Search for Supersymmetry in pp Collisions at $\sqrt{s} = 13$ TeV in the Single-Lepton Final State Using the Sum of Masses of Large-Radius Jets

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Results are reported from a search for supersymmetric particles in proton-proton collisions in the final state with a single lepton, multiple jets, including at least one b-tagged jet, and large missing transverse momentum. The search uses a sample of proton-proton collision data at $\sqrt{s} = 13$ TeV recorded by the CMS experiment at the LHC, corresponding to an integrated luminosity of 35.9 fb^{-1}. The observed event yields in the signal regions are consistent with those expected from standard model backgrounds. The results are interpreted in the context of simplified models of supersymmetry involving gluino pair production, with gluino decay into either on- or off-mass-shell top squarks. Assuming that the top squarks decay into a top quark plus a stable, weakly interacting neutralino, scenarios with gluino masses up to about 1.9 TeV are excluded at 95% confidence level for neutralino masses up to about 1 TeV.

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A central goal of the physics program of the CMS experiment at the CERN LHC [1] is the search for new particles and phenomena beyond the standard model (SM), in particular, for supersymmetry (SUSY) [2–9]. During 2016, CMS recorded a data sample of proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}, significantly extending the sensitivity to the production of new heavy particles. The search described here focuses on a generically important experimental signature that is also strongly motivated by SUSY phenomenology. This signature includes a single lepton (an electron or a muon), several jets, arising from the hadronization of energetic quarks and gluons, at least one b-tagged jet, indicative of processes involving third generation quarks, and, finally, $\vec{p}_T^{\text{miss}}$, the missing momentum in the direction transverse to the beam. A large value of $p_T^{\text{miss}} \equiv |\vec{p}_T^{\text{miss}}|$ can arise from the production of high momentum, weakly interacting particles that escape detection. Searches for SUSY in the single-lepton final state have been performed by both ATLAS and CMS at $\sqrt{s} = 7$ and 8 TeV [10–13] and at $\sqrt{s} = 13$ TeV [14–17]. The present analysis, which introduces extended binning and other improvements, is based largely on methodologies described in detail in Ref. [16], which include the use of large-radius jets and related kinematic variables.

In models based on SUSY, new particles are introduced such that all fermionic (bosonic) degrees of freedom in the SM are paired with corresponding bosonic (fermionic) degrees of freedom in the extended theory. The discovery of a Higgs boson with low mass [18–23] provides a key motivation for SUSY. Stabilizing the Higgs boson mass at a low value, without invoking extreme fine-tuning of parameters, is a major theoretical challenge, referred to as the gauge hierarchy problem [24–29]. This stabilization can be achieved in so-called natural SUSY models [30–34], in which several of the SUSY partners are constrained to be light [33]: the top squarks $\tilde{t}_L$ and $\tilde{t}_R$, which have the same electroweak couplings as the left- (L-) and right- (R-) handed top quarks, respectively, the bottom squark with L-handed couplings, $\tilde{b}_L$, the gluino $\tilde{g}$; and the Higgsinos $\tilde{H}$. This search targets gluino pair production, which has a relatively large cross section for a given mass, with gluino decay $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$. This process can arise from $\tilde{g} \to \tilde{t}_1\bar{t}$, where the lighter top squark mass eigenstate $\tilde{t}_1$ is produced either on or off mass shell. The symbol $\tilde{\chi}_1^0$ denotes the lightest neutralino, an electrically neutral mass eigenstate that is in general a mixture of the Higgsinos and electroweak gauginos. In R-parity conserving SUSY models [35,36] in which the $\tilde{\chi}_1^0$ is the lightest supersymmetric particle, the $\tilde{\chi}_1^0$ is stable and can, in principle, account for some or all of the astrophysical dark matter [37–39]. The scenario with off-mass-shell top squarks is denoted as T1tttt [40] in simplified model scenarios [41–43]. In natural SUSY models, the top squark is typically lighter than the gluino, so we also search for scenarios with on-shell top squarks, denoted as T5tttt.

