Abstract

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 the same is a good discriminator for those new physics models wherein the couplings have a chiral structure different than that in the Standard Model (SM). In this note 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 usual jet sub structure technique we study robustness of these observables for a benchmark process, $W' \rightarrow tb$. 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 which reflect the polarization. We study the efficiency of these variables for two new physics processes where which give rise to boosted top quarks: (i) decay of the top squark in the context of supersymmetry searches, and (ii) decays of the Kaluza-Klein(KK) graviton and KK gluon, in Randall Sundrum(RS) 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 (BSM) is also investigated in detail.
1 Introduction

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, top quark can be closely related to the phenomenon of electroweak symmetry breaking. This may be either in 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 of its couplings, both responsible both for the production and decay has always received special attention [1,2], and holds the potential of offering us a glimpse of BSM. To this end an important and interesting property is its polarization which is reflected in the 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 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 SM it is purely left chiral due to the V-A nature of the $t-b-W$ interaction. Any modification of this interaction at the production vertex deviating from the SM would change the polarization of produced top quark. Hence, the measurement of polarization of top quark is expected to reveal the structure of $t-b-W$ coupling responsible both for production and decay of the top quark, as well as the effect of any other new physics at the production vertex. 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 decay distributions of charged lepton in collider is discussed in great detail in the literature [10–15]. Moreover, top polarization also has been studied well using the matrix element method [6,16–18].

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 in scenario where a heavy particle decays to top quark, which is boosted and in principle also polarized. To be specific, we consider two processes, $W' \rightarrow tb$ and the decay of superpartner of top, stop ($\tilde{t}$). The polarization of the produced top depends on the chiral structure of the couplings responsible for the decay and can be tuned to produce either the left or right polarized top. 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 quark 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 measurement of polarization of boosted top quark though a challenging task, is of great import 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 semi-leptonically decaying top quark is the best candidate for studying the spin effects as the charged lepton having the largest spin analyzing power is easy to identify, and not much affected by soft QCD radiation [10]. The price to pay for the leptonic decay is low branching ratio, and difficulties in finding an isolated lepton originated from boosted top. In addition, presence of multiple sources of missing energy makes it difficult to reconstruct the top quark momentum. However, reconstruction of top quark momentum for leptonic decay, even in the presence of many sources of missing energy is likely to be feasible following a very non trivial algorithm [19].

The above arguments suggest that the hadronic decay mode of top quark is more favorable one to reconstruct the boosted top quark, and study its spin effect where the down-type quark from $W$ decay plays the same role as the charged lepton. It is to be noted that the reconstruction of jets and its identification corresponding to the down-type quark from $W$ decay involved certain level of uncertainties. The decay products of boosted top quark in its hadronic channel are identified by
employing the powerful technique of jet substructure analysis [20]. In this paper, we discuss how the polarization of boosted top quark in its hadronic decay mode can be measured by constructing the polarization sensitive observables out of the momentum of subjets inside the reconstructed top jet. Polarization of boosted tops using jets at the substructure level has been discussed in the literature [17, 21, 27].

In hadronically decaying top quarks, the quark corresponding to the down-type quark from $W$ decay with the largest spin analyzing power is generally soft (in the top rest frame). 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 [17]. Notably, in this paper the author proposes a new axis taken as the weighted average of the two jet axis, where the weights are given by the probability obtained from the decay matrix element. Interestingly, there are observables [25] which could discriminate left and right polarized boosted hadronically decaying top quark without having any requirement of $W$ reconstruction or $b$ jet identification. In this case, subjects 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 energy fraction of top quark decay products, proposed in earlier studies [25], and their role as a polarimeter. Currently, tagging of high $p_T$ $b$-jets using MVA techniques with a reasonable efficiency is not difficult as shown by experimental studies [28, 29]. Therefore, we employ energy fraction of tagged high $p_T$ $b$ jets as one of the useful polarimeter, which was not studied before. In addition to these energy fraction observables, we also propose a very powerful polarization sensitive variable indirectly related to the angular distribution of the selected subjet which corresponds to the down-type quark from $W$ decay having maximum spin analyzing power. Experimentally, it is not very difficult to measure this variable. We construct an asymmetry which reflects the polarization of the decaying top unambiguously. We demonstrate the impact of the polarization sensitive observables discussed above by choosing the following benchmark process,

$$pp \rightarrow W' \rightarrow tb$$

(1)

where the $W'$ gauge boson couples only with left or right handed top quark and top is assumed to decay, $t \rightarrow bW$ with 100% branching ratio. We simulate process of Eq. (1) and study observables which have a potential to discriminate between the left and right porpoised top quarks. After demonstrating efficacy of these variables as a polarimeter for completely polarised top quarks, we use them to situations in which the top polarization has a value different from $\pm 1$. For example, top squark, produced in pairs at the LHC decays to top quark accompanied by the lightest neutralino ($\tilde{\chi}_1^0$), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ [30]. 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 type of interactions. A detailed study shows how the polarization of 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 top quark can shed some light about the couplings in supersymmetric(SUSY) theories. Similar studies are also carried out using our proposed observables in the process where polarized top quarks are produced from the decay of Kaluza-Klein(KK) excited states.

