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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

The ATLAS Collaboration

Many extensions of the standard model predict the existence of new colored particles, such as the squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) 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 and 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 (LSP) is stable and escapes detection, giving rise to events with significant missing transverse momentum. In decay chains with charginos ($\tilde{q}_L \to q\tilde{\chi}^+, \tilde{g} \to q\tilde{\chi}^+$), chargino decay to the LSP 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 [4–8].

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 significant 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/constrained minimal supersymmetric standard model) framework [7, 8] 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, $\tan\beta = 3$, $\mu > 0$ and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% confidence level.

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ALPGEN \cite{14} 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++ \cite{15} v2.4.2. The SUSY particle spectra and decay modes are calculated with ISAJET \cite{16} v7.75. The SUSY samples are normalized using next-to-leading order (NLO) cross sections as determined by Prospino \cite{17} v2.1. All signal and background samples are produced using the ATLAS MC09 parameter tune \cite{18} and a GEANT4 based \cite{19} detector simulation \cite{20}.

Criteria for electron and muon identification closely follow those described in Ref. \cite{21}. Electrons in the signal region are required to pass the “tight” selection criteria, with $p_T > 20 \text{ GeV}$ 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 SCT hits, and a number of TRT 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 $p_T > 20 \text{ GeV}$ and $|\eta| < 2.4$ are considered. For the final selection, the distance between the $z$ coordinate of the primary vertex and that of the extrapolated muon track at the point of closest approach to the primary vertex must be less than 10 mm.

Jets are reconstructed using the anti-$k_T$ jet clustering algorithm \cite{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 using $p_T$- and $\eta$-dependent calibration factors obtained from Monte Carlo and validated with extensive test-beam and collision-data studies \cite{24}. Only jets with $p_T > 20 \text{ GeV}$ 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 only considered 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 non-collision backgrounds \cite{24}.

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 $p_T > 20 \text{ GeV}$, but over the full calorimeter coverage $|\eta| < 4.9$, and the selected lepton), any additional non–isolated 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 $p_T > 20 \text{ GeV}$ is required. Events are rejected if they contain a second identified lepton with $p_T > 20 \text{ GeV}$, because they are the subject of a future analysis. At least three jets with $p_T > 30 \text{ GeV}$ are required, the leading one of which must have $p_T > 60 \text{ GeV}$. In order to reduce the background of events with fake $E_T^{\text{miss}}$ from mismeasured jets, the missing transverse momentum vector $E_T^{\text{miss}}$ is required not to point in the direction of any of the three leading jets: $\Delta \phi(jet_i, E_T^{\text{miss}}) > 0.2$ ($i = 1, 2, 3$). The transverse mass between the lepton and the missing transverse momentum vector, $m_T = \sqrt{2 \cdot p_T \cdot E_T^{\text{miss}} \cdot (1 - \cos(\Delta \phi(\ell, E_T^{\text{miss}})))}$, 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: $m_{\text{eff}} > 500 \text{ GeV}$. The efficiency for the SUSY signal in the MSUGRA/CMSSM model defined earlier varies between 0.01% for $m_{1/2} = 100 \text{ GeV}$ and 4% for $m_{1/2} = 350 \text{ GeV}$, 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.

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, 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 purely 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 GeV $< E_T^{\text{miss}} < 80 \text{ GeV}$ and 40 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 \cite{23} 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 mul-
tjet control region is defined by demanding low missing transverse momentum, $E_{\text{miss}} < 40$ GeV, and low transverse mass, $m_T < 40$ GeV. This QCD control region is only used 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. [12], is then used to estimate the number of QCD multijet events with fake leptons in the signal region after final selection criteria: $0.0^{+0.5}_{-0.0}$ in the muon channel and $0.0^{+0.3}_{-0.0}$ in the electron channel.

Data are compared to expectations in Figure 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.

