Probing the Quantum Interference between Singly and Doubly Resonant Top-Quark Production in pp Collisions at root $s=13$ TeV with the ATLAS Detector

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Top-quark pair ($t\bar{t}$) production is one of the most widely studied processes at the Large Hadron Collider (LHC) and is a key background to many searches for physics beyond the standard model (BSM). The differential cross section for $t\bar{t}$ has been measured [1–5] and calculated [6–8] across a wide kinematic range with high accuracy. However, all of these results treat the decay of the top quark to a $b$-quark and $W$ boson in the narrow-width approximation, separating $t\bar{t}$ production from production of a single top quark in association with a $W$ boson and a $b$-quark ($tWb$). Because of their identical $WWbb$ final states, processes with one or two timelike top-quark propagators (called singly and doubly resonant, respectively) interfere. Standard ad hoc methods of modeling this interference [9–12] are a significant source of uncertainty for many BSM searches [13–18]. Traditional measurements of production of a single top quark with an associated $W$ boson ($tW$) are designed to be insensitive to such effects [19–21]. Recent fixed-order calculations of the full next-to-leading-order (NLO) $pp \rightarrow \ell^+\nu\ell^−\bar{\nu}b\bar{b}$ process [22–26] include proper treatment of the interference and have set the stage for corresponding predictions matched to a parton shower [27]. However, there are no measurements available to assess the modeling in a region sensitive to interference effects.

This Letter presents a novel way to test different models of the interference between $t\bar{t}$ and $tWb$, using 36.1 fb$^{-1}$ of proton-proton ($pp$) collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS detector in 2015 and 2016. The measurement targets the dilepton final state, characterized by a pair of oppositely charged leptons ($ee, \mu\mu, \text{or } e\mu$) originating from $W$-boson decays [28], associated with jets containing $b$-hadrons ($b$-jets) and missing transverse momentum due to undetected neutrinos. The contributions from doubly and singly resonant amplitudes (and hence also their interference) to the combined cross section depend on the invariant mass of the $bW$ pairs in the event, $m_{bW}$. In this analysis, the charged lepton is used as a proxy for the $W$ boson and a differential cross section is measured as a function of the invariant mass of a $b$-jet and a lepton. There is ambiguity in forming this mass, so

$$m_{b\ell_{\text{min}}} = \min\{\max(m_{b\ell_1}, m_{b\ell_2}), \max(m_{b\ell_1}, m_{b\ell_2})\}$$

is used, where the $b_i$ and $\ell_i$ represent the two $b$-jets and leptons, respectively. This choice is inspired by the minimax procedure used to construct the stransverse mass [29,30] and measure the top mass [31]. At leading order, for doubly resonant events at parton level, $m_{b\ell}^\text{min} < \sqrt{m_t^2 + m_W^2}$, where $m_t$ and $m_W$ are the top-quark and $W$-boson masses, respectively. Because of suppression of the doubly resonant contribution, the differential cross section above this kinematic endpoint has increased sensitivity to interference effects.

ATLAS is a multipurpose particle detector designed with nearly full $4\pi$ coverage in a solid angle [32]. Lepton and jet reconstruction and identification used in this paper are

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described in Ref. [33] and are briefly summarized in the following. Electrons and muons are required to have transverse momentum $p_T > 28$ GeV, pseudorapidity $|\eta| < 2.47$ (2.5) for electrons (muons), and meet a series of quality criteria [35,36], denoted “tight” in Ref. [33]. Jets are clustered from topologically connected calorimeter cells [37] using the anti-$k_t$ jet algorithm [38] with radius parameter $R = 0.4$ implemented in FASTJET [39] and calibrated to particle level [40]. Jets are identified as originating from $b$-quarks with a multivariate classifier using observables sensitive to lifetimes, production mechanisms, and decay properties of $b$-hadrons [41]. The tagging efficiency is determined in simulated $t\bar{t}$ events to be 60% (85%) for the tight (loose) tagging criterion.

