Higgs pair production in SMEFT at full NLO QCD: an investigation of truncation effects

PhD fellow talk, Monday 12:00

Jannis Lang   mainly based on [2204.13045 [hep-ph]] with Gudrun Heinrich and Ludovic Scyboz | March 27, 2023

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The Higgs potential

- Higgs boson plays prominent role in SM

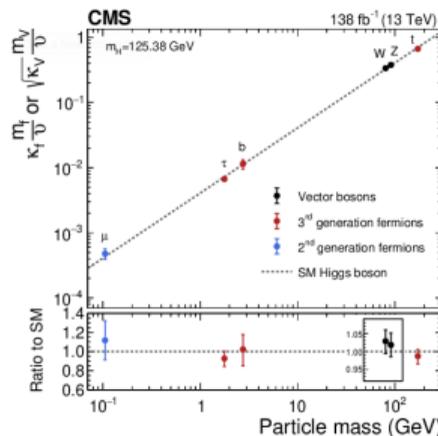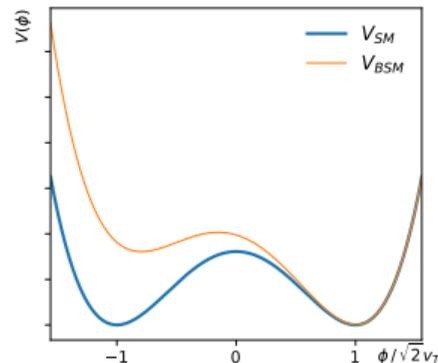- $V_{SM}(\phi) = \lambda \left(\phi^\dagger \phi - \frac{v^2}{2} \right)^2$

$\rightarrow$ EW symmetry breaking $\quad (\phi \sim \frac{h+v}{\sqrt{2}})$

$\quad V_{SM} \sim \frac{m_h^2}{2} h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4 \quad$ with $\lambda = \frac{m_h^2}{2v^2}$ (tree-level)

$\rightarrow$ v leads to mass terms of SM particles with direct relation to Higgs couplings

- Impressive experimental results on Higgs couplings

- Higgs self interaction?

[2211.01216]

Motivation   SMEFT and HEFT   Status of EFT calculations in $gg \rightarrow hh$ Benchmark study   Power counting and $\mathcal{O}_{tG}$ Summary

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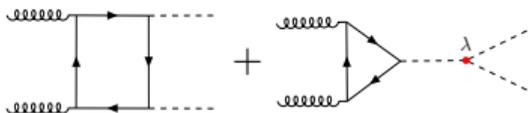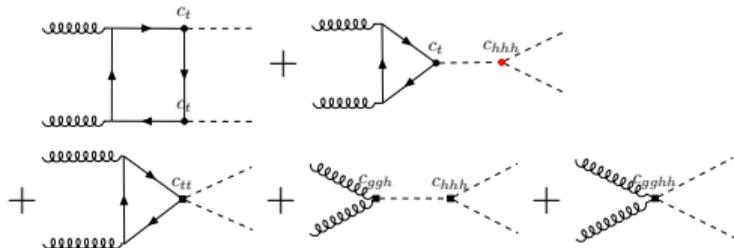
Why study EFT phenomenology in *hh* production?

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

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

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

$\Rightarrow$ Bottom-up EFT! (for non-resonant production)

[2207.00043]

[2211.01216]

Motivation ○●○   SMEFT and HEFT ○○○○○○○   Status of EFT calculations in $gg \rightarrow hh$ ○○   Benchmark study ○○○   Power counting and $\mathcal{O}_{tG}$ ○○○   Summary

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Outline

Motivation   SMEFT and HEFT   Status of EFT calculations in $gg \rightarrow hh$ Benchmark study   Power counting and $\mathcal{O}_{tG}$ Summary
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Effective field theory basics

Top-down perspective

- Effective low-energy description from integrating out heavy d.o.f. (i.e. heavy particles)
- Example: 4-fermion from heavy boson (cf. Fermi theory of EW interaction) and heavy top limit

$$\rightarrow \qquad \left(+\mathcal{O}\left(\frac{E^4}{M^4}\right)\right) \qquad \rightarrow \qquad \Delta\mathcal{L} = \frac{C}{M^2}\bar{\psi}_i\gamma^\mu\psi_j\bar{\psi}_k\gamma_\mu\psi_l$$

$$\rightarrow \qquad \left(+\mathcal{O}\left(\frac{E^4}{m_t^4}\right)\right) \qquad \rightarrow \qquad \Delta\mathcal{L} = \frac{\tilde{C}}{m_t^2}\left(\phi^\dagger\phi\right)G_{\mu\nu}^a G^{a\,\mu\nu}$$

⇒ Classically non-renormalisable operators!

- However, well applicable for low energies due to $\frac{1}{M^2}$ suppression
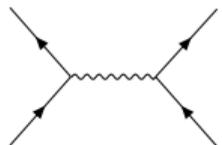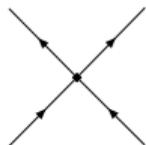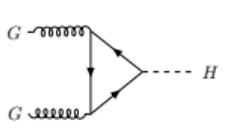
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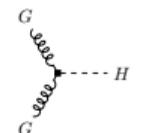
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Two bottom-up EFT systematics: SMEFT vs. HEFT

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 $\phi(x)$
- BSM: decoupling New Physics
- Canonical counting ($\Rightarrow$ expansion in $\frac{1}{\Lambda}$):

