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)

(Received 13 June 2018; revised manuscript received 6 August 2018; published 12 October 2018)

This Letter presents a novel way to test different models of the interference between \( t\bar{t} \) and \( t\bar{b}W \), 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

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

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 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.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI. Funded by SCOAP\(^3\).
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 $\eta$ satisfying $|\eta| < 2.47$ (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-2.2.1 and the 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 $t\bar{t} + tWb$ 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-BOX-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 $m_{bW} \sim m_t$. 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 ($e^\pm e^\mp$, $\mu^\pm \mu^\mp$, $e^\pm \mu^\mp$). Events with a same-flavor lepton pair having invariant mass $m_{\ell\ell} < 10$ 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 $t\bar{t} + tWb$ signal process. The dominant background at high $m_{b\bar{b}}^{\text{minmax}}$ 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 $m_{b\bar{b}}^{\text{minmax}}$ 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 $m_{\ell\ell}$ 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 $t\bar{t} + tWb$ signal
FIG. 1. (a) The $m_{\text{HF}}^{\text{minimax}}$ distribution in the three-$b$-tag region, constructed from the two $b$-jets with largest $p_T$. The predicted $t\bar{t} +$ 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. (b) The detector-level $m_{\text{HF}}^{\text{minimax}}$ distribution, with signal selection and background estimation as described in the text. The total predicted events are shown for both the DR and DS definitions of the $tW$ process, with uncertainties on the respective estimates indicated by separate error bars. Uncertainties include all statistical and systematic sources. The rightmost bin of each distribution includes contributions from events beyond the displayed axis limit.

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 $m_{\ell\ell}$ 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 $m_{\text{HF}}^{\text{minimax}}$ 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 $m_{\text{HF}}^{\text{minimax}}$, 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 $m_{\text{HF}}^{\text{minimax}} > 160$ 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 $m_{\text{HF}}^{\text{minimax}} \gtrsim m_t$ than the DS scheme. However, the DS scheme better models the $m_{\text{HF}}^{\text{minimax}}$ shape over the same range of values. The DR and DS predictions generally bracket the data in the region of large $m_{\text{HF}}^{\text{minimax}}$, 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.
The results are presented as a normalized fiducial differential cross section, giving constraints on predictions for the full $t\bar{t} + tWb$ process.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNISW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Sklodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [78].


[50] F. Cascioli, P. Maierhöfer, N. Moretti, S. Pozzorini, and F. Siegert, NLO matching for \( t\bar{t}b\bar{b} \) production with massive \( b \)-quarks, Phys. Lett. B 734, 210 (2014).


[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.


[62] ATLAS Collaboration, Measurements of fiducial cross-sections for \( t\bar{t} \) production with one or two additional \( b \)-jets in \( pp \) collisions at \( \sqrt{s} = 8 \) TeV using the ATLAS detector, Eur. Phys. J. C 76, 11 (2016).

[63] ATLAS Collaboration, Search for the Standard Model Higgs boson produced in association with top quarks and decaying into a \( b\bar{b} \) pair in \( pp \) collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS detector, Phys. Rev. D 97, 072016 (2018).

[64] CMS Collaboration, Measurement of the cross section ratio \( \sigma_{bb}/\sigma_{tt} \) in \( pp \) collisions at \( \sqrt{s} = 8 \) TeV, Phys. Lett. B 746, 132 (2015).

[65] CMS Collaboration, Measurements of \( t\bar{t} \) cross sections in association with \( b \) jets and inclusive jets and their ratio using dilepton final states in \( pp \) collisions at \( \sqrt{s} = 13 \) TeV, Phys. Lett. B 776, 355 (2018).

