Summary of professional accomplishments

Kazuki Sakurai

1 Scientific degrees

- 25 March 2009, Doctor of Science in physics, Nagoya University (Japan),
  Thesis title: *Phenomenology of Models with Non-Universal Sfermion Masses*
  Advisor: Prof. Nobuhiro Maekawa
- 21 March 2006, Master of Science in physics, Nagoya University (Japan)
  Thesis title: *Analysis of* $\tau \to \mu\gamma$ *and* $\mu \to e\gamma$ *processes in supersymmetric grand unified theories*
  Advisor: Prof. Nobuhiro Maekawa

2 Academic career

02.2017 – present	Assistant Professor, Institute of Theoretical Physics, Faculty of Physics, University of Warsaw
10.2015 – 01.2017	Research Associate, Institute for Particle Physics Phenomenology, University of Durham, Durham, United Kingdom
10.2013 – 09.2015	Research Associate, King's College London, London, United Kingdom
10.2011 – 09.2013	Postdoctoral Fellow, Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
04.2011 – 09.2011	Special Assistant Professor, Nagoya University, Nagoya, Japan
10.2009 – 03.2011	Postdoctoral Fellow, Cavendish Laboratory and Department of Applied Mathematics and Theoretical Physics (DAMTP), University of Cambridge, Cambridge, United Kingdom
04.2009 – 09.2009	Postdoctoral Fellow, High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

3 About the candidate

I completed my master education in the particle physics group in Nagoya University in 2006, under the supervision by Prof. Nobuhiro Maekawa. In 2009 I acquired Ph.D in particle physics also at Nagoya University. My thesis title was "Phenomenology of models with non-universal sfermion masses" and my Ph.D advisor was Prof. Nobuhiro Maekawa. During the period between April 2009 and January 2017, I completed several postdoctoral fellow positions at: KEK in Tsukuba (Japan), University of Cambridge in Cambridge (UK), Deutsches Elektronen-Synchrotron (DESY) in Hamburg (Germany), King's College London in London (UK) and the Institute for Particle Physics Phenomenology in Durham (UK). I also took a special assistant professor position at Nagoya University from April to September in 2011. Since February 2017, I am an assistant professor at the Institute of Theoretical Physics, University of Warsaw.

I am an expert in phenomenology of the Standard Model and models beyond it. In my master's and Ph.D theses, I have investigated theoretical and phenomenological aspects of a type of supersymmetric models motivated by E_6 grand unified theories. My recent works focused more on physics at the Large Hadron Collider (LHC) as well as future high energy colliders. I have published several pioneering works in recasting the LHC results into various new physics models using Monte Carlo simulations. I have also studied various novel signatures at the LHC within and beyond the Standard Model.

I am the main author of the computer code `Fastlim`, which is a tool to estimate the LHC constraint on models beyond the Standard Model using a novel semi-analytical approach. I am actively involved also in the `MasterCode` project, which confronts various models with the latest and comprehensive experimental results. The collaboration consists of ~ 10 experimentalists and ~ 10 theorists worldwide and regularly publish papers in prestigious journals.

During my career, I published more than 50 research articles in scientific journals, including seven before obtaining Ph.D degree. My papers were cited more than 1400 times according to HEP search engine INSPIRE (`http://inspirehep.net/author/profile/K.Sakurai.1`). I gave more than 50 talks at international conferences and invited seminars. I serve as a referee for the *Journal of High Energy Physics*, the *European Physical Journal C* and the *Physical Letters B.* I organized a couple of scientific events and conferences. I was a local organizer of the BUSSTEPP 2015 summer school and the Planck 2017 conference. I have been teaching at the University of Warsaw since 2017. I have taught Quantum Mechanics tutorials for undergraduate students in English. I will be teaching the same course as well as the Electromagnetism for undergraduate students in English. My past teaching experience includes tutorials in University of Cambridge and BUSSTEPP summer schools in 2015 and 2016. I have given an invited lecture course in the PIER Helmholtz Graduate Week at University of Hamburg and DESY in 2016.

4 Scientific achievement: Hunting for Exotic Signatures at the LHC

4.1 Series of articles

[H1] D. Gonçalves, **K. Sakurai** and M. Takeuchi, *Mono-top Signature from Supersymmetric $t\bar{t}H$ Channel*, Phys. Rev. D **94** (2016) no.7, 075009 [arXiv:1604.03938 [hep-ph]].
citations: 7, contribution: 60%

[H2] D. Gonçalves, **K. Sakurai** and M. Takeuchi, *Tagging a monotop signature in natural SUSY*, Phys. Rev. D **95** (2017) no.1, 015030 [arXiv:1610.06179 [hep-ph]].
citations: 8, contribution: 60%

[H3] M. Badziak, A. Delgado, M. Olechowski, S. Pokorski and **K. Sakurai**, *Detecting underabundant neutralinos*, JHEP **1511** (2015) 053 [arXiv:1506.07177 [hep-ph]].
citations: 29, contribution: 80%

[H4] K. Rolbiecki and **K. Sakurai**, *Long-lived bino and wino in supersymmetry with heavy scalars and higgsinos*, JHEP **1511** (2015) 091 [arXiv:1506.08799 [hep-ph]].
citations: 10, contribution: 80%

[H5] J. Ellis, D. S. Hwang, **K. Sakurai** and M. Takeuchi, *Disentangling Higgs-Top Couplings in Associated Production*, JHEP **1404** (2014) 004 [arXiv:1312.5736 [hep-ph]].
citations: 76, contribution: 60%

[H6] J. Ellis and **K. Sakurai**, *Search for Sphalerons in Proton-Proton Collisions*, JHEP **1604** (2016) 086 [arXiv:1601.03654 [hep-ph]].
citations: 8, contribution: 80%

