Inclusive Search for Supersymmetry Using Razor Variables in \( pp \) Collisions at \( \sqrt{s} = 7 \) TeV

S. Chatrchyan et al.\(^*\)
(CMS Collaboration)

(Received 8 January 2013; published 23 August 2013)

An inclusive search is presented for new heavy particle pairs produced in \( \sqrt{s} = 7 \) TeV proton-proton collisions at the LHC using 4.7 \( \pm \) 0.1 fb\(^{-1}\) of integrated luminosity. The selected events are analyzed in the 2D razor space of \( M_R \), an event-by-event indicator of the heavy particle mass scale, and \( R \), a dimensionless variable related to the missing transverse energy. The third-generation sector is probed using the event heavy-flavor content. The search is sensitive to generic supersymmetry models with minimal assumptions about the superpartner decay chains. No excess is observed in the number of events beyond that predicted by the standard model. Exclusion limits are derived in the CMSSM framework as well as for simplified models. Within the CMSSM parameter space considered, gluino masses up to 800 GeV and squark masses up to 1.35 TeV are excluded at 95% confidence level depending on the model parameters. The direct production of pairs of top or bottom squarks is excluded for masses as high as 400 GeV.

DOI: 10.1103/PhysRevLett.111.081802
PACS numbers: 14.80.Ly, 12.60.Jv, 13.85.Rm

Models with softly broken supersymmetry (SUSY) [1] predict heavy superpartners of the standard model (SM) particles. Experimental searches for \( R \)-parity [2] conserving SUSY have focused on signatures combining energetic hadronic jets and leptons or photons from the decays of pair-produced squarks and gluinos, with large missing transverse energy (\( E_T^{\text{miss}} \)) from the two weakly interacting lightest neutral superpartners (LSPs) produced in separate decay chains. Recent publications include results from both the Tevatron [3,4] and the Large Hadron Collider (LHC) [5–26].

In SUSY models, the scale of soft SUSY breaking is related to the scale of electroweak symmetry breaking. This implies either that the soft-breaking mass parameters cannot be too large, or that the smallness of the electroweak scale is explained by large cancellations arising from relations among these parameters in the high-energy theory. The latter possibility is complicated by large radiative corrections, particularly those induced by the soft-breaking parameters that are responsible for the masses of the top and bottom squarks, the superpartners of the third-generation quarks. It is thus of special importance to search for the lightest allowed top and bottom squarks, whose decays will be enriched in heavy-flavor quarks.

In this Letter we present results of an inclusive search for new heavy particles. The analysis is designed to be largely independent of the details of the decay chains and measures deviations from the characteristic distributions of the relevant SM processes in the razor variable plane [27,28]. It is generically sensitive to the production of pairs of heavy particles, provided that the decays of these particles produce significant \( E_T^{\text{miss}} \), that these particles are substantially heavier than any SM particle, and that they are strongly produced in high-energy proton-proton collisions. The selection requires only two or more energetic reconstructed calorimeter objects [29]. The selected events are sorted hierarchically into exclusive data samples, categorized according to the lepton multiplicity in the event. The analysis is repeated with the requirement of the presence of a bottom-quark jet (\( b \)-jet) to search for third-generation-enhanced SUSY signatures. The major backgrounds are top production and vector boson production in association with jets. Using Monte Carlo simulation, we verified that the contribution from other SM processes (e.g., single top production or the pair production of electroweak vector bosons) is negligible.

