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EFT descriptions of Higgs boson pair production

Annual Meeting of the CRC TRR 257, A1b

Jannis Lang | March 11, 2024

INSTITUTE FOR THEORETICAL PHYSICS

Mainly based on collaborative research works:

[1] JHEP 08 (2022) 079 [Heinrich,JL,Scyboz '22]

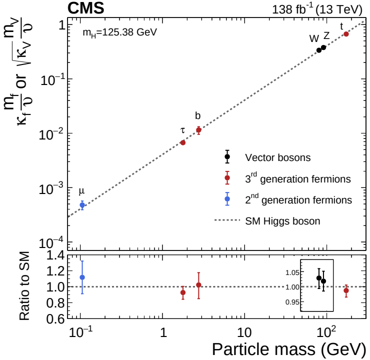
[2] https://arxiv.org/abs/2304.01968 [CERN LHC Higgs WG4 note]

[3] https://arxiv.org/abs/2310.18221 [Di Noi,Gröber,Heinrich,JL,Vitti '23]

[4] https://arxiv.org/abs/2311.15004 [Heinrich,JL '23]

Relevance of *hh* production in an EFT framework

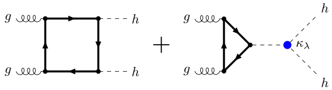
- Impressive experimental results on Higgs couplings!

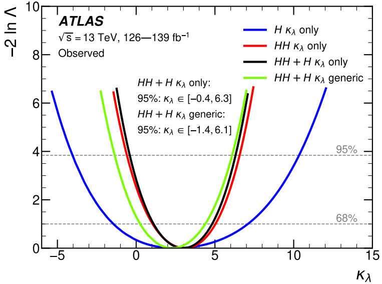


[2207.00043]

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

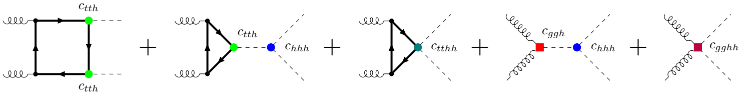
$\Rightarrow$ κ_λ accessible in *hh* production:





[2211.01216]

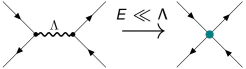
- More consistent approach: Bottom-up EFT (assuming scale separation)



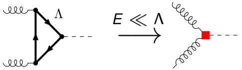
Effective field theory basics

Top-down perspective

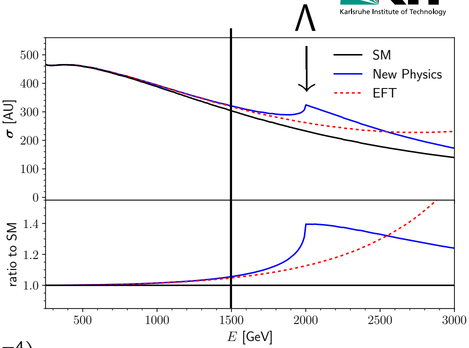
- Effective low-energy description integrating out heavy particles with mass $M \sim \Lambda$
- Example: Fermi theory of weak interaction and heavy top limit



$$\longrightarrow \Delta\mathcal{L} = \frac{C}{\Lambda^2}\bar{\psi}_i\gamma^\mu\psi_j\,\bar{\psi}_k\gamma_\mu\psi_l + \mathcal{O}\left(\Lambda^{-4}\right)$$



$$\longrightarrow \Delta\mathcal{L} = \frac{g_s^2 C'}{(16\pi^2)\Lambda^2}\left(\phi^\dagger\phi\right) G^a_{\mu\nu}G^{a\,\mu\nu} + \mathcal{O}\left(\Lambda^{-4}\right)$$



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

- Standard Model Effective Field Theory (SMEFT)
- Higgs Effective Field Theory (HEFT)

Two bottom-up EFT systematics: SMEFT vs. HEFT

d_c : canonical dimension
$L, \mathbf{L}$: loop factor $(16\pi^2)^{-1}$
g_s : strong coupling

SMEFT:

- Decoupling scenario for $\Lambda \to \infty$: doublet Higgs
- Expansion of contributions according to $\mathcal{O}\left(\Lambda^{-d_c}\,(g_s^2 L)^{l_{\text{QCD}}}\,\mathbf{L}^{l_{\text{non-QCD}}}\right)$

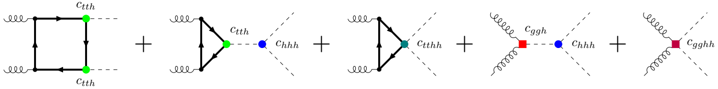
$$\Delta\mathcal{L}_{\text{SMEFT}}^{\text{lead}} = \frac{\mathcal{C}_{H\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{\mathcal{C}_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) + \frac{\mathcal{C}_{H}}{\Lambda^2}(\phi^\dagger\phi)^3 + \frac{\mathcal{C}_{tH}}{\Lambda^2}\left((\phi^\dagger\phi)(\bar{Q}_L t_R\tilde{\phi}) + \text{H.c.}\right) + \frac{\mathcal{C}_{HG}}{\Lambda^2}(\phi^\dagger\phi)\,G^a_{\mu\nu}G^{a\,\mu\nu}$$

HEFT:

- Non-decoupling scenario: singlet Higgs
- Contributions ordered by loop expansion

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

$\mathcal{M}_{\text{HEFT}}^{\text{LO}} =$



Two bottom-up EFT systematics: SMEFT vs. HEFT

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$$+ \frac{\mathcal{C}_{tH}}{\Lambda^2}\left((\phi^\dagger\phi)(\bar{Q}_L t_R\tilde{\phi}) + \text{H.c.}\right) + \frac{\mathcal{C}_{HG}}{\Lambda^2}(\phi^\dagger\phi)\,G^a_{\mu\nu}G^{a\,\mu\nu}$$

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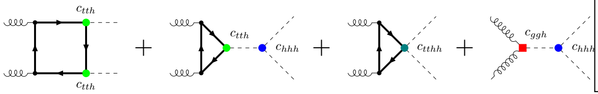
$$\mathcal{M}^{\text{LO}}_{\text{HEFT}} =$$



