Theoretical status: HH in the SM & EFT's

Ludovic Scyboz

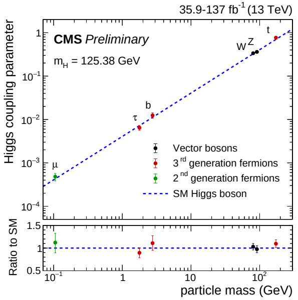
Royal Society Research Grant (RP/R1/180112)

Higgs 2022, Pisa, Nov 11$^{\text{th}}$ 2022

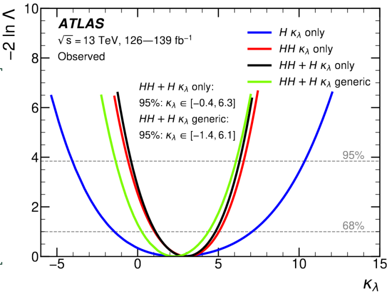
Why measure Higgs pair production?

The Higgs potential

- Impressive experimental results on Higgs couplings!



[CMS-PAS-HIG-19-006]



[ATLAS 2211.01216]

- $V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$

- EW symmetry breaking (in the SM: $\mu^2 = \lambda v^2, m_H = 2\lambda v^2$)

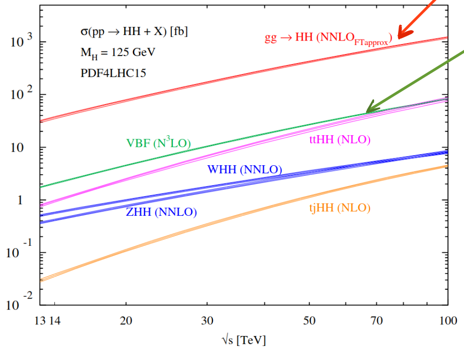
$$\to V(H) = \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

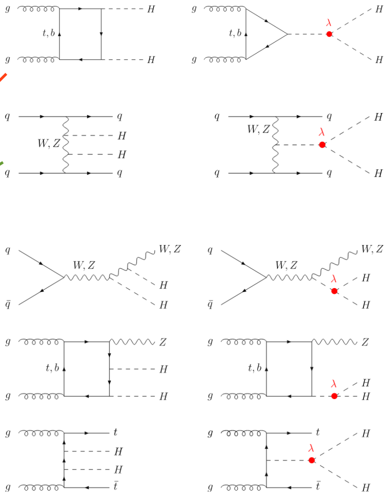
- SM: Higgs self-couplings are fixed by m_H and v

LHC production channels

$$\sigma(pp \to HH) \sim 30\,\text{fb at } \sqrt{s} = 14 \text{ TeV!}$$

(Large destructive interference)





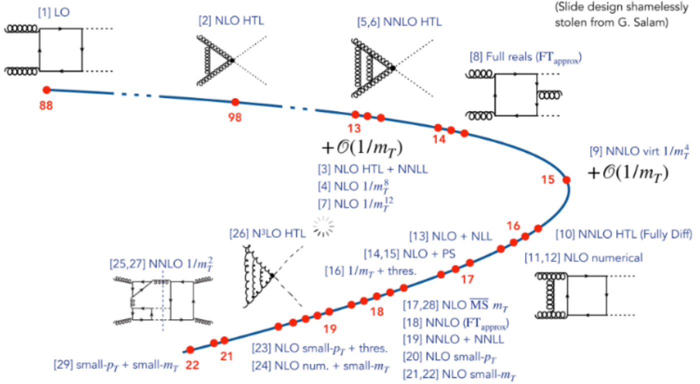
[Reviews in Physics 5 (2020) 100045]

SM: gg fusion

Borrowed from M. Spira

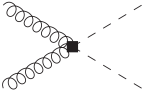
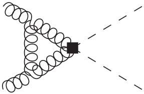
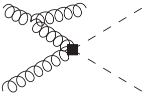
An approximate history (30 years in 30 seconds)

(Slide design shamelessly stolen from G. Salam)



[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22;

The Heavy-Top Limit (HTL)

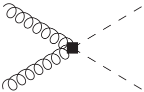
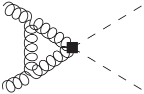
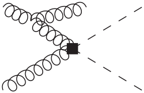
	$\mathcal{M}_B$	$\mathcal{M}_V$	$\mathcal{M}_R$
HTL $(m_t \to \infty)$ [Dawson, Dittmaier, Spira '98]			

The Heavy-Top Limit (HTL)

$$F = \frac{\mathrm{d}\sigma_B^{\mathrm{FT}}}{\mathrm{d}\sigma_B^{\mathrm{HTL}}}$$

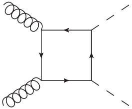
$\mathcal{M}_B$ $\mathcal{M}_V$ $\mathcal{M}_R$

HTL
$(m_t \to \infty)$

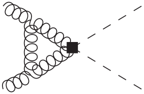
B.-i. HTL

[DDS '98]

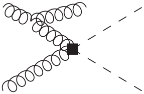


[Glover, van der Bij '88]

