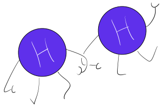
Technical summary of EFT's for Higgs Pairs

Ludovic Scyboz



based on

JHEP 09 (2021) 161	[de Florian, Fabre, Heinrich, Mazzitelli, LS]
2204.13045	[Lang, Heinrich, LS]
(in preparation)	[Alasfar, Cadamuro, Dimitriadi, Ferrari, Gröber, Heinrich, Carlson, Lang, Ördek, Pereira Sanchez, LS]

Royal Society Research Grant (RP/R1/180112)

SMEFT & HEFT overview and available tools

Two different EFT approaches

- SMEFT:
  - $H \equiv \mathrm{SU}(2)_L \times U(1)_Y$ doublet
  - Canonical dimension counting ($\sim 1/\Lambda^n$)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \mathcal{O}(\frac{1}{\Lambda^3})$$

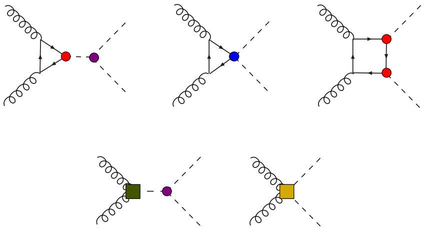
- HEFT:
  - $H \equiv$ EW singlet
  - Chiral dimension counting d_χ ($\equiv$ loop counting)

$$\mathcal{L}_{\mathrm{HEFT}} = \mathcal{L}_{(d_\chi=2)} + \sum_{L=1}^{\infty} \sum_i \left(\frac{1}{16\pi^2}\right)^L c_i^{(L)} O_i^{(L)}$$

- SMEFT:

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

- HEFT:



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

SMEFT	HEFT
⊕ Deviations from SM naturally small	⊕ No *a priori* relations between coefficients
⊕ Popular, minimal, simpler theory	⊕ NLO and NNLO' results available with full top mass
⊕ Straightforward combination with single-Higgs fits	⊕ SMEFT $\subset$ HEFT
⊖ Less general than HEFT	⊖ Some couplings only constrainable in hh

$\rightsquigarrow$ different 'priors' around UV completion

SMEFT	HEFT
⊕ Deviations from SM naturally small	...*riori* relations ... coefficients
⊕ Popular, minimal, ... simpler theory ...	... NNLO' results ...able with full top mass
⊕ Straightforwa... with single-Hig...	SMEFT $\subset$ HEFT
⊖ Less general tha... ...T	⊖ Some couplings only constrainable in hh

→ see Raquel's talk

$\rightsquigarrow$ different 'priors' around UV completion

Available MC tools

HEFT

- LO and NLO $m_t \to \infty$ `HPAIR` [Gröber, Mühlleitner, Spira, Streicher '15]
- Full top-mass dependent NLO QCD corrections to $gg \to hh$ [Borowka et al '16], [Baglio et al '18]
  - ... incorporated within HEFT [Buchalla, Celis, Capozi, Heinrich, LS '18]
  - ... and in `Powheg-BOX-V2/ggHH` [Heinrich, Jones, Kerner, LS '20]
- NNLO' (NLO full-m_t + NNLO $m_t \to \infty$) predictions [de Florian, Fabre, Heinrich, Mazzitelli, LS '21]

SMEFT

- LO and NLO $m_t \to \infty$ `HPAIR` [Gröber, Mühlleitner, Spira, Streicher '15]
- NLO full-m_t available in `Powheg-BOX-V2/ggHH_SMEFT` with various truncation options [Heinrich, Lang, LS '22]

HEFT

- LO and NLO $m_t \to \infty$ `HPAIR` [Gröber, Mühlleitner, Spira, Streicher '15]
- Full top-mass dependent NLO QCD corrections to $gg \to hh$ [Borowka et al '16], [Baglio et al '18]
  - ... incorporated within HEFT [Buchalla, Celis, Capozi, Heinrich, LS '18]
  - ... and in `Powheg-BOX-V2/ggHH` [Heinrich, Jones, Kerner, LS '20]
- NNLO' (NLO full-m_t + NNLO $m_t \to \infty$) predictions [de Florian, Fabre, Heinrich, Mazzitelli, LS '21]

