Abstract: An inclusive search is presented for new heavy particle pairs produced in $s^*=7$ TeV proton-proton collisions at the LHC using 4.7±0.1 fb$^{-1}$ of integrated luminosity. The selected events are analyzed in the 2D razor space of MR, 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: https://doi.org/10.1103/PhysRevLett.111.081802

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-92413
Journal Article
Published Version

Originally published at:
CMS Collaboration; Chatrchyan, S; Khachatryan, V; Sirunyan, A M; et al; Chiochia, V; Kilminster, B; Robmann, P (2013). Inclusive Search for Supersymmetry Using Razor Variables in pp Collisions at $s^*=7$ TeV. Physical Review Letters. 111(8):081802.
DOI: https://doi.org/10.1103/PhysRevLett.111.081802
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

*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 \( \tilde{q}_1, \tilde{q}_2 \), with \( \tilde{q}_i \rightarrow j_i \tilde{X}^0 \), 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 \( M_R \equiv [(|\vec{p}_1^h|^2 + |\vec{p}_2^h|^2)^{1/2} - (|\vec{p}_1^l|^2 + |\vec{p}_2^l|^2)^{1/2}]^{1/2} \) 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 \( M_\Delta \equiv (M_1^2 - M_2^2)/M_\Delta \) 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 \( M_1^R \) is defined as \( M_1^R \equiv [(1/2)(E_{miss}^1(p_T^1 + p_T^2) - E_{miss}^2(p_T^1 + p_T^2))^{1/2} \), where \( \vec{p}_T^{1,2} \) are the transverse momentum vectors of the two megajets and \( E_{miss} \) is the missing transverse momentum vector (also referred to as missing transverse energy). The razor dimensionless ratio is defined as \( R \equiv (M_1^R/M_R) \). For signal events \( M_1^R \) 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 \( \Delta E/E \approx 100\%/\sqrt{E/\text{GeV}} \pm 5\% \). 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 \( E_{miss}^T \). 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 \( \Sigma_{\text{track}} p_T^2 \) 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, \( E_{miss}^T \), 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.

| Lepton boxes | \( M_R > 300 \text{ GeV}, \ 0.11 < R^2 < 0.5 \) |
|--------------|---------------------------------|
| ELE-MU       | \( p_T^\mu > 20 \text{ GeV}, \ p_T^e > 15 \text{ GeV} \) |
| MU-MU        | \( p_T^{MU1} > 15 \text{ GeV}, \ p_T^{MU2} > 10 \text{ GeV} \) |
| ELE-ELE      | \( p_T^{ELE1} > 20 \text{ GeV}, \ p_T^{ELE2} > 10 \text{ GeV} \) |
| MU          | \( p_T^{MU} > 12 \text{ GeV} \) |
| ELE          | \( p_T^{ELE} > 20 \text{ GeV} \) |
| HAD box      | \( M_R > 400 \text{ GeV}, \ 0.18 < R^2 < 0.5 \) |

TABLE I. Razor boxes definition. The variables and requirements are explained in the text.
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 background model obtained in the fit region is extrapolated to the final fit performed in each fit region (FR) defined by the yield of a given fit sample in the box. No significant discrepancy is observed between the data and the fit model in any of the six boxes [29].

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 background model obtained in the fit region is extrapolated to the final fit performed in each fit region (FR) defined by the yield of a given fit sample in the box. No significant discrepancy is observed between the data and the fit model in any of the six boxes [29].

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 background model obtained in the fit region is extrapolated to the final fit performed in each fit region (FR) defined by the yield of a given fit sample in the box. No significant discrepancy is observed between the data and the fit model in any of the six boxes [29].

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 background model obtained in the fit region is extrapolated to the final fit performed in each fit region (FR) defined by the yield of a given fit sample in the box. No significant discrepancy is observed between the data and the fit model in any of the six boxes [29].

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 background model obtained in the fit region is extrapolated to the final fit performed in each fit region (FR) defined by the yield of a given fit sample in the box. No significant discrepancy is observed between the data and the fit model in any of the six boxes [29].

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 background model obtained in the fit region is extrapolated to the final fit performed in each fit region (FR) defined by the yield of a given fit sample in the box. No significant discrepancy is observed between the data and the fit model in any of the six boxes [29].

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 background model obtained in the fit region is extrapolated to the final fit performed in each fit region (FR) defined by the yield of a given fit sample in the box. No significant discrepancy is observed between the data and the fit model in any of the six boxes [29].

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 background model obtained in the fit region is extrapolated to the final fit performed in each fit region (FR) defined by the yield of a given fit sample in the box. No significant discrepancy is observed between the data and the fit model in any of the six boxes [29].

