Searches for light- and heavy-flavour three-jet resonances in pp collisions at sqrt(s) = 8 TeV

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Abstract: A search for three-jet hadronic resonance production in pp collisions at a centre-of-mass energy of 8 TeV has been conducted by the CMS Collaboration at the LHC with a data sample corresponding to an integrated luminosity of 19.4 fb−1. The search method is model independent, and events are selected that have high jet multiplicity and large values of jet transverse momenta. The signal models explored assume R-parity-violating supersymmetric gluino pair production and have final states with either only light-flavour jets or both light- and heavy-flavour jets. No significant deviation is found between the selected events and the expected standard model multijet and View the MathML source tt¯ background. For a gluino decaying into light-flavour jets, a lower limit of 650 GeV on the gluino mass is set at a 95% confidence level, and for a gluino decaying into one heavy- and two light-flavour jets, gluino masses between 200 and 835 GeV are, for the first time, likewise excluded.

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1. Introduction

Hadronic multijet final states at hadron colliders offer a unique window on many possible extensions of the standard model (SM), although with the view partly obscured by large backgrounds due to SM processes. Many of these extensions predict resonances, such as heavy coloured fermions transforming as octets under $SU(3)_c$ [1–4] or supersymmetric gluinos that undergo $R$-parity-violating (RPV) decays to three quarks [5–7]. Recent studies from the Fermilab Tevatron Collider and the CERN Large Hadron Collider (LHC) employed the jet-ensemble technique. For this technique, jets are associated into unique combinations of three jets (triplets). Additional selection requirements are imposed to suppress the large backgrounds due to SM processes and to enhance sensitivity to strongly decaying resonances. These analyses set lower mass limits based upon resonance fits for gluinos undergoing RPV decays. The CDF Collaboration at the Tevatron excluded gluino masses below 144 GeV [8] using data from pp collisions at 1.96 TeV, while the CMS Collaboration at the LHC excluded masses below 460 GeV [9,10] with data from pp collisions at 7 TeV. An additional search at the LHC by the ATLAS Collaboration, also based on data collected with pp collisions at 7 TeV, has extended these limits to 666 GeV [11].

Presented here are the results of dedicated searches for pair-produced three-jet resonances in multijet events from pp collisions at $\sqrt{s} = 8$ TeV, with one search being inclusive with respect to parton flavours and the second requiring at least one jet from the resonance decay to be identified as a bottom-quark jet (b jet). This latter, heavy-flavour search is the first of its kind and probes additional RPV couplings. The results are based on a data sample of pp collisions at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of $19.4 \pm 0.5$ fb$^{-1}$ [12] collected with the CMS detector [13] at the LHC in 2012. Events with at least six jets, each with high transverse momentum ($p_T$) with respect to the beam direction, are selected and investigated for evidence of three-jet resonances consistent with strongly coupled supersymmetric particle decays. The event selection criteria are optimised in the context of the gluino signal mentioned above [5–7], using a simplified model where the gluinos decay with a branching fraction of 100% to quark jets. However, the generic features of the selection criteria provide a model-independent basis that can be used when examining extensions of the SM, since any exotic three-jet resonance with a narrow width, sufficient cross section, and high-$p_T$ jets would be expected to produce a significant bump on the smoothly falling SM background of our search. Additionally, low trigger thresholds and the application of b-jet identification make it possible to use SM top quark–antiquark (t ¯t) events to validate the analysis techniques.

2. The CMS experiment

The central feature of the CMS apparatus [13] is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are...
a silicon pixel and strip tracker, a lead tungstate electromagnetic calorimeter (ECAL), and a hadron calorimeter (HCAL) that consists of brass layers and scintillator sampling calorimeters. Muons are measured in gas ionisation detectors embedded in the steel return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing radially outwards from close to the nominal interaction point, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the anticlockwise-beam direction. The polar angle \(\theta\) is measured with respect to the positive z axis, the azimuthal angle \(\phi\) is measured in the x–y plane, and the pseudorapidity \(\eta\) is defined as \(\eta = -\ln(\tan(\theta/2))\). Energy deposits from hadronic jets are measured using the ECAL and HCAL. The energy resolution for photons with \(E_T \approx 60\) GeV varies between 1.1% and 2.6% over the solid angle of the ECAL barrel, and from 2.2% to 5% in the endcaps. The HCAL, when combined with the ECAL, measures jets with a resolution \(\Delta E/E \approx 100\%\sqrt{E_T/\text{GeV}} \lesssim 5\%\). [14]. The ECAL provides coverage in pseudorapidity \(|\eta| < 1.479\) in a barrel region and \(1.479 < |\eta| < 3.0\) in two endcap regions. In the region \(|\eta| < 1.74\), the HCAL cells have widths of 0.087 in \(\eta\) and 0.087 in \(\phi\). In the \(\eta–\phi\) plane, and for \(|\eta| > 1.48\), the HCAL cells map on to 5 × 5 ECAL crystals arrays to form calorimeter towers projecting radially outwards from close to the nominal interaction point. At larger values of \(|\eta|\), the size of the towers increases, and the matching ECAL arrays contain fewer crystals. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies, subsequently used to provide the energies and directions of hadronic jets.

