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Jet substructure probe to freeze-in dark matter in alternative cosmological background

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Abstract The non-thermally produced freeze-in dark matter is an attractive alternative to look beyond the weakly interacting massive particle (WIMP) paradigm. With the singlet-doublet dark matter model, a simple extension to the standard model (SM), we probe the light dark matter parameter space, assuming feeble couplings between SM particles and the dark matter candidate. We tried to show how non-standard cosmological background affects dark matter production in the early Universe and alters the search strategy at colliders. We found that the prompt decay search using the jet substructure analysis is more effective than the existing displaced vertex searches.

1 Introduction

The existence of dark matter (DM) in our Universe is motivated from various astrophysical and cosmological observations at large scale. However, our knowledge about the nature of DM is very limited, apart from its gravitational interactions, non-baryonic nature and contribution to the energy density of the Universe. Experiments such as WMAP [1] and PLANCK [2] quantified the current DM abundance by analyzing the cosmic microwave background anisotropy. Among different DM models, one of the most popular ones is the *weakly interacting massive particles* (WIMP). However, null results from all direct [3–5], indirect [6], and collider [7, 8] experiments have resulted in alternate DM models such as non-thermally produced ones. One of these non-thermal DM are those produced in the early Universe via the freeze-in mechanism [9]. This class of DM is assumed to have been produced from negligible initial abundance and then decouples from the thermal bath without coming in thermal equilibrium while non-relativistic due to their feeble coupling with the ordinary matter. The feeble coupling prevents it from being in thermal equilibrium with the thermal bath and naturally explains the null results across experiments.

However, the DM being produced in the early Universe before the Big Bang Nucleosynthesis (BBN), the cosmology of this era has important consequences on the DM phenomenology. We explore here a scenario where the energy density of the pre-BBN Universe is dominated by another fluid (say, ϕ) along with radiation. This fluid redshifts differently which results in a fast-expanding Universe [10, 11] affecting the DM production.

In this proceeding based on Ref. [12], we considered the singlet-doublet model [13] to examine the impact of non-standard cosmology on the phenomenology of freeze-in DM and its prospects at the Large Hadron Collider (LHC). We tried to show that the presence of alternate cosmological background demands a larger interaction rate which in turn alters the search strategy of frozen-in DM at colliders from the usual displaced vertex searches. We are interested in looking at the final states that consist of $Z/W/h$-bosons along with large missing energy. These bosons are expected to be boosted as they are produced by decay of the heavy mediators resulting in interesting

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signature of their hadronic decay products. We employed the jet substructure analysis on the hadronic decay products analyzed with boosted decision tree (BDT) algorithm to probe a significant region of the parameter space that is usually inaccessible with the earlier displaced vertex searches with this model.

2 The singlet–doublet dark matter model

We extend the standard model (SM) with a singlet Dirac fermion (χ) and an SU$(2)_L$ Dirac fermion doublet, $\Psi = \left(\psi^+ \;\; \psi^0\right)^T$ with hypercharge 0 and 1/2, respectively, both odd under $\mathcal{Z}_2$ symmetry. The Lagrangian of the extended sector is given by

$$\mathcal{L}_f = i\overline{\chi}\gamma^\mu\partial_\mu\chi + i\overline{\Psi}\gamma^\mu D_\mu\Psi + m_\chi\overline{\chi}\chi + m_\Psi\overline{\Psi}\Psi + y\overline{\Psi}H\chi + h.c., \tag{1}$$

where m_χ and m_Ψ are masses of the singlet and the doublet fermions, respectively and y is the Yukawa-like coupling with the SM sector. After electroweak (EW) symmetry breaking the neutral fields ψ^0 and χ mix to give the new physical states χ_1 and χ_2 with masses m_1 and m_2, respectively, and thereby new interactions such as $h-\chi_2-\chi_1$, $Z-\chi_2-\chi_1$, $W^\pm-\psi^\mp-\chi_1$ open up. We assume $m_2 \gg m_1$ and $y \ll 1$ to obtain the correct relic density via the freeze-in production of the DM candidate χ_1. In this limit, with $m_1 \approx m_\chi$ and $m_2 \approx m_\Psi$, the mixing angle takes the form

$$\sin\theta \approx \frac{yv}{\sqrt{2}(m_2-m_1)}, \tag{2}$$

where v is the vacuum expectation value of the SM Higgs.

