# Krzysztof Piotr Rolbiecki

## 1 Scientific degrees

- 22 September 2008, Ph.D. in physics (summa cum laude), University of Warsaw
  Thesis title: *One-loop corrections in the supersymmetric model with CP phases*
  Advisor: Prof. Jan Kalinowski
  Referees: Prof. Marek Zrałek, Dr. Janusz Rosiek

- 2 September 2003, Master's degree in theoretical physics, University of Warsaw
  Thesis title: *Study of gaugino sector of the supersymmetric model*
  Advisor: Prof. Jan Kalinowski
  Referee: Dr. Janusz Rosiek

## 2 Academic career

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|---|---|
| 10.2014 – present | Assistant Professor, Institute of Theoretical Physics, Faculty of Physics, University of Warsaw |
| 10.2012 – 01.2016 | Postdoctoral Fellow, Instituto de Física Teórica, Universidad Autónoma de Madrid and Consejo Superior de Investigaciones Científicas, Madrid, Spain |
| 10.2010 – 09.2012 | Postdoctoral Fellow (wissenschaftlicher Mitarbeiter), Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany |
| 10.2008 – 09.2010 | Postdoctoral Fellow (Experienced Researcher) European Research Network HEPTools, Institute for Particle Physics Phenomenology, Durham University, Durham, United Kingdom |

## 3 About the candidate

I graduated in theoretical particle physics (M.Sc.) from the Faculty of Physics, University of Warsaw in 2003. My advisor was Prof. Jan Kalinowski. In 2008 I obtained Ph.D. in particle physics also from the University of Warsaw. My thesis was titled "One-loop corrections in

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the supersymmetric model with CP phases" and my Ph.D. advisor was Prof. Jan Kalinowski. Between October 2008 and January 2016 I completed three Postdoctoral Fellow positions at: the Institute for Particle Physics Phenomenology in Durham, DESY in Hamburg, and the Universidad Autónoma de Madrid. Since February 2014 I am an Assistant Professor at the Institute of Theoretical Physics, University of Warsaw.

I am an expert in particle physics at present and future high energy colliders. At the beginning of my career I was mainly involved in studies of supersymmetric models at the prospective International Linear Collider (ILC). This was the topic of both my master's and Ph.D. theses. During my stay in Durham I started studies of beyond Standard Model physics – supersymmetry, extra dimensions models, composite models, vector-like fermions – at the Large Hadron Collider (LHC). This is my principal research subject nowadays, though I am still involved in physics prospects at future lepton colliders. My interests also cover physics at the planned high luminosity upgrade of the LHC and future hadron colliders.

I am a co-author of the computer code `CheckMATE`, which is a tool to compare predictions of arbitrary theoretical models with results obtained at the LHC. The `CheckMATE` collaboration involves researchers from Germany, France and South Africa. I am also interested in applications of machine learning in particle physics. I joined two collaborations, BSM-AI and iDark, that aim at using machine learning techniques in collider and dark matter physics.

During my career I published 34 research articles in scientific journals, including four before obtaining the Ph.D. degree. According to the HEP search engine INSPIRE[1] my papers were cited more than 1400 times and my h-index is 20. I gave more than 50 talks at international conferences and invited seminars. I organized several scientific events and conferences; currently I am a scientific secretary of the Planck 2017 conference. I serve as a referee for the *Journal of High Energy Physics* and the *European Physical Journal C*. Since 2016 I am also teaching at the University of Warsaw. My past teaching experience includes tutorials at the University of Durham and summer schools in Spain. I am the Principal Investigator in the SONATA grant awarded by the Polish Science Centre.

## 4 Scientific achievement: Top squarks physics at the LHC

### 4.1 Series of articles

[1] **K. Rolbiecki**, J. Tattersall and G. Moortgat-Pick, *Towards measuring the stop mixing angle at the LHC*, Eur. Phys. J. **C71** (2011) 1517 [arXiv:0909.3196 [hep-ph]].
IF: 3.631, citations: 29, contribution: 80%

[2] G. Moortgat-Pick, **K. Rolbiecki**, J. Tattersall, *Momentum reconstruction at the LHC for probing CP-violation in the stop sector*, Phys. Rev. **D83** (2011) 115012 [arXiv:1008.2206 [hep-ph]].
IF: 4.558, citations: 15, contribution: 60%

[3] **K. Rolbiecki** and K. Sakurai, *Light stops emerging in WW cross section measurements?*, JHEP **1309** (2013) 004 [arXiv:1303.5696 [hep-ph]].

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[1] `http://tinyurl.com/rolbiecki-inspire`

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IF: 6.220, citations: 38, contribution: 70%

[4] J. S. Kim, **K. Rolbiecki**, K. Sakurai and J. Tattersall, *'Stop' that ambulance! New physics at the LHC?*, JHEP **1412** (2014) 010 [arXiv:1406.0858 [hep-ph]].
IF: 6.111, citations: 48, contribution: 60%

[5] **K. Rolbiecki** and J. Tattersall, *Refining light stop exclusion limits with* $W^+W^-$ *cross sections*, Phys. Lett. **B750** (2015) 247 [arXiv:1505.05523 [hep-ph]].
IF: 4.787, citations: 14, contribution: 80%

[6] J. S. Kim, **K. Rolbiecki**, R. Ruiz, J. Tattersall and T. Weber, *Prospects for natural SUSY*, Phys. Rev. **D94** (2016) 095013 [arXiv:1606.06738 [hep-ph]].
IF: 4.506, citations: 8, contribution: 45%

Total IF: 29.8

### 4.2 Introduction

The standard model in particle physics and the standard model in cosmology (ΛCDM model) provide a very precise and experimentally viable description of physics at very short and large distances. On the other hand, both models have serious shortcomings that give strong arguments that neither of them is complete. It suffices to mention the unknown origin of dark matter and dark energy, the hierarchy and naturalness problems, or the unknown mechanisms of inflation and baryogenesis. Searches for new physics that would answer these questions is one of the main goals of the ATLAS [7] and CMS [8] experiments at the Large Hadron Collider. Some of these questions may be answered during the ongoing second run with the center-of-mass energy $\sqrt{s} = 13$ TeV.

