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TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

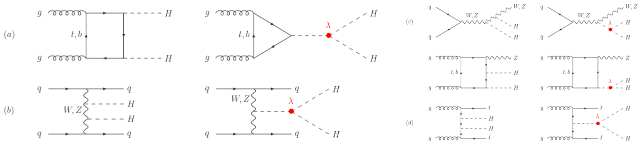
Precise SMEFT predictions for di-Higgs production

Higgs Physics: Part 2, Thursday ∼4:12 pm

Jannis Lang mainly based on [2204.13045] with Gudrun Heinrich and Ludovic Scyboz | May 25, 2023

INSTITUTE FOR THEORETICAL PHYSICS

What do we mean by “precise SMEFT predictions”?



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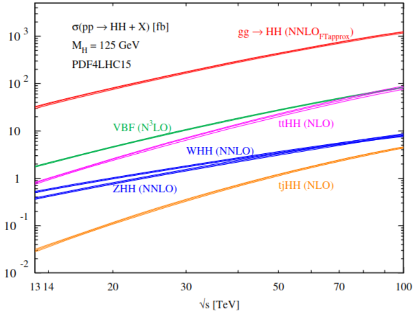
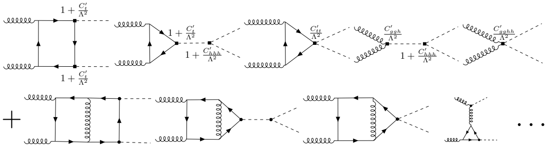


- Selection of *hh* channels

$\rightarrow$ Only consider $gg \rightarrow hh$ channel

- Higher order corrections by SM couplings (explicit loops)

$\rightarrow$ NLO QCD corrections



What do we mean by “precise SMEFT predictions”?

- Higher order terms in (defining) EFT expansion parameter

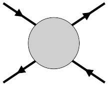
$\rightarrow$ Only dim-6 operators considered (leading order in Λ^{-2})

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \mathcal{O}\left(\Lambda^{-4}\right)$$

- Assigning additional hierarchy to EFT Wilson coefficients (UV assumption)

$\rightarrow$ Stringent Flavor assumption ($m_f := 0$, except m_t), differentiating potentially tree- with strictly loop-induced operators (implicit loop factor in Wilson coefficient)

$$U_l(3) \times U_e(3) \times U_Q(2) \times U_t(2) \times U_d(3)$$



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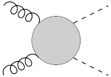

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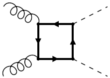

Two bottom-up EFT systematics: SMEFT vs. HEFT

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SMEFT:

- Linear Higgs sector: light Higgs contained in EW doublet field $\phi(x)$
- Canonical counting, truncate expansion at Λ^{-2} (only CP even operators)

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

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

HEFT:

- Non-linear theory (EWχL), motivation as analogue to chiral pert. theory
- Light Higgs is EW gauge singlet
- Expansion in $\frac{f^2}{\Lambda^2} \sim \frac{1}{16\pi^2}$ ($\Rightarrow$ loop counting)

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

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

Two bottom-up EFT systematics: SMEFT vs. HEFT

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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 $\mathcal{O}\left(\Lambda^{-2}\right)$ in Lagrangian ($C_{H,kin} = C_{H\Box} - 4C_{HD}$)

However, formally:

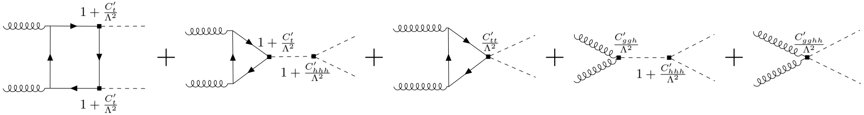
$c_i \sim \mathcal{O}(1)$ possible $\quad\leftrightarrow\quad \frac{E^2}{\Lambda^2}C_i \ll 1$

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

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

SMEFT truncation

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

$\mathcal{M} =$  $+ \dots$

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

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

(a) Truncation at leading order of expansion of powers in Λ^{-2} of cross section $\Rightarrow$ applicable choice

