1 Name

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2 Scientific degrees

- April 2011: Ph.D. in physics (with distinction), University of Warsaw
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3 Academic career

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4 Indication of achievement resulting from art. 16 sec. 2 of the Act of 14 March 2003 on academic degrees and academic title, and degrees and title in the field of art

4.1 Title of the scientific achievement (series of articles):

Implications of the Higgs boson properties measurements
on supersymmetric extensions of the Standard Model

4.2 Series of articles

[H1] **M. Badziak**, E. Dudas, M. Olechowski and S. Pokorski, “*Inverted Sfermion Mass Hierarchy and the Higgs Boson Mass in the MSSM*,” JHEP **1207** (2012) 155 [arXiv:1205.1675 [hep-ph]].

Impact Factor (IF): 5.618, citations: 34

[H2] **M. Badziak**, “*Yukawa unification in SUSY SO(10) in light of the LHC Higgs data*,” Mod. Phys. Lett. A **27** (2012) 1230020 [arXiv:1205.6232 [hep-ph]].

IF: 1.110, citations: 25

[H3] **M. Badziak**, M. Olechowski and S. Pokorski, “*Light staus and enhanced Higgs diphoton rate with non-universal gaugino masses and SO(10) Yukawa unification*,” JHEP **1310** (2013) 088 [arXiv:1307.7999 [hep-ph]].

IF: 6.220, citations: 18

[H4] **M. Badziak**, Z. Lalak, M. Lewicki, M. Olechowski and S. Pokorski, "*Upper bounds on sparticle masses from muon g-2 and the Higgs mass and the complementarity of future colliders*," JHEP **1503** (2015) 003 [arXiv:1411.1450 [hep-ph]].

IF: 6.023, citations: 21

[H5] **M. Badziak**, M. Olechowski and S. Pokorski, "*New Regions in the NMSSM with a 125 GeV Higgs*," JHEP **1306** (2013) 043 [arXiv:1304.5437 [hep-ph]].

IF: 6.220, citations: 87

[H6] B. Allanach, **M. Badziak**, C. Hugonie and R. Ziegler, "*Light Sparticles from a Light Singlet in Gauge Mediation*," Phys. Rev. D **92** (2015) 1, 015006 [arXiv:1502.05836 [hep-ph]].

IF: 4.506, citations: 16

[H7] B. C. Allanach, **M. Badziak**, G. Cottin, N. Desai, C. Hugonie and R. Ziegler, "*Prompt Signals and Displaced Vertices in Sparticle Searches for Next-to-Minimal Gauge Mediated Supersymmetric Models*," Eur. Phys. J. C **76** (2016) no.9, 482 [arXiv:1606.03099 [hep-ph]].

IF: 5.297, citations: 16

[H8] **M. Badziak** and C. E. M. Wagner, "*Enhancing the Higgs associated production with a top quark pair*," JHEP **1605** (2016) 123 [arXiv:1602.06198 [hep-ph]].

IF: 6.063, citations: 13

[H9] **M. Badziak** and C. E. M. Wagner, "*Enhanced Higgs associated production with a top quark pair in the NMSSM with light singlets*," JHEP **1702** (2017) 050 [arXiv:1611.02353 [hep-ph]].

IF: 5.541, citations: 13

[H10] **M. Badziak** and K. Harigaya, "*Supersymmetric D-term Twin Higgs*," JHEP **1706** (2017) 065 [arXiv:1703.02122 [hep-ph]].

IF: 5.541, citations: 11

[H11] **M. Badziak** and K. Harigaya, "*Minimal Non-Abelian Supersymmetric Twin Higgs*," JHEP **1710** (2017) 109 [arXiv:1707.09071 [hep-ph]].

IF: 5.541, citations: 8

[H12] **M. Badziak** and K. Harigaya, "*Asymptotically Free Natural Supersymmetric Twin Higgs Model*," Phys. Rev. Lett. **120**, 211803 (2018) [arXiv:1711.11040 [hep-ph]].

IF: 8.839, citations: 2

4.3 Introduction

The state-of-the-art theory of the fundamental interactions is the Standard Model (SM) which is a quantum field theory with the $SU(3)_{\rm c} \times SU(2)_{\rm L} \times U(1)_{\rm Y}$ gauge symmetry. The SM has been remarkably successful in explaining available experimental data. Nevertheless, the SM is not perfect and there are many indications that it is just an effective theory which properly describes nature only for relatively low energies. One of the main problems of the SM is the hierarchy problem. It originates from the presence of a large hierarchy between the Planck scale and the electroweak scale, $M_{\rm Pl}/M_{\rm EW} \approx 10^{17}$. In quantum field theory the presence of so vastly different scales is unnatural because loop corrections tend to suppress differences between scales. In the context of the SM, quantum corrections to the Higgs mass parameter are quadratically divergent with a cut-off scale of the theory. If the SM is the correct theory up to the Planck scale then the tree-level and the loop contributions would be of the order of $(10^{19}\ \text{GeV})^2$ and would have to cancel each other with an extreme precision to obtain a proper electroweak scale of the order of 100 GeV. Such a fine-tuned cancellation of two huge (a priori independent) numbers seems to be extremely unnatural.

The stability of the hierarchy of scales may be obtained by introducing a symmetry that forbids quadratically divergent quantum corrections. The lack of such symmetry for scalar fields is the origin of the hierarchy problem in the SM. On the other hand, fermions do not suffer from the problem of quadratic divergences due to the chiral symmetry which is an exact symmetry in the limit of vanishing fermion mass. This implies that introduction of a symmetry relating bosons to fermions would solve the hierarchy problem. This symmetry is known as supersymmetry (SUSY). Since none of the superpartners of the SM particles has been observed so far SUSY cannot be exact symmetry of nature. However, it can be broken softly i.e. such that quantum corrections to the Higgs mass are only logarithmically divergent. Thus, supersymmetric models can naturally solve the hierarchy problem if the superpartners masses, especially the stops (superpartners of the top quark) masses, are not much above the electroweak scale which implies good prospects for discovery of SUSY in the experiments at the LHC at CERN near Geneva.

