Physics Letters B 718 (2012) 329–347

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for three-jet resonances in pp collisions at $\sqrt{s}=7$ TeV ☆

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ARTICLE INFO

Article history:
Received 14 August 2012
Received in revised form 18 October 2012
Accepted 19 October 2012
Available online 24 October 2012
Editor: M. Doser

Keywords:
CMS
Physics
Three-jet resonances
R-parity-violation

ABSTRACT

Results are reported from a search for the production of three-jet resonances in pp collisions at a center-of-mass energy $\sqrt{s}=7$ TeV. The study uses the data sample collected by the CMS experiment at the LHC in 2011, corresponding to an integrated luminosity of 5.0 fb^{-1}. Events with high jet multiplicity and a large scalar sum of jet transverse momenta are analyzed for the presence of resonances in the three-jet invariant mass spectrum. No evidence for a narrow resonance is found in the data, and limits are set on the cross section for gluino pair production in an R-parity-violating supersymmetry model, for gluino masses greater than 280 GeV. Assuming a branching fraction for gluino decay into three jets of 100%, gluino masses below 460 GeV are excluded at 95% confidence level. These results significantly extend the range of previous limits.

Many extensions of the standard model (SM) predict the existence of new, strongly interacting particles that lead to final states with high jet multiplicities. Examples of such particles include gluinos in R-parity-violating (RPV) SUSY models [1,2], or more generally any colored fermion resonance that transforms as an octet under $SU(3)_C$ [3–6]. Despite large production cross sections predicted by many of these models, the vast majority of current experimental searches are insensitive to them because they use signal selection criteria based on low jet multiplicities, such as dijet resonances, or require the presence of large missing transverse energy. While this strategy has proved effective in establishing cross section limits for many models of physics beyond the SM up to TeV mass scales [7,8], the currently published limits for models predicting high jet multiplicity final states [9–11] are much less stringent. Specifically, there are only two published results from searches involving six-jet final states at hadron colliders, one from the Tevatron [12] and the other from the Large Hadron Collider (LHC) [13], which exclude RPV gluinos with masses below 144 GeV and between 200 and 280 GeV, respectively.

This Letter presents the results of a search for three-jet resonances in multijet events in proton–proton (pp) collisions at $\sqrt{s}=$ 7 TeV. The event sample was collected using the Compact Muon Solenoid (CMS) detector [14] at the LHC. The integrated luminosity is 4.98 ± 0.11 fb^{-1} [15], corresponding to the CMS data sample recorded in 2011. In this extension of previous CMS results [13] using 35 pb^{-1} of data, events with at least six high-transverse-momentum (p_T) jets are investigated for evidence of three-jet resonances using the jet-ensemble technique [12,13].

The CMS detector is a multi-purpose apparatus described in detail in Ref. [14]. A high-resolution silicon pixel and strip tracker, immersed in the 3.8 T magnetic field of the superconducting solenoid, provides charged particle tracking coverage for $|\eta|<2.5$, where $\eta=-\ln[\tan(\theta/2)]$ is the pseudorapidity, and θ is the polar angle measured with respect to the counterclockwise proton beam direction. Jet energy deposits are measured using electromagnetic (ECAL) and hadronic (HCAL) calorimeters. The finely-segmented lead-tungstate crystal ECAL consists of a barrel and two endcap regions. The ECAL barrel covers the pseudorapidity range $|\eta|<1.4$ with a granularity of $\Delta\eta\times\Delta\phi=0.0174\times0.0174$, where ϕ is the azimuthal angle, measured in radians, and the endcaps cover $1.4<|\eta|<3.0$. The HCAL extends out to an $|\eta|$ of about 5.0. Its central and endcap regions consist of brass/scintillator sampling calorimeters that cover $|\eta|<3.0$ with a granularity of $\Delta\eta\times\Delta\phi=0.087\times0.087$ for central rapidities. Further coverage is provided by a steel/quartz-fiber Cherenkov calorimeter. Muons are measured in gas detectors embedded in the steel return yoke outside the solenoid.

Events are recorded using a two-tiered trigger system [14]. Objects satisfying the requirements at the first level are passed to the high-level trigger (HLT) which further reduces the total recorded rate. Triggers based on the scalar sum of all transverse energy from jets (H_T), reconstructed using only calorimeter information, are used to select events. To reduce the effects of multiple pp interactions in the same bunch crossings (pileup), which produce

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http://dx.doi.org/10.1016/j.physletb.2012.10.048

a large number of low-p_T particles, jets considered in the HLT selection are required to have $p_T > 40$ GeV. The HLT threshold for H_T ranged from 350 to 750 GeV over the course of the 2011 data collection period, depending on the instantaneous luminosity.

