Research Proposal

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1 Introduction: Nature vs. Naturalness?

The recent discovery of what appears to be the Higgs boson at the Large Hadron Collider (LHC) is the crowning achievement of the Standard Model of particle physics. In this seeming triumph of theoretical and experimental efforts at the high energy frontier, however, lies a pressing question: *is that it*?

1.1 Naturalness vs. the Large Hadron Collider

It's not due to presumptuousness that physicists ask for more, but rather pragmatism. As constructed, the Standard Model appears to break down at short distances: quantum corrections want to push the Higgs mass to be more than fifteen orders of magnitude larger than its observed value—this is the so called 'Hierarchy problem'. This is a problem of 'naturalness,' the principle that nature should not depend on finely tuned cancellations between classical and quantum effects. Thus, one expects new physics at scales not too far from the Higgs mass which can cancel the unwanted quantum effects. Unfortunately, nature has remained coy in the early stages of the LHC era. The collider's data has betrayed nothing of the new physics that physicists have expected. This has ruled out large swaths of the preferred parameter space of many proposed models for new physics and has led many to start to reconsider the implications of how the data constrains natural models of new physics.

1.2 Dark matter vs. the Standard Model

Astrophysics has already provided the first definitive hints for physics beyond the Standard Model in the discovery of dark matter, the hitherto unknown component of the cosmic matter density that seeded galaxies in the early universe. Dark matter has been observed through its gravitational interactions, though the particle or particles that comprise it have yet to be detected in a laboratory experiment. Some of the most promising candidates for dark matter—'weakly interacting massive particles' (WIMPs)—make use of the observation that new particles with an interaction strength roughly that of the Standard

Model Higgs sector and a mass not too far from the Higgs would yield just the observed dark matter density in the universe. This so-called 'WIMP miracle' suggests that dark matter may be intimately connected to the new physics that addresses the Hierarchy problem. The latest bounds from dark matter direct detection experiments, however, is analogous to that of the LHC: null results have led to severe constraints on the dark matter candidates in many models of new physics.

1.3 Nature vs. weak descriptions of strong physics

Historically, one direction beyond the Standard Model has been through strong coupling, or 'technicolor.' While these models fell out of favor due to incompatibility with electroweak precision data, variants of these ideas have found new applications in model building in the LHC era due to powerful dualities discovered in the 1990s that allow one to describe non-perturbative physics with an equivalent calculable description. My research has focused on weakly coupled descriptions of strongly coupled physics—warped extra dimensions, nonlinear realizations, and Seiberg duality—and their applications to models of new physics accessible to particle and dark matter experiments. These types of models can generate precisely the types of particle spectra and interactions that can solve the Hierarchy problem and save the WIMP miracle within the restrictive experimental constraints that have suffocated more conventional frameworks.

2 Emergent electroweak symmetry

One novel ultraviolet completion of the Standard Model proposes that electroweak symmetry—the underlying framework of the Higgs boson—is an emergent phenomenon coming from dynamics not present at higher energies. This is an idea in condensed matter physics that has found a niche in high energy physics through tools like the AdS/CFT correspondence which allows one to construct explicit models which realize this. An intriguing realization of this idea is based on Seiberg duality and identifies the electroweak sector as the 'magnetic' dual of a more fundamental 'electric' theory at high energies.

Such a framework can manifest itself in a way which is very different from the usual minimal supersymmetric Standard Model (MSSM). In particular, it can easily realize to the 'light stop' scenario that is now preferred by early LHC constraints on naturalness. With collaborators I have been exploring the collider implications of such a scenario, focusing on understanding how the LHC constraints can impose nontrivial bounds on the structure of a complete UV realization of the light stop scenario rather than the phenomenological 'simplified models' that are usually used as benchmarks [1].

This construction—referred to as 'minimally composite supersymmetric Standard Model' because the the Higgs and tops appear as bound states of more fundamental particles—is a useful representative model for testing how the light stop scenario affects other aspects of a theory. For example, when parameters are fixed to generate light stops, what are the typical dark matter candidates and are these automatically stable or is additional structure required? Further, the simplest composite models do not offer a straightforward way to generate the observed flavor hierarchy, which is rather unlike the Randall-Sundrum model of a warped extra dimension which inspires the intuitive understanding of the structure of the composite models. Can such an 'anarchic flavor' structure be embedded in the composite construction?

In this way, one may learn valuable lessons about the implications of LHC naturalness constraints on UV model building beyond what can be gleaned through simplified models. If naturalness is realized through the light stop scenario, then these studies will form the basis for the set of tools used for understanding the larger framework of supersymmetry that is just beyond the TeV scale.

3 Goldstone fermion dark matter

Nonlinear realizations describe the low-energy degrees of freedom of strongly coupled theories with spontaneously broken symmetries. When combined with supersymmetry, the Goldstone bosons of these theories are complex fields with 'Goldstone fermion' super-partners. These, in turn, offer novel 'weakly interacting massive particle' dark matter candidates which can be interpreted as low energy bound states of unknown high energy physics.

