Search for Supersymmetry in Events with Three Leptons and Missing Transverse Momentum in $\sqrt{s} = 7$ TeV $pp$ Collisions with the ATLAS Detector

G. Aad et al.*

(ATLAS Collaboration)

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A search for the weak production of charginos and neutralinos decaying to a final state with three leptons (electrons or muons) and missing transverse momentum is presented. The analysis uses 2.06 fb$^{-1}$ of $\sqrt{s} = 7$ TeV proton-proton collision data delivered by the Large Hadron Collider and recorded with the ATLAS detector. Observations are consistent with standard model expectations in two signal regions that are either depleted or enriched in Z-boson decays. Upper limits at 95% confidence level are set in $R$-parity conserving phenomenological minimal supersymmetric and simplified models. For the simplified models, degenerate lightest chargino and next-to-lightest neutralino masses up to 300 GeV are excluded for mass differences from the lightest neutralino up to 300 GeV.

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Supersymmetric (SUSY) extensions [1–9] of the standard model (SM) naturally address the gauge hierarchy problem [10–12] by postulating the existence of SUSY particles, or “sparticles”, with spin differing by one-half unit with respect to that of their SM partner. If $R$-parity [13–17] is conserved, sparticles can only be pair-produced and will eventually decay into SM particles and the lightest SUSY particle (LSP) which is stable. Charginos ($\tilde{\chi}_i^\pm$, $i = 1, 2$) and neutralinos ($\tilde{\chi}_j^0$, $j = 1, 2, 3, 4$) are the mass eigenstates formed from the linear superposition of the SUSY partners of the Higgs and electroweak gauge bosons. These are the Higgsinos, and the winos, zino, and bino, collectively known as gauginos. Naturalness requires $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^0$ (and third-generation sparticles) to have masses in the hundreds of GeV range [18]. In scenarios where first and second generation sfermion masses are larger than few TeVs, the direct production of weak gauginos may be the dominant SUSY process at the Large Hadron Collider (LHC).

Leptonic decays of charginos include sneutrinos ($\tilde{\nu}\ell^\pm$), sleptons ($\tilde{\ell}\ell^\pm$) or $W$ bosons ($W^{\pm}\ell^\mp$), while those of unstable neutralinos include sleptons ($\ell\ell^\pm$) or $Z$ bosons ($Z^{\mp}\tilde{\chi}_1^0$). When both gauginos decay leptonically, a distinctive signature with three leptons and significant missing transverse momentum can be observed; the latter originating from the two undetected LSPs and the neutrinos.

This Letter presents the first search with the ATLAS detector for the weak production of charginos and neutralinos decaying to a final state with three leptons (electrons or muons) and missing transverse momentum. The analysis is based on 2.06 fb$^{-1}$ of proton-proton collision data delivered by the LHC at a center-of-mass energy $\sqrt{s} = 7$ TeV between March and August 2011. The search significantly extends the current mass limits on charginos and neutralinos [19–22] and yields sensitivity in the mass region preferred by naturalness.

In this analysis, observations are interpreted in the phenomenological minimal supersymmetric SM (pMSSM [23]) and in simplified models [24]. In the pMSSM the masses of the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ depend on the gaugino masses $M_1$ and $M_2$, the Higgs mass parameter |$\mu$|, and $\tan\beta$, the ratio of the expectation values of the two Higgs doublets. The masses of the gluinos, squarks and left-handed sleptons are chosen to be larger than 1 TeV, while the right-handed sleptons (including third-generation ones) are assumed to be degenerate with $m_{\tilde{\ell}_R} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\ell}_R})/2$. In these scenarios, decays to sleptons are favored. In the simplified models, the masses of the relevant particles (mass degenerate winolike $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$, binolike $\tilde{\chi}_1^0$, $\tilde{\nu}^0; \tilde{\ell}_1^0$) are the only free parameters of the theory. The $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are produced via the $s$-channel exchange of a virtual gauge boson and decay via left-handed sleptons, including staus, and sneutrinos of mass $m_{\tilde{\nu}} = m_{\tilde{\ell}_k} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\ell}_k})/2$ with a branching ratio of 50% each.

