

Machine learning tagged boosted dark photon: A signature of fermionic portal matter at the LHC

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(Received 26 November 2024; accepted 25 September 2025; published 27 October 2025)

We use a hybrid deep neural network (HDNN) to identify a boosted dark photon jet as a signature of a heavy vectorlike fermionic portal matter (PM) connecting the visible and the dark sectors. In this work, the fermionic PM, which mixes only with the Standard Model (SM) third-generation up-type quark, predominantly decays into a top quark and a dark photon pair. The dark photon then promptly decays to a pair of standard model fermions via the gauge kinetic mixing. We have analyzed two different final states, namely, (i) exactly one tagged dark photon and exactly one tagged top quark jet, and (ii) at least two tagged dark photons and at least one tagged top quark jet at the 13 and 14 TeV LHC center of mass energies. Both these final states receive significant contributions from the pair and single production processes of the top partner. The rich event topology of the signal processes, i.e., the presence of a boosted dark photon and top quark jet pair, along with the fact that the invariant mass of the system corresponds to the mass of the top partner, help us to significantly suppress potential SM backgrounds. We have shown that one can set a 2σ exclusion limit of ~ 2.3 TeV on the top partner mass with $\sin\theta_L = 0.1$ and assuming 100% branching ratio of the top partner in the final state with exactly one tagged dark photon and exactly one tagged top quark jet at the 14 TeV LHC center of mass energy assuming 300 fb^{-1} of integrated luminosity.

DOI: [10.1103/hy69-1bp1](https://doi.org/10.1103/hy69-1bp1)

I. INTRODUCTION

Extending the Standard Model (SM) of particle physics with an additional dark sector (DS) gives a theoretically well-motivated framework to explain the existence of dark matter (DM) and its associated phenomenology. So far, various theoretical models within this framework have been proposed in the literature. Many of these scenarios consider the DS interacting with the SM sector via portal interactions [1–4]. A gauge kinetic mixing portal is one such example for the DS-SM interaction. The simplest way to realize it

would be to assume that the dark sector contains an Abelian dark $U(1)_d$ gauge group under which all the SM particles are neutral. The corresponding gauge boson, i.e., the dark photon, becomes massive via the (dark) Higgs mechanism.

Any ultraviolet completion of such a model will introduce additional particlelike states, known as the portal matter, which are charged under both the SM and the $U(1)_d$ gauge groups. These states can be either scalars or fermions. Here, we consider an additional vectorlike fermion, specifically a vectorlike quark (VLQ), as a portal matter that produces the gauge kinetic mixing via loop contribution. The VLQ can also mix with the SM fermions depending on its charge assignment. We assume the VLQ to be a singlet under the $SU(2)_L$ interaction and carry $+2/3$ unit of $U(1)_Y$ charge. As it also has a nonzero $U(1)_d$ charge, a Yukawa-type interaction involving the VLQ, a SM up-type quark, and the Higgs is not allowed. However, a similar Yukawa-type interaction term can be introduced with a charged dark Higgs, which can generate the mixing between SM fermions and the vectorlike quark as it

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acquires a nonzero vacuum expectation value (VEV). To avoid the current constraints on the VLQ mixing with the first two generations of quarks, we assume the VLQ mixes only with the third-generation quark with the same electric charge, i.e., the top quark. (In a broader setup, a VLQ that transforms nontrivially under $SU(2)_L$ is another possibility, but it is beyond the scope of the present article.) Earlier, Refs. [5,6] showed that, in such a setup, the VLQ could predominantly decay to a top quark and a dark photon or a dark Higgs, while its traditional decay modes, such as $T_p \rightarrow bW$, tZ , and th , became suppressed. The origin of the large branching ratio into these nonstandard modes can be traced to the hierarchies between (i) the SM top quark and VLQ mass, (ii) the VEVs of the two Higgs fields, and (iii) the mixing angle of the SM top quark with the VLQ and their mass ratio [5,6]. Other nonstandard decay modes of VLQs have attracted significant attention in the current literature [7–31].

VLQs as portal matters have been getting due attention—there are dedicated studies on their searches in collider experiments [1,2,4,6,13,18,25,32–34]. The main focus of the current study is to analyze the LHC signatures of such a vectorlike quark in the mass range¹ of 800 GeV to ~ 2.8 TeV, decaying into a highly boosted dark photon and a top quark. In this scenario, the dark photon decays into SM fermions via gauge kinetic mixing, controlled by the corresponding gauge kinetic mixing parameter, ϵ . Depending on the dark photon mass, this parameter is strongly constrained by various experiments, including low-energy ones [37,38]. For the mass range 1–10 GeV (relevant for our LHC analysis), the bound on the kinetic mixing parameter is $\epsilon \lesssim 10^{-3}$. However, a very small ϵ could result in the dark photon decaying outside the detector. We fix this parameter by requiring the dark photon to decay promptly into SM final states ($\gamma_d \rightarrow f\bar{f}$, where f = leptons, quarks) inside the detector. Nevertheless, a long-lived dark photon decaying inside the detector presents an interesting possibility, which will be explored in future work.

Searching for dark photon signals at collider experiments is an ongoing quest. In this article, we propose a machine learning (ML) based method to identify a highly boosted dark photon in its hadronic decay mode, which can carry the imprint of a heavy VLQ acting as a portal matter at collider experiments. Machine learning techniques have been used widely in the field of particle physics, in particular, in the context of jet physics [39–52]. To identify dark photon jets we employ an algorithm based on a hybrid deep neural network (HDNN) framework. This approach

combines a convolutional neural network (CNN) and a multilayer perceptron (MLP) [53–55]. The CNN models jet images, and the MLP captures the jet-level features of both signal (initiated by dark photons) and background (initiated by other particles) jets. We focus on a light dark photon of mass around 10 GeV, which is more likely to be mimicked by background jets, making the jet invariant mass a poor discriminator. We show how the use of HDNN can significantly improve the tagging efficiency of such low-mass dark photons over that obtained by naive cut based selection algorithm.

We emphasize that one of our objectives is to provide a method for identifying a boosted dark-photon jet among various other jets present in an event. This task essentially involves the *binary classification* between a dark photon jet and other nondark photon jets, such as those initiated by quarks, gluons, τ leptons, or top quarks, across a wide range of transverse momenta. Moreover, even though we consider dark photon production in the decay of a heavy VLQ that mixes only with the up-type third-generation quark in this paper, our analysis of dark photon tagging is more general and applicable to VLQs mixing with other generations as well. The tagging algorithm functions effectively across a wide range of VLQ masses, with only a moderate change in the tagging efficiency. The technique employed in this work can be used whenever the decay of a heavy particle produces a highly boosted “light exotic particle” (such as the dark photon).

The present work focuses on two different final states: (i) exactly one tagged dark photon and exactly one tagged top quark jet (ED1ET1), and (ii) at least two tagged dark photons and at least one tagged top quark jet (AD2AT1) in the context of the 13 and 14 TeV LHC center-of-mass energies. Most studies in the literature focus on single and pair production separately while by choosing different final states. However, disentangling these two processes is generally challenging. As we will demonstrate, the final states we consider—mainly to characterize the single and pair productions of the top partner—exhibit a significant admixture of both processes. Moreover, the relative admixture of these two processes in a given final state strongly depends on the mixing angle between the top and top partner. Thus, it becomes crucial to analyze different final states rather than individual single and pair production processes. We propose a set of kinematic observables, based on the topology of the signal events, to suppress the SM background and optimize the signal significance in these final states. In addition, we also consider the current LHC limits on the model and constrain the relevant parameter space.

The rest of the paper is organized as follows. In Sec. II, we briefly describe the theoretical framework we have considered. Section III consists of collider analysis of the signal and background processes. Results and discussions are presented in Sec. IV. Finally, we conclude in Sec. V.

¹This closely corresponds to the mass range of the top partner or other heavy resonances decaying to a top quark and another boson, as considered in several experimental studies [35,36]. In our case, we have slightly extended this range to account for the possibility that the top partner can decay into nonstandard modes with sizable branching ratios.

TABLE I. Representations of the relevant fields under the full symmetry group of the theory. Here, t' is the third generation up-type quark of the SM in interaction basis and T' is the vectorlike top partner also in the interaction basis.

Fields	$SU(3)_C$	$SU(2)_L$	Y	Y_d
t'_R	3	1	2/3	0
b_R	3	1	-1/3	0
$Q_L = \begin{pmatrix} t'_L \\ b'_L \end{pmatrix}$	3	2	1/6	0
Φ	1	2	1/2	0
T'_L	3	1	2/3	1
T'_R	3	1	2/3	1
Φ_d	1	1	0	1

II. THEORETICAL FRAMEWORK

In this section, we will briefly summarize the theoretical framework detailed in [5,6]. We have considered an extension of the SM with a VLQ transforming under the $SU(2)_L$ gauge group as a singlet while being charged under both the $U(1)_Y$ and an additional $U(1)_d$ gauge groups with corresponding charges, +2/3 and +1, respectively. The gauge boson corresponding to the $U(1)_d$ gauge group is referred to as “dark photon” and the SM particles are neutral under this gauge group.

The model also contains a complex scalar field Φ_d that is singlet under the SM gauge group and charged under $U(1)_d$. The charge assignment of the relevant fields under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_d$ gauge group are presented in Table I. The complex scalar field Φ_d is accountable for the mixing of the VLQ with SM fermions having same charges and generating the mass for the dark photon via the Higgs mechanism in the dark sector. In this work we have considered VLQ mixing with only the top quark to avoid flavor constraints.

Below we describe three relevant sectors corresponding to the above-mentioned model, namely, the (i) gauge ($\mathcal{L}_{\text{Gauge}}$), (ii) scalar ($\mathcal{L}_{\text{Scalar}}$), and (iii) fermion ($\mathcal{L}_{\text{Fermion}}$) sectors.

(i) Gauge sector:

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4} G_{\mu\nu}^a G^{a,\mu\nu} - \frac{1}{4} W_{\mu\nu}^i W^{i,\mu\nu} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} + \frac{\epsilon'}{2 \cos \theta_W} B'_{d,\mu\nu} B'^{\mu\nu} - \frac{1}{4} B'_{d,\mu\nu} B'^{\mu\nu}, \quad (1)$$

where $G_{\mu\nu}^a$ are the $SU(3)_C$ field strength tensor with $a = 1, \dots, 8$; $W_{\mu\nu}^i$ are $SU(2)_L$ field strength tensor with $i = 1, 2, 3$; $B'_{\mu\nu}$ is that of the $U(1)_Y$ and $B'_{d,\mu\nu}$ corresponds the field strength tensor of the additional $U(1)_d$ group. The kinetic mixing term between the $U(1)_Y$ and $U(1)_d$ field strength tensors is parametrized by ϵ' .

(ii) Scalar sector

$$\mathcal{L}_{\text{Scalar}} = |D_\mu \Phi|^2 + |D_\mu \Phi_d|^2 - V(\Phi, \Phi_d) \quad (2)$$

Here, Φ represents the SM Higgs field, while Φ_d denotes the corresponding Higgs field in the dark sector. The gauge covariant derivative in general has the form

$$D_\mu = \partial_\mu - ig_S t^a G_\mu^a - ig T^i W_\mu^i - ig' Y B'_\mu - ig'_d Y_d B'_{d,\mu} \quad (3)$$

In this expression, g_S , g , g' , and g'_d are the coupling constants corresponding to the $SU(3)_C$, $SU(2)_L$, $U(1)_Y$, and $U(1)_d$ gauge groups, respectively. Here, t^a and T^i are the generators of the $SU(3)_C$ and $SU(2)_L$ groups, respectively in appropriate representation. Also, Y and Y_d corresponds to the $U(1)_Y$ and $U(1)_d$ charges, respectively.

The scalar potential takes the form

$$V(\Phi, \Phi_d) = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4 - \mu_{h_d}^2 |\Phi_d|^2 + \lambda_{h_d} |\Phi_d|^4 + \lambda_{hh_d} |\Phi|^2 |\Phi_d|^2 \quad (4)$$

The fluctuation of the two scalar fields around the classical minima can be parametrized as

$$\Phi = \begin{pmatrix} 0 \\ \frac{v_{\text{EW}} + h'}{\sqrt{2}} \end{pmatrix}, \quad \Phi_d = \frac{1}{\sqrt{2}} (v_d + h'_d) \quad (5)$$

Where v_{EW} is fixed at 246 GeV, by the masses of the electroweak gauge bosons while v_d can be fixed by the dark gauge coupling (g_d) and the mass of the dark photon. However, we will work with v_d and m_{γ_d} as free parameters.

As a consequence of this, $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_d$ is reduced to $SU(3)_C \times U(1)_{\text{EM}}$ and the gauge bosons corresponding to the broken generators becomes massive.

The scalar mass matrix can be diagonalized using the orthogonal transformation described below,

$$\begin{pmatrix} h \\ h_d \end{pmatrix} = \begin{pmatrix} \cos \theta_S & -\sin \theta_S \\ \sin \theta_S & \cos \theta_S \end{pmatrix} \begin{pmatrix} h' \\ h'_d \end{pmatrix} \quad (6)$$

In the mass eigenbasis, h corresponds to the observed Higgs with mass $m_h = 125$ GeV, while h_d denotes the dark Higgs field with mass m_{h_d} . The free parameters of the scalar sector are the scalar mixing angle θ_S , m_{h_d} , and v_d .

(iii) Fermion sector: The lagrangian for the fermion sector focusing solely on the 3rd generation quarks

and VLQ is given by,

$$\mathcal{L}_{\text{Fermion}} = \bar{Q}_L i \not{D} Q_L + \bar{t}'_R i \not{D} t'_R + \bar{b}_R i \not{D} b_R + \bar{T}' i \not{D} T' + \mathcal{L}_{\text{Yuk}} \quad (7)$$

where $\mathcal{L}_{\text{Yuk}}$ is given by,

$$\mathcal{L}_{\text{Yuk}} = -y_b \bar{Q}_L \Phi b_R - y_t \bar{Q}_L \tilde{\Phi} t'_R - \lambda_T \Phi_d \bar{T}'_L t'_R - m_T \bar{T}'_L t'_R + \text{H.c.} \quad (8)$$

When Φ and Φ_d get VEVs, the mass matrix in t' and T' basis takes the form,

$$\mathcal{L}_{u3-\text{mass}} = -\bar{\chi}_L \mathcal{M} \chi_R + \text{H.c.}, \quad (9)$$

where

$$\chi_\tau = \begin{pmatrix} t'_\tau \\ T'_\tau \end{pmatrix}, \quad \mathcal{M} = \begin{pmatrix} \frac{y_t v_{\text{EW}}}{\sqrt{2}} & 0 \\ \frac{\lambda_T v_d}{\sqrt{2}} & m_T \end{pmatrix}, \quad (10)$$

and $\tau = L, R$.

One requires a biunitary transformation of the following kind in order to diagonalize the above mass matrix

$$\begin{pmatrix} t_L \\ T_{pL} \end{pmatrix} = \begin{pmatrix} \cos \theta_L & -\sin \theta_L \\ \sin \theta_L & \cos \theta_L \end{pmatrix} \begin{pmatrix} t'_L \\ T'_L \end{pmatrix}, \quad \begin{pmatrix} t_R \\ T_{pR} \end{pmatrix} = \begin{pmatrix} \cos \theta_R & -\sin \theta_R \\ \sin \theta_R & \cos \theta_R \end{pmatrix} \begin{pmatrix} t'_R \\ T'_R \end{pmatrix} \quad (11)$$

The lighter mass eigenstate (t) appearing in above equation will be identified as the observed top quark having mass, $m_t = 173.5$ GeV and T_p denotes the heavier mass eigenstate, to be referred as the top partner. Mass of the top partner (m_{T_p}) and the mixing angle involving the left chiral top and top partner fields (θ_L) are the two free parameters of the fermion sector. The parameters appearing in the Lagrangian of the fermion sector can be written in terms of these free parameters as,

$$\lambda_T = \frac{(m_{T_p}^2 - m_t^2) \sin 2\theta_L}{\sqrt{2} v_d \sqrt{m_t^2 \cos^2 \theta_L + m_{T_p}^2 \sin^2 \theta_L}} \quad (12)$$

$$m_T = \frac{m_t m_{T_p}}{\sqrt{m_t^2 \cos^2 \theta_L + m_{T_p}^2 \sin^2 \theta_L}} \quad (13)$$

In the context of the present work, the relevant independent free parameters of the model described above are m_{T_p} ,

$\sin \theta_L$, m_{γ_d} , v_d , m_{h_d} , $\sin \theta_S$. The gauge kinetic mixing parameter (ϵ) is also a free parameter² of this model, however, we set it to a fixed value consistent with the observations.

A. Constraints

Even though the model parameters are considered free some of them are subjected to constraints coming from observations and theoretical consistency. Below we present three such important constraints on the parameters that represent a portal interaction between the SM and the dark sector.

(i) *Gauge sector* (ϵ): The kinetic mixing parameter is strongly constrained by various low-energy observations in the case of a massive dark photon scenario. These constraints on ϵ depend significantly on the mass of the dark photon [37,38]. For dark photons with mass $m_{\gamma_d} \gtrsim$ a few GeVs, the allowed range of ϵ is $\lesssim 10^{-3}$. However, since we will be interested in the case where the dark photon decays inside the detector, we restrict working with arbitrarily small value of ϵ consistent as it plays a crucial role in the context of dark photon tagging. For example, if the $\epsilon \sim 10^{-7}$, the decay of dark photon will decay with a displaced vertex that can be utilized as an additional feature to enhance its tagging efficiency. However, in the present work, we only consider the prompt decay of the dark photon by fixing the value of ϵ at 10^{-4} . Any other value in the range $10^{-3} - 10^{-6}$ is acceptable as long as it meets the above requirements. We leave the long-lived dark photon scenario for future work.

