Neutral Long-Lived Particles at Future Colliders

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September 1, 2020

Abstract

We propose to perform a comprehensive comparison of the sensitivity of proposed future colliders/detectors to electrically-neutral LLPs. We propose to initially focus on Higgs-portal hidden sector scenarios, and consider additional scenarios (gauge-portal, heavy neutral leptons, RPV SUSY, etc.) person-owner permitting. We plan to study a variety of production modes and lifetimes, ranging from effectively prompt to invisible, using ID-, calorimeter-, MS-, and MET-based signatures. In order to understand how future detectors can maximize sensitivity to these unconventional signatures, we also plan to investigate the impact of various detector functionalities, such as precision timing and tracking at L1.

Introduction

Among the three possible renormalizable portals between the Standard Model (SM) and a potential hidden sector (HS), the Higgs portal is particularly interesting as constraints from the LHC and elsewhere remain relatively weak. Probing this scenario at future colliders is therefore extremely important.

In Higgs-portal scenarios, mixing between the SM Higgs boson (H) and HS state(s) induces a small effective coupling between the Higgs boson and the HS, allowing for the possibility of exotic Higgs boson decays into the HS. Depending on the nature of the HS, these HS states (X) may be stable or decay back to the SM fermions with lifetimes ranging from effectively prompt to detector stable. Various possible H production modes, X decay modes, and the unconstrained X lifetime, results in a vast array of potential final state signatures. To simplify, we will concentrate on two-body $H \to XX$ decays with X decaying invisibly or to fermion pairs.

For such models, five distinct signatures have been studied at the LHC:

1. prompt $X \to f\bar{f}$ decay
2. $X \to f\bar{f}$ decays within the tracker
3. $X \to f\bar{f}$ decays within the hadronic calorimeter
4. $X \to f\bar{f}$ decays within the muon spectrometer (MS)
5. $H \to$ invisible decays

We propose to perform a comprehensive comparison of the sensitivity of proposed future colliders, considering each of these five signatures. We will consider pp, ee, and $\mu\mu$ colliders at various center of mass energies. In the case of a pp machine, we we will consider additional energies beyond the standard 100 TeV benchmark, in order to determine how the sensitivity is affected.

Prompt signatures

For prompt X decays, SM backgrounds pose a significant challenge. In this regime, we plan to use signal and background MC samples produced with Delphes fast simulation to assess the sensitivity of various proposed machines.

Tracker-based signatures

Hadronic X decays within the tracker are generally indistinguishable from one another, all of which yield a displaced vertex (DV) signature. In this regime, proposed lepton and hadron colliders present distinct challenges.

At a future hadron collider with unprecedented pileup conditions, fake DVs resulting from the crossing of uncorrelated tracks will likely represent the dominant background source. We propose to evaluate this background contribution by using fast simulation to explicitly overlay pileup interactions and reconstruct DVs, using an algorithm similar to that employed by ATLAS, while also incorporating precision timing information. We will consider two scenarios: gluon fusion Higgs boson production with tracker-based trigger capabilities, and subdominant production modes with VBF and leptonic triggers.

Future lepton colliders will be considered as well, where the dominant background is expected to be beam-induced, necessitating the usage of full simulation for accurate estimation.

Calorimeter-based signatures

In this regime, most hadronic X decays are also indistinguishable from one another, though experimentally detection algorithms are tuned differently for leptonic and hadronic X decay modes. Modern experimental detection techniques use Deep Neural Networks (DNNs), starting from low-level calorimeter clusters to differentiate between Standard Model backgrounds, beam-halo interactions, pile-up, and signal. As a primary effort, we propose to develop heuristics to understand signal and background rates in the various detectors. As each DNN and its training must be tailored for the detector, it is not likely a separate model can be developed for each detector geometry. Further, a pixelated calorimeter, similar to CMS's planned HGCal for the HL-LHC, likely will require a very different approach. However, a fast simulation will give many of the tools they need to estimate signal and backgrounds.

MS-based signatures

Given its large volume, the ATLAS muon spectrometer has a good acceptance for a broad range or lifetimes, and the low multiple scattering of charged particles makes it a powerful instrument for multi-track vertex reconstruction. Detector timing information has proved to be very efficient in rejecting SM, machine induced, and cosmic backgrounds. Based on the current ATLAS detector layout, we propose to develop an LLP trigger selection using timing information from a detector based on RPC and TGC technologies. Moreover, we propose to improve the current MS vertex reconstruction strategy to cope with higher background levels by including timing information in the vertex fit. The background will be scaled based on the current MS measurements and assuming the same amount of shielding material between the proton-proton interaction point and the MS. A higher detector granularity, expected at future colliders, will be mimicked for these studies.

Invisible signatures

Searches for the Higgs boson to invisible final states have been performed by both ATLAS [2, 3] and CMS [5], and constrain the invisible branching fraction to around 13%. Projections for the HL-LHC predict that the branching fraction will continue to improve, to within a few percent [1], depending on the improvements of the theoretical uncertainties. For sufficiently long-lived X the decay products will invisible, and therefore Higgs to invisible searches will provide some sensitivity for a range of models [4].

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