T.V. OBIKHOD, I.A. PETRENKO

Institute for Nuclear Research, Nat. Acad. of Sci. of Ukraine
*(47, Prosp. Nauky, Kyiv 03680, Ukraine; e-mail: obikhod@kinr.kiev.ua)*

UDC 539.120

# MASS RECONSTRUCTION OF MSSM HIGGS BOSON

*The problems of the Standard Model, as well as questions related to Higgs boson properties led to the need to model the ttH associated production and the Higgs boson decay to a top quark pair within the MSSM model. With the help of computer programs MadGraph, Pythia, and Delphes and using the latest kinematic cuts taken from experimental data obtained at the LHC, we have predicted the masses of MSSM Higgs bosons, A and H.*

*Keywords*: MSSM Higgs boson, top quark, $b$-tagging, computer modeling, the mass of a Higgs boson.

## 1. Introduction

The study of the properties of a Higgs boson discovered in 2012 is one of the main objectives of the LHC [1]. The importance of the experiments is related to the refinement of the channels of formation and decay of the Higgs boson, which shows that there are deviations of more than $2\sigma$ from the Standard Model (SM). Such data, together with the theoretical predictions of new physics, such as supersymmetry and the theory of extra dimensions, lead to the need to model the properties of the Higgs boson beyond the SM (BSM) such as production cross sections, angular distributions, and masses of supersymmetric Higgs bosons.

The existence of SM problems related to the impossibility of combining gravity with the other three types of interactions, the problem of radiative corrections to the Higgs boson mass, neutrino oscillations, and dark matter and dark energy problems lead to the introduction of new theories, one of which is supersymmetry. There are many supersymmetric theories. We will further use Minimal Supersymmetric Standard Model (MSSM) for the prediction of new supersymmetric particles – superpartners of the Higgs boson. The advantage of such a search lies not only in the possibility of going beyond the framework of the SM, but also in the small mass of the Higgs superparticles provided by the new theories. Such searches could be implemented both at the existing LHC collider, and at future accelerators of the type ILC or FCC. To establish a deviation from the SM behavior, the next goal is to identify the nature of the electro-weak symmetry breaking (EWSB), which is connected with properties of the top quark and Higgs boson interactions. Predictions for the coupling of the Higgs boson to top quarks directly influence the measurements of the production and decay rates and angular correlations. Therefore, this information can be used to study whether the data are compatible with the SM predictions for the Higgs boson. Since the QCD and electroweak gauge interactions of top quarks have been well established, the top Yukawa coupling might differ from the SM value. Therefore, the measurement of the $ttH$ production rate and the $tt$ decay of an $A$ boson can provide a direct information about the top-Higgs Yukawa coupling, probably the most crucial coupling to fermions. The anomalous interaction of the Higgs boson with the top quark, has been experimentally studied through the measurement of the Higgs boson production in association with a top quark, [2]. According to the combined analysis of the experimental data at the LHC, the constrain on the top quark Yukawa coupling, $y_t$, within $[-0.9, -0.5]$ and $[1.0, 2.1] \times y_t^{\mathrm{SM}}$ were obtained. Recent ATLAS Higgs results using Run-2 data at a center-of-mass energy of 13 TeV with up to an integrated luminosity of 80 fb$^{-1}$ to probe BSM coupling for the $tH + ttH$ processes [3] showed that the Higgs boson will continue to provide an important probe for new physics and beyond.

To implement the searches for the MSSM Higgs bosons and to facilitate their findings, we chose a specific search channels and the methods by which the corresponding superparticles were identified. Using the latest experimental data for the $ttH$ production of a Higgs boson [4], $b$-tagging algorithm, MadGraph,

---

Pythia, and Delphes programs, and latest kinematic cuts we predicted the masses of superparticles, $A$ and $H$.

## 2. B-Tagging Identification and Reconstruction of MSSM Higgs Boson Masses

The top-quark Yukawa coupling $y_t$ is parametrized as

$$L_{Htt} = -\frac{m_t}{v} H\bar{t}(a_t + ib_t\gamma_5)\, t,$$

where $m_t$ is the top-quark mass, $v = 174$ GeV is the vacuum expectation value, and the coefficient $a$ ($b$) denotes the CP-even (CP-odd) coupling, respectively.

Examples of Feynman diagrams for the considered $tt$ and $ttH$ processes are presented in Fig. 1.