HEFT	Warsaw
c_{hhh}	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}\mathcal{C}_H + 3\frac{v^2}{\Lambda^2}\mathcal{C}_{H;\,\text{kin}}$
c_{tth}	$1 + \frac{v^2}{\Lambda^2}\mathcal{C}_{H;\,\text{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t}\mathcal{C}_{tH}$
c_{tthh}	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t}\mathcal{C}_{tH} + \frac{v^2}{\Lambda^2}\mathcal{C}_{H;\,\text{kin}}$
c_{ggh}	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s(\mu)}\mathcal{C}_{HG}$
c_{gghh}	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s(\mu)}\mathcal{C}_{HG}$

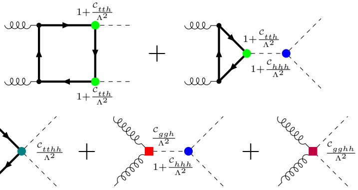
Not generally applicable:

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

SMEFT truncation

SMEFT truncation of amplitude $\left(\frac{\mathcal{C}_i}{\Lambda^2} = c_i - c_{i,sm}\right)$:

$\mathcal{M}^{\text{LO}}_{\text{SMEFT}} =$



$$= \underbrace{\mathcal{M}^{\text{LO}}_{\text{SM}}}_{\mathcal{O}\left((g_s^2 L)\right)} + \underbrace{\mathcal{M}^{\text{LO}}_{\text{dim6}}}_{\mathcal{O}\left(\Lambda^{-2}(g_s^2 L)\right)} + \underbrace{\mathcal{M}^{\text{LO}}_{\text{dim6}^2}}_{\mathcal{O}\left(\Lambda^{-4}(g_s^2 L)\right)}$$

SMEFT truncation of cross section:

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

SMEFT truncation

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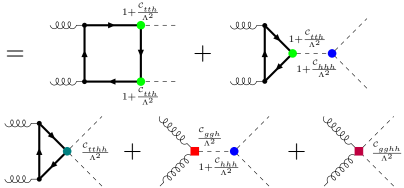
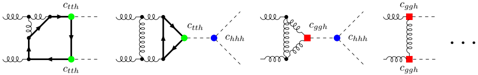
$\mathcal{M}^{\text{LO}}_{\text{SMEFT}} =$



$= \underbrace{\mathcal{M}^{\text{LO}}_{\text{SM}}}_{\mathcal{O}((g_s^2 L))} + \underbrace{\mathcal{M}^{\text{LO}}_{\text{dim6}}}_{\mathcal{O}(\Lambda^{-2}(g_s^2 L))} + \underbrace{\mathcal{M}^{\text{LO}}_{\text{dim6}^2}}_{\mathcal{O}(\Lambda^{-4}(g_s^2 L))}$

⇒ Implemented at NLO QCD in the `POWHEG BOX` translating `ggHH` → `ggHH_SMEFT`:



SMEFT truncation of cross section:

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

Reals: Modified version of 1-loop ME provider `GoSam`

Virtuals: Adjust grids encoding 2-loop corrections

$$\mathcal{V}_{\text{fin}} = \sum a_i \, C_{hhh}^{n_{hhh,i}} \, C_{tth}^{n_{tth,i}} \, C_{tthh}^{n_{tthh,i}} \, C_{ggh}^{n_{ggh,i}} \, C_{gghh}^{n_{gghh,i}}$$

Invariant mass distributions at NLO QCD [1]

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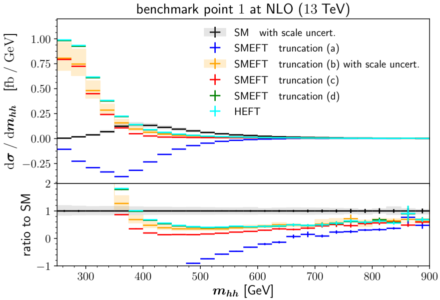
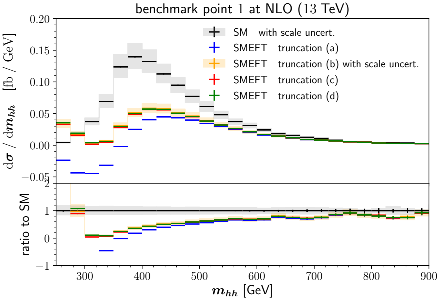
[Capozi, Heinrich '19] [2]

- HEFT benchmark 1: enhanced low-m_{hh} region

c_{hhh}	c_{tth}	c_{tthh}	c_{ggh}	c_{gghh}	$\mathcal{C}_{H;\,kin}$	$\mathcal{C}_{H}$	$\mathcal{C}_{tH}$	$\mathcal{C}_{HG}$	Λ
5.105	1.1	0	0	0	4.95	−6.81	3.28	0	1 TeV



$\Lambda = 1$ TeV



$\Lambda = 2$ TeV

- Truncation (a): negative cross section

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

- Distributions converge for increasing Λ

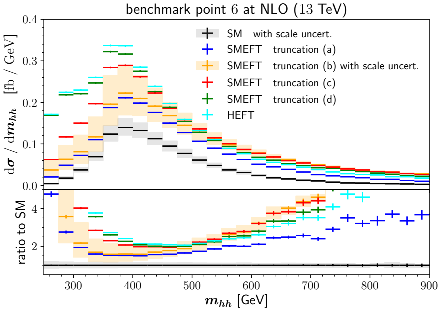
$\Rightarrow$ Consistent with measure for truncation validity

Invariant mass distributions at NLO QCD [1]

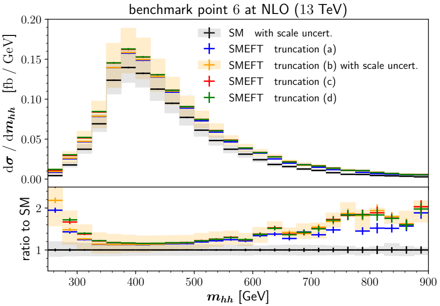
[Capozi, Heinrich '19] [2]

