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Authors
Aad, G
Abbott, B
Abdallah, J
et al.

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Search for Gluinos in Events with Two Same-Sign Leptons, Jets, and Missing Transverse Momentum with the ATLAS Detector in pp Collisions at $\sqrt{s} = 7$ TeV

G. Aad et al.*
(ATLAS Collaboration)
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A search is presented for gluinos decaying via the supersymmetric partner of the top quark using events with two same-sign leptons, jets, and missing transverse momentum. The analysis is performed with 2.05 fb$^{-1}$ of integrated luminosity from pp collisions at $\sqrt{s} = 7$ TeV collected by the ATLAS detector at the LHC. No excess beyond the standard model expectation is observed, and exclusion limits are derived for simplified models where the gluino decays via the supersymmetric partner of the top quark and in the minimal supergravity and constrained minimal supersymmetric standard model framework. In those scenarios, gluino masses below 550 GeV are excluded at 95% C.L. within the parameter space considered, significantly extending the coverage with respect to existing limits. Depending on the model parameters, gluino masses up to 750 GeV can also be excluded at 95% C.L.

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Supersymmetry (SUSY) [1–7] is a theory beyond the standard model (SM) which predicts new bosonic partners for the existing fermions and fermionic partners for the known bosons. In the framework of a generic $R$-parity conserving minimal supersymmetric extension of the SM, SUSY particles are produced in pairs [8,9] and the lightest supersymmetric particle is stable, providing a possible candidate for dark matter.

In SUSY models, the gluino is a strongly interacting Majorana fermion. Pair-produced gluinos therefore have an equal probability to produce a pair of leptons that have the same charge [same-sign (SS)] and the opposite charge from their decays. The supersymmetric partner of the top quark (top squark) has two mass eigenstates with $\tilde{t}_1$ being the lightest. Top quarks and $\tilde{t}_1$ squarks can be produced in the decay of the gluino via $\tilde{g} \tilde{g} \rightarrow t\tilde{t}_1\tilde{t}_1, t\tilde{t}_1\tilde{t}_1, t\tilde{t}_1\tilde{t}_1$ [10–14]. The $\tilde{t}_1$ squark can further decay to the lightest chargino ($\tilde{\chi}_1^+$) or lightest neutralino ($\tilde{\chi}_0^0$) via $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$ or $\tilde{t}_1 \rightarrow t\tilde{\chi}_0^0$ producing isolated leptons in the semileptonic top-quark decay or in the leptonic $\tilde{\chi}_1^+$ decay and enriching the signal events with two or more leptons, jets, and missing transverse momentum ($E_T^{\text{miss}}$) from the undetected neutralinos. This analysis considers events with a pair of isolated SS leptons, multiple high-$p_T$ jets, and large $E_T^{\text{miss}}$. The requirement of SS leptons in the event suppresses the contribution from SM processes and thus enhances the potential signal significance even for final state topologies with relatively soft jet kinematics. This Letter presents the first search for gluino-mediated top squark production using the SS signature, although other searches with SS leptons have been performed [15–18]. The analysis presented here complements the results of the ATLAS search based on a single lepton plus $b$ jets [19], enhancing the sensitivity in the experimentally difficult region near the kinematic limit for the production of two top quarks and a neutralino and for the region with low top squark masses.

ATLAS is a general-purpose detector [20] at the LHC. This search uses pp collision data recorded from March to August 2011 at a center-of-mass energy of 7 TeV. The data set corresponds to a total integrated luminosity of 2.05 ± 0.08 fb$^{-1}$ [21,22] after the application of data quality requirements. Events are selected by using single lepton and dilepton triggers that have constant efficiency as a function of lepton $p_T$ above the offline $p_T$ cuts used in the analysis.

Jets are reconstructed from three-dimensional calorimeter energy clusters by using the anti-$k_T$ jet algorithm [23,24] with a radius parameter of 0.4. The measured jet energy is corrected for inhomogeneities in, and for the noncompensating nature of, the calorimeter by using $p_T$- and $\eta$-dependent correction factors [25]. Only jet candidates with $p_T > 20$ GeV within $|\eta| < 2.8$ are retained. Events with any jet that fails the jet quality criteria designed to remove noise and noncollision backgrounds [25] are rejected.

