Search for a Supersymmetric Partner to the Top Quark in Final States with Jets and Missing Transverse Momentum at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad et al.*
(ATLAS Collaboration)
(Received 7 August 2012; published 20 November 2012)

A search for direct pair production of supersymmetric top squarks ($\tilde{t}_1$) is presented, assuming the $\tilde{t}_1$ decays into a top quark and the lightest supersymmetric particle, $\chi^0_1$, and that both top quarks decay to purely hadronic final states. A total of 16 (4) events are observed compared to a predicted standard model background of $13.5^{+3.7}_{-3.6}(4.4^{+4.1}_{-1.7})$ events in two signal regions based on $\int L dt = 4.7 \text{ fb}^{-1}$ of $pp$ collision data taken at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC. An exclusion region in the $\tilde{t}_1$ versus $\chi^0_1$ mass plane is evaluated: $370 < m_{\tilde{t}} < 465$ GeV is excluded for $m_{\chi^0_1} \sim 0$ GeV while $m_{\tilde{t}} = 445$ GeV is excluded for $m_{\chi^0_1} \leq 50$ GeV.

DOI: 10.1103/PhysRevLett.109.211802

The standard model (SM) is a successful but incomplete theory of particle interactions. Supersymmetry (SUSY) [1–9] provides an elegant cancellation of the quadratic mass divergences that would accompany a SM Higgs boson by introducing supersymmetric partners of all SM particles, such as a scalar partner of the top quark ($\tilde{t}$). Like $t\bar{t}$, direct $\tilde{t}\tilde{t}$ production is produced primarily through gluon fusion at the Large Hadron Collider (LHC). The production cross section depends mostly on the mass of the top partner and has minimal dependence on other SUSY parameters [10–12]. The LHC enables searches for direct $\tilde{t}\tilde{t}$ production at higher mass scales than previous accelerators [13–27]. The viability of SUSY as a scenario to stabilize the Higgs potential and to be consistent with electroweak naturalness [28,29] is tested by the search for $\tilde{t}$ below the TeV scale.

In this Letter, we present a search for direct $\tilde{t}\tilde{t}$ production assuming $t \rightarrow t\chi^0_1 \rightarrow bW\chi^0_1$, where $t_1$ is the lightest $t$ eigenstate and $\chi^0_1$ represents the lightest supersymmetric particle (LSP) in $R$-parity conserving models [30–34]. We target events where both $W$ bosons decay hadronically, yielding a final state with six high transverse momentum ($p_T$) jets from the all-hadronic $t\tilde{t}$ final state and large missing transverse momentum ($E_T^{miss}$) from the LSPs. The kinematics of both top quarks can therefore be fully specified by the visible decay products. Additionally, SM backgrounds from all-hadronic $t\tilde{t}$ are suppressed as there is no intrinsic $E_T^{miss}$ except from semileptonic $c$- and $b$-quark decays. The dominant background consists of $t\tilde{t}$ events that contain a $W \rightarrow \ell \nu$ decay where the lepton ($\ell$), often of $\tau$ flavor, is either lost or misidentified as a jet. These events also have large $E_T^{miss}$ from the neutrino ($\nu$).

The data were acquired during 2011 in LHC $pp$ collisions at a center-of-mass energy of 7 TeV with the ATLAS detector [35], which consists of tracking detectors surrounded by a 2 T superconducting solenoid, calorimeters, and a muon spectrometer in a toroidal magnetic field. The high-granularity calorimeter system, with acceptance coverage $|\eta| < 4.9$ [36], is composed of liquid argon with lead, copper, or tungsten absorbers and scintillator tiles with steel absorbers. This data set, composed of events with a high-$p_T$ jet and large $E_T^{miss}$ as selected by the trigger, corresponds to an integrated luminosity of 4.7 fb$^{-1}$ with a relative uncertainty of 3.9% [37–39].

