Higgs pair production including EWChL contributions

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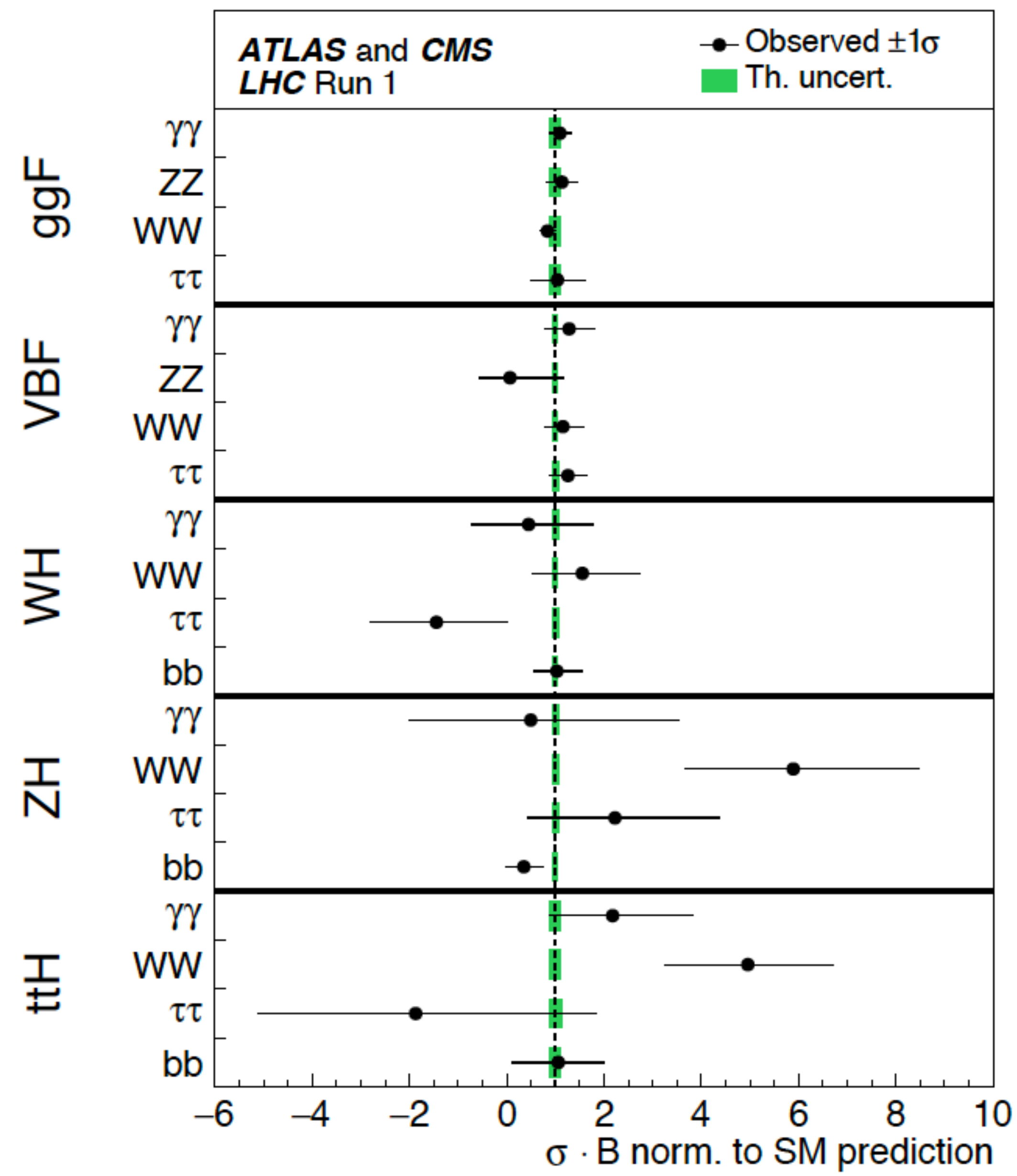
Motivation

- Discovery of the Higgs boson: most important discovery in our understanding of Electroweak symmetry breaking.
- The hierarchy problem and other open questions in SM motivate us to explore extensions to the Higgs sector.
- SM is very well tested. If there are new physics effects they are likely to show up in the Higgs sector, but no evidence of new physics has been found up to date.
- New physics may hide at higher scales, therefore a low energy approximation of new physics can allow us to parametrize new physics contributions.
- So we work in an Effective Field Theory (EFT) framework, in particular the one provided by the Electroweak Chiral Lagrangian (EWChL) [Buchalla et al. arXiv: 1307.5017v3].

EWChL

- EWChL is an effective field theory framework which includes deviations from the standard model.
- EWChL provide a non linear realization of the electroweak symmetry breaking sector.
- Non standard couplings in the Higgs sector in principle can be large in this framework. Most of the Higgs couplings are well constrained already, but not the top Yukawa coupling and even less the Higgs self coupling.
- Therefore we only consider the Higgs sector within the EWChL framework. In particular the Higgs boson pair production because it allows to study the Higgs boson self coupling.
- We focus on the gluon fusion channel because it has the biggest cross section.