The paper is organized as follows. In Sec. 2 we briefly discuss the kinematics of decay products in the context of polarized top decays, Then in Sec. 3 we identify observables which can be used to obtain information about the polarization of top quark. In Sec. 4 we study the application of those proposed variables in top squark decay which can produce top quarks which are not necessarily completely polarized. In Sec. 5 similar studies are carried out in the context of Randall Sundrum(RS) model where polarized top quarks are produced in the decay of new resonances. Finally in Sec. 6 we summarize our results.
2 Polarized top quark decays

It is instructive to review briefly the effect of top polarization on the kinematics of its decay products, before we proceed further to discuss our results. In the SM, the top quark has $\sim 70\%$ branching fraction for the hadronic channel, $t \to b \, W^+ \to b \, u \, \bar{d}$, where $u(\bar{d})$-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 \[31,32\],

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_f} = \frac{1}{2} (1 + \mathcal{P}_0 \kappa_f \cos \theta_f) \]  

(2)

where $\kappa_f$ is the spin analyzing power of the respective decay particles, i.e. $f = b, \bar{d}, u$ and $W$. The spin analyzing power $\kappa_f$, 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 $^{10}$. Here $\theta_f$ is the angle between the fermion (or $W$) and top spin direction, in the top quark rest frame, and $\mathcal{P}_0$ is the polarization of the produced top ($-1 \leq \mathcal{P}_0 \leq 1$). Notice that when 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 $\kappa_b \approx -0.4$, to study the top polarization. The reconstructed $W$, on the other hand, with opposite spin analyzing power of $b$ quark ($\kappa_W \approx 0.4$), in the top quark rest frame can also serve as a good candidate for top spin analysis. Therefore, the kinematic distribution of down-type quark or $b$-jet($or\, W$) is supposed to provide considerable handle to study top polarization, as mentioned in the previous section, from here on, we take the spin direction of the top to be quantized along the momentum direction of the top. The correction to the tree level values of spin analyzing power of hadronic decay products is found to be at the level of 3-4% $^{16,33}$.

As pointed out earlier, identification of subjet corresponding to $\bar{d}(d)$ quark from $W^+(W^-)$ decay having maximum spin analyzing power is non trivial, specially in the busy environment of 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 try to identify the subjet with large spin analyzing power using the following methods:

1. The subjet which is aligned along the $b$-like jet, i.e. constitutes a minimum invariant mass with the $b$-jet.

2. The harder of the two subjets which have the minimum $k_T$ distance between each other $^{25}$. 

3. Besides these, $b$-jet itself can be used as a good candidate to study top polarization, provided it can be tagged even with high momentum. Currently, techniques are developed using MVA based methods to tag $b$-jets of high $p_T$ $^{34,35}$. 

Furthermore in this context, we propose a new observable indirectly related to the angular distribution of the decay products of top, 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 the subjet $j_1$, $\approx 50\%$ to $60\%$ $^{16,17}$ of cases will act as a proxy for the parton-level $d$ quark, which has the maximum spin-analyzing power. Next we construct the matrix $\Lambda$ corresponding to Lorentz transformation to boost the tagged top jet in the lab frame to its rest frame. Then we define a four-vector $T^\mu \equiv (m_P, 0, 0, 0)$ in the lab frame which is approximately same as the frame of the heavy parent particle (decaying to top) produced almost at rest. Suppose the matrix $\Lambda$ applies a boost along the direction of top jet momentum in the lab frame to go back to top jet rest frame. Hence the following Lorentz transformations

\[ T'^\mu \equiv \Lambda^\mu_\nu \, T^\nu \]

\[ j'^\mu \equiv \Lambda^\mu_\nu \, j^\nu_1 \]
bring the momentum vectors $T^\mu$ and $j_1^\mu$ to top rest frame. Clearly, the direction of vector $T^\prime$ in the top rest frame will be opposite to the direction of top jet momentum in the lab frame. The role of vector $T^\prime$ is to carry the information of top jet momentum direction in lab frame to its rest frame. The momentum distribution of $j_1^\prime$ vector is guided by the polarization of top quark. Hence in the top rest frame, the angular separation between $j_1^\prime$ and $T^\prime$ is expected to show the effect of polarization of the parent top quark. With this understanding, we construct the observable,

$$\cos \theta^\star \equiv \frac{T^\prime \cdot j_1^\prime}{|T^\prime| |j_1^\prime|}$$

(3)

to use it as a potential polarimeter. Identifying $j_1$ following above method, the angular variable $\cos \theta^\star$ can be computed easily. In the next section, we demonstrate the robustness of $\cos \theta^\star$. Along with this, we also discuss various kinematic observables simulating the benchmark process, Eq. 1, and present a comparative study of these observables in measuring polarization of boosted and hadronically decaying top quarks.

