Boosted Top quark polarization

Rohini Godbole[⋆1], Monoranjan Guchait[†2], Charanjit K. Khosa[§3], Jayita Lahiri[‡4], Seema Sharma[¶5] and Aravind H. Vijay[†6]

[⋆] *Centre for High Energy Physics, Indian Institute of Science, Bangalore-560012, India*

[†] *Department of High Energy Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai-400005, India*

[§] *Department of Physics and Astronomy, University of Sussex, Brighton, BN1 9RH, United Kingdom*

[‡] *Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, HBNI, Chhatnag Road, Jhunsi, Allahabad - 211 019, India*

[¶] *Indian Institute of Science Education and Research, Pune-411008, India*

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 it 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 jet sub structure technique, we study 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 which reflect the polarization. We study the efficacy 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]Email: rohini@iisc.ac.in
[2]Email: guchait@tifr.res.in
[3]Email: charanjit.kaur@sussex.ac.uk
[4]Email: jayitalahiri@hri.res.in
[5]Email: seema@iiserpune.ac.in
[6]Email: aravind.vijay@tifr.res.in

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 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 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 the tensor structure 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 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 in scenario where decay of a heavy particle results in a top quark which is boosted, and in principle also polarized. To be specific, we consider few new physics processes, where polarized top quarks originate from heavy particles such as $W' \to tb$, the superpartner of top, top squark($\tilde{t}$), 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 measurement of polarization of 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, semi-leptonic 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 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. Reconstruction of 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 non trivial algorithm [22].

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 involves 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 [23]. 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 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, 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 [19]. 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 [28] which 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 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 MVA techniques with a reasonable efficiency is not difficult as shown by experimental studies [31,32]. Therefore, we employ energy fraction of tagged high p_T b jets as one of the useful polarimeter [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 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 following benchmark process,

$$pp \rightarrow W' \rightarrow tb \tag{1}$$

where the W' gauge boson couples with both left and right handed top quark which is assumed to decay, $t \rightarrow bW$ with 100% branching ratio. We simulate the process of Eq. 1 and study the observables which have a 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 where the top polarization has a value different from ± 1. For example, top squark, produced in pairs at the LHC decay to top quark accompanied by the lightest neutralino($\tilde{\chi}_1^0$), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ [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 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 possibly can shed some light about the $\tilde{t}_1 - t - \tilde{\chi}_1^0$ couplings in supersymmetric(SUSY) theories. Similar studies are also carried out 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 the 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 [34],

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} \quad = \quad \frac{1}{2}\left(1 + \mathcal{P}_0 \kappa_f \cos\theta_f\right) \tag{2}$$

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] ($-1 \leq \mathcal{P}_0 \leq 1$) 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 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. In principle, the reconstructed W, on the other hand, with opposite spin analyzing power of 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 down-type quark or b-jet(or W) is expected to provide considerable handle to study 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, 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 [28].

3. In addition, b-jet 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 [39, 40].

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 about $\approx 50\%$ 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 top quark. In the lab frame, the direction of momentum and the spin of top jet is opposite to each other for left handed, and in the same direction for the right handed top quark. Hence the angular correlation between the momenta of j_1 sub jet and topjet is expected to show effect of polarization of the parent top quark. With this understanding, we construct the observable, namely $\cos\theta^\star$, as defined,

$$\cos\theta^* \quad \equiv \quad \frac{\vec{t_j} \cdot \vec{j}_1'}{\left|\vec{t_j}\right| \left|\vec{j}_1'\right|}, \tag{3}$$

where $\vec{t}_j$ is the momentum of reconstructed top jet in the lab frame, and $\vec{j}_1'$ is the sub jet momentum in 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 lab 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,

3 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 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 [23, 41–45]. In this technique, topjets are tagged by finding the substructures of fat jets following BDRS mass drop [23] and filtering method using `HEPTopTagger2` [23, 41–44].

The matrix element for the benchmark process, Eq. 1, is generated using the `FeynRules` [46] corresponding to the W' effective model [47] in `MadGraph_aMC@NLO` [48] at $\sqrt{s} = 13$ TeV to generate left handed and right handed top quark via s-channel. It is to be noted that the whole process up to the top decays to jets are treated in 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` [49, 50]. 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 [51, 52],

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

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 same as it's chirality. In the simulation, fat jets are reconstructed using `Cambridge/Aachen` (C/A) [53] algorithm setting the jet size parameter $R = 1$, and required to have transverse momentum $p_T > 200$ GeV and $|\eta| < 4$. Generated events consisting of fat jets are passed through `HEPTopTagger2` to tag 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 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 also reported by ATLAS collaboration [54]. 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 case of right handed top quarks (in the lab frame), the $\bar{d}$ 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 case of right handed top quarks, the subjets are better separated than the case for 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. As 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 right handed (helicity) top and 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 topjet

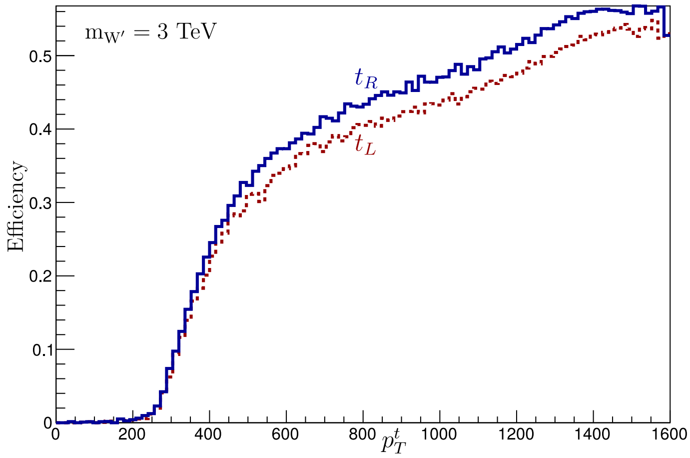


Figure 1: Top tagging efficiency for left (t_L) and right chiral (t_R) top quark for the process $pp \to W' \to tb$ with $m_{W'} = 3$ TeV.

corresponding to 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,

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

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.,

$$\begin{aligned} z_k \quad &= \quad \frac{\max(E_i, E_j)}{E_t}, \text{ where } d_{ij} \text{ is minimum.} \\ \text{and } E_t \quad &: \quad \text{energy of the top jet,} \end{aligned} \tag{6}$$

acts as a good polarimeter [28]. For the sake of comparison, 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 where the energy fraction z_k is shown (solid) along with the truth level distribution(dashed) for both left and right handed top quark originating from W' decay. As expected, it is seen that by matching subjets with the parton level quarks, about 50% of the cases, 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 that the $\bar{d}$ quark is maximally correlated with the top spin, hence for left-handed top (in the lab 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 mostly b-like with comparatively harder energy. For right handed top quark case, we observe mostly the same kind of pairing, but with harder $\bar{d}$-like subjet and softer b like subjet.