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

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

$$\mathcal{L}_{SMEFT}^{(Warsaw)} \supset \frac{C_{H\Box}}{\Lambda^2} \left(\phi^\dagger \phi\right) \Box \left(\phi^\dagger \phi\right) + \frac{C_{HD}}{\Lambda^2} \left(\phi^\dagger D_\mu \phi\right) \left(\phi^\dagger D^\mu \phi\right) + \frac{C_H}{\Lambda^2} \left(\phi^\dagger \phi\right)^3$$

$$+ \frac{C_{uH}}{\Lambda^2} \left(\left(\phi^\dagger \phi\right) \bar{q}_L \tilde{\phi} t_R + \text{h.c.}\right) + \frac{C_{HG}}{\Lambda^2} \left(\phi^\dagger \phi\right) G_{\mu\nu}^a G^{a\,\mu\nu} \underbrace{+ \frac{C_{uG}}{\Lambda^2} \left(\bar{q}_L \sigma^{\mu\nu} T^a G_{\mu\nu}^a \tilde{\phi} t_R + \text{h.c.}\right)}_{\text{subdominant (UV assumption)} \to \text{last part}}$$

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

Motivation ○○○ | SMEFT and HEFT ○●○○○○○ | Status of EFT calculations in $gg \to hh$ ○○ | Benchmark study ○○○ | Power counting and $\mathcal{O}_{tG}$ ○○○ | Summary ○

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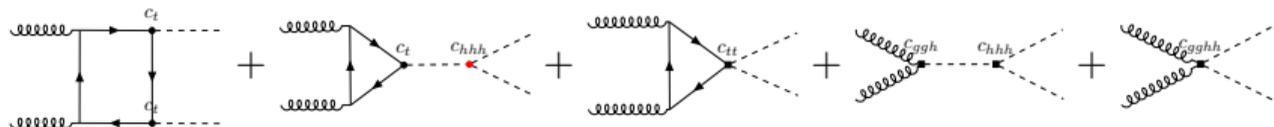
Two bottom-up EFT systematics: SMEFT vs. HEFT

HEFT:
- Non-linear theory (EWχL), motivation as analogue to chiral pert. theory
- Light Higgs is EW gauge singlet
- BSM: can be strongly coupling New Physics
- Chiral dimension of operators $d_\chi(\partial, \bar\psi\psi, g, y) = 1$
- Expansion in $\frac{f^2}{\Lambda^2} \sim \frac{1}{16\pi^2}$ ($\Rightarrow$ loop counting)   (f energy scale of non-decoupling theory)

$$\mathcal{L}_{HEFT} \sim \mathcal{L}_{HEFT}^{LO} + \sum_{L=1}\sum_i \left(\frac{1}{16\pi^2}\right)^L c_i \mathcal{O}_i^{d_\chi=2+2L}$$

$\Rightarrow$ Relevant parts for $gg \to hh$:

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

Motivation ○○○   SMEFT and HEFT ○○●○○○○○   Status of EFT calculations in $gg \to hh$ ○○   Benchmark study ○○○   Power counting and $\mathcal{O}_{tG}$ ○○○   Summary ○

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Two bottom-up EFT systematics: SMEFT vs. HEFT

SMEFT:

$$\mathcal{L}_{SMEFT}^{(Warsaw)} \supset \frac{C_{H\Box}}{\Lambda^2} \left(\phi^\dagger \phi\right) \Box \left(\phi^\dagger \phi\right) + \frac{C_{HD}}{\Lambda^2} \left(\phi^\dagger D_\mu \phi\right) \left(\phi^\dagger D^\mu \phi\right) + \frac{C_H}{\Lambda^2} \left(\phi^\dagger \phi\right)^3$$

$$+ \frac{C_{uH}}{\Lambda^2} \left(\left(\phi^\dagger \phi\right) \bar{q}_L \tilde{\phi} t_R + \text{h.c.}\right) + \frac{C_{HG}}{\Lambda^2} \left(\phi^\dagger \phi\right) G^a_{\mu\nu} G^{a\,\mu\nu}$$

HEFT:

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

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

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

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

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SMEFT truncation

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

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

$\Rightarrow$ 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

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SMEFT truncation of cross section

$$\sigma \simeq \begin{cases} \sigma_{\mathsf{SM}} + \sigma_{\mathsf{SM}\times\mathrm{dim6}} \\[2em] \sigma_{(\mathsf{SM}+\mathrm{dim6})\times(\mathsf{SM}+\mathrm{dim6})} \\[2em] \sigma_{(\mathsf{SM}+\mathrm{dim6})\times(\mathsf{SM}+\mathrm{dim6})} + \sigma_{\mathsf{SM}\times\mathrm{dim6}^2} \\[2em] \sigma_{\left(\mathsf{SM}+\mathrm{dim6}+\mathrm{dim6}^2\right)\times\left(\mathsf{SM}+\mathrm{dim6}+\mathrm{dim6}^2\right)} \end{cases}$$

(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 amplitude
$\Rightarrow$ 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 consistent, however, negative (differential) cross section can appear for too large Wilson coefficients

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

Motivation
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SMEFT and HEFT
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Status of EFT calculations in $gg \to hh$
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Benchmark study
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Power counting and $\mathcal{O}_{tG}$
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NLO cross section heatmaps in SMEFT

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

(a)

(b)

(d)

- Large area of negative cross section for truncation (a)

- Non-trivial shape for HEFT-like option (d)

- Flat directions differ substantially

Motivation
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SMEFT and HEFT
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Status of EFT calculations in $gg \rightarrow hh$
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Benchmark study
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Public implementations

