Measuring the Polarization of Boosted Hadronic Tops

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Abstract: We propose a new technique for measuring the polarization of hadronically
decaying boosted top quarks. In particular, we apply a subjet-based technique to events
where the decay products of the top are clustered within a single jet. The technique requires
neither \(b\)-tagging nor \(W\)-reconstruction, and does not rely on assumptions about either the
top production mechanism or the sources of missing energy in the event. We include
results for various new physics scenarios made with different Monte Carlo generators to
demonstrate the robustness of the technique.
1. Introduction

The top quark, with its large coupling to the Higgs sector, plays an important role in models of physics beyond the Standard Model. Indeed, many such models posit the existence of top partner states (e.g. the stop squark of SUSY [1] and the $T'$ of little Higgs models [2]) or otherwise couple the top to new physics in a special way (as with KK-gluons [3]). Measuring the couplings of the top to new states is therefore essential in distinguishing the correct model of physics beyond the Standard Model.

One especially interesting aspect of these couplings is their chirality: whether or not they distinguish left- from right-handed tops. Fortunately, the large mass of the top, which makes its study so interesting for electroweak physics, makes it possible to imagine measuring the chiral couplings of the top directly. Unlike the other quarks, the top decays before hadronization, so information about its spin is transferred to the distributions of its decay products [4]. On the other hand, the large mass of the top also means that in order for the chiral couplings of tops to new physics to translate into observable top polarization signals, the tops must be significantly boosted, as chirality only becomes equivalent to helicity in the massless limit. Boosted tops are therefore a natural and interesting place to look for polarization signals.

Conventional methods for measuring the polarization of non-boosted tops begin by reconstructing the top rest frame and considering the angular distributions of its decay products.
products in that frame, and often focus on the semi-leptonic decay mode, which can be fully reconstructed if the only missing energy in the event comes from the neutrino. Such techniques have been extended to events where the hadronic top is boosted, but the lepton from the leptonic top decay is still isolated. This isolated lepton can then be used to measure the polarization of its parent top, either by reconstructing the $t\bar{t}$ system \cite{5} or through the shape of the lepton $p_T$ spectrum \cite{6}.

When the top quark is highly boosted, however, requiring an isolated lepton begins to require a significant acceptance price. Moreover, while the large spin analyzing power of the lepton in standard model top decay makes it particularly useful for top polarization studies, it is also desirable to develop techniques which can measure polarization in boosted tops without the need for an isolated lepton. Being able to study polarization in boosted hadronic tops increases acceptance, and has the additional feature of flexibility: unlike leptonic tops, hadronic tops are fully reconstructable in events with multiple sources of missing energy. For highly boosted tops, the finite angular resolution of the detector makes complete reconstruction of the system difficult, and angular distributions in the top rest frame are no longer optimal observables.

Here we present a technique to measure the polarization of a boosted top in its hadronic decay mode using the energy fraction distribution of a particular subjet. This new method does not require high-$p_T$ $b$-tagging, which is known to be challenging. We also do not require $W$ reconstruction inside the top jet. Again, as we are considering hadronic tops, this technique measures top polarization using information from the top jet alone, independent of other objects in the event. It does not involve the reconstruction of top rest frame, or rely upon the measurement of missing momentum.

While identification of boosted hadronic tops above the QCD background is challenging, many promising approaches have been developed \cite{7, 5, 6, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19}. In this article we will assume that the boosted top candidates can be identified through one of these methods.

We will begin by motivating our choice of a subjet-based technique for studying the substructure of a top-jet. Then we will propose an algorithm useful for measuring the top polarization and discuss its interpretation. Finally, we will demonstrate the robustness of the algorithm by testing it in different physics scenarios with data from different parton shower models.

2. Looking Inside a Top Jet

Here we will discuss the different techniques used to study boosted hadronic tops. This will give us a chance to motivate our use of subjets while outlining other possibilities.

In the past, two distinct approaches have been taken to analyze top jets. One approach uses jet shape variables \cite{15, 16, 13} to define a function on the constituents of a top jet (in practice, the constituents will be calorimeter cells), treating each constituent independently. The other approach \cite{13, 14, 18, 19} defines a function on the subjets formed by reclustering the constituents of a larger jet. Functions then depend upon the constituent four-momenta.
only through the total four-momentum of the subjet they are clustered into, rather than
upon each constituent four-momentum independently.