ATLAS [25] is a multipurpose particle detector with forward-backward symmetric cylindrical geometry. It includes an inner tracker (ID) immersed in a 2 T magnetic field providing precision tracking of charged particles for pseudorapidities $|\eta| < 2.5$ [26]. Calorimeter systems with either liquid argon or scintillating tiles as the active media provide energy measurements over the range $|\eta| < 4.9$. The muon detectors outside the calorimeters are contained in a toroidal magnetic field produced by air-core superconducting magnets with field integrals varying from 1 to 8 T·m. They provide trigger and high-precision tracking capabilities for $|\eta| < 2.4$ and $|\eta| < 2.7$, respectively.

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

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Electrons must satisfy tight identification criteria and fulfil $|\eta| < 2.47$ and $E_T > 10$ GeV, where $|\eta|$ and $E_T$ are determined from the calibrated clustered energy deposits in the electromagnetic calorimeter matched to an ID track. Muons are reconstructed by combining tracks in the ID and tracks in the muon spectrometer [27]. Reconstructed muons are considered as candidates if they have transverse momentum $p_T > 10$ GeV, $|\eta| < 2.4$, and transverse impact parameter with respect to the primary vertex $|d_0| < 0.2$ mm. “Tagged” leptons are electrons and muons, well separated from each other and from candidate jets. “Signal” leptons are tagged leptons for which the scalar sum of the tracks’ transverse momenta within $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} < 0.2$ around the lepton candidate is less than 10% of the $E_T$ for electrons, and less than 1.8 GeV for muons. Jets are reconstructed from clustered energy deposits calibrated at the electromagnetic scale using the anti-$k_t$ algorithm [28] with a radius parameter of 0.4. The jet energy is corrected to account for the non-compensating nature of the calorimeter using correction factors obtained from Monte Carlo (MC) simulation and parameterized as a function of the jet $E_T$ and $\eta$ [29]. Jets considered in this analysis have $E_T > 20$ GeV and $|\eta| < 2.8$. Jets are identified as containing a $b$-quark, and thus called “$b$-tagged”, using a multivariate technique based on quantities such as the impact parameter of the tracks associated to the secondary vertex, tracks in jet and other jet shape information, consistent with the expected topology of $b$-quark decays. The $b$-tagging algorithm [30] correctly identifies $b$-quark jets in top decays with an efficiency of 60% and misidentifies jets containing light-flavor quarks and gluons with a rate of $<1\%$, for jets with $|\eta| < 2.5$ and jet $E_T > 20$ GeV. The missing transverse momentum, $E_T^{\text{miss}}$, is the magnitude of the vector sum of the transverse momentum or transverse energy of all $p_T > 10$ GeV muons, $E_T > 10$ GeV electrons, $E_T > 20$ GeV jets, and calibrated calorimeter clusters with $|\eta| < 4.5$ not associated to these objects [31].

Several MC generators are used to simulate SM processes and SUSY signals relevant for this analysis. HERWIG [32] is used to simulate diboson processes ($WW^{(*)}$, $ZZ^{(*)}$, $WZ^{(*)}$), while MADGRAPH [33] is used for the $t\bar{t}W^{(*)}/Z^{(*)}$ processes. MC@NLO [34] is chosen for the simulation of single and pair production of top quarks, while ALPGEN [35] is used to simulate $W^{(*)}/Z^{(*)} +$ jets. Expected diboson yields are normalized using next-to-leading order (NLO) QCD predictions obtained with MCFM [36,37]. The top-quark pair-production cross-section is normalized to approximate next-to-next-to-leading (NNLO) order calculations [38] and the $t\bar{t}W^{(*)}/Z^{(*)}$ contributions are normalized to NLO results [39]. The QCD NNLO FEWZ [40,41] and MCFM cross-sections are used for NNLO normalization of the $Z$ + light-flavor jets and $Z$ + heavy-flavor jets processes, respectively. The choice of the parton distribution functions (PDFs) depends on the generator. MRST 2007 LO* [42] sets are used for HERWIG, CTEQ6L1 [43] with MADGRAPH and ALPGEN, and CTEQ6.6 [44] with MC@NLO. The pMSSM and simplified model samples are produced with HERWIG and HERWIG++ [45], respectively, and the yields are normalized to the NLO cross-sections obtained from PROSPINO [46] using the PDF set CTEQ6.6 with the renormalization/factorization scales set to the average of the relevant gaugino masses. Fragmentation and hadronization for the ALPGEN and MC@NLO (MADGRAPH) samples are performed with HERWIG (PYTHIA [47]). For all MC samples, the propagation of particles through the ATLAS detector is modeled using GEANT4 [48,49]. The effect of multiple proton-proton collisions from the same or different bunch crossings is incorporated into the simulation by overlaying additional minimum bias events onto hard scatter events using PYTHIA. Simulated events are weighted to match the distribution of the mean number of interactions per bunch crossing observed in data.