It should be also emphasized that SUSY may solve also other drawbacks of the SM. In particular, the lightest supersymmetric particle is a good candidate for dark matter while thanks to new supersymmetric particles with masses close to the electroweak scale the gauge couplings unify with a very good precision at the unification scale of the order of 10^{16} GeV. In this class of models it is also possible to explain the baryon asymmetry of the Universe as well as to provide a model of inflation.

Supersymmetric models may be directly tested by searches for supersymmetric particles at colliders such as the LHC. Thanks to the discovery of the Higgs boson [1, 2] and the measurements of its properties such as the mass or the couplings to the SM particles, it is also possible to indirectly probe SUSY because the structure of supersymmetric spectrum determines these properties. Investigation of the implications of these measurements on various aspects of supersymmetric models is the leading theme of the series of articles described here.

4.4 Minimal Supersymmetric Standard Model (MSSM)

The most studied supersymmetric model is the Minimal Supersymmetric Standard Model (MSSM), see e.g. [3] for an introduction to this model. The Higgs sector of this model include two $SU(2)_L$ doublets: H_u and H_d. The up-type and down-type SM fermions obtain their masses via the Yukawa interactions with H_u and H_d, respectively, as a consequence of the electroweak symmetry breaking induced by the vacuum expectation values v_u and v_d, respectively. There are five Higgs bosons in the MSSM spectrum and two of them are neutral and CP-even. Physical Higgs bosons are linear combinations of neutral components of the Higgs doublets, H_u^0 and H_d^0. The Higgs particle that couples to the SM particles in a way similar to the SM Higgs boson is dominated by H_u^0. The mass squared of this Higgs boson in the one-loop approximation is given by:

$$m_h^2 \approx M_Z^2 \cos^2(2\beta) + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{\text{SUSY}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\text{SUSY}}^2}\left(1 - \frac{X_t^2}{12 M_{\text{SUSY}}^2}\right)\right], \tag{1}$$

where $\tan\beta \equiv v_u/v_d$, $M_{\text{SUSY}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ is a geometric mean of physical stop masses while $X_t \equiv A_t - \mu/\tan\beta$, where A_t is the soft SUSY breaking top trilinear coupling at the M_{SUSY} scale.

The first term in the above equation is the tree-level contribution. Notice that the tree-level Higgs mass in MSSM is bounded from above by the Z^0 boson mass of about 91 GeV. Therefore, obtaining the 125 GeV Higgs mass [4] is possible only if very large quantum corrections are present. The quantum corrections, which are approximately given by the second term in equation (1), are dominated by the loop diagrams involving stops. One of the implications of the Higgs mass measurement is that in the MSSM with stop masses of the order of $\mathcal{O}(1)$ TeV large stop mixing, parametrized by X_t, is necessary because only for $|X_t|/M_{\rm SUSY} \approx \sqrt{6}$ the theoretical prediction for the Higgs mass agrees with the LHC measurements.

Large value of $|X_t|$ which is necessary to obtain the observed Higgs mass in MSSM for relatively light stops requires large value of $|A_t|$, This problematic from a theoretical point of view because many mechanism of SUSY breaking, such as gauge mediation or anomaly mediation, predict small value of $|A_t|$ at the mediation scale of SUSY breaking. We showed in [H1] that a large contribution to the Higgs mass from the stop mixing can be obtained in models with the inverted sfermion mass hierarchy in which the first two generations of sfermions are much heavier than the third one, even if A_t vanishes at the mediation scale of SUSY breaking. In this class of models a large value of $|A_t|/M_{\rm SUSY}$ is generated by the two-loop effects in the renormalization group equations induced by sfermions which are non-negligible if the first two generations of sfermions have masses $\mathcal{O}(10)$ TeV. In consequence, the Higgs mass in this class of models is typically in the vicinity of 125 GeV for the stop masses $\mathcal{O}(1)$ TeV. Models with inverted sfermion mass hierarchy are strongly motivated by the results of experiments searching for rare flavour-changing processes and by the LHC which set the strongest constraints on masses of the first two generations of sfermions. Our observation made this class of models even more attractive in light of the Higgs boson discovery.

One of the attractive features of MSSM is the fact that it predicts unification of all three gauge couplings of the SM at the Grand Unified Theory (GUT) scale of the order of 10^{16} GeV. This allows to speculate that above the GUT scale the strong and electroweak interactions are described in a unified way by a Grand Unified Theory. GUTs are based on some bigger gauge group which have the SM gauge group as its subgroup. A particularly interesting candidate on the gauge group of GUT is SO(10) because its irreducible representation **16** accommodates all SM fermions of a given generation and a singlet which may play a role of right-handed neutrino whose existence is strongly suggested by observations of the neutrino oscillations. An important feature of supersymmetric GUTs based on the SO(10) gauge group is the prediction of unification of the top, bottom and tau Yukawa couplings at the GUT scale. In contrast to the gauge coupling unification, which generically occurs in MSSM, the Yukawa coupling unification strongly depends on the structure of supersymmetric spectrum. Therefore, demanding the Yukawa unification condition imposes important constraints on the spectrum of supersymmetric particles, which makes GUTs more predictive.

