Załącznik nr 3

Autopresentation of scientific accomplishments (autoreferat)

1 Name

Kamila Irena Kowalska

2 Scientific degrees

- Master's degree in theoretical physics, Warsaw University, July 2001

  Thesis: *Gauge and Yukawa coupling unification in the extended Minimal Supersymmetric Standard Model*
  Advisor: Professor Stefan Pokorski

- Ph.D. degree in physics, Warsaw University, September 2006

  Thesis: *Flavour physics in supersymmetric models with horizontal U(1) symmetry*
  Advisor: Professor Stefan Pokorski

3 Employment in academic institutions

- June 2011 - December 2012: research specialist in National Centre for Nuclear Research, Warsaw

- from December 2012 - present: assistant professor (adiunkt) in National Centre for Nuclear Research, Warsaw

- October 2015 - September 2017: postdoctoral fellow at Technical University Dortmund, Germany

4 Scientific accomplishment

In the sense of article 16, paragraph 2 of the Act on Academic Degrees and Academic Title, and on Degrees and Title in Arts, 14 March 2003 (Dz. U. 2016 r. poz. 882 ze zm. w Dz. U. z 2016 r. poz. 1311).

a) Title of scientific achievement - a monographic series of publications

Status of supersymmetric extensions of the Standard Model in light of the data from the LHC Runs I and II

b) The monographic series of publications

[H1] Kamila Kowalska, Leszek Roszkowski, Enrico Maria Sessolo,
Two ultimate tests of constrained supersymmetry,
JHEP **1306** (2013) 078 (arXiv:1302.5956).

[H2] Kamila Kowalska, Enrico Maria Sessolo,
Natural MSSM after the 8 TeV LHC run,
Phys.Rev. **D88** (2013) 7, 075001 (arXiv:1307.5790).

[H3] Kamila Kowalska,
Phenomenology of SUSY with General Flavour Violation,
JHEP **1409** (2014) 139 (arXiv:1406.0710).

[H4] Kamila Kowalska, Leszek Roszkowski, Enrico Maria Sessolo, Andrew Williams,
GUT-inspired SUSY and the muon g-2 anomaly: prospects for LHC 14 TeV,
JHEP **1506** (2015) 020 (arXiv:1503.08219).

[H5] Kamila Kowalska,
Phenomenological MSSM in light of new 13 TeV LHC data,
Eur.Phys.J. **C76** (2016) no.12, 684 (arXiv:1608.02489).

[H6] Kamila Kowalska, Enrico Maria Sessolo,
MSSM fits to the ATLAS 1 lepton excess,
Eur.Phys.J. **C77** (2017) no.2, 79 (arXiv:1611.01852).

c) Description of the scientific goals and results of the series of publications with discussion of possible applications

4.1 Introduction

The Standard Model (SM) of particle physics is a quantum field theory with a gauge symmetry spontaneously broken via the Higgs mechanism. Within its framework the fundamental elements of nature are quarks and leptons whose interactions are described as an exchange of interaction quanta, the so-called gauge bosons. The SM is one of the most successful theories in history and its predictions have been positively verified by a great number of experiments. The most spectacular confirmation of its validity were the discoveries of the electroweak (EW) gauge bosons and of the top quark, the experimental determination of their interactions in agreement with the theoretical predictions and, more recently, the discovery of the Brout-Englert-Higgs boson.[1]

In spite of all its successes, however, the SM cannot be considered the final theory of nature as it fails to explain some important phenomena that have been experimentally observed in recent decades. First of all, it does not provide a viable dark matter candidate with properties consistent with astronomical observations. Secondly, it fails to reveal the nature and origin of dark energy. Thirdly, it does not provide a mechanism of generating masses for neutrinos, whose oscillations have been first measured in the late nineties. Last but not least, the flavor structure of the SM, manifested in the hierarchical structure of Yukawa matrices, does not have any theoretical explanations and is determined only by experimental measurements. Moreover, there are also some theoretical issues that seem to suggest that a new, more complete theory can exist at higher energy scales. One of them is the so-called hierarchy problem, which originates from the fact that masses of the scalar fields in the SM are not protected against quantum corrections. Another theoretical hint in favor of high-scale physics is the behavior of the gauge couplings when evaluated at energy scales much higher than the one characteristic for the SM. The magnitude of all three couplings, calculated at around 10^{16} GeV, seems to approach a common value, which might suggest the presence of a new unified fundamental interaction. Such scenarios are known as Grand Unified Theories (GUT).

For all these reasons the hunt for a theory beyond the Standard Model (BSM) has been for years one of the main factors determining the direction of research in elementary particles physics. There is a plethora of various theoretical BSM scenarios that have been proposed and investigated during the last thirty years or so. One of the most thoroughly studied and yet very promising is *supersymmetry* (SUSY). SUSY is an additional symmetry of nature that relates bosonic and fermionic degrees of freedom. In a supersymmetric version of the SM every particle has a so-called superpartner, an extra particle with a spin that differs by one half from its own spin. As a consequence, the radiative corrections to the Higgs scalar mass induced by bosons and fermions exchanged in the loops cancel each other and the hierarchy problem is avoided.

A straightforward consequence of SUSY is that bosons and fermions belonging to the same supermultiplet have the same masses. This is, however, in contradiction with experimental observations as no SUSY particle has ever been detected. Therefore one needs to assume that SUSY is broken. A standard parametric way to achieve it is to extend the Lagrangian by the so-called soft SUSY-breaking (SSB) terms, dimension-four operators that do not cause ultraviolet divergences to appear in the scalar masses. The size of these new parameters then determines the energy scale at which the SUSY particles should show up in the visible spectrum. Before the launch of the LHC it was commonly expected that this new physics scale corresponds to the energy of around 1 TeV.[2]

Beside solving the hierarchy problem, SUSY presents also other advantages. It allows for unification of the gauge couplings, as well as it provides a natural candidate for dark matter in the form of the lightest supersymmetric particle (LSP). It is then hardly surprising that in recent years a huge intellectual and financial effort has been put to experimentally look for SUSY. Given a large

[1]For brevity referred to as the "Higgs boson" hereafter.

[2]These expectations were strongly related to the concept of *naturalness* [1, 2], i.e. the property that all the parameters in the theory should be of the same order. It is, however, disputable whether naturalness is truly a feature that should define the BSM physics.

number and diverse properties of new particles postulated by even its simplest realizations, various experimental approaches have been proposed.

First of all, superpartners of the SM particles can be directly produced at the colliders if only the energy scale of the collided beams is large enough. Here is where the Large Hadron Collider (LHC), the world's largest and most powerful particle colliding machine, comes into play. The Run I operation was inaugurated in 2010, with the 7 TeV center-of-mass energy of the proton-proton collisions. No convincing trace of SUSY or any other exotic particles has been found, in spite of a vast number of analyzed decay channels and dedicated searches. In December 2014, after a two-year-long shutdown, the LHC started its Run II operation almost doubling the proton beam energy and gathering an impressive amount of around 35 fb^{-1} of data by March 2017. To some disappointment, still no trace of SUSY has been detected, although the number and variety of experimental analyses allowed to place lower limits on typical masses of superpartners, which are now believed to be heavier than 1 TeV.[3]

Secondly, the presence of SUSY can be also inferred indirectly. Even if superpartners are too heavy to be directly produced at the LHC, they could affect the low-energy properties of the SM particles in a way that can be measured and quantified experimentally, for example by adding loop-driven corrections to such phenomenological observables like decay rates, branching ratios or life-times. The most powerful observables of that kind are derived from decays of heavy B-mesons, measured with an ever increasing precision at the LHC. One of them, the branching ratio $\text{BR}\,(\text{B}_\text{s} \to \mu^+\mu^-)$, is rightly considered to be a smoking gun for any BSM physics.

And finally, it should be stressed that the lack of experimental confirmation of SUSY in the direct or indirect searches at the LHC does not need to render the whole theoretical concept invalid. To the contrary, the fact that superpartners can stay beyond the reach of the present-day proton colliders is perfectly consistent with the one great discovery made by the LHC so far, the Higgs boson at 125 GeV. The significance of this discovery for particle physics cannot be overestimated. It proves that the concept of spontaneous symmetry breaking, one of the most elegant and at the same time powerful theoretical ideas of modern physics, is actually correct. Given the central role of the Higgs boson in the quantum field theory, it is then of utmost importance to scrutinize its properties as they may provide us with a hint regarding the nature of SUSY.

4.2 Summary of the scientific goals

The main scientific goal of the series of publications included in the habilitation was to analyze various SUSY extensions of the SM in the light of experimental data from the LHC Runs I and II. The results would provide useful hints regarding which of the extensions fits the data best, and can be therefore considered the most promising candidate for the BSM physics.

Sec. 4.3 is dedicated to a detailed analysis of the outcome of direct SUSY searches at the LHC, whose negative results provide ever stronger lower bounds on superpartner masses, discussed in publications [H2] and [H5]. At the same time, several $2-3\sigma$ excesses in the number of the observed events over the SM background were reported by experimental collaborations, which could suggest that a discovery of a new SUSY particle is just around the corner. Such a possibility was analyzed in publication [H6] and the results are summarized in Sec. 4.4. Finally, the available experimental data allows to estimate future sensitivity for a given LHC search, assuming the experimental setup

[3] In Sec. 4.3 it will be discussed in more detail whether, and to what extent, such general statements about the allowed SUSY masses can be formulated.

and the search strategy will remain more or less the same. Such an analysis has been performed in publication [H4] and will be reported in Sec. 4.5.