(ii) *Scalar sector* ($\sin \theta_S$): The mixing angle between the SM Higgs and the dark Higgs is constrained by various observations such as, direct searches at the LEP experiment, LHC heavy Higgs searches, the Higgs signal strength measurement, correction to the W boson mass, perturbative unitarity and LHC Higgs invisible searches. [56–61]. However, these constraints depend on the mass of the dark Higgs and the dark Higgs VEV (v_d). For dark Higgs in the mass range ($10 \text{ GeV} \leq m_{h_d} < 100 \text{ GeV}$) and $v_d \sim v_{\text{EW}}$ the LEP experiment provides a stringent lower limit of 0.9–0.998 on the allowed values of $|\sin \theta_S|$. In the range $100 \text{ GeV} \leq m_{h_d} \leq 400 \text{ GeV}$, the strongest limit on $|\sin \theta_S| < 0.2$ comes from the LHC heavy Higgs searches [59,61]. For higher masses, the stringent limit comes from the correction to the W boson mass. In fact, $|\sin \theta_S| \gtrsim 0.14$ can be ruled out for $m_{h_d} \sim 1 \text{ TeV}$ [61]. The mixing angle is also constrained by the Higgs invisible searches in

² ϵ is related to ϵ' via $\epsilon = \epsilon' / \sqrt{1 - \epsilon'^2 / \cos^2 \hat{\theta}_W}$, where $\cos \hat{\theta}_W = \cos \theta_W + \mathcal{O}(\epsilon^2)$.

the case when $h \rightarrow \gamma_d \gamma_d$ is allowed. The CMS [62] and ATLAS [63] limits on this invisible branching ratio set a strong constraint on the mixing angle as a function of the dark Higgs VEV:

$$|\sin \theta_S| \leq 4.6 \times 10^{-4} \left(\frac{v_d}{\text{GeV}} \right) \sqrt{\text{BR}_{\text{lim}}} \quad (14)$$

where BR_{lim} is 0.15 (CMS) and 0.107 (ATLAS). For $v_d = 100$ GeV, this translates to $|\sin \theta_S| \leq 0.018$ (CMS) and 0.015 (ATLAS). Throughout our analyses we set, $|\sin \theta_S| = 10^{-4}$.

- (iii) *Fermion sector* (λ_T): The perturbative unitarity requirement coming from the process $h_d t \rightarrow h_d t$ process controlled by the parameter λ_T gives an upper bound on it, $\lambda_T < 4\sqrt{2\pi}$. On the other hand the reality condition on the top and top partner mixing angle ($\sin \theta_L$) also gives an independent constraint on λ_T .

The mixing angle can be written as,

$$|\sin \theta_L| = \frac{1}{2} \left[\frac{2m_{T_p}^2 - 2m_t^2 - \lambda_T^2 v_d^2}{m_{T_p}^2 - m_t^2} \times \left(1 - \sqrt{1 - \frac{8\lambda_T^2 v_d^2 m_t^2}{(2m_{T_p}^2 - 2m_t^2 - \lambda_T^2 v_d^2)^2}} \right) \right]^{1/2} \quad (15)$$

The reality requirement implies $|\lambda_T| < \sqrt{2}(m_{T_p} - m_t)/v_d$ [5,6] The combination of both of these can together be given as,

$$|\lambda_T| < \sqrt{2} \min \left(\frac{m_{T_p} - m_t}{v_d}, 4\sqrt{\pi} \right) \quad (16)$$

B. T_p decay width

In this model, the top partner decays to both in the standard ($T_p \rightarrow bW, tZ, th$) and nonstandard ($T_p \rightarrow t\gamma_d, th_d$) modes. Below we present the partial decay widths of the top partner in various decay modes in the limit $|\sin \theta_d|, |\sin \theta_S|, \epsilon, m_t/m_{T_p} \ll 1$ [6,64,65].

- (i) $T_p \rightarrow bW$

$$\Gamma(T_p \rightarrow bW) \approx \frac{1}{16\pi} \frac{m_{T_p}^3}{v_{\text{EW}}^2} \sin^2 \theta_L \quad (17)$$

- (ii) $T_p \rightarrow tV (V = Z, \gamma_d)$

$$\Gamma(T_p \rightarrow tZ) \approx \frac{1}{32\pi} \frac{m_{T_p}^3}{v_{\text{EW}}^2} \sin^2 \theta_L \cos^2 \theta_L \quad (18)$$

and

$$\Gamma(T_p \rightarrow t\gamma_d) \approx \frac{1}{32\pi} \frac{m_{T_p}^3}{v_d^2} \sin^2 \theta_L \cos^2 \theta_L \times \left(1 + \frac{m_{T_p}^2 m_t^2}{D^2} \right) \quad (19)$$

- (iii) $T_p \rightarrow tS (S = h, h_d)$

$$\Gamma(T_p \rightarrow th) \approx \frac{1}{32\pi} \frac{m_{T_p}^3}{v_{\text{EW}}^2} \sin^2 \theta_L \cos^2 \theta_L \quad (20)$$

and,

$$\begin{aligned} \Gamma(T_p \rightarrow th_d) \approx & \frac{1}{32\pi} \frac{m_{T_p}^3}{v_d^2} \sin^2 \theta_L \cos^2 \theta_L \\ & \times \frac{m_{T_p}^4}{D^2} \left(\sin^4 \theta_L + \frac{m_t^2}{m_{T_p}^2} \cos^4 \theta_L \right. \\ & \left. + 4 \frac{m_t^2}{m_{T_p}^2} \sin^2 \theta_L \cos^2 \theta_L \right) \end{aligned} \quad (21)$$

where, $D = m_t^2 \cos^2 \theta_L + m_{T_p}^2 \sin^2 \theta_L$.

We use the following values for the relevant SM parameters to calculate the top partner decay branching ratios and the cross section in the later part of our analysis [66],

$$\begin{aligned} m_h &= 125.5 \text{ GeV}, & m_t &= 173.2 \text{ GeV}, & m_b &= 4.18 \text{ GeV} \\ m_W &= 80.377 \text{ GeV}, & m_Z &= 91.187 \text{ GeV}, & v_{\text{EW}} &= 246 \text{ GeV} \end{aligned} \quad (22)$$

In Fig. 1, we depict the branching ratio of the top partner in various modes as a function of $\sin \theta_L$ for various choices of $v_d, m_{\gamma_d}, m_{h_d}$, and m_{T_p} .

III. COLLIDER ANALYSIS

In this section, we detail the collider analysis of signal and background processes. We have considered both the single ($pp \rightarrow T_p j$) and the pair ($pp \rightarrow T_p \bar{T}_p$) production of the vector like top partner. We have used MadGraph5_aMC@NLO (version 3.2.0) [67] event generator to simulate both the single and pair production processes of top partner at 13 and 14 TeV LHC energies. In order to achieve this, we have implemented the model described in Sec. II at the Lagrangian level with the help of FeynRules [68]. The universal FeynRules output [69] is then interfaced with MadGraph5_aMC@NLO for event generation. We have

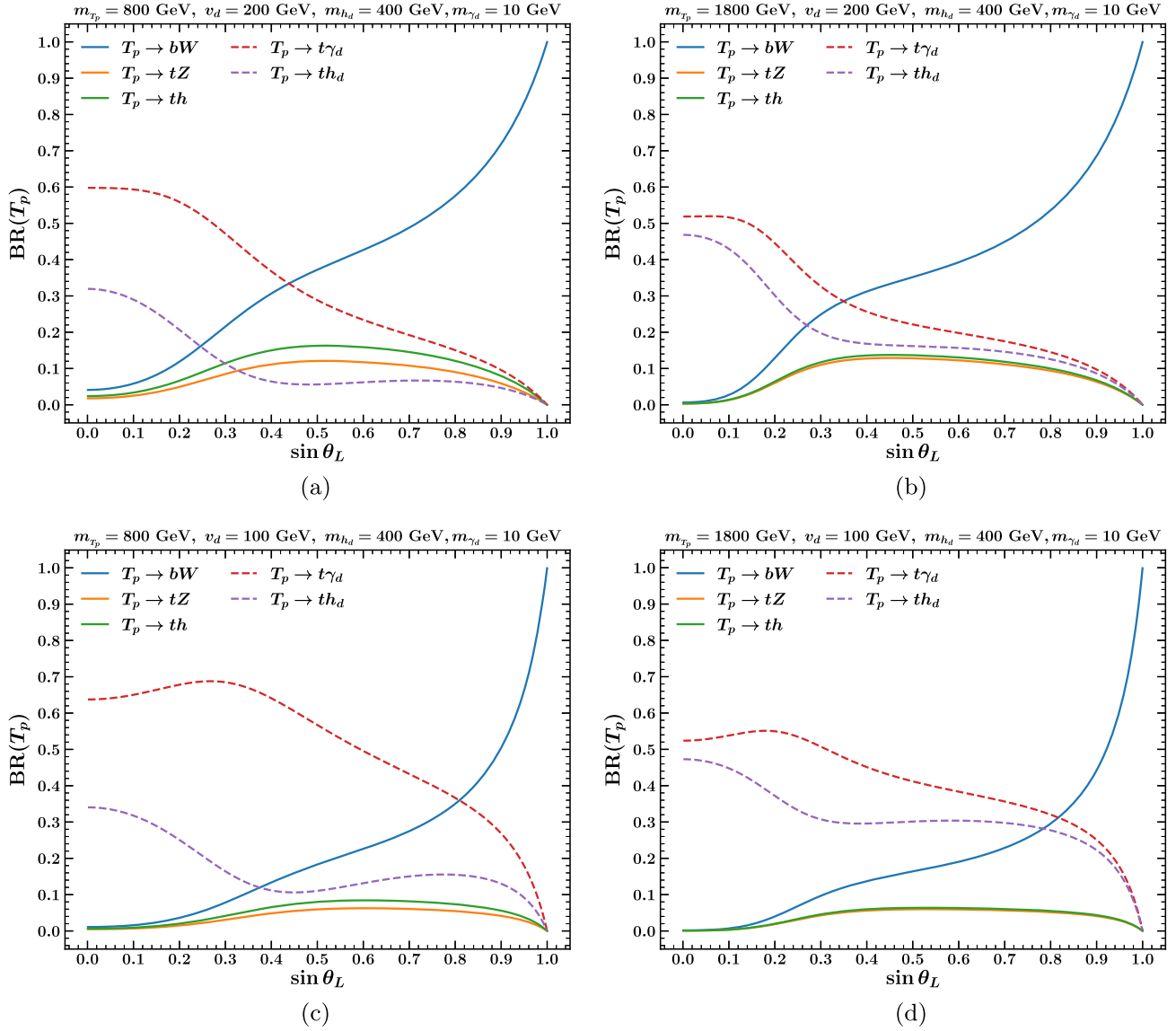


FIG. 1. Top partner branching ratio in the standard (solid line) and nonstandard modes (dashed line) as a function of the mixing angle between top and top partner ($\sin \theta_L$) for different benchmark points, (a) $m_{T_p} = 800$ GeV and (b) $m_{T_p} = 1.8$ TeV with $v_d = 200$ GeV and $m_{h_d} = 400$ GeV. The same for (c) $m_{T_p} = 800$ GeV and (d) $m_{T_p} = 1.8$ TeV with $v_d = 100$ GeV and $m_{h_d} = 200$ GeV. The dark photon mass is assumed to be 10 GeV for all the four plots.

used NNPDF (version 2.3) [70] parton distribution functions to simulate the parton-parton hard scattering in a pp collision. Events generated by MadGraph are then interfaced with Pythia (version 8.307) [71] for parton shower, hadronization, and further analysis. The energy and momenta of all the final state objects are smeared with appropriate Gaussian smearing function to take into account the finite detector resolution effects. The details of smearing function parametrization can be found in [6].

In this work, we are considering the top partner decaying to a top quark and dark photon. The dark photon further decays to SM fermions via the gauge kinetic mixing parameter. Since the top partner is expected to be heavy

($\gtrsim 0.8$ TeV) in order to satisfy the current LHC bounds, the top and the dark photon produced in the decay of it are highly boosted. *One of our primary objectives in this study is to investigate the hadronic decays of the dark photon and the top quark, along with their subsequent identification and reconstruction.*

We use an HDNN framework that uses a combination of convolutional neural network and multilayer perceptron to identify and reconstruct a dark photon jet while a jet initiated by a top quark is reconstructed using Johns Hopkins top tagger [72]. To ensure the hadronic decays of the top quark and the dark photon we have vetoed events with isolated leptons. We first proceed with the

identification and reconstruction of jets originating from the light exotic particle—specifically, the dark photon in this analysis. In order to achieve this we cluster all the final state hadrons to construct jets of radius 0.4 using anti- k_T jet clustering algorithm (AK4). We have used FastJet (v3.4.0) [73] to cluster the hadrons.

Out of all the jets thus formed, we select only those with $p_T > 200$ GeV as potential dark photon jet candidates and prepare jet images and other high level features for HDNN based identification. We have utilized two different images of a single high p_T jet of clustering radius 0.4 in the $\eta - \phi$ plane and a subjet inside it with radius 0.2 around the jet center, using corresponding granularities 0.1 and 0.025, respectively. In addition, a set of crucial jet level features, such as, p_T , p_T fraction, charge multiplicity and charge multiplicity fraction of the potential dark photon jet candidates help us identify a dark photon-initiated jet very effectively. It is possible to achieve an average tagging efficiency of 30% to 93% for the dark photon jet in the top partner mass range, 0.8–2.8 TeV. The average mistagging rate for the nondark photon jets, present in both the signal and SM background varies in the range 1.0% to 2.6%. Details of the HDNN-based identification and reconstruction of the dark photon jets are provided in this Appendix A. Events are considered for further analysis only if they contain at least one identified dark photon jet.

The remaining part of the event analysis proceeds in the following manner depending on the number of identified dark photon jets:

- (1) If *exactly one* HDNN-tagged dark photon jet is identified, we remove³ all of its constituents and recluster the remaining hadrons of that event with a total E_T dependent clustering radius R using Cambridge-Aachen (C-A) clustering algorithm [74]. The reclustering is done only if the total E_T of the remaining hadrons is more than 400 GeV. These jets are then analyzed using Johns Hopkins top tagger to identify a boosted top quark structure in it. We keep the event if a top quark initiated jet is obtained. A subset of this event category will give rise to a final state comprising *exactly one* dark photon jet and *exactly one* top quark jet which predominantly consists of contributions coming from the single production of top partner, with only a small fraction arising from pair production of the top partner.
- (2) If *more than one* dark photon jets are identified, we remove the constituents of the identified dark photon jets pairwise. If there are *two* dark photon jets, we remove the constituents of both—the leading and subleading dark photon jets—simultaneously, if it is

³We identify and remove the constituents of the dark photon jets before the top reconstruction to make sure same total E_T dependent clustering radius, as used in our previous analysis [6], where the dark photon was treated as an invisible particle.

TABLE II. Choices of jet clustering radius(R), minimum jet p_T fraction carried by the subjet (δp), minimum Manhattan distance between two subjets (δr) for various range of total transverse momentum in an event excluding the contribution of dark photon transverse momentum.

E_T	400	600	800	1000	1600	2600
R	1.4	1.2	1.0	0.8	0.6	0.4
δp	0.10	0.10	0.05	0.05	0.05	0.05
δr	0.19	0.19	0.19	0.19	0.19	0.19

three then we have three possible pairs. We consider each possible pair one at a time and remove all the constituents of that pair. The remaining hadrons in all the cases are then reclustered as prescribed before with a total E_T dependent clustering radius R to find a top structure in the jets thus formed using Johns Hopkins top tagger. This has been done keeping in mind the topology of events where the top partner is pair produced and further decays to a top quark and a dark photon giving rise to *exactly two* dark photon jets in the final state. We keep an event only if *at least one* top quark jet is identified in these events. Therefore, this category primarily contains events from pair production of the top partner, with a small fraction from single production of the top partner.

The Johns Hopkins top tagger mentioned above, iteratively declusters a C-A clustered jet to identify the substructure inside a fat jet of radius R . The J-H top tagging algorithm requires the specification of the following additional parameters: the fraction of the jet p_T carried by a subjet and the Manhattan distance (defined as $|\Delta\eta| + |\Delta\phi|$) between two subjets to satisfy minimum values, δ_p and δ_r , respectively to be considered as hard and resolved. We tabulate, in Table II, the values of R , δ_p and δ_r for different total transverse momentum of an event [6].

A key motivation for choosing the J-H top tagger is to allow a qualitative comparison with the methodology adopted in Ref. [6], where a similar approach was used for boosted top tagging with a total E_T -dependent jet clustering radius. While more recent neural networks methods, such as ResNeXt-inspired convolutional networks [75] and ParticleNet [76] architectures that treat jets as point clouds, have demonstrated improved performance in capturing intricate jet substructure, we refrain from introducing an additional ML-based tagger here. Since our work already implements a HDNN-based tagging algorithm for dark photon jets, we adopt the J-H top tagger for boosted top tagging in order to keep the analysis tractable. This choice also facilitates a direct comparison between the present analysis and that of Ref. [6], allowing us to validate that the same reconstruction strategy remains effective.

In Table III, we summarize the effect of basic cut, i.e., requiring *at least two* central jets (defined with $p_T > 20$ GeV

TABLE III. The effects of cut flow on cross sections for the single and pair production of the top partner at both $\sqrt{s} = 13$ and 14 TeV LHC center of mass energies. $\sin \theta_L = 0.1$ is assumed to estimate the cross section for the various benchmark points assuming $\text{BR}(T_p \rightarrow t\gamma_d) = 100\%$ and $\text{BR}(\gamma_d \rightarrow q\bar{q}) = 100\%$. In addition, $v_d = 200$ GeV, $m_{\gamma_d} = 10$ GeV and $m_{h_d} = 400$ GeV are used to obtain the above results.

