Search for supersymmetry in multijet events with missing transverse momentum in proton-proton collisions at 13 TeV

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)
(Received 25 April 2017; published 25 August 2017)

A search for supersymmetry is presented based on multijet events with large missing transverse momentum produced in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV. The data, corresponding to an integrated luminosity of 35.9 fb^{-1}, were collected with the CMS detector at the CERN LHC in 2016. The analysis utilizes four-dimensional exclusive search regions defined in terms of the number of jets, the number of tagged bottom quark jets, the scalar sum of jet transverse momenta, and the magnitude of the vector sum of jet transverse momenta. No evidence for a significant excess of events is observed relative to the expectation from the standard model. Limits on the cross sections for the pair production of gluinos and squarks are derived in the context of simplified models. Assuming the lightest supersymmetric particle to be a weakly interacting neutralino, 95% confidence level lower limits on the gluino mass as large as 1800 to 1960 GeV are derived, and on the squark mass as large as 960 to 1390 GeV, depending on the production and decay scenario.

DOI: 10.1103/PhysRevD.96.032003

I. INTRODUCTION

The standard model (SM) of particle physics describes many aspects of weak, electromagnetic, and strong interactions. However, it requires fine-tuning [1] to explain the observed value of the Higgs boson mass [2], and it does not provide an explanation for dark matter. Supersymmetry (SUSY) [3–10], a widely studied extension of the SM, potentially solves these problems through the introduction of a new particle, called a superpartner, for each SM particle, with a spin that differs from that of its SM counterpart by a half unit. Additional Higgs bosons and their superpartners are also introduced. The superpartners of quarks and gluons are squarks $\tilde{q}$ and gluinos $\tilde{g}$, respectively, while neutralinos $\tilde{\chi}^0$ and charginos $\tilde{\chi}^{\pm}$ are mixtures of the superpartners of the Higgs and electroweak gauge bosons. Provided that the masses of gluinos, top squarks, and bottom squarks are no heavier than a few TeV, SUSY can resolve the fine-tuning problem [1,11–13]. Furthermore, in R-parity [14] conserving SUSY models, the lightest SUSY particle (LSP) is stable and might interact only weakly, thus representing a dark matter candidate.

In this paper, we present a search for squarks and gluinos produced in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV. Squark and gluino production have large potential cross sections in pp collisions, thus motivating this search. The study is performed in the multijet final state, i.e., the visible elements consist solely of jets. Other $\sqrt{s} = 13$ TeV inclusive multijet SUSY searches were presented in Refs. [15–20]. We assume the conservation of R parity, meaning that the squarks and gluinos are produced in pairs. The events are characterized by the presence of jets and undetected, or "missing," transverse momentum, where the missing transverse momentum arises from the weakly interacting and unobserved LSPs. The data, corresponding to an integrated luminosity of 35.9 fb^{-1}, were collected in 2016 with the CMS detector at the CERN LHC. The analysis is performed in four-dimensional exclusive regions in the number of jets N_{jet}, the number of tagged bottom quark jets $N_{b\text{-jet}}$, the scalar sum H_{T} of the transverse momenta p_{T} of jets, and the magnitude $H_{\mathrm{T}}^{\mathrm{miss}}$ of the vector p_{T} sum of jets. The number of observed events in each region is compared with the expected number of SM events to search for excesses in the data.

The study is an extension of that presented in Ref. [17], using improved analysis techniques and around 16 times more data. Relative to Ref. [17], the following principal modifications have been made. First, the search intervals in N_{jet} and H_{T} are given by $N_{\mathrm{jet}} \geq 2$ and $H_{\mathrm{T}} > 300$ GeV, compared with $N_{\mathrm{jet}} \geq 4$ and $H_{\mathrm{T}} > 500$ GeV in Ref. [17]. Inclusion of events with $N_{\mathrm{jet}} = 2$ and 3 increases the sensitivity to squark pair production. The lower threshold in H_{T} provides better sensitivity to scenarios with small mass differences between the LSP and the squark or gluino. Second, the rebalance-and-smear technique [21,22] is introduced as a complementary means to evaluate the quantum chromodynamics (QCD) background, namely the background from SM events with multijet final states produced exclusively through the strong interaction. Third, the search interval in $H_{\mathrm{T}}^{\mathrm{miss}}$ is given by $H_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV,

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

TABLE XI. Observed numbers of events and prefit background predictions in the aggregate search regions. The first uncertainty is statistical and the second is systematic.

