Search for scalar bottom quark pair production with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV


DOI
10.1103/PhysRevLett.108.181802

Publication date
2012

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):
https://doi.org/10.1103/PhysRevLett.108.181802
Supersymmetry (SUSY) [1–9] is a theory that provides an extension of the standard model (SM) and naturally resolves the hierarchy problem by introducing supersymmetric partners of the known bosons and fermions. In the framework of a generic $R$-parity conserving minimal supersymmetric extension of the SM, the MSSM, SUSY particles are produced in pairs and the lightest supersymmetric particle is stable, providing a possible candidate for dark matter. The scalar partners of right-handed and left-handed quarks (squarks) can mix to form two mass eigenstates. In a large variety of models, the lightest supersymmetric particle is the lightest neutralino ($\tilde{\chi}^0_1$) and the mass of the lightest scalar bottom quark eigenstate (sbottom, $\tilde{b}_1$) can be significantly lower than the other squark masses. Consequently, $\tilde{b}_1$ could be produced with large cross sections at the Large Hadron Collider (LHC). In this Letter, a search for direct sbottom pair production is presented, assuming a SUSY particle mass hierarchy such that the sbottom decays exclusively into a $b$ quark and a $\tilde{\chi}^0_1$. The expected signal is characterized by the presence of two jets originating from the hadronization of the $b$ quarks and missing transverse momentum—its magnitude is referred to as $E_{\text{miss}}^\text{miss}$ in the following—resulting from the undetected neutralinos. Results of searches for direct sbottom production have been previously reported by the Tevatron [10,11] and LEP [12] experiments. The search described here extends these results using 2.05 fb$^{-1}$ of 7 TeV $pp$ collision data recorded by the ATLAS experiment at the LHC.

The ATLAS detector [13] consists of inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer with a toroidal magnetic field. The inner detector, in combination with the 2 T field from the solenoid, provides precision tracking of charged particles for $|\eta| < 2.5$ [14]. It consists of a silicon pixel detector, a silicon strip detector, and a straw tube tracker that also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. It is composed of sampling calorimeters with either liquid argon or scintillating tiles as the active media. The muon spectrometer has separate trigger and high-precision tracking chambers which provide muon identification and measurement for $|\eta| < 2.7$.

This search uses data recorded between March and August 2011 at the LHC. After the application of beam, detector, and data quality requirements, the data set corresponds to a total integrated luminosity of $2.05 \pm 0.08$ fb$^{-1}$ [15,16]. The data are selected with a three-level trigger system that requires a high transverse momentum ($p_T$) jet and missing transverse momentum [17]. Events are required to have a reconstructed primary vertex associated with five or more tracks, consistent with the beam spot position.

Jets are reconstructed offline from three-dimensional topological calorimeter energy clusters by using the anti-$k_T$ jet algorithm [18,19] with a radius parameter of 0.4. The measured jet energy is corrected for inhomogeneities and for the noncompensating nature of the calorimeter by using $p_T$- and $\eta$-dependent correction factors ([20] and references therein). Only jet candidates with $p_T > 20$ GeV within $|\eta| < 2.8$ are retained. During the data-taking period, a localized electronics failure in the liquid argon barrel calorimeter created an inactive region in the second and third calorimeter layers ($\Delta\eta \times \Delta\phi \approx 1.4 \times 0.2$) in which on average 30% of the incident jet energy is not measured. If either of the two selected leading jets fall in this region the event is rejected. The loss in signal acceptance is smaller than 10% for the models considered.
Electron candidates are required to have $p_T > 20$ GeV, $|\eta| < 2.47$, and satisfy the “medium” selection criteria reported in [21]. Muon candidates are required to have $p_T > 10$ GeV, $|\eta| < 2.4$ and are identified as a match between an extrapolated inner detector track and one or more track segments in the muon spectrometer. Additional requirements are applied to electron and muon candidates when defining lepton ($\ell = e, \mu$) control regions. In this case, electrons must have $p_T > 25$ GeV, pass the “tight” selection criteria in [21] and be isolated—the $p_T$ sum of tracks within a cone in the $(\eta, \phi)$ plane of radius $\Delta R = 0.2$ around the candidate, $\Sigma p_T$, must be less than 10% of the electron $p_T$. Muons must have $p_T > 25$ GeV, longitudinal and transverse impact parameter within 1 mm and 0.2 mm of the primary vertex, respectively, and $\Sigma p_T < 1.8$ GeV. Following the object reconstruction described above, overlaps between jet candidates and electrons or muons are resolved. Any jet within a distance $\Delta R = 0.2$ of a “medium” electron candidate is discarded. Any remaining lepton within $\Delta R = 0.4$ of a jet is discarded.