$F\times$



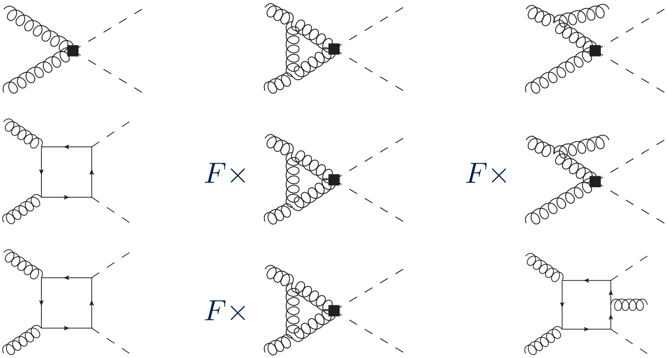
$F\times$



The Heavy-Top Limit (HTL)

$$\boxed{F = \frac{\mathrm{d}\sigma_B^{\mathrm{FT}}}{\mathrm{d}\sigma_B^{\mathrm{HTL}}}}$$

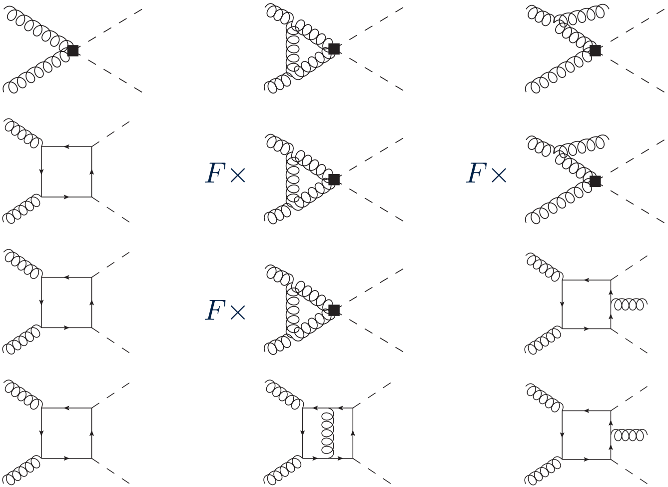
	$\mathcal{M}_B$	$\mathcal{M}_V$	$\mathcal{M}_R$
HTL ($m_t \to \infty$)			
B.-i. HTL		$F\times$	$F\times$
$\mathrm{FT}_{\mathrm{approx}}$ [Maltoni, Vryonidou, Zaro '14]		$F\times$	



The Heavy-Top Limit (HTL)

$$\boxed{F = \frac{\mathrm{d}\sigma_B^{\mathrm{FT}}}{\mathrm{d}\sigma_B^{\mathrm{HTL}}}}$$

	$\mathcal{M}_B$	$\mathcal{M}_V$	$\mathcal{M}_R$
HTL ($m_t \to \infty$)			
B.-i. HTL		$F\times$	$F\times$
$\mathrm{FT}_{\mathrm{approx}}$		$F\times$	
Full theory			

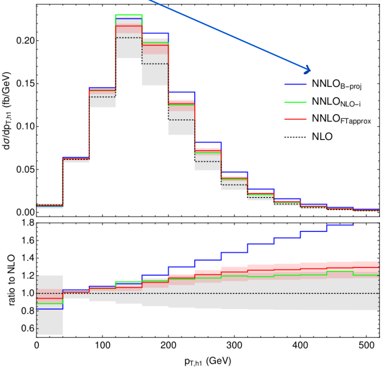


[Borowka et al. ’16]
[Baglio et al. ’18, ’20]

Top-mass effects [Grazzini et al. '18]

- NLO_{m_t} + NNLO ($m_t \to \infty$)
- + NNLL [de Florian, Mazzitelli '18]
- With 3 different approximations to the m_t-effects

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\text{NLO}_{\text{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\text{NNLO}_{\text{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
$\text{NNLO}_{\text{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
$\text{NNLO}_{\text{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. $\text{NNLO}_{\text{FTapprox}}$	±2.6%	±2.7%	±3.4%	±4.6%
$\text{NNLO}_{\text{FTapprox}}$/NLO	1.118	1.116	1.096	1.067

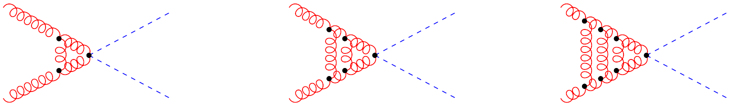


HTL at higher-order

- $m_t \to \infty$: integrate out top-quark DOFs & match to SM

  [Spira '16], [Gerlach, Herren, Steinhauser '18]

- Range of validity: $250\,\mathrm{GeV} = 2m_H < \sqrt{\hat{s}} \ll 2m_t \sim 350\,\mathrm{GeV}$
- Reduces the number of internal scales $\rightsquigarrow$ easier integrals



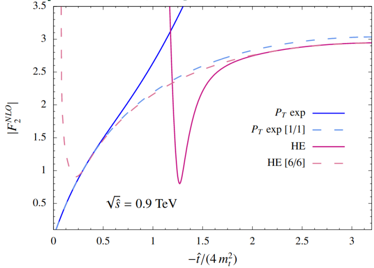
[Dawson, Dittmaier, Spira '98] [de Florian, Mazzitelli '13] [Chen, Li, Shao, Wang '20]

