Identifying the $b$ quark inside a boosted hadronically decaying top quark using jet substructure in its center-of-mass frame

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In this paper we study the identification of the $b$ quark inside a boosted hadronically decaying top quark in the center-of-mass frame of the jet. We demonstrate that the method can be used to greatly reduce the QCD jet background even in a very high pileup condition. The method has a much smaller fake rate for QCD jets compared to typical $b$ quark identification algorithms in jets at the same signal efficiency. When combining the $b$ quark identification in the center-of-mass frame of the jet with jet substructure information, we can improve the rejection rate of QCD jet background by almost an order of magnitude while maintaining the same identification efficiency for the boosted top quark.

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Many new physics (NP) extensions beyond the standard model (SM) predict new heavy resonances with masses at the TeV scale. Some of these heavy resonances, such as a new heavy gauge boson $Z'$ or Kaluza-Klein gluons from the bulk Randall-Sundrum model, or a right-handed charged gauge boson $W'_R$, can predominantly decay to a final state containing top quarks. Searches for new heavy resonances decaying to top quark final states have been very actively pursued to look for NP by the ATLAS and CMS experiments at the LHC. Because the top quarks from the heavy resonance decay are highly boosted, their hadronically decaying products are so collimated that they are often reconstructed as single jets in the experiments. In this paper, we define a hadronically decaying top as the top quark for which the $W$ boson daughter decays hadronically, hereafter referred as a $t$ jet. Although the invariant mass of the reconstructed jet ($m_{\text{jet}}$) can be used to identify the $t$ jets from QCD jets, where the QCD jets are defined as those jets initiated by a quark other than top or gluon, it does not provide enough discriminating power to effectively distinguish $t$ jets from the overwhelming QCD background in many analyses. Techniques based on jet substructure information have been developed as additional experimental handles to identify boosted hadronically decaying top quarks.

Since the top quark decays almost exclusively to a $W$ boson and $b$ quark final state, identifying the $b$ quark from the top decay by exploring its long lifetime can provide additional distinguishing power for the boosted hadronically decaying top quark. While the identification of isolated jets stemming from the hadronization of $b$ quarks ($b$-tagging) has been widely used in many experimental measurements, its application in boosted hadronic top decay is more difficult because the charged tracks associated with the $b$ quark need to be disentangled from the ones generated by the $W$ boson. In this paper, we extend the studies presented in Refs. [22, 23] to explore the identification of the $b$ quark inside a $t$ jet in the center-of-mass frame of the jet. We demonstrate that the method can greatly reduce the QCD jet background while maintaining a high identification efficiency of the boosted top quark even in an environment with very large numbers of multiple interactions per event (pileup).

We use boosted $t$ jets, from the SM process of a top-antitop pair ($tt$) production, as a benchmark to study the identification of the $b$ quark inside. We only consider the background from the SM dijet production because its cross section is several orders of magnitude larger than those of other SM backgrounds.

All the events used in this analysis are produced using the Pythia 6.421 event generator for $pp$ collisions at 14 TeV center-of-mass energy. The spread of the beam interaction point is assumed a Gaussian distribution with a width of $0.025$ mm in the longitudinal (transverse) direction. In order to evaluate the performance of the proposed $b$ quark identification method with the currently expected experimental conditions at the LHC, we generate Monte Carlo events with different average numbers of pileup and then repeat our studies for each scenario. To simulate the finite resolution of the calorimeter detector at the LHC, we divide the $(\eta, \phi)$ plane into $0.1 \times 0.1$ cells. We sum over the energy of particles entering each cell in each event, other than the neutrinos and muons, and assume a massless pseudoparticle, also referred to as an energy cluster that has the same energy and points to the center of the cell. These energy clusters are fed into the FastJet 3.0.1 package for jet reconstruction. The jets are reconstructed using the anti-$k_T$ algorithm with a distance parameter of $R = 0.6$. The anti-$k_T$ jet algorithm is the default one used at the ATLAS and CMS experiments. As for the charged tracks, their momentum and vertex positions are smeared according to the expected resolutions of the ATLAS detector.

We select jets with $p_T \geq 600$ GeV and $|\eta| \leq 1.9$ as $t$ jet candidates, where $p_T$ and $\eta$ are the transverse momentum and pseudorapidity of the jet, respectively. We further require that the $t$ jet candidates have $50$ GeV $\leq m_{\text{jet}} \leq 350$ GeV. All the $t$ jet candidates in an event are kept for further analysis. For $b$-tagging, only charged tracks with $p_T > 1$ GeV and $|\eta| < 2.5$ are considered. They are also
required to satisfy the criteria that \(|d_0| < 1\) mm and \(|z_0 - z_{pv}| \sin \theta < 1.5\) mm, where \(d_0\) and \(z_0\) are the transverse and longitudinal impact parameter of the charged track, \(z_{pv}\) is the longitudinal position of the primary vertex, and \(\theta\) is the polar angle of the charged track. A charged track is considered to be associated with a jet if the distance parameter of \(\Delta R\) between the track and the jet is less than 0.6.

