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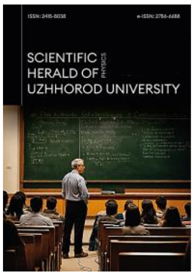

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Three models, MSSM, 2HDM, NMSSM, for supersymmetry searches at the LHC

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Abstract

Relevance. Supersymmetry is a theory that provides an elegant solution to Standard Model problems related to the interaction hierarchy, dark matter candidates, and corrections to the Higgs boson mass. Searching for supersymmetric particles is a key focus of the LHC, exploring various decay modes and potential links to recent ATLAS and CMS observations.

Purpose. The purpose of the study is to use modern software to select the optimal theory for the predictions of the manifestations of supersymmetry in the LHC experiment.

Methodology. A complex methodology was used for the analysis and synthesis of relevant experimental and theoretical material, computer modeling and a comparative-analytical research method.

Results. The research results are summarized in three tables, each corresponding to MSSM, 2HDM, and NMSSM models, with relevant scenarios. For supersymmetry searches, two parameter spaces were defined: scenario 1 without experimental constraints and scenario 2 based on experimental data. Analysis of the Higgs boson production cross-sections through gluon-gluon and bottom-quark interactions showed that the NMSSM model is optimal, yielding the highest cross-section for the lightest CP-even Higgs in gluon fusion. The MSSM model had the largest cross-section for CP-odd Higgs production. No significant changes were observed in CP-odd Higgs production for 2HDM across scenarios 1 and 2. The cross-sections in gluon fusion, especially for the NMSSM model, align with experimental data presented the greatest value for the production of the lightest and CP-even Higgs bosons, MSSM model yields the best results for the lightest and CP-odd Higgs bosons in the second scenario.

Conclusions. For the search for superparticles, both theoretical models, in this case, this is the NMSSM model, and the parameter space of the considered models are of significant importance. At the same time, it is necessary to note the growth of the cross section for all models with increasing energy at the collider LHC.

Keywords: supersymmetry; gluon-gluon fusion; parameters of model; production cross sections; Higgs boson.

Introduction

Physicists are confident that the Standard Model (SM) cannot be the final theory of elementary particle physics, there is a deeper theory of the microworld. To complete the picture, it is necessary to deal with experimental data of the insufficiency of the theory. The SM of particle physics is both successful and incomplete. Summary of ratios with respect to theory for several SM total and fiducial production cross-section measurements from Run 2 and 3 which show deviations from SM predictions for many

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channels of particle production is presented in Standard Model Summary Plots October 2023 [1]. There are also problems with studying the properties of the Higgs boson when comparing experimental data and theoretical predictions of Higgs boson production and decay modes obtained by the ATLAS collaboration [2]. SM predictions led physicists to new discoveries, such as the Higgs boson. But it cannot explain the existence of dark matter, the mysterious substance that makes up 85% of the matter in the universe, or explain the mass of the Higgs boson [2-5].

For decades, a set of theories known as supersymmetry seemed to provide an elegant solution [6-8]. Particles can be divided into two categories: fermions and bosons. In supersymmetric theories, each particle has a "superpartner" with many similar properties. The idea of symmetry between fermions and bosons arose in the early 1970s to solve a mathematical problem with string theory [9; 10]. In 1974, J. Wess and B. Zumino [11] discovered that a wide class of quantum field theories could be made supersymmetric. Researchers soon developed theories that the particles and their superpartners could have different masses [12]. Along with explaining the Higgs mass, supersymmetry offered other theoretical advantages. The lightest stable supersymmetric particle would be a promising candidate for dark matter [13; 14]. In addition, one would observe the unification of the electromagnetic, weak and the strong forces at extremely high energies, suggesting that the fundamental forces we observe were united in the early universe [15].

The relevance of our work is that the community is moving in different directions of experimental and theoretical searches to study the manifestations of supersymmetry [16-18]. The goal of our work is to find the optimal supersymmetric model for a targeted search for superpartners of the Higgs boson. The objective of the study is to apply computer simulations to the three most prominent supersymmetric models MSSM [19], 2HDM [20], NMSSM [21] using two scenarios for calculating the Higgs boson production cross sections and for prediction of the optimal model and parameter space for the experimental searches of superpartners.

Prospects for the Discovery of Supersymmetry

One of the main candidates for the role of Beyond SM (BSM) physics is supersymmetry (SUSY) and the theories constructed with its help. SUSY has not yet been discovered experimentally and it remains a mathematical phenomenon. The discovery of superparticles will become one of the main discoveries in particle physics in recent decades, so much attention is paid to the search for SUSY at the LHC. If it exists, then the capabilities of the LHC depend on the range of the superparticle masses:

– less than 1 TeV – for the first discoveries, a luminosity of 0.1 fb^{-1} is sufficient;

– 1–2 TeV – for the first discoveries 1^{-10} fb^{-1} is sufficient;

– 5 TeV – SLHC phase required;

– the LHC will not be able to detect noticeably heavier superparticles.