[66] CMS Collaboration, Search for \( t\bar{t}H \) production in the \( H \rightarrow b\bar{b} \) 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 \( ep \) 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 $m_{T_{\mu\tau}}^{\min}$. 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.
(ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4aDepartment of Physics, Ankara University, Ankara, Turkey
4bIstanbul Aydin University, Istanbul, Turkey
4cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
6High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
7Department of Physics, University of Arizona, Tucson, Arizona, USA
8Department of Physics, University of Texas at Arlington, Arlington, Texas, USA
9Physics Department, National and Kapodistrian University of Athens, Athens, Greece
10Physics Department, National Technical University of Athens, Zografou, Greece
11Department of Physics, University of Texas at Austin, Austin, Texas, USA
12Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
12bIstanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
12cDepartment of Physics, Bogazici University, Istanbul, Turkey
12dDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
13Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
14Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
15Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
15aPhysics Department, Tsinghua University, Beijing, China
15cDepartment of Physics, Nanjing University, Nanjing, China
15dUniversity of Chinese Academy of Science (UCAS), Beijing, China
16Department of Physics, University of Belgrade, Belgrade, Serbia
17Department for Physics and Technology, University of Bergen, Bergen, Norway
18Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
19Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
20Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
21School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
22Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
23aDipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
23bINFN Sezione di Bologna, Bologna, Italy
24Physikalisches Institut, Universität Bonn, Bonn, Germany
25Department of Physics, Boston University, Boston, Massachusetts, USA
26Department of Physics, Brandeis University, Waltham, Massachusetts, USA
27aTransilvania University of Brasov, Brasov, Romania
27bHoria Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
27cDepartment of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
27dNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
27eUniversity Politehnica Bucharest, Bucharest, Romania
27fWest University in Timisoara, Timisoara, Romania
28aFaculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
28bDepartment of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
66Dipartimento di Fisica, Università di Milano, Milano, Italy
67INFN Sezione di Napoli, Napoli, Italy
68Dipartimento di Fisica, Università di Napoli, Napoli, Italy
69INFN Sezione di Pavia, Pavia, Italy
70INFN Sezione di Pisa, Pisa, Italy
71Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
72INFN Sezione di Roma, Roma, Italy
73INFN Sezione di Roma Tor Vergata, Roma, Italy
74Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
75INFN Sezione di Roma Tre, Roma, Italy
76Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
77INFN-TIFPA, Trento, Italy
78AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
79Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
80Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
81Joint Institute for Nuclear Research, Dubna, Russia
82Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJJ), Juiz de Fora, Brazil
83Universidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
84Instituto Federal de Educação, Ciência e Tecnologia de São Paulo, São Paulo, Brazil
85KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
86AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
87Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
88Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
89Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
90Physics Department, Lancaster University, Lancaster, United Kingdom
91Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
92Institut für Physik, Universität Mainz, Mainz, Germany
93CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
94School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
95School of Physics, University of Melbourne, Victoria, Australia
96Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
97P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
98Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
99Department of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
100Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
101Department of Physics, McGill University, Montreal, Quebec, Canada
102School of Physics, University of Melbourne, Victoria, Australia
103Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
104Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
105Faculty of Physics, Ludwig-Maximilians-Universität München, München, Germany
106Department of Physics, University of Kentucky, Lexington, Kentucky, USA
107P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
108School of Physics, University of Melbourne, Victoria, Australia
109Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
110National Research Nuclear University MEPhI, Moscow, Russia
111D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
112CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
113Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

152002-17
TRIUMF, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada

Division of Physics and Tonomaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA

Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Department of Physics, University of Illinois, Urbana, Illinois, USA

Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, Connecticut, USA

Yerevan Physics Institute, Yerevan, Armenia

\(^{165a}\)Deceased.

\(^{165b}\)Also at Department of Physics, King’s College London, London, United Kingdom.

\(^{165c}\)Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.

\(^{165d}\)Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

\(^{165e}\)Also at TRIUMF, Vancouver, British Columbia, Canada.

\(^{165f}\)Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

\(^{165g}\)Also at Department of Physics, California State University, Fresno, California, USA.

\(^{165h}\)Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

\(^{165i}\)Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.

\(^{165j}\)Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

\(^{165k}\)Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

\(^{165l}\)Also at Universita di Napoli Parthenope, Napoli, Italy.

\(^{165m}\)Also at Institute of Particle Physics (IPP), Canada.

\(^{165n}\)Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.

\(^{165o}\)Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.

\(^{165p}\)Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

\(^{165q}\)Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.

\(^{165r}\)Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

\(^{165s}\)Also at Borough of Manhattan Community College, City University of New York, New York, USA.

\(^{165t}\)Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

\(^{165u}\)Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

\(^{165v}\)Also at Louisiana Tech University, Ruston, Louisiana, USA.

\(^{165w}\)Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

\(^{165x}\)Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.

\(^{165y}\)Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.

\(^{165z}\)Also at Graduate School of Science, Osaka University, Osaka, Japan.

\(^{166a}\)Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

\(^{166b}\)Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

\(^{166c}\)Also at Near East University, Nicosia, North Cyprus, Nicosia, Cyprus.

\(^{166d}\)Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

\(^{166e}\)Also at CERN, Geneva, Switzerland.

\(^{166f}\)Also at Department of Physics, Stanford University, USA.

\(^{166g}\)Also at Department of Physics, University of Chicago, Chicago, USA.

\(^{166h}\)Also at Hellenic Open University, Patras, Greece.

\(^{166i}\)Also at The City College of New York, New York, New York, USA.

\(^{166j}\)Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain.

\(^{166k}\)Also at Department of Physics, California State University, Sacramento, California, USA.

\(^{166l}\)Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

\(^{166m}\)Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
Also at National Research Nuclear University MEPhI, Moscow, Russia.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.