In Sec. 4.6 implications of the discovery of a Higgs boson with a mass of 125 GeV are discussed in the framework of two SUSY models, in which SUSY-breaking is mediated to the visible sector by gravitational interactions at the energies of the order of 10^{16} GeV (GUT-scale). Publication [H1] investigated this issue in a scenario with minimal flavor violation, while [H3] additionally took into account the impact of soft SUSY-breaking terms that allow to mix squarks of different generations but of the same electrical charge.

Finally, in Sec. 4.7 the impact on SUSY models of the results from B-physics LHC experiments will be briefly summarized, based on the findings of publication [H1].

4.3 Lower bounds on SUSY masses

By now both ATLAS and CMS, the two LHC experiments dedicated to broad-spectrum searches for BSM physics, have collected a large amount of data corresponding to an integrated luminosity of around $35\,\mathrm{fb}^{-1}$. Both collaborations have performed tens of different analyses that allowed them to put lower limits on the masses of various SUSY particles.

However, the interpretation of such results in the framework of a specific SUSY model is not all straightforward. The exclusion bounds published by the experimental collaborations are valid only for particular scenarios, the so-called Simplified Model Scenarios (SMS). Within the SMS framework it is assumed that the SUSY spectrum consists of only several (usually two) light states, one of them being the neutralino LSP. The other, next-to-LSP particle, can be either charged under color, like gluino or squark, or under the EW group only, like chargino, slepton or heavier neutralino. Besides, the decay branching ratio in the channel analyzed by the collaborations is usually set to be equal to 100%.

In more realistic scenarios, however, such simplifying assumptions do not need to hold. If other light particles are present in the SUSY spectrum, the derived exclusion limits can be altered in several ways. First of all, the analyzed branching ratio can be less than 100% as new decay channels may open. As a result, the sensitivity of a search will decrease. Secondly, the presence of additional particles at the intermediate steps of a decay chain can make such a chain significantly longer. Consequently the final decay objects will be less energetic or even different from the ones considered in the SMS. Therefore, in order to evaluate the impact of the LHC SUSY searches in a complete and self-consistent way, it is essential to be able to *reinterpret* the experimental SMS results within the framework of more complex SUSY models. This is generally done by numerically simulating each subsequent step of the experimental analysis and then applying it to the model of interest.

The reinterpretation, however, is a complex and time consuming computational work involving the usage of a wide set of numerical codes. Therefore, an implementation of such a scheme into an automatized numerical tool is an essential prerequisite of any phenomenological analysis. The first simple version of a numerical package designed to reinterpret direct LHC SUSY searches in th GUT-constrained SUSY models was introduced in [P11]. Later on, the code has been significantly developed and upgraded in [H2] and [H5] to accommodate any user-defined SUSY (or not SUSY) scenario.

In the following I will briefly describe the structure of the code, emphasizing those elements that constituted my original contribution. A computational pipe-line is based on six modules interfaced together:

- supersymmetric spectrum generator (`SOFTSUSY`) [3],
- branching ratio calculator (`SUSY-HIT`) [4],
- scattering level event generator (`PYTHIA`) [5],
- detector response simulator (`PGS` 4 [6], `DELPHES` [7]),
- search-dependent efficiency/signal calculator (*original work*),
- supersymmetric signal likelihood calculator (*original work*).

The first four modules use the publicly available numerical codes according to the following algorithm. For every point in the supersymmetric parameter space the spectrum is calculated with `SOFTSUSY` and decay branching ratios with `SUSY-HIT`. Then a sample of events at the scattering level is generated with `PYTHIA` and the hadronization products are passed to the fast detector simulator `PGS` 4 ([H2]) or `DELPHES` ([H5]). The CMS and ATLAS detector cards are used with the settings recommended by both collaborations. Also the b-tagging algorithm implemented in `DELPHES` is tuned in order to reproduce the corresponding efficiencies reported by CMS and ATLAS. This step is particularly important, since b-tagging plays a crucial role in deriving the exclusion bounds for the squarks of the third generation.

From the physical objects produced by the detector simulator (i.e. jets, electron, muons, missing energy) the kinematical variables proper of the considered search are constructed within the efficiency calculator, closely following the prescription of the experimental papers. The kinematical cuts are then applied to a sample of events generated by the detector simulator, and the acceptances/efficiencies ϵ for every bin are calculated as the fraction of events that pass all the cuts. Finally, the number of signal events in a given bin is calculated as $s = \epsilon \times \sigma_{NLO} \times \int L$, where $\int L$ is the integrated luminosity. The NLO+NNL cross-sections σ_{NLO} provided by the LHC SUSY Cross Section Working Group are used. An original efficiency/signal calculator must be constructed separately for every LHC SUSY search considered.

The obtained signal yields are finally statistically compared to the publicly available observed (o) and background (b) yields provided in the experimental papers. This is done using an original likelihood calculator. The systematic uncertainties on the background yields, δb, are accounted for by convolving the Poisson distribution with the Gaussian distribution,

$$\mathcal{L}(o, s, b) = \int P(o|s, \bar{b}) G(\bar{b}|b, \delta b) d\bar{b} \,. \tag{1}$$

The likelihood function $\mathcal{L}$ for each bin is thus calculated, and the final likelihood for each point is a product of the likelihoods for each separate bin. The appropriate confidence level (C.L.) is obtained from the $\delta\chi^2$ variable as $\delta\chi^2 = 2\log(\mathcal{L}/\mathcal{L}_{MAX})$. The 95% C.L. corresponds to $\delta\chi^2 = 5.99$. Alternatively, the C.Ls exclusion method can be approximated by calculating the integral of the marginalized likelihood function.

The results obtained with the reinterpretation tool need to be validated against the experimental findings within a given SMS framework. This can be done in two different ways: by comparing the calculated efficiencies with the ones quoted in the experimental papers for several chosen benchmark points; and by comparing corresponding 95% C.L. exclusion limits on superpartner masses.

An example of the first type is presented in Table 1, which shows a comparison of the experimental cut flows (which are the efficiencies calculated after each of the subsequent kinematical cuts

Cuts	$E_T^{\rm miss} > 200$ GeV, $p_T(\rm jet_1)$	N_{jet}	$(\Delta\phi(E_T^{\rm miss},\rm jet))_{\rm min}$	$p_T(\rm jet_2)$	$E_T^{\rm miss}/\sqrt{H_T}$	$m_{\rm eff}(\rm incl)$
SR2 - ATLAS	77.0%	75.9%	67.8%	67.8%	44.5%	20.8%
SR2 - our tool	77.6%	77.6%	68.6%	67.8%	45.3%	22.5%
SR3 - ATLAS	84.8%	83.5%	66.1%	49.3%	19.6%	3.8%
SR3 - our tool	85.2%	85.2%	66.1%	47.3%	19.1%	5.2%

Table 1: Comparison of the cut flows for the signal point $(m_{\tilde{q}}, m_{\chi_1^0}) = (1000, 400)$ GeV in the 0-lepton + 2-6 jets + $E_T^{\rm miss}$ ATLAS $3.2\,\rm fb^{-1}$ search [8] and in the reinterpretation tool, in the signal regions SR2 and SR3 (published in [H5]).

has been applied) provided by the ATLAS Collaboration in 0-lepton + 2-6 jets + $E_T^{\rm miss}$ search with $3.2\,\rm fb^{-1}$ of 13 TeV data [8], and the results calculated using the reinterpretation tool for a signal benchmark point $(m_{\tilde{g}}, m_{\chi_1^0}) = (1100, 700)$ GeV. Tags SR2 and SR3 correspond to two exclusive signal regions. In all the cases both efficiencies are in a very good agreement, indicating that the experimental procedure has been implemented correctly.

The second validation method is presented in Fig. 1, which shows a distribution of the SMS points excluded at the 99.7% C.L. as gray diamonds, at the 95.0% C.L. as cyan circles, and at the 68.3% C.L. as blue triangles. Fig. 1(a) corresponds to the CMS 3-lepton search with 8.2 $\rm fb^{-1}$ of 8 TeV data for direct EW production [9], while Fig. 1(b) to the already mentioned ATLAS 0-lepton + 2-6 jets search for the squark production. The solid black lines show the published 95% C.L. contours by ATLAS and CMS. Once more, a very good agreement between the experimental and reinterpreted results is observed, which indicates that the derivation of the likelihood exclusion function is correct.

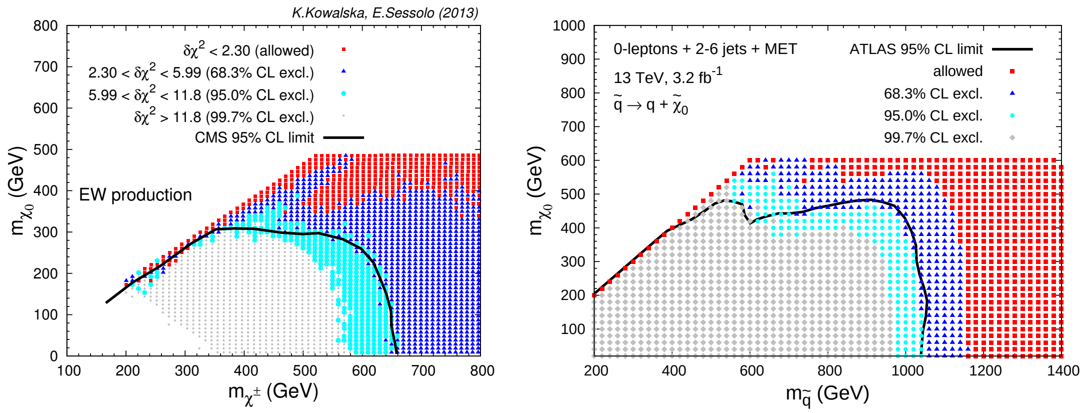
The numerical tool described above has been used in several phenomenological analyses to test viability of various SUSY scenarios in light of the LHC data.