In [H2] we investigated impact of the 125 GeV Higgs mass measurement on predictions on the spectrum of supersymmetric particles in the SO(10) models with top, bottom and tau Yukawa coupling unification. We showed that obtaining the correct Higgs mass requires masses of the most supersymmetric particles to be beyond the discovery reach of the LHC. However, we identified several particles, including gluino, right-handed sbottom, the down-type squark and the heavier Higgs boson doublet which are within reach of the LHC. Existence of such relatively light particles requires a negative sign of the μ parameter and the soft gaugino masses at the GUT scale by a SUSY breaking F-term in 24-dimensional representation of $SU(5) \subset SO(10)$. Such mechanism of SUSY breaking leads to specific non-universal gaugino masses at the GUT scale given by the relation $M_2 = 3M_1 = -3M_3/2$. We also showed that in this class of models the couplings of the observed Higgs boson to SM particles are within one percent from the corresponding couplings of the SM Higgs boson, which makes it impossible to test this model at the LHC via precise measurements of the production and decay channels of the Higgs boson.

However, we showed in [H3] that assuming the most general structure of non-universal gaugino masses it is possible to have some deviations from the SM prediction in the Higgs decay to two photons. This is possible if light strongly-mixed stau (superpartner of tau) with mass of the order of 100 GeV is present in the spectrum. We showed that in such a case the partial decay width of the Higgs boson decaying to two photons can be larger than in the SM even by 30% after taking into account all phenomenological constraints. Such a large deviation from the SM prediction can be tested at the LHC. We also identified in [H3] the relations between the gaugino masses that must be satisfied to significantly enhance the partial decay width of the Higgs boson decaying to two photons. In particular, fulfilling these relations is possible when SUSY is broken simultaneously by a singlet F-term and the F-term in 24-dimensional representation of $\mathrm{SU}(5) \subset \mathrm{SO}(10)$.

As we already mentioned in the introduction, one of the main motivations for supersymmetric particles to be relatively light is the solution of the hierarchy problem of the SM. However, in light of the LHC results MSSM cannot be fully natural. This is because the Higgs mass measurements imply the stop masses at least at the level of 1 TeV and in addition the LHC set strong lower bounds on gluino masses which for typical MSSM spectra are around 2 TeV. Therefore, obtaining proper electroweak symmetry breaking requires strong fine-tuning of parameters. These experimental results lead to speculate that naturalness might not be a good guiding principle towards theory beyond the SM because this is very subjective. Allowing for such possibility one has to face the question whether there are any other arguments that suggest existence of light supersymmetric particles. We showed in [H4] that there exist an upper bound on masses of some supersymmetric particles assuming that MSSM explains the experimental result for muon anomalous magnetic moment $(g-2)_\mu$ [5] which exceeds the SM prediction by more than 3σ [6]. The key observation of this article was the existence of an upper bound on stop masses in spite of the fact that their direct contribution to theoretical prediction for $(g-2)_\mu$ is negligibly small. This is because the dominant contribution from supersymmetric particles, mainly charginos, neutralinos, smuon and muon sneutrino, to $(g-2)_\mu$ is proportional to $\tan\beta$. The $\tan\beta$ parameter is also crucial from the point of view of the Higgs mass because it determines its tree-level value in MSSM. As a result of our analyses we showed that the $(g-2)_\mu$ measurement implies a lower bound on $\tan\beta$. In consequence, there is an upper bound on quantum correction to the Higgs mass which originates from the fact that the Higgs mass cannot be bigger than the observed value of 125 GeV. Since this quantum correction is dominated by stops, this imposes an upper bound on their masses. We showed that lower bounds on chargino and smuon masses from experiments at LEP which are around 100 GeV imply $\tan\beta \gtrsim 2$, which implies an upper bound on the stop masses of the order of $\mathcal{O}(10^4)$ TeV. Using generic LHC on chargino and smuon masses, which are at the level of few hundred GeV, the upper bound on the stop masses becomes much stronger, around 10 TeV. Nevertheless, the LHC constraints become weaker than the LEP constraints under specific circumstances when masses of supersymmetric particles are strongly degenerate. More general constraints on chargino and smuon masses may be obtained in planned lepton colliders. For example, the electron-positron collider ILC with the center of mass energy $\sqrt{s} = 500$ GeV may constrain chargino and smuon masses from below at the level of 250 GeV which would be sufficient to set the upper bound on stop masses around 10 TeV. Stops with such masses are beyond the reach of the LHC but they may be discovered by planned proton collider with the center of mass energy of 100 TeV. Our results show big complementarity of the lepton and hadron colliders which should be able at least some of supersymmetric particles if MSSM is responsible for the observed value of the muon anomalous magnetic moment.

4.5 Next-to-Minimal Supersymmetric Standard Model (NMSSM)

Due to the problems of MSSM to accommodate the 125 GeV Higgs mass for light stops, we focused on investigation of an extension of the MSSM model, known as Next-to-Minimal Supersymmetric Standard Model (NMSSM). An introduction to this model can be found e.g. in [7]. In this model the MSSM spectrum is extended by a superfield S which is a singlet under the SM gauge group. This superfield couples in the superpotential to the MSSM Higgs doublets: $\lambda S H_u H_d$. A primary motivation for this model was to generate the μ parameter via spontaneous electroweak symmetry breaking in which scalar component of S also receives a vacuum expectation value. After the Higgs mass measurement the NMSSM model became a subject of intensive studies mainly due to its Higgs sector because the new coupling $\lambda S H_u H_d$ generates additional tree-level contribution to the Higgs mass.

