Search for new phenomena in $t\bar{t}$ events with large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ with the ATLAS detector


DOI
10.1103/PhysRevLett.108.041805

Publication date
2012

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Search for New Phenomena in $t\bar{t}$ Events with Large Missing Transverse Momentum in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad et al. *

(ATLAS Collaboration)

(Received 22 September 2011; published 26 January 2012)

A search for new phenomena in $t\bar{t}$ events with large missing transverse momentum in proton-proton collisions at a center-of-mass energy of 7 TeV is presented. The measurement is based on 1.04 fb$^{-1}$ of data collected with the ATLAS detector at the LHC. Contributions to this final state may arise from a number of standard model extensions. The results are interpreted in terms of a model where new top-quark partners are pair-produced and each decay to an on-shell top (or antitop) quark and a long-lived undetected neutral particle. The data are found to be consistent with standard model expectations. A limit at 95% confidence level is set excluding a cross section times branching ratio of 1.1 pb for a top-partner mass of 420 GeV and a neutral particle mass less than 10 GeV. In a model of exotic fourth generation quarks, top-partner masses are excluded up to 420 GeV and neutral particle masses up to 140 GeV.

DOI: 10.1103/PhysRevLett.108.041805

PACS numbers: 14.65.Jk, 12.60.−i, 13.85.Rm

The top quark holds great promise as a probe for new phenomena at the TeV scale. It has the strongest coupling to the standard model Higgs boson, and as a consequence it is the main contributor to the quadratic divergence in the Higgs boson mass. Thus, assuming the “naturalness” hypothesis of effective quantum field theory, light top partners (with masses below about 1 TeV) should correspond to one of the most robust predictions of solutions to the hierarchy problem.

In this Letter, a search is presented for pair-produced exotic top partners $T\bar{T}$, each decaying to a top quark and a stable, neutral weakly interacting particle $A_0$, which in some models may be its own antiparticle. The final state for such a process ($T\bar{T} \rightarrow t\bar{t}A_0A_0$) is identical to $t\bar{t}$, though with a larger amount of missing transverse momentum ($E_T^{\text{miss}}$) from the undetected $A_0$ pair. In supersymmetry models with $R$-parity conservation, $T$ is identified with the stop squark and $A_0$ with the lightest supersymmetric particle, the neutralino ($\chi_0$) [1] or the gravitino ($\tilde{G}$) [2]. The $t\bar{t} + E_T^{\text{miss}}$ [3] signature appears in a general set of dark matter motivated models, as well as in other standard model (SM) extensions, such as the above-mentioned supersymmetry models, little Higgs models with $T$-parity conservation [4–6], models of universal extra dimensions (UED) with Kaluza-Klein parity [7], models in which baryon and lepton number conservation arises from gauge symmetries [8], or models with third-generation scalar leptoquarks. Many of these models provide a mechanism for electroweak symmetry breaking and predict dark matter candidates, which can be identified indirectly through their large $E_T^{\text{miss}}$ signature.

The search is performed in the $t\bar{t}$ single-lepton channel where one $W$ boson produced by the top pair decays to a lepton-neutrino pair ($W \rightarrow l\nu$, including $\tau$ decays to $e$ or $\mu$) and the other $W$ boson decays to a pair of quarks ($W \rightarrow q\bar{q}'$), resulting in a final state with an isolated lepton of high transverse momentum, four or more jets, and large $E_T^{\text{miss}}$. The observed yield in this signal region is compared with standard model expectations. A 95% confidence level limit on the cross-section times branching ratio $BR(T\bar{T} \rightarrow t\bar{t}A_0A_0)$ is quoted. In the model of exotic fourth generation up-type quarks [9] the $T\bar{T}$ production cross section is predicted to be approximately 6 times higher than for stop squarks with a similar mass [3], due to the multiple spin states of two $T$’s compared to scalar stops. For this model the cross-section limits are converted to an exclusion curve in the $T$ vs $A_0$ mass parameter space. A search for these exotic top-quark partners was performed in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV by the CDF Collaboration [10]. The data were found to be consistent with SM expectations. A 95% confidence level limit was set excluding a top-partner mass of 360 GeV for a neutral particle mass less than 100 GeV. A recent update by CDF in the all-jets channel excludes top-partner masses up to 400 GeV [11].