A further set of criteria is imposed on events passing the trigger. Events are required to contain at least one well-reconstructed primary event vertex [16]. Jets are required to have $p_T > 70$ GeV and $|\eta| < 3.0$, which suppresses background and minimizes pileup effects. Events with pair-produced gluinos are expected to have high jet multiplicity and large values of H_T. We therefore require events to contain at least six jets, and to have a total scalar sum of jet p_T exceeding 900 GeV. The latter requirement ensures that the trigger is fully efficient for these events.

Individual objects reconstructed using the CMS particle-flow algorithm [17] serve as input for jet reconstruction. The particle-flow algorithm [17] combines calorimeter information with reconstructed tracks to identify individual particles such as photons, leptons, and both neutral and charged hadrons within jets. The energy of photons is obtained directly from the calibrated ECAL measurement. The determination of the energy of electrons comes from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the sum of all energy from bremsstrahlung photons associated to the track. The energy of muons is obtained from the corresponding track momentum. Charged hadron energy is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for hardware zero-suppression effects, and calibrated for the non-linear response of the HCAL. Finally, the energy of neutral hadrons is obtained from the corresponding calibrated ECAL and HCAL energies.

Jet reconstruction is performed using the anti-k_t algorithm [18] with a distance parameter of 0.5 in η–ϕ space. Jet energy scale corrections [19] derived from data and Monte Carlo (MC) simulation are applied to account for the non-linear and non-uniform response of the HCAL. A small residual correction factor is included to correct for differences in jet response between the detector and its simulation. The combined corrections are on the order of 5–10%, and their corresponding uncertainties range from 1 to 6%, depending on the jet pseudorapidity and p_T. Jet quality criteria [20] are applied to remove misidentified jets, which arise primarily from calorimeter noise. For both data and simulated signal events, more than 99.8% of all selected jets satisfy these criteria. After imposing all selection requirements, 114 599 events remain.

The benchmark signal model for the analysis features pair-produced gluinos, whose production and decay are simulated using the PYTHIA [21] v6.424 event simulation program with the CTEQ6L1 parton distribution function (PDF) set [22]. The gluino decay is modeled as an effective RPV coupling between the gluino and three light quarks, with a branching fraction of 100%. All superpartners except the gluino are decoupled, such that the mass of the squark is assumed to be much larger than that of the gluino [23]. The natural width of the gluino resonance is taken to be much smaller than the resolution of the detector, and no intermediate particles are produced in the gluino decay. The gluino mass is varied between 250 and 500 GeV in steps of 50 GeV, and additional mass points are generated at 750, 1000, 1250, and 1500 GeV. The leading-order (LO) cross section from PYTHIA is 92 pb for a gluino mass of 250 GeV and 2.1 pb for a gluino mass of 450 GeV, falling to about 1.3×10^{-5} pb for a gluino mass of 1500 GeV. Next-to-leading-order (NLO) correction factors (K-factors) are calculated using the PROSPINO [24] program and are applied to the LO cross sections. These values rise from 1.8 for a gluino mass of 250 GeV to 2.1 for a gluino mass of 450 GeV, and to 4.6 for a gluino mass of 1500 GeV, with corresponding

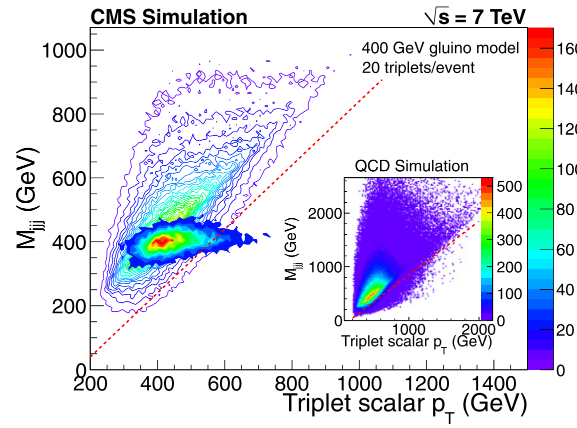

Fig. 1. Simulated triplet jet mass M_{jjj} versus the triplet scalar p_T of all 20 triplets for a gluino mass of 400 GeV, shown as a contoured distribution, with that of the triplets whose jets all originate from the same gluino parent overlaid. The overlaid "correct" triplets are shown to lie along a horizontal line corresponding to the generated gluino mass, while the behavior of all other triplets resembles the expectation for the QCD background, which is shown in the inset. All triplets falling to the right of the dashed line pass the requirement of Eq. (1) for a value of $\Delta = 160$ GeV.

uncertainties on the NLO cross sections of 15.1, 15.9, and 27.9%, respectively. Simulation of the CMS detector response is performed using GEANT4 [25].