Jets are constructed from three-dimensional clusters of calorimeter cells using the anti-$k_T$ algorithm with a distance parameter of 0.4 [39,40]. Jet energies are corrected [41] for losses in material in front of the active calorimeter layers, detector inhomogeneities, the noncompensating nature of the calorimeter, and the impact of multiple overlapping $pp$ interactions. These corrections are derived from test beam, cosmic-ray, and $pp$ collision data, and from a detailed GEANT4 [42] detector simulation [43]. Jets containing a $b$-hadron are identified with an algorithm exploiting both the impact parameter and secondary vertex information [44,45]. A factor correcting for the slight differences in the $b$-tagging efficiency between data and the GEANT4 simulation is applied to each jet in the simulation. The $b$-jets are restricted to the fiducial region of the tracker, $|\eta| < 2.5$. Non-$b$ backgrounds are minimized by requiring either $\geq 1$ $b$-jets with a selection corresponding to a 60% efficiency with a low $<0.2\%$ misidentification rate (tight), or $\geq 2$ $b$-jets each with 75% efficiency but a higher $\approx 1.7\%$ misidentification rate per $b$-jet (loose).

The $E_T^{miss}$ is the magnitude of $p_T^{miss}$, the negative vector sum of the $p_T$ of the clusters of calorimeter cells, calibrated according to their associated reconstructed object (e.g., jets and electrons), and of the $p_T$ of muons above 10 GeV.
within \(|\eta| < 2.4\). Events containing \(E_T^{\text{miss}}\) induced by jets associated with calorimeter noise or noncollision backgrounds [46], or by cosmic-ray muons [47,48], are removed from consideration. Large \(p_T^{\text{miss}}\) collinear with a high-\(p_T\) jet could indicate a significant fluctuation in the reconstructed jet energy or the presence of a semileptonic \(c\)- or \(b\)-quark decay. Therefore, the difference in azimuthal angle \((\Delta \phi)\) between the \(p_T^{\text{miss}}\) and any of the three highest-\(p_T\) jets in the event, \(\Delta \phi(p_T^{\text{miss}},\text{jet})\), is required to be \(>\pi/5\) radians. Fluctuations in the \(E_T^{\text{miss}}\) are also suppressed by requiring that the \(\Delta \phi\) between the above computed \(p_T^{\text{miss}}\) and one calculated with the tracking system, using tracks having \(p_T > 0.5\) GeV, is \(< \pi/3\) radians.

Events are required to have at least one jet with \(p_T > 130\) GeV in \(|\eta| < 2.8\) and \(E_T^{\text{miss}} > 150\) GeV to ensure full efficiency of the trigger. At least five other jets having \(p_T > 30\) GeV and \(|\eta| < 2.8\) must be present. In addition to the jet and \(E_T^{\text{miss}}\) requirements, events containing “loose” electrons [49,50] with \(p_T > 20\) GeV and \(|\eta| < 2.47\) that do not overlap with any jet within \(\Delta R < 0.4\), where \(\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}\), are rejected. Similarly, events with muons [47–51] having \(p_T > 10\) GeV and \(|\eta| < 2.4\) that are separated by \(\Delta R > 0.4\) from the nearest jet are rejected. A jet with \(1–4\) tracks and \(\Delta \phi(p_T^{\text{miss}},\text{jet}) < \pi/5\) indicates a likely \(W \rightarrow \tau \nu\) decay. Events with such \(\tau\)-like jets that have transverse mass 

\[
m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \Delta \phi)} < 100\text{ GeV}
\]

are rejected.

The presence of high-\(p_T\) top quarks that decay through \(t \rightarrow bW \rightarrow b\ell \nu\) in the \(t\bar{t}t_1\) final state is exploited to further reduce SM backgrounds by only considering events with reconstructed three-jet invariant masses consistent with the top-quark mass \((m_t)\). A clustering technique resolves the combinatorics associated with high-multiplicity jet events. The three closest jets in the \(\eta-\phi\) plane are combined to form one triplet; a second triplet is formed from the remaining jets by repeating the procedure. The resulting three-jet mass \((m_{jjj})\) spectrum is shown in Fig. 1 for the control region constructed from \(\ell +\text{jets}\) events (defined below). There is a clear peak associated with the hadronically decaying top quarks above a small non-\(t\bar{t}\) background. A requirement of \(80 < m_{jjj} < 270\) GeV is placed on each reconstructed triplet in the event. The kinematics of the \(t \rightarrow bW \rightarrow \ell \nu\) decay is exploited to further reduce the dominant \(\ell +\text{jets} \bar{t}\) background, as the \(m_T^{\text{jet}}\) distribution of the \(p_T^{\text{miss}}\) and \(b\)-jet \((m_T^{\text{jet}})\) has an end point at \(m_t\). When there are \(\geq 2\) loose \(b\)-jets, the \(m_T^{\text{jet}}\) for the \(b\)-jet closest to the \(p_T^{\text{miss}}\) is required to be \(>175\) GeV. The largest \(m_T^{\text{jet}}\), calculated for each of the four highest-\(p_T\) jets, is required to be \(>175\) GeV in the case of only one tight \(b\)-jet.

