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Beyond the Bump-Hunt: A Game Plan for Discovering Dynamical Dark Matter at the LHC

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Abstract. Dynamical Dark Matter (DDM) is an alternative framework for dark-matter physics in which an ensemble of individual constituent fields with a spectrum of masses, lifetimes, and cosmological abundances collectively constitute the dark-matter candidate, and in which the traditional notion of dark-matter stability is replaced by a balancing between lifetimes and abundances across the ensemble. In this talk, we discuss the prospects for distinguishing between DDM ensembles and traditional dark-matter candidates at hadron colliders — and in particular, at the upgraded LHC — via the analysis of event-shape distributions of kinematic variables. We also examine the correlations between these kinematic variables and other relevant collider variables in order to assess how imposing cuts on these additional variables may distort — for better or worse — their event-shape distributions.

INTRODUCTION

Dynamical Dark Matter (DDM) [1, 2] is an alternative framework for dark-matter physics in which an ensemble of individual constituent fields with a spectrum of masses, lifetimes, and abundances collectively constitute the dark-matter candidate, and in which the traditional notion of dark-matter stability is replaced by a balancing between lifetimes and abundances across the ensemble. In these proceedings, we discuss the prospects for distinguishing between DDM ensembles and traditional dark-matter candidates at hadron colliders. Simple “bump-hunting” searches are typically insufficient for this purpose; rather, an analysis of the full distributions of event-shape variables is required. Distribution-based searches of this sort are particularly subtle because cuts imposed on the data for the purpose of background reduction can distort event-shape distributions in unexpected ways, thereby obscuring signals of new physics. Nevertheless, they can serve to distinguish DDM ensembles from traditional dark-matter candidates.

One class of DDM scenarios for which this analysis strategy can be particularly fruitful are those wherein the ensemble constituents are produced via the decays of additional, heavier “parent” particles which are charged under $SU(3)_c$ color and can therefore be pair-produced copiously at hadron colliders. For example, in cases in which each parent particle decays to a single ensemble constituent and a pair of hadronic jets, we find that the invariant-mass distribution of these two jets could provide a distinctive signal of Dynamical Dark Matter [3]. Similarly, in cases in which the parent particle decays primarily into a single ensemble constituent and a single jet, we find that the M_{T2} distribution can likewise provide such a signal [4]. In these proceedings, we discuss the prospects for observing a signal in each of these two cases at the upgraded LHC. In addition, we also examine the correlations between the kinematic variable used in the event-shape analysis and other relevant kinematic variables in order to assess how imposing cuts on these additional variables may distort the event-shape distribution in question. All of these results are discussed in more detail in Refs. [3, 4].

DISTINGUISHING DDM ENSEMBLES USING KINEMATIC DISTRIBUTIONS

As discussed above, the analysis of event-shape distributions can be particularly fruitful for distinguishing DDM ensembles in scenarios in which the ensemble constituents are produced via the decays of some additional, strongly-interacting parent particle ψ . We begin by providing a concrete example of a scenario in which such an analysis could yield potentially yield a statistically significant signal of dark-sector non-minimality within the first 30 fb⁻¹ of integrated luminosity at the upgraded LHC. In particular, let us consider the case in which ψ is a color-octet fermion and the constituent particles χ_n of the DDM ensemble to be color-singlet fermions which are also singlets under the rest of the SM gauge group. Moreover, let us also assume that the decay width Γ_ψ of ψ is dominated by contributions from an effective interaction Lagrangian of the form

$$\mathcal{L}_{\text{eff}} = \sum_n \left[\frac{c_n}{\Lambda^2} (\bar{q}_i t_{ij}^a \psi^a) (\bar{\chi}_n q_j) + \text{h.c.} \right], \quad (1)$$

where q denotes a SM quark, where Λ is the cutoff scale of the effective theory, where c_{na} is the dimensionless operator coefficient associated with $\mathcal{O}_n^{(a)}$, where t_{ij}^a is the generator of $SU(3)$ in the fundamental representation, where the indices i and j label the states in the fundamental representation, and where a labels the states in the adjoint representation. These contributions give rise to three-body decays of the form $\psi \rightarrow jj\chi_n$, where j denotes a hadronic jet. Finally, we shall assume that the operator coefficients c_n scale according to a power-law of the form

$$c_n = c_0 \left(\frac{m_n}{m_0} \right)^\gamma, \quad (2)$$

where c_0 is the operator coefficient of the lightest ensemble constituent and where γ is a general power-law index. Both c_n and γ are taken to be free parameters of the model. Moreover, we shall assume a mass spectrum of the form

$$m_n = m_0 + n^\delta \Delta m, \quad (3)$$

where m_0 is the mass of the lightest ensemble constituent and where the dimensionless index δ and the mass-splitting parameter Δm are likewise taken to be free parameters. In what follows, we shall adopt the convention that $\Delta m > 0$ and $\delta > 0$ in order to ensure that m_n increases monotonically with n .

