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Studies of highly-boosted top quarks near the TeV scale using jet masses at the LHC

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Studies of highly-boosted top quarks produced inclusively in pp collisions at $\sqrt{s} = 14$ TeV are discussed. Using Monte Carlo models after a fast detector simulation, it is shown that jet masses alone provide a sensitive probe for top quarks produced inside high-p_T jets. The hadronic decays of such top quarks can be studied in a data-driven approach by analysing shapes of jet-mass distributions. It is shown that inclusive production of boosted top quarks can be observed if it has a cross section at least twice larger than the prediction from the approximate next-to-next-to-leading-order (aNNLO) calculation for the $t\bar{t}$ process. The $t\bar{t}$ process with the nominal aNNLO strength can be measured using the masses of jets after a b-tagging.

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I. INTRODUCTION

Heavy particles with masses above a TeV decaying to top quarks can lead to an enhanced cross section of top quarks compared to the Standard Model expectations. The fact that such a cross section can be more than doubled for top quarks with high transverse momenta (p_T(top)) was recognized [1] almost immediately after the discovery of top quarks at the Tevatron. However, the Standard Model predictions on top quark cross section have not yet been confronted with experimental data for transverse energies close to the TeV scale.

According to the Standard Model, inclusive production of top quarks is dominated by the $t\bar{t}$ process. Top-quark production includes contributions from single top quark processes (t- and s-channels) and from Wt. Top quarks can also be produced via associated Higgs production. Finally, top quarks at very large p_T(jet) can originate from fragmentation, but no data exist to constrain this process.

Currently, there are several high-p_T measurements of top quarks focusing on the $t\bar{t}$ event topology. The D0 collaboration has reported the $t\bar{t}$ cross section up to $p_T(\text{top}) = 350$ GeV [2]. The CDF collaboration [3] performed searches for highly-boosted top quarks, but statistics was insufficient to support the claim for observation of top-quark production at $p_T(\text{top}) > 400$ GeV. At the LHC, ATLAS performed [4] searches for Z' extending the reach in p_T(top) up to 500 GeV, but without cross section measurements. CMS recently measured the top quark p_T distribution up to $p_T(\text{top}) = 400$ GeV [5].

The measurement of top-quark cross sections at very large transverse momenta is challenging. For large jet transverse momenta, the identification of leptons (muons and electrons) from the W decay is difficult since they are often collimated with $b-$jets from the top decays. This leads to a reduced electron efficiency due to isolation requirements and large fake rates for muons due to the presence of b-quark decay products. In addition, a b-tagging technique suffers from an inefficiency for large p_T(jet) and poor separation between the signal and multijet background events.

Because of the above reasons, the main focus of this analysis is the hadronic-final state characteristics of jets which are expected to be sensitive to the production of hadronically decaying top quarks with large p_T(top). For such studies, jet masses and jet shapes are often discussed as a useful tool for the identification of top quarks and for reduction of the overwhelming rate from conventional QCD processes [6, 7].

In this paper, we adopt a strategy based on a high-precision measurement of shapes of jet masses. Using realistic Monte Carlo (MC) simulations after a fast detector simulation, we show that hadronic decays of highly-boosted top quarks can be observed by performing a data-driven analysis of jet-mass shapes near the 170 GeV region, without any additional technique involving jet substructure variables. This article shows that this method becomes feasible if the top-quark yield in the fiducial region $p_T(\text{top}) > 0.8$ TeV is a factor two or more larger than the expectation from the best understood $t\bar{t}$ process. Given large theoretical uncertainties for the $t\bar{t}$ process at large p_T(top) and a number of other not well understood sources (see Sect. I A) contributing to top quark production at large p_T(top), this approach can be promising for observation of inclusively produced top quarks. Moreover, we also demonstrate that a $b-$tagging can substantially increase the signal-over-background ratio, leading to observation of top jets from $t\bar{t}$.