Among numerous models that try to address the issues within the Standard Model of particle physics, one of the most studied is supersymmetry; see e.g. a review article [9]. Supersymmetric models enhance the Poincaré symmetry of space-time by adding generators of spin transformations. In this setup, each of the Standard Model particles has a superpartner with the same quantum numbers and the spin different by 1/2. They would also be expected to have equal masses. Because we do not observe these new particles, they should be much heavier than their Standard Model counterparts, which implies that supersymmetry has to be broken by a yet unknown mechanism.

Such a construction may appear rather complicated as it requires more than doubling of the particle spectrum and a vast number of new parameters. Nevertheless, once we precisely define the mechanism of supersymmetry breaking, the number of free parameters is reduced to just a handful. At the same time, one can elegantly explain the Higgs mechanism of the electroweak symmetry breaking in the Standard Model by the so-called radiative symmetry breaking. Additionally, the new particles stabilize the mass of the Higgs boson, that is "unnaturally" small within the Standard Model. This is the above-mentioned naturalness problem. The lightest supersymmetric particle turns out to be a very good candidate for the mysterious dark matter filling the universe. Some supersymmetric models can also provide an explanation of inflation and baryogenesis mechanisms on top of that.

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Those features of supersymmetry promoted it to become one the most widely studied extensions of the Standard Model. However, the searches for supersymmetry at the LEP and Tevatron colliders gave null results. Nevertheless, the case for finding supersymmetry at the LHC remains strong [10, 11]. The two general purpose experiments, ATLAS and CMS, have dedicated working groups for supersymmetry searches, which shows the importance of supersymmetry in our quest for new physics.

A prominent role in the supersymmetric models can be attributed to the partners of the Standard Model top quarks and gluons. They are called top squarks (or simply "stops"), $\tilde{t}$, and gluinos, $\tilde{g}$, respectively. To a large extent, the details of the electroweak symmetry breaking mechanism are explained by them, which then provides masses to all the particles within the Standard Model. The discovery of the Higgs boson of mass 125 GeV [12, 13] further motivates searches for stops in the context of the small hierarchy problem.

Within the minimal supersymmetric standard model there are two top squarks, $\tilde{t}_L$ and $\tilde{t}_R$, that transform as the representations $(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ and $(\mathbf{3}, \mathbf{1}, \frac{2}{3})$ of the Standard Model gauge group $SU(3) \times SU(2) \times U(1)$. After the electroweak symmetry breaking they mix to give two mass eigenstates according to the formula:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \mathcal{R}_{\tilde{t}} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}}\, \mathrm{e}^{-\mathrm{i}\phi_{\tilde{t}}} \\ -\sin\theta_{\tilde{t}}\, \mathrm{e}^{\mathrm{i}\phi_{\tilde{t}}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}, \tag{1}$$

where $\mathcal{R}_{\tilde{t}}$ is a unitary matrix, and the mixing angles $\cos\theta_{\tilde{t}}$ and $\phi_{\tilde{t}}$ are defined in terms of the supersymmetric lagrangian parameters; see e.g. [1]. The detailed values of parameters in the above formula have a large impact on, for example, the calculation of radiative corrections to the Higgs boson mass. Because of their important role, the top squarks are extensively discussed in theoretical literature and are one of the main search targets at the LHC [14, 15].

The series of six publications which form this scientific accomplishment is my contribution to the discussion of the top squarks properties and searches. The first two articles provide analyses of new signals due to top squarks that could allow for a precise determination of some parameters of the underlying supersymmetric model. The following two papers are devoted to the analysis of anomalies that appeared in last years at ATLAS and CMS. Finally, the two most recent papers analyze current and future limits for production of stops and gluinos. These limits and projections were derived for the light stop simplified model and the natural supersymmetry model.

### 4.3 Discussion of results

The first articles of the series, [1] and [2], were written before the LHC started its operation. Their goal was to propose method for measuring parameters that define the supersymmetric top squarks sector, in particular the mixing angle $\cos\theta_{\tilde{t}}$ and the complex CP violating phase $\phi_{\tilde{t}}$ defined in Eq. (1). In Ref. [1] we proposed a measurement that relies on a functional dependence of branching fractions to different final states,

$$\tilde{t}_1 \to \tilde{\chi}_i^+ b\,, \qquad \tilde{t}_1 \to \tilde{\chi}_j^0 t\,, \tag{2}$$

driven the mixing angle $\cos\theta_{\tilde{t}}$ and the phase $\phi_{\tilde{t}}$. The branching ratios can vary significantly and leading to different experimental signatures. In order to avoid reliance on difficult measurement

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of the total cross section at the LHC, we introduced ratios of branching fractions for various combinations of the final states. The paper analyzed several realistic and phenomenologically motivated scenarios defining properties of the chargino and neutralino sectors (supersymmetric partners of the electroweak gauge bosons and the Higgs boson). The estimated precision was in the range of 10%, depending on an actual scenario.