A radiative mass splitting between the charge states ($\psi^\pm$) and neutral state (ψ^0) is generated due to the loops of the EW gauge boson [14, 15], so that mass splitting $\mathcal{O}[260-340]$ MeV can be produced for the considered range of $m_\Psi \in [100-2000]$ GeV. For simplicity, we would neglect the mass splitting for the dark matter phenomenology and assume that the masses of all the heavy states are equal such that $m_{\psi^\pm} = m_2 = m_\Psi$.

3 Dark matter in the fast-expanding Universe

The faster expansion rate of the Universe is sourced by the existence of an additional species, ϕ in the pre-BBN era which makes the total energy density as $\rho = \rho_{\text{rad}} + \rho_\phi$, ρ_{rad} being the contribution from the radiation. The new fluid ϕ adds an extra term, $\rho_\phi \propto a^{-6}$ which represents the kination domination regime and manifests the fast expanding scenario. The modified Hubble expansion rate is given by

$$H = \left(\frac{\rho}{3M_{\text{Pl}}}\right)^{1/2} = \left(\frac{\rho_{\text{rad}}+\rho_\phi}{3M_{\text{Pl}}}\right)^{1/2} = \frac{\pi\bar{g}_\star^{1/2}}{3\sqrt{10}}\frac{T^2}{M_{\text{Pl}}}\left(\frac{T}{T_r}\right) \tag{3}$$

where T_r represents the temperature when the energy densities of ϕ and radiation are equal. From 3, we see that non-standard behavior of the cosmology depends on the parameter, T_r. As T_r decreases the Universe redshifts faster. However, BBN observations have constrained T_r to be $\geq 15.4^{1/4}$ MeV in this kination domination regime [10].

In the early Universe, the DM is produced via the freeze-in mechanism from the scattering and decay of the bath particles starting from negligible number density. This freeze-in number density is built upon the Yukawa-like coupling (y) and the non-standard parameter T_r. The DM production happens in two phases—before and after electroweak symmetry breaking (EWSB). Therefore, the thermally averaged decay width is estimated as

$$\langle\Gamma_\Psi\rangle = \langle\Gamma_{\Psi\to H\chi}\rangle\;\Theta(T-T_{\text{EW}}) + \langle\Gamma_{\chi_2\to h\chi} + \Gamma_{\chi_2\to h\chi} + \Gamma_{\psi^\pm\to h\chi}\rangle\Theta(T_{\text{EW}}-T), \tag{4}$$

where $T_{\text{EW}}(= 160$ GeV$)$ is the temperature of the EWSB. The freeze-in DM relic density is obtained using the relation

$$\Omega_\chi h^2 = 2.755\times 10^8 \times m_\chi \times Y_\chi(x\to\infty), \tag{5}$$

where Y_χ is the DM abundance that can be obtained by solving the Boltzmann equation $dY_\chi/dz = \langle\Gamma_\Psi\rangle Y_\Psi^{\text{eq}}(T)/Hz$ where $z(= m_\chi/T)$ is a dimensionless variable. In Fig. 1, we have shown the contours of the correct relic density

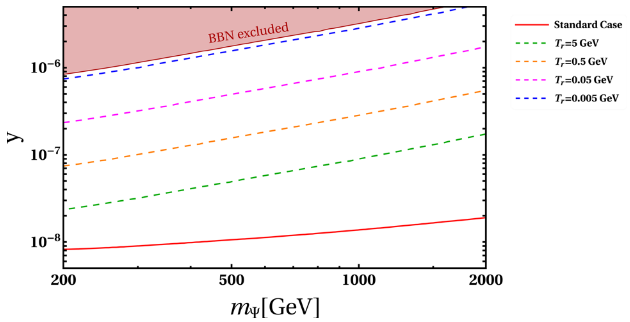

Fig. 1 Contours of the measured dark matter relic density $\Omega h^2 = 0.12$ are shown for different non-standard cosmology parameters (T_r) (dashed lines) on the Yukawa coupling (y) and doublet mass (m_ψ) plane. The solid line represents the standard cosmology (radiation dominated). Dark matter mass is fixed at $m_\chi = 12$ keV

