Research statement

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Particle physics is enjoying very exciting times. As a result of an intense experimental activity in different areas, several major questions have been recently answered and many long-standing mysteries are starting to be unravelled. The most prominent of these recent discoveries is the new boson found at the LHC by the ATLAS and CMS collaborations. Although it is soon to claim the discovery of the Higgs boson, the particle physics community should be congratulated for another breakthrough that will certainly make a huge leap in our understanding of the dynamics of the electroweak scale. Similarly, important progress has been made in neutrino physics, where the small θ_{13} angle has been finally measured, and dark matter, with several cutting edge experiments scrutizing its properties (and even providing tentative hints for an indirect discovery [1, 2]).

My research has focused on the connection between extensions of the standard model (SM) and the ongoing experiments that probe them. In particular, motivated by the open questions in neutrino physics and the leptonic sector, I have studied several neutrino mass models and their phenomenology in colliders and low energy experiments. Furthermore, I have explored the link between the mechanism behind neutrino mass generation and other areas such as lepton flavor violation, the Higgs boson mass and dark matter.

Despite its success, the standard model has several issues that make us believe that some more fundamental theory exists. For example, the SM neither includes neutrino masses, nor it has a valid dark matter candidate. Similarly, the pattern of fermion masses and mixings is simply unexplained. In addition, major theoretical issues also exist, the most popular being the hierarchy problem, namely, the fact that scalar particles are extremely sensitive to high energy scales. When one tries to address these issues in a single framework, links among them are typically found. This allows to test particular models in several independent ways, relating signatures at colliders to signatures in low energy and dark matter experiments. This approach, favored by the aforementioned current activity in different experimental areas, makes it possible to probe models otherwise only indirectly (and even superficially) tested.

One of the central topics in my current research is lepton flavor violation (LFV). Lepton flavor is indeed violated by neutrino oscillations, but no signal in the charged lepton sector has been observed so far. It is well known that the SM augmented by neutrino masses leads to negligible rates for LFV processes. However, most extensions of the SM (supersymmetry, extra dimensions, little Higgs models ...) contain the necessary ingredients to increase these rates to observable levels, thus giving a clear hint of physics beyond the SM. Furthermore, different extensions lead to different hierarchies among the LFV observables. For example, in the MSSM the rate for $\mu \to eee$ is known to be typically much lower than the one for $\mu \to e\gamma$, whereas they can be of the same order in little Higgs models (see [3] for a comparison of different models regarding hierarchies among observables). Therefore, in order to discriminate among models one needs to search for LFV in as many channels as possible and fully understand the relations among observables for a given model.

Together with my collaborators, I have recently challenged the common lore about LFV in supersymmetry (SUSY), showing that Z-penguin contributions, usually neglected or found to be rather small [4, 5], can indeed be dominant in models with an extended leptonic sector [6]. This was latter shown explicitly in the case of trilinear R-parity violation [7] and in the inverse seesaw [8]. Relations among observables in these scenarios are very different from those of the pure MSSM. For example, the most constraining observable is not $\mu \to e\gamma$, but $\mu - e$ conversion in nuclei. Some open questions regarding this issue, like the origin of the non-decoupling behavior of the Z-penguins, are still to be addressed. Furthermore, although the examples discussed so far have been worked out in a SUSY context, the Z-penguin enhancement is not restricted to supersymmetric models. Therefore, I would like to explore the implications of the Z-penguin dominance in non-SUSY models.

Moreover, in most models the flavor violating parameters also have an impact on flavor conserving observables. I would like to study potential correlations between LFV and observables such as R_k, leptonic electric dipole models and the muon $g - 2$. Approaches based on effective field theory are known to be very

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useful for this purpose and complementary to detailed studies in particular models.

