Search for Supersymmetry Using Final States with One Lepton, Jets, and Missing Transverse Momentum with the ATLAS Detector in \( \sqrt{s} = 7 \) TeV \( pp \) Collisions

G. Aad et al.*
(ATLAS Collaboration)
(Received 11 February 2011; published 28 March 2011)

This Letter presents the first search for supersymmetry in final states containing one isolated electron or muon, jets, and missing transverse momentum from \( \sqrt{s} = 7 \) TeV proton-proton collisions at the LHC. The data were recorded by the ATLAS experiment during 2010 and correspond to a total integrated luminosity of 35 pb\(^{-1}\). No excess above the standard model background expectation is observed. Limits are set on the parameters of the minimal supergravity framework, extending previous limits. Within this framework, for \( A_0 = 0 \) GeV, \( \tan \beta = 3 \), and \( \mu > 0 \) and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% confidence level.

DOI: 10.1103/PhysRevLett.106.131802

PACS numbers: 12.60.Jv, 13.85.Rm, 14.80.Ly

Many extensions of the standard model predict the existence of new colored particles, such as the squarks (\(q\)) and gluinos (\(g\)) of supersymmetric (SUSY) theories [1], which could be accessible at the LHC. The dominant SUSY production channels are squark-(anti)squark, squark-gluino, and gluino-gluino pair production. Squarks and gluinos are expected to decay to quarks, gluons, and the SUSY partners of the gauge bosons (charginos \(\tilde{\chi}^{\pm}\) and neutralinos \(\tilde{\chi}^0\)), leading to events with energetic jets. In \(R\)-parity conserving SUSY models [2], the lightest supersymmetric particle is stable and escapes detection, giving rise to events with significant missing transverse momentum. In decay chains with charginos (\(q_L \rightarrow q\tilde{\chi}^\pm\) and \(g \rightarrow g\tilde{\chi}^\pm\)), chargino decay to the lightest supersymmetric particle can produce a high-momentum lepton. Currently, the most stringent limits on squark and gluino masses come from the LHC [3] and from the Tevatron [4–7].

This Letter reports on a search for events with exactly one isolated high-transverse momentum (\(p_T\)) electron or muon, at least three high-\(p_T\) jets, and missing transverse momentum. An exact definition of the signal region will be given elsewhere in this Letter. From an experimental point of view, the requirement of an isolated lepton suppresses the QCD multijet background and facilitates triggering on interesting events. In addition to the signal region, three control regions are considered for the most important standard model backgrounds. A combined fit to the observed number of events in these four regions, together with an independent estimate of jets misidentified as leptons in QCD multijet events, is used to search for an excess of events in the signal region.

The analysis is sensitive to any new physics leading to such an excess and is not optimized for any particular model of SUSY. The results are interpreted within the MSUGRA-CMSSM (minimal supergravity or constrained minimal supersymmetric standard model) framework [8,9] in terms of limits on the universal scalar and gaugino mass parameters \(m_0\) and \(m_1/2\). These are presented for fixed values of the universal trilinear coupling parameter \(A_0 = 0\) GeV, ratio of the vacuum expectation values of the two Higgs doublets \(\tan \beta = 3\), and Higgs mixing parameter \(\mu > 0\), in order to facilitate comparison with previous results.

The ATLAS detector [10] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near \(4\pi\) coverage in solid angle [11]. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field and by high-granularity liquid-argon sampling electromagnetic calorimeters. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The endcap and forward regions are instrumented with liquid-argon calorimetry for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids, a system of precision tracking chambers, and detectors for triggering.

The data used in this analysis were recorded in 2010 at the LHC at a center-of-mass energy of 7 TeV. Application of beam, detector, and data-quality requirements results in a total integrated luminosity of 35 pb\(^{-1}\), with an estimated uncertainty of 11% [12]. The data have been selected with single lepton (\(e\) or \(\mu\)) triggers. The detailed trigger requirements vary throughout the data-taking period, but the thresholds are always low enough to ensure that leptons with \(p_T > 20\) GeV lie in the efficiency plateau.

