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Identifying 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 boosted hadronically decaying top quarks using jet substructure in the center-of-mass frame of the jet. We demonstrate that the method can greatly reduce the QCD jet background while maintaining high identification efficiency of the boosted top quark even in a very high pileup condition. Applications to searches for heavy resonances that decay to a $t\bar{t}$ final state are also discussed.

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I. INTRODUCTION

Search for and discovering new physics (NP) beyond the standard model (SM) has been one of the main physics motivations to build the Large Hadron Collider (LHC). One prominent path to find NP is through model independent searches for possible new particles beyond the SM. Many extensions of the 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 (KK) gluons from the bulk Randall-Sundrum model, can predominantly decay to a top-anti-top quark pair ($t\bar{t}$) final state [1–4]. Because of the energy scale of these processes, the top quarks from the heavy resonance decay receive a significant Lorentz boost. Their hadronically decaying products are usually so collimated that they can be only reconstructed as single jets in the experiments.

In recent years, many theoretical studies have been performed to investigate the signature of boosted hadronically decaying top quarks [5–16], where a hadronically decaying top is defined as the top quark whose W boson daughter decays hadronically. Several experimental searches for heavy new resonances decaying to $t\bar{t}$ final states have also been carried out by the ATLAS and CMS experiments at the LHC [17, 18]. The measurements exclude a production of such a new heavy resonance with a mass up to 1-2 TeV, depending on the NP model used for the theoretical interoperation of the results. In all those studies and measurements, the complete final state of the top quark decay is reconstructed as a single jet, hereafter referred as t jet. The invariant mass of the reconstructed jet (m_{jet}) is used to distinguish the t jets from QCD jets, where the QCD jets are defined as those jets initiated by a non-top quark or gluon. Since the jet mass alone may not provide sufficient discriminating power to effectively separate t jets from the overwhelming QCD background in many analyses, techniques based on jet substructure information, such as jet shape observables [19], filtering [20], pruning [21, 22] and trimming [23], are typically implemented as additional experimental handles to identify boosted hadronically decaying t quarks.

In our previous paper [24], we introduce a new approach to study jet substructure in the center-of-mass

frame of the jet. We demonstrated that it can be used to discriminate the boosted heavy particles from the QCD jets and the method is complementary to other jet substructure algorithms. A similar idea has also been explored to search for hadronically decaying Higgs boson [25]. In this paper, we will extend the studies presented in Ref. [24] to focus on identifying the 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 in the environment of a very large number of multiple interactions per event (pileup). Using an example of applications, we show a good prospective on search for heavy mass particles in the $t\bar{t}$ decay channel at the LHC.

This paper is organized as follows: In Section II, we describe the event sample used in the study. Section III discusses the method to identify t jets using jet substructure in the jet center-of-mass frame and its performance. An example of the application of our method is given in Section IV. We conclude in Section V.

II. EVENT SAMPLE

We use boosted t jets, from the SM process of $t\bar{t}$ production, as a benchmark to study the identification of boosted hadronically decaying top quark with our proposed jet substructure method. For simplicity we only consider the background from the SM dijet production since its cross section is several orders of magnitudes larger than those of other SM background. In addition, we also generate events to simulate a heavy-particle X that decays to a $t\bar{t}$ final state.

All the events used in this analysis are produced using the Pythia 6.421 event generator [26] for the pp collision at 14 TeV center-of-mass energy. In order to simulate the finite resolution of the Calorimeter detector at the LHC, we divide the (η, ϕ) plane into 0.1×0.1 cells. We sum over the energy of particles entering each cell in each event, except for the neutrinos and muons, and replace it with a massless pseudoparticle of the same energy, also referred to an energy cluster, pointing to the center of the cell.

These pseudoparticles are fed into the FastJet 3.0.1 [27] package for jet reconstruction. The jets are reconstructed using the anti- k_T algorithm [28] with a distance parameter of $\Delta R = 0.6$. The anti- k_T jet algorithm is the default one used at the ATLAS and CMS experiments. In order to evaluate the performance of top jet identification with the currently expected experimental conditions at the LHC, we generate MC events with different average numbers of multiple interactions per event [26] and then repeat our studies for each scenarios. We compare the results to the one in the ideal experimental condition that has no pileup.

