PROCEEDINGS OF SCIENCE

Overview of searches, prospects, what are we missing?

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Feebly interacting particles (FIP) are present in many scenarios of physics beyond the Standard Model. The physics from the FIP can have different imprints in the phenomenology as dark matter, heavy neutral leptons, long-lived particles, axion-like particles, dark showers, etc. It is a vast landscape to explore, however, LHC experiments have currently several searches that try to cover the different signatures that FIP present. The coverage of ATLAS and CMS during the first runs have been very successful. Run 3 looks promising since more data will be acquired and new identification techniques will be applied. However, technical improvements are not enough to cover all the possibilities, new strategies and proposals are necessary to make real progress in the understanding of the nature of FIPs.

The Eleventh Annual Conference on Large Hadron Collider Physics (LHCP2023)
22-26 May 2023
Belgrade, Serbia

[*] Speaker

PoS(LHCP2023)163

1. Overview of searches.

Given the importance of the FIPs there are many searches in the LHC that are specific of this group of particles. These searches are usually separated in different groups depending on the physical problem they solve. Some of the most searched and famous categories within the FIP paradigm are Dark Matter, Heavy Neutral Leptons, Long-lived particles, Axion-like Particles and Dark Photons.

Dark matter One of the most long-standing problems in particle physics is the understanding of the nature of Dark Matter. According to the observations we know that the DM particle should be neutral and it also should couple very weak to the SM fields in order to fulfil the experimental constraints. The way the DM couples fo the SM fields can be used to constrain its parameter space when combining different search approaches. One of the most common searches is looking at the production of DM particles together with some external object (jet, lepton, photon, etc) and the search of the mediator particle between the DM sector and the SM fields. In that sense both ATLAS and CMS experiments from LHC are making a great effort with more than 80 publications in this subject (excluding conference notes).[1] These two strategies allow to cover signicantly the parameter space in terms of mass and couplings [2, 3]. One of the main advantages of these searches is the complementarity with direct detection searches [4, 5]. Collider searches present a better performance than direct detection experiments at low DM masses and also their bounds are almost independent from the DM mass.

Heavy Neutral Leptons Heavy neutral leptons (HNL) can appear in extensions of the SM that connect to the leptonic sector to explain the origin of neutrino masses. Despite the origin of neutrino masses, they can be used to explain unsolved puzzles such as dark matter, baryon asymmetry... These heavy neutral leptons can have Majorana or Dirac nature and their decays are dictated by their coupling to the SM sector that is usually small. For that reason there are models where due to their tiny couplings to the leptonic sector the HNL can be long-lived leading to displaced vertices. Both ATLAS and CMS have searches for HNL in different models. One of them is the production of HNL using 1 lepton plus a displaced vertex [6, 7]. Both detectors show similar performance with bounds that lie in the range 2 GeV $< m_N <$ 14 GeV for values of the mixing parameter $10^{-7} < m_N < 10^{-3}$. HNL can be present in models with left-right symmetries [8]. In that case the HNL is searched together with the vector boson W_R in the two same flavor leptons plus jets. In order to differentiate between Dirac or Majorana HNL they analyse opposite sign or opposite plus same sign leptons respectively. They found exclusion of HNL up to $m_N <$ 3 TeV and $m_{W_R} <$ 6 TeV for the W_R.

Long-lived particles Long-lived particles can travel through the detectors and may decay in their different parts (calorimeters, muon chamber...). The are present in many phenomenological models, some of them motivated by small couplings. Nowadays it has become a popular and interesting topic and increasing efforts are made in order to optimize this kind of searches. Despite the efforts from ATLAS and CMS efforts to measure long-lived particles, long distance detectors are needed (FASER, MATHUSLA, ShiP, CODEX-b, AL3X...) As an example ATLAS and CMS search for a

[1] See Ref. [1] for a review of the DM benchmarks and searches from both ATLAS and CMS.

Higgs boson decaying into long-lived particles, being scalars or dark photons [9, 10]. The displaced vertices are reconstructed in different parts of the detector what makes it really challenging, however both experiments are sensitive to decay lengths in the range 10^{-4} m $< c\tau <$ 10^{3} m. Long-distance detector are crucial to do complementary searches to the ones in the LHC. The FASER experiment released recently data from their searches for dark photons decaying into a $e^{+}e^{-}$ pair [11]. Since no events are found in the signal region they are able to impose limits that are complementary to the ones existing at low masses.