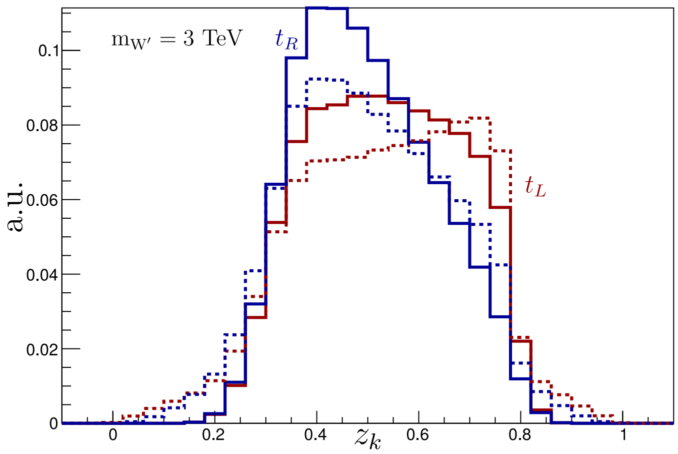


Figure 2: The energy fraction z_k (Eq. 6) for left (red) and right handed (blue) top quark for $m_{W'} = 3$ TeV. The dashed lines correspond to the observable at the partonic level.

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 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 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 [39, 40]. 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 in this context is $\cos\theta^\star$(Eq. 3). The distribution of this angular observable for left and right-handed top quark 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) and top-spin are in the opposite direction at the lab frame in case of left handed top, and are in same direction for right handed top. On the other hand, the momentum direction of the sub jet j_1 having maximum spin analyzing power ($\bar{d}$-type quark), and with comparatively less energy (in the top rest frame), is opposite to the spin direction 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 but 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.

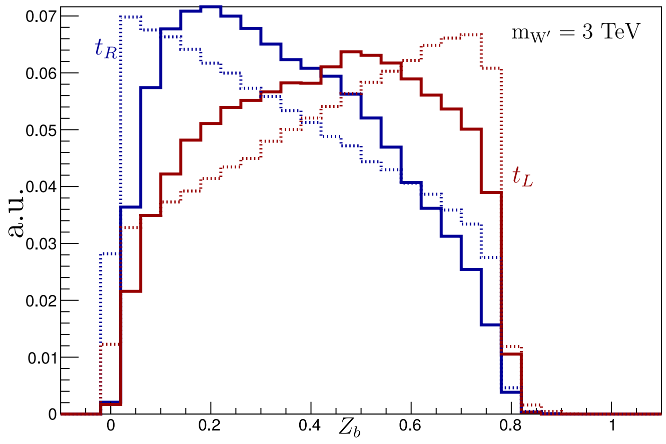


Figure 3: Energy fraction of b-like subjet for partonic (dashed) and reconstructed top jet using `HEPTopTagger2` (solid).

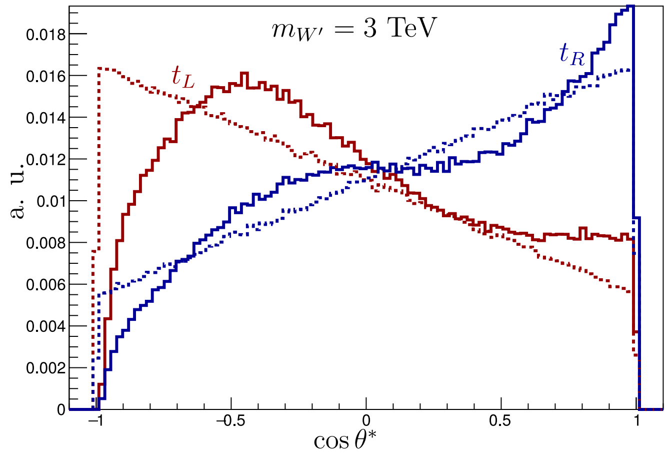


Figure 4: The $\cos\theta^*$ distribution for $m_{W'} = 3$ TeV for reconstructed top jet (solid) and partonic (dashed).

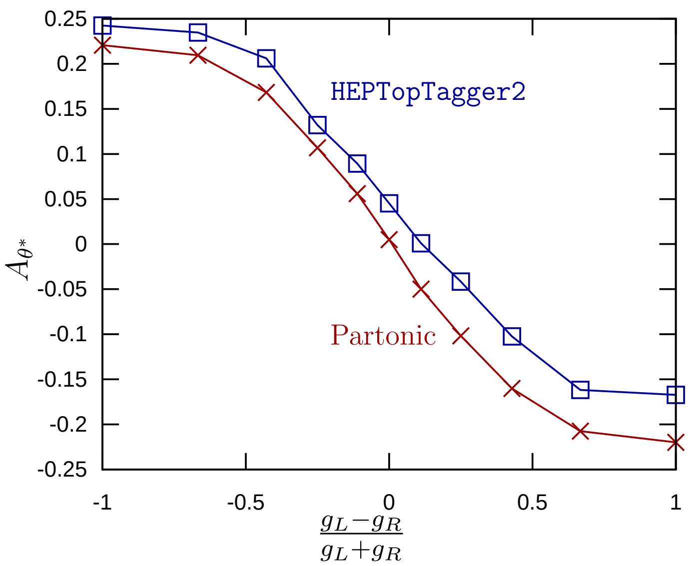


Figure 5: The asymmetry (Eq. 8) for parton level and tagged tops for $m_{W'} = 3$ TeV.