ATLAS, CMS collaboration
arXiv:1606.02266

BSM gg→HH state of art

- Cross section parametrization see e.g. [Azatov et al. arXiv:1502.00539]:

$$\sigma_{LO} = \sigma_{LO,SM}[A_1 c_{thh}^4 + A_2 c_{tthh}^2 + (A_3 c_{thh}^2 + A_4 c_{ghh}^2) c_{hhh}^2 + A_5 c_{gghh}^2 + (A_6 c_{tthh} + A_7 c_{hhh} c_{tth}) c_{tth}^2$$
$$+ (A_8 c_{hhh} c_{thh} + A_9 c_{ghh} c_{hhh}) c_{tthh} + A_{10} c_{tthh} c_{cgghh} + (A_{11} c_{ghh} c_{hhh} + A_{12} c_{gghh}) c_{thh}^2$$
$$+ (A_{13} c_{hhh} c_{ghh} + A_{14} c_{gghh}) c_{thh} c_{hhh} + A_{15} c_{ghh} c_{gghh} c_{hhh}]$$

- NLO HEFT calculation including dimension 6 operators [Gröeber et al. arXiv:1504.06577] .

- Presentation of Benchmark points in order to explore the BSM parameters space see e.g. [Carvalho et al. arXiv:1507.02245].

Benchmark	c_{hhh}	c_{thh}	c_{tthh}	c_{ggh}	c_{gghh}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	$-\frac{1.6}{3}$	-0.2
3	1.0	1.0	-1.5	0.0	$\frac{0.8}{3}$
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	$\frac{1.6}{3}$	$\frac{1.0}{3}$
6	2.4	1.0	0.0	$\frac{0.4}{3}$	$\frac{0.2}{3}$
7	5.0	1.0	0.0	$\frac{0.4}{3}$	$\frac{0.2}{3}$
8	15.0	1.0	0.0	$-\frac{2.0}{3}$	$-\frac{1.0}{3}$
9	1.0	1.0	1.0	-0.4	-0.2
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	$\frac{2.0}{3}$	$\frac{1.0}{3}$
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

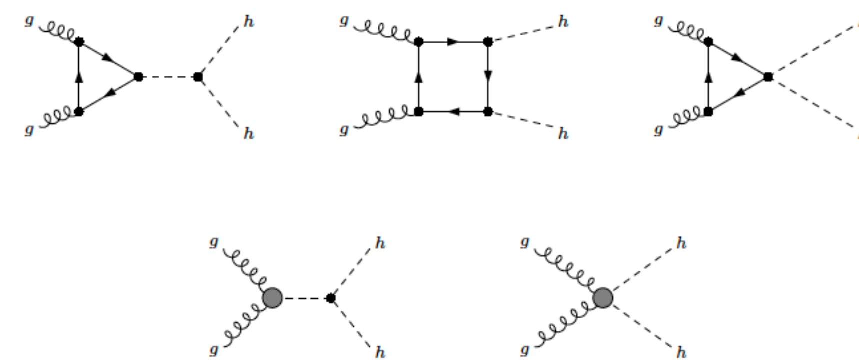
- NLO SM full top mass dependent calculation including variation of the Higgs self coupling [Borowka et al. arXiv:1608.04798].

- NNLO HEFT results including dimension 6 operators [de Florian et al. arXiv:1704.05700].

EWChL for gg→HH

- At leading order there are 5 different diagrams: 2 SM-like diagrams and 3 totally new diagrams.

$$L_{gg\to hh} \supset -m_t\bar{t}t\left(c_{tth}\frac{h}{v}+c_{tthh}\frac{h^2}{2v^2}\right)-c_{hhh}\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + \frac{g_s^2}{16\pi^2}\langle G_{\mu\nu}G^{\mu\nu}\rangle\left(c_{ghh}\frac{h}{v}+c_{gghh}\frac{h^2}{2v^2}\right)$$



Groeber et al. arXiv:1504.06577

- The Feynman amplitude of this process can be written as:

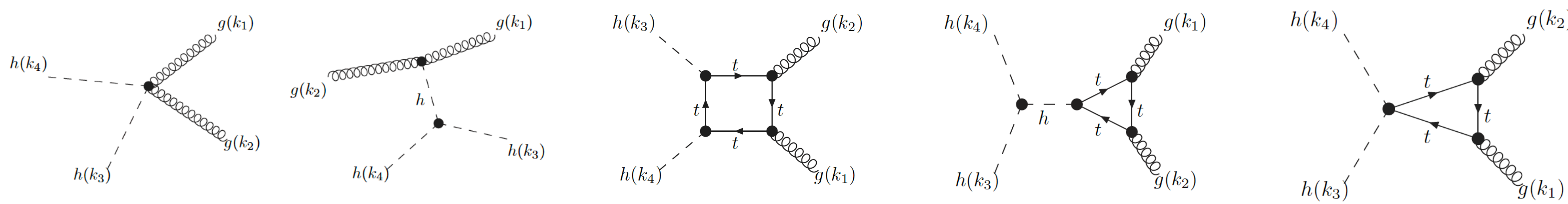
$$\boxed{M^{\mu\nu} = F_1 T_1^{\mu\nu} + F_2 T_2^{\mu\nu}}$$

$$T_1^{\mu\nu} = -g^{\mu\nu} + \frac{k_1^\nu k_2^\mu}{(k_1\cdot k_2)} \qquad T_2^{\mu\nu} = g^{\mu\nu} + \frac{1}{k_T^2(k_1\cdot k_2)}\left(m_h^2 k_1^\nu k_2^\mu - 2(k_1\cdot k_3)k_3^\nu k_2^\mu - 2(k_2\cdot k_3)k_3^\mu k_1^\nu\right) + 2(k_1\cdot k_2)k_3^\mu k_3^\nu)$$