- HEFT benchmark 6: close-by double peaks

c_{hhh}	c_{tth}	c_{tthh}	c_{ggh}	c_{gghh}	$\mathcal{C}_{H;\,\mathrm{kin}}$	$\mathcal{C}_{H}$	$\mathcal{C}_{tH}$	$\mathcal{C}_{HG}$	Λ
-0.684	0.9	$-\frac{1}{6}$	0.5	0.25	0.561	3.80	2.20	0.0387	1 TeV



$\Lambda = 1$ TeV



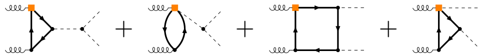
$\Lambda = 2$ TeV

- No negative cross sections
- Typical shape not recovered for SMEFT (except for (d))
- Difference HEFT$\leftrightarrow$(d) mainly from $\alpha_s(\mu)$
- Shapes converge faster for increasing Λ

Amplitude with $\mathcal{C}_{tG}$ and 4-top insertion [4]

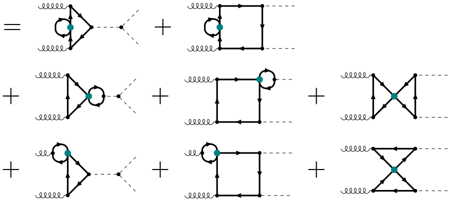
$$\mathcal{L}_{\text{tG}} = \frac{\mathcal{C}_{tG}}{\Lambda^2}\left(\left(\bar{Q}_L \sigma^{\mu\nu} T^a t_R \tilde{\phi}\right) G^a_{\mu\nu} + \text{H.c.}\right)$$

$\mathcal{M}_{\text{tG}} =$



$$\mathcal{L}_{\text{4t}} = \frac{\mathcal{C}^{(1)}_{Qt}}{\Lambda^2}\left(\bar{Q}_L \gamma^\mu Q_L\right) \bar{t}_R \gamma_\mu t_R + \frac{\mathcal{C}^{(8)}_{Qt}}{\Lambda^2}\left(\bar{Q}_L \gamma^\mu T^a Q_L\right) \bar{t}_R \gamma_\mu T^a t_R + \frac{\mathcal{C}^{(1)}_{QQ}}{\Lambda^2}(\ldots) + \frac{\mathcal{C}^{(8)}_{QQ}}{\Lambda^2}(\ldots) + \frac{\mathcal{C}_{tt}}{\Lambda^2}(\ldots)$$

$\mathcal{M}_{\text{4t}} =$



- $\mathcal{M}_{\text{tG}}, \mathcal{M}_{\text{4t}} \sim \mathcal{O}\left((g_s^2 L)\, \mathbf{L}\, \Lambda^{-2}\right)$ subleading w.r.t. $\mathcal{M}^{\text{LO}}_{\text{dim6}} \sim \mathcal{O}\left((g_s^2 L)\, \Lambda^{-2}\right)$
- 4-top contributions factorise in 1-loop structures $\Rightarrow$ Added analytically to `ggHH_SMEFT`
- Cross check with `GoSam` or multi-loop framework `alibrary` (`QGraf`, `FORM`, `Kira`, `pySecDec`)

Amplitude with $\mathcal{C}_{tG}$ and 4-top insertion [3,4]

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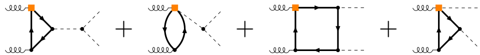
$$\mathcal{L}_{\text{tG}} \sim \frac{\mathcal{C}_{tG}}{\Lambda^2}\,\bar{t}\sigma^{\mu\nu}T^a t\,\frac{h+v}{\sqrt{2}}\,G^a_{\mu\nu}$$

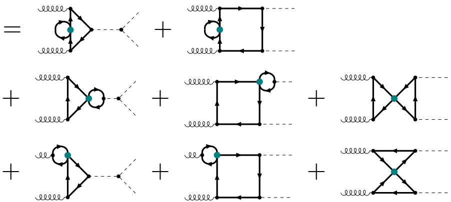
$$\mathcal{M}_{\text{tG}} =$$



Chiral currents!
$\mathbb{P}_{L/R} = (1 \mp \gamma_5)/2$

$$\mathcal{L}_{4\text{t}} \sim \frac{\mathcal{C}^{(1)}_{Qt}}{\Lambda^2}\,\bar{t}\mathbb{P}_R\gamma^\mu\mathbb{P}_L t\,\bar{t}\mathbb{P}_L\gamma_\mu\mathbb{P}_R t + \frac{\mathcal{C}^{(8)}_{Qt}}{\Lambda^2}\,\bar{t}\mathbb{P}_R\gamma^\mu\mathbb{P}_L T^a t\,\bar{t}\mathbb{P}_L\gamma_\mu\mathbb{P}_R T^a t + \frac{\mathcal{C}^{(1)}_{QQ}}{\Lambda^2}(\dots) + \frac{\mathcal{C}^{(8)}_{QQ}}{\Lambda^2}(\dots) + \frac{\mathcal{C}_{tt}}{\Lambda^2}(\dots)$$

$$\mathcal{M}_{4\text{t}} =$$



- $\mathcal{M}_{\text{tG}}, \mathcal{M}_{4\text{t}} \sim \mathcal{O}\left((g_s^2 L)\,\mathbf{L}\,\Lambda^{-2}\right)$ subleading w.r.t. $\mathcal{M}^{\text{LO}}_{\text{dim6}} \sim \mathcal{O}\left((g_s^2 L)\,\Lambda^{-2}\right)$
- 4-top contributions factorise in 1-loop structures $\Rightarrow$ Added analytically to `ggHH_SMEFT`
- Cross check with `GoSam` or multi-loop framework `alibrary` (`QGraf`, `FORM`, `Kira`, pySecDec)
- Study structure of different γ_5 scheme choices in dimensional regularisation

4-top contributions and the γ_5 scheme [3,4]

