THE STUDY OF THE PROPERTIES OF THE EXTENDED HIGGS BOSON SECTOR WITHIN hMSSM MODEL

T. V. Obikhod [*]***, E. A. Petrenko***

Institute for Nuclear Research National Academy of Sciences of Ukraine, 03028 Kyiv, Ukraine

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Using the latest experimental data, performed by ATLAS Collaboration and within the framework of the Minimal Supersymmetric Standard Model, we presented the calculations for cross sections times branching fractions, $\sigma \times Br$, as a functions of the CP-even, H, Higgs boson mass, CP-odd, A, Higgs boson mass and charged, $H^{\pm}$, Higgs boson mass. Using the restricted parameter set, received from the hMSSM+HDECAY and "low-tb-high" scenarios, with the help of the computer programs SOFTSUSY, Prospino and SusHi, we received the large values of $\sigma \times Br$ for A and H bosons at tanβ=2 for the planned 14 TeV at the LHC and found the large $\sigma \times Br$ at tanβ=30 for charged Higgs boson. The obtained results are of experimental interest as they are connected with the experimental searches for new physics beyond the Standard Model at the LHC.

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1. INTRODUCTION

The searches for supersymmetry (SUSY) are motivated by the solutions of the most important problems: the hierarchy problem, gauge coupling unification and dark matter problem [1]. Experimental searches for SUSY in the most probable channels for the superparticle production at the LHC did not lead to the desired results and set new lower limits in the mass range about 2 TeV for gluino and squarks [2]. This fact led to the need for SUSY searches in other sectors, for example, in the electroweak sector. As highlighted in CERN Courier [3]: "Based on data recorded in 2016, CMS has covered models of electroweak production of "wino"-like charginos and neutralinos with searches in different final states.

More results are expected soon, and the sensitivity of the searches will largely profit from the extension of the data set in the remaining two years of LHC Run 2". Another important sector for SUSY searches in low mass range of 1 TeV are the searches for extended Higgs boson sector predicted by Minimal Supersymmetric Standard Model (MSSM) [4], that consists of five Higgs bosons: CP even Higgs bosons, h and H, CP odd Higgs boson, A, charged Higgs bosons, $H^{\pm}$.

The purpose of our paper is to calculate the production cross section of such particles at the energy of 14 TeV at the LHC in the most optimal space of parameters of the MSSM model.

2. OPTIMAL PARAMETER SPACE FOR STUDYING OF THE PROPERTIES OF MSSM HIGGS BOSONS

The masses of five Higgs bosons of MSSM model at tree level are calculated through the masses of gauge boson, M_W, M_Z, and two additional parameters such as the pseudoscalar mass, M_A and the ratio of vacuum expectation values of two Higgs doublets, tan$\beta \equiv \upsilon_u/\upsilon_d$ [5]:

$$M^2_{H^{\pm}} = M^2_A + M^2_W \ ,$$

$$M^2_{h,H} = \frac{1}{2}\left(M^2_A + M^2_Z \mp \sqrt{(M^2_A+M^2_Z)^2 - 4M^2_A M^2_Z \cos^2 2\beta} \right) .$$

In the paper [6] the theoretical predictions of the MSSM Higgs particles in the low tanβ regime, $1 \leq$tan$\beta \leq 3$ are reviewed, with the assumption that SUSY should be in the range of 1 TeV. It was showed that the heavier MSSM neutral H/A and charged $H^{\pm}$ states can decay into gauge bosons, lighter Higgs bosons and top quarks, presented in Fig.1.

In the Handbook of LHC Higgs cross sections, 2017 [5] are given examples of sensitivity on the [tanβ, M_A] parameter space for the "model independent" hMSSM approach [6], compared to the second approach [7] so called "low-tb-high" approach in the MSSM, that is orthogonal to the one previous. Relative differences in BR(H→ WW) between the predictions of the "low-tb-high" scenario and the corresponding predictions obtained with the hMSSM+HDECAY combination are presented in Fig.2.

[*]Corresponding author E-mail address: obikhod@kinr.kiev.ua

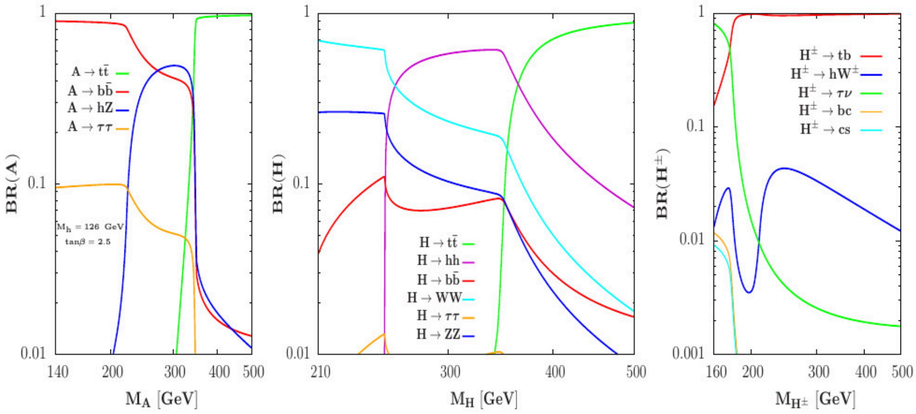


Fig.1. *The branching ratios as functions of masses of MSSM Higgs bosons (A left, H center, $H^{\pm}$ right) for tanβ=2.5, from [6]*