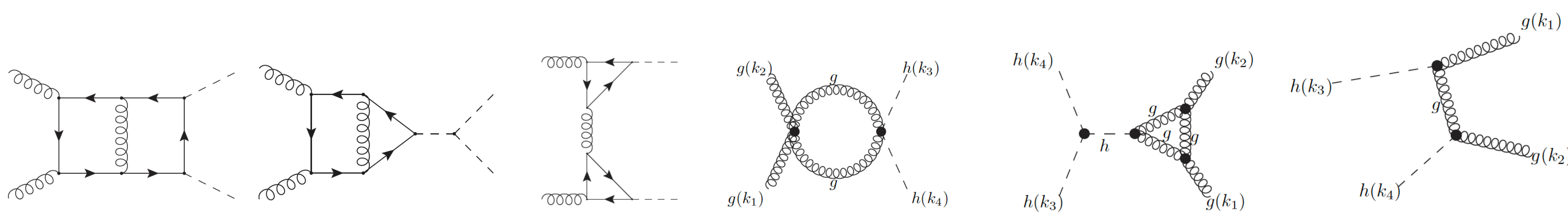
- In order to compute the deviations of the model, we need to know the contributions of these new diagrams to the form factors F_1 and F_2.

gg→HH contributions in the EWChL framework

Leading order



NLO QCD virtual



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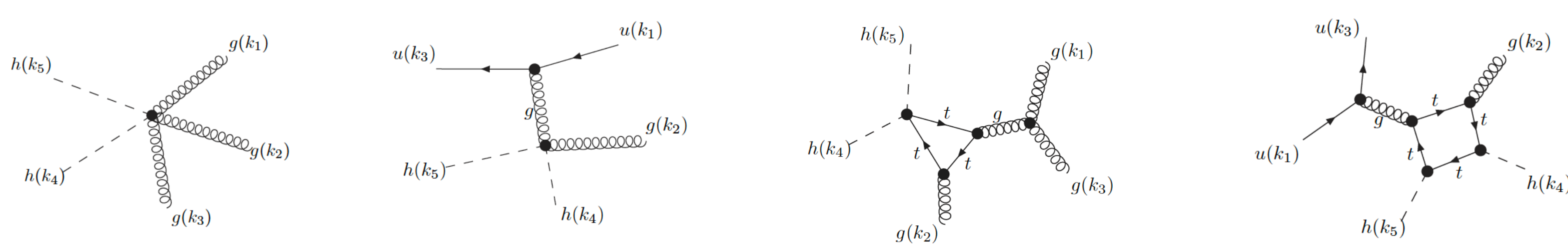
NLO QCD real



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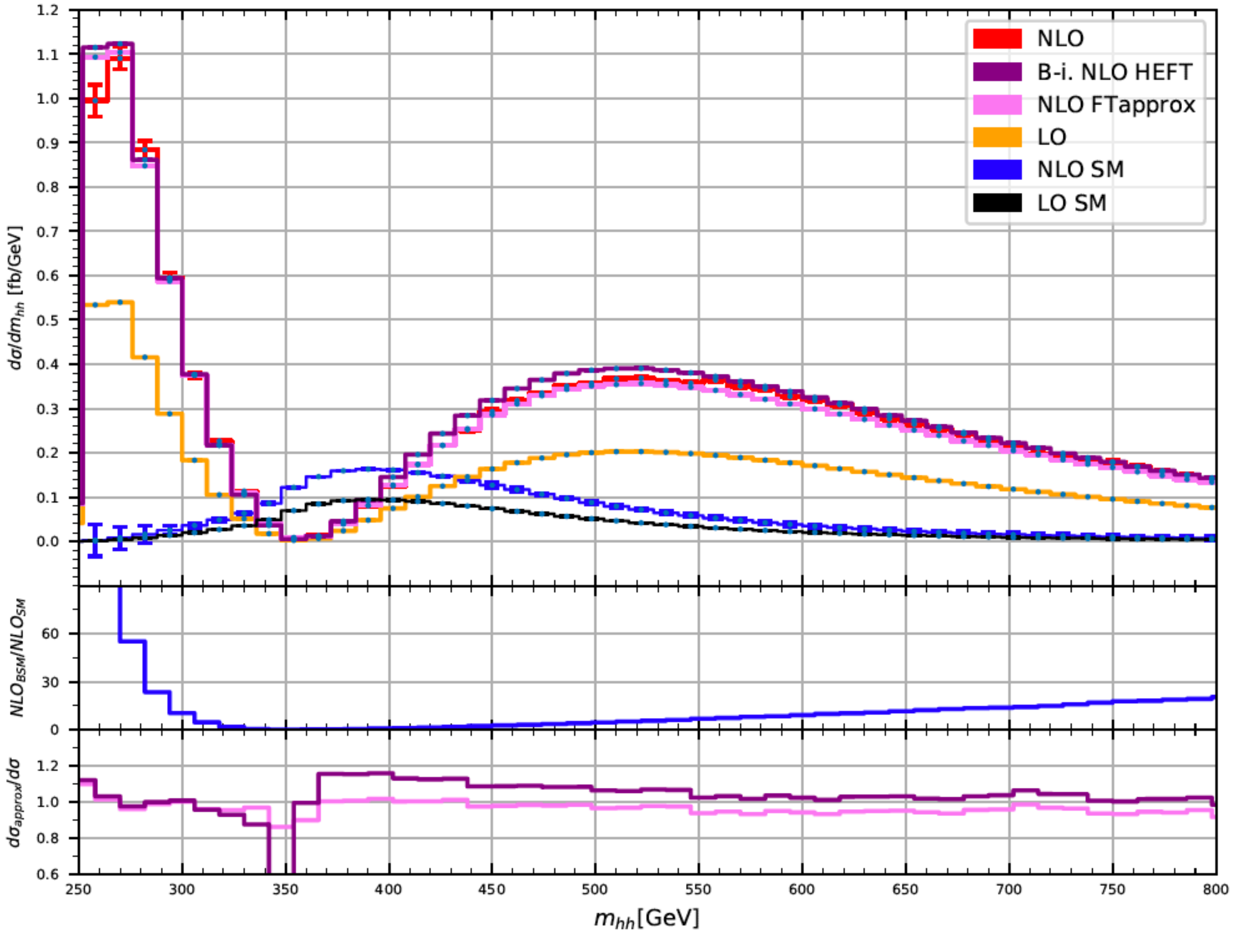
Method of the calculation