The event-shape distribution on which we shall focus with regard to this DDM scenario is the invariant-mass distribution of the two hadronic jets produced via the decay of a single ψ particle. The differential partial width for the decay process $\psi \rightarrow jj\chi_n$ with respect to the invariant mass m_{jj} into a final state involving a particular ensemble constituent χ_n is found to be [3]

$$\frac{d\Gamma_{\psi n}}{dm_{jj}} = \frac{c_n^2 m_{jj} \sqrt{m_\psi^4 - 2m_\psi^2(m_{jj}^2 + m_n^2) + (m_{jj}^2 - m_n^2)}}{96(2\pi)^3 m_\psi^3 \Lambda^4} \left[m_\psi^4 + m_\psi^2(m_{jj}^2 - 2m_n^2) - 2m_{jj}^4 + m_{jj}^2 m_n^2 + m_{jj}^4 \right]. \quad (4)$$

The corresponding partial width for $\psi \rightarrow jj\chi_n$ is

$$\Gamma_{\psi n} = \frac{c_n^2}{384(2\pi)^3 \Lambda^4 m_\psi^3} \left[m_\psi^8 - 8m_\psi^2 m_n^2 (m_\psi^4 - m_n^4) + 12m_\psi^4 m_n^4 \ln \left(\frac{m_n^2}{m_\psi^2} \right) \right]. \quad (5)$$

Furthermore, since we are assuming decays of this sort dominate the total width Γ_ψ of ψ , this total width is simply $\Gamma_\psi \equiv \sum_n \Gamma_{\psi n}$. The corresponding total differential dijet invariant-mass distribution is sum of the m_{jj} distributions for each individual decay channel, as given by Eq. (4), each weighted by the corresponding decay branching $\text{BR}_{\psi n} \equiv \Gamma_{\psi n} / \Gamma_\psi$:

$$\frac{1}{\Gamma_\psi} \frac{d\Gamma_\psi}{dm_{jj}} = \sum_{n=0}^{n_{\text{max}}} \left(\frac{1}{\Gamma_{\psi n}} \frac{d\Gamma_{\psi n}}{dm_{jj}} \times \text{BR}_{\psi n} \right), \quad (6)$$

where n_{max} is the value of n corresponding to the heaviest χ_n kinematically accessible in ψ decay.

The invariant-mass distributions associated with a variety of different DDM parameter choices in this scenario are displayed in Fig. 1. It is evident from the figure that when δ (or Δm) is large and the mass-splittings between

FIGURE 1. Invariant-mass distributions for the DDM ensembles considered here, shown for increasing δ with fixed $m_\psi = 1500$ GeV, $m_0 = 200$ GeV, and $\Delta m = 200$ GeV. The left, center, and right panels show results for $\delta = 0.5$, $\delta = 1$, and $\delta = 2$, respectively. In each panel, the red, orange, green, blue, and purple curves correspond to $\gamma = \{-2, -1, 0, 1, 2\}$, respectively, while the black curve shows the result for a traditional dark-matter candidate with $m_\chi = m_0$.

the χ_n are significant, individual mass edges from two or more of the χ_n can be resolved. By contrast, when δ (and δm) are small, features associated with the individual χ_n cannot be resolved and no mass edge whatsoever is apparent; however the overall m_{jj} distribution assumes a characteristic “bell” shape which nevertheless distinguishes it from the m_{jj} distributions associated with traditional dark-matter candidates.