III. JET SUBSTRUCTURE IN THE REST FRAME

In this section we describe the method to study jet substructure of the t jets in the center-of-mass frame of the jet in order to distinguish them from the QCD jets. We select jets with $p_T \geq 600$ GeV and $|\eta| \leq 1.9$ as t jet candidates, where p_T and η are the transverse momentum and pseudorapidity of the jet. We further require that the t jet candidates have $50 \text{ GeV} \leq m_{\text{jet}} \leq 350 \text{ GeV}$. In case there are more than one candidate in an event, all of them are kept for further analysis.

A. Center-of-mass frame of a jet

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 $p_\mu^{\text{rest}} \equiv (m_{\text{jet}}, 0, 0, 0)$. A jet consists of its constituent particles. The distribution of the constituent particles of a boosted t jet in its center-of-mass frame has a three body decay topology as in the top quark rest frame. On the other hand, the constituent particle distribution of a QCD jet in its rest frame does not correspond to any physical state and is more likely to be isotropic.

B. Reclustering in the jet reset frame

We recluster the energy clusters of a jet to reconstruct subjets in the jet rest frame. The reclustering is done by using the Cambridge-Aachen (CA) sequential jet reconstruction algorithm [29] with a modified distance parameter of $\Delta\theta = 0.6$, where θ is defined as the angle between two pseudoparticles in the jet rest frame. We reject jets that have less than 3 subjets with $E_{\text{jet}} > 10$ GeV, where E_{jet} is the energy of a subjet in the jet reset frame. In the ideal situation without any pileup effects, this requirement rejects roughly 60% of the QCD jets, while keeping almost all the signal t jets. However, the rejection power drops significantly when the average numbers of multiple interactions per event increases. When the average pileup at the LHC reaches 50 (100) per event,

more than 70% (90%) of the QCD jets have at least 3 subjets with $E_{\text{jet}} > 10$ GeV.

The mass of a jet has a large dependence on the pileup condition, its distribution shifts to higher values when the pileup condition gets worse. However, this effect is greatly reduced if we calculate the mass of a jet using its subjets in the center of mass frame of the jet, as shown in Fig. 1. Because of the smaller area covered by its cone size and the isotropic distribution of the constituent particles of QCD jets from pileup in the jet rest frame, a reconstructed subjet in the jet rest frame includes much less deposited energies from additional multiple interactions. One advantage of reclustering in the jet rest frame is that two nearby energy clusters that have different momenta in the lab frame can be easily separated geometrically after they are boosted back to the center-of-mass frame of the jet if they are originated by different partons from top decaying. We also point out that the rest frame subjet algorithm is infrared and collinear safe if an infrared and collinear safe jet algorithm is used for the rest frame subjet clustering. All the sophisticated jet-grooming algorithms introduced in the lab frame, such as pruning [21, 22] and trimming [23], can be easily incorporated.

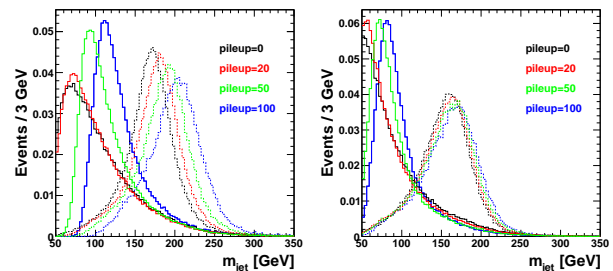


FIG. 1: The jet mass distributions of the QCD jets (solid line) and signal t jets (dashed line) of the SM $t\bar{t}$ production from MC simulated events before (left) and after (right) reclustering in the jet rest frame under different pileup conditions. The mass of the jet after the reclustering is calculated using the three subjets with the highest energies in the jet rest frame. All the distributions are normalized to unity.

C. Jet substructure variables

We introduce several jet substructure variables to identify boosted t jets. All of them are calculated using the subjet information in the jet rest frame. They are:

- E_{j_1} , E_{j_2} and E_{j_3} : E_{j_i} is the energy of the subject j_i in the center-of-mass frame of the jet. The j_1 , j_2 and j_3 denote the subjets with the first, second and third highest energy.