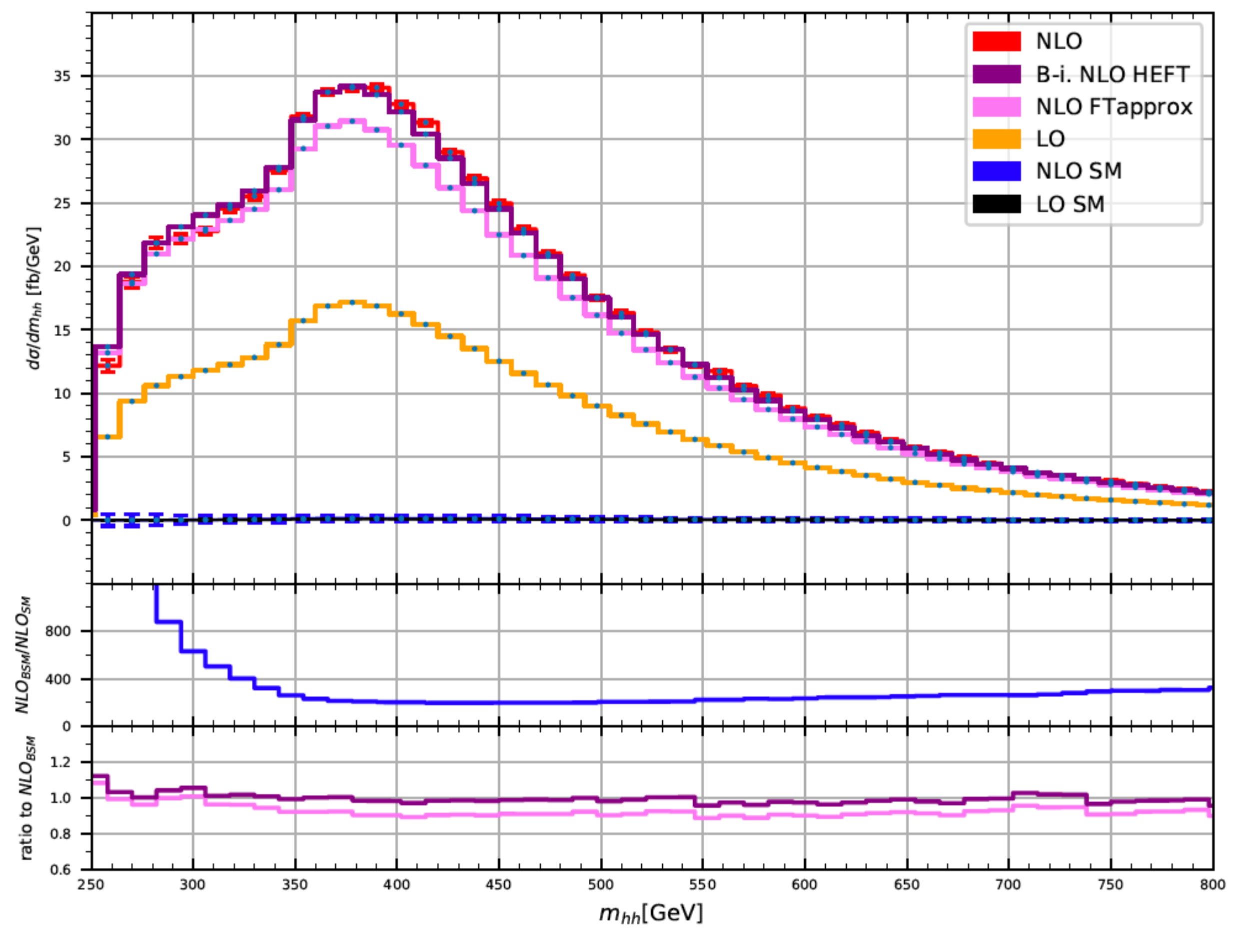
- In order to obtain the LO QCD cross section and the NLO QCD real corrections we used a C++ code linked to GoSam [Cullen et al. arXiv:1404.7096].
- We produced a model file based on the EWChL in UFO format read by GoSam.
- For the NLO QCD virtual correction we used the two-loop integrals computed for the SM case [Borowka et al. arXiv:1608.04798] as far as possible and then manipulated the results using a python script.
- Within our setup we can produce the full top mass dependent NLO QCD cross section and differential distributions.
- In the following we will show preliminary distributions for some of the benchmark points and compare them with SM results.

