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Research Interests/Proposal

Application for the Postdoctoral Position at the Instituto Superior Tecnico

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"*What is the nature of dark matter?*" is currently one of the most fascinating and fundamental questions in physics, and its answer would greatly advance our understanding of the universe. If dark matter (DM) is assumed to be a weakly-interacting massive particle (WIMP), its relic density calculation automatically yields a result in agreement with the observed value, provided only that its mass is in the $\lesssim$ TeV range. This is taken by many to suggest that the physics of DM is somehow intimately linked to the weak scale. Moreover, it is also otherwise widely-held that new physics should simultaneously appear around the weak scale. Indeed, this year, the impressively early discovery by CMS & ATLAS of a particle consistent with a Standard Model (SM) Higgs boson with mass of $\sim$ 125 GeV comes as a very exciting result, and it supports the argument from particle physics that there should be new physics beyond the SM. Thus, this discovery may only be the first of many important discoveries to emerge from investigations focused on weak-scale physics. As direct detection (DD) sensitivities continue to improve, and given that the outlook for future experimental upgrades are promising, it is highly important to understand the interplay between the results of underground experiments and the information that we receive from the LHC. My current work is focused on the *complementarity* between DD and LHC physics, and the study of simple DM models and effective field theories. The following describes my past and current research in DM phenomenology and ideas for future work.

A major part of my work regarding DM and LHC physics had been in the context of Anomaly Mediated SUSY Breaking (AMSB)[1] models [1] [2], a class of supersymmetric models where particle masses receive contributions from the supergravity anomaly. In studying models in which AMSB contributions dominate, we were able to determine the prospects for detection of the supersymmetric particles at the LHC and in DM searches. We found, for instance, that it was possible to detect as well as *distinguish* between different AMSB models at the LHC [3]. This was achieved by examining the shape of the di-lepton mass distribution for each AMSB model, each having its own unique features (mass edges, peaks, *etc.*) arising from the variations in the neutralino-Z boson coupling structures. Notably, we also projected that the future Xenon 1 Ton experiment would be up to 3 times more sensitive to the most important parameter in AMSB models (the gravitino mass) when compared to one year of LHC 14 TeV data [4], showing that DD searches have the potential to be highly competitive with those of colliders. Moreover, we found that the spin-independent WIMP-nucleon cross section for AMSB models has the experimentally-interesting quality that it is bounded from below for a given DM mass. This implies that the outcome of DD experiments are either to detect DM from AMSB or to completely exclude

[1] While AMSB DM co-annihilations lead to too little DM in standard cosmology, other mechanisms, such as the late decays of massive particles (*e.g.* gravitinos, moduli, *etc.*), could augment and replenish the final abundances.

the model. Xenon 1 Ton, for example, would be sensitive enough to probe the entire parameter space of the models up to a DM mass of $\sim$ 800 GeV. Finally, in [5], we considered the specific scenario where DM is produced non-thermally through late-time decays of the $axino$ field (that is, the supersymmetric partner of the Peccei-Quinn axion) into wino- or higgsino-like DM. In this final work, DM was composed of both thermal relics and axions, and it was shown that these models with too little thermal DM were likely to attain a satisfactory abundance in this non-thermal DM production scenario.

Presently, we are following a search strategy based on $monojets$ in our study of DM at the LHC for the Inert Doublet Model (IDM) [6]. If DM particles are produced directly in a hard process, a single jet (monojet) from initial state radiation can recoil against the DM and can serve as a good probe of DM kinematic properties [7]. IDM is a simple extension of the SM by a single complex scalar doublet endowed with a $\mathbb{Z}_2$ symmetry that prevents it from participating in electroweak symmetry breaking and from interacting with SM fermions. The lightest IDM particle is also rendered stable by the symmetry and is therefore the DM candidate provided it is also neutral. For our purposes, we are mainly interested in the production of DM in association with gauge bosons: if highly-boosted and hadronically-decaying, the boson can mimic a jet. Such a "monojet" could pass standard triggers and provide a signal that stands out over background [8], providing a potential avenue for discovery. For the current analysis we have implemented the model in CalcHEP for signal events and produced background parton-level events with MadGraph 5. All events are showered with Pythia 8, and further analyzed using the Delphes Detector Simulation program. After applying the monojet constraints [9] to the model, we will be able to continue our analysis in terms of DD cross section limits.