Electron candidates are required to have $p_T > 20$ GeV, $|\eta| < 2.47$ and satisfy the ”tight” selection criteria defined in Ref. [26]. They are also required to be isolated: The scalar sum of $p_T$ of tracks within a cone in the $\eta - \phi$ plane of radius $\Delta R = 0.2$ around the candidate excluding its own track, $\Sigma_{p_T}$, must be less than 10% of the electron $p_T$. Muon candidates are required to have $p_T > 20$ GeV, $|\eta| < 2.4$ and are identified by matching an extrapolated inner detector track and one or more track segments in the muon spectrometer [27]. They must have longitudinal and
transverse impact parameters within 1 and 0.2 mm of the primary vertex [28], respectively, and Σ_{p_T} < 1.8 GeV.

The calculation of \( E_T^{\text{miss}} \) [29] is based on the vectorial sum of the \( p_T \) of the reconstructed jets (with \( p_T > 20 \) GeV and \(| \eta | < 4.5 \)), leptons, and the calorimeter energy clusters not belonging to reconstructed objects.

During part of the data-taking period, a localized electronics failure in the electromagnetic calorimeter created a dead region (\( \Delta \eta \times \Delta \phi \approx 1.4 \times 0.2 \)). For jets in this region, a correction to their energy is made by using the energy depositions in the neighboring cells and is propagated to \( E_T^{\text{miss}} \). If this correction projected onto the direction of the \( E_T^{\text{miss}} \) is larger than 10 GeV or 10% of the \( E_T^{\text{miss}} \), the event is discarded [30]. Events with reconstructed electrons in the calorimeter dead region are also rejected.

Events in which the two highest-\( p_T \) leptons (\( \ell = e, \mu \)) have the same charge and with at least four jets with \( p_T > \) 50 GeV are selected. In addition, two signal regions are considered: SR1, which requires \( E_T^{\text{miss}} > 150 \) GeV, and SR2, which in addition requires \( m_T > 100 \) GeV, where \( m_T \) is the transverse mass of the \( E_T^{\text{miss}} \) and the highest-\( p_T \) lepton defined as \( m_T^\ell = 2p_T^{\ell}E_T^{\text{miss}}[1-\cos(\Delta \phi(\ell, E_T^{\text{miss}}))] \). This final \( m_T^\ell \) cut helps reduce the \( tt \) background. The signal regions are optimized based on several models where SS dileptons are produced in gluino decays. In signals such as the MSUGRA-CMSSM (minimal supergravity or constrained minimal supersymmetric standard model) [31,32], the directions of the lepton and \( \tilde{\chi}_1^0 \) are strongly correlated, as they originate from the decay of a common parent particle (usually \( \tilde{\chi}_1^0 \) or the next-to-lightest neutralino \( \tilde{\chi}_2^0 \)). This leads to a softer \( m_T \) spectrum than that found in gluino-mediated top squark signal models, where the lepton and the \( \tilde{\chi}_1^0 \) originate from different parent particles and are thus uncorrelated.

Simulated Monte Carlo (MC) 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 [33], fixing the top-quark mass at 172.5 GeV and using the next-to-leading-order (NLO) parton density function (PDF) set CTEQ6.6 [34]. Samples of \( W + \) jets and \( Z + \) jets with both light- and heavy-flavor jets are generated with ALPGEN [35] and PDF set CTEQ6L1 [36]. The fragmentation and hadronization for the ALPGEN and MC@NLO samples are performed with HERWIG [37], using JIMMY [38] for the underlying event. Samples of \( t \bar{t}, t \bar{t}W, \) and \( t \bar{t}WW \) (referred to as \( t \bar{t} + X \)) are generated with MADGRAPH [39] interfaced to PYTHIA [40]. The total LO cross section for these samples is 0.39 pb and is normalized to NLO by using a K factor of 1.3 [41]. Diboson samples are generated with HERWIG for \( W^\pm W^\mp, \) \( WZ, \) and \( ZZ \) processes and with MADGRAPH for \( W^\pm W^\mp \) \( q \bar{q} \) processes. The total NLO cross section for the diboson background is 71 pb [42,43]. SUSY signal processes are simulated for various models by using HERWIG++ [37] v2.4.2. The SUSY sample yields are normalized to the results of NLO calculations, as obtained by using PROSPINO [44] v2.1. The CTEQ6.6M [45] parameterization of the PDFs is used. The tunings of the MC parameters of Ref. [46] are used in the production of the MC samples, which are processed through a detector simulation [47] based on GEANT4 [48]. Effects of multiple proton-proton interactions per bunch crossing are included in the simulation.