$\sqrt{s}$ (TeV)	Process	m_{T_p} (TeV)	Production cross section (fb)	Basic cut (fb)	$p_T \geq 200$ GeV (fb)	γ_d tagging (fb)	Top tagging (fb)
13	$T_p \bar{T}_p$	0.8	190.00	132.19	131.44	75.10	14.28
		1.0	42.70	30.45	30.40	22.09	5.15
		1.2	11.40	8.33	8.32	6.84	1.86
		1.4	3.42	2.58	2.58	2.25	0.66
		1.6	1.11	0.86	0.86	0.78	0.24
		1.7	0.64	0.5	0.5	0.46	0.14
		1.8	0.38	0.30	0.30	0.28	0.09
		2.0	0.13	0.11	0.11	0.10	0.03
	$T_p j$	0.8	72.03	56.88	49.95	14.74	2.86
		1.0	37.57	30.27	28.18	14.10	3.29
		1.2	20.92	17.18	16.42	10.69	2.81
		1.4	12.16	10.13	9.82	7.33	2.02
		1.6	7.33	6.24	6.08	4.90	1.31
		1.7	5.72	4.9	4.8	3.97	1.02
		1.8	4.50	3.90	3.82	3.22	0.84
		2.0	2.82	2.49	2.45	2.13	0.53
14	$T_p \bar{T}_p$	0.8	249.61	173.12	172.35	98.47	18.71
		1.0	58.16	41.63	41.58	30.13	7.03
		1.2	16.15	11.90	11.90	9.77	2.61
		1.4	5.06	3.82	3.82	3.32	0.97
		1.6	1.72	1.34	1.34	1.21	0.37
		1.8	0.61	0.49	0.49	0.45	0.14
		1.9	0.38	0.30	0.30	0.28	0.09
		2.0	0.23	0.18	0.18	0.17	0.05
		2.2	0.09	0.07	0.07	0.07	0.02
		2.4	0.034	0.029	0.029	0.027	0.008
		2.5	0.021	0.018	0.018	0.017	0.005
		2.6	0.014	0.012	0.012	0.011	0.003
	$T_p j$	0.8	88.12	69.63	61.11	17.80	3.60
		1.0	46.89	37.72	35.05	17.55	4.14
		1.2	26.65	21.86	20.86	13.55	3.50
		1.4	15.81	13.21	12.76	9.47	2.58
		1.6	9.70	8.26	8.06	6.48	1.72
		1.8	6.09	5.27	5.18	4.35	1.09
		1.9	4.87	4.26	4.18	3.57	0.92
		2.0	3.91	3.45	3.40	2.95	0.74
		2.2	2.54	2.25	2.23	1.98	0.48
		2.4	1.67	1.51	1.49	1.34	0.31
		2.5	1.36	1.23	1.22	1.11	0.26
		2.6	1.11	1.01	1.00	0.92	0.20

and $|\eta| < 2.5$), no isolated leptons and $H_T > 500$ GeV, followed by requirement of tagging *at least one* dark photon jet out of jets having $p_T > 200$ GeV and *at least one* tagged top quark in an event for the signal process.

We have analyzed two different final states, namely,

- (i) *EDIETI*: *exactly one* dark photon jet + *exactly one* top quark jet ($\gamma_d + t$) and,

- (ii) *AD2ATI*: *at least two* dark photon jets + *at least one* top quark jet ($\geq 2\gamma_d + \geq t$).

This categorization of final states have been done keeping in mind the event topology of the single and pair production of the top partner. The schematic diagram illustrating the topology of the final states is depicted in Fig. 2. However, given the finite tagging efficiencies for

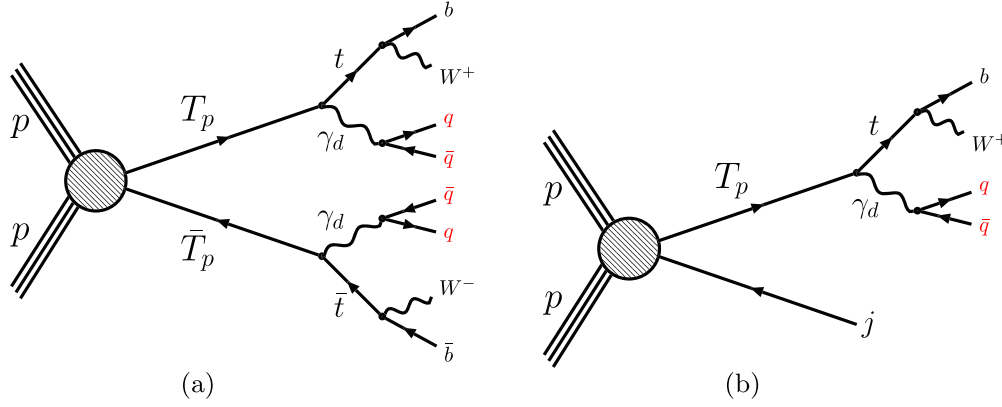


FIG. 2. Schematic diagrams of signal processes: (a) $pp \rightarrow T_p \bar{T}_p$ and (b) $pp \rightarrow T_p j$ with subsequent decays of $T_p \rightarrow t\gamma_d$ and $\gamma_d \rightarrow q\bar{q}$.

both the top quark and the dark photon the two final states are populated by events coming from both single and pair production of top partner. For example, with $\sin \theta_L = 0.1$ the AD2AT1 final state receives contribution dominantly from the pair production of top partner process (99.8% to 60.4% for m_{T_p} in the range 0.8 TeV to 2.6 TeV) with the remaining contribution coming from single production of the top partner process.⁴ In contrast, the ED1ET1 final state consists of a substantial admixture of both single (21.8% to 99.8% for m_{T_p} in the range 0.8 TeV to 2.6 TeV) and pair production of the top partner.

The relevant standard model backgrounds for both the final states are $V(W/Z) + \text{jets}$, $t\bar{t} + \text{jets}$, $t\bar{t}W$, $VV + \text{jets}$, $t\bar{t}Z$, tW , tj and QCD multijet processes, which give rise to one or more top quark jets and jets mistagged as dark photon. The QCD multijet process [6], despite its overwhelming cross section can be controlled not only because of the requirement of one or more mistagged dark-photon and a boosted top quark but also due to the fact that the *invariant mass* of the *mistagged* top-quark and dark photon jet system to peak at the mass of a heavy particle [$\sim \mathcal{O}(\text{TeV})$]. Hence, given the rich topology of the signal events, namely, the presence of one or more boosted dark photon initiated jet(s) along with jets coming from highly boosted top quarks, we focus on SM processes containing either one or more top quark or the presence of an EW vector boson as our potential SM backgrounds.

The other subdominant backgrounds like $t\bar{t}H$, tZj and tHj . At the next-to-leading order (NLO) level the cross section for these backgrounds in their hadronic final states with $H_T > 500$ GeV are $\sigma_{t\bar{t}H} = 344.5$ fb [NLO + NLL] [77], $\sigma_{tZj} = 217$ fb [NLO_{QCD+EW}] [78], and, $\sigma_{tHj} = 17.3$ fb [NLO_{QCD+EW}] [78], respectively. After dark photon tagging and top tagging requirement, these reduce to

⁴To estimate the relative contribution of these two subprocesses, we have assumed 100% branching ratio for both top partner-decaying to a top and dark photon and dark photon-decaying in hadronic mode.

0.19 fb ($t\bar{t}H$), 0.13 fb (tZj), and 0.01 fb (tHj). They will further be reduced after the implementation of the hard cuts (for, e.g., invariant mass of the top–dark photon pair to lie within a window) mentioned later in this section. Hence, their effective contribution is neglected in the estimation of signal significance although we keep the contribution of $t\bar{t}W$ and $t\bar{t}Z$ in our analysis as representatives of these subdominant backgrounds.

In Table IV, the effect of basic cut followed by the requirement of tagging *at least one* dark photon jet out of jets having $p_T > 200$ GeV and *at least one* tagged top quark in an event for the SM background processes are summarized. The $V + \text{jets}$, $t\bar{t} + \text{jets}$ and $VV + \text{jets}$ background has been generated with the highest jet multiplicity *two* at the matrix element level and implemented MLM [79] jet parton matching algorithm to avoid double counting. In this analysis the $V + \text{jets}$, $VV + \text{jets}$ and tj are considered at LO, $t\bar{t} + \text{jets}$ and tW are considered at aN³LO and $t\bar{t}Z$, $t\bar{t}W$ are considered at NLO + NNLL in QCD by multiplying the leading order cross sections obtained from MadGraph with appropriate k -factors [6].

One can see from Table IV that the requirement of boosted dark photon jet in the SM background event gives a suppression factor of more than 1 in 100 (can also be seen in Appendix A). In addition, requirement of the presence of at least one boosted top quark jet in the final state reduces the SM background by a factor of 4 to 7 depending on the particular SM background process.

A. Kinematic variables

For both the final state considered in this analysis the following set of kinematic variables is found to be useful for separating the signal from the background events.

1. Transverse momentum of tagged dark photon

In Figs. 3 and 4 we plot the transverse momentum, defined as $p_T = \sqrt{p_x^2 + p_y^2}$, of the HDNN identified dark

TABLE IV. The effects of cut flow on cross sections for the SM background processes relevant for our analysis at both $\sqrt{s} = 13$ and 14 TeV LHC center of mass energies.

$\sqrt{s}$ (TeV)	Process	Production cross section ^a (fb)	Basic cut (fb)	$p_T \geq 200$ GeV (fb)	γ_d tagging (fb)	Top tagging (fb)
13	$V + \text{jets}$	142980.0	140928.14	127905.52	4342.12	140.38
	$t\bar{t} + \text{jets}$	41728.84	41600.33	28001.31	504.81	92.47
	tj	2084.11	2072.00	1813.11	67.43	13.02
	tW	1537.61	1533.13	1141.30	27.16	4.50
	$VV + \text{jets}$	1087.00	786.08	781.80	49.40	2.21
	$t\bar{t}Z$	863.00	490.29	138.75	3.11	0.46
	$t\bar{t}W$	566.00	273.52	64.43	1.67	0.30
14	$V + \text{jets}$	170950.00	168381.60	152876.26	5132.34	162.95
	$t\bar{t} + \text{jets}$	51297.49	51141.77	34459.14	620.22	105.61
	tj	2477.80	2461.50	2130.53	79.01	15.38
	tW	2188.40	2182.11	1632.11	38.87	6.27
	$VV + \text{jets}$	1315.00	952.07	946.64	60.00	2.69
	$t\bar{t}Z$	1045.00	600.27	173.52	3.99	0.56
	$t\bar{t}W$	653.00	320.24	76.65	1.96	0.35

^aThe production cross section for SM $V + \text{jets}$, $t\bar{t} + \text{jets}$, tW , $VV + \text{jets}$ and tj background processes is quoted with $H_T \geq 500$ GeV for both 13 and 14 TeV LHC center of mass energies.

photon jet for two different final states considered in this analysis at $\sqrt{s} = 13$ and 14 TeV, respectively.

$$M_{\gamma_d t} = \sqrt{|(p_{\gamma_d}^j + p_t^j)^2|},$$

2. Invariant mass of the top-dark photon pair

We show the invariant mass distribution of the top-dark photon jet pair, defined as

in Figs. 5 and 6 for two different final states considered in this analysis at $\sqrt{s} = 13$ and 14 TeV, respectively.

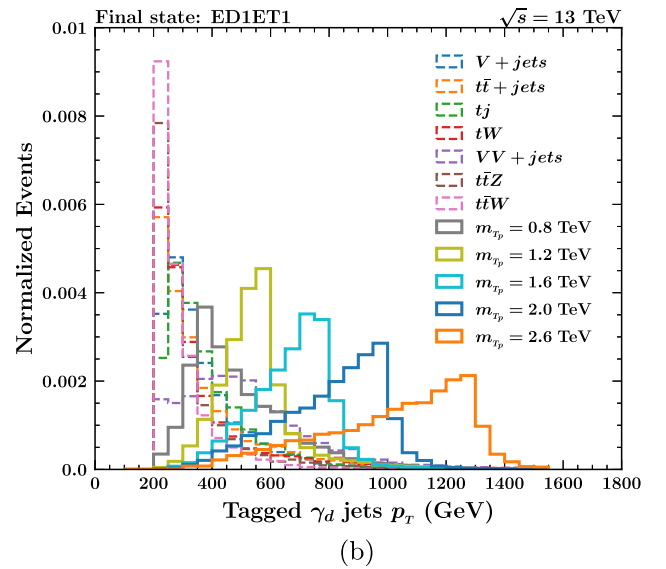
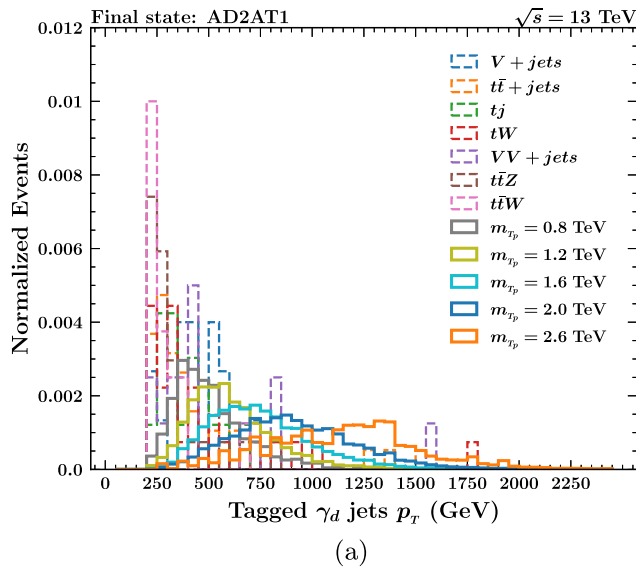


FIG. 3. Transverse momentum distributions of the HDNN identified dark photon jet for signal and backgrounds in the (a) AD2AT1 and (b) ED1ET1 final states at 13 TeV LHC center of mass energy.

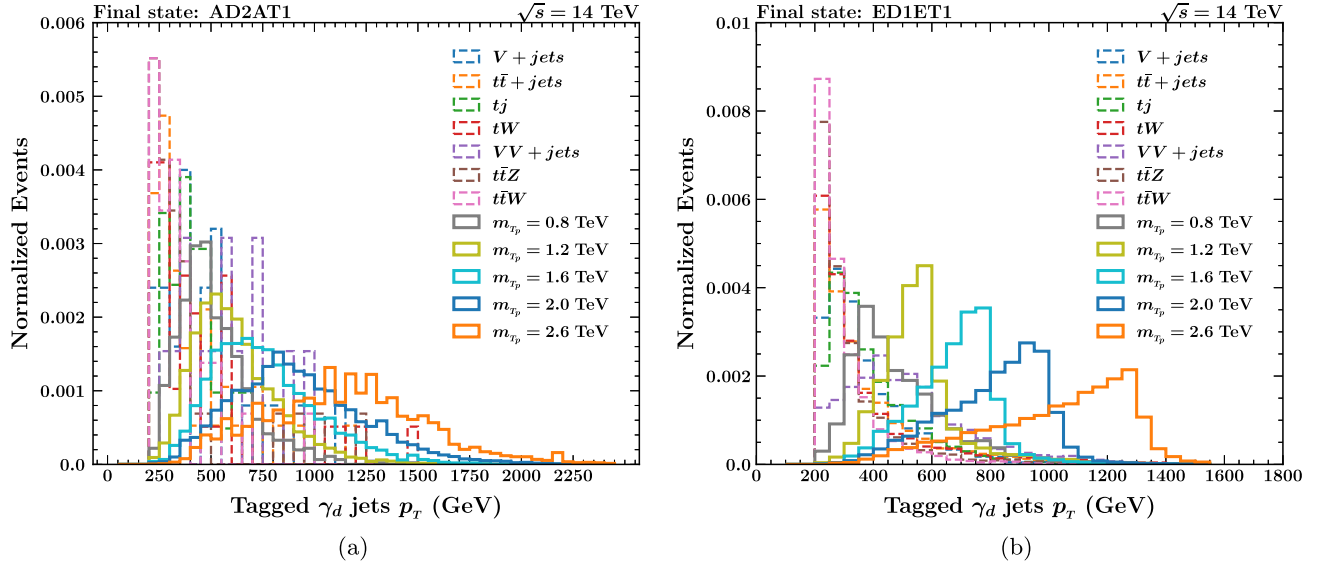


FIG. 4. Transverse momentum distributions of the HDNN identified dark photon jet for signal and backgrounds in the (a) AD2AT1 and (b) ED1ET1 final states at 14 TeV LHC center of mass energy.

Based on the distributions of these kinematic variables we decide to apply a set of cuts to optimize the statistical significance of signal over the background in two different final states:

- (i) Transverse momentum of the dark photon jet, $p_T^j > p_{T0}$.
- (ii) The invariant mass of the dark photon-top quark system to satisfy $\alpha \leq M_{\gamma_{dt}} \leq \beta$.

The values of the cut parameters collectively called C_0 , are listed in Table V for various choices of benchmark points.

IV. RESULTS AND DISCUSSIONS

In this section we present the results of our analysis. Tables VI and VII contains the event rate for AD2AT1 and ED1ET1 final states, respectively, at both 13 TeV and 14 TeV LHC center of mass energies. In Table VI, we show the effect of cut flow in AD2AT1 final state for both signal and background. As mentioned earlier, the final state $\geq 2\gamma_d + \geq t$ which consists of *at least two dark photons and at least one top tagged jets*, has contributions from

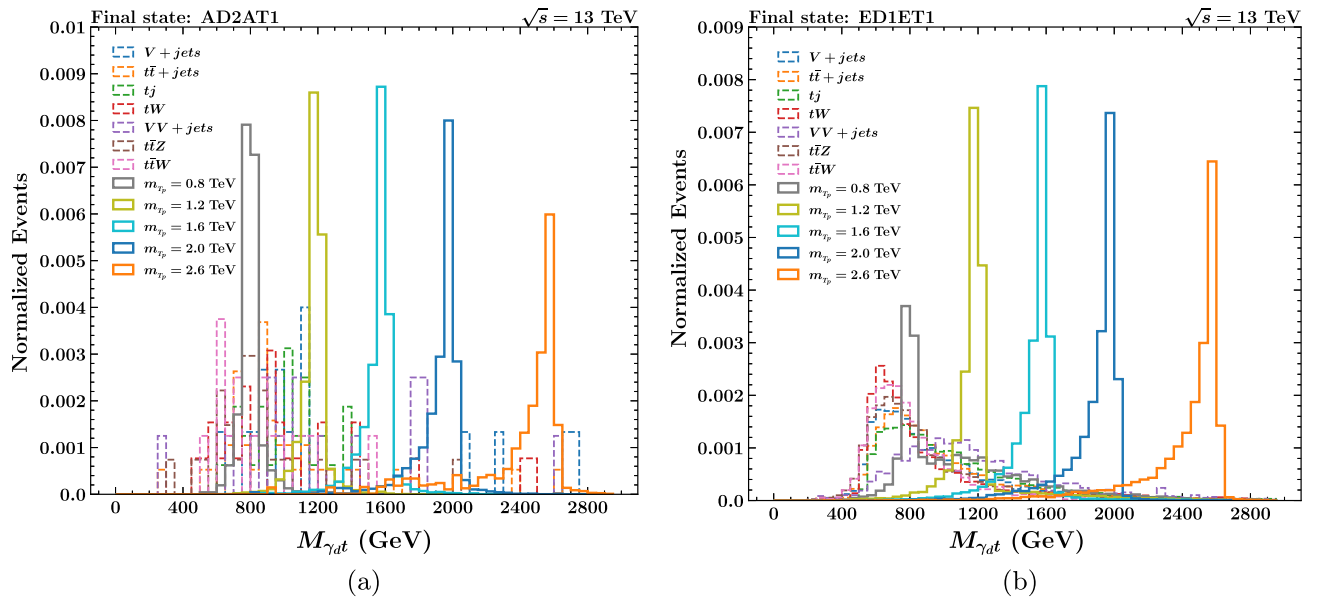


FIG. 5. Invariant mass distribution of the identified dark photon and top quark system for signal and background in the (a) AD2AT1 and (b) ED1ET1 final states at 13 TeV LHC center of mass energy.