[H7] M. Papucci, **K. Sakurai**, A. Weiler and L. Zeune, *Fastlim: a fast LHC limit calculator*, Eur. Phys. J. C **74** (2014) no.11, 3163 [arXiv:1402.0492 [hep-ph]].
citations: 74, contribution: 80%

4.2 Introduction

For the last over 40 years the Standard Model (SM) of particle physics has been extremely successful in describing elementary interactions of elementary particles. However, the SM leaves several intriguing puzzles unanswered. This includes the gauge hierarchy problem, asking for a mechanism to stabilize the Higgs potential, and observations of the Dark Matter (DM) in astrophysics, strikingly demonstrating that the SM is incomplete. Currently, particle physics has been given a lot of new information thanks to a wealth of data collected at the world's most powerful particle accelerator, the Large Hadron Collider (LHC) at CERN, colliding protons with the unprecedented energy of 13 TeV. The LHC has achieved a major breakthrough by discovering the Higgs boson in 2012 [1]. The LHC was also long-awaited because of its capability of directly testing the physics well above the electroweak scale, where new physics underling the SM is expected to emerge. However, the big surprise is that, at the time of writing, no conclusive evidence for new degrees of freedom in the mass range up to O(1) TeV has been found, excluding the *bulk* of the parameter spaces of many new physics models. This makes the hierarchy problem in the SM even more pronounced and intriguing.

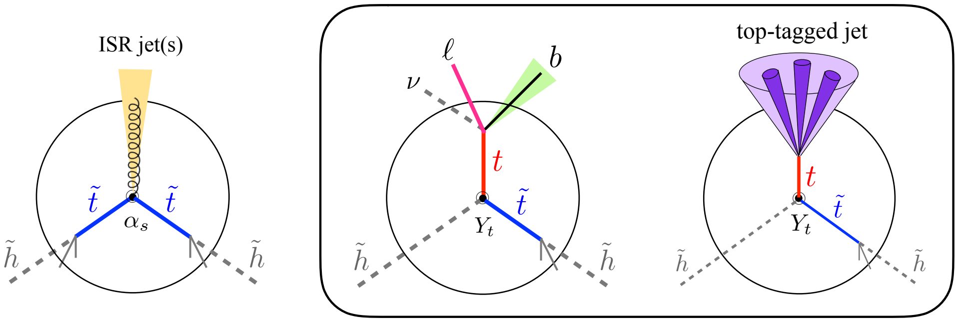
The statement that the LHC has not found any interesting excesses over the SM background largely depends on the details of the analyses performed by the ATLAS and CMS collaborations, which are necessarily biased by our presupposed knowledge on new physics. Currently, their analyses adopt the "simplified model" approach [2], which assume only a couple of new particles with artificially fixed decay branching ratios: for example, pair production of scalar quarks decaying 100% into a quark and a stable neutralino. This approach has a great advantage for clear presentation of exclusion limits and is sufficient to investigate the *bulk* of the new physics parameter spaces. However, if the underlying theory is drastically different from what we have presupposed in the analysis, the signatures can be more complex, subtle and/or exotic. Those signatures can be easily missed by the current analysis methods based on handful simplified models. At this stage of the LHC experiment, it is very important to propose possible rare and unconventional signatures, which could have been overlooked in the current set of analyses, and suggest a new strategy to look for them. In the series of publications listed above, I have contributed to this task. The main conclusions and achievements of those articles will be discussed one by one in the next subsection.

Another important direction of studies is related to the question what one can learn from an *existing* set of simplified model analyses about more realistic models which contain corners of parameter space that are not covered by a single simplified model. These lines of studies will also help to identify holes (unconstrained regions) in the parameter space, which in turn helps to find overlooked signatures in those regions and design new analyses to fill the holes, as discussed in the previous paragraph. The conventional approach to constrain an arbitrary model in light of LHC data is to perform Monte Carlo (MC) simulations and compare the estimated signal yield with the observed data. Although this method is quite generic, it requires generation of millions of MC events to assess a single model point. This task is very time-consuming and needs significant amount of computer resources, which often becomes a bottleneck of systematic survey of concrete new physics scenarios. In Ref. [H7] I have tackled this problem and developed a novel semi-analytical method, which I have implemented in the computer code, `Fastlim`. This tool can test an arbitrary supersymmetric (SUSY) model by confronting it with various results obtained by ATLAS and CMS in a fraction of second. We made this code publicly available so that any theorists and experimentalists can use the code for their study, contributing significantly to the community. Currently, the tool has been used world-wide and in particular playing a crucial role in one of the large scale global fit collaborations, `MasterCode`, which will be described later in more detail. Furthermore, this work [H7] was one of the first studies addressing the aforementioned problem and created a new and growing research area in developing tools for recasting LHC results [3–6]. The methodology underlying `Fastlim` is quite generic and can be applied to other research fields requiring intensive computations. More detailed description of Ref. [H7] will be given in the following subsection.

4.3 Discussion and results

4.3.1 Exotic signatures

In the first two articles [H1] and [H2] , I have proposed and investigated the analyses targeting a novel *mono-top* signature arising in so-called natural SUSY models [7] where the scalar top (stop, $\tilde{t}$) and the lightest SUSY particle (LSP) are almost mass degenerate. This corner of SUSY parameter space is, though well-motivated by the naturalness argument, known to be difficult to be constrained because the decay products of $\tilde{t}$ become very soft and are easily missed in the background. The existing analyses have so far only focused on a pair production of stops followed by their decays into the neutralino LSP ($\tilde{\chi}_1^0$). In such a process, a pair of invisible $\tilde{\chi}_1^0$s is produced in the back-to-back configuration in the transverse plane, cancelling out the total transverse missing energy $\not{E}_T$. The events therefore very much look like the SM background.



mono jet + $E_T^{\rm miss}$ + soft

mono top + $E_T^{\rm miss}$ + soft

Figure 1: The mono-jet (left) vs mono-top (middle and right) signatures. These schematic pictures show a projection of the event on the plane perpendicular to the beam pipe. Only the particles going through the circle may be detected except for invisible particles represented by the dashed lines, which are the neutral higgsino or the neutrino. The short grey lines represent the decay products of the $\tilde{t}$ that are very soft and may or may not be detected.