The SM backgrounds are evaluated using a combination of MC simulation and data-driven techniques. SM processes that generate events containing jets which are misidentified as leptons or where a lepton from a \( b- \) or \( c- \) hadron decay is selected are collectively referred to as “fake-lepton” background. It generally consists of semileptonic \( t \bar{t} \), single-top, \( W + \) jets, and strong light- and heavy-flavor jet production. The contribution from the fake-lepton background is estimated from data with a method similar to that described in Refs. [49,50] by loosening the lepton identification and isolation criteria. For electrons the “medium” criteria are used instead of the “tight” criteria [26], and for both electrons and muons the isolation criterion is relaxed. The method counts the number of observed events containing loose-loose, loose-tight, tight-loose, and tight-tight lepton pairs. The probability of loose real leptons passing the tight selection criteria is obtained by using a \( Z \rightarrow \ell^+ \ell^- \) sample. The probability of fake leptons to pass the tight selection criteria is determined as a function of the lepton \( p_T \) by using multijet control samples obtained by requiring two SS leptons and low \( E_T^{\text{miss}} \). By using these probabilities, relations are obtained for the observed event counts in the signal regions as functions of the numbers of events containing fake-fake, fake-real, real-fake, and real-real lepton pairs. These can be solved simultaneously to estimate the number of background events [49,50]. The results of the estimations have been validated with data in control regions obtained by reversing the \( E_T^{\text{miss}} \) or jet multiplicity cuts used in the signal regions.

Background events from charge misidentification (dominated by electrons which have undergone hard bremsstrahlung with subsequent photon conversion) are estimated by using a partially data-driven technique [16]. The probability of charge misidentification is calculated from MC simulations and corrected by consideration of the number of events in the data with SS electron pairs and invariant mass within 15 GeV of the \( Z \)-boson mass. This probability is applied to \( t \bar{t} \) MC events producing \( e^\pm \ell^\mp \) pairs to evaluate the number of SS events from incorrect charge assignment in each signal region. The probability of misidentifying the charge of a muon and the contributions in the signal regions from charge misidentification of \( Z/\gamma^* \) jets and other SM backgrounds are negligible.

Contributions from other SM background sources (dyboson and \( t \bar{t} + X \)) are evaluated by using the MC samples described above. In these processes, real SS lepton pairs are produced, and their contribution to the signal regions can be described with MC simulations. In particular, the
contribution from the experimentally unmeasured $t \bar{t} + X$ processes has been studied by using several MC generators. The background from cosmic rays is evaluated with data by using the method in Ref. [16], and its contribution is negligible in the signal regions.

Systematic uncertainties are estimated in the signal regions for the background and the SUSY signal processes. The primary sources of systematic uncertainties in the background are the jet energy scale calibration (35%), the jet energy resolution (10%), uncertainties on lepton and jet reconstruction and identification (5%), and MC modeling and theoretical cross section uncertainties (40%–70%). In particular, the theoretical uncertainties on the cross section of the $t \bar{t} + X$ processes are found to be between 35% and 55% by varying factorization and renormalization scales and 25% due to PDF uncertainties. In addition, a 50% uncertainty is assigned on the $K$ factor used to obtain the NLO cross section [41]. In the fake-lepton background estimation, systematic uncertainties are assigned to the probabilities for loose fake leptons to pass the tight selection. This accounts for potentially different compositions of the signal and control regions. These uncertainties vary in the 10%–80% range depending on the lepton $p_T$ and are evaluated by using data samples with jets of different energies. The absolute uncertainty for each background source is given in Table I. Systematic uncertainties on the signal expectations are evaluated through variations of the factorization and renormalization scales between half and twice their default values and by including the uncertainty on $\alpha_s$ and on the PDF provided by CTEQ6. Uncertainties are calculated for individual SUSY processes. The total uncertainty varies in the 20%–40% range for the considered MC signals. Any correlations of the systematic uncertainties in signals and background are taken into account.

