL `HPAIR` [Gröber,Mühlleitner,Spira,Streicher '15]
- Full $m_t$ NLO QCD `POWHEG-BOX-V2/ggHH` [Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Zirke '16] [Heinrich,Jones,Kerner,Luisoni,Vryonidou '17] [Heinrich,Jones,Kerner,Luisoni,Scyboz '18] [Heinrich,Jones,Kerner,Scyboz '20]

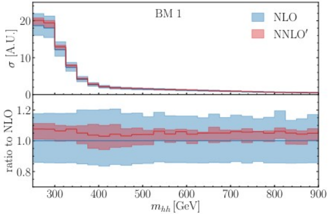
## SMEFT

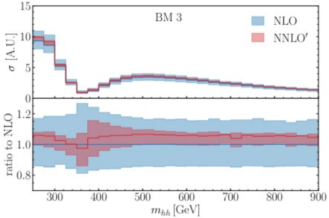
- LO and NLO QCD HTL `HPAIR` [Gröber,Mühlleitner,Spira,Streicher '15]
- LO (1-loop) including chromo-magnetic operator SMEFT@NLO + `MG5_aMC@NLO` [Degrande,Durieux,Maltoni,Mimasu,Vryonidou,Zhang '20]
- LO including chromo-magnetic operator SMEFTsim + `MG5_aMC@NLO` [Brivio,Jiang,Trott '17] [Brivio '20]
- Full $m_t$ NLO QCD `POWHEG-BOX-V2/ggHH_SMEFT` with truncation options [Heinrich,JL,Scyboz '22]

# State-of-the-art: NNLO′ QCD HEFT [de Florian,Fabre,Heinrich,Mazitelli,Scyboz '21]

Combinations of results

- Full $m_t$ NLO QCD
  [Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Zirke '16]
  [Heinrich,Jones,Kerner,Luisoni,Vryonidou '17]
  [Heinrich,Jones,Kerner,Luisoni,Scyboz '18]
  [Heinrich,Jones,Kerner,Scyboz '20]
- NNLO QCD in HTL
  [de Florian,Fabre,Mazitelli '16]




$$\begin{aligned}\frac{\sigma_{BSM}}{\sigma_{SM}} = & a_1 \cdot c_t^4 + a_2 \cdot c_{tt}^2 + a_3 \cdot c_t^2 c_{hhh}^2 + a_4 \cdot c_{ggh}^2 c_{hhh}^2 + a_5 \cdot c_{gghh}^2 + a_6 \cdot c_{tt} c_t^2 + a_7 \cdot c_t^3 c_{hhh} \\ & + a_8 \cdot c_{tt} c_t c_{hhh} + a_9 \cdot c_{tt} c_{ggh} c_{hhh} + a_{10} \cdot c_{tt} c_{gghh} + a_{11} \cdot c_t^2 c_{ggh} c_{hhh} + a_{12} \cdot c_t^2 c_{gghh} \\ & + a_{13} \cdot c_t c_{hhh}^2 c_{ggh} + a_{14} \cdot c_t c_{hhh} c_{gghh} + a_{15} \cdot c_{ggh} c_{hhh} c_{gghh} + a_{16} \cdot c_t^3 c_{ggh} \\ & + a_{17} \cdot c_t c_{tt} c_{ggh} + a_{18} \cdot c_t c_{ggh}^2 c_{hhh} + a_{19} \cdot c_t c_{ggh} c_{gghh} + a_{20} \cdot c_t^2 c_{ggh}^2 \\ & + a_{21} \cdot c_{tt} c_{ggh}^2 + a_{22} \cdot c_{ggh}^3 c_{hhh} + a_{23} \cdot c_{ggh}^2 c_{gghh} + a_{24} \cdot c_{ggh}^4 + a_{25} \cdot c_{ggh}^3 c_t\end{aligned}$$

- $a_i$ for inclusive cross section published

$\Rightarrow$ Reduction of scale uncertainty by factor $\sim 2$

# POWHEG code ggHH

[Heinrich,Jones,Kerner,Scyboz '20]

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- Built on previous NLO SM calculation with full $m_t$ dependence

  [Borowka,Greiner,Heinrich,Jones,Kerner,et al. '16]
  [Heinrich,Jones,Kerner,Luisoni,Vryonidou '17]
  [Heinrich,Jones,Kerner,Luisoni,Scyboz '19]

- `mtdep` $\begin{cases} \text{0-2: HTL approximations} \\ \text{3: full } m_t \text{ dependence} \end{cases}$

- $m_h = 125$ GeV and $m_t = 173$ GeV fixed for grids encoding virtual (2-loop) corrections!

- Matching to parton shower (Pythia or Herwig) available

$\Rightarrow$ Available at http://powhegbox.mib.infn.it

Usage of code:

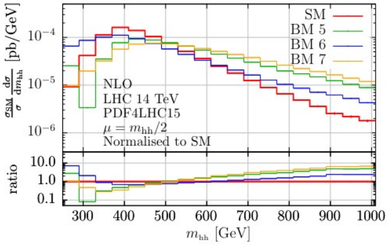
```
! ggHH production parameters:
mtdep 3                  ! 0: Higgs effective field theory (HEFT)
!                          1: Born improved HEFT
!                          2: approximated full theory (FTapprox)
!                          3: full theory

hmass 125                ! Higgs boson mass
topmass 173              ! top quark mass (THIS VALUE IS HARD CODED IN THE VIRTUAL
                         ! MATRIX ELEMENT AND FOR CONSISTENCY HAS NOT TO BE CHANGED WHEN
                         ! RUNNING FULL THEORY PREDICTIONS - i.e. mtdep=3)
hdecaymode -1            ! PDG code for Higgs boson decay products (it affects only the SMC)
!                          allowed values are:
!                          0 all decay channels open
!                          1-6 d dbar, u ubar,..., t tbar (as in HERWIG)
!                          7-9 e+ e-, mu+ mu-, tau+ tau-
!                          10  W+W-
!                          11  ZZ
!                          12  gamma gamma
!                          -1  all decay channels closed

! Values of the Higgs couplings w.r.t SM
chhh      1.0           ! Trilinear Higgs self-coupling
ct        1.0           ! Top-Higgs Yukawa coupling
ctt       0.0           ! Two-top-two-Higgs (tthh) coupling
cggh      0.0           ! Effective gluon-gluon-Higgs coupling
cgghh     0.0           ! Effective two-gluon-two-Higgses coupling
```