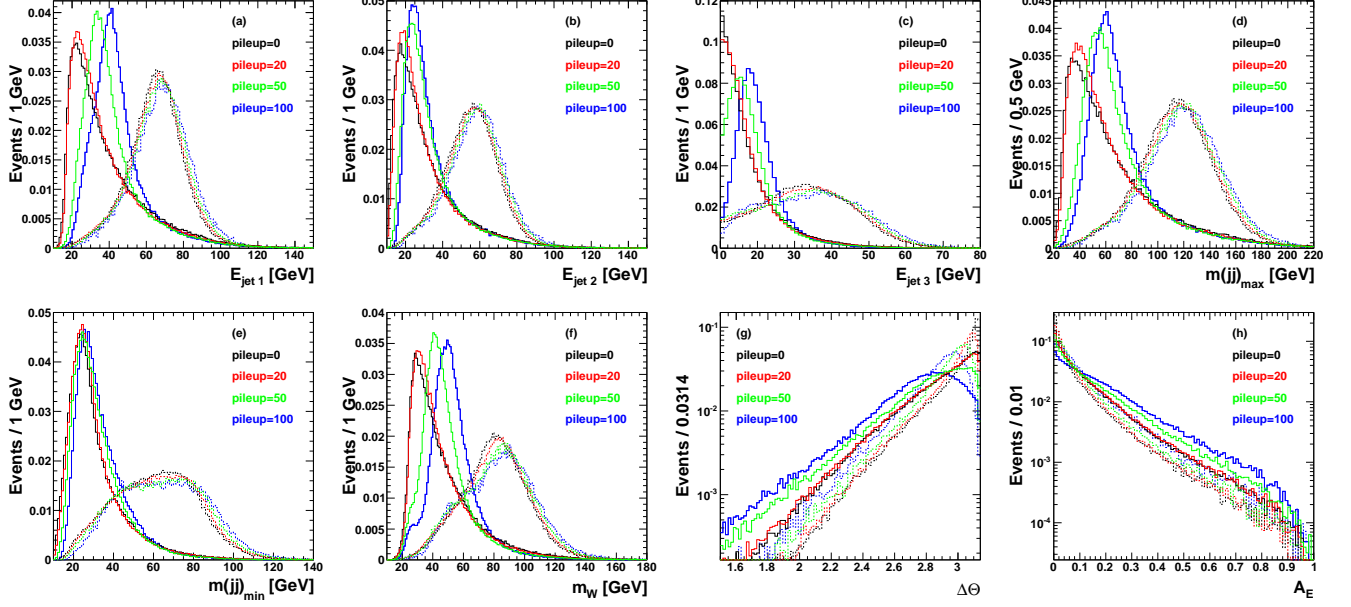


FIG. 2: The distributions of the jet substructure variables defined in the text for the MC simulated QCD jet background (solid line) and t jet signal (dashed line) from the SM $t\bar{t}$ production under different pileup conditions. The jets used in the evaluation of the jet substructure performance are required to have $p_T \geq 600$ GeV, $50 \text{ GeV} \leq m_{\text{jet}} \leq 350 \text{ GeV}$ and at least 3 subjets with $E_{\text{jet}} > 10$ GeV in its rest frame. All the distributions are normalized to unity.