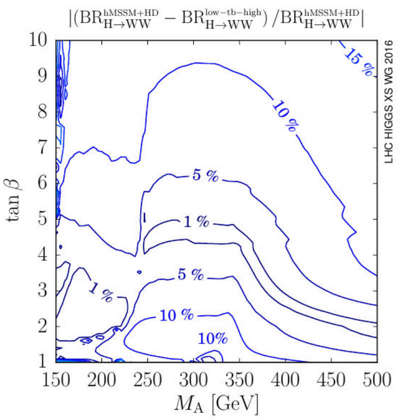


Fig.2. *Relative differences in BR(H→WW) between the hMSSM+HDECAY scenario and the "low-tb-high" scenario, from [5]*

The results of ATLAS [8] and CMS [9] Collaborations excluded at the 95% confidence level (CL) a significant part of the [tanβ, M_A] plane. We'll use the benchmark scenarios of the model independent approach for the Higgs sector, the hMSSM with M_h = 125 GeV for the experimental limits on the cross sections times branching ratios in the context of the MSSM [10]. The results for the branching fractions received with the program HDECAY [11] for the Higgs decays in the [tanβ, M_A] plane are displayed in Fig.3 with red area for the large decay rates and blue area for the small one.

The production cross sections for A and H bosons are displayed in Fig.4 in the [tanβ, M_A] hMSSM parameter space for 14 TeV at the LHC.

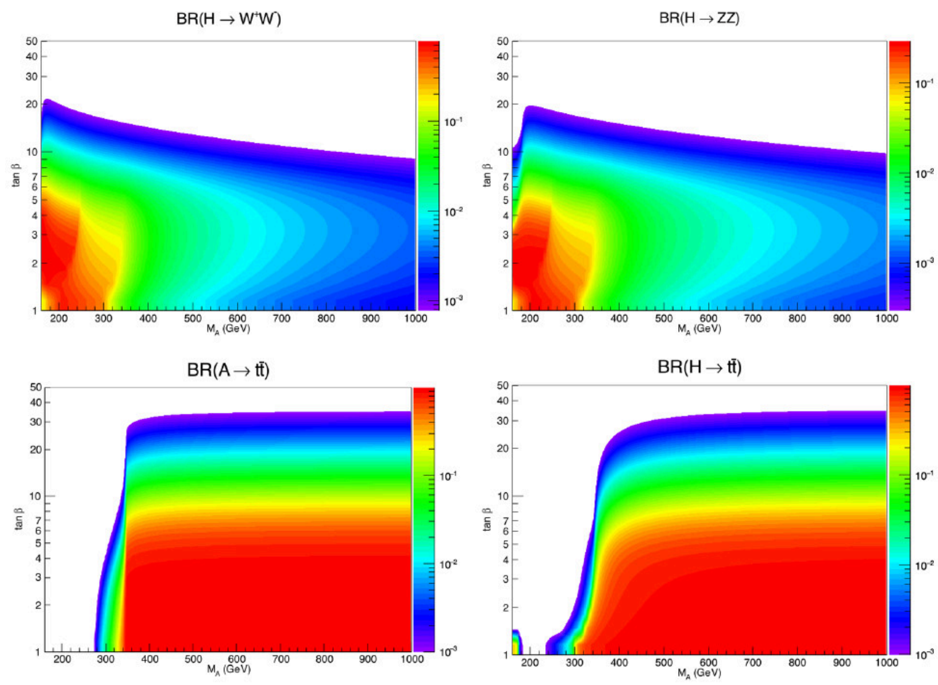


Fig.3. *The branching ratios of the neutral Higgs bosons in the [tanβ; M_A] parameter space of the hMSSM model, from [12]*