A key success of the LHC is the discovery of the Higgs boson. Since the LHC was built primarily to search for new BSM physics, it is the experimental work determining the properties of the Higgs boson that is fundamental in the further searches for BSM physics [22]. The advantage of the Higgs boson is that even if the superparticles are too heavy to be produced directly at the LHC, physicists will be able to test SUSY predictions for Higgs bosons. Unlike SM, supersymmetric theories have several Higgs bosons with different properties, including electrically charged ones. Since the discovery of the Higgs boson (or bosons) and careful study of their properties will be an important stage in the SUSY searches, there are many SUSY models related to the properties of vacuum and used in experimental searches for extended sectors of Higgs bosons.

Study of Higgs Bosons of Supersymmetric Models

To determine whether non-standard experimental effects can be described by SUSY, non-supersymmetric models will require work by theorists. There are many different versions of SUSY theories, and each of them has many free parameters. When experimentalists look for SUSY, they will not be trying to test the entire infinite set of possible theories. Instead, a few simple reference SUSY models are selected and fit to the data is tested for them. We decided to simulate Higgs boson production cross sections for the three most popular models: MSSM, 2HDM, NMSSM. We have calculated the production cross sections of the Higgs boson at 13 TeV and 14 TeV for gluon-gluon and bottom-bottom fusions, presented in Figure 1, for different sets of parameters.

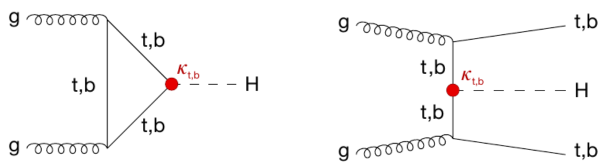

Figure 1. Feynman diagrams for the leading Higgs boson interactions: left – Higgs boson production in ggH, right – associated production with a top or bottom quark pair (ttH or bbH)

Source: [23].

The parameter space for the three models, taken from experimental constraints is given in Table 1.

Table 1. The parameter space for the three models

MSSM		2HDM		NMSSM
tan B = 5 mh = 120.76 mH = 149.11 mA = 130	Scenario 1	tan B = 5 mh = 125 mH = 150 mA = 300	Scenario 1	tan B = 4 mH1 = 65.3 mH2 = 125.71 mA1= 74.34 mA2= 997.66
tan B = 2 mh = 125.76 mH = 600 mA = 360	Scenario 2	tan B = 5 mh = 500 sin(a -B) = 0.5	Scenario 2	

Using SusHi program [24] we have calculated the production cross sections of the Higgs bosons at 13 TeV and 14 TeV for gluon-gluon and bottom-bottom fusions. The results of calculations are in Tables 2, 3, 4.

Table 2. Higgs boson production cross sections calculated in the framework 2HDM model at 13 and 14 TeV for two scenarios, pb

2HDM 13TEV, Scenario 1	2HDM 14TEV, Scenario 1
h ggh 39.4 bbh 3.14 H ggh 13.8 bbh 5.84 A ggh 0.985 bbh 0.590	h ggh 39.4 bbh 3.56 H ggh 15.5 bbh 6.65 A ggh 0.985e-01 bbh 0.59
2HDM 13TEV, Scenario 2	2HDM 14TEV, Scenario 2
h ggh 0.3 bbh 3.14 10^{-6} H ggh 1.1 10^{-2} bbh 5.34 10^{-8} A ggh 1.29 10^{-2} bbh 5.90 10^{-7}	h ggh 0.336 bbh 3.56 10^{-6} H ggh 1.31 10^{-2} bbh 6.7 10^{-8} A ggh 1.49 10^{-2} bbh 6.93 10^{-7}

Table 3. Higgs boson production cross sections calculated in the framework MSSM model at 13 and 14 TeV for two scenarios, pb

MSSM 13TEV, Scenario 1	MSSM 14TEV, Scenario 1
h ggh 19.2 bbh 8.29 H ggh 22.5 bbh 3.97 A ggh 6.05 bbh 11.4	h ggh 21.6 bbh 9.36 H ggh 25.4 bbh 3.86 A ggh 6.83 bbh 0.13
MSSM 13TEV, Scenario 2	MSSM 14TEV, Scenario 2
h ggh 21.6 bbh 1.42 H ggh 1.19 bbh 2.66 10^{-3} A ggh 11.5 bbh 4.49 10^{-2}	h ggh 24.4 bbh 1.60 H ggh 1.44 bbh 3.26 10^{-3} A ggh 13.5 bbh 5.32 10^{-2}