Bin	H_T^{miss} [GeV]	H_T [GeV]	N_{jet}	$N_{b\text{-jet}}$	Lost-e/μ	$\tau \to$ had	$Z \to \nu\bar{\nu}$	QCD	Total pred.	Obs.
1	>500	>500	≥2	0	842^{+25+48}_{-25-46}	753^{+16+65}_{-16-65}	$5968^{+48+360}_{-47-350}$	$21.4^{+0.6+8.5}_{-0.6-7.1}$	$7584^{+63+370}_{-62-360}$	7838
2	>750	>1500	≥3	0	$4.8^{+2.2+0.6}_{-1.6-0.6}$	$4.2^{+1.3+0.3}_{-0.9-0.3}$	$45.8^{+5.1+5.2}_{-4.3-4.9}$	$0.47^{+0.06+0.18}_{-0.06-0.16}$	$55.2^{+6.2+5.3}_{-5.0-4.9}$	71
3	>500	>500	≥5	0	$111.0^{+6.4+8.3}_{-6.3-7.9}$	$127.6^{+5.9+8.5}_{-5.7-8.6}$	558^{+15+36}_{-14-34}	$9.4^{+0.2+3.5}_{-0.2-3.1}$	806^{+19+38}_{-18-37}	819
4	>750	>1500	≥5	0	$1.82^{+0.82+0.26}_{-0.59-0.21}$	$2.8^{+1.1+0.2}_{-0.7-0.2}$	$18.1^{+3.3+2.7}_{-2.6-2.6}$	$0.37^{+0.06+0.15}_{-0.06-0.13}$	$23.0^{+3.8+2.7}_{-2.9-2.6}$	25
5	>750	>1500	≥9	0	$0.23^{+0.27+0.14}_{-0.17-0.07}$	$0.28^{+0.50+0.08}_{-0.21-0.07}$	$0.00^{+0.82+0.00}_{-0.00-0.00}$	$0.05^{+0.03+0.02}_{-0.03-0.02}$	$0.6^{+1.1+0.2}_{-0.4-0.1}$	1
6	>500	>500	≥2	≥2	$46.9^{+8.9+3.1}_{-5.9-3.0}$	$44.0^{+4.4+3.2}_{-3.4-3.2}$	102^{+2+14}_{-1-14}	$2.5^{+0.3+1.5}_{-0.2-1.3}$	196^{+13+15}_{-9-15}	216
7	>750	>750	≥3	≥1	$11.5^{+4.1+1.0}_{-2.2-0.9}$	$13.7^{+3.0+1.2}_{-2.0-1.2}$	87^{+3+10}_{-3-10}	$0.87^{+0.15+0.34}_{-0.11-0.31}$	113^{+8+10}_{-5-10}	123
8	>500	>500	≥5	≥3	$6.6^{+3.3+0.6}_{-2.3-0.6}$	$5.3^{+1.9+0.9}_{-1.1-0.9}$	$6.8^{+0.5+2.8}_{-0.3-2.8}$	$0.87^{+0.20+0.96}_{-0.17-0.70}$	$19.5^{+5.2+3.2}_{-3.4-3.1}$	17
9	>750	>1500	≥5	≥2	$1.3^{+1.4+0.2}_{-0.6-0.2}$	$1.8^{+1.3+0.4}_{-0.7-0.4}$	$1.20^{+0.41+0.33}_{-0.19-0.33}$	$0.13^{+0.07+0.06}_{-0.04-0.05}$	$4.4^{+2.8+0.6}_{-1.3-0.6}$	6
10	>750	>750	≥9	≥3	$0.00^{+0.66+0.00}_{-0.00-0.00}$	$0.00^{+0.65+0.00}_{-0.00-0.00}$	$0.00^{+0.15+0.00}_{-0.00-0.00}$	$0.03^{+0.07+0.04}_{-0.02-0.01}$	$0.0^{+1.3+0.0}_{-0.0-0.0}$	0
11	>300	>300	≥7	≥1	328^{+12+21}_{-12-20}	380^{+10+22}_{-9-22}	193^{+8+38}_{-6-38}	69^{+1+29}_{-1-26}	969^{+23+57}_{-22-55}	890
12	>750	>750	≥5	≥1	$7.2^{+2.8+0.8}_{-1.6-0.7}$	$7.7^{+2.4+0.8}_{-1.4-0.8}$	$26.6^{+2.4+3.9}_{-1.8-3.7}$	$0.65^{+0.14+0.26}_{-0.11-0.23}$	$42.2^{+5.7+4.0}_{-3.5-3.9}$	48

[1] R. Barbieri and G. F. Giudice, Upper bounds on supersymmetric particle masses, Nucl. Phys. **B306**, 63 (1988).