Each approach has both advantages and disadvantages. Subjets can reduce the effects
of soft contamination\(^1\) by summing together constituents so that softer particles have a
proportionally smaller influence. However, care must be taken because some quantities one
can form from subjets, such as invariant mass, can be extremely sensitive to calorimeter
spacing and out-of-cone radiation. Fortunately, as long as one avoids these troublesome
quantities a subjet-based analysis can be made fairly robust. For our algorithm below,
we will only rely upon the relative hardness and separation of the subjets, both quantities
which are fairly insensitive to additional soft radiation and detector effects.

Jet shape variables, because they treat each jet constituent independently, are more
amenable to higher order calculations than variables defined with subjets. However, these
variables can become very sensitive to the effects of contamination. As an example, consider
the \textit{planar flow} jet shape of \cite{15}, which is equivalent (up to an overall constant) to \(\text{det } S^\perp\)
defined in \cite{13}. The planar flow of a jet is defined as

\[ Pf = \frac{4\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2)^2} \]  

where \(\lambda_{1,2}\) are the two eigenvalues of the matrix

\[ I_{kl}^w = \sum_i w_i p_{i,k} p_{i,l} w_i w_i \]  

where \(w_i\) is the energy and \(p_{i,k}\) the \(k\)th transverse momentum component of the \(i\)th jet con-
stituent. This quantity essentially decomposes the jet’s radiation into two moments \(\lambda_{1,2}\),
similar to moments of inertia, so that if the jet is symmetric about its center then \(Pf \approx 1\).
Planar flow is useful in top-quark studies because top jets are relatively symmetric about
their center (corresponding to higher values of planar flow), while QCD events are domi-
nated by a single emission (corresponding to a lower value of planar flow). Unfortunately,
planar flow weights each constituent according to its transverse momenta relative to the jet
axis, so that as the radius of a jet is varied soft radiation towards the edge of a jet begins
to dominate and all events are skewed toward higher \(Pf^2\). To demonstrate this sensitivity
and how it can be reduced through the use of subjets, we have included Fig. 1, showing the
calculation of planar flow at matrix element level, after showering, and after reclustering
using subjets. The subjets are formed using the procedure described in Section 4 using
\(R = 0.2\) cones. Here one can see the large corrections to the matrix element results that
are attributable to soft radiation. Of course, one can mitigate this effect by using smaller
cones (the authors of \cite{15} used \(R = 0.4\)), as the amount of diffuse soft radiation clustered
into the top jet goes roughly as \(R^2\), yet even in this regime the effect of soft contamination
can still be significant, especially near \(Pf \approx 0\).

\(^1\)Contamination, radiation clustered within the top jet that did not arise from the top decay, can be the
result of initial state radiation, multiple interactions, or wide angle emissions from other parts of the event.

\(^2\)While soft effects can skew Pf toward higher values, it remains difficult for QCD jets to be skewed all
the way toward \(Pf \sim 1\). Thus, while the distributions of Pf are sensitive to soft effects, they can still be
used as effective top/QCD discriminants.
Figure 1: Comparison of planar flow for left-handed tops (left figure) and right-handed tops (right figure). For each set of samples we compute the planar flow using the three partonic decay products of the top (black, solid), the constituents of the showered jet using a small $R = 0.4$ cone (blue, dotted), the constituents of the showered jet using a larger $R = 1.0$ cone (magenta, dot-dashed), and the three $R_{sub} = 0.2$ subjets formed from the $R = 0.4$ top-jet constituents (red, dashed). These events are taken from the decay of a $3$ TeV $Z'$ into two tops, clustered using the anti-$k_T$ algorithm, where we have required the top jet’s mass satisfy $140$ GeV $< m_J < 210$ GeV. Note that the peak of the red/black distributions near $Pf \sim 0$ can be ascribed to configurations where two of the partons become collinear, or where one parton becomes particularly soft.

To be sure, jet shape variables (including planar flow) are very useful and will likely play a role in boosted top chirality measurements. A simple counting exercise shows that after requiring the reconstruction of the $W$ mass, top four-vector, and allowing for axial symmetry, there are still three remaining degrees of freedom encoded in the matrix element that can be mapped out by jet shape variables. However, to simplify the discussion and avoid complicated issues of contamination and higher-order corrections we will use the rest of the paper to focus on quantities calculated using subjets.