It is widely-held that the prospect of directly probing DM properties at the LHC is encouraging. In order to perform a phenomenological study, in practice, one starts with a model and wishes to compare cross section calculations with real data. However, there are numerous factors in putting together a program of study of DM at the LHC. Furthermore, such studies may require simulations that tend to be complicated for several reasons:

- as described above, numerous independently-developed programs often must be used together or in succession;
- it can be difficult to discern which sets of observables are appropriate for a given DM model;
- analysis implementation is non-trivial.

It would therefore be of tremendous value to DM theorists to have a set of tools that are tailored to perform the LHC analysis specifically for DM models. These tools would need to be practical and generally applicable to many DM scenarios, allowing the user to perform fast and accurate analyses on their model of choice without the need of extensive programming. While moving forward with our own original DM/LHC research, gradually adding more models to our library, the software would be developed in parallel. In the end, the tools we develop would facilitate making estimates of discovery signals for the LHC experiments and making comparisons with DM limits. An extended view for this project would be to develop packages that will include classes for kinematic collider variables[2], tools for Bayesian parameter analysis, and other utilities intended to facilitate the comparison of event simulation results with both collider and DM constraints. The program interface[3] would be seamless and easy-to-use, much to the benefit of the larger dark matter community.

The range of possible qualities that DM may possess is wide and varied. However, the hints we have available indicate that the physics of DM may be tied to the weak scale. It is therefore crucial that we be rigorous in our understanding of the theory and the different types of data available to us. We must also be equally creative in devising our methods of searching for DM at the TeV scale. In this way, we have the best chance of understanding what the nature of dark matter is. Thanks very much for your attention and for accepting this application for the postdoctoral position at the Instituto Superior Tecnico.

References

[1] S. P. de Alwis, Phys. Rev. D **77** (2008) 105020 [arXiv:0801.0578 [hep-th]].

[2] L. Randall and R. Sundrum, Nucl. Phys. B **557** (1999) 79 [hep-th/9810155].

[3] H. Baer, S. de Alwis, K. Givens, S. Rajagopalan and H. Summy, JHEP **1005** (2010) 069 [arXiv:1002.4633 [hep-ph]].

[4] H. Baer, R. Dermisek, S. Rajagopalan and H. Summy, JCAP **1007** (2010) 014 [arXiv:1004.3297 [hep-ph]].

[5] H. Baer, A. Lessa, S. Rajagopalan and W. Sreethawong, JCAP **1106** (2011) 031 [arXiv:1103.5413 [hep-ph]].

[6] N. G. Deshpande and E. Ma, Phys. Rev. D **18** (1978) 2574.

[7] P. J. Fox, R. Harnik, J. Kopp and Y. Tsai, Phys. Rev. D **85** (2012) 056011 [arXiv:1109.4398 [hep-ph]].

[8] D. Borah and J. M. Cline, Phys. Rev. D **86** (2012) 055001 [arXiv:1204.4722 [hep-ph]].

[9] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1209** (2012) 094 [arXiv:1206.5663 [hep-ex]].

[10] A. Barr, C. Lester and P. Stephens, J. Phys. G **29**, 2343 (2003) [arXiv:hep-ph/0304226].

[11] K. T. Matchev and M. Park, arXiv:0910.1584 [hep-ph].

[12] D. R. Tovey, JHEP **0804**, 034 (2008) [arXiv:0802.2879 [hep-ph]].

[2] The number of kinematic variables that will potentially aid in the identification of DM is growing; see for example the stransverse mass variables $M_{T_2}, M_{T_{2_\parallel}}, M_{T_{2_\perp}}$ [10], the family of contransverse masses $M_{CT}, M_{CT_\parallel}, \&\ M_{CT_\perp}$ [12][11].

[3] The interface would most likely be written using interactive Python.