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Search for Heavy Higgs Bosons $A/H$ Decaying to a Top Quark Pair in $pp$ Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

M. Aaboud et al.
(ATLAS Collaboration)
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A search for heavy pseudoscalar ($A$) and scalar ($H$) Higgs bosons decaying into a top-antitop quark pair ($t\bar{t}$) has been performed with 20.3 fb$^{-1}$ of proton-proton collision data collected by the ATLAS experiment at the Large Hadron Collider at a center-of-mass energy $\sqrt{s} = 8$ TeV. Interference effects between the signal process and standard model $t\bar{t}$ production, which are expected to distort the signal shape from a single peak to a peak-dip structure, are taken into account. No significant deviation from the standard model prediction is observed in the $t\bar{t}$ invariant mass spectrum in final states with an electron or muon, large missing transverse momentum, and at least four jets. The results are interpreted within the context of a type-II two-Higgs-doublet model. Exclusion limits on the signal strength are derived as a function of the mass $m_{A/H}$ and the ratio of the vacuum expectation values of the two Higgs fields, $\tan\beta$, for $m_{A/H} > 500$ GeV.

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Introduction.—The production of new particles at the Large Hadron Collider (LHC) with masses close to the TeV scale is predicted by many models of physics beyond the standard model (SM). In this Letter, a search for massive pseudoscalar and scalar resonances decaying into a top-antitop quark pair ($t\bar{t}$) is presented. It is the first search in this final state to take into account the significant interference between the signal and the background from SM $t\bar{t}$ production. The search is conducted on a sample of $pp$ collision data with an integrated luminosity of 20.3 fb$^{-1}$ at a center-of-mass energy $\sqrt{s} = 8$ TeV, collected with the ATLAS detector [1].

New pseudoscalar ($A$) and scalar ($H$) states coupling strongly to $t\bar{t}$ are predicted by a class of models in which the Higgs sector is extended to include a second Higgs doublet, the two-Higgs-doublet models (2HDMs) [2]. These models are motivated by many theories beyond the SM, such as supersymmetry [3–8] and axion models [9]. In 2HDMs of type II [2], such as the minimal supersymmetric standard model (MSSM) [10–14], these states decay predominantly into $t\bar{t}$ pairs if $m_{A/H} \geq 500$ GeV and the ratio of the vacuum expectation values of the two Higgs fields, $\tan\beta$, is small ($\tan\beta \lesssim 3$).

To date, this parameter region has not been probed directly by searches in other final states [15–20] or by previous searches for $t\bar{t}$ resonances [21–25]. The latter, which aim to identify resonant excesses in the $t\bar{t}$ invariant mass ($m_{t\bar{t}}$) spectrum, have a reduced sensitivity to 2HDM signatures as they do not take into account interference effects between the signal and the dominant background from SM $t\bar{t}$ production. These are significant for (pseudo) scalar Higgs bosons with masses above the $t\bar{t}$ production threshold where the interference between the gluon-gluon ($gg$) initiated loop production and the irreducible background from SM $t\bar{t}$ production yields a non-negligible imaginary term in the amplitude, which at the LHC is dominated by $gg \rightarrow t\bar{t}$ production [26–31]. As a result of the interference, the signal shape is distorted from a Breit-Wigner peak to a peak-dip structure.

The results of the search are interpreted in a $CP$-conserving type-II 2HDM with a softly broken $Z_2$ symmetry [32]. The lighter of the two neutral $CP$-even states, $h$, is assumed to be the Higgs boson discovered at a mass of $m_h = 125$ GeV [33,34] with couplings as predicted by the SM. This corresponds to the condition $\sin(\alpha - \beta) = 1$, referred to as the alignment limit, where $\alpha$ denotes the mixing angle between the two $CP$-even states. The parameter $m_{12}$ of the $Z_2$ breaking term of the potential is taken to be $m_{12}^2 = m_A^2 \tan\beta/(1 + \tan^2\beta)$. In this model, the production cross sections and widths of $A$ and $H$, as well as the signal shape, are determined by $\tan\beta$ and the masses $m_A$ and $m_H$. The search results are derived assuming mass degeneracy, $m_H = m_A$, such that both processes contribute to the $m_{t\bar{t}}$ spectrum, a scenario motivated, for example, by the MSSM [32]. We also consider two scenarios in which only the interference pattern of either $A$ or $H$ appears in the $m_{t\bar{t}}$ spectrum [35].