The razor kinematic variables are based on the generic process of the pair production of two heavy particles, each decaying to an undetected particle plus visible decay products. The razor kinematic variables are used to test, event by event, the hypothesis that the reconstructed particles in the events represent the visible portion of the decays of two heavy particles, each producing also an invisible particle. Regardless of its complexity, each event is treated as a dijetlike event by grouping all the physics objects detectable in the calorimeters (hadronic jet candidates and isolated electrons) into two megajets [28]. Muons are considered invisible objects, in order to minimize the differences between the razor variables computed after the event reconstruction and the corresponding values derived from the calorimetric jets at the trigger level. Assuming the pair of megajets accurately reconstructs the visible portion of the parent particle decays, the signal

\( \ast \) Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
kinematics is equivalent, for example, to pair production of heavy squarks \( q_1, q_2 \), with \( q_i \rightarrow j_i \tilde{X}^0 \), where the \( \tilde{X}^0 \) are LSPs and \( j_i \) denotes the visible products of the decays.

The \( M_R \) razor kinematic variable is defined in terms of the momentum of the two megajets as \( M_R = \sqrt{[(p_T^1)^2 + (p_T^2)^2]}/2 \) and is, by construction, invariant under longitudinal boosts. In the approximation of massless megajets and negligible initial-state \( p_T \), \( M_R \) equals \( \gamma_\Delta M_\Delta \), where \( M_\Delta = (M^2_j - M^2_{\tilde{q}})/M_\Delta \) is twice the magnitude of the momentum of either megajet in the respective squark rest frame, and \( \gamma_\Delta \) is the boost factor from the center-of-mass frame to the squark rest frames. Note that this definition of \( M_R \) is amended from that in [28] to avoid configurations where the razor variable is ill defined due to unphysical Lorentz transformations.

The razor observable \( M_R^2 \) is defined as \( M_R^2 = [(1/2)(E_T^{\text{miss}}(p_T^1 + p_T^2) - E_T^{\text{miss}}(p_T^1 + p_T^2))]/2 \), where \( p_T^{1,2} \) are the transverse momentum vectors of the two megajets and \( E_T^{\text{miss}} \) is the missing transverse momentum vector (also referred to as missing transverse energy). The razor dimensionless ratio is defined as \( R = (M_R^2/M_R) \). For signal events \( M_R^2 \) has a maximum value (a kinematic endpoint) of \( M_\Delta \), so \( R \) has a maximum value of approximately one. Thus signal events are characterized by a distribution in \( M_R \) that peaks around \( M_\Delta \), and a distribution in \( R \) that peaks around 0.5, in stark contrast with, for example, QCD multijet background events, whose distribution in either \( R \) or \( M_R \) is exponentially suppressed away from zero [28,29]. These properties determine a region of the 2D razor space where the standard model background is reduced while the signal is retained.

A detailed description of the CMS detector can be found elsewhere [30]. A superconducting solenoid provides an axial magnetic field of 3.8 T. The silicon pixel and strip tracker, the high-resolution crystal electromagnetic calorimeter (ECAL), and the brass and scintillator hadron calorimeter (HCAL) are contained within the solenoid. Muons are detected in gas-ionization chambers embedded in the steel return yoke. The HCAL, combined with the ECAL, measures the jet energy with a resolution \( \Delta E/E = 100\%/\sqrt{E/\text{GeV}} \pm 5\% \). CMS uses a coordinate system with the origin located at the nominal collision point, and the pseudorapidity is defined as \( \eta = -\ln[\tan(\theta/2)] \), where the polar angle \( \theta \) is defined with respect to the counterclockwise beam direction.

The analysis uses a set of dedicated triggers that apply lower thresholds on the values of \( R \) and \( M_R \) computed online from the reconstructed jets and \( E_T^{\text{miss}} \). Three trigger categories are used: (i) hadronic razor triggers applying threshold requirements [29] on \( R \) and \( M_R \) in events with at least two jets of \( p_T > 56 \) GeV; (ii) muon razor triggers that have looser \( R \) and \( M_R \) requirements than the hadronic triggers and combined with at least one muon in the central part of the detector (barrel) with \( p_T > 10 \) GeV; (iii) electron razor triggers with similar \( R \) and \( M_R \) requirements to those used for muons and with at least one electron of \( p_T > 12 \) GeV satisfying loose isolation criteria. In addition, a set of nonrazor triggers is used to define control data samples.