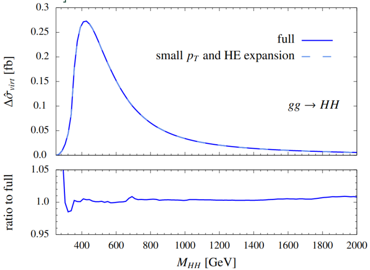
Kinematic expansions

- $\frac{1}{m_t}$: valid when $\sqrt{\hat{s}} < 2 \cdot m_t$ [Davies et al. '18, '21]
- High-E, $m_H \ll m_t \ll \hat{s}, |\hat{t}|$: $\sqrt{s} \gtrsim 800$ GeV [Davies et al. '18]
- Small-p_t^H: $\sqrt{s} \lesssim 750$ GeV [Bonciani et al. '18]
- Large-m_t, and top threshold expansion via Padé ansatz: $\sqrt{s} \lesssim 700$ GeV [Gröber, Maier, Rauh '18]

- Small-p_T and high-E expansions with Padé approximants

[Bellafronte, Degrassi, Giardino, Gröber, Vitti '22]





→ see talk by L. Bellafronte

HTL N^{3}LO [Chen, Li, Shao, Wang '20]

Ingredients:

- N^{3}LO single Higgs

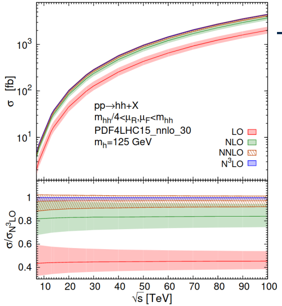
  [Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15]

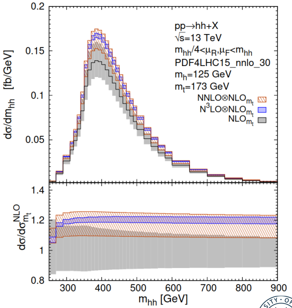
- + 2-loop 4-point functions

  [Banerjee, Borowka, Dhani, Gehrmann, Ravindran '18]

- Good perturbative convergence
- PDF uncertainty > scale uncertainty

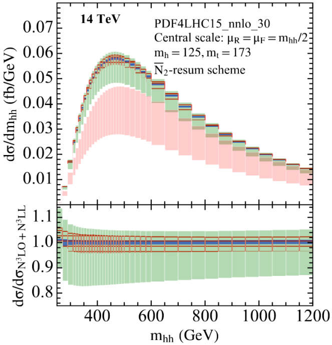
Order \ $\sqrt{s}$	13 TeV	14 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$
N^{3}LO	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$

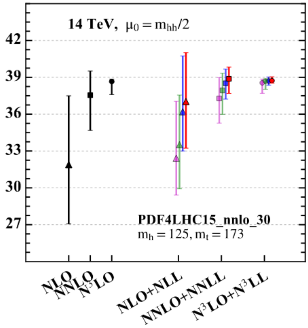




Matched N^{3}LO + N^{3}LL [Aijath, Shao '22]

- Threshold resummation at N^{3}LL matched to N^{3}LO calculation by [Chen, Li, Shao, Wang '20]
- Scale uncertainty below %-level
- m_b effects?



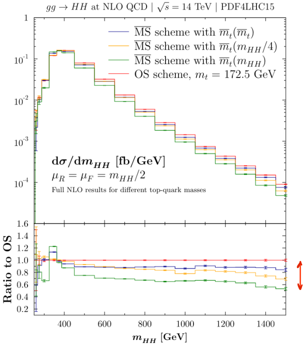


$\sqrt{s}$	13 TeV	14 TeV
NLO$_{m_t}$	$27.56^{+13.9\%}_{-12.7\%}$	$32.64^{+13.5\%}_{-12.47\%}$
(NNLO + NNLL) $\otimes$ NLO$_{m_t}$	$33.33^{+3.0\%}_{-3.3\%}$	$39.42^{+3.0\%}_{-3.4\%}$
N^{3}LO $\otimes$ NLO$_{m_t}$	$33.43^{+0.50\%}_{-2.8\%}$	$39.56^{+0.50\%}_{-2.7\%}$
(N^{3}LO + N^{3}LL) $\otimes$ NLO$_{m_t}$	$33.47^{+0.88\%}_{-0.85\%}$	$39.60^{+0.85\%}_{-0.87\%}$

- As scale and $\mathcal{O}(1/m_t^2)$ uncertainties are going down, we might need to worry about other sources

$$\overline{m}_t = \frac{m_t}{1+\frac{4}{3}\frac{\alpha_s(m_t)}{\pi}+K_2\left(\frac{\alpha_s(m_t)}{\pi}\right)^2+K_3\left(\frac{\alpha_s(m_t)}{\pi}\right)^3}$$

[Baglio et al. '18, '20]

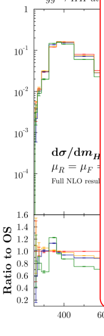


$$\begin{aligned}
\kappa_\lambda = -10: &\quad \sigma_{tot} = 1438(1)^{+10\%}_{-6\%}\ \text{fb},\\
\kappa_\lambda = -5: &\quad \sigma_{tot} = 512.8(3)^{+10\%}_{-7\%}\ \text{fb},\\
\kappa_\lambda = -1: &\quad \sigma_{tot} = 113.66(7)^{+8\%}_{-9\%}\ \text{fb},\\
\kappa_\lambda = 0: &\quad \sigma_{tot}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