A combined fit to the number of observed events in the signal and control regions is performed. The assumption that the Monte Carlo 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 $E_{\text{miss}}$. 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: $L(n|b, \theta) = P_s \times P_W \times P_T \times P_Q \times C_{\text{Syst}}$, where $n$ represents the number of observed events in 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 in 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 $E_{\text{miss}}$ and $m_T$ distributions in signal and control regions. These uncertainties are determined by variation of the Monte Carlo generator, as well as by variations of internal generator parameters. Finite statistics 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 [20], $b$-tagging uncertainties, and the uncertainty on the luminosity.

Systematic uncertainties on the SUSY signal are esti-

![Figure 1](image-url)

**FIG. 1:** Top: $E_{\text{miss}}$ 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.
imated by variation of the factorization and renormalization scales in Prospino and by including the parton density function (PDF) uncertainties using the eigenvector sets provided by CTEQ6 [27]. Uncertainties are calculated separately for the individual production processes. Within the relevant kinematic range, typical uncertainties resulting from scale variations are 10–16%, whereas PDF uncertainties vary from 5% for $q\bar{q}$ production to 15–30% for $\tilde{q}\tilde{q}$ 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 data is consistent with the standard model expectation.

Limits are set on contributions of new physics to the signal region. These limits are obtained from a second combined fit to the four regions, this time allowing for a signal in all four regions, and leaving all nuisance parameters free. The limits are then derived from the profile likelihood ratio, $\Lambda(s) = -2[\ln L(n|s, \hat{b}, \hat{\theta}) - \ln L(n|\hat{s}, \hat{b}, \hat{\theta})]$, where $s$, $\hat{b}$ and $\hat{\theta}$ maximize the likelihood function and $\hat{b}$ and $\hat{\theta}$ maximize the likelihood for a given choice of $s$. In the fit, $s$ and $\hat{s}$ are constrained to be non-negative. The test statistic is $\Lambda(s)$. The exclusion $p$-values are obtained from this using pseudo-experiments and the limits set are one-sided upper limits [28].

From the fit to a model with signal events only in the signal region, a 95% CL 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% CL 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, the results are interpreted as limits in the $m_0 - m_{1/2}$ plane, as shown in Figure 2. For the model considered and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% CL. The limits depend only moderately on $\tan\beta$.

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 MSUGRA/CMSSM, and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% CL. These ATLAS results exceed previous limits set by other experiments [3, 6].

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TABLE I: Numbers of observed events in the signal and background control regions, as well as their estimated values from the fit (see 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>Electron channel</th>
<th>Signal region</th>
<th>Top region</th>
<th>W region</th>
<th>QCD region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>1</td>
<td>80</td>
<td>202</td>
<td>1464</td>
</tr>
<tr>
<td>Fitted top events</td>
<td>$1.34 \pm 0.52$ (1.29)</td>
<td>$65 \pm 12$ (63)</td>
<td>$32 \pm 16$ (31)</td>
<td>$40 \pm 11$</td>
</tr>
<tr>
<td>Fitted W/Z events</td>
<td>$0.47 \pm 0.40$ (0.46)</td>
<td>$11.2 \pm 4.6$ (10.2)</td>
<td>$161 \pm 27$ (146)</td>
<td>$170 \pm 34$</td>
</tr>
<tr>
<td>Fitted QCD events</td>
<td>$0.0^{+0.3}_{-0.0}$</td>
<td>$3.7 \pm 7.6$</td>
<td>$9 \pm 20$</td>
<td>$1254 \pm 51$</td>
</tr>
<tr>
<td>Fitted sum of background events</td>
<td>$1.81 \pm 0.75$</td>
<td>$80 \pm 9$</td>
<td>$202 \pm 14$</td>
<td>$1464 \pm 38$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Muon channel</th>
<th>Signal region</th>
<th>Top region</th>
<th>W region</th>
<th>QCD region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>1</td>
<td>93</td>
<td>165</td>
<td>346</td>
</tr>
<tr>
<td>Fitted top events</td>
<td>$1.76 \pm 0.67$ (1.39)</td>
<td>$85 \pm 11$ (67)</td>
<td>$42 \pm 19$ (33)</td>
<td>$50 \pm 10$</td>
</tr>
<tr>
<td>Fitted W/Z events</td>
<td>$0.49 \pm 0.36$ (0.71)</td>
<td>$7.7 \pm 3.3$ (11.6)</td>
<td>$120 \pm 26$ (166)</td>
<td>$71 \pm 16$</td>
</tr>
<tr>
<td>Fitted QCD events</td>
<td>$0.0^{+0.5}_{-0.0}$</td>
<td>$0.3 \pm 1.2$</td>
<td>$3 \pm 12$</td>
<td>$225 \pm 22$</td>
</tr>
<tr>
<td>Fitted sum of background events</td>
<td>$2.25 \pm 0.94$</td>
<td>$93 \pm 10$</td>
<td>$165 \pm 13$</td>
<td>$346 \pm 19$</td>
</tr>
</tbody>
</table>