# POWHEG code ggHH

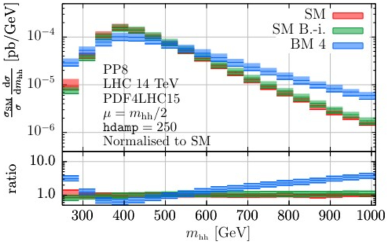
[Heinrich,Jones,Kerner,Scyboz '20]

Usage of code:

- Built on previous NLO SM calculation with full $m_t$ de
  [Borowka,
  [Heinrich,
  [Heinrich,
- mtdep
- $m_h =$
  grids
- Match
  available




Fixed order




Matched to PYTHIA-8

SMC)

cgghh 0.0 ! Effective two-gluon-two-Higgses coupling

⇒ Available at http://powhegbox.mib.infn.it

# POWHEG code ggHH_SMEFT

[Heinrich,JL,Scyboz '22]

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- Built on NLO HEFT ggHH
- usesmeft $\begin{cases} \text{0: HEFT operators} \\ \text{1: SMEFT operators} \end{cases}$
- multiple-insertion $0, \ldots, 3$
  $\updownarrow$
  truncation option $(a), \ldots, (d)$
- No RGE effects of Wilson coefficients

$\Rightarrow$ Available at http://powhegbox.mib.infn.it

Usage of code (only new part of input file shown):

```
! Choose EFT parametrization
usesmeft    1        ! 0: use HEFT parametrization and ignore CHbox, CH, CuH, CHG (no truncat
                     ! 1: use SMEFT (Warsaw) parametrization and ignore chhh, ct, ctt, cggh,
                     ! 2: use HEFT parametrization and ignore CHbox, CH, CuH, CHG (with trunc

! Values of the Higgs couplings w.r.t SM: HEFT parametrization
chhh      1.0       ! Trilinear Higgs self-coupling
ct        1.0       ! Top-Higgs Yukawa coupling
ctt       0.0       ! Two-top-two-Higgs (tthh) coupling
cggh      0.0       ! Effective gluon-gluon-Higgs coupling
cgghh     0.0       ! Effective two-gluon-two-Higgses coupling

! Values of the Higgs couplings using SMEFT (Warsaw) parametrization (Wilson coefficients ent
Lambda      1.0      ! EFT counting mass Scale (in TeV)
CHbox       0.0      ! Kinetic term of SU(2)_L singlet (with d'Alembert operator)
CHD         0.0      ! second Kinetic term
CH          0.0      ! Additional term to Higgs potential
CuH         0.0      ! Modified Yukawa term
CHG         0.0      ! Higgs-Glue-Glue operator

! Truncation options:
! 3: cross section based on |A_SM+A_dim6+A_dbldim6|^2
! 2: cross section based on |A_SM+A_dim6|^2+2*Re(A_SM x conj(A_dbldim6))
! 1: cross section based on |A_SM+A_dim6|^2
! 0: cross section based on |A_SM|^2+2*Re(A_SM*conj(A_dim6))
multiple-insertion  1
```

# Updated HEFT benchmarks

Published in WG note

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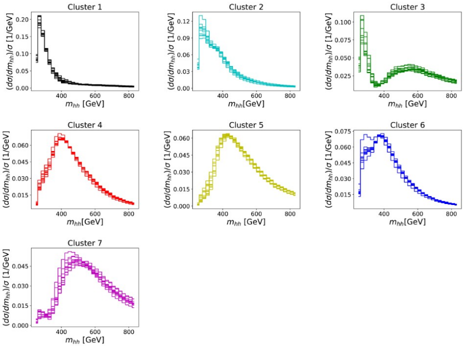
| benchmark | $c_{hhh}$ | $c_t$ | $c_{tt}$ | $c_{ggh}$ | $c_{gghh}$ |
|---|---|---|---|---|---|
| SM | 1 | 1 | 0 | 0 | 0 |
| 1* | 5.105 | 1.1 | 0 | 0 | 0 |
| 2* | 6.842 | 1.033 | $\frac{1}{6}$ | $-\frac{1}{3}$ | 0 |
| 3 | 2.21 | 1.05 | $-\frac{1}{3}$ | 0.5 | 0.5 |
| 4* | 2.79 | 0.9 | $-\frac{1}{6}$ | $-\frac{1}{3}$ | $-\frac{1}{2}$ |
| 5 | 3.95 | 1.17 | $-\frac{1}{3}$ | $\frac{1}{6}$ | $-\frac{1}{2}$ |
| 6* | $-0.684$ | 0.9 | $-\frac{1}{6}$ | 0.5 | 0.25 |
| 7 | $-0.10$ | 0.94 | 1 | $\frac{1}{6}$ | $-\frac{1}{6}$ |




[Capozi, Heinrich '19]

- Shape clusters defined using unsupervised ML
- Benchmarks chosen with clear shape features and satisfying experimental constraints
- * denotes updated benchmark point, new constraints: $0.83 \leq c_t \leq 1.17$ (and $|c_{tt}| \leq 0.05$ for 1*)