3 Boosted top polarization

The top quark produced through the decay of a heavy BSM particle, e.g. Eq. 1, is expected to be boosted. Hence the decay products of top will be collimated, and form a single fat jet of large cone size. Identification of boosted objects using jet substructure technique is now very well established and tested \cite{20, 36–40}. In this technique, topjets are tagged by finding the substructures of fat jets following BDRS mass drop \cite{20} and filtering method using HEPTopTagger2 \cite{20, 36–39}.

The matrix element for the benchmark process, Eq. 1, is generated using the FeynRules \cite{41} corresponding to the $W'$ effective model \cite{42} in MadGraph5_aMC@NLO \cite{43} to generate left handed and right handed top quark via s-channel, the partonic events are then showered using PYTHIA8 \cite{44}. This model is an extension of the SM, including an additional interaction of fermions to $W'$ boson following the lowest-order effective lagrangian, described in Refs \cite{45, 46},

$$\mathcal{L} = \frac{V_{ij}}{2\sqrt{2}} \bar{t}_i \gamma^\mu (g_R(1 + \gamma_5) + g_L(1 - \gamma_5)) W'_\mu f_j + h.c.$$  

(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. In the simulation, fat jets are reconstructed using Cambridge/Aachen (C/A) \cite{47} algorithm setting the jet size parameter $R = 1$, and required to have transverse momentum $p_T > 200$ GeV and $|\eta| < 4$. Events produced consisting of fat jets are passed through HEPTopTagger2 to reconstruct top jet by BDRS mass drop method using 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 size $\Delta R = 0.3$. As mentioned in earlier sections, the momentum distribution of subjets of polarized boosted top quark are guided by its state of polarization. This fact leads to a difference in the tagging efficiency for left and right handed top quark as reported by the ATLAS collaboration \cite{48}. 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 lab frame), the $d$ quark is more boosted while the other two quarks ($b,u$) are less boosted and hence more separated as compared to left handed tops where $b,u$ quarks are more boosted and hence less separated. It implies that in the right handed top quarks, the subjets are better separated than the subjets from left handed top quarks. This difference of kinematics and separation between the subjets in left handed and right handed tops leads to the small difference in top tagging efficiency as seen from Fig. 1.
Figure 1: Top tagging efficiency for left ($t_L$) and right handed ($t_R$) top quark for the process $pp \rightarrow W' \rightarrow tb$ with $m_{W'} = 3$ TeV.

Now we present the kinematic observables discussed in the previous section, which could be used to distinguish the left and right handed boosted top quark. As a first step, we study the energy fraction variable ($z_k$) suggested in Ref. [25], where the subjet ‘$k$’ is identified via the following algorithm. The tagged topjet corresponding to boosted 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,

$$d_{ij} = \min(p_{T_i}^2, p_{T_j}^2)R_{ij}^2,$$

where $R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$. The energy fraction of the harder jet $j_k$ of this pair is defined as $z_k$ [25], i.e.,

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

where $d_{ij}$ is minimum.

and $E_t$: energy of the top jet,

which acts as a good top polarimeter [25]. Tagging the topjet using HEPTopTagger2, we obtain $z_k$ out of three subjets. For the sake of comparison, in order to understand how the $z_k$ works, we also compute it using the partonic (truth) level information. The results are presented in Fig. 2 where the energy fraction $z_k$ is shown along with the truth level distribution (dashed) for both left and right handed top quark originating from $W'$ decay. Interestingly, it is seen that simply by matching subjets with the parton level quark, most of the time ($\sim 50\%$) algorithm chooses $b$-like (d-like) subjet in the left (right)-handed top quark case.

As mentioned in the previous section that the $\bar{d}$ quark is maximally correlated with the top spin, like the charged lepton in semi-leptonic decay of top quark. Thus for left-handed top (in the lab frame), the $\bar{d}$ quark tends to be soft and the minimum $k_T$ pair therefore tends to involve the $d$-like subjet where as the other one mostly $b$-like with comparatively harder energy. For right handed top quark case, we observe mostly the same kind of pairing but with harder $d$-like subjet and softer $b$ like subjet.
Figure 2: The subjet energy fraction $z_k$ (Eq. 3) for left (red curve) and right handed (blue curve) top quark for $m_{W'} = 3$ TeV. The dashed lines correspond to the observable at the partonic level.

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 consider another observable, the energy fraction of $b$-like subjet, which is defined as follows:

$$Z_b = \frac{E_b}{E_t}$$

(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 are developed to tag $b$-subjets inside boosted tagged top jets. The tagging efficiency is found to be around $\sim 50 - 70\%$ depending on background rejection [34, 35]. For 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 to discriminate the left and right handed top quark is $\cos \theta^\star$ (Eq. 3). The distribution of this angular observable for left and right-handed top quark are shown in Fig. 4. Remarkably, this observable demonstrates very strong correlation with the polarization of the parent top quark. The $\vec{T}'$ (as defined in the previous section) and top-spin are in the same direction at the top rest frame in case of left handed top quark, and are in opposite direction in the case of right handed tops. Note that, as mentioned also in the previous section, the $\vec{T}'$ in the top rest frame is opposite to the direction of the momentum of top quark in the lab frame. On the other hand, the momentum direction of the jet having maximum spin analyzing power (down-type quark), and with comparatively less energy (in the top rest frame), is along the spin direction of the top quark. This argument explains why $\cos \theta^\star$ is preferred to be positive for left handed and negative for right handed top quarks, as shown in Fig. 4.