of the dark matter in the plane of the Yukawa coupling and doublet mass at Dm mass of 12 keV. It can be seen that as the parameter T_r decreases the required value of the coupling increases. We also marked in red shade the area excluded by BBN resulting from the constraint on the value of T_r.

4 Collider phenomenology

Despite the tiny coupling of the freeze-in DM to the SM, it can be produced via the intermediate heavier dark sector particles with gauge coupling to SM. These dark sector particles, i.e., charged and neutral fermions are produced via s-channel pair or associated production. These fermions finally decay promptly to $Z/W/h$-bosons along with the DM candidates which results in missing energy signal at detector. The signal topology is depicted in Fig. 2,

$$pp \;\rightarrow\; f\overline{f} \;\rightarrow\; VV\chi_1\overline{\chi}_1 \;\rightarrow\; 2J_{\text{CA8}} + \not{E}_T, \tag{6}$$

where $f \equiv \chi_2$, $\psi^\pm$, $V \equiv Z$, $W^\pm$, h. The hadronic decay products of the gauge bosons deposits energy in the hadron calorimeter. We cluster these calorimeter towers with large radius ($R = 0.8$) using anti-k_T algorithm. These objects are then reclustered using the Cambridge-Aachen algorithm, and used in the subsequent analysis. These clusters are identified as J_{CA8} as in Eq. 6.

The dominant background contributions come from $V + jets$ where $V \equiv Z, W$ when the Z-bosons decay invisibly or the leptonic decays of W-bosons are missed at the detector. Other contributions come from $VV + jets$, mono-top, and top-pair backgrounds. We used the usual simulation pipeline with `MadGraph5`, `Pythia8`, `Delphes`, and `FastJet` for generating parton-level events, hadronizing, simulating detector effects, and clustering the tower objects to form jets. We selected the simulated events that pass the following baseline criteria:

(i) at least 2 fatjets with transverse momentum, $p_T(J_i) > 180$ GeV,

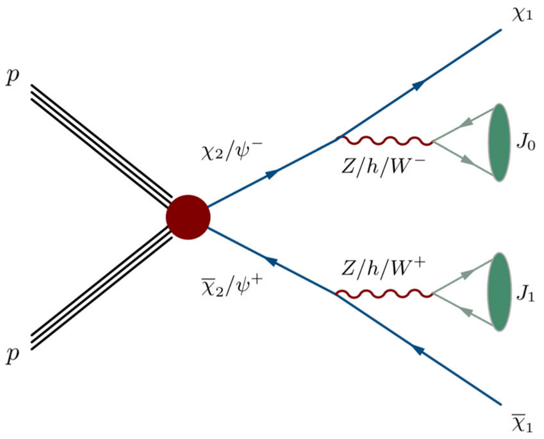

Fig. 2 Feynman diagram for the production of heavy BSM fermions pair at the LHC, finally generating a pair of DM candidates along with massive bosons thst gives hadronic decay clusters as boosted jets $J_{i=0,\,1}$