mhh distributions (Preliminary)



Benchmark 1

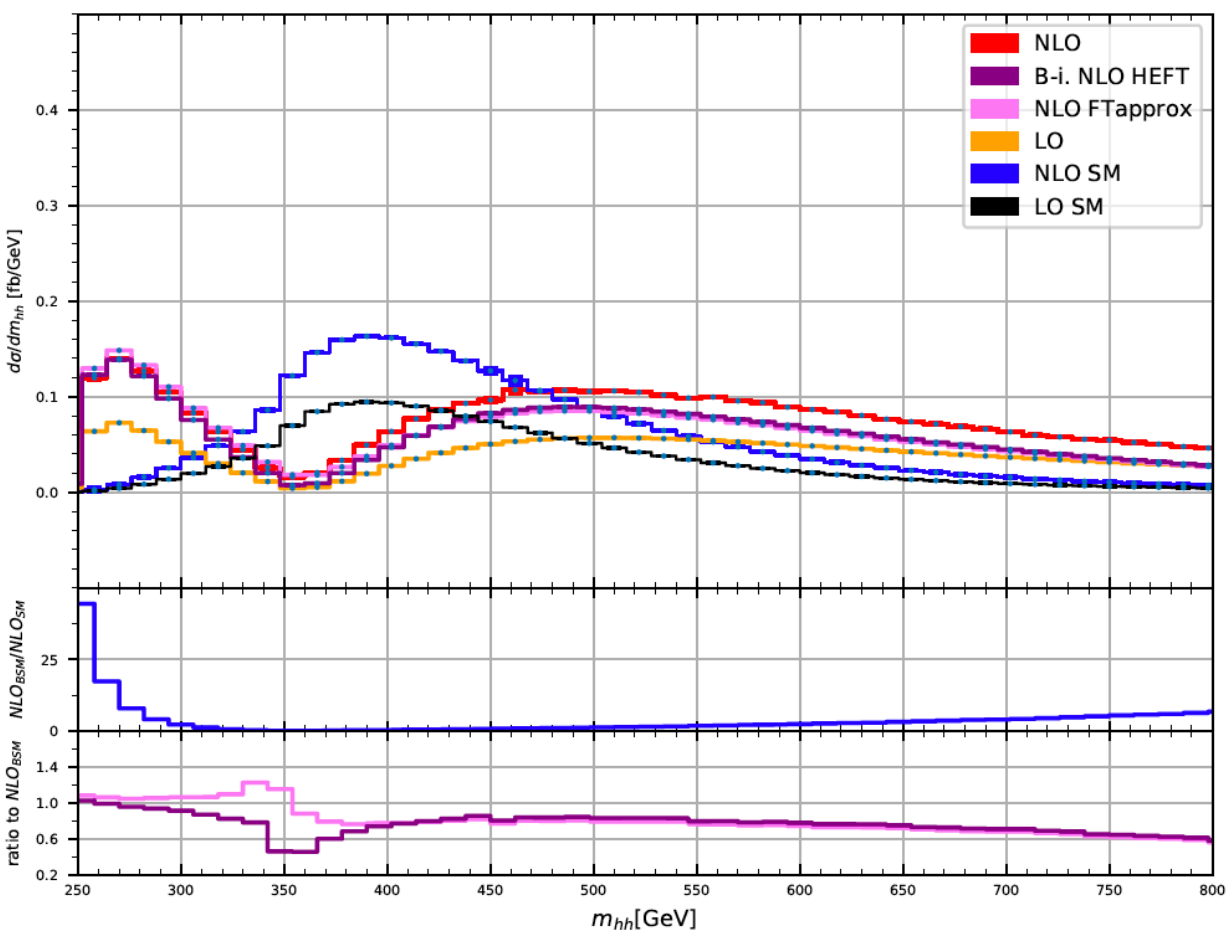
$$c_{hhh} = 7.5, c_{tth} = 1, c_{tthh} = -1, c_{ghh} = c_{gghh} = 0$$