Fully simulated Monte Carlo event samples are used to develop and validate the analysis procedure, compute

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

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detector acceptance and reconstruction efficiency, and aid in the background determination. Samples of events for background processes are generated as described in detail in Ref. [13]. For the major backgrounds, top quark pair and $W +$ jets production, MC@NLO [14] v3.41 and ALCGEN [15] v2.13 are used. Further samples include QCD multijet events, single top production, diboson production, and Drell-Yan dilepton events.

Monte Carlo signal events are generated with HERWIG++ [16] v2.4.2. The SUSY particle spectra and decay modes are calculated with ISAJET [17] v7.75. The SUSY samples are normalized by using next-to-leading order cross sections as determined by PROSPINO [18] v2.1. All signal and background samples are produced by using the ATLAS MC09 parameter tune [19] and a GEANT4 based [20] detector simulation [21].

Criteria for electron and muon identification closely follow those described in Ref. [22]. Electrons are reconstructed based on the presence of a cluster in the electromagnetic calorimeter matched to a track in the ID. Electrons in the signal region are required to pass the "tight" selection criteria, with $p_T > 20$ GeV and $|\eta| < 2.47$. Events are always vetoed if a "medium" electron is found in the electromagnetic calorimeter transition region $1.37 < |\eta| < 1.52$.

Muons are required to be identified either in both ID and MS systems (combined muons) or as a match between an extrapolated ID track and one or more segments in the MS. The ID track is required to have at least one pixel hit, more than five silicon microstrip detector hits, and a number of transition radiation tracker hits that varies with $\eta$. For combined muons, a good match between ID and MS tracks is required, and the $p_T$ values measured by these two systems must be compatible within the resolution. The summed $p_T$ of other ID tracks within a distance $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.2$ around the muon track is required to be less than 1.8 GeV. Only muons with $p_T > 20$ GeV and $|\eta| < 2.4$ are considered.

Jets are reconstructed by using the anti-$k_t$ jet clustering algorithm [23] with a radius parameter $R = 0.4$. The inputs to this algorithm are clusters of calorimeter cells seeded by cells with energy significantly above the measured noise. Jets are constructed by performing a four-vector sum over these clusters, treating each cluster as an $(E, \vec{p})$ four-vector with zero mass. Jets are corrected for calorimeter non-compensation, upstream material, and other effects by using $p_T$- and $\eta$-dependent calibration factors obtained from Monte Carlo calculations and validated with extensive test-beam and collision-data studies [24]. Only jets with $p_T > 20$ GeV and $|\eta| < 2.5$ are considered. If a jet and a medium electron are both identified within a distance $\Delta R < 0.2$ of each other, the jet is discarded. Furthermore, identified medium electrons or muons are considered only if they satisfy $\Delta R > 0.4$ with respect to the closest remaining jet. Events are discarded if they contain any jet failing basic quality selection criteria, which reject detector noise and noncollision backgrounds [25].

The calculation of the missing transverse momentum $E_T^{\text{miss}}$ is based on the modulus of the vectorial sum of the $p_T$ of the reconstructed objects (jets with $p_T > 20$ GeV, but over the full calorimeter coverage $|\eta| < 4.9$, and the selected lepton), any additional nonisolated muons, and the calorimeter clusters not belonging to reconstructed objects.

Events are required to have at least one reconstructed primary vertex with at least five associated tracks. The selection criteria for signal and control regions are based on Monte Carlo studies prior to examining the data. The signal region is defined as follows. At least one identified electron or muon with $p_T > 20$ GeV is required. The cut value is motivated by the trigger thresholds as well as by the suppression of backgrounds. Events are rejected if they contain a second identified lepton with $p_T > 20$ GeV, because they are the subject of a future analysis. At least three jets with $p_T > 30$ GeV are required, the leading one of which must have $p_T > 60$ GeV. In order to reduce the background of events with fake $E_T^{\text{miss}}$ from mismeasured jets, the missing transverse momentum vector $\vec{E}_T^{\text{miss}}$ is required not to point in the direction of any of the three leading jets: $\Delta \phi(\text{jet}, E_T^{\text{miss}}) > 0.2$ ($i = 1, 2, 3$). Further cuts are motivated by the suppression of backgrounds, in particular, from top quark and $W +$ jets production, while retaining efficiency for the SUSY signal. The transverse mass between the lepton and the missing transverse momentum vector, $m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos[\Delta \phi(\ell, E_T^{\text{miss}})])}$, is required to be larger than 100 GeV. $E_T^{\text{miss}}$ must exceed 125 GeV and must satisfy $E_T^{\text{miss}} > 0.25 m_{\text{eff}}$, where the effective mass $m_{\text{eff}}$ is the scalar sum of the $p_T$ of the three leading jets, the $p_T$ of the lepton, and $E_T^{\text{miss}}$. Finally, a cut is applied on the effective mass: $m_{\text{eff}} > 500$ GeV. The $m_{\text{eff}}$ variable has been shown to give a good discrimination between signal and background and can be used to quantify the mass scale of SUSY events in case a signal is observed [26]. The efficiency for the SUSY signal in the MSUGRA-CMSSM model defined earlier varies between 0.01% for $m_{1/2} = 100$ GeV and 4% for $m_{1/2} = 350$ GeV, with a smaller dependence on $m_0$, for the electron channel and the muon channel separately. The inefficiency is dominated by the leptonic branching fractions in the SUSY signal for $m_{1/2} > 150$ GeV.