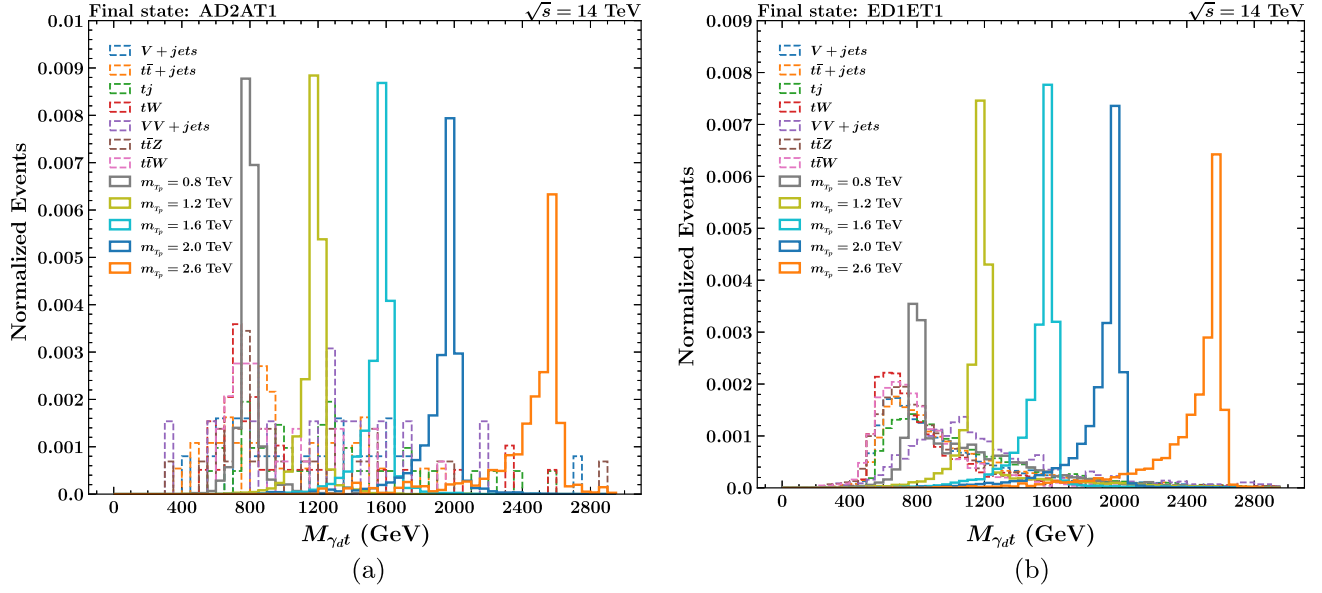


FIG. 6. Invariant mass distribution of the identified dark photon and top quark system for signal and background in the (a) AD2AT1 and (b) ED1ET1 final states at 14 TeV LHC center of mass energy.

both the pair and single production of the top partner. The single production of top partner contributes when at least one or more nondark photon jets are mistagged as dark photon jets. This final state also receives contributions from standard model background processes, e.g., $V + \text{jets}$, $t\bar{t} + \text{jets}$, tj , tW , $VV + \text{jets}$, $t\bar{t}Z$ and $t\bar{t}W$ as already mentioned, with the dominant contribution coming from the $V + \text{jets}$ and $t\bar{t} + \text{jets}$ background. The requirement of *at least two* dark photon jets in this final state suppresses the SM background significantly due to the low mistagging rate. One can see from the Table VI that the invariant mass of the *tagged top quark and dark photon* system can effectively suppress the standard model background in this final state.

In Table VII, we show the effect of cut flow in ED1ET1 final state for both signal and background. The final state $\gamma_d + t$ which consists of *exactly one dark photon and exactly one top tagged jets*, also receive contribution from

both the pair and single production of the top partner processes. However, the relative contribution of these two processes strongly depends on the mass (m_{T_p}) and the mixing angle ($\sin \theta_L$). For example, at $\sin \theta_L = 0.1$ the single production cross section exceeds the pair production cross section beyond 1 TeV [5,6]. On the other hand, for very small $\sin \theta_L$ ($\lesssim 0.02$) both the final state cross sections will be dominated by the pair production process. The SM backgrounds for this final state are identical to those mentioned in the AD2AT1 case. The combination of the two kinematic variables, namely, (i) the transverse momentum of the tagged dark photon jet and, (ii) the invariant mass of the *tagged top quark and dark photon* system help us to optimize the signal significance in this case.

The SM background for $\gamma_d + t$ final state which is dominated by the $V + \text{jets}$ and $t\bar{t} + \text{jets}$ processes is larger by a factor of 200 or more than that in the $\geq 2\gamma_d + \geq t$ final

TABLE V. Values of the cut parameters (C_0): top-dark photon invariant mass window (α, β) and minimum dark photon transverse momentum (p_{T0}) in GeV for various choices of benchmark points in two different final states (i.e., AD2AT1 and ED1ET1) at $\sqrt{s} = 13$ TeV and 14 TeV in the context of LHC.

Final state	$\sqrt{s}$ (TeV)	C_0 (GeV)	m_{T_p} (TeV)	
			0.8–1.2	1.4–2.6
AD2AT1	13 & 14	α	$m_{T_p} - 100$	$m_{T_p} - 150$
		β	$m_{T_p} + 100$	$m_{T_p} + 100$
ED1ET1	13 & 14	p_{T0}	$0.33 \times m_{T_p}$	
		α	$m_{T_p} - 100$	
		β	$m_{T_p} + 50$	

TABLE VI. The effects of cut flow on cross sections for both the signal and the total SM background along with the signal significance in the AD2AT1 ($\geq 2\gamma_d + \geq t$) final state at $\sqrt{s} = 13$ TeV (139 fb^{-1}) and at $\sqrt{s} = 14$ TeV (300 fb^{-1}). The cross sections presented above after the final state requirement and the invariant mass cut assume $\text{BR}(T_p \rightarrow t\gamma_d) = 100\%$ and $\text{BR}(\gamma_d \rightarrow q\bar{q}) = 100\%$. The signal cross sections are quoted separately for two different subprocesses for various choices of m_{T_p} and the corresponding total SM background cross sections are highlighted in *italics*. We have assumed $\sin \theta_L = 0.1$, $v_d = 200$ GeV, $m_{\gamma_d} = 10$ GeV, and $m_{h_d} = 400$ GeV to estimate the cross sections and the signal significance. The estimated signal significances presented in the last two columns assume 100% and *actual* $\text{BR}(T_p \rightarrow t\gamma_d)$, respectively, along with $\text{BR}(\gamma_d \rightarrow q\bar{q}) = 60\%$.

$\sqrt{s}$ (TeV)	m_{T_p} (TeV)	Final state cross section		$M_{\gamma_d t} \in [\alpha, \beta]$		Significance	
		(fb)		(fb)		$\text{BR}(T_p)_{100}$	$\text{BR}(T_p)_a$
		$T_p j$	$T_p \bar{T}_p$	$T_p j$	$T_p \bar{T}_p$		
13	0.8	0.007	3.553	0.007	3.184	12.9	5.8
			<i>1.086</i>		<i>0.422</i>		
	1.0	0.011	1.734	0.008	1.530	8.6	3.5
			<i>1.086</i>		<i>0.239</i>		
	1.2	0.013	0.813	0.009	0.697	5.2	1.9
			<i>1.086</i>		<i>0.174</i>		
	1.4	0.011	0.348	0.007	0.313	3.4	1.2
			<i>1.086</i>		<i>0.091</i>		
	1.5	0.008	0.231	0.006	0.204	2.5	0.8
			<i>1.086</i>		<i>0.089</i>		
14	0.8	0.011	4.553	0.009	4.129	22.5	10.4
			<i>1.764</i>		<i>0.435</i>		
	1.0	0.025	2.367	0.020	2.101	14.1	5.6
			<i>1.764</i>		<i>0.417</i>		
	1.2	0.019	1.150	0.015	0.988	8.3	2.9
			<i>1.764</i>		<i>0.349</i>		
	1.4	0.014	0.512	0.010	0.421	4.6	1.5
			<i>1.764</i>		<i>0.308</i>		
	1.6	0.009	0.229	0.007	0.198	2.4	0.7
			<i>1.764</i>		<i>0.257</i>		
	1.7	0.007	0.145	0.004	0.124	1.7	0.5
			<i>1.764</i>		<i>0.195</i>		
	1.8	0.006	0.094	0.004	0.078	1.5	0.4
			<i>1.764</i>		<i>0.111</i>		
	2.0	0.004	0.039	0.002	0.031	0.7	0.2
			<i>1.764</i>		<i>0.104</i>		

state. However, the estimated signal significance in this final state for a given benchmark point is higher than that in the $\geq 2\gamma_d + \geq t$ final state. This is due to the fact that for $\sin \theta_L = 0.1$ and $m_{T_p} \geq 1$ TeV, the single production cross section is higher than the pair production cross section.

The last two columns of Table VI and VII gives an estimate of signal significance for two different assumptions of the top partner branching ratio. The column labeled

by $\text{BR}(T_p)_{100}$ assumes 100% branching ratio while $\text{BR}(T_p)_a$ represents the actual branching ratio for the top partner, respectively. The branching ratio for the dark photon decaying hadronically is assumed to be 60% throughout our analysis.

To set exclusion limits on the parameter space we use the following definition as obtained from the profile likelihood ratio method [80–82],

TABLE VII. The effects of cut flow on cross sections for both the signal and the total SM background along with the signal significance in the $EDIETI$ ($\gamma_d + t$) final state at $\sqrt{s} = 13$ TeV (139 fb^{-1}) and at $\sqrt{s} = 14$ TeV (300 fb^{-1}). The cross sections presented above after the final state requirement, the minimum transverse momentum threshold and the invariant mass cut assume $\text{BR}(T_p \rightarrow t\gamma_d) = 100\%$ and $\text{BR}(\gamma_d \rightarrow q\bar{q}) = 100\%$. The signal cross sections are quoted separately for two different subprocesses for various choices of m_{T_p} and the corresponding total SM background cross sections are highlighted in italics. We have assumed $\sin \theta_L = 0.1$, $v_d = 200$ GeV, $m_{\gamma_d} = 10$ GeV, and $m_{h_d} = 400$ GeV to estimate the cross sections and the signal significance. The estimated signal significances presented in the last two columns assume 100% and *actual* $\text{BR}(T_p \rightarrow t\gamma_d)$, respectively, along with $\text{BR}(\gamma_d \rightarrow q\bar{q}) = 60\%$.

$\sqrt{s}$ (TeV)	m_{T_p} (TeV)	Final state cross section (fb)		$p_T \geq p_{T0}$ (fb)		$M_{\gamma_d t} \in [\alpha, \beta]$ (fb)		Significance $\text{BR}(T_p)_{100}$ $\text{BR}(T_p)_a$	
		$T_p j$	$T_p \bar{T}_p$	$T_p j$	$T_p \bar{T}_p$	$T_p j$	$T_p \bar{T}_p$		
13	0.8	2.854	10.245	2.782	9.979	2.514	2.272	4.1	2.1
		<i>254.52</i>		<i>181.341</i>		<i>42.826</i>			
	1.0	3.275	3.245	3.106	3.071	2.772	1.021	5.1	2.7
		<i>254.52</i>		<i>112.37</i>		<i>20.964</i>			
	1.2	2.797	0.982	2.562	0.879	2.197	0.321	4.8	2.6
		<i>254.52</i>		<i>71.612</i>		<i>11.248</i>			
	1.4	2.006	0.287	1.780	0.246	1.441	0.088	4.1	2.2
		<i>254.52</i>		<i>47.533</i>		<i>5.925</i>			
	1.5	1.602	0.159	1.379	0.133	1.089	0.048	3.3	1.8
		<i>254.52</i>		<i>32.470</i>		<i>3.998</i>			
	1.6	1.299	0.088	1.106	0.073	0.830	0.027	2.9	1.5
		<i>254.52</i>		<i>32.470</i>		<i>3.998</i>			
	1.8	0.838	0.027	0.682	0.022	0.487	0.008	2.3	1.2
		<i>254.52</i>		<i>22.360</i>		<i>2.096</i>			
	1.9	0.667	0.015	0.536	0.012	0.371	0.004	1.8	1.0
		<i>254.52</i>		<i>18.760</i>		<i>1.946</i>			
	2.0	0.525	0.008	0.414	0.006	0.280	0.002	1.6	0.9
		<i>254.52</i>		<i>15.939</i>		<i>1.364</i>			
14	0.8	3.590	13.664	3.511	13.339	3.167	3.270	7.8	3.9
		<i>292.505</i>		<i>210.700</i>		<i>45.233</i>			
	1.0	4.117	4.456	3.908	4.196	3.499	1.327	8.7	4.6
		<i>292.505</i>		<i>136.306</i>		<i>24.345</i>			
	1.2	3.476	1.365	3.189	1.229	2.736	0.434	8.0	4.3
		<i>292.505</i>		<i>89.607</i>		<i>13.861</i>			
	1.4	2.559	0.433	2.264	0.364	1.814	0.133	6.8	3.6
		<i>292.505</i>		<i>61.513</i>		<i>7.663</i>			
	1.6	1.708	0.134	1.450	0.109	1.100	0.040	4.8	2.5
		<i>292.505</i>		<i>42.318</i>		<i>5.600</i>			
	1.8	1.083	0.044	0.884	0.035	0.622	0.013	3.8	2.0
		<i>292.505</i>		<i>29.28</i>		<i>2.671</i>			
	2.0	0.737	0.015	0.581	0.012	0.389	0.004	2.9	1.5
		<i>292.505</i>		<i>20.713</i>		<i>1.844</i>			
	2.2	0.474	0.005	0.365	0.004	0.231	0.001	2.3	1.2
		<i>292.505</i>		<i>14.742</i>		<i>0.983</i>			
	2.4	0.309	0.002	0.236	0.0013	0.141	4×10^{-4}	1.7	0.9
		<i>292.505</i>		<i>10.355</i>		<i>0.697</i>			
	2.6	0.202	6×10^{-4}	0.150	5×10^{-4}	0.090	1×10^{-4}	1.1	0.6
		<i>292.505</i>		<i>6.976</i>		<i>0.563</i>			

$$\sigma_{\text{excl}} = \sqrt{2 \left[s - b \ln \left(1 + \frac{s}{b} \right) \right]} \quad (23)$$

Here σ_{excl} quantifies the median exclusion statistical significance estimation. s is expected number of signal events and b is the expected number of background events.

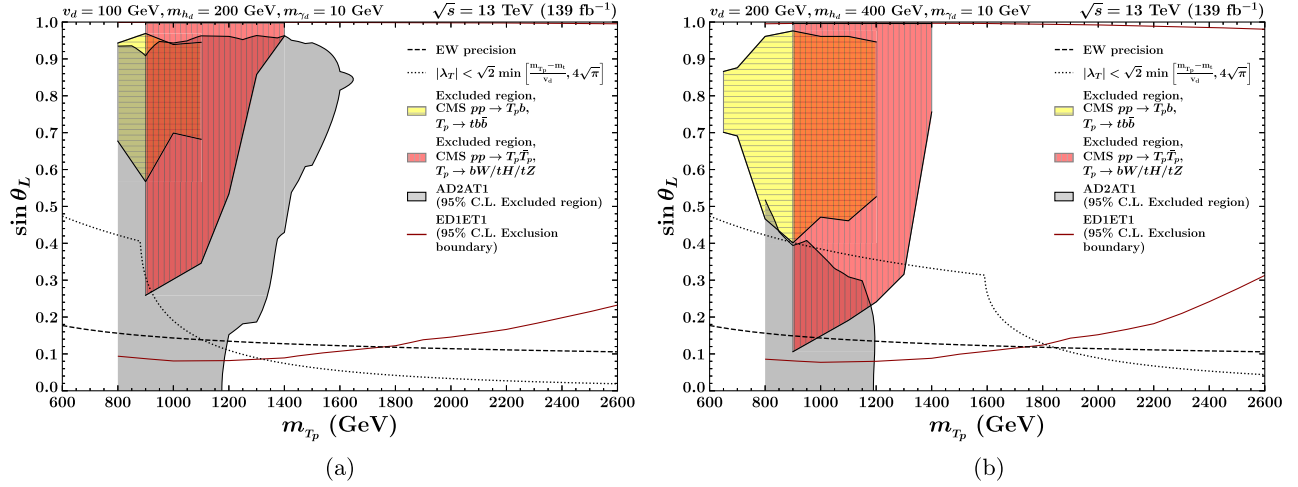


FIG. 7. Various exclusion limits in the $\sin \theta_L - m_{T_p}$ plane. The exclusion limits set by the CMS data [83,84] in the context of our model, as mentioned in the text, are represented by the horizontally hatched (yellow shaded) region and vertically hatched (red shaded) region, respectively. The constraints coming from the Eq. (16) and the electroweak precision measurements are depicted, respectively by dotted (black) and dashed (black) lines. The region bounded between two solid (red) lines and the gray colored region are disfavored with 95% CL using our analyses in the ED1ET1 and AD2AT1 final states, respectively, assuming actual $\text{BR}(T_p \rightarrow t\gamma_d)$ at $\sqrt{s} = 13$ TeV with 139 fb^{-1} of integrated luminosity. The two illustrative subfigures correspond to (a) $v_d = 100 \text{ GeV}$, $m_{h_d} = 200 \text{ GeV}$ and $m_{\gamma_d} = 10 \text{ GeV}$ and (b) $v_d = 200 \text{ GeV}$, $m_{h_d} = 400 \text{ GeV}$ and $m_{\gamma_d} = 10 \text{ GeV}$.

