Physics Letters B 783 (2018) 114–139

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for R-parity violating supersymmetry in pp collisions at $\sqrt{s} = 13$ TeV using b jets in a final state with a single lepton, many jets, and high sum of large-radius jet masses

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ARTICLE INFO

Article history:
Received 24 December 2017
Received in revised form 9 June 2018
Accepted 12 June 2018
Available online 19 June 2018
Editor: M. Doser

Keywords:
CMS
Physics
Supersymmetry

ABSTRACT

Results are reported from a search for physics beyond the standard model in proton–proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV. The search uses a signature of a single lepton, large jet and bottom quark jet multiplicities, and high sum of large-radius jet masses, without any requirement on the missing transverse momentum in an event. The data sample corresponds to an integrated luminosity of 35.9 fb^{-1} recorded by the CMS experiment at the LHC. No significant excess beyond the prediction from standard model processes is observed. The results are interpreted in terms of upper limits on the production cross section for R-parity violating supersymmetric extensions of the standard model using a benchmark model of gluino pair production, in which each gluino decays promptly via $\widetilde{g} \to$ tbs. Gluinos with a mass below 1610 GeV are excluded at 95% confidence level.

1. Introduction

Searches for physics beyond the standard model (SM) are motivated by several considerations, including theoretical problems associated with explaining the observed mass of the Higgs boson in the presence of quantum corrections (the hierarchy problem) [1], and astrophysical evidence for dark matter [2]. While the SM has been successful in describing a vast range of phenomena, its inability to address these theoretical and experimental issues makes it an incomplete description of fundamental particles and their interactions.

Supersymmetry (SUSY), a proposed extension of the SM, provides possible solutions to these problems [3–12]. The hierarchy problem can be addressed by SUSY models with a sufficiently low-mass top squark and gluino, and the lightest supersymmetric particle (LSP), if stable, is a potential dark matter candidate [1,13–16]. That stability is assured in R-parity conserving (RPC) SUSY models, where the R-parity of a particle is defined as $(-1)^{2s+3(B-L)}$ with s, B, and L denoting the spin, baryon number, and lepton number of the particle, respectively [17].

Recent searches at the CERN LHC have set stringent limits on RPC SUSY production, as mass limits for the models studied are reaching ∼1 TeV for the top squark [18–20] and ∼2 TeV [21–26] for the gluino. Due to these limits, there is mounting tension in the ability of RPC SUSY models to explain the hierarchy problem with little fine tuning. These RPC SUSY searches, however, typically require signatures with significant missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) resulting from the undetected LSPs, while in R-parity violating (RPV) SUSY, the LSP is not stable and decays to SM particles, which removes the large $p_{\mathrm{T}}^{\mathrm{miss}}$ signature. Though this disfavors the LSP as a dark matter candidate, it allows RPV SUSY models to evade constraints from typical RPC SUSY searches.

Given that there is no fundamental theoretical reason for R-parity conservation, RPV SUSY yields an important class of models that can ease the tension between natural solutions to the hierarchy problem and current experimental limits. In addition, the absence of a $p_{\mathrm{T}}^{\mathrm{miss}}$ requirement can allow RPV SUSY searches to be sensitive to a parameter space of RPC SUSY where only a small amount of $p_{\mathrm{T}}^{\mathrm{miss}}$ is expected, such as in models where the mass splitting between the supersymmetric particles is small. Therefore, RPV SUSY searches help to complete the coverage of SUSY parameter space.

The additional R-parity violating terms in the superpotential are

$$W = \frac{1}{2}\lambda^{ijk} L_i L_j \overline{\mathrm{e}}_k + \lambda'^{ijk} L_i Q_j \overline{\mathrm{d}}_k + \frac{1}{2}\lambda''^{ijk} \overline{\mathrm{u}}_i \overline{\mathrm{d}}_j \overline{\mathrm{d}}_k + \mu'^{i} L_i H_u. \quad (1)$$

Here L_i, Q_j, and H_u are SU(2) doublets corresponding to leptons, quarks, and the Higgs boson, respectively. The fields $\overline{\mathrm{e}}_k$, $\overline{\mathrm{u}}_i$, and

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https://doi.org/10.1016/j.physletb.2018.06.028

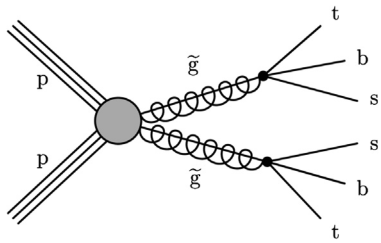

Fig. 1. Example diagram for the simplified model used as the benchmark signal in this analysis.

$\overline{\mathrm{d}}_j$ are the charged lepton, up-type quark, and down-type quark SU(2) singlets, while the various λ and μ factors denote the coupling strengths for their corresponding interaction. Color indices are suppressed and letters i, j, k denote generation indices. More details on RPV SUSY can be found in Ref. [27].

This search is motivated by a particular model of R-parity violation, minimal flavor violating (MFV) SUSY [28], in which the R-parity violating couplings arise from the SM Yukawa couplings. This makes the third generation RPV couplings large and those of the first two generations small, which is consistent with the strong experimental constraints from proton decay searches on baryon and lepton number violation involving the lightest two generations [27]. The coupling λ''^{ijk} must be antisymmetric in the last two indices because of gauge invariance, which requires λ''^{tbb} to be 0. Therefore, the largest allowed MFV coupling is λ''^{tbs}.