The existing analyses have, for this reason, been using a type of events where the system of two stops are kicked by hard QCD initial state radiation (ISR). Such events are characterised by a mono-jet plus moderate $\not{E}_T$ recoiled against the jet, as illustrated in the left panel of Fig. 1.

We have first pointed out in [H1] that the process of 3-particle production, $pp \to \tilde{t}\tilde{\chi}_1^0 t$, is also useful to search for this parameter region. The production rate of this process becomes particularly large when the LSP is composed dominantly by the higgsino states since the strength of the interaction is given by the large top Yukawa coupling. This dependency is important because one can prove the higgsino component in the $\tilde{\chi}_1^0$ by comparing the rates of this channel with the conventional $pp \to \tilde{t}\tilde{t}^*$ production rate. Since the $\tilde{t}$ effectively behaves as an invisible particle due to the mass degeneracy, the final state of this 3-particle production is characterised by the mono-top plus $\not{E}_T$, as illustrated in the middle and right diagrams in Fig. 1. Unlike the mono-jet channel, the events are easily distinguishable from the SM background due to the presence of a charged lepton in the leptonic channel (see the middle diagram in Fig. 1) studied in [H1] or a fat jet in the hadronic channel (the right diagram in Fig. 1) investigated in detail in [H2]. We have also demonstrated in [H1] that the helicity measurement for the produced top-quark is possible, which measures the L-R composition of the lightest stop.

In [H3] and [H4] we have investigated the experimental signatures of the supersymmetric models under the assumption that sfermions (as well as higgsinos depending on the models) are considerably heavier than the gauginos and inaccessible at the LHC [8]. Such scenarios has attracted a lot of attention after the LHC Run 1, since they are consistent with the null results of SUSY searches as well as the measurements of the Higgs boson with $m_H = 125$ GeV.

In [H3] I have investigated how the parameter space of the electroweakly interacting supersymmetric particles will be constrained in the future LHC and the Dark Matter (DM) direct detection measurements. We have performed an exhaustive numerical survey including the cases of Bino-Wino, Bino-higgsino and Wino-higgsino mixed DM. First of all, the bulk of Bino-like DM region is excluded due to the overproduction of the DM abundance, except for the region

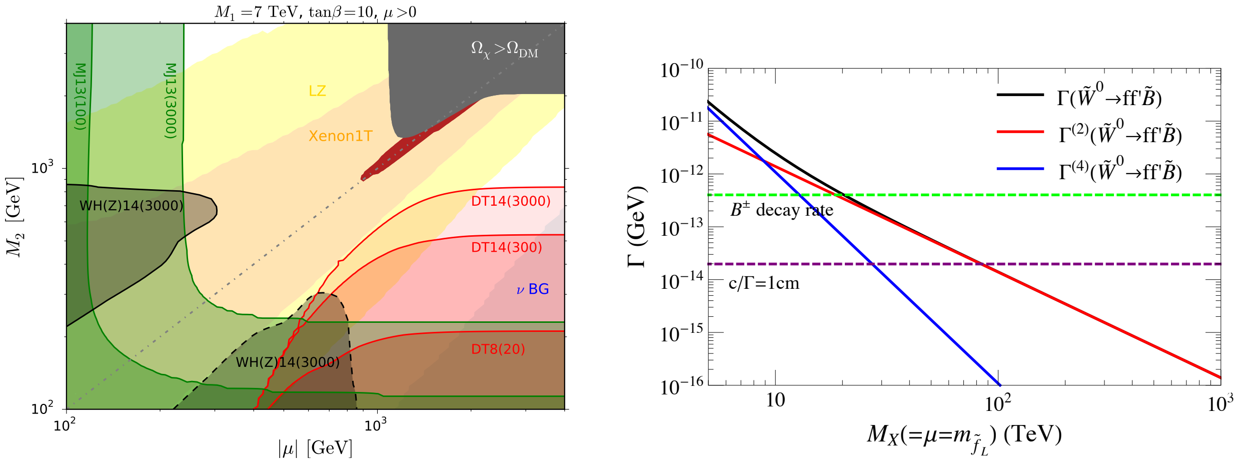


Figure 2: **Left**: the current DM constraints and the future prospects in the μ-M_2 plane. The top-right dark grey and the dark red regions are excluded by the relic density overproduction constraint and the current direct DM detections, respectively. The light orange and yellow areas are the regions where the future DM detection experiments [9, 10] have the sensitivity. Finally, the light green and red areas are the regions where the mono-jet channel and disappearing track channel are sensitive at the high luminosity LHC with 3 ab^{-1}. **Right**: the decay rate of the neutral Wino with the Bino LSP as a function of $M_X \equiv |\mu| = m_{\tilde{f}_L}$.

where the mass splitting between the Bino and the other state is very small and the coannihilation mechanism is operative. An interesting result was found in the Wino-higgsino region, which exhibits the following complementarity between the LHC and DM measurements: if the higgsinos and Wino are significantly mixed, the interaction between the DM and nuclei becomes large and the DM detection experiments are sensitive, while the sensitivity at the LHC is poor because the cross-sections are small and the signature is not spectacular. In the opposite limit, where the LSP is dominantly higgsino- or Wino-like, the DM experiments loose the sensitivity, whereas striking signatures, the *disappearing track* and the *mono-jet* signatures, are expected at the LHC for the Wino-like and higgsino-like scenarios, respectively. The result is summarised in the left panel of Fig. 2, where the top-right dark grey and the dark red regions are excluded by the overproduction of the DM and the current direct DM detection experiments, respectively. The light orange and yellow areas are the regions where the future DM detection experiments [9, 10] have the sensitivity. Finally, the light green and red areas are the regions where the mono-jet channel and disappearing track channel are sensitive at the high luminosity LHC with 3 ab^{-1}. One can see that the majority of the parameter space will be explored by the combination of the future collider and DM experiments.

