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Supersymmetry Breaking, Gauge Mediation, and the LHC

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1 Executive Summary

Prof. David Shih was supported by a DOE Early Career Award from 2010-2015. His research during this time focused on understanding, interpreting, and making predictions for the data coming from the Large Hadron Collider in terms of supersymmetry (SUSY), one of the most well-motivated frameworks for physics beyond the Standard Model. SUSY predicts many new particles (called "superpartners") that could be discovered at the LHC, yet its parameter space is extremely vast, and there are many constraints on it from precision tests of the Standard Model.

Gauge mediated SUSY breaking (GMSB) is a promising class of supersymmetric models that automatically satisfies the precision constraints. Prior work of Meade, Seiberg and Shih in 2008 established the full, model-independent parameter space of GMSB, which they called "General Gauge Mediation" (GGM). During the first half of 2010-2015, Shih and his collaborators thoroughly explored the parameter space of GGM and established many well-motivated benchmark models for use by the experimentalists at the LHC. Through their work, the current constraints on GGM from LEP, the Tevatron and the LHC were fully elucidated, together with the possible collider signatures of GMSB at the LHC. This ensured that the full discovery potential for GGM could be completely realized at the LHC.

In July 2012, the ATLAS and CMS experiments at the LHC announced the discovery of the Higgs boson with a mass of 125 GeV. This major milestone represented the final piece of the Standard Model and immediately had a huge impact on both the theoretical and experimental HEP communities. Along with many others, Shih shifted his focus to understanding the implications of the 125 GeV Higgs for physics beyond the Standard Model. He wrote one of the earliest papers interpreting the Higgs discovery for supersymmetry. A 125 GeV Higgs poses an interesting challenge for supersymmetry, which prefers a much lower value for the Higgs mass. In a series of papers, Shih and his collaborators thoroughly mapped out the different model-building avenues that could achieve a 125 GeV Higgs in the MSSM. Interestingly, the majority of these models predict that the superpartners should be heavier than expected, and should not have been seen yet at the LHC. But they could be within reach at Run II, which holds exciting promise for the near future.

2 Accomplishments

2.1 Collider Phenomenology of GGM and Natural SUSY

Shih and collaborators pioneered the model-independent study of GGM collider signatures, being among the first to employ "simplified models" to characterize the parameter space of GGM. In their work, Shih and collaborators classified the myriad possibilities that could be used to discover gauge mediation at the LHC. The goal was to not only identify promising final states for discovery, but also to formulate simple, model-independent benchmark parameter spaces for experimentalists to use when designing and optimizing searches, and reporting their results. With these benchmark parameter spaces in hand, Shih has worked on deriving limits from LEP, Tevatron and LHC searches, and formulating new search strategies to extend the reach at the LHC. This work has led to a number of ongoing collaborations with experimentalists, both at Rutgers and elsewhere. Shih worked closely with Rutgers experimentalists (Yuri Gershtein, Eva Halkiadakis and Sunil Somalwar), helping to design GGM searches for multi-lepton, multi-photon, and photon+lepton signatures. In addition, Shih and collaborators have also assisted with analyses carried out by various LHC groups around the world, including groups at Brown, Cambridge, Copenhagen, Fermilab, Nordita, Rutgers, UC Davis, UC San Diego, UC Santa Cruz, University of Michigan, and Yale.

A more detailed description of Shih's papers on the collider phenomenology of GGM is as follows:

- In a paper with Patrick Meade and Matt Reece, Shih investigated the collider signatures of heavy, long-lived neutralino NLSPs decaying to Z-bosons and gravitino [3]. This novel signature had not been studied in detail before, and Shih et al showed that a combination of searches using the inner detector and the muon spectrometer could yield a wide range of potential early LHC discoveries for NLSP lifetimes ranging from $10^{-1} - 10^{5}$ mm. They further showed that events from $Z(l^+l^-)$ can be used for detailed kinematic reconstruction, leading to accurate determinations of the neutralino mass and lifetime (and by inference, the SUSY-breaking scale). In particular, they examined the prospects for detailed event study at ATLAS using the ECAL (making use of its timing and pointing capabilities) together with the TRT, or using the muon spectrometer alone. Finally, they also demonstrated that there is a region in parameter space where the Tevatron could potentially discover new physics in the delayed $Z(l^+l^-)$+MET channel. While their discussion centers on gauge mediation, many of the results apply to any scenario with a long-lived neutral particle decaying to charged particles.