$\bar{\gamma}_5$ in 4-dim: (1) $\{\bar{\gamma}_5, \bar{\gamma}^\mu\} = 0$ (2) $\mathrm{Tr}\left[\bar{\gamma}^{\mu_1}\bar{\gamma}^{\mu_2}\bar{\gamma}^{\mu_3}\bar{\gamma}^{\mu_4}\bar{\gamma}_5\right] = -4i\,\bar{\epsilon}^{\mu_1\mu_2\mu_3\mu_4}$ (3) $\mathrm{Tr}\left[\Gamma_1\Gamma_2\bar{\gamma}_5\right] = \mathrm{Tr}\left[\Gamma_2\bar{\gamma}_5\Gamma_1\right]$

γ_5 in D-dim: **NDR**: $\{\gamma_5, \gamma^\mu\} = 0$ **BMHV**: $\gamma_5 \equiv \bar{\gamma}_5 = i\gamma^0\gamma^1\gamma^2\gamma^3$

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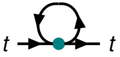
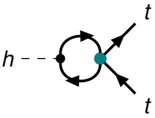
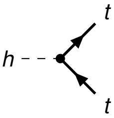


$$= \frac{\mathcal{C}_{Qt}^{(1)} + c_F \mathcal{C}_{Qt}^{(8)}}{\Lambda^2}\left(B_{m_t} + K_{m_t}\right) \times$$

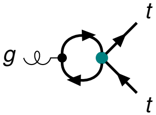
$$K_{m_t} = \begin{cases} -\frac{m_t^2}{8\pi^2} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$



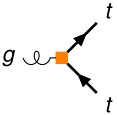
$$= \left(\frac{\mathcal{C}_{Qt}^{(1)} + c_F \mathcal{C}_{Qt}^{(8)}}{\Lambda^2}\right)\left(B_{h\bar{t}t} + K_{m_t} - \frac{v^3}{\sqrt{2}m_t}K_{tH}\right) \times$$



$$K_{tH} = \begin{cases} \frac{\sqrt{2}m_t\left(4m_t^2 - m_h^2\right)}{16\pi^2 v^3} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$



$$= \frac{\mathcal{C}_{Qt}^{(1)} + \left(c_F - \frac{c_A}{2}\right)\mathcal{C}_{Qt}^{(8)}}{\mathcal{C}_{tG}} K_{tG} \times$$



$$K_{tG} = \begin{cases} -\frac{\sqrt{2}m_t g_s}{16\pi^2 v} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$

4-top contributions and the γ_5 scheme [3,4]

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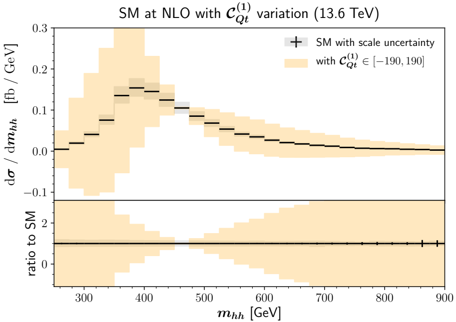
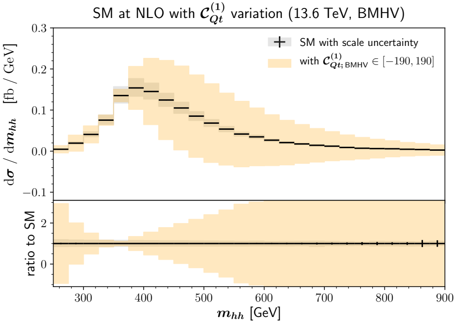


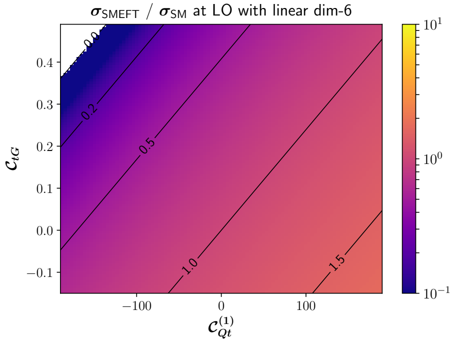


Ranges from $\mathcal{O}\left(\Lambda^{-2}\right)$ marginalised fits of [2105.00006 (SMEFiT collaboration, Ethier et al.)]

- Amplitude structure for single 4-top Wilson coefficients γ_5 scheme dependent

4-top contributions and the γ_5 scheme [3,4]

NDR: $\{\gamma_5, \gamma^\mu\} = 0$



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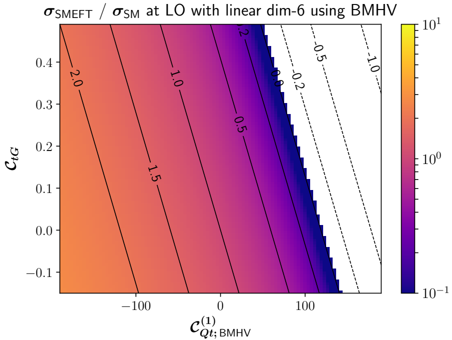

Ranges from $\mathcal{O}(\Lambda^{-2})$ marginalised fits of [2105.00006 (SMEFiT collaboration, Ethier et al.)]

