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

Aaboud, M.; The ATLAS Collaboration; Wolf, T.M.H.

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Probing the Quantum Interference between Singly and Doubly Resonant Top-Quark Production in \( pp \) Collisions at \( \sqrt{s}=13 \) TeV with the ATLAS Detector

M. Aaboud et al.*
(ATLAS Collaboration)

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This Letter presents a normalized differential cross-section measurement in a fiducial phase-space region where interference effects between top-quark pair production and associated production of a single top quark with a W boson and a \( b \)-quark are significant. Events with exactly two leptons (ee, \( \mu \mu \), or \( e\mu \)) and two \( b \)-tagged jets that satisfy a multiparticle invariant mass requirement are selected from 36.1 fb\(^{-1}\) of proton-proton collision data taken at \( \sqrt{s}=13 \) TeV with the ATLAS detector at the LHC in 2015 and 2016. The results are compared with predictions from simulations using various strategies for the interference. The standard prescriptions for interference modeling are significantly different from each other but are within 2\( \sigma \) of the data. State-of-the-art predictions that naturally incorporate interference effects provide the best description of the data in the measured region of phase space most sensitive to these effects. These results provide an important constraint on interference models and will guide future model development and tuning.

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Top-quark pair (\( tt \)) 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 \( tt \) 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 \( tt \) 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) \( pp \to \ell^+\nu\ell^-\bar{b}b \) 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 \( tt \) 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, \( \mu \mu \), 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

\[
m_{b\ell}^{\text{minimax}} = \min \{ \max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1}) \}
\]

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 transverse mass [29,30] and measure the top mass [31]. At leading order, for doubly resonant events at parton level, \( m_{bW}^{\text{minimax}} < \sqrt{m_t^2 - m_W^2} \), 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

*Full author list given at the end of the article.

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The signal process, combined with events with a single lepton trigger and a multivariate classifier, is used to estimate the background to the $t\bar{t}+tWb$ signal process. The dominant backgrounds are from high-mass resonances and $Z$+jets, which are well modeled. The next largest contribution is from heavy flavor, which is estimated using events with same-flavor lepton pairs, misidentified from photon conversions, and from events with heavy flavor. The additional jet veto suppresses $t\bar{t}+tWb$ events, which can have large $m_{\text{miss}}$ maxima 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 $t\bar{t}+tWb$ signal process. The dominant background at high $m_{\text{miss}}$ is $t\bar{t}+HF$, where a $b$-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 $1.49 \pm 0.05(\text{stat}) \pm 0.20(\text{syst})$ 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 $m_{\text{miss}}$ 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 $t\bar{t}+HF$ events when $m_{\text{miss}}$ 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 $m_{\text{miss}}$ 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 $VV+\text{jets}$ are estimated using simulation. Uncertainties in the simulation-based extrapolations are described below. The $t\bar{t}+tWb$ signal
The unfolding procedure corrects detector-level [68] observables to particle level using a Bayesian method [69] with one iteration, optimized to minimize the average uncertainty per bin. The particle-level selection is defined to be as close as possible to the detector-level selection to minimize simulation-based corrections for acceptance effects and the detector resolution when unfolding. The definitions of particle-level objects are given in Ref. [70] with the following choices and modifications: (1) jets are clustered from all simulated particles with a mean lifetime $\tau > 30$ ps excluding muons and neutrinos to reduce model dependence, (2) jets are identified as $b$-jets if a $b$-hadron is found within the jet cone. Particle-level events must pass the same event selection as detector-level events, including the $m_{c\ell}$ requirement. To avoid contamination from $t\bar{t} +$ HF production, events with three or more particle-level $b$-jets with $p_T > 5$ GeV are rejected.

There are two categories of systematic uncertainties in the measurement: experimental and theoretical modeling. These affect the result via the background prediction that is subtracted from data or through the model used to unfold the data to particle level. Experimental uncertainties result from potential mismodeling in the reconstruction and identification of the jets [40], $b$-jets [71], and leptons [35,36]. The background subtraction introduces uncertainty from the limited number of events in the control regions. A suite of simulation samples with alternative settings are used to assess the theoretical uncertainties in modeling the $t\bar{t}$, $tW$, $t\bar{t} +$ HF, and $Z +$ jets processes [72,73]. A further uncertainty is assessed by varying the composition of the $t\bar{t} + tWb$ signal according to the uncertainty in the total cross sections of the singly and doubly resonant processes. An additional uncertainty is assessed for $t\bar{t} +$ HF by comparing the prediction obtained using POWHEG +PYTHIA 6 with that using the SHERPA $t\bar{t} + b\bar{b}$ sample. Furthermore, to ensure that the bias from the choice of interference scheme used in the unfolding is small, the procedure is repeated using the DS scheme. Finally, as another test of the unfolding, the particle-level $m_{b\bar{b}}^{\text{minimax}}$ spectrum is reweighted to attain better agreement between the corresponding detector-level distribution and the data. Unfolding this reweighted distribution using the nominal unweighted simulation gives a measure of the method non-closure, which is assessed as an additional uncertainty [74].