The CMS detector uses a two-tier trigger system to collect data. Events satisfying the requirements at the first level are passed to the high-level trigger (HLT), whose output is recorded and limited to a total rate of \(\sim 350\) Hz. An HLT requirement based on at least six jets, reconstructed with only calorimeter information, is used to select events. With the jets ordered in descending \(p_T\) values, the \(p_T\) threshold at the HLT for the fourth jet is 60 GeV and, for the sixth jet, 20 GeV. For events passing all offline requirements described in Section 4, the total trigger efficiency is at least 98%.

The CMS particle-flow algorithm [15] combines calorimeter information with reconstructed tracks to identify individual particles such as photons, leptons, and neutral and charged hadrons. The photon energy is obtained directly from calibrated measurements in the ECAL. The energy of electrons is determined from a combination of the track momentum at the primary interaction vertex [16], the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons associated with the track in the offline reconstruction. The muon energy is obtained from the corresponding track momentum. The energy for a charged hadron is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for zero-suppression effects and calibrated for the nonlinear response of the calorimeters. Finally, the energy of a neutral hadron is obtained from the corresponding calibrated ECAL and HCAL energies. The particle-flow objects serve as input for jet reconstruction, performed using the anti-\(k_t\) algorithm [17–19] with a distance parameter of 0.5. The jet transverse momentum resolution is typically 15% at \(p_T = 10\) GeV, 8% at 100 GeV, and 4% at 1 TeV; when jet clustering is based only upon the calorimeter energies, the corresponding resolutions are about 40%, 12%, and 5%.

Jet energy scale corrections [20] derived from data and Monte Carlo (MC) simulation are applied to account for the nonlinear and nonuniform response of the calorimeters. In data, a small residual correction factor is included to correct for differences in jet response between data and simulation. The combined corrections are approximately 5–10%, and their corresponding uncertainties range from 1–5%, depending on the pseudorapidity and energy of the jet. Jet quality criteria [21] are applied to remove misidentified jets, which arise primarily from calorimeter noise. In both data and simulated signal events, more than 99.8% of all selected jets satisfy these criteria.

### 3. Signal event simulation

Pair-produced gluinos are used to model the signal. Gluino production and decay are simulated using the Pythia [22] event generator (v6.424), with each gluino decaying to three quarks through the \(\lambda''_{ud}\) quark RPV coupling [23], where \(u\) and \(d\) refer to any up- or down-type quark, respectively. Two different scenarios are considered for this coupling, resulting in both an inclusive search similar to previous analyses [8–11] and a new heavy-flavour search. For the first case, the coupling of \(\lambda''_{u(12)}\), where the three numerical subscripts of \(\lambda\) refer to the quark generations of the corresponding \(u–d–d\) quarks, is set to a non-zero value, giving a branching fraction of 100% for the gluino decay to three light-flavour quarks. The second case, represented by \(\lambda''_{u(13)}\) or \(\lambda''_{d(22)}\), covers gluino decays to one b quark and two light-flavour quarks. The mass of the generated gluino signal ranges from 200 to 500 GeV in 50 GeV steps, with additional mass points at 750, 1000, 1250, and 1500 GeV. For the generation of this signal, all superpartners except the gluino are taken to be decoupled and heavy (i.e. beyond the reach of the LHC), the natural width of the gluino resonance is taken to be much smaller than the mass resolution of the detector of approximately 4–8% in the mass range investigated, and no intermediate particles are produced in the gluino decay. Simulation of the CMS detector response is performed using the Geant4 [24] package.