(b) Truncation at leading order of expansion of powers in Λ^{-2} of amplitude $\Rightarrow$ applicable choice

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

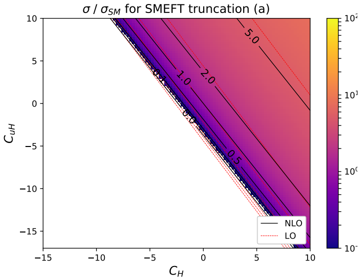
(d) Complete insertion, naive translation SMEFT $\leftrightarrow$ HEFT

- Truncation (a) formally most consistent, however, negative (differential) cross section can appear for too large Wilson coefficients

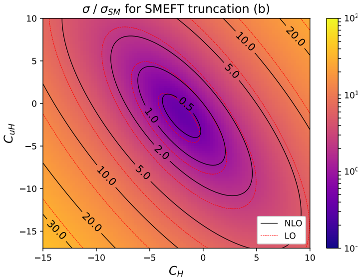
$\Rightarrow$ Perform analysis for truncation (a) and (b) separately!

NLO cross section heatmaps in SMEFT

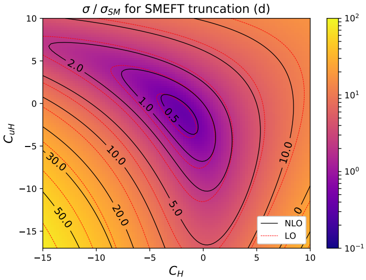
Generated at $\sqrt{s} = 13$ TeV with $\Lambda = 1$ TeV



(a)



(b)



(d)

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

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]
  [Buchalla,Capozi,Celis,Heinrich,Scyboz '18]
  [Heinrich,Jones,Kerner,Luisoni,Scyboz '19]
  [Heinrich,Jones,Kerner,Scyboz '20] $\Leftarrow$
- **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] $\Leftarrow$

Naive benchmark translation

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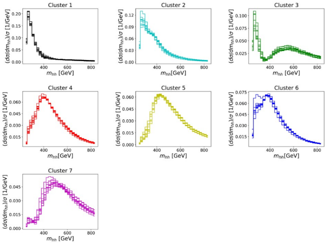
Consider HEFT benchmark points with following characteristic m_{hh} shapes

[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?

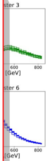
C_{HG} obtained using $\alpha_s(m_Z) = 0.118$

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	-



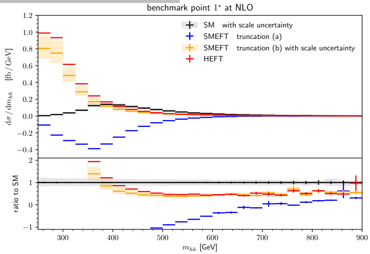
$\Rightarrow$ SMEFT expansion based on $E^2 \frac{C_i}{\Lambda^2} \ll 1$ justified?

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

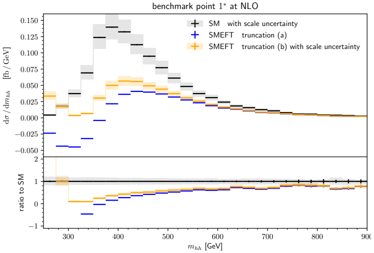
- Benchmark 1*:

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

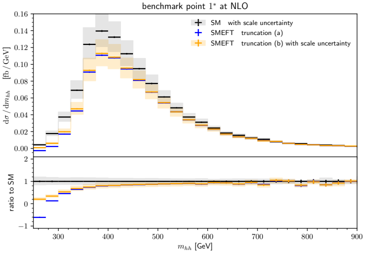
Generated with `ggHH_SMEFT` in `POWHEG-BOX-V2`