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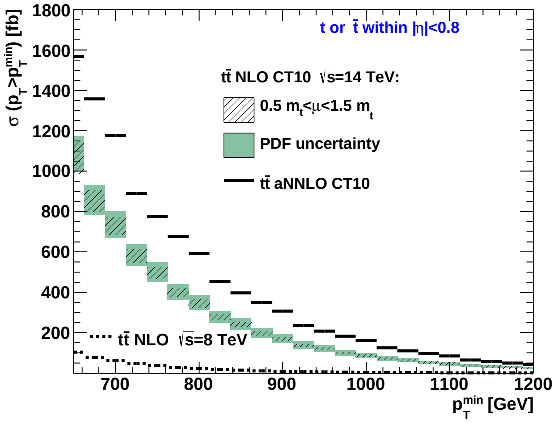


FIG. 1. The NLO and aNNLO cross sections for the number of top quarks in the $t\bar{t}$ process as a function of transverse momenta for $|\eta| < 0.8$. The hatched area shows the renormalization scale uncertainty for NLO, while the filled green area shows the PDF uncertainty (see the text of Sect. I A). The dashed line shows the NLO cross section for $\sqrt{s} = 8$ TeV.

A. Theoretical calculations for inclusive top production

There are several Standard Model processes contributing to inclusive top-quark production at large p_T(jet). The best studied process is the $t\bar{t}$ process when each boosted top quark gives origin to a jet. Single-top production ($t-$ and $s-$channels) and top-quark associated production are other sources of top-quark jets. In this case, no second jet originated from a hadronically decaying top quark is expected. Top quarks within a single high-p_T jet can be produced due to flavor-changing processes and fragmentation. Finally, new resonance physics most readily contributes to the high-p_T region.

For the present analysis, the theoretical calculation for high-p_T top quarks was performed at next-to-leading-order (NLO) using the MCFM 6.3 program [8] based on the CT10 parton density functions (PDF) [9]. The renormalization (μ_R) and factorization (μ_F) scales were varied between $m(\text{top}) - m(\text{top})/2$ and $m(\text{top}) + m(\text{top})/2$, keeping the renormalization and factorization scales to be the same. The PDF uncertainty was calculated from 53 CT10 PDF sets. A check was performed with the POWHEG program [10] which uses a p_T dependent (dynamic) scale (which is considered to be more appropriate at large p_T(top)). It was found that this model is in good agreement with the MCFM prediction assuming the estimated renormalization and factorization scale uncertainties.

Near partonic threshold for $t\bar{t}$ production the contributions from soft-gluon emission become dominant. The soft-gluon corrections to the double-differential top cross section in transverse momentum and rapidity can be resummed at next-to-next-to-leading-logarithm (NNLL) accuracy via the two-loop soft anomalous dimension matrices [11]. The resummed result has been expanded at fixed order to next-to-next-to-leading order (NNLO) and, after integration over rapidity, used to calculate the top quark transverse momentum distribution, $d\sigma/dp_T$. This approximate next-to-next-to-leading-order (aNNLO) calculation from NNLL soft-gluon resummation leads to a factor of two larger $t\bar{t}$ cross section at large p_T(top) compared to NLO.

Figure 1 shows the NLO and aNNLO cross sections for top quarks from the $t\bar{t}$ process in pp collisions at the center-of-mass energy $\sqrt{s} = 14$ TeV. The cross sections are presented as a function of the transverse momentum cut in the pseudorapidity region $|\eta| < 0.8$. The expected PDF uncertainty is about 20% (shown as filled band on Fig. 1), while the renormalization scale uncertainty is smaller. For a comparison, the cross section for $\sqrt{s} = 8$ TeV is also shown but without uncertainties. Assuming an integrated luminosity of 10 fb^{-1}, the NLO calculation predicts 3500 top quarks in the all decay channel in the fiducial volume p_T(top) > 0.8 TeV. This number is expected to increase to 5920 top quarks for the aNNLO. The contribution to the top quark yield from single-top production ($t-$channel [12], $s-$channel [13], and Wt production [14]) is expected to be smaller [11] than for the $t\bar{t}$ process.

Although the main focus of this study are jets with p_T(jet) > 0.8 TeV, it should be pointed out that contributions to such jets from top quarks with p_T(top) lower than 0.8 TeV are possible due to jet-energy resolution effects. In order to take into account such effects, top quarks were generated at lower p_T(top) than the minimum p_T(jet) $= 0.8$ TeV used in this analysis. In the following studies, top quarks were generated using MC models with p_T(top) > 0.65 TeV. Then their rate was scaled to 15690 top quarks as predicted by the aNNLO for the fiducial region p_T(top) > 0.65 TeV assuming an integrated luminosity of 10 fb^{-1}.