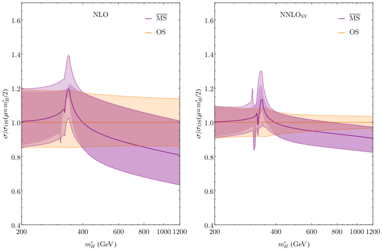
m_t-scheme uncertainty

- As scale and $\mathcal{O}(1/m_t^2)$ uncertainties are going down, we might need to worry about other sources

[Baglio e



[Mazzitelli '22]



NNLO (soft-virtual approximation)

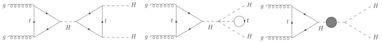
$\longleftarrow$ single off-shell H^*

$$\Delta\sigma^{HH}_{\mathrm{LO}} \sim +33\% - 30\% \; (+6.3\% - 11\%) \, ,$$
$$\Delta\sigma^{HH}_{\mathrm{NLO}} \sim +19\% - 20\% \; (+3.9\% - 6.3\%) \, ,$$
$$\Delta\sigma^{HH}_{\mathrm{NNLO}} \sim +7.7\% - 10\% \; (+2.2\% - 3.1\%) \, ,$$

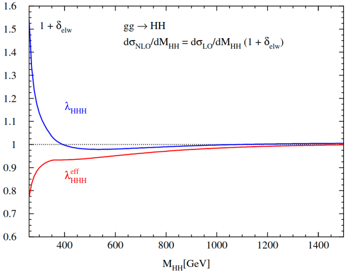
$\longleftarrow$ HH estimate

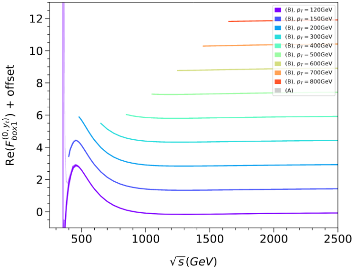
EW corrections

- Nice progress (N^3LO HTL) in QCD, but what about EW corrections?
- Single (off-shell) H: $\delta_{EW} \sim 5\%$



- Top-Yukawa induced EW corrections to HH investigated [Mühlleitner, Schlenk, Spira '22]
- Leading 2-loop Yukawa corrections [Davies, Mishima, Schönwald, Steinhauser, Zhang '22]

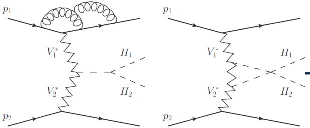




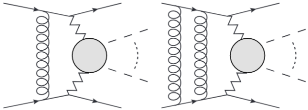
→ see talks by M. Spira, H. Zhang

SM: VBF production

VBF: state-of-the-art



- VBF probes c_{HHH}, c_{2V} and c_V
- Typically computed in the DIS approximation
  - NLO: non-factorisable $\equiv 0$ by colour conservation
  - NNLO: $\mathcal{O}\left(\frac{1}{N_C^2}\right)$-suppressed contribution ($\times\pi^2$ Glauber)

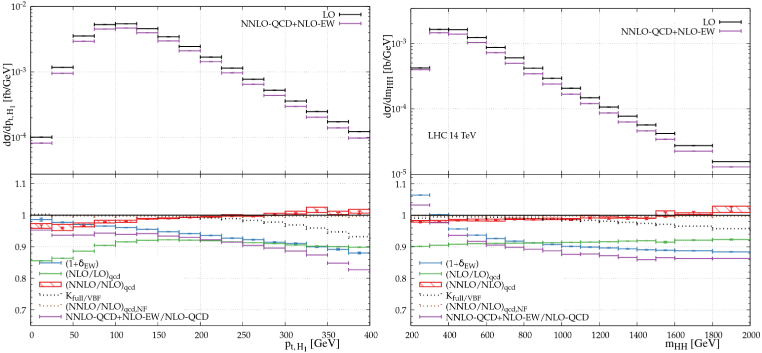


- Inclusive N^{3}LO QCD [Dreyer, Karlberg '18]
- Fully-differential NNLO QCD [Dreyer, Karlberg '18] + NLO EW

[Dreyer, Karlberg, Lang, Pellen '20]

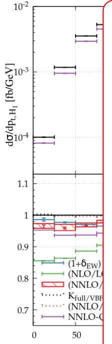
$\sigma_{\mathrm{LO}}^{\mathrm{full}}$	$\delta_{\mathrm{NLO\ QCD}}^{\mathrm{full}}$	$\delta_{\mathrm{NNLO\ QCD}}^{\mathrm{VBF}}$	$\delta_{\mathrm{NLO\ EW}}^{\mathrm{full}}$	$\sigma_{\mathrm{NNLO\ QCD}\times\mathrm{NLO\ EW}}$	$\delta_{\mathrm{NNLO\ QCD}}^{\mathrm{NF}}$ [fb]
$0.78444(9)^{+0.0825}_{-0.0694}$	$-0.07110(13)$	$-0.0115(5)$	$-0.0476(2)$	$0.6684(5)^{+0.002}_{-0.0004}$	$-0.001766(7)$
$^{+10.5\%}_{-8.8\%}$	-9.1%	-1.5%	-6.1%	$-14.8\%^{+0.3\%}_{-0.06\%}$	-0.23%