HEFT

$$\boxed{\text{HTL = Heavy top limit } (m_t \to \infty)}$$

- 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]
  [Buchalla,Capozi,Celis,Heinrich,Scyboz '18]
  [Heinrich,Jones,Kerner,Luisoni,Scyboz '19]
  [Heinrich,Jones,Kerner,Scyboz '20] ⇐

- **Non-public** state-of-the-art NNLO′ (HTL NNLO, full m_t NLO) [de Florian,Fabre,Heinrich,Mazitelli,Scyboz '21]

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] ⇐

Motivation
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SMEFT and HEFT
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Status of EFT calculations in $gg \to hh$
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Benchmark study
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Summary
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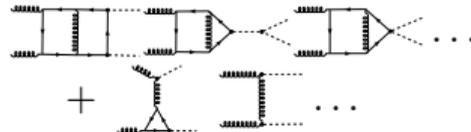
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Amplitude evaluation in ggHH_SMEFT

$$\mathcal{M}_{gg \to hh} = \epsilon(p_1)_\mu \epsilon(p_2)_\nu \left(\mathcal{F}_1 \cdot T_1^{\mu\nu} + \mathcal{F}_2 \cdot T_2^{\mu\nu} \right)$$

[Glover, van der Bij '87]

Born: Analytic expressions for form factors $\mathcal{F}_1$ and $\mathcal{F}_2$ (tree and 1-loop contributions)

Real: $|\mathcal{M}_{gg \to hhg}|^2$, $|\mathcal{M}_{qg \to hhq}|^2$, $|\mathcal{M}_{q\bar{q} \to hhg}|^2$ and crossings evaluated using (private) modified version of **GoSam** 1-loop ME generator

Virtual: 2-loop diagrams in HEFT are similar to SM $\Rightarrow$ reweighting

HEFT virtuals are available as function of 23 grids a_i

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

$\Rightarrow$ Grids can be directly reused for SMEFT (considering translation and truncation) up to counter terms and special treatment for truncation (b), where additional 1-loop contributions are added

Motivation
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SMEFT and HEFT
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Status of EFT calculations in $gg \to hh$
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Benchmark study
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Power counting and $\mathcal{O}_{tG}$
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Summary
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Naive benchmark translation

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

[Capozi, Heinrich '19]
[https://cds.cern.ch/record/2843280]

- 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}	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 $\alpha_s(m_Z) = 0.118$

Motivation
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SMEFT and HEFT
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Status of EFT calculations in $gg \rightarrow hh$
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Benchmark study
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Power counting and $\mathcal{O}_{tG}$
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Naive benchmark translation

Con...
with...

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	-

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

Motivation
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SMEFT and HEFT
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Status of EFT calculations in $gg \to hh$
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Invariant mass distributions at NLO QCD ($\sqrt{s} = 13$ TeV)

KIT
Karlsruhe Institute of Technology

- Benchmark 1*:

Generated with ggHH_SMEFT
in POWHEG-BOX-V2

c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\text{kin}}$	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

Motivation · SMEFT and HEFT · Status of EFT calculations in $gg \to hh$ · **Benchmark study** · Power counting and $\mathcal{O}_{tG}$ · Summary

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

KIT
Karlsruhe Institute of Technology

- Benchmark 6*:

Generated with ggHH_SMEFT
in POWHEG-BOX-V2

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 α_s scale dependence

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Loop counting in SMEFT ("weak" UV assumption)

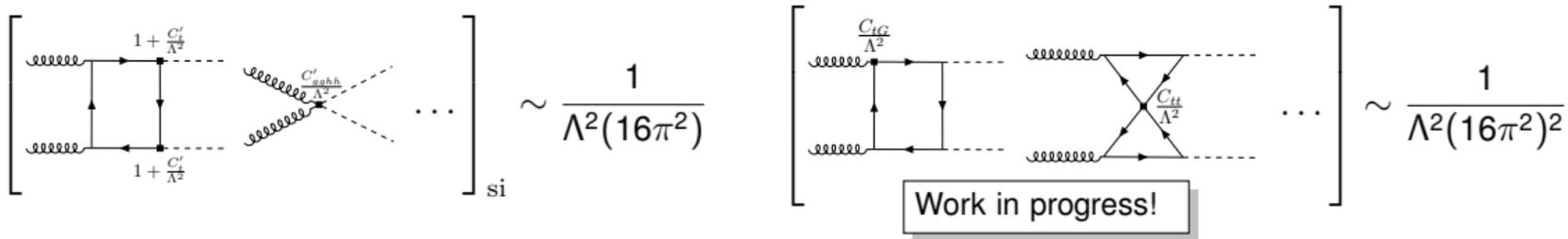Considering couplings of general renormalisable UV physics [Arzt, Einhorn, Wudka '94] or using chiral dimensions [Buchalla, Heinrich, Müller-Salditt, Pandler '22] leads to:

(κ generic weak coupling, $\quad d_\chi(\partial, \bar{\psi}\psi, \kappa) = 1, \quad C(6, d_\chi) \sim \frac{1}{\Lambda^2} \left(\frac{1}{16\pi^2}\right)^{(d_\chi - 4)/2}$)

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

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

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

$$\left[\ldots \right]_{\text{si}} \sim \frac{1}{\Lambda^2 (16\pi^2)} \qquad \left[\ldots \right] \sim \frac{1}{\Lambda^2 (16\pi^2)^2}$$

Work in progress!