The ATLAS detector [12] consists of an inner detector tracking system (ID) surrounded by a superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID consists of pixel and silicon microstrip detectors inside a transition radiation tracker which provide tracking in the region $|\eta| < 2.5$ [13]. The electromagnetic calorimeter is a lead-liquid argon (LAr) detector in the barrel ($|\eta| < 1.475$) and end cap ($1.375 < |\eta| < 3.2$) regions. Hadron calorimetry is based on two different detector technologies.

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

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
The barrel ($|\eta| < 0.8$) and extended barrel ($0.8 < |\eta| < 1.7$) calorimeters are composed of scintillator and steel, while the hadronic end cap calorimeters ($1.5 < |\eta| < 3.2$) are copper and LAr. The forward calorimeters ($3.1 < |\eta| < 4.9$) are instrumented with copper and LAr and tungsten and LAr, providing electromagnetic and hadronic energy measurements, respectively. The MS consists of three large superconducting toroids with 24 coils, a system of trigger chambers, and precision tracking chambers which provide muon momentum measurements up to $|\eta|$ of 2.7.

The analysis is based on data recorded by the ATLAS detector in 2011 using $1.04 \text{ fb}^{-1}$ of integrated luminosity. The data were collected using electron and muon triggers. Requirements that ensure the quality of beam conditions, detector performance, and data are imposed. Monte Carlo (MC) event samples with full ATLAS detector simulation [14] based on the GEANT4 program [15] and corrected for all known detector effects are used to model the signal process and most of the backgrounds. The multijet background is modeled using data control samples rather than the simulation. The background sources are separated into four main categories according to their importance: dilepton $t\bar{t}$ (where both $W$ bosons decay to a lepton-neutrino pair: $W \to \ell \nu$); single-lepton $t\bar{t}$ and $W + \text{jets}$; multijet production; and other electroweak processes, such as diboson production, single top, and $Z + \text{jets}$. The $t\bar{t}$ and single top samples are produced with MC@NLO [16], while the $W + \text{jets}$ and $Z + \text{jets}$ samples are generated with ALPGEN [17]. HERWIG [18] is used to simulate the parton shower and fragmentation, and JIMMY [19] is used for the underlying event simulation. The diboson background is simulated using HERWIG. The $t\bar{t}$ cross section is normalized to approximate next-to-next-to-leading order (NNLO) calculations [20], the inclusive $W + \text{jets}$ and $Z + \text{jets}$ cross sections are normalized to NNLO predictions [21], and the cross sections of the other backgrounds are normalized to NLO predictions [22]. Additional corrections to the MC predictions are extracted from the data, as described below.

Electron and muon candidates are selected as for other recent ATLAS top-quark studies using the single-lepton signature [23]. Jets are reconstructed using the anti-$k_T$ [24] algorithm with the distance parameter $R = 0.4$. To take into account the differences in calorimeter response to electrons and hadrons, a $p_T$- and $\eta$-dependent factor, derived from simulated events and validated with data, is applied to each jet to provide an average energy scale correction [25] corresponding to the energies of the reconstructed particles.

In the calorimeter, the energy deposited by particles is reconstructed in three-dimensional clusters. These clusters are calibrated according to the associated reconstructed high-$p_T$ object. The energy of these clusters is summed vectorially, and projections of this sum in the transverse plane correspond to the negative of the $E_T^{\text{miss}}$ components [26]. Clusters not associated with any high-$p_T$ object and muons reconstructed in the MS are also included in the $E_T^{\text{miss}}$ calculation.