This distinguishing characteristic of $\cos \theta^\star$ is exploited constructing the measurable event asymmetry defined as,

$$A_{\theta^\star} = \frac{N_{\cos(\theta^\star)>0} - N_{\cos(\theta^\star)<0}}{N_{\cos(\theta^\star)>0} + N_{\cos(\theta^\star)<0}}$$

(8)

where $N$ represents the number of events for the given condition of $\cos \theta^\star$, either positive or negative.
The asymmetry defined as 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 variation 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 where four momenta of parton level quarks are used. One can see that in the left-handed case i.e. when \(g_L = 1\) and \(g_R = 0\), the observed asymmetry is positive, since dominantly left handed top quarks are produced, whereas it is negative for opposite case i.e. for \(g_L = 0, g_R = 1\).

4 Top polarization in stop decay

In this section we demonstrate the impact of discriminating observables defined by Eq. 3, 6 and 7 in distinguishing left and right polarized top quarks originating from top squark decays. Top squark, a colored sparticle can be produced at the LHC in proton-proton collision, and subsequently it decays in a variety of channels depending on its mass and composition, leading to a very diverse signatures.
and Yukawa coupling flips it, hence, the wino (\(\tilde{\chi}^0\)) will preserve the chirality of interacting fermions while the Higgsino (\(\tilde{\chi}^0\)) components in \(\tilde{\chi}^0\) will flip it. Therefore, compositions of \(\tilde{\chi}^0\) and mixture of \(\tilde{t}_1\) state together determine the polarization of top quark from \(\tilde{t}_1\) decay. For example, in some extreme cases we show the polarization(100%) of top quark in Table 1.

In this study we focus on the decay channel of top squark, 
\[
\tilde{t}_1 \rightarrow t\chi^0_1,
\]
which can be the dominant one with large branching ratio for a certain parameter space. The coupling between \(\tilde{t}_1\), \(t\) and \(\chi^0\) at the tree level is given by,
\[
\mathcal{L} = \tilde{\chi}^0_1 (g^{t\tilde{t}L} P_L + g^{t\tilde{t}R} P_R) t \tilde{t}_1 + h.c,
\]
determines the polarization of top quark in the final state. The electroweak correction to this decay is at the level of few percent \[49\]. The form of \(g^{t\tilde{t}L}\) and \(g^{t\tilde{t}R}\) are given as,
\[
g^{t\tilde{t}L} = -\sqrt{2} g_2 \left[ \frac{1}{2} Z_{12} + \frac{1}{6} \tan(\omega_W) Z_{11}^* \right] \cos \theta_t - \left[ \frac{g_2 m_t Z_{14}^*}{\sqrt{2} m_W \sin(\beta)} \right] \sin \theta_t \tag{11}
\]
\[
g^{t\tilde{t}R} = \left[ \frac{2 \sqrt{2}}{3} g_2 \tan(\omega_W) Z_{11} \right] \sin \theta_t - \left[ \frac{g_2 m_t Z_{14}}{\sqrt{2} m_W \sin(\beta)} \right] \cos \theta_t. \tag{12}
\]

The compositions of \(\tilde{\chi}^0_1\) and mixing of \(\tilde{t}_1\) are related with the respective physical states as:
\[
\chi^0_1 = Z_{11} \tilde{B} + Z_{12} \tilde{W}_3 + Z_{13} \tilde{H}_d + Z_{14} \tilde{H}_u
\]
\[
\tilde{t}_1 = \tilde{t}_L \cos \theta_t + \tilde{t}_R \sin \theta_t
\]
where \(\theta_t\) is the mixing angle between \(\tilde{t}_L\) and \(\tilde{t}_R\) states and \(Z_{ij}\) are the mixing elements in the neutralino sector. The couplings, \(g^{t\tilde{t}L}\) and \(g^{t\tilde{t}R}\) receive contribution from both the gauge and Higgs sectors via the composition of neutralino, as shown \[50\]. As we know, the gauge interaction conserves chirality and Yukawa coupling flips it, hence, the wino (\(\tilde{\chi}^0\)) and bino (\(\tilde{B}\)) components in \(\tilde{\chi}^0\) will preserve the chirality of interacting fermions while the Higgsino (\(\tilde{H}_u\) and \(\tilde{H}_d\)) components will flip it. Therefore, compositions of \(\tilde{\chi}^0\) and mixture of \(\tilde{t}_1\) state together determine the polarization of top quark from \(\tilde{t}_1\) decay. For example, in some extreme cases we show the polarization(100%) of top quark in Table 1.