- NNLO QCD implemented in public MC: `proVBFHH` [Cacciari, Dreyer, Karlberg, Salam, Zanderighi, (Tancredi)]



[Dreyer, Karlberg, Lang, Pellen '20]

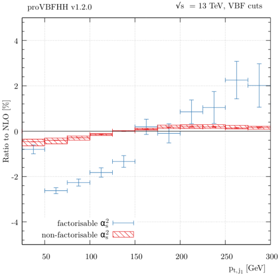
- NNLO QCD implemented in public MC: `proVBFHH` [Cacciari, Dreyer, Karlberg, Salam, Zanderighi, (Tancredi)]

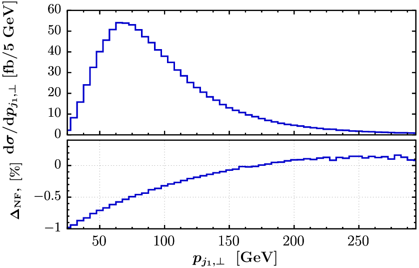


[Dreyer

Non-factorisable contributions in the eikonal approximation

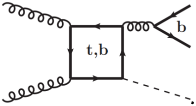
$\rightarrow$ effect of $\mathcal{O}(-0.5\%)$ inclusively





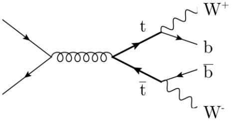
[Dreyer, Karlberg, Tancredi '20, '22] [Liu, Melnikov, Penin '19]

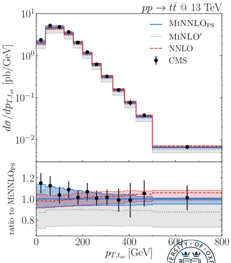
HH backgrounds



- $b\bar{b}H$
  - Included at LO (in ggF NNLOPS) [ATLAS 2112.11876] with additional 100% uncertainty
  - NLO QCD corrections (HTL) [Deutschmann, Maltoni, Wiesemann, Zaro '18]
  - Complete NLO (QCD&EW) corrections known [Pagani, Shao, Zaro '20]
  - Amplitudes for $b\bar{b}H$ in the 5FS known at NNLO [Badger, Hartanto, Krys, Zoia '21]

- $t\bar{t}$ $(W^+W^-b\bar{b})$
  - Typically simulated at NLO QCD (`Powheg`): large theory uncertainty
  - MiNNLO$_{\text{PS}}$ [Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi '21]





HH in Effective Field Theories

- 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)

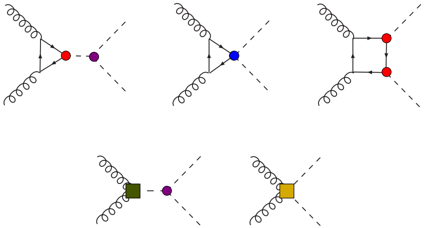
$$\mathcal{L}_{\mathrm{HEFT}} = \mathcal{L}_{(d_\chi=2)} + \sum_{L=1}^{\infty}\sum_i \left(\frac{1}{16\pi^2}\right)^L c_i^{(L)} O_i^{(L)}$$

- SMEFT:

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

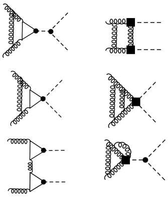
- HEFT:

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

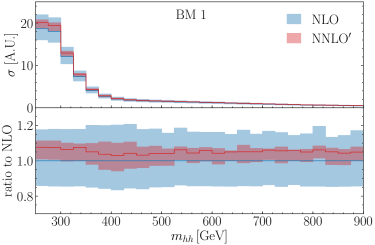


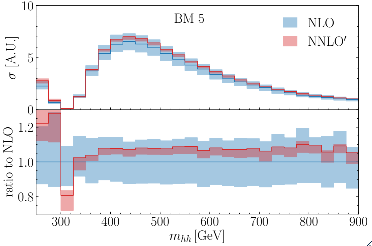
HEFT NNLO' QCD [de Florian, Fabre, Heinrich, Mazzitelli, LS '21]

- NLO_{m_t} [Borowka et al. '16],[Buchalla, Capozi, Celis, Heinrich, LS '18] $+$ NNLO $(m_t \to \infty)$ [de Florian, Fabre, Mazzitelli '16]



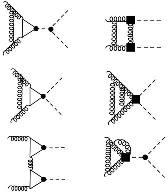
$$\begin{aligned}\sigma_{\text{BSM}}/\sigma_{\text{SM}} = {} & a_1\, c_t^4 + a_2\, c_{tt}^2 + a_3\, c_t^2 c_{hhh}^2 + a_4\, c_{ggh}^2 c_{hhh}^2 + a_5\, c_{gghh}^2 + a_6\, c_{tt} c_t^2 + a_7\, c_t^3 c_{hhh} \\ & + a_8\, c_{tt} c_t\, c_{hhh} + a_9\, c_{tt} c_{ggh} c_{hhh} + a_{10}\, c_{tt} c_{gghh} + a_{11}\,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