Events are selected with exactly one isolated electron or muon that passes the following kinematic selection criteria. Electrons are required to satisfy $E_T > 25 \text{ GeV}$ and $|\eta| < 2.47$. Electrons in the region between the barrel and the end cap electromagnetic calorimeters ($1.37 < |\eta| < 1.52$) are removed. Muon candidates are required to satisfy $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$. These selected leptons lie in the efficiency plateau of the single-lepton triggers. Only events with four or more reconstructed jets with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$ are selected. To reduce the single-lepton $t\bar{t}$ and $W + \text{jets}$ background, events are required to have $E_T^{\text{miss}} > 100 \text{ GeV}$ and $m_T > 150 \text{ GeV}$, where $m_T$ is the transverse mass of the lepton and $E_T^{\text{miss}}$ [27]. Events with either a second lepton candidate with $p_T > 15 \text{ GeV}$ or a track with $p_T > 12 \text{ GeV}$, with no other tracks with $p_T > 3 \text{ GeV}$ within $\Delta R = 0.4$ ($\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$), are rejected in order to reduce the contribution from $t\bar{t}$ dilepton events. In particular, the isolated track veto is useful in reducing single-prong hadronic $\tau$ decays in $t\bar{t}$ dilepton events. A summary of the background estimates and a comparison with the observed number of selected events passing all selection criteria are shown in Table I. A total yield of $101 \pm 16$ events is expected from SM sources, and 105 events are observed in data. The background composition is similar in the electron and muon channels.

The dominant background arises from $t\bar{t}$ dilepton final states in which one of the leptons is not reconstructed, is outside the detector acceptance, or is a $\tau$ lepton. In all such cases, the $t\bar{t}$ decay products include two high-$p_T$ neutrinos, resulting in large $E_T^{\text{miss}}$ and $m_T$ tails. In MC simulation, the second lepton veto removes 45% of the dilepton $t\bar{t}$ and 10% of the single-lepton $t\bar{t}$ in the signal region. The veto performance is validated in the data in several control regions both enhanced and depleted in dilepton $t\bar{t}$. Based on the data-MC agreement in these control regions a 10% uncertainty is assigned to the veto efficiencies modeled in MC simulation.

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton $t\bar{t}$</td>
<td>$62 \pm 15$</td>
</tr>
<tr>
<td>Single-lepton $t\bar{t}/W + \text{jets}$</td>
<td>$33.1 \pm 3.8$</td>
</tr>
<tr>
<td>Multijet</td>
<td>$1.2 \pm 1.2$</td>
</tr>
<tr>
<td>Single top</td>
<td>$3.5 \pm 0.8$</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>$0.9 \pm 0.3$</td>
</tr>
<tr>
<td>Dibosons</td>
<td>$0.9 \pm 0.2$</td>
</tr>
<tr>
<td>Total</td>
<td>$101 \pm 16$</td>
</tr>
</tbody>
</table>

Data | 105
The next largest background comes from single-lepton sources, including $W +$ jets and $t\bar{t}$ with one leptonic $W$ decay. Both the normalization and the shape of the $m_T$ distribution for this combined background are extracted from the data. First, the yield of the single-lepton background estimated from simulation is normalized in the control region $60 \text{ GeV} < m_T < 90 \text{ GeV}$ to the data which gives a correction of $(-5 \pm 3\%)$. Next, the shape of the $m_T$ distribution in MC is compared with data in various signal-depleted control regions, where events satisfy the signal event selection but have fewer than four jets. In these control samples events with identified $b$ jets, based on lifetime $b$ tagging [23], are rejected in order to reduce the dilepton $t\bar{t}$ background, such that these control samples are dominated by $W +$ jets events; the corresponding loss of single-lepton $t\bar{t}$ from this $b$-jet veto is accounted for in the systematic uncertainties. A comparison between data and MC in this control region shows that MC systematically underestimates the tails of the $m_T$ distribution above $150 \text{ GeV}$, and a shape correction is derived that results in a $(15 \pm 10\%)$ increase of the expected yield in the signal region.