SMEFT

- LO and NLO $m_t \to \infty$ `HPAIR` [Gröber, Mühlleitner, S
- NLO full-m_t available in `Powheg-BOX-V2` various truncation options [Heinric

→ see Jannis Lang's talk

HEFT results for $gg \to hh$ at NNLO' QCD

hh @ NNLO' in HEFT

`POWHEG-BOX-V2/ggHH`

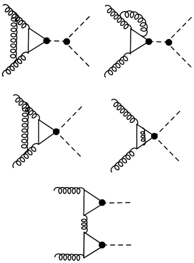
[Heinrich, Jones, Kerner, LS '20]

NLO exact m_t

[Buchalla, Capozi, Celis, Heinrich, LS '18]

NNLO (B.-i.) HTL

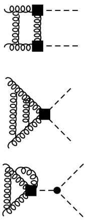
[de Florian, Fabre, Mazzitelli '16]



[de Florian, Fabre, Heinrich, Mazzitelli, LS '21]

Approximate NNLO (NNLO')

(similarly to [Grazzini, Heinrich, Jones et al '18] for SM)



Inclusive results at $\sqrt{s} = 14$ TeV

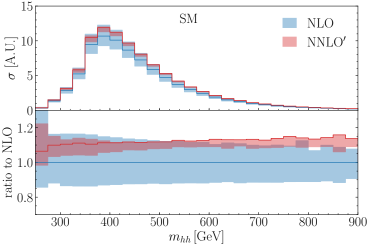
Benchmark points from [Capozi, Heinrich '19]

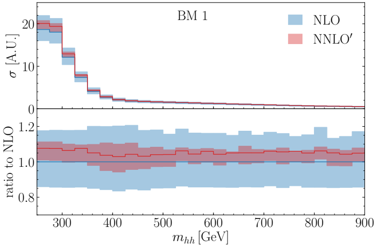
(identified through m_{hh}-shape ML classification at NLO QCD)

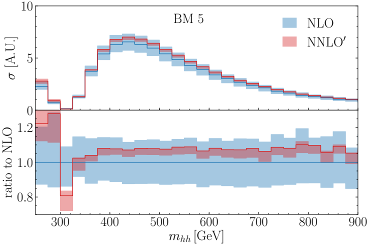
benchmark	c_t	c_{hhh}	c_{tt}	c_{ggh}	c_{gghh}	σ_{NLO} [fb]	$\sigma_{\mathrm{NNLO'}}$ [fb]	K_{NLO}	$K_{\mathrm{NNLO'}}$	ratio to SM
SM	1	1	0	0	0	$32.90^{+14\%}_{-16\%}$	$36.69^{+0.0\%}_{-4.3\%}$	1.66	1.85	1.00
1	0.94	3.94	$-\frac{1}{3}$	0.5	$\frac{1}{3}$	$222.6^{+18\%}_{-14\%}$	$237.2^{+2.7\%}_{-5.4\%}$	1.90	2.03	6.47
2	0.61	6.84	$\frac{1}{3}$	0.0	$-\frac{1}{3}$	$168.1^{+20\%}_{-16\%}$	$191.1^{+7.1\%}_{-8.6\%}$	2.14	2.43	5.21
3	1.05	2.21	$-\frac{1}{3}$	0.5	0.5	$151.9^{+17\%}_{-14\%}$	$159.9^{+2.1\%}_{-5.2\%}$	1.84	1.92	4.36
4	0.61	2.79	$\frac{1}{3}$	-0.5	$\frac{1}{6}$	$63.14^{+20\%}_{-16\%}$	$69.57^{+8.9\%}_{-9.1\%}$	2.14	2.37	1.90
5	1.17	3.95	$-\frac{1}{3}$	$\frac{1}{6}$	-0.5	$154.8^{+14\%}_{-13\%}$	$166.7^{+0.0\%}_{-3.7\%}$	1.64	1.75	4.54
6	0.83	5.68	$\frac{1}{3}$	-0.5	$\frac{1}{3}$	$179.4^{+20\%}_{-16\%}$	$200.1^{+5.9\%}_{-9.3\%}$	2.16	2.41	5.45
7	0.94	-0.10	1	$\frac{1}{6}$	$-\frac{1}{6}$	$131.1^{+22\%}_{-17\%}$	$146.2^{+12\%}_{-11\%}$	2.26	2.54	3.98