Our primary aim is to determine to degree to which the characteristic invariant-mass distribution associated with a particular DDM ensemble cannot be reproduced by *any* traditional DM model, regardless of the mass m_χ , spin, or other properties of the dark-matter candidate. Thus, in order to quantify the statistical significance with which any such m_{jj} distribution is truly distinctive in this sense, we adopt the following procedure. We canvass the range $0 < m_\chi < m_\psi$, with a finite step size and evaluate the m_{jj} distribution for each value of m_χ included in our survey. We then compare this distribution with the m_{jj} distribution associated with the DDM model in question. In particular, we partition the range of allowed dijet invariant masses $m_{jj}^{(\min)} \leq m_{jj} \leq m_\psi - m_0$ into n_b bins, where $m_{jj}^{(\min)}$ is some particular invariant-mass threshold imposed in order to eliminate potential issues with low statistics in bins with small m_{jj} . The width of each bin is taken to be equal to the dijet invariant-mass resolution Δm_{jj} at the minimum m_{jj} in the bin. This invariant-mass resolution is dominated by the uncertainty ΔE_j in the measurement of the energies E_j of the individual jets; hence we take $(\Delta m_{jj})/m_{jj} \approx (\Delta E_j)/E_j$. Moreover, since we are particularly interested in the prospects for distinguishing DDM ensembles at the LHC, we take $(\Delta m_{jj})/m_{jj}$ to be equal to the jet-energy resolution for the ATLAS detector [5]. The jet-energy resolution for the CMS detector [6, 7] is quite similar.

For each value of m_χ in our survey, we compare the resulting m_{jj} distribution with the corresponding distribution for the particular DDM model under study. As our measure of the goodness of fit in each case, we adopt the χ^2 statistic

$$\chi^2(m_\chi) = \sum_k \frac{[X_k - \mathcal{E}_k(m_\chi)]^2}{\sigma_k^2}, \quad (7)$$

where the index k labels the bin, X_k is the expected population of events in bin k in the DDM model, $\mathcal{E}_k(m_\chi)$ is the expected population of events in bin k in a traditional dark-matter model in which the dark-matter particle has mass m_χ , and $\sigma_k^2 X_k(1 - X_k/N_e)$ is the variance in X_k due to statistical uncertainties. The minimum value

$$\chi_{\min}^2 \equiv \min_{m_\chi} \{\chi^2(m_\chi)\} \quad (8)$$

from among these individual $\chi^2(m_\chi)$ values represents the degree to which the m_{jj} distribution associated with the DDM ensemble under study can be distinguished from the most similar m_{jj} distribution obtained for any traditional dark-matter candidate. Thus, we adopt $\chi_{\min}^2$ as our final measure of the distinctiveness of the m_{jj} distribution associated with this DDM model. Finally, in order to render the interpretation of these results more straightforward, we determine an effective statistical significance a given $\chi_{\min}^2$ value by comparing it to a χ^2 distribution with $n_b - 1$ degrees of freedom, computing the corresponding p -value, and assessing the number of standard deviations away from the mean to which the same p -value would correspond for a Gaussian distribution.

FIGURE 2. Contour plots showing the minimum significance level at which the m_{jj} distribution predicted in the DDM model characterized by the parameters m_ψ , m_0 , Δm , δ , and γ can be differentiated from the m_{jj} distribution predicted in any traditional dark-matter model. In the panels shown, we have fixed $m_\psi = 1500$ GeV and $m_0 = 200$ GeV, and taken $m_{jj}^{(\min)} = 200$ GeV as our minimum m_{jj} threshold. The results shown in each panel correspond to a signal-event count of $N_e = 1000$, events; the left, center, and right panels of the figure show results for $\Delta m = \{50, 200, 500\}$ GeV, respectively.

In Fig. 2, we show how the significance of differentiation varies as a function of δ and γ with Δm , m_0 , and m_ψ held fixed. In all of the panels shown, we have set $m_\psi = 1500$ GeV and $m_0 = 200$ GeV, and we have taken $m_{jj}^{(\min)} = 200$ GeV as our minimum m_{jj} threshold and a step size of 100 GeV in our scan over m_χ . The results shown in each panel correspond to a signal-event count of $N_e = 1000$ events, which corresponds to an integrated luminosity of roughly $\mathcal{L}_{\text{int}} \approx 30 \text{ fb}^{-1}$ for pair-production of a color-octet parent particle with this value of m_ψ at $\sqrt{s} = 14$ TeV. The left, center, and right panels show the results for $\Delta m = \{50, 200, 500\}$ GeV, respectively.