The calculation of $E_T^{\text{miss}}$ is based on the magnitude of the vectorial sum of the $p_T$ of the reconstructed jets (with $p_T > 20$ and $|\eta| < 4.5$), leptons—including nonisolated muons—and the calorimeter clusters not belonging to reconstructed objects [22]. Events must pass basic quality criteria against detector noise and noncollision backgrounds and are selected with at least one jet with $p_T > 130$ GeV and $E_T^{\text{miss}} > 130$ GeV to ensure full trigger efficiency, and one additional jet with $p_T > 50$ GeV. Both jets are required to be associated to the primary interaction and to originate from a $b$ quark using a tagging algorithm that exploits both impact parameter and secondary vertex information. Jets are tagged for $|\eta| < 2.5$ and the parameters of the algorithm are chosen such that a tagging efficiency of 60%, 10%, and <1% is achieved for $b$ jets, $c$ jets, and light flavor or gluon jets, respectively, in $t\bar{t}$ events in Monte Carlo (MC) simulation [23]. Events with identified electron or muon candidates or additional jets with $p_T > 50$ GeV are vetoed to exploit the topology of the addressed signal. The multijet background contribution with large $E_t^{\text{miss}}$, due to the mismeasurement of the jet energies in the calorimeters or to neutrino production in heavy quark decays, is suppressed by requiring the smallest azimuthal separation between the $E_t^{\text{miss}}$ direction and any of the two leading jets, $\Delta \phi_{\text{min}}$, to be above 0.4. If a third jet with $30 < p_T < 50$ GeV is found in the event, its azimuthal separation with the $E_t^{\text{miss}}$ must be above 0.2, where jets with $p_T$ below 30 GeV are not used due to the large expected contribution from multiple interactions. In addition, the ratio of $E_T^{\text{miss}}$ to the scalar sum of $E_T^{\text{miss}}$ and the transverse momenta of the two leading jets is required to be above 0.25. A selection based on the boost-corrected transverse mass [24], $m_{CT}$, is employed to further discriminate sbottom pair production from SM background processes.

For two identical decays of heavy particles into two visible particles $v_1$ and $v_2$, and into invisible particles, the transverse mass [25] is defined as $(p_T(v_1) + p_T(v_2))^2 - (p_T(v_1) - p_T(v_2))^2)^{1/2}$. The boost-corrected transverse mass conservatively corrects to account for boosts in the transverse plane due to initial state radiation and hence protects the expected endpoint in the distribution. In the case of sbottom pair production with $b_1 \rightarrow b_h \tilde{g}$, $m_{CT}$ is expected to have an endpoint at $[m(b_1)^2 - m(\tilde{g})^2]/m(b_1)$. To maximize the sensitivity across the $b_1 - \tilde{g}^0$ mass plane, three signal regions (SRs) are defined as a function of the $m_{CT}$ threshold, with $m_{CT} > 100$, 150 and 200 GeV.

Simulated event samples are used to aid in the description of the background and to model the SUSY signal. Top quark pair and single top production are simulated with MC@NLO [26], fixing the top quark mass at 172.5 GeV, and the next-to-leading-order (NLO) parton density function (PDF) set CTEQ6.6 [27]. Samples of $W +$ jets, $Z +$ jets with light and heavy flavor jets, and $t\bar{t}$ with additional $b$ jets, $t\bar{t}bb$, are generated with ALPGEN [28] and PDF set CTEQ6L1 [29]. The fragmentation and hadronization for the ALPGEN and MC@NLO samples are performed with HERWIG [30], using JIMMY [31] for the underlying event. Samples of $Zt\bar{t}$ and $Wt\bar{t}$ are generated with MADGRAPH [32] interfaced to PYTHIA [33]. Diboson ($WW$, $WZ$, $ZZ$) samples are generated with HERWIG. All background cross sections are normalized to the results of higher order calculations [34]. The signal samples are generated in the MSSM framework at fixed $b_1$ and $\tilde{g}^0$ masses, with $BR(b_1 \rightarrow b \tilde{g}^0) = 100\%$, using the HERWIG++ v2.4.2 Monte Carlo program. The SUSY sample yields are normalized to the results of NLO calculations, as obtained using the PROSPINO [35] v2.1 program. The CTEQ6.6M [36] parameterization of the PDFs is used and the renormalization and factorization scales, $\mu_R, \mu_F = \mu$, are set to the sbottom mass. NLO cross sections vary between 12 pb and 0.05 pb for sbottom masses in the range 200–500 GeV. The MC samples are produced using parameters tuned as described in [37,38] and are processed through a detector simulation [39] based on GEANT4 [40]. Effects of multiple proton-proton interactions per bunch crossing are included in the simulation.