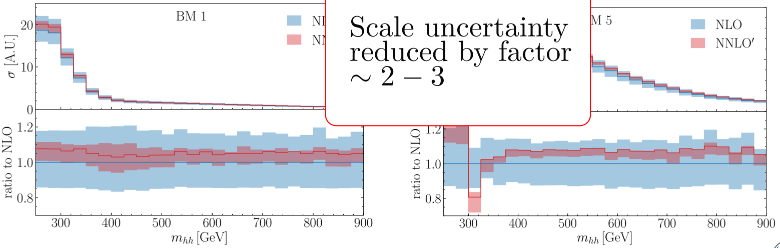


HEFT NNLO' QCD [de Florian, Fabre, Heinrich, Mazzitelli, LS '21]

- NLO$_{m_t}$ [Borowka et al. '16],[Buchalla, Capozi, Celis, Heinrich, LS '18] $+$ NNLO $(m_t \to \infty)$ [de Florian, Fabre, Mazzitelli '16]

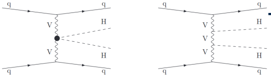


$$\begin{aligned}\sigma_{\mathrm{BSM}}/\sigma_{\mathrm{SM}} = {} & a_1\, c_t^4 + a_2\, c_{tt}^2 + a_3\, c_t^2 c_{hhh}^2 + a_4\, c_{ggh}^2 c_{hhh}^2 + a_5\, c_{gghh}^2 + a_6\, c_{tt} c_t^2 + a_7\, c_t^3 c_{hhh} \\ & + a_8\, c_{tt} c_t\, c_{hhh} + a_9\, c_{tt} c_{ggh} c_{hhh} + a_{10}\, c_{tt} c_{gghh}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

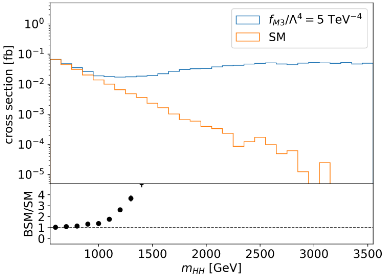


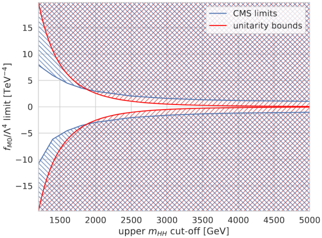
Scale uncertainty reduced by factor $\sim 2-3$

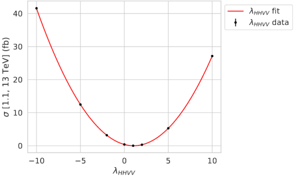
Dim-8 operators for HH [Cappati, Covarelli, Torrielli, Zaro '22]

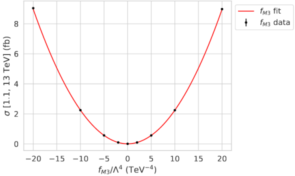


- Investigation of constraints on dimension-8 operators in VBF, ZHH (and $gg \to VVH$)
- `aMC@NLO` at LO QCD



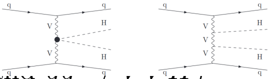




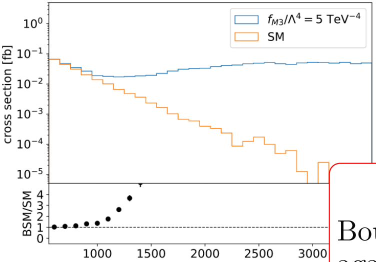


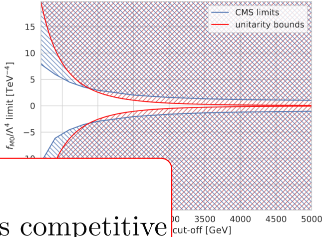
$\to$ see talk by A. Cappatti

Dim-8 operators for HH [Cappati, Covarelli, Torrielli, Zaro '22]

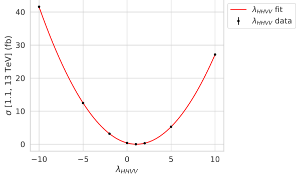


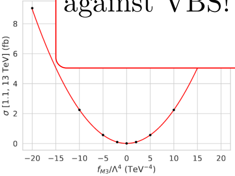
- Investigation of constraints on dimension-8 operators in VBF, ZHH (a
- `aMC@NLO` at LO QCD





Bounds competitive against VBS!

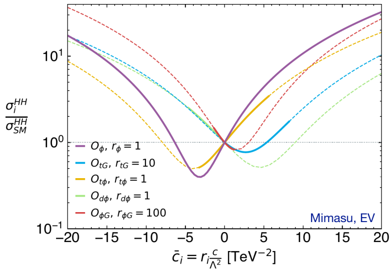


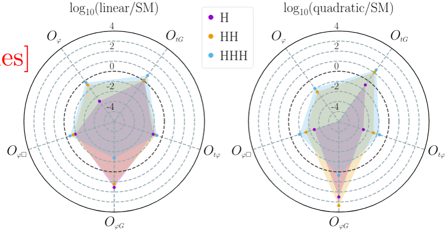


→ see talk by A. Cappatti

- Automated NLO SMEFT implementation (not limited to HH)
- Dimension-6 operators (Warsaw basis)
- Interface to `MadGraph` [Alwall et al. '14]

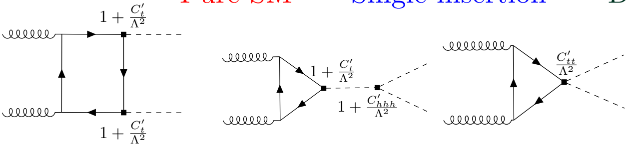
[Taken from E. Vryonidou's slides]