The multijet background is extracted from the data using techniques similar to those described in Ref. [23]. The techniques exploit the fact that the lepton isolation efficiency is different in signal and multijet events. In both lepton channels the contribution to the signal region is consistent with zero.

The contributions from single top, diboson production ($WW$, $WZ$, and $ZZ$), and $Z +$ jets are estimated using MC simulation, normalized to the theoretical cross section and total integrated luminosity.

The background yields estimated from MC simulated events are affected by systematic uncertainties related to the modeling of detector performance, reconstruction, and object identification. The largest of these uncertainties are from the jet energy scale [25] (approximately 5%–7% on the jet $p_T$, including a contribution from pileup effects, leading to an 11% uncertainty on the background event yield), and from the performance of the second lepton veto in dilepton $t\bar{t}$ (10%). Other uncertainties include those on the lepton momentum scales and trigger and reconstruction efficiencies. Lepton momentum scales and resolutions are determined from fits to the $Z$-mass peak. Trigger and reconstruction efficiencies are evaluated using tag-and-probe measurements in $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$ events. To evaluate the effect of lepton momentum and jet energy scale uncertainties, the $E_T^{miss}$ and $m_T$ are recalculated for each uncertainty on selected objects. Other small uncertainties affecting the $E_T^{miss}$ calculation are due to multiple $pp$ interactions, jets with $p_T$ below 20 GeV, and calorimeter clusters that are not associated to a selected object [28]. Additionally, theoretical cross-section uncertainties from choice of scales and parton distribution functions are considered for these background sources, as are the effects of using alternative MC generators, shower models, and initial- and final-state radiation tunings [23]. Finally, the 3.7% uncertainty on the integrated luminosity [29] is applied to each background source.

The systematic uncertainties applied to data-driven backgrounds are determined from the data. The dominant uncertainty for single-lepton backgrounds is due to the $(15 \pm 10\%)$ shape correction, and is derived from the variation in the measured correction in different control regions and from uncertainties in the $b$-tagging efficiency. The uncertainty on the single-lepton normalization of $(-5 \pm 3\%)$ includes equal contributions from limited data statistics in the $W$ mass region and expected differences between the $W +$ jets and single-lepton $t\bar{t}$ contributions to the signal and control regions. A 100% systematic uncertainty is assigned to the small estimated multijet yield.

The expected and observed event yields are consistent within statistical and systematic uncertainties. Therefore, the results are interpreted as a limit on the possible non-SM contribution to the selected sample. A model involving pair production of heavy quarklike objects ($T\bar{T}$), each forced to decay to a top quark and a scalar neutral $A_0$, is chosen to establish these limits.

MADGRAPH [30] is used to simulate the signal process with the parton distribution function set CTEQ6L1 [31], and PYTHIA [32] is used to simulate the parton shower and fragmentation. A grid of $T$ and $A_0$ masses is generated with $300 \text{ GeV} \leq m(T) \leq 450 \text{ GeV}$ and $10 \text{ GeV} \leq m(A_0) \leq 150 \text{ GeV}$. Each sample is normalized to the cross section calculated at approximate NNLO in QCD using HATHOR [33], ranging from 8.0 pb for a $T$ mass of 300 GeV to 0.66 pb for a $T$ mass of 450 GeV. Using this grid of signal samples, the efficiency times acceptance for the $T\bar{T}$ signal model is parametrized as a function of the $T$ and $A_0$ masses to generate the expected signal event yield for any pair of masses. The combined acceptance times signal selection efficiency varies between 3% and 5% for small $A_0$ masses and decreases to between 2% and 4% for larger $A_0$ masses.