The research during my PhD focused mainly on one of the most popular extensions of the SM, supersymmetry, whose main purpose is to solve the hierarchy problem. Although most minimal models are already in strong tension after the unsucessful LHC searches, non-minimal ones are still in good shape. One of these non-minimal SUSY frameworks is R-parity violation ($\not{R}_p$). When constructing a supersymmetric model one finds new gauge and SUSY invariant interactions, not present in the SM, that lead to lepton and baryon number violation. If they were simultaneously present in the lagrangian, the proton would have a fast decay rate, contrary to the experimental observation. For that reason, one usually introduces a discrete symmetry called R-parity that forbids the L and B violating terms. However, if one is less restrictive and allows for lepton number violation, the proton remains stable and non-zero neutrino masses and mixings are generated [9]. This is a good phenomenological motivation to consider $\not{R}_p$ models.

Moreover, most SUSY searches are designed to look for missing energy (MET) in the final state. When R-parity is broken the LSP decays, typically inside the detectors, thus reducing dramatically the amount of MET. This in turn reduces the excluding power of the current LHC data and relaxes the bounds on the SUSY particles [10, 11]. As a result of this, the SUSY scale can be lowered closer to the electroweak scale, alleviating the little hierarchy problem generated by the current exclusion limits (only valid in R-parity conserving models). Thus, one concludes that $\not{R}_p$ models are also well motivated from a theoretical point of view.

I have worked on several aspects of R-parity violation (see for example [12–14]) and I would like to keep working in this direction. This type of models also serves as a perfect workbench to explain the pattern of neutrino masses and mixings [15, 16], leading to tight correlations among the different neutrino mixing angles. These ideas will be tested in the near future, when the neutrino oscillation parameters are measured with better accuracy. This is a line of research that I also would like to pursue.

Another good reason to consider non-minimal SUSY models is a hefty Higgs boson. If the new bosonic particle found at the LHC is interpreted in terms of a Higgs boson, a mass in the 125 GeV range would clearly add more tension to minimal supersymmetric models, where very large corrections from the top-stop sector would be required. This in turn would imply very heavy stops, raising questions related to fine-tuning and naturalness. In fact, this problem is not alleviated at all when neutrino masses are introduced into the game. In [17] my collaborators and I performed a systematic analysis of the Higgs boson mass in the three variants of the canonical seesaw mechanism (type I, II and III) embedded in a CMSSM framework, concluding that very heavy SUSY particles, typically out of reach for the LHC at $\sqrt{s} = 14$ TeV, are necessary. This motivates further extensions of the MSSM where additional contributions to the Higgs mass are present: either F-term contributions, like in the NMSSM, or D-term contributions from enlarged gauge groups. Furthermore, these new contributions may also come from extended leptonic sectors, providing a link to neutrino masses and lepton flavor violation.

If neutrino masses are generated at energies not far from the electroweak scale, interesting signatures in the Higgs sector can also be observed. Several works have recently explored this possibility, showing that the Higgs decays $h \to \nu_L \nu_R$ have indeed good perspectives at the LHC [18–20]. The subsequent decay of the right-handed neutrino leads to final states with either 2 jets + 1 lepton + MET or 2 leptons + MET. Current LHC data already constrain the parameter space of some well motivated neutrino mass models. I find very attractive this connection between neutrino mass generation at low energies, Higgs phenomenology and collider physics.

Finally, there might be a link between dark matter and neutrino masses. A clear example is sterile neutrino dark matter with a mass in the KeV range. Large scale structure simulations seem to favor this option since it can reproduce the observed structures better than the usual cold dark matter candidate. This possibility has been deeply explored, but very few complete models exist. I would like to extend my field of expertise in this direction, poorly studied in the literature. A more indirect connection between dark matter and neutrino mass generation can be found in constrained SUSY models, where the spectrum is deformed with respect to that of the CMSSM due to the existence of a high energy seesaw scale. I explored this idea in the context of a non-minimal SUSY left-right model [21, 22] that incorporates the seesaw mechanism and leads to automatic R-parity conservation at low energies. In such scenarios the neutralino relic abundance is strongly changed and the viable regions in the SUSY parameter space shifted [23]. This connection should also be considered due to its implications in collider experiments and dark matter searches.

To conclude, my research can be summarized as the study of neutrino mass models and their phenomenology at the electroweak scale. I plan to keep working in this direction, open to other theoretical or phenomenological projects related to neutrino mass generation and its connection to SUSY phenomenology, the

Higgs boson mass, lepton flavor violation, dark matter and collider physics.

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