

STUDYING THE VBF H_{jj} AND H_{jjj} HIGGS BOSON PRODUCTION IN QCD AND EFT THEORY

T.V. Obikhod, Ie.A. Petrenko

Institute for Nuclear Research NAS of Ukraine, Kyiv, Ukraine

E-mail: obikhod@kinr.kiev.ua

The discovery of the Higgs boson made it possible not only to study its physical properties and update its search strategies but also to apply new theoretical constructs to explain its properties. Within the framework of the VBF Higgs boson production process in association with two H_{jj} and three jets H_{jjj} , we modeled its kinematic properties and calculated its production cross-sections. The calculations were carried out within two theories, QCD and EFT for both SM processes and for the MSSM and NMSSM models within the framework of the BSM physics searches.

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INTRODUCTION

The advent of the LHC has transformed hadron physics into a high-precision field, where large $p_{T\$} events at large angles are not uncommon. The search for physics beyond the Standard Model (SM) implies not only the inclusion of higher-order corrections to SM processes but also a change in the search strategy based on theoretical predictions [1]. At the same time, it is necessary to have universal and accurate simulations for different models, including not only QCD theory but also others, such as the effective field theory (EFT) [2].$

The Higgs boson signal in 2012 was just the beginning of studying its properties: how strongly it interacts with other particles, to see the production and decay modes of the Higgs boson connected with the information on its couplings to elementary particles. The study of the vector-boson fusion (VBF) Higgs boson production processes is related to the accuracy of the electroweak coupling constant measurement, which is necessary to test the mechanism of spontaneous electroweak symmetry breaking. Therefore, it is extremely important to separate VBF events from other background processes, which are achieved by the signature of the VBF process: the Higgs boson is selected in association with two jets that are strongly separated in rapidity and form a two-jet system with a high invariant mass to suppress the contribution of the s-channel. Perturbative next-to-leading order (NLO) corrections to the QCD Higgs boson production event are considered, in which the two hardest jets have a rapidity of less than 4.5, which guarantees their detection in the opposite hemispheres [3].

We also study Higgs boson production via VBF in a three-jet association to match NLO-QCD calculations with the parton shower program. To describe the jet activity properties in VBF reactions, additional jets are used to suppress QCD backgrounds by central jet vetoes. Uncertainties due to parton shower effects are moderate for the third-jet distributions, in contrast to calculations for Higgs production in a two-jet association [4].

The paper contains six sections. Section 3 presents calculations of the VBF Higgs boson production cross

sections under the corresponding kinematic and mass constraints on the jets for three different models, SM, MSSM, and NMSSM. The calculations for the same processes within the EFT theory are given in section 4. The calculations for three-jet events are being reviewed in section 5. In section 6 the obtained results are analyzed, the order of magnitude of the obtained cross-sections of the processes is compared and the best model within the QCD approach is selected. The results of the EFT and QCD approximations are considered and corresponding conclusions are given.

1. STUDYING OF VBF H_{jj} PROCESS WITHIN THE FRAMEWORK OF QCD THEORY

Understanding the nature of the Higgs boson is associated with its couplings to fermions and gauge bosons [5]. Such coupling measurements are provided by the VBF processes [6], where the Higgs boson is produced via quark-scattering mediated by weak gauge boson exchange, $pp \rightarrow H_{jj}$ (Fig. 1).

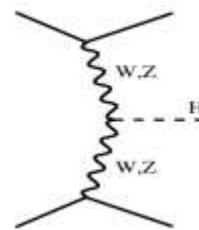


Fig. 1. Illustration of the VBF H_{jj} process

We present a VBF simulation of the Higgs boson production in association with two jets obtained at the LHC. The MadGraph5_aMC@NLO computer program [1] was used to calculate the NLO-QCD corrections. The efficiently suppressed QCD backgrounds with large cross sections to the H_{jj} production processes are significant advantages for the accuracy of computer modeling of the presented process.

We carried out modeling of the VBF Higgs boson production cross sections with appropriate kinematic restrictions [3], presented in Table 1.