3. Top Polarimetry With Subjets

We will now explore methods for using subjets to measure the polarization of a collimated hadronic top. In what follows, we will assume we are working with jets tagged as tops, as discussed in [13, 15, 16, 14, 20], and subsequently decomposed into three subjets (a prescription for such a decomposition is given later).

3.1 Choosing a Polarimeter

One observable sensitive to the polarization of the top is the distribution of energy among the its three decay products in the lab frame. In the collinear limit, the lab-frame energy fraction of the $i$th subjet, $z_i = E_i/E_{top}$, depends only on the energy and angular distributions in the top rest frame, and can serve as a robust variable to measure polarization.
While energy fractions are not Lorentz invariant for finite top mass, and in particular are not invariant under longitudinal boosts, frame dependence enters only at order \( m_t/E_t \), and therefore, for highly boosted top quarks, energy fraction variables become fixed, stable quantities \(^3\). The question then becomes how to select the subjet to be used as a polarimeter.

The most obvious candidate for the job is the \( b \)-jet \([21, 22]\), identified either directly through \( b \)-tagging or indirectly by first finding the light quarks from the \( W \). However, the identification of the \( b \) and \( W \) poses some experimental difficulties. Even in isolation, the efficiency of \( b \)-tagging drops by a factor of 2–3 at high \( p_T \) while light quark rejection is degraded by roughly a factor of 3 \([6, 10, 23, 24, 25]\). When the \( b \)-jet is situated within a collimated top jet, the additional tracks from the neighboring light quark subjets present added complications for \( b \)-tagging algorithms.

Another possible method of identifying the \( b \)-jet is to do so indirectly, by finding the \( W \). One approach to identifying the \( W \) is to look for two jets with an invariant mass within the \( W \) mass window. However, the subjet invariant mass distributions are distorted both by contamination from soft radiation and by imperfect subjet reconstruction, as well as by the finite size of the calorimeter. The invariant mass \( m_{ij} \) of two nearby subjets is approximately proportional to their separation in \( R \), and for subjets whose centers are separated by \( \Delta R_{ij} \lesssim 0.5 \), the uncertainty associated with the calorimeter granularity \( \delta R \sim 0.1 \) can be significant. Distinguishing the correct \( W \) subjet pair from amongst the three choices, all of which are typically within a factor of two of each other, then becomes difficult.

Another possible strategy to identify the \( b \)-jet is to look for hard splittings within the top jet. As discussed in \([13]\), the energy sharing of a parton branching \( A \to BC \),

\[
z(A \to BC) \equiv \min(E_B, E_C)/E_A,
\]

discriminates between hard splittings from decays, \( z \sim 0.5 \), and soft splittings more characteristic of QCD, \( z \sim 0 \). If the \( W \) decay products were well-separated from the \( b \)-jet, one could identify the \( b \) by unwinding the clustering of the top jet until there were two subjets and tagging the \( b \) as the one with smaller \( z \) (so the \( W \) subjet would be the one with a harder splitting). Unfortunately, because the \( W \) has a mass on the same order as that of the top, the \( W \) decay products are not well-separated from the \( b \), so upon unwinding the top jet by one step one often finds that the \( b \)-jet has been clustered with a lighter jet from the \( W \) decay.

We propose here an alternate subjet selection algorithm, based on \( k_T \) distances between subjets, which does not require either \( b \) or \( W \) identification. While the algorithm is conceptually less straightforward than those based on attempting to identify specific partons within the top jet, it yields a distinct separation between chiralities and is robust under showering and detector effects. Consider the \( k_T \) distance measure between two four-momenta \( i \) and \( j \),

\[
d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)R_{ij}^2,
\]

\(^4\)Depending on the boost of the top quark, it might also be desirable to consider subjet \( p_T \) fractions, as the \( m_t/E_t \) corrections to the collinear limit differ for energy and \( p_T \) fractions.
Figure 3: Energy fraction of the parton selected by our algorithm, broken down by parton identity. The events shown here correspond to tops produced from a 3 TeV resonance.

Figure 2: Energy fraction $z_K$ of the parton selected by the $k_T$-based algorithm for different top polarizations. The events shown here correspond to tops produced from a 3 TeV resonance.

where $R^2_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$. Of the three $d_{ij}$ one can form from the three top subjets, consider the smallest. Our top polarimeter is the energy fraction $z_K$ of the harder jet $j_K$ in the minimum $k_T$ distance pair. We plot the distribution of this variable at parton level for different chiralities in Fig. 2. The variable shows a clear distinction between right- and left-handed top quarks, with right-handed tops peaked at smaller values of $z_K$, and left-handed tops preferring larger values of $z_K$.

