Dark Matter and Long-Lived Particles at the Large Hadron Collider

Context

The Large Hadron Collider (LHC) at CERN has opened new avenues in the exploration of theories beyond the Standard Model of particle physics. Run 3 will start in March 2022 with a 50% increase in luminosity, and will deliver more than twice as much data than has so far been collected. This presents our best hope for discovery or confirmation of new physics at the energy frontier, with optimism in the community high that light can be shed on the anomalies in B-meson decays, in Kaon decays, or the muon magnetic moment, by discovering a particle responsible for them. There is also hope that dark matter could be directly produced, linking the two infinities of high energies and cosmology.

Since no direct evidence has been seen so far, new physics will have to be uncovered in the details, hiding via weak couplings or compressed spectra: in other words, it may have unusual features not easily described by naive models. There is now a large effort in the community to understand the anomalies seen in the data, and at the same time understand the implications of Run 2 for the most promising solutions to the big problems, while moving away from the old "standard theoretical candles" such as minimal supersymmetry. This process is hugely complicated, because most current bounds are connected to severe assumptions and hold generally either within very specific scenarios or within simplified models that consist of minimal extensions of the Standard Model.

Perhaps the greatest hope for discoveries through looking at new signatures during Run 3 will be to look for **long lived particles (LLPs)**, such as ***axion-like particles*** **(ALPs)**, and those with dark sectors producing ***dark showers***. Such particles also appear in (corners of) even mundane theories (*e.g.* Minimal Dark Matter, or t-channel dark matter models [1]), and currently have limited coverage at colliders: there is an opportunity to gain access to completely new regions of the new physics parameter space. The PIs in this proposal are involved in a larger ANR project led by M.H. Genest (Grenoble), and including an LPNHE team, to develop new searches and recast them *ab initio*; this proposal aims to complement this effort with a ***parallel but independent project*** to develop a unified framework which will encompass *all* known and new types of searches. It will therefore especially benefit from interactions with the LPNHE group of B. Laforge, J. Ocariz, L. Roos and B. Malescu.

Indeed such a unified framework should consist of a strategy to confront any model to the results of searches for new phenomena across multiple experiments. It should be able to compare LHC searches, consistency checks with cosmology, flavour physics, Higgs physics and electroweak precision tests. There exist calculations and tools for many of these tasks (which the PIs of this proposal have played leading roles in developing), and the challenge will be to combine them in an efficient way. The major bottleneck remains LHC searches.

The state of the art for collider constraints from the theory side consists of either:

(a) The simplified model approach [2], where experimental upper limits on a signal production rate are compared with predictions obtained from new particle production and decay rates, or representative efficiencies related to detector and analysis selection effects provided by the experiments.

(b) Simulation of signals attempting to reverse-engineer experimental analyses [3] aka recasting, which is more general but very slow – and suffers greatly from holes in the information provided by the experiments.

While method (a) would be tempting to use as a first pass, only a fraction of analyses provide a simplified model description, and the assumptions (*e.g.* assuming two nearly-degenerate new particles) are not widely valid. Moreover, as discussed in [4], in approach (a) combining channels is too permissive. On the other hand, it is impractical or impossible to recast a given model against every analysis, and one must choose wisely which signatures to target.

Objectives and scientific approach

We propose to develop a new approach to assessing generic new physics models, starting with a Lagrangian and ending with a decision on whether it is excluded or discoverable at current or future experiments. The idea is to use a new, much simpler, approach to estimating the order of magnitude of particle production cross sections and decays, and then use this plus the information of the quantum numbers to automatically choose relevant signatures and analyses. It should decide whether a simplified model approach for the reinterpretation of the LHC results is applicable, and if not launch the appropriate recasting where necessary, for a model not excluded by other observations.

To estimate the LHC sensitivity to a given model, one first needs to relate the model to the corresponding set of relevant collider signatures that can be probed, as well as to the associated (existing) LHC analyses. In the simplified model approach, the former is derived from input production and decay process rates that have to be computed manually, while the latter is extracted from hard-coded relationships between signatures and analyses. The derivation of those production cross-sections can however be cumbersome, especially for complicated models with heavy combinatorics.

The first axis of the thesis aims to relate in an automatic way a Lagrangian describing uniquely the model dynamics to the list of relevant LHC analyses to constrain it. We developed a method allowing for an efficient automatic calculation of all the decay processes associated with a given model [5]. This method has been shown to be more precise and 10-100 times faster than former techniques. By generalising the concept for production rates, we will design an efficient and novel way to perform numerical cross section calculations accurately. The idea relies on several levels of approximations that are more and more precise, so that one can quickly target the set of processes that are relevant for a given model and decide about undertaking the exact calculations only in this case, saving thus a large amount of computing power. From this stage, it becomes straightforward to derive the collider signatures of the model and therefore a list with the new physics analyses potentially relevant for probing it through an internal dictionary of analyses and signatures.

The second axis of the thesis involves the estimation of the sensitivity of the LHC to a model:

- For the relevant analyses that are available from simplified model LHC re-interpretation programs, one can quickly evaluate whether the model is excluded in a not so precise manner.
- For the relevant analyses that are available from Monte-Carlo-based re-interpretation programmes, one can precisely (but not so quickly) evaluate whether the model is excluded.
- Extra analyses will need to be implemented in both frameworks. In addition, Monte-Carlo-based re-implementations can always be used to generate inputs relevant for the simplified-model-based approach. Moreover, more information about specific analyses may be required – especially for LLP searches – compared to what is in the public domain, to obtain an accurate prediction, and here a close collaboration between theorists and experimentalists (at the LPNHE in particular) is vital.