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 where 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, where as it is positive for the 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 constructed discriminating observables Eq. 3, 6 and 7 in distinguishing the 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 decays in a variety of channels depending on its mass and composition, leading to many diverse signatures. We focus on the decay channel of top squark,

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

which can be the dominant mode with 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,

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

determines the polarization of top quark in the final state. The electroweak correction to this decay channel is at the level of few percent [55]. The form of couplings $g^{\tilde{t}_{1L}}$ and $g^{\tilde{t}_{1R}}$ are,

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

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

The compositions of $\tilde{\chi}_1^0$ and mixing of $\tilde{t_1}$ are related with the respective physical states as:

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

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 neutralino [56]. As we know, the gauge interaction conserves chirality and 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 1. The polarization of the top quark produced in the $\tilde{t}_1$ decay, in the rest frame of the decaying top squark, can be calculated easily, and is given by [24,35,36,57–59]:

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

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 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 pair in the process,

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

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 where 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]

Table 1: 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

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, of course to focus only on hadronic decay mode of the other top quark avoiding recombinatorial issues [43]. We set relevant parameters as,

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

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. In simulation, the events are selected as:

- 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 [53] fatjets of $R = 1.0$ using `fastjet` [60] and then passed through `HEPTopTagger2` and demand the event with at least one top tagged fat jet. 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 physical mass of the top quark.

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

Clearly the distributions show different pattern for left and right handed top quarks coming from top squark decay in the two cases. As expected, events are crowded towards 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, 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 $\cos\theta^\star$, shown in Fig. 8. Evidently, this distribution demonstrate as before, a very clear distinction between left and right polarized top quark. Based on this angular variable, we calculate the asymmetry as defined by Eq. 8 [59]. 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. $\theta_{\tilde{t}}$). We systematically study the variation of A_{θ^*}. The dependence of it on $\theta_{\tilde{t}}$ is studied 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).

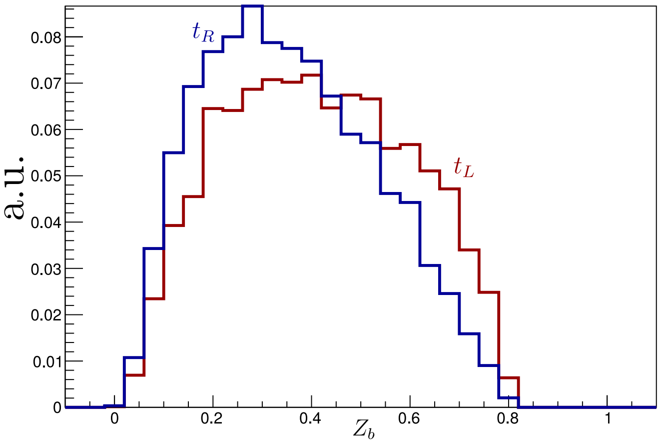


Figure 6: The b quark energy fraction Z_b for the event presented by Eq. 14, LSP is pure bino ($\tilde{\chi}_1^0 = \tilde{B}$) and $\tilde{t}_1$ is either pure $\tilde{t}_L$ (red) or $\tilde{t}_R$ (blue).

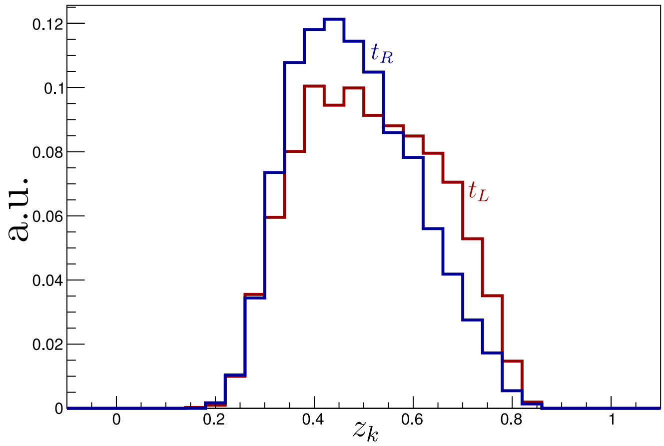


Figure 7: Same as Fig. 6 but for z_k.

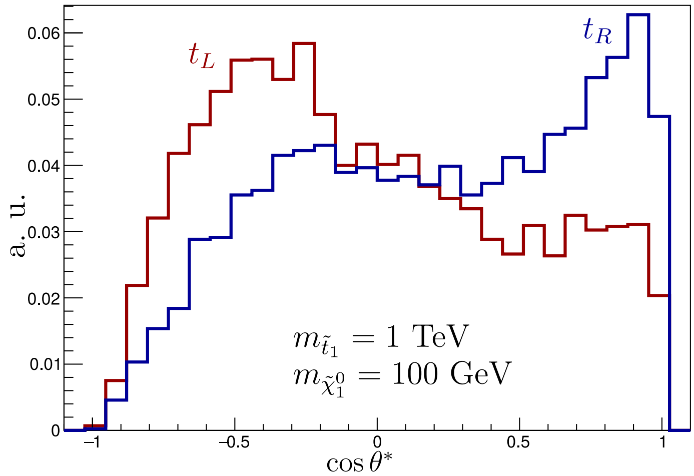
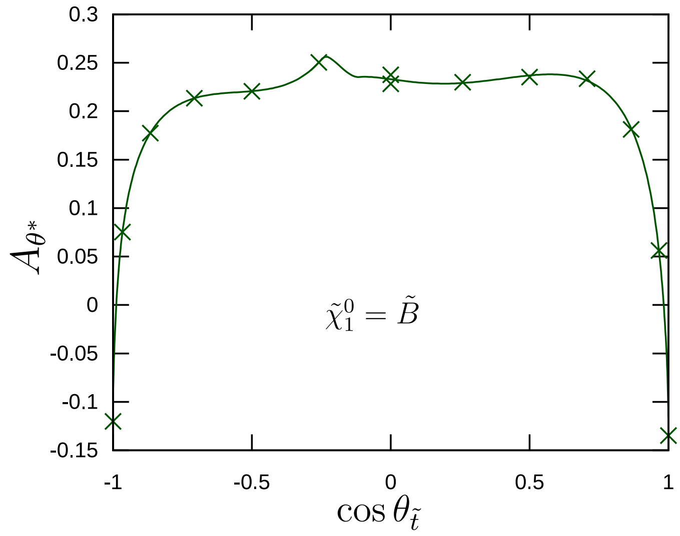


Figure 8: The distribution of $\cos\theta^*$ (Eq. 3) corresponding to the case: LSP is pure bino ($\tilde{\chi}_1^0 = \tilde{B}$) and $\tilde{t}_1$ is either pure $\tilde{t}_L$ (red) or $\tilde{t}_R$ (blue).