In publication [H2] the impact of direct 8 TeV SUSY searches on the parameter space of the so-called *natural* scenarios was investigated. Natural spectra are characterized by the presence of light stops and sbottoms (which are not as much constrained by the LHC searches as the first two generations' squarks), light higgsinos (fermionic SUSY partners of the Higgs scalars), and by heavy remaining squarks. Such scenarios were of great interest at the beginning of the LHC era, since they allowed to minimize the amount of the EW *fine-tuning*, an unwanted tuning between the various parameters of the model.[4]

In [H2] three different types of natural spectra were considered. In the first case the spectrum consisted of light stops, sbottoms, and Higgsino-like neutralinos, while the other particles were assumed to be out of the experimental reach. In the second case an additional light gluino was present. Finally, the most complex spectrum comprised also light sleptons, wino-like chargino, and a bino-like neutralino. On the experimental side, three LHC SUSY searches from the 8 TeV data set have been reinterpreted: stop production at ATLAS with 20.7/fb of data [10], CMS 11.7/fb inclusive search for squarks and gluinos with the variable α_T [11], and CMS 9.2/fb EW production with 3 leptons in the final state [9].

It was shown that, when considering SUSY spectra of increasing complexity with respect to the SMS ones, and at the same time combining the exclusion bounds from different LHC searches in a statistically correct way, two competing effects can emerge. On the one hand, a more complex spectrum involves longer decay chains, which can - for some specific choices of the model parameters

[4] See, for example, [P8] for a formal definition of the fine-tuning and some related discussions.



(a) (b)

Figure 1: (a) Our simulation of the CMS 3-lepton search with 8.2 fb^{-1} of 8 TeV data for direct EW production [9] assuming a decay chain $\tilde{\chi}_2 \to l\tilde{l}$, $\tilde{\chi}^{\pm} \to \nu\tilde{l}$ (published in [H2]). (b) Our simulation of the ATLAS 0-lepton search with 3.2 fb^{-1} of data for direct squark production [8] assuming a decay chain $\tilde{q} \to q\chi_1^0$ (published in [H5]). Points that are excluded at the 99.7% C.L. are shown as gray diamonds, at the 95.0% C.L. as cyan circles, and at the 68.3% C.L. as blue triangles. The points shown as red squares are considered as allowed. The solid black lines show the published 95% C.L. contours by ATLAS and CMS.

- lead to decay topologies to which an individual search is not sensitive, and thus reduce the expected SUSY signal strength. On the other hand, a statistical combination of different searches that allows to cover a wider range of possible decay topologies would strongly limit the available parameter space for complex, well separated spectra. Moreover, in the case when the considered LHC searches can be treated as statistically independent, the combined likelihood function can actually be stronger than its equivalent for each individual search, thus allowing to test and exclude a larger parameter space. Those conclusions strongly emphasized the need to correctly reinterpret and combine the results of various experimental LHC searches in any phenomenological SUSY analysis.

Publication [H5] was an extension and an upgrade of the analyses initiated in [H2]. In this study I analyzed, for the first time in the literature, the impact of the 13 TeV LHC data with luminosity of $\sim 14\,\mathrm{fb}^{-1}$ on the allowed parameter space of the phenomenological MSSM described by 19 independent parameters (p19MSSM). It is the most general parametrization of the soft SUSY-breaking part of the lagrangian under the assumption of minimal flavor violation, therefore the lower bounds on SUSY masses derived within its framework should be treated as *absolute* ones, which need to be satisfied by any phenomenologically viable SUSY model.

To perform the analysis, twelve experimental searches published by the ATLAS Collaboration were implemented and reinterpreted with the numerical tool described at the beginning of this section, and combined 95% C.L. exclusion bounds on the superpartner masses were derived.[5] To quantify the total impact of the LHC 13 TeV data, I combined the individual searches through "the-best-of" strategy, i.e. using for each model point the result from the search that presented the best sensitivity. It was found that 25% of model points can be excluded at 95% C.L. by a combination of the implemented searches. In particular, the SUSY spectrum allowed after the 13 TeV LHC results

[5] An upper bound of 4 TeV has been applied to the superpartner masses as a hard cut.

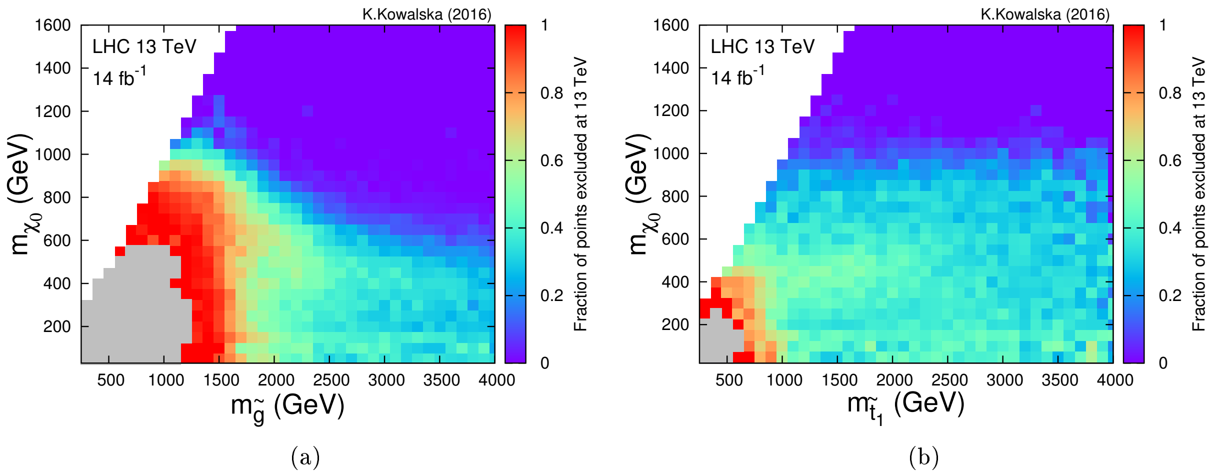


Figure 2: Percentage of p19MSSM points excluded at 95% C.L. by a combination of twelve 13 TeV ATLAS SUSY searches projected into (a) $(m_{\tilde{g}}, m_{\chi_1^0})$ plane, and (b) $(m_{\tilde{t}_1}, m_{\chi_1^0})$ plane. Published in [H5].

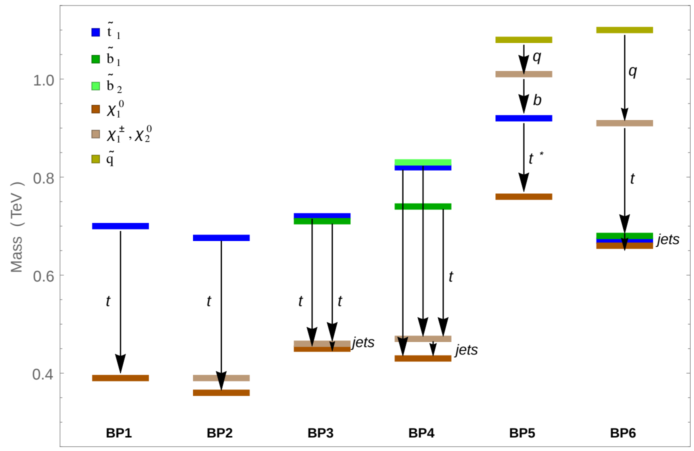
were taken into account presents stops heavier than at least 400 GeV, gluinos heavier than at least 790 GeV, and squarks of the first and second generation heavier than at least 440 GeV. The limits are lifted to 750 GeV, 1450 GeV, and 720 GeV, respectively, if the mass of the lightest neutralino is small.[6]

To illustrate the findings of the study, in Fig. 2 the percentage of the p19MSSM model points is presented that are excluded at 95% C.L. by a combination of the SUSY searches in (a) $(m_{\tilde{g}}, m_{\chi_1^0})$ plane, and in (b) $(m_{\tilde{t}_1}, m_{\chi_1^0})$ plane. In gray those mass bins are shown that have been excluded already at 8 TeV. Red color indicates those parts of the parameter space where 100% of points is excluded by the 13 TeV data, and therefore can be interpreted as a 95%C.L. lower bound on the sparticle mass. Due to the much larger production cross-section, much heavier gluinos than stops can be excluded.

I conclude this section by summarizing the most important results obtained in the publications [H2] and [H5]:

- The results of the direct LHC SUSY searches, interpreted by the experimental collaborations in the framework of the SMS, need to be correctly reinterpreted in order to be applied to any "user-defined" SUSY scenario.
- To deal with this issue, a versatile numerical tool has been developed and extensively used in phenomenological analyses dedicated to determining the allowed masses of the superpartners. (Other applications of the tool will be presented in Sec. 4.4 and Sec. 4.5.)
- There still exist corners of the parameter space (or, in other words, combinations of the superpartner masses), in which the colored superpartners can be relatively light, well below 1 TeV. This usually requires at least two SUSY particles with similar masses, which are henceforth referred to as *compressed spectra*.

[6] By now, a wide set of the LHC searches based on $\sim 40\,\mathrm{fb}^{-1}$ of data has been made available, so the present lower bounds on the superpartner masses are actually somehow stronger.