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 background model obtained in the fit region is extrapolated to the final fit performed in each fit region (FR) defined by the yield of a given fit sample in the box. No significant discrepancy is observed between the data and the fit model in any of the six boxes [29].
The shape of the observed exclusion curves reflect the CLs of the experiments, and the value of background-only and signal-plus-background pseudoexperiments. The fit is performed in the $R^2$-$M_R$ fit region (FR as shown in Fig. 2) and projected into the full analysis region. The full error on the total background prediction is drawn in these projections, including the one due to variation of the nuisance parameters.

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 $\ln Q = \ln(L(s+b|H)/L(b|H))$, where $H$ is the hypothesis under test: $H_1$ (signal plus background) or the null hypothesis $H_0$ (background only). Given the distribution of $\ln Q$ for background-only and signal-plus-background pseudoexperiments, and the value of $\ln Q$ observed in the data, we calculate $\text{CL}_{s+b}$ and $1 - \text{CL}_{b}$ [54,55]. From these values the $\text{CL}_s = \text{CL}_{s+b}/\text{CL}_{b}$ is computed for that model point. A point in the constrained minimal supersymmetric standard model (CMSSM) plane is excluded at 95% confidence level (CL) if $\text{CL}_s < 0.05$. 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 $m_0$, respectively. The observed limit is less constraining than the median-expected limit at lower $m_0$ due to an excess of observed events in the HAD box at large $R^2$, 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 $m_0$.

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 $Z \rightarrow \ell^+\ell^-$ 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 (SR$i$). 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 $(m_0, m_{1/2})$ CMSSM plane (drawn according to [61]) with $\tan \beta = 10$, $A_0 = 0$ GeV, and $\text{sgn}(\mu) = +1$. 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 a factor of 3 cross section enhancement or reduction are corresponding to the NLL-NLO cross section. Exclusion curves and the LSP mass, as well as the exclusion curve corresponding to the NLL-NLO cross section. 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 $M_2$ 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 $m(\tilde{q}) \sim m(\tilde{g})$ 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, SF0690030s09 and ERDF (Estonia); Academy of Finland, MECh, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OAKA 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); SEIDI 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 Academy of Finland, 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.

[1] P. Ramond, Phys. Rev. D 3, 2415 (1971); Y. A. Gelfand and E. P. Likhtman, JETP Lett. 13, 323 (1971); D. V. Volkov and V. P. Akulov, JETP Lett. 16, 438 (1972); J. Wess and B. Zumino, Nucl. Phys. B70, 39 (1974); P. Fayet, Nucl. Phys. B90, 104 (1975).
[2] G. R. Farrar and P. Fayet, Phys. Lett. 76B, 575 (1978).
[3] V. M. Abazov et al. (D0 Collaboration), Phys. Lett. B 660, 449 (2008).
[4] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 102, 121801 (2009).
[5] CMS Collaboration, Phys. Rev. Lett. 109, 171803 (2012).
[6] CMS Collaboration, Phys. Rev. D 86, 072010 (2012).
[7] ATLAS Collaboration, Eur. Phys. J. C 71, 1647 (2011).
[8] ATLAS Collaboration, Phys. Lett. B 701, 186 (2011).
[9] ATLAS Collaboration, Phys. Rev. Lett. 106, 131802 (2011).
[10] ATLAS Collaboration, Eur. Phys. J. C 71, 1682 (2011).
[11] CMS Collaboration, J. High Energy Phys. 08, (2011) 155.
[12] CMS Collaboration, Phys. Lett. B 698, 196 (2011).
[13] CMS Collaboration, J. High Energy Phys. 06 (2011) 077.
[14] CMS Collaboration, J. High Energy Phys. 06 (2011) 026.
[15] CMS Collaboration, Phys. Lett. B 716, 260 (2012).
[16] CMS Collaboration, J. High Energy Phys. 06 (2012) 169.
[17] CMS Collaboration, J. High Energy Phys. 08 (2012) 110.
[18] CMS Collaboration, Phys. Rev. Lett. 109, 071803 (2012).
[19] CMS Collaboration, J. High Energy Phys. 10 (2012) 018.
[20] ATLAS Collaboration, Phys. Rev. Lett. 108, 241802 (2012).
[21] ATLAS Collaboration, Phys. Rev. D 85, 112006 (2012).
[22] ATLAS Collaboration, Phys. Lett. B 714, 180 (2012).
[23] ATLAS Collaboration, Phys. Lett. B 714, 197 (2012).
[24] ATLAS Collaboration, Phys. Rev. Lett. 108, 261804 (2012).
[25] ATLAS Collaboration, Phys. Lett. B 715, 44 (2012).
[26] ATLAS Collaboration, Eur. Phys. J. C 73, 2362 (2013).
[27] C. Rogan, arXiv:1006.2727.
[28] CMS Collaboration, Phys. Rev. D 85, 012004 (2012).
[29] CMS Collaboration, “Inclusive search for pair production of new heavy particles at CMS using the razor variables” (unpublished). See Supplemental Material on the razor variables and their modeling at http://link.aps.org/supplemental/10.1103/PhysRevLett.111.081802.
[30] CMS Collaboration, JINST 3, S08004 (2008).
[31] CMS Collaboration, CMS Physics Analysis Summary Report No. CMS-PAS-TKR-10-005, 2012, http://cds.cern.ch/record/1427247.
[32] CMS Collaboration, J. High Energy Phys. 10, (2011) 132.
[33] M. Cacciari, G. P. Salam, and G. Soyez, J. High Energy Phys. 04 (2008) 063.
[34] CMS Collaboration, CMS Physics Analysis Summary Report No. CMS-PAS-JME-10-010, 2010, http://cds.cern.ch/record/1308178.
[35] CMS Collaboration, CMS Physics Analysis Summary Report No. CMS-PAS-PFT-09-001, 2009, http://cds.cern.ch/record/1194487.
[36] CMS Collaboration, CMS Physics Analysis Summary Report No. CMS-PAS-BTV-10-001, 2010, http://cds.cern.ch/record/1279144.