Two signal regions (SR) are defined including the above kinematic and mass requirements. The first, which requires \(E_T^{\text{miss}} > 150\) GeV (SRA), is optimized for low \(m_{t_1}\), while the second, requiring \(E_T^{\text{miss}} > 260\) GeV (SRB), is used for higher \(m_{t_1}\). Using these signal regions, the search is most sensitive to \(t\bar{t}r_1\) production with \(350 \leq m_{t_1} \leq 500\) GeV and \(m_{\bar{t}_1} \ll m_{t_1}\). Signal events are simulated using HERWIG++ [52] with the MRST2007LO* [53] parton distribution functions (PDF) generated with the \(t\bar{t}\) and \(\chi_1^0\) masses at fixed values in a grid with 50 GeV spacing. The mixing between \(t\bar{t}_L\) and \(t\bar{t}_R\) is chosen such that the lightest scalar top is mostly the partner of the right-handed top quark. The branching fraction of \(t \rightarrow t\chi_1^0\) is set to 100% and the top-quark mass is set to 172.5 GeV. Signal cross sections are calculated to next-to-leading order in the strong coupling constant, including the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO + NLL) [10–12]. The nominal production cross section and associated uncertainty are taken from an envelope of cross section predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [54]. The \(t\bar{t}r_1\) cross section for \(m_{t_1} = 400\) GeV is \(\sigma_{t\bar{t}r_1} = 0.21 \pm 0.03\) pb.

In the signal region, the dominant source of SM backgrounds is \(t\bar{t} \rightarrow \tau +\text{jets}\) events where the \(\tau\) lepton is reconstructed as a jet. Additional, smaller, backgrounds include other \(t\bar{t} \rightarrow \ell +\text{jets}\) final states, \(t\bar{t} + V\) where \(V\) represents a \(W\) or \(Z\) boson, single top-quark production, \(V + \text{jets}\), and \(VV + \text{jets}\). The \(t\bar{t}\) events are produced with ALPGEN [55] using the CTEQ6L1 PDF [56] and interfaced to HERWIG [57,58] for particle production and JIMMY [59] for the underlying event model. TAUOLA was used to model the decay of \(\tau\) leptons [60]. Additional \(t\bar{t}\) samples generated with MC@NLO [61,62] and ACERMC [63], interfaced to HERWIG and JIMMY, are used to estimate event generator
systematic uncertainties. Samples of \( \bar{t}t + V \) are produced with MADGRAPH [64] interfaced to PYTHIA [58,65,66]. Single top events are generated with MC@NLO [67,68] and ACERMC. The associated production of W and Z bosons and light and heavy-flavor jets is simulated using ALPGEN; diboson production is simulated with SHERPA [69].

All samples are passed through the GEANT4 simulation of the ATLAS detector, and are reconstructed in the same manner as the data. The simulation includes the effect of multiple \( pp \) interactions and is weighted to reproduce the observed distribution of the number of interactions per bunch crossing. SM event samples are normalized to the observed distribution of the number of interactions per bunch crossing. SM event samples are normalized to the results of higher-order calculations using the cross sections

\[
\sigma_{\text{SM}} = \frac{\text{observed}}{\text{expected}}
\]

and light and heavy-flavor jets is simulated using ALPGEN; consistent with originating from a

\[
E_T^{\text{miss}} = p_T + \text{miss}
\]