It is worth to mention here some features of the distributions shown in this 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 produced top quark is pre-dominantly left handed, leading to $\cos\theta^*$ negative, (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 hyper charge, the abundance of 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 mixtures of gauginos and Higgsinos the variation of $A_{\theta^\star}$ 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 $A_{\theta^\star}$ 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 $\tilde{B}$ content in



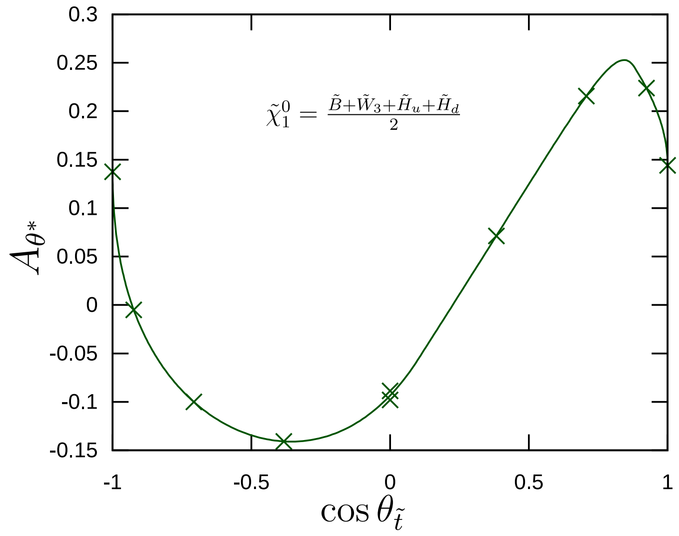


Figure 9: Variation of asymmetry with the composition of $\tilde{t}_1$ for the cases of pure bino like(left) and equally mixed $\tilde{\chi}_1^0$ states(right).

$\tilde{\chi}_1^0$ 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 $Z_{14} = -\sqrt{1 - Z_{11}^2}$. Due to 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. It implies that for $\cos\theta_{\tilde{t}} = 1(0)$, the asymmetry 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 $\tilde{t}_R$. In Fig. 10(Right) the variation of A_{θ^*} with wino(Z_{12}) and Higgsino like LSP(Z_{14}) setting $Z_{11} = Z_{13} = 0$ are presented. 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}. 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 iso-spin interaction having larger magnitude than the hyper-charge interaction. It is obvious that the variation of asymmetry for $\tilde{t}_R$ case is essentially unaffected, since it does not couple to the winos. Obviously, if the composition of $\tilde{\chi}_1^0$ be 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 top quark, and the nature of couplings involved in the process. In future, if top squark is discovered, and its polarization is measured, then it will allow us to constrain the compositions of top squark with respect to the mixings of the neutralino, provided we have some idea about the neutralino sector as well.

5 Top polarization in RS models

In this section we study the production of polarized top quark in extended Randall-Sundrum(RS) models [61, 62], 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 [63]. 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 [64] of having a natural solution of Yukawa hierarchy problem [65–67]. 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

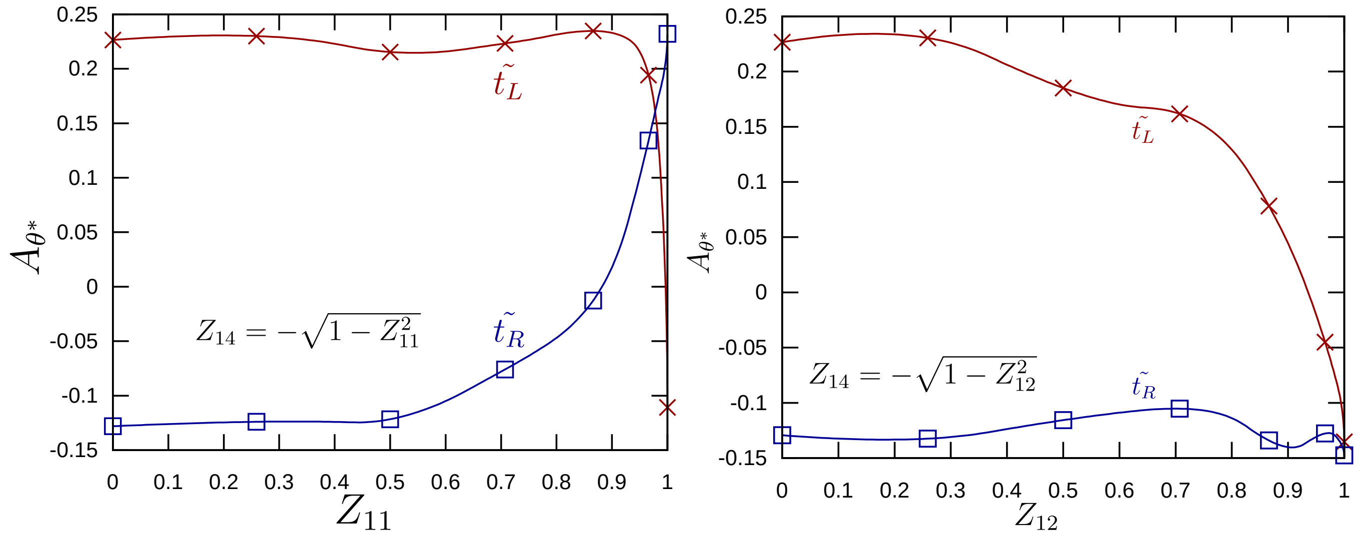


Figure 10: Variation of asymmetry (Eq. 8) with the composition of bino and wino like $\tilde{\chi}_1^0$ for the cases of $\tilde{t}_1 = \tilde{t}_L$ and $\tilde{t}_1 = \tilde{t}_R$.

two classes, we consider KK-gluon (flavor violating) and KK-graviton (G_{KK}) decay where we get single top and $t\bar{t}$ 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" [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 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,

$$
\begin{aligned}
pp \to g_{KK} &\to t_L \bar{c}_L \to \text{Hadronic final states} \quad \text{(both s and t-channel)} \\
pp \to g_{KK} &\to t\bar{t} \to \text{Semi-leptonic final states} \quad \text{(s-channel)}
\end{aligned}
$$

We used the available `FeynRules` model [68,69] file and events are generated with `MadGraph5`. Showering and hadronization are done using `Pythia6` [50]. 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 $\frac{\sum_i p_T^i(\Delta R<0.3)}{p_T^l} < 0.3$.