Due to the high $\widetilde{\mathrm{g}}\widetilde{\mathrm{g}}$ cross section and large value of λ''^{tbs}, a search for the pair production of gluinos that decay via $\widetilde{\mathrm{g}} \to \mathrm{t}\overline{\widetilde{\mathrm{t}}} \to \mathrm{tbs}$ is well motivated. The simplified model [29,30] that is used in the interpretation makes several assumptions about the SUSY mass spectrum. It is assumed that squarks other than the top squark are much heavier than the gluino, so they do not affect the gluino decay, and the branching ratio of $\widetilde{\mathrm{g}} \to \mathrm{t}\overline{\widetilde{\mathrm{t}}} \to \mathrm{tbs}$ is 100%. The top squark is assumed to be virtual in its decay. This results in a three-body decay, so searches for dijet resonances, i.e., $\overline{\widetilde{\mathrm{t}}} \to \mathrm{bs}$, are not applicable in this scenario. It is further assumed that the gluinos decay promptly. An example diagram for this simplified model is shown in Fig. 1. Although this benchmark is used for interpreting results, the search is structured to be generically sensitive to high-mass signatures with large jet and bottom quark jet multiplicities and either little or no $p_{\mathrm{T}}^{\mathrm{miss}}$, which are potential features of other models of physics beyond the SM. Previous limits on such MFV models were obtained by the ATLAS and CMS Collaborations at $\sqrt{s} = 8\,\mathrm{TeV}$ [31–33] and by the ATLAS Collaboration at $\sqrt{s} = 13\,\mathrm{TeV}$ [34], excluding gluino masses below $\sim 1\,\mathrm{TeV}$ and $1.6\,\mathrm{TeV}$, respectively.

This analysis searches in a single-lepton (electron or muon) final state for an excess of events with a large number of identified bottom quark (b-tagged) jets in regions determined as a function of the jet multiplicity and the sum of masses of large-radius jets, M_{J}. Signal events are expected to contribute to this final state through the leptonic decay of one of the top quarks while populating the high jet multiplicity and high M_{J} kinematic regions due to the hadronic decay of the second top quark and the additional bottom and strange quark jets. The four b quarks, two from the top quark decays and two from the top squark decays, provide a high b-tagged jet multiplicity signature. The quantity M_{J} was proposed in phenomenological studies [35–37] and was first used for RPC SUSY searches by the ATLAS Collaboration in all-hadronic final states [38,39] and by the CMS Collaboration in single-lepton events [26,40].

2. The CMS detector, samples, and event selection

This search uses a sample of proton–proton collision data at a center-of-mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$ corresponding to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$, which was collected by the CMS experiment during 2016. The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are the charged particle tracking systems, composed of silicon-pixel and silicon-strip detectors, and the calorimeter systems, consisting of a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter. Muons are identified and measured by gas-ionization detectors embedded in the magnetic flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, is given in Ref. [41].

The background predictions use Monte Carlo (MC) simulation samples with corrections to the normalization and shape of distributions measured in data control samples. MadGraph5_amc@nlo 2.2.2 is used in leading-order mode [42,43] to generate the $\mathrm{t\bar{t}}$, W + jet, quantum chromodynamics multijet (QCD), and Drell–Yan background processes with extra partons. Comparison to a powheg 2.0 [44–46] sample generated at next-to-leading order (NLO) shows that the NLO effects do not have a significant impact. The $\mathrm{t\bar{t}W}$, $\mathrm{t\bar{t}Z}$, $\mathrm{t\bar{t}t\bar{t}}$, and t-channel single top quark production backgrounds are generated with MadGraph5_amc@nlo 2.2.2 in NLO mode [47], while the tW, $\mathrm{\bar{t}W}$, and s-channel single top quark processes are generated with powheg 2.0. The $\mathrm{t\bar{t}}$, W + jet, and QCD samples are generated with up to 2, 4, 2 extra partons, respectively. All samples are generated using a top quark mass of 172.5 GeV and with the NNPDF3.0 set of parton distribution functions (PDF) [48]. For the fragmentation and showering of partons, the generated samples are interfaced with PYTHIA 8.205 [49] and use the CUETP8M1 tune to describe the underlying event [50]. All samples use the highest precision cross sections available [51–57]. The detector response is simulated with Geant4 [58]. Simulated samples are processed through the same reconstruction algorithms as the data.

The signal samples are generated with up to two extra partons in leading-order mode and dynamic factorization and renormalization scales by MadGraph5_amc@nlo 2.2.2. The same fragmentation, parton showering, simulation, and event reconstruction procedure as for the background samples is used. The samples are normalized to NLO + next-to-leading logarithmic cross sections [59].

The reconstruction of objects in an event proceeds from the candidate particles identified by the particle-flow (PF) algorithm [60], which uses information from the tracker, calorimeters, and muon systems to identify the candidates as charged or neutral hadrons, photons, electrons, or muons. Charged-particle tracks are required to originate from the event primary vertex (PV), which is the reconstructed vertex with the largest value of summed physics-object squared transverse momentum (p_{T}). The physics objects used for the PV reconstruction are those returned by a jet finding algorithm [61,62] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_{T} of those objects.

Electrons are reconstructed by pairing a charged-particle track with an ECAL supercluster [63]. The resulting electron candidates are required to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.5$, and to satisfy identification criteria designed to remove hadrons misidentified as electrons, photon conversions, and electrons from heavy-flavor hadron decays. Muons are reconstructed by associating tracks in the muon system with those found in the silicon tracker [64]. Muon candidates are required to satisfy $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $|\eta| < 2.4$,