Data and Monte Carlo samples.—This analysis closely follows the resolved-topology analysis in Ref. [22]. Events with signatures compatible with $t\bar{t} \rightarrow W^+bW^−\bar{b}$, with one
The signal process $gg \rightarrow A/H \rightarrow t\bar{t}$, including the decays of the top quarks and resulting $W$ bosons, was simulated using MadGraph5_aMC@NLO [38] v2.3.3 with the model of Ref. [39], which implements the $A/H$ production through loop-induced gluon-gluon fusion with loop contributions from top and bottom quarks at leading order (LO) in QCD. The CT10 set [40] of parton distribution functions (PDFs) was used and the renormalization and factorization scales were set to $\sqrt{\sum p_T^2} + m^2$.

For the statistical interpretation, the $t\bar{t}$ invariant mass distributions in the signal regions in data were compared to a combination of the expected distributions from all background processes $B$, the pure signal process $S$, and the signal-plus-interference component $S + I$ for a given signal hypothesis, as illustrated in Eq. (1) below. The most reliable description of the $t\bar{t}$ background [41] is obtained at next-to-leading order (NLO) with PowHEG-Box [42–45] + Pythia6 [46]. Therefore, the $S + I$ contribution was modeled separately from this background process by modifying the MadGraph5_aMC@NLO software to remove the pure SM $t\bar{t}$ process to yield only the $S + I$ contribution on an event-by-event basis. The nominal $t\bar{t}$ background prediction in $m_{t\bar{t}}$ is in good agreement with that obtained from MadGraph5_aMC@NLO in all signal regions. The $S + I$ events obtained with the modified software can have positive or negative weights. Figure 1 shows the $t\bar{t}$ invariant mass distributions for the $S$ and $S + I$ components in a model with $\tan\beta = 0.68$ and a pseudoscalar of mass $m_A = 500$ GeV. The $S + I$ component exhibits a peak-dip structure with the minimum around $m_{A/H}$ for all signal hypotheses studied in this search. The width of both the $S$ and $S + I$ distribution decreases with increasing $\tan\beta$.

The $S + I$ distributions from the modified MadGraph5_aMC@NLO software were validated against those from the unmodified program. The latter were obtained by generating a large inclusive sample $S + I + B_{\bar{t}}$ for a given parameter point and a LO SM $t\bar{t}$ background $B_{t\bar{t}}$ sample with the same generator settings. The difference between the resulting two $m_{t\bar{t}}$ distributions corresponds to the $S + I$ component, which agrees with that obtained with the modified software within 0.4% across the whole spectrum. The difference is taken as a systematic uncertainty in $S + I$.

Pythia6 with the Perugia 2011c set of tuned parameters [47] was used to model the parton shower and hadronization for all $S$ and $S + I$ samples and the stable particles obtained after hadronization were passed through the ATLAS fast detector simulation [48]. The effects of additional collisions within the same or nearby bunch crossings were simulated by overlaying additional $pp$ collisions, simulated with Pythia V8.1 [49], on each event. Correction factors were applied to adjust the trigger and selection efficiencies in simulated events to those measured in data. The $S$ and $S + I$ samples with this setup were generated separately for pseudoscalar and scalar Higgs bosons.