The data sample was collected with a single-muon trigger ($p_T > 18$ GeV) or a single-electron trigger ($E_T > 20$ or 22 GeV, depending on the instantaneous luminosity). At least one signal lepton is required to have triggered the event and have $p_T(E_L) > 20$ GeV (25 GeV) for muons (electrons). Events recorded during normal running conditions are analyzed if at least one of the reconstructed primary vertices has more than four tracks associated to it. Events containing jets with $|\eta| < 4.9$ and failing the quality criteria described in Ref. [29] are rejected to suppress both collisional and noncollisional background. Selected events must contain exactly three signal leptons. As leptonic decays of $\chi_1^0$ yield same-flavor opposite-sign (SFOS) lepton pairs, the presence of at least one such pair is required. The invariant mass of any SFOS lepton pair must be above 20 GeV to suppress background from low mass resonances and the missing transverse momentum must satisfy $E_T^{\text{miss}} > 50$ GeV.

Two signal regions are then defined: a “$Z$-depleted” region (SR1), with no SFOS pairs having invariant mass within 10 GeV of the nominal $Z$-boson mass; and a “$Z$-enriched” one (SR2), where at least one SFOS pair has an invariant mass within 10 GeV of the $Z$-boson mass. Events in SR1 are further required to contain no $b$-tagged jets to suppress contributions from $b$-jet-rich backgrounds, where a fake lepton could originate from a heavy-flavor decay. The SR1 and SR2 selections target SUSY events with intermediate slepton or on-mass-shell $Z$-boson decays, respectively.

Several SM processes contribute to the background in SR1 and SR2. A background process is considered “irreducible” if it leads to events with three real and isolated leptons, referred to as “real” leptons below. These include diboson ($WZ^{(*)}$ and $ZZ^{(*)}$) and $t\bar{t}W^{(*)}/Z^{(*)}$ production, where the gauge boson may be produced off-mass-shell. Their contribution is determined using the corresponding MC
samples, for which lepton and jet selection efficiencies are corrected to account for differences with respect to data. A "reducible" process has at least one "fake" object, that is either a lepton from a semileptonic decay of a heavy-flavor quark or an electron from an isolated photon conversion. The contribution from misidentified light-flavor quarks is negligible. The reducible background includes single- and pair-production of top-quark and $W W^{(*)}$ or $W^{(*)}/Z^{(*)}$ produced in association with jets or photons. The dominant component is the production of top quarks, with a contribution of 1% or less from $Z^{(*)} +$ jets production. The reducible background is estimated using a "matrix method" similar to that described in Ref. [50].

In this implementation of the matrix method, the signal lepton with the highest $p_T$ or $E_T$ is taken to be real, which is a valid assumption in 99% of the cases, based on MC studies. The number of observed events with one or two fakes is then extracted from a system of linear equations linking the number of events with two additional signal or tagged candidates to the number of events with two additional candidates that are either real or fake. The coefficients of the linear equations are functions of the real lepton identification efficiencies and of the fake object misidentification probabilities. The identification efficiency is measured in data using lepton candidates from $Z \rightarrow \ell \ell$ decays.