# Naive benchmark translation

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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

| benchmark ($^*$ = modified) | $c_{hhh}$ | $c_t$ | $c_{tt}$ | $c_{ggh}$ | $c_{gghh}$ | $C_{H,\mathrm{kin}}$ | $C_H$ | $C_{uH}$ | $C_{HG}$ | $\Lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 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 $\alpha_s(m_Z) = 0.118$

# Naive benchmark translation

Co

**Total cross section** generated at $\sqrt{s} = 13$ TeV

| benchmark | $\sigma_{\text{NLO}}$[fb] option (b) | K-factor option (b) | ratio to SM option (b) | $\sigma_{\text{NLO}}$[fb] option (a) | $\sigma_{\text{NLO}}$[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 | - |

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

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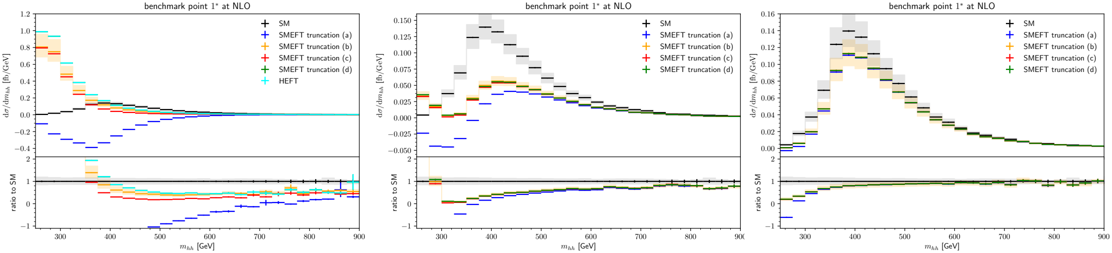
- Benchmark 1$^*$:

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




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

- Truncation (a): negative cross sections
- Shape approaches SM for increasing $\Lambda$

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

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

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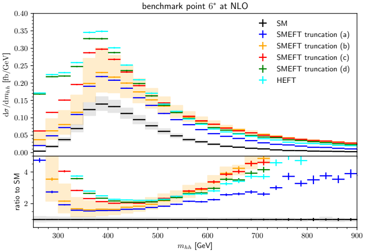
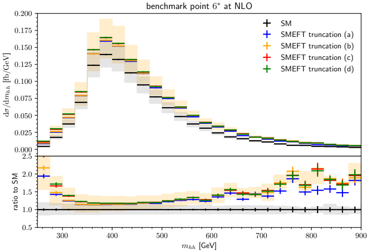
- Benchmark 6*:

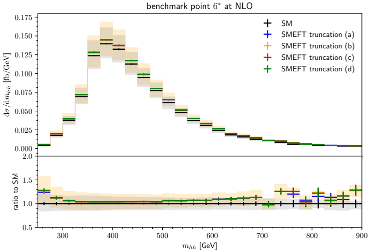
| $c_{hhh}$ | $c_t$ | $c_{tt}$ | $c_{ggh}$ | $c_{gghh}$ | $C_{H,\text{kin}}$ | $C_H$ | $C_{uH}$ | $C_{HG}$ |
|---|---|---|---|---|---|---|---|---|
| $-0.684$ | 0.9 | $-\frac{1}{6}$ | 0.5 | 0.25 | 0.561 | 3.80 | 2.20 | 0.0387 |




$\Lambda = 1$ 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 $\alpha_s$ scale dependence

# Estimating theory uncertainties

$$\Delta\sigma \sim {}^{+\Delta_{\text{scale +}}}_{-\Delta_{\text{scale -}}} \quad {}^{+\Delta_{m_t\text{ scheme +}}}_{-\Delta_{m_t\text{ scheme -}}} \quad \pm \Delta_{\text{num. grid}} \quad (\pm\Delta_{\text{EFT trunc.}}) \quad \pm \Delta_{\text{PDF}+\alpha_s} \quad \pm \Delta_{\text{EW}}$$

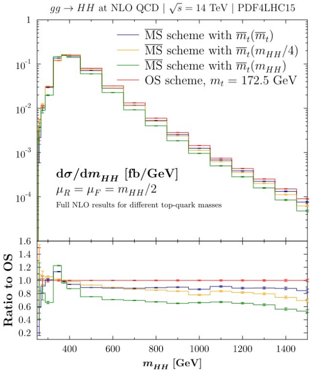
- $\Delta_{\text{EW}}$: Full NLO EW unknown, only partial results of top Yukawa [Davies,Mishima,Schönwald,Steinhauser,Zhang '22] [Mühlleitner,Schlenk,Spira '22]
- $\Delta_{\text{PDF}+\alpha_s} \approx 3\%$ ($\sqrt{s} = 13$ TeV): B.I. NNLO HTL and employing PDF4LHCNNLO [twiki *hh* cross group] stable for $c_{hhh}$ variation, but might rise if tail enhanced
- $\Delta_{\text{EFT trunc.}}$: No quantitative prescription, qualitative observation of truncation options
- $\Delta_{\text{scale }\pm}$: Determined by 7-point variation of $\mu_R,\ \mu_F = \{0.5,\ 1,\ 2\} \cdot \mu_0$ $\mathcal{O}(15\%)$ for NLO QCD SM, 15 - 20% for NLO QCD SMEFT truncation (b) benchmark $1^*$& $6^*$
- $\Delta_{m_t\text{ scheme }\pm}$: In principle needs determination for each point in EFT parameter space! (not yet available)
- $\Delta_{\text{num. grid}}$: Numerical uncertainty of grids for virtual contribution, not covered by Monte Carlo statistical uncertainty of POWHEG!