- Together with Josh Ruderman, Shih studied the Tevatron signatures of promptly-decaying slepton co-NLSPs in the context of GGM [1]. The signatures consist of trileptons plus MET and same-sign dileptons plus MET. Focusing first on electroweak production, where the Tevatron has an advantage over the early LHC, they established four simple benchmark scenarios within the parameter space of GGM which qualitatively capture all the relevant phenomenology. They derived limits on these benchmarks from existing searches, estimated the discovery potential with 10/fb, and discussed ways in which these searches can be optimized for slepton co-NLSPs. They also analyzed the Tevatron constraints on a scenario with light gluinos that could be discovered at the early LHC. Overall, they found that the Tevatron still has excellent reach for the discovery of SUSY in multilepton final states. Finally, they commented on the possible interpretation of a mild "excess" in the CDF same-sign dilepton search in terms of slepton co-NLSPs.

- In another paper with Josh Ruderman, Shih studied the Tevatron limits and LHC discovery potential for a wide class of GMSB scenarios in which the next-to-lightest superpartner (NLSP) is a promptly-decaying neutralino [13]. These scenarios give rise to signatures involving hard photons, W's, Z's, jets and/or higgses, plus missing energy. In order to characterize these signatures, Ruderman and Shih defined a small number of minimal spectra, in the context of GGM, which are parameterized by the mass of the NLSP and the gluino. Using these minimal spectra, they determined the most promising discovery channels for general neutralino NLSPs. They found that the 2010 dataset could already cover new ground with strong production for all NLSP types. With the 2011-2012 dataset, they found that the LHC would also have sensitivity to direct electroweak production of neutralino NLSPs. This work was published while the LHC experiments were planning and carrying out their searches for supersymmetry with the first full year of data. It turned out to be very influential for a variety of searches.[1][2][3]

- Together with Yevgeny Kats (a Rutgers postdoc), Shih studied the phenomenology of light stops at the Tevatron and LHC [10]. This scenario is especially well motivated, because light stops are expected in any fully natural realization of supersymmetry. They studied this in the context of GGM, where a stop NLSP decays into a W, b and gravitino. Focusing on the case of prompt decays, they simulated several existing Tevatron and LHC analyses that would be sensitive to this scenario, and found that they allowed the stop to be as light as 150 GeV,

[1] S. Chatrchyan *et al.* [CMS Collaboration], "Search for supersymmetry in events with a lepton, a photon, and large missing transverse energy in pp collisions at sqrt(s) = 7 TeV," JHEP **1106**, 093 (2011) [arXiv:1105.3152 [hep-ex]].

[2] **CMS** Collaboration, "Search for supersymmetry with photons, jets and MET," CMS PAS SUS-11-009.

[3] G. Aad *et al.* [ATLAS Collaboration], "Search for Diphoton Events with Large Missing Transverse Momentum in 1 fb^{-1} of 7 TeV Proton-Proton Collision Data with the ATLAS Detector," arXiv:1111.4116 [hep-ex].

mostly due to the large ttbar background. With more data, they showed that existing LHC analyses would be able to push the limit up to at least 180 GeV. This work has received interest from ATLAS and CMS experimentalists who search for new physics in the ttbar-like final states. In the next round of LHC publications, direct searches and limits optimized for stop NLSPs stimulated by this work are expected to be revealed.

- Finally, the culmination of Shih's work on GGM signatures came in a paper together with Yevgeny Kats, Matt Reece, and Patrick Meade [11]. Following the release of most of the 1/fb supersymmetry searches at the LHC, they thoroughly investigated the current status of supersymmetry in light of the latest searches at the LHC, using GGM as a well-motivated signature generator that leads to many different simplified models. They considered all possible promptly-decaying NLSPs in GGM, and by carefully reinterpreting the existing LHC searches, they derived limits on both colored and electroweak SUSY production. Overall, the coverage of GGM parameter space was shown to be quite good, but much discovery potential still remains even at 7 TeV. Shih and collaborators identified several regions of parameter space where the current searches are the weakest, typically in models with electroweak production, third generation sfermions or squeezed spectra, and they suggested how ATLAS and CMS might modify their search strategies given the understanding of GMSB at 1/fb. In particular, they proposed the use of a new kinematic variable, which they called leptonic MT2 to suppress ttbar backgrounds. Because they expressed their results in terms of simplified models, they have broader applicability beyond the GGM framework, and give a global view of the current LHC reach. Their results on 3rd generation squark NLSPs in particular can be viewed as setting direct limits on naturalness.