Table 4. Higgs boson production cross sections calculated in the framework NMSSM model at 13 and 14 TeV, pb

NMSSM 13TEV	NMSSM 14TEV
h ggh 48.6 bbh 1.83 H ggh 25.9 bbh 0.26 A ggh 6.98 10^{-2} bbh 4.69 10^{-2}	h ggh 53.8 bbh 2.03 H ggh 29.3 bbh 2.93 10^{-1} A ggh 7.75 10^{-2} bbh 5.22 10^{-2}

Comparison of calculations of Higgs boson production cross sections within two models MSSM and 2HDM is presented in Table 5.

Table 5. Comparison of calculations of Higgs boson production cross sections for two scenarios within two models

MSSM	2HDM
Scenario 1	Scenario 2
ggh/bbh~2.3 ggH/bbH~6.6 bbA/ggA~1.88	ggh/bbh~11 ggH/bbH~2.4 ggA/bbA~10^4
Scenario 1	Scenario 2
ggH/bbH~429 (14 TeV) ggH/bbH~451 (13 TeV) ggh/bbh~15.2 bbA/ggA~0.004	ggH/bbH ~10^5 ggh/bbh ~10^5 ggA/bbA ~10^4

Conclusions

As part of the search for superparticles using three supersymmetric models of the extended sector of Higgs bosons, MSSM, 2HDM, NMSSM, using experimental restrictions on the parameter space, we obtained the following results:

- NMSSM has the maximum contribution to the cross sections of ggh(H) processes, but not for bbh(H) ones;
- an increase in energy leads to an increase in cross sections;
- an increase in energy almost does not change the ratio of cross sections for 2HDM_13_14(h,ggh)/NMSSM_13_14;
- the cross section is larger for MSSM model for A boson;
- there is no increase in the cross sections in the 2HDM model for the A boson for 1 and 2 scenarios for ggA process;
- 2nd scenario MSSM ggH/bbH~429 (14 TeV)-451 (13 TeV) and 2nd scenario bbA/ggA~0.004;
- 2HDM 2 scenario ggh/bbh~10^5, 2 scenario ggH/bbH~10^5, 1 scenario ggA/bbA~10^4, 2 scenario ggA/bbA~10^4.

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Not applicable.

Conflict of Interest

There are none.

References

[1] ATLAS Collaboration. Standard Model Summary Plots October 2023. ATL-PHYS-PUB-2023-039. Geneva; 2023.

[2] Englert C. Learning New Tricks with more than one Higgs. URL: https://indico.cern.ch/event/1334507/contributions/5972827/attachments/2880056/5045516/2024_CERN.pdf

[3] Trimble V. Existence and nature of dark matter in the universe. *Annu Rev Astron Astrophys*. 1987;25:425–472.

[4] Hinshaw G, Weiland JL, Hil RS, Odegard N, Larson D, Bennett CL, Dunkley J, Gold B, Greason MR, Jarosik N, Komatsu E, Nolta MR, Page L, Spergel DN, Wollack E, Halpern M, Kogut A, Limon M, Meyer SS, Tucker GS, Wright EL. Five-year Wilkinson microwave anisotropy probe (WMAP) observations: Data processing, sky maps, and basic results. *Astrophys J Suppl*. 2009;180(2):225–245.

[5] Aharonov Y, Komar A, Susskind L. Superluminal Behavior, Causality, and Instability. *Phys Rev*. 1969;182(5):1400–1403.

[6] Golfand Y, Likhtman E. Extension of the Algebra of Poincare Group Generators and Violation of P Invariance. *JETP Lett*. 1971;13:323-326.

[7] Freund P. Introduction to Supersymmetry. Cambridge: Cambridge University Press; 1988.