We define the center-of-mass frame (rest frame) of a jet as the frame where the four-momentum of the jet is equal to \(p_{\mu} \equiv (m_{jet}, 0, 0, 0)\). The distribution of pseudoparticles of a boosted \(t\) jet in its center-of-mass frame has a three-body decay topology as in the top quark rest frame. We recluster the energy clusters of a jet to reconstruct subjets in the jet rest frame using a modified \(e^+e^-\) Cambridge jet reconstruction algorithm \[28\]. The algorithm performs sequential recombination of the pair of pseudoparticles that is closest in angle \(\Theta\), except for \(\Theta > 0.6\), where \(\Theta\) is defined as the angle between two pseudoparticles in the jet rest frame. The implementation of the modified \(e^+e^-\) Cambridge jet algorithm is done by replacing the distance parameter of the existing \(e^+e^-\) Cambridge jet algorithm in the FastJet 3.0.1 \[20\] package with the new choice of the distance parameter \(\Theta\). We only retain jets that have at least three subjets each with energy \(E_{jet} > 10\) GeV in the \(t\) jet rest frame. In the ideal situation with no pileup effects, this requirement rejects approximately 60\% of the QCD jets, while keeping almost all the signal \(t\) jets. However, the rejection power drops significantly when the average number of multiple interactions per event increases to 50 (100), in which more than 70\% (90\%) of the QCD jets have at least three subjets with \(E_{jet} > 10\) GeV. Currently the maximum average number of pileup at LHC is slightly less than 20; with expected higher energy and luminosity in the future, it is expected to reach 50, and even 100 in the worst case scenario.

The most straightforward way to identify the \(b\) quarks inside \(t\) jets is to apply existing \(b\)-tagging algorithms in a jet directly. In this paper we study the tagging algorithms based on charged track impact parameters as the algorithms are widely used in many experiments. They are also among the official \(b\)-tagging methods used by the ATLAS experiment \[29\]. The impact parameters of tracks are computed with respect to the primary vertex. They typically have significant nonzero values for the charged tracks from the \(b\) hadron decays because of its long lifetime. The impact parameter is signed to further discriminate the tracks from \(b\)-hadron decay from tracks originating from the primary vertex based on the fact that the decay position of the \(b\) hadron lies along its flight path. The sign of transverse impact parameter \(d_0\) is determined using the jet momentum \(\vec{p}_{jet}\), the track momentum \(\vec{p}_{trk}\) at the point of the closest approach \(x_{trk}\) \[29\] to the primary vertex position \(x_{pv}\):

\[
\text{sign}(d_0) = (\vec{p}_{jet} \times \vec{p}_{trk}) \cdot (\vec{p}_{trk} \times (x_{pv} - x_{trk})).
\]

The sign of longitudinal impact parameter \(z_0\) is measured by the sign of \((\eta_{jet} - \eta_{trk}) \times z_{0, trk}\), where \(\eta_{jet}\) is the pseudorapidity of the jet, and \(\eta_{trk}\) and \(z_{0, trk}\) are the pseudorapidity and longitudinal impact parameter of the charged track at the position \(x_{trk}\), respectively.

The distributions of the signed impact parameter significances for tracks in QCD jets and signal \(t\) jets are shown in Figs \[4\] (a) and (b). The significance is defined as the ratio between the impact parameter and its uncertainty \(\sigma\). While we can clearly see a much higher fraction of tracks from the signal \(t\) jets with larger impact parameter significance than the ones from the QCD jets, the distributions are rather symmetrical and it is contradictory to the expectation and observation in the typical \(b\) jet tagging algorithm, where the impact parameter distributions from tracks associated with \(b\) jets tend to have positive signs \[29\], while the experimental resolution generates a random sign for the tracks originating from the primary vertex. Studies show that the loss of the sign correlation is caused by the mismeasurement of the \(b\) quark direction. Unlike a typical \(b\) jet, the direction of the \(t\) jet is different from the \(b\) quark direction inside. This correlation is further reduced by the inclusion of the charged tracks generated by the \(W\) bosons in the \(t\) jets.

The identification can be significantly enhanced using the jet rest frame algorithm. We boost all the tracks associated with a \(t\) jet candidate back to the center-of-mass frame of the jet. A charged track is considered to be associated with a subjet only if their angular separation is less than 0.6 in the jet rest frame. By doing so, we separate the tracks that originate from different partons of the top quark and reject many tracks from underlying events and pileup. The impact parameters of the tracks associated with a subjet are then calculated using the subjet momentum in the lab frame. The distributions of the signed impact parameter significances for the tracks associated with subjets in QCD jets and subjets containing a \(b\) quark (\(b\) subjets) in signal \(t\) jets are shown in Fig \[4\] (c) and (d). Their differences are much more predominant comparing to the ones before using the jet rest frame method. The impact parameter significances of the tracks associated with a \(b\) subjet in the \(t\) jet rest frame show a much larger fraction of positive tail distributions.