Besides the collider phenomenology of GGM, Shih has also been interested in the current status of natural SUSY models in light of the stringent constraints from Run I of the LHC. This work resulted in a recent paper in collaboration with Matt Strassler, Jared Evans, and Yevgeny Kats [16]. In a model-independent fashion, Shih et al. surveyed the current limits on natural SUSY scenarios with kinematically accessible gluinos and light stops and Higgsinos. This involved an enormous amount of "recasting" work, whereby essentially all relevant 7-8 TeV LHC searches for new physics (and even some relevant SM measurements) were reinterpreted and applied to the models of interest. Shih et al argued that nearly all natural SUSY models with accessible gluinos give rise to top quarks, significant MET and/or high multiplicity, and that the presence of just one of these signatures is enough to rule out gluinos up to ~ 1 TeV. Shih et al. also identified the handful of general-purpose LHC searches which are sufficient to fully cover the space of natural SUSY models. Finally, they identified the few gaps in coverage that remain – models with no MET, no tops, and low multiplicity. Their paper has garnered significant interest from the experimental community, and work is already underway to address the remaining gaps using the existing LHC dataset. Hopefully this will lead to complete coverage of kinematically-accessible natural SUSY in time for the restart of the LHC.

2.2 Implications of the 125 GeV Higgs for Supersymmetry

The second major topic of Shih's research has been the implications of the 125 GeV Higgs for supersymmetry. Approximately halfway through the period covered by his Early Career Award, the Higgs boson was discovered at the LHC with a mass of 125 GeV. Needless to say, this major discovery has had an enormous impact on both the experimental and theoretical HEP community. Shih's work has focused on the implications of the Higgs mass for supersymmetry. The 125 GeV Higgs poses an interesting challenge for SUSY, and especially for the MSSM.

Shih wrote on of the earliest papers interpreting the 125 GeV Higgs in terms of supersymmetry, together with Patrick Draper, Patrick Meade, and Matt Reece, following the announcement by ATLAS and CMS of exciting hints for a Standard Model-like Higgs boson at a mass of approximately 125 GeV. Motivated by this, Shih and collaborators explored the potential consequences for the MSSM and low scale SUSY-breaking. As is well-known, a 125 GeV Higgs implies either extremely heavy stops ($\gtrsim$ 10 TeV), or near-maximal stop mixing. Shih et al. reviewed and quantified these statements, and investigated the implications for models of low-scale SUSY breaking such as gauge mediation where the A-terms are small at the messenger scale. For such models, they found that either a gaugino must be superheavy or the NLSP is long-lived. Furthermore, stops will be tachyonic at high scales. These are very strong restrictions on the mediation of supersymmetry breaking in the MSSM, and suggest that if the Higgs truly is at 125 GeV, viable models of gauge-mediated supersymmetry breaking are reduced to small corners of parameter space or must incorporate new Higgs-sector physics.

In subsequent works, Shih and collaborators investigated the interesting model-building challenge of how to achieve large A-terms from a more fundamental model. Since A-terms do not emerge easily from GMSB, they require additional, possibly flavor-violating couplings between messengers and the MSSM. The question of how to generate such A-terms from such "extended GMSB" models was not well explored prior to the Higgs discovery.

- Shih, together with Nathaniel Craig (joint Rutgers/IAS postdoc), Simon Knapen (Shih's graduate student) and Yue Zhao (Scott Thomas's graduate student), published a paper investigating how to achieve the 125 GeV Higgs mass in weakly-coupled models of extended GMSB [20]. In this paper, Shih et al. identified a major obstacle to generating large A-terms, namely that extremely large Higgs mass-squareds are also generated, preventing electroweak symmetry breaking. They dubbed this the A/m_H^2 problem in analogy with the more well-known μ/B_μ problem. Shih et al. showed how to solve the A/m_H^2 problem by coupling messengers of minimal gauge mediation to the Higgs fields. In doing so, they constructed what is possibly the first complete model of GMSB which simultaneously generates viable superpartner spectra, viable couplings for the Higgs sector, and a Higgs mass of 125 GeV. By extending these couplings to the NMSSM, they achieved a complete model in the sense that it also generated μ and $B\mu$. Shih and collaborators showed how their model is consistent with all current LHC constraints, and how it makes definitive predictions for the LHC which can be tested at 14 TeV.