In NMSSM the observed Higgs h is in general a linear combination of scalar components of the Higgs doublets, H_u and H_d, and the singlet S. Quite generally the mass of that Higgs can be written in the following way:

$$m_h^2 = M_Z^2 \cos^2(2\beta) + (\delta m_h^2)^{\rm rad} + \lambda^2 v^2 \sin^2(2\beta) + (\delta m_h^2)^{\rm mix} \,. \tag{2}$$

The first two terms correspond to the MSSM Higgs mass where the first term is the tree-level contribution while the second one is the quantum correction dominated by stops. The third term is the new contribution which originates from the coupling $\lambda S H_u H_d$. Notice that this new contribution is maximized for $\tan\beta = 1$, in contrast to the MSSM tree-level contribution which is maximal in the limit of large $\tan\beta$. This is the reason why small $\tan\beta$ and large λ was the most studied case in the literature because this way the tree-level Higgs mass can be substantially enhanced and, hence, the stop masses required to obtain $m_h \approx 125$ GeV can be reduced. In [H5] we showed that the tree-level Higgs mass can be significantly bigger than in the MSSM also for large $\tan\beta$ when the contribution to the Higgs mass proportional to λ is negligible. The new region of parameter space that we identified is characterized by the existence of a Higgs scalar with mass smaller than 125 GeV whose main component is the singlet. In the case when the observed Higgs substantially mixes with this singlet, the tree-level Higgs mass of the observed Higgs gets positive contribution which is parametrized by the last term in equation (2).

Since the new Higgs scalar s is light there are constraints on its mass and couplings to the SM particles which set an upper bound on the size of the correction to the Higgs mass from mixing. In a good approximation one can neglect effects of the heavy MSSM Higgs doublet on the Higgs mass. In this approximation the correction from mixing is given by:

$$\Delta_{\rm mix} = m_h - \sqrt{m_h^2 - \overline{g}_s^2 \left(m_h^2 - m_s^2\right)} \approx \frac{\overline{g}_s^2}{2}\left(m_h - \frac{m_s^2}{m_h}\right) + \mathcal{O}(\overline{g}_s^4) \,, \tag{3}$$

where $\overline{g}_s$ is the coupling between s and the massive SM gauge bosons (normalized to the corresponding coupling of the SM Higgs). In the last approximated equality we assumed $\overline{g}_s^2 \ll 1$ which is required by the experimental constraints. We see that in order to obtain large value of $\Delta_{\rm mix}$ a small mass of s and large value of $\overline{g}_s^2$ is preferred. The main constraints on the parameter space come from the Higgs searches by the experiments at LEP. We showed that after taking into account these constraints $\Delta_{\rm mix}$ can reach even 5-6 GeV but only for a small range of m_s between 90 a 100 GeV. The correction to the tree-level Higgs mass of this size allows to obtain $m_h \approx 125$ GeV even for stops with the mass of around 500 GeV.

In [H5] we also noticed an important impact on the allowed value of $\Delta_{\rm mix}$ of effects of the mixing with the heavy Higgs doublet H. Even though impact of H on the Higgs is typically negligible, its effects on the couplings of h and s are non-negligible. This is because the H couplings to b quarks are proportional to $\tan\beta$. Therefore, even a small admixture of the heavy doublet in the mass eigenstates of h and s may significantly modify their couplings to b quarks. This is extremely important from the point of view of the LEP constraints which were the most stringent for particles decaying to $b\bar{b}$. We showed that with the appropriate choice of the NMSSM parameters it is possible to suppress the coupling of s to b quarks. In this region of parameter space the LEP constraints are strongly relaxed and the correction $\Delta_{\rm mix}$ is allowed to be even above 5 GeV for a wide range of m_s between $m_h/2$ ($\approx$ 62.5 GeV) up to about 110 GeV.

We identified several interesting phenomenological implications of the region that we found. First of all, the suppression of the s coupling to b quarks implies an enhancement of the h coupling to b quarks. This means that the branching ratios for the Higgs decaying into gauge bosons are suppressed. Moreover, the Higgs-singlet mixing implies suppression of the Higgs production cross-section at the LHC. Therefore, precision measurements of production and decays of the Higgs are an important tool for testing this model. Secondly, the suppression of the s coupling to b quarks implies strong suppression of the total decay width of s. This leads to the enhancement of $BR(s \to \gamma\gamma)$ by an order of magnitude as compared to the SM Higgs boson with the same mass. In consequence, the s signal in the $\gamma\gamma$ channel may be stronger than for the SM Higgs boson even after taking into account the fact that the s production cross-section at the LHC is strongly suppressed (because of the dominant singlet component in s).

The new mechanism for increasing the Higgs mass in NMSSM that we found opened new possibilities for models of SUSY breaking. One of the most attractive models of SUSY breaking are gauge mediation model [8] in which SUSY breaking is mediated to the visible sector by gauge interactions. The main advantage of this class of models is that the matrices of soft SUSY breaking squared masses are diagonal which strongly suppresses flavour-changing processed, in agreement with the experimental data. However, in minimal models of gauge mediation in the MSSM framework accommodating the measured Higgs mass requires very heavy stops and gluinos with masses above 5 TeV [9], which is in conflict with naturalness of electroweak symmetry breaking. The first-generation squark masses are even larger which gives no chance to discover supersymmetric particles at the LHC. Moreover, in the minimal models it is hard to explain values of parameters μ and $B\mu$ required for proper electroweak symmetry breaking, which is known as $\mu - B\mu$ problem [10].

In light of the above problems of minimal models implementation of gauge mediation in the NMSSM framework would be interesting. However, using the gauge mediation mechanism for the singlet sector is not sufficient to obtain proper electroweak symmetry breaking. A solution to this problem was proposed in [11] where soft SUSY breaking terms for the singlet sector were generated by coupling the singlet to the messenger fields which made proper electroweak symmetry breaking possible. In the model proposed in [11], which we dubbed the DGS model (from the author's surnames), the parameters μ and $B\mu$ are generated dynamically (by providing a vacuum expectation value for the scaler component of the superfield S). However, the authors of [11] concluded that accommodating the measured Higgs mass in their model requires very heavy stops (and other supersymmetric particles), even heavier than in MSSM.

