Boosted top quark polarization

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In top quark production, the polarization of top quarks, decided by the chiral structure of couplings, is likely to be modified in the presence of any new physics contribution to the production. Hence, it is a good discriminator for those new physics models wherein the couplings have a chiral structure different than that in the Standard Model. In this paper, we construct probes of the polarization of a top quark decaying hadronically, using easily accessible kinematic variables such as the energy fraction or angular correlations of the decay products. Tagging the boosted top quark using the jet substructure technique, we study the robustness of these observables for a benchmark process, $W' \to tb$. We demonstrate that the energy fraction of b jet in the laboratory frame and a new angular variable, constructed by us in the top rest frame, are both very powerful tools to discriminate between the left and right polarized top quarks. Based on the polarization-sensitive angular variables, we construct asymmetries that reflect the polarization. We study the efficacy of these variables for two new physics processes that give rise to boosted top quarks: (i) the decay of the top squark in the context of supersymmetry searches and (ii) decays of the Kaluza-Klein (KK) graviton and KK gluon, in the Randall-Sundrum model. Remarkably, it is found that the asymmetry can vary over a wide range about +20% to −20%. The dependence of asymmetry on top quark couplings of the new particles present in these models beyond the SM is also investigated in detail.

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I. INTRODUCTION

The top quark is an interesting object in the standard model (SM), since it is the heaviest known fermion and it has the strongest coupling with the Higgs boson, close to unity. It decays before hadronization, and hence soft QCD effects do not wash out its spin information, and the decay product kinematic distributions reflect the same. Because of its large mass, the top quark can be closely related to the phenomenon of electroweak symmetry breaking. This may be in either the context of the Higgs model or any alternative mechanism by which fundamental particles acquire masses. Therefore, understanding the properties of the top quark, specifically the Lorentz structure of its couplings, responsible both for the production and decay has always received special attention [1,2] and holds the potential of offering us a glimpse of beyond the SM (BSM). To this end, an important and interesting property is its polarization, which is reflected in the kinematics of its decay products.

In hadron colliders, top quarks are produced as $t\bar{t}$ pairs via strong interaction or in association with a b quark or W boson via electroweak interaction. Note that in the case of pair production the top quarks are mostly unpolarized, due to the vector nature of the dominant QCD couplings, although their spins are correlated. These spin-spin correlations are studied quite well, both theoretically and experimentally [3–9]. On the other hand, the produced single top quark is polarized, and in the SM, it is purely left chiral due to the V-A nature of the $t-b-W$ interaction. Any modification of the tensor structure of this interaction at the production vertex deviating from the SM would

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change the polarization of the produced top quark. Hence, the measurement of polarization of the top quark is expected to be a good probe of new physics in interactions responsible for the production of the top quark. Angular distribution of decay products, in particular the visible lepton from its semileptonic decay, is found to carry polarization information of the parent top quark [10]. Extraction of polarization information of top quark by exploiting the various kinematic distributions of charged lepton is discussed in great detail in the literature [10–17]. Moreover, top polarization also has been studied well using the matrix element method [6,18–20]

In this study, we attempt to develop a strategy to measure the top quark polarization in its hadronic decay, in particular when it is boosted. The main motivation of this study is in the context of new physics searches for scenarios in which decay of a heavy particle results in a top quark that is boosted, and in principle also polarized. To be specific, we consider a few new physics processes, in which polarized top quarks originate from heavy particles such as W', top squark ($\tilde{t}$, the superpartner of top) and Kaluza-Klein states in extra-dimension models. The polarization of the produced top depends on the chiral structure of the respective couplings responsible for the decay of the new physics particle. In view of the current exclusion limits on these particles, it is clear that the top quarks produced in the decay would be highly boosted. All the decay products from boosted top quarks emerge in a single cone along the direction of top quark without much angular separation, which makes it difficult to construct clean polarization-sensitive observables. Thus, the measurement of polarization of the boosted top quark, though a challenging task, is of great importance for developing a tool to probe the nature of top couplings with new particles in the context of new physics searches. Ideally, as we mentioned already, the semileptonic decay mode of the top quark is very well suited for studying the spin effects, as the charged lepton with the largest spin analyzing power is easy to identify and is not affected much by soft QCD radiation [10]. Equally importantly, angular distribution of the lepton with respect to the spin direction for a polarized top quark is unchanged by anomalous tbW couplings, to linear order [11–14,21], and hence is a good probe of top polarization unaffected by new physics in decay. The price to pay for the leptonic decay is a low branching ratio, and difficulties in finding an isolated lepton originated from a boosted top. In addition, the presence of multiple sources of missing energy makes it difficult to reconstruct the top quark momentum. Reconstruction of the top quark momentum for leptonic decay, even in the presence of many sources of missing energy, is likely to be feasible but needs a very nontrivial algorithm [22].

These arguments prompt us to conclude that the hadronic decay mode of top quark is the favored over the leptonic decay mode for studying polarization of boosted top quarks as this decay mode provides the possibilities of accurate top momentum reconstruction. The down-type quark from W decay plays the same role as the charged lepton (in leptonic decay mode) in the spin studies. It is to be noted that the reconstruction of subjets and their identification, in particular, the subjet associated with the down-type quark from W decay, involve a certain level of uncertainties. The decay products of the boosted top quark in its hadronic channel are identified by employing the powerful technique of jet substructure analysis [23]. In this paper, we discuss how the polarization of the boosted top quark in its hadronic decay mode can be measured by constructing the polarization-sensitive observables out of the momenta of subjets inside the reconstructed top jet. Polarization of boosted tops using jets at the substructure level has been discussed in the literature [19,24–30].

For hadronically decaying polarized top quarks, the down-type quark from W decay with the largest spin analyzing power is mostly softer than the other two quarks in the top rest frame, as its momentum is opposite to the boost direction of the W due to the angular correlations. Certainly, in this analysis, the main challenge is to retrieve the identity of this quark as accurately as possible. Many interesting proposals, in this context, are summarized in Ref. [19]. Notably, in this paper, we propose a new axis taken as the weighted average of the two jet axis, in which the weights are given by the probability obtained from the decay matrix element. Interestingly, there are observables [28] that could discriminate left and right polarized boosted hadronically decaying top quarks without requiring W reconstruction or b-jet identification. In this case, subjets with good spin-analyzing power are identified by requiring the corresponding pair of subjets with the minimum k_T distance. In our study, focusing on the single-top polarization effects, first, we revisit some of these observables, namely, the energy fraction of top quark decay products, proposed in earlier studies [28], and their role as a polarimeter. Currently, tagging of high p_T b jets using multivariate analysis techniques with reasonable efficiency is not difficult, as shown by experimental studies [31,32]. Therefore, we employ the energy fraction of tagged high p_T b jets as one of the useful polarimeters [33]. In addition to these energy fraction observables, we also propose a robust polarization-sensitive variable related indirectly to the angular distribution of the selected subjet corresponding to the down-type quark from W decay. Experimentally, it is not very difficult to measure this variable event by event. Exploiting this observable, an asymmetry of the event can be predicted, which may reflect the polarization of the decaying top unambiguously. We demonstrate the impact of the polarization-sensitive observables discussed above by choosing the benchmark process

$$pp \to W' \to tb, \tag{1}$$

where the W' gauge boson couples with both left- and right-handed top quark, which is assumed to decay, $t \to bW$ with

100% branching ratio. We simulate the process of Eq. (1) and study the observables that have the potential to discriminate between left and right polarized top quarks. After demonstrating efficacy of these variables as a polarimeter for completely polarized top quarks, we use them in situations in which the top polarization has a value different from ± 1. For example, each of the top squark produced in pairs at the LHC decay to top quarks accompanied by the lightest neutralino ($\tilde{\chi}_1^0$), $\tilde{t}_1 \to t\tilde{\chi}_1^0$ [9]. The polarization of this top quark is controlled by the $\tilde{t}_1 - t - \tilde{\chi}_1^0$ coupling, which has both gauge and Yukawa types of interactions. A detailed study shows how the polarization of the top quark from top squark decay can be identified by measuring the asymmetry of events. The dependence of this asymmetry and its sensitivity to the variation of this coupling strength is investigated. This study reveals how the polarization of the top quark could shed some light on the $\tilde{t}_1 - t - \tilde{\chi}_1^0$ couplings in supersymmetric (SUSY) theories. Similar studies are also carried out in the process in which polarized top quarks are produced from the decay of Kaluza-Klein (KK) excited states.