We form a likelihood of the tracks associated with a jet. The measured impact parameter significances \(S_i\) of the \(i\)th track in a jet are compared to predefined functions for both \(b\) jet and non-\(b\) jet hypothesis, \(b(S_i)\) and \(u(S_i)\), where \(b(S)\) and \(u(S)\) are the smoothed and normalized distributions of the charged tracks that are associated with \(b\) subjets in the signal \(t\) jets and the subjets in the QCD jets, respectively. The ratio of the probabilities \(b(S_i)/u(S_i)\) defines a weight \(W_i\). A jet weight \(W_{jet}\) is then computed as the sum of the \(W_i\) from all the tracks associated with the subjet. In case there are no tracks associated with a subject, its jet weight is assigned to be zero. For comparison, we also calculate the jet weights for QCD jets and signal \(t\) jets using all the associated tracks without applying subjet re-clustering in the jet rest frame. The distributions of jet weights are
FIG. 1: The signed transverse impact parameter significance $d_0/\sigma_{d_0}$ and longitudinal impact parameter significance $z_0/\sigma_{z_0}$ under different pileup conditions, where $\sigma_{d_0}$ and $\sigma_{z_0}$ are defined as the experimental uncertainties of the measured impact parameter $d_0$ and $z_0$, respectively. In (a) and (b), the solid (dashed) lines represent the distributions of the charged tracks from the QCD (signal $t$) jets. In (c) and (d), the solid (dashed) lines represent the distributions of the charged tracks associated with the subjets ($b$ subjets) in the jet rest frame from QCD (signal $t$) jets. All the distributions are normalized to unity.

shown in Fig. 2. Again, the signal and background distribution calculated using subjet information in the jet rest frame show much more significant separations.

The final $b$ quark identification variable is constructed using a boosted decision tree (BDT) algorithm with the jet weights of the 3 leading subjets in the jet rest frame in order to take into account their correlations. In order to compare to the application of typical $b$-tagging algorithms on $t$ jets, we also construct a BDT variable using the jet weights that are calculated with all the associated charged tracks. The signal efficiency of $t$ jets by identifying the $b$ quark inside vs. the background rejection of QCD jets for the BDT variable is shown in Fig. 3. Regardless of the pileup conditions, the $b$ quark identification method in the jet rest frame we propose can easily reduce the contribution of the QCD jet background by approximately 100, with only a factor of three reduction for the $t$ jet signal identification efficiency. Its performance is a few times better than the direct application of typical $b$-tagging on boosted $t$ jets. As shown in Fig. 3, the performance of the tagger is generally slightly better with higher pileup. Studies show that
FIG. 2: The jet weight distributions of transverse and longitudinal impact parameter significances under different pileup conditions. In (a) and (b), the solid (dashed) lines represent the distributions of the charged track associated with QCD (signal $t$) jets. In (c) and (d), the solid (dashed) lines represent the distributions of the charged tracks associated with non-$b$ ($b$) subjets in the jet rest frame. All the distributions are normalized to unity.

this is an effect that is caused by the selection of jets used in the evaluation of the $b$-tagging performance. In our studies, we use only jets that have $p_T > 600$ GeV, $50 \text{ GeV} < m_{\text{jet}} < 350$ GeV and at least 3 subjets with $E_{\text{jet}} > 10$ GeV in its rest frame. As a result, when pileup increases, many QCD jets that otherwise would not satisfy the jet selection criteria are selected.

The addition of the identification of a $b$ quark inside $t$ jets can be used to improve existing top taggers [30] that are solely used on jet substructure information. Here we demonstrate such an application by combining the jet weights in the jet rest frame with the other jet substructure variables introduced in Ref. [22], such as the energies of the three leading subjets, the invariant mass of each two subjet combinations, the energy asymmetry between $W$ candidate and $b$ jet candidate in the jet rest frame, as well as the opening angle between them. A BDT variable is subsequently formed using the variable described above. As shown in Fig. 3 the background rejection achieved by the new top tagger based on both $b$ identification and jet substructure in the jet rest frame is almost an order of magnitude higher compared to the ones that only rely on the jet substructure information [22, 30]. This observation implies that 2 orders of magnitude fur-
ther reduction can be achieved for the dominant QCD background in the searches for new heavy resonance decaying to a $t\bar{t}$ final state, and therefore greatly improve the expected experimental sensitivities.

In conclusion, we study the identification of the $b$ quark inside boosted hadronically decaying top quark in the center-of-mass frame of the jet. We demonstrate that the method can greatly reduce the QCD jet background while maintaining a high identification efficiency of the boosted top quark even under a very large pileup condition. We compare the method to the commonly used $b$-tagging algorithm in a jet, and show that our method has a much smaller fake rate of the QCD jets for the same efficiency. When combining the $b$ tagging in the center-of-mass frame of the top jet with the jet substructure information, we can improve the rejection rate of QCD jet background by almost an order of magnitude while maintaining the same identification efficiency of the boosted top quark. The study shows a good prospect for the search for heavy mass particles in the decay channels containing $t$ quarks with the LHC experiments at 14 TeV center-of-mass energy.

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