The next paper [2] concentrates on a measurement of the complex phase $\phi_{\tilde t}$. The method uses triple products of momenta in cascade decay chains of top squarks. Due to spin correlations, such triple products are a sensitive probe of complex phases appearing in the mixing matrix and couplings of top squarks. Such observables were often studied in the context of linear $e^+e^-$ colliders. In Ref. [16] we applied them for the first time at the LHC in a realistic, fully hadronic study. Reference [2] further develops the idea in the top squark sector. The measurement of triple products requires reconstruction of the center-of-mass reference frame for the full production process of the stop pair. In this frame the asymmetries in the triple products are maximal, hence the sensitivity is greatly improved. The reconstruction of momenta of invisible and intermediate particles is performed by solving a set of kinematical equations. In this way, one can include the momenta of intermediate particles in the triple products. Scenarios for which the analysis was carried out are currently excluded, but the method remains viable at future hadronic colliders with center-of-mass energies of 33 TeV and 100 TeV.

The following paper [3] was motivated by an apparent excess – with respect to the Standard Model expectations – in the $pp \to W^+W^-$ cross section measurements at the LHC [17, 18]. We proposed there, that the discrepancy could be explained by an additional signal due to the production of light top squarks. In the model considered in Ref. [3], the top squarks would decay as

$$\tilde t_1 \to \tilde\chi_1^\pm\, b \to \tilde\chi_1^0\, W^{(*)}\, b \to \tilde\chi_1^0\, \ell\, \nu_\ell\, b\,, \tag{3}$$

with on-shell or nearly on-shell $W$ bosons. The chargino $\tilde\chi_1^\pm$ would have to be only slightly lighter than the stop, so that the $b$-jet produced in the two-body stop decay, $\tilde t_1 \to \tilde\chi_1^\pm b$, would be too soft to be reconstructed. The chargino would further decay with an on- or off-shell $W$, contributing to the dilepton final state. Therefore, the additional signal would imitate the final state expected in the Standard Model $W^+W^-$ pair production process. In particular, one would expect low missing transverse momentum similar to neutrinos originating from $W$ bosons. According to our Monte Carlo simulations, the best fit squark mass would be around 200 GeV. Because the measurement of $W^+W^-$ production cross section has relatively large theoretical and experimental uncertainties, we proposed an observable based on the momenta of the final state leptons [19]:

$$\cos\theta^*_{\ell\ell} = \tanh\left(\frac{\Delta\eta_{\ell\ell}}{2}\right)\,, \qquad \Delta\eta_{\ell\ell} = \eta_{\ell_1} - \eta_{\ell_2}\,, \tag{4}$$

where $\Delta\eta_{\ell\ell}$ is a difference of the pseudorapidities of the leading and the trailing lepton. This variable is the cosine of the polar angle of leptons with respect to the beam axis in the frame where the pseudorapidities of the leptons are equal and opposite. Being a function of the difference of pseudorapidities, $\cos\theta^*_{\ell\ell}$ is longitudinally boost-invariant. Such the observable would have much better sensitivity than the cross section measurement alone.

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We explored further this idea in Ref. [4]. The analysis was extended by inclusion of new measurements of $W^+W^-$ cross sections at the higher center-of-mass energy, other Standard Model cross sections, and direct limits on production of various supersymmetric particles. We took into account 12 experimental analyses from the ATLAS and CMS experiments. They were implemented in the computer code `CheckMATE`, which was used to scan the parameter space defined by masses of top squarks and other supersymmetric particles. In this way, we have identified the masses, which provided the best description of all available data. It turned out that the model could consistently explain also another apparent excess in the final state of three leptons and missing transverse momentum. Both papers initiated a discussion about other possible explanations of the excess in $W^+W^-$ pair production [20–22]. Several research groups proposed improved calculations of the $W^+W^-$ cross section within the Standard Model, that took into account specific requirements of this measurement. The following experimental results [23, 24] with more integrated luminosity seemed to suggest that the discrepancy could be explained solely using the Standard Model without invoking new physics.

With the above results in mind and the new calculations of the Standard Model $W^+W^-$ cross section we proposed in Ref. [5] to use this measurement to derive new constraints on the production of light top squarks. It turned out that the new method is particularly sensitive to the production of top squarks with mass below 200 GeV; see Figure 1. In particular, we were able to exclude the top squarks with the mass approximately equal to the sum of masses of $W$ boson and the lightest supersymmetric particle: $m_{\tilde{t}_1} \approx m_{\tilde{\chi}^0_1} + m_W + m_b$. Assuming that the top squark decay proceeds as

$$\tilde{t}_1 \to b\,W\,\tilde{\chi}^0_1 \qquad \text{or} \qquad \tilde{t}_1 \to b\,f\,f'\,\tilde{\chi}^0_1, \tag{5}$$

the $W^+W$ measurement allows us to exclude top squarks up to 220 GeV for the lightest neutralino mass of approximately 130 GeV. We also note the additional exclusion for stop masses $\sim$170–190 GeV for decay mode $\tilde{t}_1 \to t\tilde{\chi}^0_1$, where an intermediate top quark is nearly on-shell. These limits are cited in the current edition of the Particle Data Group report [25].