Event samples for both the $S$ and $S + I$ components for different values of $(m_{A/H}, \tan\beta)$ were obtained from signal samples $S$ after the detector simulation by applying an event-by-event reweighting. This reweighting substantially reduces the computing time required. The weight is the ratio of the MadGraph5_aMC@NLO matrix elements, calculated from the four-momenta of the incoming gluons and outgoing top quarks of the generated event with the new and the old values of $(m_{A/H}, \tan\beta)$, respectively. All $S + I$ and a small number of $S$ samples were obtained through reweighting. Signal hypotheses with $m_{A/H} < 500$ GeV were not considered as they require an accurate modeling of the Higgs boson decay into virtual top quarks and the implementation of higher-order corrections that are not available in the MadGraph5_aMC@NLO model. The requirement $\tan\beta \geq 0.4$ was imposed to ensure the perturbativity of the top-quark Yukawa coupling [2].

Correction factors $K_s$ were applied to normalize the generated signal ($S$) cross section to the value calculated at partial next-to-next-to-leading-order (NNLO) precision in
QCD [50–52]. The correction factor for the interference component \( I \) is \( K_I = \sqrt{K_S \times K_B} \), as suggested in Ref. [53], where \( K_B = 1.87 \) is the correction factor to normalize the total cross section of the SM \( t \bar{t} \) background generated at LO with MADGRAPH to the cross section calculated at NNLO accuracy in the strong coupling constant \( \alpha_s \), including resummation of next-to-next-to-leading-logarithmic soft gluon terms. The values of \( K_S \) range between two and three for the tested signal hypotheses.

Event selection.—The event selection criteria for the signal regions provide a high selection efficiency for \( t \bar{t} \) events. Only events with a resolved topology, in which the three jets from the hadronically decaying top quark are well separated in the detector, are selected. This is the most efficient selection strategy for signal hypotheses with \( m_A = H < 800 \text{ GeV} \). Events with a merged topology, in which the top quark is reconstructed as a single jet, are not considered. The event reconstruction and selection criteria are identical to those in Ref. [22] except that events that would satisfy the criteria for both topologies are classified as “resolved” instead of “merged.”

Events are required to contain exactly one isolated electron [54] or muon [55] with \( p_T > 25 \text{ GeV} \) and pseudorapidity \( |\eta| < 2.5 \) [56]. Events must have large missing transverse momentum, \( E_T^{\text{miss}} > 20 \text{ GeV} \), computed as the magnitude of the negative vector sum of lepton and jet transverse momenta [57]. In addition, \( E_T^{\text{miss}} + m_W > 60 \text{ GeV} \) is required to further suppress the contribution from multijet events, where \( m_W \) is the lepton–jet transverse mass [22]. Events must contain at least 100 hadronic jets with \( p_T > 25 \text{ GeV} \) and \( |\eta| < 2.5 \), reconstructed using the anti-\( k_T \) algorithm [58,59] with radius parameter \( R = 0.4 \). Jets from additional collisions in the same bunch crossing are rejected using dedicated tracking and vertex requirements [60]. At least one of the jets must be identified as originating from the decay of a light-hadron (jet) using a multivariate tagging algorithm with a 70% efficiency for b-jets and light-quark and gluon mistag rates of 0.5%–2% [61].

Event reconstruction.—Jets are assigned to the top quarks using a \( \chi^2 \) algorithm that relies on kinematic constraints and the expected values of the top quark and W boson masses [22]. The invariant mass \( m_{t\bar{t}}^{\text{reco}} \) of the candidate \( t\bar{t} \) pair is reconstructed from the four selected jets, the lepton, and the \( E_T^{\text{miss}} \) vector. The experimental resolution for the \( t\bar{t} \) invariant mass is 8% for \( m_{A/H} = 500 \text{ GeV} \). Events in the \( e + \) jets and \( \mu + \) jets channels are classified into three categories, based on whether a b-tagged jet was assigned to either the hadronically or the semileptonically decaying top quark, or to both of them. Each category defines a signal region; hence six orthogonal signal regions are used in the statistical analysis.