The signal efficiencies vary across the $b_1 - \tilde{g}^0$ mass plane. As an example, for the SR with $m_{CT} > 150$ GeV the efficiencies are found to be between 1% and 6% as the sbottom mass increases from 200 GeV to 500 GeV, and between 6% and 2% as $\Delta m = m(b_1) - m(\tilde{g})^2$ decreases. The sensitivity for $\Delta m$ below 130 GeV is limited by the selection in $m_{CT}$ and the trigger-driven requirements on the leading jet $p_T$ and $E_T^{\text{miss}}$.

The main SM processes contributing to the background are top quark pair and single top production as well as associated production of $W/Z$ bosons with heavy flavor jets—referred to as $Z +$ h and $W +$ h, respectively. In particular, the signal region with $m_{CT} > 100$ GeV is
dominated by semileptonic \( t\bar{t} \) events as a consequence of the \( m_{\text{CT}} \) endpoint at 135 GeV in top pair production, while the signal regions with \( m_{\text{CT}} > 150, 200 \) GeV are dominated by the irreducible \( Z + \text{hf} \) production with \( Z \rightarrow \nu \bar{\nu} \) decay, followed by \( W + \text{hf} \) production with \( \tau \nu \). Contributions from multijet, diboson, and associated production of \( \tau \nu \) with \( W, Z \) or additional \( b \) jets are subdominant. Noncollision backgrounds were found to be negligible.

The estimation of the main background processes is carried out by defining data control regions where each background component is dominant. The background estimate in each SR is derived through “transfer factors” equivalent to the ratio of expected event yields in the signal and control regions estimated using the MC simulation. The contributions from top and \( W + \text{hf} \) production are estimated using a transfer factor from a control region where events have exactly one electron or muon, \( E^{\text{miss}} > 80 \) GeV, and at least two \( b \) jets with \( p_T > 130 \) GeV and 50 GeV. The transverse mass of the \((\ell, E^{\text{miss}})\) system is required to be between 40 GeV and 100 GeV to select events containing \( \ell \nu \). The contribution to this control region from other SM processes accounts for less than 10% of the total and is estimated from simulation. The \( Z + \text{hf} \) contribution is estimated using a transfer factor from a control region where events have two opposite-sign same-flavor leptons \((\ell^+ \ell^-)\), at least two \( b \) jets with \( p_T > 80 \) GeV and 50 GeV, and invariant mass of the two leptons \( m_{\ell\ell} \) between 81 GeV and 101 GeV (Z-mass interval). In addition, the transverse momentum of the \((\ell^+, \ell^-), E^{\text{miss}}\) system is required to be greater than 50 GeV. The contribution from top quark production in this control region accounts for about 50% of the total and is subtracted using a sideband estimate in two 40 GeV mass windows above and below the Z-mass interval.

The subdominant background contribution from dibosons, \( Zt, Wt, t\bar{t}b \) is estimated using MC simulation and increases from 1% to 10% of the total SM prediction as the selection cut on \( m_{\text{CT}} \) increases from 100 GeV to 200 GeV. Finally, the residual multijet background is estimated using data. A sample of multijet events with large \( E^{\text{miss}} \) is constructed starting from multijet events with low \( E^{\text{miss}} \) and smearing the momenta of jets with response functions. This prediction is tuned in a multijet dominated control region where the requirement on \( \Delta \phi_{\text{min}} \) is inverted [41]. The contribution is found to be less than 5% across the SRs.