We have assumed 139 fb^{-1} (300 fb^{-1} and 3 ab^{-1}) of integrated luminosity at 13 (14) TeV LHC center of mass energy to obtain the signal significance.

We also consider implications of existing LHC analyses in the context of an extension of standard model with a singlet vectorlike top quark partner by CMS collaboration. The CMS data corresponding to an integrated luminosity of 137 fb^{-1} at 13 TeV center of mass energy has set limits on the $\sigma(pp \rightarrow T_p b q) \times \text{BR}(T_p \rightarrow t b \bar{b})$ as a function of the top partner mass in fully hadronic final state consisting a total of seven jets, where five jets come from the decay of the top partner and three of them are b quark jets [83]. We also use the CMS limit on top partner pair production cross section times branching ratio in the context of the same model in three different final states: single-lepton channel, same-sign dilepton channel, and “multilepton” channel with at least three leptons, corresponding to an integrated luminosity of 137 fb^{-1} at 13 TeV center of mass energy [84]. We recast these bounds in the context of the model considered in this work where the vectorlike top quark acts as a portal matter and the branching ratio of the top partner in the SM mode is not necessarily fixed by the mass of the top partner (m_{T_p}) and mixing angle ($\sin \theta_L$) between the top quark and top partner. As already mentioned in Sec. II and in [6], the top partner branching ratios both in the standard (bW, tZ, th) and in the nonstandard ($t\gamma_d, th_d$) modes also depend on the vacuum expectation value of the dark Higgs (v_d), mass of the dark photon (m_{γ_d}) and mass of the dark Higgs (m_{h_d}).

We use above CMS data to set limit in the $\sin \theta_L - m_{T_p}$ plane and corresponding exclusion limit is depicted in

Fig. 7. The gray filled exclusion region and solid (red) exclusion boundary in Fig. 7 corresponds to expected 95% confidence level (CL) obtained assuming $p - p$ collision center of mass energy to be 13 TeV at an integrated luminosity of 139 fb^{-1} in the AD2AT1 and ED1ET1 final states, respectively. In Figs. 8 and 9, we also present the expected 95% CL exclusion limits in the $\sin \theta_L - m_{T_p}$ plane using our analysis assuming $\sqrt{s} = 14$ TeV at an integrated luminosity of 300 fb^{-1} and 3 ab^{-1} , respectively. The bounds coming from Eq. (16) and electroweak precision data are also shown by dotted and dashed line, respectively in these plots. One can see that a large fraction of the region excluded by CMS data is already disfavored by these constraints. However, all these bounds depend considerably on the choices of v_d, m_{h_d} and m_{γ_d} . We illustrate this dependency for two different sets of these parameters. The Figs. 7(a), 8(a), and 9(a), correspond to $v_d = 100 \text{ GeV}$, $m_{h_d} = 200 \text{ GeV}$, $m_{\gamma_d} = 10 \text{ GeV}$ whereas the Figs. 7(b), 8(b), and 9(b) correspond to $v_d = 200 \text{ GeV}$, $m_{h_d} = 400 \text{ GeV}$, $m_{\gamma_d} = 10 \text{ GeV}$.

If one compares the Figs. 7(a) and 7(b), it can be clearly seen how the bound obtained by the CMS data is relaxed if we decrease v_d and m_{h_d} . This is due to the reduction of branching ratio in the SM decay modes of the top partner. The complementary behavior can be noted in the exclusion regions obtained by our analyses in these subfigures (and also in the subfigures of Figs. 8 and 9).

In Figs. 7–9, one can see that the exclusion regions in both the AD2AT1 and ED1ET1 final states display a significant dependency on $\sin \theta_L$. This is due to the fact that, both of these final states comprises significant

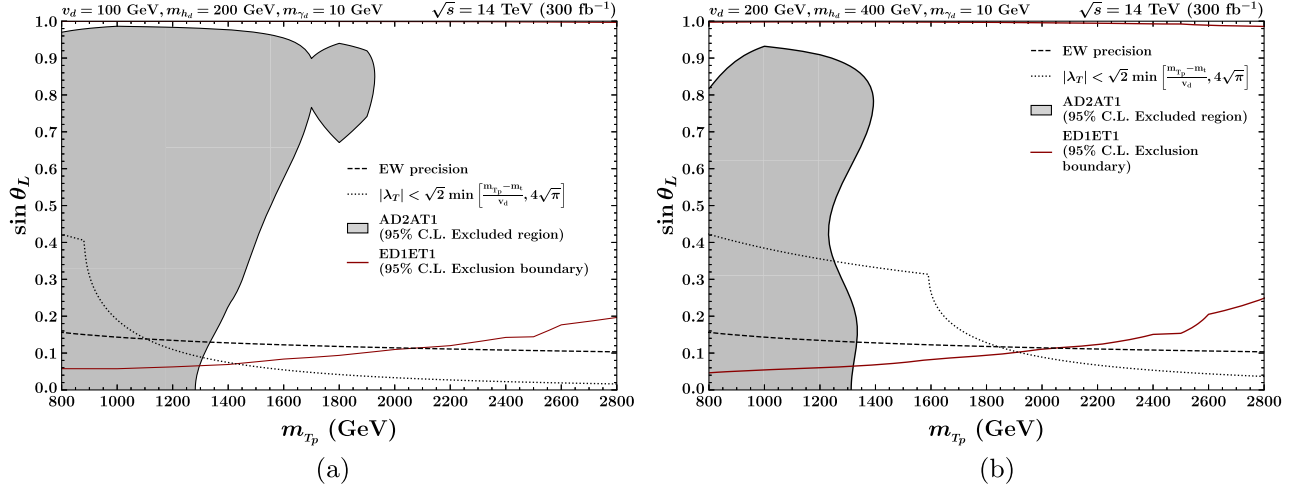


FIG. 8. Various exclusion limits in the $\sin \theta_L - m_{T_p}$ plane. The constraints coming from the Eq. (16) and the electroweak precision measurements are depicted, respectively by dotted (black) and dashed (black) lines. The region bounded between two solid (red) lines and the gray colored region are disfavored with 95% CL using our analyses in the ED1ET1 and AD2AT1 final states, respectively, assuming actual $\text{BR}(T_p \rightarrow t\gamma_d)$ at $\sqrt{s} = 14$ TeV with 300 fb^{-1} of integrated luminosity. The two illustrative subfigures correspond to (a) $v_d = 100 \text{ GeV}$, $m_{h_d} = 200 \text{ GeV}$, $m_{\gamma_d} = 10 \text{ GeV}$ and (b) $v_d = 200 \text{ GeV}$, $m_{h_d} = 400 \text{ GeV}$, $m_{\gamma_d} = 10 \text{ GeV}$.

admixture of single and pair production of top partner processes. The $\sin \theta_L$ dependency in the contribution from pair production enters through branching ratio of the top partner into top and dark photon mode, while for the contribution coming from the single production, $\sin \theta_L$ dependency enters through both production cross section and branching ratio. The exclusion regions in the AD2AT1 final state can be understood as follows: At low $\sin \theta_L$, the single production cross section is much smaller than the pair production cross section. At the same time,

$\sigma(T_p \bar{T}_p) \times \text{BR}^2(T_p \rightarrow t\gamma_d)$ is enhanced due to the larger branching ratio compared to higher $\sin \theta_L$ values (see Fig. 1). As a result, the signal significance is primarily driven by pair production at low $\sin \theta_L$. On the other hand, at higher values of $\sin \theta_L$ the contribution from single production becomes substantial and can dominate over the pair production cross section for higher m_{T_p} values. However, both of these contributions suffer branching ratio suppression at higher $\sin \theta_L$ values, leading to an intricate interplay between them in the estimation of signal

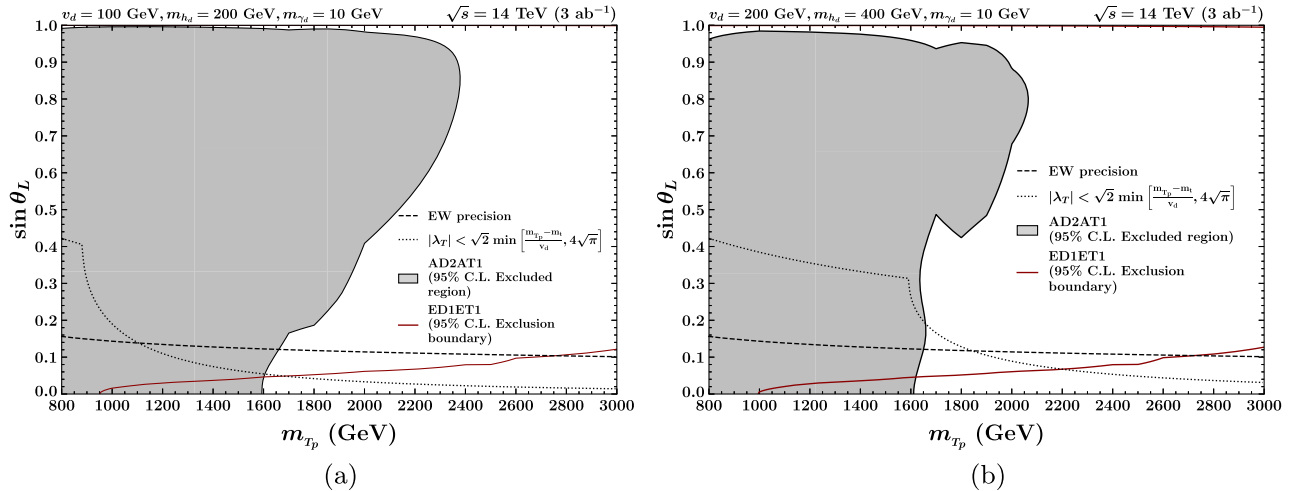


FIG. 9. Various exclusion limits in the $\sin \theta_L - m_{T_p}$ plane. The constraints coming from the Eq. (16) and the electro-weak precision measurements are depicted, respectively by dotted (black) and dashed (black) lines. The region bounded between two solid (red) lines and the gray colored region are disfavored with 95% CL using our analyses in the ED1ET1 and AD2AT1 final states, respectively, assuming actual $\text{BR}(T_p \rightarrow t\gamma_d)$ at $\sqrt{s} = 14$ TeV with 3 ab^{-1} of integrated luminosity. The two illustrative subfigures correspond to (a) $v_d = 100 \text{ GeV}$, $m_{h_d} = 200 \text{ GeV}$, $m_{\gamma_d} = 10 \text{ GeV}$ and (b) $v_d = 200 \text{ GeV}$, $m_{h_d} = 400 \text{ GeV}$, $m_{\gamma_d} = 10 \text{ GeV}$.

significance. This is illustrated in Fig. 17 for four different choices of benchmark points. The exclusion region in the ED1ET1 final state on the other hand can be discerned as follows: As can be seen in Fig. 18, the contribution to this final state is dominated by single production of top partner for a wide range of $\sin\theta_L$ values. Therefore, the exclusion limit is predominantly driven by the $\sigma(T_p j) \times \text{BR}(T_p \rightarrow t\gamma_d)$ as a function of $\sin\theta_L$ and has a much simpler behavior unlike AD2AT1 case. The exclusion regions bounded by the two solid (dark red) lines corresponding to this final state are also depicted in Figs. 7–9.

From Fig. 7, we can see that top partner mass approximately up to 1.17 TeV can be ruled out using the 13 TeV (139 fb^{-1}) LHC data in the AD2AT1 final state for $\sin\theta_L \leq 0.96$ assuming $v_d = 100 \text{ GeV}$ and $m_{h_d} = 200 \text{ GeV}$. For $v_d = 200 \text{ GeV}$ (and $m_{h_d} = 400 \text{ GeV}$) with other parameters kept fixed, in the region $\sin\theta_L \leq 0.22$, m_{T_p} approximately up to 1.19 TeV can be excluded with $\geq 2\sigma$ significance. The same plot also depicts that the region corresponding to $\sin\theta_L \geq 0.23(0.32)$ and m_{T_p} upto 2.6 TeV is disallowed by the 13 TeV (139 fb^{-1}) LHC data in the ED1ET1 final state assuming $v_d = 100(200) \text{ GeV}$. There is a small region in the top right corner of Fig. 7(b) for $v_d = 200 \text{ GeV}$ which will still be allowed by the same data in the ED1ET1 final state.

Similar exclusion limits can be obtained at 14 TeV LHC center of mass energy corresponding to two different integrated luminosities, i.e., 300 fb^{-1} and 3 ab^{-1} , and these are highlighted in Figs. 8 and 9, respectively. For example, in the AD2AT1 final state, we illustrate that the top partner masses approximately up to 1.6 TeV is disfavored for $\sin\theta_L \leq 0.99(0.98)$ assuming $v_d = 100(200) \text{ GeV}$. In addition, the exclusion limit can reach up to $m_{T_p} \sim 2.8(2.35) \text{ TeV}$ at $\sin\theta_L = 0.85(0.8)$ assuming $v_d = 100(200) \text{ GeV}$. In contrast, with 3 ab^{-1} of integrated luminosity we have obtained a 2σ exclusion limit on $\sin\theta_L$ as low as 0.1 up to $m_{T_p} = 3.0(2.8) \text{ TeV}$ assuming $v_d = 100(200) \text{ GeV}$ in the ED1ET1 final state.

V. CONCLUSIONS

We have considered an extension of the SM with a vectorlike fermion having same quantum number as that of the right-handed top quark under the SM gauge group. In addition, the model also possesses a local $U(1)_d$ symmetry with corresponding gauge boson, i.e., the dark photon. The top partner is charged under the local $U(1)_d$ gauge group while all the SM particles are neutral under it. The $U(1)_d$ symmetry is spontaneously broken by the nonzero vacuum expectation value of an additional scalar field. The top partner in this model decays to both standard ($T_p \rightarrow bW, tZ, th$) and nonstandard modes ($T_p \rightarrow t\gamma_d, th_d$). The key feature of this model is that the top partner substantially decays to the nonstandard

modes while the branching ratio in the corresponding standard modes are suppressed in a wide range of parameter space.

The dark photon in this scenario is considered unstable and promptly decays to a pair of SM fermions via the gauge kinetic mixing. The dark photon produced in the decay of the heavy top-partner is highly boosted, and corresponding decay products are extremely collimated. A crucial part of our analysis is to isolate a dark photon initiated jet in presence of other hadronic activity in a given event. In particular isolating it from the highly boosted top-quark and/or other jets present in the same event while also efficiently reducing the mistagging rate of nondark photon jets present in the SM background processes. We have used a hybrid deep neural network based algorithm to identify the highly boosted dark photon initiated jet on an event-by-event basis for the low mass dark photon ($\sim 5\text{--}20 \text{ GeV}$). The method proposed in this work to identify a dark photon jet can be applied to other light exotic particles in their hadronic decay mode if highly boosted. However, our method is not sensitive to the spin of the light exotic particle. We have been able to achieve an average tagging efficiency of 30% to 93% for the dark photon jet in the top partner mass range, 0.8–2.8 TeV while the corresponding average mistagging rate for nondark photon jets present in the signal and in the SM background varies in the range 1.0% to 2.6% using a HDNN binary classifier trained over a sample corresponding to $m_{T_p} = 1.4 \text{ TeV}$, $v_d = 200 \text{ GeV}$, $m_{h_d} = 400 \text{ GeV}$, and $m_{\gamma_d} = 5 \text{ GeV}$.

We have considered two different final states for our analysis, namely, (i) at least two tagged dark photon jets along with at least one tagged top quark jet and, (ii) exactly one tagged dark photon jet along with exactly one tagged top quark jet. We have explored the topology of the signal events, namely, the presence of highly boosted top and dark photon structure along with the fact that the invariant mass of the combined system peaks at around the mass of the top partner. These immensely help us to reduce the contribution coming from the SM $V + \text{jets}$, $t\bar{t} + \text{jets}$, $t\bar{t}W$, $t\bar{t}Z$, tW , and tj backgrounds. We have shown that with the help of certain kinematic observables such as the transverse momentum of the dark photon jet and the invariant mass of the top quark-dark photon jet system it is possible to exclude top partner masses up to 1.2 (1.6) TeV and 1.5 (1.9) TeV in the AD2AT1 and ED1ET1 final states respectively, at 13 TeV LHC center of mass energy with 139 fb^{-1} integrated luminosity assuming actual (100%) branching ratio of the top partner and $\sin\theta_L$ to be 0.1 with $\sim 2\sigma$ significance.

Additionally, we have also presented exclusion limits in the $\sin\theta_L - m_{T_p}$ plane using CMS data corresponding to 137 fb^{-1} integrated luminosity at 13 TeV LHC center of mass energy in the fully hadronic and multilepton (which includes single, same-sign dilepton and at least three leptons) final states in the context of single and pair

production of vectorlike top partner, respectively. For $\sin\theta_L > 0.3$ one can exclude m_{T_p} in the range 0.9–1.4 TeV assuming $v_d = 200$ GeV. However, this limit can be relaxed if one assumes $v_d < 200$ GeV.

Finally, we have presented the 2σ exclusion limits in the $\sin\theta_L - m_{T_p}$ plane at $\sqrt{s} = 13$ TeV (139 fb^{-1}) and $\sqrt{s} = 14$ TeV (300 fb^{-1} and 3 ab^{-1}) assuming the *actual* branching ratio of top partner to the top quark and the dark photon ($T_p \rightarrow t\gamma_d$) for two different final states. Our analysis indicates that for $m_{T_p} \lesssim 1.6$ TeV, nearly the entire range of $\sin\theta_L$ (i.e., $\sin\theta_L \leq 0.99(0.96)$ for $v_d = 100(200)$ GeV) can be excluded with 95% confidence level using $\sqrt{s} = 14$ TeV (3 ab^{-1}) of data in the AD2AT1 final state. Additionally, the exclusion limit can reach up to $m_{T_p} \sim 2.38(2.07)$ TeV at $\sin\theta_L = 0.86(0.8)$, assuming $v_d = 100(200)$ GeV. Similarly, in the ED1ET1 final state, the analysis presented in this work shows that values of $\sin\theta_L$ as low as 0.03 (0.1) can be excluded with 95% confidence level for $m_{T_p} \leq 1.2(2.8)$ TeV at $\sqrt{s} = 14$ TeV and 3 ab^{-1} of integrated luminosity, assuming $v_d = 200$ GeV.