All common systematic uncertainties for MC-based backgrounds are applied to this signal model. These include the uncertainties on the jet energy scale, lepton reconstruction efficiencies and scales, integrated luminosity, and the dilepton veto efficiency. Overall, the systematic uncertainty on the signal acceptance times efficiency varies between 11% and 14%, and is largest for those samples with a $T$-$A_0$ mass difference closest to the top quark mass. The theoretical uncertainties on the signal cross section vary between 10% to 15% and originate mainly from the choice of scales ($m_T / 2 < \mu_R = \mu_F < 2m_T$, where $\mu_R$ and $\mu_F$ are the renormalization and factorization scale) and parton distribution functions.

The $E_T^{miss}$ and $m_T$ distributions for data are shown in Fig. 1 and compared with the background and signal predictions. There is no significant evidence of an excess over the SM prediction, and the kinematics are well modeled.
From the observed event yield and the predicted signal and background event yields after all cuts, a frequentist confidence interval on the signal hypothesis is calculated for various assumed $T$ and $A_0$ masses, assuming Gaussian systematic uncertainties. Correlations between signal and background uncertainties are included. Figure 2 shows the region of parameter space excluded at the 95% confidence level. As the mass difference between the $T$ and $A_0$ approaches the top-quark mass, the $A_0$ contributes less momentum to the $E_T^{\text{miss}}$, and signal becomes indistinguishable from SM $t\bar{t}$. Assuming a $T \bar{T} \rightarrow t\bar{t}A_0A_0$ branching ratio of 100%, signal points with $T$ mass up to 420 GeV are excluded at the 95% confidence level for an $A_0$ mass below 10 GeV, as are signal points with $330 \text{ GeV} < m(T) < 390 \text{ GeV}$ for an $A_0$ mass below 140 GeV. Figure 3 shows the cross-section times branching ratio excluded at the 95% confidence level versus $T$ mass, for an $A_0$ mass of 10 GeV. A cross-section times branching ratio of 1.1 (1.9) pb is excluded at the 95% confidence level for a $T$ mass of 420 (370) GeV and an $A_0$ mass of 10 (140) GeV. The estimated acceptance times efficiency for spin-$\frac{1}{2}$ $T \bar{T}$ models is consistent within systematic uncertainties with that for scalar models, such as pair production of stop squarks (with a $t\bar{t}X_0X_0$ final state) or third-generation leptoquarks (with a $t\bar{t}v\tilde{v}$, $\tilde{t}\tilde{t}$ final state). The cross-section limits presented in Fig. 3 are therefore approximately valid for such models, although the predicted cross section is typically below the current sensitivity.

In summary, in 1.04 fb$^{-1}$ of data in $pp$ collisions at a center-of-mass energy of 7 TeV, there is no evidence of an
excess of events with large $E_T^{miss}$ in a sample dominated by $t\bar{t}$ events. Using a model of pair-produced quarklike objects decaying to a top quark and a heavy neutral particle, a limit is established excluding masses of these top partners up to 420 GeV and stable weakly interacting particle masses up to 140 GeV (see Fig. 2). In particular, a cross-section times branching ratio of 1.1 pb is excluded at the 95% confidence level for $m(T) = 420$ GeV and $m(A_0) = 10$ GeV. The cross-section limits are approximately valid for a number of models of new phenomena.

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; BMWF, 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, MPO, CR, and VSC CR, Czech Republic; DNRF, DNSRC, and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Germany; BMDF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, The Netherlands; RCN, Norway; MNiSW, Poland; GRICES, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF, and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, U.K.; DOE and NSF, U.S. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (The Netherlands), PIC (Spain), ASGC (Taiwan), RAL (U.K.), and BNL (U.S.), and in the Tier-2 facilities worldwide.

[13] The azimuthal angle $\phi$ is measured around the beam axis and the polar angle $\theta$ is the angle from the beam axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$.
[27] The transverse mass is defined by the formula $m_T = \sqrt{p_T^2 + E_{T\text{miss}}^2 (1 - \cos(\phi - \phi_{T\text{miss}}))}$, where $p_T$ is the $p_T$ of the muon (electron) and $\phi$ ($\phi_{T\text{miss}}$) is the azimuthal angle of the lepton ($E_{T\text{miss}}$).