In the last paper of the series [6] we revisited the constraints on the natural supersymmetry model [31]. It assumes that the only light supersymmetric particles in the spectrum are those responsible for the radiative symmetry breaking and controlling the mass of the light Higgs boson: higgsinos, top squarks and gluino. The model attracts a lot of attention nowadays, because of its minimal particle content, while ensuring the correct breaking of the electroweak symmetry. The current constraints on the model were obtained using several ATLAS searches for gluinos and third generation squarks at the center-of-mass energy $\sqrt{s} = 13$ TeV and total integrated luminosity 3 fb$^{-1}$. The results were then extrapolated to higher luminosities, 20–3000 fb$^{-1}$. Our results show that by the end of the last phase of the LHC data-taking one can expect exclusion limits up to mass of 1500 GeV for top squarks and up to 2500 GeV for gluinos. The most important result obtained in the paper are the expected $5\sigma$ sensitivity after collecting the total luminosity of 3000 fb$^{-1}$ for the natural supersymmetry model. By comparing the expected exclusion limits at different stages of the LHC experiment, we concluded that the limits obtained in year 2016 will cover most of the discoverable parameter space available at center-of-mass energy 14 TeV; see Figure 2. This can be explained by noting that any exclusion at 95% confidence level advances much faster compared to the amount of data required for the $5\sigma$ discovery. Therefore, if we want to keep a promise of new physics discovery at the LHC, the first

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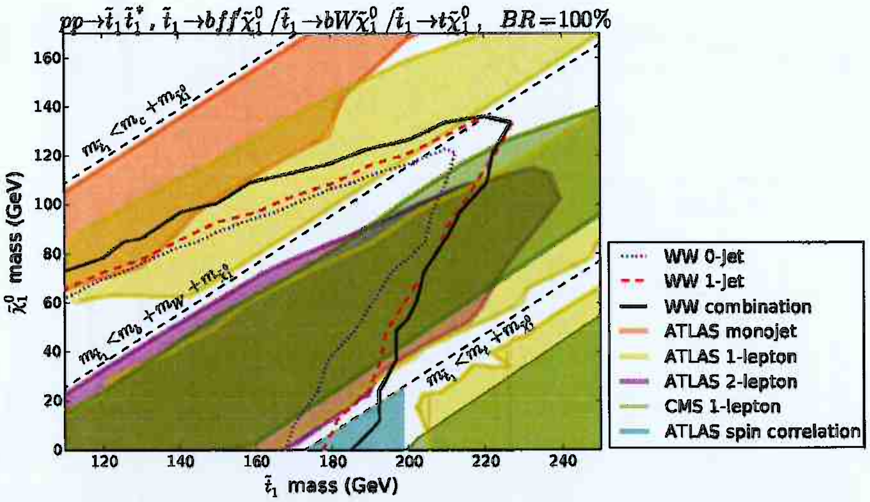

Figure 1: The exclusion limits for stop pair-production in $m_{\tilde{t}_1}$–$m_{\tilde{\chi}_1^0}$ plane assuming that only decay modes listed above the plot are allowed. The dotted-blue line denotes the exclusion using 0-jet signal region and the red-dashed 1-jet signal region of Ref. [23]. The black solid-line is for the combined exclusion. The experimental exclusions were extracted from the following studies: ATLAS monojet [26], ATLAS 1-lepton [27], ATLAS 2-lepton [28], CMS 1-lepton [29], ATLAS spin correlation [30]. From Ref. [5].

signal of discrepancy between the Standard Model predictions and experimental data should start to emerge in year 2016 or 2017 at the latest. This conclusion could be perhaps somewhat softened once one makes optimistic assumptions about the future experimental uncertainties. Nevertheless, the lack of any signal in the near future will undoubtedly cast a shadow on the prospects of new physics discovery at the LHC.

### 4.4 Summary

The series of publications I presented here is an important part of studies of supersymmetric models at the LHC. It covers different aspects of supersymmetry searches: from the methods to determine the parameters of the top squarks sector to deriving the limits on their production in the current and future experiments. This topic is certainly far from being over and because of the special role of top squarks in supersymmetric models one can expect further experimental searches and new theoretical developments. My goal in the near future is to continue those ideas, in particular within two international collaborations, `CheckMATE` [32–34] and `SUSY-AI` [35, 36], that are briefly discussed in the next part of this document.

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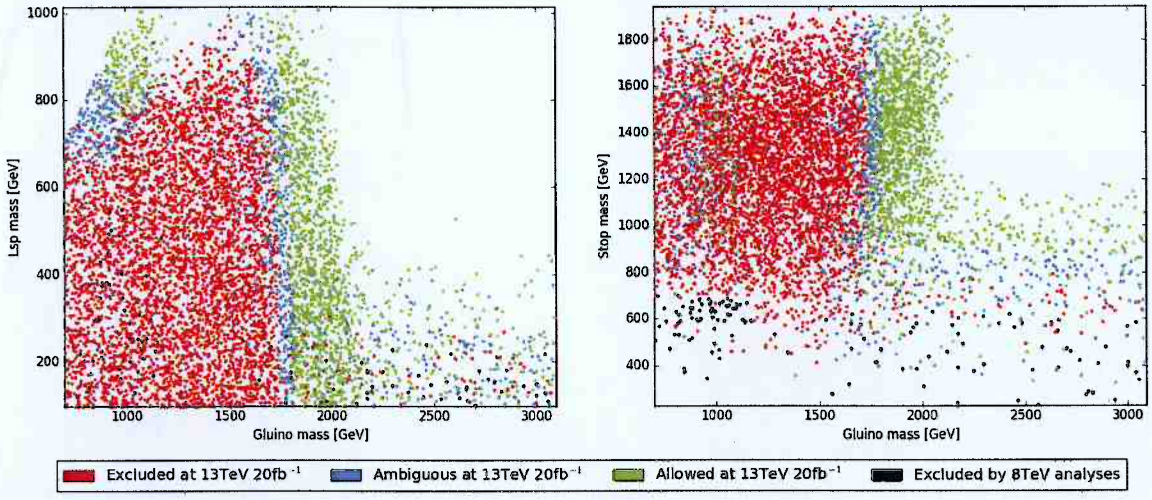