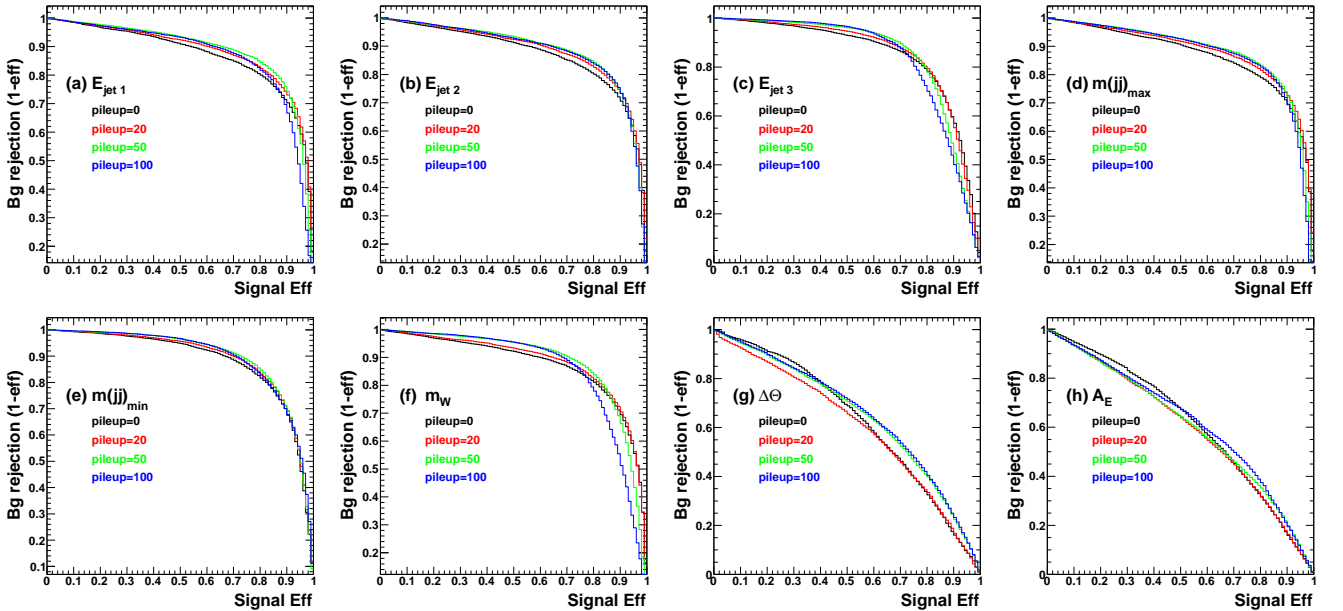


FIG. 3: The background rejection of QCD jets vs. the signal efficiency of t jets for the jet substructure variables in different pileup conditions. The jets used in the evaluation of the jet substructure performance are required to have $p_T \geq 600$ GeV, $50 \text{ GeV} \leq m_{\text{jet}} \leq 350 \text{ GeV}$ and at least 3 subjets with $E_{\text{jet}} > 10$ GeV in its rest frame.

- m_W : it is defined as m_{j_1, j_3} , the invariant mass of the combination of subjet j_1 and j_3 in the jet rest frame.
- $m(jj)_{\max}$ and $m(jj)_{\min}$: they are defined as $m(jj)_{\max} \equiv \max(m_{j_1, j_2}, m_{j_2, j_3})$ and $m(jj)_{\min} \equiv \min(m_{j_1, j_2}, m_{j_2, j_3})$.
- Asymmetry of the energy A_E : it is defined as $A_E = (E_W - E_{j_2})/(E_W + E_{j_2})$, where E_W is the sum of the energies E_{j_1} and E_{j_3} .
- $\Delta\Theta$: it is defined as the opening angle between $\vec{p}_{j_1} + \vec{p}_{j_3}$ and \vec{p}_{j_2} , where \vec{p}_{j_i} , $i = 1, 2$ and 3 , is the momentum of the subjet j_i in the jet rest frame.

The distributions of the jet substructure variables are shown in Fig. 2 for t jet signal and QCD jet background under different pileup conditions. The corresponding signal efficiencies of t jets vs. the background rejections of QCD jets are shown in Fig. 3. We see a significant difference between the signal and background distributions for those jet substructure variables. All of them show some dependence on the pileup conditions. The effects are slightly less for the t jet signal than the QCD jet background. As shown in Fig. 3, although the performance of the jet substructure variables varies with respect to different average number of multiple interaction per event, it does not show any significant degradation of its rejection power of the QCD jet background while retaining the same t jet signal identification efficiency.

D. Boosted decision tree top tagger

Most jet substructure variables that we introduced in previous section are strongly correlated with each other. In order to unitize the maximum discriminating powers of those variables, multivariable analysis techniques, such as neural network, boosted decision tree (BDT), etc, are typically necessary to combine their informations. In this section, we demonstrate such an application by constructing a BDT variable using the following jet substructure quantities: E_{j_1} , E_{j_2} , E_{j_3} , m_W , $m(jj)_{\max}$, $m(jj)_{\min}$, A_E and $\Delta\Theta$. Note that the signal and background separation power of the variables A_E and $\Delta\Theta$ is not as good as the others, as shown in Fig. 2 and 3. However, their correlations with the other variables are relatively small (less than 30 % in most cases). As a result, we keep them in the BDT algorithm to add additional discriminating power. We study the BDT algorithm using MC events generated with different average number of multiple interactions per event and optimize their performances separately. The signal efficiency of t jets vs. the background rejection of QCD jets for the BDT variable is shown in Fig. 4. Regardless of the pileup conditions, the jet substructure variables we proposed 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. In principle, we expect that the tagger