(a)

Figure 3: Benchmark spectra that can fit the ATLAS 1 lepton + (b-)jets + $E_T^{\rm miss}$ excesses [12]. The colors are associated with each sparticle as described in the legend. We indicate the SM particle emitted at every step of the decay chain next to the corresponding arrow. Published in [H6].

4.4 Fitting a putative SUSY signal

In the previous section it was discussed how the lower limits on superpartner masses can be derived based on the negative data from the LHC, and consequently what is the status of the low-scale SUSY in the middle of the 13 TeV Run II. In this section I will address an opposite question: does the available experimental data can actually signal that a SUSY particle can soon be discovered? And if so, how such a discovery could be anticipated in a statistically convincing way?

Among tens of decay channels analyzed by ATLAS and CMS, the vast majority presents an excellent agreement with the expectation of the SM. There are, however, several searches, in which the reported number of the observed events is statistically larger than the predicted SM background. Such discrepancies, for which the statistical significance does not allow to claim a discovery, yet which may seem too large for a mere statistical fluctuation, are called *anomalies*. They usually tend to attract some attention in the particle physics community, as they may be the first signals of the new physics that just need more data to be finally confirmed.

In publication [H6] we dedicated some attention to the anomaly arising in the 1-lepton ATLAS search [12], which showed a 3.3σ excess in the so-called `DM-low` bin, and less significant 2.6σ and 2.2σ excesses in the bins called `bC2x-diag` and `SR1`, respectively. The bins correspond to particular choices of kinematical variables designed to discriminate between the SUSY signal and the SM background, which for this analysis were chosen as missing energy, transverse momentum, and asymmetric transverse momentum. Incidentally, note that the 1-lepton signature is of particular importance, as it may signalize pair production of top squarks, which in many SUSY scenarios are the lightest color sparticles crucial for determination of the Higgs boson mass (see Sec. 4.6).

Following the strategy established in publication [H5], the analysis of [H6] was performed in the framework of the p19MSSM. We found a few types of spectra that could fit the putative SUSY signal and at the same time were not excluded by other LHC searches implemented in [H5] (see Sec. 4.3). Those spectra could be roughly grouped in two categories, illustrated in Fig. 3. The first class, benchmark points BP1-BP4, is characterized by the presence of one stop or stop and sbottoms with masses in the ballpark of $700 - 800\,\mathrm{GeV}$ and a neutralino LSP of mass around $400\,\mathrm{GeV}$, with or without the additional presence of an intermediate chargino. In the second type of scenarios, benchmark points BP5 and BP6, stop, lightest chargino, sbottom if present, and the neutralino are about or heavier than $\sim 650\,\mathrm{GeV}$ and the signal originates from cascade decays of squarks of the 1st and 2nd generation, which should have the mass of $1.1 - 1.2\,\mathrm{TeV}$. We also calculated the global χ^2 statistics with respect to all implemented ATLAS searches for the benchmark scenarios and for the SM expectation, showing that the putative signal is favored globally with respect to the background only hypothesis.

Another important element of the study was to show that, in general, an excess reported by one experimental collaboration does not need to be confirmed by an apparently similar analysis presented by another collaboration. This may seem counterintuitive and is not at all obvious before a full numerical reinterpretation and a statistical comparison of both sets of results is performed.

We closely investigated this issue using as an example the CMS 1-lepton search [13]. In this analysis exactly the same experimental signature as in the ATLAS one [12] was tested, yet it did not present any significant excess of the observed events over the SM background. We statistically compared the two searches and found that their predictions were perfectly consistent. The reason for this is twofold. First of all, kinematical variables used by CMS, as well as the subsequent definitions of the signal bins, differed in some details from the ones employed by ATLAS. Secondly, both collaborations have different strategies of background calculation, which in the case of CMS is usually more conservative. As a consequence, in the latter case the background-only hypothesis did not correspond to the maximum of the probability function, indicating that the SM alone was not statistically favored. In fact, we calculated that in the CMS search the χ^2 statistics for the SM background was $\chi^2_{SM} = 9.8$, while for two benchmark signal scenarios shown in Fig. 3, BP1 and BP5, it read $\chi^2_{\mathrm{BP1}} = 11.3$ and $\chi^2_{\mathrm{BP5}} = 8.8$, respectively. It means that in the CMS search the goodness of the fit for a putative SUSY signal observed by ATLAS was in general only slightly worse, and sometimes even better, than the SM-only hypothesis, indicating that both analyses were statistically consistent.

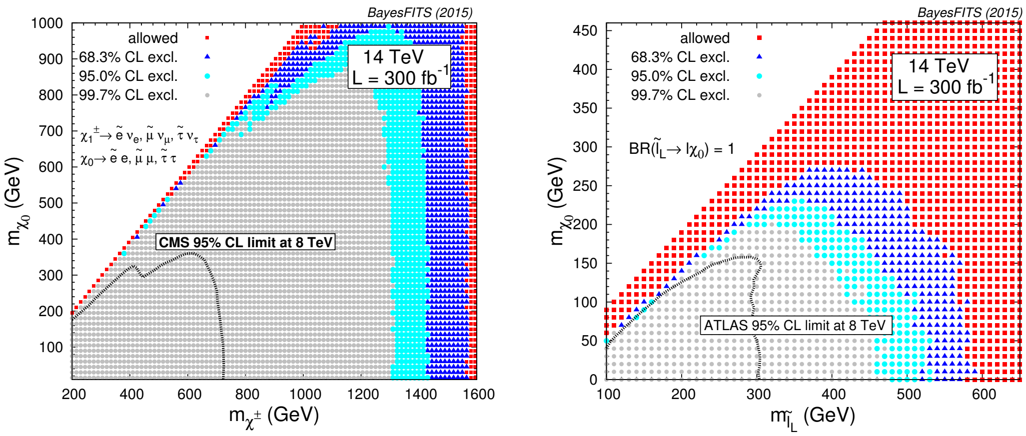
The most important findings of the publication [H6] can be summarized as follows:

- There are several classes of SUSY spectra that could fit the observed ATLAS 1-lepton anomaly, all of them pointing towards the existence of color scalars with masses below 1 TeV.[7]
- There does not need to be a contradiction between observation and non-observation of a signal in apparently similar experimental analyses. The consistency of the two must be investigated case by case.
- Since the correct statistical treatment of the data plays a crucial role, the LHC reinterpretation package described in Sec. 4.3 is a perfect tool to perform such an analysis.
- A consistent statistical procedure to investigate putative discoveries at the LHC has been established.

4.5 Sensitivity of SUSY searches at higher energies and luminosities

Yet another advantage of the LHC reinterpretation tool introduced in Sec. 4.3 is that it can be used to make sensitivity projections of the available SUSY searches for higher energies of the proton

[7] In the end, the excess reported in [12] was not confirmed with more data, meaning it was just a statistical fluctuation.



(a) (b)

Figure 4: Projected exclusion bounds for the LHC 14 TeV run with $L = 300\,\mathrm{fb}^{-1}$. (a) 3-lepton search for $\chi_1^{\pm}\tilde{\chi}_2^0$ production with intermediate sleptons at CMS [15]. (b) 2-lepton search for $\tilde{e}_L\tilde{e}_L$ production at ATLAS [14]. The color code is the same as in Fig. 1. The bounds from the 8 TeV run are shown as dotted black lines. Published in [H4].

beam and for higher luminosities. Such an analysis can provide a useful insight on whether a given SUSY scenario has a chance to be eventually tested in the future runs of the LHC.

In publication [H4] it was investigated to what extent the LHC will be able to probe a large class of GUT-inspired SUSY models with gaugino non-universality, which additionally show agreement with the bounds from the anomalous magnetic moment of the muon, $(g-2)_\mu$, as well as with the relic density of dark matter and the Higgs mass measurement. To this end, we performed a detailed numerical simulation of two 8 TeV searches for electroweakino and slepton production, ATLAS 2-lepton [14] and CMS 3-lepton [15] searches. Our goal was to derive projections for the LHC 14 TeV run with an assumed default value of integrated luminosity $L = 300\,\mathrm{fb}^{-1}$.

As the first step, we simulated in each case the dominant SM backgrounds. For the 3-lepton search these are WZ and $t\bar{t}$ production, as well as rare SM processes such as $t\bar{t}Z/W/H$ and triboson production. For the 2-lepton search the dominant background comes from diboson production and $t\bar{t}$ production. Background events were generated at the LO using `MadGraph5_aMC@NLO` [16] and showered using `PYTHIA`. The cross-sections were calculated at the NLO using `MadGraph5_aMC@NLO`. The efficiencies for the background samples were derived applying kinematical cuts reported in the experimental papers, and the number of background events was calculated as the product of the efficiency, luminosity and cross-section. The uncertainty in the number of background events was evaluated as the sum in quadrature of two terms: the uncertainty of the cross-section determination given by `MadGraph`; and the statistical uncertainty of the efficiency determination with the Monte Carlo simulation.

The background generation was validated at 8 TeV by comparing our results to the number of expected background events reported by ATLAS and CMS, as well as by deriving our own exclusion bounds for two SMS considered by the collaborations. In both cases we obtained very good agreement with the official experimental results.

As the next step, we repeated the whole procedure assuming the proton beam energy of 14 TeV.

We calculated the projected exclusion bounds by setting the number of observed events equal to the expected number of background events. In Fig. 4(a) we present the projected 14 TeV sensitivity of the 3-lepton CMS search for chargino-neutralino production with slepton-mediated decays with integrated luminosity $L = 300\,\text{fb}^{-1}$. The color code is the same as in Fig. 1. We found that the lower bound on the chargino mass for a neutralino LSP lighter than $\sim 900\,\text{GeV}$ can be extended in the future up to $\sim 1400\,\text{GeV}$, which is a factor 1.5 increase with respect to the 8 TeV result. A similar projection in the case of slepton pair-production is illustrated in Fig. 4(b).