The lepton is treated as a jet of the same energy and momentum, mimicking the effect of the \( \tau \) lepton. Effects of additional \( E_T^{\text{miss}} \) from the \( \tau \) neutrino are smaller than the statistical uncertainties. The normalization is scaled by 0.66 ± 0.05 to bring the \( \geq 6 \) jet \( \ell + \) jets ALPGEN \( \bar{t}t \) events into agreement with the data after recalculating all quantities except \( E_T^{\text{miss}} \); the uncertainty quoted here is statistical only. This scale factor is used in Figs. 1–3. The normalization is validated with an orthogonal \( \bar{t}t \)-dominated sample created from SRA by selecting events with \( \tau \)-like jets; the requirement on \( m_T^{\text{jet}} \) is removed to increase the sample size. The \( m_T \) of \( \tau \)-like jets is shown in Fig. 2, where the \( \bar{t}t \) sample has been normalized as described above. Expectations from the simulation agree with the data within uncertainties. Contributions to the signal region from QCD multijet and all-hadronic \( \bar{t}t \) production are estimated with a data-driven technique [71]. Jets are smeared in a low-\( E_T^{\text{miss}} \) data sample using response functions derived from control regions dominated by multijet events. The expected number of such events is 0.2 ± 0.2 in SRA after the full event selection.

The \( E_T^{\text{miss}} \) distribution in SRA is shown in Fig. 3 for data, for the SM backgrounds, and for expectations of \( \bar{t}t \)-like production with \( m_{\bar{t}t} = 400 \) GeV and \( m_{\chi} = 1 \) GeV. Numbers of events and combined statistical and systematic uncertainties, for both SRA and SRB, are tabulated in Table I. Uncertainties in the event generators, including the impact of initial- and final-state radiation, are the dominant source of systematic uncertainty of 28% (23%) for the background in SRA (SRB). Other major sources of uncertainty include 22% (32%) for the jet energy calibration, 6.5% (6.8%) for jet energy resolution, 5.9% (6.2%) for \( b \)-jet identification, and 1.4% (1.5%) for \( E_T^{\text{miss}} \) in SRA (SRB).
TABLE I. The numbers of expected events for the SM backgrounds and an example SUSY signal point, and the observed number of events in data. The 95% C.L. upper limit on the observed (expected) visible cross section, as defined in the text, is appended below.

<table>
<thead>
<tr>
<th>Process</th>
<th>SRA</th>
<th>SRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>$E_T^{miss}$ &gt; 150 GeV</td>
<td>$E_T^{miss}$ &gt; 260 GeV</td>
</tr>
<tr>
<td></td>
<td>9.2 ± 2.7</td>
<td>2.3 ± 0.6</td>
</tr>
<tr>
<td>$t\bar{t} + W/Z$</td>
<td>0.8 ± 0.2</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>Single top</td>
<td>0.7 ± 0.4</td>
<td>0.2 ± 0.3</td>
</tr>
<tr>
<td>$Z$ + jets</td>
<td>1.3 ± 0.1</td>
<td>0.9 ± 0.7</td>
</tr>
<tr>
<td>$W$ + jets</td>
<td>1.2 ± 0.1</td>
<td>0.5 ± 0.4</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Multijets</td>
<td>0.2 ± 0.2</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td>Total SM</td>
<td>13.5 ± 3.7</td>
<td>4.4 ± 1.7</td>
</tr>
<tr>
<td>SUSY ($m_{\tilde{t}<em>1}, m</em>{\tilde{g}}$) = (400, 1) GeV</td>
<td>14.8 ± 4.0</td>
<td>8.9 ± 3.1</td>
</tr>
<tr>
<td>Data (observed)</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Visible cross section limit [fb]</td>
<td>2.9 (2.5)</td>
<td>1.3 (1.3)</td>
</tr>
</tbody>
</table>