The paper is organized as follows. In Sec. II, we briefly discuss the kinematics of decay products in the context of polarized top decays, Then, in Sec. III, we identify observables that can be used to obtain information about the polarization of the top quark. In Sec. IV, we study the application of the proposed variables in top squark decay that can produce top quarks that are not necessarily completely polarized. In Sec. V, similar studies are carried out in the context of the Randall-Sundrum (RS) model in which polarized top quarks are produced in the decay of new resonances. Finally, in Sec. VI, we summarize our results.

II. POLARIZED TOP QUARK DECAYS

It is instructive to briefly review the effect of top polarization on the kinematics of its decay products before we proceed further in discussing our results. In the SM, the top quark has an approximately 70% branching fraction for the hadronic channel, $t \to bW^+ \to bu\bar{d}$, where the $u(\bar{d})$ quark represents the up- (down-)type quarks. The angular distribution of any of the decay products from the top quark (in the top rest frame) can be written as [34]

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}(1 + \mathcal{P}_0\kappa_f\cos\theta_f), \qquad (2)$$

where κ_f is the spin-analyzing power of the respective decay particles, i.e., $f = b$, $\bar{d}$, u, and W. $\mathcal{P}_0$ is the polarization of the decaying top [24,35–37] ($-1 \le \mathcal{P}_0 \le 1$). Here, θ_f is the angle between the fermion (or W) and top spin direction, in the top quark rest frame. The spin-analyzing power κ_f can be calculated, and its values are given by $\kappa_{\bar{d}} = 1$, $\kappa_u \approx -0.3$, and $\kappa_b \approx -0.4$ at tree level in the SM [10]. Notice that when the top decays hadronically the down-type quark ($\bar{d}$) has the maximum spin-analyzing power; i.e., it is strongly correlated with the top spin. However, the b quark is also a good candidate with $\kappa_b \approx -0.4$ for studying the top polarization. In principle, the reconstructed W, with spin-analyzing power opposite that of the b quark ($k_W \approx 0.4$), in the top quark rest frame can also serve as a good top spin analyzer. Therefore, the kinematic distribution of the down-type quark or b jet (or W) is expected to provide a considerable handle for studying top polarization, and we take the spin direction of the top to be quantized along its momentum direction. The corrections to the tree-level values of spin-analyzing power of hadronic decay products are found to be at the level of 3%–4% [18,38].

As pointed out earlier, the identification of the subjet corresponding to the $\bar{d}(d)$ quark from $W^+(W^-)$ decay having maximum spin-analyzing power is nontrivial, especially in the busy environment of the hadron collider and in particular when the three jets are not well separated because of large boost of the parent top quark. To this end, we use the different methods to identify the subjets with large spin analyzing power:

(1) One choice is the subjet which is aligned along the b-like subjet and therefore has the minimum invariant mass with the b-like subjet.
(2) The second choice is to find the subjet pair which have minimum k_T distance between them and choose the harder of these two.
(3) The third choice is the b-like subjet itself which is a good candidate for the top polarization studies, provided it can be tagged, even at high momenta.

Furthermore, in this context, we propose a new observable indirectly related to the angular distribution of the decay products of a top quark, which turns out to be very robust in measuring the top polarization. To construct this observable, the b-like subjet inside the tagged top jet is identified after reconstructing the W mass out of three subjets. We label the constituent subjets of reconstructed W as j_1 and j_2 such that $m_{bj_1} < m_{bj_2}$. Indeed, approximately 50% to 60% [18,19] of cases j_1 will act as a proxy for the parton-level d quark, which has the maximum spin-analyzing power. The momentum direction of j_1 is guided by the polarization of the top quark. In the laboratory frame, the direction of momentum and the spin of the top jet are opposite to each other for left-handed top quark and in the same direction for the right-handed top quark. Hence, the angular correlation between the momenta of j_1 subjet and top jet is expected to show the effect of polarization of the parent top quark. With this understanding, we construct the observable, namely, $\cos\theta^\star$, defined as

$$\cos\theta^* \equiv \frac{\vec{t}_j \cdot \vec{j}_1{}'}{|\vec{t}_j||\vec{j}_1{}'|}, \qquad (3)$$

where $\vec{t}_j$ is the momentum of the reconstructed top jet in the laboratory frame and $\vec{j}_1{}'$ is the subjet momentum in the top jet rest frame. Essentially, this variable is defining the direction of the momentum of the subjet j_1 in the top rest frame, with respect to the direction of top jet momentum in the laboratory frame. Hence, identifying the momentum of the subjet j_1, following the above method, the angular variable $\cos\theta^*$ can be computed easily. In the next section, we demonstrate the robustness of $\cos\theta^\star$ along with other kinematics observables as presented above, considering a benchmark process, Eq. (1).

III. BOOSTED TOP POLARIZATION

The top quark produced through the decay of a heavy BSM particle [Eq. (1)] is expected to be boosted. Hence, the decay products of the top will be collimated and form a single fat jet of large cone size. Identification of boosted objects using the jet substructure technique is now very well established and tested [23,39–43]. In this technique, top jets are tagged by finding the substructures of fat jets following the Butterworth-Davison-Rubin-Salam (BDRS) mass drop [23] and filtering method using HEPTopTagger2 [23,39–42].

The matrix element for the benchmark process, Eq. (1), is generated using the FeynRules [44] corresponding to the W' effective model [45] in MadGraph_aMC@NLO [46] at $\sqrt{s} =$ 13 TeV to generate the left-handed and right-handed top quarks via the s channel. It is to be noted that the whole process up to the top decays to jets is treated in the matrix element and hence the production and decay are not factored separately, which ensures accurate treatment of finite widths and interference terms with the spin effects. The partonic events are then showered using PYTHIA8 [47,48]. This model is an extension of the SM, including an additional interaction of fermions to the W' boson following the lowest-order effective Lagrangian, described in Refs. [49,50],

$$\mathcal{L} = \frac{V_{ij}}{2\sqrt{2}} \bar{f}_i \gamma^\mu (g_R(1+\gamma_5) + g_L(1-\gamma_5)) W'_\mu f_j + \text{H.c.} \quad (4)$$

It is clear from the above equation that the coupling strengths, g_R and g_L, decide the polarization of the produced top quark in W' decay. For instance, if $g_L = 1$ and $g_R = 0$, the produced top quark will be left chiral, and if $g_L = 0$ and $g_R = 1$, it will be right chiral. For the case, $m_{W'} \gg m_t$, the produced top is highly boosted, and hence its helicity (polarization) is almost the same as its chirality. In the simulation, fat jets are reconstructed using the Cambridge/Aachen (C/A) algorithm, setting the jet size parameter $R = 1$ and requiring transverse momentum $p_T >$ 200 GeV and $|\eta| < 4$. Generated events consisting of fat jets are passed through HEPTopTagger2 to tag top jet by the Butterworth-Davison-Rubin-Salam mass drop method using the default set of parameters for mass cuts and filtering. The correspondence of the parent top quark with the reconstructed top jet is ensured by matching with cone

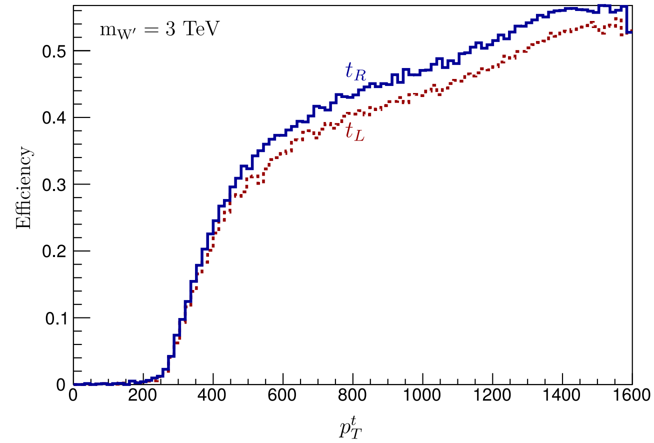

FIG. 1. Top tagging efficiency for left (t_L) and right chiral (t_R) top quark for the process $pp \to W' \to tb$ with $m_{W'} = 3$ TeV.

size $\Delta R = 0.3$. As mentioned in earlier sections, the momentum distribution of subjets of the boosted top quark are guided by its state of polarization. This fact leads to a difference in the tagging efficiency for the left- and right-handed top quarks, as also reported by the ATLAS Collaboration [51]. We also observed this difference as shown in Fig. 1, the top tagging efficiency for both left-handed and right-handed cases as a function of p_T of the parent top quark.

As can be seen from Eq. (2) and the following discussion on spin-analyzing power, in the case of right-handed top quarks (in the laboratory frame), the $\bar{d}$ quark is more boosted, while the other two quarks (b and u) are less boosted, and hence more separated as compared to left-handed tops in which b and u quarks are more boosted and hence less separated. This implies that in the case of right-handed top quarks the subjets are better separated than for the case of left-handed top quarks. This difference of kinematics for left-handed and right-handed tops leads to a small difference in top tagging efficiency, as seen from Fig. 1.