# $m_t$ renormalisation scheme uncertainty

[Baglio,Campanario,Glaus,Mühlleitner,Spira,Streicher '18]
[Baglio,Campanario,Glaus,Mühlleitner,Ronca,Spira,Streicher '20]
[Baglio,Campanario,Glaus,Mühlleitner,Ronca,Spira '20]

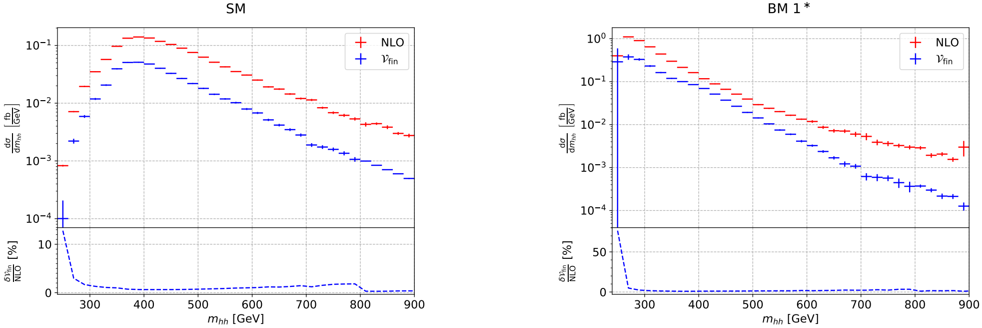
$$\bar{m}_t(m_t) = \frac{m_t}{1 + \frac{4}{3}\frac{\alpha_s(m_t)}{\pi} + K2\left(\frac{\alpha_s(m_t)}{\pi}\right)^2 + K_3\left(\frac{\alpha_s(m_t)}{\pi}\right)^3}$$

- Prediction depends on $m_t$ scheme (on-shell vs. $\overline{MS}$ with varying scale)
- Uncertainty sensitive to choice of $c_{hhh} = \kappa_\lambda$
- Sensitivity to variations of $c_t$, $c_{tt}$ expected




$$\begin{aligned}
\kappa_\lambda = -10 &: \quad \sigma_{tot} = 1438(1)^{+10\%}_{-6\%}\ \text{fb},\\
\kappa_\lambda = -5 &: \quad \sigma_{tot} = 512.8(3)^{+10\%}_{-7\%}\ \text{fb},\\
\kappa_\lambda = -1 &: \quad \sigma_{tot} = 113.66(7)^{+8\%}_{-9\%}\ \text{fb},\\
\kappa_\lambda = 0 &: \quad \sigma_{tot} = 61.22(6)^{+6\%}_{-12\%}\ \text{fb},\\
\kappa_\lambda = 1 &: \quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%}\ \text{fb},\\
\kappa_\lambda = 2 &: \quad \sigma_{tot} = 13.2(1)^{+1\%}_{-23\%}\ \text{fb},\\
\kappa_\lambda = 2.4 &: \quad \sigma_{tot} = 12.7(1)^{+4\%}_{-22\%}\ \text{fb},\\
\kappa_\lambda = 3 &: \quad \sigma_{tot} = 17.6(1)^{+9\%}_{-15\%}\ \text{fb},\\
\kappa_\lambda = 5 &: \quad \sigma_{tot} = 83.2(3)^{+13\%}_{-4\%}\ \text{fb},\\
\kappa_\lambda = 10 &: \quad \sigma_{tot} = 579(1)^{+12\%}_{-4\%}\ \text{fb}
\end{aligned}$$

# Numerical grids uncertainty




- Low (and high) $m_{hh}$ region very sparsely populated in virtual grids, due to small contribution in SM

⇒ $\mathcal{O}\,(12\,\%)$ uncertainty for SM in first bin not represented by Monte Carlo statistical uncertainty in `POWHEG`

⇒ Uncertainty much worse for scenarios with enhanced low $m_{hh}$ region

# Reweighting of NLO HEFT

- NLO MC programs are nice, **but** computationally expensive

$\Rightarrow$ Reweighting using set of MC samples!

- Expansion of inclusive and differential cross section:

$$\sigma_{hh}^{\text{NLO}} = Poly(\mathbf{c}, \mathbf{A}) = \mathbf{c}^{\mathsf{T}} \cdot \mathbf{A}$$

$$\frac{d\sigma_{hh}}{dm_{hh}} = Poly(\mathbf{c}, d\mathbf{A}|m_{hh}) = \mathbf{c}^{\mathsf{T}} \cdot d\mathbf{A}$$

- **A** and $d$**A** with respective covariance matrix $\Sigma_{(d)\mathbf{A}}$ derived using least square fit of 63 MC samples
- $d$**A** available for $m_{hh} \in [250, 1050]$ GeV in 20 GeV bins and two broader bins $[1050, 1200]$ GeV and $[1200, 1400]$ GeV
- 3 sets for scale variation $\mu_R = \mu_F = \{\frac{1}{2}, 1, 2\} \cdot \mu_0$ with $\mu_0 = \frac{m_{hh}}{2}$

$$\begin{aligned}
\sigma_{hh}^{\text{NLO}} = & A_1 c_t^4 + A_2 c_{tt}^2 + (A_3 c_t^2 + A_4 c_{ggh}^2) c_{hhh}^2 \\
& + A_5 c_{gghh}^2 + (A_6 c_{tt} + A_7 c_t c_{hhh}) c_t^2 \\
& + (A_8 c_t c_{hhh} + A_9 c_{ggh} c_{hhh}) c_{tt} + A_{10} c_{tt} c_{gghh} \\
& + (A_{11} c_{ggh} c_{hhh} + A_{12} c_{gghh}) c_t^2 \\
& + (A_{13} c_{hhh} c_{ggh} + A_{14} c_{gghh}) c_t c_{hhh} \\
& + A_{15} c_{ggh} c_{gghh} c_{hhh} + A_{16} c_t^3 c_{ggh} \\
& + A_{17} c_t c_{tt} c_{ggh} + A_{18} c_t c_{ggh} c_{hhh} \\
& + A_{19} c_t c_{ggh} c_{gghh} + A_{20} c_t^2 c_{ggh}^2 \\
& + A_{21} c_{tt} c_{ggh}^2 + A_{22} c_{ggh}^3 c_{hhh} \\
& + A_{23} c_{ggh}^2 c_{gghh}
\end{aligned}$$