Employing the results of the full numerical simulation in our phenomenological study we were able to demonstrate that the parameter space of the analyzed SUSY scenarios falls within the sensitivity of the 14 TeV run with $300\,\text{fb}^{-1}$ virtually in its entirety. This opens up an interesting possibility that, if the $(g-2)_\mu$ anomaly is real and will be confirmed by future dedicated experiments, its explanation within this large class of models will be bound to give clear signatures at the LHC. If this does not happen, the models will be excluded.

4.6 Discovery of the Higgs boson

The greatest success of the LHC so far was the discovery of the Higgs boson in July 2012 [17, 18]. This only scalar particle of the SM plays within its framework a fundamental role as it is responsible for the EW symmetry breaking and for generating masses of all quarks and charged leptons, as well as of the EW gauge bosons.

To evaluate the impact of this discovery on the BSM physics, one needs to first understand the origin of the Higgs boson mass. The scalar potential of the Higgs field ϕ is given by

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \,, \tag{2}$$

where $\mu^2 < 0$ is the bare mass term and λ is the quartic coupling. In the SM both parameters are *a priori* unconstrained and can only be determined from the experimental data. To reproduce the measured masses of the W and Z bosons, the ratio $-\mu^2/\lambda$ needs to be fixed as $-\mu^2/\lambda = 4M_W^2/g_2^2$. Then, the observed mass of the Higgs boson, $m_h = 125\,\text{GeV}$, allows one to calculate the bare mass term as $-2\mu^2 = m_h^2$, and consequently to fix the quartic coupling at $\lambda \simeq 0.12$.[8]

In the minimal supersymmetric extension of the SM the situation is significantly different. First of all, it contains not one but two Higgs scalars, as required by gauge anomaly cancellation and holomorphicity of the superpotential. Secondly, and more importantly, an interesting and unique feature of supersymmetric theories is that the scalar potential does not need to be added by hand to the lagrangian, but it is completely determined by the other interactions in the theory. This is a natural consequence of the fact that in a SUSY framework scalars and fermions belong to the same supermultiplets. The so-called D-term contributions to the scalar potential are fixed by the gauge interactions, while the F-term contributions by the Yukawa couplings. Finally, an additional contribution to the bare mass parameter comes from the soft SUSY-breaking part of the lagrangian. Taking it all into account, the full scalar potential of the Higgs fields take the form

$$\begin{aligned} V \;&=\; \left(|\mu|^2 + m_{H_u}^2\right)|H_u^0|^2 + \left(|\mu|^2 + m_{H_d}^2\right)|H_d^0|^2 - (bH_u^0 H_d^0 + \text{c.c.}) \\ &\quad + \frac{1}{8}(g_2^2 + g_1^2)\left(|H_u^0|^2 - |H_d^0|^2\right)^2 \,. \end{aligned} \tag{3}$$

[8] This particular value of λ has important consequences for stability of the vacuum in the SM. This is an interesting research topic, although beyond the scope of this review.

Here μ is a superpotential parameter, which plays a role of a supersymmetric version of the Higgs boson mass, while m_{H_u} and m_{H_d} are soft SUSY-breaking masses of the Higgs scalars H_u^0 and H_d^0. Note that the scalar quartic coupling, equivalent of λ in Eq. (2), is not a free parameter anymore but it is totally determined by a combination of g_2 and g_1, EW and hypercharge gauge couplings, respectively.

The latter property has very important consequences. Unlike in the SM, where the tree-level mass of the Higgs boson is a free parameter of the model that can always be adjusted to fit the experimental data, in the MSSM it is fully calculable and limited from above by the mass of the Z-boson,

$$m_h \leq M_Z |\cos(2\beta)| \,, \tag{4}$$

where $\tan\beta$ is defined as a ratio of vacuum expectation values of the Higgs scalars H_u^0 and H_d^0. Since the LEP measurements put the lower limit on m_h at 114 GeV, it has been known for years that large radiative corrections are needed to accommodate such a heavy Higgs boson in the framework of the MSSM. After the actual mass m_h had been measured by the LHC to be around 125 GeV, this issue became even more pressing.

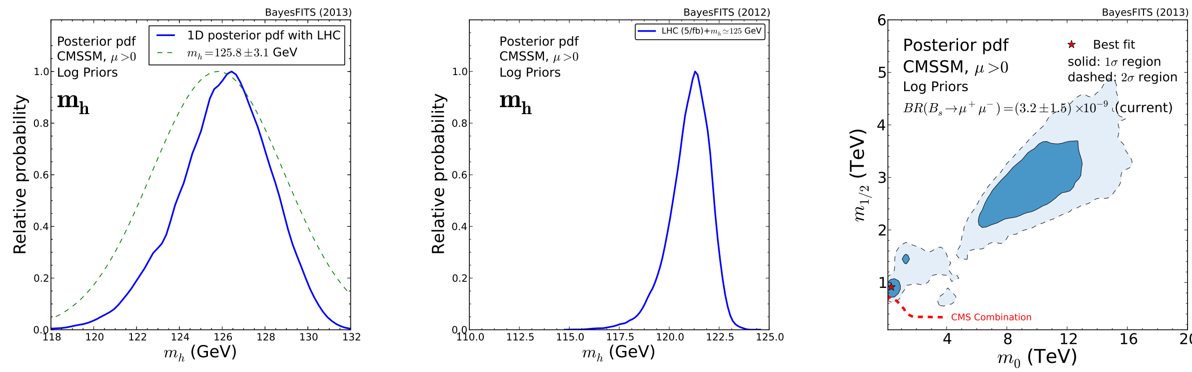
On the other hand, the required radiative corrections are necessarily driven by the SUSY particles running in the loops. Therefore, one can take the LHC measurement as an opportunity to indirectly test the SUSY part of the spectrum. Such a research strategy would be then complementary to the direct SUSY searches discussed in Sec. 4.3 - Sec. 4.5. Note that this is a similar way of reasoning that allowed theorists to make a quite precise determination of the top quark mass well before it was discovered, by analyzing top-driven loop corrections to the masses of Z and W.

Publication [H1] followed that very approach and investigated the impact of the Higgs boson discovery on the allowed parameter space of a particular SUSY model, the so-called constrained MSSM (CMSSM). In this scenario one assumes that SUSY breaking is mediated from the hidden to the visible sector by gravitational interactions. As a consequence, the soft SUSY-breaking terms of the lagrangian are generated at the energies of around $\sim 10^{16}$ GeV. An attractive feature of the CMSSM, which also makes this scenario very predictive, is the fact that it is described by only 4 free parameters. These are the unified scalar mass m_0, the unified gaugino mass $m_{1/2}$, $\tan\beta$, and a unified trilinear coupling A_0 that describes three-scalar interactions between the Higgs bosons and the sfermions. On top of that, the renormalization group (RG) evolution between the high and the EW scales introduces additional correlations among these *a priori* independent parameters.

To understand the dependence of the Higgs boson mass on the parameters of the CMSSM, let us recall that the largest loop contribution to m_h comes from the stop sector [19],

$$\Delta m_h^2 = \frac{3}{8\pi^2 v^2} Y_t^4 v_2^4 \ln\frac{\tilde{m}^2}{m_t^2} + \frac{3 v_2^4}{8\pi^2 v^2}\left[\frac{\tilde{X}_t^2}{\tilde{m}^2}\left(Y_t^2 - \frac{\tilde{X}_t^2}{12\tilde{m}^2}\right)\right] , \tag{5}$$

where Y_t denotes the top Yukawa coupling, m_t - mass of the top quark, $\tilde{m}$ stands for the average mass of the stops, and $v = 246$ GeV is a combination of the vacuum expectation values of the Higgs scalars, v_1 and v_2. Finally, $\tilde{X}_t$ denotes mixing in the stop sector and is given by $\tilde{X}_t = Y_t A_{33}^t - Y_t \mu \cot\beta$. From Eq. (5) one can immediately infer that in general there are two ways to enhance a stop-driven loop correction to the Higgs boson mass. First, by increasing the average stop mass parameter $\tilde{m}$. Second, by maximizing the stop mixing parameter, $X_t^{\max} = \sqrt{6}\,\tilde{m}$. In the CMSSM the stop mass is directly related to the soft SUSY-breaking parameter m_0. Additionally,



(a) (b) (c)

Figure 5: Probability distribution of the Higgs boson mass in the CMSSM (blue line) with m_0 scanned up to (a) 20 TeV, and (b) 4 TeV. (c) Favored parameter space in the plane of $(m_0, m_{1/2})$. The 68% (1σ) credible regions are shown in dark blue, and the 95% (2σ) credible regions in light blue. Published in [H1].