Events, after detector- and beam-related noise cleaning, are required to have at least one high-quality reconstructed interaction vertex [31]. When multiple vertices are found, the one with the highest associated \( \sum p_T^2 \) is selected. The electron and muon candidate reconstruction and identification criteria are described in Ref. [32]. Electrons and muons are required to lie within \( |\eta| < 2.5 \) and 2.1, respectively, and to satisfy the identification and selection requirements from [32]. Jets are reconstructed from calorimeter energy deposits using the infrared-safe anti-\( k_T \) algorithm [33] with radius parameter 0.5. Jets are corrected for nonuniformities of the calorimeter response using energy- and \( \eta \)-dependent correction factors. Only jet candidates with \( p_T > 40 \) GeV within \( |\eta| < 3.0 \) are retained. The jet energy scale uncertainty for these corrected jets is 5% [34]. To match the trigger requirements, the \( p_T \) of the two leading jets is required to be greater than 60 GeV. The transverse momentum imbalance in the event, \( E_T^{\text{miss}} \), is reconstructed using the particle flow algorithm [35].

The reconstructed jets are grouped into two megajets [29]. The megajets are constructed as a sum of the four-momenta of their constituent objects. After the baseline selection and calculation of the variables \( R \) and \( M_R \), the events are assigned to one of six final-state boxes according to whether the event has zero, one, or two isolated leptons, divided according to lepton flavor (electrons and muons) as shown in Table I.

The requirements given in Table I define the full analysis regions of the \( R^2/M_R \) plane, where the analysis is performed for each box. They are the loosest possible requirements that allow for the valid background description, while at the same time maintaining fully efficient triggers. To prevent ambiguities for events satisfying the selection requirements of more than one box [29], the boxes are arranged in a predefined hierarchy, as given in Table I. Each event is uniquely assigned to the first box whose criteria are satisfied by the event.

Six additional boxes are formed for events with at least one 2-jet tagged using the track-counting high-efficiency (TCHE) \( b \)-tagging algorithm with 1% misidentification.

<table>
<thead>
<tr>
<th>Lepton boxes</th>
<th>( M_R &gt; 300 ) GeV, 0.11 ( &lt; R^2 &lt; 0.5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELE-MU</td>
<td>( p_T &gt; 20 ) GeV, ( p_T^n &gt; 15 ) GeV</td>
</tr>
<tr>
<td>MU-MU</td>
<td>( p_T^{n1} &gt; 15 ) GeV, ( p_T^{n2} &gt; 10 ) GeV</td>
</tr>
<tr>
<td>ELE-ELE</td>
<td>( p_T^1 &gt; 20 ) GeV, ( p_T^2 &gt; 10 ) GeV</td>
</tr>
<tr>
<td>MU</td>
<td>( p_T^n &gt; 12 ) GeV</td>
</tr>
<tr>
<td>ELE</td>
<td>( p_T^n &gt; 20 ) GeV</td>
</tr>
</tbody>
</table>

HAD box \( M_R > 400 \) GeV, 0.18 \( < R^2 < 0.5 \)
rate [36,37]. These six boxes define the razor inclusive analysis of data samples with enhanced heavy-flavor content. The typical $b$-tagging efficiency is 65% [38].

The razor analysis is guided by studies of simulated events generated with the PYTHIA6 [39] and MADGRAPH [40] Monte Carlo programs, implemented using the CMS GEANT4-based [41] detector simulation, and then processed by the same software as that used to reconstruct data. Events with QCD multijets, top quarks, and electroweak (V) vector bosons are generated with MADGRAPH interfaced with PYTHIA for parton showering, hadronization, and the underlying event description. $V + \text{jets}$ events are generated with up to four additional tree-level strong emissions and $t\bar{t} + \text{jets}$ with up to three. To generate Monte Carlo samples for the rest of the background model obtained in the fit region is extrapolated through studies based on simulation. The 2D representation of the background shape in the fit region, as demonstrated by the pseudoexperiments is used to calculate a priori the background shape parameters. The results are incorporated in the final fits as a set of Gaussian penalty terms [51,52] for the parameters $k_j$, $M_{R,j}$, and $R_{0,j}$ multiplying the final likelihood [Eq. (2)]. The rms values of the penalty terms for the $k_j$ parameters are typically $\sim 30\%$.