Values provided along with WG note!
(to be found in HEPdata)

# Reweighting of NLO HEFT and statistical uncertainties

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- Weights obtained according to $w_{\text{HEFT}} = \frac{Poly(\mathbf{c}, d\mathbf{A}|m_{hh})}{Poly(\mathbf{c}_{\text{SM}}, d\mathbf{A}|m_{hh})}$
- Corresponding uncertainty calculated using $\delta_{w_{\text{HEFT}}} = \sqrt{\mathbf{J}_w \Sigma_{d\mathbf{A}} \mathbf{J}_w^{\text{T}}}$ with

$$\mathbf{J}_w = \frac{\mathbf{c}^{\text{T}}}{Poly(\mathbf{c}_{\text{SM}}, d\mathbf{A}|m_{hh})} - \frac{Poly(\mathbf{c}, d\mathbf{A}|m_{hh}) \cdot \mathbf{c}_{\text{SM}}^{\text{T}}}{Poly(\mathbf{c}_{\text{SM}}, d\mathbf{A}|m_{hh})^2}.$$

- Final statistical uncertainty in reweighted bin $j$

$$\delta^j = N^j \sqrt{\left(\frac{\delta^j_{w_{\text{HEFT}}}}{w^j_{\text{HEFT}}}\right)^2 + \left(\frac{\delta^j_{\text{SM}}}{N^j_{\text{SM}}}\right)^2}, \quad \text{with}$$

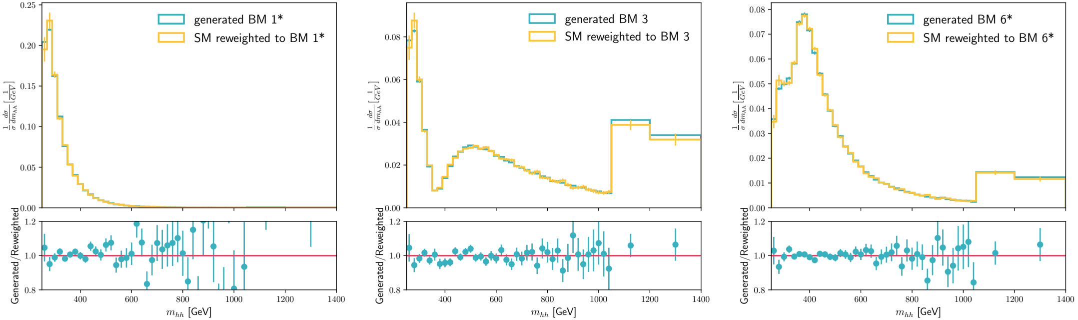
$N^j$: sum of weighted events

$N^j_{\text{SM}}$: sum of weighted SM events

$w^j_{\text{HEFT}}$: weight

$\delta^j_{\text{SM}}$: weighted statistical uncertainty for SM events

# Validation of reweighting method




$\Rightarrow$ Very good agreement for $m_{hh}$ distribution!

# Summary

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- SMEFT and HEFT both valid EFT approaches based on different assumptions
- Public implementations listed & usage of full NLO QCD implementations in `POWHEG` shown
- List of HEFT benchmarks updated
- BM study: Naive translation from HEFT $\rightarrow$ SMEFT can lead out of validity of $\frac{1}{\Lambda^2}$ expansion

$\Rightarrow$ We advocate to study both EFT representations separately

- Discussion of uncertainties
- Reweighting procedure and validation presented, coefficients published with WG note

$\Rightarrow$ More details in (upcoming) WG note!

# Virtual grids for ggHH_SMEFT

Split matrix in kinematic part times coupling coefficient for HEFT and SMEFT

$$\begin{aligned}
\mathcal{M}_{LO} :=& m_1 \cdot c_t^2 + m_2 \cdot c_t c_{hhh} + m_3 \cdot c_{tt} + m_4 \cdot c_g c_{hhh} + m_5 \cdot c_{gg} \\
=& m_1 + m_2 + \frac{1}{\Lambda^2}\left(2m_1 \cdot C_t' + m_2 \cdot (C_t' + C_{hhh}') + m_3 \cdot C_{tt}' + m_4 \cdot C_g' + m_5 \cdot C_{gg}'\right) + \frac{1}{\Lambda^4}\left(m_1 \cdot C_t'^2 + m_2 \cdot C_t' C_{hhh}'\right) \\
\mathcal{M}_{NLO} :=& M_1 \cdot c_t^2 + M_2 \cdot c_t c_{hhh} + M_3 \cdot c_{tt} + M_4 \cdot c_g c_{hhh} + M_5 \cdot c_{gg} + M_6 \cdot c_g^2 + M_7 \cdot c_g c_t \\
=& M_1 + M_2 + \frac{1}{\Lambda^2}\left(2M_1 \cdot C_t' + M_2 \cdot (C_t' + C_{hhh}') + M_3 \cdot C_{tt}' + M_4 \cdot C_g' + M_5 \cdot C_{gg}' + M_7 \cdot C_g'\right) \\
&+ \frac{1}{\Lambda^4}\left(M_1 \cdot C_t'^2 + M_2 \cdot C_t' C_{hhh}' + M_6 \cdot C_g'^2 + M_7 \cdot C_g' C_t'\right)
\end{aligned}$$