3.2 Operation of the algorithm

The success of the jet $j_K$ selected by this algorithm as a polarimeter depends on multiple aspects of the angular and energy distributions of daughter partons in polarized top decay, which for reference are reviewed in the Appendix. In order to explain the success of our polarimeter, we first consider how the algorithm functions at parton level. The identities of the partons picked out by the algorithm differ between right- and left-handed tops. In Fig. 3 we break down the contributions to the variable $z_K$ by parton identity.

The anti-down quark is maximally correlated with the top spin, and thus for left-handed tops the $d$ tends to be
soft. For left-handed tops the minimum-$k_T$ pair therefore tends to involve the $d$, and in such pairs the other parton ($b$ or $u$) is the harder of the two. The algorithm therefore picks out first $b$ quarks, which take a larger fraction of the top energy, and secondarily $u$’s, with $d$ quarks a distant third.

For right-handed tops, where the top energy is shared more equitably among the daughter partons, angular correlations play a more central role. The $d$-quark is now both more central and harder than predicted by pure phase space (due, again, to its maximal correlation with the top spin). Therefore in order to reconstruct the necessary invariant masses, the $\Delta R$ separation between the $d$ and the $u$ and $b$ quarks must be smaller than for pure phase space, and the minimum $k_T$ pair then tends to involve the $d$. For right-handed tops, the algorithm thus dominantly selects the $d$-quark, as can be seen in Fig. 4. While the $d$ is preferentially emitted along the top direction of motion, its energy fraction distribution nonetheless falls off at high energies, as the lab-frame $d$-quark energy fraction depends on the energy of the $d$-quark in the top rest frame as well as the angle of emission. The contribution of the $b$-quark to the variable $z_K$ comes mostly from hard $b$’s recoiling against soft transverse $W$’s.

At high parton energy fraction $z_K$, the algorithm dominantly selects the hardest parton: $b$ and $u$ for left-handed tops, $b$ and to a lesser extent $u, d$ for right-handed tops. At intermediate energy fractions, the origin of the $u$ and $d$ partons from a common $W$ comes to dominate. The $k_T$ distance between the $u$ and the $d$ is bounded from above, as the $u$ and the $d$ must reconstruct the $W$. In events without hierarchical energy distributions, the minimum $k_T$ distance thus tends to be between the decay products of the $W$. Therefore, at intermediate energy fractions, the parton selected by the algorithm is predominantly the $d$ (for right-handed tops) or the $u$ (for left-handed tops). This can be seen already in Fig. 3, and is further demonstrated in Fig. 4.

Finally, we note that all of these arguments are based upon the assumption that one can go from the collider coordinate system to one oriented around the top direction of motion without significant effects. This assumption does not hold exactly, because the detector geometry is not invariant under rotations around the axis defined by the top direction of motion, and because the $k_T$ algorithm used to select the subjet $j_K$ makes reference to the collider coordinate system through the definition of transverse momentum. Therefore, events which differ from each other only by a rotation around the top axis of motion appear differently both in the detector and in the subjet selection algorithm. Interference terms between right- and left-handed tops generically then do not completely cancel. However, as the magnitude of the interference contribution is determined by the components of the parton momenta transverse to the top momentum, these effects are of order $m_t/E_t$, a subleading effect for large boosts.

### 3.3 Implementation

To implement this algorithm in practice one must have a technique for finding three subjets within the top jet. The exact procedure one uses to identify the subjets is not important, but for concreteness we detail the method used in our study. One advantage of our subjet-
Figure 4: Energy fraction of the $b$ quark, broken down according to which two partons in the event belong to the pair with minimum $k_T$ for left-handed tops (left side) and right-handed tops (right side). Note that the contents of the plots are stacked. At high energy fractions, the $W$ and its decay products are soft, and the minimum $k_T$ pair tends to involve one of the $W$ decay products together with the $b$. At intermediate energy fractions, the minimum $k_T$ pair tends to be the $W$ decay products. At small energy fractions, the $b$ begins to appear as the softer of the two partons in the minimum $k_T$ pair. The effect is more pronounced for right-handed tops, which have a less hierarchical distribution of energy among the three daughter partons. The events shown correspond to tops produced from a 3 TeV resonance.