[2] ATLAS and CMS Collaborations, Combined measurement of the Higgs boson mass in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS experiments, Phys. Rev. Lett. **114**, 191803 (2015).

[3] P. Ramond, Dual theory for free fermions, Phys. Rev. D **3**, 2415 (1971).

[4] Y. A. Golfand and E. P. Likhtman, Extension of the algebra of Poincaré group generators and violation of P invariance, JETP Lett. **13**, 323 (1971).

[5] A. Neveu and J. H. Schwarz, Factorizable dual model of pions, Nucl. Phys. **B31**, 86 (1971).

[6] D. V. Volkov and V. P. Akulov, Possible universal neutrino interaction, JETP Lett. **16**, 438 (1972).

[7] J. Wess and B. Zumino, A Lagrangian model invariant under supergauge transformations, Phys. Lett. **49B**, 52 (1974).

[8] J. Wess and B. Zumino, Supergauge transformations in four dimensions, Nucl. Phys. **B70**, 39 (1974).

[9] P. Fayet, Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino, Nucl. Phys. **B90**, 104 (1975).

[10] H. P. Nilles, Supersymmetry, supergravity and particle physics, Phys. Rep. **110**, 1 (1984).

[11] S. Dimopoulos and G. F. Giudice, Naturalness constraints in supersymmetric theories with nonuniversal soft terms, Phys. Lett. B **357**, 573 (1995).

[12] R. Barbieri and D. Pappadopulo, S-particles at their naturalness limits, J. High Energy Phys. 10 (2009) 061.

[13] M. Papucci, J. T. Ruderman, and A. Weiler, Natural SUSY endures, J. High Energy Phys. 09 (2012) 035.

[14] G. R. Farrar and P. Fayet, Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry, Phys. Lett. **76B**, 575 (1978).

[15] ATLAS Collaboration, Search for pair production of gluinos decaying via stop and sbottom in events with b-jets and large missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. D **94**, 032003 (2016).

[16] ATLAS Collaboration, Search for squarks and gluinos in final states with jets and missing transverse momentum at $\sqrt{s} = 13$ TeV with the ATLAS detector, Eur. Phys. J. C **76**, 392 (2016).

[17] CMS Collaboration, Search for supersymmetry in the multijet and missing transverse momentum final state in pp collisions at 13 TeV, Phys. Lett. B **758**, 152 (2016).

[18] CMS Collaboration, Search for new physics with the M_{T2} variable in all-jets final states produced in pp collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 10 (2016) 006.

[19] CMS Collaboration, Inclusive search for supersymmetry using razor variables in pp collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. D **95**, 012003 (2017).

[20] CMS Collaboration, A search for new phenomena in pp collisions at $\sqrt{s} = 13$ TeV in final states with missing transverse momentum and at least one jet using the α_T variable, Eur. Phys. J. C **77**, 294 (2017).

[21] CMS Collaboration, Search for new physics with jets and missing transverse momentum in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 08 (2011) 155.

[22] CMS Collaboration, Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 06 (2014) 055.

[23] N. Arkani-Hamed, P. Schuster, N. Toro, J. Thaler, L.-T. Wang, B. Knuteson, and S. Mrenna, MARMOSET: The path from LHC data to the new standard model via on-shell effective theories, arXiv:hep-ph/0703088.