B. Monte Carlo simulations

Top quark jets in pp collisions were modeled using PYTHIA8 [16] and HERWIG++ [17] MC models assuming pp collisions at a center-of-mass energy of $\sqrt{s} = 14$ TeV. As discussed above, the number of top quarks in the fiducial region p_T(top) > 0.65 TeV was scaled to the aNNLO cross section assuming an integrated luminosity of 10 fb^{-1}.

In addition to the top-quark initiated jets, QCD background due to jets originating from light-flavor quarks and gluons were considered. Hadronic jets from all QCD processes (but excluding the $t\bar{t}$ production), were generated using PYTHIA8 and HERWIG++. The MC inclusive cross section of jets was corrected to match the NLO prediction estimated with the NLOjet++ program [18]. The estimated scaling factor was found to be close to 10%.

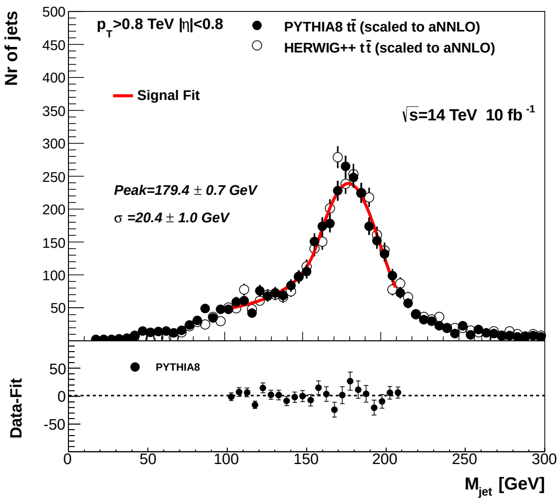


FIG. 2. Expectations for the jet mass distribution initiated by top quarks using PYTHIA8 and HERWIG++ after the fast detector simulation. The jet selection cuts are $p_T(\text{jet}) > 0.8$ TeV and $|\eta(\text{jet})| < 0.8$. The number of initial top quarks is normalized to the aNNLO for $p_T(\text{top}) > 0.65$ TeV. The expected number of top jets shown in this figure is 3,500, with 2,200 in the Gaussian core $140 < M_{\text{jet}} < 200$ GeV. The jet masses generated with PYTHIA8 were fitted in the mass range 100-210 GeV using a Crystal Ball function [15]. The bottom plot shows the fit residuals. The fit has χ^2/ndf=1.3.

The samples for $t\bar{t}$ and for the QCD dijet background events were processed through a fast detector simulation based the DELPHES 2.0.3 framework [19] assuming the ATLAS detector geometry. The most crucial in such simulation are detector resolutions for hadronic and electromagnetic calorimeters of the ATLAS detector. Those were taken from the default DELPHES setting based on the ATLAS studies [20, 21].

C. Jet mass reconstruction

Events after the fast detector simulation were selected if they contain at least one jet reconstructed with the anti-k_T algorithm [22] with a distance parameter of 0.6. This distance parameter is the most optimal to collect the decay products of hadronically decaying top quarks inside jets with $p_T(\text{jet}) > 0.8$ TeV [7]. Jets were reconstructed with the FastJet package [23] using the DELPHES calorimeter cell positions and energies.

The final jets were selected with $p_T(\text{jet}) > 0.8$ TeV and $|\eta(\text{jet})| < 0.8$. For the current analysis, the central calorimeter region is used in order to avoid biases in the reconstruction of jet shapes and in order to increase the signal over background ratio for boosted top searches: for $p_T(\text{top}) > 0.8$ TeV, top quarks from the $t\bar{t}$ process are predominantly produced in the very central rapidity region.