[37] CMS Collaboration, CMS Physics Analysis Summary Report No. CMS-PAS-BTV-11-004, 2012, http://cds.cern.ch/record/1427247.
[38] CMS Collaboration, JINST 8, P04013 (2013).
[39] T. Sjostrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026.
[40] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, J. High Energy Phys. 06 (2011) 128.
[41] S. Agostinelli et al. (GEANT4 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003).
[42] B. C. Allanach, Comput. Phys. Commun. 143, 305 (2002).
[43] M. M. Mühlleitner, A. Djouadi, and M. Spira, Acta Phys. Pol. B 38, 635 (2007).
[44] P. Z. Skands et al., J. High Energy Phys. 07 (2004) 036.
[45] W. Beenakker, R. Höpker, M. Spira, and P. M. Zerwas, Nucl. Phys. B492, 51 (1997).
[46] A. Kulesza and L. Motyka, Phys. Rev. Lett. 102, 111802 (2009).
[47] A. Kulesza and L. Motyka, Phys. Rev. D 80, 095004 (2009).
[48] W. Beenakker, S. Brensing, M. Krämer, A. Kulesza, E. Laenen, and J. Nissen, J. High Energy Phys. 12 (2009) 041.
[49] W. Beenakker, S. Brensing, M. Krämer, A. Kulesza, E. Laenen, L. Motyka, and J. Nissen, Int. J. Mod. Phys. A 26, 2637 (2011).
[50] M. Krämer, A. Kulesza, R. van der Leeuw, M. Mangano, S. Padhi, T. Plehn, and X. Portell, arXiv:1206.2892.
[51] G. F. de Montricher, R. A. Tapia, and J. R. Thompson, Ann. Stat. 3, 1329 (1975).
[52] W. Verkerke and D. P. Kirkby, arXiv:physics/0306116.
[53] R. J. Barlow, Nucl. Instrum. Methods Phys. Res., Sect. A 297, 496 (1990).
[54] A. L. Read, J. Phys. G 28, 2693 (2002).
[55] T. Junk, Nucl. Instrum. Methods Phys. Res., Sect. A 434, 435 (1999).
[56] CMS Collaboration (CMS), CMS Physics Analysis Summary Report No. CMS-PAS-SMP-12-008, 2012, http://cds.cern.ch/record/1434360.
[57] N. Arkani-Hamed, B. Knuteson, S. Mrenna, P. Schuster, J. Thaler, N. Toro, and L.-T. Wang, arXiv:hep-ph/0703088.
[58] J. Alwall, P. C. Schuster, and N. Toro, Phys. Rev. D 79, 075020 (2009).
[59] J. Alwall, M.-P. Le, M. Lisanti, and J. G. Wacker, Phys. Rev. D 79, 015005 (2009).
[60] D. Alves et al. (LHC New Physics Working Group), J. Phys. G 39, 105005 (2012).
[61] K. Matchev and R. Remington, arXiv:1202.6580.
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
12a 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
Università di Firenze, Firenze, Italy
INFN Laboratori Nazionali di Frascati, Frascati, Italy
INFN Sezione di Genova, Genova, Italy
Università di Genova, Genova, Italy
INFN Sezione di Milano-Bicocca, Milano, Italy
Università di Milano-Bicocca, Milano, Italy
INFN Sezione di Napoli, Napoli, Italy
Università di Napoli “Federico II”, Napoli, Italy
Università della Basilicata (Potenza), Napoli, Italy
Università G. Marconi (Roma), Napoli, Italy
INFN Sezione di Padova, Padova, Italy
Università di Padova, Padova, Italy
Università di Trento (Trento), Padova, Italy
INFN Sezione di Pavia, Pavia, Italy
Università di Pavia, Pavia, Italy
INFN Sezione di Perugia, Perugia, Italy
Università di Perugia, Perugia, Italy
INFN Sezione di Pisa, Pisa, Italy
Università di Pisa, Pisa, Italy
Scuola Normale Superiore di Pisa, Pisa, Italy
INFN Sezione di Roma, Roma, Italy
Università di Roma, Roma, Italy
INFN Sezione di Torino, Torino, Italy
Università di Torino, Torino, Italy
Università del Piemonte Orientale (Novara), Torino, Italy
INFN Sezione di Trieste, Trieste, Italy
Università di Trieste, Trieste, Italy
Kangwon National University, Chunchon, Korea
Kyungpook National University, Daegu, Korea
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
Korea University, Seoul, Korea
University of Seoul, Seoul, Korea
Sungkyunkwan University, Suwon, Korea
Vilnius University, Vilnius, Lithuania
Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
Universidad Iberoamericana, Mexico City, Mexico
Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
University of Auckland, Auckland, New Zealand
University of Canterbury, Christchurch, New Zealand