Table 1
Parameter restrictions for simulations of Hjj production

Minimum p_T	20 GeV
Fixed ren scale Fixed fact scale for pdf1 Fixed fact scale for pdf2	40.21
Min invariant mass of a jet pair	400 GeV 500 GeV 600 GeV
Minimum p_T for at least one heavy final state	20 GeV
Minimum p_T for at least one jet	20 GeV
Minimum p_T for the leading jet	25 GeV
Minimum p_T for the second jet	20 GeV
Minimum p_T for the third jet	20 GeV

We carried out process modeling within the framework of QCD with and without the NNPDF30_nnlo_as_0118 pdf function. As a part of the search for physics beyond the SM, we compared the modeling of SM, MSSM, and NMSSM processes in the framework of Hjj cross-section calculations, presented in Tables 2 and 3.

Table 2
Production cross-sections for $pp \rightarrow hjj$ process within three models with pdf function

M_{mjj}	Model	13 TeV	14 TeV	100 TeV
400	SM	1.735 ± 0.009	2.001 ± 0.01	28.13 ± 0.092
	mssm	1.664 ± 0.0095	1.911 ± 0.0085	26.97 ± 0.086
	Nmssm	2.16 ± 0.012	2.492 ± 0.012	35.16 ± 0.12
500	SM	1.501 ± 0.0062	1.709 ± 0.01	
	mssm	1.431 ± 0.0067	1.64 ± 0.011	
	Nmssm	1.863 ± 0.0079	2.132 ± 0.014	
600	SM	1.285 ± 0.0074	1.491 ± 0.012	
	mssm	1.228 ± 0.0072	1.426 ± 0.01	
	Nmssm	1.6 ± 0.0089	1.86 ± 0.012	

Comparison of the obtained results presented in Tables 2 and 3 shows the highest value of the production cross-section of Hjj processes with pdf function and for Nmssm model with a limitation on the mass of the two-jet process in the region of 400 GeV. Moreover, the priority of this model is seen for all energies, 13, 14, and 100 TeV. As for calculations within this model for other invariant masses (500, 600 GeV), the software we use does not allow us to perform these calculations for the energy at the 100 TeV collider.

To understand the kinematics of the process and to ensure the correctness of the chosen kinematic constraints, simulations of the distribution of transverse momentum and rapidity were carried out in Figs. 2, 3.

Table 3
Production cross-sections for $pp \rightarrow hjj$ the process within three models without pdf function

M_{mjj}	Model	13 TeV	14 TeV	100 TeV
400	SM	1.563 ± 0.007	1.778 ± 0.0062	23.28 ± 0.077
	mssm	1.498 ± 0.0067	1.708 ± 0.0062	22.16 ± 0.074
	Nmssm	1.948 ± 0.0088	2.228 ± 0.011	28.96 ± 0.099
500	SM	1.362 ± 0.0054	1.542 ± 0.009	
	mssm	1.302 ± 0.0066	1.48 ± 0.0098	
	Nmssm	1.692 ± 0.0077	1.915 ± 0.011	
600	SM	1.168 ± 0.0061	1.348 ± 0.0082	
	mssm	1.119 ± 0.006	1.293 ± 0.0086	
	Nmssm	1.456 ± 0.0073	1.683 ± 0.011	

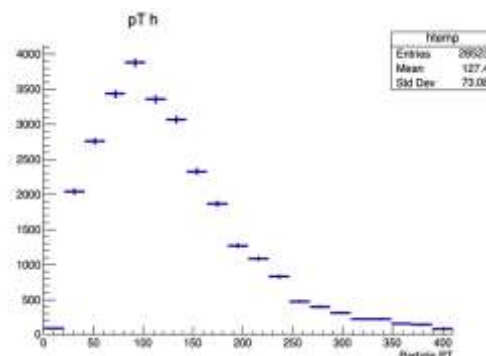


Fig. 2. Transverse momentum distributions for the $pp \rightarrow hjj$ process at 14 TeV

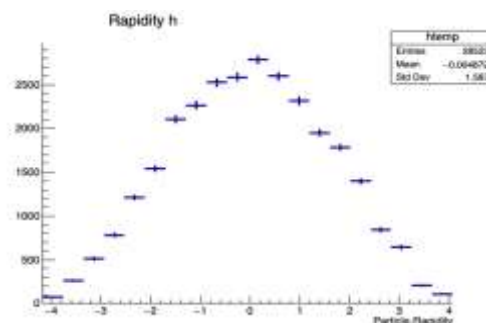


Fig. 3. The distribution for the rapidity for $pp \rightarrow hjj$ process at 14 TeV

The results of the modeling demonstrate the peripheral nature of the process under consideration and the clear dependence of the number of events on the value of the transverse momentum.

