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

The ATLAS Collaboration

Abstract

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 MSUGRA/CMSSM framework. In those scenarios, gluino masses below 550 GeV are excluded at 95% CL 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% CL.
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Supersymmetry (SUSY) \([1][2]\) 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 (MSSM), SUSY particles are produced in pairs \([3][4]\) 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 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 (stop) 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 \( \tilde{g} \rightarrow \tilde{t}_1 \tilde{t}_1^\ast, \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \tilde{t}_1 \) \([5][6]\). The \( \tilde{t}_1 \) squark can further decay to the lightest chargino (\( \tilde{\chi}^+_1 \)) or lightest neutralino (\( \tilde{\chi}^0_1 \)) via \( \tilde{t}_1 \rightarrow b \tilde{\chi}^+_1 \) or \( \tilde{t}_1 \rightarrow t \tilde{\chi}^0_1 \) producing isolated leptons in the semi-leptonic top quark decay or in the leptonic \( \tilde{\chi}^+_1 \) decay and enhancing 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 article presents the first search for gluino-mediated stop production using the SS signature although other searches with SS leptons have been performed \([7][8][9][10][11][12][13][14][15][16][17][18][19][20] \). The analysis presented here complements the results of the ATLAS search based on single lepton plus \( b \)-jets \([13]\), 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 stop 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 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 non-compensating nature of, the calorimeter by using \( p_T \)- and \( \eta \)-dependent correction factors \([25]\). Only jet candidates with \( p_T > 20 \text{ GeV} \) within \( |\eta| < 2.8 \) are retained. Events with any jet that fails the jet-quality criteria designed to remove noise and non-collision backgrounds \([25]\) are rejected.

Electron candidates are required to have \( p_T > 20 \text{ GeV} \), \( |\eta| < 2.47 \) 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 \( p_T > 20 \text{ GeV} \), \( |\eta| < 2.4 \) 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 parameter within 1 mm and 0.2 mm of the primary vertex \([28]\), respectively, and \( \Sigma_{p_T} < 1.8 \text{ GeV} \).

The calculation of \( E_{T}^\text{miss} \) \([29]\) is based on the vectorial sum of the \( p_T \) of the reconstructed jets (with \( p_T > 20 \text{ GeV} \) 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 \((\Delta \eta \times \Delta \phi \simeq 1.4 \times 0.2)\). For jets in this region, a correction to their energy is made using the energy depositions in the neighbouring cells, and is propagated to \( E_{T}^\text{miss} \). If this correction projected onto the

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direction of the $E_{T}^{miss}$ is larger than 10 GeV or 10% of the $E_{T}^{miss}$, 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 $E_{T}^{miss} > 150$ GeV; and SR2, which in addition requires $m_{T} > 100$ GeV, where $m_{T}$ is the transverse mass of the $E_{T}^{miss}$ and the highest-$p_{T}$ lepton defined as $m_{T}^{T} = 2p_{T}^{\ell}E_{T}^{miss}(1 - \cos(\Delta\phi(\ell, E_{T}^{miss}))$. This final $m_{T}$ cut helps reducing the $t\bar{t}$ 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 $\tilde{\chi}^{0}_{1}$ or the next-to-lightest neutralino, $\tilde{\chi}^{0}_{2}$ (or $\tilde{\chi}^{0}_{1}$) from the decay of a common parent particle (usually $\tilde{\chi}^{0}_{1}$ or the next-to-lightest neutralino, $\tilde{\chi}^{0}_{2}$). This leads to a softer $m_{T}$ spectrum than that found in gluino-mediated stop signal models, where the lepton and the $\tilde{\chi}^{0}_{1}$ 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 $W+\text{jets}$ and $Z+\text{jets}$ 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 $t\bar{t}Z$, $t\bar{t}W$ and $t\bar{t}W$ (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 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 $W^{\pm}W^{\mp}$qq processes. The total NLO cross section for the diboson background is 71 pb [42, 43]. SUSY signal processes are simulated for various models using HERWIG++ [37] v2.4.2. The SUSY sample yields are normalized to the results of NLO calculations, as obtained 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 semi-leptonic $t\bar{t}$, single top, $W+\text{jets}$ 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 Ref. [49, 50] by loosening the lepton identification and isolation criteria. For electrons the ‘medium’ criteria are used instead of the ‘tight’ criteria [49], 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 using a $Z \rightarrow \ell^{+}\ell^{-}$ sample. The probability of loose fake leptons to pass the tight selection criteria is determined as a function of the lepton $p_{T}$ using multijet control samples obtained by requiring two SS leptons and low $E_{T}^{miss}$. 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 $E_{T}^{miss}$ 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 using a partially data-driven technique [16]. The probability of charge misidentification is calculated from MC and corrected by consideration of the number of events in 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 $e^{\pm}\ell^{\mp}$ 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 $Z/\gamma^{*}+\text{jets}$ and other SM backgrounds are negligible.