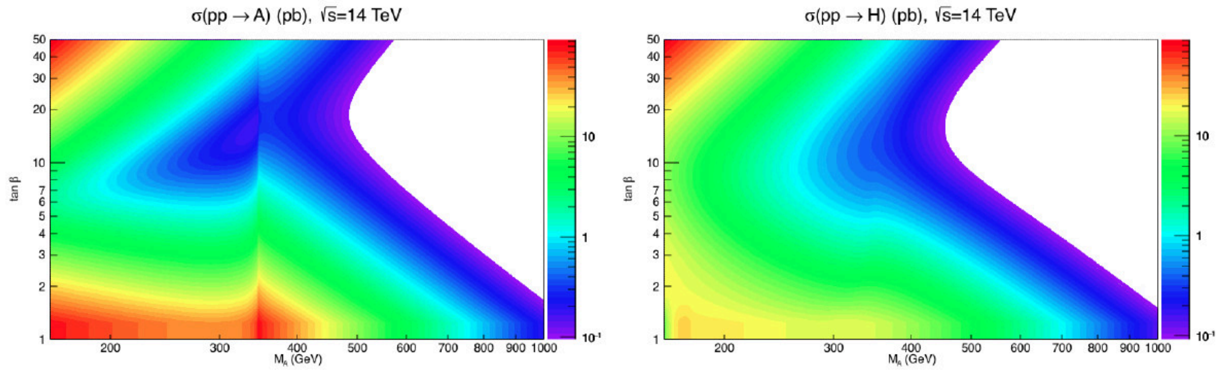
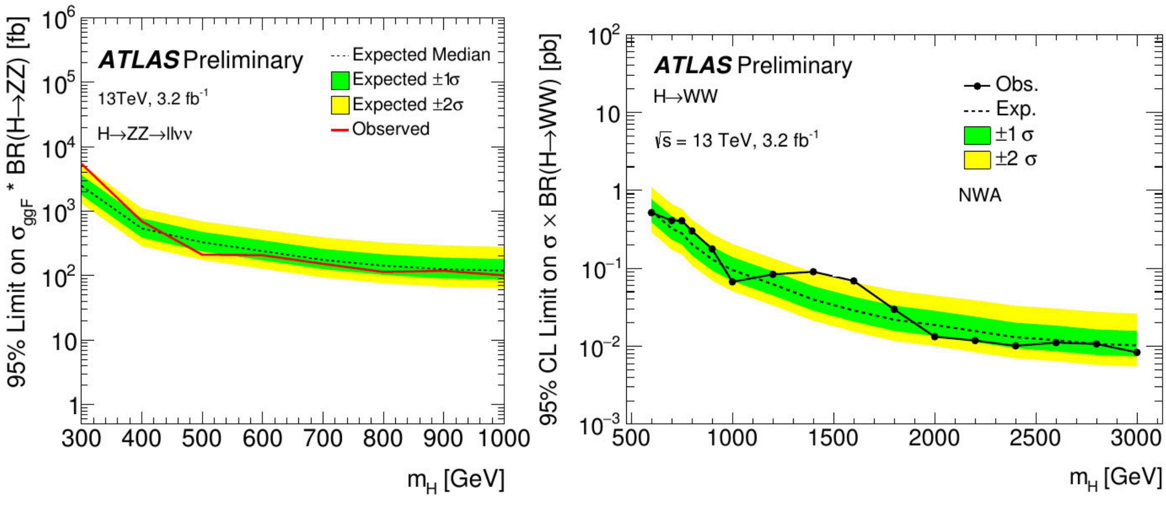


Fig.4. *The production cross sections of the Higgs bosons A (left) and H (right) at the LHC with $\sqrt{s}$=14 TeV in the [tanβ; M_A] hMSSM plane, from [12]*

3. CALCULATIONS OF THE PRODUCTION CROSS SECTIONS TIMES BRANCHING FRACTIONS FOR HIGGS BOSONS

1) CP-even Higgs boson, H.

Searches for heavy Higgs bosons by Run-2 ATLAS Collaboration at the LHC in the $H \to ZZ$ and $H \to WW$ decay channels are relevant due to the possibility of evidence for new particles beyond the Standard Model. The limits on $\sigma(pp \to H) \times BR(H \to ZZ)$ and $\sigma(pp \to H) \times BR(H \to WW)$ at 95% CL from [13] and [14] correspondingly are presented in Fig.5.



(a) (b)

Fig.5. *Limits on $\sigma(pp \to H) \times BR(H \to ZZ)$ (a) and $\sigma(pp \to H) \times BR(H \to WW)$ (b) via gluon-gluon fusion at 95% CL*

Using the restricted parameter set for [tanβ; M$_A$] plane, presented in the previous section and computer programs SusHi [15] and SOFTSUSY4.0 [16], we calculated $\sigma(pp \to H) \times BR(H \to ZZ)$ and $\sigma(pp \to H) \times BR(H \to WW)$ for $\sqrt{s}$=14 TeV at the LHC, presented in Fig.6.