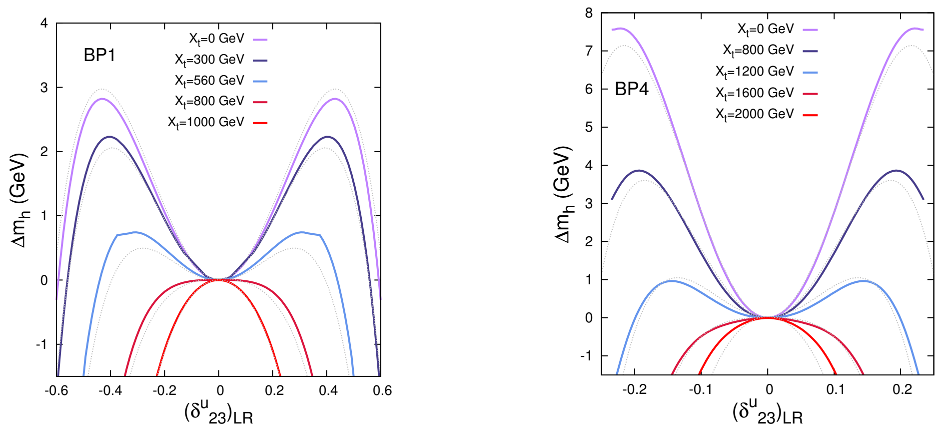
it is strongly affected by the gluino via the RG evolution, which makes is dependent on $m_{1/2}$. On the other hand, $\tilde{X}_t$ is directly related to the initial value of the trilinear coupling A_0.

Publication [H1] was one of the first studies in the literature in which the analyzed range for the unified scalar mass m_0 was extended up to 20 TeV (in the previous studies is did not exceed 4 TeV). This allowed us to test the part of the parameter space in which large mixing was not necessary to explain the Higgs boson mass measured by the LHC. In Fig. 5(a) we show a probability distribution of m_h calculated in the framework of the CMSSM (blue solid line), and the shape of the Gaussian likelihood function with the central value of 125 GeV (green dashed line). One can see that the maxima of the two coincide, indicating the ability of the CMSSM to fit the experimental data within the considered parameter range.

For a comparison, in Fig. 5(b) we present the same Higgs mass distribution taken from [P11], in which the parameter m_0 was varied up only to 4 TeV. While the likelihood function (not shown on the plot) has in this case exactly the same shape like the one in Fig. 5(a), the maximum of the m_h probability distribution corresponds to $m_h \sim 121$ GeV. This feature suggested a slight tension between the measurement of the Higgs boson mass at 125 GeV and very light SUSY spectrum and was one of the motivation for the research undertaken in [H1].

Finally, note that the maximum of m_h distribution in Fig. 5(a) corresponds to an extended 2σ credible region (marked in light blue) of relatively large m_0 and $m_{1/2}$ in Fig. 5(c), which in turn implies large masses of the top squarks. This feature indicates that after the Higgs boson discovery color sparticles are actually expected to be heavy, which is perfectly consistent with their non-observation in the direct SUSY searches discussed in Sec. 4.3.

In publication [H3] the idea explored in [H1] has been extended into the class of SUSY models with the so-called General Flavor Violation. In this setup, contrarily to what is assumed in the CMSSM and in many other most popular SUSY scenarios, the soft SUSY-breaking scalar mass matrices and the trilinear coupling matrices are not necessarily diagonal. As a consequence, sfermions of the same electric charge but different flavors can mix with each other, generating SUSY-specific contributions to flavor-changing neutral current (FCNC) processes. To goal of the study performed



(a) (b)

Figure 6: The enhancement of the Higgs boson mass m_h due to flavour violating parameter $(\delta^u_{23})_{LR}$ and stop mixing term $\tilde{X}_t$ for benchmark points (a) BP1, and (b) BP4, described in the text. Published in [H3].

in [H3] was to investigate to which extent the Higgs boson mass can be actually enhanced by those new non-diagonal soft SUSY-breaking terms without introducing either heavy stops or maximal stop mixing.

To analyze that issue I derived, for the first time in the literature, approximate formulae that allowed to quantify the effect analytically. Let us define off-diagonal terms of the up-squarks mass matrix as $(\delta^u_{ij})_{AB}$, where $i,j = 1,2,3$ are generation (flavor) index, while $A,B = L,R$ denote transformation properties of an up-squark under the $SU(2)_L$ gauge symmetry. The impact of $(\delta^u_{23})_{LR}$ on the Higgs boson mass is then given by

$$\begin{aligned}\Delta m_h^2((\delta^u_{23})_{LR}) &= \frac{3}{4\pi^2}\left\{Y_t^2\sin^2\beta\left[(\delta^u_{33})^2\tilde{m}_3^2+\frac{1}{2}(\delta^u_{23})^2_{LR}\frac{\tilde{m}_2^2\tilde{m}_3^2}{\tilde{m}_2^2-\tilde{m}_3^2}\ln\left(\frac{\tilde{m}_2^2}{\tilde{m}_3^2}\right)\right]\right.\\ &+ (\delta^u_{23})^4_{LR}\frac{\tilde{m}_2^4\tilde{m}_3^4}{v^2(\tilde{m}_2^2-\tilde{m}_3^2)^2}\left(2-\frac{\tilde{m}_2^2+\tilde{m}_3^2}{\tilde{m}_2^2-\tilde{m}_3^2}\ln\left(\frac{\tilde{m}_2^2}{\tilde{m}_3^2}\right)\right)-\frac{\tilde{m}_3^4}{6v^2}(\delta^u_{33})^4\\ &- \left.\frac{(\delta^u_{33})^2(\delta^u_{23})^2_{LR}}{v^2}\left[\frac{2}{\sqrt{6}}\frac{\tilde{m}_2^2\tilde{m}_3^4}{\tilde{m}_2^2-\tilde{m}_3^2}\left|2-\frac{\tilde{m}_2^2+\tilde{m}_3^2}{\tilde{m}_2^2-\tilde{m}_3^2}\ln\left(\frac{\tilde{m}_2^2}{\tilde{m}_3^2}\right)\right|^{1/2}\right]\right\}. \qquad (6)\end{aligned}$$

In the above expression hierarchical diagonal entries of the squark mass matrix are allowed, with the first two generations having the same common mass $\tilde{m}_2$, while the mass of the third generation is given by $\tilde{m}_3$. Standard flavor-conserving mixing between the left and right stops is also taken into account and captured by a parameter $\delta^u_{33} = \tilde{m}_3\frac{\tilde{X}_t v_2}{\sqrt{2}}$. Note that Eq. (6) is an extension and generalization of the well known result of Eq. (5), to which it converges when $(\delta^u_{23})_{LR} = 0$. The same formula is also valid for $(\delta^u_{13})_{LR}$, with an interchange of indices $2 \to 1$.

In Fig. 6 the impact of non-zero $(\delta^u_{23})_{LR}$ on the Higgs boson mass is illustrated for two SUSY benchmark points. BP1 is characterized by degenerate diagonal entries in the up-squark mass matrix, $\tilde{m}_3 = \tilde{m}_2 = 560\,\text{GeV}$, while for BP4 a large hierarchy is introduced, $\tilde{m}_3 = 750\,\text{GeV}$ and $\tilde{m}_2 = 5000\,\text{GeV}$. If there is no mixing in the stop sector, $\tilde{X}_t = 0$, the enhancement impact of $(\delta^u_{23})_{LR}$ can be significant, reaching 3 GeV for BP1 and even 7 GeV for BP4, in which case it is additionally magnified by non-degeneracy of $\tilde{m}_2$ and $\tilde{m}_3$. The situation changes for $\tilde{X}_t \neq 0$ due to the presence of a negative term $\sim (\delta^u_{33})^2(\delta^u_{23})^2_{LR}$. This new contribution can easily dilute the Higgs boson mass enhancement obtained through $(\delta^u_{23})_{LR}$ if $\tilde{X}_t$ becomes large enough with respect to $\tilde{m}_3$.

One should not forget, however, that the magnitude of non-diagonal entries in the soft SUSY-breaking mass matrices is bounded by a set of experimental constraints. These come from the measurements of the FCNC transitions [20] and of the CKM matrix elements [21]. Since in both cases SUSY loop contributions are proportional to $(\delta^u_{ij})_{LR}$, one needs to make sure that the values allowing for a large Higgs mass enhancement are consistent with the data. It turns out that for the parameter $(\delta^u_{23})_{LR}$ the impact of experimental constraints can indeed be dramatic. $(\delta^u_{23})_{LR} \neq 0$ is totally excluded for BP4, while for BP1 it is limited to $[-0.45 : 0.35]$, still allowing the maximal m_h enhancement. Contrarily, $(\delta^u_{13})_{LR} \neq 0$ remains virtually unconstrained.

I will not discuss here the impact of $(\delta^u_{12})_{LR}$ as it is always negative and makes m_h decrease (the corresponding analytical formula can be found in [H3]). Similarly, I will not elaborate on the Higgs boson mass enhancement due to parameters $(\delta^u_{ij})_{LL}$ and $(\delta^u_{ij})_{RR}$. It turns out that these contributions are proportional to the mass scale of the EW sector and therefore can be safely neglected.

The most important findings of the publications [H1] and [H3] can be summarized as follows:

- In order to accommodate in the SUSY framework the Higgs boson with the mass of 125 GeV, large radiative corrections are needed.
- Color sparticles with masses in the ballpark of 10 TeV are to be expected after the Higgs boson discovery.
- Radiative corrections can also be enhanced either by large mixing in the stop sector, or by large off-diagonal terms in the up-squark mass matrix.

4.7 Interplay with flavor physics

In 2012 the LHCb Collaboration reported the first evidence of an excess in the rare decay $B_s \to \mu^+\mu^-$ [22]. In the SM the decay amplitude for this process is strongly suppressed both by helicity and by the smallness of the corresponding CKM matrix elements. New physics contributions, on the other hand, can in principle be much larger, making $B_s \to \mu^+\mu^-$ one of the best indirect probes of the BSM phenomena.