- 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 fatjets constructed with $R = 1.0$. 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 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 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 top-philic model discussed in Ref. [62]. 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

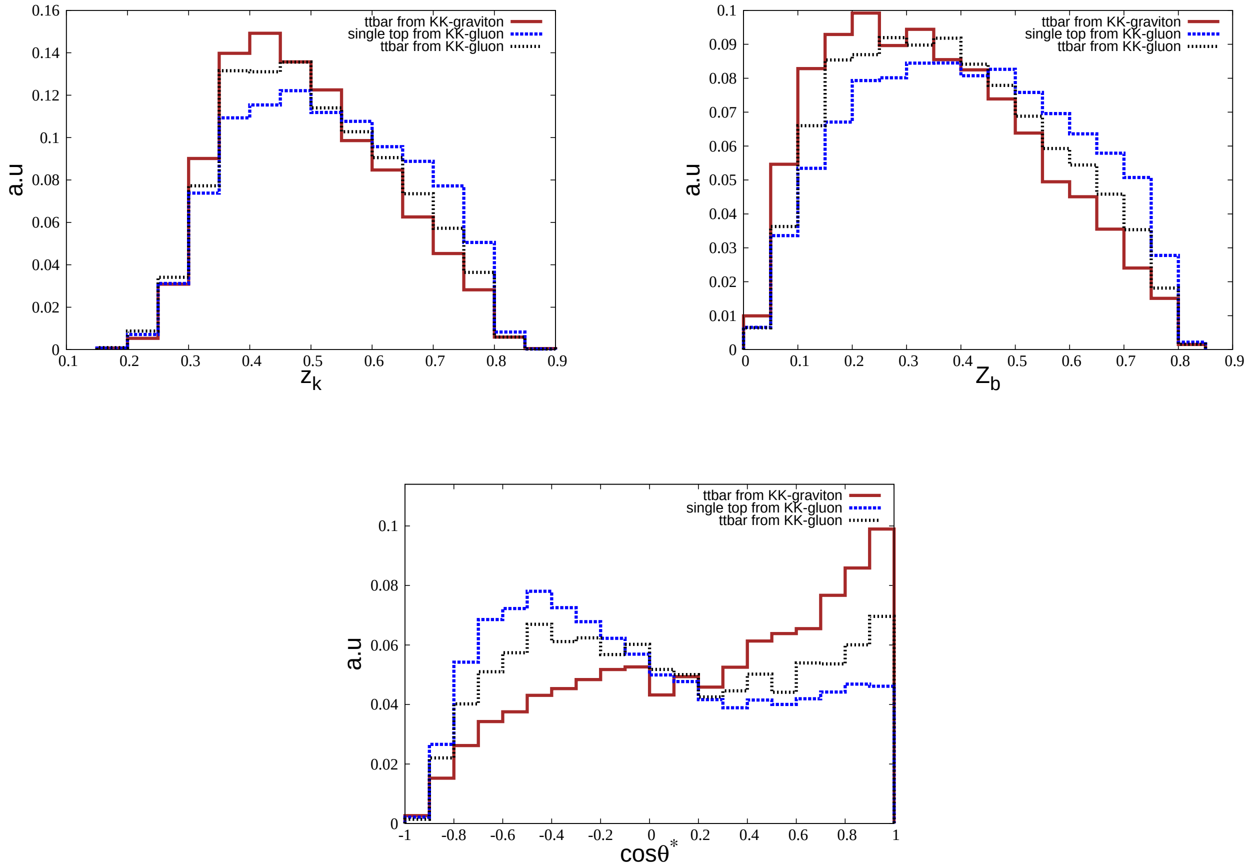


Figure 11: The z_k(top left), Z_b(top right) and $\cos\theta^*$(bottom center) distribution of reconstructed top jets for single top and $t\bar{t}$ pair production from KK-gluon of mass 4 TeV and $t\bar{t}$ pair from KK-graviton of mass 4 TeV.

follows:

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

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

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

here $\eta_{\mu\nu} = \text{diag}(1, -1, -1, -1)$ is the Minkowski metric tensor, and $D_\mu = \partial_\mu + i(2/3) g_1 B_\mu + i g_s G^a_\mu$ is the covariant derivative corresponding to each fermion. We consider the process $pp \to G_{KK} \to t\bar{t}, (t \to W^+ b, W^+ \to jj), (\bar{t} \to W^- \bar{b}, W^- \to l^- \bar{v}_l)$ + 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 $\cos\theta^*$ for KK-graviton mass of 4 TeV. This value of 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 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 is indeed $\cos\theta^*$. In case of left-chiral top produced from KK-graviton, the distribution is more populated in the lower range of $\cos\theta^*$ and for right-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 extend this study to top-philic model and consider non-zero coupling of KK-graviton with both left- and right-chiral top quark, and calculated the asymmetry for the θ^* 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 defined,

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

with

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

This equation suggests a new parameterization, 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 $k_R = 0$, implies $|\cos\theta_{RS}| = 1$, i.e only the left-chiral top couples to the KK-graviton and while $k_L = 0$ and $|k_R| = 1$ means $\cos\theta_{RS} = 0$ so the coupling of right-chiral top to the KK-graviton is non-zero.

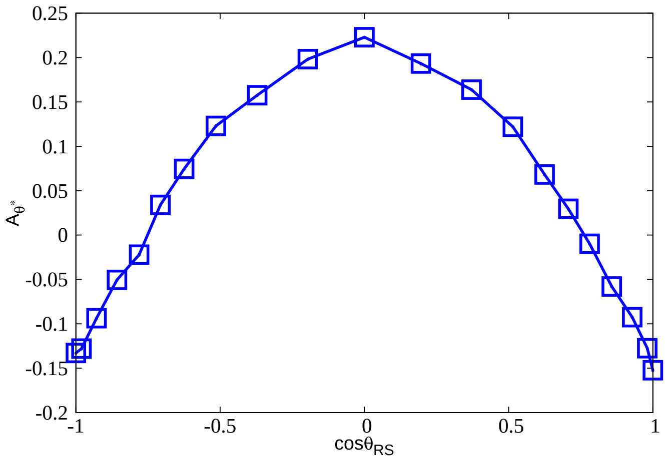


Figure 12: The $A_{\theta*}$ asymmetry for tagged tops for KK-graviton mass of 3 TeV.