The work of [H4] is one of the attempts to develop a new way of looking for the split SUSY scenario at the LHC. In this article we have pointed out that there are bunch of overlooked long-lived signatures in the split SUSY scenario when the higgsinos are very heavy. Before our work, it has been known that the long-lived gluino is a powerful signature of split SUSY at the LHC [11] because the gluino interact with the other gauginos only via squarks, which are assumed to be very heavy in this scenario. Therefore, gluinos may be long-lived ($\Gamma_{\tilde{g}\to \rm LSP}/m_{\tilde{g}} \ll 1$) if those squarks are heavier than O(100) TeV. We showed in this paper that the same argument holds for the other gauginos (Winos and Binos). The Winos and Binos have interaction only via the left-handed sfermions and higgsinos. If Winos are heavier than Binos, the Wino tends to be long-lived if both the sfermions and higgsinos are much heavier than the TeV scale. For example, we have found that if $M_2 > M_1$, the life-time of the second lightest neutralino is given by

$$\begin{aligned} c\tau_{\tilde{W}^0} &\simeq \frac{4\alpha^2}{15\pi}\frac{(|M_2|-|M_1|)^5}{m_h^4}\frac{\sin^2 2\beta}{\sin^2 2\theta_W}\frac{m_b^2}{|\mu^2|} \\ &\simeq 1\mathrm{cm}\cdot\Big(\frac{|\mu|}{100\mathrm{TeV}}\Big)^2\Big(\frac{|M_2|-|M_1|}{50\mathrm{GeV}}\Big)^{-5}\Big(\frac{\sin 2\beta}{1}\Big)^{-2}, \end{aligned} \tag{1}$$

where μ is the mass of higgsinos, M_1 and M_2 are the mass of Bino and Wino, respectively, and $\tan\beta \equiv v_u/v_d$ is the ratio of the Higgs vacuum expectation values in the MSSM. The decay of neutral Wino is dominated by the SM-like Higgs boson exchange and in the long-lived region the Higgs is typically off-shell. The signature will become the displaced $h^* \to b\bar{b}$ vertex with $m_{b\bar{b}} < m_h$. Similarly, the Bino can be long-lived, if the mass hierarchy is reversed ($|M_1| > |M_2|$). The corresponding life-time formulae can be found in [H4].

The Effective Field Theory (EFT) approach is a powerful model-independent method to study scenarios of new physics. Even if new particles are heavy and cannot be produced at the LHC, their effects can, in principle, be seen as a modification of the couplings for the existing operators and introduction of new operators that do not exist in the SM. These change the interactions among the SM particles. Therefore, precision measurements of the properties of the SM particles have great potential to discover new physics. The Higgs boson (or a Higgs-like particle), discovered at CERN in 2012, is a perfect candidate for this program. In [H5] we have investigated how the CP nature of this particle can be constrained by the measurements at the LHC. We introduced a modification of the Higgs-top-top coupling as

$$\mathcal{L} \ni -\frac{m_t}{v}\big(\kappa_t\bar{t}t + i\tilde{\kappa}_t\bar{t}\gamma_5 t\big)h\,, \tag{2}$$

where the operator in the first term preserves the CP invariance (CP-even), whilst the second term maximally violates CP (CP-odd). In particular, the SM gives $\kappa_t = 1$ and $\tilde{\kappa}_t = 0$. For convenience, we introduce a CP phase as $\xi_t \equiv \arctan(\tilde{\kappa}_t/\kappa_t)$. In [H5] we showed that ξ_t is not much constrained by the current measurements of the Higgs production and decays [1] (the main constraints come from $gg \to h \to \gamma\gamma/W^+W^-$). For example, $\xi_t \sim \pm\frac{\pi}{2}$ is still allowed at 1σ level. We then have investigated how the CP violating phase ξ_t may impact on the associated Higgs production with one ($pp \to thj$) or two ($pp \to \bar{t}th$) top-quarks, which may be measured at the high luminosity LHC. We showed that the effect of non-zero ξ_t impacts on $\sigma(thj)/\sigma(\bar{t}th)$, the invariant mass distribution of the thj and $t\bar{t}h$ systems, as well as various angular distributions. The left panel of Fig. 3 shows one of such examples, where the distribution of the azimuthal angular difference, $\Delta\phi_{\ell^+\ell^-}$, between the two leptons produced from the top quark decays is plotted at the rest frame of the $t\bar{t}$ system. The deviation from $\xi_t = 0$ is a clear indication of the CP violation and new physics.