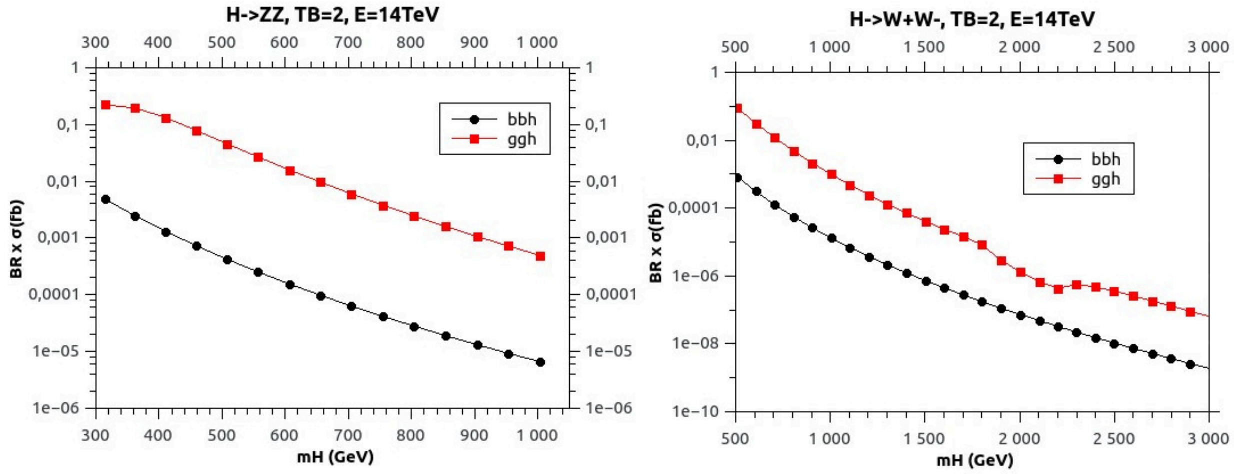


Fig.6. *$\sigma(pp \to H) \times BR(H \to ZZ)$ (left) and $\sigma(pp \to H) \times BR(H \to WW)$ (right) for $\sqrt{s}$=14 TeV at the LHC*

From Fig.6 we can see the increase in value $\sigma \times Br$ for ggh fusion process compared with bbh fusion process of heavy Higgs boson, H production. Since the branching ratios for the decays $H \to bb$ and $H \to tt$ are significant values according to our calculations with SOFTSUSY4.0 program, we have performed calculations of $\sigma(pp \to H) \times BR(H \to tt)$ and $\sigma(pp \to H) \times BR(H \to bb)$ for the planned at the LHC energy of 14 TeV, presented in Fig.7.

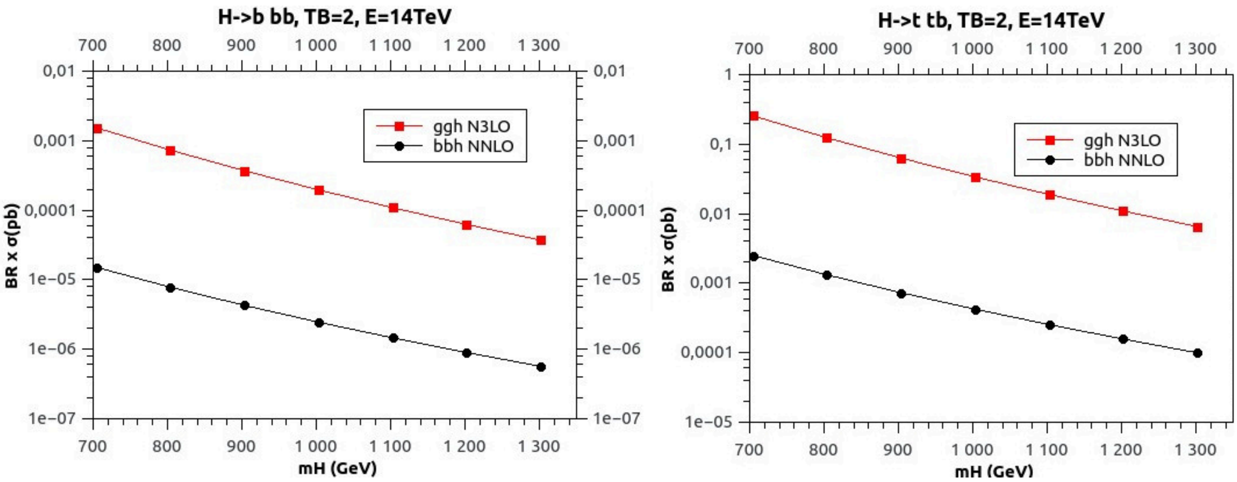


Fig.7. *$\sigma(pp \to H) \times BR(H \to bb)$ (left) and $\sigma(pp \to H) \times BR(H \to tt)$ (right) for $\sqrt{s}$=14 TeV at the LHC*

From the comparison of our calculations, presented above, we can see significant predominance of the values $\sigma \times Br$ for the second variant (see Fig.7) compared to the first one (see Fig.6). It is also important to stress the necessity of N3LO calculations for essential enlargement of the $\sigma \times Br$ value.