G. N. Kim,[77] M. S. Kim,[77] J. Lee,[77] S. Lee,[77] S. W. Lee,[77] Y. D. Oh,[77] S. Sekmen,[77] D. C. Son,[77] Y. C. Yang,[77] A. Lee,[78] H. Kim,[79] D. H. Moon,[79] G. Oh,[79] J. A. Brochero Cifuentes,[80] J. Goh,[80] T. J. Kim,[80] S. Cho,[81] S. Choi,[81] Y. Go,[81] D. Gyun,[81] S. Ha,[81] B. Hong,[81] Y. Jo,[81] Y. Kim,[81] K. Lee,[81] K. S. Lee,[81] S. Lee,[81] J. Lim,[81] S. K. Park,[81] Y. Roh,[81] J. Almond,[82] J. Kim,[82] J. S. Kim,[82] H. Lee,[82] K. Lee,[82] K. Nam,[82] S. B. Oh,[82] B. C. Radburn-Smith,[82] S. h. Seo,[82] U. K. Yang,[82] H. D. Yoo,[82] G. B. Yu,[82] M. Choi,[83] H. Kim,[83] J. H. Kim,[83] J. S. H. Lee,[83] I. C. Park,[83] G. Ryu,[83] Y. Choi,[84] C. Hwang,[84] J. Lee,[84] I. Yu,[84] V. Dudenas,[85] A. Juodagalvis,[85] J. Vaitkus,[85] I. Ahmed,[86] Z. A. Ibrahim,[86] M. A. B. Md Ali,[86,dd] F. Mohamad Idris,[86,ee] W. A. T. Wan Abdullah,[86] M. N. Yusli,[86] Z. Zolkapli,[86] H. Castilla-Valdez,[87] E. De La Cruz-Burelo,[87] I. Heredia-De La Cruz,[87,ff] R. Lopez-Fernandez,[87] J. Mejia Guisao,[87] A. Sanchez-Hernandez,[87] S. Carrillo Moreno,[88] C. Oropeza Barrera,[88] F. Vazquez Valencia,[88] I. Pedraza,[89] H. A. Salazar Ibarguen,[89] C. Uribe Estrada,[89] A. Morelos Pineda,[90] D. Krofcheck,[91] P. H. Butler,[92] A. Ahmad,[93] M. Ahmad,[93] Q. Hassan,[93] H. R. Hoorani,[93] A. Saddique,[93] M. A. Shah,[93] M. Shoaib,[93] M. Waqas,[93] H. Bialkowska,[94] M. Bluj,[94] B. Boimska,[94] T. Frueboes,[94] M. Górski,[94] M. Kazana,[94] K. Nawrocki,[94] K. Romanowska-Rybinska,[94] M. Szleper,[94] P. Zalewski,[94] K. Bunkowski,[95] A. Byszuk,[95,gg] K. Doroba,[95] A. Kalinowski,[95] M. Konecki,[95] J. Krolikowski,[95] M. Misiura,[95] M. Olszewski,[95] A. Pyskir,[95] M. Walczak,[95] P. Bargassa,[96] C. Beirão Da Cruz E Silva,[96] B. Calpas,[96] A. Di Francesco,[96] P. Faccioli,[96] M. Gallinaro,[96] J. Hollar,[96] N. Leonardo,[96] L. Lloret Iglesias,[96] M. V. Nemallapudi,[96] J. Seixas,[96] O. Toldaiev,[96] D. Vadruccio,[96] J. Varela,[96] S. Afanasiev,[97] P. Bunin,[97] M. Gavrilenko,[97] I. Golutvin,[97] I. Gorbunov,[97] A. Kamenev,[97] V. Karjavin,[97] A. Lanev,[97] A. Malakhov,[97] V. Matveev,[97,hh,ii] V. Palichik,[97] V. Perelygin,[97] S. Shmatov,[97] S. Shulha,[97] N. Skatchkov,[97] V. Smirnov,[97] N. Voytishin,[97] A. Zarubin,[97] Y. Ivanov,[98] V. Kim,[98,jj] E. Kuznetsova,[98,kk] P. Levchenko,[98] V. Murzin,[98] V. Oreshkin,[98] I. Smirnov,[98] V. Sulimov,[98] L. Uvarov,[98] S. Vavilov,[98] A. Vorobyev,[98] Yu. Andreev,[99] A. Dermenev,[99] S. Gninenko,[99] N. Golubev,[99] A. Karneyeu,[99] M. Kirsanov,[99] N. Krasnikov,[99] A. Pashenkov,[99] D. Tlisov,[99] A. Toropin,[99] V. Epshteyn,[100] V. Gavrilov,[100] N. Lychkovskaya,[100] V. Popov,[100] I. Pozdnyakov,[100] G. Safronov,[100] A. Spiridonov,[100] A. Stepennov,[100] M. Toms,[100] E. Vlasov,[100] A. Zhokin,[100] T. Aushev,[101] A. Bylinkin,[101,ii] M. Chadeeva,[102,ll] P. Parygin,[102] D. Philippov,[102] S. Polikarpov,[102] E. Popova,[102] V. Rusinov,[102] V. Andreev,[103] M. Azarkin,[103,ii] I. Dremin,[103,ii] M. Kirakosyan,[103,ii] A. Terkulov,[103] A. Baskakov,[104] A. Belyaev,[104] E. Boos,[104] M. Dubinin,[104,mm] L. Dudko,[104] A. Ershov,[104] A. Gribushin,[104] V. Klyukhin,[104] O. Kodolova,[104] I. Lokhtin,[104] I. Miagkov,[104] S. Obraztsov,[104] S. Petrushanko,[104] V. Savrin,[104] A. Snigirev,[104] V. Blinov,[105,nn] Y. Skovpen,[105,nn] D. Shtol,[105,nn] I. Azhgirey,[106] I. Bayshev,[106] S. Bitioukov,[106] D. Elumakhov,[106] V. Kachanov,[106] A. Kalinin,[106] D. Konstantinov,[106] V. Krychkine,[106] V. Petrov,[106] R. Ryutin,[106] A. Sobol,[106] S. Troshin,[106] N. Tyurin,[106] A. Uzunian,[106] A. Volkov,[106] P. Adzic,[107,oo] P. Cirkovic,[107] D. Devetak,[107] M. Dordevic,[107] J. Milosevic,[107] V. Rekovic,[107] J. Alcaraz Maestre,[108] M. Barrio Luna,[108] M. Cerrada,[108] N. Colino,[108] B. De La Cruz,[108] A. Delgado Peris,[108] A. Escalante Del Valle,[108] C. Fernandez Bedoya,[108] J. P. Fernández Ramos,[108] J. Flix,[108] M. C. Fouz,[108] P. Garcia-Abia,[108] O. Gonzalez Lopez,[108] S. Goy Lopez,[108] J. M. Hernandez,[108] M. I. Josa,[108] A. Pérez-Calero Yzquierdo,[108] J. Puerta Pelayo,[108] A. Quintario Olmeda,[108] I. Redondo,[108] L. Romero,[108] M. S. Soares,[108] A. Álvarez Fernández,[108] J. F. de Trocóniz,[109] M. Missiroli,[109] D. Moran,[109] J. Cuevas,[110] C. Erice,[110] J. Fernandez Menendez,[110] I. Gonzalez Caballero,[110] J. R. González Fernández,[110] E. Palencia Cortezon,[110] S. Sanchez Cruz,[110] I. Suárez Andrés,[110] P. Vischia,[110] J. M. Vizan Garcia,[110] I. J. Cabrillo,[111] A. Calderon,[111] B. Chazin Quero,[111] E. Curras,[111] M. Fernandez,[111] J. Garcia-Ferrero,[111] G. Gomez,[111] A. Lopez Virto,[111] J. Marco,[111] C. Martinez Rivero,[111] P. Martinez Ruiz del Arbol,[111] F. Matorras,[111] J. Piedra Gomez,[111] T. Rodrigo,[111] A. Ruiz-Jimeno,[111] L. Scodellaro,[111] N. Trevisani,[111] I. Vila,[111] R. Vilar Cortabitarte,[111] D. Abbaneo,[112] E. Auffray,[112] P. Baillon,[112] A. H. Ball,[112] D. Barney,[112] M. Bianco,[112] P. Bloch,[112] A. Bocci,[112] C. Botta,[112] T. Camporesi,[112] R. Castello,[112] M. Cepeda,[112] G. Cerminara,[112] E. Chapon,[112] Y. Chen,[112] D. d'Enterria,[112] A. Dabrowski,[112] V. Daponte,[112] A. David,[112] M. De Gruttola,[112] A. De Roeck,[112] E. Di Marco,[112,pp] M. Dobson,[112] B. Dorney,[112] T. du Pree,[112] M. Dünser,[112] N. Dupont,[112] A. Elliott-Peisert,[112] P. Everaerts,[112] G. Franzoni,[112] J. Fulcher,[112] W. Funk,[112] D. Gigi,[112] K. Gill,[112] F. Glege,[112] D. Gulhan,[112] S. Gundacker,[112] M. Guthoff,[112] P. Harris,[112] J. Hegeman,[112] V. Innocente,[112] P. Janot,[112] O. Karacheban,[112,p] J. Kieseler,[112] H. Kirschenmann,[112] V. Knünz,[112] A. Kornmayer,[112,m] M. J. Kortelainen,[112] C. Lange,[112] P. Lecoq,[112] C. Lourenço,[112] M. T. Lucchini,[112] L. Malgeri,[112] M. Mannelli,[112] A. Martelli,[112] F. Meijers,[112] J. A. Merlin,[112] S. Mersi,[112] E. Meschi,[112] P. Milenovic,[112,qq] F. Moortgat,[112] M. Mulders,[112] H. Neugebauer,[112] S. Orfanelli,[112] L. Orsini,[112] L. Pape,[112] E. Perez,[112] M. Peruzzi,[112] A. Petrilli,[112] G. Petrucciani,[112] A. Pfeiffer,[112] M. Pierini,[112] A. Racz,[112] T. Reis,[112] G. Rolandi,[112,rr] M. Rovere,[112] H. Sakulin,[112] C. Schäfer,[112] C. Schwick,[112] M. Seidel,[112] M. Selvaggi,[112] A. Sharma,[112] P. Silva,[112] P. Sphicas,[112,ss] J. Steggemann,[112] M. Stoye,[112] M. Tosi,[112] D. Treille,[112] A. Triossi,[112] A. Tsirou,[112]