An extended and unbinned maximum likelihood (ML) fit is performed in each box using ROOFIT [52]. The fit performed in the fit region of the $R^2$-$M_R$ plane provides the description of the SM background in the full plane. The likelihood function for a given box is written as [53]

$$L_b = \frac{e^{\sum_{j\in SM} N_j}}{N!} \prod_{i=1}^{N} \left( \sum_{j\in SM} N_j P_j(M_{R,i}, R^2) \right),$$

where $N$ is the total event yield in the box, the sum runs over all the SM processes relevant for that box, and $N_j$ is the yield of a given fit sample in the box.

The values of the shape parameters that maximize the likelihood in these fits, along with the corresponding covariance matrix, are used to define the background model and the uncertainty associated with it. Additional background shape uncertainties due to the choice of the functional form were found to be negligible [29].

The result of the ML fit projected on $M_R$ and $R^2$ is shown in Fig. 1 for the HAD box. No significant discrepancy is observed between the data and the fit model in any of the six boxes [29].

To establish the compatibility of the background model with the observed data set, we define six signal regions (SR$i$) in the tail of the background distribution. Using the background model returned by the ML fit, we derive the distribution of the expected yield in each SR$i$ using pseudoexperiments accounting for correlations and uncertainties on the parameters describing the background model. For each of the SR$i$ the distribution of the number of events derived by the pseudoexperiments is used to calculate a two-sided $p$ value (as shown for the HAD box in Fig. 2), corresponding to the probability of observing an equal or less probable outcome for a counting experiment in each signal region. The $p$ values test the compatibility of the observed number of events in data with the SM expectation obtained from the background parametrization. We quote
Data gluino-gluino production dominating at low and high across the parameter space with squark-squark and changing relevant SUSY strong production processes. The shape of the observed exclusion curves reflect the CL calculate experiments, and the value of background-only and signal-plus-background pseudoex- t slope first component in component, and a component that encapsulates both the steep-slope component denoted as signal plus background (SR) or the null hypothesis ln logarithm of the likelihood ratio SR, together with the observed yield. The median and the mode of the yield distribution for each SR, together with the observed yield.

For each box we consider the test statistic given by the logarithm of the likelihood ratio lnQ = ln(L(s + b|H)/L(b|H)), where H is the hypothesis under test: H1 (signal plus background) or the null hypothesis H0 (background only). Given the distribution of lnQ for background-only and signal-plus-background pseudoexperiments, and the value of lnQ observed in the data, we calculate CLs+b and 1 − CLb [54,55]. From these values the CLs = CLs+b/CLb is computed for that model point. A point in the constrained minimal supersymmetric standard model (CMSSM) plane is excluded at 95% confidence level (C.L.) if CLs < 0.05. The result is shown in Fig. 3. The shape of the observed exclusion curves reflect the changing relevant SUSY strong production processes across the parameter space with squark-squark and gluino-gluino production dominating at low and high m0, respectively. The observed limit is less constraining than the median-expected limit at lower m0 due to an excess of observed events in the HAD box at large R2, where squark-pair production dominates over gluino-pair production.

Cascading decays of gluinos yield more leptons than decays of squarks. Thus, relative to hadronic boxes, the contribution of lepton boxes increases with m0.