Now, we present the kinematic observables discussed in the previous section, which could be used to distinguish the left- and right-handed boosted top. In a first step, we study the energy fraction variable (z_k), which is also suggested in Ref. [28]. As stated before, the jet corresponding to $\bar{d}$ is relatively harder for the right-handed (helicity) top, and the b-like jet is harder when it is left handed (helicity). With this understanding, we define and then examine the z_k variable. The tagged top jet corresponding to the top quark contains at least three subjets. Among the three possible combinations, the pair of subjets having the smallest k_T distance is identified. The k_T distance d_{ij} is defined as

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) R_{ij}^2, \quad (5)$$

where $R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$. The energy fraction of the harder jet j_k of this pair having smallest k_T is defined as z_k [28], i.e.,

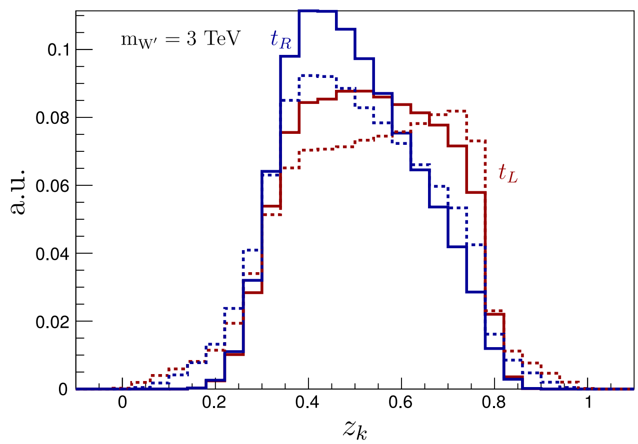

FIG. 2. The energy fraction z_k [Eq. (6)] for the left- (red) and right-handed (blue) top quarks for $m_{W'} = 3$ TeV. The dashed lines correspond to the observable at the partonic level.

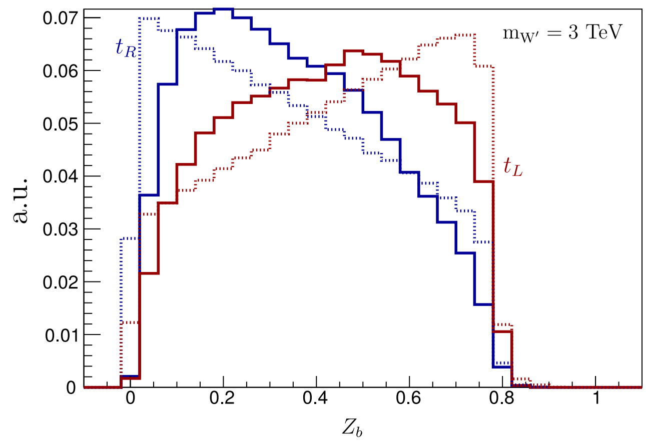

FIG. 3. Energy fraction of b-like subjet for partonic (dashed) and reconstructed top jet using HEPTopTagger2 (solid).

$$z_k = \frac{\max(E_i, E_j)}{E_t}, \tag{6}$$

for i, j such that d_{ij} is minimum, and E_t is the energy of the top jet, acts as a good polarimeter [28].In order to understand how the z_k works, we also compute it using the partonic- (truth-)level information. Both the results are presented in Fig. 2, in which the energy fraction z_k is shown (solid) along with the truth-level distribution (dashed) for both the left- and right-handed top quarks originating from W' decay. As expected, it is seen that by matching subjets with the parton-level quarks, about 50% of the cases, the algorithm chooses b-like subjets for the left-handed top quarks case and d-like subjets for the right-handed top quarks.

As mentioned in the previous section, the $\bar{d}$ quark is maximally correlated with the top spin; hence, for the left-handed top (in the laboratory frame), the $\bar{d}$ quark tends to be soft. Thus, the minimum k_T pair tends to involve the $\bar{d}$-like subjet, and the other one is mostly b like with comparatively harder energy. For right-handed top quark case, we observe mostly the same kind of pairing, but with a harder $\bar{d}$-like subjet and softer b-like subjet.

Notice that the shape of z_k distribution is not so different from partonic level at the intermediate values of $z_k \approx 0.5$. Thus, the energy fraction variable z_k can play the role of a polarimeter in differentiating the left- and right-handed top quark.

We present another observable, the energy fraction of b-like subjet, defined as follows:

$$Z_b = \frac{E_b}{E_t}. \tag{7}$$

Distributions of this variable (Z_b) are presented in Fig. 3 for both left- and right-handed top quarks. In our simulation, b-like subjets are identified through matching with the parton-level b quark. Recently, techniques were developed to tag b subjets inside boosted tagged top jets. The tagging efficiency is found to be around approximately 50%–70%, depending on background rejection [52,53]. For the left-handed top quark, the b jet carries most of the energy of the top jet, whereas for the right-handed case, it carries relatively less energy. Comparing the distribution between z_k (Fig. 2) and Z_b (Fig. 3), it is found that Z_b provides a better distinction between left- and right-handed top quark.

The third observable, which we already discussed in this context, is $\cos\theta^\star$ [Eq. (3)]. The distribution of this angular observable for the left- and right-handed top quarks as shown in Fig. 4 shows remarkable correlation with the polarization of the parent top quark. The $\vec{t}_j$, as defined in the previous section, is opposite to top spin direction for the case of left handed top and along the top spin direction for the case of right-handed top. On the other hand, the momentum direction of the subjet j_1 having maximum

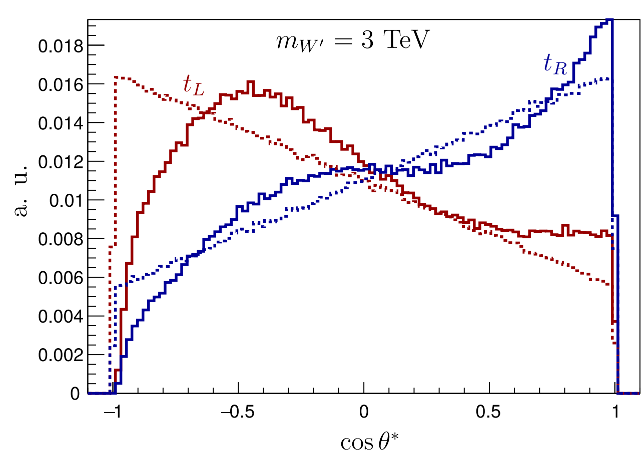

FIG. 4. The $\cos\theta^*$ distribution for $m_{W'} = 3$ TeV for reconstructed top jet (solid) and partonic (dashed).

spin-analyzing power ($\bar{d}$-type quark), and with comparatively less energy (in the top rest frame), is either opposite (for left handed) or along (for right-handed) the momentum (in lab frame) of the top quark. This argument explains why $\cos\theta^\star$ is preferred to be positive for right-handed and negative for left-handed top quarks, as shown in Fig. 4. The dotted lines in this figure represent the same quantity constructed out of the parton-level momenta of the top decay products. As we can see, although the reconstructed distributions are smeared, the correlation of the distribution with polarization is maintained. By default, the proposed variables Eq. (3), (6), and (7) are sensitive to the parton showering model used in event generators. However, these effects are expected to be very small since these variables are constructed as a ratio of two momenta.

This distinct characteristic of $\cos\theta^\star$ is exploited in constructing the event asymmetry defined as

$$A_{\theta^*} \equiv \frac{N_{\cos\theta^*>0} - N_{\cos\theta^*<0}}{N_{\cos\theta^*>0} + N_{\cos\theta^*<0}}, \tag{8}$$

where N represents the number of events for the given condition of $\cos\theta^\star$, either positive or negative.

The asymmetry defined above is expected to be very sensitive to the type of couplings [see Eq. (4)], which decide the polarization of the top quark in the process, Eq. (1). The behavior of it with the combination of couplings $(g_L - g_R)/(g_L + g_R)$ is presented in Fig. 5 along with the parton-level distribution in which four momenta of quarks are used. One can clearly see that in the left-handed case, i.e., $g_L = 1$ and $g_R = 0$, the observed asymmetry is negative, since dominantly right-handed top quarks are produced, whereas it is positive for the opposite case, i.e., for $g_L = 0$, $g_R = 1$.