It is necessary to reconstruct as many final particles as possible for the disentanglement of decay products of the exotic particles from the SM background. The $B$-tagging identification connected with $b$-quark signatures has following features and benefits for the experimental determination of primary particles:

- hadrons containing $b$-quarks have sufficient lifetime;
- presence of a secondary vertex (SV);
- tracks with large impact parameter (IP);
- the bottom quark is much more massive, with mass about 5 GeV, and thus its decay products have higher transverse momentum;
- $b$-jets have higher multiplicities and invariant masses;
- the $B$-decay produces often leptons.

We carried out a comprehensive computer modeling of the MSSM Higgs boson mass using MadGraph, Pythia, and Delphes programs. With the help of the program MadGraph, we carried out a calculation of the production cross-sections of the processes under consideration. The simulation of further developments, i.e. all information on decomposition products and their kinematic data, was produced using the Pythia program. In our calculations with the Pythia program, we used the latest experimental constraints on the low $\tan\beta$ region covered by the $ttH$, $H \to tt$ processes [5]. The calculation of the response of a detector to the resulting array of events was carried out using the Delphes program. We made a selection of events on the basis of additional kinematic restrictions associated with the peculiarities of the reactions under consideration and the $b$-tagging method.

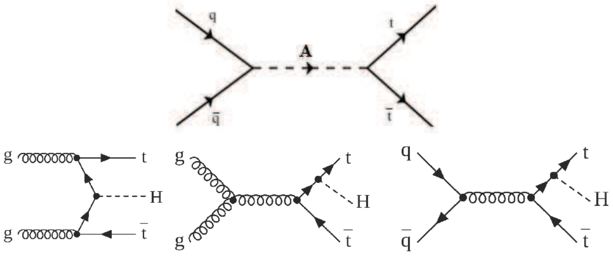

***Fig. 1.*** Examples of Feynman diagrams for the $pp \to A$ (up) and $pp \to ttH$ (down) production process from [4]

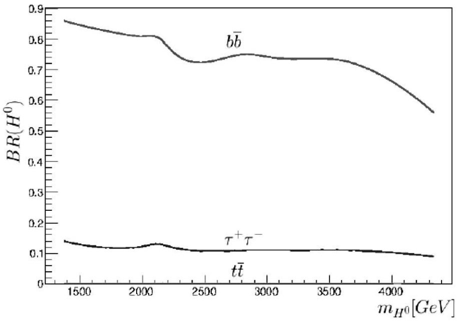

***Fig. 2.*** Branching ratios of $H$ to $bb$ (red), $\tau^+\tau^-$ (blue), and $tt$ (green)

Let us consider these processes separately and in more details.

### *2.1. pp → A → tt process*

The importance of the formation of a top quark pair is associated both with the possibility of a good identification of top quarks using the $b$-tagging algorithm and with the search for new physics due to the Yukawa constants of the top-quark and Higgs boson interaction [6]. The SM makes predictions for the coupling of the Higgs boson to a top quark. Therefore, the measurement of the decay rates of the observed state yields the information which can be used to probe whether data are compatible with the SM predictions for the Higgs boson. Loop-induced vertices allow probing for BSM contributions of new particles in the loops. In addition, it must be said that the the measuring of the properties of top pair quarks also sheds light on the stability of the electroweak vacuum [7]. The importance of this section is connected with the improvement of the searches for $H \to tt$ by studying the fully leptonic and semileptonic final states [8]. The results of our calculations presented in [9] are shown in Fig. 2.

