Exotic Higgs Production at the LHC

The discovery of the Higgs boson at the LHC [1, 2] amounts to empirical verification of the theoretical capstone of the Standard Model (SM) of particle physics. This finding evinced the enormous success of the SM in explaining phenomena over a wide range of energy scales with remarkable simplicity. But rather than resting on the laurels of this fantastic discovery, the compelling physics program is now to understand deeply what more the observed Higgs can tell us about physics beyond the Standard Model (BSM).

The Higgs is the first exploration of the scalar sector of our universe, as within the SM it is the only fundamental particle without intrinsic spin. In the spin-one sector of the universe, vector bosons exhibit a wide range of phenomena, from Coulomb interactions to spontaneously-broken symmetries to color confinement. The fermion sector of our universe also contains a humongous diversity of particles with masses spanning some fifteen orders of magnitude, charged under different gauge groups and displaying disparate behaviors. Very little of this structure was historically derived from first principles; we had to empirically discover this wealth of particles and phenomena. So purely on these general grounds there is a strong possibility that this new sector may likewise contain a medley of scalar particles which have different roles and behaviors, and we should pursue a robust physics program to search for them. Interestingly, any two scalar particles are generically allowed to interact with each other, and so the discovery of the Higgs directly opens a window to this new scalar sector.

Past these general expectations, we have stronger reasons to suspect the Higgs may interact with such new particles, as the Higgs plays a key role in proposed solutions to many puzzles which require BSM physics. Its role of giving mass to SM particles can be extended to solve the mystery of nonzero neutrino masses if exotic ‘sterile neutrinos’ exist [3]. Its job breaking electroweak symmetry makes it crucial to many solutions to the problem of generating more matter than antimatter (baryogenesis) if additional scalars couple to it to make the electroweak phase transition first-order [4]. Since it’s a scalar it also provides an intriguing ‘portal’ to dark particles which do not have SM quantum numbers, which leads to many models of dark matter in which interactions with the Higgs are the best of way of learning about the nature of the dark sector [5]. In each of these cases - and many others - new BSM particles solve observed puzzles in conjunction with the Higgs. This makes the Higgs a very clear place to look for a more complete understanding of BSM physics.

While one may wish to look directly for the new particles that solve these puzzles, often times that is not possible. If they’re very massive, or if they interact with the SM only through the Higgs, then we will often either not be able to directly produce them at colliders, or not be able to directly detect them if they are produced. Yet we can still indirectly probe their presence by looking for subtler signs involving the Higgs - for example modifications of its interactions with SM particles which are the telltale sign of new, as-yet-unforeseen particles. Several searches for such deviations have already taken place (e.g. [6, 7]), but no general systematic understanding of which searches would be useful and what they will tell us about BSM physics has yet been laid out, which is our purpose in the current work.

The framework of effective field theory (EFT) gives us a systematic procedure for understanding what effects any particular new, unseen particle would have on the interactions between the Higgs and SM particles even when the new particle is very massive [8]. This technology allows us to determine which possible experimental signals may appear in particle detectors as a result of these new particles. The class of signals of interest to us we call ‘Higgs + X’ final states, representing the production of a Higgs boson in association with some other SM particle(s), collectively denoted ‘X’. Depending on what the new particle is, this X may stand for stable SM particles like the electron or photon which we can directly detect, or like neutrinos which interact too weakly and whose presence we can only infer through a mismatch between the momenta of detected particles and the demand of momentum conservation. Or the X may stand for heavy SM states which are themselves unstable and decay to a variety of lighter SM states we ultimately detect. While the
possibilities may seem endless, EFT offers us a clear path to organizing these final states in terms of which may occur from the presence of a new states, and which are most probable and thus the best places to look. And in the other direction, our understanding of EFT allows us to interpret searches for these signals to learn about the presence of new BSM physics even when we can’t directly produce the new particles.

With this understanding of which ‘Higgs + X’ final states will give us useful information about new BSM physics, our tasks are then two-fold. Some searches for such final states have already been done, and we will perform Monte Carlo simulations of particle collisions at the LHC and their interactions with the detectors to determine the extent to which these searches have probed the existence of these new particles. A systematic description of what current analyses tell us has not yet been performed, and having this will provide an important map of what Higgs + X searches have told us about new particles. Secondly, organizing this map will concurrently reveal which final states have not yet been searched for, and so point to a well-motivated class of searches to perform in the future to look for new physics. But there is a subtlety here, which is that new particles may have other effects beyond modifying Higgs interactions. In the interest of an efficient allocation of resources, we must determine in each case whether the Higgs + X search is the most useful way to look for these new particles, or whether other searches provide better coverage of the effects of particular new particles. These two efforts together will allow us to focus the efforts of experimentalists on the maximally useful Higgs + X final states, and allow us to fully understand the insight these searches provide into the existence of BSM physics.

Umut is well-prepared to carry out both of these tasks, with my assistance and full support. We spent last summer getting him tooled up on our simulation pipeline [9]. This is a series of software which simulates high-energy proton-proton interactions and particle physics processes at the LHC, then models the complicated QCD physics of confinement and hadronization, and then determines how the outgoing final state physics objects will interact with the CMS or ATLAS particle detectors to give a model for the data seen by experimentalists. These simulations, together with Monto Carlo techniques to efficiently sample high-dimensional integrals, allow us to gain a numerical handle on otherwise-intractable physics processes and statistically understand how current data or future searches constrain BSM physics models. Last summer Umut mastered this full pipeline and used it to simulate a particular Higgs + X search [7], finding full agreement between his results and those in the literature. Furthermore he was able to use his analysis to place constraints on some supersymmetric extensions of the SM. In that success he displayed not only his mastery of all of these pieces of physics software, but also an understanding of the particle physics involved and a comprehension of the research process. That experience, in conjunction with his advanced course preparation, will allow him to excel in both prongs of our research plan described above.

References


[9] W. not enough space to properly cite all of the particle physics software Umut has used let me at least give the names along with apologies to their authors: FeynRules, SOFTSUSY, MadGraph, Pythia, Delphes and MadAnalysis.