2) CP-odd Higgs boson, A.

In this section we have considered the following decay processes of A boson: $A \to bb$ and $A \to tt$. The consideration of these processes of A boson decay is connected with the large value of branching ratio, that is represented in Fig.1. As we have calculated the process $A \to Zh$ in [17] and currently there are no other experimental data, for future experimental searches it was of interest to perform calculations for the two other decay channels from the three maximal. Using the computer programs SOFTSUSY4.0 and SusHi, we have performed the calculations of $\sigma \times Br$ for CP-odd Higgs boson, A. As the branching ratio for A boson is maximal for the decays $A \to bb$ and $A \to tt$ in the selected set of parameters, it was interesting to calculate $\sigma \times Br$ for this both processes over a wide range of boson masses, from 500 GeV to 3450 GeV. The results of our calculations are presented in Fig.8.

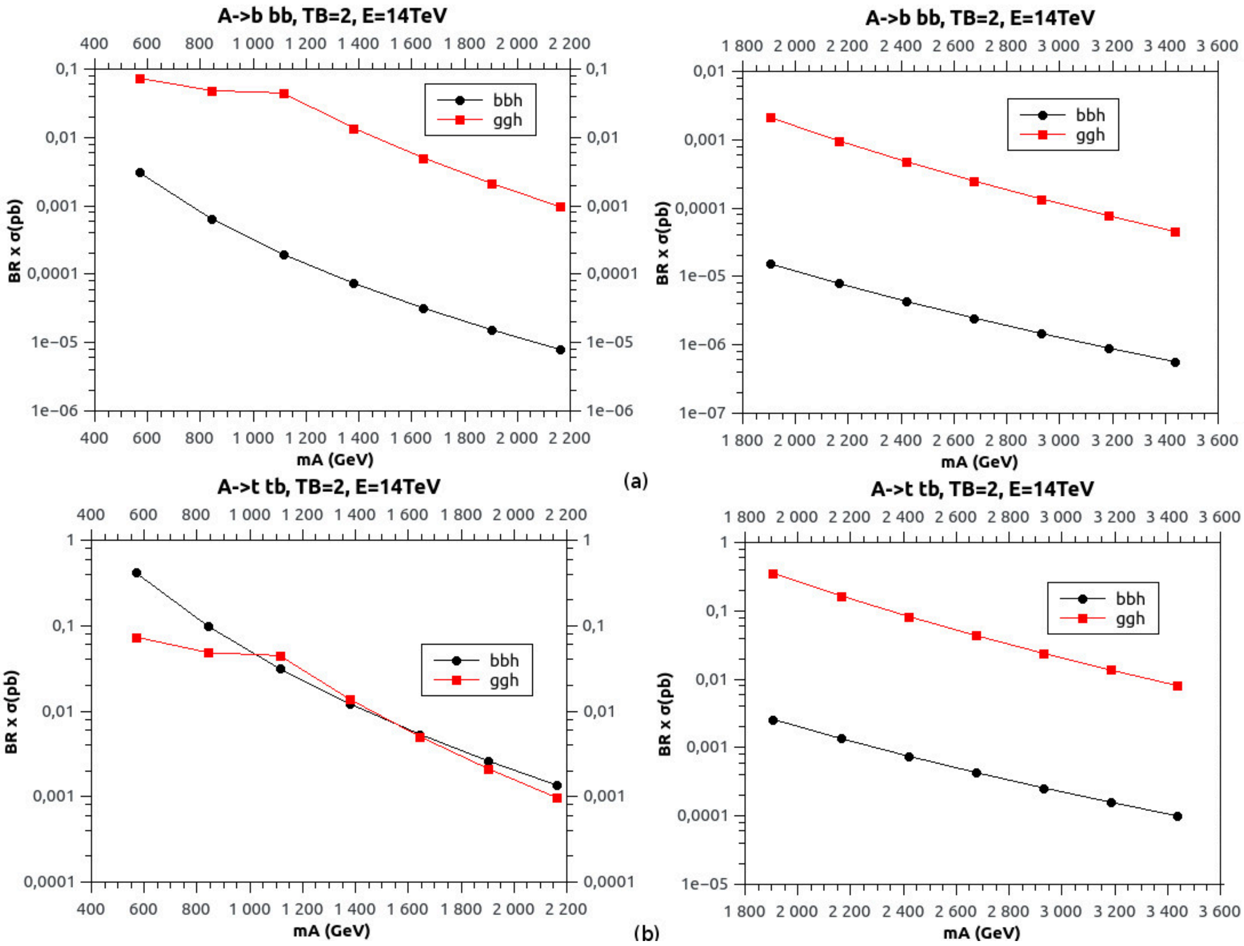


Fig.8. *$\sigma(pp \to A) \times BR(A \to bb)$ in the mass range 500...2200 GeV (left) and 1800...3450 GeV (right) (a) and $\sigma(pp \to A) \times BR(A \to tt)$ in the mass range 500...2200 GeV (left) and 1800...3450 GeV (right) (b)*