The principal background arises from multijet events produced in strong interaction (QCD) processes. All other SM processes, such as fully-hadronic decays of top quark pairs, are predicted to make a negligible contribution. The QCD background arises primarily from events with two high-p_T jets from a hard interaction, combined with gluon jets from initial- or final-state radiation. We use the jet-ensemble technique to reconstruct the gluino candidates and to suppress background. The six highest-p_T jets in each event are combined in all possible three-jet combinations (triplets), resulting in 20 unique triplets per event. For signal events, at most two of the triplets correspond to a parent gluino, while the other triplets constitute a combinatorial background. Thus, background arises not only from QCD multijet events, but also from the signal events themselves. To improve sensitivity to the presence of a three-jet resonance, a requirement that exploits the observed linear correlation between the triplet mass and the scalar sum of the three jets' p_T values in background triplet combinations is imposed. We require

$$M_{jjj} < \sum_{i=1}^{3} p_T^i - \Delta, \quad (1)$$

where M_{jjj} is the triplet mass, $\sum_{i=1}^{3} p_T^i$ is the sum of the magnitudes of the transverse momenta of the jets within the triplet, and Δ is an offset adjusted to optimize signal sensitivity. Note that for signal triplets, M_{jjj} is fixed by the gluino mass and thus independent of its three jets' scalar p_T sum. Fig. 1 shows the simulated triplet mass versus the triplet scalar p_T for a gluino mass of 400 GeV. The value of Δ is determined by maximizing the ratio of the number of signal triplets to the sum of the number of signal and background triplets in a two-standard-deviation (σ) interval about the mean of a Gaussian function that describes the gluino mass peak. A common value $\Delta = 160$ GeV, which maximizes sensitivity to signal, is used for all gluino masses considered, and typically at most one triplet per event survives the requirement from Eq. (1). The fraction of signal triplets, whose jets all originate from the same parent gluino, that pass this requirement ranges from 2 to 13% depending on the gluino mass, while the efficiency to select all other triplet combinations in a signal event is below 1%.

After the final selection, residual background remains from both QCD multijet events and the combinatorial background triplets in possible gluino signal events. The latter contribute only minimally, and the shape of their mass distribution is found to be similar to that of the dominant QCD multijet background. We therefore consider the two background components together and parameterize their shape using the smoothly falling distribution [26] given by:

$$\frac{d\sigma}{dM_{jjj}} = \frac{P_0(1 - M_{jjj}/\sqrt{s})^{P_1}}{(M_{jjj}/\sqrt{s})^{P_2 + P_3 \ln(M_{jjj}/\sqrt{s})}}. \tag{2}$$

The parameters P_0, P_1, P_2, and P_3 have values of $(61.0 \pm 1.8) \times 10^3$ GeV^{-1}, 53.8 ± 0.7, -1.90 ± 0.04, and -0.13 ± 0.01, respectively, as determined by fitting this function to the data sample in the range from 260 to 1625 GeV using a χ^2 minimization technique. Thus, any potential signal would manifest itself as a localized positive deviation from the expectation of the background fit.

To estimate the number of signal events expected after all selection criteria are applied, the sum of a Gaussian function that represents the signal and the four-parameter function (Eq. (2)) that models the background are fitted to the simulated gluino M_{jjj} distribution, for $M_{jjj} > 260$ GeV. Below 260 GeV, the triplet mass distribution falls off rapidly due to restrictions imposed by the H_T threshold in the HLT. The width of the Gaussian function modeling the signal varies according to the detector resolution from 17 GeV for a gluino mass of 250 GeV, to 100 GeV for a gluino mass of 1500 GeV, as determined from simulation. The integral of the Gaussian component provides the estimate for the expected number of signal triplets reconstructed, and the value of this integral, divided by the number of signal events generated, determines the signal acceptance for each gluino mass. The signal acceptance per event includes all selection criteria and is parameterized with a second-order polynomial as a function of gluino mass. The event acceptance is 0.25% for a gluino of mass 250 GeV, 1.5% for a gluino of mass 450 GeV, and rises to 2.6% for a gluino of mass 1500 GeV.