Figure 2: Plots showing the natural supersymmetry points that can be discovered at $\sqrt{s} = 14$ TeV with $\mathcal{L} = 3000$ fb$^{-1}$ under the assumption that the current systematic errors will remain constant. We classify these points as excluded, ambiguous within Monte Carlo uncertainty and allowed at 13 TeV with 20 fb$^{-1}$ and those already excluded at 8 TeV. Left: $m_{\tilde{g}}$ vs $m_{\tilde{\chi}_1^0}$; Right: $m_{\tilde{g}}$ vs $m_{\tilde{t}_1}$. From Ref. [6].

## 5 Other scientific achievements

### 5.1 Bibliometric data

### According to Web of Science

As of: 15.03.2017
Number of published articles: 34
Sum of the times cited: 343
Sum of times cited without self-citations: 300
h-index: 12

### According to Inspire

Source: `http://tinyurl.com/rolbiecki-inspire`
As of: 15.03.2017
Number of research articles: 35
(including 2 under review and 4 before Ph.D.)
Other papers: 20
Sum of the times cited: 1413
Total Impact Factor: 166.6
h-index: 20

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### 5.2 Discussion

My remaining publications can be grouped into several categories that I will discuss in the following subsections.

#### Computer tools

I am a co-author of the computer code `CheckMATE` [32–34] that allows models of new physics to be easily tested (*recasted*) against the recent LHC data. To achieve this goal, the core of `CheckMATE` now contains over 60 LHC analyses of which 12 are from the 13 TeV run. The program utilizes the fast detector simulation based on `Delphes 3` [37], which was tuned to reproduce performance of the ATLAS and CMS detectors. The recently published version, `CheckMATE 2`, now integrates the Monte Carlo event generation via `Madgraph 5` [38] and `Pythia 8` [39]. This allows users to go directly from a SLHA file or a UFO model to the result of whether a model is allowed or not. In addition, the integration of the event generation step leads to a significant increase in the speed of the program. The code is one of the main tools used for recasting in the phenomenology community.

The second collaboration, `SUSY-AI` [35, 36], aims to use machine learning techniques to test if a particular parameter set of the minimal supersymmetric model is excluded by LHC data. Normally, such an assessment requires the time consuming generation of scattering events, the simulation of the detector response, the event reconstruction, cross section calculations and analysis code to test against several hundred signal regions defined by the ATLAS and CMS experiments. In our approach, machine learning is used to predict within a fraction of millisecond if a model is excluded or not directly from the input parameters. `SUSY-AI` and its future BSM derivatives will help to solve the problem of recasting LHC results for any model of new physics in multidimensional parameter spaces, where it is required to analyze thousands of points in a very short time.

#### Searches for new physics at the LHC

One of the above-mentioned papers [6] discussed natural supersymmetry. I analyzed this model from a more theoretical perspective in two other papers. In Ref. [40] we studied naturalness of different scenarios within the minimal supersymmetric standard model. The analysis was based on the widely accepted measure of naturalness [41]. The novelty was in applying the two-loop renormalization group equations and carefully taking into account the requirement to obtain the Higgs boson mass in agreement with the LHC measurement. The results were further compared to the LHC searches for supersymmetry. The idea was continued in Ref. [42], where we applied the method to another supersymmetric model with extended sparticle spectrum.

A lot of effort was directed in the recent years towards *recasting*. By recasting one usually means deriving limits on a new model using LHC results from an analysis of another new physics model or Standard Model measurements. This means that the old data are used in a new context. `CheckMATE` is a popular example of a computer code used for recasting. In Ref. [43] we considered bounds on the compressed supersymmetry models. Such models are extremely challenging at the LHC due to low missing transverse momentum. Instead, we proposed to use leptonic final states, that normally require much less missing energy. In Ref. [44] we studied another model with low missing transverse momentum: the $R$-parity violating model, in which the lightest supersymmetric particle further decays to quarks and leptons. We found that also in this challenging scenario one can derive meaningful constraints thanks to the broad program of LHC searches.

Another interesting idea was discussed in Ref. [19]. We proposed there a method of distinguishing models that predict different spins of the new particles. As discussed before, in a supersymmetric model the new particles have spin different by $1/2$ from their Standard Model partners. On the other hand, in the Kaluza-Klein models of extra dimensions the new particles have spins the same as the corresponding Standard Model particles. In Ref. [19] we provided a method to resolve this ambiguity. In case a new signal will be discovered at the LHC such an information could help to direct further searches.

In December 2015 the ATLAS and CMS experiments announced an excess in the measurement of the diphoton spectrum at high invariant masses. Since in both experiments the excess occurred at the mass of approximately 750 GeV this led to a vast number of theoretical speculations. I was a coauthor of several studies looking at the excess in the context of different new physics models [45–48]. We also provided a model-independent analysis of the compatibility of the excess with 8 TeV LHC data [49]. In the end, the subsequent measurements [50, 51] refuted the idea of new physics origin of the excess. Nevertheless, those studies allowed me to learn in more detail several new theoretical ideas, in particular vector-like quark models.