Backgrounds from several standard model processes could contaminate the signal region. Top quark pair production and $W +$ jets production backgrounds are estimated from a combined fit to the number of observed events in three control regions, by using Monte Carlo simulations to derive the background in the signal region from the control regions. The background determination of QCD multijet production with a jet misidentified as an isolated lepton is data driven. Remaining backgrounds from other sources are estimated with simulations.
The three control regions have identical lepton and jet selection criteria as the signal region. The top control region is defined by a window in the two-dimensional plane of $30 \text{ GeV} < E_T^{\text{miss}} < 80 \text{ GeV}$ and $40 \text{ GeV} < m_T < 80 \text{ GeV}$ and by requiring that at least one of the three leading jets is tagged as a $b$-quark jet. For the $b$ tagging, the secondary vertex algorithm SV0 [27] is used, which, for $p_T = 60 \text{ GeV}$ jets, provides an efficiency of 50% for $b$-quark jets and a mistag rate of 0.5% for light-quark jets. The $W$ control region is defined by the same window in the $E_T^{\text{miss}} - m_T$ plane but with the requirement that none of the three hardest jets is $b$ tagged. The QCD multijet control region is defined by demanding low missing transverse momentum $E_T^{\text{miss}} < 40 \text{ GeV}$ and low transverse mass $m_T < 40 \text{ GeV}$. This QCD control region is used only to estimate the QCD multijet background contribution to other background regions but not to the signal region. Instead, the electron and muon identification criteria are relaxed, obtaining a “loose” control sample that is dominated by QCD jets. A loose-tight matrix method, in close analogy to that described in Ref. [13], is then used to estimate the number of QCD multijet events with fake leptons in the signal region after final selection criteria: $0.0^{+0.5}_{-0.3}$ in the muon channel and $0.0^{+0.0}_{-0.0}$ in the electron channel.

Data are compared to expectations in Fig. 1. The standard model backgrounds in the figure are normalized to the theoretical cross sections, except for the multijet background, which is normalized to data in the QCD multijet control region. The data are in good agreement with the standard model expectations. After final selection, one event remains in the signal region in the electron channel and one event remains in the muon channel. Figure 1 also shows the expected distributions for the MSUGRA-CMSSM model point $m_0 = 360$ GeV and $m_1/2 = 280$ GeV. For this benchmark point, 2.9 signal events would be expected in the signal region, with an acceptance of 2.9% (3.0%) in the electron (muon) channel.

A combined fit to the number of observed events in the signal and control regions is performed. The assumption that the Monte Carlo simulation is able to predict the backgrounds in the signal region from the control regions is validated by checking additional control regions at low $m_T$ and at low $E_T^{\text{miss}}$. The defined control regions are not completely pure, and the combined fit takes the expected background cross-contaminations into account. The likelihood function of the fit can be written as $L(n|s, b, \theta) = P_S \times P_W \times P_T \times P_Q \times C_{\text{Syst}}$, where $n$ represents the number of observed events in the data, $s$ is the SUSY signal to be tested, $b$ is the background, and $\theta$ represents the systematic uncertainties, which are treated as nuisance parameters with a Gaussian probability density function. The four $P$ functions on the right-hand side are Poisson probability distributions for event counts in the defined signal ($S$) and control regions ($W$, $T$, and $Q$ for $W$, top pair, and QCD multijets, respectively), and $C_{\text{Syst}}$ represents the constraints on systematic uncertainties, including correlations.