We consider the following final state via the production of top squark and it’s subsequent decay to study the implication of those kinematic observables discussed in the last section, namely \(z_k\), \(Z_b\) and \(\cos\theta^*\). The process can be read as,
\[
pp \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow t \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow (bjj) (b\ell\nu\ell) \tilde{\chi}^0_1 \tilde{\chi}^0_1.
\]

We select the final state containing one isolated lepton (either electron or muon) and at least one b jet with 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 to focus only on hadronic decay of the other top quark avoiding recombinatorial issues \[38\]. We set relevant parameters as,
\[
m_{\tilde{\chi}^0_1} = 100 \text{ GeV} \quad m_{\tilde{t}_1} = 1 \text{ TeV} \quad \tan \beta = 10
\]
and the lightest neutralino is assumed to be 100% bino. Events are generated using MadGraph5 with the minimal supersymmetric standard model(MSSM) and appropriately setting the composition of \(\tilde{t}_1\) and \(\tilde{\chi}^0\). The complete chain described by Eq. 13 is generated using the matrix element to ensure accurate preservation of spin effects. In simulation, the events are selected as:

| \(\chi^0_1\)          | \(t\)    | t chirality  |
|----------------------|----------|--------------|
| Bino like or Wino Like | \(t_L\)  | \(t_L\)      |
|                      | \(\tilde{t}_L\) | \(\tilde{t}_L\) |
| Higgsino            | \(\tilde{t}_L\) | \(\tilde{t}_R\) |
|                      | \(\tilde{t}_R\) | \(\tilde{t}_L\) |

Table 1: Chirality of top quark from \(\tilde{t}_1\) decay (Eq. 9) for different compositions of neutralino and top squark states.
at least 1 hard ($p_T > 20$ GeV) and isolated lepton with $|\eta| < 2.5$, isolation is ensured by demanding the momentum fraction $\frac{\sum_{(\Delta R < 0.3), i} |p_T^i|}{p_T^\ell} < 0.3$.

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

- Top jet is tagged by clustering the particles into C/A [47] fatjets of $R = 1.0$ using fastjet [51] and then passed through HEPTopTagger2 and demand the event with at least one top tagged fatjet. If there are more than one top tagged fatjet, we use the top jet which is best reconstructed i.e by checking the reconstructed mass closer to the actual mass of the top quark.

The impact of those energy fraction variables, $z_k$ (Eq. 6) and $Z_b$ (Eq. 7) to the top polarization, are presented in Fig. 6 and Fig. 7. Clearly the distributions show different pattern for left and right handed top quarks coming from stop decay. As expected, events are crowded towards higher(lower) region for left(right) handed top quarks. Hence, measurement of these variables clearly indicate the state of polarization of top in this decay channel. As presented before, more robust variable in this context is $\cos \theta^*$ presented in Fig. 8 for this process. Evidently, this distribution presents as before, a very clear distinction between left and right polarized top quark. Based on this angular variable, we calculate the asymmetry observable as defined by Eq. 8 [30]. It is obvious that this asymmetry is expected to be very sensitive to the composition of neutralino and the chirality of $\tilde{t}_1$ (i.e. $\theta_{\tilde{t}_1}$), and the variation of $A_{\theta^*}$ is studied very systematically. The dependence of $A_{\theta^*}$ on $\theta_{\tilde{t}_1}$ is studied fixing the composition of $\tilde{\chi}_0^0$ 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 $\tilde{\chi}_0^0$ (right).

Figure 6: The $b$ quark energy fraction $Z_b$ (Eq. 7) for the event Eq. 13. LSP is pure bino ($\tilde{\chi}_0^0 = \tilde{B}$) and $\tilde{t}_1$ is either pure $\tilde{t}_L$ (red) or $\tilde{t}_R$ (blue).

Figure 7: Same as Fig. 6 but for $z_k$. 
It is worth to mention here some features of the distributions shown in this figure. For a pure bino like case (left plot), and for larger values of $|\cos \theta_{\tilde{t}}| \sim 1$, $\tilde{t}_1$ and $\tilde{\chi}^0_1$ couplings become, $g^L \gg g^R$, i.e produced top quark is pre-dominantly left handed, leading to $\cos \theta^* > 0$, (see Fig. 8), and making asymmetry $A_{\theta^*}$ positive (Eq. 8). With the decrease of the magnitude of $\cos \theta_{\tilde{t}}$, the right handed coupling part $g^R_{\tilde{t}}$ gradually becomes important, leading to the production of both left and right handed top quarks. Since, the coupling of $\tilde{t}_R$ with $\tilde{\chi}^0_1$ is twice that of $\tilde{t}_L$ due to the hyper charge, the abundance of right handed top is more than left handed top quarks. Hence, $A_{\theta^*}$ turns out to be negative, and it does not change much even with the change of $\cos \theta_{\tilde{t}}$, and finally again becomes positive near $\cos \theta_{\tilde{t}} = 1$. In the case of equal mixtures of gauginos and Higgsinos the variation of $A_{\theta^*}$ 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($g^R_{\tilde{t}}$) 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 $A_{\theta^*}$ negative, as it is clearly observed. For intermediate values of $\cos \theta_{\tilde{t}}$, the left handed top quarks are also produced making the asymmetry positive, and for $\cos \theta_{\tilde{t}} > 0$ and beyond, again the population of $\tilde{t}_R$ goes up, making asymmetry negative.

