Double Displaced Vertices: A New Strategy for Unmasking Non-Minimal Dark Sectors at Colliders

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Double displaced vertices (DDVs) — and multiple displaced vertices (MDVs) more broadly — represent a novel experimental signature of new physics which can arise in a variety of BSM scenarios involving non-minimal dark sectors and in other scenarios involving multiple exotic neutral particles with sizable decay lengths. Existing displaced-vertex searches may not be optimized for the detection of such signatures. Thus, an effort to develop dedicated search strategies and analysis techniques for probing such signals at the LHC and future colliders will help further the overall goals of both the energy-frontier and theory-frontier physics programs in the next decade and beyond.

EF Topical Groups:
■ (EF09) BSM: More general explorations
■ (EF10) BSM: Dark Matter at colliders

TF Topical Groups:
■ (TF07) Collider phenomenology

Introduction:

While the Standard Model (SM) has provided a successful description of the interactions among the fundamental particles in nature, there are still open questions that the SM cannot answer. These open questions revolve around issues such as the nature of dark matter, dark energy, the strong-CP problem, and the gauge hierarchy puzzle. Motivated by these issues, many proposals for extending the SM predict exist and predict the existence of new particles at the TeV scale. High-energy colliders such as the LHC would allow us to probe such new physics. Unfortunately, while traditional LHC searches have significantly constrained many possible extensions of the SM, they have not yet resulted in the discovery of such new physics at the TeV scale.

Of course, it is possible that new physics might lie within regions of parameter space to which the LHC is not optimally sensitive. One such class of signatures which have recently received a great deal of attention involve displaced vertices [1–4]. Indeed, many models in which underlying symmetries are softly broken contain particles with nearly degenerate masses. Such particles are therefore relatively long-lived and can result in detectable displaced vertices when they decay inside a collider detector. Likewise, in "portal" scenarios in which the dark and SM sectors are coupled via additional particles (e.g., dark photons or scalar mediators), the couplings for the relevant interactions are often highly suppressed. Thus such scenarios also give rise to long-lived BSM particles. In an effort to improve the prospects for detecting displaced vertices, both ATLAS and CMS are currently upgrading their timing modules for the upcoming runs [5–7]. Thus, it is expected that the LHC will have improved sensitivity to such signatures [8].

Double displaced vertices:

As the standard WIMP paradigm has come under increasing experimental stress, non-minimal dark-sector models are attracting a great deal of attention. Such models typically contain multiple dark-sector states χ_n, some of which can be long-lived. As a result, if a heavier χ_n state is produced at a collider, its subsequent cascade decays would result in multiple sequential displaced vertices. Given this motivation, we propose and investigate a novel signature which may be accessible at the upcoming LHC run and at future colliders: multiple displaced vertices (MDVs). Indeed double displaced vertices (DDVs) provide a particularly minimal example of this phenomenon and illustrates many of the salient ideas.

An example of a process leading to an MDV signature is illustrated in Fig. 1. In Fig. 1(a), we show a Feynman diagram in which a heavy state χ_n undergoes sequential decays to lighter dark-sector states χ_m with $m < n$. In the example shown, each decay also produces two quarks, but in general any visible-sector states might be produced, thereby leading to a rich array of possible phenomenologies. In Fig. 1(b), we illustrate the particular case in which a DDV arises from the initial collision of two protons.

Searches for DDV/MDV signatures can be useful for unmasking a variety of BSM scenarios, and thus represent a generic analysis tool for probing regions of theory space hitherto unexplored. Indeed, many different kinds of theoretical models can give rise to the sorts of effective scenarios illustrated in Fig. 1. For example, the quarks that appear in Fig. 1 can alternatively be leptons. There also exist many possible ways of realizing the effective four-point interactions $\chi_n\chi_m\bar{q}q$ that underpin such processes. One possibility is that these interactions arise through an s-channel mediator ϕ. Letting ψ represent the generic fermionic SM fields which couple

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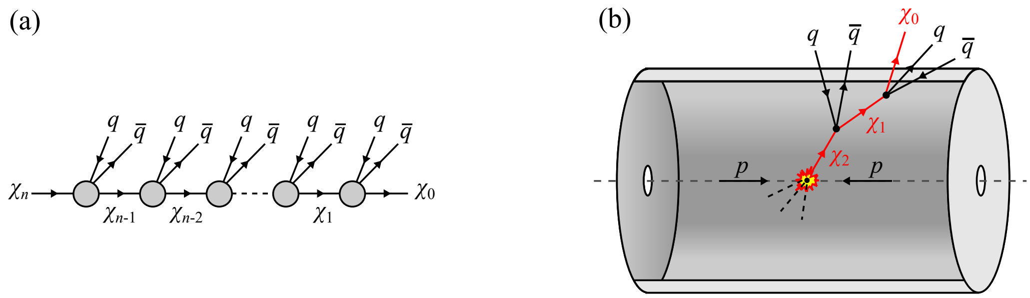