The total systematic uncertainty on the background expectations varies from 21% to 44%, increasing with the \( m_{\text{CT}} \) selection applied, and is dominated by the uncertainty due to finite data statistics in the control regions. The next dominant uncertainty on the SM estimates derives from the residual uncertainties on the theoretical modeling of the top background. It varies between 10% and 15% depending on the SR and is evaluated using additional MC samples: aceMC [42,43], for the impact of initial and final state radiation, PYTHIA and POWHEG [44] for choice of fragmentation model and generator. The residual uncertainties on the \( W + \text{hf} \) and \( Z + \text{hf} \) theoretical modeling account for less than 5% of the total uncertainty. Finally, the experimental uncertainties on the \( b \)-tagging efficiency and jet energy scale and resolution are also considered; across the SRs they vary between 5% and 8% and between 6% and 9%, respectively.

For the SUSY signal processes, uncertainties on renormalization and factorization scales and on the PDF affect the theoretical cross section. PDF uncertainties are estimated using the CTEQ6.6M PDF error eigenvector set and are between 7% and 16% depending on the bottom mass. The variation of renormalization and factorization scales by a factor of 2 changes the nominal signal cross section, \( \sigma_{\text{nom}} \), by \( \pm 15\% \), independently of \( m_{\tilde{b}} \). In the following, the cross sections calculated with scale settings \( 2 \times \mu \) and \( \mu/2 \) are referred to as \( \sigma_{\text{min}} \) and \( \sigma_{\text{max}} \), respectively. The impact of detector-related uncertainties, such as the jet energy scale and \( b \)-tagging, on the signal event yields varies between 35% and 45% and is dominated by the uncertainties on the \( b \)-tagging efficiency.

Table I reports the observed number of events and the SM predictions before the \( m_{\text{CT}} \) selection and for each SR. Both transfer factor and MC estimates are given. The data are in good agreement with the SM background expectations within uncertainties in all cases. Figure 1 shows the measured \( m_{\text{CT}} \) and \( E^{\text{miss}} \) distributions before \( m_{\text{CT}} \) selection compared to the SM predictions. MC estimates are rescaled to match the total integral predicted by the transfer factor estimates for \( Z + \text{hf} \) and the sum of top and \( W + \text{hf} \), respectively. For illustrative purposes, the distributions expected for the MSSM scenario with sbottom and neutralino masses of 300 GeV and 100 GeV, respectively, are added to the SM predictions. The results are translated into 95% confidence-level (C.L.) upper limits on contributions from new physics using the CLs prescription [45]. The SR with the best expected sensitivity at each point in parameter space is adopted as the nominal result. Figure 2 shows the observed and expected exclusion limits at 95% C.L. in the \( \tilde{b}_1 - \tilde{\chi}_1^0 \) mass plane, assuming \( \text{BR}(\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0) = 100\% \). Systematic uncertainties are treated as nuisance parameters and their correlations are taken into account. For the MSSM scenarios considered, the upper limit at 95% C.L. on the sbottom masses obtained in the most conservative hypothesis, \( \sigma_{\text{min}} \), is 390 GeV for \( m_{\tilde{b}_1} = 0 \). The limit becomes 405 GeV for \( \sigma_{\text{nom}} \) and 420 GeV for \( \sigma_{\text{max}} \). Neutralino masses of 120 GeV are excluded for \( 275 < m_{\tilde{b}_1} < 350 \) GeV. The three signal regions are used to set limits on the effective cross section of new physics models, \( \sigma_{\text{eff}} \), including the effects of experimental acceptance and efficiency. The observed (expected)
TABLE I. Expected and measured number of events for an integrated luminosity of 2.05 fb⁻¹.

<table>
<thead>
<tr>
<th>m_{CT} [GeV]</th>
<th>Top, W + hf TF (MC)</th>
<th>Z + hf TF (MC)</th>
<th>Others MC + JS</th>
<th>Total SM</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>67 ± 10</td>
<td>23 ± 8</td>
<td>3.6 ± 1.5</td>
<td>94 ± 16</td>
<td>96</td>
</tr>
<tr>
<td>(60 ± 25)</td>
<td>(16 ± 9)</td>
<td></td>
<td></td>
<td>(80 ± 35)</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>36 ± 10</td>
<td>23 ± 9</td>
<td>3.1 ± 1.6</td>
<td>62 ± 13</td>
<td>56</td>
</tr>
<tr>
<td>(34 ± 16)</td>
<td>(12 ± 7)</td>
<td></td>
<td></td>
<td>(49 ± 25)</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>12 ± 5</td>
<td>12 ± 6</td>
<td>2.7 ± 0.9</td>
<td>27 ± 8</td>
<td>28</td>
</tr>
<tr>
<td>(13 ± 8)</td>
<td>(8.3 ± 4.7)</td>
<td></td>
<td></td>
<td>(24 ± 13)</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>3.2 ± 1.6</td>
<td>3.9 ± 3.2</td>
<td>1.0 ± 0.9</td>
<td>8.1 ± 3.5</td>
<td>10</td>
</tr>
<tr>
<td>(4.1 ± 3.4)</td>
<td>(2.8 ± 1.5)</td>
<td></td>
<td></td>
<td>(8.0 ± 4.9)</td>
<td></td>
</tr>
</tbody>
</table>