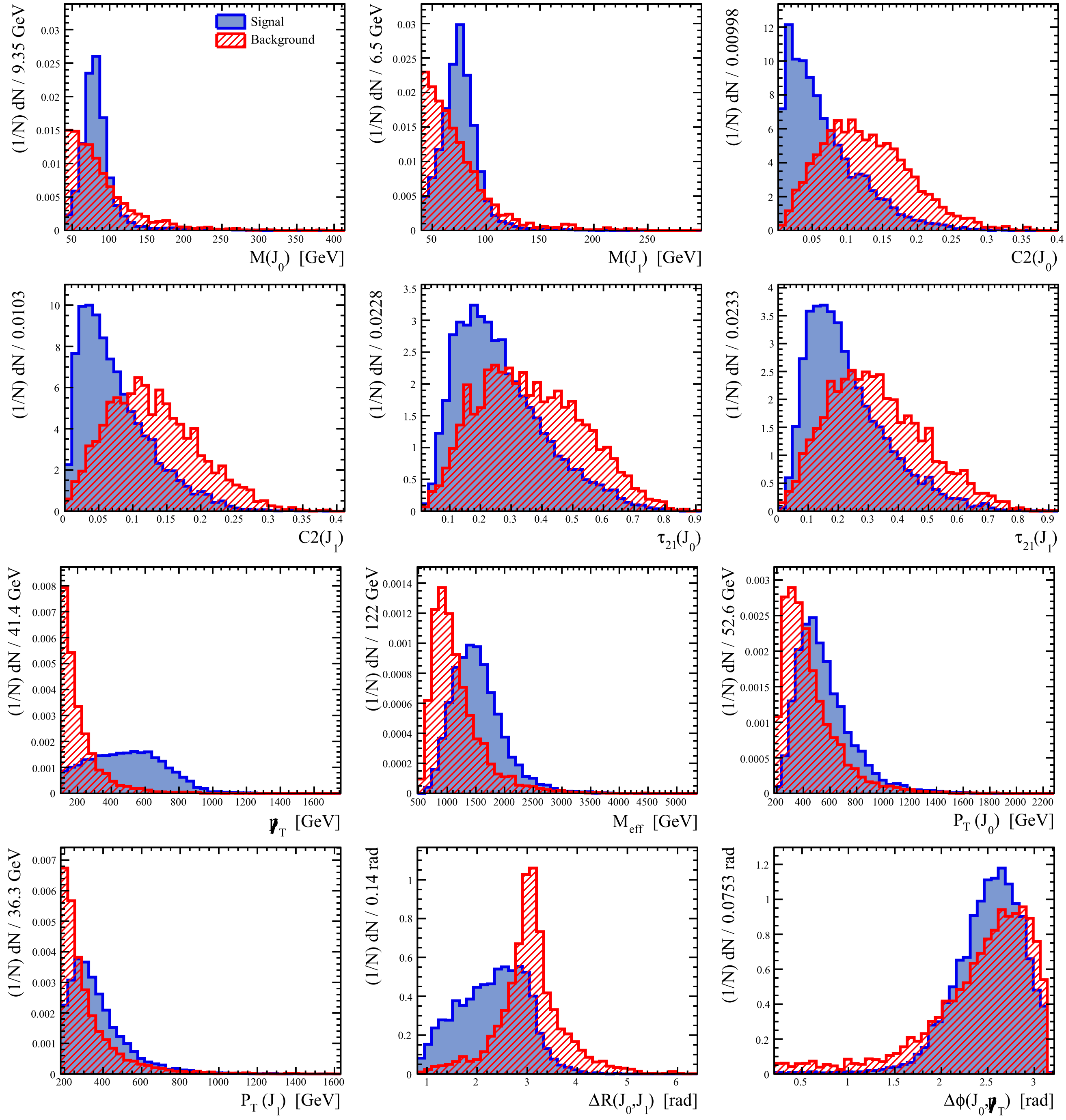

Fig. 3 Normalized distributions of the input high-level variables characterizing the fatjets used in the multivariate analysis for the discrimination of signal (blue-shaded lines) and the backgrounds (red-hatched lines)

(ii) missing transverse momentum, $\not p_T > 100$ GeV,
(iii) no lepton with $p_T(\ell) > 10$ GeV and pseudorapidity, $|\eta(\ell)| < 2.4$,
(iv) difference in azimuthal angle, $|\Delta\phi(\not p_T, J_{0,1})| > 0.2$.

The events are further subjected to two more cuts, namely, (i) b-tagged slimjet ($R = 0.4$) veto and (ii) pruned fatjet masses higher than 40 GeV, before using them for multivariate analysis (MVA) using the BDT algorithm with the `TMVA` package [16].