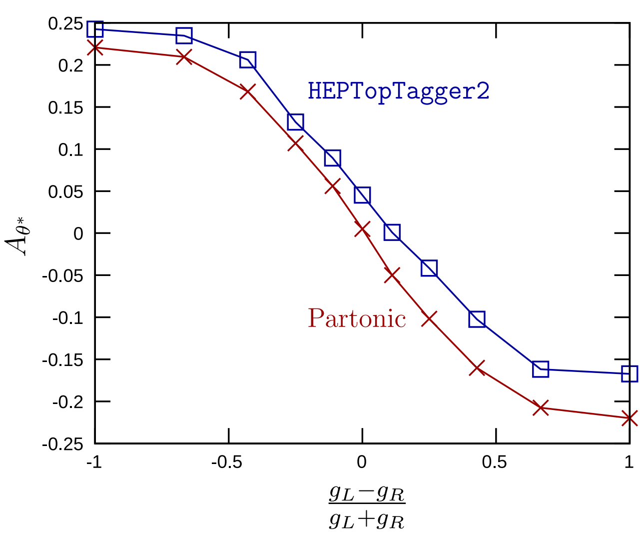

FIG. 5. The asymmetry [Eq. (8)] for parton-level and tagged tops for $m_{W'} = 3$ TeV.

IV. TOP POLARIZATION IN STOP DECAY

In this section, we demonstrate the impact of constructed discriminating observables, Eqs. (3), (6), and (7), in distinguishing the left and right polarized top quarks originating from top squark decays. Top squark is a colored particle and can be produced at the LHC in pp collision. It then subsequently decays in a variety of channels decided by the compositions and masses of the sparticles. We focus on the decay channel of the top squark,

$$\tilde{t}_1 \to t\tilde{\chi}_1^0, \tag{9}$$

which can be the dominant mode with a large branching ratio for a certain region of parameter space where the neutralino $\tilde{\chi}_1^0$ is assumed to be the lightest supersymmetric particle. The coupling between $\tilde{t}_1$, t and $\tilde{\chi}_1^0$ at the tree level is given by

$$\mathcal{L} = \bar{\tilde{\chi}}_1^0 (g^{\tilde{t}_{1L}} P_L + g^{\tilde{t}_{1R}} P_R) t \tilde{t}_1 + \text{H.c.}, \tag{10}$$

and determines the polarization of the top quark in the final state. The electroweak correction to this decay channel is at the level of few percent [54]. The form of couplings $g^{\tilde{t}_{1L}}$ and $g^{\tilde{t}_{1R}}$ is

$$g^{\tilde{t}_{1L}} = -\sqrt{2} g_2 \left[\frac{1}{2} Z_{12}^* + \frac{1}{6}\tan(\theta_W) Z_{11}^*\right]\cos\theta_{\tilde{t}} - \left[\frac{g_2 m_t Z_{14}^*}{\sqrt{2} m_W \sin(\beta)}\right]\sin\theta_{\tilde{t}} \tag{11}$$

$$g^{\tilde{t}_{1R}} = \left[\frac{2\sqrt{2}}{3} g_2 \tan(\theta_W) Z_{11}\right]\sin\theta_{\tilde{t}} - \frac{g_2 m_t Z_{14}}{\sqrt{2} m_W \sin(\beta)}\cos\theta_{\tilde{t}}. \tag{12}$$

The compositions of $\tilde{\chi}_1^0$ and mixing of $\tilde{t}_1$ are related with the respective physical states as

$$\tilde{\chi}_1^0 = Z_{11}\tilde{B} + Z_{12}\tilde{W}_3 + Z_{13}\tilde{H}_d + Z_{14}\tilde{H}_u$$
$$\tilde{t}_1 = \tilde{t}_L \cos\theta_{\tilde{t}} + \tilde{t}_R \sin\theta_{\tilde{t}},$$

where Z_{ij} are the mixing elements in the neutralino sector and $\theta_{\tilde{t}}$ is the mixing angle between $\tilde{t}_L$ and $\tilde{t}_R$ states. The couplings,$g^{\tilde{t}_{1L}}$ and $g^{\tilde{t}_{1R}}$ receive contribution from both the gauge and Higgs sectors via the composition of the neutralino [55]. As we know, the gauge interaction conserves chirality, and the Yukawa coupling flips it; hence, the Wino ($\tilde{W}_3$) and Bino ($\tilde{B}$) components in $\tilde{\chi}_1^0$ will preserve the chirality of interacting fermions, while the Higgsino ($\tilde{H}_u$ and $\tilde{H}_d$) components will flip it. This scenario is presented in Table I. The polarization of the top quark produced in the $\tilde{t}_1$ decay, in the rest frame of the decaying

TABLE I. Chirality of top quark from $\tilde{t}_1$ decay [Eq. (9)] for different compositions of neutralino and top squark states.

$\tilde{\chi}_1^0$	$\tilde{t}_1$	t chirality
Bino like or Wino like	$\tilde{t}_L$	t_L
	$\tilde{t}_R$	t_R
Higgsino like	$\tilde{t}_L$	t_R
	$\tilde{t}_R$	t_L

top squark, can be calculated easily and is given by [24,35,36,56–58]

$$\mathcal{P}_0 = \frac{(|g^{\tilde{t}_{1L}}|^2 - |g^{\tilde{t}_{1R}}|^2)\mathcal{K}^{1/2}\left(1, \frac{m_t^2}{m_{\tilde{t}_1}^2}, \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{t}_1}^2}\right)}{(|g^{\tilde{t}_{1L}}|^2 + |g^{\tilde{t}_{1R}}|^2)\left(1 - \frac{m_t^2}{m_{\tilde{t}_1}^2} - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{t}_1}^2}\right) - 4\frac{m_t m_{\tilde{\chi}_1^0}}{m_{\tilde{t}_1}^2}\mathrm{Re}(g^{\tilde{t}_{1L}} g^{\tilde{t}_{1R}*})}, \tag{13}$$

where

$$\mathcal{K}(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2yz - 2zx.$$

The above expression was derived using the definition

$$\mathcal{P}_0 = \frac{\#t(\lambda_t = 1) - \#t(\lambda_t = -1)}{\#t(\lambda_t = 1) + \#t(\lambda_t = -1)},$$

where λ_t is the helicity of the top and # refers to the number of events.

We see that the polarization of the top produced in the $\tilde{t}_1$ decay depends on the compositions of $\tilde{\chi}_1^0$ as well as the on $L - R$ mixing in the $\tilde{t}_1$, along with the masses $m_{\tilde{\chi}_1^0}$, $m_{\tilde{t}_1}$, and m_t. The last dependence comes through the kinematic functions and also through the couplings $g^{\tilde{t}_{1L}}$ and $g^{\tilde{t}_{1R}}$. We study the implication of the kinematic observables discussed in the last section, namely, z_k, Z_b, and $\cos\theta^*$, by considering top quarks produced in the decay of top squark produced in pairs in the process,

$$pp \to \tilde{t}_1\bar{\tilde{t}}_1 \to t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \to (bjj)(b\ell\nu_\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0. \tag{14}$$

Clearly, the $\tilde{t}_1$ and $\bar{\tilde{t}}_1$ are not necessarily produced at rest, and hence the polarization of the decay top quarks can be different from that given by Eq. (13). However, the polarization in the frame in which the $\tilde{t}_1$ is moving can be obtained from it in a very transparent way, if need be, in terms of that in the rest frame of the decaying top, as discussed in Ref. [37].

We select the final state containing one isolated lepton (either an electron or muon) and at least one b jet with a large amount of missing energy due to the presence of weakly interacting neutralinos. Leptons are considered in order to have less contamination from the SM backgrounds, mainly from QCD production, and, of course, to focus only on the hadronic decay mode of the other top quark avoiding recombinatorial issues [41]. We set relevant parameters as

$$m_{\tilde{\chi}_1^0} = 100\ \text{GeV}; \qquad m_{\tilde{t}_1} = 1\ \text{TeV}; \qquad \tan\beta = 10.$$

Events are generated using MadGraph5 with the minimal supersymmetric standard model (MSSM), appropriately setting the composition of $\tilde{t}_1$ and $\tilde{\chi}_1^0$. The complete chain described in Eq. (14) is generated using the matrix element to ensure accurate preservation of spin effects. The top jet are tagged by clustering the particles into C/A [59] fatjets of $R = 1.0$ using FASTJET [60] and then passed through HEPTopTagger2, if there are more than one top tagged fatjets in an event, we use the top jet which is best reconstructed i.e., by checking the reconstructed mass closest to the physical mass of the top quark. During the simulation, the events are subject to the following selection criteria:

(i) At least one hard ($p_T > 20$ GeV) and isolated lepton with $|\eta| < 2.5$ isolation is ensured by demanding the momentum fraction $\frac{\sum_{(\Delta R<0.3),i} p_{T_i}}{p_{T_\ell}} < 0.3$).