Motivation SMEFT and HEFT Status of EFT calculations in $gg \to hh$ Benchmark study Power counting and $\mathcal{O}_{tG}$ Summary

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Effects of chromomagnetic operator (PRELIMINARY)

- Benchmark 1* with $\mathcal{O}_{tG}$:

$C_{H,\text{kin}}$	C_H	C_{uH}	C_{HG}	C_{tG}
4.95	-6.81	3.28	0	$\{0, \pm0.0387\}$

(variation using same value as C_{HG} of benchmark 6*)

benchmark point 1* at NLO with chromo variation

benchmark point 1* at NLO with chromo variation

- Effect of C_{tG} variation with explicit loop suppression within scale uncertainty
- ⇒ Subdominant contribution (in this UV scenario)!

Motivation
○○○

SMEFT and HEFT
○○○○○○○○

Status of EFT calculations in $gg \to hh$
○○

Benchmark study
○○○

Power counting and $\mathcal{O}_{tG}$
○●○

Summary
○

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March 27, 2023

18/20

Effects of chromomagnetic operator (PRELIMINARY)

- Benchmark 6* with $\mathcal{O}_{tG}$:

$C_{H,\mathrm{kin}}$	C_H	C_{uH}	C_{HG}	C_{tG}
0.561	3.80	2.20	0.0387	$\{0, \pm 0.0387\}$

benchmark point 6* at NLO with chromo variation
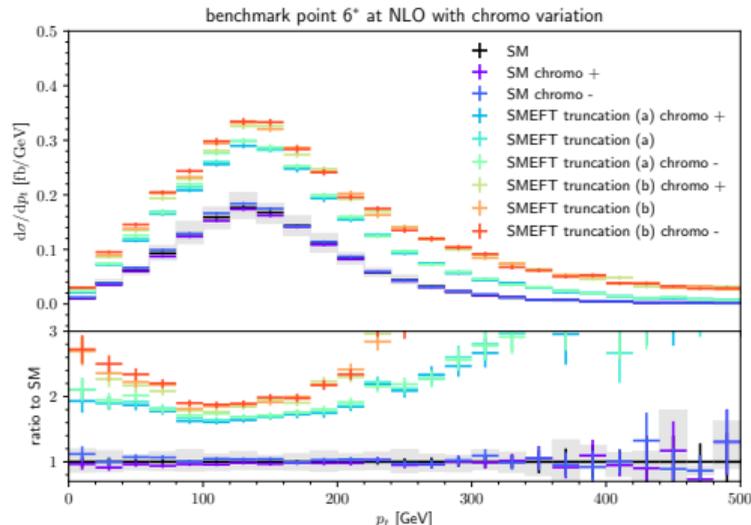
benchmark point 6* at NLO with chromo variation

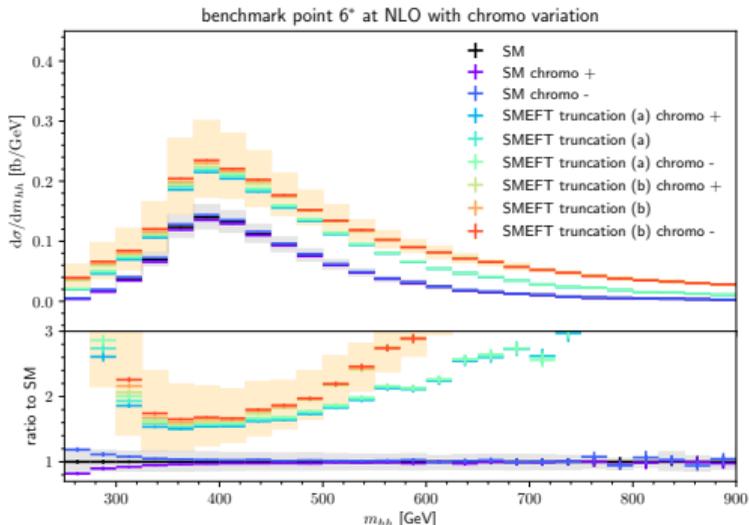- Effect of C_{tG} variation with explicit loop suppression within scale uncertainty
- ⟹ Subdominant contribution (in this UV scenario)!

Motivation   SMEFT and HEFT   Status of EFT calculations in $gg \rightarrow hh$ Benchmark study   Power counting and $\mathcal{O}_{tG}$ Summary

Jannis Lang − hh production at NLO QCD in SMEFT and truncation effects   March 27, 2023   19/20

Summary

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

- Status of EFT calculations in $gg \rightarrow hh$

- 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

- More information about this project: [Heinrich,JL,Scyboz '22]
- More information about EFT in Higgs pair production: [https://cds.cern.ch/record/2843280]

$\Rightarrow$ In progress: Inclusion of chromo-magnetic and 4-fermion operator contributions, RGE evolution of Wilson coefficients

$\Rightarrow$ Further outlook: y_t and EW corrections when SM results are available, ...

Motivation · SMEFT and HEFT · Status of EFT calculations in $gg \rightarrow hh$ · Benchmark study · Power counting and $\mathcal{O}_{tG}$ · Summary

Jannis Lang − hh production at NLO QCD in SMEFT and truncation effects   March 27, 2023   20/20