excluded values of σ_{diff} at 95% C.L. are 13.4 fb, 9.6 fb, and 5.6 fb (15.2 fb, 9.2 fb, and 4.7 fb), respectively, for m_{CT} > 100, 150, and 200 GeV.

In summary, we report results of a search for sbottom pair production in pp collisions at √s = 7 TeV, based on 2.05 fb⁻¹ of ATLAS data. The events are selected with large E_T^{miss} and two jets consistent with originating from b quarks in the final state. The results are in agreement with SM predictions for backgrounds and translate into 95% C.L. upper limits on sbottom and neutralino masses in a given MSSM scenario for which the exclusive decay b_1 → bχ_1⁰ is assumed. For neutralino masses below 60 GeV, sbottom masses up to 390 GeV are excluded, significantly extending previous results.

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; DNRF, DNSRC, 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), CERN-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.


ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis coinciding with the axis of the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. 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

\[ \eta = -\ln\tan(\theta/2) \]


(ATLAS Collaboration)
28 Department of Physics, Carleton University, Ottawa ON, Canada
29 CERN, Geneva, Switzerland
30 Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
31a Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
31b Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
32 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
32b Department of Modern Physics, University of Science and Technology of China, Anhui, China
32c Department of Physics, Nanjing University, Jiangsu, China
32d 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, New York, USA
35 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
36b INFN Sezione di Genova, Italy
36a INFN Gruppo Collegato di Cosenza, Italy
36b 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, Texas, USA
40 DESY, Hamburg and Zeuthen, Germany
41 Department of Physics, Duke University, Durham, North Carolina, USA
42 SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
43 INFN Laboratori Nazionali di Frascati, Frascati, Italy
44 Institute for Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
45 Department of Physics, Technical University Dresden, Dresden, Germany
46 SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br, Germany
48 Section de Physique, Université de Genève, Geneva, Switzerland
49b INFN Sezione di Genova, Italy
49a INFN Gruppo Collegato di Cosenza, Italy
50a E. Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi, Georgia
50b High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
51 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
52 SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
53 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
54 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
55 Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
56 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
57c ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
58 Faculty of Science, Hiroshima University, Hiroshima, Japan
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 Department of Physics, Indiana University, Bloomington, Indiana, USA
61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
62 University of Iowa, Iowa City, Iowa, USA
63 Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
64 Joint Institute for Nuclear Research, Dubna, Russia
65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
66 Graduate School of Science, Kobe University, Kobe, Japan
67 Kyoto University of Education, Kyoto, Japan
68 University of Louisville, Louisville, Kentucky, USA
69 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
70 Physics Department, Lancaster University, Lancaster, United Kingdom
71 INFN Sezione di Lecce, Italy
71b Dipartimento di Fisica, Università del Salento, Lecce, Italy
72 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
73 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
74 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
75 Department of Physics and Astronomy, University College London, London, United Kingdom
76 Department of Physics and Astronomy, University College London, London, United Kingdom

Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot, and CNRS/IN2P3, Paris, France
Fysiska Institutionen, Lunds Universitet, Lund, Sweden
Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
INFN Sezione di Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P. N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli, Italy
Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
Department of Physics, New York University, New York, New York, USA
Ohio State University, Columbus, Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
INFN Sezione di Pavia, Italy
Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal
Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina SK, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
INFN Sezione di Roma I, Italy
Dipartimento di Fisica, Università La Sapienza, Roma, Italy
176 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 BC, 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 Universita` di Napoli Parthenope, Napoli, Italy.
k Also at Institute of Particle Physics (IPP), Canada.
l Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
m 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, 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, Guanzhou, China.

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

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 High Energy Physics, Chinese Academy of Sciences, Beijing, China.

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 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.