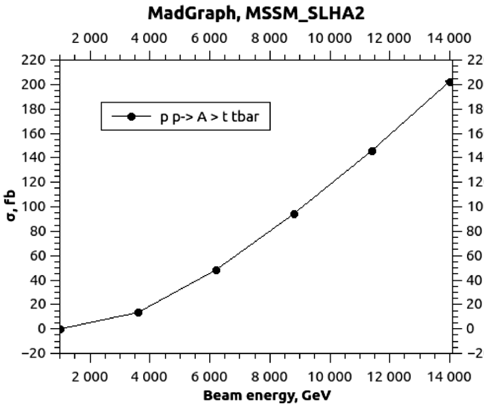

***Fig. 3.*** Production cross section of the $pp \to A \to t\bar{t}$ process

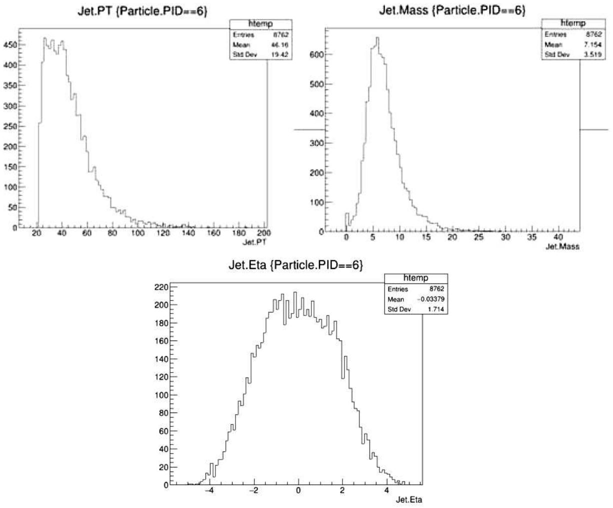

***Fig. 4.*** Modeling of kinematic properties of jets from the reaction $pp \to A \to tt$: jet $\mathrm{p}_T$ distribution (left) and jet mass (right) (*a*); jet $\eta$ distribution (*b*)

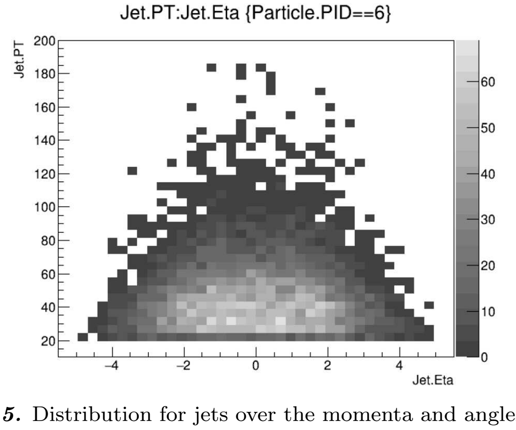

***Fig. 5.*** Distribution for jets over the momenta and angles for the reaction $pp \to A \to tt$

The most probable decay channels for a CP-even boson, $H$, are the following:

- bb;
- $\tau^+\tau^-$;
- $t\bar{t}$.

We are dealing with massive MSSM particles which prefer to decay into the most massive decay products, for example, into a top-anti-top quark pair. So, we will consider the decay of the CP-odd Higgs boson into a top-anti-top quark pair, $A \to t\bar{t}$. With the help of the program MadGraph, we calculated the production cross-section of the $pp \to A \to t\bar{t}$ process presented in Fig. 3.

The increase of the production cross-section with the energy at the LHC and its large value for the formation of an $A$ boson, about 0.2 pb at the energy of 14 TeV, lead to the conclusion about the importance of the consideration of this channel of formation and decay of the MSSM Higgs boson. Kinematic properties of decay products of $A$ boson at the energy 14 TeV were modeled and presented in Fig. 4.

From Fig. 4, we see that jet $p_T$ is maximal in the region of 30–50 GeV/c and then sharply decreases in the region of 120–140 GeV/c. The average jet mass is about 5–7 GeV/c, which is in accordance with the mass of the $b$-quark, into which the top quark decays with a probability of 99.8%. The angular distribution of the decay products shown in Fig. 4, $b$ indicates the predominant direction of the decay products in the direction of angles from 35° to 90° to the axis of the proton-proton collision. In Fig. 5, we present the distribution for jets over the momenta and angles.

Using the distribution of Fig. 5, we can pick out the most high-energetic jets and present their separation in Fig. 6.

Using the data of Fig. 6, we can predict the mass of the $A$ boson, which is about 360 GeV/c, since the momentum is equal to the mass at high energies.

### *2.2. ttH production process*

We considered a combined analysis of proton-proton collision data at center-of-mass energies of $\sqrt{s} = 7$, 8, and 13 TeV, corresponding to integrated luminosities up to 5.1, 19.7, and 35.9 fb$^{-1}$, respectively. In this experiment, the observation of the $ttH$ production with a significance of 5.2 standard deviations above the background-only hypothesis, at a Higgs boson mass of 125.09 GeV was reported in [4]. Then we consid-