041805-5
129 Physics Department, University of Regina, Regina, Saskatchewan, Canada
130 Ritsumeikan University, Kusatsu, Shiga, Japan
131 INFN Sezione di Roma I, Roma, Italy
132 Dipartimento di Fisica, Università La Sapienza, Roma, Italy
133 INFN Sezione di Roma Tor Vergata, Italy
134 Dipartimento di Fisica, Università Roma Tor Vergata, Roma, Italy
135 INFN Sezione di Roma Tre, Roma, Italy
136 Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco
137 Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat, Morocco
138 Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000, Morocco
139 Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
140 Faculté des Sciences, Université Mohammed V, Rabat, Morocco
141 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
142 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
143 Department of Physics, University of Washington, Seattle, Washington, USA
144 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
145 Department of Physics, Shinshu University, Nagano, Japan
146 Fachbereich Physik, Universität Siegen, Siegen, Germany
147 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
148 SLAC National Accelerator Laboratory, Stanford, California, USA
149 Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
150 Department of Physics, University of Johannesburg, Johannesburg, South Africa
151 School of Physics, University of the Witwatersrand, Johannesburg, South Africa
152 The Oskar Klein Centre, Stockholm, Sweden
153 Department of Physics, Stockholm University, Stockholm, Sweden
154 Institution of Physics, Academia Sinica, Taipei, Taiwan
155 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
156 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
157 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
158 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
159 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
160 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
161 Department of Physics, University of Toronto, Toronto, Ontario, Canada
162 TRIUMF, Vancouver, British Columbia, Canada
163 Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
164 Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
165 Science and Technology Center, Tufts University, Medford, Massachusetts, USA
166 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
167 INFN Gruppo Collegato di Udine, Udine, Italy
168 ICTP, Trieste, Italy
169 Dipartimento di Fisica, Università di Udine, Udine, Italy
170 Department of Physics, University of Illinois, Urbana, Illinois, USA
171 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
172 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
173 Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
174 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
175 Waseda University, Tokyo, Japan
176 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
177 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
178 Fachbereich Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
179 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
174Department of Physics, Yale University, New Haven, Connecticut, USA
175Yerevan Physics Institute, Yerevan, Armenia
176Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

aDeceased.
bAlso at Laboratorio de Instrumentacao e Fisica Experimental de Particulas–LIP, Lisboa, Portugal.
cAlso at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
dAlso at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
eAlso at CPPM, Aix-Marseille Universite and CNRS/IN2P3, Marseille, France.
fAlso at TRIUMF, Vancouver, BC, Canada.
gAlso at Department of Physics, California State University, Fresno, CA, USA.
hAlso at Fermilab, Batavia, IL, USA.
iAlso at Department of Physics, University of Coimbra, Coimbra, Portugal.
jAlso at Universita di Napoli Parthenope, Napoli, Italy.
kAlso at Institute of Particle Physics (IPP), Canada.
lAlso at Department of Physics, Middle East Technical University, Ankara, Turkey.
mAlso at Louisiana Tech University, Ruston, LA, USA.

nAlso at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.
oAlso at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
pAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
qAlso at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
rAlso at Manhattan College, New York, NY, USA.
sAlso at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
tAlso at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
uAlso at High Energy Physics Group, Shandong University, Shandong, China.
vAlso at Section de Physique, Université de Genève, Geneva, Switzerland.
wAlso at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
xAlso at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
yAlso at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
zAlso at California Institute of Technology, Pasadena, CA, USA.

aaAlso at Institute of Physics, Jagiellonian University, Krakow, Poland.
bbAlso at Department of Physics, Oxford University, Oxford, United Kingdom.
ccAlso at Institute of Physics, Academia Sinica, Taipei, Taiwan.

.ddAlso at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
eAlso at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.
ffAlso at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

#Also at Department of Physics, Nanjing University, Jiangsu, China.