The dominant sources of systematic uncertainties in the background estimates arise from Monte Carlo modeling of the shape of the $E_T^{\text{miss}}$ and $m_T$ distributions in signal and control regions. These uncertainties are determined by

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**FIG. 1 (color online).** Top: $E_T^{\text{miss}}$ distribution after lepton and jet selection. Center: $m_T$ distribution after lepton and jet selection. Bottom: Effective mass distribution after final selection criteria except for the cut on the effective mass itself. All plots are made for the electron and muon channel combined. Yellow bands indicate the uncertainty on the Monte Carlo prediction from finite Monte Carlo statistics and from the jet energy scale uncertainty.
TABLE I. Numbers of observed events in the signal and background control regions, as well as their estimated values from the fit (see the text), for the electron (top part) and muon (bottom part) channels. The central values of the fitted sum of backgrounds in the control regions agree with the observations by construction. For comparison, nominal Monte Carlo expectations are given in parentheses for the signal region, the top control region, and the W control region.

<table>
<thead>
<tr>
<th></th>
<th>Electron channel</th>
<th>Muon channel</th>
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<tbody>
<tr>
<td></td>
<td>Signal region</td>
<td>Top region</td>
</tr>
<tr>
<td>Observed events</td>
<td>1</td>
<td>80</td>
</tr>
<tr>
<td>Fitted top events</td>
<td>1.34 ± 0.52 (1.29)</td>
<td>65 ± 12 (63)</td>
</tr>
<tr>
<td>Fitted W/Z events</td>
<td>0.47 ± 0.40 (0.46)</td>
<td>11.2 ± 4.6 (10.2)</td>
</tr>
<tr>
<td>Fitted QCD events</td>
<td>0.0 ± 0.00</td>
<td>3.7 ± 7.6</td>
</tr>
<tr>
<td>Fitted sum of background events</td>
<td>1.81 ± 0.75</td>
<td>80 ± 9</td>
</tr>
</tbody>
</table>

|                     | Signal region    | Top region  | W region  | QCD region |
| Observed events     | 1                | 93          | 165       | 346        |
| Fitted top events   | 1.76 ± 0.67 (1.39) | 85 ± 11 (67) | 42 ± 19 (33) | 50 ± 10 |
| Fitted W/Z events   | 0.49 ± 0.36 (0.71) | 7.7 ± 3.3 (11.6) | 120 ± 26 (166) | 71 ± 16 |
| Fitted QCD events   | 0.0 ± 0.00       | 0.3 ± 1.2   | 3 ± 12    | 225 ± 22   |
| Fitted sum of background events | 2.25 ± 0.94 | 93 ± 10    | 165 ± 13 | 346 ± 19 |

variation of the Monte Carlo generator, as well as by variations of internal generator parameters. The finite size of the data sample in the background control regions also contributes to the uncertainty. Experimental uncertainties are varied within their determined range and are dominated by the jet energy scale uncertainty [28], b-tagging uncertainties, and the uncertainty on the luminosity.

Systematic uncertainties on the SUSY signal are estimated by variation of the factorization and renormalization scales in PROSPINO and by including the parton density function uncertainties using the eigenvector sets provided by CTEQ6.6 [29]. Uncertainties are calculated separately for the individual production processes. Within the relevant kinematic range, typical uncertainties resulting from scale variations are 10%–16%, whereas parton density function uncertainties vary from 5% for $\tilde{q} \tilde{q}$ production to 15%–30% for $\tilde{g} \tilde{g}$ production.

The result of the combined fit to signal and control regions, leaving the number of signal events free in the signal region while not allowing for a signal contamination in the other regions, is shown in Table I. The observed number of events in the data is consistent with the standard model expectation.