II. RESULTS

A. Masses of top jets

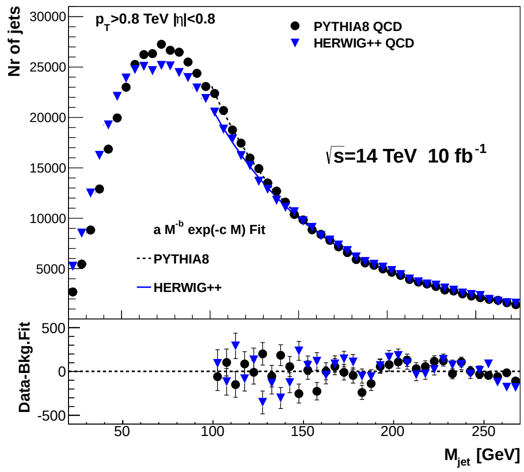
As is well known, jet masses are sensitive to the presence of top-quark decays. Figure 2 shows the masses (M_{jet}) of jets initiated by top quarks ("top jets") using PYTHIA8 and HERWIG++ after the fast detector simulation. The jet selection cuts are $p_T(\text{jet}) > 0.8$ TeV and $|\eta(\text{jet})| < 0.8$. The jet masses include contributions from all-top decays (including leptonic decays of W bosons). The jet mass distribution can be described by a Crystal Ball function [15] which has a Gaussian core (with a mean m_0 and a width σ) and a power-law tail with an exponent n to account for energy losses of hadronic decays or leptonic W decays. The parameter α defines the transition between the Gaussian and the power-law functions. Figure 2 shows the fit with the Crystal Ball function using PYTHIA8 . The peak position of the Gaussian component, which is intended to describe fully-hadronic decays, is close to 180 GeV with the width $\sigma \simeq 20$ GeV. Figure 2 shows that the difference in shapes between PYTHIA8 and HERWIG++ is small and thus can be neglected.

B. Jet masses for light-flavor jets

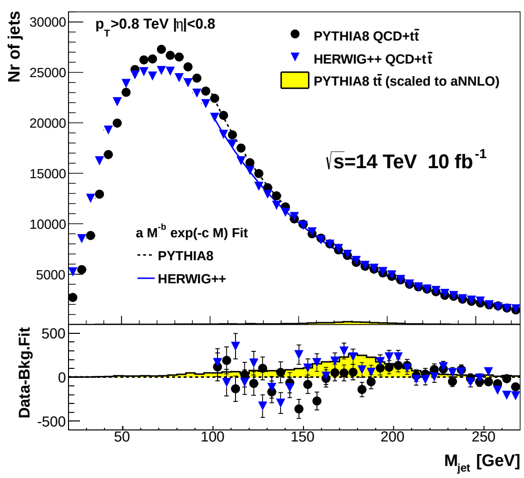
The mass distribution of jets originating from light quarks and gluons is distinct from jet masses initiated by top quarks. Figure 3(a) shows the M_{jet} distributions for light-flavor QCD jets (without the $t\bar{t}$ process) for PYTHIA8 and HERWIG++ after the fast detector simulation. The number of light-flavor jets was scaled to the expectation from the NLOjet++ program as discussed before. Events with W+jet events where also studied in the context of a possible contribution to the jet-mass shape. It was shown that W+jet events do not distort the region near $M_{\text{jet}} \simeq 170 - 180$ GeV.

The jet masses for light jets can reasonably be described by the functional form $a \cdot M_{\text{jet}}^{-b} \cdot \exp(-c \cdot M_{\text{jet}})$, where a, b and c are free parameters. A similar function was previously used in the measurement of hadronic W/Z decays in two-jet mass spectra [24]. A fit using this function provides a MC independent way to search for any significant deviations from the jet mass shape which is expected to be falling in the tails. The fit residuals for PYTHIA8 and HERWIG++ show no significant deviation from zero.

The inclusion of top quarks modifies M_{jet} near the 170 GeV region. Figure 3(b) shows the expectation for M_{jet} assuming the contribution from the $t\bar{t}$ process. The top jets were simulated using PYTHIA8 , while their yield was scaled to the aNNLO calculation. The fit using $a \cdot M_{\text{jet}}^{-b} \cdot \exp(-c \cdot M_{\text{jet}})$ was performed in the range $100 < M_{\text{jet}} < 270$ GeV. The fit residuals do not show any significant



(a)Jet mass distribution without $t\bar{t}$ process.

