

HHH workshop

Friday 14 July 2023 - Sunday 16 July 2023

Dubrovnik



Book of Abstracts

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HHH prospects

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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.

Afternoon session / 12

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

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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 ($\cancel{b}\cancel{b}$), which introduces a combinatorial challenge known as the *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 $\cancel{b}\cancel{b} \rightarrow \cancel{b}\cancel{b}$ reconstruction possibilities, i.e., two “resolved” small-radius jets each containing a cascade initiated by a \cancel{b} quark or one “boosted” large-radius jet containing a merged cascade initiated by a $\cancel{b}\cancel{b}$ 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 $\cancel{b}\cancel{b}$ production at the LHC.

Afternoon session / 13

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

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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.

Afternoon session / 14

HHH, the Higgs potential and electroweak baryogenesis

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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.

Morning session / 15

Introduction to HHH: SM and BSM phenomenology

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Morning session / 16

Overview of HH experimental results from CMS

Corresponding Author: marko.stamenkovic@cern.ch

Lessons learned from HH: from analyses strategy to background modelling

Afternoon session / 17

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

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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.

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Open discussion - experimentalists and theorists requests exchange

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

What are experimentalists requests to theorists?

What are theorists requests to experimentalists?

Morning session / 19

General ATLAS flavour tagging

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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.

Morning session / 20

ATLAS b-jet trigger

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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.

Morning session / 21

Boosted flavour tagging algorithms in ATLAS

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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.

Morning session / 22

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

Corresponding Author: marina.kolosova@cern.ch

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.

Morning session / 23

Dissecting multi-Higgs production in new physics models

Corresponding Author: andreas.papaefstathiou@cern.ch

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.

Afternoon session / 24

Phenomenology of flavoured 3HDMs

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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.

Afternoon session / 25

Triple-Higgs production at LHC and future hadron colliders

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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 $2\ell 2\ell 4\ell$ 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 $2 \rightarrow 2$ scattering amplitudes and

apply the results to $\mathbb{X}\mathbb{X}\rightarrow hh$ and hhh processes, where $\mathbb{X}=\mathbb{X},\mathbb{Y}$. As a result, we present constraints on differential distributions as appropriate to the study of $\mathbb{X}\mathbb{X}\rightarrow hh$ and hhh processes.

Afternoon session / 26

Investigating the trilinear Higgs coupling through triple Higgs production

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Triple Higgs production is of interest because it involves the quartic Higgs coupling $\mathbb{X}4$, 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 $\mathbb{X}3$. The latter dependence could be used to improve the experimental sensitivity on $\mathbb{X}3$ 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 $\mathbb{X}3$ 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.

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Coffee break

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

Open session to continue the discussion between experimentalists and theorists

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

Closing session / 29

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

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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.

Closing session / 30

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

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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.

Closing session / 31

Highlights of HHH workshop

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Welcome talk + logistics

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Closing session / 33

Overview on BSM scenarios with enhancements in HH and HHH

Corresponding Author: tania.robens@cern.ch

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.

Morning session / 34

QCD overview

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Morning session / 35

Experimental perspectives on HHH production

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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.

Afternoon session / 36

HHH - (a few) experimental thoughts

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