Samples of simulated data are used in the design of the measurement, estimation of the background, and the unfolding procedure. POWHEG-BOX [42] v1 and v2 were used to simulate $tW$ and $t\bar{t}$ events, respectively, with PYTHIA 6.428 [43], the five-flavor scheme (5FS) CT10 [44] parton distribution function (PDF) set, and Perugia 2012 [45] collection of tuned parameters. An identical configuration except using PYTHIA 8.183 and POWHEG-BOX-v2 for $tW$ was included for particle-level comparisons. Alternative samples used POWHEG-BOX-v2 or MADGRAPH5_aMC@NLO (MG5_aMC) 2.2.2 [46], each interfaced to Herwig++ 2.7.1 [47] with the UE-EE-5 set of tuned parameters [48] and CT10 PDF set. The $t\bar{t} + b\bar{b}$ process [49] was generated using SHERPA 2.1.1 [50] plus OPENLOOPS [51] with the CT10 four-flavor scheme PDF. The $V +$ jets and $VV +$ jets ($V = W, Z$) processes were generated with SHERPA-BOX-v2 or MG5_aMC@NLO (MG5_aMC) 2.2.2 [46], each interfaced to Herwig++ 2.7.1 [47] with the UE-EE-5 set of tuned parameters [48] and CT10 PDF set. Associated production of $t\bar{t}$ with a boson ($tW$) was generated using MG5_aMC 2.2.2 combined with PYTHIA 8.186 [52], the NNPDF2.3LO PDF set [53] and the A14 set of tuned parameters [54]. All predictions, including the $t\bar{t}$ and $tW$ processes, are normalized to next-to-next-to-leading-order or next-to-leading-order cross sections [6,46,50,55,56]. All samples of simulated data were processed using the full ATLAS detector simulation [57] based on GEANT 4 [58].

The signal process is combined $t\bar{t} + Wb$ production [59]. A calculation of the $e^+\nu\mu^-\bar{\nu}b\bar{b}$ process in the four-flavor scheme at NLO was implemented in POWHEG-B ox-Res [27,60] with PYTHIA 8.226. Here, resonance-aware matching allows the inclusion of off-shell top-quark effects at NLO, and the interference term is included. Alternatively, predictions are obtained from the exclusive $t\bar{t}$ and $tWb$ samples described above, where the definition of the $tW$ process is chosen to enable combination with the corresponding $t\bar{t}$ calculation. This is nontrivial at NLO, where care must be taken to avoid double-counting $tWb$ events with $m_{b\bar{b}} \sim m_t$. The default scheme for combining the $t\bar{t}$ and $tW$ processes at NLO adopted here is diagram removal (DR) [9] in which all doubly resonant amplitudes are removed from the $tW$ sample. Other choices exist where doubly resonant contributions are canceled out by gauge-invariant subtraction terms (diagram subtraction, DS) [9] or are only included in the interference terms (DR2) [10,12]. For a more detailed review of possible $tW$ definitions, see Ref. [11]. Finally, all $t\bar{t}$ events with $b$-jets not associated with top-quark decays are classified as $t\bar{t} +$ heavy flavor ($t\bar{t} + HF$) and treated separately from the signal process.

Events are selected with single-lepton triggers [61] and required to have a pair of opposite-charge leptons ($e^+\nu\mu^-\bar{\nu}$, $\mu^+\mu^-\bar{\nu}$, $e^+\mu^-\bar{\nu}$). Events with a same-flavor lepton pair having invariant mass $m_{ee} < 10$ GeV or within 15 GeV of the $Z$-boson mass are rejected to suppress contributions from low-mass resonances and $Z +$ jets. Events are required to have exactly two jets with $p_T > 25$ GeV and $|\eta| < 2.5$ which satisfy the tight $b$-tagging criterion and no additional jets that pass the looser $b$-tagging requirement. This $b$-jet veto suppresses $t\bar{t} + HF$ events, which can have large $m_{b\bar{b}}^{\text{minmax}}$ when a selected $b$-jet does not originate from a top-quark decay.