Estimating theory uncertainties

$$\Delta\sigma \sim {}^{+\Delta_{\text{scale}+}}_{-\Delta_{\text{scale}-}} \quad {}^{+\Delta_{m_t \text{scheme}+}}_{-\Delta_{m_t \text{scheme}-}} \quad \pm\,\Delta_{\text{num. grid}} \quad (\pm\Delta_{\text{EFT trunc.}}) \quad \pm\,\Delta_{\text{PDF}+\alpha_s} \quad \pm\,\Delta_{\text{EW}}$$
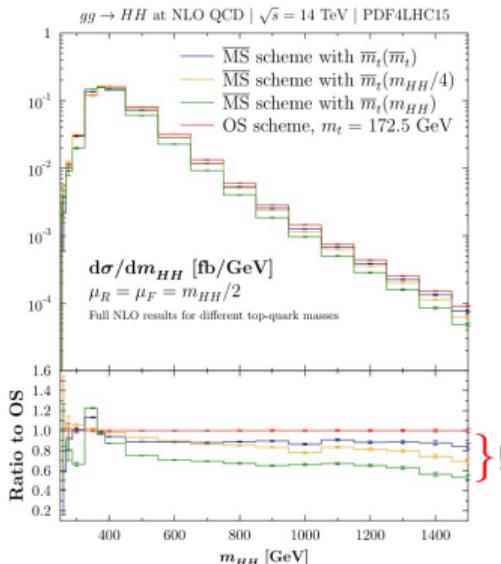
- Δ_{EW}: Full NLO EW unknown, only partial results of top Yukawa [Davies,Mishima,Schönwald,Steinhauser,Zhang '22] [Mühlleitner,Schlenk,Spira '22]

- $\Delta_{\text{PDF}+\alpha_s} \approx 3\%$ ($\sqrt{s} = 13$ 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`!

Uncertainties EFT systematics: canonical vs. loop Virtual grids for SMEFT Code usage HEFT benchmarks Reweighting SMEFT reweighting

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m_t renormalisation scheme uncertainty

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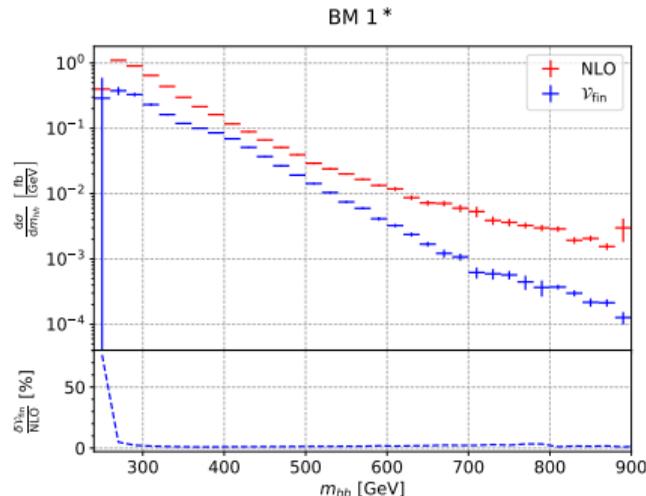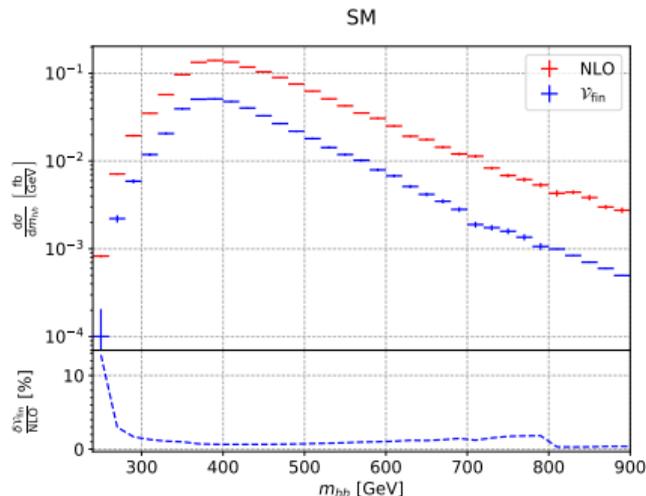[Baglio,Campanario,Glaus,Mühlleitner,Ronca,Spira '20]

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

- 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

$gg \to HH$ at NLO QCD | $\sqrt{s} = 14$ TeV | PDF4LHC15

$\overline{MS}$ scheme with $\bar{m}_t(\bar{m}_t)$
$\overline{MS}$ scheme with $\bar{m}_t(m_{HH}/4)$
$\overline{MS}$ scheme with $\bar{m}_t(m_{HH})$
OS scheme, $m_t = 172.5$ GeV

$\mathrm{d}\sigma/\mathrm{d}m_{HH}$ [fb/GeV]
$\mu_R = \mu_F = m_{HH}/2$
Full NLO results for different top-quark masses

Ratio to OS

m_{HH} [GeV]

$\kappa_\lambda = -10:$ $\sigma_{tot} = 1438(1)^{+10\%}_{-6\%}$ fb,

$\kappa_\lambda = -5:$ $\sigma_{tot} = 512.8(3)^{+10\%}_{-7\%}$ fb,

$\kappa_\lambda = -1:$ $\sigma_{tot} = 113.66(7)^{+8\%}_{-9\%}$ fb,

$\kappa_\lambda = 0:$ $\sigma_{tot} = 61.22(6)^{+6\%}_{-12\%}$ fb,

$\kappa_\lambda = 1:$ $\sigma_{tot} = 27.73(7)^{+4\%}_{-18\%}$ fb,

$\kappa_\lambda = 2:$ $\sigma_{tot} = 13.2(1)^{+1\%}_{-23\%}$ fb,

$\kappa_\lambda = 2.4:$ $\sigma_{tot} = 12.7(1)^{+4\%}_{-22\%}$ fb,

$\kappa_\lambda = 3:$ $\sigma_{tot} = 17.6(1)^{+9\%}_{-15\%}$ fb,

$\kappa_\lambda = 5:$ $\sigma_{tot} = 83.2(3)^{+13\%}_{-4\%}$ fb,

$\kappa_\lambda = 10:$ $\sigma_{tot} = 579(1)^{+12\%}_{-4\%}$ fb

Uncertainties   EFT systematics: canonical vs. loop   Virtual grids for SMEFT   Code usage   HEFT benchmarks   Reweighting   SMEFT reweighting