From Fig.8 we can see the predominance of the ggh process of A boson formation over the bbh one except for the (b) case of $A \to tt$ process in the mass range of 500...2200 GeV with interesting intersection points between bbh and ggh processes. It is also necessary to stress the largest value of $\sigma \times Br$ for the smallest masses, m_A, what is easily explained in connection with the lower mass of the Higgs boson A.

3) charged Higgs bosons, H±.

As is known [18], the production of charged Higgs boson depends on its mass and for $m_{H^+} > m_t$, H^+ production mode is associated with a top quark, as illustrated in Fig.9.

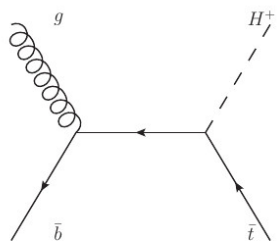


Fig.9. *Leading-order Feynman diagram for the production of H^+ in association with a top quark in five flavor scheme*

In Fig.10 are shown the expected and observed limits for the production of $H^+ \to tb$ in association with a top quark, bands for 68% (in green) and 95% (in yellow) confidence intervals and the signal prediction in the m_h^{mod-} benchmark scenario of the MSSM [19].

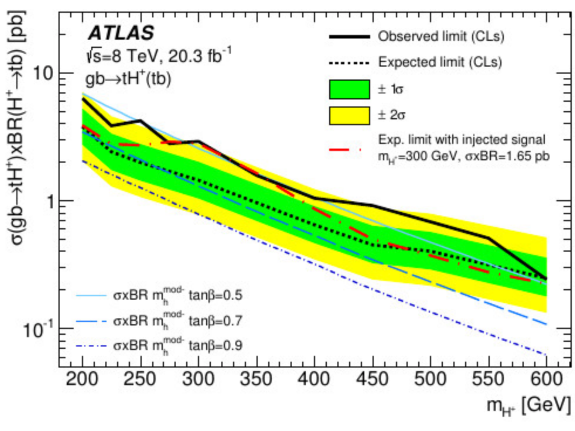


Fig.10. *Expected and observed limits for the production o f $H^+ \to tb$ in association with a top quark, from [18]*

As model points with 0.5 $\leq \tan\beta \leq$ 0.6, $\tan\beta \approx$ 0.5, $\tan\beta$=0.7 and $\tan\beta$=0.9 are excluded in the H^+ mass range of 200...600 GeV obtained also in other scenarios of MSSM, it would be interesting to do the calculations of $\sigma \times Br$ for tanβ=2. For the studying of properties of charged Higgs bosons, $H^{\pm}$, we have used the set of parameters of MSSM model to calculate the cross-sections of tH^{+} production with the help of the software program PROSPINO [20] with data implemented from the latest computer program SOFTSUSY4.0. The corresponding results for $\sigma(pp \to tH^{+})BR(H^{+} \to tb)$, obtained for the parameter set of tanβ=2 and for the energy of 14 TeV in the mass range of mH^{+}=500...1200 GeV are presented in Fig.11.

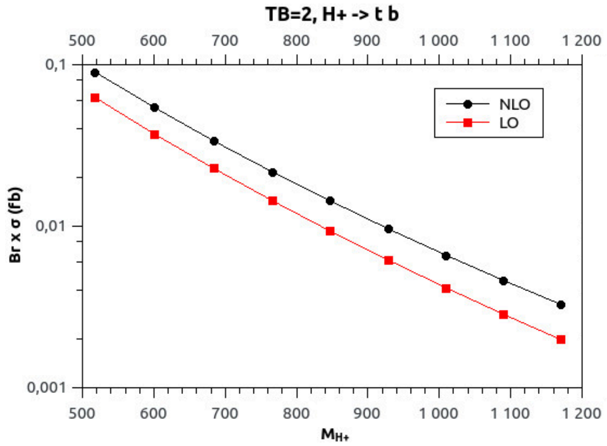


Fig.11. *$\sigma(pp \to tH^{+})BR(H^{+} \to tb)$ for 14 TeV at the LHC in the mass range of m_{H^+}=500...1200 GeV*

Another most visible decay channel of a charged Higgs boson is $H^{+} \to \tau\nu$. Its searches in association with a single top quark were performed by ATLAS Collaboration at the LHC with proton–proton collision at $\sqrt{s}$=13 TeV corresponding to an integrated luminosity of 3.2 fb^{-1}. The analysis of experimental data leads to 95% CL upper limits on the $\sigma(pp \to [b]tH^{\pm})BR(H^{\pm} \to \tau\nu)$, between 1.9 pb and 15 fb, for m_{H+}=200...2000 GeV, that is presented in Fig.12.