Our collider analysis is applicable to scenarios where a top partner decays into a top quark and a neutral, light exotic particle that subsequently decays promptly into a pair of Standard Model fermions.

ACKNOWLEDGMENTS

We would like to thank Arun Nayak, Satyaki Bhattacharya, and Shilpi Jain for useful discussions. S.V. is thankful for support provided by Council of Scientific and Industrial Research (CSIR, India) under CSIR-UGC NET Fellowship (File No. : 09/934(0017)/2020-EMR-I).

DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: HDNN IDENTIFICATION OF DARK PHOTON JETS

In this section we will detail the strategy of identifying a highly boosted dark photon jet produced in the decay of the top partner. The method described below can be applied to the dark photon produced in the decay of top partner in a wide range of its mass. Our main purpose is to identify a dark photon initiated jet in an event using hybrid deep neural network.

To identify a dark photon initiated jet in an event consisting of hadrons, we cluster the stable hadrons (including photons coming from π^0) using anti- k_T clustering algorithm with a clustering radius (R) of 0.4 to form jets. This choice of clustering radius results in a sharper jet invariant mass peak for the jet associated with the

parton-level dark photon⁵ as can be seen in Fig. 10. The jet momentum are reconstructed out of its constituents using p_T -recombination scheme. However, one can also use other recombination schemes such as (E -recombination) as the method employed below is not sensitive to any particular recombination scheme.

1. Inputs

The inputs of our hybrid deep neural network, are certain one and two-dimensional features of the potential dark photon jet candidates having $p_T > 200$ GeV. we use both the constituent level and jet level information to capture the intricate features of both, the dark photon jets and the nondark photon jets in a binary classification framework [53–55].

The constituent level information, represented by jet images, is processed using a convolutional neural network. The CNN is adept at recognizing complex structures, such as localized p_T deposits or distinctive jet shapes. Whereas the jet-level information is processed using a multilayered perceptron. These jet level information include key features like transverse momentum of the jets, fraction of transverse momentum in a smaller cone to that of the whole jet, charge multiplicity, and charge multiplicity fraction in a smaller cone to that of the whole jet. These features offer a summary of the jet's kinematics and characteristics of the particle content.

2. Jet image preprocessing

Jet image preprocessing is a crucial step to enhance the interpretability and comparability of the underlying structures within jets as well as making it easier for the HDNN model to converge faster as well as for the loss function to get closer to the global minima. To standardize the jet images in $\eta - \phi$ plane we process each jet image through three stages, namely,

- (1) *Centering constituents*: This process begins by centering the jet constituents along the center of the jet maintaining the range of ϕ in $[-\pi, \pi]$. This is achieved by transforming the η and ϕ coordinates into relative distances $\Delta\eta$ and $\Delta\phi$ from the jet's center. This centering allows for a more consistent and clearer visualization of the decay structure within the jet.
- (2) *Rotating the image*: Once centered, the jet image is rotated along its principal axes to align the primary structure in a standardized orientation.
- (3) *Flipping the image*: The image is flipped to ensure that any additional radiations appear in the first quadrant, facilitating easier comparisons between different jets.

⁵For the parton level true dark photon jet tagging, we ensure that the distance in the $\Delta\eta - \Delta\phi$ plane between the jet and the parton-level dark photon is minimum and within 0.02.

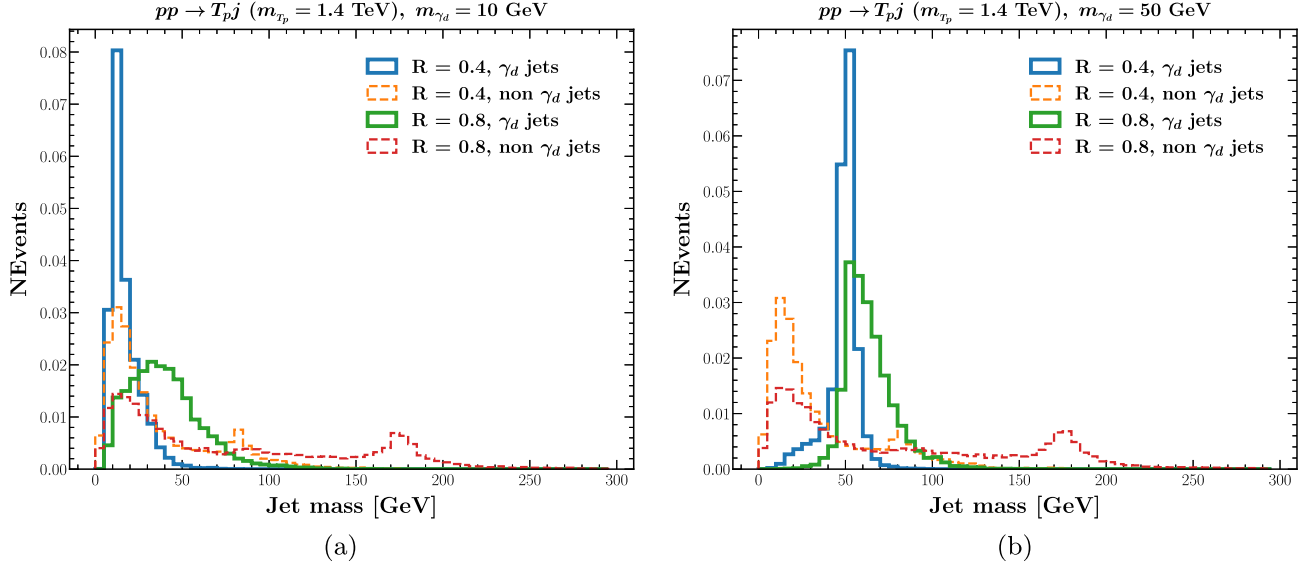


FIG. 10. Jet mass distribution for two clustering radii, 0.4 and 0.8, comparing dark photon jets and nondark photon jets. The top partner mass is fixed at 1.4 TeV, while the dark photon mass is varied as follows: (a) 10 GeV, (b) 20 GeV.

- (4) *Pixelating the image*: Finally, the image is discretized the region into a 16×16 grid with each pixel weighted by the sum of the transverse momentum in it.

This preprocessing sequence results in more uniform and comparable jet images, which are useful in helping the HDNN model to learn a standardized and coherent set of data. Moreover, the average jet images as shown in Fig. 11 give a visual representation of the preprocessed images for the dark photon and nondark photon jets in the $\Delta\eta - \Delta\phi$ plane.

3. Constituent level input

The figures in this section display average jet images (averaged over 10,000 individual jet images) that give a visual representation of the p_T deposition of jet constituents in the $\Delta\eta - \Delta\phi$ plane for both dark photon jets and nondark photon jets. The images are prepared with two different granularities, both having 16×16 pixels size.

In Figs. 11(a) and 11(b) we depict the jet images with a granularity of 0.1×0.1 covering a $\Delta\eta - \Delta\phi$ range from -0.8 to 0.8 for the dark photon jets and nondark photon jets, respectively. These images include contributions from all the charged, neutral hadrons and photons, capturing the full hadronic content and providing a comprehensive representation of the jet's internal structure. Such an image captures the correlation of transverse momentum of the jet constituents with the pseudorapidity and azimuthal angle making it a key component in differentiating between the dark photon jets and nondark photon jets.

On the other hand, in Figs. 11(c) and 11(d), we present jet images with a finer granularity of 0.025×0.025 over a smaller $\Delta\eta - \Delta\phi$ range from -0.2 to 0.2 . These images

include only the contributions from charged hadrons and photons. Such a finer resolution is possible if one couples the information of the ECAL energy deposition of the photons and HCAL energy deposition of the charged hadrons along with the tracker information associated with the charged hadrons. This higher resolution allows for a more detailed examination of the jet core, where most of the transverse momentum is concentrated in the actual dark photon initiated jet. These two layers will act as two channels of the image input to the CNN part of HDNN architecture.

4. Jet level input

The jet level features shown in Fig. 12 play an important role in differentiating a dark photon jet from jets initiated by particles other than the dark photon. Figure 12(a) shows the transverse momentum (p_T) distribution, Fig. 12(b) examines the p_T fraction, i.e., the ratio of total p_T within a cone of radius 0.2 around the jet center to that within the entire AK4 jet for the parton level tagged dark photon jet and nondark photon jets coming from the signal ($T_p j$) itself and other SM background processes. The later variable highlights the amassing of transverse momentum for the actual dark photon jet within the jet core and is particularly significant in capturing the more highly collimated p_T depositions. Figure 12(c) focuses on charge multiplicity, i.e., the number of charged hadrons within the potential dark photon jet candidate. Finally, the charge multiplicity fraction, i.e., the ratio of the number of charged hadrons within a cone of radius 0.2 around the jet center to that within the entire AK4 jet is shown in Fig. 12(d). All these features enhance the ability to differentiate a dark photon jet from other nondark photon jets.

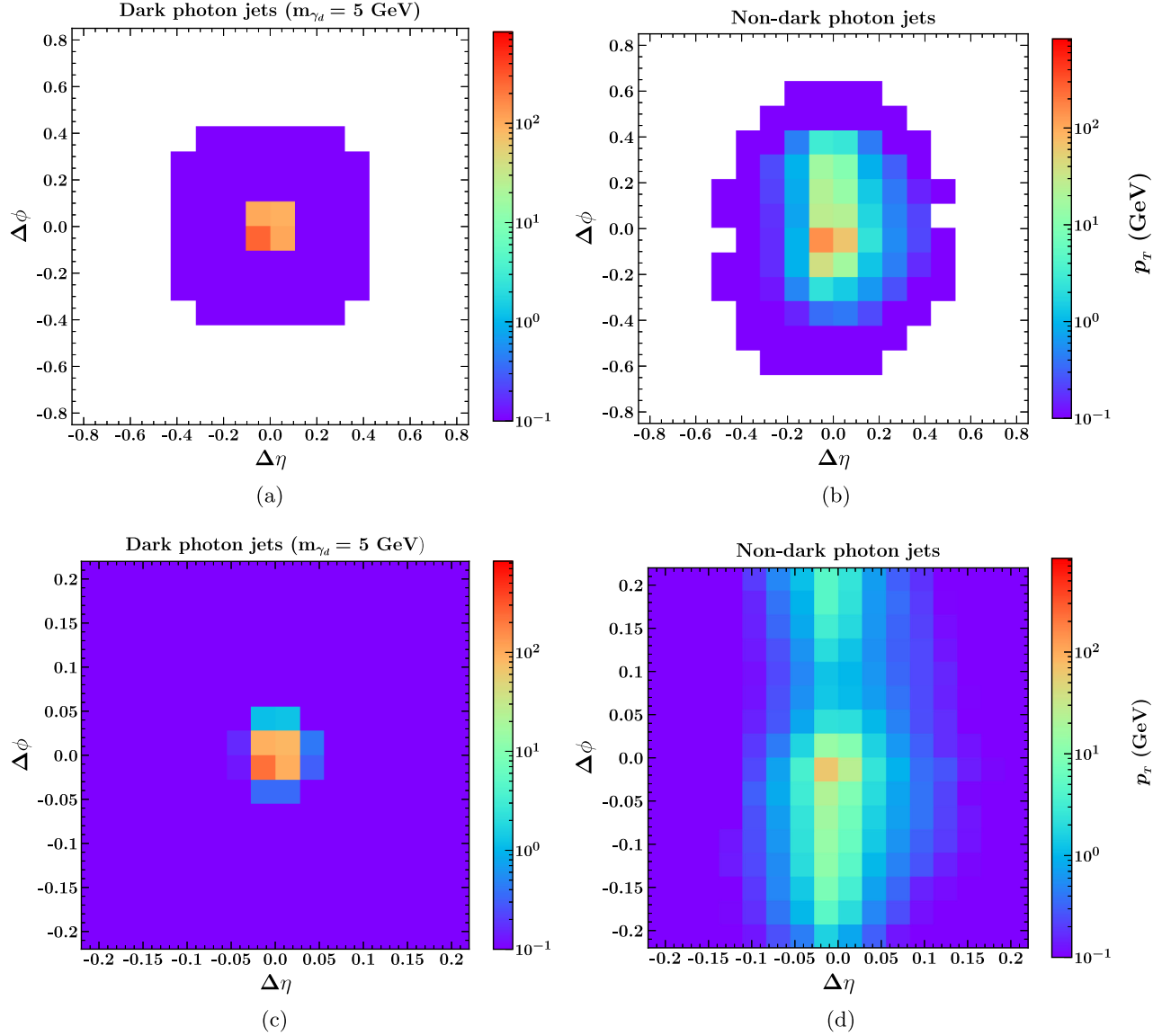


FIG. 11. Average jet images for (a) true dark photon jets ($m_{\gamma_d} = 5$ GeV) and (b) nondark photon jets in the $\Delta\eta - \Delta\phi$ plane in the range -0.8 to 0.8 with granularity of 0.1×0.1 assuming $m_{T_p} = 1.4$ TeV. (c) and (d) represents the same as in (a) and (b) respectively, but in the $\Delta\eta - \Delta\phi$ range of -0.2 to 0.2 with granularity of 0.025×0.025 . Both the images above are obtained by using AK4 jets with p_T -scheme recombination.

5. Network architecture

The model is built to effectively process both jet images and jet-level features, making it well-suited for tasks like jet classification or tagging. The jet images are structured as $16 \times 16 \times 2$ arrays, where the individual 16×16 array represents each channel as mentioned earlier. The image input undergoes several convolutional layers, starting with a 2D convolutional layer with 32 filters and a 3×3 kernel. We also use additional padding to preserve the original image size allowing the network to preserve the spatial information throughout the layers. After this, the dimension of the array becomes $16 \times 16 \times 32$. The convolution operation is followed by a parametric rectified linear unit

(PReLU) activation which introduces nonlinearity, and helps the model capture complex patterns in the data. Next, another 2D convolutional layer with 64 filters is applied. The array dimension now changes $16 \times 16 \times 64$ at this stage. A third 2D convolutional layer with 64 filters is applied before the image is flattened into a 1D vector of shape 16384, converting the spatial features into a vector that can be combined with the jet-level features. Simultaneously, the jet-level features, representing kinematic variables like jet p_T , charge multiplicity, p_T and charge multiplicity fractions, are processed through a multilayered perceptron with 64 neurons and PReLU activation. This transformation results in a latent space

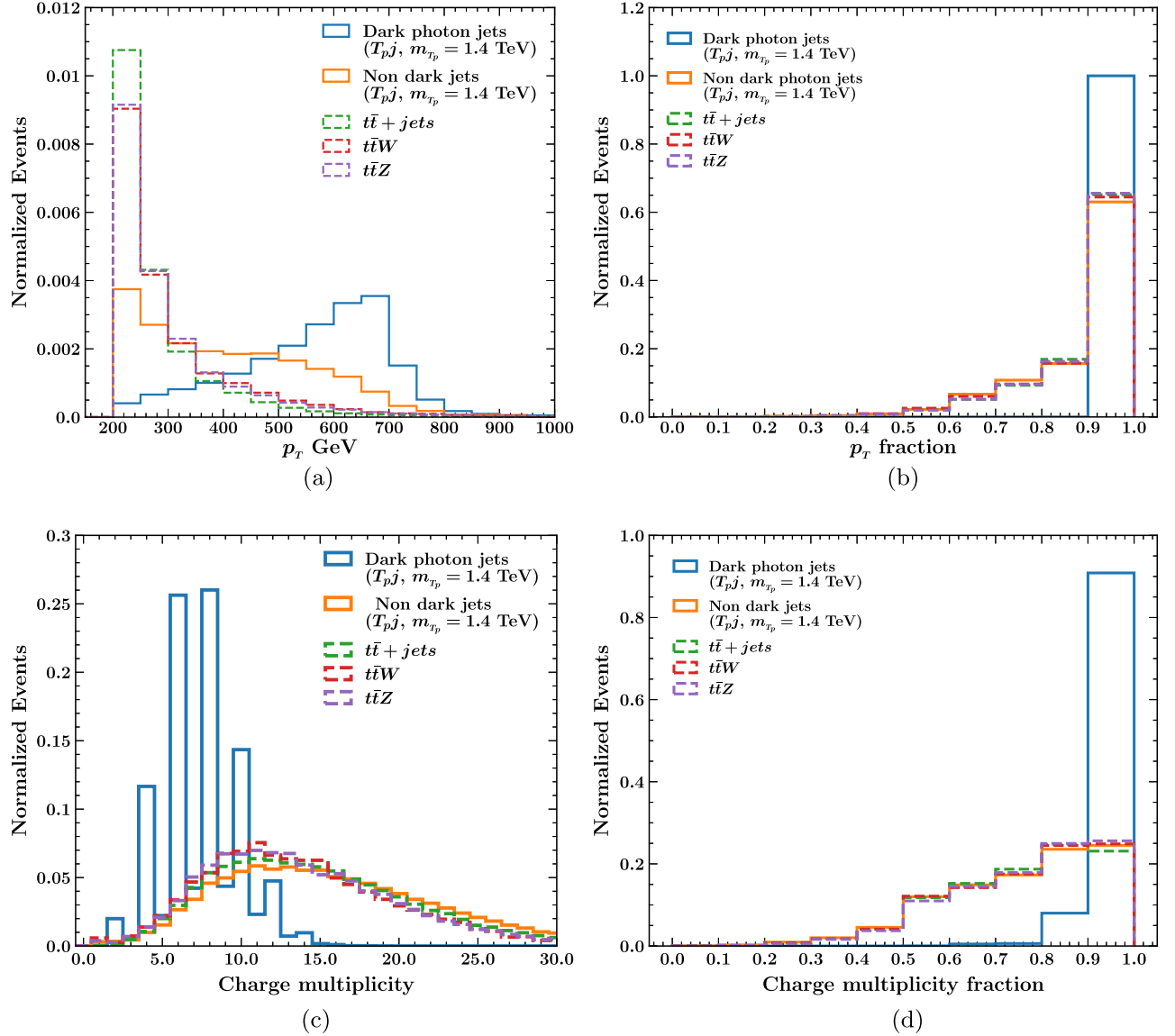


FIG. 12. (a) p_T distribution, (b) ratio of total p_T within a cone of radius 0.2 around the jet center to that within the entire AK4 jet, (c) charge multiplicity distribution, and (d) ratio of the number of charged hadrons within a cone of radius 0.2 around the jet center to that within the entire AK4 jet for the parton level tagged dark photon jet and nondark photon jets coming from the signal (T_{pj}) itself and other SM background processes.

vector with 64 features, that complements the resultant vector resulting from flattened output from the convolutional neural network part of the HDNN. These two vectors, i.e., one from the flattened jet image and the other from the jet-level features, are concatenated into a combined feature vector. At this point, the model performs dimensionality reduction through a series of fully connected layers. The first dense layer, with 64 neurons and PReLU activation. Another dense layer with 32 neurons follows, further compressing the feature vector. Finally, a dense layer with 16 neurons reduces the feature space further. The final output is generated through a sigmoid activation on a single neuron, providing a probability score between 0 and 1 for binary classification.