(ii) Hard missing transverse momentum with $p_T^{\text{miss}} >$ 30 GeV.

(iii) Demand the event has at least one top tagged fat jet.

The impact of top polarization on the energy fraction variables, Z_b [Eq. (7)] and z_k [Eq. (6)], is presented in Figs. 6 and 7. Here, we assume $\tilde{\chi}_1^0$ to be a pure Bino. The expected top polarizations in the rest frame of $\tilde{t}_1$, for the cases in which $\tilde{t}_1$ is pure $\tilde{t}_L$ or $\tilde{t}_R$, for the choice of masses of the $\tilde{t}_1$ and the $\tilde{\chi}_1^0$, are $\mp$ 0.9994, respectively. Because of the rather large mass of the $\tilde{t}_1$ considered, the polarization in the laboratory frame in which $\tilde{t}_1$ is produced is not very different from this value as the $\tilde{t}_1$ is produced mostly at rest [37].

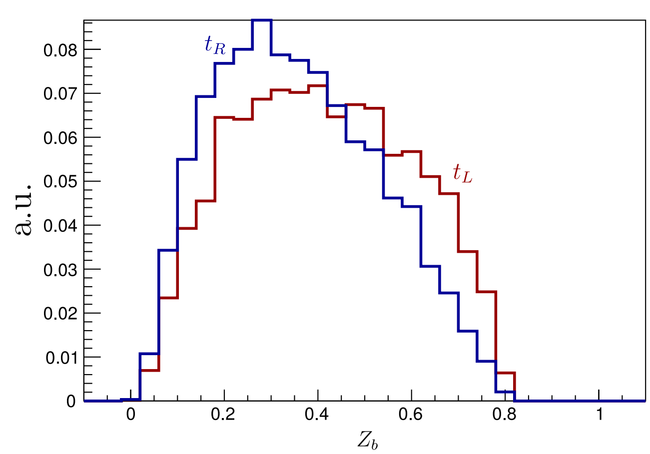

FIG. 6. The b quark energy fraction Z_b for the event presented by Eq. (14). Lightest supersymmetric particle (LSP) is a pure Bino ($\tilde{\chi}_1^0 = \tilde{B}$), and $\tilde{t}_1$ is either pure $\tilde{t}_L$ (red) or $\tilde{t}_R$ (blue) giving rise to a t_L or t_R respectively in its decay.

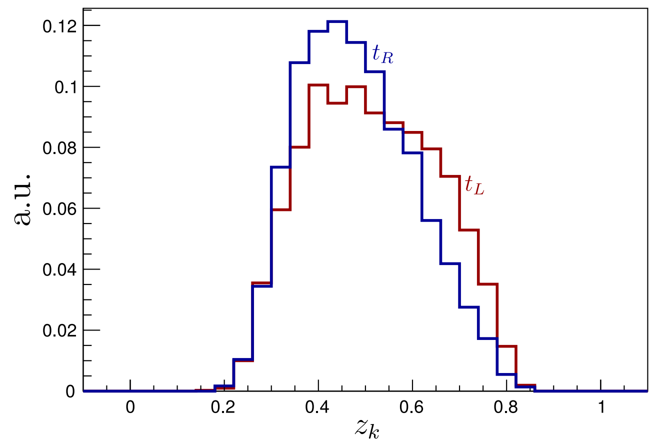

FIG. 7. Same as Fig. 6 but for z_k.

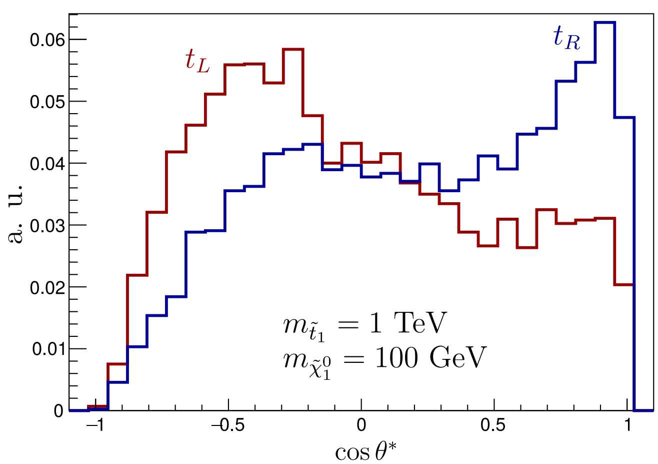

FIG. 8. Same as Fig. 6 but for $\cos\theta^*$ [Eq. (3)].

Clearly, the distributions show different patterns for left- and right-handed top quarks coming from top squark decay in the two cases. As expected, events are crowded toward the higher (lower) region for left- (right-)handed top quarks. Perhaps, a selection as $z_k(Z_b) \geq 0.5$ can clearly distinguish the region dominated by left-handed top quarks. Hence, the measurement of these variables clearly indicates the state of polarization of the top in this decay channel. As presented before, a more robust variable in this context is $\cos\theta^\star$, shown in Fig. 8. Evidently, this distribution demonstrates, as before, a very clear distinction between left and right polarized top quarks. Based on this angular variable, we calculate the asymmetry as defined by Eq. (8) [58]. It is obvious that this asymmetry is expected to be very sensitive to the composition of the neutralino and the chirality of $\tilde{t}_1$ (i.e., $\theta_{\tilde{t}}$). We systematically study the variation of A_{θ^*}. The dependence of it on $\theta_{\tilde{t}}$ is studied by fixing the composition of $\tilde{\chi}_1^0$, and results are presented in Fig. 9 for a pure bino like ($Z_{11} = 1$) LSP scenario (left) and for equal contents ($Z_{11} = Z_{12} = Z_{13} = Z_{14} = \frac{1}{2}$) of four states in $\tilde{\chi}_1^0$ (right).

It is worth it to mention here some features of the distributions shown in Fig. 9. For a pure bino like case (left plot) and larger values of $|\cos\theta_{\tilde{t}}| \sim 1$, $\tilde{t}_1$ and $\tilde{\chi}_1^0$ couplings become $g^{\tilde{t}_L} \gg g^{\tilde{t}_R}$; i.e., a produced top quark is predominantly left handed, leading to negative $\cos\theta^*$ (see Fig. 8) and hence making A_{θ^*} negative [Eq. (8)]. With the decrease of magnitude of $\cos\theta_{\tilde{t}}$, the right-handed coupling part $g_R^{\tilde{t}_1}$ gradually becomes important, leading to the production of both left- and right-handed top quarks. Since the coupling of $\tilde{t}_R$ with $\tilde{\chi}_1^0$ is twice that of $\tilde{t}_L$ due to the hypercharge, the abundance of the right-handed top is more than left-handed top quarks. Hence, $A_{\theta^\star}$ turns out to be positive and does not change much, even with the change of $\cos\theta_{\tilde{t}}$, and finally again becomes negative for $\cos\theta_{\tilde{t}} \sim 1$. In the case of equal

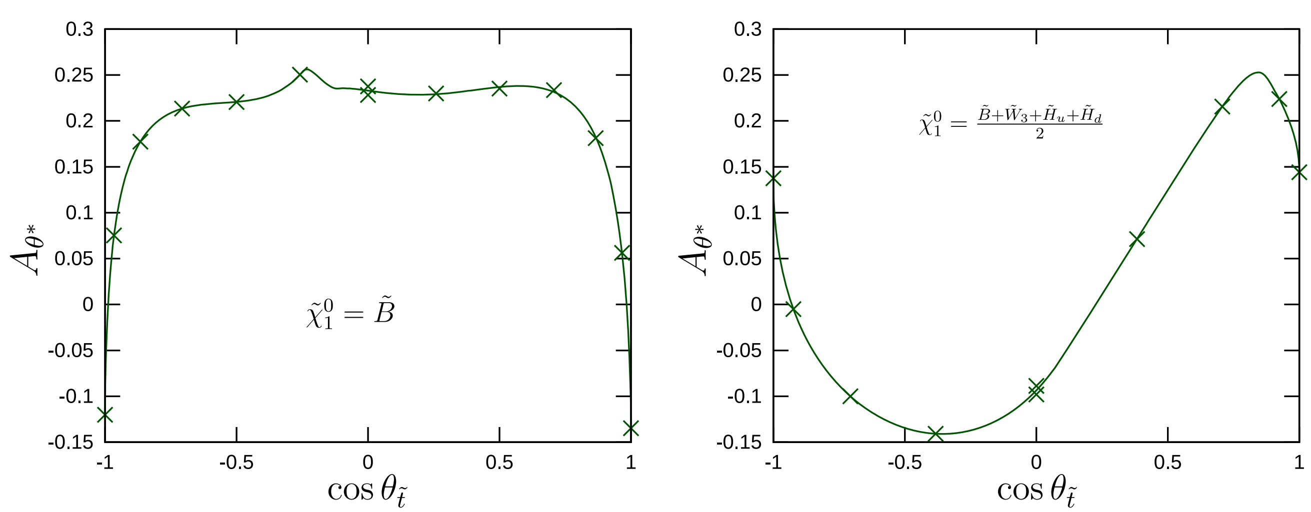

FIG. 9. Variation of asymmetry with the composition of $\tilde{t}_1$ for the cases of pure bino like (left) and equally mixed $\tilde{\chi}_1^0$ states (right).

