

Higgs Pair Production at Colliders

MITP Program

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Coordinators:

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Goals

An extremely successful campaign of measurements at LHC-Run I has allowed to confirm that the couplings of the Higgs particle with the heaviest quarks, leptons and bosons do agree (within $\sim 10\%$) with the SM predictions and are consistent with previous indirect precision measurements. Only one of such (large) couplings remains totally unconstrained from all currently available data (from the LHC and LEP), i.e. the strength of the Higgs self-interactions. This also means that the form of the Higgs potential is presently experimentally undetermined. A key, yet very challenging process to gather direct information on this coupling is double Higgs production.

The goal of the workshop was to gather theorists (from the QCD, BSM and Monte Carlo communities) and LHC experimentalists together to discuss the status and the prospects of observing, studying and then extracting information from HH production. The workshop has been planned in collaboration with the LHC Higgs Cross Section Working Group (LHCHSWG) and in the context of the corresponding HH activities of the corresponding subgroup. Even though the main focus was towards Run II, also mid- as well as long-term options (HL-LHC and future colliders) were to be addressed.

Format, style and participants of the Workshop

The format of the workshop has been chosen to maximally enhance interactions among participants, to foster discussion by raising topics during in-depth technical presentations followed by ample time public and private debates. Discussions over lunch at the Campus and dinner in town followed in smaller groups. The atmosphere has been very informal from the start (also thanks to the keynote speakers of the first morning), something that has played a role in making the younger researchers immediately comfortable and triggered discussions right away.

The program (see Appendix I) has run over 7 half-day sessions, each featuring one or two review presentations (14 in total) and a session lead by previously appointed chairpersons (5 in total). Instructions to speakers included our motto "Rather than stressing previous work we should discuss the ideas that would lead to everyone's next paper". The charge of the discussion leaders was to identify the most important points to be addressed in the list of "HH questions" (see below) and to provide a synthesis at the end.

Participants (see full list in Appendix II) have been chosen only based on their proven expertise on the field, keeping an eye on assuring balance among various aspects. A total number of 32 physicists joined, of which 22/10 theorists/experimentalists, 27/5 Europe/Out-of-Europe origin, 24/8 men/women, 18/14 young/senior physicists.

Questions addressed and scientific output

Before the start of the workshop a list of key questions was sent to all participants. While certainly not attempting here to provide a detailed summary of the discussions and results, we can confidently state that all of them were addressed and some of them indeed generated a lot of discussions among the participants. While not even trying to be exhaustive, we will list here the questions, followed by a few comments.

- 1) *How large can the $h(125)$ self-coupling and the HH cross section be in concrete models? Can other $HHXX$ couplings be accessed (i.e.: $t\bar{t}HH$, $VVHH$)?*

This has been somewhat considered the mother of all TH questions, being intimately related to importance of having experimental analyses running even when their sensitiveness is only to way cross sections way larger than those predicted by the SM. Florian Goertz and Christophe Grojean stimulated an enlightening discussion on this topic on Tue afternoon.

- 2) *How do HH searches complement with H couplings measurements from boosted $H + jet$ and off-shell H ? How does HH production help to constrain the sign of the top Yukawa coupling?*

These questions were raised and discussed on Tuesday morning and afternoons.

- 3) *How fast do New Physics contributions to HH production (i.e.: top partners) decouple?*

Ramona Groeber and Christoph Englert discussed these aspects in their talks

- 4) *What is the foreseeable future of radiative corrections and MC generators for $gg \rightarrow HH$?*

This question lead to a very lively set of presentations and discussions on Wed. The most important mid-term target is the computation of the double-box virtual contributions for $gg \rightarrow HH$, with the exact mass dependence. Efforts in estimating such effects have been presented by Eleni Vryonidou, Jonathan Grigo and the first step toward an exact computation by Gudrun Heinrich. The status of the current recommendations and future prospects has been addressed in the ensuing discussion lead by Sally Dawson.

- 5) *Which is the major bottleneck for EXP analysis with $t\bar{t}$ as a background ($bbWW$, $bb\text{-tau-tau}$)?*
- 6) *Are SM + resonant searches comprehensive enough?*

These aspects have been discussed on Monday afternoon and Wednesday morning triggered by the talks by Nick Styles, Souvik Das and Maxime Gouzevitch, in conjunction with the forthcoming results by ATLAS and CMS on Run I data. In this context, it has been extremely useful to be able to discuss the analyses in detail, allowing a direct exchange of information/requests from experiment to theory and viceversa.

7) *What is the status of other production modes (VBF, VHH, ttHH) HL-LHC and the corresponding accuracy in MC generators and EW/QCD corrections?*

The status of the MC's was reviewed by Marco Zaro, who showed that NLO (QCD)+PS accuracy has been reached in all production channels (with the exception of the above mentioned limitation in $gg \rightarrow HH$)

8) *Are there any new channels available at HL-LHC?*

9) *Do HH searches benefit from larger energy or from larger luminosity?*

10) *Which are the prospects for the next generation of colliders (ILC, FCC-hh,...)?*

The above questions have been addressed in several sessions and especially in on Thu morning in the talks by Roberto Contino and Andreas Papaefstathiou and in the following discussion lead by Aleandro Nisati. In this discussion, the participation of both experimentalists and theorists was essential to clearly identify the desiderata from each community.

Final conclusions and the successes of the program

The timing of the workshop, between Run I and Run II at the LHC, has been extremely appropriate. Our short, yet very focused, program has allowed to bring together a large fraction of the HH experts in the world, both theorists and experimentalists, young and senior scientists, from Europe and abroad.

The program was extremely successful in trigger people with very different strengths and expertise to discuss and collaborate on the challenges connected to the determination of the origin and form of the scalar sector. Many of the most pressing and sometimes controversial questions were addressed, giving the possibility of debating freely from the usual (negative) constraints (time, closed experimental collaborations, presence of non-specialized audience). A very positive and constructive atmosphere has characterized all the meetings, as confirmed also by the very positive feedbacks that we have received from the participants afterwards.

One of the main outcomes of the workshop has been to provide further motivation to all physicists interested in this challenging endeavor. Concrete actions/projects for improving QCD predictions, extending HH searches in various channels, further extend EFT and BSM predictions, and widen/deepen the experimental strategies and analyses in the current and future colliders have been clearly indicated.

Let us conclude by expressing our gratitude to the MITP (starting from an amazingly kind, warm and helpful staff to the board and director) for making our life extremely easy and for having allowed us to organize and run this program. We feel that our program has been successful and that we will collect the fruits of our work in the coming months/years.

List of participants

BAGLIO, Julien
BONDU, Olivier
CONTINO, Roberto
DAS, Souvik
DAWSON, Sally
DE FLORIAN, Daniel
ENGLERT, Christoph
FERREIRA DE LIMA, Danilo
FURLAN, Elisabetta
GOERTZ, Florian
GOUZEVITCH, Maxime
GRIGO, Jonathan
GROJEAN, Christophe
GRÖBER, Ramona
HEINRICH, Gudrun
KLUTE, Markus
MALTONI, Fabio
MÜHLLEITNER, M. Margarete
NISATI, Aleandro
OLIVEIRA, Alexandra
PAPAEFSTATHIOU, Andreas
PLEHN, Tilman
SALERNO, Roberto
SANTOS, Rui
SLAWINSKA, Magdalena
SON, Minho
SPANNOWSKY, Michael
STYLES, Nicholas
VIDAL MARONO, Miguel
VRYONIDOU, Eleni
WANG, Jian
ZARO, Marco
ZURITA, José