Limits are set on contributions of new physics to the signal region. These limits are derived from the profile likelihood ratio $\Lambda(s) = -2[\ln L(n|\hat{s}, \hat{\theta}) - \ln L(n|\hat{s}, \hat{\theta})]$, where $\hat{s}$, $\hat{\theta}$, and $\hat{\theta}$ maximize the likelihood function and $\hat{s}$ and $\hat{\theta}$ maximize the likelihood for a given choice of $s$. In the fit, $s$ and $\hat{\theta}$ are constrained to be non-negative. The test statistic is $\Lambda(s)$. The exclusion $p$ values are obtained from this by using pseudoexperiments, and the limits set are one-sided upper limits [30].

From the fit to a model with signal events only in the signal region, and leaving all nuisance parameters free, a 95% C.L. upper limit on the number of events from new physics in the signal region can be derived. This number is 2.2 in the electron channel and 2.5 in the muon channel. This corresponds to a 95% C.L. upper limit on the effective cross section for new processes in the signal region, including the effects of experimental acceptance and efficiency, of 0.065 pb for the electron channel and 0.073 pb for the muon channel.

Within the MSUGRA-CMSSM framework, limits are obtained from a second combined fit to the four regions, this time allowing for a signal in all four regions, i.e., including possible contamination of the control regions with signal events. The results are interpreted as limits in the $m_{0} - m_{1/2}$ plane, as shown in Fig. 2. For the MSUGRA-CMSSM model considered and for equal squark and gluino masses, gluino masses below 700 GeV.
are excluded at 95% C.L. The limits depend only moderately on tanβ.

In summary, the first ATLAS results on searches for supersymmetry with an isolated electron or muon, jets, and missing transverse momentum have been presented. In a data sample corresponding to 35 pb⁻¹, no significant deviations from the standard model expectation are observed. Limits on the cross section for new processes within the experimental acceptance and efficiency are set. For a chosen set of parameters within the MSUGRA-CMSSM framework, and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% C.L. These ATLAS results exceed previous limits set by other experiments [3–7].

We thank CERN for the efficient commissioning and operation of the LHC during this initial high-energy data-taking period 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; DLR, DMS, and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMWF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT, Greece; ISF, INFN, ITEP, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, The 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; DSTNRF, 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), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (The Netherlands), PIC (Spain), ASGC (Taiwan), RAL (United Kingdom), and BNL (USA) and in the Tier-2 facilities worldwide.


(ATLAS Collaboration)

1University of Albany, Albany, New York, USA
2Department of Physics, University of Alberta, Edmonton, Alberta, Canada
3Department of Physics, Ankara University, Ankara, Turkey
4Department of Physics, Dumlupinar University, Kutahya, Turkey
5Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
6Turkish Atomic Energy Authority, Ankara, Turkey
7LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
8High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
9Department of Physics, University of Arizona, Tucson, Arizona, USA
10Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
11Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12Institut de Física d’Altes Energies and Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
13Department of Physics, University of Belgrade, Belgrade, Serbia
14Institut de Física deATOMS and National Laboratory and University of California, Berkeley, California, USA

131802-14
59 Faculty of Science, Hiroshima University, Hiroshima, Japan
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 Department of Physics, Indiana University, Bloomington, Indiana, USA
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City, Iowa, USA
64 Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 INFN Sezione di Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 Department of Physics, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
81 Institut für Physik, Universität Mainz, Mainz, Germany
82 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
83 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
84 Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
85 Department of Physics, McGill University, Montreal, Quebec, Canada
86 School of Physics, University of Melbourne, Victoria, Australia
87 Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
88 Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
89 INFN Sezione di Milano, Italy
90 Dipartimento di Fisica, Università di Milano, Milano, Italy
91 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
92 Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
93 Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada
94 F.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
95 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
96 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
97 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
98 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
100 Nagasaki Institute of Applied Science, Nagasaki, Japan
101 Graduate School of Science, Nagoya University, Nagoya, Japan
102 INFN Sezione di Napoli, Italy
103 Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
104 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands
105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, The Netherlands
106 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
107 Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
108 Department of Physics, New York University, New York, New York, USA
109 The Ohio State University, Columbus, Ohio, USA
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
112 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
113 Palacký University, RCPTM, Olomouc, Czech Republic
114 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
115 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
116 Graduate School of Science, Osaka University, Osaka, Japan
Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.

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

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

Also at Department of Physics, Oxford University, Oxford, United Kingdom.

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

Also at Department of Physics, Nanjing University, Jiangsu, China.