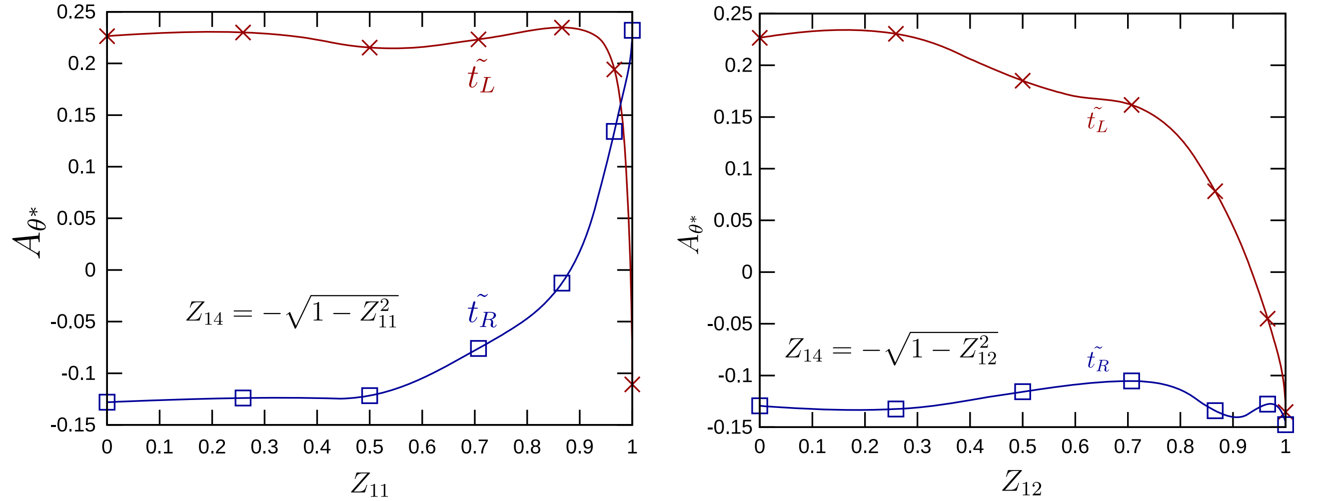

FIG. 10. Variation of asymmetry [Eq. (8)] with the composition of Bino- and wino like $\tilde{\chi}_1^0$ for the cases of $\tilde{t}_1 = \tilde{t}_L$ and $\tilde{t}_1 = \tilde{t}_R$.

mixtures of gauginos and Higgsinos, the variation of A_{θ^*} is shown in Fig. 9 (right). Again, for larger values of $|\cos\theta_{\tilde{t}}|$ (i.e., $\tilde{t}_1 \sim \tilde{t}_L$), the Higgsino contribution to the coupling ($g_R^{\tilde{t}_1}$) becomes dominant due to the dependence on the top quark mass, and since the Yukawa couplings flip the chirality, the top quark tends to be right handed, which makes A_{θ^*} positive, as it is clearly observed. For intermediate values of $\cos\theta_{\tilde{t}}$, the left-handed top quarks are also produced, making the asymmetry negative, and for $\cos\theta_{\tilde{t}} > 0$ and beyond, again the population of t_R goes up, making asymmetry positive. In Fig. 10, the variation of asymmetry on the composition of neutralinos for a given chirality of $\tilde{t}_1$ is shown. In the left plot, the magnitude of the $\tilde{B}$ content in $\tilde{\chi}_1^0$ is varied for both cases of $\tilde{t}_L(\cos\theta_{\tilde{t}} = 1)$ and $\tilde{t}_R(\cos\theta_{\tilde{t}} = 0)$ production, assuming Z_{12}, $Z_{13} = 0$ and $Z_{14} = -\sqrt{1-Z_{11}^2}$. Because of much larger Higgsino coupling, the interaction between top squark and Higgsino-like LSP dominates as compared to the gaugino case. Hence, the top quark from the decay of left (right) handed–like ($\tilde{t}_1$) becomes right (left) handed. This implies that for $\cos\theta_{\tilde{t}} = 1(0)$ the asymmetry is expected to be positive (negative). With the increase of Z_{11}, the Higgsino coupling becomes less important, and hence left (right) handed–like $\tilde{t}_1$ preferably decays to left- (right-)handed top quark, resulting in a gradual flipping of the sign of asymmetry as shown in the left figure. In the case of variation of asymmetry between the cases of Bino- and Higgsino-like LSP, the steeper curve for $\tilde{t}_L$ compared to $\tilde{t}_R$ is again a consequence of the higher hypercharge of $\tilde{t}_R$. We show the variation of A_{θ^*} with Wino content $Z_{12} = 1$ of the LSP, where the Higgsino content $Z_{14} = \sqrt{1-Z_{12}^2}$ setting $Z_{11} = Z_{13} = 0$. For the lower range of Z_{12}, the main contribution comes from the Higgsino-like coupling, and it goes down with the increase of Z_{12}. Consequently, in this case, the asymmetry for $\tilde{t}_L$ changes faster in comparison to Z_{11} variation (left), which can be attributed to the fact that the isospin interaction has larger magnitude than the hypercharge interaction. It is obvious that the variation of asymmetry for the $\tilde{t}_R$ case is essentially unaffected, since it does not couple to the Winos. Obviously, if the composition of $\tilde{\chi}_1^0$ is mixed, then the variation of A_{θ^*} is expected to be in between the two extreme cases, as shown in Fig. 10. Undoubtedly, the measurement of asymmetry is found to be a robust tool to probe the polarization of the top quark and the nature of couplings involved in the process. In the future, if the top squark is discovered and its polarization is measured, then this will allow us to constrain the compositions of the top squark with respect to the mixings of the neutralino, provided we have some idea about the neutralino sector as well.

V. TOP POLARIZATION IN RS MODELS

In this section, we study the production of the polarized top quark in extended RS models [61,62], in which the top quark can be produced from the decay of the heavy resonance of mass of a few tera-electron-volts. These resonances can be KK excited states of SM particles. Various KK excited states can be present in different RS models, depending on how the SM states propagate in the bulk [63]. Moreover, the couplings of KK states to the SM fermions may not be universal. These extended RS models have the advantage over the original RS model [64] of having a natural solution to the Yukawa hierarchy problem [65–67]. We emphasize here the fact that one can have $t\bar{t}$ or a single top as the final state, depending on which KK state is the mediator. To represent these two classes, we consider KK gluon (flavor-violating) and KK graviton (G_{KK}) decay in which we get a single top and $t\bar{t}$ final state, respectively. We also consider the case in which the KK gluon state decays into a top-antitop pair for comparison.

First, we consider a single top production, in the Kaluza-Klein gluon model [61]. This model allows flavor-violating neutral current interactions of the KK gluon. The flavor-violating localization of fermions induces flavor-violating interactions of the KK gluon. Therefore, in this model, the KK gluon will have flavor-violating neutral coupling of the form $\bar{t}\gamma_\mu q g^{*\mu}$ (where q denotes light quarks), along with the flavor-conserving neutral coupling $\bar{t}\gamma_\mu t g^{*\mu}$ [61]. We have considered a specific case in which only left-chiral couplings are allowed in the case of single top production and in particular focus on the flavor-violating decay of the KK gluon to a top quark and a charm quark. We have analyzed both $t\bar{t}$ and single top production in this model. We generate following processes:

$$pp \to g_{KK} \to t_L \bar{c}_L \to \text{hadronic final states}$$
$$(\text{both } s \text{ and } t \text{ channels})$$
$$pp \to g_{KK} \to t\bar{t} \to \text{semileptonic final states} \quad (s \text{ channel}).$$

We used the available FeynRules model [68,69] file, and events were generated with MadGraph5. Showering and hadronization were done using Pythia6 [48]. For single top events, the hadronic final state is considered, while for $t\bar{t}$ events, the following criteria are used to select events:

(i) At least one hard ($p_T > 20$ GeV) and isolated lepton is demanded. The isolation is ensured by demanding $\frac{\sum_i p_T^i(\Delta R<0.3)}{p_T^l} < 0.3$.