As a final axis, the techniques developed will be applied to the LLP (ALP and dark shower) analyses which are currently being developed, for which the recasting material should be publicly available and therefore without conflict of interest. This would consolidate and ameliorate our earlier work on the development of the MadAnalysis 5 platform for LLPs [7], and provide a means to unify the most cutting edge ways of testing – or discovering – a model of new physics.

Work plan

October 2022 – March 2023:

- As a first step, the student should implement the method of determining the most relevant production cross-sections and obtaining an order-of-magnitude estimate based on the couplings of the theory. This should be a short introductory project by itself, lasting around $6-12$ months.
- In parallel, a literature search of the analyses available in Run 2 will be undertaken, to determine the most propitious for recasting and identify what material may be available or missing. This will give the student an excellent introduction to the state of the art of the field.
- In addition, a survey of the model space of LLPs will be undertaken ***by the advisors.*** The idea will be to identify the most interesting models to apply the techniques to. In addition to traditional LLPs appropriate for existing searches, it will also involve understanding the ALP and dark QCD signature space and studying the kinematics as a function of the model parameters (lifetime of the dark hadrons, invisible fraction of dark jets, *etc.*). This will allow us to identify representative benchmark models and fix issues in dark QCD event generators.

March 2023 – October 2023:

- The outputs from the first project can then be used to determine automatically and very rapidly the most relevant channels for a given model. This can then be integrated with tools developed by the PIs into a generic toolbox covering a wide range of experiments/observations (dark matter, Higgs couplings, precision/flavour observables, ...) and will have significant impact on the community. This should take an additional six months.

March 2023 – March 2024:

- The third project will be to implement the second axis of the thesis, developing a method to decide whether a simplified model analysis or full recasting is required for a given model – or whether it is even necessary to test a point, if the cross-sections in given channels are too large or too small. This should be started in parallel to the second project, and take one year. It will have tremendous impact on the field.

March 2024 – January 2025:

- Finally, the third axis – extending the framework to ALP and dark shower searches – can be implemented. A direct application will be made on existing LLP-ALP searches to identify usually missing pieces of information, and use this as a guide for what should be provided as part of our collaboration with the AT-

LAS group of the LPNHE. The final paper should include applications to the most interesting models identified by the advisors in the first phase.
- This will require the student and advisors to develop a strategy for the recasting of dark shower searches in a simplified way, and test it against existing searches.

January 2025 – April 2025:
- Writing thesis.

Profile of the candidate, and expertise and skills to be developed during the thesis

The PhD candidate is expected to have a master degree in theoretical physics and/or particle physics, with results demonstrating an excellent mastering of essential skills for high-energy theory (quantum field theory, Standard Model physics, *etc.*). **The IPI funding will enable us to select a candidate from among the many outstanding potential students from outside the Paris system who regularly contact us but for whom the local doctoral funding application process gives a decision too late** (we routinely have to turn them away)**.**

During the thesis the candidate will develop a deep knowledge of new physics models and phenomenology with a focus on dark matter and LLPs. Achieving the predefined goals will allow the candidate to obtain a strong expertise both in the development and in the usage of various tools widely used in our community, which is a valuable expertise for most research groups in the world and therefore opens the door to a successful career in academia. On the other hand, the technical skills to be acquired in programming and computing, as well as the way of thinking in solving long and hard problems typical of high-energy particle physics, are also in high demand into the wider scientific area (including the private sector). Numerous career choices will then be available to the candidate after the thesis.

Roles of the advisors

Both advisors (M. Goodsell and B. Fuks) will fully share the supervision of the student, as we have both worked and collaborated on related topics for more than a year (*e.g.* [6,7]) and have developed a strong and internationally-recognised expertise in the development of public tools (**FeynRules**, **MadAnalysis**, **SARAH**, **HackAnalysis**) for the reinterpretation of the results of the LHC (*e.g.* [3 – 7]). We both teach Master 2 courses in the Paris area in the second semester and have a strong commitment to mentorship. The student will be provided with the material for these courses (and more) and, depending on their background, encouraged to attend.

References

(1) C. Arina, B. Fuks, L. Mantani, H. Mies, L. Panizzi and J. Salko, *Closing in on t-channel simplified dark matter models*, Phys. Lett. B 813 (2021) 136038.

(2) S. Kraml *et al.*, *SModelS: a tool for interpreting simplified-model results*, Eur. Phys. J. C 74 (2014) 2868.

(3) E. Conte and B. Fuks, *Confronting new physics theories to LHC data with MadAnalysis 5*, Int. J. Mod. Phys. A 33 (2018) 1830027; J. Araz, B. Fuks and G. Polykratis, *Simplified fast detector simulation in MadAnalysis 5*, Eur. Phys. J. C 81 (2021) 329.

(4) G. Chalons, M.D. Goodsell, S. Kraml, H. Reyes-González and S.L. Williamson, *LHC limits on gluinos and squarks in the minimal Dirac gaugino model,* JHEP 04 (2019) 113.

(5) J. Alwall, C. Duhr, B. Fuks, O. Maielaer, D.G. Öztürk and C.H. Shen, *Computing decay rates for new physics theories with FeynRules and MG5_aMC@NLO*, Comput. Phys. Commun. 197 (2015) 312.

(6) M.D. Goodsell and L. Priya, *Long Dead Winos*, arXiv:2106.08815 [hep-ph].

(7) J. Y. Araz, B. Fuks, M.D. Goodsell and M. Utsch, *Recasting LHC searches for long-lived particles with MadAnalysis 5*, arXiv:2112.05163 [hep-ph].

(8) The LHC Reinterpretation Forum [including B. Fuks and M.D. Goodsell], *Reinterpretation of LHC Results for New Physics: Status and Recommendations after Run 2*, SciPost Phys. 9 (2020) 022.