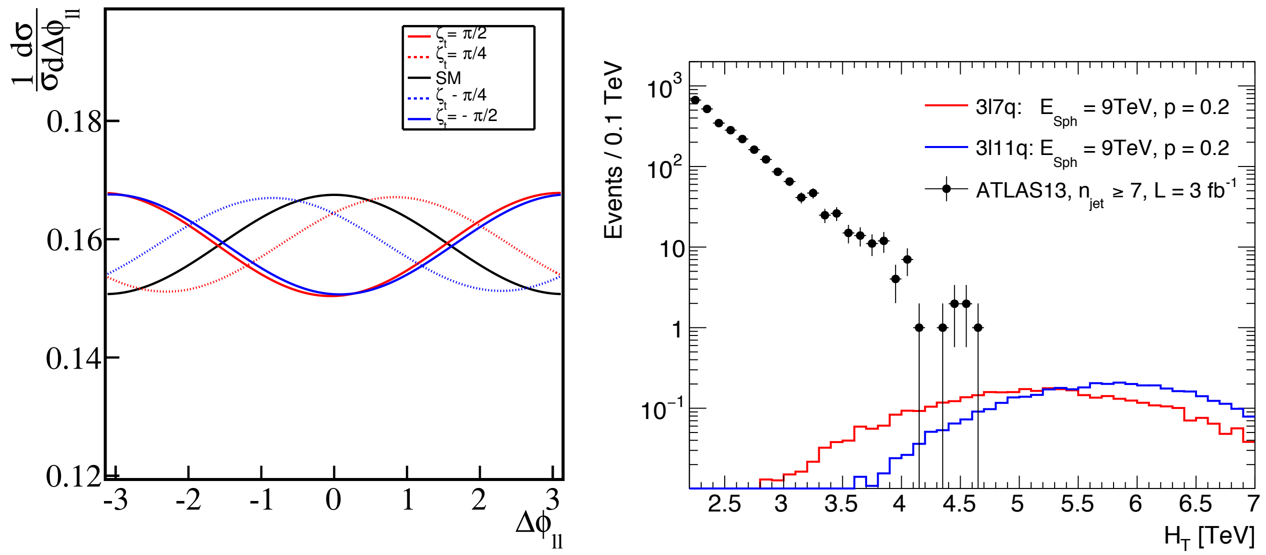


Figure 3: **Left**: the distribution of the azimuthal angular difference, $\Delta\phi_{\ell^+\ell^-}$, between the two leptons produced from the top quark decays calculated at the rest frame of the $t\bar{t}$ system. The sold black curve corresponds to the SM prediction, $\xi_t = 0$, while the other curves correspond to those with $\xi_t \neq 0$. **Right**: the distribution of the sum of p_T of all visible objects, $H_T \equiv \sum_i |p_T^i|$. The black dots represent the observed data in the ATLAS's mini black hole analysis [18]. The red and blue histograms are obtained by the Monte Carlo simulation with $\Delta n = -1$ and 1, respectively.

4.3.2 Non-perturbative signatures

The LHC experiment may not only probe the physics beyond the SM but also shed some light on a non-perturbative aspect of the SM. For example, there are some studies suggesting that sphaleron-induced processes may be observable at the LHC or future high energy colliders [12, 13]. The electroweak sector of the SM possesses degenerate vacua classified by the topological winding number, $n \in \pi_3(S^3) = \mathbb{Z}$, arising from a map from the three-dimensional space, S^3,[1] to the electroweak gauge field, which takes values in $SU(2) \simeq S^3$. These discrete vacua are separated by energy barriers, whose hight is $\simeq 9$ TeV [14]. The static, unstable solution to the equation of motion, sitting on top of the energy barrier, is called *sphaleron*. The sphaleron-induced process is a vacuum-to-vacuum transition due to a dynamical evolution of the fields going through the sphaleron.[2] The claim that the LHC may be able to produce sphaleron-induced process is still controversial and several studies suggest otherwise [15, 16]. One way to help this situation is to analyse the LHC data and place some constraint on the sphaleron-induced process arising from high energy proton-proton collisions [H6] . Such studies are also important since sphaleron plays a crucial role in the baryo- and lepto-genesis.

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[1] Here, we have chosen the topological gauge, where the gauge fields at the spatial infinity approach the same constant in every direction. This compactifies the space as $\mathbb{R}^3 \mapsto S^3$, since the spatial infinity is effectively identified as a single point.

[2] Contrary to this, a zero-energy vacuum-to-vacuum transition by quantum tunneling is called *instanton* process.

To derive the limits with the LHC data, one needs to simulate the sphaleron-induced events at the LHC. It has been known that the quantum anomaly relates the change of the winding number (Δn) with the change of each fermion number (ΔF_i) charged under $SU(2)$ as $\Delta n = \Delta F_i$ [17]. Since there are 12 $SU(2)$ doublets in the SM ((quark × 3-colours + lepton) × 3-generations = 12), the vacuum-to-vacuum transition with $\Delta n = \pm 1$ leads to effective interaction vertices involving all the 12 fermions or the anti-fermions, respectively. Since we require two quarks in the initial state, we consider the following processes:

$$\begin{aligned} qq &\to 3\bar{\ell} + 7\bar{q} \qquad && \text{for } \Delta n = -1\,, \\ qq &\to 3\ell + 11q \qquad && \text{for } \Delta n = 1\,. \end{aligned} \tag{3}$$

While the first process is sourced by the original t'Hooft operator $(qqql)^3$, the second process is generated by the modified operator $(\bar{q}\bar{q}\bar{q}\bar{l})^3(\bar{q}q)^2$ in order to have two valence quarks in the initial state.

One can see that these process predict multiple jets plus leptons in the final state, and the events look rather similar to the mini black hole events. The right panel of Fig. 3 shows the distribution of the sum of $|p_T|$ of all visible particles in the final state, $H_T \equiv \sum_i |p_T^i|$, by the red (blue) histogram for $\Delta n = (-)1$. These distributions have been compared with the the actual data (black-dotted) observed in the ATLAS's mini black hole search [18]. Since no excess has been reported, we have placed the upper limit on the positive dimensionless variable p as $p \lesssim 0.18(0.3)$ for $\Delta n = (-)1$, where p is related to the sphaleron cross-section as

$$\sigma(|\Delta n| = 1) = \frac{p}{m_W^2} \sum_{ab} \int dE \frac{d\mathcal{L}_{ab}}{dE} f(E). \tag{4}$$

In this expression, the $\frac{d\mathcal{L}_{ab}}{dE}$ is the parton luminosity function of the parton species a and b and the $f(E)$ is essentially the step function, $f(E) \simeq \Theta(E - E_{\rm Sph})$ with $E_{\rm Sph} \simeq 9$ TeV. Although the current constraint is quite mild and not conclusive to answer whether or not the sphaleron-induced process is unsuppressed at high energies, this work made an important step towards experimentally constrain such processes. In fact, this study has triggered the activities within the experimental community at the LHC to look for the sphaleron signatures. The first analysis on sphalerons has been reported very recently by CMS [19].