The value of the branching ratio measured by the LHCb, $\mathrm{BR}(B_s \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$, was consistent with the value predicted by the SM. Given the fact that SUSY contributions to the considered decay can be largely enhanced by the sixth power of $\tan\beta$, $\mathrm{BR}(B_s \to \mu^+\mu^-) \sim \tan^6\beta/m_A^4$, such an experimental result was potentially strongly constraining for the allowed parameter space of many SUSY models. Moreover, systematic and statistical uncertainties are expected to be greatly reduced with a larger amount of data, increasing a discovery power of the LHCb measurement.

In publication [H1] it was shown in the context of the CMSSM that a substantial reduction of the experimental and theoretical uncertainties in determination of $\mathrm{BR}(B_s \to \mu^+\mu^-)$ will allow to strongly disfavor some present high probability regions of the model, which otherwise would remain untested by other experiments. For the purpose of the study we assumed that the experimental uncertainty in determination of $\mathrm{BR}(B_s \to \mu^+\mu^-)$ will eventually, with about $50\,\mathrm{fb}^{-1}$ of data at $\sqrt{s} = 14\,\mathrm{TeV}$, be reduced to about 5% [23], and the same precision will also be reached by theoretical

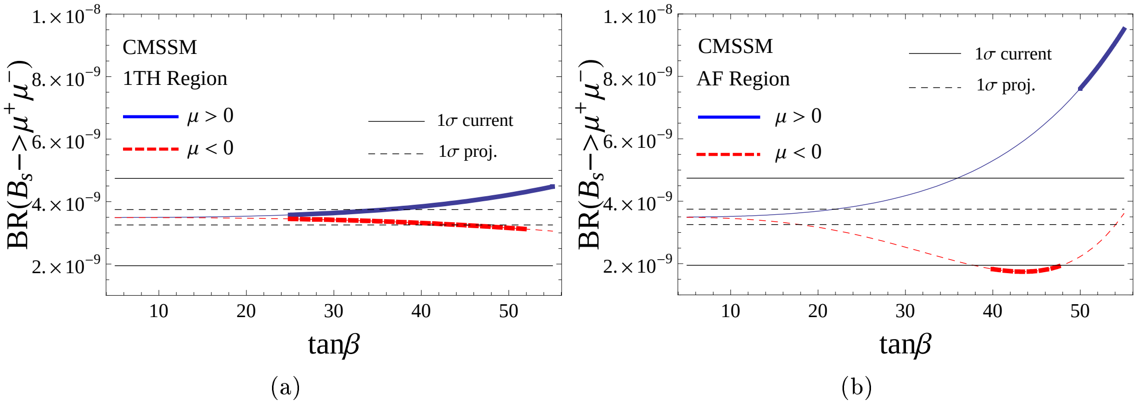


Figure 7: The dependence of $\mathrm{BR}(B_s \to \mu^+\mu^-)$ on $\tan\beta$ in the CMSSM. Solid blue line: $\mu > 0$; dashed red line: $\mu < 0$. Solid horizontal lines: current 1σ error on $\mathrm{BR}(B_s \to \mu^+\mu^-)$; dashed horizontal lines: projected error. The thick lines show the values of $\tan\beta$ typical of each region: (a) 1TH region, and (b) AF region. Published in [H1].

uncertainties.[9] Hence in the numerical analysis we set $\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{proj}} = (3.50 \pm 0.25) \times 10^{-9}$, with both theoretical and experimental uncertainties added in quadrature.

In Fig. 7 the dependence of $\mathrm{BR}(B_s \to \mu^+\mu^-)$ on $\tan\beta$ is shown for two CMSSM benchmark points. In Fig. 7(a) a representative of the so-called 1 TeV higgsino (1TH) region is presented with the input parameters given by $m_0 = 7989\,\mathrm{GeV}$, $m_{1/2} = 2854\,\mathrm{GeV}$, and $A_0 = -767\,\mathrm{GeV}$. Different colors correspond to different signs of the superpotential Higgs mass parameter, $\mu > 0$ (blue) and $\mu < 0$ (red). Thick lines indicate those values of $\tan\beta$ that give the correct relic density of dark matter. In this case the dark matter candidate is an almost purely higgsino-like neutralino [25] with the constant mass $m_{\chi_0} \simeq 1\,\mathrm{TeV}$ essentially independent on $\tan\beta$. The solid horizontal lines give the current 1σ theoretical and experimental uncertainty on the LHCb measurement, while the dashed horizontal lines denote our estimated 1σ projected uncertainties. Since this benchmark model corresponds to a relatively heavy SUSY spectrum, the branching ratio $\mathrm{BR}(B_s \to \mu^+\mu^-)$ is suppressed by large values of the pseudoscalar mass m_A and $\tan\beta$ remains largely unconstrained. One can see that even when the experimental and theoretical errors are reduced in the future, a large part of the parameter space will still be allowed by the measurement of $\mathrm{BR}(B_s \to \mu^+\mu^-)$.

An opposite situation is illustrated in Fig. 7(b), where a representative point of the so-called A-funnel (AF) region is analyzed. This scenario is characterized by $1\,\mathrm{TeV} \lesssim m_{1/2} \lesssim 2\,\mathrm{TeV}$ and the cross section for neutralino annihilation enhanced by the s-channel resonance of the pseudoscalar Higgs boson A [26]. In this case $\tan\beta$ has to be large in order to yield the correct relic density of dark matter (indicated by a thickened section of the red and blue curves). Consequently, there arises a tension with the current measurement of $\mathrm{BR}(B_s \to \mu^+\mu^-)$. Moreover, it is clear from Fig. 7(b) that future more precise determination of the branching ratio will have the potential to basically rule out the whole AF region, and thus a very broad range of the parameters m_0 and $m_{1/2}$ that will, for the most part, remain beyond the reach of direct sparticle searches at the LHC. This result clearly emphasizes the necessity of combining different complementary sets of data in order to thoroughly test the parameter space of SUSY models.

[9]Note that in a recent LHCb analysis based on $4.4\,\mathrm{fb}^{-1}$ of data [24] the experimental error has been reduced to 22%.

The most important findings of the publication [H1] are the following:

- The measurement of $\mathrm{BR}(B_s \to \mu^+\mu^-)$ can indirectly provide strong constraints on SUSY spectra. The constraints will become more and more severe with a future reduction of the statistical and theoretical uncertainties.
- Some GUT-constrained SUSY models (eg. CMSSM) can be fully tested by the end of the LHC Run II.
- In the quest for discovery of the BSM physics complementarity of different experimental measurements is the key.

4.8 Summary and outlook

In spite of a current lack of experimental confirmation, SUSY remains the best theoretically justified model of new physics. In fact, not a single measurement reported either by the LHC or by the dark matter searches disproves it, even if some particular low-scale scenarios may seem under siege. To the contrary, all the experimental results presented and discussed in this overview (direct searches, discovery of the Higgs boson, measurement of $\mathrm{BR}(B_s \to \mu^+\mu^-)$) are perfectly consistent with each other and seem to point together towards realizations of SUSY at the scales higher that it was previously expected.

This conclusion sets two complementary ways of future activities for the whole particle physics community. One is to follow a direction that has been driving the intellectual effort for the last 30 years: building new and more powerful colliding machines, which would be able to test energy ranges that remain beyond the reach of the LHC. A high luminosity upgrade of the LHC (HL-LHC), to be lunched in 2026, aims to increase the luminosity of the existing machine by a factor of 10. There are also plans to construct the International Linear Collider (ILC), an electron-positron colliding device that would ultimately surpass the HI-LHC in terms of the measurement precision, even if its nominal collision energy would be lower. When those two become operational, the kind of expertize summarized in the present review will undoubtedly turn out beneficial.

An alternative, and in my opinion very important, research path is to try to answer the question why, in spite of so many well justified expectations raised in the pre-LHC era, no new physics has yet been found. It may well be that a paradigm of naturalness on which most of the BSM scenarios proposed and analyzed over the recent years were based is simply not correct and more theoretical effort is needed to define and establish a new one. If that is the case, negative rresults of the SUSY searches at the LHC still give us an important lesson.

5 Other scientific achievements

5.1 Bibliometric data (as of July, 2018)

According to inSPIRE

number of papers: 21
number of citations: 641
number of citations without self-citations: 511
h-index (Hirsch index): 12
total impact factor (the sum of 5-year journal impact factors): 83

According to Web of Science

number of papers: 21
number of citations: 443
number of citations without self-citations: 411
h-index (Hirsch index): 11

5.2 Other publications and their main results

5.2.1 After PhD

[P1] Kamila Kowalska, Enrico Maria Sessolo,
The discreet charm of higgsino dark matter - a pocket review,
Advances in High Energy Physics **2018** (2018) 6828560 (arXiv:1802.04097).

In this study we reviewed the current constraints and prospects for detection of higgsino dark matter in low-scale supersymmetry. After having performed a survey of all potential dark matter particles in the MSSM we argued that the (nearly) pure higgsino is the only candidate emerging virtually unscathed from the wealth of observational data of recent years.

[P2] Kamila Kowalska, Enrico Maria Sessolo,
Gauge contribution to the $1/N_F$ *expansion of the Yukawa coupling beta function*,
JHEP **1804** (2018) 027 (arXiv:1712.06859).

We provided, for the first time in the literature, a closed analytical form for the gauge contribution to the beta function of a generic Yukawa coupling in the limit of large N_F, where N_F is the number of heavy vector-like fermions charged under an abelian or non-abelian gauge group. The resummed expression is finite and for the abelian case presents a pole at the same location as for the corresponding gauge beta function.

[P3] Kamila Kowalska, Enrico Maria Sessolo,
Expectations for the muon g-2 in simplified models with dark matter,
JHEP **1709** (2017) 112 (arXiv:1707.00753).