Misidentification probabilities for each fake type (heavy-flavor, conversion) and for each reducible background process are obtained using simulated events with one signal and two tagged leptons. These misidentification probabilities are then corrected using the ratio (fake scale factor) of the misidentification probability in data and that in MC simulation obtained in dedicated control samples. For heavy-flavor fakes, the correction factor is measured in $b\bar{b}$ events, while for conversion fakes it is determined in a sample of photons radiated from a muon in $Z \rightarrow \mu \mu$ decays. A weighted average misidentification probability is then calculated by weighing the corrected type- and process-dependent misidentification probabilities according to the process cross section.

An additional source of background is due to events with two signal leptons and one virtual photon converting into two muons, one with $p_T$ above 10 GeV. The contribution from events in which both muons from the virtual photons have $p_T$ above 10 GeV is negligible due to the requirement on the dilepton pair invariant mass. For events with only one muon above threshold, an upper limit of 0.5 ± 0.5 in SR1 and of 0.7 ± 0.7 in SR2 is obtained from data as follows. The number of observed events with exactly two signal leptons and $E_T^{miss} > 50$ GeV is rescaled by the probability that any of the signal leptons could have radiated the converted photon. This probability is measured in events with $E_T^{miss} < 50$ GeV as the ratio of number of events with three signal muons with trilepton invariant mass within 10 GeV of the nominal Z boson mass to the number of events with two signal muons having the dilepton mass in the same mass window.

The matrix method has been tested using MC events and shown to be accurate within 2%. The background predictions have been validated in a region dominated by $Z^{(*)} +$ jets production (VR1: three signal leptons, $30 < E_T^{miss} < 50$ GeV) and in one dominated by top pair-production (VR2: three signal leptons, SFOS lepton pairs vetoed, $E_T^{miss} > 50$ GeV). The data and predictions are in agreement within the quoted statistical and systematic uncertainties as shown in Table I.

Several sources of systematic uncertainty are considered in the signal regions. The systematic uncertainties affecting the MC based estimates (irreducible background yield, misidentification probabilities, signal yield) include the theoretical cross-section uncertainty due to scale and PDFs, the acceptance uncertainty due to PDFs, jet energy scale, jet energy resolution, lepton energy scale, lepton energy resolution, lepton efficiency, $b$-tagging efficiency, event quality selection, and the uncertainty on the luminosity. In SR1, the total uncertainty on the irreducible background is 17%. This includes the uncertainty on the acceptance due to PDFs (14%), that on the theoretical cross section due to scale and PDFs (7%), and that from the limited number of simulated events (10%), while all the remaining uncertainties on the irreducible background in this signal region range between 0.5%–5%. The total uncertainty on the reducible background is 29%. This includes an uncertainty on the object misidentification probability of 10%–30% from the sources listed above. The uncertainty from the dependence of the misidentification probability on $E_T^{miss}$ (0.4%–17%) and the uncertainty on the fake scale factors (10%–50%) are also included in the total, together with the uncertainty from the limited number of data events with three tagged leptons, of which at least one is a signal lepton. The total uncertainties on the signal cross-section range between 10%–15%. These include uncertainties due to the renormalization and factorization scale, $\alpha_S$, and PDFs. The maximum uncertainty obtained from either the CTEQ6.6 or the MSTW [51] PDF set is used. In SR2, the values of systematic uncertainties are similar to those obtained in SR1. The only exceptions