Contributions from other SM background sources (diboson and $t\bar{t}+X$) are evaluated 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. In particular, the contribution from the experimentally unmeasured $t\bar{t}+X$ processes has been studied using several MC generators. The background from cosmic rays is evaluated with data 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%), MC modeling and theoretical cross section uncertainties (40%-70%). In
particularly, the theoretical uncertainties on the cross section of the $t\bar{t} + X$ processes are found to be between 35%-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 \cite{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 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.

<table>
<thead>
<tr>
<th></th>
<th>SR1</th>
<th>SR2</th>
</tr>
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<tbody>
<tr>
<td>$t\bar{t} + X$</td>
<td>0.37 ± 0.26</td>
<td>0.21 ± 0.16</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.05 ± 0.02</td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td>Fake-lepton</td>
<td>0.34 ± 0.20</td>
<td>&lt; 0.17</td>
</tr>
<tr>
<td>Charge mis-ID</td>
<td>0.08 ± 0.01</td>
<td>0.039 ± 0.007</td>
</tr>
<tr>
<td>Total SM</td>
<td>0.84 ± 0.33</td>
<td>0.27 ± 0.24</td>
</tr>
</tbody>
</table>

Table I: Number of expected SM background events together with the number of observed events in 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 $\sigma_{\text{vis}} = \sigma \times \epsilon \times A$, together with the ±1σ errors on the expected limits are also shown.

$\sigma_{\text{exp}}^\text{SR1} [fb] < 1.6 < 1.5$

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 $g \rightarrow t\bar{t}\chi^0_1$ in $gg$ pair-produced events with $m_{\tilde{g}} = 650$ GeV and $m_{\chi^0_1} = 150$ 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 background is observed with $E_T^{\text{miss}} > 150$ GeV. SM is estimated to be less than one event for each signal region with no events observed in data. Limits at 95% confidence level (CL) are derived on the visible cross section $\sigma_{\text{vis}} = \sigma \times \epsilon \times A$ 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 geometric and kinematic cuts at particle level and $\epsilon$ is the detector reconstruction, identification and trigger efficiency. For the signal shown in Figure 1, the acceptance and efficiency are 1.5% and 55%, respectively. Limits are set using the $CL_s$ prescription, as described in Ref. \cite{51}. The results are given in Table I.

The results obtained in SR2 are interpreted in a simplified model where gluinos are only produced in pairs, the stop ($m_{\tilde{t}} = 1.2$ 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 stop 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% CL. For a neutralino mass of 100 GeV, gluino masses
below 715 GeV are similarly excluded. The $-1\sigma$ 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 generalised in terms of production cross section upper limits at 95% CL for $\tilde{g}\tilde{g}$ pair production processes with the produced particles decaying into $t\bar{t}\chi_1^0$ final states, as also shown in Figure 2.