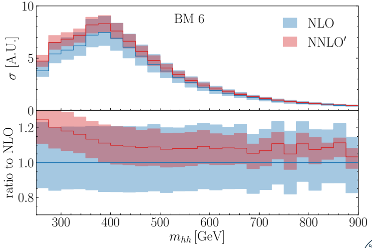
$(K_i = \sigma_i / \sigma_{\mathrm{LO}})$

Results


SM
NLO
NNLO′
σ [A.U.]
ratio to NLO
m_{hh} [GeV]


BM 1
NLO
NNLO′
σ [A.U.]
ratio to NLO
m_{hh} [GeV]


BM 5
NLO
NNLO′
σ [A.U.]
ratio to NLO
m_{hh} [GeV]


BM 6
NLO
NNLO′
σ [A.U.]
ratio to NLO
m_{hh} [GeV]

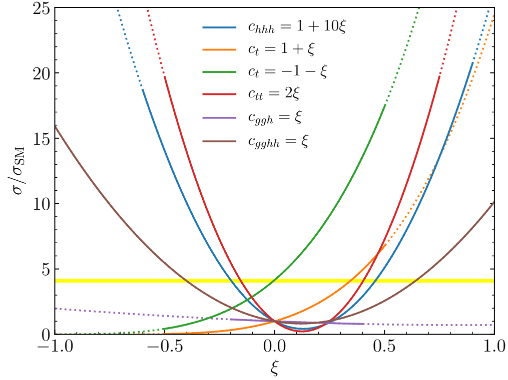
- At NNLO: function of 25 coefficients $a_1, \ldots, a_{25}$

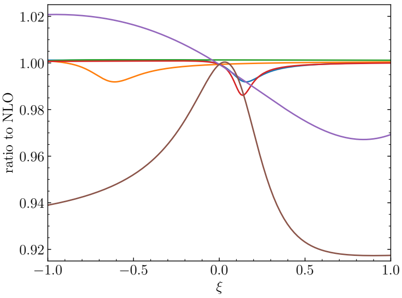
$$\begin{aligned}\sigma_{\rm BSM}/\sigma_{\rm SM} = {} & a_1\, c_t^4 + a_2\, c_{tt}^2 + a_3\, c_t^2 c_{hhh}^2 + a_4\, c_{ggh}^2 c_{hhh}^2 + a_5\, c_{gghh}^2 + a_6\, c_{tt} c_t^2 + a_7\, c_t^3 c_{hhh} \\ & + a_8\, c_{tt} c_t\, c_{hhh} + a_9\, c_{tt} c_{ggh} c_{hhh} + a_{10}\, c_{tt} c_{gghh} + a_{11}\,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

- We give the values of the a_i coefficients, as fitted to our NNLO' results (for $\mu_R = \mu_F = \{\frac{1}{2}, 1, 2\} \cdot \frac{m_{hh}}{2}$) at $\sqrt{s} = 14$ TeV

hh constraints

- yellow: "current" limit on σ [ATLAS-CONF-2021-016]
- solid: allowed range on individual couplings from experiment

