

# HHH workshop



## Report of Contributions

Contribution ID: 11

Type: **not specified**

## HHH prospects

In this talk I will explore the behaviour of multi-Higgs boson production, with a focus on triple Higgs boson production, in the context of various new physics models. I will discuss theories that incorporate higher-dimensional operators, and models with one or two additional singlet scalar fields.

**Presenters:** BIJL, Pim (Nikhef and UvA); DU PREE, Tristan Arnoldus (Nikhef National institute for subatomic physics (NL))

Contribution ID: 12

Type: **not specified**

## Reconstruction of boosted and resolved multi-Higgs-boson final states with symmetry-preserving attention

*Friday 14 July 2023 14:00 (30 minutes)*

The production of multiple Higgs bosons at the CERN LHC provides a direct way to measure the trilinear and quartic Higgs self-interaction strengths as well as potential access to beyond the standard model effects that can enhance production at large transverse momentum  $\cancel{T}$ . The largest event fraction arises from the fully hadronic final state in which every Higgs boson decays to a bottom quark-antiquark pair ( $b\bar{b}$ ), which introduces a combinatorial challenge known as the `\emph{jet assignment problem}`: assigning jets to sets representing Higgs boson candidates. Symmetry-preserving attention networks (SPA-Nets) have been introduced to address this challenge for a given event topology. However, the complexity of this challenge increases when simultaneously considering both  $b \rightarrow b\bar{b}$  reconstruction possibilities, i.e., two “resolved” small-radius jets each containing a cascade initiated by a  $b$  quark or one “boosted” large-radius jet containing a merged cascade initiated by a  $b\bar{b}$  pair. The latter improves reconstruction efficiency at large  $\cancel{T}$ . In this work, we introduce a generalization to the SPA-Net approach to simultaneously consider both boosted and resolved reconstruction possibilities and unambiguously interpret an event as “fully resolved,” “fully boosted,” or in between. We report the performance of baseline methods, the original SPA-Net approach, and our generalized version on nonresonant  $b\bar{b}$  production at the LHC.

**Co-author:** STAMENKOVIC, Marko (Brown University (US))

**Presenters:** LI, Haoyang (Univ. of California San Diego (US)); STAMENKOVIC, Marko (Brown University (US))

**Session Classification:** Afternoon session

Contribution ID: 13

Type: **not specified**

## Improving Multi-Higgs sensitivity in the hadronic final state using machine learning

*Friday 14 July 2023 15:00 (30 minutes)*

One of the central goals of the physics program at the future colliders is to elucidate the origin of electroweak symmetry breaking, including precision measurements of the Higgs sector. This includes a detailed study of Higgs boson pair production, which can reveal the Higgs self-interaction strength through the gluon fusion mode as well as the coupling between Higgs and vector bosons through the vector boson fusion mode. Since the discovery of the Higgs boson, a large campaign of measurements of the properties of the Higgs boson has begun and many new ideas have emerged during the completion of this program. One such idea is the use of highly boosted and merged hadronic decays of the Higgs boson ( $H \rightarrow b\bar{b}$ ,  $H \rightarrow WW \rightarrow q\bar{q}q\bar{q}$ ) with machine learning methods to improve the signal-to-background discrimination. In this project, we champion the use of these modes to boost the sensitivity of future collider physics programs to Higgs boson pair production and the Higgs self-coupling. In this presentation, we aim to demonstrate the advantages of graph neural networks over standard cut-based event selection methods to achieve better sensitivity.

**Presenters:** DIAZ, Daniel (Univ. of California San Diego (US)); DUARTE, Javier Mauricio (Univ. of California San Diego (US)); GANGULY, Sanmay (University of Tokyo (JP))

**Session Classification:** Afternoon session

Contribution ID: 14

Type: **not specified**

## HHH, the Higgs potential and electroweak baryogenesis

*Friday 14 July 2023 15:30 (30 minutes)*

The search for the HHH process at the LHC targets both the quartic and trilinear Higgs self-couplings, and thereby provides important information about the shape of the Higgs potential. Indirectly, it could also give insight in the matter-antimatter asymmetry observed in the universe. This presentation discusses the relation of the HHH process with the mechanism of electroweak symmetry breaking and the impact of the HHH study at the LHC on the understanding of electroweak baryogenesis.