$\Lambda = 1$ TeV



$\Lambda = 2$ TeV



$\Lambda = 4$ TeV

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

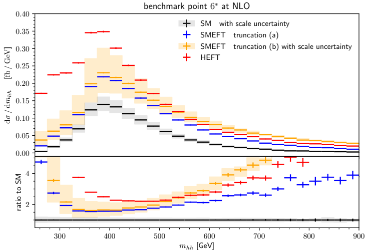
$\Rightarrow$ Valid HEFT point invalid in SMEFT after direct translation

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

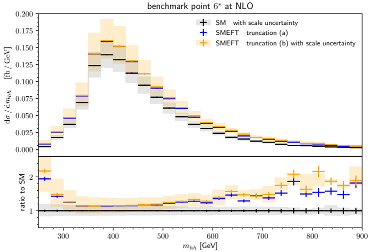
- Benchmark 6^*:

Generated with `ggHH_SMEFT` in `POWHEG-BOX-V2`

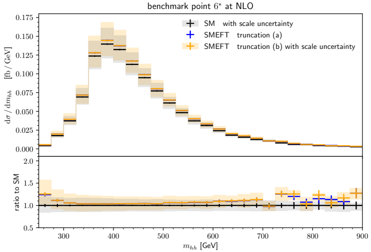
C_{hhh}	C_t	C_{tt}	C_{ggh}	C_{gghh}	$C_{H,\mathrm{kin}}$	C_H	C_{uH}	C_{HG}
-0.684	0.9	$-\frac{1}{6}$	0.5	0.25	0.561	3.80	2.20	0.0387



$\Lambda = 1$ TeV



$\Lambda = 2$ TeV



$\Lambda = 4$ TeV

- No negative cross section
- No shoulder left
- Shape indistinguishable from SM for $\Lambda = 4$ TeV within scale uncertainties

Estimating theory uncertainties

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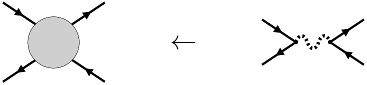
$$\Delta\sigma \sim {}^{+\Delta_{\text{scale}\,+}}_{-\Delta_{\text{scale}\,-}} \quad {}^{+\Delta_{m_t\text{ scheme}\,+}}_{-\Delta_{m_t\text{ scheme}\,-}} \quad \pm \Delta_{\text{num. grid}} \quad (\pm\Delta_{\text{EFT trunc.}}) \quad \pm \Delta_{\text{PDF}+\alpha_s} \quad \pm \Delta_{\text{EW}}$$

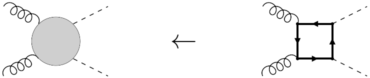
- Δ_{EW}: Full NLO EW unknown, only partial results of top Yukawa [Davies,Mishima,Schönwald,Steinhauser,Zhang '22] [Mühlleitner,Schlenk,Spira '22]
- $\Delta_{\text{PDF}+\alpha_s} \approx 3\%$ ($\sqrt{s} = 13$ TeV): B.I. NNLO HTL and employing `PDF4LHCNNLO` [twiki *hh* cross group] stable for c_{hhh} 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) [Baglio et al '18] [Baglio et al '20] [Baglio et al '20]
- $\Delta_{\text{num. grid}}$: Numerical uncertainty of grids for virtual contribution, not covered by Monte Carlo statistical uncertainty of `POWHEG`!

Loop counting in SMEFT ("weak" UV assumption)

Assuming UV is renormalisable QFT leads to: [Arzt, Einhorn, Wudka '94] [Buchalla, Heinrich, Müller-Salditt, Pandler '22]
(κ generic weak coupling, $d_\chi(\partial, \bar{\psi}\psi, \kappa) = 1$)



VS.