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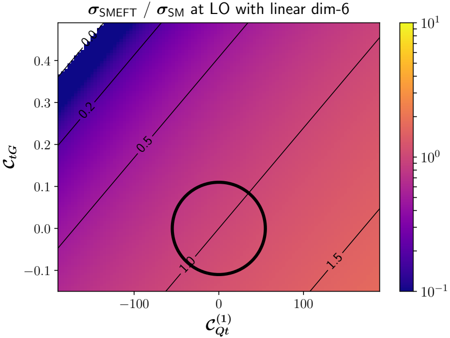

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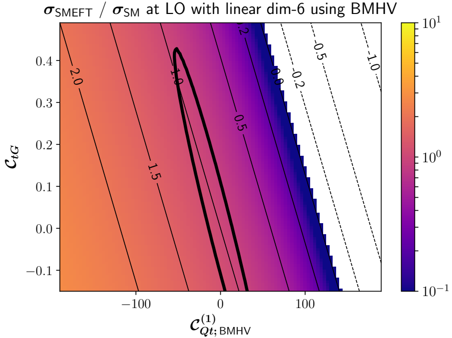

$$C_{tH}^{\mathrm{BMHV}} = C_{tH}^{\mathrm{NDR}} + \frac{\sqrt{2}m_t\left(4m_t^2 - m_h^2\right)}{16\pi^2 v^3}\left(C_{Qt}^{(1)} + c_F C_{Qt}^{(8)}\right)$$

$$C_{tG}^{\mathrm{BMHV}} = C_{tG}^{\mathrm{NDR}} - \frac{\sqrt{2}m_t g_s}{16\pi^2 v}\left(C_{Qt}^{(1)} + \left(c_F - \frac{c_A}{2}\right) C_{Qt}^{(8)}\right)$$

- equivalent parameterisation of new physics

$\Rightarrow$ γ_5 scheme independence requires multi-parameter contributions

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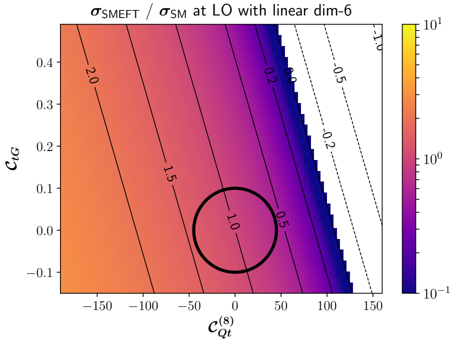

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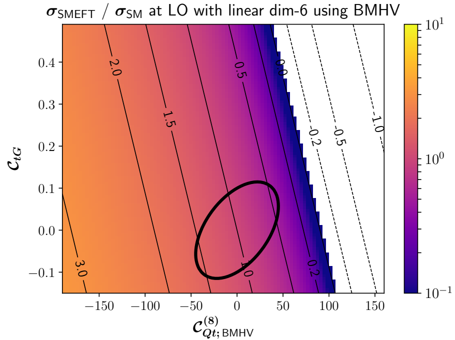

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Summary

- State-of-the-art SMEFT predictions with ggHH_SMEFT:
  (Public and implemented in the POWHEG BOX)

  $\mathcal{C}_H$,$\mathcal{C}_{tH}$,$\mathcal{C}_{HG}$,$\mathcal{C}_{H;\,\text{kin}}$@**NLO QCD**

  $\mathcal{C}_{tG}$ & $\mathcal{C}_{Qt}^{(1)}$,$\mathcal{C}_{Qt}^{(8)}$,$\mathcal{C}_{QQ}^{(1)}$,$\mathcal{C}_{QQ}^{(8)}$,$\mathcal{C}_{tt}$

  truncation options

  γ_5 schemes **NDR** & **BMHV**

- Naive translation from HEFT $\rightarrow$ SMEFT can lead out of validity of Λ^{-2} expansion
- γ_5 scheme independence at higher orders requires inclusive selection of contributions
- $gg \rightarrow h(h)$ can potentially help to improve global fits of $\mathcal{C}_{Qt}^{(1)}$ and $\mathcal{C}_{Qt}^{(8)}$

Future directions

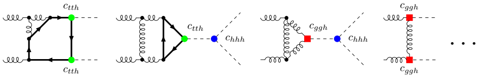
- Scale dependence of Wilson coefficients
- EW corrections required for complete subleading operator contribution
- Exhaustive study of γ_5 schemes in EFTs

Public implementations of EFT tools for $gg \to hh$

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

Higgs Effective Field Theory (HEFT):

- LO and NLO QCD HTL `HPAIR` [Gröber,Mühlleitner,Spira,Streicher '15]
- Full m_t NLO QCD `POWHEG-BOX-V2/ggHH` [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]



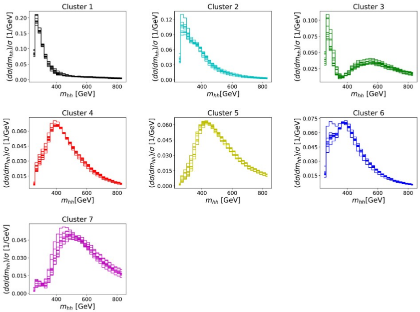
Standard Model Effective Field Theory (SMEFT):

- LO and NLO QCD HTL `HPAIR` [Gröber,Mühlleitner,Spira,Streicher '15]
- LO (1-loop) including $\mathcal{C}_{tG}$ SMEFT@NLO + `MG5_aMC@NLO` [Degrande,Durieux,Maltoni,Mimasu,Vryonidou,Zhang '20]
- Full m_t NLO QCD `POWHEG-BOX-V2/ggHH_SMEFT` with truncation options [1] + $\mathcal{C}_{tG}$ and 4-top [4] ⇐

Naive benchmark translation

Consider HEFT benchmark points
with characteristic m_{hh}-distributions:

- Benchmark 1: enhanced low m_{hh} region
- Benchmark 6: close-by double peaks
- benchmark 3: enhanced low m_{hh} region
  and second local maximum above $m_{hh} \simeq 2m_t$



[Capozi, Heinrich '19]
[2]

benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$\mathcal{C}_{H;\,kin}$	$\mathcal{C}_H$	$\mathcal{C}_{tH}$	$\mathcal{C}_{HG}$	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
3	2.21	1.05	$-\frac{1}{3}$	0.5	0.25^*	13.5	2.64	12.6	0.0387	1 TeV