2. STUDYING OF VBF HJJ PROCESS IN EFT THEORY

EFT is an approach in theoretical physics based on the idea of describing physical phenomena for any pre-selected energy scale, from the minimum to the maximum energy scale. This theory is convenient for describing various sections of physics, including elementary particle physics. As a more the fundamental theory is lacking it is necessary to resort to an EFT description of a physical system, which has next advantages:

- EFT radically simplifies calculations by ignoring aspects that are not important for the problem at hand;
- By extracting the appropriate degrees of freedom, new symmetries may emerge that would otherwise remain hidden;
- When working with problems that have several different scales, EFTs allow us to focus on one scale to perform RG summations of large logarithms;
- EFT is convenient because if perturbation theory fails, you can pick up other degrees of freedom within the new EFT.

Notably, EFT with massive fields finds a broad range of applications in particle physics, including quantum chromodynamics, high spin particles, and dark matter candidates. This method is agnostic to how electroweak symmetry is broken, so the consideration of mass eigenstates allows the formulation of EFT to be much simpler and more convenient for phenomenological applications. In the framework of the Higgs effective field theory [2] we considered its link to a few scenarios of physics beyond the SM and received the production cross-sections presented in Table 4

Table 4
Production cross sections for $pp \rightarrow hjj$ process with pdf function within EFT theory

M_{mjj}	Model	13 TeV	14 TeV	100 TeV
400	SM	1.73 ± 0.0083	1.996 ± 0.01	28.25 ± 0.084
	mssm	1.663 ± 0.0092	1.917 ± 0.0094	26.96 ± 0.083
	Nmssm	2.162 ± 0.012	2.489 ± 0.012	35.14 ± 0.12
500	SM	1.498 ± 0.0065	1.996 ± 0.01	
	mssm	1.427 ± 0.0063	1.64 ± 0.011	
	Nmssm	1.859 ± 0.0089	2.132 ± 0.01	
600	SM	1.498 ± 0.0065	1.492 ± 0.012	
	mssm	1.225 ± 0.007	1.424 ± 0.0096	
	Nmssm	1.593 ± 0.0088	1.853 ± 0.011	

The analysis of the obtained results shows that the cross-sections of Tables 2 and 4 almost coincide for all

models and at all levels. However, for the SM, a significant increase in the cross-section for the EFT is observed at an invariant mass of the two-jet state of 600 GeV at an energy at the collider of 13 TeV

3. STUDYING OF VBF Hjjj PROCESS WITHIN THE QCD THEORY

The observation of two forward tagging jets in Higgs production via the VBF at the LHC is crucial for background suppression. In addition to forward tagging jets, the veto of any additional jet activity in the central region leads to further suppression of QCD backgrounds. If any additional jet with momentum higher than the minimum value p_T is detected in addition to the two forward tagging jets, the events are discarded [7].

We present a realization of Higgs boson production via VBF in association with three jets. We accurately described the properties of the additional jet in VBF reactions to suppress QCD backgrounds in Table 1. Due to the low virtuality of the exchanged weak bosons, the tagging jets arising from the scattered quarks are located in the front and back regions of the detector, while the central region exhibits little jet activity due to the t-channel exchange. These features can be used to suppress QCD backgrounds with a large cross-section at the LHC. Feynman diagrams of such processes are shown in Fig. 4.