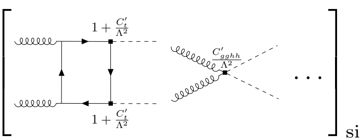
$$\mathcal{O}_{tH} \sim [\kappa^3] \, (\phi^\dagger \phi) \, \bar{q}_L \tilde{\phi} t_R \quad \Rightarrow \frac{C_{tH}}{\Lambda^2} \sim \frac{1}{\Lambda^2}$$

$$\mathcal{O}_{tt} \sim [\kappa^2] \bar{t}_R \gamma_\mu t_R \, \bar{t}_R \gamma^\mu t_R \quad \Rightarrow \frac{C_{tt}}{\Lambda^2} \sim \frac{1}{\Lambda^2} \,,$$

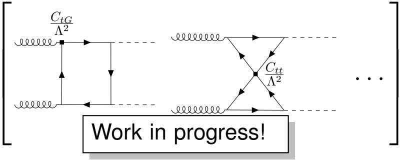
$$\mathcal{O}_{HG} \sim [\kappa^4] \, (\phi^\dagger \phi) \; G^a_{\mu\nu} G^{a\,\mu\nu} \quad \Rightarrow \frac{C_{HG}}{\Lambda^2} \sim \frac{1}{\Lambda^2 \, (16\pi^2)}$$

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

$\Rightarrow$ Chromomagnetic operator enters at same order as 2-loop 4-fermion operator contribution:



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



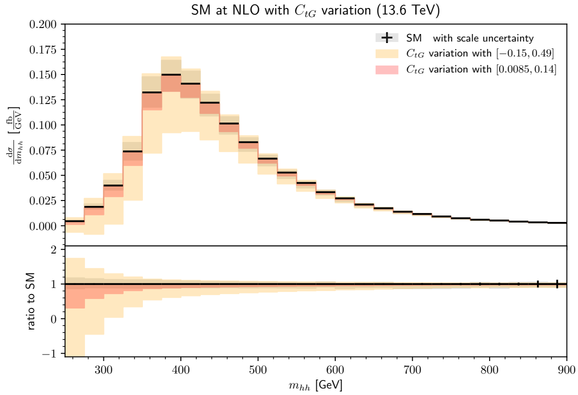
$$\sim \frac{1}{\Lambda^2 (16\pi^2)^2}$$

Effects of chromomagnetic operator (PRELIMINARY)

- SM with C_{tG} variation using $\mathcal{O}\left(\Lambda^{-2}\right)$ constraints from [SMEFiT Collaboration, Ethier et al '21]:

C_{tG}	
individual	marginalised
$g_s\,[0.007, 0.111]$	$g_s\,[-0.127, 0.403]$

- Better constrained by other processes



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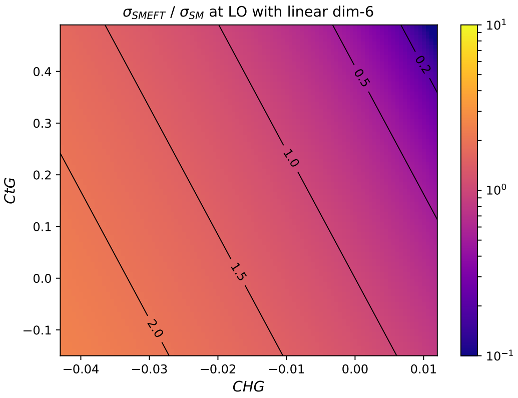

Effects of chromomagnetic operator (PRELIMINARY)

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C_{tG}	
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g_s $[0.007, 0.111]$	g_s $[-0.127, 0.403]$

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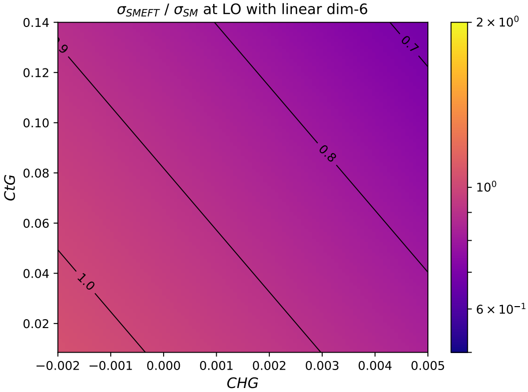


Summary

- Status of SMEFT precision in di-Higgs (ggF)

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

- 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 (expected to be relevant, see e.g. [2212.05067] [2109.02987] . . .)