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

$\mathcal{C}_{HG}$ obtained using $\alpha_s(m_Z) = 0.118$

Naive benchmark translation

Total cross section generated at $\sqrt{s} = 13$ TeV [1]

benchmark	σ_{NLO}[fb] option (b)	σ_{NLO}[fb] option (a)	σ_{NLO}[fb] HEFT
SM	$27.94^{+13.7\%}_{-12.8\%}$	-	-
$\Lambda = 1$ TeV			
1	$71.95^{+20.1\%}_{-15.7\%}$	-57.64	91.62
3	$68.69^{+9.4\%}_{-9.5\%}$	30.15	70.20
6	$70.18^{+18.8\%}_{-15.5\%}$	50.82	87.9
$\Lambda = 2$ TeV			
1	$14.53^{+12.6\%}_{-12.2\%}$	6.44	-
3	$30.80^{+14.4\%}_{-13.6\%}$	28.41	-
6	$34.80^{+16.8\%}_{-14.9\%}$	33.6	-

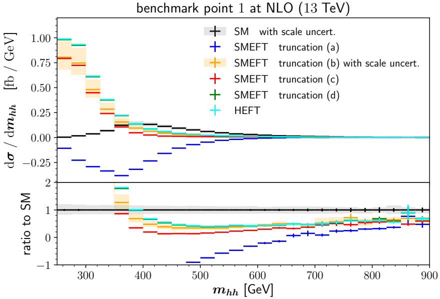
Co
witl
eV
eV
eV
eV
$\Rightarrow$ .118

Invariant mass distributions at NLO QCD [1]

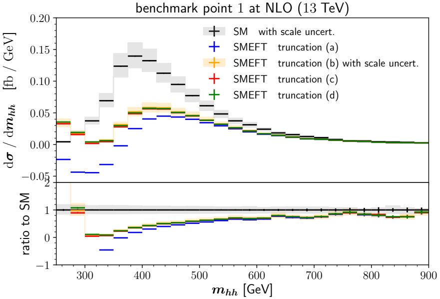
[Capozi, Heinrich '19] [2]

- HEFT benchmark 1: enhanced low-m_{hh} region

C_{hhh}	C_{tth}	C_{tthh}	C_{ggh}	C_{gghh}	$\mathcal{C}_{H;\,\text{kin}}$	$\mathcal{C}_H$	$\mathcal{C}_{tH}$	$\mathcal{C}_{HG}$	Λ
5.105	1.1	0	0	0	4.95	-6.81	3.28	0	1 TeV



$\Lambda = 1$ TeV



$\Lambda = 2$ TeV

- Truncation (a): negative cross section

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

- Distributions converge for increasing Λ

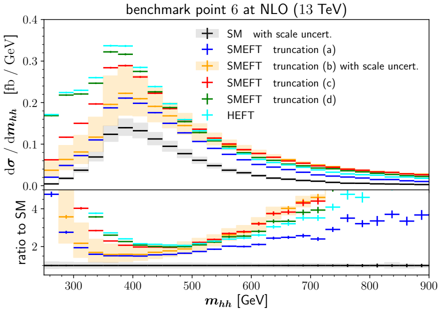
$\Rightarrow$ Consistent with measure for truncation validity

Invariant mass distributions at NLO QCD [1]

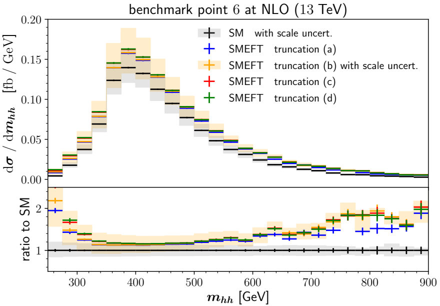
[Capozi, Heinrich '19] [2]

- HEFT benchmark 6: close-by double peaks

c_{hhh}	c_{tth}	c_{tthh}	c_{ggh}	c_{gghh}	$\mathcal{C}_{H;\,\text{kin}}$	$\mathcal{C}_H$	$\mathcal{C}_{tH}$	$\mathcal{C}_{HG}$	Λ
-0.684	0.9	$-\frac{1}{6}$	0.5	0.25	0.561	3.80	2.20	0.0387	1 TeV



$\Lambda = 1$ TeV



$\Lambda = 2$ TeV

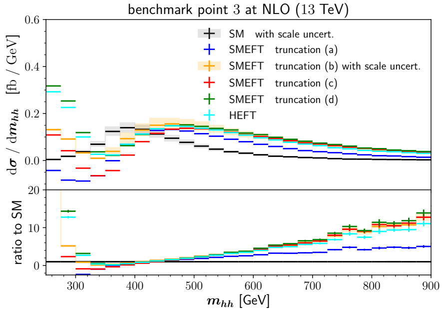
- No negative cross sections
- Typical shape not recovered for SMEFT (except for (d))
- Difference HEFT$\leftrightarrow$(d) mainly from $\alpha_s(\mu)$
- Shapes converge faster for increasing Λ

Invariant mass distributions at NLO QCD [1]

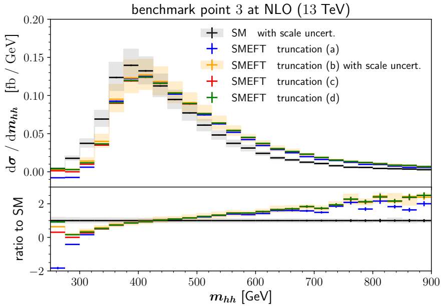
[Capozi, Heinrich '19] [2]

- HEFT benchmark 3: enhanced low-m_{hh} region and 2nd local maximum

c_{hhh}	c_{tth}	c_{tthh}	c_{ggh}	c_{gghh}	$\mathcal{C}_{H;\,kin}$	$\mathcal{C}_H$	$\mathcal{C}_{tH}$	$\mathcal{C}_{HG}$	Λ
-0.684	0.9	$-\frac{1}{6}$	0.5	0.25	0.561	3.80	2.20	0.0387	1 TeV



$\Lambda = 1$ TeV



$\Lambda = 2$ TeV

Estimating theory uncertainties

[Li,Si,Wang,Zhang,Zhao '24]