The systematic uncertainty on the signal acceptance is evaluated as follows. The uncertainty related to the jet energy scale [19] is evaluated by varying the jet energy scale correction within its uncertainties, then recalculating the acceptance for different gluino mass values. The largest difference with respect to the nominal acceptance is taken as the systematic uncertainty and ranges from 9 to 18%. The difference between the calculated gluino acceptance at each mass point and the parameterized acceptance is taken as an uncertainty for each mass value and varies from 1 to 18%. The level of initial- and final-state radiation is varied following a prescription used in many other results [27], where the relative amount of each is separately increased and decreased with respect to the nominal value. The associated uncertainty is evaluated in a similar manner to that described for the jet energy scale uncertainties. The difference of 3 to 5% with respect to the nominal acceptance is taken as the systematic uncertainty. To determine the effect of pileup on the signal acceptance, the MC signal samples are reweighted such that the distribution of reconstructed primary vertices is shifted high and then low by one standard deviation compared to the nominal analysis (in the nominal analysis, the MC distribution is reweighted to correspond to the measured distribution). The acceptance procedure is repeated at both points and the largest difference with respect to the nominal acceptance is taken as the systematic uncertainty, which varies from 1 to 3%. The uncertainty corresponding to the choice of PDF set is evaluated by reweighting the events to correspond to each of its associated eigenvector sets and repeating the acceptance calculation. The difference, added in quadrature from all sets, is 4% and is taken as the systematic uncertainty. To estimate the uncertainty due to the choice of background parameterizations, alternate functions were fit to the data and compared

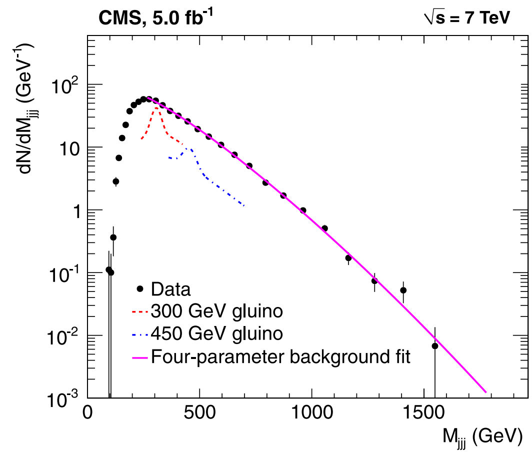

Fig. 2. Mass distribution for selected jet triplets. The four-parameter background fit is shown by the solid line. The NLO expectation for a 300 GeV gluino signal is shown by the dotted line, and that of a 450 GeV gluino signal by the dash-dotted line. Each of the two is normalized to the integrated luminosity of the data sample.

to the default fit. The results of each of these fits agree within statistical uncertainties, and the largest deviation from any of the alternate fits to the default fit is taken as the systematic uncertainty, ranging from 1.3% at a mass of 300 GeV to 2.9% at a mass of 500 GeV. These contributions, combined with those from the luminosity measurement (2.2%), yield a total systematic uncertainty on the signal acceptance between 14 and 26%, depending on the gluino mass.

The measured mass distribution for the selected jet triplets is shown in Fig. 2, where the four-parameter background fit is represented by the solid line. The expectation for a 300 GeV and a 450 GeV gluino signal are also included as a dotted and dash-dotted line, respectively, and each is normalized to the integrated luminosity of the data sample. We choose the width of bins to equal 10% of the mass value. This yields bin widths in general correspondence with the expected instrumental mass resolution.

To search for an excess in the number of triplets with respect to the expected background, we compute the difference between the measured number of triplets observed in each mass bin and the number of triplets predicted in this bin by the background fit. Fig. 3 shows this difference, normalized to the background prediction (Fig. 3a) and to the uncertainty in the background prediction (Fig. 3b). In both cases, the predicted background is in agreement with the data over the full mass range.

Because no excess of events is observed in the measured mass distribution, we proceed to place upper limits on the cross section times the branching fraction for the production of three-jet resonances in the data. Both observed and expected limits are calculated using a modified frequentest CL$_s$ method with a one-sided profile likelihood test statistic [28]. The background model parameters and their corresponding uncertainties are taken from the fit of the four-parameter background function (Eq. (2)) to the data. The uncertainties on the parameters that describe the background shape are included as log-normal constraints, and they are 1.3% for P_1, 2.2% for P_2, 8.6% for P_3, with a normalization uncertainty on P_0 of 3%. The central value of each parameter is set to the best fit value and the width to one standard deviation. The range is truncated at $\pm 3\sigma$. In addition to the background parameters, log-normal constraints are included for the acceptance and integrated luminosity. These systematic uncertainties are treated as global constraints in the likelihood.