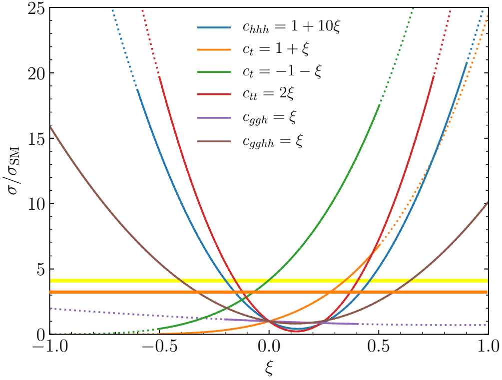


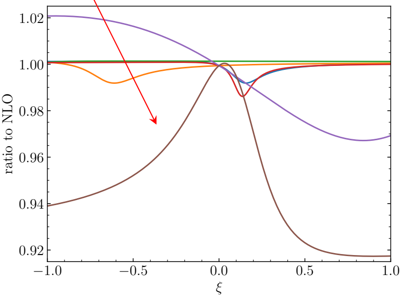


hh constraints

- orange: current limit on σ [ATLAS-CONF-2021-052]
- solid: allowed range on individual couplings from experiment

$\dfrac{\sigma_{\mathrm{NNLO}'}}{\sigma_{\mathrm{NLO}}} \Big/ \dfrac{\sigma_{\mathrm{NNLO}'}}{\sigma_{\mathrm{SM}}} \sim 8\%$





SMEFT results at NLO QCD
(& truncation uncertainties)

- Lagrangian level

$$
\begin{aligned}
\Delta\mathcal{L}_{\text{Warsaw}} = {} & \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) \\
& + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3 + \left(\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L\phi^c t_R + h.c.\right) \\
& + \frac{C_{HG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{\mu\nu,a}
\end{aligned}
$$

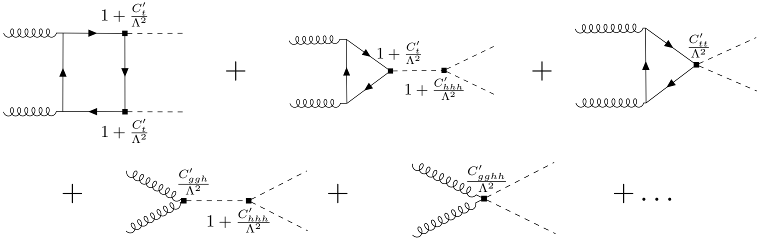
Constructing the cross section

- Lagrangian level

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

- Amplitude-level

$\mathcal{M} =$



$$\mathcal{M} = \underbrace{\mathcal{M}_{\mathrm{SM}}}_{\text{Pure SM}} + \underbrace{\mathcal{M}_{\mathrm{dim}_6}}_{\text{Single-insertion}} + \underbrace{\mathcal{M}_{\mathrm{dim}_6^2}}_{\text{Double-insertion}}$$

▷ At amplitude-squared level:

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

- Compare coefficients at Lagrangian level

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}	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s}\,C_{HG}$
c_{gghh}	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s}\,C_{HG}$

with $C_{H,\text{kin}} := C_{H,\Box} - \frac{1}{4}\,C_{HD}$.

- Implemented in `Powheg-BOX-V2/ggHH_SMEFT` [Heinrich, Lang, LS ’22]

```
! Values of the Higgs couplings using SMEFT (Warsaw) parametrization (Wilson coefficients enter as C/Lambda^2)
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
```

- Implemented in `Powheg-BOX-V2/ggHH_SMEFT` [Heinrich, Lang, LS '22]

```
! Values of the Higgs couplings using SMEFT (Warsaw) parametrization (Wilson coefficients enter as C/Lambda^2)
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
```

Λ

$C_{H,\Box}, C_{HD}, \ldots$

(d)
(c)
(b)
(a)

SMEFT @ NLO with full-m_t

- Implemented in `Powheg-BOX-V2/ggHH_SMEFT` [Heinrich, Lang, LS '22]