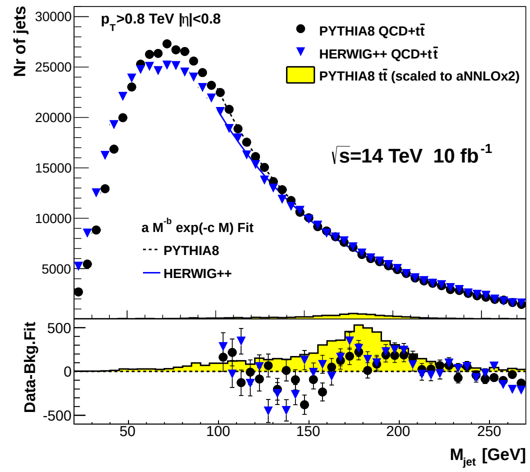


(b)Jet mass distribution with the $t\bar{t}$ process.

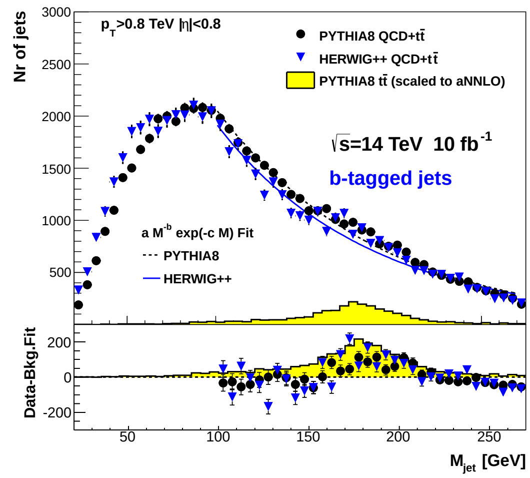
FIG. 3. Expectations for the jet-mass distributions for the MC models after the fast detector simulation. The rate of light-flavor jets is scaled to the NLO prediction for inclusive jets. The jet masses are shown for (a) assuming no $t\bar{t}$ process and, (b) with the $t\bar{t}$ process included. A χ^2 fit was performed using the background function $a \cdot M_{\rm jet}^{-b} \cdot \exp\left(-c \cdot M_{\rm jet}\right)$ in the mass range $100 < M_{\rm jet} < 270$ GeV. The jet mass prediction shown in (b) as shaded histograms is based on `PYTHIA8` $t\bar{t}$ scaled to the aNNLO. The fit quality is χ^2/ndf=1.9 for (a) and χ^2/ndf=2.1 for (b).

excess above zero, indicating that the extraction of the top signal assuming the nominal aNNLO yield for $t\bar{t}$ can be challenging.

The situation is different if the top-quark yield is somewhat larger than the $t\bar{t}$ expectation. For example, Fig. 4(a) shows what happens when the top signal has a factor of two larger cross section than the aNNLO prediction shown before. The signal is difficult to miss; the



(a)Masses of jets with the $t\bar{t}$ signal scaled by two.

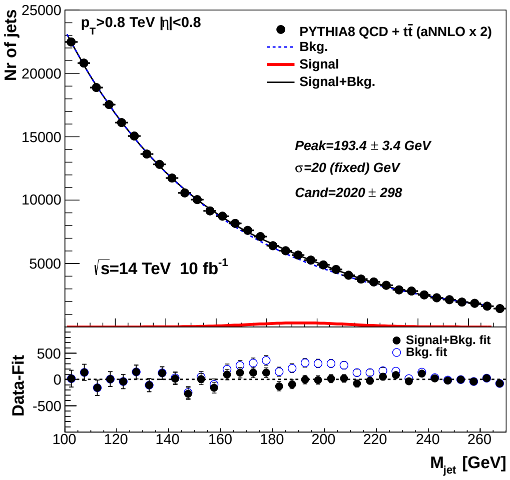


(b)Masses of jets with the $t\bar{t}$ signal after b-tagging.