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 case of 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 to look for the new physics but also guide us in identifying its nature.

6 Summary

Top quark polarization carries the information which can provide 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 kinematic distributions of decay products from top quark, including angular correlations among themselves, are strongly correlated with it's helicity. From the conservation of momentum and spin in the hadronic mode of top decay, it can be shown that the anti-fermion 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 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 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. Moreover, 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 lab frame. It is to be noted that previously b-tagged jets were not used 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 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 anti-fermion 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 lab 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, selection of $\cos\theta^\star$ 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 was found to be very effective to measure 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 are studied for two new physics scenarios 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. 14), 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 $\cos\theta^\star$ 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 top squark sector. Evidently, the measurement of asymmetry can shed some insight about the model, in particular the helicity of top squark and nature of neutralinos, which might be 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 with large cross sections which have identical final state as the processes considered here. In order to achieve signal sensitivity at a reasonable level, these backgrounds need to be suppressed by applying kinematic selections. It is really challenging, and worth to study how those background optimization cuts affect our observations. Therefore, one needs to carry out a dedicated analysis matching the experimental constrains at the LHC, and establish the robustness of our strategy to identify the top quark polarization [72].

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References

[1] M. Beneke *et al.*, "Top quark physics," in *1999 CERN Workshop on standard model physics (and more) at the LHC, CERN, Geneva, Switzerland, 25-26 May: Proceedings*, pp. 419–529. 2000. `arXiv:hep-ph/0003033 [hep-ph]`. `http://weblib.cern.ch/abstract?CERN-TH-2000-100`.

[2] U. Husemann, "Top-Quark Physics: Status and Prospects," *Prog. Part. Nucl. Phys.* **95** (2017) 48–97, `arXiv:1704.01356 [hep-ex]`.

[3] V. D. Barger, J. Ohnemus, and R. J. N. Phillips, "Spin Correlation Effects in the Hadroproduction and Decay of Very Heavy Top Quark Pairs," *Int. J. Mod. Phys.* **A4** (1989) 617.

[4] P. Uwer, "Maximizing the spin correlation of top quark pairs produced at the Large Hadron Collider," *Phys. Lett.* **B609** (2005) 271–276, `arXiv:hep-ph/0412097 [hep-ph]`.

[5] G. Mahlon and S. J. Parke, "Angular correlations in top quark pair production and decay at hadron colliders," *Phys. Rev.* **D53** (1996) 4886–4896, `arXiv:hep-ph/9512264 [hep-ph]`.

[6] M. Baumgart and B. Tweedie, "A New Twist on Top Quark Spin Correlations," *JHEP* **03** (2013) 117, `arXiv:1212.4888 [hep-ph]`.

[7] **CDF** Collaboration, T. Aaltonen *et al.*, "Measurement of $t\bar{t}$ Spin Correlation in $p\bar{p}$ Collisions Using the CDF II Detector at the Tevatron," *Phys. Rev.* **D83** (2011) 031104, `arXiv:1012.3093 [hep-ex]`.

[8] **CMS** Collaboration, V. Khachatryan *et al.*, "Measurements of t t-bar spin correlations and top quark polarization using dilepton final states in pp collisions at sqrt(s) = 8 TeV," *Phys. Rev.* **D93** no. 5, (2016) 052007, `arXiv:1601.01107 [hep-ex]`.

[9] **ATLAS** Collaboration, G. Aad *et al.*, "Measurement of Spin Correlation in Top-Antitop Quark Events and Search for Top Squark Pair Production in pp Collisions at $\sqrt{s} = 8$ TeV Using the ATLAS Detector," *Phys. Rev. Lett.* **114** no. 14, (2015) 142001, `arXiv:1412.4742 [hep-ex]`.

[10] M. Jezabek, "Top quark physics," *Nucl. Phys. Proc. Suppl.* **37B** no. 2, (1994) 197, `arXiv:hep-ph/9406411 [hep-ph]`.

[11] B. Grzadkowski and Z. Hioki, "Angular distribution of leptons in general $t\bar{t}$ production and decay," *Phys. Lett.* **B529** (2002) 82–86, `arXiv:hep-ph/0112361 [hep-ph]`.

[12] B. Grzadkowski and Z. Hioki, "Decoupling of anomalous top decay vertices in angular distribution of secondary particles," *Phys. Lett.* **B557** (2003) 55–59, `arXiv:hep-ph/0208079 [hep-ph]`.

[13] R. M. Godbole, S. D. Rindani, and R. K. Singh, "Lepton distribution as a probe of new physics in production and decay of the t quark and its polarization," *JHEP* **12** (2006) 021, `arXiv:hep-ph/0605100 [hep-ph]`.

[14] R. M. Godbole, S. D. Rindani, and R. K. Singh, "Lepton distribution in top decay: A probe of new physics and top- polarization," *Pramana* **69** (2007) 915–919.

[15] R. M. Godbole, K. Rao, S. D. Rindani, and R. K. Singh, "On measurement of top polarization as a probe of $t\bar{t}$ production mechanisms at the LHC," *JHEP* **11** (2010) 144, `arXiv:1010.1458 [hep-ph]`.

[16] K. Hagiwara, H. Yokoya, and Y.-J. Zheng, "Probing the CP properties of top Yukawa coupling at an e^+e^- collider," *JHEP* **02** (2018) 180, `arXiv:1712.09953 [hep-ph]`.

[17] A. Jueid, "Probing anomalous Wtb couplings at the LHC in single t-channel top quark production," *Phys. Rev.* **D98** no. 5, (2018) 053006, `arXiv:1805.07763 [hep-ph]`.

[18] A. Brandenburg, Z. G. Si, and P. Uwer, "QCD corrected spin analyzing power of jets in decays of polarized top quarks," *Phys. Lett.* **B539** (2002) 235–241, `arXiv:hep-ph/0205023 [hep-ph]`.