**Presenters:** KARKOUT, Osama (Nikhef National institute for subatomic physics (NL)); DU PREE, Tristan Arnoldus (Nikhef National institute for subatomic physics (NL))

**Session Classification:** Afternoon session

Contribution ID: 15

Type: **not specified**

## **Introduction to HHH: SM and BSM phenomenology**

*Friday 14 July 2023 10:30 (30 minutes)*

**Presenter:** FUKS, Benjamin

**Session Classification:** Morning session

Contribution ID: 16

Type: **not specified**

## Overview of HH experimental results from CMS

*Friday 14 July 2023 11:30 (30 minutes)*

Lessons learned from HH: from analyses strategy to background modelling

**Presenter:** STAMENKOVIC, Marko (Brown University (US))

**Session Classification:** Morning session

Contribution ID: 17

Type: **not specified**

## Complementing constraints of the Higgs potential shape with triple-Higgs searches at the LHC

*Friday 14 July 2023 14:30 (30 minutes)*

The discovery of the Higgs boson in 2012 was a triumph for the Standard Model (SM) of particle physics and the mechanism of electroweak symmetry breaking. An essential ingredient to this mechanism is the Higgs field potential, which is introduced ad-hoc and assumed to be Mexican-hat shaped in the SM, but cannot be derived from first principles. It is therefore important to probe this shape experimentally. Current measurements of single Higgs boson production only probe the area around minimum of the potential. To determine its exact shape, measurements of processes involving self-couplings of  $N$  Higgs bosons ( $H^N$ ) are needed. While there is an extensive existing research programme to extract the triple Higgs coupling (HHH) from di-Higgs production, little attention is currently given to the quartic Higgs coupling (HHHH) which can be extracted from searches for triple Higgs production. In this talk, we will demonstrate how experimental searches for triple Higgs production can complement the ongoing di-Higgs programme. Starting from the sensitivities of both search types to the HHH and HHHH coupling we estimate experimental precision for upcoming LHC runs to arrive at a first projection for LHC era measurements.

**Presenters:** MOSER, Brian (CERN); ARNOLD, Hannah (Nikhef); STAMENKOVIC, Marko (Brown University (US))

**Session Classification:** Afternoon session



Contribution ID: 18

Type: **not specified**

## **Open discussion - experimentalists and theorists requests exchange**

*Friday 14 July 2023 16:30 (1h 30m)*

Townhall discussion based on feedback received by participants - organised through slides

What are experimentalists requests to theorists?

What are theorists requests to experimentalists?

Contribution ID: 19

Type: **not specified**

## General ATLAS flavour tagging

*Saturday 15 July 2023 09:30 (30 minutes)*

An introduction to the ATLAS Flavour Tagging, which covers the new Run 3 tagger development. In addition to the tagger itself, we will also cover the calibration programs and other statistical treatments.

**Presenter:** LIU, Bingxuan (Simon Fraser University (CA))

**Session Classification:** Morning session

Contribution ID: 20

Type: **not specified**

## ATLAS b-jet trigger

*Saturday 15 July 2023 10:00 (30 minutes)*

Several new b-jet triggering strategies have been deployed for ATLAS Run 3. We will show the preliminary performance plots and discuss its impact on the Run 3 HHH program. In particular, we will initialize a discussion on what new triggers should be implemented for the rest of Run 3 and HL-LHC, in order to probe the full phase space.

**Presenter:** CHEN, Maggie (University of Oxford (GB))

**Session Classification:** Morning session

Contribution ID: 21

Type: **not specified**

## Boosted flavour tagging algorithms in ATLAS

*Saturday 15 July 2023 10:30 (30 minutes)*

There has been quite some advancements in the area of boosted flavour tagging in ATLAS. We will discuss the baseline tagger performance and in particular a dedicated low mass  $a \rightarrow b\bar{b}$  tagger.