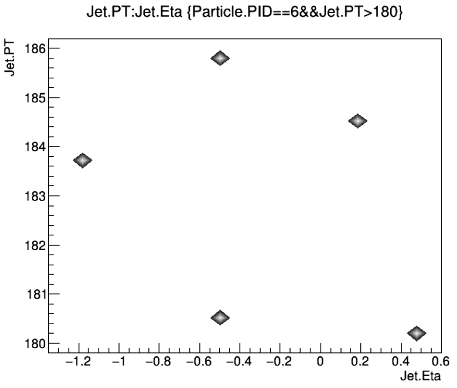

***Fig. 6.*** The most energetic jets in the $p_T$ range 180–186 GeV/c and the jet $\eta > |1.2|$ for the reaction $pp \to A \to tt$

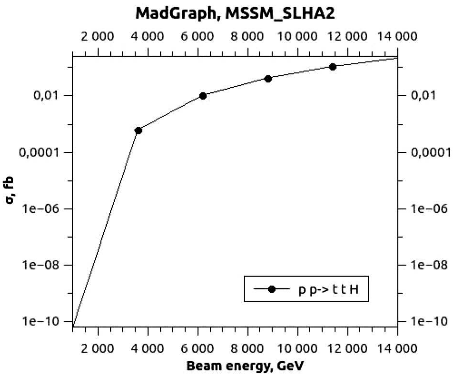

***Fig. 7.*** Production cross-section of the $pp \to Htt$ process as a function of the energy range at the LHC

ered the decay process of the Higgs boson, $H \to bb$, as the most probable [9].

Using the program MadGraph, we calculated the production cross-sections $pp \to Htt$ of a Higgs boson via the proton-proton interaction. Our calculations for the range of 2–14 TeV at the LHC are presented in Fig. 7.

With the program Pythia, we simulated a further development of events. The detector response to the received array of events was modeled by the program Delphes. Thus, our simulation was maximally close to the experimental conditions.

The results of calculations of the jet mass range and the eta distribution of jets are presented in Fig. 8. The events were selected with the following cuts: the number of jets, $N_{\text{charged}} >$ or $\sim$4, transverse momentum, $p_T > 80$ GeV, $B_{\text{tag}} = 1$, mass of one $b$-jet, $M > 4$ GeV. From the jet distribution in Fig. 4, we conclude that the mass of jets of about 16–20 GeV for the minimal number of jets equal to 4 corresponds to the $b$-jet distribution and to the corresponding angular distribution of jet flux signals about the selected distribution of the jet flow in the direction perpendicular to the proton collision axis with $\theta \sim 40°–90°$.

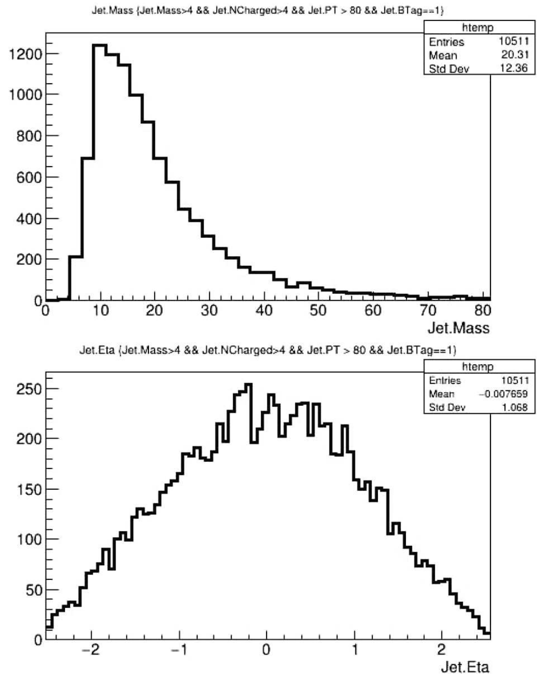

***Fig. 8.*** Modeling of the jet mass range ($a$) and the angular distribution of jets ($b$)

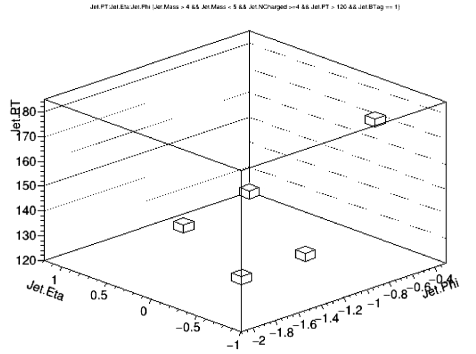

***Fig. 9.*** Modeled angular and $p_T$ jet distributions

As a result of the detector response calculations for the process $pp \to Htt \to Hbbbb$ with $N = 5000$ initial events and corresponding cross section of about 0.517 fb at 14 TeV at the LHC, we get the angular and $p_T$ jet distributions presented in Fig. 9.