The observed and expected 95% confidence level (CL) upper limits on the gluino pair production cross section times branch-

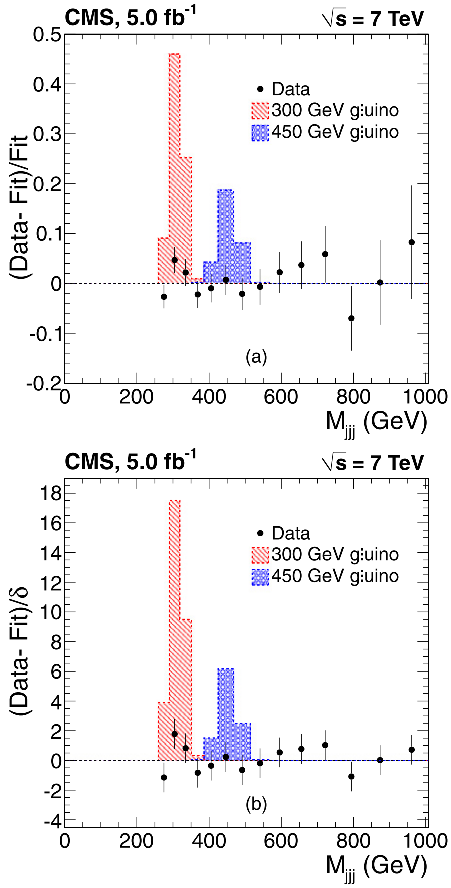

Fig. 3. Difference between the measured triplet mass distribution and the fitted background parametrization, divided by the fitted value (a) or by the statistical uncertainty δ on the fitted value (b), shown for both data and the NLO expectation of two gluino models, one with a gluino mass of 300 GeV and the other with a gluino mass of 450 GeV.

ing fraction as a function of gluino mass are presented in Fig. 4. The corresponding 95% CL lower limit on the gluino mass is determined by finding the mass value at which the limit line crosses that of the NLO gluino cross section, assuming a branching fraction for the signal model of 100%. We perform the search in the region of M_{jjj} above 280 GeV and exclude masses below 460 GeV at 95% CL.

In summary, a search has been performed for three-jet resonance production in pp collisions at a center-of-mass energy of 7 TeV, using a data sample corresponding to an integrated luminosity of 5.0 fb^{-1}. Events having the properties of high jet multiplicity and large scalar sum of jet p_T, which are expected signatures of high-mass hadronic resonances, were analyzed for the presence of signal events, and no evidence for a narrow resonance was found. For a mass range above 280 GeV, the production of gluinos, modeled as an effective RPV coupling between the gluino and three light quarks with a branching fraction of 100%, has been excluded for masses below 460 GeV at 95% CL. These are the most stringent limits to date.

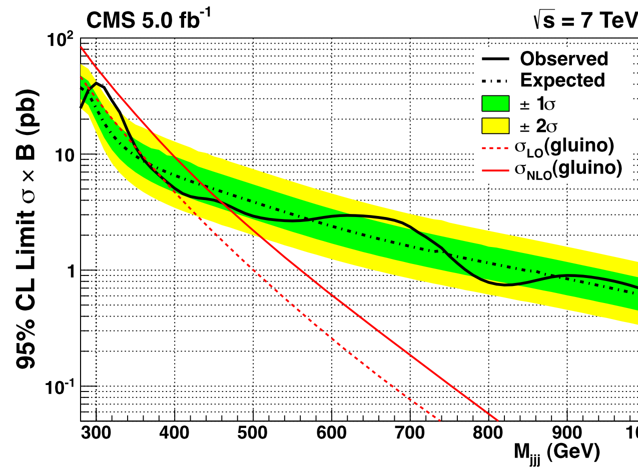

Fig. 4. Observed and expected 95% CL upper limits on the cross section times branching fraction for gluino pair production followed by RPV decay of each gluino to three light-flavored quark jets. Also shown are the $\pm 1\sigma$ and $\pm 2\sigma$ bands on the expected limit, as well as the theoretical LO and NLO cross sections for gluino production, assuming a branching fraction of a gluino decay into three jets of 100%.

Acknowledgements

The authors would like to thank Michael Park and Yue Zhao for providing theoretical calculations. We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MEYS (Czech Republic); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, 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); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie programme and the European Research Council (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Austrian Science Fund (FWF); 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 Council of Science and Industrial Research, India; the Compagnia di San Paolo (Torino); and the HOMING PLUS programme of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund.

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