FIG. 1. (a) A decay chain in which a dark-sector state χ_n undergoes successive decays into increasingly lighter dark-sector states χ_m with $m < n$. In the example shown, each individual decay occurs through a three-body process of the form $\chi_n \to \chi_m q\bar{q}$ resulting in the emission of two quarks. (b) A schematic depiction of a process which leads to an MDV signature.

directly to ϕ, we then obtain an interaction Lagrangian of the schematic form

$$\mathcal{L}_{\rm int} \;=\; \sum_{\psi} c_\psi \phi \bar{\psi}\psi + \sum_{m,n} c_{mn}\phi\bar{\chi}_m\chi_n \;, \qquad (1)$$

where c_ψ and c_{mn} denote the couplings between the mediator and the fields of the visible and dark sectors, respectively. Indeed, for sufficiently heavy mediators, this Lagrangian gives rise to the phenomena illustrated in Fig. 1 in the special case in which ψ represents an SM quark. Likewise, an alternative possibility is that our effective four-point interactions take place through a t-channel mediator. Our interaction Lagrangian in this case takes the schematic form

$$\mathcal{L}_{\rm int} \;=\; \sum_{\psi}\sum_{n} c_{\psi n}\phi^\dagger\bar{\chi}_n\psi + {\rm h.c.} \qquad (2)$$

While both interaction Lagrangians allow our dark-sector constituents χ_n to be produced at colliders — and also potentially allow these states to decay, with the simultaneous emission of visible-sector states — the mediator ϕ in the t-channel case can carry SM charges. If these include color charges, the mediator particles can be copiously pair-produced on shell at hadron colliders. The decay cascades precipitated by the subsequent decays of these mediators can therefore contribute significantly to signal-event rates in the detection channels of interest. The interaction in Eq. (2) is also comparatively minimal, with the production and decay processes occurring through a single common interaction.

In order to study the role that DDVs (and indeed MDVs more generally) might play as a search strategy for new physics, we shall investigate a DDV-producing benchmark model involving three dark-sector Dirac fermions χ_n with similar quantum numbers, where the index $n = 0, 1, 2$ labels these fermions in order of increasing mass. We shall also assume that each χ_n couples to an additional heavy scalar mediator ϕ of mass m_ϕ and hypercharge $Y_\phi = -2/3$ which transforms as a fundamental triplet under the $SU(3)_c$ gauge group of the SM and as a triplet under the approximate flavor symmetry of the right-handed up-type quarks. Motivated by the rather minimal interaction Lagrangian in Eq. (2), we shall then take the coupling between ϕ and each χ_n to take the form

$$\mathcal{L}_{\rm int} = \sum_{q}\sum_{n=0}^{2}\left[c_{nq}\phi^\dagger\bar{\chi}_n P_R q + {\rm h.c.}\right], \qquad (3)$$

where $q \in \{u, c, t\}$ denotes an up-type SM quark, where P_R is the usual right-handed projection operator, and where c_{nq} is a dimensionless coupling constant.

This model (which is similar to the model introduced in Ref. [9]) represents one of the simplest scenarios for new physics which gives rise to DDVs. The interactions inherent in Eq. (3) imply that χ_2 and χ_1 are unstable and decay via three-body processes of the form $\chi_n \to \chi_m q\bar{q}$, where χ_m is lighter than χ_n. Therefore, when a χ_2 particle is produced at a collider, it can decay a macroscopic distance from the primary interaction vertex into a quark/anti-quark pair and a χ_1 particle. The latter can then subsequently decay a further macroscopic distance from the first displaced vertex into another quark/anti-quark pair and a χ_0 particle. We thus obtain *two decay vertices which are macroscopically separated both from each other and from the primary vertex*. Indeed, both of these decay vertices occur within the same decay chain stemming from the same initial event.

Standard displaced-vertex searches are not optimized for such possibilities. *It is therefore critical that a dedicated search strategy be developed for such new-physics signatures — a strategy in which a crucial role will no doubt be played by the high-resolution timing information from the timing layers which are being in installed at both ATLAS and CMS.* Moreover, the additional kinematic information that can be extracted from DDV events (and MDV events more generally) will also enhance our ability to measure the properties of the BSM states involved after the initial discovery is made. As part of our study, we plan to assess the degree to which relevant physical quantities such as masses, spins, and couplings can be measured at the LHC and at future colliders. We will also develop techniques for making such measurements.

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