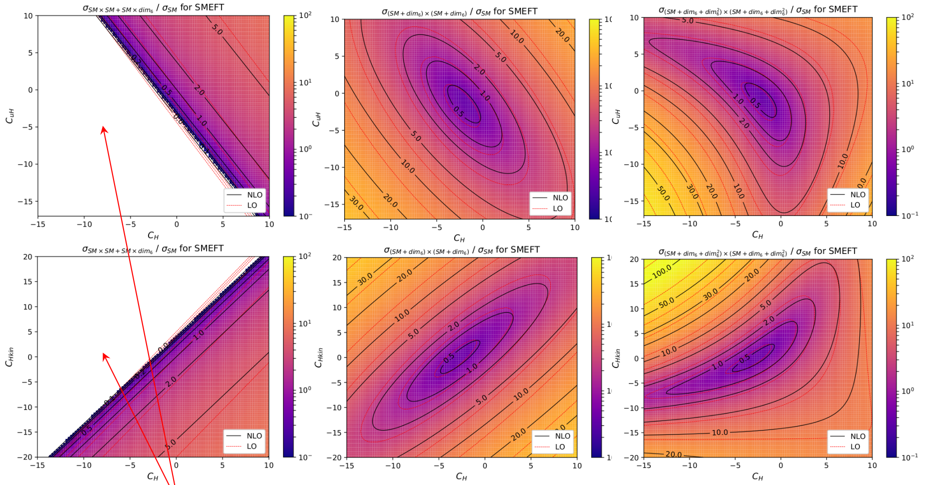
```
! Values of the Higgs couplings using SMEFT (Warsaw) parametrization (Wilson coefficients enter as C/Lambda^2)
Lambda      1.0      ! EFT counting mass Scale (in TeV)
CHbox       0.0      ! Kinetic term of SU(2)_L singlet (with d'Alembert operator)
CHD         0.0      ! second Kinetic term
CH          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
```

NEW

$\rightarrow$ see Jannis's talk on Friday

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

Linear (a) | Quadratic (b) | HEFT-like (d)

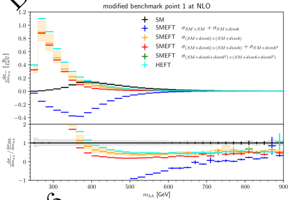


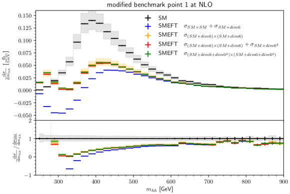
Invalid points in SMEFT!

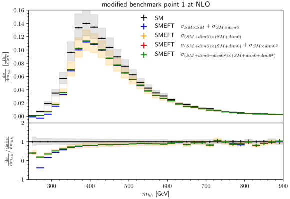
Differential m_{hh} @ 13 TeV

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

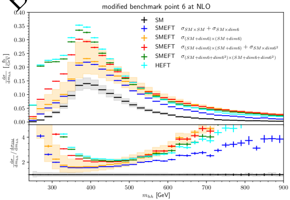
BM 1

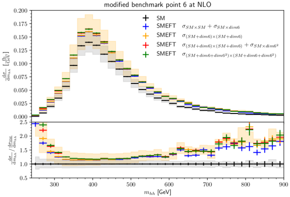


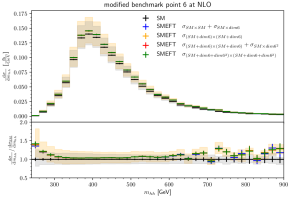




BM 6







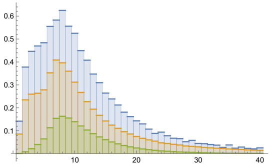
Discussion & new directions

Preliminary results from EFT hh Working group

New benchmark points

- Constraints have tightened since benchmark points were identified in [Heinrich, Capozi '18]
- Updated HEFT m_{hh} benchmarks from the same NLO dataset, reflecting tighter constraints in independent measurements (e.g. $t\bar{t}H$)

benchmark (* = modified)	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	0.25*
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	$\frac{1}{6}$	$-\frac{1}{6}$