This model is particularly effective because it leverages both the spatial information from the jet images and the nonspatial, one dimensional jet-level features. By applying convolutional layers to the jet images, the model preserves the structure of the transverse momentum distribution across the jet, while the dense layers allow for kinematic variables of the jet.

6. Training and validation

The model is trained on a dataset of 240,000 samples, which is split into training and validation sets, with 80% of the data (192,000 samples) used for training and the remaining 20% (48,000 samples) used for validation.

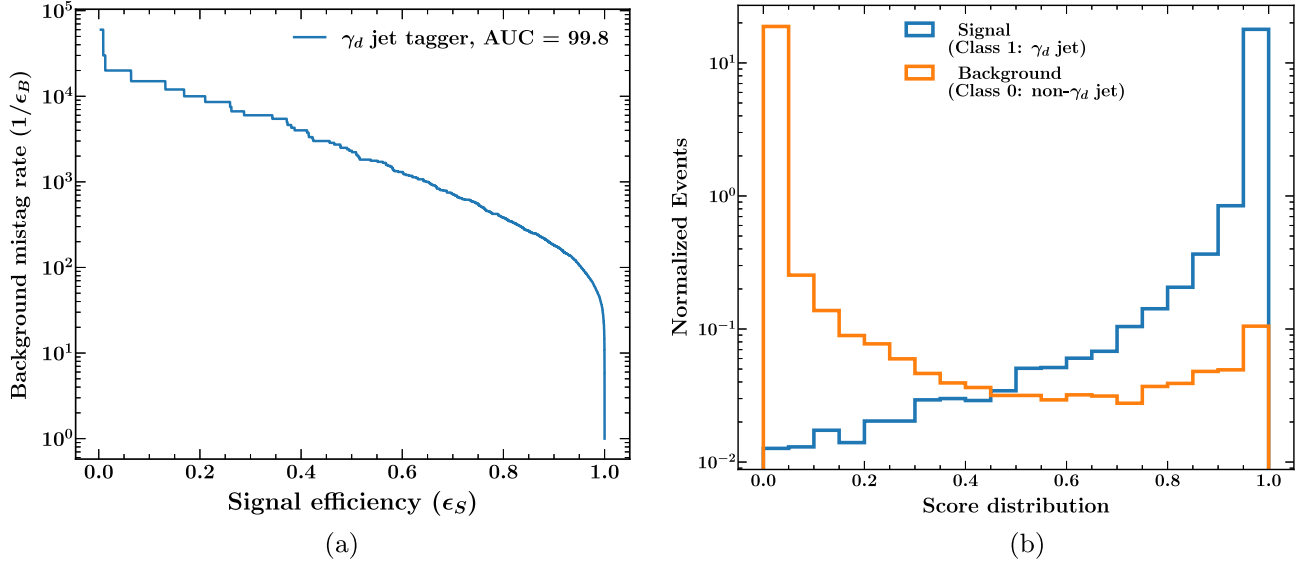


FIG. 13. (a) ROC curve and (b) Score distribution for the test sample containing 60,000 parton level tagged dark photon jets and 60,000 nondark photon jets.

The dataset is generated using a benchmark point $m_{T_p} = 1.4$ TeV, $v_d = 200$ GeV, $m_{h_d} = 400$ GeV, and $m_{\gamma_d} = 5$ GeV, in conjunction with the standard model parameters specified in Eq. (22).

The training dataset includes both signal and background samples. The signal component consists of dark photon-initiated jets, as well as high- p_T ($p_T > 200$ GeV) nondark photon jets, both originating from the $T_p j$ process. In addition, background samples are included from $t\bar{t} +$ jets, $t\bar{t}W$, and $t\bar{t}Z$ SM processes. Each dataset is constructed with an equal admixture of dark photon jets (labeled as 1) and nondark photon jets (labeled as 0), ensuring a balanced training sample.

Additionally, an independent test dataset comprising 120,000 samples is used to evaluate the model's performance. During training, the model is optimized over multiple epochs, each consisting of forward and backward pass.

In each epoch, the training data is fed into the model in batches. During the forward pass, the input data is processed through various layers of the network to produce a binary output. The model's predictions are compared with the actual labels using a binary cross-entropy loss function [85], defined as

$$\text{Loss} = -\frac{1}{N} \sum_{i=1}^N [y_i \log(p_i) + (1 - y_i) \log(1 - p_i)]$$

Where y_i represents the true label, p_i is the predicted probability for the positive class, and N is the number of samples in the batch. This loss function penalizes the model for incorrect predictions, with the penalty increasing as the prediction diverges from the true label.

We use Adam optimizer [86] to update the model's weights based on the gradients of the loss function with respect to the weights, calculated during the backward pass. The gradients are computed using backpropagation, where the error from the loss function is propagated backward through the network, updating the weights to minimize the loss. During training, the model is evaluated on the validation set at the end of each epoch to monitor its performance. We use early stopping, which halts training if the validation loss stops improving for a set number of epochs and learning rate reduction when the validation loss plateaus to prevent overfitting and improve training efficiency. After training, the model's performance is evaluated on a separate test dataset, providing an unbiased estimate of its generalization ability.

7. Model performance

Our test sample contains 60,000 parton level tagged γ_d jets and 60,000 non- γ_d jets images and corresponding jet level feature that were described in Appendix A 4. Other essential parameters used for the test dataset is same as that used for training and validation described in A 6. In Fig. 13, we illustrate the performance of our binary classification model through two key visualizations: the ROC curve and the score distribution for both signal and background events. The ROC curve in Fig. 13(a) provide a comprehensive view of the model's ability to distinguish between γ_d and non- γ_d jets, with the signal efficiency plotted against the background rejection rate across different decision thresholds. A curve that approaches the top-left corner signifies a better-performing model, as it indicates high signal efficiency and strong background suppression. Additionally, the score distribution in Fig. 13(b) shows

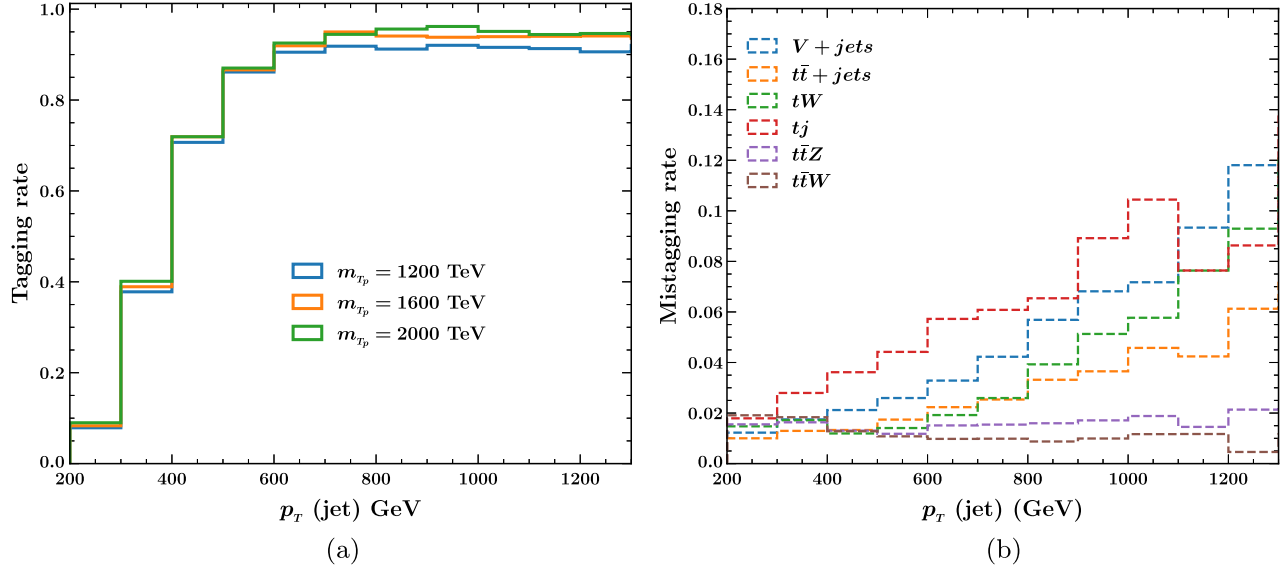


FIG. 14. Tagging and mistagging rates in various transverse momentum bins for (a) parton level tagged dark photon coming from $T_p j$ process and (b) nondark photon jets coming various sources.

the clear separation achieved by the HDNN model to distinguish between a γ_d jet and a non- γ_d jet. Based on the performance of the classifier on the test sample, we set the working point at a threshold of 0.4, achieving a true positive rate of ~ 0.93 and a false positive rate of ~ 0.02 .

8. Efficiency

In Fig. 14, we present the tagging and mistagging rate as a function of jet p_T . We have been able to achieve an average tagging efficiency of 30% to 93% for the true dark photon jet in the top partner mass range, 0.8–2.8 TeV and $m_{\gamma_d} = 10$ GeV for a HDNN classifier that is trained with a sample corresponding to $m_{T_p} = 1.4$ TeV, and $m_{\gamma_d} = 5$ GeV. The average mistagging rate for the corresponding nondark photon jets present in the signal and in the SM background varies in the range 1.0% to 2.6%. For the present work it is more than sufficient to distinguish a high p_T true dark photon initiated jet having some characteristic features described above significantly different from jets initiated by other particles. In this work, we choose this setup to obtain the results quoted in Secs. III and IV.

In Figs. 15 and 16, we present a comparative study of average jet images for the true dark photon jets for different sets of m_{T_p} and m_{γ_d} and two choices of granularity, 0.1×0.1 and 0.025×0.025 , respectively. A close look at Figs. 15 and 16 shows that as the value of m_{T_p} increases, the p_T deposition in the $\Delta\eta$ - $\Delta\phi$ plane becomes more collimated around the center. For m_{T_p} values different from 1.4 TeV, the average jet images exhibit significant variations in their p_T distribution in the $\Delta\eta$ - $\Delta\phi$ plane. However,

for $m_{T_p} > 1.4$ TeV, the difference in jet images compared to $m_{T_p} = 1.4$ TeV is less likely to be captured by the classifier. This is primarily due to the limited resolution of the hadronic calorimeter and the tracker, which makes it harder to distinguish between these more energetic but similarly shaped jets (for a fixed m_{γ_d}).

In contrast, for $m_{T_p} < 1.4$ TeV, the p_T deposition is more diffuse and spread out, extending beyond just a few central pixels in the jet image. This leads to more noticeable differences in the average jet images compared to the $m_{T_p} = 1.4$ TeV case. Instead, they resemble more closely the features of nondark photon jets arising from the signal or Standard Model backgrounds. This qualitative trend is consistent with the estimated tagging efficiencies reported in Tables VIII and IX.

We have chosen to train our HDNN classifier using a dataset corresponding to $m_{T_p} = 1.4$ TeV. However, this is not a rigid choice. The classifier also performs well when trained on samples within the range $1.2 \text{ TeV} \leq m_{T_p} \leq 1.6 \text{ TeV}$, with no significant loss in tagging efficiency for higher m_{T_p} values. The selection of $m_{T_p} = 1.4$ TeV is motivated by the observation that the HDNN classifier maintains stable performance for $m_{T_p} > 1.4$ TeV, while still performing reasonably well at lower values, such as $m_{T_p} = 1.0$ and 1.2 TeV. This robustness is primarily due to the reasons explained above. As expected, the classifier's performance begins to deteriorate significantly when applied to much lower m_{T_p} values, such as $m_{T_p} = 0.8$ TeV.

In Table VIII, we summarize the tagging efficiencies of identifying a true dark photon jet over a wide range of parameter space using a HDNN framework that is

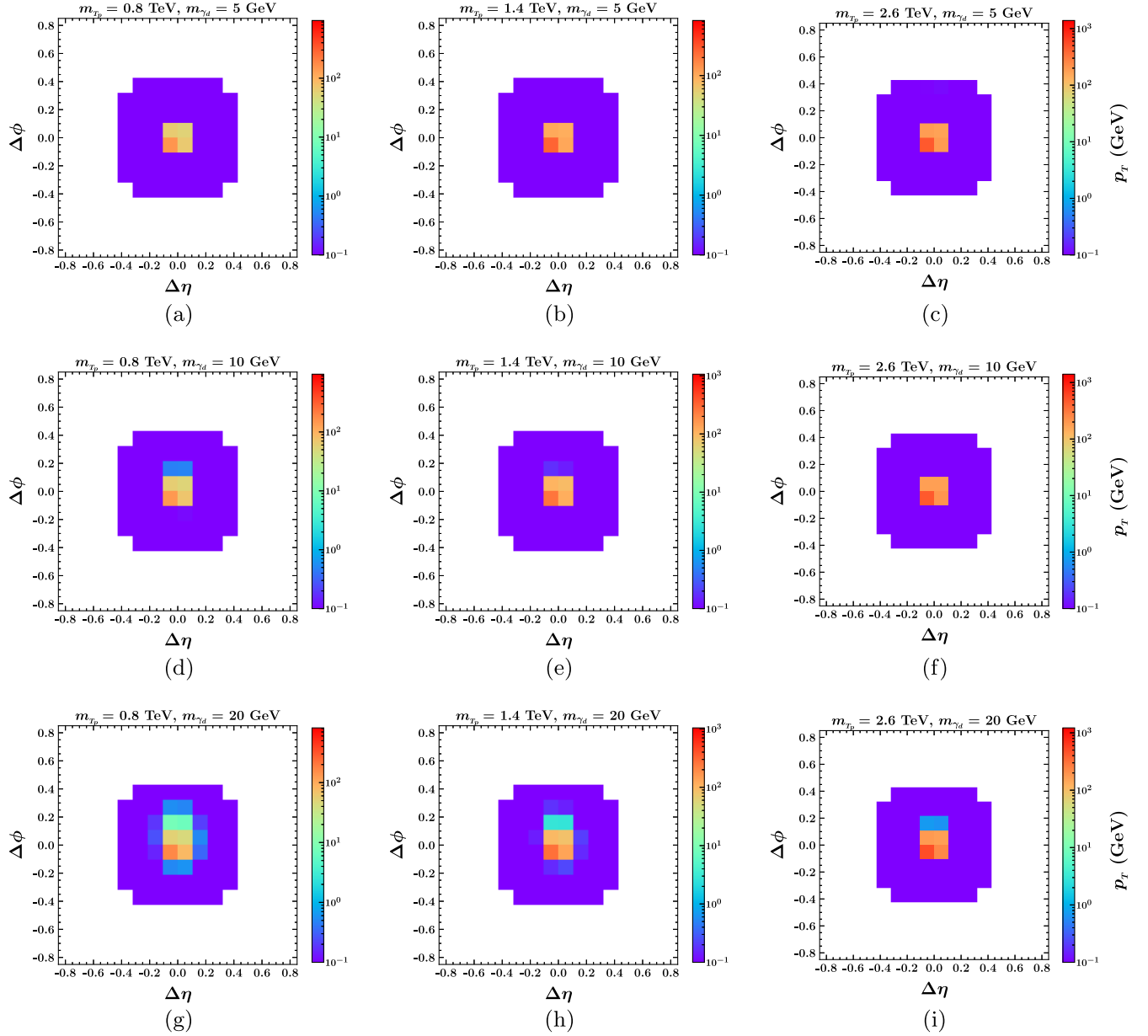


FIG. 15. Average jet images of true dark photon jets in the $\Delta\eta$ – $\Delta\phi$ plane, spanning the range -0.4 to 0.4 with a granularity of 0.1×0.1 . The individual subplots in this figure correspond to different combinations of $[m_{\gamma_d}, m_{T_p}]$ as follows: (a) [5 GeV, 0.8 TeV], (b) [5 GeV, 1.4 TeV], (c) [5 GeV, 2.6 TeV], (d) [10 GeV, 0.8 TeV], (e) [10 GeV, 1.4 TeV], (f) [10 GeV, 2.6 TeV], (g) [20 GeV, 0.8 TeV], (h) [20 GeV, 1.4 TeV], (i) [20 GeV, 2.6 TeV]. The above jet images are obtained by using AK4 jet clustering algorithm with p_T -scheme recombination.

trained over a sample corresponding to $m_{T_p} = 1.4$ TeV, $m_{\gamma_d} = 5$ GeV. The range of parameter space includes m_{T_p} in the range $\{0.8, 2.8\}$ TeV for two different choices of dark photon masses, $m_{\gamma_d} = 5, 10$ GeV. To distinguish dark photon-initiated jets from nondark photon jets, we impose a threshold value 0.4 on the binary classifier probability score. Similarly, Table IX highlights the tagging efficiencies obtained with the same HDNN framework for the same range of parameters as in Table VIII, however, trained over a sample with $m_{T_p} = 1.4$ TeV and $m_{\gamma_d} = 10$ GeV. In this

case, we choose a threshold of 0.48. All other model parameters remain consistent with those detailed in A 6.