The heavier particles in our model, $\psi^\pm$, χ_2, while decaying, impart a significant boost to the daughter gauge bosons (h, Z, $W^\pm$). These bosons can be reconstructed by the hadronic clusters of its decay products with a

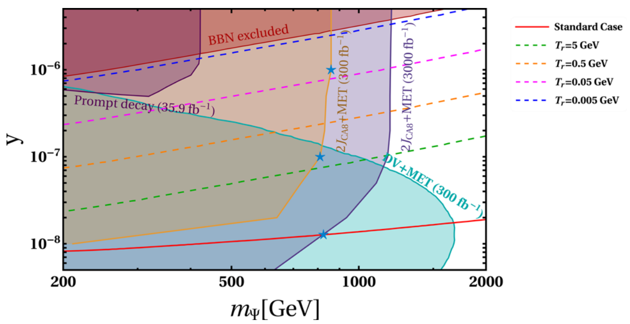

Fig. 4 Exclusion limits at 14 TeV c.m. energy at LHC with $\mathcal{L}_{\rm int}$ = 300 fb^{-1} (orange-shade) and 3000 fb^{-1} (blue-shade) for a DM mass 12 keV. The excluded region from the previous displaced vertex search with 300 fb^{-1} of luminosity and prompt search at LHC with 35.9 fb^{-1} are shown in cyan and purple shaded regions, respectively

larger cone radius. To uncover the 2-prong substructures encoded in these clusters, we used in our MVA analysis the following jet substructure variables:

- pruned jet mass ($M_{\rm prun}(J_{0,1})$) [17],
- 2-point energy correlation double ratio ($C_2^{(\beta)}$) [18], and
- N-subjettiness ratio ($\tau_{21} = \tau_2/\tau_1$) [19].

We also used some additional observables that appeared sensitive—missing transverse momentum $\not{p}_T$, effective mass $M_{\rm eff}$, transverse momentum of the two fatjets $p_T(J_{0,1})$, distance between the 2 fatjets in $\eta - \phi$ plane $\Delta R(J_0, J_1)$, and the azimuthal angle between $\not{p}_T$ and the leading fatjet $\Delta\phi(\not{p}_T,\, J_0)$. The normalized distribution of the input variables are shown in Fig. 3.

We employed the adaptive boosted decision tree (BDT) algorithm and optimized the MVA analysis using the significance formula $sig = S/\sqrt{S+B}$, S and B being signal and background events that survived the BDT cut. We scanned the relic allowed parameter space of the freeze-in DM in the same $m_\Psi - y$ plane as 1 and gave a 2σ exclusion limits for integrated luminosities of $\mathcal{L}_{int}$ = 300 fb^{-1} and 3000 fb^{-1} as shown in Fig. 4. For comparison, we have also shown the excluded regions by previous studies with displaced vertex search (at 300 fb^{-1}) [20] and prompt search at LHC (at 35.9 fb^{-1}) [21] with cyan and purple shades. We see that our analysis could probe a larger area in the parameter space when the coupling is substantially large to trigger a prompt decay of the mediators. We found that while at 300 fb^{-1} luminosity the bound on the doublet mass can reach up to 860 GeV, and with the increased luminosity of 3000 fb^{-1} it goes beyond 1.2 TeV.

5 Conclusion

The conventional strategy for a collider probe of freeze-in DM has been via the displaced vertex search. With a simple extension of the SM with a singlet and a doublet fermion, and assuming a fast-expanding Universe prior to the BBN epoch, we showed that searches with displaced signature become ineffective to probe the larger coupling region. However, the prompt searches using the jet substructure analysis can access a larger part of the parameter space and constrain it. Our analysis with BDT algorithm put strong constraints on the plane of Yukawa-like coupling and heavy mediator mass at 14 TeV LHC for integrated luminosities of 300 fb^{-1} and 3000 fb^{-1}, respectively. However, for a conclusive evidence for the nature of the DM and its cosmological history, combining collider constraints with detailed astrophysical probes is imperative.

Data availability statement Data sets generated during the current study are available from the corresponding author on reasonable request.

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