Portraying Double Higgs at the HL-LHC and Future Colliders

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We propose to examine the discovery potential for double Higgs production at the HL-LHC and future colliders in the final states resulting from the $hh \to (b\bar{b})(W^\pm W^\mp)$ channel. We hope to improve on the signal significance by adopting a deep learning framework and making full use of the relevant kinematics along with the resulting jet, lepton and neutrino images.

The discovery of the Higgs boson (h) with a mass $m_h = 125$ GeV jumpstarted a comprehensive program of precision measurements of all Higgs couplings. The current results for the couplings to fermions and gauge bosons appear to be in agreement with the predictions of the Standard Model (SM). However, probing the triple and quartic Higgs self-couplings is notoriously difficult. Yet, the knowledge of those couplings is crucial for understanding the exact mechanism of electroweak symmetry breaking and the origin of mass in our universe. The observation of double Higgs production and the associated measurement of the triple Higgs coupling are guaranteed physics targets in the next run of the Large Hadron Collider (LHC) and at future colliders.

The Higgs self-interaction is parameterized as $V = \frac{m_h^2}{2}h^2 + \kappa_3\lambda_3^{\rm SM} v h^3 + \frac{1}{4}\kappa_4\lambda_4^{\rm SM} h^4$, where $\lambda_3^{\rm SM} = \lambda_4^{\rm SM} = \frac{m_h^2}{2v^2}$ are the SM values, κ_3 and κ_4 parameterize deviations from those, and $v \approx 256$ GeV is the Higgs vacuum expectation value. In order to access κ_3 (κ_4), one has to measure the double (triple) Higgs boson production at the high luminosity (HL) LHC or at future colliders.

Due to the small signal cross-section (σ_{hh}), *it is necessary to combine as many different channels as possible to discover double Higgs production and study the triple Higgs coupling* [1]. Among all possible channels, one specific process, $hh \to (b\bar{b})(W^\pm W^\mp)$, has so far been relatively overlooked, although it has the second largest branching fraction. This is mainly due to the large SM background cross-section $\sigma_{bknd} \sim 10^5 \sigma_{hh}$ (at the 14 TeV LHC), which is predominantly due to top quark pair production ($t\bar{t}$). In particular, there have been very few studies on the resulting dilepton final state [2–6]. The existing analyses employ sophisticated algorithms (neural networks (NN) [3], deep neural networks (DNN) [4, 7], boosted decision tree (BDT) [5, 6], etc.) to increase the signal sensitivity, but show somewhat pessimistic results, with a significance no better than 1σ at the HL-LHC with 3 ab^{-1} luminosity [3–6].

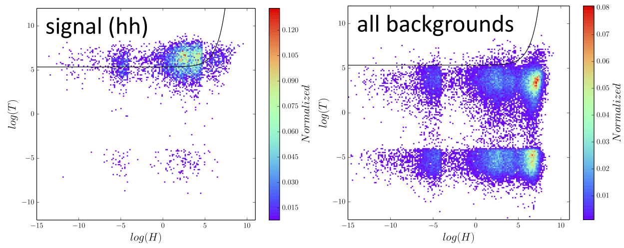

FIG. 1: Two-dimensional correlation plots for Higgsness and Topness for signal (left) and all backgrounds (right). The solid curve represents a suitable cut to maximize the signal significance.

We propose to first investigate the dilepton final state resulting from $hh \to (b\bar{b})(W^\pm W^\mp)$ with the aid of machine learning and clever kinematics. In Ref. [8], we suggested a novel method to enhance the signal significance for hh production in this channel. The idea was to maximize the use of kinematic information for the dominant background (dilepton $t\bar{t}$ production). We defined two new kinematic functions, *Topness* and *Higgsness*, which characterize features of the major ($t\bar{t}$) background and of hh events, respectively [8]. The idea is to explore the typical correlations between these kinematic variables for the case of signal and $t\bar{t}$ production, as shown in Fig. 1. Signal events are expected to populate the upper-left corner, while background events are expected to be found in the bottom-right corner. The solid curve represents a suitable cut to maximize the signal significance. The method also utilizes two less common variables, the subsystem M_{T2} (or subsystem M_2) [9–11] for $t\bar{t}$ and the subsystem $\sqrt{\hat{s}}_{min}$ (or subsystem M_1) [11–13] for hh production. In principle, these features may be learned by a neural network from the complete final state kinematic information, but in practice, this is very difficult to do, thus it is desirable to use both low-level and high-level variables as inputs to the neural network.

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Another difference between the signal ($hh \to WW^* \to b\bar{b}\ell\bar{\ell}\nu\bar{\nu}$) and the dominant background ($t\bar{t} \to b\bar{b}\ell\bar{\ell}\nu\bar{\nu}$) is that the two b-quarks in the signal arise from a color-singlet (h) and therefore, the hadrons from their decays tend to be closer to each other [14–17]. In Ref. [18], we applied a color-flow analysis (for the first time for double Higgs) and demonstrated a significant increase in the final significance.