4.3.3 Theoretical tools

It is important at the current stage of the LHC physics to develop a tool to confront theoretical models with the LHC results. The ATLAS and CMS collaborations analyse their data and derive the limit on a particular 2-dimensional parameter plane of a particular model. It is not obvious how that data and analysis constrain other parameter regions or models. One way to re-interpret the reported analysis result into an arbitrary model is to simulate the signal events, including detector simulation, and perform the same cut-and-count based analysis. Although this procedure is quite generic and straightforward, it resorts to time-consuming Monte Carlo (MC) simulation and requires a large amount computer resources. Therefore, this type of MC-based method is not helpful if one is interested in many models or a large parameter volume. In [H7] we tackled this problem and developed a semi-analytical recasting method, which we have implemented in a computer program `Fastlim`.

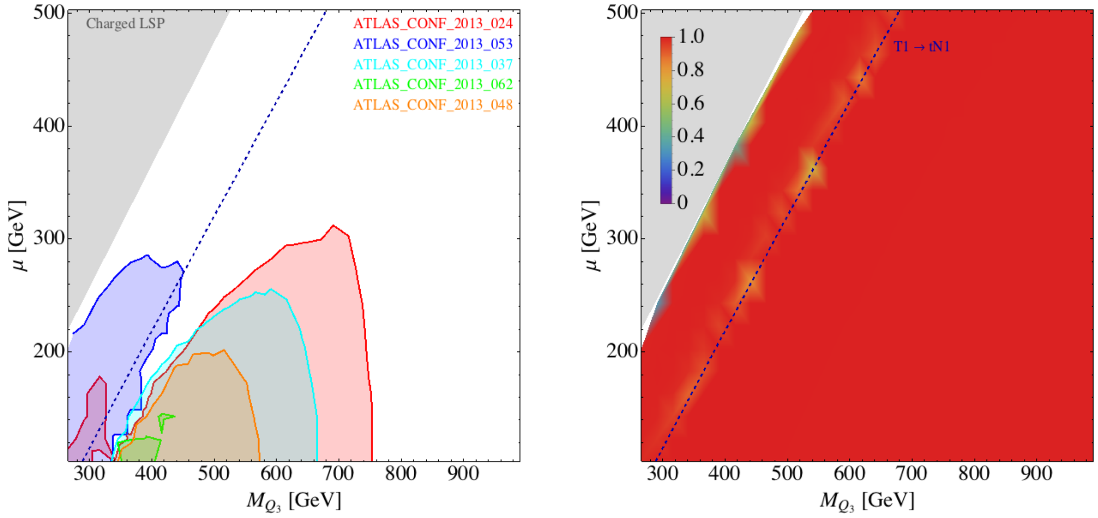

Figure 4: The left panel shows the 95 % CL excluded regions obtained by various ATLAS analyses in the $(M_{\tilde{Q}_3}, \mu)$ plane. The right panel shows the coverage, $\sum_i^{\rm implemented} \sigma_i/\sigma_{\rm total}$, of the topologies implemented in `Fastlim` to the total SUSY cross-section of the model points.

Our semi-analytical method starts by realising that the signal events falling into the signal region a, $N^a_{\rm sig}$, is composed of the contributions from many different event topologies (productions and decays). Namely, we have $N^a_{\rm sig} = \sum_i^{\rm topologies} N^a_i$, where N^a_i is the contribution from the topology i for the signal region a. Each contribution can then be written as $N^a_i = \sigma_i \epsilon^a_i \mathcal{L}$, where $\mathcal{L}$ is the luminosity, ϵ^a_i is the efficiency of topology i for a, and the partial cross-section σ_i can be given by the production cross-section times branching ratio. For example in supersymmetric models, we can write

$$\begin{aligned} \sigma^a_{\rm sig} &= \sigma_{\tilde{q}\tilde{q}} \cdot {\rm BR}^2_{\tilde{q}\to q\tilde{\chi}^0_1} \cdot \epsilon^a_{[\tilde{q}\to q\tilde{\chi}^0_1]^2}(m_{\tilde{q}}, m_{\tilde{\chi}^0_1}) \\ &+ \sigma_{\tilde{g}\tilde{g}} \cdot {\rm BR}^2_{\tilde{g}\to qq\tilde{\chi}^0_1} \cdot \epsilon^a_{[\tilde{g}\to qq\tilde{\chi}^0_1]^2}(m_{\tilde{g}}, m_{\tilde{\chi}^0_1}) \\ &+ \cdots \end{aligned} \tag{5}$$

Here, we made explicit that the efficiency of $[\tilde{q} \to q\tilde{\chi}^0_1]^2$ depends only on $m_{\tilde{q}}$ and $m_{\tilde{\chi}^0_1}$ and that of $[\tilde{g} \to qq\tilde{\chi}^0_1]^2$ only on $m_{\tilde{g}}$ and $m_{\tilde{\chi}^0_1}$. In this formula, ϵ^a_i needs to be estimated by MC simulation, whereas computations for σ_i and BR are straightforward and instant. The fact that ϵ^a_i depends only on a few mass parameters makes us think that if they are evaluated once at various mass points, one can interpolate the grid table and extract the value immediately. Following this idea, we have generated the efficiency grid tables for various analyses and typical event topologies of coloured particles. Using those tables we implemented this semi-analytical recasting method in `Fastlim`.