Jannis Lang − hh production at NLO QCD in SMEFT and truncation effects   March 27, 2023   22/20
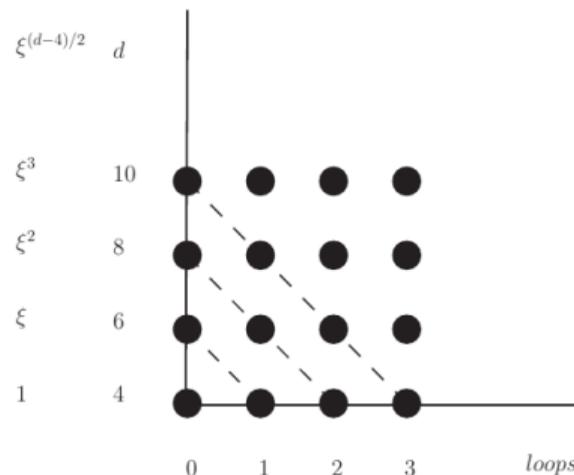
Numerical grids uncertainty

SM

BM 1 *

- Low (and high) m_{hh} region very sparsely populated in virtual grids, due to small contribution in SM
- $\Rightarrow \mathcal{O}\,(12\,\%)$ uncertainty for SM in first bin not represented by Monte Carlo statistical uncertainty in POWHEG
- $\Rightarrow$ Uncertainty much worse for scenarios with enhanced low m_{hh} region

Uncertainties ○○●   EFT systematics: canonical vs. loop ○   Virtual grids for SMEFT ○○   Code usage ○○   HEFT benchmarks ○   Reweighting ○○○○   SMEFT reweighting ○

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EFT systematics: canonical vs. loop counting

$$\xi = \frac{v^2}{f^2}$$

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

- Canonical counting in rows, valid if $\xi \ll \frac{f^2}{\Lambda}$

- Loop counting in columns, valid if $\xi \sim 1$

[Buchalla,Catà,Krause 14']

Uncertainties   EFT systematics: canonical vs. loop   Virtual grids for SMEFT   Code usage   HEFT benchmarks   Reweighting   SMEFT reweighting

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Virtual grids for ggHH_SMEFT

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

$$\mathcal{M}_{LO} := m_1 \cdot c_t^2 + m_2 \cdot c_t c_{hhh} + m_3 \cdot c_{tt} + m_4 \cdot c_g c_{hhh} + m_5 \cdot c_{gg}$$

$$= m_1 + m_2 + \frac{1}{\Lambda^2} \left(2m_1 \cdot C_t' + m_2 \cdot (C_t' + C_{hhh}') + m_3 \cdot C_{tt}' + m_4 \cdot C_g' + m_5 \cdot C_{gg}' \right) + \frac{1}{\Lambda^4} \left(m_1 \cdot C_t'^2 + m_2 \cdot C_t' C_{hhh}' \right)$$

$$\mathcal{M}_{NLO} := M_1 \cdot c_t^2 + M_2 \cdot c_t c_{hhh} + M_3 \cdot c_{tt} + M_4 \cdot c_g c_{hhh} + M_5 \cdot c_{gg} + M_6 \cdot c_g^2 + M_7 \cdot c_g c_t$$

$$= M_1 + M_2 + \frac{1}{\Lambda^2} \left(2M_1 \cdot C_t' + M_2 \cdot (C_t' + C_{hhh}') + M_3 \cdot C_{tt}' + M_4 \cdot C_g' + M_5 \cdot C_{gg}' + M_7 \cdot C_g' \right)$$

$$+ \frac{1}{\Lambda^4} \left(M_1 \cdot C_t'^2 + M_2 \cdot C_t' C_{hhh}' + M_6 \cdot C_g'^2 + M_7 \cdot C_g' C_t' \right)$$

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

$$|\mathcal{M}_{NLO}|^2 = a_1 \cdot c_t^4 + a_2 \cdot c_t^2 c_{tt} + a_3 \cdot c_t^2 c_{hhh}^2 + a_4 \cdot c_{ggh}^2 c_{hhh}^2 + a_5 \cdot c_{ggh}^2 + a_6 \cdot c_{tt} c_t^2 + a_7 \cdot c_t^3 c_{hhh} + a_8 \cdot c_{tt} c_t c_{hhh} + a_9 \cdot c_{tt} c_{ggh} c_{hhh}$$

$$+ a_{10} \cdot c_{tt} c_{ggh} + a_{11} \cdot c_t^2 c_{ggh} c_{hhh} + a_{12} \cdot c_t^2 c_{ggh} + a_{13} \cdot c_t c_{hhh}^2 c_{ggh} + a_{14} \cdot c_t c_{hhh} c_{ggh} + a_{15} \cdot c_{ggh} c_{hhh} c_{gghh} + a_{16} \cdot c_t^3 c_{ggh}$$

$$+ a_{17} \cdot c_t c_{tt} c_{ggh} + a_{18} \cdot c_t c_{ggh}^2 c_{hhh} + a_{19} \cdot c_t c_{ggh} c_{gghh} + a_{20} \cdot c_t^2 c_{ggh}^2 + a_{21} \cdot c_{tt} c_{ggh}^2 + a_{22} \cdot c_{ggh}^3 c_{hhh} + a_{23} \cdot c_{ggh}^2 c_{gghh} ,$$

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.