Interplay of multiple operators: need for global fits

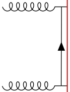
$$\mathcal{M} = \underbrace{\mathcal{M}_{\text{SM}}}_{\text{Pure SM}} + \underbrace{\mathcal{M}_{\text{dim}_6}}_{\text{Single-insertion}} + \underbrace{\mathcal{M}_{\text{dim}_6^2}}_{\text{Double-insertion}}$$

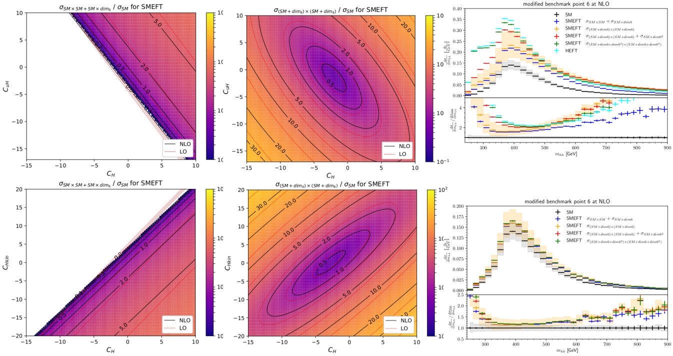


$+ \ldots$

▷ At amplitude-squared level:

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

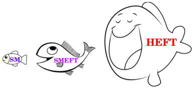




→ see talk by J. Lang

$$\sigma_{(SM+dim6)\times(SM+dim6)} + \sigma_{SM\times dim6^2} \quad (c)$$

$$\sigma_{(SM+dim6+dim6^2)\times(SM+dim6+dim6^2)} \quad (d)$$



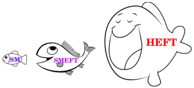
[Gomez-Ambrosio, Llanes-Estrada, Salas-Bernardez, Sanz-Cillero '22]

- Flare function

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \frac{1}{2}\mathcal{F}(h)\partial_\mu w^i \partial^\mu w^j \left(\delta_{ij} + \frac{w_i w_j}{v^2 - w^2}\right)$$
$$\mathcal{F}(h) = 1 + \sum a_n \left(\frac{h}{v}\right)^n$$

$$\mathcal{L}_{\rm SMEFT} = \frac{v^2}{4}\mathcal{F}(h_1)\langle D_\mu U^\dagger D^\mu U\rangle + \frac{1}{2}(\partial_\mu h_1)^2 - V(h) - \frac{c_{H\Box}((v+h_1)^3 - v^3))}{3\Lambda^2}V'(h_1)$$
$$\mathcal{F}(h_1) = 1 + \left(\frac{h_1}{v}\right)\left(2 + 2\frac{c_{H\Box}v^2}{\Lambda^2}\right) + \ldots + \left(\frac{h_1}{v}\right)^4\left(2\frac{c_{H\Box}v^2}{3\Lambda^2}\right)$$

- With correlations between flare function coefficients
- Connection to geometry: scalar loop corrections $\sim$ curvature of the scalar manifold metric [Guo et al. '15],[Alonso et al. '16]



[Gomez-Ambrosio, Llanes-Estrada, Salas-Bernardez, Sanz-Cillero '22]

- Flare function

$\mathcal{L}$

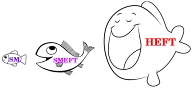
$$\mathcal{L}_{\rm SMEFT} = \underbrace{|\partial H|^2}_{=\mathcal{L}_{\rm SM}} + \underbrace{\frac{1}{2}\left[\frac{8|H|^2}{v^2}\left((\mathcal{F}^{-1})'\,(2|H|^2/v^2)\right)^2 - 1\right]\frac{(\partial|H|^2)^2}{2|H|^2}}_{=\Delta\mathcal{L}_{\rm BSM}}$$

Possible non-analyticity

Correlations accurate at order Λ^{-2}	Correlations accurate at order Λ^{-4}	Λ^{-4} Assuming SMEFT perturbativity
$\Delta a_2 = 2\Delta a_1$		$\lvert\Delta a_2\rvert \leq 5\lvert\Delta a_1\rvert$
$a_3 = \frac{4}{3}\Delta a_1$	$(a_3 - \frac{4}{3}\Delta a_1) = \frac{8}{3}(\Delta a_2 - 2\Delta a_1) - \frac{1}{3}(\Delta a_1)^2$	
$a_4 = \frac{1}{3}\Delta a_1$	$(a_4 - \frac{1}{3}\Delta a_1) = \frac{5}{3}\Delta a_1 - 2\Delta a_2 + \frac{7}{4}a_3 =$	those for a_3, a_4, a_5, a_6
	$= \frac{8}{3}(\Delta a_2 - 2\Delta a_1) - \frac{7}{12}(\Delta a_1)^2$	
$a_5 = 0$	$a_5 = \frac{8}{5}\Delta a_1 - \frac{22}{15}\Delta a_2 + a_3 =$	all the same
	$= \frac{6}{5}(\Delta a_2 - 2\Delta a_1) - \frac{1}{3}(\Delta a_1)^2$	
$a_6 = 0$ SMEFT	$a_6 = \frac{1}{6}a_5$ SMEFT	SMEFT