(ii) A cut on the missing transverse energy has also been applied. i.e., $\not{E}T > 30$ GeV.

We passed the selected events through HEPTopTagger2 to tag the top jets out of fat jets constructed with $R = 1.0$. The $t\bar{t}$ final state produced via the s-channel mediation of the KK gluon is unpolarized, and a single top produced via s- and t-channel exchange of the KK gluon is left chiral. In Fig. 11, we present the z_k, Z_b, and $\cos\theta^*$ distribution for $t\bar{t}$ and single top. We have considered the KK gluon mass of 4 TeV, which is allowed by the current experimental bound [70].

We also consider $t\bar{t}$ production from KK graviton in the top-philic model discussed in Ref. [62]. In this model, the right-chiral top quark will be localized near the IR brane, and the KK graviton is also localized near the IR brane. Therefore, the KK graviton will have dominant coupling to

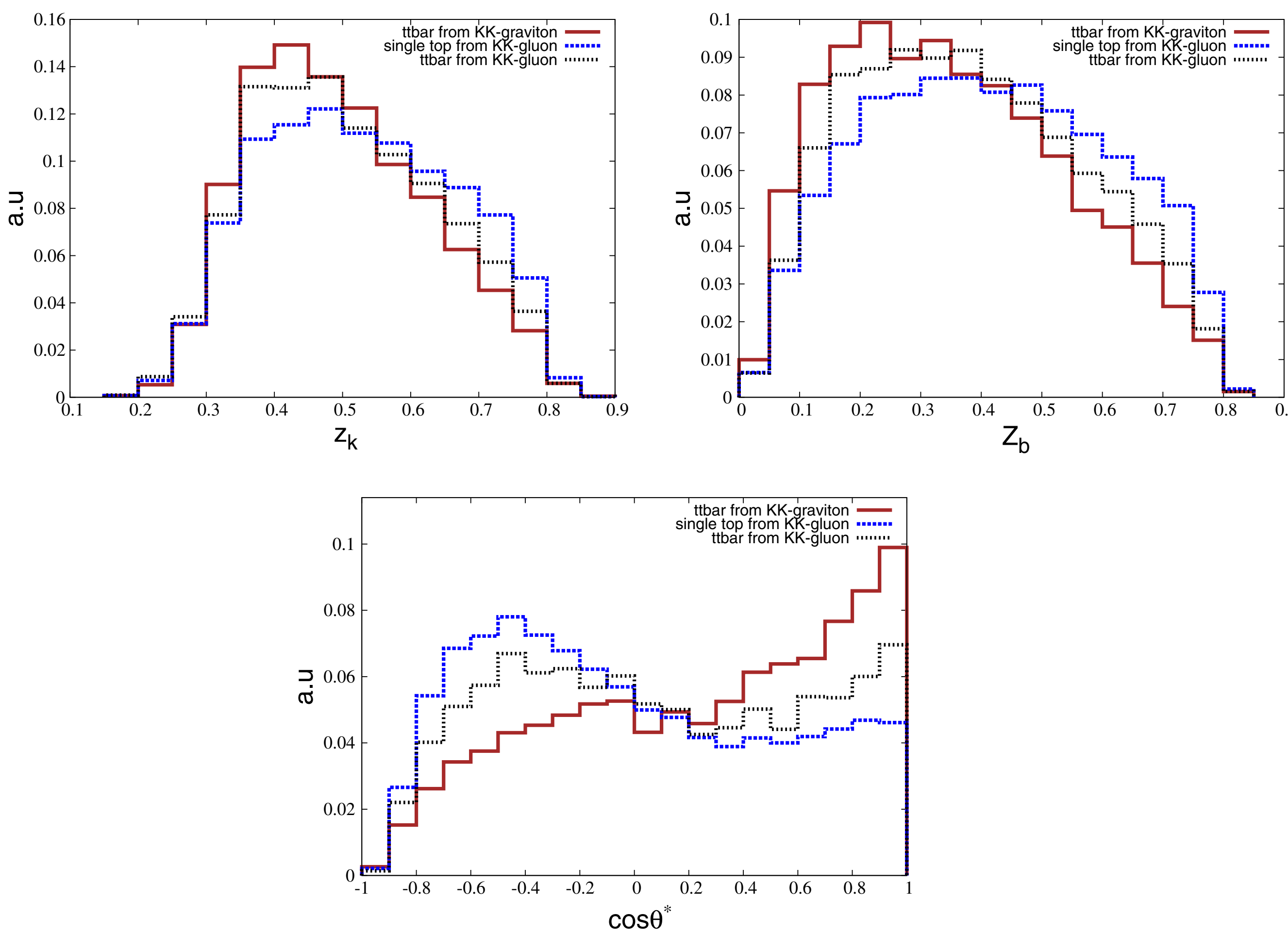

FIG. 11. The z_k (top left), Z_b (top right), and $\cos\theta^*$ (bottom center) distribution of reconstructed top jets for single top and $t\bar{t}$ pair production from a KK gluon of mass 4 TeV and $t\bar{t}$ pair from a KK graviton of mass 4 TeV.

right-chiral fermions, and hence the produced top quark will be right chiral. The corresponding Lagrangian is

$$\mathcal{L}_F = -\frac{1}{\Lambda} G^{\mu\nu} \mathcal{T}^F_{\mu\nu},$$

where $G^{\mu\nu}$ is the graviton field, and $\mathcal{T}^F_{\mu\nu}$ is the energy-momentum tensor of the fermion fields,

$$\begin{aligned}\mathcal{T}^F_{\mu\nu} = \sum_{f=u,d,l} \Bigg[& \frac{i}{4} \bar{f}_R (\gamma^\mu D^\nu + \gamma^\nu D^\mu) f_R \\ & - \frac{i}{4} (D^\mu \bar{f}_R \gamma^\nu + D^\nu \bar{f}_R \gamma^\mu) f_R \\ & - i\eta^{\mu\nu} \left\{ \bar{f}_R \gamma^\rho D_\rho f_R - \frac{1}{2} D^\rho (\bar{f}_R \gamma_\rho f_R) \right\} \Bigg], \end{aligned} \qquad (15)$$

where $\eta_{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$ is the Minkowski metric tensor and $D_\mu = \partial_\mu + i(2/3) g_1 B_\mu + i g_s G^a_\mu$ is the covariant derivative corresponding to each fermion. We consider the process $pp \to G_{KK} \to t\bar{t}, (t \to W^+ b, W^+ \to jj), (\bar{t} \to W^- \bar{b}, W^- \to l^- \bar{\nu_l}) + \mathrm{H.c.}$ In this case also, the event generation process and selection criteria are the same as the KK gluon case.

In Fig. 11, we also show the distributions for z_k, Z_b, and $\cos\theta^*$ for the KK graviton mass of 4 TeV. This value of the KK graviton mass is consistent with the experimental results [71]. In this model, the KK graviton couples only to the right-chiral top quark, as mentioned earlier. Therefore, the tops produced through $t\bar{t}$ pair production from the KK graviton decay will be right chiral. A comparison among the three curves in each panel of Fig. 11 indicates that the discriminating potential of the z_k variable is less promising than the other two variables considered. The b-subjet energy fraction, Z_b, shows a better discriminating performance between left-chiral, right-chiral, and unpolarized tops, which are produced from different resonances. It is clear from this figure that the best discriminator and a robust observable in the tagger environment are indeed $\cos\theta^*$. In the case of a left-chiral top produced from the KK graviton, the distribution is more populated in the lower range of $\cos\theta^*$, and for a right-chiral top quark produced from the KK gluon, it is peaked around a higher range of $\cos\theta^*$. For an unpolarized top from the KK gluon, the distribution is comparatively more uniformly distributed across the whole range of $\cos\theta^*$. It is clear from these plots that the variable $\cos\theta^*$ not only gives us information about the chiral structure of the top quark coupling but also helps us to distinguish between different models. The KK graviton and KK gluon have different coupling structures with the top quark. But as they produce the top quark with different polarization, these observables can also be utilized to distinguish between these two types of resonances.

