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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)

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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.

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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 ($W \rightarrow \ell \nu$, 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. In the absence of signal an upper 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.

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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 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 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: $W \rightarrow l\nu$); single-lepton $t\bar{t}$ and $W + j$; multijet production; and other electroweak processes, such as diboson production, single top, and $Z + j$. The $t\bar{t}$ and single top samples are produced with MC@NLO [16], while the $W + j$ and $Z + j$ 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 $W + j$ and $Z + j$ 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 $E_T^{miss}$ components [26]. Clusters not associated with any high-$p_T$ object and muons reconstructed in the MS are also included in the $E_T^{miss}$ calculation.

Events are selected with exactly one isolated electron or muon that passes the following kinematic selection criteria. Electrons are required to satisfy $E_T > 25$ 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 $p_T > 20$ 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 $p_T > 25$ GeV and $|\eta| < 2.5$ are selected. To reduce the single-lepton $t\bar{t}$ and $W + j$ background, events are required to have $E_T^{miss} > 100$ GeV and $m_T > 150$ GeV, where $m_T$ is the transverse mass of the lepton and $E_T^{miss}$ [27]. Events with either a second lepton candidate with $p_T > 15$ GeV or a track with $p_T > 12$ GeV, with no other tracks with $p_T > 3$ 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 $E_T^{miss}$ 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 $t\bar{t}/W + j$</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>$Z + j$</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>
<tr>
<td>Data</td>
<td>105</td>
</tr>
</tbody>
</table>
The next largest background comes from single-lepton sources, including $W + \text{jets}$ 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 $W + \text{jets}$ 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 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 $Z + \text{jets}$ 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 $E_T^{\text{miss}}$ and $m_T$ are recalculated for each uncertainty on selected objects. Other small uncertainties affecting the $E_T^{\text{miss}}$ 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 $W + \text{jets}$ 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 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 ($m_T/2 < \mu_F = \mu_R < 2m_T$, where $\mu_R$ and $\mu_F$ are the renormalization and factorization scale) and parton distribution functions.

The $E_T^{\text{miss}}$ 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.
As the mass difference between the region of parameter space excluded at the 95% confidence level for an $A_0$ mass of 10 GeV, as are signal points with $m(T) < 390$ 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-$1/2$ $T\bar{T}$ models is consistent within systematic uncertainties with that for scalar models, such as pair production of stop squarks (with a $\tilde{t}\tilde{t}X_0X_0$ final state) or third-generation leptoquarks (with a $\tilde{t}\nu_r\tilde{\nu}_r$ 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 $E_T^{\text{miss}}$ in a sample dominated by $tt$ 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.

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[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 $m_T = \sqrt{p_T^2 + E_T^{\text{miss}}^2 (1 - \cos(\phi_T - \phi_{\text{miss}}))}$, where $p_T$ is the $p_T$ ($E_T$) of the muon (electron) and $\phi_T$ ($\phi_{\text{miss}}$) is the azimuthal angle of the lepton ($E_T^{\text{miss}}$).
University Politehnica Bucharest, Bucharest, Romania
West University in Timisoara, Timisoara, Romania
Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa, Ontario, Canada
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago, Chile
Departamento de Fisica, Universidad Técnica Federico Santa María, Valparaiso, Chile
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Modern Physics, University of Science and Technology of China, Anhui, China
Department of Physics, Nanjing University, Jiangsu, China
High Energy Physics Group, Shandong University, Shandong, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
Nevis Laboratory, Columbia University, Irvington, New York, USA
Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
INFN Gruppo Collegato di Cosenza, Italy
Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas, Texas, USA
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern-und Teilchenphysik, Technical University Dresden, Dresden, Germany
Department of Physics, Duke University, Durham, North Carolina, USA
SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
Section de Physique, Université de Genève, Geneva, Switzerland
INFN Sezione di Genova, Genova, Italy
Dipartimento di Fisica, Università di Genova, Genova, Italy
E. Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi, Georgia
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
Department of Physics, Hampton University, Hampton, Virginia, USA
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Science, Hiroshima University, Hiroshima, Japan
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Indiana University, Bloomington, Indiana, USA
Institut für Astro-und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City, Iowa, USA
Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
INFN Sezione di Lecce, Lecce, Italy
Dipartimento di Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Physics Department, University of Regina, Regina, Saskatchewan, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
INFN Sezione di Roma I, Roma, Italy
Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Università Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre, Roma, Italy
Dipartimento di Fisica, Università Roma Tre, Roma, Italy
INFN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Università Roma Tre, Roma, Italy
Dipartimento di Fisica, Università Roma Tre, Roma, Italy
Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat, Morocco
Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000, Morocco
Faculté des Sciences, Université Mohamed Premier et LPTPM, Oujda, Morocco
Faculté des Sciences, Université Mohammed V, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
Department of Physics, University of Washington, Seattle, Washington, USA
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
SLAC National Accelerator Laboratory, Stanford, California, USA
Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Department of Physics, University of Johannesburg, Johannesburg, South Africa
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University, Stockholm, Sweden
The Oskar Klein Centre, Stockholm, Sweden
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto, Ontario, Canada
TRIUMF, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
Science and Technology Center, Tufts University, Medford, Massachusetts, USA
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
INFN Gruppo Collegato di Udine, Udine, Italy
ICTP, Trieste, Italy
Dipartimento di Fisica, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana, Illinois, USA
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
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
Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

041805-17
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 Universit´e 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 Universit´a 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 f¨ur Experimentalphysik, Universit¨at 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, Universit´e de Genˆeve, 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.
eeAlso 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 Nucl´eaire et de Hautes Energies, UPMC and Universit´e Paris-Diderot and CNRS/IN2P3, Paris, France.
##Also at Department of Physics, Nanjing University, Jiangsu, China.