Benchmark 4

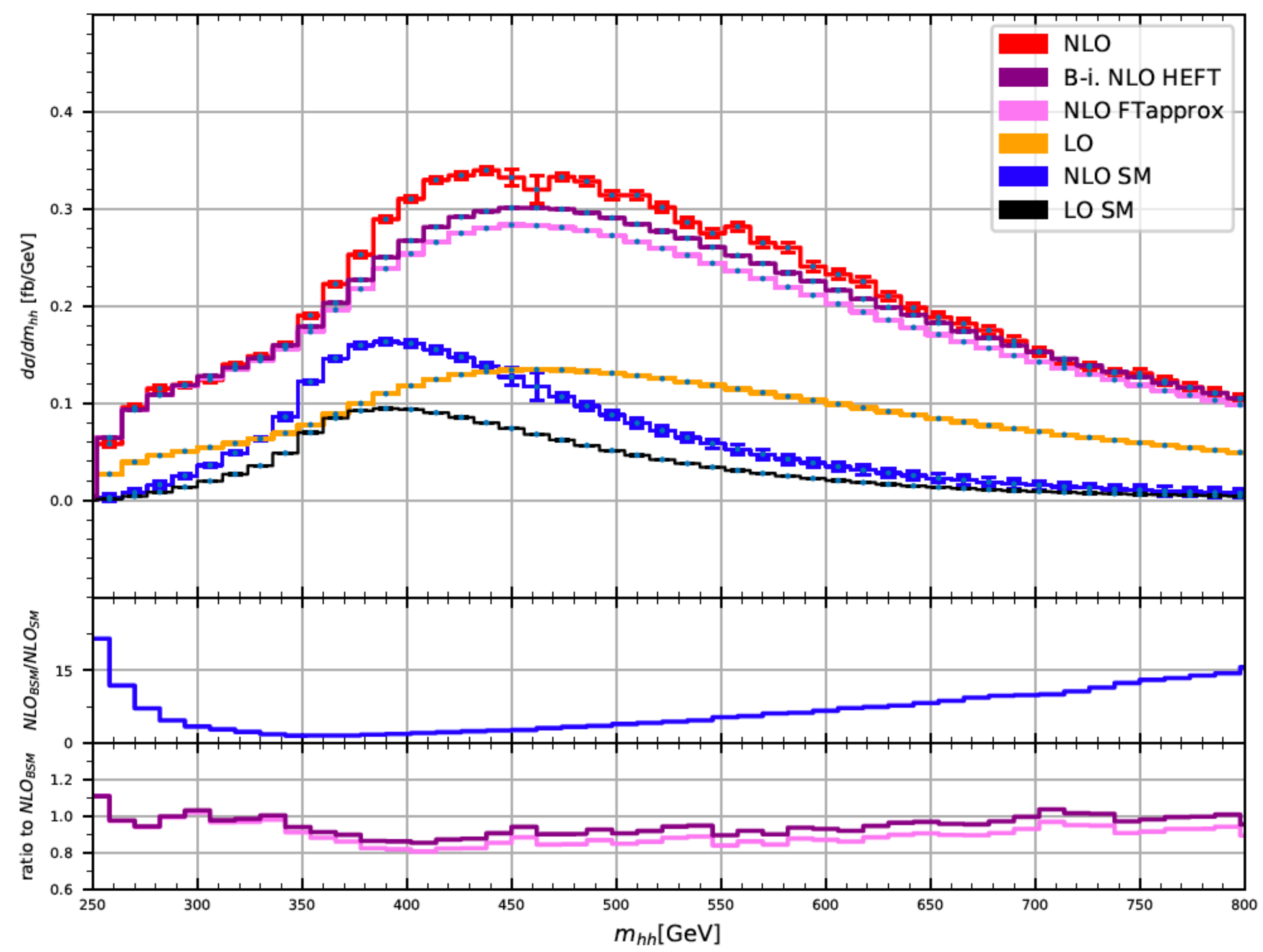
$$c_{hhh} = -3.5, c_{tth} = 1.5, c_{tthh} = -3, c_{ghh} = c_{gghh} = 0$$

mhh distributions (Preliminary)



Benchmark 5

$$c_{hhh} = 1, c_{tth} = 1, c_{tthh} = 0, c_{ghh} = \frac{1.6}{3}, c_{gghh} = \frac{1}{3}$$



Benchmark 9

$$c_{hhh} = 1, c_{tth} = 1, c_{tthh} = 1, c_{ghh} = -0.4, c_{gghh} = -0.2$$

Cross section fit

- Analyzing the behavior of the cross section, fixing four of the five BSM parameters and changing the remaining one, we obtain a set of data which we fit to determine the 15 coefficients.