The results shown in Fig. 2 indicate that throughout a substantial region of parameter space, it is possible to distinguish our toy DDM model from traditional dark-matter scenarios at a 5σ significance level or higher. The most favorable region is that in which $\gamma \gtrsim 0.5$. The dependence on γ is due to the fact that the branching fractions $\text{BR}_{\psi n}$ of ψ to the heavier χ_n are proportionally larger for $\gamma > 0$. Decays to these heavier χ_n increasingly dominate the width of ψ as γ increases, and as a result, the invariant-mass distribution for the ensemble typically becomes more distinctive. By contrast, for smaller values of γ , the branching fractions to the heavier modes are suppressed, and the m_{jj} distribution for the ensemble resembles that of a traditional dark-matter model with $m_\chi = m_0$. An exception to this rule occurs when Δm and γ are both large and the width of ψ is dominated by decays to χ_1 rather than χ_0 , resulting in an m_{jj} distribution that resembles that of a traditional dark-matter candidate with $m_\chi = m_1$. The dependence of the significance of differentiation on Δm and δ arises due to the fact that the interplay between these parameters controls the mass splittings between the different ensemble constituents and thus determines the number of χ_n which are kinematically accessible in ϕ decay. When both of these parameters are small, a significant multiplicity of χ_n are kinematically accessible; however, as Δm and δ increase, the number of χ_n into which ψ can decay decreases and, as a result, the m_{jj} distribution increasingly resembles that of a traditional dark-matter candidate with $m_\chi = m_0$.

CUTS AND CORRELATIONS IN DISTRIBUTION-BASED SEARCHES

As discussed in the Introduction, correlations between kinematic variables can have profound effects on distribution-based searches for DDM ensembles. In order to demonstrate the role these effects can play in searches for dark-sector non-minimality, we provide a concrete example of a DDM scenario in which correlations have a significant impact on the prospects for distinguishing dark-sector non-minimality at the LHC. In this scenario, we shall once again take the constituent particles χ_n to be color-singlet fermions with a mass spectrum of the form given in Eq. (3). However, we shall take the parent particle ψ to be a color-triplet scalar. Furthermore, we shall also assume that ϕ couples to the χ_n

via the interaction Lagrangian

$$\mathcal{L}_{\text{int}} = \sum_{n=0}^N \sum_q \left[c_n \psi^\dagger \bar{\chi}_n u_R + \text{h.c.} \right]. \quad (9)$$

where u_R denotes a right-handed up quark, where the c_n are dimensionless coupling coefficients, and where N is the number of χ_n kinematically accessible in ψ decays. Once again, we shall assume that the c_n scale with n according to a power law of the form given in Eq. (2), where γ and c_0 are taken to be free parameters. We also assume that the decay width of ψ is dominated by decay processes of the form $\phi \rightarrow q\bar{\chi}_n$ to such an extent that all other contributions to that width can safely be neglected, and that all such decay processes occur promptly within the detector.

Other than variables that characterize the angular size and substructure of the two jets (considerations which are not particularly relevant for this analysis), events in the dijet + $\cancel{E}_T$ channel are completely characterized by only six independent degrees of freedom: the six components of the momenta $\vec{p}_1$ and $\vec{p}_2$ of the jets j_1 and j_2 , respectively. A number of kinematic variables can be constructed from these six degrees of freedom; however, in what follows, we shall focus on those which are found [4] to be particularly sensitive to the structure of the dark sector, including:

- The magnitude $\cancel{E}_T$ of the missing transverse momentum in the event.
- The standard M_{T2} variable [8].

In addition, our analysis must incorporate a number of additional variables which are not necessarily particularly sensitive to the structure of the dark sector, but which are useful for background reduction. Indeed the contribution to the total event rate in the dijet + $\cancel{E}_T$ channel from SM background processes is quite significant; thus, in order to have any hope of detecting a signal of dark matter at all, stringent cuts must be imposed on the data in order to reduce these backgrounds. A minimum cut on $\cancel{E}_T$ is generally useful for reducing these SM backgrounds, as are cuts on the following variables:

- The scalar sum $H_{T_{jj}}$ of the transverse jet momenta p_{T_1} and p_{T_2} .
- The variable $\alpha_T \equiv p_{T_2}/m_{jj}$ [9, 10], where m_{jj} is the invariant mass of j_1 and j_2 .

The latter variable is effectively a measure of the degree to which the two leading jets in the event are back-to-back. A minimum cut on this variable on the order of $\alpha_T \gtrsim 0.55$ has been shown to be extremely effective in reducing the sizable background from QCD processes [11, 12].