Systematic uncertainties.—The impact of the systematic uncertainties on both the normalization and the shape of the \( m_{t\bar{t}}^{\text{reco}} \) distributions is taken into account. The average impact of the dominant uncertainties on the event yields is summarized in Table I.

The experimental uncertainties with the largest impact on the event yields and the shape of the \( m_{t\bar{t}}^{\text{reco}} \) distributions are those related to the jet energy scale (JES) and the jet energy resolution (JER) [63,64], followed by uncertainties on the b-tagging efficiency and misidentification rates [61]. The uncertainties related to leptons include those in the reconstruction and isolation efficiency, the single-lepton triggers, and the energy scale and resolution [54,55].

The uncertainty of 6.5% in the NNLO + NNLQ cross section for SM \( t\bar{t} \) production is the dominant uncertainty in the total background normalization [22]. Modeling uncertainties affecting the shape of the \( m_{t\bar{t}}^{\text{reco}} \) distribution for the SM \( t\bar{t} \) background are also taken into account. These uncertainties are expressed as an uncertainty in the yield and are shown. Dots (⋯) indicate that an uncertainty is not applicable to a sample.

**Table I.** Average impact of the dominant uncertainties on the estimated yields for the total background and for a pseudoscalar \( A \) at a mass of 500 GeV and \( \tan \beta = 0.68 \) in percent of the nominal value for all signal regions combined. Only uncertainties with a yield impact > 0.5% are shown. Dots (⋯) indicate that an uncertainty is not applicable to a sample.

<table>
<thead>
<tr>
<th>Systematic uncertainties [%]</th>
<th>Total background</th>
<th>( S )</th>
<th>( S + I )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity [62]</td>
<td>1.7</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>PDF</td>
<td>2.5</td>
<td>2.1</td>
<td>12</td>
</tr>
<tr>
<td>( t\bar{t} ) initial-final state radiation</td>
<td>3.2</td>
<td>⋯</td>
<td>⋯</td>
</tr>
<tr>
<td>( t\bar{t} ) parton shower + fragmentation</td>
<td>4.9</td>
<td>⋯</td>
<td>⋯</td>
</tr>
<tr>
<td>( t\bar{t} ) normalization</td>
<td>5.7</td>
<td>⋯</td>
<td>⋯</td>
</tr>
<tr>
<td>( t\bar{t} ) event generator</td>
<td>0.5</td>
<td>⋯</td>
<td>⋯</td>
</tr>
<tr>
<td>Top quark mass</td>
<td>0.5</td>
<td>2.2</td>
<td>13</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>6.4</td>
<td>4.9</td>
<td>9.3</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>1.3</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td>b-tagging: b-jet efficiency</td>
<td>1.5</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>b-tagging: c-jet efficiency</td>
<td>0.2</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Electron efficiency</td>
<td>0.3</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Muon efficiency</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Signal MC scales</td>
<td>⋯</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Reweighting</td>
<td>⋯</td>
<td>⋯</td>
<td>5.0</td>
</tr>
<tr>
<td>MC statistical uncertainty</td>
<td>0.5</td>
<td>2.4</td>
<td>11</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>11</td>
<td>10</td>
<td>25</td>
</tr>
</tbody>
</table>
include uncertainties related to the choice of NLO event generator, the modeling of the parton shower and fragmentation, the modeling of gluon initial- and final-state radiation, and the value of the top quark mass \( m_t \). Other sources of uncertainty related to the various background components are described in Ref. [22].