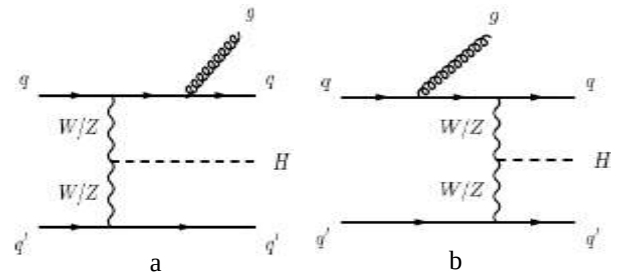


Fig. 4. Tree-level diagrams for VBF Hjjj production

The inclusion of the constraints presented in Table 1 and the use of the MadGraph5_aMC@NLO computer program makes it possible to calculate the cross sections of the three-jet processes, Table 5.

Comparison of the obtained data for three-jet events with the data in Table 2 for two-jet processes leads us to the conclusion about the same nature of the behavior of the obtained data (with minor exceptions), i.e.: a decrease in the cross-section of the process with an increase in the invariant mass of the two jets; an increase in the cross-section with an increase in the energy at the collider from 13 to 100 TeV; the largest value of the cross-section for the Nmssm model.

We compared our calculations with the data from the articles [1, 7] and found a good match in the order of magnitude for both two-jet and three-jet events. Moreover, the cross-section value of three-jet events is two orders of magnitude smaller than that of two-jet events, which confirms the level of influence of three-jet constraints on the cross-section of the process Hjjj.

Table 5
Production cross-sections for $pp \rightarrow hjjj$ process with pdf function within three models with pdf function

M_{mjj}	Model	13 TeV	14 TeV	100 TeV
400	SM	$0.0056 \pm 3.6e-05$	$0.0071 \pm 4.8e-05$	0.4203 ± 0.0018
	mssm	$0.005269 \pm 3.6e-05$	$0.006554 \pm 4.7e-05$	0.3979 ± 0.002
	Nmssm	$0.00695 \pm 4.8e-05$	$0.008677 \pm 6.4e-05$	0.5306 ± 0.0019
500	SM	$0.00555 \pm 3.6e-05$	$0.002748 \pm 2e-05$	0.2192 ± 0.0009
	mssm	$0.001998 \pm 1.3e-05$	$0.002599 \pm 1.8e-05$	0.2088 ± 0.00095
	Nmssm	$0.002663 \pm 1.6e-05$	$0.003436 \pm 2.6e-05$	0.2773 ± 0.0013
600	SM	$0.0008912 \pm 6.1e-06$	$0.001149 \pm 7.2e-06$	0.1242 ± 0.00055
	mssm	$0.0008457 \pm 5.8e-06$	$0.001082 \pm 6.6e-06$	0.1169 ± 0.00048
	Nmssm	$0.001115 \pm 7.9e-06$	$0.001436 \pm 8.6e-06$	0.1553 ± 0.00066

CONCLUSIONS

In the context of studying the properties of the Higgs boson, we presented two processes of its VBF formation: two-jet and three-jet. Comparison of the obtained results showed that our calculations coincided by order of magnitude with the calculations of other scientists for both types of processes. In addition, we carried out modeling of the BSM theories and found that the largest cross section is for the Nmssm model.

Comparison with the EFT, which is popular recently due to its flexibility and universality, led us to the conclusion that the cross sections of the Higgs boson production calculated within the framework of this theory are larger for the EFT SM model compared to the SM QCD calculations. The kinematic distributions constructed by us confirmed a strict dependence on the transverse momentum value and indicated a large number of events at large angles.

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ВИВЧЕННЯ ВЕКТОРНОГО БОЗОННОГО ЗЛИТТЯ H_{jj} ТА H_{jjj} БОЗОНА ХІГСА У КХД- ТА EFT-ТЕОРІЇ

Т.В. Обіход, Є.О. Петренко

Відкриття бозона Хігса дозволило не тільки вивчити його фізичні властивості та оновити стратегії пошуку, але й застосувати нові теоретичні конструкції для пояснення його властивостей. У рамках процесу утворення бозона Хігса VBF у поєднанні з двома H_{jj} і трьома струменями H_{jjj} ми змоделювали його кінематичні властивості та розраховували поперечні перерізи. Розрахунки проводилися в рамках двох теорій КХД і EFT для моделі SM та для моделей MSSM і NMSSM у рамках пошуків фізики BSM.