$\mathcal{L}_{\rm SMEFT}$ ... $V'(h_1)$

- Wit
- Con ... the scal



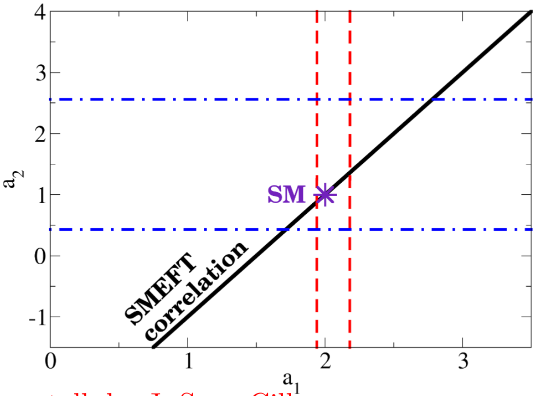
[Gomez-Ambrosio, Llanes-Estrada, Salas-Bernardez, Sanz-Cillero '22]

- Flare function

$\mathcal{L}$

$\mathcal{L}_{\mathrm{SMEFT}}$ ... $V'(h_1)$

- Wit
- Con ... the scal



→ see talk by J. Sanz-Cillero

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]
- SMEFT@NLO & `MG5_aMC@NLO` [Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang '20]
- NLO full-m_t available in `Powheg-BOX-V2/ggHH_SMEFT` with various truncation options [Heinrich, Lang, LS '22]

PRELIMINARY

Upcoming Pub-Note [Alasfar, Cadamuro, Dimitriadi, Ferrari, Gröber, Heinrich, Carlson, Lang, Sjölin, Ördek, Sánchez, LS, 22xx.xxxxx]

- Updated BMs from [Heinrich, Capozi '18]
- Review of uncertainty sources
- Set of NLO (full-m_t) A_i coefficients (incl. and diff.) w. full correlations, and scale variations
- Speed-up of event generation by reweighting SM samples

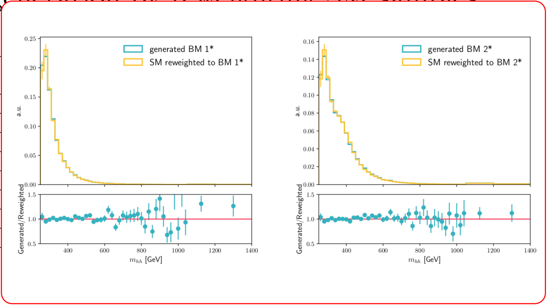
benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1*	5.105	1.1	0	0	0
2*	6.842	1.033	$\frac{1}{6}$	$-\frac{1}{3}$	0
3*	2.21	1.05	$-\frac{1}{3}$	0.5	0.25*
4*	2.79	0.9	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$
6*	−0.684	0.9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

PRELIMINARY

Upcoming Pub-Note [Alasfar, Cadamuro, Dimitriadi, Ferrari, Gröber, Heinrich, Carlson, Lang, Sjölin, Ördek, Sánchez, LS, 22xx.xxxxx]

- Updated BMs from [Heinrich, Capozi '18]
- Review of uncertainty sources
- Set of NLO (full-m_t) A_i coefficients (incl. and diff.) w. full correlations, and scale variations
- Speed-up of event generation by reweighting SM samples

benchmark (* = modified)	c_{hhh}	c_t	c_{tt}
SM	1	1	0
1*	5.105	1.1	0
2*	6.842	1.033	$\frac{1}{6}$
3*	2.21	1.05	$-\frac{1}{3}$
4*	2.79	0.9	$-\frac{1}{6}$
5	3.95	1.17	$-\frac{1}{3}$
6*	−0.684	0.9	$-\frac{1}{6}$
7	−0.10	0.94	1



BSM medley

Though I was asked to present results in SM and EFT's only, there are very many results from BSM models as well!

- 2HDM triple-Higgs coupling [Arco, Heinemeyer, Herrero '20, '21, '22]
- 2HDM: GW and c_{HHH} [Biekötter et al. '21, '22]
- HH with an extra scalar singlet [Abouabid et al '21],[Adhikari, Lane, Lewis, Sullivan '22] $\rightarrow$ see talk by I. Lewis
- Radiative corrections to c_{hhh} in the 2HDM Bahl, Braathen, Weiglein '22]
- SFOEWPT $\leftrightarrow$ 2HDM-EFT [Anisha, Biermann, Englert, Mühlleitner '22]
- c_{hhh} in CP-violating NMSSM [Borschensky, Dao, Gabelmann, Mühlleitner, Rzehak '22] $\rightarrow$ see talk by H. Rzehak
- ...

Summary

- Much progress on theoretical front in recent years
  - ggF: NLO (full QCD), N^{3}LO (HTL)
  - VBF: N^{3}LO (incl.), NNLO QCD + NLO EW (diff.), non-factorisable contributions
- Leaps on both the theory and the experimental fronts!

- Two different EFT approaches:
  - SMEFT: linear realisation, $H \in$ doublet, Wilson coefficients naturally small, partial correlations
  - 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)

- Many other interesting developments (EW corrections, m_t-scheme, higher-D-operator constraints, generic EFT considerations...)