The following full text is a preprint version which may differ from the publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/94056

Please be advised that this information was generated on 2017-12-14 and may be subject to change.
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

ATLAS Collaboration
(Dated: December 6, 2011)

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. The search is carried out in the single-lepton channel, characterized by an isolated lepton of high transverse momentum, four or more jets and large missing transverse momentum. 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.

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 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 ($E_T^{miss}$) 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 $t\bar{t}+E_T^{miss}$ $[3]$ 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 $[4, 5]$, models of universal extra dimensions (UED) with Kaluza-Klein parity $[6]$, models in which baryon and lepton number conservation arises from gauge symmetries $[7]$ 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 $E_T^{miss}$ 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 $E_T^{miss}$. The observed yield in this signal region is compared with the SM expectation. 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 $[8]$ the $T\bar{T}$ production cross-section is predicted to be approximately six times higher than for stop squarks with a similar mass $[8]$, 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 endcap ($1.375 < |\eta| < 3.2$) regions. Hadron calorimetry is based on two different detector technologies. The barrel ($|\eta| < 0.8$) and extended barrel ($0.8 < |\eta| < 1.7$) calorimeters are composed of scintillator/steel, while the hadronic endcap calorimeters ($1.5 < |\eta| < 3.2$) are copper/LAr. The forward calorimeters ($3.1 < |\eta| < 4.9$) are instrumented with copper/LAr and tungsten/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.
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 based on the GEANT4 program and corrected for all known detector effects are used to model the signal process and most of the backgrounds. The multi-jet 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 $\ell\ell$ (where both $W$ bosons decay to a lepton-neutrino pair; $W \rightarrow \ell \nu$); single-lepton $\ell$ and $W$+jets; multi-jet production; and other electroweak processes, such as diboson production, single top, and $Z$+jets. The $\ell\ell$ and single top samples are produced with MC@NLO, while the $W$+jets and $Z$+jets samples are generated with ALPGEN. HERWIG is used to simulate the parton shower and fragmentation, and JIMMY is used for the underlying event simulation. The diboson background is simulated using HERWIG. The $\ell\ell$ cross-section is normalized to approximate next-to-next-to-leading order (NNLO) calculations, the inclusive $W$+jets and $Z$+jets cross-sections are normalized to NNLO predictions, and the cross-sections of the other backgrounds are normalized to NLO predictions. 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. Jets are reconstructed using the anti-$k_T$ 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 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. 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 $E_T > 25$ GeV and $|\eta| < 2.47$. Electrons in the region between the barrel and the endcap 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 $W$+jets background, events are required to have $E_T^{\text{miss}} > 100$ GeV and $m_T > 150$ GeV, where $m_T$ is the transverse mass of the lepton and $E_T^{\text{miss}}$. 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.

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton $\ell\ell$</td>
<td>62 $\pm$ 15</td>
</tr>
<tr>
<td>Single-lepton $\ell/W$+jets</td>
<td>33.1 $\pm$ 3.8</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>1.2 $\pm$ 1.2</td>
</tr>
<tr>
<td>Single top</td>
<td>3.5 $\pm$ 0.8</td>
</tr>
<tr>
<td>$Z$+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>

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, 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.

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 GeV $< m_T < 90$ 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, are rejected in order to reduce
the dilepton $\tilde{t}\bar{t}$ 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 GeV, and a shape correction is derived that results in a $(15 \pm 10)\%$ increase of the expected yield in the signal region.

The multi-jet 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 multi-jet 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 $E_T^{\text{miss}}$ 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 [22] 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 multi-jet 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 quark-like objects ($T\bar{T}$), each forced to decay to a top quark and a scalar neutral $A_0$, is chosen to establish these limits.

\textsc{MadGraph} [31] is used to simulate the signal process with the parton distribution function set CTEQ6L1 [31], and \textsc{Pythia} [22] 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 \textsc{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 renormalisation 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.