We also present the tagging efficiencies for identifying true dark photon jets in Table X, using a HDNN classifier trained over a wide range of dark photon masses ($m_{\gamma_d} = 5, 10$, and 20 GeV) for a fixed top partner mass ($m_{T_p} = 1.4$ TeV). We use a probability threshold value 0.4 to achieve an optimized tagging efficiency for higher values of m_{T_p} comparable to the dedicated classifiers trained on individual dark photon mass values. However,

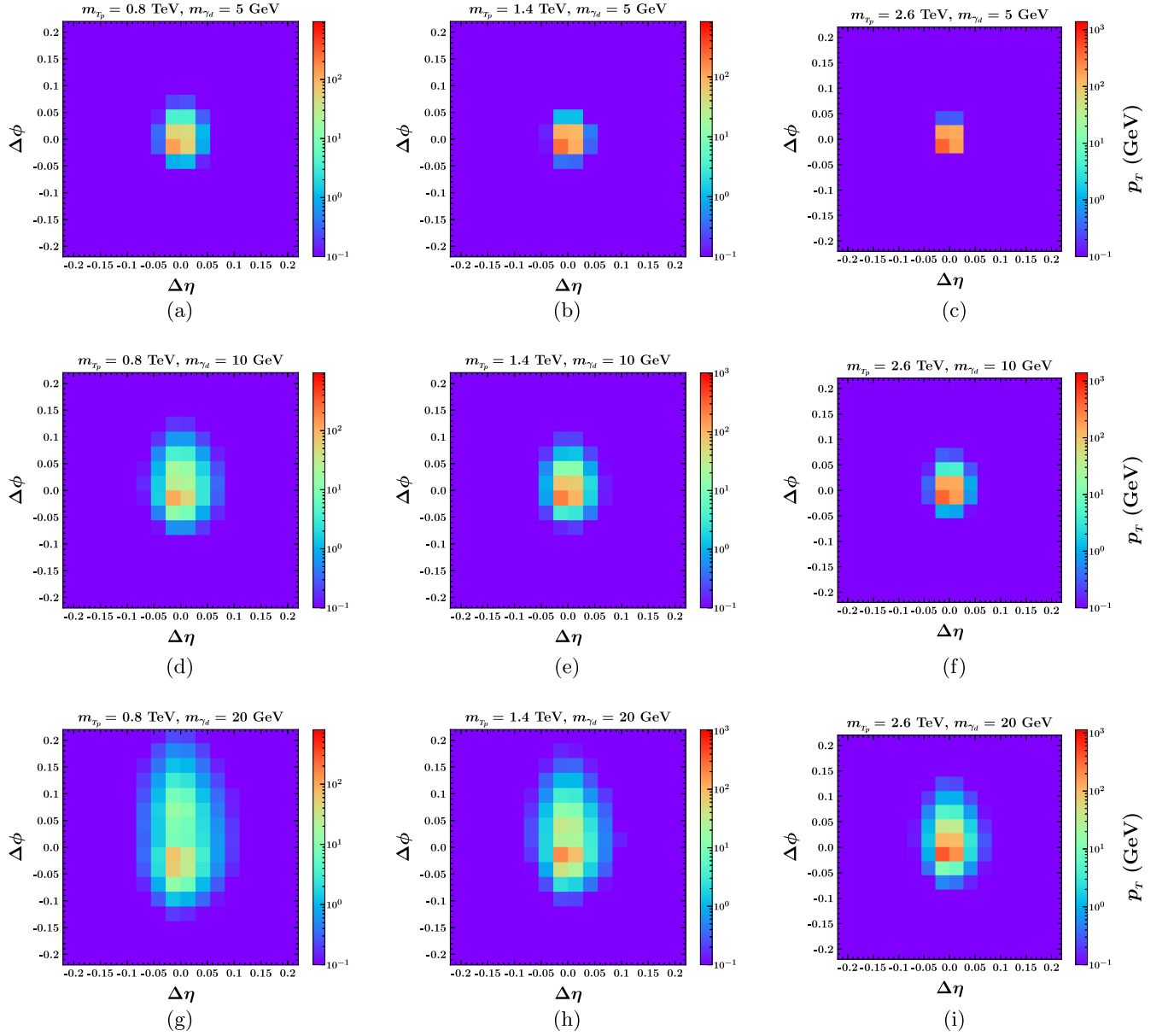


FIG. 16. Average jet images of true dark photon jets in the $\Delta\eta - \Delta\phi$ plane, spanning the range -0.2 to 0.2 with a granularity of 0.025×0.025 . The individual sub-plots in this figure correspond to different combinations of $[m_{\gamma_d}, m_{T_p}]$ as follows: (a) [5 GeV, 0.8 TeV], (b) [5 GeV, 1.4 TeV], (c) [5 GeV, 2.6 TeV], (d) [10 GeV, 0.8 TeV], (e) [10 GeV, 1.4 TeV], (f) [10 GeV, 2.6 TeV], (g) [20 GeV, 0.8 TeV], (h) [20 GeV, 1.4 TeV], (i) [20 GeV, 2.6 TeV]. The above jet images are obtained by using AK4 jet clustering algorithm with p_T -scheme recombination.

TABLE VIII. Identification efficiency of the true dark photon jet for various choices of m_{T_p} in the range, $\{0.8, 2.8\}$ TeV using the HDNN framework for two different dark photon masses. The training sample corresponds to $m_{\gamma_d} = 5$ GeV and $m_{T_p} = 1.4$ TeV as mentioned in the text (see Appendix A 6).

m_{γ_d} (GeV)	m_{T_p} (TeV)							
	0.8	1.0	1.2	1.4	1.6	2.0	2.6	2.8
5	86	89	91	93	94	95	95	95
10	30	51	66	76	82	88	92	93

TABLE IX. The same as in Table VIII, however, the training sample corresponds to $m_{\gamma_d} = 10$ GeV and $m_{T_p} = 1.4$ TeV with all other parameters kept same as mentioned in the text.

m_{γ_d} (GeV)	m_{T_p} (TeV)							
	0.8	1.0	1.2	1.4	1.6	2.0	2.6	2.8
5	59	74	83	87	89	92	94	94
10	77	85	88	91	93	94	95	95

TABLE X. Identification efficiency of the true dark photon jet for various choices of m_{T_p} in the range, $\{0.8, 2.8\}$ TeV using the HDNN framework for different choices of dark photon masses in the range, $\{5, 20\}$ GeV. The training samples correspond to $m_{\gamma_d} = 5, 10$, and 20 GeV with $m_{T_p} = 1.4$ TeV.

m_{γ_d} (GeV)	m_{T_p} (TeV)							
	0.8	1.0	1.2	1.4	1.6	2.0	2.6	2.8
5	88.1	90.5	92.4	93.3	93.9	94.5	94.9	94.9
7	83.7	89.3	90.7	92.8	93.7	94.4	94.9	95.3
10	73.6	83.5	87.3	90.6	92.3	93.7	94.9	94.9
15	63.2	77.2	83.4	87.7	89.6	92.4	94.4	94.2
20	53.5	69.2	79.5	85.2	88.4	91.4	93.3	93.7

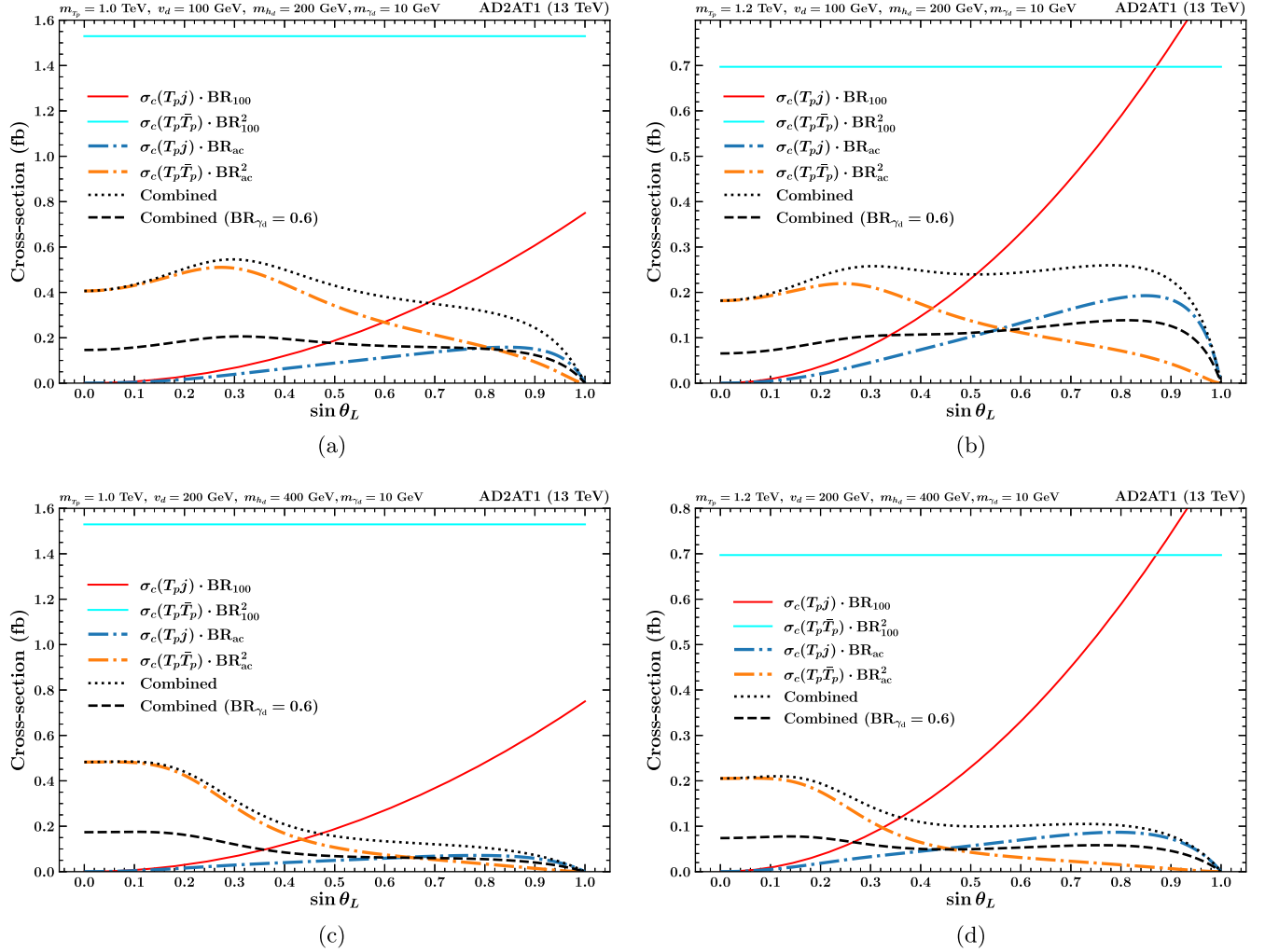


FIG. 17. The solid cyan (red) line represents the contribution to the total cross section in the $AD2AT1$ final state coming from $T_p \bar{T}_p$ ($T_p j$) subprocess after applying the m_{T_p} dependent invariant mass cut listed in Table V assuming $BR(T_p \rightarrow t\gamma_d) = 100\%$. The dashed-dot blue (orange) line depicts the same coming from $T_p \bar{T}_p$ ($T_p j$) after applying the invariant mass cut assuming *actual* $BR(T_p \rightarrow t\gamma_d)$. The dotted black represents the sum of the two contributions with *actual* $BR(T_p \rightarrow t\gamma_d)$. All the curves except dashed black line correspond to $BR(\gamma_d \rightarrow \text{hadrons}) = 100\%$. The dashed black line corresponds to the combined contributions with $BR(\gamma_d \rightarrow \text{hadrons}) = 60\%$. The subplots illustrate four representative benchmark points: (a) and (b) correspond to $v_d = 100$ GeV, $m_{h_d} = 200$ GeV, and $m_{\gamma_d} = 10$ GeV, for $m_{T_p} = 1.0$ TeV and 1.2 TeV, respectively. Similarly, (c) and (d) represent $v_d = 200$ GeV, $m_{h_d} = 400$ GeV, and $m_{\gamma_d} = 10$ GeV, with $m_{T_p} = 1.0$ TeV and 1.2 TeV, respectively.

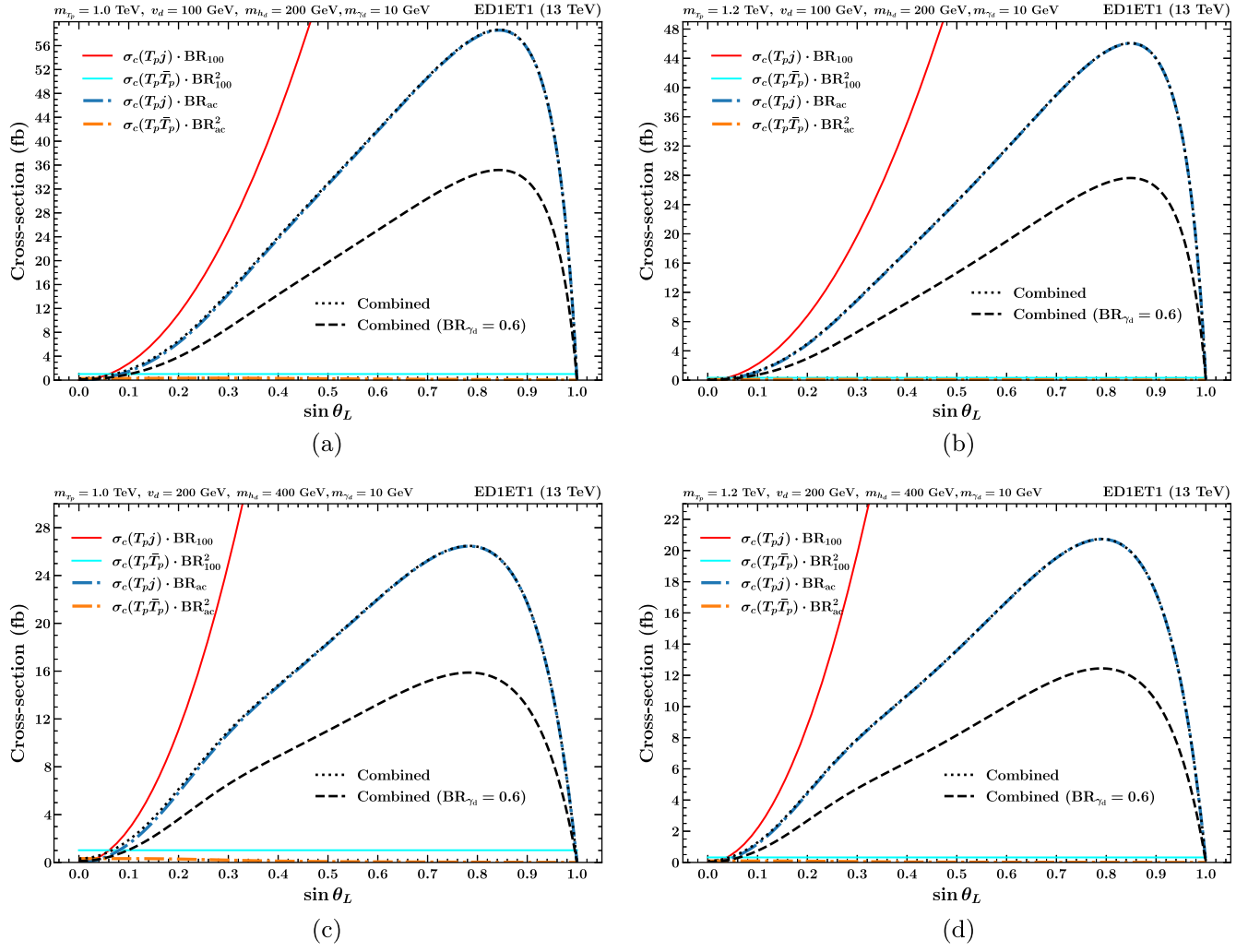


FIG. 18. The solid cyan (red) line represents the contribution to the total cross section in the *ED1ET1* final state coming from $T_p \bar{T}_p$ ($T_p j$) subprocess after applying the m_{T_p} dependent invariant mass cut listed in Table V assuming $\text{BR}(T_p \rightarrow t\gamma_d) = 100\%$. The dashed-dot blue (orange) line depicts the same coming from $T_p \bar{T}_p$ ($T_p j$) after applying the invariant mass cut assuming *actual* $\text{BR}(T_p \rightarrow t\gamma_d)$. The dotted black represents the sum of the two contributions with *actual* $\text{BR}(T_p \rightarrow t\gamma_d)$. All the curves except dashed black line correspond to $\text{BR}(\gamma_d \rightarrow \text{hadrons}) = 100\%$. The dashed black line corresponds to the combined contributions with $\text{BR}(\gamma_d \rightarrow \text{hadrons}) = 60\%$. The subplots illustrate four representative benchmark points: (a) and (b) correspond to $v_d = 100$ GeV, $m_{h_d} = 200$ GeV, and $m_{\gamma_d} = 10$ GeV, for $m_{T_p} = 1.0$ TeV and 1.2 TeV, respectively. Similarly, (c) and (d) represent $v_d = 200$ GeV, $m_{h_d} = 400$ GeV, and $m_{\gamma_d} = 10$ GeV, with $m_{T_p} = 1.0$ TeV and 1.2 TeV, respectively.

this approach normally results in a higher background mistagging rate. Additionally, we depict the model's performance on intermediate mass points ($m_{\gamma_d} = 7$ GeV and 15 GeV) to assess its generalization capability beyond the specific training points in the same table.

The HDNN classifier yields an improved tagging (mistagging) efficiencies when compared with that obtained by a simple cut-based selection—where a jet is identified as a dark photon-initiated jet if its $p_T \geq 400$ GeV and both the p_T fraction and charge multiplicity fraction exceed 0.8 . For $m_{T_p} = 1.4$ TeV and $m_{\gamma_d} = 10$ GeV, the naive cut based

analysis yields a tagging efficiency of approximately 63% , albeit with a significantly higher average mistagging rate of $\sim 11\%$.

APPENDIX B: DEPENDENCY OF $\sigma_c(T_p \bar{T}_p) \cdot \text{BR}^2$ AND $\sigma_c(T_p j) \cdot \text{BR}$ ON $\sin \theta_L$

In this section, we illustrate the $\sin \theta_L$ dependency of the signal cross section obtained after imposing the C_0 cuts in two different final states, namely, AD2AT1 in Fig. 17 and ED1ET1 in Fig. 18.

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