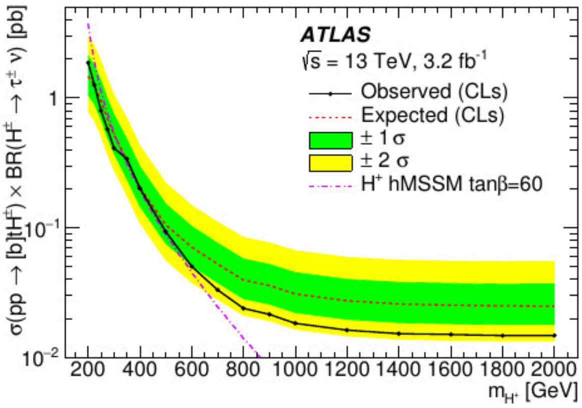


Fig.12. *Observed and expected 95% CL exclusion limits for heavy charged Higgs boson production as a function of m_{H+}, from [21]*

From these experimental data tanβ = 42...60 for m_{H+}=200 GeV and tanβ=60 for the H^{+} mass range from 200 to 340 GeV were excluded. So we have considered two cases of tanβ=2 and 30 for comparison of the value of $\sigma(pp \to [b]tH^{\pm})BR(H^{\pm} \to \tau\nu)$ for these two cases, presented in Fig.13.

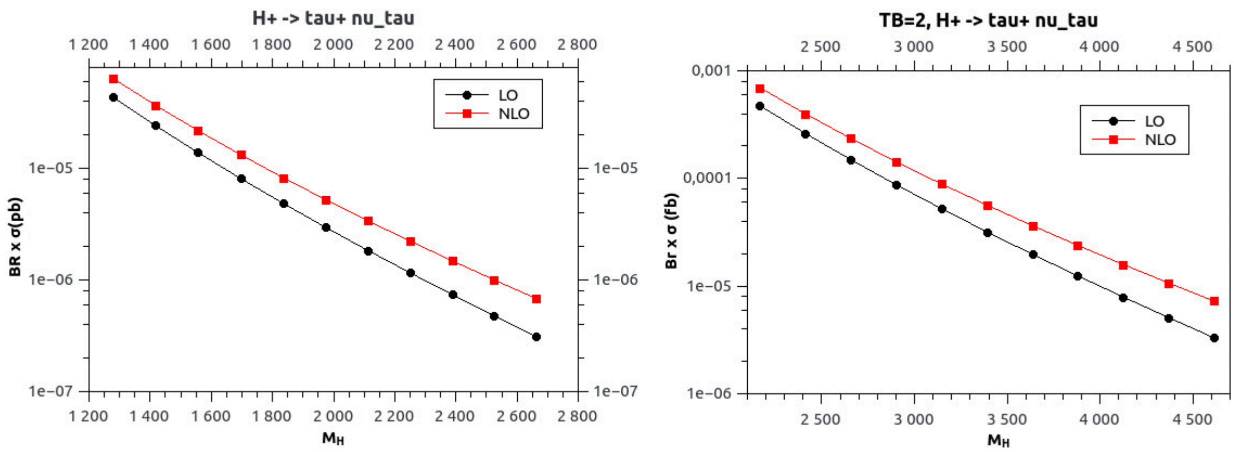


Fig.13. *$\sigma(pp \to [b]tH^{\pm})BR(H^{\pm} \to \tau\nu)$ for (a) tanβ=30 in the mass range m_H^{+}=1200...2650 GeV and (b) tanβ=2 in the mass range m_H^{+}=2200...4600 GeV with the planned 14 TeV at the LHC*

From Fig.13 the predominance in the value of $\sigma(pp \to [b]tH^{\pm})BR(H^{\pm} \to \tau\nu)$ for the variant (a) is obvious but we can see the larger values of $\sigma(pp \to [b]tH^{\pm})BR(H^{\pm} \to \tau\nu)$ for tanβ=30 in the range of the mass intersection of charged Higgs boson, m_H^{+}=2200...2650 GeV for (a) and (b) variants. In addition, it is known that for $m_{H^+} > m_t$ the dominant decay of H^{+} is $H^{+} \to tb$, but for large values of tanβ is observed a substantial contribution from $H^{+} \to \tau\nu$ [21]. For comparison we calculated $\sigma(pp \to tH^{+})BR(H^{+} \to tb)$ for tanβ=30 for 14 TeV at the LHC, presented in Fig.14.