In this paper we have also studied the status of the natural SUSY model [7] in light of the Run-1 LHC using `Fastlim`. Fig. 4 shows some of our results. The left panel of Fig. 4 shows the excluded regions by various analysis in the $(M_{\tilde{Q}_3}, \mu)$ plane, whereas the right panel shows how much the event topologies implemented in `Fastlim` cover the actual signal event sample. One can see that `Fastlim` accounts for almost all the signal events, meaning that the result is robust and accurate.[3] One can also see that the limit is quite weak just below the blue dotted diagonal line ($\mu = M_{\tilde{Q}_3} - m_t$), because in this region there are many events where one of pair produced $\tilde{t}_1$ decays into $t + \tilde{\chi}^0_{1,2}$ and the other into $b + \tilde{\chi}^\pm_1$, and no experimental analysis has targeted such asymmetric topologies. This proves, as mentioned in the Introduction, that these lines of study tell not only the status of the new physics model but also the holes of current analyses and give clues to improve it.

4.4 Summary

The series of works I described here contributes to the LHC physics from various aspects within and beyond the Standard Model. In [H1] and [H2] we have proposed a novel mono-top signature that gives us information on the stop sector in the light stop scenarios. The works of [H3] and [H4] concern the scenarios where the sfermions are significantly heavier than the LHC energy scale. The future prospects and complementarity between the LHC and the direct dark matter detection experiments have been shown in [H3] . In [H4] we have found interesting parameter regions where novel long-lived signatures are present due to the suppressed decay rates of the electroweak gauginos. A way to model-independently constrain the CP structure of the top-Higgs coupling have been studied in [H5] exploiting $pp \to t\bar{t}h$ and $pp \to thj$ ($\bar{t}hj$) channels. Furthermore, the possibility of observing sphalerons at the LHC has been examined in [H6] , which triggered the activity within the experimental community to look for this signature, leading to the first analysis in this direction by CMS [19]. Finally, in [H7] we have developed a theoretical tool which computes the LHC constraints in arbitrary SUSY models without resorting time-consuming Monte Carlo simulation.

Some of these studies have been followed up recently. For example, we have extended the mono-top analysis for extra-dimensional models [20], where the mass degeneracy assumed in this channel is more naturally justified. We have recently studied the CP-violating Higgs interaction operators up to dimension-5 exploiting the perturbative unitarity constraint [21]. We also extended our study on sphalerons in light of IceCube experiment [22]. Some of those works will be mentioned in the remaining part of the document.

All of these works provide unique and significant contributions to the LHC physics. Among them I consider the following three papers particularly important. In [H4] we have found several new long-lived signatures in well motivated models. This work is timely and significant since ATLAS and CMS experiments have recently been put great effort to look for these long-lived signatures in their datasets. In [H5] we have studied how the top-Higgs interaction can be constrained by looking into the angular distributions of the final state particles in the $pp \to t\bar{t}h$ and $pp \to thj$ ($\bar{t}hj$) processes. The work is also very timely and important, since the $pp \to t\bar{t}h$ process have been observed very recently by ATLAS and CMS [23, 24]. The discussion has started to constrain the top-Higgs coupling using the angular distributions of the final state particles in this process. The work [H7] is also very important, since this tool have been used in other important phenomenological studies worldwide. For example, the tool have extensively been used in the MasterCode project, which confronts various new physics models with comprehensive experimental results including the LHC, which will be described in more detail later in

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[3] In case the coverage is less than 100%, `Fastlim` underestimates the limit. In this sense, obtained result is always conservative.

this document. The work [H7] also opens up a new growing field in developing tools to calculate the LHC constraints in a fast and accurate manner.

5 Other scientific achievements

5.1 Bibliometric data

According to Web of Science

As of: 04.07.2018
Number of published articles: 55
Sum of the times cited: 683
Sum of times cited without self-citations: 595
h-index: 17
ResearcherID: `http://www.researcherid.com/rid/S-9670-2017`
ORCID: `https://orcid.org/0000-0001-8817-714X`

According to Inspire

Source: `http://inspirehep.net/author/profile/K.Sakurai.1`
As of: 04.07.2018
Number of research articles: 55 (4 before Ph.D.)
Other papers: 5
Sum of the times cited: 1434
Total Impact Factor: 275.952
h-index: 22

5.2 Discussion

In the following subsections I will briefly describe some of my recent publications that are not included in the list of selected papers discused above.

Rare signatures in the Standard Model and beyond

We explored in Ref. [21] various CP violating modifications of the Higgs interactions and studied their consequences from the point of view of perturbative unitarity. For example, we showed that if the CP violating $t\bar{t}h$ interaction as in Eq. (2) is introduced with $\tilde{\kappa}_t \sim 1$, the perturbative unitarity requires a new state below ~ 8 TeV. We found generally stronger constraints for the Higgs-gauge sector compared to the Higgs-fermion sector, while the CP violating Higgs-gauge interaction, $\mathcal{L} \ni C_{hhZ}\mathcal{O}_{hhZ}$, $\mathcal{O}_{hhZ} = h(\partial_\mu h)Z^\mu$ is an exception because this operator does not render the perturbative amplitude growing as increasing $\sqrt{\hat{s}}$. We have shown however that the future $gg \to Z^* \to hh$ measurement can greatly constraint this possibility.