[10] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis coinciding with the axis of the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$.
Bellaterra (Barcelona), Spain
12 University of Belgrade\(^{(a)}\), Institute of Physics, P.O. Box 57, 11001 Belgrade; Vinca Institute of Nuclear Sciences\(^{(b)}\) M. Petrovica Alasa 12-14, 11000 Belgrade, Serbia, Serbia
13 University of Bergen, Department for Physics and Technology, Allegaten 55, NO - 5007 Bergen, Norway
14 Lawrence Berkeley National Laboratory and University of California, Physics Division, MS50B-6227, 1 Cyclotron Road, Berkeley, CA 94720, United States of America
15 Humboldt University, Institute of Physics, Berlin, Newtonstr. 15, D-12489 Berlin, Germany
16 University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, Sidlerstrasse 5, CH - 3012 Bern, Switzerland
17 University of Birmingham, School of Physics and Astronomy, Edgbaston, Birmingham B15 2TT, United Kingdom
18 Bogazici University\(^{(a)}\), Faculty of Sciences, Department of Physics, TR - 80815 Bebek-Istanbul; Dogus University\(^{(b)}\), Faculty of Arts and Sciences, Department of Physics, 34722, Kadıköy, İstanbul; Gaziantep University, Faculty of Engineering, Department of Physics Engineering, 27310, Şehitkamil, Gaziantep, Turkey; Istanbul Technical University\(^{(c)}\), Faculty of Arts and Sciences, Department of Physics, 34469, Maslak, İstanbul, Turkey
19 INFN Sezione di Bologna\(^{(a)}\); Università di Bologna, Dipartimento di Fisica, viale C. Berti Pichat, 6/2, IT - 40127 Bologna, Italy
20 University of Bonn, Physikalisches Institut, Nussallee 12, D - 53115 Bonn, Germany
21 Boston University, Department of Physics, 590 Commonwealth Avenue, Boston, MA 02215, United States of America
22 Brandeis University, Department of Physics, MS057, 415 South Street, Waltham, MA 02454, United States of America
23 Universidade Federal do Rio De Janeiro, COPPE/EE/IF \(^{(a)}\), Caixa Postal 68528, Ilha do Fundao, BR - 21945-970 Rio de Janeiro; \(^{(b)}\)Universidade de Sao Paulo, Instituto de Fisica, R.do Matao Trav. R.187, Sao Paulo - SP, 05508 - 900, Brazil
24 Brookhaven National Laboratory, Physics Department, Bldg. 510A, Upton, NY 11973, United States of America
25 National Institute of Physics and Nuclear Engineering\(^{(a)}\) Bucharest-Magurele, Str. Atomistilor 407, P.O. Box MG-6, R-077125, Romania; University Politehnica Bucharest\(^{(b)}\), Rectorat - AN 001, 313 Splaiul Independentei, sector 6, 060042 Bucuresti; West University\(^{(c)}\) in Timisoara, Bd. Vasile Parvan 4, Timisoara, Romania
26 Universidad de Buenos Aires, FCEyN, Dto. Fisica, Pab I - C. Universitaria, 1428 Buenos Aires, Argentina
27 University of Cambridge, Cavendish Laboratory, J J Thomson Avenue, Cambridge CB3 0HE, United Kingdom
28 Carleton University, Department of Physics, 1125 Colonel By Drive, Ottawa ON K1S 5B6, Canada
29 CERN, CH - 1211 Geneva 23, Switzerland
30 University of Chicago, Enrico Fermi Institute, 5640 S. Ellis Avenue, Chicago, IL 60637, United States of America
31 Pontificia Universidad Católica de Chile, Facultad de Física, Departamento de Física\(^{(a)}\), Avda. Vicuna Mackenna 4860, San Joaquín, Santiago; Universidad Técnica Federico Santa María, Departamento de Física\(^{(b)}\), Avda. España 1680, Casilla 110-V, Valparaíso, Chile