Figure 1 shows the distribution of the number of jets with $p_T > 50$ GeV for events with 2 SS leptons and the $E_{T}^{\text{miss}}$ distribution for events with 2 SS leptons and at least four jets with $p_T > 50$ GeV. The contributions from all the SM backgrounds are shown together with their total statistical and systematic uncertainties. For illustration, the distribution for a signal obtained with the decay $g \rightarrow t \bar{t} X_1$ in $g g$ pair-produced events with $m_g = 650$ GeV and $m_{X_1} = 150$ GeV is also shown. The data are in agreement with the SM background expectation, and once four jets of $p_T > 50$ GeV are required no event is observed with $E_{T}^{\text{miss}} > 150$ GeV.

Table I shows the number of expected events in the signal regions for each background source together with the observed number of events. The expectation from the SM is estimated to be less than one event for each signal region with no events observed in the data. Limits at 95% confidence level (C.L.) are derived on the visible cross section $\sigma_{\text{vis}} = \sigma \times e \times A$, where $\sigma$ is the total production cross section for any new signal producing SS dileptons, $A$ is the acceptance defined by the fraction of events passing

| TABLE I. Number of expected SM background events together with the number of observed events in the data. The errors are a combination of the uncertainties due to MC statistics, statistical uncertainties in control regions, and systematic uncertainties. Observed and expected upper limits at 95% confidence level on $\sigma_{\text{vis}} = \sigma \times e \times A$, together with the $\pm 1\sigma$ errors on the expected limits, are also shown. |
|---|---|
| $t \bar{t} + X$ | $0.37 \pm 0.26$ | $0.21 \pm 0.16$ |
| Diboson | $0.05 \pm 0.02$ | $0.02 \pm 0.01$ |
| Fake-lepton | $0.34 \pm 0.20$ | <0.17 |
| Charge mis-ID | $0.08 \pm 0.01$ | $0.039 \pm 0.007$ |
| Total SM | $0.84 \pm 0.33$ | $0.27 \pm 0.24$ |
| Observed | 0 | 0 |
| $\sigma_{\text{vis}}^{\text{obs}}$ [fb] | <1.6 | <1.5 |
| $\sigma_{\text{vis}}^{\text{exp}}$ [fb] | <1.7$^{+0.5}_{-0.1}$ | <1.6$^{+0.2}_{-0.1}$ |

FIG. 1 (color online). Number of jets with $p_T > 50$ GeV for events with 2 SS leptons (top) and the $E_{T}^{\text{miss}}$ distribution for events with 2 SS leptons and at least 4 jets with $p_T > 50$ GeV (bottom). Errors on data points are statistical, while the error band on the SM background represents the total uncertainty. The component labeled “Fake-lepton” is evaluated by using data as described in the text. The component labeled “$Z/\gamma^* +$ jets” is estimated from MC simulations. No estimation of the charge mis-ID is included in the distribution. The component labeled “Signal” corresponds to a signal obtained with the decay $g \rightarrow t \bar{t} X_1$ via off mass-shell $t$ ($m_t = 1.2$ TeV) in $g g$ pair-produced events with $m_g = 650$ GeV and $m_{X_1} = 150$ GeV.
geometric and kinematic cuts at particle level, and $\epsilon$ is the detector reconstruction, identification, and trigger efficiency. For the signal shown in Fig. 1, the acceptance and efficiency are 1.5% and 55%, respectively. Limits are set by using the $CL_{s}$ prescription, as described in Ref. [51]. The results are given in Table I.

The results obtained in SR2 are interpreted in a simplified model where gluinos are produced only in pairs, the top squark ($m_{\tilde{t}} = 1.2$ TeV) is heavier than the gluino, and only the gluino three-body decay $\tilde{g} \rightarrow t\bar{t}\chi^{0}_{1}$ via an off-shell top squark is allowed. Figure 2 shows the limit in the gluino-neutralino mass plane. For a gluino mass of 650 GeV, neutralino masses below 215 GeV are excluded at 95% C.L. For a neutralino mass of 100 GeV, gluino masses below 715 GeV are similarly excluded. The $\pm 1\sigma$ uncertainty limit on the expected limit lies outside the range of the figure as a consequence of the low number of expected signal events and a total signal uncertainty that reaches close to 50%. The results can be generalized in terms of production cross section upper limits at 95% C.L. for $\tilde{g} \tilde{g}$ pair production processes with the produced particles decaying into $t\bar{t}\chi^{0}_{1}$ final states, as also shown in Fig. 2.