In [H6] we showed that the spectrum of the NMSSM particles in the DGS models can be relatively light if one allows for existence of a light singlet which enhances the Higgs mass via Higgs-singlet mixing. This is very non-trivial result taking into account the fact that the entire NMSSM spectrum is determined in this model by only four free parameters. Moreover, maximization of $\Delta_{\rm mix}$ fixes two of those parameters while $m_h \approx 125$ GeV fixes the mass scale for supersymmetric particles. As a result, the model is extremely predictive and the only free parameter that determines phenomenological predictions is the messenger scale $M_{\rm mess}$ at which SUSY breaking is mediated to the visible sector by the messenger fields. We showed that the stop masses in the DGS model with a light singlet can be around 1 TeV, while gluino and first-generation squarks may have masses around 1.5 TeV. Such small masses of supersymmetric particles can be obtained when m_s is in the range 90-100 GeV. An additional bonus of this scenario is the fact that such values of m_s allow also to explain an intriguing excess of events observed by experiments at LEP [12].

One of the most interesting phenomenological predictions of the DGS with a light singlet is that the Next-to-the-Lightest Supersymmetric Particle (NLSP) is long-lived with a brand new decay channel. This is because the role of the NLSP is played by the lightest neutralino $\tilde{N}_1$ which is strongly dominated by singlino (the fermionic component of the superfield S). The NLSP has mass around 100 GeV and decays to essentially massless gravitino $\tilde{G}$ LSP (Lightest Supersymmetric Particle) and pseudoscalar singlet a_1 with a mass of few tens of GeV which typically decays to $b\bar{b}$ pair:

$$\tilde{N}_1 \to a_1\tilde{G} \to b\bar{b}\tilde{G}\,. \tag{4}$$

Particularly interesting case is when $M_{\rm mess}$ is relatively low, of the order of $\mathcal{O}(10^6)$ GeV, because in such a case the decay length of $\tilde{N}_1$ is of the order of $\mathcal{O}$(cm)–$\mathcal{O}$(m) so it still decays within the LHC detector. This leads to displaced vertices and missing energy $E_T^{\rm miss}$. $E_T^{\rm miss}$ is the energy of the neutral gravitino which cannot be reconstructed. The displaced vertices signature is very unusual so we devoted the next article [H7] to a more detailed phenomenological analysis of such events. The cross-section for direct production of $\tilde{N}_1$ at the LHC is negligibly small. $\tilde{N}_1$ can be produced, however, in cascade decays of supersymmetric particles initiated by the production of squarks and/or gluinos from proton collisions at the LHC. As a result, the final state is very complicated and includes jets, leptons, $E_T^{\rm miss}$ and several displaced vertices in which pairs of b-jets are created. This type of signatures has not been analysed before so we performed simulations to check whether there are any constraints from the LHC. We showed that the existing analyses searching for displaced vertices are completely insensitive to these signatures because most of the supersymmetric events do not pass the experimental cuts. We proposed a new method to search for such signals by using less aggressive cuts for parameters related to displaced vertices. Relaxing the cuts increases also the number of the SM background events so in order to compensate this effect we introduced new cuts, similar to those used to reduce background in standard prompt searches for supersymmetric particles, which are characterized e.g. by large values of $E_T^{\rm miss}$ and transverse momenta p_T of jets.

The next two articles [H8] and [H9] were an attempt to answer the question how much one can enhance the associated production of the Higgs boson with a top quark pair $t\bar{t}$, $t\bar{t}h$ in short, in the framework of supersymmetric models. Motivation for these studies was the fact that after the end of the run I of the LHC with the centre of mass energy $\sqrt{s} = 7$ TeV and 8 TeV (in the years of 2011-2012) the measurements of the Higgs boson properties have not shown any significant deviations from the SM predictions in dominant Higgs production channels at the LHC despite the fact that the precision of these measurements, especially in the gluon fusion, has reached the level of $\mathcal{O}(10)\%$. This implies that the only Higgs production channel in which observation of significant deviations from the SM at the LHC is still possible is the $t\bar{t}h$ process. This is because the Higgs production cross-section in the $t\bar{t}h$ channel is three orders of magnitude small than the total Higgs production cross-section at the LHC with centre of mass energy $\sqrt{s} = 8$ TeV. Such cross-section is too small for the precise measurement of $t\bar{t}h$ to be possible in the first run of the LHC. On the other hand, it is large enough to make it possible at the LHC with $\sqrt{s} = 13$ TeV where integrated luminosity is expected to be larger by more than a factor 100, while the $t\bar{t}h$ cross-section about four times larger, than in run I of the LHC. Additional motivation for these studies was the fact that in the run I of the LHC, as well as in the run II of the LHC with $\sqrt{s} = 13$ TeV, an enhancement of events was observed in searches for the Higgs boson produced in the $t\bar{t}h$ channel. The biggest deviation from the SM was observed in multilepton and $\gamma\gamma$ channels which suggests enhanced $t\bar{t}h$ signal for the Higgs boson decaying to pairs of photons and pairs of gauge bosons $W^\pm$ and Z^0.