Uncertainties ○○○   EFT systematics: canonical vs. loop ○○○   **Virtual grids for SMEFT** ○○   Code usage ○○   HEFT benchmarks ○   Reweighting ○○○○   SMEFT reweighting ○

Jannis Lang − *hh* production at NLO QCD in SMEFT and truncation effects   March 27, 2023   25/20

POWHEG code ggHH

[Heinrich,Jones,Kerner,Scyboz '20]

Usage of code:

- Built on previous NLO SM calculation with full m_t dependence

  [Borowka,Greiner,Heinrich,Jones,Kerner,et al. '16]
  [Heinrich,Jones,Kerner,Luisoni,Vryoniou '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

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

```
! 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
```

Uncertainties   EFT systematics: canonical vs. loop   Virtual grids for SMEFT   Code usage   HEFT benchmarks   Reweighting   SMEFT reweighting
○○○   ○○○○   ○○○○   ●○   ○   ○○○○   ○

Jannis Lang − hh production at NLO QCD in SMEFT and truncation effects   March 27, 2023   26/20

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
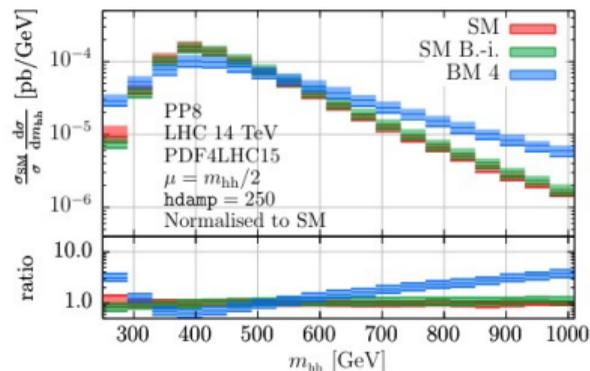 available

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

Fixed order — Matched to PYTHIA-8

Uncertainties
○○○

EFT systematics: canonical vs. loop
○

Virtual grids for SMEFT
○

Code usage
●○

HEFT benchmarks
○

Reweighting
○○○○

SMEFT reweighting
○

Jannis Lang − *hh* production at NLO QCD in SMEFT and truncation effects

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POWHEG code ggHH_SMEFT

[Heinrich,JL,Scyboz '22]

KIT
Karlsruhe Institute of Technology

- Built on NLO HEFT ggHH

- usesmeft $\begin{cases} 0: \text{HEFT operators} \\ 1: \text{SMEFT operators} \end{cases}$