Simulated event samples for SM background processes are used to determine correction factors, typically near unity, that are used in conjunction with observed event yields in control regions to determine the SM background contribution in the signal regions. The production of $t\bar{t}$ + jets, W + jets, Z + jets, and QCD multijet events is simulated with the MC generator MadGraph5_amc@nlo@nlo 2.2.2

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gluino decay $\tilde{g} \to \tilde{t}_1 \bar{t}$ with $\tilde{t}_1 \to t\tilde{\chi}_1^0$ (T5tttt model), the results are generally similar, except at low neutralino masses, where the excluded gluino mass is somewhat lower. These results extend previous gluino mass limits by about 300 GeV and are among the most stringent constraints on these simplified models of SUSY to date.

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[1] L. Evans and P. Bryant, LHC machine, J. Instrum. **3**, S08001 (2008).
[2] P. Ramond, Dual theory for free fermions, Phys. Rev. D **3**, 2415 (1971).
[3] Yu. A. Gol'fand and E. P. Likhtman, Extension of the algebra of Poincaré group generators and violation of P invariance, JETP Lett. **13**, 323 (1971).
[4] A. Neveu and J. H. Schwarz, Factorizable dual model of pions, Nucl. Phys. **B31**, 86 (1971).
[5] D. V. Volkov and V. P. Akulov, Possible universal neutrino interaction, JETP Lett. **16**, 438 (1972).
[6] J. Wess and B. Zumino, A lagrangian model invariant under supergauge transformations, Phys. Lett. **49B**, 52 (1974).
[7] J. Wess and B. Zumino, Supergauge transformations in four dimensions, Nucl. Phys. **B70**, 39 (1974).
[8] P. Fayet, Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino, Nucl. Phys. **B90**, 104 (1975).
[9] H. P. Nilles, Supersymmetry, supergravity and particle physics, Phys. Rep. **110**, 1 (1984).
[10] ATLAS Collaboration, Search for supersymmetry in final states with jets, missing transverse momentum and one isolated lepton in $\sqrt{s} = 7$ TeV pp collisions using 1 fb^{-1} of ATLAS data, Phys. Rev. D **85**, 012006 (2012); **87**, 099903(E) (2012).
[11] ATLAS Collaboration, Search for squarks and gluinos in events with isolated leptons, jets and missing transverse momentum at $\sqrt{s} = 8$ TeV with the ATLAS detector, J. High Energy Phys. 04 (2015) 116.
[12] CMS Collaboration, Search for supersymmetry in pp collisions at $\sqrt{s} = 7$ TeV in events with a single lepton, jets, and missing transverse momentum, J. High Energy Phys. 08 (2011) 156.
[13] CMS Collaboration, Search for supersymmetry in pp collisions at $\sqrt{s} = 8$ TeV in events with a single lepton, large jet multiplicity, and multiple b jets, Phys. Lett. B **733**, 328 (2014).
[14] 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).
[15] ATLAS Collaboration, Search for gluinos in events with an isolated lepton, jets and missing transverse momentum at $\sqrt{s} = 13$ TeV with the ATLAS detector, Eur. Phys. J. C **76**, 565 (2016).
[16] CMS Collaboration, Search for supersymmetry in pp collisions at $\sqrt{s} = 13$ TeV in the single-lepton final state using the sum of masses of large-radius jets, J. High Energy Phys. 08 (2016) 122.
[17] CMS Collaboration, Search for supersymmetry in events with one lepton and multiple jets in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. D **95**, 012011 (2017).
[18] ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B **716**, 1 (2012).
[19] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B **716**, 30 (2012).
[20] CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV, J. High Energy Phys. 06 (2016) 081.
[21] CMS Collaboration, Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV, Eur. Phys. J. C **75**, 212 (2015).
[22] ATLAS Collaboration, Measurement of the Higgs boson mass from the $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ channels with