### Supersymmetry in $e^+e^-$ colliders

I consider Ref. [52] as one of the most interesting among my papers discussing discovery potential of lepton colliders. The goal was to study mass-degenerate higgsinos at the planned International Linear Collider (ILC) in a close collaboration with the experimental group in Hamburg. Using Monte Carlo methods and a detailed simulation of the detector response we found that the masses of higgsinos can be measured with an accuracy of 1 GeV and the mass differences between higgsino-like chargino and neutralinos with an accuracy of about 100 MeV. We also studied determination of mixing angles in the higgsino sector and prospects for measurement of supersymmetric model parameters. The precision expected at the ILC gives indirect sensitivity to the parameters in the range of several TeV, otherwise not accessible experimentally. Some of the ideas were further developed in Ref. [53], which also discussed another types of mass-degenerate particles.

I was also involved in studies of charge-parity (CP) violation and its experimental signatures at the ILC. CP violation is an important ingredient of supersymmetric models since it can explain baryon asymmetry in the universe. Two papers [54, 55] (both before obtaining Ph.D. degree) analyzed three-body decays of neutralinos, where CP violation can be observed in triple products of spin and momenta. Another proposed method for study of CP violating effects was a comparison of cross sections for chargino production [56] in different channels. The advantage of these methods is that any asymmetry in the observables automatically implies the presence of complex couplings, which signal CP violation regardless of other parameters of the model. A very detailed analysis, including Monte Carlo and detector simulation, of prospects for such measurements was performed in Ref. [57].

The other papers about supersymmetry at the ILC are devoted to searches of electroweakly

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interacting particles. The high precision of measurements achievable at the ILC gives access to a number of states virtually invisible at the LHC [58, 59]. Furthermore, it is possible to distinguish electroweak sectors of various supersymmetric models [60]. Those studies also show the importance of interplay between the searches at the LHC and ILC.

Finally, I am a coauthor of two review papers about supersymmetry. In the first one [61], a convention was proposed, that detailed methods of performing and presenting calculations of radiative corrections in supersymmetric models. The goal was to facilitate comparisons between numerical results obtained by different groups. The second article [62] discusses many aspects of supersymmetry searches at a linear $e^+e^-$ collider and also includes prospects for precision Standard Model measurements. It summarizes the state of the art of physics studies at such the machine in preparation for a final decision regarding the construction of the ILC.

## References

[1] K. Rolbiecki, J. Tattersall, and G. Moortgat-Pick, *Towards Measuring the Stop Mixing Angle at the LHC*, Eur. Phys. J. **C71** (2011) 1517, [`arXiv:0909.3196`].

[2] G. Moortgat-Pick, K. Rolbiecki, and J. Tattersall, *Momentum reconstruction at the LHC for probing CP-violation in the stop sector*, Phys. Rev. **D83** (2011) 115012, [`arXiv:1008.2206`].

[3] K. Rolbiecki and K. Sakurai, *Light stops emerging in WW cross section measurements?*, JHEP **09** (2013) 004, [`arXiv:1303.5696`].

[4] J. S. Kim, K. Rolbiecki, K. Sakurai, and J. Tattersall, *'Stop' that ambulance! New physics at the LHC?*, JHEP **12** (2014) 010, [`arXiv:1406.0858`].

[5] K. Rolbiecki and J. Tattersall, *Refining light stop exclusion limits with $W^+W^-$ cross sections*, Phys. Lett. **B750** (2015) 247–251, [`arXiv:1505.05523`].

[6] J. S. Kim, K. Rolbiecki, R. Ruiz, J. Tattersall, and T. Weber, *Prospects for natural SUSY*, Phys. Rev. **D94** (2016), no. 9 095013, [`arXiv:1606.06738`].

[7] **ATLAS** Collaboration, G. Aad et al., *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[8] **CMS** Collaboration, S. Chatrchyan et al., *The CMS Experiment at the CERN LHC*, JINST **3** (2008) S08004.

[9] S. P. Martin, *A Supersymmetry primer*, `hep-ph/9709356`. [Adv. Ser. Direct. High Energy Phys. 18, 1 (1998)].

[10] **ATLAS** Collaboration, G. Aad et al., *Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 – interpreted in the phenomenological MSSM*, JHEP **10** (2015) 134, [`arXiv:1508.06608`].

[11] **CMS** Collaboration, V. Khachatryan et al., *Phenomenological MSSM interpretation of CMS searches in pp collisions at $\sqrt{s} = 7$ and 8 TeV*, JHEP **10** (2016) 129, [`arXiv:1606.03577`].

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[12] **ATLAS** Collaboration, G. Aad et al., *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. **B716** (2012) 1–29, [`arXiv:1207.7214`].

[13] **CMS** Collaboration, S. Chatrchyan et al., *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. **B716** (2012) 30–61, [`arXiv:1207.7235`].

[14] **ATLAS** Collaboration, G. Aad et al., *ATLAS Run 1 searches for direct pair production of third-generation squarks at the Large Hadron Collider*, Eur. Phys. J. **C75** (2015), no. 10 510, [`arXiv:1506.08616`]. [Erratum: Eur. Phys. J. C76, no. 3, 153 (2016)].

[15] **CMS** Collaboration, A. M. Sirunyan et al., *Searches for pair production of third-generation squarks in $\sqrt{s} = 13$ TeV pp collisions*, `arXiv:1612.03877`.

[16] G. Moortgat-Pick, K. Rolbiecki, J. Tattersall, and P. Wienemann, *Probing CP Violation with and without Momentum Reconstruction at the LHC*, JHEP **01** (2010) 004, [`arXiv:0908.2631`].

