Probing new physics in the laboratory and in space

Ovchynnikov, M.

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Summary

In the 20th century, attempts to explain the variety of particle physics phenomena, together with two scientific revolutions – special relativity and quantum mechanics, have resulted in the development of the Standard Model of particle physics (SM). The current status of SM is dual. Being extremely successful in describing very precisely countless particle physics experiments at accelerators, the SM fails to explain several well-established phenomena that are known as Beyond the Standard Model (BSM) phenomena: dark matter in the Universe, neutrino oscillations, and the origin of matter-antimatter asymmetry of the Universe. This suggests that the SM has to be extended.

Unfortunately, the BSM phenomena do not tell us about the precise way in which SM has to be extended, and a lot of different extensions may equally explain the BSM phenomena. In order to find hints where to go we have to study observational signatures that may be caused by various extensions of the SM. This thesis is devoted to studying two kinds of such searches: accelerator experiments, and cosmological observations. The two approaches are complementary: accelerator experiments probe short-lived particles and cosmological signatures constrain long-lived particles.

At accelerator experiments, the new particles may be produced and then searched in particular by their decays or scatterings. In order to define the target parameter space for upcoming experiments, it is important to know constraints coming from past experiments. For these purposes, I have re-analyzed bounds coming from the past experiment CHARM to a model of Heavy Neutral Leptons (HNLs), which is an extension that adds massive fermions that may be directly responsible for the resolution of all BSM phenomena. I have found that previously reported bounds on HNLs from CHARM are underestimated by two orders of magnitude, in dependence on properties of HNLs. Next, I have considered searches for displaced vertices at the Large Hadron Collider (LHC) and studied their potential to probe decays of different feebly interacting particles (FIPs). Due to the short distance between the FIP production point and the decay volume, of the order of $l_{\text{min}} = \mathcal{O}(\text{mm})$, such kind of search is able to close the gap between the parameter space of FIPs that are ruled out by past experiments and the domain which may be probed by dedicated experiments, which have larger $l_{\text{min}} \gtrsim 1$ m. In particular, I have demonstrated for the first time the potential of the muon tracker at CMS to search for FIPs, using as examples HNLs, Higgs-like scalar and Chern-Simons portals. Next, I have considered FIP scattering, and studied how scatterings of FIPs off hadrons may be distinguished from

SM neutrino scatterings, dependent on the mass of a particle that mediates the scattering. Considering these signatures, I have estimated the sensitivity of SND@LHC, a recently approved experiment at the LHC, to the model of light dark matter interacting with SM particles via the leptophobic portal.

Cosmological signatures typically provide the lower bound on the values of FIP's couplings. The most important observations for short-lived FIPs are BBN and CMB, which may be sensitive to FIPs with lifetimes as small as few $\times\ 10^{-2}$ s. I have found that light long-lived mesons such as $\pi^{\pm}$ and $K^{\pm/0}$ efficiently convert protons into neutrons, which may lead to a significant increase of the ^{4}He abundance if such mesons are present in the primordial plasma at temperatures below 1.5 MeV. Using analytic considerations, I have derived a model-independent bound on FIP lifetimes from BBN from this effect. An important parameter that is changed by short-lived FIPs and may affect CMB is the effective number of degrees of freedom N_{eff}. Studying the impact of heavy FIPs with $m_{\text{FIP}} \gg T$ on N_{eff}, I have found that FIPs with lifetimes $\tau_{\text{FIP}} \lesssim 0.1$ s decrease N_{eff} even if decaying mostly into neutrinos, which is due to the fact that neutrinos from decays of FIPs store most of their energy in EM plasma during their thermalization.

Finally, I have applied these model-independent results to the case of HNLs. I have studied their cosmological production, considering the parameter space of HNLs that either never entered thermal equilibrium, or entered it and then decoupled. Then, I have derived bounds from BBN at the level $\tau_N \lesssim 0.02$ s, which are a factor of five stronger than those reported previously in the literature, and from CMB, finding in particular that HNLs with masses $m_N \gtrsim 70$ MeV may decrease N_{eff}.