In Ref. [25] we examined a possibility of observing the triple Higgs production process, $pp \to hhh$. This channel is important since it serves as the most promising direct probe of the quartic Higgs self-coupling, $\mathcal{L}_{\rm int} \ni c_4 hhhh$. Since the production rate at the LHC is tiny,

$\mathcal{O}(0.1)$ fb, we studied this process assuming a future 100 TeV proton-proton collider, at which the cross-section is substantially larger, ~ 5 fb [26], in the SM. In this paper we performed the first feasibility study using realistic Monte Carlo simulations with the most promising $4b + 2\gamma$ channel. We found that $S/\sqrt{B}$ reaches at most ~ 1 even with 30 ab^{-1}. On the other hand, the triple Higgs production is rather sensitive to the higher dimensional operators. For example, we demonstrated if $\mathcal{L}_{\rm int} \ni \frac{\lambda}{v^2} c_6 |H|^6$ is introduced with v and λ being the Standard Model Higgs vacuum expectation value and the quartic coupling, the triple Higgs production measurement can exclude the regions other than $c_6 \in [-0.7, 1.0]$ and $\in [1.7, 3.0]$ at 2-σ level with 30 ab^{-1}.

Not only the LHC but also other experiments may have the potential to probe high energy interactions of the SM and beyond. In Ref. [22] we investigated how the IceCube experiment [27] can search for the non-perturbative sphaleron processes. We considered creation of sphalerons by collisions between high-energy cosmic neutrinos and the quarks in the ice. In order for this process to occur, the centre-of-mass energy must be higher than ~ 9 TeV to overcome the energy barrier between the distinct electroweak vacua. The kinematics tells us the neutrino energy must be as high as $E_\nu = \frac{s}{2 x m_N} \gtrsim 10^9$ GeV, where we used $\sqrt{s} \sim 9$ TeV, $m_N \sim 1$ GeV and the energy fraction of the quark $x \sim 0.04$. Interestingly, the existence of neutrinos with energy around $\sim 10^9$ GeV has been predicted [28] from decays of the pions created by the GZK [29] processes, $p\gamma_{\rm CMB} \to \Delta^+ \to p\pi^0, n\pi^+$. Using the null result of such high energy interactions during 4-years of data taking at the IceCube [30], we have estimated the limit on the dimensionless parameter, p, in Eq. (4). The obtained limit, $p < 0.1$, was found to be comparable or slightly stronger than the limit from the LHC13 with 3 fb^{-1}, but we estimated the LHC will surpass the IceCube sensitivity quickly as the luminosity increases.

Global likelihood analyses for supersymmetric models

Whether or not the evidence of new physics is present in the experimental data, it is important to interpret them to update our experimental knowledge on new physics. If the data shows some deviations from the SM, one can try to determine what new physics scenario is responsible for the anomaly. Even in the opposite case, one can examine what parameter regions of new physics scenarios are still consistent with the data. With such the "landscape of new physics" in hand, one can then investigate implications to the theoretical problems and look for experimental strategies to further constrain the remaining regions.

There are several challenges for such global analyses. First of all, contemporary experiments are very complex and dealing with huge data. For instance, assessing the LHC constraint in the conventional method takes tens of minutes for a single parameter point. Of course, the experiments besides LHC are also very relevant. One should take the dark matter direct/indirect detection constraints, B-physics measurement, the Higgs property measurement and the low energy precision measurements, such as the muon $g-2$, into consideration. Furthermore, the volume of the theory parameter space is huge. For example, the most general version of phenomenological MSSM has 19 parameters and exploration of such a huge parameter volume is computationally very expensive.

The `MasterCode` collaboration, in which I am heavily involved, aims at such an ambitious global likelihood study. The collaboration consists of ~ 20 members, where about equal numbers of theorists and experimentalists are involved. We overcome the aforementioned problems by deploying various computational tools centred around the `MultiNest` sampling algorithm. For example, we use `FeynHiggs` and `HiggsBounds/Signal` for calculations of the Higgs observables, `SuFla/SuperIso` for the B-physics observables and `Fastlim` for the LHC constraints. Here `Fastlim` takes a crucial role because it enables us to assess the LHC constraint in a fraction of a second per model point. `MultiNest` is a tool to efficiently sample the parameter points with a large likelihood. It quickly finds local maxima of the global likelihood and samples points efficiently around those regions.

Since I have joined the collaboration in 2014, `MaterCode` has published the results of six global likelihood analyses for new physics scenarios: pMSSM-10 [31], the dark matter properties [32], SU(5) SUSY-GUT [33], Anomaly Mediated SUSY Breaking (AMSB) [34], pMSSM-11 [35] and sub-GUT [36], where pMSSM-n stands for phenomenological MSSM with n parameters. Here, I shall take the first article and describe the main findings below.

In [31] we performed a likelihood analysis on pMSSM with 10 parameters:

$$M_1, M_2, M_3, m_{\tilde{q}_{1,2}}, m_{\tilde{q}_3}, m_{\tilde{l}}, m_A, A, \mu, \tan\beta\,.$$

We found that, unlike more constrained models, e.g. CMSSM, this scenario allows a supersymmetric explanation of the muon $g-2$ anomaly (3-σ level) consistently with the LHC constraint. This is because masses of the coloured and uncoloured particles are not strongly correlated in this scenario, which makes it possible to push up the coloured particle masses to evade the LHC constraint, while keeping the sleptons and electroweak gauginos light so that they can give sizeable contribution to the muon $(g-2)$. We also found that in the preferred region where the muon $(g-2)$ is explained, the Wino is very close in mass to the LSP Bino and the dark matter abundance is determined by the gaugino coannihilation mechanism. This Wino-Bino mass degeneracy is necessary to evade the strong limit from chargino-neutralino direct searches at the LHC. As a consequence of this near mass degeneracy, the DM is mixture of Bino, Wino and higgsinos and the DM direct detections become quite sensitive to this region. In particular, we have shown all the 1-σ region preferred in this analysis is within the reach of the next generation DM direct detection experiments, such as LZ [9] and Xenon-1T [10]. Also found is that the charginos and neutralinos are lighter than 500 GeV in the 2-σ region, and they are within the reach of the International e^+e^- Linear Collider with $\sqrt{s} \sim 1$ TeV. The result of this study encourages different experiments to look for supersymmetry that is motivated by the muon $(g-2)$ anomaly.

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