In Fig. 10 the dependence of asymmetry on the composition of neutralinos for a given chirality of state of $\tilde{t}_1$ is shown. In the left plot, the magnitude of $\tilde{B}$ content in $\tilde{\chi}^0_1$ 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 $Z_{14} = -\sqrt{1-Z_{11}^2}$. Due to much larger Higgsino coupling, the interaction between top squark and Higgsino like LSP dominates as compared to the gaugino case. So the top quark from the decay of left(right) handed like ($\tilde{t}_1$), becomes right(left) handed. It implies that for $\cos \theta_{\tilde{t}_1} = 1(0)$, the asymmetry expected to be negative(positive). Clearly, 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 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 present also the variation of $A_{\theta^*}$ with wino($Z_{12}$) and Higgsino like LSP($Z_{14}$) setting $Z_{11} = Z_{13} = 0$. Very similar type of pattern of variation of asymmetry is observed for both cases. In the right figure for lower range of $Z_{12}$, the main contribution comes due to the Higgsino like coupling, and it goes down with the increase of $Z_{12}$. Notice that, in this case the asymmetry for $\tilde{t}_L$ changes faster in comparison to $Z_{14}$ variation(left) which is due to the iso-spin interaction having larger magnitude than the hyper-charge interaction. It is obvious that the fall of asymmetry for $\tilde{t}_R$ case is essentially unaffected since it does not couple to the winos. Now, if the composition of $\tilde{t}_1$ be mixed other than the pure state what we have considered, the variation should be in between the two extreme cases those shown in Fig. 10. Undoubtedly, the measurement of asymmetry is found to be a robust tool to probe the polarization of top quarks, and the nature.

Figure 8: The distribution of $\cos \theta^*$ (Eq. [3]) corresponding to the case: LSP is pure bino ($\tilde{\chi}^0_1 = \tilde{B}$) and $\tilde{t}_1$ is either pure $\tilde{t}_L$ (red) or $\tilde{t}_R$ (blue).
Figure 9: Variation of asymmetry (Eq. 8) with the composition of $\tilde{t}_1$ for the cases of pure $\tilde{\chi}^0_1$ and equally mixed $\tilde{\chi}^0_1$ states.

5 Top polarization in RS models

In this section we study the production of polarized top quark in extended Randall-Sundrum(RS) models [52, 53], where top quark can be produced from the decay of the heavy resonance of mass of few TeV. These resonances can be Kaluza Klein (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 [54]. Moreover, the couplings of KK-states to the SM fermions may not be universal. These extended RS models have an advantage over the original RS model [55] of having a natural solution of Yukawa hierarchy problem [56–58]. We emphasize here on the fact that, one can have $t\bar{t}$ or single top as the final state depending on which KK state is the mediator. To represent these two classes, we consider KK-gluon (flavour violating ) and KK-graviton ($G_{KK}$) decay where we get $t\bar{t}$ final state respectively. We also consider the case when KK-gluon state decays into a top-antitop pair for comparison.

First we consider, a single top production, in “Kaluza-Klein Gluon Model” [52]. 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 $\bar{t}\gamma_{\mu}gg^{\mu}$ (where $q$ denotes light quarks), along with the flavor-conserving neutral coupling $\bar{t}\gamma_{\mu}gg^{\mu}$ [52]. We have considered a specific case when only left-chiral couplings are allowed in 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,

$$pp \rightarrow g_{KK} \rightarrow t_L\bar{c}_L \rightarrow \text{Hadronic final states} \quad (\text{both s and t-channel})$$

$$pp \rightarrow g_{KK} \rightarrow t\bar{t} \rightarrow \text{Semi-leptonic final states} \quad (s\text{-channel})$$

We used the available FeynRules model [59,60] file and events are generated with MadGraph5. Showering and hadronization are done using Pythia6. For single top events, hadronic final state is considered while for $t\bar{t}$ events, the following criteria is used to select events:
• At least one hard ($p_T > 20$ GeV) and isolated lepton is demanded. The isolation is ensured by demanding $\sum_i p_i T (\Delta R < 0.3) < 0.3$.

• A cut on the missing transverse energy has also been applied i.e. $E_T > 30$ GeV.

We passed the selected events through HEPTopTagger2 to tag the top from fatjet with radius $R = 1.0$. The $t\bar{t}$ final state produced via s-channel mediation of KK-gluon are unpolarized and single top produced via s- and t-channel exchange of KK-gluon will be left-chiral. We present the $z_k, Z_b$ and $\cos \theta^*$ distribution at HEPTopTagger2 level for $t\bar{t}$ and single top in Fig. 11. We have considered KK-gluon mass of 4 TeV which is allowed by the current experimental bound [61].