FIGURE 3. A comparison of the normalized M_{T2} (left panel), α_T (center panel), and $H_{T_{jj}}$ (right panel) distributions associated with traditional dark-matter candidates as well as DDM ensembles. In each panel, the black curves correspond to distributions for a representative set of traditional dark-matter candidates, while the colored curves in the left, middle, and right panels correspond to the DDM parameter choices $m_\psi = 1$ TeV, $m_0 = 200$ GeV, $\delta = 1$, and $\Delta m = \{50, 300, 500\}$ GeV, respectively, with $\gamma = 0$ (red), $\gamma = 1$ (yellow), and $\gamma = 2$ (blue). The M_{T2} distribution shown corresponds to a trial mass $\tilde{m} = 0$.

All data sets used in this study were generated at the parton level using MadGraph 5/MadEvent 1.4.8 [13] with model files obtained from the FeynRules [14] package as inputs. The effects of detector uncertainties were accounted for by smearing the values for the magnitude p_T of the transverse momentum, the azimuthal angle ϕ , and the pseudorapidity η obtained for each jet in the parton-level data set by Gaussian smearing functions with widths equal to the jet- p_T , pseudorapidity, and azimuthal-angle resolutions of the CMS detector [15, 16], respectively. In addition,

we also incorporate a set of precuts into our analysis in order to mimic a realistic detector acceptance for the LHC detectors. In particular, we require that the two highest- p_T jets in the event each satisfy $p_{T_j} \geq 40$ GeV and $|\eta_j| \leq 3$, and that the separation $\Delta R_{jj} \equiv \sqrt{(\Delta\eta_{jj})^2 + (\Delta\phi_{jj})^2}$ between those two jets in (η, ϕ) space is $\Delta R_{jj} \geq 0.4$.

In Fig. 3, we display the event-shape distributions for M_{T2} (left panel), α_T (center panel), and $H_{T_{jj}}$ associated with a number of traditional dark-matter models characterized by different values of m_χ , as well as the distributions associated with a number of DDM ensembles characterized by different values of γ for fixed $m_0 = 100$ GeV, $\Delta m = 50$ GeV, and $\delta = 1$. Note that these distributions have been normalized so that the total area under each is unity. Note also that all of the M_{T2} distributions shown in the figure correspond to a trial mass $\tilde{m} = 0$. This choice of $\tilde{m}$ generally yields the most distinctive distributions because the range of possible M_{T2} values narrows as $\tilde{m}$ is increased from zero.

The results shown in the left panel of Fig. 3 indicate that the event-shape distribution of the M_{T2} variable is particularly sensitive to the structure of the dark sector. Indeed, we find [4] that this variable typically provides the best prospects for distinguishing DDM ensembles in this channel at the LHC. By contrast, the results shown in the center panels suggest that the event-shape distribution of the α_T variable is not particularly sensitive to the structure of the dark sector and therefore not particularly useful for distinguishing among different dark-matter scenarios. The results shown in the right panel indicate that the event-shape distribution of $H_{T_{jj}}$ also displays some sensitivity to the structure of the dark sector. This suggests that care must be taken when imposing cuts on this variable for the purpose of background reduction, since such cuts may affect the data arising in different dark-matter models very differently. Indeed, this is merely a particularly striking example of how cuts imposed on one collider variable may have a significant impact on the event-shape distributions of others — a consideration which we now discuss in greater detail.

FIGURE 4. Scatter plots illustrating the correlations between M_{T2} and the selection variables α_T (top row) and $H_{T_{jj}}$ (bottom row) for a trial mass $\tilde{m} = 0$. The left panel in each row shows the results for traditional dark-matter models with $m_\chi = 0$ (red), $m_\chi = 400$ GeV (green), and $m_\chi = 800$ GeV (blue), while the right panel in each row shows the results for three DDM models, with $m_0 = 100$ GeV, $\Delta m = 50$ GeV, $m_\phi = 1$ TeV, and $\gamma = 0$ (red), $\gamma = 1$ (green), and $\gamma = 2$ (blue).