From the Fig.14 and 13 it can be concluded about the largest values of $\sigma(pp \to tH^{+})BR(H^{+} \to tb)$ in contrast with $\sigma(pp \to [b]tH^{\pm})BR(H^{\pm} \to \tau\nu)$ for the same tanβ=30, but the increase of the value $\sigma(pp \to [b]tH^{\pm})BR(H^{\pm} \to \tau\nu)$ for the larger tanβ was stressed above.

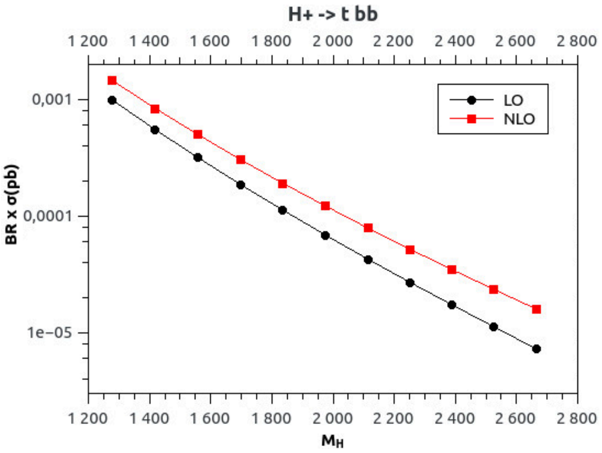


Fig.14. *$\sigma(pp \to tH^{+})BR(H^{+} \to tb)$ for 14 TeV at the LHC in the mass range of m_H^{+}=1200...2650 GeV*

4. CONCLUSIONS

Using the restricted parameter set of the hMSSM model, presented in [5] and [12] for the extended sector of Higgs bosons as well as the latest experimental data on the observed and expected CL exclusion limits for Higgs boson production, performed by ATLAS Collaboration [13], [14], [18], [21] with the help of software programs SOFTSUSY4.0, SusHi and PROSPINO we have calculated $\sigma \times Br$ for CP-even Higgs boson, H, CP-odd Higgs boson, A and charged Higgs bosons, $H^{\pm}$. From our calculations we can conclude about the large values of the $\sigma \times Br$ at small tanβ=2 for chosen decay channels of Higgs bosons for the energy at the LHC of 14 TeV. But for the charged Higgs boson are obtained another results, that are connected with larger values of tanβ.

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ИЗУЧЕНИЕ СВОЙСТВ РАСШИРЕННОГО СЕКТОРА БОЗОНА ХИГГСА В РАМКАХ hMSSM-МОДЕЛИ

Т. В. Обиход, Е. А. Петренко

Используя последние экспериментальные данные, полученные ATLAS коллаборацией, в рамках Минимальной суперсимметричной стандартной модели, мы представили расчеты по сечениям умноженным на ширины распадов, $\sigma\times$Br, как функции массы CP-четного H бозона Хиггса, CP-нечетного A бозона Хиггса и заряженного, $H^{\pm}$ бозона Хиггса. Использование ограниченного набора параметров, полученных из hMSSM + HDECAY и "low-tb-high"сценариев, с помощью компьютерных программ SOFTSUSY, Prospino и SusHi, дало возможность получить большие значения $\sigma\times$Br для A и H бозонов при tanβ = 2 для запланированных 14 ТэВ на LHC и большое значение $\sigma\times$Br при tanβ = 30 для заряженного бозона Хиггса. Полученные результаты представляют собой интерес для эксперимента, поскольку они связаны с экспериментальными поисками новой физики за пределами Стандартной модели на LHC.

ВИВЧЕННЯ ВЛАСТИВОСТЕЙ РОЗШИРЕНОГО СЕКТОРА БОЗОНА ХІГГСА В РАМКАХ hMSSM-МОДЕЛІ

Т. В. Обіход, Є. О. Петренко

Використовуючи останні експериментальні дані, отримані ATLAS колаборацією, у рамках Мінімальної суперсиметричної стандартної моделі, ми представили розрахунки по перерізам утворення помноженим на ширини розпадів, $\sigma\times$Br, як функції маси CP-парного H бозона Хіггса, CP-непарного A бозона Хіггса і зарядженого $H^{\pm}$ бозона Хіггса. Використання обмеженого набору параметрів, отриманого з hMSSM + HDECAY і "low-tb-high"сценаріїв, за допомогою комп'ютерних програм SOFTSUSY, Prospino і SusHi, дало можливість отримати великі значення $\sigma\times$Br задля A і H бозонів при tanβ = 2 для запланованих 14 ТеВ на LHC і велике значення $\sigma\times$Br при tanβ = 30 для зарядженого бозона Хіггса. Отримані результати є важливими для експерименту, оскільки вони пов'язані із експериментальними пошуками нової фізики за межами Стандартної моделі на LHC.