We also consider $t\bar{t}$ production from KK-graviton in top-philic model discussed in Ref. [53]. In this model, right-chiral top quark will be localized near the infra-red (IR) brane and the KK-graviton is also localized near the IR brane. Therefore KK-graviton will have dominant coupling to right-chiral fermions and hence the produced top quark will be right-chiral. The corresponding Lagrangian is as follows:

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

where $G^{\mu\nu}$ is the graviton field, $T_{\mu\nu}^F$ is the energy-momentum tensor of the fermion fields.

$$T_{\mu\nu}^F = \sum_{f=u,d,l} \left[ \frac{i}{4} \bar{f}_R (\gamma^\mu D^\nu + \gamma^\nu D^\mu) f_R - \frac{i}{4} (D^\mu \bar{f}_R \gamma^\nu + D^\nu \bar{f}_R \gamma^\mu) f_R 
- i \eta^{\mu\nu} \left( \bar{f}_R \gamma^\rho D_\rho f_R - \frac{1}{2} D_\rho (\bar{f}_R \gamma_\rho f_R) \right) \right],$$

(14)

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

In Fig. 11 we also show the distributions for $z_k, Z_b$ and $\cos \theta^*$ at the HEPTopTagger2 level for KK-graviton mass of 4 TeV. This value of KK-graviton mass is consistent with the experimental results [62]. 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. If we compare the three curves in each panel of Fig. 11 we can see the discriminating
Figure 11: The $z_k$ (top left), $Z_b$ (top right) and $\cos \theta^*$ (bottom center) distribution at HEPTopTagger2 level for single top and $t\bar{t}$ pair from KK-gluon of mass 4 TeV and $t\bar{t}$ pair from KK-graviton of mass 4 TeV.

The potential of $z_k$ variable is less promising than the other two variables considered. The $b$-subjet energy fraction, $Z_b$ performs a better distinction 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 is indeed $\cos \theta^*$. In case of right-chiral top produced from KK-graviton, the distribution is more populated in the lower range of $\cos \theta^*$ and for left-chiral top quark produced from KK-gluon it is peaked around higher range of $\cos \theta^*$. For unpolarized top from 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 top quark with different polarization, these observables can also be utilized to distinguish between these two types of resonances.

Next we have extended this top-philic model and considered non-zero coupling of KK-graviton with both left- and right-chiral top quark and we have calculated the asymmetry for the $\theta^*$ observable, as we did for top production from $W'$ decay and stop decay in MSSM. We have introduced parameters $k_L$ and $k_R$ in the Lagrangian, as follows,

$$\mathcal{L}_F = -\frac{1}{\Lambda} G^{\mu \nu} \mathcal{T}^{F}_{\mu \nu},$$
This Eq. 15 suggests a new parametrization, in terms of angular variable \( \theta_{RS} \) for the calculation of asymmetry, where \( \cos \theta_{RS} = \frac{k_L}{\sqrt{k_L^2 + k_R^2}} \). When \( |k_L| = 1 \) and \( k_R = 0 \) \( \Rightarrow \) \( |cos \theta_{RS}| = 1 \), only the left-chiral top couples to the KK-graviton and while \( k_L = 0 \) and \( |k_R| = 1 \) \( \Rightarrow cos \theta_{RS} = 0 \) only the coupling of right-chiral top to the KK-graviton is non-zero.

\[
\mathcal{T}_{\mu\nu} = \sum_{f=u,d,l,\nu} \left( \frac{k_R}{\sqrt{k_L^2 + k_R^2}} \left[ \frac{i}{4} \bar{f}_R (\gamma^\mu D^\nu + \gamma^\nu D^\mu) f_R - \frac{i}{4} (D^\mu \bar{f}_R \gamma^\nu + D^\nu \bar{f}_R \gamma^\mu) f_R \right] - i \eta^{\mu\nu} \right) \left[ \bar{f}_R \gamma^\rho D_\rho f_R - \frac{1}{2} D_\rho (\bar{f}_R \gamma^\rho f_R) \right] + \frac{k_L}{\sqrt{k_L^2 + k_R^2}} \left[ \frac{i}{4} \bar{f}_L (\gamma^\mu D^\nu + \gamma^\nu D^\mu) f_L - i \eta^{\mu\nu} \left( \bar{f}_L \gamma^\rho D_\rho f_L - \frac{1}{2} D_\rho (\bar{f}_L \gamma^\rho f_L) \right) \right] - \frac{g_W}{\sqrt{2}} V_{ij} \bar{f}_u \gamma^\mu P_L f_d W_\mu^+ + \frac{g_W}{\sqrt{2}} U_{ij} \bar{f}_l \gamma^\mu P_L f_\nu W_\mu^- + h.c \right) 
\]

\[
- \frac{g_W}{\sqrt{2}} V_{ij} \bar{f}_u \gamma^\mu P_L f_d W_\mu^+ + \frac{g_W}{\sqrt{2}} U_{ij} \bar{f}_l \gamma^\mu P_L f_\nu W_\mu^- + h.c \right) \left( \mu \leftrightarrow \nu \right) \right) .
\]

\[15\]

