Snowmass proposal

Detection of Hidden Sector Dark Matter at the LHC and Elsewhere

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Abstract: We propose that probes of the hidden sector and of the possibility that dark matter may reside there in the form of dark neutralinos, dark Dirac fermions and dark photons and their possible detection at the LHC and elsewhere and their implications for naturalness in supersymmetry are relevant topics of study at Snowmass. Also relevant for such a study is self-interacting light dark matter, and ultralight dark matter in the hidden sector and particle physics models that may incorporate them.

Detection of hidden sector dark matter from the study of long lived particles at the LHC: Supergravity models, and strings and brane models contain hidden sectors which have extra gauge groups and may also contain matter. Although the hidden sector is a singlet of the visible sector gauge group communication between the visible and the hidden sector can still occur. Aside from gravitational interactions between the two sectors, they can also communicate via portals such as the Higgs portal [1] and via gauge kinetic mixing [2], Stueckelberg mass mixings [3, 4] as well as a combination of the two [5] between a hidden sector $U(1)_X$ and the hypercharge $U(1)_Y$ of the visible sector. The mixing of $U(1)_X$ and $U(1)_Y$ results in six neutralinos four of which are the visible sector neutralinos and the remaining two are dark neutralinos. The dark neutralinos interact with the visible sector only feebly. However, if one of the dark neutralinos is the LSP of the extended model it will constitute dark matter. Suppose now that the LSP of the MSSM sector is charged. In this case the charged sparticle will be long-lived but eventually decay into the dark neutralino. Once produced, such a long-lived particle will leave a visible track in the inner detector at the LHC and will look like a heavy muon. Realistic cases have been analyzed recently [6–8].

Here we will discuss the analyses of [7, 8]. The first of these is the case when the lightest sparticle in the MSSM sector is a stau [8]. Here for a range of feeble couplings the stau will have a lifetime large enough that it will produce a visible track inside the detector and then decay inside the detector into a tau and the dark neutralino. The decay will show a kink in the visible track providing evidence of dark matter via a missing energy signal. The second case we consider is one where the lightest sparticle in the MSSM sector is a stop [7]. Here we assume a range of feeble couplings so the stop will have a lifetime large enough that it will produce an R-hadron which will leave a visible track inside the detector but its decay will occur outside. In a realistic model one must show that the desired amount of relic density can be produced for the dark neutralino. It is shown in [8] that in this case one needs a combination of freeze-out and freeze-in to generate the relic density. The freeze-out contribution arises from the freeze-out relic density of the stops when they go out of thermal equilibrium and subsequently decay into the dark neutralino. The freeze-in relic density arises by the out-of-equilibrium decays of sparticles after the inflationary period. Here the R-hadron track will appear as a heavy muon. A study of the associated R-hadron was carried out at 14 TeV HL-LHC and at 27 TeV for a possible future high energy HE-LHC. The analysis shows that at HL-LHC, an integrated luminosity ~ 230 fb^{-1} is needed to discover a 1.4 TeV stop which is right around the corner once the LHC is back to collecting more data. The integrated luminosity for discovery is greatly reduced at HE-LHC where an integrated luminosity as low as 20 fb^{-1} is sufficient to discover a 1.4 TeV stop and an integrated luminosity of ~ 800 fb^{-1} is sufficient to discover a 2.3 TeV stop. Further test of this class of hidden sector dark matter models can come from a new generation of future detectors which explore the lifetime frontier such as MATHUSLA [10] and FASER [11] and which can detect decays significantly away from the vertex.

Hidden sector dark matter and natural supersymmetry: Dark neutralinos also have implications for naturalness in supersymmetry. Thus models which have the Higgs mixing parameter μ relatively small (compared to the soft parameters) would lead to a higgsino-like neutralino. A small μ is one of the criteria for naturalness in supersymmetry but such models would lead to copious annihilation of neutralinos in the early universe and consequently to a neutralino relic density significantly below the experimental value and would require an additional component. Suppose now that the dark neutralinos are not the LSP but they contribute to the LSP relic density. As discussed above, the dark neutralinos could be produced by non-thermal out-of-equilibrium processes and their subsequent decay to the LSP would contribute an additional amount to the observed relic density thus making the small μ models viable. Quantitative analyses show this to be the case [9]. The sparticle spectrum predicted in these models is consistent with the current experimental lower bounds. The proposed mechanism enlarges the parameter space of natural supersymmetric models defined by small μ. Some of the enlarged parameter space of the proposed models may be probed by direct detection experiments while some of the other models may be testable at HL-LHC and HE-LHC. The models considered have a very compressed electroweakino spectrum consisting of charginos and neutralinos which lie in the range 250 GeV to $\sim$ 870 GeV. However, we show that with appropriate procedures to suppress the background, some of the parameter points are discoverable at the HL-LHC with as low as 260 fb^{-1} of integrated luminosity. The discoverable mass range is pushed further to reach $\sim$ 870 GeV at HE-LHC with a required integrated luminosity ranging from as little as 70 fb^{-1} up to $\sim$ 2000 fb^{-1}.

Dark Dirac fermions, dark photons and self-interacting dark matter: The hidden sector may contain matter, i.e., dark Dirac fermions which can constitute dark matter. The dark Dirac fermions can interact via dark photons and generate self-interactions which may help explain the structure of galaxies at short distances such as resolution of the cusp-core problem. The desired mass of this type of dark matter lies in the MeV-GeV range. Such dark matter is also constrained by galaxy and Bullet cluster data which constrain σ/m. The Stueckelberg formalism with kinetic mixing is an ideal framework for the study of this type of dark matter [12]. Aside from that, light dark matter is of considerable interest as it is the subject of current and future dark matter detection experiments. Thus SuperCDMS Soudan [13] has put stringent limits on dark matter masses between 40 eV to 500 eV with kinetic mixing of dark photons up to values below 10^{-15} for particle masses below $\sim$ keV. At SuperCDMS SNOLAB [14] dark matter with masses $\leq$ 10 GeV will be probed. These constraints are relevant to the study of hidden sector portals. In addition ultralight dark matter which extends the mass range of hidden sectors to 10^{-21} eV [15] and particle physics models in SUGRA and strings [16] which can accommodate such dark matter are worthy of further study.

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