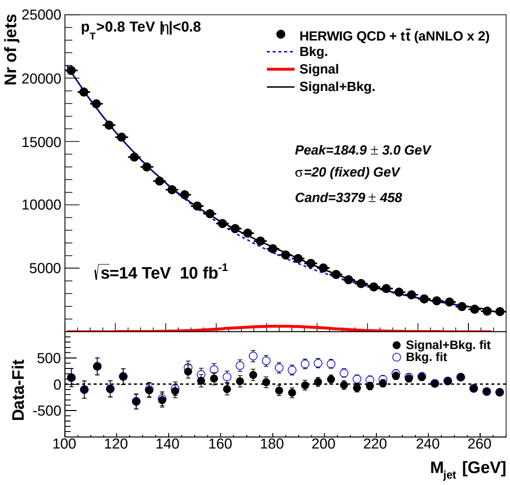
FIG. 4. (a) Expectations for the jet mass distributions using `PYTHIA8` and `HERWIG++` after the fast detector simulation. For the simulation, top quarks were added to light-flavor jets. The QCD dijet background was scaled to the NLO inclusive jet cross section. A χ^2 fit was performed using the background function $a \cdot M_{\rm jet}^{-b} \cdot \exp\left(-c \cdot M_{\rm jet}\right)$ in the mass range $100 < M_{\rm jet} < 270$ GeV. (a) The `PYTHIA8` expectation with the normalisation from the aNNLO for $t\bar{t}$ was scaled by a factor two. (b) The same distribution using the $t\bar{t}$ signal yield predicted by the aNNLO after applying the b-tagging for background and top jets. The fit quality using the background function is χ^2/ndf=2.7 for (a) and χ^2/ndf=3.5 for (b).

residuals of the fit near $M_{\rm jet} \simeq 180$ GeV show an excess above zero and have rather characteristic S-shape form due to the pull from the signal region. This is more apparent for `HERWIG++` than for `PYTHIA8`, indicating a model dependence of this observation.

Another way of looking at the effect of top quarks on



(a)PYTHIA jet mass with the $t\bar{t}$ signal scaled by two.



(b)HERWIG jet mass with the $t\bar{t}$ signal scaled by two.

FIG. 5. The distributions of jet masses for $p_T(\text{jet}) > 0.8$ TeV and $|\eta(\text{jet})| < 0.8$ for MCs after the fast detector simulation. The jet masses include contributions from $t\bar{t}$ assuming that the $t\bar{t}$ cross section is a factor two larger than the aNNLO cross section. A simultaneous χ^2 fit was performed in the mass range $100 < M_{\text{jet}} < 270$ GeV using the function $a \cdot M_{\text{jet}}^{-b} \cdot \exp(-c \cdot M_{\text{jet}})$ for the background description plus a Gaussian to describe the excess near 170 GeV. To improve the fit stability, the width of the Gaussian is fixed to 20 GeV as expected for top jets. The bottom plots show the fit residuals with respect to the fitted signal plus background function, as well as with respect to the background component of the combined fit.

the jet mass distribution is to reduce the contribution of light-flavor jets using a b-tagging technique. Figure 4(b) shows the jet masses with the nominal $t\bar{t}$ signal strength, but after applying a b-tagging using the DELPHES [19] setting. It assumes a 40% $b-$quark reconstruction efficiency, 10% and 1% misstag rates due to $c-$quark and light-flavor jets, respectively. The b-tagging increases the signal-over-background ratio and the $t\bar{t}$ signal is clearly observed.

The scenario when the cross section of boosted top quarks is higher than the $t\bar{t}$ prediction was further studied in Fig. 5 when a potential excess of top jets near the 170 GeV region is extracted using a signal plus background function. As before, light-flavor jets were combined with top jets from the $t\bar{t}$ process. For this hypothetical scenario, the yield of the latter process was scaled by a factor of two with respect to the aNNLO prediction. The signal function is assumed to be a Gaussian with the width of 20 GeV as expected for the top jets (see Fig. 2).

The number of top quarks included in the simulation for $p_T(\text{top}) > 0.65$ TeV was 11,840 (5920 top quarks from the aNNLO times two, see Sect. I A). This leads to 4,400 top jets with $p_T(\text{jet}) > 0.8$ TeV contributing to the $M_{\text{jet}} \simeq 170$ GeV region (2,200 top jets in the Gaussian core shown in Fig. 2 times two). According to the fit shown in Fig. 5, the number of extracted top jets is between 2,000-3,400, depending on the MC simulation. This number was extracted by integrating the Gaussian component of the background plus signal fit. Thus, the extracted number of top jets is close to the expected number of top jets included in the simulation, but there is some indication that the signal-plus-background fit somewhat underestimates the number of top jets.