32 Institute of High Energy Physics, Chinese Academy of Sciences\(^{(a)}\), P.O. Box 918, 19 Yuquan Road, Shijing Shan District, CN - Beijing 100049; University of Science & Technology of China (USTC), Department of Modern Physics\(^{(b)}\), Hefei, CN - Anhui 230026; Nanjing University, Department of Physics\(^{(c)}\), Nanjing, CN - Jiangsu 210093; Shandong University, High Energy Physics Group\(^{(d)}\), Jinan, CN - Shandong 250100, China
33 Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, FR - 63177 Aubière Cedex, France
34 Columbia University, Nevis Laboratory, 136 So. Broadway, Irvington, NY 10533, United States of America
35 University of Copenhagen, Niels Bohr Institute, Blegdamsvej 17, DK - 2100 Kobenhavn 0, Denmark
36 INFN Gruppo Collegato di Cosenza\(^{(a)}\); Università della Calabria, Dipartimento di Fisica\(^{(b)}\), IT-87036 Arcavacata di Rende, Italy
37 Faculty of Physics and Applied Computer Science of the AGH-University of Science and Technology, (FPACS, AGH-UST), al. Mickiewicza 30, PL-30059 Cracow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, PL - 31342 Krakow, Poland
39 Southern Methodist University, Physics Department, 106 Fondren Science Building, Dallas, TX 75275-0175, United States of America
40 University of Texas at Dallas, 800 West Campbell Road, Richardson, TX 75080-3021, United States of America
41 DESY, Notkestr. 85, D-22603 Hamburg and Platanenallee 6, D-15738 Zeuthen, Germany
42 TU Dortmund, Experimentelle Physik IV, DE - 44221 Dortmund, Germany
43 Technical University Dresden, Institut für Kern- und Teilchenphysik, Zellescher Weg 19, D-01069 Dresden, Germany
44 Duke University, Department of Physics, Durham, NC 27708, United States of America
University Street, Montreal, Quebec H3A 2T8, Canada
87 University of Melbourne, School of Physics, AU - Parkville, Victoria 3010, Australia
88 The University of Michigan, Department of Physics, 2477 Randall Laboratory, 500 East University, Ann Arbor, MI 48109-1120, United States of America
89 Michigan State University, Department of Physics and Astronomy, High Energy Physics Group, East Lansing, MI 48824-2320, United States of America
90 INFN Sezione di Milano\(^{(a)}\); Università di Milano, Dipartimento di Fisica\(^{(b)}\), via Celoria 16, IT - 20133 Milano, Italy
91 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Independence Avenue 68, Minsk 220072, Republic of Belarus
92 National Scientific & Educational Centre for Particle & High Energy Physics, NC PHEP BSU, M. Bogdanovich St. 153, Minsk 220040, Republic of Belarus
93 Massachusetts Institute of Technology, Department of Physics, Room 24-516, Cambridge, MA 02139, United States of America
94 University of Montreal, Group of Particle Physics, C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, H3C 3J7, Canada
95 P.N. Lebedev Institute of Physics, Academy of Sciences, Leninsky pr. 53, RU - 117 924 Moscow, Russia
96 Institute for Theoretical and Experimental Physics (ITEP), B. Cheremushkinskaya ul. 25, RU 117 218 Moscow, Russia
97 Moscow Engineering & Physics Institute (MEPhI), Kashirskoe Shosse 31, RU - 115 409 Moscow, Russia
98 Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (MSU SINP), 1(2), Leninskie gory, GSP-1, Moscow 119991 Russian Federation, Russia