We have used together the following kinematic constraints: rapidity $-0.5 < y < 0.5$, mass of jets of about $4 < M < 5$ GeV, number of charge jets, $N_{\text{charged}} > 4$, transverse momentum, $p_T > 120$ GeV, parameter of the MSSM model, $M_H \sim 500$ GeV. Thus, we selected the toughest and most massive jets that can be formed from the decay process of the CP-even Higgs boson of the MSSM model. As we can see from Fig. 9, the approximate mass of one jet is about 150–170 GeV/c. We used the fact that each of the protons has an energy of 7 TeV, giving a total collision energy of 14 TeV. At this energy, the protons move at about 0.999999990 of the speed of light. Knowing the most probable Higgs boson decay channel, $H \to bb$, we conclude that the mass of the CP-even Higgs boson is about 300–340 GeV/c.

## 3. Conclusions

We have considered the most important channels of the MSSM Higgs boson production and decay. Since these channels are associated with the formation and decay of top quarks, whose properties shed light on the instability of the electroweak vacuum, the study of such reactions seems the most relevant to us. In addition, the MSSM Higgs bosons are the lightest supersymmetric particles predicted by supersymmetry. Therefore, finding their masses at the LHC collider is possible in the near future, which would remove a lot of theoretical questions related to the symmetries and unification of interactions. Using the programs MadGraph, Pythia, and Delphes to simulate the processes and to model the response of a detector, as well as strict kinematic cuts on the angles and momenta of particles taken from the experimental data, we have calculated the masses of the $A$ boson equal to 360 GeV/c and $H$ boson equal approximately to 320 GeV/c.

*Our thanks to the organizers of the conference "New Trends in High-Energy Physics," Odessa, Ukraine May 12–18, 2019 and, in particular, to Laszlo L. Jenkovszky for organizing an important scientific event on topical issues of high-energy physics.*

1. Y. Liu, S. Moretti. Probing anomalous top-Higgs couplings at the HL-LHC via $H \to WW^*$ decay channels. *Chin. Phys. C* **43** (1), 013102 (2019).
2. R. Goncalo. Recent highlights in top quark and Higgs boson physics from the LHC. *J. Phys.: Conf. Series* **1137**, 012012 (2019).
3. W. Leight. Studies of the SM Higgs Boson and Searches for BSM Higgs Bosons with the ATLAS Detector. *Acta Phys. Polon. B Proc. Sup.* **9** (3), 561 (2016).
4. CMS Collaboration. Observation of $ttH$ production. *Phys. Rev. Lett.* **120**, 231801 (2018).
5. C. Gao, M. Luty, M. Mulhearn, N. Neill, Z. Wang. Searching for additional Higgs bosons via Higgs cascades. *Phys. Rev. D* **97** (7), 075040 (2018).
6. LHC Higgs Cross Section Working Group. Handbook of LHC Higgs Cross Sections: 3. Higgs Properties. arXiv:1307.1347 [hep-ph].
7. S. Alekhin, A. Djouadi, S. Moch. The top quark and Higgs boson masses and the stability of the electroweak vacuum. *Phys. Lett. B* **716**, 214 (2012).
8. M. Guchait, A. Vijay. Probing heavy charged Higgs boson at the LHC. *Phys. Rev. D* **98** (11), 115028 (2018).
9. T.V. Obikhod. Experimental searches for the extended Higgs sector at the LHC. *Prob. Atom. Sci. Technol. Series: Nucl. Phys. Invest.* **67**, 3 (2016).

Received 08.07.19

*Т.В. Обіход, Е.О. Петренко*

### РЕКОНСТРУКЦІЯ МАСИ MSSM БОЗОНА ХІГГСА

Резюме

Проблеми Стандартної Моделі, а також питання, пов'язані з властивостями бозона Хіггса, призвели до необхідності моделювання $ttH$ асоційованого утворення і розпаду бозона Хіггса на топ кваркову пару в рамках MSSM моделі. За допомогою комп'ютерних програм MadGraph5, Pythia8 і Delphes3 та використання останніх кінематичних обмежень, взятих з експериментальних даних, отриманих на LHC, ми передбачили маси MSSM бозонів Хіггса, $A$ і $H$.