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

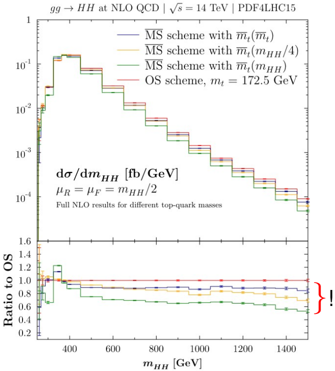
- $\Delta_{\text{scale}\,\pm}$: Determined by 7-point variation of $\mu_R,\ \mu_F = \{0.5,\ 1,\ 2\} \cdot \mu_0$
  $\mathcal{O}(15\%)$ for NLO QCD SM, 15 - 20% for NLO QCD SMEFT truncation (b) benchmark 1& 6
- $\Delta_{m_t\text{ scheme}\,\pm}$: In principle needs determination for each point in EFT parameter space! (not yet available) [Baglio et al '18] [Baglio et al '20] [Baglio et al '20]
- $\Delta_{\text{num. grid}}$: Numerical uncertainty of $\mathcal{V}_{\text{fin}}$ due to grid population, not covered by Monte Carlo statistical uncertainty of `POWHEG`!
- $\Delta_{\text{EFT trunc.}}$: No quantitative prescription, qualitative observation of truncation options
- $\Delta_{\text{PDF}+\alpha_s} \approx 3\%$ ($\sqrt{s} = 13$ TeV): B.I. NNLO HTL and employing `PDF4LHCNNLO` [twiki *hh* cross group]
  stable for c_{hhh} variation, but might rise if tail enhanced
- Δ_{EW}: NLO EW for SM available, 10% effects w.r.t. LO QCD for threshold and tails [Bi,Huang,Ma,Yu '23]
  unknown for EFT scenario, combines with subleading operator contributions!

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]

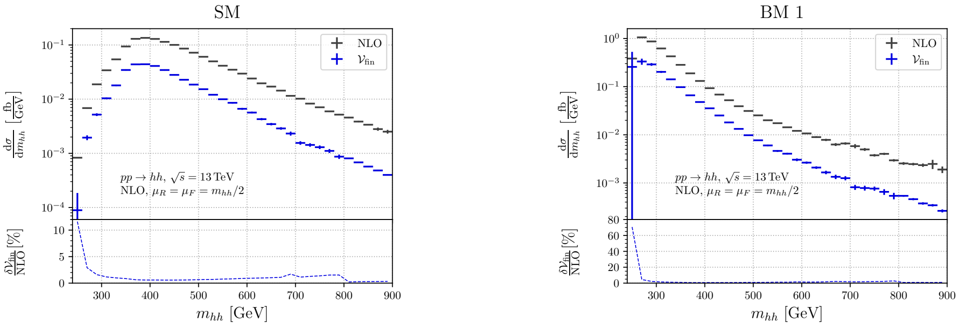
$$\bar{m}_t(m_t) = \frac{m_t}{1 + \frac{4}{3}\frac{\alpha_s(m_t)}{\pi} + K2\left(\frac{\alpha_s(m_t)}{\pi}\right)^2 + K_3\left(\frac{\alpha_s(m_t)}{\pi}\right)^3}$$

- 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



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

Numerical grids uncertainty

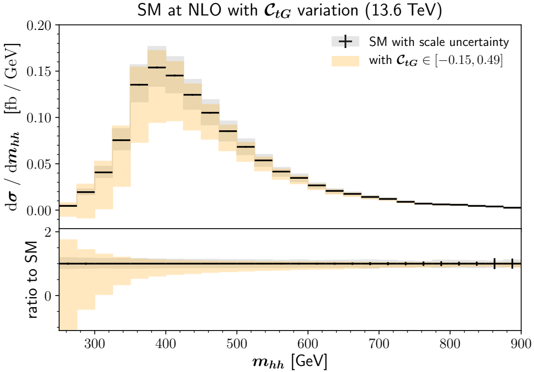


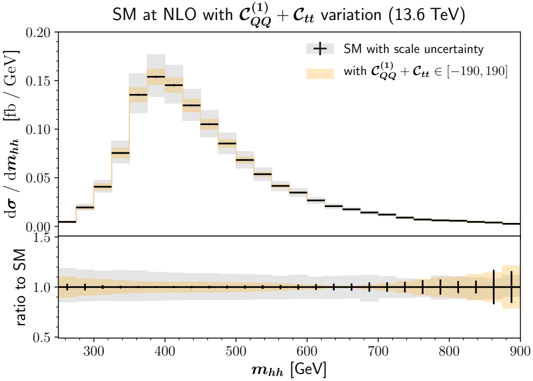
- Low (and high) m_{hh} region very sparsely populated in virtual grids, due to small contribution in SM

$\Rightarrow$ $\mathcal{O}(12\,\%)$ 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

$\mathcal{C}_{tG}$ and irrelevant 4-top contributions [4]





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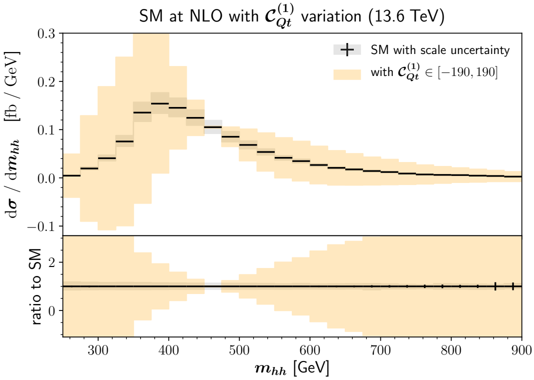