The virtual grids, given as kinematic coefficients $a_i$ of the squared matrix element

$$\begin{aligned}
|\mathcal{M}_{NLO}|^2 =& a_1 \cdot c_t^4 + a_2 \cdot c_{tt}^2 + a_3 \cdot c_t^2 c_{hhh}^2 + a_4 \cdot c_{ggh}^2 c_{hhh}^2 + a_5 \cdot c_{gghh}^2 + a_6 \cdot c_{tt} c_t^2 + a_7 \cdot c_t^3 c_{hhh} + a_8 \cdot c_{tt} c_t c_{hhh} + a_9 \cdot c_{tt} c_{ggh} c_{hhh} \\
&+ a_{10} \cdot c_{tt} c_{gghh} + a_{11} \cdot c_t^2 c_{ggh} c_{hhh} + a_{12} \cdot c_t^2 c_{gghh} + a_{13} \cdot c_t c_{hhh}^2 c_{ggh} + a_{14} \cdot c_t c_{hhh} c_{gghh} + a_{15} \cdot c_{ggh} c_{hhh} c_{gghh} + a_{16} \cdot c_t^3 c_{ggh} \\
&+ a_{17} \cdot c_t c_{tt} c_{ggh} + a_{18} \cdot c_t c_{ggh}^2 c_{hhh} + a_{19} \cdot c_t c_{ggh} c_{gghh} + a_{20} \cdot c_t^2 c_{ggh}^2 + a_{21} \cdot c_{tt} c_{ggh}^2 + a_{22} \cdot c_{ggh}^3 c_{hhh} + a_{23} \cdot c_{ggh}^2 c_{gghh} ,
\end{aligned}$$

can be understood as combinations of $m_i \times M_i$ obtained from $\mathcal{M}_{LO} \times \mathcal{M}_{NLO}$. After rearrangement, the squared matrix elements entering the truncated cross sections in SMEFT (slide 7) are expressed in terms of the same $a_i$, except for truncation (b), where

$$\Delta\sigma_{(b)} = m_2 \times M_4 \cdot \frac{C_{ggh}'(C_{hhh}' - C_t')}{\Lambda^4} + m4 \times M_7 \frac{C_{ggh}'^2}{\Lambda^4}$$

needs to be added.

# NLO cross section

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

| benchmark | $\sigma_{\mathrm{NLO}}$[fb] option (b) | K-factor option (b) | ratio to SM option (b) | $\sigma_{\mathrm{NLO}}$[fb] option (a) | $\sigma_{\mathrm{NLO}}$[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 |
| $3^*$ | $69.20^{+11.7\%}_{-10.3\%}$ | 1.82 | 2.47 | 29.64 | 72.43 |
| $6^*$ | $72.51^{+20.6\%}_{-16.4\%}$ | 1.90 | 2.60 | 52.89 | 91.40 |
| $\Lambda = 2$ TeV | | | | | |
| $1^*$ | $14.03^{+12.0\%}_{-11.9\%}$ | 1.56 | 0.502 | 5.58 | - |
| $3^*$ | $30.81^{+16.0\%}_{-14.4\%}$ | 1.71 | 1.10 | 28.35 | - |
| $6^*$ | $35.39^{+17.5\%}_{-15.2\%}$ | 1.76 | 1.27 | 34.18 | - |

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

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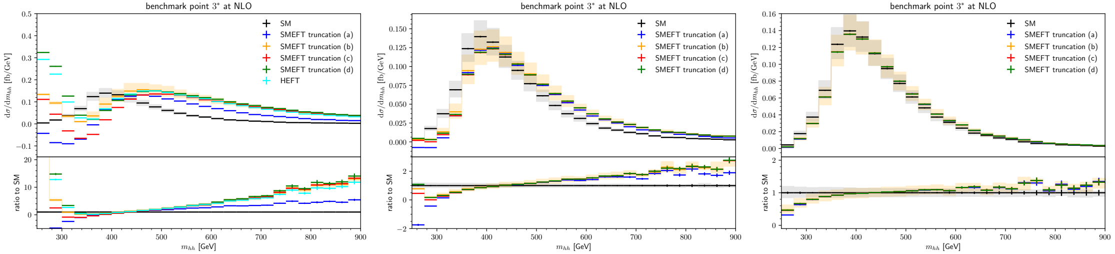
- Benchmark $3^*$:

| $C_{hhh}$ | $C_t$ | $C_{tt}$ | $C_{ggh}$ | $C_{gghh}$ | $C_{H,\text{kin}}$ | $C_H$ | $C_{uH}$ | $C_{HG}$ |
|---|---|---|---|---|---|---|---|---|
| 2.21 | 1.05 | $-\frac{1}{3}$ | 0.5 | $0.25^*$ | 13.5 | 2.64 | 12.6 | 0.0387 |




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

- Truncation (c): double operator insertion quite substantial
- Shape close but distinguishable from SM for increasing $\Lambda$