We estimate the systematic uncertainty on the signal shape model due to parton density functions (point by point up to 30%), jet energy scale (point by point up to 1%), and lepton identification (using Z → ℓ+ℓ− data, 1% per lepton), as well as on the signal yield due to the luminosity uncertainty (2.2%) [56], the theoretical cross section (point by point up to 15%), razor trigger efficiency uncertainty

FIG. 2 (color online). The p values corresponding to the observed number of events in the HAD box signal regions (SRi). The green region indicates the fit region in the HAD box. Similar results are obtained for the other boxes.

FIG. 3 (color online). Observed (solid blue curve) and median-expected (dashed curve, shown with its ±1 standard deviation uncertainty band) 95% C.L. limits in the (m0, m1/2) CMSSM plane (drawn according to [61]) with tanβ = 10, A0 = 0 GeV, and sgn(μ) = +1. Shown separately are the observed HAD-only (solid crimson) and leptonic-only (solid green) 95% C.L. limits.
For simplified models we exclude up to 1 TeV for gluinos using a data sample of both the inclusive and the LSP mass in each of the simplified model studies, for the 95% C.L. excluded largest parent mass as a function of 1.35 TeV, and for a factor of 3 cross section enhancement or reduction are corresponding to the NLL-NLO cross section [29]. Figure 4 shows also produced as well as for further results. In this model processes.

FIG. 4 (color online). Summary of the 95% CL excluded largest parent mass as a function of the LSP mass in each of the simplified models studied. Results from the inclusive razor analysis (upper bars) and the b-jet razor analysis (lower bars) are shown.

(2%), and lepton trigger efficiency uncertainty (3%). In the b-tag analysis path an additional systematic is considered for the b-tagging efficiency (between 6% and 20% in $p_T$ bins [36]). We consider variations of the function modeling the signal uncertainty (log-normal versus Gaussian) as well as the $R^2$ and $M_R$ binning choice, finding negligible deviations in the result.

The results are also interpreted as cross section limits on a number of simplified models [57], where a limited set of hypothetical particles and decay chains are introduced to produce a given topological signature. Specific applications of these ideas have appeared in Refs. [58–60]. For each model studied, the excluded cross section at 95% C.L. is derived as a function of the mass of the produced particles (gluinos or squarks, depending on the model) and the LSP mass, as well as the exclusion curve corresponding to the NLL-NLO cross section. Exclusion curves for a factor of 3 cross section enhancement or reduction are also produced as well as for ±1 standard deviation variations in the NLL-NLO cross section [29]. Figure 4 shows the 95% C.L. excluded largest parent mass as a function of the LSP mass in each of the simplified model studies, for both the inclusive and b-jet versions of the analysis.

In summary, we performed a search for squarks and gluinos using a data sample of 4.7 fb$^{-1}$ of CMS data at $\sqrt{s} = 7$ TeV proton-proton collisions in the razor variable space using a 2D shape description of the relevant standard model processes.

No significant excess over the background expectations is observed, and the results are presented as a 95% C.L. limit in the ($m_0$, $m_{1/2}$) CMSSM parameter space. For $m(\tilde{g}) \sim m(\tilde{q})$ we exclude squarks and gluinos up to 1.35 TeV, and for $m(\tilde{q}) > m(\tilde{g})$ we exclude gluinos up to 800 GeV. For simplified models we exclude up to 1 TeV for the gluino mass and up to 800 GeV for the first and second generation squark masses. For direct production of pairs of top and bottom squarks we exclude top and bottom squark masses up to 400 GeV depending on the LSP mass.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MEYS (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SFo690030s09 and ERDF (Estonia); Academy of Finland, MEQ, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS, and RFBR (Russia); MSTD (Serbia); SEIDE and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEPCenter, IPST, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie program and the European Research Council (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of Czech Republic; the Council of Science and Industrial Research, India; the Compagnia di San Paolo (Torino); the Weston Havens Foundation (US) and the HOMING PLUS program of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund.