[19] B. Tweedie, "Better Hadronic Top Quark Polarimetry," *Phys. Rev.* **D90** no. 9, (2014) 094010, `arXiv:1401.3021 [hep-ph]`.

[20] **D0** Collaboration, V. M. Abazov *et al.*, "Evidence for spin correlation in $t\bar{t}$ production," *Phys. Rev. Lett.* **108** (2012) 032004, `arXiv:1110.4194 [hep-ex]`.

[21] R. M. Godbole, M. E. Peskin, S. D. Rindani, and R. K. Singh, "Why the angular distribution of the top decay lepton is unchanged by anomalous tbW couplings," *Phys. Lett.* **B790** (2019) 322–325, `arXiv:1809.06285 [hep-ph]`.

[22] T. Plehn, M. Spannowsky, and M. Takeuchi, "Boosted Semileptonic Tops in Stop Decays," *JHEP* **05** (2011) 135, `arXiv:1102.0557 [hep-ph]`.

[23] J. M. Butterworth, A. R. Davison, M. Rubin, and G. P. Salam, "Jet substructure as a new Higgs search channel at the LHC," *Phys. Rev. Lett.* **100** (2008) 242001, `arXiv:0802.2470 [hep-ph]`.

[24] J. Shelton, "Polarized tops from new physics: signals and observables," *Phys. Rev.* **D79** (2009) 014032, `arXiv:0811.0569 [hep-ph]`.

[25] Y. Kitadono and H.-n. Li, "Jet substructures of boosted polarized hadronic top quarks," *Phys. Rev.* **D93** no. 5, (2016) 054043, `arXiv:1511.08675 [hep-ph]`.

[26] J. S. Conway, R. Bhaskar, R. D. Erbacher, and J. Pilot, "Identification of High-Momentum Top Quarks, Higgs Bosons, and W and Z Bosons Using Boosted Event Shapes," *Phys. Rev.* **D94** no. 9, (2016) 094027, `arXiv:1606.06859 [hep-ex]`.

[27] T. Lapsien, R. Kogler, and J. Haller, "A new tagger for hadronically decaying heavy particles at the LHC," *Eur. Phys. J.* **C76** no. 11, (2016) 600, `arXiv:1606.04961 [hep-ph]`.

[28] D. Krohn, J. Shelton, and L.-T. Wang, "Measuring the Polarization of Boosted Hadronic Tops," *JHEP* **07** (2010) 041, `arXiv:0909.3855 [hep-ph]`.

[29] B. Bhattacherjee, S. K. Mandal, and M. Nojiri, "Top Polarization and Stop Mixing from Boosted Jet Substructure," *JHEP* **03** (2013) 105, `arXiv:1211.7261 [hep-ph]`.

[30] Y. Kitadono and H.-n. Li, "Jet substructures of boosted polarized top quarks," *Phys. Rev.* **D89** no. 11, (2014) 114002, `arXiv:1403.5512 [hep-ph]`.

[31] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV," *JINST* **13** no. 05, (2018) P05011, `arXiv:1712.07158 [physics.ins-det]`.

[32] **ATLAS** Collaboration, M. Aaboud *et al.*, "Measurements of b-jet tagging efficiency with the ATLAS detector using $t\bar{t}$ events at $\sqrt{s} = 13$ TeV," *JHEP* **08** (2018) 089, `arXiv:1805.01845 [hep-ex]`.

[33] J. Roy, "Probing leptoquark chirality via top polarization at the Colliders," `arXiv:1811.12058 [hep-ph]`.

[34] M. Jezabek and J. H. Kuhn, "Lepton Spectra from Heavy Quark Decay," *Nucl. Phys.* **B320** (1989) 20–44.

[35] G. Mahlon and S. J. Parke, "Single top quark production at the LHC: Understanding spin," *Phys. Lett.* **B476** (2000) 323–330, `arXiv:hep-ph/9912458 [hep-ph]`.

[36] R. Schwienhorst, C. P. Yuan, C. Mueller, and Q.-H. Cao, "Single top quark production and decay in the t-channel at next-to-leading order at the LHC," *Phys. Rev.* **D83** (2011) 034019, `arXiv:1012.5132 [hep-ph]`.

[37] V. Arunprasath, R. M. Godbole, and R. K. Singh, "Polarization of a top quark produced in the decay of a gluino or a stop in an arbitrary frame," *Phys. Rev.* **D95** no. 7, (2017) 076012, `arXiv:1612.03803 [hep-ph]`.

[38] W. Bernreuther, P. González, and C. Mellein, "Decays of polarized top quarks to lepton, neutrino and jets at NLO QCD," *Eur. Phys. J.* **C74** no. 3, (2014) 2815, `arXiv:1401.5930 [hep-ph]`.

[39] A. M. Sirunyan *et al.*, "Identification of heavy-flavour jets with the cms detector in pp collisions at 13 tev," *Journal of Instrumentation* **13** no. 05, (2018) P05011. `http://stacks.iop.org/1748-0221/13/i=05/a=P05011`.

[40] **ATLAS Collaboration** Collaboration, "Boosted Higgs ($\to b\bar{b}$) Boson Identification with the ATLAS Detector at $\sqrt{s} = 13$ TeV," Tech. Rep. ATLAS-CONF-2016-039, CERN, Geneva, Aug, 2016. `https://cds.cern.ch/record/2206038`.

[41] T. Plehn and M. Spannowsky, "Top Tagging," *J. Phys.* **G39** (2012) 083001, arXiv:1112.4441 [hep-ph].

[42] G. Kasieczka, T. Plehn, T. Schell, T. Strebler, and G. P. Salam, "Resonance Searches with an Updated Top Tagger," *JHEP* **06** (2015) 203, arXiv:1503.05921 [hep-ph].

[43] T. Plehn, M. Spannowsky, M. Takeuchi, and D. Zerwas, "Stop Reconstruction with Tagged Tops," *JHEP* **10** (2010) 078, arXiv:1006.2833 [hep-ph].

[44] T. Plehn, G. P. Salam, and M. Spannowsky, "Fat Jets for a Light Higgs," *Phys. Rev. Lett.* **104** (2010) 111801, arXiv:0910.5472 [hep-ph].