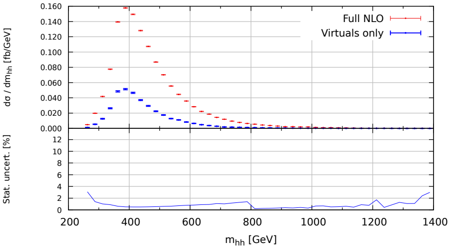
Old BM 6
New BM 6
SM

Statistical uncertainty from numerical grid

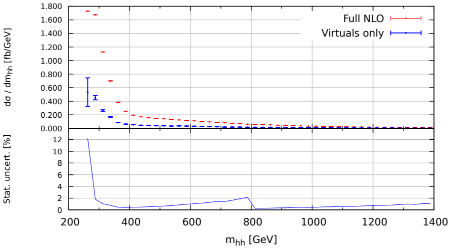
- Uncertainty from full-m_t two-loop virtuals numerical grid (populated to SM m_{hh} distribution)
  - $\lesssim 2\%$ in SM, $\sim 8 - 12\%$ in first m_{hh} bin for some benchmark points

- Limits of the numerical grid show up in HEFT...
- Low-p_t expansion + high-E?

SM



BM 1



MC reweighting

- `ggHH`/`ggHH_SMEFT` integration & event generation is costly ($\sim$ 350 CPU h / BM point)
- Scans in EFT space with dedicated samples not practical...

- $\rightarrow$ Reweight SM sample by differential A_i coefficients

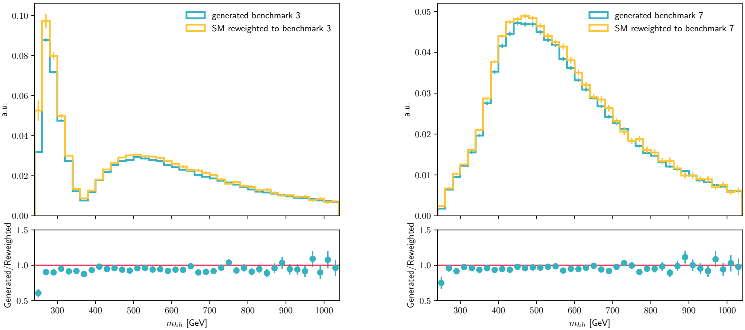
$$
\begin{aligned}
\sigma_{\mathrm{BSM}}/\sigma_{\mathrm{SM}} = {} & a_1\, c_t^4 + a_2\, c_{tt}^2 + a_3\, c_t^2 c_{hhh}^2 + a_4\, c_{ggh}^2 c_{hhh}^2 + a_5\, c_{gghh}^2 + a_6\, c_{tt} c_t^2 + a_7\, c_t^3 c_{hhh} \\
& + a_8\, c_{tt} c_t\, c_{hhh} + a_9\, c_{tt} c_{ggh} c_{hhh} + a_{10}\, c_{tt} c_{gghh}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

MC reweighting

PRELIMINARY

- `ggHH`/`ggHH_SMEFT` integration & event ge[...] is costly (~ 350 CPU h / BM point)
- Scans in EFT space with dedicated samples not pra[...].

- $\rightarrow$ Reweight SM sample by differential A_i coefficients



[Figures from C. Dimitriadi, L. Pereira Sanchez]

- Two different EFT approaches:
  - SMEFT: linear realisation, $H \in$ doublet, Wilson coefficients C_i naturally small
  - HEFT: non-linear, $H \in$ singlet, Wilson coefficients formally $\sim \mathcal{O}(1)$, no relations between e.g. c_{ggh} and c_{gghh}
- hh is a nice playground to study differences between these EFT's (e.g. whether the Higgs sector is realised (non-)linearly)

Tools

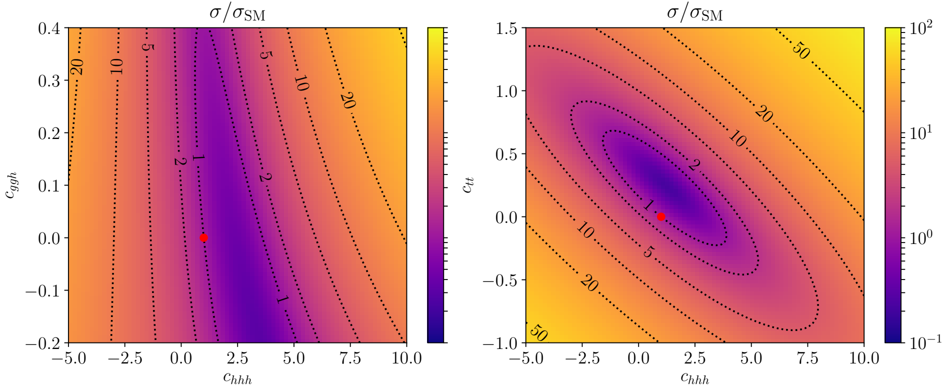
- Multiple tools to investigate higher-order corrections, top-mass effects, truncation uncertainties
  - `HPAIR` (HTL), `ggHH` and `ggHH_SMEFT` (finite m_t), ...