---

5 Vrije Universiteit Brussel, Brussel, Belgium
6 Université Libre de Bruxelles, Bruxelles, Belgium
7 Ghent University, Ghent, Belgium
8 Université Catholique de Louvain, Louvain-la-Neuve, Belgium
9 Université de Mons, Mons, Belgium
10 Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
11 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
12 Universidade Estadual Paulista, São Paulo, Brazil
12b Universidade Federal do ABC, São Paulo, Brazil
13 Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
14 University of Sofia, Sofia, Bulgaria
15 Institute of High Energy Physics, Beijing, China
16 State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
17 Universidad de Los Andes, Bogota, Colombia
18 Technical University of Split, Split, Croatia
19 University of Split, Split, Croatia
20 Institute Rudjer Boskovic, Zagreb, Croatia
21 University of Cyprus, Nicosia, Cyprus
22 Charles University, Prague, Czech Republic
23 Academy of Scientific Research and Technology of the Arab Republic of Egypt,
   Egyptian Network of High Energy Physics, Cairo, Egypt
24 National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
25 Department of Physics, University of Helsinki, Helsinki, Finland
26 Helsinki Institute of Physics, Helsinki, Finland
27 Lappeenranta University of Technology, Lappeenranta, Finland
28 DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
29 Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
30 Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse,
   CNRS-IN2P3, Strasbourg, France
31 Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules,
   CNRS-IN2P3, Villeurbanne, France
32 Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon,
   Villeurbanne, France
33 Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
34 RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
35 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
36 RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
37 Deutsches Elektronen-Synchrotron, Hamburg, Germany
38 University of Hamburg, Hamburg, Germany
39 Institut für Experimentelle Kernphysik, Karlsruhe, Germany
40 Institute of Nuclear Physics “Demokritos”, Aghia Paraskevi, Greece
41 University of Athens, Athens, Greece
42 University of Ioannina, Ioannina, Greece
43 KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
44 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
45 University of Debrecen, Debrecen, Hungary
46 Panjab University, Chandigarh, India
47 University of Delhi, Delhi, India
48 Saha Institute of Nuclear Physics, Kolkata, India
49 Bhabha Atomic Research Centre, Mumbai, India
50 Tata Institute of Fundamental Research-EHEP, Mumbai, India
51 Tata Institute of Fundamental Research-HECR, Mumbai, India
52 Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
53a INFN Sezione di Bari, Bari, Italy
53b Università di Bari, Bari, Italy
53c Politecnico di Bari, Bari, Italy
54a INFN Sezione di Bologna, Bologna, Italy
54b Università di Bologna, Bologna, Italy
55a INFN Sezione di Catania, Catania, Italy
55b Università di Catania, Catania, Italy
56a INFN Sezione di Firenze, Firenze, Italy
56a Università di Firenze, Firenze, Italy
57 INFN Laboratori Nazionali di Frascati, Frascati, Italy
58a INFN Sezione di Genova, Genova, Italy
58b Università di Genova, Genova, Italy
59a INFN Sezione di Milano-Bicocca, Milano, Italy
59b Università di Milano-Bicocca, Milano, Italy
60a INFN Sezione di Napoli, Napoli, Italy
60b Università di Napoli “Federico II”, Napoli, Italy
60c Università della Basilicata (Potenza), Napoli, Italy
60d Università G. Marconi (Roma), Napoli, Italy
61a INFN Sezione di Padova, Padova, Italy
61b Università di Padova, Padova, Italy
61c Università di Trento (Trento), Padova, Italy
62a INFN Sezione di Pavia, Pavia, Italy
62b Università di Pavia, Pavia, Italy
63a INFN Sezione di Perugia, Perugia, Italy
63b Università di Perugia, Perugia, Italy
64a INFN Sezione di Pisa, Pisa, Italy
64b Università di Pisa, Pisa, Italy
64c Scuola Normale Superiore di Pisa, Pisa, Italy
65a INFN Sezione di Roma, Roma, Italy
65b Università di Roma, Roma, Italy
66a INFN Sezione di Torino, Torino, Italy
66b Università di Torino, Torino, Italy
66c Università del Piemonte Orientale (Novara), Torino, Italy
67a INFN Sezione di Trieste, Trieste, Italy
67b Università di Trieste, Trieste, Italy
68 Kangwon National University, Chunchon, Korea
69 Kyungpook National University, Daegu, Korea
70 Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
71 Korea University, Seoul, Korea
72 University of Seoul, Seoul, Korea
73 Sungkyunkwan University, Suwon, Korea
74 Vilnius University, Vilnius, Lithuania
75 Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
76 Universidad Iberoamericana, Mexico City, Mexico
77 Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