[45] D. E. Kaplan, K. Rehermann, M. D. Schwartz, and B. Tweedie, "Top Tagging: A Method for Identifying Boosted Hadronically Decaying Top Quarks," *Phys. Rev. Lett.* **101** (2008) 142001, arXiv:0806.0848 [hep-ph].

[46] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, "FeynRules 2.0 - A complete toolbox for tree-level phenomenology," *Comput. Phys. Commun.* **185** (2014) 2250–2300, arXiv:1310.1921 [hep-ph].

[47] B. Fuks and R. Ruiz, "A comprehensive framework for studying W' and Z' bosons at hadron colliders with automated jet veto resummation," *JHEP* **05** (2017) 032, arXiv:1701.05263 [hep-ph].

[48] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations," *JHEP* **07** (2014) 079, arXiv:1405.0301 [hep-ph].

[49] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, "An Introduction to PYTHIA 8.2," *Comput. Phys. Commun.* **191** (2015) 159–177, arXiv:1410.3012 [hep-ph].

[50] T. Sjostrand, S. Mrenna, and P. Z. Skands, "PYTHIA 6.4 Physics and Manual," *JHEP* **05** (2006) 026, arXiv:hep-ph/0603175 [hep-ph].

[51] Z. Sullivan, "Fully Differential W' Production and Decay at Next-to-Leading Order in QCD," *Phys. Rev.* **D66** (2002) 075011, arXiv:hep-ph/0207290 [hep-ph].

[52] D. Duffty and Z. Sullivan, "Model independent reach for W-prime bosons at the LHC," *Phys. Rev.* **D86** (2012) 075018, arXiv:1208.4858 [hep-ph].

[53] Y. L. Dokshitzer, G. D. Leder, S. Moretti, and B. R. Webber, "Better jet clustering algorithms," *JHEP* **08** (1997) 001, arXiv:hep-ph/9707323 [hep-ph].

[54] **ATLAS** Collaboration, M. Aaboud *et al.*, "Search for $W' \to tb$ decays in the hadronic final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," *Phys. Lett.* **B781** (2018) 327–348, arXiv:1801.07893 [hep-ex].

[55] A. Djouadi, W. Hollik, and C. Junger, "QCD corrections to scalar quark decays," *Phys. Rev.* **D55** (1997) 6975–6985, arXiv:hep-ph/9609419 [hep-ph].

[56] M. Drees, R. Godbole, and P. Roy, *Theory and phenomenology of Sparticles: an account of four-dimensional N=1 supersymmetry in high-energy physics*. World Scientific, Singapore, 2004. https://cds.cern.ch/record/873465.

[57] E. Boos, H. U. Martyn, G. A. Moortgat-Pick, M. Sachwitz, A. Sherstnev, and P. M. Zerwas, "Polarization in sfermion decays: Determining tan beta and trilinear couplings," *Eur. Phys. J.* **C30** (2003) 395–407, `arXiv:hep-ph/0303110 [hep-ph]`.

[58] M. Perelstein and A. Weiler, "Polarized Tops from Stop Decays at the LHC," *JHEP* **03** (2009) 141, `arXiv:0811.1024 [hep-ph]`.

[59] G. Belanger, R. M. Godbole, L. Hartgring, and I. Niessen, "Top Polarization in Stop Production at the LHC," *JHEP* **05** (2013) 167, `arXiv:1212.3526 [hep-ph]`.

[60] M. Cacciari, G. P. Salam, and G. Soyez, "Fastjet user manual," *The European Physical Journal C* **72** no. 3, (Mar, 2012) 1896. `https://doi.org/10.1140/epjc/s10052-012-1896-2`.

[61] P. M. Aquino, G. Burdman, and O. J. P. Eboli, "A Signal for a theory of flavor at the LHC," *Phys. Rev. Lett.* **98** (2007) 131601, `arXiv:hep-ph/0612055 [hep-ph]`.

[62] C.-Q. Geng, D. Huang, and K. Yamashita, "LHC Searches for Top-philic Kaluza-Klein Graviton," *JHEP* **10** (2018) 046, `arXiv:1807.09643 [hep-ph]`.

[63] T. Gherghetta, "A Holographic View of Beyond the Standard Model Physics," in *Physics of the large and the small, TASI 09, proceedings of the Theoretical Advanced Study Institute in Elementary Particle Physics, Boulder, Colorado, USA, 1-26 June 2009*, pp. 165–232. 2011. `arXiv:1008.2570 [hep-ph]`.

[64] L. Randall and R. Sundrum, "A Large mass hierarchy from a small extra dimension," *Phys. Rev. Lett.* **83** (1999) 3370–3373, `arXiv:hep-ph/9905221 [hep-ph]`.

[65] A. Pomarol, "Gauge bosons in a five-dimensional theory with localized gravity," *Phys. Lett.* **B486** (2000) 153–157, `arXiv:hep-ph/9911294 [hep-ph]`.

[66] T. Gherghetta and A. Pomarol, "Bulk fields and supersymmetry in a slice of AdS," *Nucl. Phys.* **B586** (2000) 141–162, `arXiv:hep-ph/0003129 [hep-ph]`.

[67] Y. Grossman and M. Neubert, "Neutrino masses and mixings in nonfactorizable geometry," *Phys. Lett.* **B474** (2000) 361–371, `arXiv:hep-ph/9912408 [hep-ph]`.

[68] E. Drueke, J. Nutter, R. Schwienhorst, N. Vignaroli, D. G. E. Walker, and J.-H. Yu, "Single Top Production as a Probe of Heavy Resonances," *Phys. Rev.* **D91** no. 5, (2015) 054020, `arXiv:1409.7607 [hep-ph]`.

[69] R. Sekhar Chivukula, E. H. Simmons, and N. Vignaroli, "Distinguishing dijet resonances at the LHC," *Phys. Rev.* **D91** no. 5, (2015) 055019, `arXiv:1412.3094 [hep-ph]`.

[70] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Search for resonant $t\bar{t}$ production in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Submitted to: JHEP* (2018) , `arXiv:1810.05905 [hep-ex]`.

[71] **ATLAS** Collaboration, T. A. collaboration, "Search for diboson resonances in hadronic final states in 79.8 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector,".

[72] M. Guchait, S. Bhattacharya, and A. H. Vijay *In Prepration* (2019) .