In order to explore this issue further, we turn to directly examine the correlations between the variables α_T and $H_{T_{jj}}$, which are important background reduction, and the M_{T2} variable, which is important for distinguishing between minimal and non-minimal dark sectors. These correlations are illustrated in the scatter plots displayed in Fig. 4 for a benchmark set of traditional dark-matter models (left column) and DDM ensembles (right column) — again for a

trial mass $\tilde{m} = 0$. Each data point in each panel corresponds to a single event chosen randomly from the Monte-Carlo data sample for that model: its color indicates the model with which it is associated and its coordinates indicate the values x and y of the two kinematic variables X and Y of interest for the corresponding event. Thus, the density of points within the region (x, y) to $(x + \delta x, y + \delta y)$ indicates the relative likelihood of values for X and Y within that range occurring in combination.

The results shown in Fig. 4 clearly illustrate that non-trivial correlations exist between both α_T and $H_{T_{jj}}$ and M_{T2} . In particular, we see that imposing a minimum cut of the form $H_{T_{jj}} > H_{T_{jj}}^{\min}$ will preferentially select events associated with decays to lighter χ_n , thereby effectively washing out contributions to the M_{T2} distribution from the heavier ensemble constituents that could serve as a signal of DDM. By contrast, a cut of the form $\alpha_T > \alpha_T^{\min}$ on α_T has the opposite effect: while such a cut reduces the total number of signal events, it also results in a segregation of the surviving data points corresponding to different value of m_n into different ranges of M_{T2} . This implies that cuts on α_T are not only effective in reducing SM backgrounds, but can also serve to *amplify* distinctions between the shapes of the M_{T2} distributions associated with different dark-matter models.

FIGURE 5. The value of the statistic $G_{\min}$ for the M_{T2} distributions associated with several DDM ensembles as a function of the minimum cut $\alpha_T^{\min}$ imposed on α_T (left panel) and as a function of the minimum cut $H_{T_{jj}}^{\min}$ imposed on $H_{T_{jj}}$ (right column). In each case, the precuts discussed above are the only other cuts imposed on the data. The curves shown in all panels correspond to the parameter choices $m_0 = 100$ GeV, $\Delta m = 50$ GeV, and $\delta = 1$, and the M_{T2} curves correspond to a trial mass $\tilde{m} = 0$.

The procedure we adopt in order to assess the distinctiveness of the M_{T2} distribution associated with a particular DDM ensemble is similar to the procedure used above. In particular, we canvass the range of traditional dark-matter masses $0 < m_\chi < m_\psi$ with a finite step size, determine the M_{T2} distribution for each value of m_χ in the survey, compute a goodness-of-fit statistic between this distribution and the M_{T2} distribution for the DDM ensemble after partitioning both distributions into n_b bins, and take the minimum value obtained for this statistic as our final measure of distinctiveness. The only difference is that in this case, we adopt the quantity $G(m_\chi) \equiv -2 \ln \lambda(m_\chi)$, where $\lambda(m_\chi)$ is the ratio of the likelihood functions for the two distributions, as our goodness-of-fit statistic. Thus, we take

$$G_{\min} \equiv \min_{m_\chi} \{G(m_\chi)\} \quad (10)$$

as our final measure of the distinctiveness of the distribution associated with the DDM ensemble. Once again, we estimate the statistical significance for a given value of $G_{\min}$ by comparing this value to a χ^2 distribution with $n_b - 1$ degrees of freedom in order to compute a p -value, and then assessing the number of standard deviations away from the mean to which the same p -value would correspond for a Gaussian distribution.

In Fig. 5 we show how our measure of distinctiveness $G_{\min}$ depends on the threshold cuts $\alpha_T^{\min}$ and $H_{T_{jj}}^{\min}$ imposed on α_T and $H_{T_{jj}}$. Once again, the precuts are the only additional cuts imposed on the data. The left panel of the figure shows that while $G_{\min}$ generally decreases with increasing $\alpha_T^{\min}$ due to the overall reduction in number of signal events, it does not do so monotonically. Indeed, for all curves shown, $G_{\min}$ actually *rises* with increasing $\alpha_T^{\min}$ within the range $0.4 \lesssim \alpha_T^{\min} \lesssim 0.55$ as a result of the advantageous correlations between α_T and M_{T2} . By contrast, the corresponding curves in the right panel fall monotonically with $H_{T_{jj}}^{\min}$ due to the loss in statistics. This is to be expected, as we have seen that there is no advantageous correlation between $H_{T_{jj}}$ and M_{T2} which can be exploited to offset this loss.