**Presenter:** KARKOUT, Osama (Nikhef National institute for subatomic physics (NL))

**Session Classification:** Morning session

Contribution ID: 22

Type: **not specified**

## **CMS heavy flavour tagging: novel HH and HHH trigger strategy for Run 3**

*Saturday 15 July 2023 11:30 (30 minutes)*

Recent progress in heavy flavour tagging as well as boosted flavour tagging has enabled the CMS experiment to probe rare Higgs processes with more sensitivity than ever. In this talk, we will discuss the novel HH and HHH trigger strategy deployed for Run 3.

**Presenter:** KOLOSOVA, Marina (University of Florida (US))

**Session Classification:** Morning session

Contribution ID: 23

Type: **not specified**

## Dissecting multi-Higgs production in new physics models

*Saturday 15 July 2023 12:00 (30 minutes)*

In this talk I will explore the behaviour of multi-Higgs boson production, with a focus on triple Higgs boson production, in the context of various new physics models. I will discuss theories that incorporate higher-dimensional operators, and models with one or two additional singlet scalar fields.

**Presenter:** Dr PAPAEFSTATHIOU, Andreas (Kennesaw State University, GA, USA)

**Session Classification:** Morning session

Contribution ID: 24

Type: **not specified**

## Phenomenology of flavoured 3HDMs

*Saturday 15 July 2023 14:00 (30 minutes)*

I will overview our recent advances in studies of various phenomenological implications of multi-Higgs extensions of the Standard Model constrained by additional symmetries. A particular focus would be on 3HDMs, with some of their basic implications on Higgs and flavour physics.

**Presenter:** PASECHNIK, Roman (Lund university)

**Session Classification:** Afternoon session

Contribution ID: 25

Type: **not specified**

## Triple-Higgs production at LHC and future hadron colliders

After the discovery of Higgs boson, Standard Model (SM) has been test successfully. However, experimental data suggests that new physics (NP) beyond SM should exist. Measurements of Higgs properties and couplings are essential to search for NP. Multi-Higgs production processes at colliders are important to reconstruct the Higgs potential and to study the mechanism of electroweak symmetry breaking. In this talk, we study the triple-Higgs production via gluon-gluon fusion (ggF) and vector-boson fusion (VBF) at LHC and future hadron colliders, using an effective Lagrangian to describe potential NP. For the ggF process, we explore the potential for the discovery of the triple-Higgs signal in the  $4\ell 2\ell$  and  $2\ell 2\ell \pm 4\ell + \ell$  channel. Our Monte-Carlo simulation shows that the discovery of SM signals is a challenging task for the future hadron collider. For the VBF process, we derive theoretical constraints on the parameter space from the unitarity of  $2 \rightarrow \ell$  scattering amplitudes and apply the results to  $\ell\ell \rightarrow hh$  and  $hhh$  processes, where  $\ell = \mu, \tau$ . As a result, we present constraints on differential distributions as appropriate to the study of  $\ell\ell \rightarrow hh$  and  $hhh$  processes.

**Presenter:** ZHAO, Zhijie

**Session Classification:** Afternoon session



Contribution ID: 26

Type: **not specified**

## Investigating the trilinear Higgs coupling through triple Higgs production

*Saturday 15 July 2023 14:30 (30 minutes)*

Triple Higgs production is of interest because it involves the quartic Higgs coupling  $\lambda_4$ , which however will be very difficult to constrain experimentally during the next decades, but also because of its significant dependence on the trilinear Higgs coupling  $\lambda_3$ . The latter dependence could be used to improve the experimental sensitivity on  $\lambda_3$  in combination with the experimental information that can be obtained from di-Higgs production. The impact of triple Higgs production in this context is limited by the small signal cross section and the large QCD background rates that contribute. We explore the prospects for constraining  $\lambda_3$  via triple Higgs production at the HL-LHC by considering different final state signatures under idealised conditions, and investigate signal-background discrimination through Neural Networks, which are necessitated in order to fully exploit the available information in the data.