Next, we extend this study to the top-philic model and consider nonzero coupling of the KK graviton with both a left- and right-chiral top quark and calculate the asymmetry for the θ^* observable, as we did for top production from W' decay and stop decay in the MSSM. We have introduced parameters k_L and k_R in the Lagrangian, defined as

$$\mathcal{L}_F = -\frac{1}{\Lambda} G^{\mu\nu} \mathcal{T}^F_{\mu\nu},$$

with

$$\begin{aligned}\mathcal{T}^F_{\mu\nu} = \sum_{f=u,d,l,\nu_l} \Bigg(& \frac{k_R}{\sqrt{k_L^2 + k_R^2}} \Bigg[\frac{i}{4} \bar{f}_R (\gamma^\mu D^\nu + \gamma^\nu D^\mu) f_R - \frac{i}{4} (D^\mu \bar{f}_R \gamma^\nu + D^\nu \bar{f}_R \gamma^\mu) f_R \\ & - i\eta^{\mu\nu} [\bar{f}_R \gamma^\rho D_\rho f_R - \frac{1}{2} D^\rho (\bar{f}_R \gamma_\rho f_R)] \Bigg] + \frac{k_L}{\sqrt{k_L^2 + k_R^2}} \Bigg[\frac{i}{4} \bar{f}_L (\gamma^\mu D^\nu + \gamma^\nu D^\mu) f_L \\ & - \frac{i}{4} (D^\mu \bar{f}_L \gamma^\nu + D^\nu \bar{f}_L \gamma^\mu) f_L - i\eta^{\mu\nu} [\bar{f}_L \gamma^\rho D_\rho f_L - \frac{1}{2} D^\rho (\bar{f}_L \gamma_\rho f_L)] \\ & - \eta_{\mu\nu} \left(\frac{g_W}{\sqrt{2}} V_{ij} \bar{f}_{u_i} \gamma^\rho P_L f_{d_j} W^+_\rho + \frac{g_W}{\sqrt{2}} U_{ij} \bar{f}_{l_i} \gamma^\rho P_L f_{\nu_j} W^-_\rho + h.c \right) \\ & - \left(\frac{g_W}{\sqrt{2}} V_{ij} \bar{f}_{u_i} \gamma_\mu P_L f_{d_j} W^+_\nu + \frac{g_W}{\sqrt{2}} U_{ij} \bar{f}_{l_i} \gamma_\mu P_L f_{\nu_j} W^-_\nu + h.c + (\mu \leftrightarrow \nu) \right) \Bigg] \Bigg). \end{aligned} \qquad (16)$$

This equation suggests a new parametrization, in terms of angular variable θ_{RS} for the calculation of asymmetry, where $\cos\theta_{RS} = \frac{k_L}{\sqrt{k_L^2 + k_R^2}}$. When $|k_L| = 1$ and $|k_R| = 0$, we get $|\cos\theta_{RS}| = 1$, i.e., only the left-chiral top couples to the KK graviton. Likewise, when $|k_L| = 0$ and $|k_R| = 1$ we get $|\cos\theta_{RS}| = 0$, i.e., only the right-chiral top couples to the KK graviton.

The asymmetry A_{θ^*} for the tagged tops as a function of $\cos\theta_{RS}$ is presented in Fig. 12. The asymmetry is negative for the left-chiral case and positive for the right-chiral case. In this figure, we notice an interesting feature that the magnitude of asymmetry $|A(\theta^*)|$ is larger for the right-chiral top than in the left-chiral case. The reason behind this is the sharp falling of the $\cos\theta^*$ distribution in the case of a

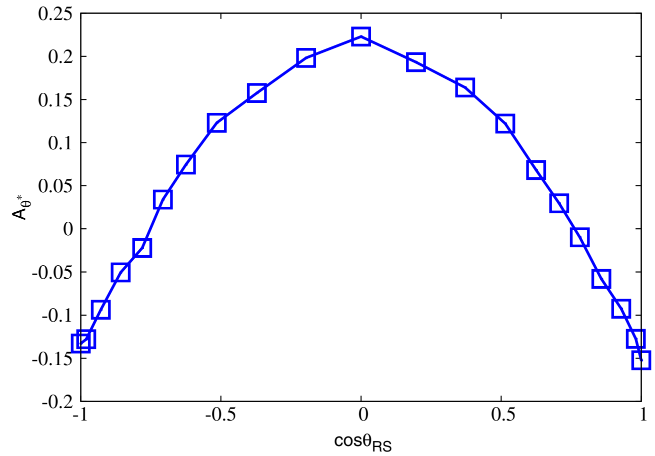

FIG. 12. The A_{θ^*} asymmetry for tagged tops for the KK graviton mass of 3 TeV.

left-chiral top quark, when $\cos\theta^* \sim 1$ (see Fig 11). Clearly, the asymmetry is a robust and efficient probe of new physics, which produces polarized top quarks. Its deviation from the SM prediction will indicate the presence of polarization-sensitive new physics in the top sector. The angular observable $\cos\theta^*$ and the asymmetry A_{θ^*} together will not only help us look for the new physics but also guide us in identifying its nature.

VI. SUMMARY

Top quark polarization carries the information that can provide deeper insight about its couplings with fermions and gauge bosons. Hence, probing the coupling of the top quark through the measurement of its polarization could indicate the presence of new physics. The kinematic distributions of decay products from the top quark, including angular correlations among themselves, are strongly correlated with its helicity. From the conservation of momentum and spin in the hadronic mode of top decay, it can be shown that the antifermion from W decay is very sensitive to polarization in comparison to other decay products. However, it is very challenging to identify this polarization-sensitive decay product for a highly boosted top quark of which decay products are not very well separated and come out within a fat jet. In this study, we attempt to develop a strategy to study the polarization of boosted top quark, focusing on its hadronic decay mode by considering a benchmark process, Eq. (1). The boosted top quark is tagged using jet substructure method with clear identification of subjets. We identify the subjet corresponding to the decay (antifermion) product from W decay and obtain its energy fraction in the laboratory frame, which is found to be a very useful sensitive variable to distinguish the left- and right-handed top quarks. Moreover, the availability of techniques to tag b jets with very high transverse momentum inside a tagged top jet also motivates us to use tagged b jets as another object to identify top quark polarization by measuring its energy fraction in the laboratory frame. It is to be noted that previously b-tagged jets were not used in this context due to the lack of a proper b-tagging tool. It is observed that for a hard (soft) b-tagged jet or untagged jet, the probability of a mother top quark being left (right) handed is higher; i,e., the hardness of jets clearly distinguishes the left- and right-handed top quark (see Fig. 3 and 4). Furthermore, we also propose a new observable based on the angular correlations among hadronic top decay products. Again, identifying the subjet corresponding to the antifermion from W decay, we construct an angular observable in the top rest frame, between the direction of a subjet and the boosted tagged top momentum in the laboratory frame. This angular variable, namely, $\cos\theta^\star$ [Eq. (3)], turns out to be very robust to identify the polarization of boosted top quark, as shown in Fig. 4. Evidently, the distribution of $\cos\theta^\star$ unambiguously discriminates events due to the left- and right-handed top quarks. Based on this feature, we define an asymmetry [Eq. (8)] of an event that is found to be very effective for measuring polarization. Obviously, this asymmetry is very sensitive to the couplings, as shown in Fig. 5. The asymmetry varies within a wide range from $+20\%$ to -20% for $g_{R(L)} = 1(0)$ to $g_{L(R)} = 1(0)$. Understandably, the measurement of asymmetry is a good indication of the nature of couplings.

The impact of these constructed polarization-sensitive variables is studied for two new physics scenarios in which polarized top quarks are produced from top squark decay in SUSY searches and KK gluon and graviton decay in the RS model. In top squark decay [Eq. (14)], the couplings, and hence the polarization, depend on the details of SUSY parameters. The energy fraction variables and angular observable are presented by setting certain benchmark parameters and top squark mass. Remarkably, the $\cos\theta^\star$ is observed to be very robust. The variation of polarization asymmetry is studied for various input model parameters, including mixing angles in stop and neutralino sectors. Huge asymmetry is observed, ranging from $+15\%$ to -25%, depending on the mixing angles in the top squark sector. Evidently, the measurement of asymmetry can shed some light on the model, in particular, the helicity of the top squark and the nature of neutralinos, which might be very useful information in reconstructing models. A similar exercise is also carried out in the context of the RS model. The substantial impact of these constructed variables is observed in this model, and, again, the measured asymmetry might be a useful tool to pin down the nature of couplings in this model. It is to be noted that there are SM physics processes with large cross sections that have final states identical to the processes considered here. To achieve signal sensitivity at a reasonable level, these backgrounds need to be suppressed by applying kinematic selections. It is really challenging and worth it to study how those background optimization cuts affect our observations. Therefore, one needs to carry out a dedicated analysis that matches the experimental constraints at the LHC and establish the robustness of our strategy to identify the top quark polarization [72].

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