The systematic uncertainty due to experimental sources ranges from 1% to 14%, with leading contributions from the jet energy scale and resolution and the $b$-tagging efficiency. Theoretical uncertainties associated with the 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 $m_{b\bar{b}}^{\text{minimax}}$, 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 $m_{b\bar{b}}^{\text{minimax}} > 160$ 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 $m_{b\bar{b}}^{\text{minimax}} \gtrsim m_t$ than the DS scheme. However, the DS scheme better models the $m_{b\bar{b}}^{\text{minimax}}$ shape over the same range of values. The DR and DS predictions generally bracket the data in the region of large $m_{b\bar{b}}^{\text{minimax}}$, 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.
at higher masses [76]. The calculation from MG5_aMC using the DR scheme is presented alongside the corresponding DR2 calculation to directly compare the two interference treatments with other inputs held constant. The full $\ell^+\ell^-\nu\nu$ prediction [77] obtained from POWHEG-Box-Res models $m_{\text{minimax}}^{bb}$ well across the full distribution, including the region beyond the top-quark mass where predictions using traditional models of the interference diverge.

In summary, a measurement of a region sensitive to the interference between doubly and singly resonant top-quark pair production is presented. This is an original constraint on this interesting region of phase space that will be important for future model development and tuning.

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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The $p$ values comparing data and predictions from events simulated with various models of the interference, all interfaced to PYTHIA 8. Test statistics are constructed from the full $m_{\text{minimax}}^{bb}$ distribution and for the subset $m_{\text{minimax}}^{bb} > 160$ GeV.

<table>
<thead>
<tr>
<th>Model</th>
<th>All bins $m_{\text{minimax}}^{bb}$</th>
<th>$m_{\text{minimax}}^{bb} &gt; 160$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWHEG-Box $t\bar{t} + tW$ (DR)</td>
<td>0.71</td>
<td>0.40</td>
</tr>
<tr>
<td>POWHEG-Box $t\bar{t} + tW$ (DS)</td>
<td>0.77</td>
<td>0.56</td>
</tr>
<tr>
<td>MG5_aMC $t\bar{t} + tW$ (DR)</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>MG5_aMC $t\bar{t} + tW$ (DR2)</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>POWHEG-Box $\ell^+\ell^-\nu\nu$</td>
<td>0.92</td>
<td>0.95</td>
</tr>
</tbody>
</table>


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


[66] CMS Collaboration, Search for $t\bar{t}H$ production in the $H \to b\bar{b}$ decay channel with leptonic $t\bar{t}$ decays in proton-proton collisions at $\sqrt{s} = 13$ TeV, arXiv:1804.03682.

[67] ATLAS Collaboration, Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with $b$-tagged jets in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector, Eur. Phys. J. C 74, 3109 (2014); Addendum 76, 642(A) (2016).

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


[71] ATLAS Collaboration, Measurements of b-jet tagging efficiency with the ATLAS detector using $t\bar{t}$ events at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 08 (2018) 89.


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 $m_{T_{\text{min}}}$. 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.

165a TRIUMF, Vancouver, British Columbia, Canada
165b Division of Physics and Astronomy, York University, Toronto, Ontario, Canada
166 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
167 Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
167 Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada
167 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
167 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
168 Department of Physics, University of Warwick, Coventry, United Kingdom
169 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
170 Department of Physics, University of Illinois, Urbana, Illinois, USA
171 Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
172 Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
173 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
175 Department of Physics, University of Warwick, Coventry, United Kingdom
176 Waseda University, Tokyo, Japan
177 Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
178 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
179 Fakultät für Matematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
180 Department of Physics, Yale University, New Haven, Connecticut, USA
181 Yerevan Physics Institute, Yerevan, Armenia

a Deceased.
b Also at Department of Physics, King’s College London, London, United Kingdom.
c Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
d Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
e Also at TRIUMF, Vancouver, British Columbia, Canada.
f Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
g Also at Department of Physics, California State University, Fresno, California, USA.
h Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
i Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.
j Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
k Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
l Also at Universita di Napoli Parthenope, Napoli, Italy.
m Also at Institute of Particle Physics (IPP), Canada.

Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.
Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.
Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
Also at Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Borough of Manhattan Community College, City University of New York, New York, USA.
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
Also at Louisiana Tech University, Ruston, Louisiana, USA.
Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.
Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
Also at Graduate School of Science, Osaka University, Osaka, Japan.
Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
Also at Near East University, Nicosia, North Cyprus, Mersin, Turkey.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
Also at CERN, Geneva, Switzerland.
Also at Department of Physics, Stanford University, USA.
Also at Manhattan College, New York, New York, USA.
Also at Hellenic Open University, Patras, Greece.
Also at The City College of New York, New York, New York, USA.
Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain.
Also at Department of Physics, California State University, Sacramento, California, USA.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.