**Presenter:** STYLIANOU, Panagiotis

**Session Classification:** Afternoon session

Contribution ID: 27

Type: **not specified**

## Coffee break

Contribution ID: 28

Type: **not specified**

## **Open discussion - experimentalists and theorists requests exchange [part 2] or break-out rooms discussions**

*Saturday 15 July 2023 16:00 (1h 30m)*

Open session to continue the discussion between experimentalists and theorists

Additional possibility for break-out rooms in smaller group if needed

Contribution ID: 29

Type: **not specified**

## Scrutinising the Higgs quartic coupling at a future 100 TeV proton-proton collider

*Sunday 16 July 2023 11:00 (30 minutes)*

The Higgs potential consists of an unexplored territory in which the electroweak symmetry breaking is triggered, and it is moreover directly related to the nature of the electroweak phase transition. Measuring the Higgs boson cubic and quartic couplings, or getting equivalently information on the exact shape of the Higgs potential, is therefore an essential task. We discuss options for related direct measurements at a future proton-proton collider operating at a centre-of-mass energy of 100 TeV, focusing on a final states with b-tagged jets and either tau leptons or photons.

**Presenter:** FUKS, Benjamin**Session Classification:** Closing session

Contribution ID: 30

Type: **not specified**

## Triple Higgs boson production at a 100 TeV proton-proton collider

*Sunday 16 July 2023 11:30 (30 minutes)*

We consider triple Higgs boson production at a future 100 TeV proton-proton collider.

We perform a survey of viable final states and compare and contrast triple production to Higgs boson pair production.

Focussing on the  $hhh \rightarrow (bb)(bb)(\gamma\gamma)$  final state we construct a baseline analysis for the Standard Model scenario and simple deformations demonstrating that the process merits investigation in the high-luminosity phase of the future collider as a new probe of the self-coupling sector of the Higgs boson.

**Presenter:** SAKURAI, Kazuki (University of Warsaw)

**Session Classification:** Closing session

Contribution ID: 31

Type: **not specified**

## Highlights of HHH workshop

*Sunday 16 July 2023 12:00 (30 minutes)*

**Presenter:** KONIGSBERG, Jacobo (University of Florida (US))

**Session Classification:** Closing session

Contribution ID: 32

Type: **not specified**

## Welcome talk + logistics

*Friday 14 July 2023 10:15 (15 minutes)*

**Presenter:** BRIGLJEVIC, Vuko (Rudjer Boskovic Institute (HR))

Contribution ID: 33

Type: **not specified**

## Overview on BSM scenarios with enhancements in HH and HHH

*Sunday 16 July 2023 10:30 (30 minutes)*

I will give a short overview on models with extended scalar sectors that allow for triple scalar final states, including most recent theoretical and experimental constraints.

**Presenter:** ROBENS, Tania Natalie (Rudjer Boskovic Institute (HR))

**Session Classification:** Closing session



Contribution ID: 34

Type: **not specified**

## QCD overview

*Friday 14 July 2023 11:00 (30 minutes)*

**Presenter:** ZANDERIGHI, Giulia (Max Planck Society (DE))

**Session Classification:** Morning session

Contribution ID: 35

Type: **not specified**

## Experimental perspectives on HHH production

*Friday 14 July 2023 12:00 (30 minutes)*

There has recently been increased theoretical interest in tri-Higgs production, but no experimental search or measurement has yet been performed. Several significant challenges would be faced, including signal identification and discrimination against background, modelling of complex background processes, and interpretation of the data. This talk will present an experimentalist's view of these challenges, together with lessons learned from past studies targeting di-Higgs production, particularly at ATLAS, and an overview of techniques which may potentially be useful to address them.

**Presenter:** BALUNAS, William (University of Cambridge (GB))

**Session Classification:** Morning session

Contribution ID: 36

Type: **not specified**

## HHH - (a few) experimental thoughts

*Saturday 15 July 2023 15:00 (30 minutes)*

**Presenter:** LANDSBERG, Greg (Brown University (US))

**Session Classification:** Afternoon session