<table>
<thead>
<tr>
<th>Selection</th>
<th>VR1</th>
<th>VR2</th>
<th>SR1</th>
<th>SR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}W^{(<em>)}/Z^{(</em>)}$</td>
<td>1.4 ± 1.1</td>
<td>0.7 ± 0.6</td>
<td>0.4 ± 0.3</td>
<td>2.7 ± 2.1</td>
</tr>
<tr>
<td>$ZZ^{(*)}$</td>
<td>6.7 ± 1.5</td>
<td>0.03 ± 0.04</td>
<td>0.7 ± 0.2</td>
<td>3.4 ± 0.8</td>
</tr>
<tr>
<td>$WZ^{(*)}$</td>
<td>61 ± 11</td>
<td>0.4 ± 0.2</td>
<td>11 ± 2</td>
<td>58 ± 11</td>
</tr>
<tr>
<td>Reducible Bkg.</td>
<td>56 ± 35</td>
<td>14 ± 9</td>
<td>14 ± 4</td>
<td>7.5 ± 3.9</td>
</tr>
<tr>
<td>Total Bkg.</td>
<td>125 ± 37</td>
<td>15 ± 9</td>
<td>26 ± 5</td>
<td>72 ± 12</td>
</tr>
<tr>
<td>Data</td>
<td>122</td>
<td>12</td>
<td>32</td>
<td>95</td>
</tr>
</tbody>
</table>
are the uncertainty from the limited number of simulated events (4%) and the uncertainty on the reducible background (52%). In all of the above, the value used for the uncertainty on the luminosity is 3.7%.

The numbers of observed events and the prediction for SM backgrounds in SR1 and SR2 are reported in Table I. The probability that the background fluctuates to the observed number of events or higher is calculated in the frequentist approach and found to be 19% in SR1 and 6% in SR2. The distributions of the $E_T^{\text{miss}}$ in the two signal regions are presented in Fig. 1. The yield in SR1 for one of the simplified model scenarios ($m_{\tilde{\chi}^{\pm}_1}$, $m_{\tilde{\chi}^{0}_1}$, $m_{\tilde{l}^+_1}$, $m_{\tilde{l}^-_1}$ = 250, 250, 175, 100 GeV) is also shown for illustration purposes.

No significant excess of events is found in either signal region. Upper limits on the visible production cross-section of 9.9 fb in SR1 and 23.8 fb in SR2 are placed at 95% confidence level (C.L.) with the modified frequentist prescription [52]. No corrections for the effects of experimental resolution, acceptance and efficiency are applied. All systematic uncertainties and their correlations are taken into account via nuisance parameters. The corresponding expected limits are 7.1 and 14.1 fb, respectively. In SR2, the observed limit on the visible cross-section is less stringent than the expected limit because of the upwards fluctuation in the number of events in data with respect to the expected background. SR1 provides better sensitivity in the parameter space considered and the limits are interpreted in simplified models and pMSSM scenarios with $M_1$ = 100 GeV and $\tan\beta = 6$ (Fig. 2). The chosen $M_1$ value leads to a sizable mass splitting between $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^{0}_1$ and therefore to a large acceptance. The value of $\tan\beta$ does not have a significant impact on $\sigma(p p \to \tilde{\chi}^{\pm}_1 \tilde{\chi}^{0}_1) \times BR(\tilde{\chi}^{\pm}_1 \to \ell\ell\tilde{\chi}^{0}_1)$, which varies by $\sim$10% if $\tan\beta$ is raised to 10.
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((ATLAS Collaboration)