The typical 'WIMP' dark matter candidates in the MSSM require a tuned spectrum to account for the several orders of magnitude difference between the annihilation rate required for the correct relic abundance and the upper limit on the WIMP–nucleon cross section from direct detection experiments. In work with collaborators, I showed that the Goldstone fermion construction can avoid this tuning since the annihilation rate is naturally fixed by interactions with the nonlinearly realized sector while the direct detection cross section is controlled by mixing with the Higgs sector [2]. We found that for a global Abelian symmetry broken at the TeV scale, one naturally obtains a 100 GeV scale Higgs-portal WIMP candidate whose direct detection rate is suppressed by three orders of magnitude.

The effective theory of Goldstone fermions can also furnish indirect detection signals through anomaly-induced couplings of the Goldstone boson to photons and gluons. We are currently exploring the extent to which these signals can be Sommerfeld enhanced with particular focus on doing a consistent matching of the non-relativistic theory with a singular potential to the nonlinear quantum field theory [3].

Recent claims of a 130 GeV line in the γ-ray spectrum observed by the Fermi satellite offer an interesting playground for the Goldstone fermion construction. For example, one may consider the supersymmetric limit of a pseudo-Goldstone Higgs model where the Goldstone fermion and its scalar superpartner are able to generate the 130 GeV line while the interactions with the Higgs are governed by the nonlinear sigma model and control relic abundance and direct detection rate.

4 Signatures of strong coupling

In addition to building top-down models based on weakly coupled descriptions of strong coupling, I am also interested in better understanding how experiments constrain these models and how, in turn, these models can suggest novel searches for new physics.

4.1 Flavor and low energy constraints

In past work I have contributed to the development of the `SUSY_FLAVOR` code for the numerical calculation of flavor-changing observables in the general MSSM, focusing on the loop-level contributions that may decrease (rather than increase, as conventionally expected) the $B_s \to \mu^+\mu^-$ branching ratio [4]. This work led to an exploration of loop-induced, flavor-changing dipole operators in the Randall-Sundrum model of a warped extra dimension, which is related by the AdS/CFT correspondence to four-dimensional models of strong coupling. In a series of papers [5], I developed a manifestly 5D calculation which explained the loop-level finiteness of these operators and gave the first numerical predictions from this class of models.

4.2 Collider of naturalness

The same-sign di-lepton (SS2L) channel is an ideal signature to search for new Majorana fermions such as the superpartners of the Standard Model gauge bosons. Motivated by natural supersymmetry with R-parity violation, one may consider effective theories where a gluino decays into a boosted stop which, in turn, decays into a pair of collimated jets. We are currently exploring the extent to which jet substructure can improve the reach of these searches and provide an additional handle for extracting information about the spectrum of new particles [6].

5 Outlook

The experimental data expected over next three years will probe the parameter space of conventional naturalness at colliders and will push the limits of dark matter direct detection experiments. My goal for this period is to focus on the interplay between models of new physics motivated by strong coupling and the these expected experimental results. Concrete ultraviolet models provide a road map for the types of principles required to match to experimental results and can also provide insight for ways to improve experimental search techniques.

References

[1] C. Csáki, R. Houtz, J. Terning, and P. Tanedo, "Phenomenology of the minimally composite supersymmetric Standard Model (in preparation),".

[2] B. Bellazzini, C. Csaki, J. Hubisz, J. Shao, and P. Tanedo, "Goldstone Fermion Dark Matter," *JHEP* **1109** (2011) 035, `arXiv:1106.2162 [hep-ph]`.

[3] B. Bellazzini, M. Cliche, and P. Tanedo, "Sommerfeld enhancement with singular potentials (in preparation),".

[4] A. Dedes, J. Rosiek, and P. Tanedo, "Complete One-Loop MSSM Predictions for $B \to$ lepton lepton' at the Tevatron and LHC," *Phys.Rev.* **D79** (2009) 055006, arXiv:0812.4320 [hep-ph]. A. Crivellin, J. Rosiek, P. Chankowski, A. Dedes, S. Jaeger, *et al.*, "SUSY_FLAVOR v2: A Computational tool for FCNC and CP-violating processes in the MSSM," arXiv:1203.5023 [hep-ph].

[5] C. Csaki, Y. Grossman, P. Tanedo, and Y. Tsai, "Warped penguin diagrams," *Phys.Rev.* **D83** (2011) 073002, arXiv:1004.2037 [hep-ph]. M. Blanke, B. Shakya, P. Tanedo, and Y. Tsai, "The Birds and the Bs in RS: The $b \to s\gamma$ penguin in a warped extra dimension," *JHEP* **1208** (2012) 038, arXiv:1203.6650 [hep-ph].

[6] J. Berger, M. Perelstein, M. Saelim, and P. Tanedo, "Searching for R-parity violation with SS2L and jet substructure (in preparation),".