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...
A cross-section times branching ratio of 1.1 pb is excluded at the 95% confidence level versus a mass of 10 GeV. The estimated acceptance times background, including the overflow, is 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 quark-like 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; STC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COC, Colombia; MPO CR and VSC CR, Czech Republic; DNRF, DSNRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, 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, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, 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, United Kingdom; DOE and NSF, United States of America. 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 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

[13] The pseudorapidity is defined as $\eta \equiv -\ln \tan(\theta/2)$.
[27] The transverse mass is defined by the formula $m_\ell = \sqrt{2p_\ell^T E_\ell^{\text{miss}} (1 - \cos(\phi - \phi_\ell^{\text{miss}}))}$, where $p_\ell^T$ is the $p_T$ ($E_\ell^T$) of the muon (electron) and $\phi_\ell^{\text{miss}}$ is the azimuthal angle of the lepton ($E_\ell^{\text{miss}}$).
Universidad Técnica Federico Santa María, Valparaíso, Chile
32 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) High Energy Physics Group, Shandong University, Shandong, China
33 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
34 Nevis Laboratory, Columbia University, Irvington NY, United States of America
35 Niels Bohr Institute, University of Copenhagen, København, Denmark
36 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
37 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas TX, United States of America
40 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham NC, United States of America
45 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Science, Hiroshima University, Hiroshima, Japan
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (a) INFN Sezione di Lecce; (b) Dipartimento di Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jozef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 Department of Physics, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
81 Institut für Physik, Universität Mainz, Mainz, Germany
82 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
83 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
84 Department of Physics, University of Massachusetts, Amherst MA, United States of America
85 Department of Physics, McGill University, Montreal QC, Canada
86 School of Physics, University of Melbourne, Victoria, Australia
87 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
88 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
89 (a)INFN Sezione di Milano; (b)Dipartimento di Fisica, Università di Milano, Milano, Italy
90 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
91 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
92 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
93 Group of Particle Physics, University of Montréal, Montréal QC, Canada
94 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
95 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
96 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
97 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
98 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
100 Nagasaki Institute of Applied Science, Nagasaki, Japan
101 Graduate School of Science, Nagoya University, Nagoya, Japan
102 (a)INFN Sezione di Napoli; (b)Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
103 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
104 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
106 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
107 Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
108 Department of Physics, New York University, New York NY, United States of America
109 Ohio State University, Columbus OH, United States of America
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
112 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
113 Palacký University, RCPTM, Olomouc, Czech Republic
114 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
115 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
116 Graduate School of Science, Osaka University, Osaka, Japan
117 Department of Physics, University of Oslo, Oslo, Norway
118 Department of Physics, Oxford University, Oxford, United Kingdom
119 (a)INFN Sezione di Pavia; (b)Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
120 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
121 Petersburg Nuclear Physics Institute, Gatchina, Russia
122 (a)INFN Sezione di Pisa; (b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
124 (a)Laboratorio de Instrumentación e Física Experimental de Partículas - LIP, Lisboa, Portugal; (b)Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
126 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
127 Czech Technical University in Prague, Praha, Czech Republic
128 State Research Center Institute for High Energy Physics, Protvino, Russia
129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
130 Physics Department, University of Regina, Regina SK, Canada
131 Ritsumeikan University, Kusatsu, Shiga, Japan
132 (a)INFN Sezione di Roma I; (b)Dipartimento di Fisica, Università La Sapienza, Roma, Italy
133 (a)INFN Sezione di Roma Tor Vergata; (b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134 (a)INFN Sezione di Roma Tre; (b)Dipartimento di Fisica, Università Roma Tre, Roma, Italy
135 (a)Faculté des Sciences Aim Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b)Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c)Université Cadi Ayyad, Faculté des sciences Semlalia