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] R. Chistov,[102,ll] M. Danilov,[102,ll] P. Parygin,[102] D. Philippov,[102] S. Polikarpov,[102] E. Tarkovskii,[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] V. Veckalns,[112,tt] G. I. Veres,[112,r] M. Verweij,[112] N. Wardle,[112] W. D. Zeuner,[112] W. Bertl,[113,a] K. Deiters,[113] W. Erdmann,[113] R. Horisberger,[113] Q. Ingram,[113] H. C. Kaestli,[113] D. Kotlinski,[113] U. Langenegger,[113] T. Rohe,[113] S. A. Wiederkehr,[113] F. Bachmair,[114] L. Bäni,[114] P. Berger,[114] L. Bianchini,[114] B. Casal,[114] G. Dissertori,[114] M. Dittmar,[114] M. Donegà,[114] C. Grab,[114] C. Heidegger,[114] D. Hits,[114] J. Hoss,[114] G. Kasieczka,[114] T. Klijnsma,[114] W. Lustermann,[114] B. Mangano,[114] M. Marionneau,[114] M. T. Meinhard,[114] D. Meister,[114] F. Micheli,[114] P. Musella,[114] F. Nessi-Tedaldi,[114] F. Pandolfi,[114] J. Pata,[114] F. Pauss,[114] G. Perrin,[114] L. Perrozzi,[114] M. Quittnat,[114] M. Rossini,[114] M. Schönenberger,[114] L. Shchutska,[114] A. Starodumov,[114,uu] V. R. Tavolaro,[114] K. Theofilatos,[114] M. L. Vesterbacka Olsson,[114] R. Wallny,[114] A. Zagozdzinska,[114,gg] D. H. Zhu,[114] T. K. Aarrestad,[115] C. Amsler,[115,vv] L. Caminada,[115] M. F. Canelli,[115] A. De Cosa,[115] S. Donato,[115] C. Galloni,[115] T. Hreus,[115] B. Kilminster,[115] J. Ngadiuba,[115] D. Pinna,[115] G. Rauco,[115] P. Robmann,[115] D. Salerno,[115] C. Seitz,[115] A. Zucchetta,[115] V. Candelise,[116] T. H. Doan,[116] Sh. Jain,[116] R. Khurana,[116] M. Konyushikhin,[116] C. M. Kuo,[116] W. Lin,[116] A. Pozdnyakov,[116] S. S. Yu,[116] Arun Kumar,[117] P. Chang,[117] Y. Chao,[117] K. F. Chen,[117] P. H. Chen,[117] F. Fiori,[117] W.-S. Hou,[117] Y. Hsiung,[117] Y. F. Liu,[117] R.-S. Lu,[117] M. Miñano Moya,[117] E. Paganis,[117] A. Psallidas,[117] J. f. Tsai,[117] B. Asavapibhop,[118] K. Kovitanggoon,[118] G. Singh,[118] N. Srimanobhas,[118] A. Adiguzel,[119,ww] F. Boran,[119] S. Damarseckin,[119] Z. S. Demiroglu,[119] C. Dozen,[119] E. Eskut,[119] S. Girgis,[119] G. Gokbulut,[119] Y. Guler,[119] I. Hos,[119,xx] E. E. Kangal,[119,yy] O. Kara,[119] A. Kayis Topaksu,[119] U. Kiminsu,[119] M. Oglakci,[119] G. Onengut,[119,zz] K. Ozdemir,[119,aaa] S. Ozturk,[119,bbb] A. Polatoz,[119] B. Tali,[119,ccc] S. Turkcapar,[119] I. S. Zorbakir,[119] C. Zorbilmez,[119] B. Bilin,[120] G. Karapinar,[120,ddd] K. Ocalan,[120,eee] M. Yalvac,[120] M. Zeyrek,[120] E. Gülmez,[121] M. Kaya,[121,fff] O. Kaya,[121,ggg] S. Tekten,[121] E. A. Yetkin,[121,hhh] M. N. Agaras,[122] S. Atay,[122]