- Shih's following works generalized the model of [20] in various directions. Together with Jared Evans (another Rutgers postdoc), they considered all weakly-coupled models where either the squark fields or the Higgs fields were coupled to messengers [17]. They thoroughly classified all such couplings consistent with perturbative $SU(5)$ unification, for a total of 31 in all. Turning on one coupling at a time, and requiring $m_h = 125$ GeV, they calculated the soft spectrum and fine tuning for each model. They found a clear difference between the "Higgs-type couplings" and the "squark type couplings" with the latter being the least fine-tuned at the $5 \times 10^2 - 10^3$ level, and the former being at least ten times more fine tuned. Along the way, they corrected a number of erroneous formulas for the soft masses that have persisted in the literature, where the role of messenger-matter mixing was not properly taken into account.

- Shih's work with Jared Evans led to a project together with Arun Thalapillil (another Rutgers postdoc) studying the precision flavor constraints on EGMSB models for A-terms. Since these models involve direct messenger-MSSM couplings, they need not be MFV, and this could lead to nontrivial flavor signatures. In their paper, Evans, Shih & Thalapillil performed the first detailed and quantitative study of the flavor violation in these models [36]. To facilitate their study, they introduced a new tool called FormFlavor for computing precision flavor observables in the general MSSM. They validated FormFlavor and their qualitative understanding of the flavor violation in these models by comparing against analytical expressions. Despite being non-MFV, Shih et al. showed that these models are protected against the strongest constraints by a special flavor texture, which they dubbed chiral flavor violation. This resulted in only mild bounds from current experiments, and exciting prospects for experiments in the near future.

- Together with Simon Knapen and Nathaniel Craig, Shih developed a completely general framework for the large class of models where the A-terms are generated through couplings between the Higgs fields and messengers of SUSY-breaking [18]. In order to construct this framework, Shih et al. had to extend the supersymmetric correlator formalism of GGM in three ways. First, they had to include an explicit messenger sector. Second, they had to include the Higgs sector of the MSSM. Finally, for consistency it was necessary to extend the formulas of GGM to next-to-leading order. The resulting framework, which Shih et al. dubbed "General Messenger Higgs Mediation" (GMHM), provided a completely general parametrization of all messenger-Higgs models.

  Using their framework, Shih et al. identified and analyzed different approaches to generating large A-terms needed for a natural Higgs at 125 GeV in the MSSM. In particular, they pointed out that the mechanism of "hidden-sector sequestering" – where anomalous dimensions in the hidden sector are used to suppress large, unwanted soft masses – could be used to generate large A-terms while suppressing large m_H^2. While hidden-sector sequestering had been previously proposed for the μ/B_μ, its application to the A/m_H^2 problem was novel. It raised the exciting possibility that both problems could be solved at once, and that $m_h = 125$ GeV could be easily and economically achieved.

- With his student Simon Knapen, Shih wrote a paper that realized precisely such a model [15]. They constructed a simple and economical model that solved both the μ/B_μ and the A/m_H^2 problems and yielded a viable Higgs mass. Using GMHM, they were able to compute the soft parameters with hidden sector sequestering quantatively for the first time. They also explored the phenomenology of this entire class of models, and discussed predictions for the LHC at 14 TeV. Overall, they found that such models are a novel and relatively unexplored route to obtaining $m_h = 125$ GeV in the MSSM with (relatively) low fine tuning.

- Finally, in a paper with Simon Knapen and two Rutgers students (Aria Basirnia and Daniel Egana), Shih presented a new mechanism to generate large A-terms at tree-level in the MSSM through the use of superpotential operators [37]. The mechanism trivially resolves the A/m^2 problem which plagues models with conventional, loop-induced A-terms. They studied both MFV and non-MFV models; in the former, naturalness motivated them to construct a UV completion using Seiberg duality. Finally, they studied the phenomenology of these models when they are coupled to minimal gauge mediation. They found that after imposing the Higgs mass constraint, these models are largely out of reach of LHC Run I, but they will be probed at Run II. The fine tuning of these models is basically the minimum possible in the MSSM.

2.3 Other projects

Together with Eva Halkiadakis and George Redlinger (two LHC experimentalists), Shih has written an invited review article on the implications of LHC Run I for physics beyond the Standard Model [38]. In this paper, they reviewed the current status of searches for new physics beyond the Standard Model at the end of Run I by the ATLAS and CMS experiments. They discussed some of the implications of these searches on the existence of TeV scale new physics, with a special focus on two open questions: the hierarchy problem, and the nature of dark matter.

In addition to his work on collider phenomenology and model-building, Shih has also maintained an interest in more formal topics. However, the motivation for these more formal works has again been from the phenomenology of SUSY model building.