[17] **ATLAS** Collaboration, G. Aad et al., *Measurement of $W^+W^-$ production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector and limits on anomalous WWZ and $WW\gamma$ couplings*, Phys. Rev. **D87** (2013), no. 11 112001, [`arXiv:1210.2979`]. [Erratum: Phys. Rev. D88, no. 7, 079906 (2013)].

[18] **CMS** Collaboration, S. Chatrchyan et al., *Measurement of $W^+W^-$ and $ZZ$ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV*, Phys. Lett. **B721** (2013) 190–211, [`arXiv:1301.4698`].

[19] G. Moortgat-Pick, K. Rolbiecki, and J. Tattersall, *Early spin determination at the LHC?*, Phys. Lett. **B699** (2011) 158–163, [`arXiv:1102.0293`].

[20] T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, and L. Tancredi, *$W^+W^-$ Production at Hadron Colliders in Next to Next to Leading Order QCD*, Phys. Rev. Lett. **113** (2014), no. 21 212001, [`arXiv:1408.5243`].

[21] P. Jaiswal and T. Okui, *Explanation of the WW excess at the LHC by jet-veto resummation*, Phys. Rev. **D90** (2014), no. 7 073009, [`arXiv:1407.4537`].

[22] P. Meade, H. Ramani, and M. Zeng, *Transverse momentum resummation effects in $W^+W^-$ measurements*, Phys. Rev. **D90** (2014), no. 11 114006, [`arXiv:1407.4481`].

[23] **CMS** Collaboration, V. Khachatryan et al., *Measurement of the $W^+W^-$ cross section in pp collisions at $\sqrt{s} = 8$ TeV and limits on anomalous gauge couplings*, Eur. Phys. J. **C76** (2016), no. 7 401, [`arXiv:1507.03268`].

[24] **ATLAS** Collaboration, G. Aad et al., *Measurement of total and differential $W^+W^-$ production cross sections in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector and limits on anomalous triple-gauge-boson couplings*, JHEP **09** (2016) 029, [`arXiv:1603.01702`].

[25] **Particle Data Group** Collaboration, C. Patrignani et al., *Review of Particle Physics*, Chin. Phys. **C40** (2016), no. 10 100001.

[26] **ATLAS** Collaboration, G. Aad et al., *Search for pair-produced third-generation squarks decaying via charm quarks or in compressed supersymmetric scenarios in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Phys. Rev. **D90** (2014), no. 5 052008, [`arXiv:1407.0608`].

KR

[27] **ATLAS** Collaboration, G. Aad et al., *Search for top squark pair production in final states with one isolated lepton, jets, and missing transverse momentum in* $\sqrt{s} = 8$ *TeV pp collisions with the ATLAS detector*, JHEP **11** (2014) 118, [`arXiv:1407.0583`].

[28] **ATLAS** Collaboration, G. Aad et al., *Search for direct top-squark pair production in final states with two leptons in pp collisions at* $\sqrt{s} = 8$ *TeV with the ATLAS detector*, JHEP **06** (2014) 124, [`arXiv:1403.4853`].

[29] **CMS** Collaboration, S. Chatrchyan et al., *Search for top-squark pair production in the single-lepton final state in pp collisions at* $\sqrt{s} = 8$ *TeV*, Eur. Phys. J. **C73** (2013), no. 12 2677, [`arXiv:1308.1586`].

[30] **ATLAS** Collaboration, G. Aad et al., *Measurement of Spin Correlation in Top-Antitop Quark Events and Search for Top Squark Pair Production in pp Collisions at* $\sqrt{s} = 8$ *TeV Using the ATLAS Detector*, Phys. Rev. Lett. **114** (2015), no. 14 142001, [`arXiv:1412.4742`].

[31] M. Papucci, J. T. Ruderman, and A. Weiler, *Natural SUSY Endures*, JHEP **09** (2012) 035, [`arXiv:1110.6926`].

[32] J. S. Kim, D. Schmeier, J. Tattersall, and K. Rolbiecki, *A framework to create customised LHC analyses within CheckMATE*, Comput. Phys. Commun. **196** (2015) 535–562, [`arXiv:1503.01123`].

[33] D. Dercks, N. Desai, J. S. Kim, K. Rolbiecki, J. Tattersall, and T. Weber, *CheckMATE 2: From the model to the limit*, `arXiv:1611.09856`.

[34] CheckMATE `http://checkmate.hepforge.org/`.

[35] S. Caron, J. S. Kim, K. Rolbiecki, R. Ruiz de Austri, and B. Stienen, *The BSM-AI project: SUSY-AI - Generalizing LHC limits on Supersymmetry with Machine Learning*, `arXiv:1605.02797`.

[36] BSM-AI `http://www.susy-ai.org/`.

[37] **DELPHES 3** Collaboration, J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, and M. Selvaggi, *DELPHES 3, A modular framework for fast simulation of a generic collider experiment*, JHEP **02** (2014) 057, [`arXiv:1307.6346`].

[38] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, JHEP **07** (2014) 079, [`arXiv:1405.0301`].

[39] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, *An Introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015) 159–177, [`arXiv:1410.3012`].

[40] J. A. Casas, J. M. Moreno, S. Robles, K. Rolbiecki, and B. Zaldívar, *What is a Natural SUSY scenario?*, JHEP **06** (2015) 070, [`arXiv:1407.6966`].

KR

[41] R. Barbieri and G. F. Giudice, *Upper Bounds on Supersymmetric Particle Masses*, Nucl. Phys. **B306** (1988) 63–76.