The procedure is as follows:

- Cluster the event with a reasonably sized cone ($\Delta R \gtrsim 0.7$) and select a top candidate.
- Take all the cells clustered into the top candidate and recluster them using a smaller cone ($\Delta R \approx 0.2$).
- Demand that there are at least three subjets, each with a substantial amount of the jet’s energy $\gtrsim 1 - 2\%$. If there are not, split the harder subjet by unwinding [13] it one step using the $k_T$ algorithm, and use the two resulting daughters along with the second hardest subjet from before.
- Now use the four-momenta of the three subjets to find the pair with the smallest $k_T$ distance measure, and compute the ratio of the energy of the more energetic jet in this minimum-$k_T$ pair to the energy of the entire top jet.

Results using this procedure are shown in the next section.

4. Examples

We will now apply the subjet-based technique developed in the previous section to some realistic examples. Our goal is to show that the technique works for fully showered events.
clustered with finite calorimeter cells using a variety of parton shower and hadronization algorithms. It is important to note that we do not consider the shape of background QCD distributions, nor do we consider any shaping effects that might arise from the effects of top tagging. A more complete experimental study would include these effects, but due to the high discriminating power of top tagging algorithms (not to mention other aspects of the event that could be used to remove background) and their relatively high efficiency, we do not expect these effects to be significant.

In what follows, our analysis is performed on events generated at matrix element level using MadGraph 4.4.17 [27] for physics at the LHC scale (14 TeV). Subsequent showering and hadronization is performed using Pythia 6.4.21 [28] and Herwig++ 2.3.2 [29]. When using Pythia, we consider parton showers generated using both virtuality (labeled as $Q^2$) and $p_T$ ordered showers. Visible final state particles are grouped into $0.1 \times 0.1$ calorimeter cells before being clustered into $R = 0.7$ jets using the anti-$k_T$ [30] algorithm. To ensure that the top decayed into visible products (and that no significant radiation was lost outside the cone) we demand that the jet mass exceed 170 GeV. We form subjets by running the anti-$k_T$ algorithm with $R = 0.2$ on the constituents of the top jet, requiring that the third most energetic subjet carry at least 1% of the top jet energy, and splitting the hardest subjet if this condition is not satisfied.

### 4.1 Tops from a resonance

We begin by studying a colored octet vector $G'$ with a chiral coupling to the top quark. This model was chosen for simplicity, but it captures the main features of well-motivated scenarios like KK-gluon production. The process under consideration is

$$gg \rightarrow G' \rightarrow t\bar{t}$$

(4.1)

where $m_{G'} = 3$ TeV. The results are shown in Fig. 5. One can see from these distributions that the characteristic shapes from matrix element level are unchanged after parton showering and hadronization, demonstrating the robustness of our subjet selection technique.
Figure 6: Energy fraction of the selected jet for results from (left to right) Herwig++, Pythia-6 ($Q^2$) and Pythia-6 ($p_T$). For each plot the solid red and dotted black lines come from right- and left-handed tops, respectively.

4.2 Tops from cascade decays

Cascade decays of an on-shell top partner (such as a stop squark or a $T'$) to a top plus missing energy are a standard signal of a broad class of well-motivated models. In the presence of multiple sources of missing energy, there is no longer enough information to solve for the rest frame of a leptonically-decaying top quark. Hadronic top quarks, which can be reconstructed independently of the other particles in the event, become a more useful source of information.

For tops produced from an un-reconstructed parent, the observable polarization signal depends on the masses of the new physics particles through the relation of the unknown parent rest frame to the lab frame, as well as through the vertex kinematics \[21\]. The lack of information about the parent rest frame reduces the observable polarization signal for tops coming from a cascade decay compared to the signal from a resonance. Nonetheless, observable signals are still possible as long as the boost of the top from its parent is dominant, allowing the chiral structure of the top production vertices to be probed.

We consider a model for production of two top partner $T'$ particles decaying into tops and sources of missing energy (labeled $A^0$). Our choice of spectrum has $m_{T'} = 2$ TeV and $m_{A^0} = 100$ GeV. The results of the analysis performed on the model are seen in Fig. 6. As for the $G'$, the distributions agree well with the parton level results and have the same qualitative shapes regardless of the generator used.