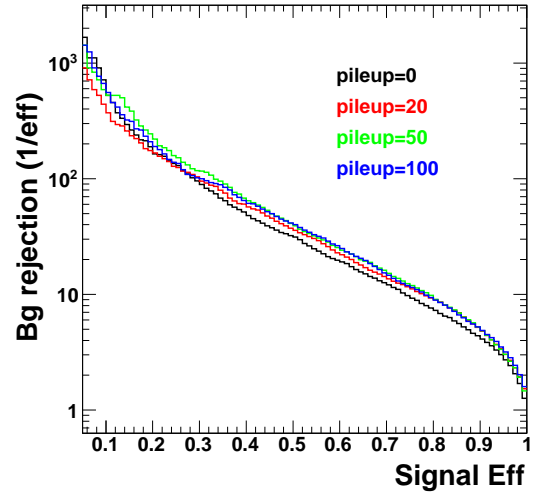


FIG. 4: The background rejection of QCD jets vs. the signal efficiency of t jets for the boosted decision tree top tagger in different pileup conditions. The jets used in the evaluation of the tagger performance are required to have $p_T \geq 600$ GeV, $50 \text{ GeV} \leq m_{\text{jet}} \leq 350 \text{ GeV}$ and at least 3 subjets with $E_{\text{jet}} > 10 \text{ GeV}$ in its rest frame.

performance gets worse when the pileup increases. As shown in Fig. 4, the performance of the tagger is actually better with higher pileups for several ranges of the signal efficiencies. This is an artificial effect that is caused by the selection of jets used in the evaluation of the tagger performance. In our studies, we only use jets that have $p_T \geq 600 \text{ GeV}$, $50 \text{ GeV} \leq m_{\text{jet}} \leq 350 \text{ GeV}$ and at least 3 subjets with $E_{\text{jet}} > 10 \text{ GeV}$ in its rest frame. As a result, when pileup increases, many QCD jets that otherwise would not satisfy the jet selection criteria are selected.

Comparing to the performance of other existing top taggers [30], the BDT top tagger based on jet substructure in the jet rest frame has similar background rejection for a given signal identification efficiency of boosted hadronically decaying top quarks. In our studies, the jets are reconstructed using a distance parameter $\Delta R = 0.6$ that is different from many other studies. We also consider the pileup conditions in extreme cases, which is absence in many of performance studies of existing top taggers. Our results show that top tagger based on jet substructure in the jet rest frame is complementary to other top tagger tools.

IV. APPLICATION

Reconstructed decays of top quarks to jets can be used to search for NP with specific final state signatures. Here we demonstrate such an application by considering a heavy resonance that decays to a $t\bar{t}$ final state: $pp \rightarrow X \rightarrow t\bar{t}$, where X is a new heavy resonance beyond

the SM, such as a new heavy gauge boson Z' or a KK gluon in the Randall-Sundrum model, etc.

We consider a search for an X signal by fully reconstructing the X signal candidate in the decay mode where both top quarks decay hadronically. Note that for such high mass (> 2.0 TeV) resonance decays, more than 90 % of the events have their decay particles from the top decay within a cone of $R < 0.6$. This makes it very difficult to identify separate subjects from top quark decays in the lab frame. As a result, we select the two leading jets with the highest and second highest energy with $p_T > 600$ GeV and $|\eta| < 1.9$ in an event as the two hadronically decaying top quark candidates. The jets are reconstructed using the anti- k_T algorithm with a distance parameter $\Delta R = 0.6$. We then subsequently combine the two top jet candidates to form the candidate of the $X \rightarrow t\bar{t}$ resonance.