The largest uncertainty in the modeling of the \( S + I \) and \( S \) components is related to the \( \mu \) value of 172.5 GeV [65]. Uncertainties related to the choice of PDF set and renormalization and factorization scales are also considered. The latter is estimated by varying the scales by factors of 0.5 and 2.0, which yields a constant \( \pm 7.3\% \) variation across the \( m_{\tilde{t}}^{\text{reco}} \) spectrum. An asymmetric variation, for which the bins at the low and high ends of the \( m_{\tilde{t}}^{\text{reco}} \) spectrum are taken as anticorrelated [66] is also considered to estimate the impact of the scale variations on the shape of the \( m_{\tilde{t}}^{\text{reco}} \) spectrum. For the \( S + I \) samples, an additional constant \( \pm 5\% \) uncertainty is included to cover the difference between reweighted and generated distributions.

Results.—A breakdown of the observed and expected event yields in the \( e + \text{jets} \) and \( \mu + \text{jets} \) channels and their total uncertainties is shown in Table II. Good agreement is found between the observed number of events in data and the expected total number of background events.

The exclusion limits are derived separately for each signal hypothesis from a profile-likelihood fit [67] of the expected \( m_{\tilde{t}}^{\text{reco}} \) distributions to the observed ones simultaneously in all signal regions, taking the statistical and systematic uncertainties into account as nuisance parameters [22]. Only bins with \( m_{\tilde{t}}^{\text{reco}} > 320 \) GeV are considered to avoid threshold effects not well described by the simulation. The shape of the binned \( m_{\tilde{t}}^{\text{reco}} \) distributions is parametrized in terms of the signal strength \( \mu \) [26,27]:

\[
\mu S + \sqrt{\mu} I + B = (\mu - \sqrt{\mu}) S + \sqrt{\mu} (S + I) + B. \tag{1}
\]

The fitted variable is \( \sqrt{\mu} \) and the case \( \mu = 1 \) (\( \mu = 0 \)) corresponds to the type-II 2HDM in the alignment limit (the background-only hypothesis). This approach relies on the assumption that, for a given signal hypothesis, the shape of the \( \tilde{t} \) invariant mass distributions for \( S \) and \( S + I \) in Eq. (1) does not change with \( \mu \). The terms \( S \) and \( S + I \) on the right-hand side of Eq. (1) correspond to the \( m_{\tilde{t}}^{\text{reco}} \) distributions obtained from the \( S \) and \( S + I \) samples, respectively, while \( B \) stands for the expected \( m_{\tilde{t}}^{\text{reco}} \) distribution of the total background.

The level of agreement between the observed and expected mass spectra is quantified in a fit under the background-only hypothesis in which only the nuisance parameters are allowed to vary. The observed \( m_{\tilde{t}}^{\text{reco}} \) spectra are compatible with the postfit expected spectra within the (constrained) uncertainty bands (Fig. 2).

The upper limits on \( \mu \) at 95% confidence level (C.L.) are obtained with the C.L.s method [68] for a number of \( \langle m_{A/\mu}, \tan \beta \rangle \) values. The upper limits at intermediate points are obtained from a linear interpolation among

FIG. 3. The 95% C.L. observed and expected exclusion regions for the type-II 2HDM (\( \mu = 1 \)) considering only a pseudoscalar \( A \) (left), only a scalar \( H \) (middle), and the mass-degenerate scenario \( m_A = m_H \) (right). Blue points indicate parameter values at which signal samples are produced.
the three closest points. In Fig. 3, the observed and expected exclusion regions for the type-II 2HDM ($\mu = 1$) are shown for the three scenarios discussed in the Introduction. The excluded values of $\tan \beta$ for the different mass hypotheses are listed in Table III.

Conclusion.—In conclusion, the search for massive pseudoscalar and scalar resonances decaying to $t \bar{t}$ in 20.3 fb$^{-1}$ of $pp$ collisions at 8 TeV recorded by the ATLAS experiment yields no statistically significant deviations from the SM prediction. The results are interpreted in a type-II 2HDM in the alignment limit, and upper limits are set on the signal strength $\mu$ at 95% C.L. in the $m_{A/H}$ versus $\tan \beta$ plane. Unlike previous searches for $t \bar{t}$ resonances, this analysis takes into account interference effects between the signal process and the background from SM $t \bar{t}$ production. It tightens significantly the previously published constraints on the 2HDM parameter space in the low $\tan \beta$ and high mass ($m_{A/H} > 500$ GeV) region.