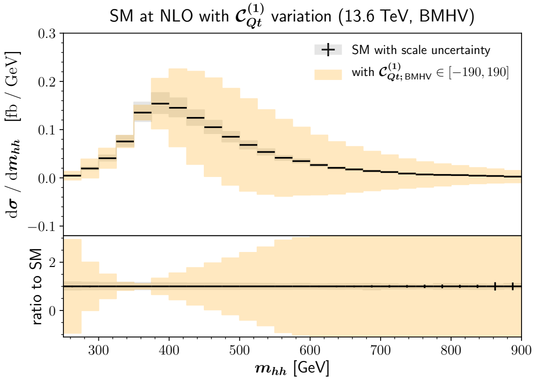

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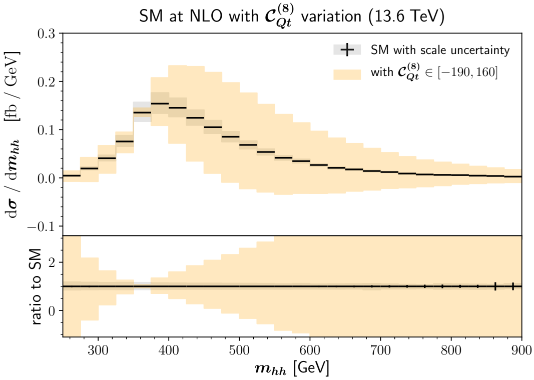

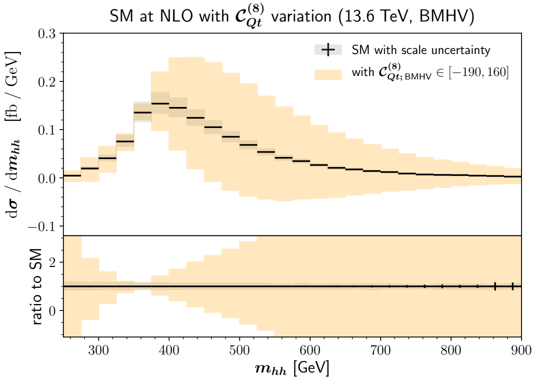

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γ_5 scheme translation

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$$\mathcal{L}_{4t} \supset \frac{\mathcal{C}_{Qt}^{(1)}}{\Lambda^2}(\bar{Q}_L\gamma^\mu Q_L)\,\bar{t}_R\gamma_\mu t_R + \frac{\mathcal{C}_{Qt}^{(8)}}{\Lambda^2}(\bar{Q}_L\gamma^\mu T^a Q_L)\,\bar{t}_R\gamma_\mu T^a t_R$$

$$\mathcal{L}_{\psi 2\phi 2D} \supset \frac{\mathcal{C}_{HQ}^{(1)}}{\Lambda^2}(\phi^\dagger i\overleftrightarrow{D}^\mu\phi)\,\bar{t}_R\gamma_\mu t_R + \frac{\mathcal{C}_{Ht}}{\Lambda^2}(\phi^\dagger i\overleftrightarrow{D}^\mu\phi)(\bar{Q}_L\gamma_\mu Q_L)$$

$$\mathcal{L}_{tG} = \frac{\mathcal{C}_{tG}}{\Lambda^2}\left((\bar{Q}_L\sigma^{\mu\nu}T^a t_R\tilde{\phi})G^a_{\mu\nu} + \text{H.c.}\right)$$

$$\mathcal{L}_{tH} = \frac{\mathcal{C}_{tH}}{\Lambda^2}\left((\phi^\dagger\phi)(\bar{Q}_L t_R\tilde{\phi}) + \text{H.c.}\right)$$

$$y_t^{\text{BMHV}} = y_t^{\text{NDR}}\left(1 - \frac{\lambda v^2}{16\pi^2}\frac{\mathcal{C}_{Qt}^{(1)} + c_F\mathcal{C}_{Qt}^{(8)}}{\Lambda^2} - \frac{\lambda v^2}{32\pi^2}\frac{\mathcal{C}_{HQ}^{(1)} - \mathcal{C}_{Ht}}{\Lambda^2} + \dots\right)$$

$$\mathcal{C}_{tH}^{\text{BMHV}} = \mathcal{C}_{tH}^{\text{NDR}} + \frac{y_t(y_t^2-\lambda)}{8\pi^2}\left(\mathcal{C}_{Qt}^{(1)} + c_F\mathcal{C}_{Qt}^{(8)}\right) - \frac{y_t(y_t^2+3\lambda)}{48\pi^2}\left(\mathcal{C}_{HQ}^{(1)} - \mathcal{C}_{Ht}\right) + \dots$$

$$\mathcal{C}_{tG}^{\text{BMHV}} = \mathcal{C}_{tG}^{\text{NDR}} - \frac{g_s y_t}{16\pi^2}\left(\mathcal{C}_{Qt}^{(1)} + \left(c_F - \frac{c_A}{2}\right)\mathcal{C}_{Qt}^{(8)}\right) + \frac{g_s y_t}{48\pi^2}\left(\mathcal{C}_{HQ}^{(1)} - \mathcal{C}_{Ht}\right) + \dots$$

More details about HEFT

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HEFT:

- Non-linear theory (EWχL)
- Motivation as analogue to chiral pert. theory
- BSM: can be strongly coupling New Physics
- Light Higgs is EW gauge singlet
- Goldstone matrix transforms non-trivially

$$D_\mu h = \partial_\mu h$$

$$U(x) \to g_L(x) U(x) g_Y^\dagger(x)\,, \qquad \text{with } U = \exp\left(i\sigma^a \varphi^a / v\right) \text{ and } g_L \in SU(2)_L,\ g_Y \in U(1)_Y \subset SU(2)_R$$

$$D_\mu U = \partial_\mu U + igW_\mu^i T_L^i U - ig' B_\mu U T_R^3$$

- 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)

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

More details about HEFT

HEFT:

- Explicit form of LO Lagrangian:

$$\mathcal{L}_{HEFT}^{LO} = \mathcal{L}_4 + \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle \left(1 + F_U(h)\right) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) - v\left[\bar{q}_L \left(\hat{Y}_u + F_{\hat{Y}_u^{(n)}}(h)\right) U \begin{pmatrix} u_R \\ 0 \end{pmatrix} \cdots + \mathrm{h.c.}\right]$$

with $F_i(h) = \sum_{n=1}^{\infty} f_i^{(n)} \left(\frac{h}{v}\right)^n$

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

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

$\mathcal{M}_{\text{HEFT}}^{\text{LO}} =$