CONCLUSIONS

Distinguishing between minimal and non-minimal dark sectors at colliders typically involves more than merely identifying an excess in the total number of signal events over background. In particular, it typically requires a detailed analysis of the shapes of relevant kinematic distributions. We have shown that DDM ensembles can give rise to characteristic signatures in such distributions which permit one to distinguish them from traditional dark-matter candidates. Moreover, we have shown that in a variety of cases, such features would provide sufficient evidence to distinguish a DDM ensemble from any traditional dark-matter candidate at the 5σ significance level at the upgraded LHC.

It is also important to note that in comparison with simple, “bump-hunting searches,” distribution-based searches of this sort involve a number of additional subtleties. For example, cuts imposed on the data for purposes of background reduction can distort event-shape distributions whenever non-trivial correlations exist between the corresponding collider variables. To illustrate the consequences such subtleties, we have examined the effect of these distortions on the event-shape distributions of the kinematic variables most sensitive to the structure of the dark sector in the dijet + E_T channel — and in particular the M_{T2} variable. We have shown that appropriately chosen cuts on particular variables (such as α_T) can actually enhance the distinctiveness of these distributions, while cuts imposed on other variables (such as $H_{T,jj}$) tend to obscure signals of non-minimality in the dark sector. More details behind all of these results can be found in Refs. [3, 4].

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REFERENCES

- [1] K. R. Dienes and B. Thomas, *Phys. Rev.* **D85**, p. 083523 (2012).
- [2] K. R. Dienes and B. Thomas, *Phys. Rev.* **D85**, p. 083524 (2012).
- [3] K. R. Dienes, S. Su, and B. Thomas, *Phys. Rev.* **D86**, p. 054008 (2012).
- [4] K. R. Dienes, S. Su, and B. Thomas, *Phys. Rev.* **D91**, p. 054002 (2015).
- [5] A. Airapetian *et al.* (ATLAS), (1999), CERN-LHCC-99-14, ATLAS-TDR-14.
- [6] V. Khachatryan *et al.* (CMS), *Phys. Rev. Lett.* **105**, p. 211801 (2010).
- [7] S. Chatrchyan *et al.* (CMS), *Phys. Lett.* **B700**, 187–206 (2013).
- [8] C. G. Lester and D. J. Summers, *Phys. Lett.* **B463**, 99–103 (1999).
- [9] V. Khachatryan *et al.* (CMS), *Phys. Lett.* **B698**, 196–218 (2013).
- [10] L. Randall and D. Tucker-Smith, *Phys. Rev. Lett.* **101**, p. 221803 (2008).
- [11] S. Chatrchyan *et al.* (CMS), *Phys. Rev. Lett.* **107**, p. 221804 (2011).
- [12] S. Chatrchyan *et al.* (CMS), *Eur. Phys. J.* **C73**, p. 2568 (2013).
- [13] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *JHEP* **06**, p. 128 (2011).
- [14] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, *Comput. Phys. Commun.* **185**, 2250–2300 (2014).
- [15] C. Collaboration (CMS), (2011), CMS-PAS-JME-10-014.
- [16] C. Collaboration (CMS), (2007), CMS-PAS-JME-07-003.
- [17] A. J. Barr, C. G. Lester, M. A. Parker, B. C. Allanach, and P. Richardson, *JHEP* **03**, p. 045 (2003).
- [18] A. Barr, C. Lester, and P. Stephens, *J. Phys.* **G29**, 2343–2363 (2003).
- [19] W. S. Cho, K. Choi, Y. G. Kim, and C. B. Park, *Phys. Rev. Lett.* **100**, p. 171801 (2008).
- [20] W. S. Cho, K. Choi, Y. G. Kim, and C. B. Park, *JHEP* **02**, p. 035 (2008).
- [21] J. Kumar, A. Rajaraman, and B. Thomas, *Phys. Rev.* **D84**, p. 115005 (2011).
- [22] G. Aad *et al.* (ATLAS), *Phys. Lett.* **B701**, 186–203 (2013).
- [23] W. Beenakker, R. Hopker, M. Spira, and P. M. Zerwas, *Nucl. Phys.* **B492**, 51–103 (1997).
- [24] W. Beenakker, M. Kramer, T. Plehn, M. Spira, and P. M. Zerwas, *Nucl. Phys.* **B515**, 3–14 (1998).
- [25] G. Aad *et al.* (ATLAS), *Phys. Lett.* **B710**, 67–85 (2013).
- [26] J. Beringer *et al.* (Particle Data Group), *Phys. Rev.* **D86**, p. 010001 (2012).