[42] J. A. Casas, J. M. Moreno, S. Robles, and K. Rolbiecki, *Reducing the fine-tuning of gauge-mediated SUSY breaking*, Eur. Phys. J. **C76** (2016), no. 8 450, [`arXiv:1602.06892`].

[43] K. Rolbiecki and K. Sakurai, *Constraining compressed supersymmetry using leptonic signatures*, JHEP **10** (2012) 071, [`arXiv:1206.6767`].

[44] M. Asano, K. Rolbiecki, and K. Sakurai, *Can R-parity violation hide vanilla supersymmetry at the LHC?*, JHEP **01** (2013) 128, [`arXiv:1209.5778`].

[45] J. S. Kim, J. Reuter, K. Rolbiecki, and R. Ruiz de Austri, *A resonance without resonance: scrutinizing the diphoton excess at 750 GeV*, Phys. Lett. **B755** (2016) 403–408, [`arXiv:1512.06083`].

[46] F. Domingo, S. Heinemeyer, J. S. Kim, and K. Rolbiecki, *The NMSSM lives: with the 750 GeV diphoton excess*, Eur. Phys. J. **C76** (2016), no. 5 249, [`arXiv:1602.07691`].

[47] V. De Romeri, J. S. Kim, V. Martín-Lozano, K. Rolbiecki, and R. Ruiz de Austri, *Confronting dark matter with the diphoton excess from a parent resonance decay*, Eur. Phys. J. **C76** (2016), no. 5 262, [`arXiv:1603.04479`].

[48] A. Biekötter, J. L. Hewett, J. S. Kim, M. Kraemer, T. G. Rizzo, K. Rolbiecki, J. Tattersall, and T. Weber, *Complementarity of Resonant Scalar, Vector-Like Quark and Superpartner Searches in Elucidating New Phenomena*, Int. J. Mod. Phys. **A32** (2017), no. 05 1750032, [`arXiv:1608.01312`].

[49] J. S. Kim, K. Rolbiecki, and R. Ruiz de Austri, *Model-independent combination of diphoton constraints at 750 GeV*, Eur. Phys. J. **C76** (2016), no. 5 251, [`arXiv:1512.06797`].

[50] **ATLAS** Collaboration, *Search for scalar diphoton resonances with 15.4 $fb^{-1}$ of data collected at $\sqrt{s} = 13$ TeV in 2015 and 2016 with the ATLAS detector*, Tech. Rep. ATLAS-CONF-2016-059, CERN, Geneva, Aug, 2016.

[51] **CMS** Collaboration, V. Khachatryan et al., *Search for high-mass diphoton resonances in proton-proton collisions at 13 TeV and combination with 8 TeV search*, Phys. Lett. **B767** (2017) 147–170, [`arXiv:1609.02507`].

[52] M. Berggren, F. Brümmer, J. List, G. Moortgat-Pick, T. Robens, K. Rolbiecki, and H. Sert, *Tackling light higgsinos at the ILC*, Eur. Phys. J. **C73** (2013), no. 12 2660, [`arXiv:1307.3566`].

[53] S. Y. Choi, T. Han, J. Kalinowski, K. Rolbiecki, and X. Wang, *Characterizing invisible electroweak particles through single-photon processes at high energy $e^+e^-$ colliders*, Phys. Rev. **D92** (2015), no. 9 095006, [`arXiv:1503.08538`].

[54] S. Y. Choi, B. C. Chung, J. Kalinowski, Y. G. Kim, and K. Rolbiecki, *Analysis of the neutralino system in three-body leptonic decays of neutralinos*, Eur. Phys. J. **C46** (2006) 511–520, [`hep-ph/0504122`].

KR

[55] J. Kalinowski and K. Rolbiecki, *CP violation in the chargino/neutralino sector of the MSSM*, Acta Phys. Polon. **B39** (2008) 1585–1592, [`arXiv:0804.0549`].

[56] K. Rolbiecki and J. Kalinowski, *CP violation at one loop in the polarization-independent chargino production in $e^+e^-$ collisions*, Phys. Rev. **D76** (2007) 115006, [`arXiv:0709.2994`].

[57] O. Kittel, G. Moortgat-Pick, K. Rolbiecki, P. Schade, and M. Terwort, *Measurement of CP asymmetries in neutralino production at the ILC*, Eur. Phys. J. **C72** (2012) 1854, [`arXiv:1108.3220`].

[58] K. Desch, J. Kalinowski, G. Moortgat-Pick, K. Rolbiecki, and W. J. Stirling, *Combined LHC/ILC analysis of a SUSY scenario with heavy sfermions*, JHEP **12** (2006) 007, [`hep-ph/0607104`].

[59] J. Kalinowski, W. Kilian, J. Reuter, T. Robens, and K. Rolbiecki, *Pinning down the Invisible Sneutrino*, JHEP **10** (2008) 090, [`arXiv:0809.3997`].

[60] G. Moortgat-Pick, S. Porto, and K. Rolbiecki, *Neutralinos betray their singlino nature at the ILC*, JHEP **09** (2014) 002, [`arXiv:1406.7701`].

[61] J. A. Aguilar-Saavedra et al., *Supersymmetry parameter analysis: SPA convention and project*, Eur. Phys. J. **C46** (2006) 43–60, [`hep-ph/0511344`].

[62] A. Arbey et al., *Physics at the $e^+e^-$ Linear Collider*, Eur. Phys. J. **C75** (2015), no. 8 371, [`arXiv:1504.01726`].

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