The number of observed events in the data is well matched by the SM background. These results are interpreted as exclusion limits for $m_{\tilde{t}_1}$ and $m_{\tilde{g}}$ using a CL$_s$ likelihood ratio combining Poisson probabilities for signal and background [72]. Systematic uncertainties are treated as nuisance parameters assuming Gaussian distributions. Uncertainties associated with jets, $b$-jets, $E_T^{miss}$, and luminosity are fully correlated between signal and background; the others are assumed to be uncorrelated. The expected limits for the signal regions are evaluated for each $(m_{\tilde{t}_1}, m_{\tilde{g}})$ point; the SR with the better expected sensitivity is used for that point. The expected and observed 95% C.L. exclusion limits, interpolating across points, are displayed in Fig. 4. The $-1\sigma$ observed limit contour that accounts for theoretical uncertainties on the SUSY cross sections is maximum at $(m_{\tilde{t}_1}, m_{\tilde{g}}) = (445, 50)$ GeV. Top squark masses between 370 and 465 GeV are excluded for $m_{\tilde{g}} \sim 0$ GeV. These values are derived from the $-1\sigma$ observed limit contour to account for theoretical uncertainties on the SUSY cross sections. The 95% C.L. upper limit on the number of events beyond the SM in each signal region, divided by the integrated luminosity, yields limits on the observed (expected) visible cross sections of 2.9 (2.5) fb in SRA and 1.3 (1.3) fb in SRB.

In conclusion, we have presented a search for the direct production of $\tilde{t}_1\tilde{t}_1$ in the $t\bar{t}0\chi^0_1$ decay channel, assuming 100% branching fraction for $\tilde{t}_1 \rightarrow t\chi^0_1$. A total of 16 (4) events are observed compared to a predicted standard model background of $13.5^{+3.7}_{-3.6}(4.4^{+1.7}_{-1.3})$ events in two signal regions based on $\int L dt = 4.7 \text{ fb}^{-1}$ of $pp$ collision data taken at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC. No evidence for $\tilde{t}_1\tilde{t}_1$ is observed in data and 95% C.L. limits are set on $\tilde{t}_1\tilde{t}_1$ production as a function of $m_{\tilde{t}_1}$ and $m_{\tilde{g}}$.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR, and VSC CR, Czech Republic; DNR, DNSRC, and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS and CEA-DSM/IRFU, France; GNAS, Georgia; BBM, 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; MNISR, 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 com-

![Fig. 4](color online). Expected and observed 95% C.L. exclusion limits in the plane of $m_{\chi_1^0}$ vs $m_{\tilde{t}_1}$, assuming 100% branching fraction for $\tilde{t}_1 \rightarrow t\chi_1^0$. The dashed line shows the expected limit at 95% C.L. with the shaded region indicating the ±1σ exclusions due to experimental uncertainties. Observed limits are indicated by the solid contour (nominal) and the dotted contours (obtained by varying the SUSY cross section by the theoretical uncertainties). The inner dotted contour indicates the excluded region. The dashed diagonal line represents the kinematic limit for the $t\chi^0_1$ final state. The numbers overlaid on the plot represent the 95% C.L. excluded visible cross sections in pb.
puting 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.

[36] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the z axis along the beam pipe. Cylindrical coordinates (r, φ) are used in the transverse plane, being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as \( \eta = -\ln(\tan(\theta/2)) \).
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 INFN Sezione di Lecce, Italy
73 Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
74 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
75 Department of Physics, Jozef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
76 School of Physics and Astronomy, Queen Mary University of London, London, 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 Physikalisches Institut, Universität Heidelberg, Heidelberg, Germany
80 Dipartimento di 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 et CNRS/IN2P3, Marseille, France
84 Department of Physics, University of Massachusetts, Amherst Massachusetts, USA
85 Department of Physics, McGill University, Montreal Quebec, Canada
86 School of Physics, University of Melbourne, Victoria, Australia
87 Department of Physics, The University of Michigan, Ann Arbor Michigan, USA
88 Department of Physics and Astronomy, Michigan State University, East Lansing Michigan, USA
89a INFN Sezione di Milano, Italy
89b 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 Massachusetts, USA
93 Group of Particle Physics, University of Montreal, Montreal Quebec, 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 and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
102 INFN Sezione di Napoli, Italy
103 Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
104 Department of Physics and Astronomy, University of New Mexico, Albuquerque New Mexico, USA
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, Université 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 INFN Sezione di Pavia, Italy
120 Dipartimento di Fisica, Università di Pavia, Pavia, Italy
121 Petersburg Nuclear Physics Institute, Gatchina, Russia
122 INFN Sezione di Pisa, Italy
123 Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh Pennsylvania, USA
125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
126 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
127 Department of Physics and Astronomy, University of Texas at Austin, Austin Texas, USA
128 Centro de Instrumentación de Física Fundamental, Universitat Autònoma de Barcelona, Bellaterra, Spain
129 Department of Physics, University of Utah, Salt Lake City Utah, USA
130 Department of Physics, University of Virginia, Charlottesville Virginia, USA
131 INFN Sezione di Varenna, Italy
132 Department of Physics, Virginia Tech, Blacksburg Virginia, USA
133 Laborator de Fisica Particulas and Fisica Experimental de Particulas, Lisboa, Portugal
134 Laboratorio de Instrumentacion y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
135 Department of Physics, University of Wisconsin, Madison Wisconsin, USA
136 Department of Physics, Woods Hole Oceanographic Institute, Woods Hole Massachusetts, USA
137 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic

211802-16
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 Saskatchewan, 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 Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco
138 Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
139 Faculté des Sciences Semlalia, Université Mohamed Premier and LPTPM, Oujda, Morocco
140 Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
141 INFN Sezione di Roma I, Italy
142 Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
143 INFN Sezione di Roma Tre, Italy
144 Faculté des Sciences Ain Chock, Faculté des Sciences de Tunis, Université de Tunis, Tunisia
145 INFN Sezione di Roma I, Italy
146 INFN Sezione di Roma Tor Vergata, Italy
147 INFN Sezione di Roma Tre, Italy
148 INFN Sezione di Roma Tor Vergata, Italy
149 INFN Sezione di Roma Tre, Italy
14a Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
14b Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
14c Department of Physics, University of Johannesburg, Johannesburg, South Africa
14d School of Physics, University of the Witwatersrand, Johannesburg, South Africa
14e Department of Physics, Stockholm University, Sweden
14f The Oskar Klein Centre, Stockholm, Sweden
14g Department of Physics, Royal Institute of Technology, Stockholm, Sweden
14h Department of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook New York, USA
14i Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
14j School of Physics, University of Sydney, Sydney, Australia
14k Institute of Physics, Academia Sinica, Taipei, Taiwan
14l Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
14m Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
14n Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
14o International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
14p Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
14q Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
14r Department of Physics, University of Toronto, Toronto Ontario, Canada
14s TRIUMF, Vancouver British Columbia, Canada
14t Department of Physics and Astronomy, York University, Toronto Ontario, Canada
14u Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki 305-8571, Japan
14v Science and Technology Center, Tufts University, Medford Massachusetts, USA
14w Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
14x Department of Physics and Astronomy, University of California Irvine, Irvine California, USA
14y INFN Gruppo Collegato di Udine, Italy
14z ICTP, Trieste, Italy
15a Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
15b Department of Physics, University of Illinois, Urbana Illinois, USA
15c Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
15d 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-CNMM), University of Valencia and CSIC, Valencia, Spain
15e Department of Physics, University of British Columbia, Vancouver British Columbia, Canada
15f Department of Physics and Astronomy, University of Victoria, Victoria British Columbia, Canada
15g Department of Physics, University of Warwick, Coventry, United Kingdom

211802-17
171 Waseda University, Tokyo, Japan
172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
173 Department of Physics, University of Wisconsin, Madison Wisconsin, USA
174 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
175 Department of Physics, Yale University, New Haven Connecticut, USA
176 Yerevan Physics Institute, Yerevan, Armenia
177 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

a Deceased.
b Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal.
c Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
e Also at TRIUMF, Vancouver British Columbia, Canada.
f Also at Department of Physics, California State University, Fresno CA, USA.
g Also at Novosibirsk State University, Novosibirsk, Russia.
h Also at Fermilab, Batavia IL, USA.
i Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
j Also at Department of Physics, UASLP, San Luis Potosi, Mexico.
k Also at Universita di Napoli Parthenope, Napoli, Italy.
l Also at Institute of Particle Physics (IPP), Canada.
m Also at Department of Physics, Middle East Technical University, Ankara, Turkey.

Also at Louisiana Tech University, Ruston LA, USA.
Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
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, New York 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, Guangzhou, China.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at Dipartimento di Fisica, Universitá 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, Université Paris-Sud and CNRS/IN2P3, Orsay, France, USA.
Also at Nevis Laboratory, Columbia University, Irvington NY, USA.
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.
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.