The results in SR2 are also interpreted considering gluino pair production followed by the $\tilde{g} \to \tilde{t}_1t$ decay. Only stop decays via $\tilde{t}_1 \to b\chi_1^\pm$ are considered with $m_{\chi_1^\pm} \approx 2m_{\tilde{g}}$ and $m_{\tilde{g}} = 60$ GeV. Figure 3 shows the exclusion limit as a function of gluino and stop masses, where gluino masses below 660 GeV are excluded at 95% CL for stop 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 Figure 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% CL for $m_0$ values below 750 GeV, and $m_{1/2}$ 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 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 quarks are produced in gluino decays and MSUGRA/CMSM scenarios. In all these signal models, gluino masses below $\sim 550$ GeV are excluded at 95% CL within the parameter space considered and gluino masses up to $\sim 750$ GeV are excluded at 95% CL, 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, 57].

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Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

Physics Department, National Technical University of Athens, Zografou, Greece

Physics Department, University of Athens, Athens, Greece

Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

Department of Physics, University of Arizona, Tucson AZ, United States of America

Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain

Department for Physics and Technology, University of Bergen, Bergen, Norway

Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

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, Boston University, Boston MA, United States of America

Department of Physics, Brandeis University, Waltham MA, United States of America

Universidade Federal de Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; Federal University of Juiz de Fora (UFJF), Juiz de Fora; Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina

Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Department of Physics, Carleton University, Ottawa ON, Canada

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

Department of Physics, Pontificia Universidad Católica de Chile, Santiago; Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

Department of High Energy Physics, Chinese Academy of Sciences, Beijing; Department of Modern Physics, University of Science and Technology of China, Anhui; Department of Physics, Nanjing University, Jiangsu; 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 NY, United States of America

Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

INFN Gruppo Collegato di Cosenza; 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 TX, United States of America

Physics Department, University of Texas at Dallas, Richardson TX, United States of America

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

Department of Physics, Duke University, Durham NC, United States of America

SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3 2700 Wiener Neustadt, Austria

INFN Laboratori Nazionali di Frascati, Frascati, Italy
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli; Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
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 IL, United States of America
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Univ. 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; Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Pisa; Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
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; Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata; Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre; Dipartimento di Fisica, Università Roma Tre, Roma, Italy
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat; Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; Faculté des Sciences, Université Mohammed Premier and LPTPM, Oujda; Faculté des Sciences, Université Mohammed V- Agdal, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
Department of Physics, University of Washington, Seattle WA, United States of America
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby BC, Canada
SLAC National Accelerator Laboratory, Stanford CA, United States of America
Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Department of Physics, University of Johannesburg, Johannesburg; School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University; The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

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

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

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

Department of Physics, University of Toronto, Toronto ON, Canada

TRIUMF, Vancouver BC; Department of Physics and Astronomy, York University, Toronto ON, Canada

Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki 305-8571, Japan

Science and Technology Center, Tufts University, Medford MA, United States of America

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

INFN Gruppo Collegato di Udine; ICTP, Trieste; Dipartimento di Chimica, Fisica e Ambient, Università di Udine, Udine, Italy

Department of Physics, University of Illinois, Urbana IL, United States of America

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Instituto de Fisica Corpuscular (IFIC) and Departamento de Fisica Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNMI), University of Valencia and CSIC, Valencia, Spain

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

Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

Waseda University, Tokyo, Japan

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

Department of Physics, University of Wisconsin, Madison WI, United States of America

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 CT, United States of America

Yerevan Physics Institute, Yerevan, Armenia

Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

Also at Laboratorio de Instrumentacoe 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, United States of America

Also at Novosibirsk State University, Novosibirsk, Russia

Also at Fermilab, Batavia IL, United States of America

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, United States of America

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, United States of America

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 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 Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
Also at Section de Physique, Université de Genève, Geneva, Switzerland
Also at Departamento de Física, Universidade de Minho, Braga, Portugal
Also at Department of Particle Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
Also at California Institute of Technology, Pasadena CA, United States of America
Also at Institute of Physics, Jagiellonian University, Krakow, Poland
Also at 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, United States of America
Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
* Deceased