# Validation of reweighting method

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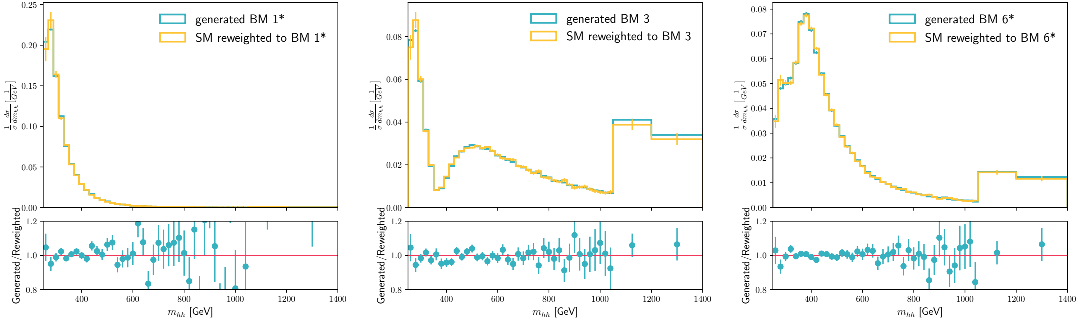
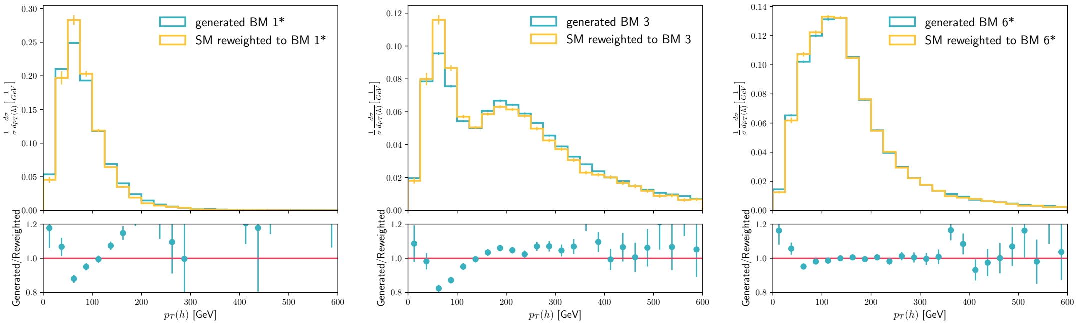



$\Rightarrow$ Very good agreement for $m_{hh}$ distribution!

# Validation of reweighting method and caveats




- Shape features reconstructed, but clearly not optimized for $p_t(h)$ distributions!
- Reweighting of SM events according to $m_{hh}$ does account which diagram type in HEFT benchmarks has dominant bin contribution $\Rightarrow$ insensitive to additional jet radiation
- For benchmarks with enhanced low $m_{hh}$ especially weaker prediction, since sparsely populated by SM events

# Loop counting in SMEFT (“weak” UV assumption)

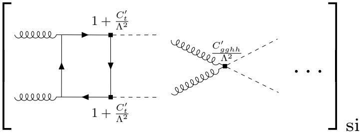
Considering couplings of general renormalisable UV physics [Arzt, Einhorn, Wudka ’94] or using chiral dimensions leads to:

$$\mathcal{O}_H \sim [\kappa^4]\,(\phi^\dagger\phi)^3 \quad \Rightarrow \frac{C_H}{\Lambda^2} \sim \frac{1}{\Lambda^2} \qquad \mathcal{O}_{HG} \sim [\kappa^4]\,(\phi^\dagger\phi)\; G^a_{\mu\nu} G^{a\,\mu\nu} \quad \Rightarrow \frac{C_{HG}}{\Lambda^2} \sim \frac{1}{\Lambda^2\,(16\pi^2)}$$

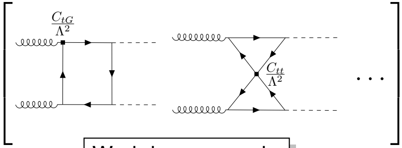
$$\mathcal{O}_{tt} \sim [\kappa^2]\bar{t}_R\gamma_\mu t_R\,\bar{t}_R\gamma^\mu t_R \quad \Rightarrow \frac{C_{tt}}{\Lambda^2} \sim \frac{1}{\Lambda^2}\,, \qquad \mathcal{O}_{tG} \sim [\kappa^4]\,(\bar{q}_L\sigma^{\mu\nu}T^a t_R)\,\tilde{\phi}\,G^a_{\mu\nu} \quad \Rightarrow \frac{C_{tG}}{\Lambda^2} \sim \frac{1}{\Lambda^2\,(16\pi^2)}$$

with $\kappa$ generic weak coupling and $\frac{C(d_\chi)}{\Lambda^2} \sim \frac{1}{\Lambda^2}\left(\frac{1}{16\pi^2}\right)^{(d_\chi-4)/2}$ [Buchalla, Heinrich, Müller-Salditt, Pandler ’22]

$\Rightarrow$ Chromomagnetic operator enters with overall loop factor suppression $\frac{1}{16\pi^2}$ compared to born:




$\sim \frac{1}{\Lambda^2(16\pi^2)}$




$\sim \frac{1}{\Lambda^2(16\pi^2)^2}$

Work in progress!

# Reweighting of MC samples within SMEFT (SKETCH)

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Parametrisation of cross section works in principle the same. Expansion in similar kinematic structures to HEFT leads to:

$$\frac{\sigma_{BSM}^{\text{SMEFT (a)}}}{\sigma_{SM}} = A_1 \cdot \left(1 + 4\frac{C'_t}{\Lambda^2}\right) + A_3 \cdot \left(1 + 2\frac{C'_t}{\Lambda^2} + 2\frac{C'_{hhh}}{\Lambda^2}\right) + (A_6 + A_8) \cdot \frac{C'_{tt}}{\Lambda^2} + A_7 \cdot \left(1 + \frac{C'_{hhh}}{\Lambda^2} + 3\frac{C'_t}{\Lambda^2}\right) + \left(A'_{11} + A'_{13} + A'_{16}\right) \cdot \frac{C'_{ggh}}{\Lambda^2} + \ldots$$