This Eq 15 suggests a new parametrization, in terms of angular variable \( \theta_{RS} \) for the calculation of asymmetry, where \( \cos \theta_{RS} = \frac{k_L}{\sqrt{k_L^2 + k_R^2}} \). When \( |k_L| = 1 \) and \( k_R = 0 \) \( \Rightarrow \) \( |cos \theta_{RS}| = 1 \), only the left-chiral top couples to the KK-graviton and while \( k_L = 0 \) and \( |k_R| = 1 \) \( \Rightarrow \) \( cos \theta_{RS} = 0 \) only the coupling of right-chiral top to the KK-graviton is non-zero.

![Figure 12: The \( A_{\theta^*} \) asymmetry for tagged tops for KK-graviton mass of 3 TeV.](image)

The asymmetry \( A_{\theta^*} \) for the tagged tops as a function of \( \cos \theta_{RS} \) is presented in Fig. 12. The asymmetry is negative for the right-chiral case and positive for the left-chiral case. In this figure we can see 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 case of left-chiral top quark when \( \cos \theta^* \sim 1 \) (see Fig 11). We can see that 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 \( A_{\theta^*} \) together will not only help us to look for the new physics but also guide us in identifying its nature.

\section{Summary}

Top quark polarization carries the information which can provide the deeper insight about its couplings with fermions and gauge bosons. Hence, probing the coupling of top quark through the measurement of its polarization, possibly can indicate the presence of new physics. The kinematics
of decay products from top quark, including angular correlations among themselves, are strongly
correlated with the handedness of top quark, which lead the characteristic feature to distinguish.
From the conservation of momentum and spin in the hadronic mode of top decay, it is known that
the anti-fermion from W decay is very sensitive to polarization in comparison to other decay prod-
ucts. However, it becomes very challenging for highly boosted top quark of which decay products
are not very well separated, and those come out within a fat jet. In this study we develop strategy
to study the polarization of boosted top quark focusing on its hadronic decay mode considering a
benchmark process, Eq. 1. The boosted top quark is tagged using jet substructure method with clear
identification of sub-jets. We identify the subjet corresponding to the decay(anti-fermion) product
from W decay, and obtain its energy fraction in the laboratory frame, which is found to be very
useful sensitive variable to distinguish the left and right handed top quark. In addition, availability
of techniques to tag b jets with very high transverse momentum and inside a tagged top jet, also
e ncourages us to use b-jets as another object to identify top quark polarization by measuring its
energy fraction in the lab frame. It is to be noted that the b tagged jets were not used before in this
context due to the lack of proper b tagging tool. It is observed that for hard(soft) b tagged jet or
untagged jet, the probability of mother top quark to be left(right) handed is more, i.e hardness of
jets clearly distinguishes the left and right handed top quark, see Fig. 3 and Fig. 4.
Furthermore, we also propose a new observable based on the angular correlations among hadronic top
decay products. Again, focusing the subjet corresponding to the anti-fermion in top decay products,
we construct an angular variable in the top rest frame, between direction of a subjet and the boosted
tagged top momentum in the lab frame. This angular variable, namely \( \cos \theta^* \) (Eq. 3) turn out to be
very robust to identify the polarization of boosted top quark, as seen in Fig.4. Evidently, selection
of \( \cos \theta^* \) unambiguously discriminate events due to the left and right handed top quark. Based on
this feature we define an asymmetry(Eq. 8) of event which can be used as a measure of polarization.
Obviously, this asymmetry is governed by the couplings as shown in Fig. 5. The asymmetry varies
from +20% to -20% for \( g_R(L) = 1(0) \) to \( g_L(R) = 1(0) \). Clearly, the measurement of asymmetry is a
good indication of the nature of couplings.

The impact of these constructed polarization sensitive variables are studied for two new physics
processes where polarized top quarks are produced from top squark decay in SUSY searches and KK
gluon and graviton decay in RS model. In top squark decay,(Eq. 13), the couplings, and hence the
polarization depend on the details of SUSY parameters. The energy fraction variables, and angular
observable are presented setting certain benchmark parameters and top squark mass. Remarkably,
the \( \cos \theta^* \) 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. Evidently, the measurement
of asymmetry can shed some insight about the model, in particular the nature of top squark and
neutralinos, which might be a very useful information in reconstructing models. Similar exercise is
also carried out in the context of RS model. The substantial impact of these constructed variables
are observed in this model, and again, the measured asymmetry might be an useful tool to pin down
the nature of couplings in this model. It is to be noted that there are SM physics processes which
are having identical final state as the process considered here, with huge cross sections. It is really
challenging and interesting to see how those backgrounds dilute our observations. One needs to carry
out dedicated analysis matching the experimental challenges at the LHC in order to establish the
robustness of our strategy to identify the top quark polarization [63].

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