A combination of data-driven and simulation-based methods is used to estimate backgrounds to the $t\bar{t} + Wb$ signal process. The dominant background at high $m_{ee}^{\text{minmax}}$ is $t\bar{t} + HF$, where an $b$-jet from a top-quark decay is not identified. This contribution is estimated from data events with at least three jets that are $b$-tagged according to the tight criterion. Simulated data is used to extrapolate the $t\bar{t} + HF$ yield measured in this region to the two-$b$-tag signal selection, giving a prediction 1.49 ± 0.05(stat) ± 0.20(syst) times larger than the prediction obtained using POWHEG+PYTHIA 6. This is consistent with the results of previous measurements, finding scale factors from 1.1 to 1.7 depending on the selection criteria [62–66]. Figure 1(a) shows the $m_{b\bar{b}}^{\text{minmax}}$ distribution for events passing the three-$b$-tag selection, constructed from the two $b$-jets with largest $p_T$. The leading two $b$-jets are both found to originate from top decays in 60% of simulated $tt + HF$ events when $m_{b\bar{b}}^{\text{minmax}}$ is below 160 GeV and less than 10% when above. Good agreement between data and prediction across the distribution demonstrates that the additional jet from heavy flavor is well modeled. The next largest background is from $Z +$ jets production, which is estimated in an analogous manner from data events with same-flavor leptons satisfying an inverted $m_{ee}^{\text{minmax}}$ requirement. In both cases, the $t\bar{t}$ contribution is subtracted before estimating the scale factor. Various checks show that this does not bias the measurement in the signal region phase space. Finally, there is a small contribution from non-prompt and misidentified leptons arising from photon conversions, heavy-flavor hadrons decaying leptonically, and jets misidentified as leptons. Following Ref. [67], this background is estimated using events with same-charge lepton pairs, after subtracting the prompt lepton contribution. Minor contributions from $tW$ and $VV +$ jets are estimated using simulation. Uncertainties in the simulation-based extrapolations are described below. The $t\bar{t} + Wb$ signal...
FIG. 1. (a) The $m_{b\ell_{\rm min}}$ distribution in the three-$b$-tag region, constructed from the two $b$-jets with largest $p_T$. The predicted $t\bar{t} + \text{HF}$ contribution from simulation is scaled to match observed data in this region. The hashed band indicates the uncertainty on the total number of predicted events, where the DR scheme is used to estimate the minor contribution from the $tW$ process. The separate uncertainty due to the interference modeling of processes with top quarks are generally the most important and range from 1% to 22% of the unfolded yields. The separate uncertainty due to the interference treatment is subdominant (22% in the largest bin of $m_{b\ell_{\rm min}}$, elsewhere 1%–8%), and everywhere much smaller than the raw difference between the DR and DS scheme predictions. The size of the data set leads to statistical uncertainties of up to 20%.

Figure 2 presents the differential cross section observed in data, normalized to the total observed cross section with this selection. Various predictions are also shown, with uncertainties included from varying the PDF set [75] and the renormalization and factorization scales. A $\chi^2$ test statistic is constructed for the various models to assess the level of agreement with the data. Correlations among uncertainties of the unfolded distribution are included, as well as theory uncertainties on the signal predictions. Results of the test are presented in Table I as $p$ values, corresponding to the observed level of agreement over the full distribution as well as the subset $m_{b\ell_{\rm min}} > 160$ GeV where the predicted differences due to interference are largest.

The $tWb$ prediction using the DR scheme gives a better description of the relative normalization of the region $m_{b\ell_{\rm min}} \gtrsim m_t$ than the DS scheme. However, the DS scheme better models the $m_{b\ell_{\rm min}}$ shape over the same range of values. The DR and DS predictions generally bracket the data in the region of large $m_{b\ell_{\rm min}}$, justifying the practice of applying their difference as a systematic uncertainty. The DR2 scheme describes the data well up to the top-quark mass, but significantly underpredicts the data.
The results are presented as a normalized fiducial differential cross section, giving constraints on predictions for the full $t\bar{t} + tWb$ process.

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[28] Events involving $W \rightarrow \tau\ell$ decays with a subsequent decay of the $\tau$ lepton to either $e/\mu/\nu$, or $\mu/\nu/\ell$, are included in the signal.


[34] Pseudorapidity is defined in terms of the angle $\theta$ with respect to the beam line as $\eta = -\ln \tan(\theta/2)$.


[59] Although it also interferes with the signal process, the contribution from fully nonresonant WWbb production is treated as background. Its contribution to the selected phase space is negligible compared to processes with top quarks.


[68] Detector level refers to the measured outputs of the detector; particle level refers to the particles which interact with the detector.


[76] For this calculation, the effect of decaying the top quarks with PYTHIA instead of the default MADSPIN configuration can be up to 20% at high $m_{\tau}\text{minmax}$. However, this change leads to poorer agreement with data and the impact of using MADSPIN for DR2 is consistent with that seen for the corresponding DR prediction.

[77] Generated $\mu\mu$ events are reweighted to account for events with same-flavor leptons and fully leptonic tau decays.

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