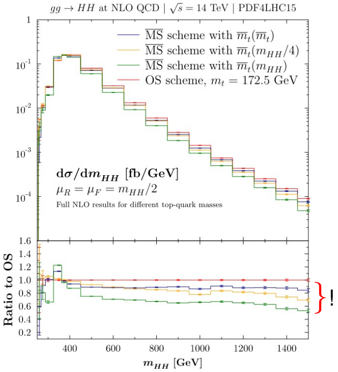
$\Rightarrow$ Further outlook: y_b effects and EW corrections when SM results are available, . . .

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]

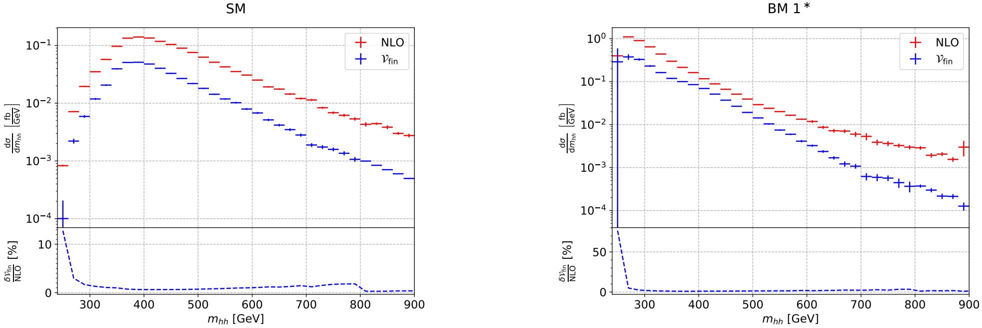
$$\bar{m}_t(m_t) = \frac{m_t}{1 + \frac{4}{3}\frac{\alpha_s(m_t)}{\pi} + K2\left(\frac{\alpha_s(m_t)}{\pi}\right)^2 + K_3\left(\frac{\alpha_s(m_t)}{\pi}\right)^3}$$

- 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

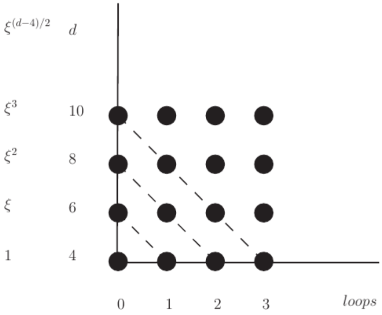
⇒ $\mathcal{O}$ (12 %) uncertainty for SM in first bin not represented by Monte Carlo statistical uncertainty in `POWHEG`

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

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']

Amplitude evaluation in ggHH_SMEFT

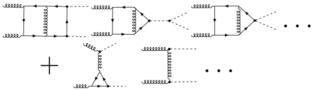
$$\mathcal{M}_{gg\to hh} = \epsilon(p_1)_\mu \epsilon(p_2)_\nu \left(\mathcal{F}_1 \cdot T_1^{\mu\nu} + \mathcal{F}_2 \cdot T_2^{\mu\nu}\right)$$ [Glover,van der Bij '87]

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 ⇒ reweighting

HEFT virtuals are available as function of 23 grids a_i



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

⇒ 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

Virtual grids for ggHH_SMEFT

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

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

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

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

needs to be added.

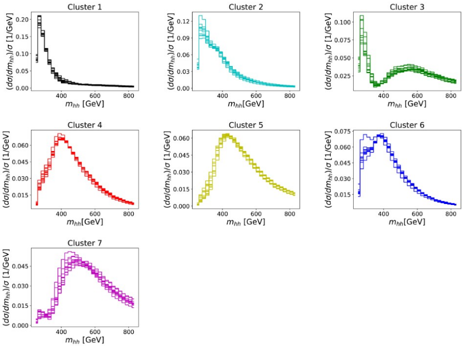
Updated HEFT benchmarks

[https://cds.cern.ch/record/2843280]

Karlsruhe Institute of Technology

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]