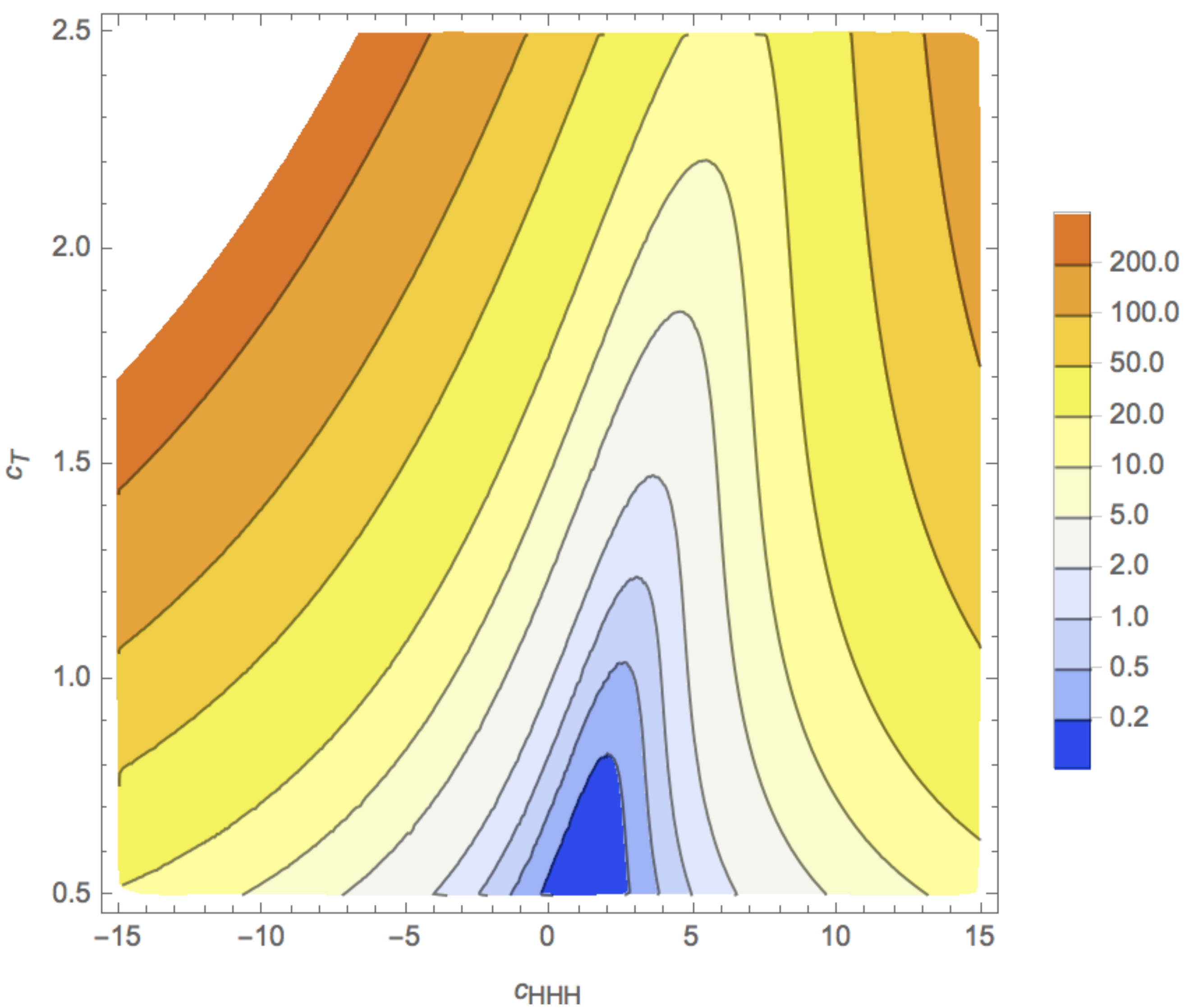
$$\begin{aligned}\sigma_{LO} =&\sigma_{LO,SM}[A_1 c_{thh}^4 + A_2 c_{tthh}^2 + (A_3 c_{thh}^2 + A_4 c_{ghh}^2) c_{hhh}^2 + A_5 c_{gghh}^2 + (A_6 c_{tthh} + A_7 c_{hhh} c_{tth}) c_{tth}^2 \\ &+ (A_8 c_{hhh} c_{thh} + A_9 c_{ghh} c_{hhh}) c_{tthh} + A_{10} c_{tthh} c_{cgghh} + (A_{11} c_{ghh} c_{hhh} + A_{12} c_{gghh}) c_{thh}^2 \\ &+ (A_{13} c_{hhh} c_{ghh} + A_{14} c_{gghh}) c_{thh} c_{hhh} + A_{15} c_{ghh} c_{gghh} c_{hhh}]\end{aligned}$$

- At NLO QCD the 15 coefficients are redefined plus there are 5 new ones.