[8] Volkov DV, Akulov VP. Possible universal neutrino interaction. In: J. Wess, V.P. Akulov (Eds.), *Supersymmetry and Quantum Field Theory*. *Lecture Notes in Physics*. Berlin, Heidelberg: Springer; 1998.
[9] Ramond P. Dual Theory for Free Fermions. *Phys Rev D*. 1971;3(10):2415–2418.
[10] Neveu A, Schwarz JH. Factorizable dual model of pions. *Nucl Phys B*. 1971;31(1):86–112.
[11] Wess J, Zumino B. Supergauge transformations in four dimensions. *Nucl Phys B*. 1974;70(1):39–50.
[12] Heinemeyer S, Stal O, Weiglein G. Interpreting the LHC Higgs search results in the MSSM. *Phys Lett B*. 2012;710(1):201–206.
[13] Jungman G, Kamionkowski M, Griest K. Supersymmetric dark matter. *Phys Rep*. 1996;267(5–6):195–373.
[14] Garrett K, Dūda G. Dark matter: A primer. *Advan Astron*. 2011;968283:1–22.
[15] Dimopoulos S, Raby S, Wilczek F. Supersymmetry and the Scale of Unification. *Phys Rev D*. 1981;24(6):1681–1683.
[16] ATLAS Collaboration. Search for supersymmetry in events with four or more charged leptons in 139fb−1 of s√=13 TeV pp collisions with the ATLAS detector. *JHEP*. 2021;7:167.
[17] Binetruy P. Supersymmetry: Theory, Experiment, and Cosmology. Oxford: Oxford University Press; 2012.
[18] Cecotti S. Supersymmetric Field Theories: Geometric Structures and Dualities. Cambridge: Cambridge University Press; 2015.
[19] Martin SP. A supersymmetry primer. In: G.L. Kane (Ed.), *Perspectives on Supersymmetry* (pp. 1-98). 1998.
[20] Branco GC, Ferreira PM, Lavoura L, Rebelo MN, Sher M, Silva JP. Theory and phenomenology of two-Higgs-doublet models. *Phys Reports*. 2012;516(1-2):1-102.
[21] Ellwanger U, Hugonie C, Teixeira AM. The Next-to-Minimal Supersymmetric Standard Model. *Phys Rep*. 2010;496:1-77.
[22] ATLAS Collaboration. Studies on the improvement of the matching uncertainty definition in top-quark processes simulated with Powheg+Pythia 8. ATL-PHYS-PUB-2023-029, CERN. Geneva; 2023.
[23] The CMS Collaboration. A portrait of the Higgs boson by the CMS experiment ten years after the discovery. *Nature.* 2022;607:60–68.
[24] Harlander RV, Liebler S, Mantler H. SusHi: A program for the calculation of Higgs production in gluon fusion and bottom-quark annihilation in the Standard Model and the MSSM. *Comput Phys Commun*. 2013;184:1605-1617.

Три моделі, MSSM, 2HDM, NMSSM, для пошуку суперсиметрії на LHC

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Анотація

Актуальність. Суперсиметрія — це теорія, яка забезпечує елегантне вирішення проблем Стандартної моделі, пов'язаних з ієрархією взаємодій, кандидатом темної матерії та поправками до маси бозону Хіггса. Пошук суперсиметричних частинок є ключовим напрямком LHC, досліджуючи різні режими розпаду та потенційні зв'язки з недавніми спостереженнями ATLAS і CMS.

Мета. Мета дослідження – за допомогою сучасного програмного забезпечення підібрати оптимальну теорію для прогнозів проявів суперсиметрії в експерименті LHC.

Методологія. Для аналізу та узагальнення відповідного експериментального та теоретичного матеріалу використовувалась комплексна методологія, комп'ютерне моделювання та порівняльно-аналітичний метод дослідження.

Результати. Результати дослідження представлені в трьох таблицях для кожної з моделей MSSM, 2HDM і NMSSM з відповідними сценаріями. Для пошуку суперсиметрії було визначено два простори параметрів: сценарій 1 без експериментальних обмежень і сценарій 2 на основі експериментальних даних. Аналіз поперечних перерізів утворення бозонів Хіггса при глюон-глюонному і ботом-кварковому взаємодіях показав, що модель NMSSM є оптимальною, що забезпечує найбільше значення перерізу утворення найлегшого і CP-парного бозонів Хіггса при глюонному злитті. Модель MSSM мала найбільший поперечний переріз утворення CP-непарного бозону Хіггса. Не спостерігалося суттєвих змін в утворенні CP-непарного Хіггса для 2HDM у сценаріях 1 і 2. Поперечні перерізи глюонного синтезу, особливо для моделі NMSSM, узгоджуються з експериментальними даними, причому модель MSSM дає найкращі результати для найлегших і CP-непарні бозонів Хіггса у сценарії 2.

Висновки. Для пошуку суперчастинок істотне значення мають як теоретичні моделі, в даному випадку це модель NMSSM, так і простір параметрів розглянутих моделей. Водночас слід відмітити зростання перерізу для всіх моделей із зростанням енергії на колайдері LHC.

Ключові слова: суперсиметрія; глюон-глюонне злиття; параметри моделі; перерізи народження; бозон Хіггса.