In [H8] we showed that appropriate structure to enhance the $t\bar{t}h$ signal and to explain the LHC results possess the Higgs sector in the type-II two-Higgs-doublet model with $\tan\beta$

around one because it allows to enhance the Higgs coupling to top quarks. This structure is, however, insufficient to significantly enhance the $t\bar{t}h$ cross-section without enhancing the Higgs production via gluon fusion at the same time, which would be in conflict with the LHC data. That is why some new particles must exist, in addition, which interfere destructively with the loop contribution from the top quark to the gluon fusion process. The above features allowing to explain the LHC results possess supersymmetric models since their Higgs sector is based on type-II two-Higgs-doublet model while the stop loop can interfere destructively with the top quark loop. We showed that enhancement of the $t\bar{t}h$ signal is not possible in MSSM but in NMSSM the $t\bar{t}h$ signal with the Higgs decaying to gauge bosons can be even two times larger than in the SM. In [H8] we focused on NMSSM with heavy singlet and showed that appropriate $t\bar{t}h$ enhancement is possible only for large values of λ which results in a Landau pole (which signals entering into non-perturbative regime) only few orders of magnitude above the electroweak scale. On the other hand, in [H9] we showed that large $t\bar{t}h$ enhancement in NMSSM can be obtained in a much more natural way if the scalar singlet is light, lighter than the observed Higgs boson. In such a case the value of λ is not required to be large and perturbative gauge coupling unification is allowed. Moreover, a necessary condition to obtain significant $t\bar{t}h$ enhancement is the existence of relatively light second Higgs doublet H, with mass of the order of few hundred GeV. The Higgs bosons from that doublet easily satisfy the LHC constraints because they typically decay into final states involving scalar or pseudoscalar singlet and such signatures have not been searched for at the LHC. These results strongly motivate studies of additional topologies in searches for new Higgs bosons at the LHC.

4.6 Supersymmetric Twin Higgs models

Another way to increase the tree-level Higgs mass, hence, to suppress the loop correction from stops required to obtain $m_h \approx 125$ GeV, is to use the Twin Higgs (TH) mechanism [13] in supersymmetric theory. The main assumption of the TH models is the existence of a second (twin) copy of the SM. In the leading approximation there exist an exact $\mathbb{Z}_2$ symmetry which exchanges the SM fields with their twin counterparts, which results in a global $SU(4)$ symmetry. The Higgs sector in TH models can be parametrized using the following potential:

$$V = \lambda \left(|H|^2 + |H'|^2\right)^2 + m^2 \left(|H|^2 + |H'|^2\right) + \Delta\lambda \left(|H|^4 + |H'|^4\right) + \Delta m^2 |H|^2 \,. \qquad (5)$$

The first two terms in the above potential respect the $\mathbb{Z}_2$ symmetry and the global $SU(4)$ symmetry. The $SU(4)$ symmetry is spontaneously broken to the $SU(3)$ symmetry which implies existence of seven Goldstone bosons. Six of them become longitudinal components of $W^\pm$ and Z^0 bosons of the SM and the twin sector which become massive. The seventh Goldstone boson is physical and corresponds to a massless Higgs boson in the limit of exact $SU(4)$ symmetry. The Higgs boson obtains mass due to small effects which break the $SU(4)$ symmetry which are parametrized by the term proportional to $\Delta\lambda$ in the potential (5). In this approximation the Higgs boson is a maximal mixture of the Higgs fields from the visible and the twin sector. In order to obtain the Higgs boson with couplings similar to those in the SM, hence to satisfy the LHC constraints, it is necessary to break the $\mathbb{Z}_2$ symmetry which is parametrized by the last term in the potential (5).

The main motivation to consider TH models is the fact that quadratically divergent corrections to the Higgs mass parameters generated by the SM top quark are cancelled by the twin top quark. Since the latter does not carry any charge of the SM it can be light without violating experimental constraints, in particular those from the LHC which imply strong lower bounds on masses of top quark partners charged under QCD (e.g. stops in supersymmetric models). This solves the little hierarchy problem of the SM. In order to solve the big hierarchy of the SM it is necessary, however, that colour-charged top quark partners appear in the spectrum at some higher energies. Thus, the TH models must be embedded in some more fundamental, e.g. supersymmetric, theory.

The potential (5) describes also in a good approximation the Higgs sector of supersymmetric TH models in the so-called decoupling limit in which Higgs bosons from the second Higgs doublet are heavy. The $SU(4)$ symmetry is broken in supersymmetric version of the TH models by the D-term associated with the electroweak symmetry which results is $\Delta\lambda = M_Z^2 \cos^2(2\beta)$. Then the tree-level Higgs mass in supersymmetric TH model is given by:

$$\left(m_h^2\right)_{\rm tree} \approx 2M_Z^2 \cos^2(2\beta) \left(1 - \frac{v^2}{f^2}\right) + \mathcal{O}(\Delta\lambda/\lambda)\,, \tag{6}$$

where $v \approx 174$ GeV is the scale of the electroweak symmetry breaking while f is the scale of the $SU(4)$ symmetry breaking. The LHC measurements of the Higgs boson properties imply $f \gtrsim 3v$. Notice that the tree-level Higgs mass is bigger than in MSSM by a factor of about $\sqrt{2}$ which means that 125 GeV can be obtained essentially without any loop corrections (in the limit of large $\tan\beta$).

Equation (6) is a good approximation of the tree-level Higgs mass only if the $SU(4)$ symmetry is approximately satisfied i.e. when λ in the potential (5) is sufficiently large. The first attempts to construct supersymmetric TH models were based on the generation of λ by an F-term of a new singlet field [14–16]. In those models $\lambda \sim \sin(2\beta)^2 \sim 1/\tan^2\beta$ is small in the region of large $\tan\beta$ which is preferred by large Higgs mass. Therefore, it is not possible to simultaneously accommodate large value of λ, necessary for the TH mechanism to work, the 125 GeV Higgs mass and light stops.