5. Conclusions

We have proposed an analysis tool useful in determining the chiral structure of the top quark’s coupling to new physics. Our method uses subjet-based techniques to probe scenarios where a highly boosted top decays hadronically. This tool requires no assumptions to be made about the production mechanism of the top or about the origin of missing energy in the event, and does not rely upon $b$-tagging or $W$ reconstruction.

By testing our method on Monte Carlo data from multiple generators using different new physics scenarios we have indicated its robustness against the effects of parton showering and calorimeter segmentation. A more complete analysis would study the shaping of
the distributions from the top tagging method using in selecting a sample, but we expect these effects to be small.

Boosted hadronic tops may provide a new window to shed light on otherwise difficult aspects of new physics at the LHC, and will certainly provide a complementary probe of physics beyond the Standard Model. Variables which can analyze the polarization of boosted hadronic tops, such as those introduced here, will fill an important slot in the analysis toolkit as we try to unravel the physics behind LHC data.

Acknowledgments

The authors would like to thank Gilad Perez, Matt Schwartz, Jesse Thaler, Chris Tully, and Peter Skands for discussions. The work of J.S. was supported in part by the DOE grants DE-FG02-96ER40949 and DE-FG02-92ER40704. The work of L.-T. W. was supported by NSF grant PHY-0756966 and DOE grant DE-FG02-90ER40542.

A. Angular Distributions in Decays of Polarized Tops

Here we collect some results on the energy and angular distributions of daughter partons in polarized top decay. To arrive at these results we assume the standard model top decay $t \to Wb$ with subsequent $W$ decay $W \to du$, and work at leading order in the narrow width approximation for both $t$ and $W$. Then, the squared matrix element for a polarized top can be written

$$|M|^2 \propto (t_\pm \cdot d)(b \cdot u)$$

where $d, b,$ and $u$ denote the momentum four-vectors of the respective partons, and $t_\pm \equiv p_t \pm m_t S$ contains information about the top polarization through the spin four-vector $S$. In the top rest frame, the spin four-vector takes the form $S^\mu = (0, \hat{s})$, where $\hat{s}$ is a unit vector defining the axis of polarization. In the narrow width approximation, and further taking $m_b = 0$, the energy of the $b$ quark is fixed at $E_b = (m_t^2 - m_W^2)/2m_t$ in the top rest frame. The full differential decay rate then depends nontrivially on two quantities, which we can take to be the down-quark energy in the top rest frame, $E_d$ and the angle of the down quark with respect to the top spin axis, $\cos \theta_d$. The differential decay rate can be written

$$\frac{1}{\Gamma} \frac{d\Gamma}{dE_d d \cos \theta_d} = \frac{12m_t^3}{m_t^2 + 2m_W^2 - 3m_W^4} E_d(m_t - 2E_d)(1 + \mathcal{P}_t \cos \theta_d)$$

where $\mathcal{P}_t$ is the top polarization, $-1 \leq \mathcal{P}_t \leq 1$ with $\mathcal{P}_t = 1, -1$ corresponding to right and left handed tops, respectively.

These results can be generalized to study the angular distribution of any given daughter parton $i$ in the top rest frame by writing [31]

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_i} = \frac{1}{2}(1 + \mathcal{P}_t \kappa_i \cos \theta_i),$$

where $\kappa_i$ is the spin analyzing power of the parton $i$, and $\cos \theta_i$ is the angle that parton makes with respect to the top spin axis in the top rest frame. The values of $\kappa_i$ for various
Table 1: Tree level values for the spin analyzing power $\kappa$ of various top daughters in top decay. The object $j$ is defined in the text.

| Parton | $b$ | $W$ | $d$ | $u$ | $j$ |
|--------|----|----|----|----|----|
| $\kappa$ | -0.4 | 0.4 | 1.0 | -0.3 | 0.5 |

choices of $i$ are listed in Tab. 1. The $d$, which corresponds to the lepton in leptonic top decays, is maximally correlated with the top spin, with $\kappa_d = 1$. In addition to the partonic $b$, $W$, $u$, and $d$, we also consider an object $j$, defined to be the softer of the two light quark jets in the top rest frame. As the $d$ tends to be softer than the $u$ in the top rest frame, this jet is the $d$-jet approximately 60% of the time [32, 33].

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