- 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_dbldim6+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
```
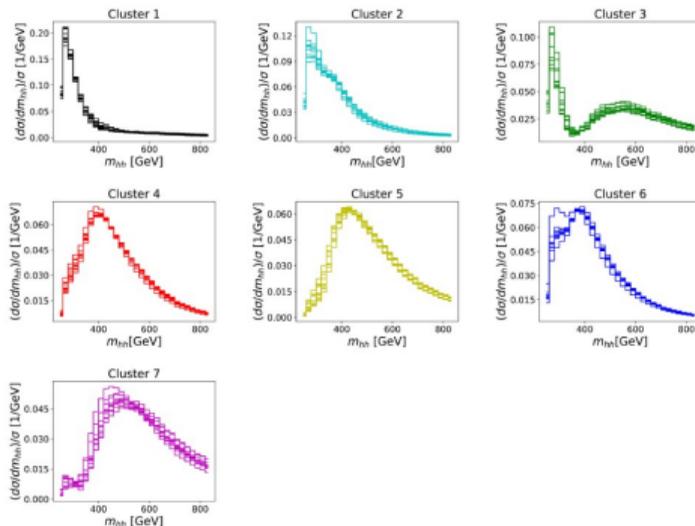
Uncertainties
○○○

EFT systematics: canonical vs. loop
○

Virtual grids for SMEFT
○

Code usage
○●

HEFT benchmarks
○

Reweighting
○

SMEFT reweighting
○

Jannis Lang − *hh* production at NLO QCD in SMEFT and truncation effects

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Updated HEFT benchmarks [https://cds.cern.ch/record/2843280]

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	$\frac{1}{6}$	$-\frac{1}{6}$

- 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*)

[Capozi, Heinrich '19]

Uncertainties   EFT systematics: canonical vs. loop   Virtual grids for SMEFT   Code usage   **HEFT benchmarks**   Reweighting   SMEFT reweighting

Jannis Lang − *hh* production at NLO QCD in SMEFT and truncation effects   March 27, 2023   28/20

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:

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

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

- $\mathbf{A}$ and $d\mathbf{A}$ with respective covariance matrix $\Sigma_{(d)\mathbf{A}}$ derived using least square fit of 63 MC samples

- $d\mathbf{A}$ 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 $\mu_0 = \frac{m_{hh}}{2}$

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

To be uploaded in HEPdata

Uncertainties   EFT systematics: canonical vs. loop   Virtual grids for SMEFT   Code usage   HEFT benchmarks   **Reweighting**   SMEFT reweighting

Jannis Lang – *hh* production at NLO QCD in SMEFT and truncation effects   March 27, 2023   29/20

Reweighting of NLO HEFT and statistical uncertainties

- Weights obtained according to $\quad w_{\text{HEFT}} = \frac{Poly(\mathbf{c}, d\mathbf{A}|m_{hh})}{Poly(\mathbf{c}_{\text{SM}}, d\mathbf{A}|m_{hh})}$

- Corresponding uncertainty calculated using $\quad \delta_{w_{\text{HEFT}}} = \sqrt{\mathbf{J}_w \Sigma_{d\mathbf{A}} \mathbf{J}_w^{\mathsf{T}}} \quad$ with

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

- Final statistical uncertainty in reweighted bin j

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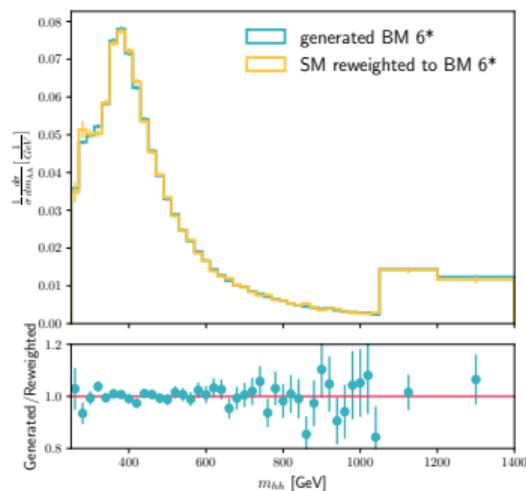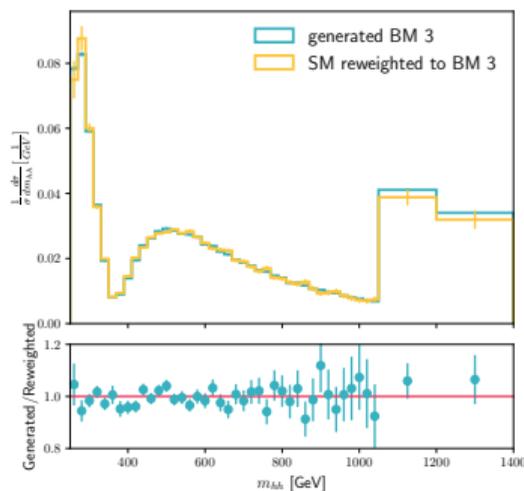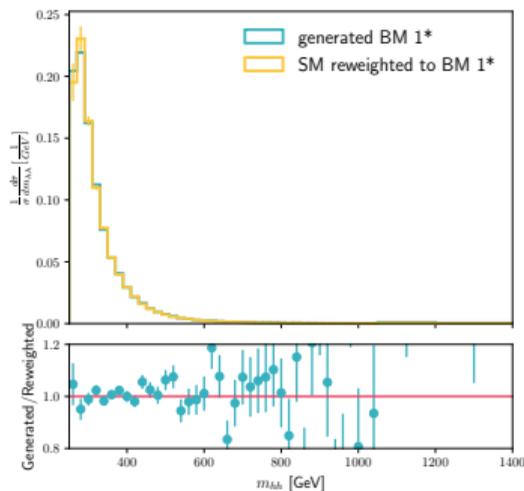
N^j: sum of weighted events

N^j_{SM}: sum of weighted SM events

w^j_{HEFT}: weight

δ^j_{SM}: weighted statistical uncertainty for SM events

Uncertainties ○○○   EFT systematics: canonical vs. loop ○   Virtual grids for SMEFT ○   Code usage ○○   HEFT benchmarks ○   **Reweighting** ○●○○   SMEFT reweighting ○

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Validation of reweighting method

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

Uncertainties
○○○

EFT systematics: canonical vs. loop
○

Virtual grids for SMEFT
○

Code usage
○○

HEFT benchmarks
○○

Reweighting
○○●○

SMEFT reweighting
○

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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

Uncertainties ○○○   EFT systematics: canonical vs. loop ○   Virtual grids for SMEFT ○   Code usage ○   HEFT benchmarks ○○   **Reweighting** ○○○●   SMEFT reweighting ○

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

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

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

$$\frac{\sigma_{BSM}^{\text{SMEFT (b)}}}{\sigma_{SM}} = A_1 \cdot \left(1 + 4\frac{C_t'}{\Lambda^2} + 4\frac{C_t'^2}{\Lambda^4}\right) + A_2 \cdot \frac{C_{tt}'^2}{\Lambda^4} + A_3 \cdot \left(1 + 2\left(\frac{C_t'}{\Lambda^2} + \frac{C_{hhh}'}{\Lambda^2}\right) + \left(\frac{C_t'}{\Lambda^2} + \frac{C_{hhh}'}{\Lambda^2}\right)^2\right) + A_4' \cdot \frac{C_{ggh}'^2}{\Lambda^4} + A_5' \cdot \frac{C_{gghh}'^2}{\Lambda^4}$$

$$+ A_6 \cdot \frac{C_{tt}'}{\Lambda^2}\left(1 + 2\frac{C_t'}{\Lambda^2}\right) + A_7 \cdot \left(1 + 3\frac{C_t'}{\Lambda^2} + \frac{C_{hhh}'}{\Lambda^2} + 2\frac{C_t'}{\Lambda^2}\left(\frac{C_t'}{\Lambda^2} + \frac{C_{hhh}'}{\Lambda^2}\right)\right) + \ldots + \Delta A_1' \cdot \frac{C_{ggh}'}{\Lambda^2}\left(\frac{C_{hhh}'}{\Lambda^2} - \frac{C_t'}{\Lambda^2}\right) + \Delta A_2' \cdot \frac{C_{ggh}'^2}{\Lambda^4}$$

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

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

- **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}	$\frac{1}{\alpha_s(\mu)}\frac{C_{gghh}'}{\Lambda^2}$	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s(\mu)}C_{HG}$

Uncertainties ○○○ | EFT systematics: canonical vs. loop ○ | Virtual grids for SMEFT ○○ | Code usage ○○ | HEFT benchmarks ○ | Reweighting ○○ | SMEFT reweighting ●

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