Final Report

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The Higgs and Supersymmetry at Run II of the LHC

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1 Executive Summary

Prof. David Shih was supported by DOE grant DE-SC0013678 from April 2015 to April 2016. His research during this year focused on the phenomenology of supersymmetry (SUSY) and maximizing its future discovery potential at Run II of the LHC. SUSY is one of the most well-motivated frameworks for physics beyond the Standard Model. It solves the “naturalness” or “hierarchy” problem by stabilizing the Higgs mass against otherwise uncontrolled quantum corrections, predicts “grand unification” of the fundamental forces, and provides many potential candidates for dark matter. However, after decades of null results from direct and indirect searches, the viable parameter space for SUSY is increasingly constrained. Also, the discovery of a Standard Model-like Higgs with a mass at 125 GeV places a stringent constraint on SUSY models. In the work supported on this grant, Shih has worked on four different projects motivated by these issues. He has built natural SUSY models that explain the Higgs mass and provide viable dark matter; he has studied the parameter space of “gauge mediated supersymmetry breaking” (GMSB) that satisfies the Higgs mass constraint; he has developed new tools for the precision calculation of flavor and CP observables in general SUSY models; and he has studied new techniques for discovery of supersymmetric partners of the top quark.

2 Accomplishments

More detailed descriptions of Shih’s completed or nearly completed projects in the period of the grant are as follows:

- Searches for supersymmetric top quarks at the LHC have been making great progress in pushing sensitivity out to higher mass, but are famously plagued by gaps in coverage around lower-mass regions where the decay phase space is closing off. Within the common stop-NLSP / neutralino-LSP simplified model, the line in the mass plane where there is just enough phase space to produce an on-shell top quark remains almost completely unconstrained. In [1], Shih and collaborators showed that is possible to define searches capable of probing a large patch of this difficult region, with $S/B \sim 1$ and significances often well beyond 5σ. The basic strategy is to leverage the large energy gain of LHC Run 2, leading to a sizable population of stop pair events recoiling against a hard jet. The recoil not only re-establishes a MET signature, but also leads to a distinctive anti-correlation between the MET and the recoil jet transverse vectors when the stops decay all-hadronically. Accounting for jet combinatorics, backgrounds, and imperfections in MET measurements, Shih et al. estimated that Run 2 will already start to close the gap in exclusion sensitivity with the first few 10s of inverse-fb. By 300/fb, exclusion sensitivity may extend from stop masses of 550 GeV on the high side down to below 200 GeV on the low side, approaching the “stealth” point at $m_{stop} = m_{top}$ and potentially overlapping with limits from top pair cross section and spin correlation measurements.

- In [2], Shih and collaborators completely characterized General Gauge Mediation (GGM) at the weak scale by solving all IR constraints over the full parameter space. This was made possible through a combination of numerical and analytical methods, based on a set of algebraic relations among the IR soft masses derived from the GGM boundary conditions in the UV. Shih et al. showed how tensions between just a few constraints determine the boundaries of the parameter space: electroweak symmetry breaking (EWSB), the Higgs mass, slepton tachyons, and left-handed stop/sbottom tachyons. While these constraints allow the left-handed squarks to be arbitrarily light, they place strong lower bounds on all of the right-handed squarks. Meanwhile, light EW superpartners are generic throughout much of the parameter space. This is especially the case at lower messenger scales, where a positive threshold correction to m_h coming from light Higgsinos and winos is essential in order to satisfy the Higgs mass constraint.

- Null results from dark matter (DM) direct detection experiments and the 125 GeV Higgs both pose serious challenges to minimal supersymmetry. In [3], Shih and his students proposed a simple extension of the MSSM that economically solves both problems: a ”dark sector” consisting of a singlet and a pair of SU(2) doublets. Loops of the dark sector fields help lift the Higgs mass to 125 GeV consistent with naturalness, while the lightest fermion in the dark sector can be viable thermal relic DM, provided that it is mostly singlet. The DM relic abundance is controlled by s-wave annihilation to tops and Higgsinos, leading to a tight relation between the relic abundance and the spin-dependent direct detection cross section. As a result, the model will be fully probed by the next generation of direct detection experiments. Finally Shih et al. discuss the discovery potential at LHC Run II.

- Shih and Jared Evans (a former Rutgers postdoc) made public `FormFlavor` [4], a Mathematica-based tool for computing a broad list of flavor and CP observables in general new physics models. Based on the powerful machinery of FeynArts and FormCalc, FormFlavor calculates the one-loop Wilson coefficients of the dimension 5 and 6 Standard Model effective Lagrangian entirely from scratch. These Wilson coefficients are then evolved down to the low scale using one-loop QCD RGEs, where they are transformed into flavor and CP observables. The last step is accomplished using a model-independent, largely stand-alone package called FFObservables that is included with FormFlavor. The SM predictions in FFObservables include up-to-date references and accurate current predictions. Using the functions and modular structure provided by FormFlavor, it is straightforward to add new observables. Currently, FormFlavor is set up to perform these calculations for the general, non-MFV MSSM, but in principle it can be generalized to arbitrary FeynArts models.

3 List of Papers

[1] S. Macaluso, M. Park, D. Shih and B. Tweedie, "Revealing Compressed Stops Using High-Momentum Recoils," JHEP **1603**, 151 (2016) doi:10.1007/JHEP03(2016)151 [arXiv:1506.07885 [hep-ph]].

[2] S. Knapen, D. Redigolo and D. Shih, "General Gauge Mediation at the Weak Scale," JHEP **1603**, 046 (2016) doi:10.1007/JHEP03(2016)046 [arXiv:1507.04364 [hep-ph]].

[3] A. Basirnia, S. Macaluso and D. Shih, "Dark Matter and the Higgs in Natural SUSY," arXiv:1605.08442 [hep-ph].

[4] J. A. Evans and D. Shih, "FormFlavor Manual," arXiv:1606.00003 [hep-ph].