Fig. 2 shows the (preliminary) cumulative average of the particle images for the signal (top panel) and the $t\bar{t}$ background (bottom panel). The origin of the (ϕ, η) plane is taken to be the center of the b quark pair and the density indicates the total p_T in each pixel. Images from the left to the right are obtained from charged hadrons, neutral hadrons, photons, leptons, neutrinos using Higgsness and neutrinos using Topness. In the previous study, we used convolutional neural networks (CNN) with the first three images (charged hadrons, neutral hadrons, photons), along with kinematic variables. The two recent studies [8, 18] show that one can enhance the signal sensitivity significantly via the interplay of kinematics and machine learning. We regard the $hh \to b\bar{b}WW^*$ channel as important as other channels such as $bb\gamma\gamma$, $bbbb$ and $bb\tau\tau$. The goal in this proposal is to further investigate all three final states in the $hh \to b\bar{b}WW^*$ channel and to combine the results.

The first improvement that we are targeting is the effective use of the momenta of the leptons and the reconstructed neutrinos. Lepton momentum information was previously used in terms of kinematic variables such as $m_{\ell\ell}$, $\Delta R_{\ell\ell}$ etc. However, since jet images are used (for color flow), it would make sense to study analogous images of leptons and neutrinos, which would naturally reveal the correlations among the b-tagged jet, leptons and neutrinos. Fig. 2 shows preliminary results for the cumulative average of the lepton images (4th column) and neutrino images (5th and 6th) for the signal (top) and the $t\bar{t}$ background (bottom) before the baseline cuts. The two neutrino images are obtained using either Higgsness (5th) or Topness (6th). Although they are only approximate, they do exhibit noticeable difference. As expected, neutrino images are supposed to the same as leptons images. We confirmed that our preliminary study with all six images using ResNets brings additional 40% improvement on the signal significance over results using traditional CNN. We also plan to try more sophisticated neural network structures such as CapsNets, and Graph Neural Networks (GNN).

First we will roughly reproduce the current 13 TeV experimental analyses by CMS [4] and ATLAS [7]. This will give us confidence on what we are trying to do. Using the same data set, we will perform our own analysis with new kinematic variables (Topness, Higgsness, M_2), color-flow, lepton images and neutrino images. Then we will repeat a similar analysis for 14 TeV and make a projection. We will also study pile-up effects. Finally, with the obtained approximate neutrino momenta, we will study shape-variables. The decay products from top quark production are more or less isotropic, while the decay products from double Higgs events are more collimated. Once $t\bar{t}$ background is under control, one should worry about the next dominant background, which is tW production.

It is interesting to notice that the signal significance in the $hh \to WW^* \to (bb)(jj\ell\nu)$ is much lower than that in the dilepton channel. A recent study [6] shows a significance of 0.13, with a much smaller signal over background ratio, although a somewhat promising result has been obtained in Ref. [19] using jet substructure. We will try to improve using new ideas (Topness, Higgsness, color-flow etc). Topness and Higgsness should be redefined properly to take into account the jet-multiplicity and the single missing neutrino. This will be the first study in the semi-leptonic channel with color-flow and new kinematics. In the semi-leptonic channel, where there is only one missing neutrino, one may impose the W on-shell condition to fix the z-component of the missing neutrino, with the transverse neutrino momentum identified with the missing transverse momentum. However, the W on-shell condition has an issue, since imaginary solutions are expected due to the detector resolution and finite width effects. We expect that Topness and Higgsness would perform better, solving the combinatorial problem.

The fully hadronic channel is not expected to provide a decent signal significance due to the large QCD background, but is a very interesting channel because of the 4-prong jet structure. In this final state, we plan to focus more on the kinematics and study how well one can tag this 4-prong jet against the backgrounds. Here the combinatorial problem is severe and we can develop some kinematic methods to resolve multiple jets. The method will be immediately applied to the resonant double Higgs production.

[1] J. Alison et al. Higgs Boson Pair Production at Colliders: Status and Perspectives. In B. Di Micco, M. Gouzevitch, J. Mazzitelli, and C. Vernieri, editors, *Double Higgs Production at Colliders Batavia, IL, USA, September 4, 2018-9, 2019*, 2019.

[2] J. Baglio, A. Djouadi, R. Gröber, M. M. Mühlleitner, J. Quevillon, and M. Spira. The measurement of the Higgs self-coupling at the LHC: theoretical status. *JHEP*, 04:151, 2013.

[3] Higgs pair production at the High Luminosity LHC. 2015.

[4] Albert M Sirunyan et al. Search for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\ell\nu\ell\nu$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV. *JHEP*, 01:054, 2018.