Axion-like particles Axion-like particles (ALPs) are hypothetical particles that appear in different contexts to solve different problems in particle physics, *e.g.* strong CP problem. One of the searches for ALPs is through their interactions with photons. Recently ATLAS and CMS have measured the light by light scattering that can be interpreted in terms of an ALP mediator [12, 13]. Their results allow to constrain the axion coupling constant to be $f^{-1} < 10^{-1}$ TeV^{-1} in a range of axion masses 200 GeV $< m_{\mathrm{ALP}} <$ 1600 GeV.

2. Prospects.

The Higgs boson discovery was a great milestone for the first runs of the LHC. However, no hints of new physics have been found so far. Nonetheless, there is still a long way until the LHC can cover all the possibilities of physics beyond the Standard model. Run 3 of LHC, not only operates at higher energy ($\sqrt{s}$ = 13.6(14) TeV) but is is also expected that double the data from LHC due to an increase in luminosity. Apart from that, the development of new techniques allow the experimentalists to refine better the data, obtaining better information that it could have been missing. One example of this is the use of unconventional trigger strategies such as *data-scouting*[14]. This method allows to save data of objects reconstructed online that otherwise could have suffered from trigger cuts, *e.g.* low p_T. More strategies together with challenges as the pile-up, promise an interesting time ahead. However, not only technical improvement is necessary in the search for new physics, but also an improvement on the proposals from the theory side.

3. What are we missing? New proposals.

Finding new physics beyond the Standard model must be a joined effort from theorists and experimentalists. For that reason, while the experimentalist are doing a great effort with the experiments at LHC, theorists must provide insightful strategies that can exploid the most of LHC data. New strategies have to be proposed to look in different ways, from cornering every new aspect of new physics to the use of simplified models that can fit all the experimental possibilities while making easy the translation of experimental data to actual complete models.

As an example of the first point, we can focus on an example related with the search of ALP via non-resonant production [15]. The usual method to test axion couplings is studying their production and subsecquent decay. In this way one can only measure and study the product of two couplings, the one involved in the production and the one of the decay. However, the authors of Ref. [15] developed a method to study only one kind of couplings. They focus on the production of the axion via vector boson fusion and its posterior decay into vector bosons. They proposed a collider analysis that can enhance this type of events an show that it is possible to measure events and constraint the coupling of the axion to vector bosons in an unique way and avoiding the inclusion of other type of couplings. This is of crucial importance when analysing ALP properties since it is a way to characterize its Lagrangian parameters univocally.

As an example of the second point we will focus on an example of the use of simplified model for the study of heavy resonant scalar production in events with missing transverse energy [16, 17] through the process $pp \to b\bar{b}\Phi(\to Z+p_{\mathrm{T}}^{\mathrm{miss}})$. This simplified framework is based on the production of a heavy scalar, Φ that decays into a Z boson and invisible particles ($\mathcal{I}$) and may include a mediator particle ($\mathcal{M}$). The framework contemplates different topologies that can lead to the same signature. This kind of signal has been already studied by ATLAS and CMS in the context of dark matter searches [18, 19]. In Ref. [17] the authors used the data from these experimental searches to translate into limits of the simplified model framework making a full collider study. They showed in their results that actual LHC data can be used to constrain the physical parameters of the framework, and at the same time be used to impose bounds on specific models, such as the two-Higgs-doublet model.

These two examples showed us how new strategies can make the most of the existing data in order to unveil physics beyond the Standard Model.

4. Conclusions.

Feebly interacting particles are present in a huge variety of beyond the Standard Model scenarios. These sectors include dark matter candidates, heavy neutral leptons, axion-like particles, long-lived particles, etc. Their tiny interaction with the SM particles imposes a great challenge for the LHC searches so special strategies or techniques are required. Currently there are multiple searches by ATLAS and CMS that explore the parameter regions of every specific subsection of the FIPs. Despite being sensitive to these scenarios, these searches cannot cover all the regions of the parameter space, since there are signatures or topologies that are not yet covered. Nonetheless, this can change with run3 of LHC and new detectors such as the long-distance ones, improving qualitatively the current situation. Furthermore, new ideas from the from experimental and theoretical sides are needed. Without such a collaboration between experimentalists and theorists we will not be able to make the best out of the LHC.

Acknowledgments

The author acknowledges the financial support by Ministerio de Universidades and “European Union-NextGenerationEU/PRTR” under the grant María Zambrano UP2021-044 (ZA2021-081). The author also thanks support by the Spanish grants PID2020-113775GB-I00 (MCIN/AEI/10.13039/501100011033) and CIPROM/2021/054 (Generalitat Valenciana).

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