For example, Shih wrote two papers on the topic of "hidden-sector sequestering". An important phenomenological requirement in the MSSM is that two crucial parameters in the Higgs sector, μ and $B\mu$, are generated with weak-scale values. Generally however, models for μ and $B\mu$ fail to do so, in that $B\mu$ comes out a hundred times too large. This is referred to as the $\mu/B\mu$ problem. One long-standing proposal for solving this problem is to suppress $B\mu$ using large and positive anomalous dimensions in a superconformal hidden sector. This so-called "hidden-sector sequestering" assumes such large positive anomalous dimensions are possible, which has never been demonstrated conclusively.

- Together with Liam Fitzpatrick, Shih studied anomalous dimensions in 4d SCFTs with weakly-coupled AdS_5 duals [12]. They developed a new method for obtaining the anomalous dimensions of non-chiral double-trace operators in N=1 superconformal field theories (SCFTs) with weakly-coupled AdS duals. Via the Hamiltonian formulation of AdS/CFT, they showed how to directly compute the anomalous dimension as a bound state energy in the gravity dual. This simplifies previous approaches based on the four-point function and the OPE. They applied their method to a class of effective AdS5 supergravity models, and they found that the binding energy can have either sign. If such models can be UV completed, they will provide the first calculable examples of SCFTs with positive anomalous dimensions.

- Together with Daniel Green, Shih wrote a paper investigating whether positive anomalous dimensions are possible in weakly-coupled SCFTs [22]. By developing techniques of conformal perturbation theory, they proved that in perturbative SCFTs, under certain general assumptions, anomalous dimensions are always negative.

Another formal topic with phenomenological motivation is R-symmetry breaking. In the MSSM, gaugino masses are forbidden by an R-symmetry. Therefore, R-symmetry breaking is a crucial phenomenological requirement. In collaboration with David Curtin, Zohar Komargodski, and Yuhsin Tsai [23], Shih wrote a paper extending a theorem he proved in 2007 about R-symmetry breaking in models of tree-level SUSY breaking (O'Raifeartaigh models). In Shih's 2007 paper, he studied O'Raifeartaigh models with a single tree-level flat direction (pseudomodulus). This pseudomodulus is lifted by quantum radiative corrections, and the location of the minimum determines whether R-symmetry is broken or not. In 2007, Shih proved that the the pseudomodulus is always fixed at the origin by one-loop corrections, provided all the R-charges of the fields are 0 or 2. So R-symmetry is never broken in such O'Raifeartaigh models. In their recent paper, Shih and collaborators extended this theorem to models with arbitrarily many pseudomoduli. The result was the same: R-charges other than 0 or 2 are necessary for R-symmetry breaking. Shih's 2007 paper had a strong impact on model building and explained why many previous attempts were unsuccessful, in that they did not break R-symmetry. He expects their generalization to have a continued influence on such model building attempts.

3 List of Papers

Papers completed by the senior investigators as well as the postdoctoral researchers supported on this grant during the full award period are listed below.

[1] J. T. Ruderman and D. Shih, "Slepton co-NLSPs at the Tevatron," JHEP **1011**, 046 (2010) [arXiv:1009.1665 [hep-ph]].

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[3] P. Meade, M. Reece and D. Shih, "Long-Lived Neutralino NLSPs," JHEP **1010**, 067 (2010) [arXiv:1006.4575 [hep-ph]].

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[5] T. T. Dumitrescu, Z. Komargodski, N. Seiberg and D. Shih, "General Messenger Gauge Mediation," JHEP **1005**, 096 (2010) [arXiv:1003.2661 [hep-ph]].

[6] P. Agrawal, Z. Chacko, C. Kilic and R. K. Mishra, "A Classification of Dark Matter Candidates with Primarily Spin-Dependent Interactions with Matter," arXiv:1003.1912 [hep-ph].

[7] K. N. Abazajian, P. Agrawal, Z. Chacko and C. Kilic, "Conservative Constraints on Dark Matter from the Fermi-LAT Isotropic Diffuse Gamma-Ray Background Spectrum," JCAP **1011**, 041 (2010) [arXiv:1002.3820 [astro-ph.HE]].

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[13] J. T. Ruderman and D. Shih, "General Neutralino NLSPs at the Early LHC," JHEP **1208**, 159 (2012) [arXiv:1103.6083 [hep-ph]].

[14] D. Kahawala and Y. Kats, "Distinguishing spins at the LHC using bound state signals," JHEP **1109**, 099 (2011) [arXiv:1103.3503 [hep-ph]].

[15] S. Knapen and D. Shih, "Higgs Mediation with Strong Hidden Sector Dynamics," JHEP **1408**, 136 (2014) [arXiv:1311.7107 [hep-ph]].

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