We investigated simplified models of new physics that could accommodate the measured value of the anomalous magnetic moment of the muon and the relic density of dark matter. We defined a set of renormalizable, SU(2)×U(1) invariant extensions of the Standard Model, each comprising an inert $\mathbb{Z}_2$-odd scalar field and one or more vector-like pairs of colorless fermions that communicate to the muons through Yukawa-type interactions. We showed that scenarios featuring only one type of new fermions become very predictive once the relic density and collider constraints are taken into account, as in this case $(g-2)_\mu$ is not enhanced by chirality flip. Conversely, for models where an additional source of chiral-symmetry violation is generated via fermion mixing, the constraints are much looser and new precision experiments with highly suppressed systematic uncertainties may be required to test the parameter space.

[P4] Andrew Bond, Gudrun Hiller, Kamila Kowalska, Daniel Litim,
Directions for model building from asymptotic safety,
JHEP **1708** (2017) 004 (arXiv:1702.01727).

We explored possibilities to UV-complete the Standard Model in an asymptotically safe manner. Minimal extensions we proposed were based on a large number of additional vector-like fermions coupled to a scalar singlet matrix field. In such a setup, it is possible to generate dynamically zeros in the RG equations of the gauge and Yukawa couplings, implying that such a theory becomes asymptotically safe in the UV. We found that asymptotic safety requires fermions in higher representations of $SU(3)_C \times SU(2)_L$ and we analyzed their experimental signatures.

[P5] Arghya Choudhury, Kamila Kowalska, Leszek Roszkowski, Enrico Maria Sessolo, Andrew J. Williams,
Less-simplified models of dark matter for direct detection and the LHC,
JHEP **1604** (2016) 182 (arXiv:1509.05771).

We constructed models of dark matter with suppressed spin-independent scattering cross section utilizing the existing simplified model framework, with the goal of mimicking some of the characteristics of more realistic models without introducing an excessively large number of parameters. We considered three cases characterized by a Dirac fermion WIMP coupled to more than one mediator: 1) heavy vector mediator and Higgs portal; 2) squark-like mediator and Higgs portal; and 3) squark-like mediator and heavy vector mediator. We showed that a complementary use of several LHC searches can strongly constrain the direct detection blind spots by setting limits on the coupling constants and mediators' mass.

[P6] Kamila Kowalska, Jacek Pawełczyk, Enrico Maria Sessolo,
Flavored gauge mediation in the Peccei-Quinn NMSSM,
JHEP **1512** (2015) 148 (arXiv:1508.04142).

We investigated a particular version of the Peccei-Quinn NMSSM characterized by an economical and rigidly hierarchical flavor structure, based on flavored gauge mediation and on theoretical constructions inspired by string theory GUTs. One of the most important results of the study was to show that, despite requiring the unavoidable introduction of large scale superpotential and soft lagrangian effective terms that are linear and quadratic in the singlet field, the model does not present fine-tuning levels higher than the ones present in the MSSM, contrary to what was commonly believed.

[P7] Mateusz Iskrzyński, Kamila Kowalska,
Exact SU(5) Yukawa matrix unification in the General Flavor Violating MSSM,
JHEP **1504** (2015) 120 (arXiv:1412.8651).

In this study we provided evidence that $SU(5)$ boundary conditions for the Yukawa matrices at the GUT-scale can be satisfied within the renormalizable R-parity-conserving MSSM if a more general flavour structure of the soft SUSY-breaking sector is allowed. In particular, we found that a non-zero $(2,3)$ element of the down-type squark mass matrix helps to achieve an approximate Yukawa unification for the second family. We also demonstrated that such a scenario is consistent with a wide set of experimental measurements, including those from the FCNC processes, which are often raised as an argument against the flavor-violating MSSM.

[P8] Kamila Kowalska, Leszek Roszkowski, Enrico Maria Sessolo, Sebastian Trojanowski,
Low fine tuning in the MSSM with higgsino dark matter and unification constraints,
JHEP **1404** (2014) 166 (arXiv:1402.1328).

In this study we examined the issue of fine tuning in the MSSM with GUT-scale boundary conditions. We analyzed several popular scenarios: CMSSM, models with non-universal gaugino masses, and models with non-universal scalar masses. We showed that the mechanism of parameter-focusing along the RGE running is, for certain specific GUT-relations, very efficient in lowering the fine tuning of the scalar and gaugino sectors in the ~ 1 TeV higgsino region with respect to the case with universal masses.

[P9] Andrew Fowlie, Kamila Kowalska, Leszek Roszkowski, Enrico Maria Sessolo, Y.-L. Sming Tsai,
Dark matter and collider signatures of the MSSM,
Phys.Rev. **D88** (2013) 5, 055012 (arXiv:1306.1567).

In this paper we performed a global statistical analysis of the so-called p9MSSM, a parametrization of the MSSM with 9 free parameters defined at the SUSY scale. We confronted the model with a set of experimental constraints including measurement of the relic density of dark matter, measurement of the Higgs boson mass, results of the LHC direct SUSY searches, the evidence for a SM-like $\mathrm{BR}\left(\mathrm{B_s} \to \mu^+\mu^-\right)$, and the measurement of $\delta\left(g-2\right)_\mu$. We found that neutralino mass consistent at 2σ with all the experimental constraints must lie in the range of $[200-500]$ GeV.

[P10] Kamila Kowalska, Shoaib Munir, Leszek Roszkowski, Enrico Maria Sessolo, Sebastian Trojanowski, Y.-L. Sming Tsai,
The Constrained NMSSM with a 125 GeV Higgs boson – A global analysis,
Phys.Rev. **D87** (2013) 11, 115010 (arXiv:1211.1693).

We performed the first global analysis of the constrained NMSSM that investigated the impact of a recently discovered Higgs boson with a mass of around 125 GeV. Since the NMSSM encompasses two scalars that in principle can be light, we considered three possible scenarios, assuming in turn that the discovered Higgs boson is: the lightest Higgs boson of the model; the next-to-lightest Higgs boson; a combination of both light scalars roughly degenerate in mass. We found that, after a set of experimental constraints was applied, the first case shows a very CMSSM-like behavior. Contrarily, the second and the third cases were disfavored by the constraints from direct detection of dark matter and from the measurement of $\mathrm{BR}\left(\mathrm{B_s} \to \mu^+\mu^-\right)$.

[P11] Andrew Fowlie, Małgorzata Kazana, Kamila Kowalska, Shoaib Munir, Leszek Roszkowski, Enrico Maria Sessolo, Sebastian Trojanowski, Y.-L. Sming Tsai,
The CMSSM Favoring New Territories: The Impact of New LHC Limits and a 125 GeV Higgs,
Phys.Rev. **D86** (2012) 075010 (arXiv:1206.0264).

In this study we performed one of the first global analyses of the CMSSM that took into account the impact of a recently discovered Higgs boson with a mass of around 125 GeV. We identified high posterior probability regions of the CMSSM parameter space as the stau-coannihilation and the A-funnel regions, with the importance of the latter being much larger due to the combined effect of the 7 TeV LHC results and of dark matter relic density. We also found that the focus point region, allowed in the pre-LHC era, was now disfavored by the Higgs boson mass measurement.

[P12] Anna Chmiel, Janusz Hołyst, Kamila Kowalska,
Scaling of human behaviour during portal browsing,
Phys.Rev. **E80** (2009) 066122 (arXiv:0904.2369).

We investigated transitions of internet users between different subpages of two Polish portals. The collected data corresponded to a 24-hour period and the number of daily visitors reached around one million at portal A and almost 4 millions at portal B. A weighted network of portal subpages was reconstructed where edge weights were defined as the numbers of corresponding transitions. We found that the distribution of time spent by a user at one subpage decays as power law with an exponent around 1.3. Moreover, an individual path of a portal user resembles of self-attracting walk on a weighted network.

5.2.2 Before PhD

[P13] Piotr Chankowski, Kamila Kowalska, Stephean Lavignac, Stefan Pokorski,
Update on Fermion Mass Models with an Anomalous Horizontal U(1) Symmetry,
Phys.Rev. **D71** (2005) 055004 (hep-ph/0501071).

In this study we considered models of fermion masses and mixings based on a gauge anomalous horizontal $U(1)$ symmetry. For the simplicity we assumed that there is only one new scalar in the theory and that horizontal charges for all the Standard Model fields have the same sign. We found that only six charge assignments were allowed after all relevant experimental data had been taken into account. We also showed that a precise description of the observed fermion masses and mixing angles can easily be obtained by multiplying the elements of the Yukawa matrices by order one parameters, which are not constrained by the $U(1)$ symmetry.

[P14] Kamila Kowalska, Krzysztof Turzyński,
On Friedmann equation and the radion stabilization in two-brane models with dynamical matter,
Acta Phys.Polon. **B34** (2003) 3947-3956.

We investigated the consequences of gravitational stabilization of a two-brane system in the presence of matter and tensions of both branes as well as the cosmological constant in the bulk. We showed that the usual form of the Friedmann equation can be retained in this situation, even though the model is not a realistic one.

[P15] Kamila Kowalska,
Neutrino masses and unification of the gauge and Yukawa couplings,
Acta Phys.Polon. **B33** (2002) 1823 (hep-ph/0203168).

I investigated the influence of non-zero neutrino masses on the unification of the gauge and Yukawa couplings in the framework of the MSSM extended by a right-handed neutrino superfield. I found that in the former case the effect of massive neutrinos is small and can be safely neglected. It appears to be much more significant if one requires $Y_b = Y_\tau$ at the GUT scale. A contribution from the neutrino Yukawa coupling can change this relation by up to $\sim 12\%$.

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