1University at Albany, Albany New York, USA
2Department of Physics, University of Alberta, Edmonton AB, Canada
3aDepartment of Physics, Ankara University, Ankara, Turkey
3bDepartment of Physics, Dumlupinar University, Kutahya, Turkey
3cDepartment of Physics, Gazi University, Ankara, Turkey
3dDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
3eTurkish Atomic Energy Authority, Ankara, Turkey
4LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5High Energy Physics Division, Argonne National Laboratory, Argonne Illinois, USA
6Department of Physics, University of Arizona, Tucson Arizona, USA
7Department of Physics, The University of Texas at Arlington, Arlington Texas, USA
8Physics Department, University of Athens, Athens, Greece
9Physics Department, National Technical University of Athens, Zografou, Greece
10Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
12aInstitute of Physics, University of Belgrade, Belgrade, Serbia
12bVinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
13Department for Physics and Technology, University of Bergen, Bergen, Norway
14Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley California, USA
15Department of Physics, Humboldt University, Berlin, Germany
16Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18aDepartment of Physics, Bogazici University, Istanbul, Turkey
18bDivision of Physics, Dogus University, Istanbul, Turkey
18cDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
18dDepartment of Physics, Istanbul Technical University, Istanbul, Turkey
18eINFN Sezione di Bologna, Italy
18fDipartimento di Fisica, Università di Bologna, Bologna, Italy
19aPhysikalisches Institut, University of Bonn, Bonn, Germany
19bDepartment of Physics, Boston University, Boston Massachusetts, USA
20Department of Physics, Brandeis University, Waltham Massachusetts, USA
21Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
22Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
23aFederal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
23bInstituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
24Physics Division, Brookhaven National Laboratory, Upton New York, USA
25aNational Institute of Physics and Nuclear Engineering, Bucharest, Romania
25bUniversity Politehnica Bucharest, Bucharest, Romania
25cWest University in Timisoara, Timisoara, Romania
26Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28Department of Physics, Carleton University, Ottawa ON, Canada
29CERN, Geneva, Switzerland
30Enrico Fermi Institute, University of Chicago, Chicago Illinois, USA
31aDepartamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
31bDepartamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
32aInstitute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
32bDepartment of Modern Physics, University of Science and Technology of China, Anhui, China
84 Department of Physics, McGill University, Montreal QC, Canada
85 School of Physics, University of Melbourne, Victoria, Australia
86 Department of Physics, The University of Michigan, Ann Arbor Michigan, USA
87 Department of Physics and Astronomy, Michigan State University, East Lansing Michigan, USA
88 INFN Sezione di Milano, Italy
89 INFN Sezione di 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 Massachusetts, USA
93 Group of Particle Physics, University of Montreal, Montreal 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 INFN Sezione di Napoli, Italy
102 Dipartimento di Fisica, Università di Napoli, Napoli, Italy
103 Department of Physics and Astronomy, University of New Mexico, Albuquerque New Mexico, USA
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 Illinois, USA
107 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
108 Department of Physics, New York University, New York New York, USA
109 Ohio State University, Columbus Ohio, USA
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman Oklahoma, USA
112 Department of Physics, Oklahoma State University, Stillwater Oklahoma, USA
113 Palacký University, RCPTM, Olomouc, Czech Republic
114 Center for High Energy Physics, University of Oregon, Eugene Oregon, USA
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 Department of Physics, University of Pennsylvania, Philadelphia Pennsylvania, USA
120 Petersburg Nuclear Physics Institute, Gatchina, Russia
121 Dipartimento di Fisica, Università di Pavia, Pavia, Italy
122 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh Pennsylvania, USA
123 Laboratorio de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
124 Departamento de Física Teórica 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 INFN Sezione di Roma I, Italy
133 Dipartimento di Fisica, Università La Sapienza, Roma, Italy
134 INFN Sezione di Roma Tor Vergata, Italy
135 Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
136 INFN Sezione di Roma Tre, Italy
137 INFN Sezione di Roma I, Italy
138 Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco
139 Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco

261804-16
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
Faculty of sciences, Mohammed V-Agdal University, 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, Shinsha University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby BC, 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, Sweden
The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, 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
Institute of Physics, Academia Sinica, Taipei, Taiwan
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 ON, Canada
TRIUMF, Vancouver BC, Canada
Department of Physics and Astronomy, York University, Toronto ON, Canada
Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki 305-8571, 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, Italy
ICTP, Trieste, Italy
Dipartimento di Chimica, Fisica e Ambiente, 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 BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC, 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
Department of Physics, Yale University, New Haven Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia
Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

Deceased.
Also at Laboratorio de Instrumentacion e Fisica Experimental de Particulas—LIP, Lisboa, Portugal.
Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at TRIUMF, Vancouver BC, Canada.
Also at Department of Physics, California State University, Fresno CA, USA.
Also at Novosibirsk State University, Novosibirsk, Russia.

Also at Fermilab, Batavia IL, USA.

Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

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, USA.

Also at Department of Physics and Astronomy, University College London, London, United Kingdom.

Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada.

Also at Department of Physics, University of Cape Town, Cape Town, South Africa.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at Manhattan College, NY NY, USA.

Also at School of Physics, Shandong University, Shandong, China.

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

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 Dipartimento di Fisica, Università La Sapienza, Roma, Italy.

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 Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at California Institute of Technology, Pasadena CA, USA.

Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France.

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

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, USA.