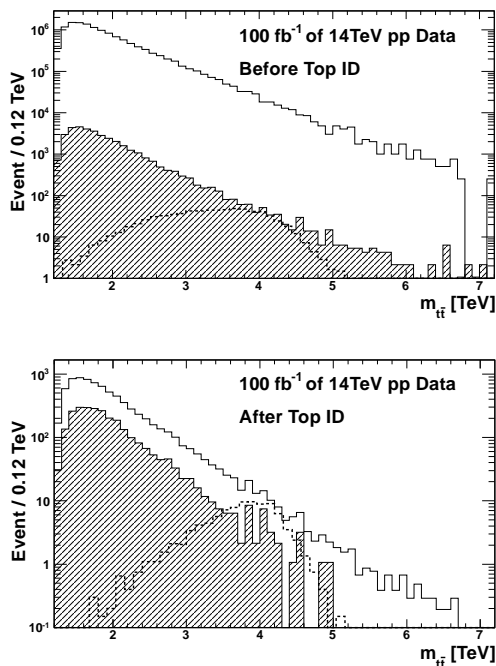


FIG. 5: The invariant mass distribution of the $X \rightarrow t\bar{t}$ candidates in the MC simulated event sample that is equivalent to 100 fb^{-1} of LHC data at 14 TeV center-of-mass energy before (top) and after (bottom) the BDT top tagger is applied. The MC events used to make the plot are generated with an assumption of 50 multiple interactions per event on average. The open histogram is the background distribution from QCD events, the hatched histogram is the background contribution from the SM $t\bar{t}$ production, and the dashed histogram is the expected signal distribution from $pp \rightarrow X \rightarrow t\bar{t}$. Here we assume a width of 100 GeV of the heavy resonance with $m_X = 4$ TeV, and the product of the production cross section of X and the branching fraction for its decay into $t\bar{t}$ pair is 10 fb.

The invariant mass distributions of the $X \rightarrow t\bar{t}$ candidates in the MC simulated event sample that is equivalent to 100 fb^{-1} of LHC data at 14 TeV center-of-mass energy are shown in Fig. 5. Here we consider that the average pileup is 50 and the mass of the heavy resonance is $m_X = 4$ TeV with a natural width of 100 GeV. The major SM backgrounds are QCD events and $t\bar{t}$ production. In order to reduce the background, we apply the hadronic top jet identification using the BDT top tagger described in Section III D. The selection criterion of the BDT variable is optimized to have approximately 40 % identification efficiency of a top jet, while keeping the fake rate of QCD jets at less than 2 %. As the result, we are able to reduce the SM background by a factor of more than 2000, while keeping roughly 15 % of the signal events. As shown in Fig. 5, such a selection dramatically improves the signal over background ratio and makes it possible for us to observe a potential $X \rightarrow t\bar{t}$ signal if the product of its production cross section and the branching fraction for its decay into a $t\bar{t}$ pair is of the order of a few tens of fb.

We repeat the study for heavy resonance X with different masses under various pileup conditions. We estimate the expected 95 % C.L. upper limit on the product of the production cross section of a heavy resonance X and the branching fraction for its decay into a $t\bar{t}$ pair. The expected limit for 100 fb^{-1} of LHC data at 14 TeV center-of-mass energy is plotted as a function of the assumed X mass, as shown in Fig. 6. All the studies show similar results. The BDT top tagger based on the jet substructure information in the jet rest frame can significantly improve our experimental sensitivities in search for $pp \rightarrow X \rightarrow t\bar{t}$. The performance of the top tagger decreases when the average number of multiple interactions per event increases. However, the degradation is rather small. Even in the case of an extreme pileup condition with 100 multiple interactions per event, the experimental sensitivity drops by less than a factor of 2 compared to the one in an ideal experiment with zero pileup.

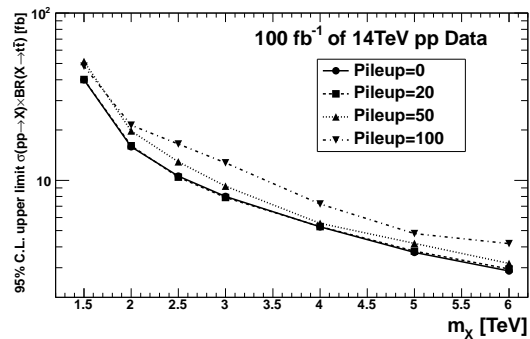


FIG. 6: The expected 95 % C.L. upper limit on the product of the production cross section of a heavy resonance X and its decaying branching fraction into a $t\bar{t}$ pair, as a function of the assumed X mass under different pileup conditions. Here we assume a width of 100 GeV of the heavy resonance and 100 fb^{-1} of LHC data at 14 TeV center-of-mass energy.

V. CONCLUSION

In this paper we study the identification of a boosted hadronically decaying top quark using jet substructure in the center-of-mass frame of the jet. We demonstrate that the method can greatly reduce the QCD jet background while maintaining high identification efficiency of the boosted hadronically decaying top quarks even in a very high pileup condition. The study shows a good prospective on search for heavy mass particles in the $t\bar{t}$ decay channel for the LHC experiments at 14 TeV center-of-mass energy.

VI. ACKNOWLEDGMENTS

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