The results in SR2 are also interpreted by considering gluino pair production followed by the $\tilde{g} \rightarrow t\bar{t}\chi^{0}_{1}$ decay. Only top squark decays $\bar{t}_{1} \rightarrow b\tilde{\chi}_{1}^{0}$ are considered with $\tilde{m}_{\chi_{1}^{0}} = 2m_{\tilde{\chi}_{1}^{0}}$ and $m_{\tilde{\chi}_{1}^{0}} = 60$ GeV. Figure 3 shows the exclusion limit as a function of the gluino and top squark masses, where gluino masses below 660 GeV are excluded at 95% C.L. for top squark masses below 460 GeV.

The results in SR1 are interpreted within the MSUGRA-CMSSM framework in terms of limits on the universal scalar and gaugino mass parameters $m_{0}$ and $m_{1/2}$, as shown in Fig. 4. These are presented for fixed values of the universal trilinear coupling parameter $A_{0} = 0$, ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta = 10$, and Higgs mixing parameter $\mu > 0$. In this model, values of $m_{1/2}$ below 300 GeV are excluded at 95% C.L. for $m_{0}$ values below 675 GeV, and values below 180 GeV are excluded over the entire $m_{0}$ region considered. These are equivalent to the exclusion of gluino masses below $\sim 550$ GeV independent of the squark mass (and gluino masses below $\sim 750$ GeV for squark masses below 1 TeV).

In summary, a search for SUSY with two SS leptons, jets, and missing transverse momentum has been performed by using 2.05 fb$^{-1}$ of ATLAS data. With no events observed in the signal regions, limits have been derived in the context of models where top squarks are produced in gluino decays and MSUGRA-CMSSM scenarios. In all these signal models, gluino masses below $\sim 550$ GeV are
excluded at 95% C.L. within the parameter space considered, and gluino masses up to ~750 GeV are excluded at 95% C.L., depending on the model parameters. The results of this analysis are complementary to and extend the current exclusion limits on the gluino mass beyond those from other ATLAS searches [19,52].

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Physics Department, National Technical University of Athens, Zografou, Greece
Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
Institute of Physics, University of Belgrade, Belgrade, Serbia
Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
Department for Physics and Technology, University of Bergen, Bergen, Norway
Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
Department of Physics, Humboldt University, Berlin, Germany
Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
Department of Physics, Bogazici University, Istanbul, Turkey
Division of Physics, Dogus University, Istanbul, Turkey
Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
Department of Physics, Istanbul Technical University, Istanbul, Turkey
INFN Sezione di Bologna, Italy
Physikalisches Institut, University of Bonn, Bonn, Germany
Department of Physics, Boston University, Boston, Massachusetts, USA
Department of Physics, Brandeis University, Waltham, Massachusetts, USA
Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
Physics Department, Brookhaven National Laboratory, Upton, New York, USA
National Institute of Physics and Nuclear Engineering, Bucharest, Romania
West University in Timisoara, Timisoara, Romania
Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa, Ontario, Canada
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Modern Physics, University of Science and Technology of China, Anhui, China
Department of Physics, Nanjing University, Jiangsu, China
School of Physics, Shandong University, Shandong, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
Nevis Laboratory, Columbia University, Irvington, New York, USA
Niels Bohr Institute, University of Copenhagen, København, Denmark
INFN Gruppo Collegato di Cosenza, Italy
Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas, Texas, USA
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
Department of Physics, Duke University, Durham, North Carolina, USA
SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
Section de Physique, Université de Genève, Geneva, Switzerland
INFN Sezione di Genova, Italy
Dipartimento di Fisica, Università di Genova, Genova, Italy
E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi, Georgia
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Department of Physics, University of Toronto, Toronto, Ontario, Canada

TRIUMF, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada

Institute of Pure and Applied Sciences, University of Tsukuba, I-1-1 Tennodai, 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

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-CNMT), University of Valencia and CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

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 Instrumentacao 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, 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 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.

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