In [H10] we showed that the TH mechanism can be in agreement with the Higgs mass measurements assuming that λ is generated a D-term of a new gauge interaction under which the Higgs and its twin partner are charged. In this article we proposed the simplest model in which the new interaction is based on the $U(1)_X$ gauge symmetry which is spontaneously broken at the scale of around 10 TeV. In this model λ is approximately given by:

$$\lambda_{U(1)_X} \approx \frac{g_X^2}{8} \cos^2(2\beta)\ , \tag{7}$$

where g_X is the gauge coupling of the new interaction. Notice that $\lambda_{U(1)_X}$ is maximized in the limit of large $\tan\beta$, similarly to the Higgs mass. We computed the Higgs mass in this model and showed that for appropriately large values of $g_X \gtrsim 1.5$ the stop masses required to obtain the correct Higgs mass can be as small as 300 GeV (in the limit of large $\tan\beta$) even without stop mixing. Such small stop masses are excluded by the LHC results but larger stop masses can be obtained by appropriately decreasing $\tan\beta$ e.g. the stop mass of 1 (2) TeV can be obtained for $\tan\beta$ around 4 (3).

It should be emphasized that in this model obtaining proper electroweak symmetry breaking requires much smaller fine-tuning (FT) of parameters than in the standard supersymmetric models or supersymmetric TH models proposed previously. FT better than 10 % can be obtained for the stop masses around 1.5 TeV assuming low mediation scale of SUSY breaking, Λ, of the order of 100 TeV. FT is smaller by an order of magnitude as compared to the MSSM.

The main drawback of the new supersymmetric TH model with the new $U(1)_X$ gauge symmetry is the fact that TH mechanism works properly only for large values of g_X which implies existence of a Landau pole for the new interaction not far above the electroweak scale. The goal of the next two articles [H11, H12] was to construct supersymmetric TH model which is perturbative in much larger range of energies. In [H11] we proposed a model with a new interaction based on the $SU(2)_X$ gauge symmetry. In contrast to the model based on the new $U(1)_X$ gauge symmetry only small fraction of fields is charged under the new gauge group: H_u and right-handed top and their twin partners belong to fundamental representations of $SU(2)_X$.

In addition, the fields S and $\bar{S}$, required to spontaneously break the new symmetry and the field E (with the corresponding twin field) introduced to cancel the $SU(2)_X \times U(1)_Y$ anomaly are also doublets of $SU(2)_X$. In this model the β function for g_X vanishes at the one-loop level. Due to this feature the Landau pole, which appears due to two-loop effects, is present much above the electroweak scale even for relatively large values of g_X at the scale of the $SU(2)_X$ symmetry breaking. In consequence, the correct Higgs mass can be obtained for very light stops even if the new interaction is perturbative up to the Planck scale.

FT in this model is better than in the model based on the $U(1)_X$ gauge symmetry. In particular, for the stop and gluino masses of 2 TeV, FT better than 10 % can be obtained for $\Lambda \lesssim 10^6$ GeV. For bigger Λ, FT is bigger due to longer renormalization group running and especially due to smaller values of g_X, hence smaller values of λ, in agreement with the perturbativity condition, which makes suppression of FT by the TH mechanism less efficient. In particular, for the mediation scale of SUSY breaking around the Planck scale FT is at the level of 1 %. Even though this is more than an order of magnitude less than in MSSM, this result is not fully satisfactory.

In [H12] we generalized this model introducing at high energies separate gauge groups $SU(2)_X$, under which the visible sector fields are charged, and $SU(2)'_X$ under which fields from the twin sector are charged. At the energy scale of several tens of TeV the $SU(2)_X \times SU(2)'_X$ symmetry is spontaneously broken to its diagonal subgroup $SU(2)_D$. Below the $SU(2)_X \times SU(2)'_X$ symmetry breaking scale the previous model is recovered but above this scale the gauge couplings of $SU(2)_X$ and $SU(2)'_X$ run separately. Thanks to smaller number of fields charged under $SU(2)_X$, the β function for g_X is negative at the one-loop level and the new interaction is asymptotically free for $g_X \lesssim 3$.

Larger values of g_X that are in agreement with the perturbativity condition allow the TH mechanism to work very well also in the case when SUSY breaking is mediated to the visible sector by gravitational interactions. FT in this case is only at the level of 5–10 % so at least two orders of magnitude better than in MSSM. The proposed model does not require any UV completion below the Planck scale.

4.7 Summary

In the series of articles described here I included various aspects of supersymmetric models in the context of the Higgs boson discovery and the measurements of its properties such as the mass and the couplings to the Standard Model particles. On the one hand, I have investigated models in which symmetries impose conditions of soft supersymmetry breaking parameters much above the electroweak scale, including Grand Unified Theories and gauge mediation models. On the other hand, I have investigated various aspects of supersymmetric models independently from the mechanism of supersymmetry breaking. My research studies have been performed in the framework of MSSM, as well as in its extensions.

The research described here is part of a very timely and widespread discussion on the electroweak symmetry breaking which in spite of the discovery of the Higgs boson has not been fully understood and certainly will be the subject of intensive research both on the experimental and the theoretical side. Minimal supersymmetric models leave many questions without satisfactory answer. This is the reason why I will continue research on constructing non-minimal supersymmetric models in the near future. I will also look for new experimental signatures of these models which are qualitatively different from the predictions of minimal supersymmetry.

5 Other scientific achievements

5.1 Bibliometric data

From Web of Science:

Number of published articles: 25
Citations: 482
Citations without self-citations: 432
Hirsch index: 13

From INSPIRE:

Source: `https://tinyurl.com/mbadz-pub`
Number of articles published in peer-reviewed journals: 25
Citations to articles published in peer-reviewed journals: 646
Hirsch index based on articles published in peer-reviewed journals: 16
Number of all scientific publications: 33
Citations to all scientific publications: 1101

5.2 Period before obtaining the Ph.D. degree

5.2.1 Inflation in supergravity models inspired by the string theory

Before obtaining Ph.D. degree my research activities focus on cosmological inflation. The main subject of my Ph.D. thesis was investigation of the relation between inflation and SUSY breaking in supergravity models inspired by the superstring theory. As was pointed out by Kallosh and Linde, in typical models of inflation derived from the string theory the gravitino mass after inflation is larger than the Hubble scale during inflation [17]. Since in this class of models the Hubble scale during inflation is typically very big, the gravitino mass after inflation is many orders of magnitude bigger than the scale of the electroweak symmetry breaking. Since the soft SUSY breaking terms are generically of the order of the gravitino mass this implies very heavy spectrum of supersymmetric particles which is far beyond the reach of the LHC. One of the main results of my Ph.D. thesis was the construction of inflationary models in which the scale of SUSY breaking can be of the order of the electroweak scale. These were the first models of this type in the literature [18–20].