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[56] The ATLAS experiment uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as η = −ln[tan(θ/2)]. Transverse momenta are computed from the three-momenta, pt, as pt = |p| sin θ.

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
4Department of Physics, Ankara University, Ankara, Turkey
4aIstanbul Aydin University, Istanbul, Turkey
4bDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4cLAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
5High Energy Physics Division, Argonne National Laboratory, Argonne Illinois, USA
6Department of Physics, University of Arizona, Tucson Arizona, USA
7Department of Physics, The University of Texas at Arlington, Arlington Texas, USA
8Physics Department, National and Kapodistrian University of Athens, Athens, Greece
9Physics Department, National Technical University of Athens, Zografou, Greece
10Department of Physics, The University of Texas at Austin, Austin Texas, USA
11Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
13Institute of Physics, University of Belgrade, Belgrade, Serbia
14Department for Physics and Technology, University of Bergen, Bergen, Norway
15Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley California, USA
16Department of Physics, Humboldt University, Berlin, Germany
17Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
20Department of Physics, Bogazici University, Istanbul, Turkey
21Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
22Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul University, Turkey
23Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

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21 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
22 INFN Sezione di Bologna, Italy
23 Physikalisches Institut, University of Bonn, Bonn, Germany
24 Department of Physics, Boston University, Boston Massachusetts, USA
25 Department of Physics, Brandeis University, Waltham Massachusetts, USA
26 Universidad Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
27 Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
28 Federal University of Sao Joao del Rei (UFJS), Sao Joao del Rei, Brazil
29 Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
29 Physics Department, Brookhaven National Laboratory, Upton New York, USA
29 Transilvania University of Brasov, Brasov, Romania
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29 Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
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33 Enrico Fermi Institute, University of Chicago, Chicago Illinois, USA
34 Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago, Chile
34a Departamento de Fisica, Universidad Técnica Federico Santa Maria, Valparaíso, Chile
34b Department of Physics, Nanjing University, Jiangsu, China
34c Physics Department, Tsinghua University, Beijing 100084, China
34d Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui, China
34e School of Physics, Shandong University, Shandong, China
34f AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
34g Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
34h Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
34i Physics Department, Southern Methodist University, Dallas Texas, USA
34j Physics Department, University of Texas at Dallas, Richardson Texas, USA
34k DESY, Hamburg and Zeuthen, Germany
34l Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
34m Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
34n Department of Physics, Duke University, Durham North Carolina, USA
34o SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
34p INFN e Laboratori Nazionali di Frascati, Frascati, Italy
34q Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
35 Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland
35a INFN Sezione di Genova, Italy
35b Dipartimento di Fisica, Università di Genova, Genova, Italy
35c E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
35d High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
35e II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
35f SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
35g II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
35h Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
35i Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge Massachusetts, USA
Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Graduate School of Science, Osaka University, Osaka, Japan.
Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.
Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
Also at CERN, Geneva, Switzerland.
Also at Georgian Technical University (GTU), Tbilisi, Georgia.
Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
Also at Manhattan College, New York NY, USA.
Also at Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile.
Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
Also at The City College of New York, New York NY, USA.
Also at School of Physics, Shandong University, Shandong, China.
Also at Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada, Portugal.
Also at Department of Physics, California State University, Sacramento CA, USA.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland.
Also at Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.
Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
Also at National Research Nuclear University MEPhI, Moscow, Russia.
Also at Department of Physics, Stanford University, Stanford CA, USA.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at Giresun University, Faculty of Engineering, Turkey.
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
Also at Department of Physics, Nanjing University, Jiangsu, China.
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.