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
National Centre for Nuclear Research, Swierk, Poland
Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
Joint Institute for Nuclear Research, Dubna, Russia
Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Institute for Nuclear Research, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
Moscow State University, Moscow, Russia
P.N. Lebedev Physical Institute, Moscow, Russia
State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
Universidad Autónoma de Madrid, Madrid, Spain
Universidad de Oviedo, Oviedo, Spain
Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
CERN, European Organization for Nuclear Research, Geneva, Switzerland
Paul Scherrer Institut, Villigen, Switzerland
Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
Universität Zürich, Zurich, Switzerland
National Central University, Chung-Li, Taiwan
aDeceased.
bAlso at Vienna University of Technology, Vienna, Austria.
cAlso at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
dAlso at California Institute of Technology, Pasadena, USA.
eAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
fAlso at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
gAlso at Suez Canal University, Suez, Egypt.
hAlso at Zewail City of Science and Technology, Zewail, Egypt.
iAlso at Cairo University, Cairo, Egypt.
jAlso at Fayoum University, El-Fayoum, Egypt.
kAlso at British University in Egypt, Cairo, Egypt.
lNow at Ain Shams University, Cairo, Egypt.
mAlso at National Centre for Nuclear Research, Swierk, Poland.
nAlso at Université de Haute Alsace, Mulhouse, France.
oAlso at Joint Institute for Nuclear Research, Dubna, Russia.
pAlso at Moscow State University, Moscow, Russia.
qAlso at Brandenburg University of Technology, Cottbus, Germany.
rAlso at The University of Kansas, Lawrence, KS, USA.
sAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
tAlso at Eötvös Loránd University, Budapest, Hungary.
uAlso at Tata Institute of Fundamental Research-HECR, Mumbai, India.
vAlso at University of Visva-Bharati, Santiniketan, India.
wAlso at Sharif University of Technology, Tehran, Iran.
xAlso at Isfahan University of Technology, Isfahan, Iran.
yAlso at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
zAlso at Facoltà Ingegneria, Università di Roma, Roma, Italy.
aaAlso at Università degli Studi Guglielmo Marconi, Roma, Italy.
abAlso at Università degli Studi di Siena, Siena, Italy.
acAlso at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.
adAlso at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
aeAlso at University of California, Los Angeles, CA, USA.
afAlso at Scuola Normale e Sezione dell’INFN, Pisa, Italy.
agAlso at INFN Sezione di Roma, Università di Roma, Roma, Italy.
ahAlso at University of Athens, Athens, Greece.
iAlso at Rutherford Appleton Laboratory, Didcot, United Kingdom.
jAlso at Paul Scherrer Institut, Villigen, Switzerland.
kAlso at Institute for Theoretical and Experimental Physics, Moscow, Russia.
lAlso at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
mAlso at Gaziosmanpasa University, Tokat, Turkey.
nAlso at Adiyaman University, Adiyaman, Turkey.
oAlso at Izmir Institute of Technology, Izmir, Turkey.
pAlso at The University of Iowa, Iowa City, IA, USA.
qAlso at Mersin University, Mersin, Turkey.
rAlso at Ozyegin University, Istanbul, Turkey.
sAlso at Kafkas University, Kars, Turkey.
tAlso at Suleyman Demirel University, Isparta, Turkey.
uAlso at Ege University, Izmir, Turkey.
vAlso at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
wAlso at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.
xAlso at University of Sydney, Sydney, Australia.
yAlso at Utah Valley University, Orem, UT, USA.
zAlso at Institute for Nuclear Research, Moscow, Russia.
aAlso at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
bAlso 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.