Open questions

- Validity of truncation options, logic of single-parameter limit extractions, fit combinations, ...

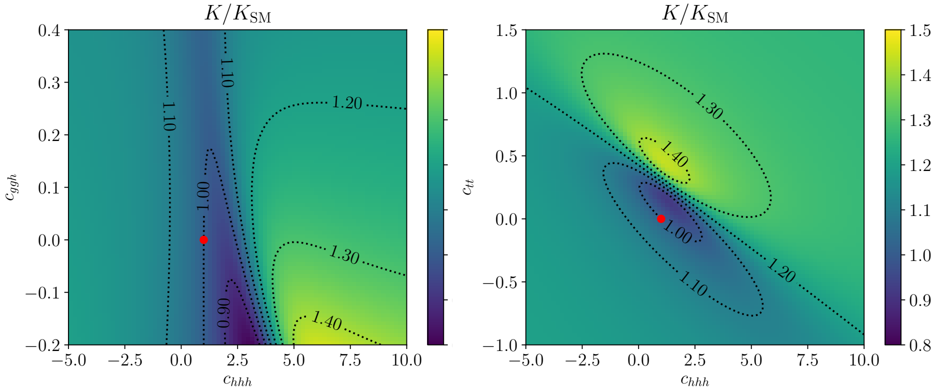
Backup

Coupling scans



K-factors

- $\frac{\sigma^{\rm BSM}_{\rm NNLO}}{\sigma^{\rm BSM}_{\rm LO}} \Big/ \frac{\sigma^{\rm SM}_{\rm NNLO}}{\sigma^{\rm SM}_{\rm LO}} \rightsquigarrow \sim 40\%$ variations depending on coupling values



A_i coefficients @ NNLO' 13 TeV

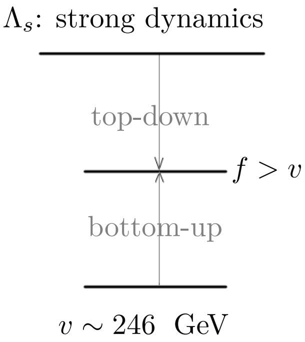
	$\mu_R = \mu_F = \mu_0$	$\mu_R = \mu_F = \mu_0/2$	$\mu_R = \mu_F = 2\mu_0$
a_1	2.2359	2.2899	2.1062
a_2	12.465	13.191	11.469
a_3	0.34254	0.36853	0.31341
a_4	0.32832	0.27278	0.3225
a_5	12.035	12.139	11.435
a_6	-9.6736	-9.967	-9.0278
a_7	-1.5785	-1.6626	-1.4625
a_8	3.4554	3.621	3.2097
a_9	2.8013	2.5608	2.6905
a_{10}	16.173	16.712	15.144
a_{11}	-1.1806	-1.2201	-1.0647
a_{12}	-5.6581	-5.6718	-5.3808
a_{13}	0.63134	0.65511	0.59109
a_{14}	2.7664	2.9025	2.581
a_{15}	2.93	2.9659	2.7499
a_{16}	-0.10785	-0.14072	-0.12683
a_{17}	0.223	0.52954	0.098154
a_{18}	0.065656	0.032461	0.082079
a_{19}	0.18294	0.22852	0.1622
a_{20}	-0.048533	-0.056875	-0.02693
a_{21}	0.12436	0.33443	0.036752
a_{22}	0.027999	0.03496	0.022263
a_{23}	0.21161	0.21764	0.15791
a_{24}	0.00047051	0.00073051	0.00031311
a_{25}	0.00077149	0.00087966	-0.00040697

Can be used at inclusive level for limit extractions!