Département de Physique, B.P. 2390 Marrakech 40000:
(d) Faculté des Sciences, Université Mohamed Premier
and LPTTPM, Oujda; (e) Faculté des Sciences, Université
Mohammed V, Rabat, Morocco
136 DSM/IRFU (Institut de Recherches sur les Lois
Fondamentales de l’Univers), CEA Saclay
(Commissariat a l’Energie Atomique), Gif-sur-Yvette,
France
137 Santa Cruz Institute for Particle Physics, University
of California Santa Cruz, Santa Cruz CA, United States
of America
138 Department of Physics, University of Washington,
Seattle WA, United States of America
139 Department of Physics and Astronomy, University
of Sheffield, Sheffield, United Kingdom
140 Department of Physics, Shinshu University, Nagano,
Japan
141 Fachbereich Physik, Universität Siegen, Siegen,
Germany
142 Department of Physics, Simon Fraser University,
Burnaby BC, Canada
143 SLAC National Accelerator Laboratory, Stanford
CA, United States of America
144 (a)Faculty of Mathematics, Physics & Informatics,
Comenius University, Bratislava; (b)Department of
Subnuclear Physics, Institute of Experimental Physics
of the Slovak Academy of Sciences, Kosice, Slovak
Republic
145 (a)Department of Physics, University of
Johannesburg, Johannesburg; (b)School of Physics,
University of the Witwatersrand, Johannesburg, South
Africa
146 (a)Department of Physics, Stockholm University;
(b)The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology,
Stockholm, Sweden
148 Department of Physics and Astronomy, Stony Brook
University, Stony Brook NY, United States of America
149 Department of Physics and Astronomy, University
of Sussex, Brighton, United Kingdom
150 School of Physics, University of Sydney, Sydney,
Australia
151 Institute of Physics, Academia Sinica, Taipei,
Taiwan
152 Department of Physics, Technion: Israel Inst. of
Technology, Haifa, Israel
153 Raymond and Beverly Sackler School of Physics and
Astronomy, Tel Aviv University, Tel Aviv, Israel
154 Department of Physics, Aristotle University of
Thessaloniki, Thessaloniki, Greece
155 International Center for Elementary Particle Physics
and Department of Physics, The University of Tokyo,
Tokyo, Japan
156 Graduate School of Science and Technology, Tokyo
Metropolitan University, Tokyo, Japan
157 Department of Physics, Tokyo Institute of
Technology, Tokyo, Japan
158 Department of Physics, University of Toronto,
Toronto ON, Canada
159 (a) TRIUMF, Vancouver BC; (b) Department of
Physics and Astronomy, York University, Toronto ON,
Canada
160 Institute of Pure and Applied Sciences, University
of Tsukuba, Ibaraki, Japan
161 Science and Technology Center, Tufts University,
Medford MA, United States of America
162 Centro de Investigaciones, Universidad Antonio
Narino, Bogota, Colombia
163 Department of Physics and Astronomy, University
of California Irvine, Irvine CA, United States of America
164 (a) INFN Gruppo Collegato di Udine; (b) ICTP,
Trieste; (c) Dipartimento di Fisica, Università di Udine,
Udine, Italy
165 Department of Physics, University of Illinois,
Urbana IL, United States of America
166 Department of Physics and Astronomy, University
of Uppsala, Uppsala, Sweden
167 Instituto de Fisica Corpuscular (IFIC) and
Departamento de Fisica Atómica, Molecular y Nuclear
and Departamento de Ingeniería Electrónica and
Instituto de Microelectrónica de Barcelona (IMB-CNM),
University of Valencia and CSIC, Valencia, Spain
168 Department of Physics, University of British
Columbia, Vancouver BC, Canada
169 Department of Physics and Astronomy, University
of Victoria, Victoria BC, Canada
170 Waseda University, Tokyo, Japan
171 Department of Particle Physics, The Weizmann
Institute of Science, Rehovot, Israel
172 Department of Physics, University of Wisconsin,
Madison WI, United States of America
173 Fakultät für Physik und Astronomie,
Julius-Maximilians-Universität, Würzburg, Germany
174 Fachbereich C Physik, Bergische Universität
Wuppertal, Wuppertal, Germany
175 Department of Physics, Yale University, New Haven
CT, United States of America
176 Yerevan Physics Institute, Yerevan, Armenia
177 Domaine scientifique de la Doua, Centre de Calcul
CNRS/IN2P3, Villeurbanne Cedex, France
a Also at Laboratorio de Instrumentacae e Fisica
Experimental de Partículas - LIP, Lisboa, Portugal
b Also at Faculdade de Ciencias and CFNUL,
Universidade de Lisboa, Lisboa, Portugal
c Also at Particle Physics Department, Rutherford
Appleton Laboratory, Didcot, United Kingdom
d Also at CPPM, Aix-Marseille Université and
CNRS/IN2P3, Marseille, France
e Also at TRIUMF, Vancouver BC, Canada
f Also at Department of Physics, California State
University, Fresno CA, United States of America
9 Also at Fermilab, Batavia IL, United States of
America
h Also at Department of Physics, University of
Coimbra, Coimbra, Portugal
i Also at Università di Napoli Parthenope, Napoli, Italy
Also at Institute of Particle Physics (IPP), Canada
Also at Department of Physics, Middle East Technical University, Ankara, Turkey
Also at Louisiana Tech University, Ruston LA, United States of America
Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
Also at Manhattan College, New York NY, United States of America
Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at High Energy Physics Group, Shandong University, Shandong, China
Also at Section de Physique, Université de Genève, Geneva, Switzerland
Also at Departamento de Física, Universidade de Minho, Braga, Portugal
Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
Also at California Institute of Technology, Pasadena CA, United States of America
Also at Institute of Physics, Jagiellonian University, Krakow, Poland
Also at Department of Physics, Oxford University, Oxford, United Kingdom
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
Also 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
Deceased