While the scenario when the number of top jets is a factor of two larger than the aNNLO prediction for $t\bar{t}$ may seem exotic at first, such an assumption may not be too far from the Standard Model expectation for top quarks produced inclusively within a jet (see the discussion in Sect.I A). Given the large difference between the aNNLO and NLO [11], higher-order QCD effects for the $t\bar{t}$ process may play a significant role in an increase of top-quark jets at very large $p_T(\text{jet})$. It is also important to mention that theoretical uncertainties, especially those related to PDF, can be as large as 20% (see Fig. 1). Less understood contributions from single-top production (about 30% at lower $p_T(\text{top})$), flavor-changing processes and from fragmentation within jets should also be considered for the inclusive production of top quarks inside jets. Taking into account all such effects, our conjecture about the factor two may not be too far from the real situation. Therefore, a better understanding of all Standard Model processes leading to top production at high $p_T(\text{jet})$ is needed.

One can also consider the discussed result from the point of view of discovery reach. The approach can be used to exclude any potential source of new physics for a number of models (such as those based on Z' and W' bosons) leading to top quarks at large $p_T(\text{jet})$. From the above consideration, any source of new physics can be excluded if it leads to a top-quark cross section above 1184 fb in the fiducial region $p_T(\text{jet}) > 0.8$ TeV and $|\eta(\text{jet})| < 0.8$. This cross section is obtained from the aNNLO $t\bar{t}$ prediction multiplied by a factor two. Note that the approach can exclude a number of exotic processes. For example, models with Z' and KaluzaKlein gluons may have larger cross sections compared to the Standard Model $t\bar{t}$ process at very large p_T(jet). As a consequence, a number of limits have been set [4, 25] excluding such models up to $1.5 - 2$ TeV without experimental observation of top quarks from the Standard Model $t\bar{t}$ process at $p_T(\text{top}) > 0.6$ TeV.

The high-precision studies of jet mass using analytic background templates may seem difficult from the instrumental point of view since we are looking for a top quark signal on top of a smoothly falling distribution which has a signal-over-background ratio at the level of 10% for the $t\bar{t}$ process. However, the assessment of systematics on the presence of a bump must have a different strategy than for a typical jet-mass measurement. Any variation of selection cuts or change in the instrumental procedure should be followed by the data-driven approach using the analytic fit to identify a bump after each systematic change, unlike a typical QCD measurement of jet masses. For example, jet-energy scale variation should lead to a change of jet masses, but the signal strength after the signal-plus-background fit should not be strongly affected given the data-driven nature of such extraction.

Finally, a possibility of using other techniques based on b-tagging, jet shapes and jet substructure can be considered, which can also help to deal with some experimentally unavoidable effects, such as pile up. These techniques have the potential to increase the signal over background ratio for M_{jet} close to 170 GeV when dealing with high-p_T inclusive jets. This has been illustrated in Fig. 4(b) when considering jets after the b-tagging. As follows from this study, if the QCD multijet background is reduced at least by a factor of two compared to the top-quark signal, the $t\bar{t}$ process should be well observed for the yield expected from the aNNLO calculation. Studies of such techniques are outside the scope of this paper and can be found elsewhere [6, 7].

III. CONCLUSIONS

This paper shows that jet masses alone, without any complicated techniques involving substructure variables, already provide a sensitive probe for inclusively produced top quarks within high-p_T jets. Due to the nature of the inclusive measurement, such technique is not based on tagging of top quarks in the opposite direction. The approach allows to study top quarks using the assumption that the background fit function has a smoothly falling shape and does not contain a hump near the 170 GeV region, thus it can be modeled analytically.

As shown in this paper, the method has the potential to detect highly-boosted top quarks if their yield is a factor of two or more larger than that from the best-understood $t\bar{t}$ process assuming the aNNLO prediction. This observation also implies that any technique capable of reducing QCD background near $M_{\text{jet}} \simeq 170$ GeV at least by a factor of two should be sufficient for the observation of boosted top quarks from the Standard Model $t\bar{t}$ process. There are other sources for inclusive production of top quarks for very large p_T(jet), but their good understanding requires further studies. Once they are understood, any enhancement of top-quark cross section over the Standard Model prediction would be indicative of the presence of new resonances at the TeV scale.

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