[5] Projected performance of Higgs analyses at the HL-LHC

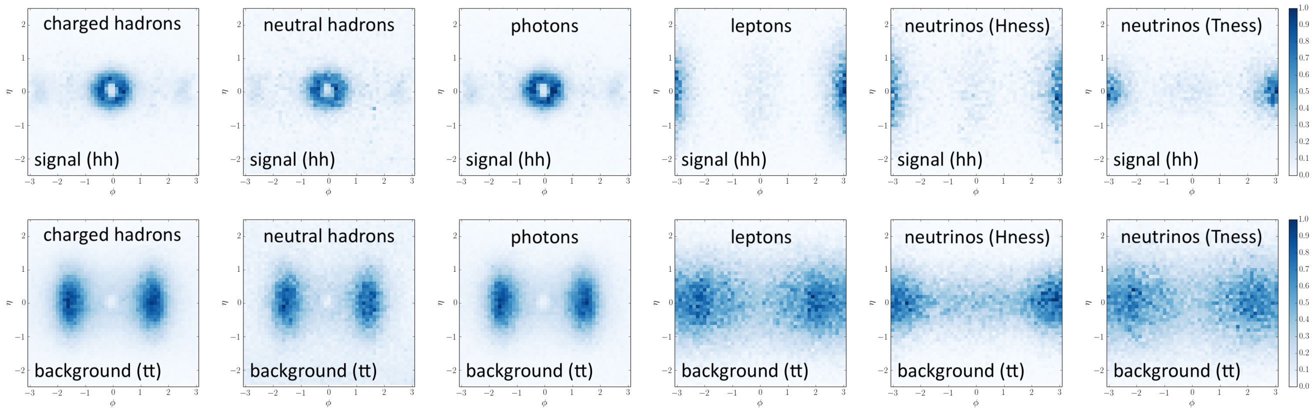

FIG. 2: The (preliminary) cumulative average of the images for the signal (top) and the $t\bar{t}$ background (bottom). The origin of the (ϕ, η) plane is taken to be the center of the b quark pair and the density indicates the total p_T in each pixel. Images from the left to the right are obtained from charged hadrons (1st column), neutral hadrons (2nd), photons (3rd), leptons (4th) and neutrinos with approximate momentum reconstruction using Higgsness and Topness (5th/6th).

for ECFA 2016. 2017.

[6] Amit Adhikary, Shankha Banerjee, Rahool Kumar Barman, Biplob Bhattacherjee, and Saurabh Niyogi. Revisiting the non-resonant Higgs pair production at the HL-LHC. *JHEP*, 07:116, 2018.

[7] Georges Aad et al. Search for non-resonant Higgs boson pair production in the $bb\ell\nu\ell\nu$ final state with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV. 2019.

[8] Jeong Han Kim, Kyoungchul Kong, Konstantin T. Matchev, and Myeonghun Park. Measuring the Triple Higgs Self-Interaction at the Large Hadron Collider. 2018.

[9] C. G. Lester and D. J. Summers. Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders. *Phys. Lett.*, B463:99–103, 1999.

[10] Michael Burns, Kyoungchul Kong, Konstantin T. Matchev, and Myeonghun Park. Using Subsystem MT2 for Complete Mass Determinations in Decay Chains with Missing Energy at Hadron Colliders. *JHEP*, 03:143, 2009.

[11] A. J. Barr, T. J. Khoo, P. Konar, K. Kong, C. G. Lester, K. T. Matchev, and M. Park. Guide to transverse projections and mass-constraining variables. *Phys. Rev.*, D84:095031, 2011.

[12] Partha Konar, Kyoungchul Kong, and Konstantin T. Matchev. $\sqrt{\hat{s}}_{min}$: A Global inclusive variable for determining the mass scale of new physics in events with missing energy at hadron colliders. *JHEP*, 03:085, 2009.

[13] Partha Konar, Kyoungchul Kong, Konstantin T. Matchev, and Myeonghun Park. RECO level $\sqrt{s}_{min}$ and subsystem $\sqrt{s}_{min}$: Improved global inclusive variables for measuring the new physics mass scale in $\not{E}_T$ events at hadron colliders. *JHEP*, 06:041, 2011.

[14] F. Maltoni, K. Paul, T. Stelzer, and S. Willenbrock. Color Flow Decomposition of QCD Amplitudes. *Phys. Rev.*, D67:014026, 2003.

[15] Jason Gallicchio and Matthew D. Schwartz. Seeing in Color: Jet Superstructure. *Phys. Rev. Lett.*, 105:022001, 2010.

[16] Morad Aaboud et al. Measurement of colour flow using jet-pull observables in $t\bar{t}$ events with the ATLAS experiment at $\sqrt{s} = 13$ TeV. *Eur. Phys. J.*, C78(10):847, 2018.

[17] Josh Cogan, Michael Kagan, Emanuel Strauss, and Ariel Schwartzman. Jet-Images: Computer Vision Inspired Techniques for Jet Tagging. *JHEP*, 02:118, 2015.

[18] Jeong Han Kim, Minho Kim, Kyoungchul Kong, Konstantin T. Matchev, and Myeonghun Park. Portraying Double Higgs at the Large Hadron Collider. *JHEP*, 09:047, 2019.

[19] Andreas Papaefstathiou, Li Lin Yang, and Jose Zurita. Higgs boson pair production at the LHC in the $b\bar{b}W^+W^-$ channel. *Phys. Rev.*, D87(1):011301, 2013.