78 Universidad Autonoma de San Luis Potosi, San Luis Potosi, Mexico
79 University of Auckland, Auckland, New Zealand
80 University of Canterbury, Christchurch, New Zealand
81 National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
82 National Centre for Nuclear Research, Swierk, Poland
83 Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
84 Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
85 Joint Institute for Nuclear Research, Dubna, Russia
86 Petersburg Nuclear Physics Institute, Gatchina (St. Petersbourg), Russia
87 Institute for Nuclear Research, Moscow, Russia
88 Institute for Theoretical and Experimental Physics, Moscow, Russia
89 Moscow State University, Moscow, Russia
90 P.N. Lebedev Physical Institute, Moscow, Russia
91 State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
92 University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
93 Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
94 Universidad Autónoma de Madrid, Madrid, Spain
95 Universidad de Oviedo, Oviedo, Spain
96 Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
97 CERN, European Organization for Nuclear Research, Geneva, Switzerland
98 Paul Scherrer Institut, Villigen, Switzerland
99 Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
100 Universität Zürich, Zurich, Switzerland
101 National Central University, Chung-Li, Taiwan
102 National Taiwan University (NTU), Taipei, Taiwan
103 Chulalongkorn University, Bangkok, Thailand
104 Cukurova University, Adana, Turkey
105 Middle East Technical University, Physics Department, Ankara, Turkey
106 Bogazici University, Istanbul, Turkey
107 Istanbul Technical University, Istanbul, Turkey
108 National Scientific Center, Kharkov Institute of Physics and Technology, Kharkiv, Ukraine
109 University of Bristol, Bristol, United Kingdom
110 Rutherford Appleton Laboratory, Didcot, United Kingdom
111 Imperial College, London, United Kingdom
112 Brunel University, Uxbridge, United Kingdom
113 Baylor University, Waco, Texas, USA
114 The University of Alabama, Tuscaloosa, Alabama, USA
115 Boston University, Boston, Massachusetts, USA
116 Brown University, Providence, Rhode Island, USA
117 University of California, Davis, Davis, California, USA
118 University of California, Los Angeles, Los Angeles, California, USA
119 University of California, Riverside, Riverside, California, USA
120 University of California, San Diego, La Jolla, California, USA
121 University of California, Santa Barbara, Santa Barbara, California, USA
122 California Institute of Technology, Pasadena, California, USA
123 Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
124 University of Colorado at Boulder, Boulder, Colorado, USA
125 Cornell University, Ithaca, New York, USA
126 Fairfield University, Fairfield, Connecticut, USA
127 Fermi National Accelerator Laboratory, Batavia, Illinois, USA
128 University of Florida, Gainesville, Florida, USA
129 Florida International University, Miami, Florida, USA
130 Florida State University, Tallahassee, Florida, USA
131 Florida Institute of Technology, Melbourne, Florida, USA
132 University of Illinois at Chicago (UIC), Chicago, Illinois, USA
133 The University of Iowa, Iowa City, Iowa, USA
134 Johns Hopkins University, Baltimore, Maryland, USA
135 The University of Kansas, Lawrence, Kansas, USA
136 Kansas State University, Manhattan, Kansas, USA
137 Lawrence Livermore National Laboratory, Livermore, California, USA
138 University of Maryland, College Park, Maryland, USA
139 Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
140 University of Minnesota, Minneapolis, Minnesota, USA
141 University of Mississippi, Oxford, Mississippi, USA
142 University of Nebraska-Lincoln, Lincoln, Nebraska, USA
143 State University of New York at Buffalo, Buffalo, New York, USA
144 Northeastern University, Boston, Massachusetts, USA
145 Northwestern University, Evanston, Illinois, USA
146 University of Notre Dame, Notre Dame, Indiana, USA
147 The Ohio State University, Columbus, Ohio, USA
148 Princeton University, Princeton, New Jersey, USA
149 University of Puerto Rico, Mayaguez, Puerto Rico
150 Purdue University, West Lafayette, Indiana, USA
151 Purdue University Calumet, Hammond, Indiana, USA
152 Rice University, Houston, Texas, USA
153 University of Rochester, Rochester, New York, USA
154 The Rockefeller University, New York, New York, USA
155 Rutgers, the State University of New Jersey, Piscataway, New Jersey, USA
156 University of Tennessee, Knoxville, Tennessee, USA
157 Texas A & M University, College Station, Texas, USA
158 Texas Tech University, Lubbock, Texas, USA
159 Vanderbilt University, Nashville, Tennessee, USA
160 University of Virginia, Charlottesville, Virginia, USA
161 Wayne State University, Detroit, Michigan, USA
162 University of Wisconsin, Madison, Wisconsin, USA
Deceased.