5.3 Period after obtaining the Ph.D. degree

After obtaining the Ph.D. degree I have investigated various aspects of models beyond the SM which can be grouped into few categories which I describe in the following.

5.3.1 Grand Unified Theories before the discovery of the Higgs boson

I have been investigating GUTs also before the discovery of the Higgs boson. In [21] we investigated the question how to explain the measurement of the muon anomalous magnetic moment in minimal GUT models based on the SO(10) gauge group satisfying simultaneously other experimental constraints, especially the constraints from the measurement of BR($b \to s\gamma$). Fulfilling this criterion was not possible in existing models of this type. We proposed a new in which it was possible to explain the measurement of the muon anomalous magnetic moment at the 2σ level. A prediction of this model was very light spectrum of supersymmetric particles with the gluino mass even below 1 TeV. At that time the first results of the LHC searches for supersymmetric particles were already known. However, none of the existing at that time constraints could not be applied to constrain the model that we proposed. This was the motivation for [22] where we performed reinterpretation of the LHC data to reliably constrain the gluino and squark masses in that model.

5.3.2 Dark matter in supersymmetric models

Another part of my research was to devoted to dark matter in supersymmetric models. The articles [23, 24] focused on neutralinos in MSSM. In [23] we performed a detailed analysis of the experimental constraints on the neutralino sector assuming that the relic density of the lightest neutralino LSP corresponds to total dark matter density in the Universe or only part of it. We showed that even in the case in which the relic density of the neutralino LSP is smaller than the dark matter density in the Universe, the neutralino LSP is strongly constrained by the dark matter direct detection experiments. We identified, however, several regions of the MSSM parameter space which cannot be excluded by the current nor the future dark matter direct detection experiments. A characteristic feature of these regions is small mass splitting between the neutralino LSP and the NLSP. We also proposed experimental strategies to study these regions at the LHC. In [24] we analysed the impact of the final results of the LUX experiment on the so-called well-tempered neutralino i.e. dark matter which is a mixture of bino and higgsino. We showed that those constraints generically exclude large values of $\tan\beta$, hence they set strong lower bound on the stop masses (from the Higgs mass measurements). We pointed out, however, that values of $\tan\beta$ close to 10 may be consistent with the LUX results if there exist relatively light second MSSM Higgs doublet and showed the complementarity of the LHC in probing this region of the parameter space.

The articles [25,26] aimed to find regions of the NMSSM parameter space in which the spin-independent cross-section for scattering of the neutralino LSP on nuclei is strongly suppressed which makes it possible to avoid current and future constraints from the dark matter direct detection experiments. In [25] we found analytically conditions on the NMSSM parameters for the suppression to occur. In particular, we showed that in the presence of a light singlet, with the mass below 125 GeV, it is much easier to suppress the spin-independent cross-section for scattering of the neutralino LSP on nuclei. In [26] we investigated how to obtain the relic density of the LSP in agreement with the result of the Planck satellite. We showed that these regions can be tested by spin-dependent interactions of the neutralino LSP with nuclei and found lower bounds on the LSP mass from the current and the future experiments. We also showed that the constraints may be strongly relaxed in the presence of a light singlet.

In [27] we focused on the case of the gravitino LSP which is a typical prediction of gauge mediation models. Gravitino is typically overproduced in the early Universe which results in destruction of the products of the Big Bang Nucleosynthesis. This is known as the gravitino problem. In [27] we proposed a new mechanism solving the gravitino problem in which the gravitino production is suppressed by many orders of magnitude thanks to suppression of the messenger couplings in the early Universe. This mechanism opens up new region of parameter space of gauge mediation models in which gravitino can play the role of the dark matter.

5.3.3 Interpretation of potential signals of new physics at the LHC

Around the end of the year 2015 the ATLAS and CMS experiments announced new results suggesting existence of a new particle with mass around 750 GeV which decays into photon pair. The articles [28, 29] were devoted to interpretation of these results within the models beyond the SM. In [28] I showed that heavy Higgs boson in two-Higgs-doublet model supplemented with vector-like fermions has the right properties to explain the LHC results. A vast majority of articles in the literature considered models constructed specifically to explain the ATLAS and the CMS results. In [29] we showed that the role of the new particle with mass of 750 GeV explaining the LHC results may be played by a pseudoscalar singlet in the NMSSM model. It was one of the very few interpretations in the framework of well-motivated supersymmetric models. Even though the existence of new particle was not confirmed by the next round of data collected by ATLAS and CMS, the above articles was an important contribution to the discussion that dominated the high energy physics community for over half a year.

I have also participated in various research projects which go beyond the categories described above. In [30] we investigated phenomenology of supersymmetric models derived from the heterotic string theory. While in [31] we studied an impact of a new gauge interaction on naturalness of the electroweak symmetry breaking in supersymmetric models where we showed that FT can be reduced by an order of magnitude as compared to the MSSM.

I am a member of the LHC Cross Section Working Group. As a part of activities within this group, I participated in preparation of recommendations for experimental collaborations in searches for the NMSSM Higgs bosons which resulted, in particular, in a chapter of a CERN monograph [32].

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