99 Ludwig-Maximilians-Universität München, Fakultät für Physik, Am Coulombwall 1, DE - 85748 Garching, Germany
100 Max-Planck-Institut für Physik, (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany
101 Nagasaki Institute of Applied Science, 536 Aba-machi, JP Nagasaki 851-0193, Japan
102 Nagoya University, Graduate School of Science, Furo-Cho, Chikusa-ku, Nagoya, 464-8602, Japan
103 INFN Sezione di Napoli\(^{(a)}\); Università di Napoli, Dipartimento di Scienze Fisiche\(^{(b)}\), Complesso Universitario di Monte Sant’Angelo, via Cintia, IT - 80126 Napoli, Italy
104 University of New Mexico, Department of Physics and Astronomy, MSC07 4220, Albuquerque, NM 87131 USA, United States of America
105 Radboud University Nijmegen/NIKHEF, Department of Experimental High Energy Physics, Heyendaalseweg 135, NL-6525 AJ, Nijmegen, Netherlands
106 Nikhef National Institute for Subatomic Physics, and University of Amsterdam, Science Park 105, 1098 XG Amsterdam, Netherlands
107 Department of Physics, Northern Illinois University, LaTourette Hall Normal Road, DeKalb, IL 60115, United States of America
108 Budker Institute of Nuclear Physics (BINP), RU - Novosibirsk 630 090, Russia
109 New York University, Department of Physics, 4 Washington Place, New York NY 10003, USA, United States of America
110 Ohio State University, 191 West Woodruff Ave, Columbus, OH 43210-1117, United States of America
111 Okayama University, Faculty of Science, Tsushima-naka 3-1-1, Okayama 700-8530, Japan
112 University of Oklahoma, Homer L. Dodge Department of Physics and Astronomy, 440 West Brooks, Room 100, Norman, OK 73019-0225, United States of America
113 Oklahoma State University, Department of Physics, 145 Physical Sciences Building, Stillwater, OK 74078-3072, United States of America
114 Palacký University, 17.listopadu 50a, 772 07 Olomouc, Czech Republic
115 University of Oregon, Center for High Energy Physics, Eugene, OR 97403-1274, United States of America
116 LAL, Univ. Paris-Sud, IN2P3/CNRS, Orsay, France
117 Osaka University, Graduate School of Science, Machikaneyama-machi 1-1, Toyonaka, Osaka 560-0043, Japan
118 University of Oslo, Department of Physics, P.O. Box 1048, Blindern, NO - 0316 Oslo 3, Norway
119 Oxford University, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom
120 INFN Sezione di Pavia\(^{(a)}\); Università di Pavia, Dipartimento di Fisica Nucleare e Teorica\(^{(b)}\), Via Bassi 6, IT-27100 Pavia, Italy
121 University of Pennsylvania, Department of Physics, High Energy Physics Group, 209 S. 33rd Street, Philadelphia, PA 19104, United States of America
122 Petersburg Nuclear Physics Institute, RU - 188 300 Gatchina, Russia
123 INFN Sezione di Pisa\(^{(a)}\); Università di Pisa, Dipartimento di Fisica E. Fermi\(^{(b)}\), Largo B. Pontecorvo 3, IT - 56127 Pisa, Italy
124 University of Pittsburgh, Department of Physics and Astronomy, 3941 O’Hara Street, Pittsburgh, PA 15260, United States of America
125 Laboratorio de Instrumentacio y Fisica Experimental de Particulas - LIP\(^{(a)}\), Avenida Elias Garcia 14-1, PT - 1000-149 Lisboa, Portugal; Universidad de Granada, Departamento de Fisica Teorica y del Cosmos and CAFPE\(^{(b)}\), E-18071 Granada, Spain