Also at Vienna University of Technology, Vienna, Austria.

Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

Also at California Institute of Technology, Pasadena, USA.

Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.

Also at Suez Canal University, Suez, Egypt.

Also at Zewail City of Science and Technology, Zewail, Egypt.

Also at Cairo University, Cairo, Egypt.

Also at Fayoum University, El-Fayoum, Egypt.

Also at British University in Egypt, Cairo, Egypt.

Now at Ain Shams University, Cairo, Egypt.

Also at National Centre for Nuclear Research, Swierk, Poland.

Also at Université de Haute Alsace, Mulhouse, France.

Also at Joint Institute for Nuclear Research, Dubna, Russia.

Also at Moscow State University, Moscow, Russia.

Also at Brandenburg University of Technology, Cottbus, Germany.

Also at The University of Kansas, Lawrence, KS, USA.

Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

Also at Eötvös Loránd University, Budapest, Hungary.

Also at Tata Institute of Fundamental Research-HECR, Mumbai, India.

Also at University of Visva-Bharati, Santiniketan, India.

Also at Sharif University of Technology, Tehran, Iran.

Also at Isfahan University of Technology, Isfahan, Iran.

Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.

Also at Università degli Studi Guglielmo Marconi, Roma, Italy.

Also at Università degli Studi di Siena, Siena, Italy.

Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.

Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.

Also at University of California, Los Angeles, CA, USA.

Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy.

Also at INFN Sezione di Roma, Università di Roma, Roma, Italy.

Also at University of Athens, Athens, Greece.

Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

Also at Paul Scherrer Institut, Villigen, Switzerland.

Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

Also at Gaziosmanpasa University, Tokat, Turkey.

Also at Adiyaman University, Adiyaman, Turkey.

Also at Izmir Institute of Technology, Izmir, Turkey.

Also at The University of Iowa, Iowa City, IA, USA.

Also at Mersin University, Mersin, Turkey.

Also at Ozyegin University, Istanbul, Turkey.

Also at Kafkas University, Kars, Turkey.

Also at Suleyman Demirel University, Isparta, Turkey.

Also at Ege University, Izmir, Turkey.

Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.

Also at University of Sydney, Sydney, Australia.

Also at Utah Valley University, Orem, UT, USA.

Also at Institute for Nuclear Research, Moscow, Russia.

Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

Also at Argonne National Laboratory, Argonne, IL, USA.
Also at Erzincan University, Erzincan, Turkey.

Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

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

Also at Kyungpook National University, Daegu, Korea.