[de Florian, Fabre, Heinrich, Mazzitelli, LS '21]

EFTs in a nutshell

- Contains dynamic degrees of freedom that one considers important at a given physical scale v
- Systematic way of integrating out DoFs appearing at a higher scale $\Lambda \gg v$
- Mass gap $\rightarrow$ expansion parameter ξ $(= \frac{E}{\Lambda}$ usually, but not obligatorily)
- Not renormalizable
- Non-local particle exchange $\rightarrow$ tower of contact operators



SMEFT from bottom up

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \frac{c_i \mathcal{O}_i^{(n)}}{\Lambda^{n-4}}$$
$$= \mathcal{L}_{\text{SM}} + \sum \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

- $\Delta L = \pm 2$ for $\mathcal{O}^{(5)}$
- $G_{\text{SMEFT}} \supset SU(3)_C \times SU(2)_L \times U(1)_Y$
- Contains the DoFs of the SM
- $\mathcal{L}_{\text{SMEFT}} \to \mathcal{L}_{\text{SM}}$ for $\frac{E}{\Lambda} \to 0$, if no other weakly-coupled, light particles exist
- 2499 CP-even operators **[Grzadkowski et al '10]**

- In particular: unbroken Higgs $\phi \in SU(2)_L$

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

- CP-odd operator $\phi^\dagger\phi\tilde{G}^a_{\mu\nu}G^{a\mu\nu}$ assumed to vanish

Note:

- Operators like $(\phi^\dagger\phi)G^a_{\mu\nu}G^{a\mu\nu}$ (containing the contraction of two field-strength tensors) can only arise through a loop in the UV-completed theory

  $\rightarrow$ respect $\mathcal{O}(\frac{1}{16\pi^2})$ in canonical counting

- Assume strong dynamics at the higher scale $\Lambda_s \gg v$ that couples to the physical Higgs h
  - Higgs portal, MCHM5 $SO(5)/SO(4)$, ...
- Global custodial symmetry $SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$
- Three scales

Scale of strong dynamics	$4\pi f \geq \Lambda_s \gg f$
Char. scale of Goldstone bosons	$f \succeq v$
EW scale	$v \sim 246$ GeV

- Expansion in $\xi = \left(\frac{v}{f}\right)^2$
- SMEFT: $\xi \ll 1$

- To leading order: $\mathcal{L}_2 =$

$$
\begin{aligned}
- &\quad \frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum \bar{\psi} i \not{D} \psi \\
+ &\quad \frac{v^2}{4}\,\langle D_\mu U^\dagger D^\mu U\rangle\,(1+F_U(h)) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) \\
- &\quad v\left[\bar{q}_L\left(Y_u + \sum_{n=1}^{\infty} Y_u^{(n)}\left(\frac{h}{v}\right)^n\right) U P_+ q_R + \bar{q}_L\left(Y_d + \sum_{n=1}^{\infty} Y_d^{(n)}\left(\frac{h}{v}\right)^n\right) U P_- q_R\right. \\
+ &\quad \left.\bar{l}_L\left(Y_e + \sum_{n=1}^{\infty} Y_e^{(n)}\left(\frac{h}{v}\right)^n\right) U P_- l_R + \text{h.c.}\right]
\end{aligned}
$$

$$
\boxed{\begin{aligned} U &\to g_L U g_R^\dagger \\ h &\to h \end{aligned}}
$$

- with the Goldstone matrix

$$
U = \exp\left(\frac{2i}{v}\varphi^a T^a\right)
$$

Power counting in the EWChL

- Order defined by counting of chiral dimensions d_χ, as opposed to canonical dimensions of $1/\Lambda$

$$d_\chi\left(A_\mu, \varphi, h\right) = 0\ , \qquad d_\chi\left(\partial, \bar{\psi}\psi, g_{\text{weak}}, y_{\text{weak}}\right) = 1$$

- Equivalent to counting loop orders:

$$d_\chi = 2L + 2$$