$$= B_0^{SM} + B_1^{(a)} \cdot \frac{C_{H,\text{kin}}}{\Lambda^2} + B_2^{(a)} \cdot \frac{C_H}{\Lambda^2} + B_3^{(a)} \cdot \frac{C_{uH}}{\Lambda^2} + B_4^{(a)} \cdot \frac{C_{HG}}{\Lambda^2}$$

$$\frac{\sigma_{BSM}^{\text{SMEFT (b)}}}{\sigma_{SM}} = A_1 \cdot \left(1 + 4\frac{C'_t}{\Lambda^2} + 4\frac{C'^{\,2}_t}{\Lambda^4}\right) + A_2 \cdot \frac{C'^{\,2}_{tt}}{\Lambda^4} + A_3 \cdot \left(1 + 2\left(\frac{C'_t}{\Lambda^2} + \frac{C'_{hhh}}{\Lambda^2}\right) + \left(\frac{C'_t}{\Lambda^2} + \frac{C'_{hhh}}{\Lambda^2}\right)^2\right) + A'_4 \cdot \frac{C'^{\,2}_{ggh}}{\Lambda^4} + A'_5 \cdot \frac{C'^{\,2}_{gghh}}{\Lambda^4}$$

$$+ A_6 \cdot \frac{C'_{tt}}{\Lambda^2}\left(1 + 2\frac{C'_t}{\Lambda^2}\right) + A_7 \cdot \left(1 + 3\frac{C'_t}{\Lambda^2} + \frac{C'_{hhh}}{\Lambda^2} + 2\frac{C'_t}{\Lambda^2}\left(\frac{C'_t}{\Lambda^2} + \frac{C'_{hhh}}{\Lambda^2}\right)\right) + \cdots + \Delta A'_1 \cdot \frac{C'_{ggh}}{\Lambda^2}\left(\frac{C'_{hhh}}{\Lambda^2} - \frac{C'_t}{\Lambda^2}\right) + \Delta A'_2 \cdot \frac{C'^{\,2}_{ggh}}{\Lambda^4}$$

$$= B_0^{SM} + B_1^{(a)} \cdot \frac{C_{H,\text{kin}}}{\Lambda^2} + B_2^{(a)} \cdot \frac{C_H}{\Lambda^2} + B_3^{(a)} \cdot \frac{C_{uH}}{\Lambda^2} + B_4^{(a)} \cdot \frac{C_{HG}}{\Lambda^2} + B_5^{(b)} \cdot \frac{C^2_{H,\text{kin}}}{\Lambda^4} + B_6^{(b)} \cdot \frac{C^2_H}{\Lambda^4} + B_7^{(b)} \cdot \frac{C^2_{uH}}{\Lambda^4} + B_8^{(b)} \cdot \frac{C^2_{HG}}{\Lambda^4}$$

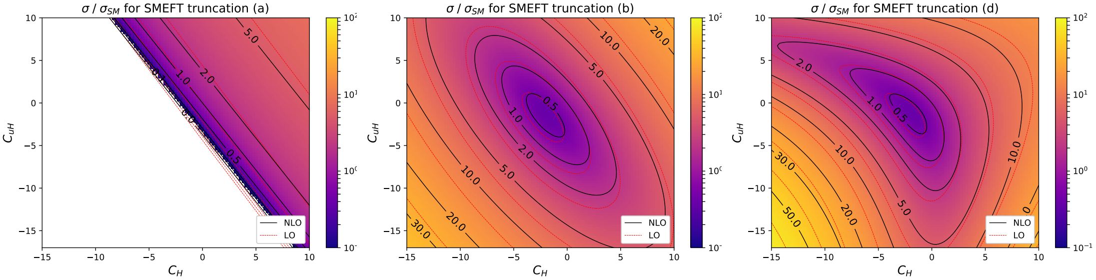
$$+ B_9^{(b)} \cdot \frac{C_{H,\text{kin}}}{\Lambda^2}\frac{C_H}{\Lambda^2} + B_{10}^{(b)} \cdot \frac{C_{H,\text{kin}}}{\Lambda^2}\frac{C_{uH}}{\Lambda^2} + B_{11}^{(b)} \cdot \frac{C_{H,\text{kin}}}{\Lambda^2}\frac{C_{HG}}{\Lambda^2} + B_{12}^{(b)} \cdot \frac{C_H}{\Lambda^2}\frac{C_{uH}}{\Lambda^2} + B_{13}^{(b)} \cdot \frac{C_H}{\Lambda^2}\frac{C_{HG}}{\Lambda^2} + B_{14}^{(b)} \cdot \frac{C_{uH}}{\Lambda^2}\frac{C_{HG}}{\Lambda^2}$$

- **CAUTION:** At least $A'_i$ need to be reevaluated for Warsaw basis, since different factors of scale dependent $\alpha_s(\mu)$ enter the calculation! $\Delta A'_i$ do not appear in HEFT (see backup on virtual grids)
- **RECOMMENDATION:** Evaluate new and separate MC samples for truncation option (a) and (b), respectively, in order to project on new expansion coefficients $B_i^{(a)}$ and $B_i^{(b)}$

| | | |
|---|---|---|
| $c_{ggh}$ | $\frac{1}{\alpha_s(\mu)} \frac{C'_{ggh}}{\Lambda^2}$ | $\frac{v^2}{\Lambda^2} \frac{8\pi}{\alpha_s(\mu)} C_{HG}$ |
| $c_{gghh}$ | $\frac{1}{\alpha_s(\mu)} \frac{C'_{gghh}}{\Lambda^2}$ | $\frac{v^2}{\Lambda^2} \frac{4\pi}{\alpha_s(\mu)} C_{HG}$ |

# NLO 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