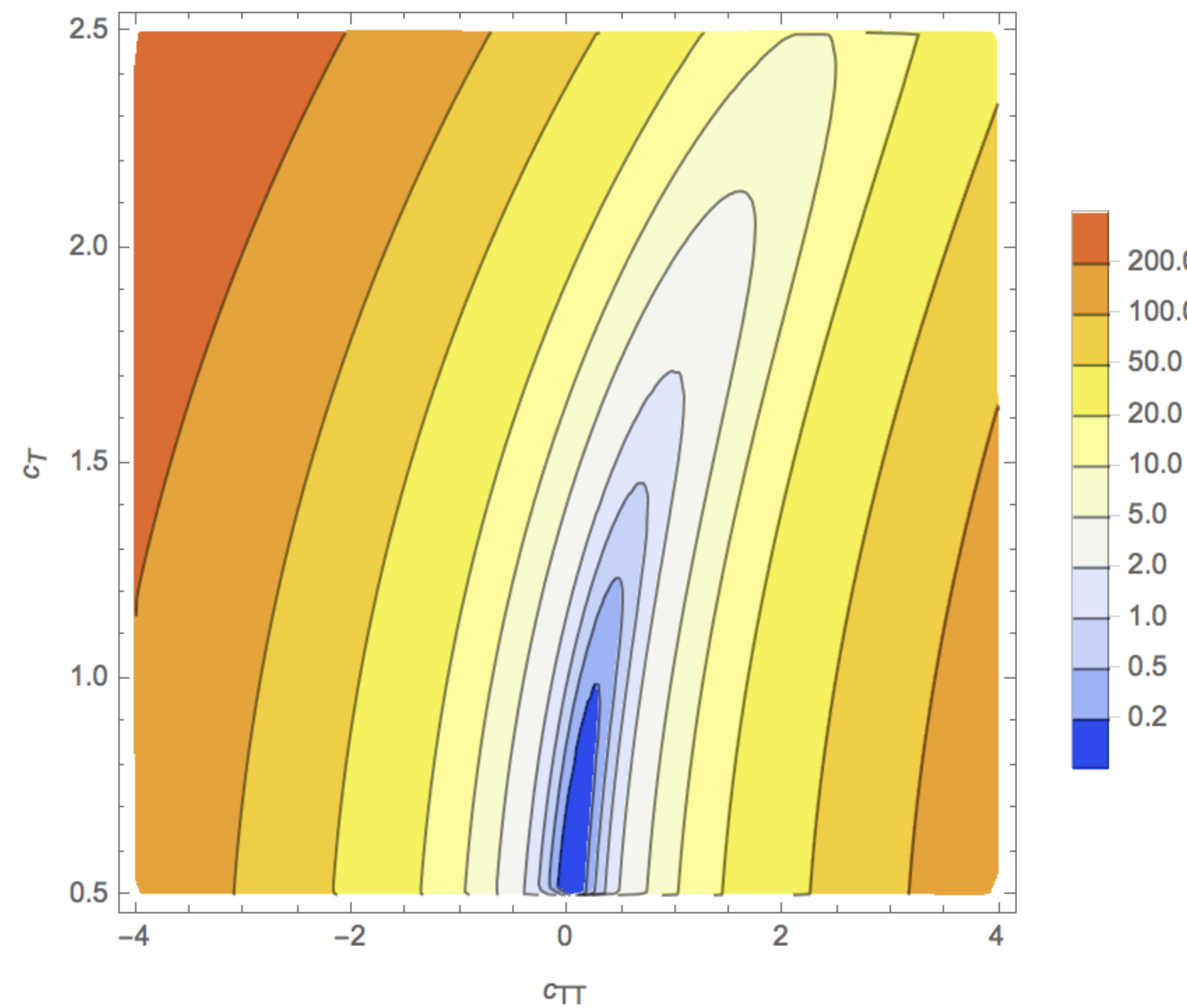
$$\begin{aligned}\sigma_{NLO} =&\sigma_{NLO,SM}[A'_1 c_{thh}^4 + A'_2 c_{tthh}^2 + (A'_3 c_{thh}^2 + A'_4 c_{ghh}^2) c_{hhh}^2 + A'_5 c_{gghh}^2 + (A'_6 c_{tthh} + A'_7 c_{hhh} c_{tth}) c_{tth}^2 \\ &+ (A'_8 c_{hhh} c_{thh} + A'_9 c_{ghh} c_{hhh}) c_{tthh} + A'_{10} c_{tthh} c_{cgghh} + (A'_{11} c_{ghh} c_{hhh} + A'_{12} c_{gghh}) c_{thh}^2 \\ &+ (A'_{13} c_{hhh} c_{ghh} + A'_{14} c_{gghh}) c_{thh} c_{hhh} + A'_{15} c_{ghh} c_{gghh} c_{hhh} + \underline{B_{16} c_{thh}^2 c_{ggh}^2 + B_{17} c_{ghh}^2 c_{thh} c_{hhh}} \\ &\underline{+ B_{18} c_{ghh} c_{thh} + B_{19} c_{gghh}^3 c_{hhh} + c_{ghh}^3 c_{hhh} + B_{20} c_{ghh}^2 c_{gghh}}]\end{aligned}$$

- Using the fitted cross section we study the behavior of the cross section as a function of the BSM parameters.
- In the following there are the LO heatmaps produced with the fitted cross section
- NLO heatmaps coming soon.

LO heat maps



c_T
2.5
2.0
1.5
1.0
0.5
−15
−10
−5
0
5
10
15
c_{HHH}
200.0
100.0
50.0
20.0
10.0
5.0
2.0
1.0
0.5
0.2



c_T
2.5
2.0
1.5
1.0
0.5
−4
−2
0
2
4
c_{TT}
200.0
100.0
50.0
20.0
10.0
5.0
2.0
1.0
0.5
0.2

Conclusion and outlook

- Computation NLO QCD corrections for the Higgs boson pair production in the gluon fusion channel within the EWChL framework.

- Evaluation of the full top mass dependent cross sections and distributions of the benchmark points up to NLO QCD.

- The analyzes show as in a BSM framework the differential cross section can deviate substantially from the SM prediction. The deviations can be of different magnitude depending on the values of the BSM couplings.

- Validation of the obtained results and production of heat maps up to NLO QCD.