### 4. Event selection

Events recorded with the six-jet trigger described above are required to contain at least one reconstructed primary vertex [16]. Since this analysis targets pair-produced three-jet resonances that naturally yield high jet multiplicity, we require events to contain at least six jets with \(|\eta| < 2.5\). To ensure that the trigger is fully efficient, we impose minimal requirements that the \(p_T\) thresholds of the fourth and sixth jets are at least 80 and 60 GeV, respectively, though we impose higher thresholds for two of our three selections, as described below.

We use the jet-ensemble technique [8–9] in this analysis to combine the six highest-\(p_T\) jets in each event into all possible unique triplets. Each event that satisfies all selection requirements will yield 20 combinations of jet triplets. For signal events, no more than two of these triplets can be correct reconstructions of the pair-produced gluinos, with the remaining 18 triplets being incorrect combinations of jets. Thus, background triplets arising from SM multijet events are supplemented by “incorrect” jet-triplet combinations from the signal events themselves. To obtain sensitivity to the presence of a three-jet resonance, an additional requirement is placed on each jet triplet to preferentially remove SM background and incorrectly combined signal triplets. This selection criterion exploits the constant invariant mass of correctly reconstructed signal triplets and the observed linear correlation between the invariant mass and scalar sum of jet \(p_T\) for background triplets and incorrectly combined signal triplets:

\[
M_{jjj} < \left( \sum_{i=1}^{3} p_T^i \right) - \Delta,
\]

where \(M_{jjj}\) is the triplet invariant mass, the \(p_T\) sum is over the three jets in the triplet (triplet scalar \(p_T\)), and \(\Delta\) is an empirically
the signal position of the gluino mass for a given trigger. We find that the peak position of the gluino mass for a given trigger is at around 400 GeV. We find that a requirement of $\Delta = 110$ GeV is used. All-hadronic $t_\ell$ decay into three jets is shown in the main plot. Triplets are selected that pass the $\Delta = 110$ GeV requirement from Eq. (1). The Gaussian signal peak of correctly reconstructed gluino triplets is represented by the gold shaded area, with its Gaussian fit shown by the blue dot-dashed line below it. The distribution of incorrectly combined triplets, shown in black, is described by a similar functional form as that used to estimate the background in data. The inset shows the signal and background estimates used in the optimisation procedure, with the expected background from SM multijet processes in red, and the signal-plus-background indicated by a blue dashed line.

The use of $b$-jet identification enables us to perform a heavy-flavour search in addition to our inclusive search for three-jet resonances. The combined secondary vertex (CSV) algorithm [26] uses variables from reconstructed secondary vertices along with track-based lifetime information to identify $b$ jets. The tagging efficiency for $b$ jets changes with the $p_T$ of the jet, ranging from 70% for jets with $100 \leq p_T \leq 200$ GeV to 55% for jets with $p_T > 500$ GeV. We study different $b$-tagging requirements for signal events with simulated gluinos that have heavy-flavour decays and use the same definition of the signal significance as for the sixth-jet $p_T$ optimisation to determine the best choice. The CSV medium operating point, with a mistagging rate of about 1% for light-flavour jets, is found to be the optimal choice for detecting a potential signal in this analysis. The requirement that each event contain at least one $b$-tagged jet ($b$ tag) increases the signal significance, and the additional requirement that all selected triplets have a $b$ tag removes a large portion of the incorrectly combined signal triplets.

For the heavy-flavour analysis, we distinguish between a low-mass region covering gluino masses between 200 and 600 GeV and a high-mass region covering larger gluino masses. For the low-mass region, we maximise signal acceptance by using jet-$p_T$ requirements of $\geq 80$ GeV for the fourth jet and $\geq 60$ GeV for the sixth jet. For the high-mass region, the sixth jet is required to have $p_T \geq 110$ GeV. For both the low- and high-mass regions, the value $\Delta = 110$ GeV is used. All-hadronic $t_\ell$ event production is a significant background in the low-mass region. We use $t_\ell$ events that produce triplets with masses in this region to help validate our analysis technique, as described below.
High-mass signal events, for both the light- and heavy-flavour signal models, have a more spherical shape than background events, which typically contain back-to-back jets and thus have a more linear shape. To significantly reduce the background in the high-mass searches, we use a sphericity variable, where the normalisation of the background component (\(\alpha, \beta\)) is unconstrained, any incorrectly combined signal triplets, if present, would be absorbed into the background estimate. The triplet invariant mass distribution for the background decreases smoothly with increasing mass, and we model this background using a four-parameter function (Eq. (2)) fitted directly to the data, except in the case of the low-mass, heavy-flavour search.

5. Background estimation and signal extraction

The dominant background for this search comes from SM multijet events, which arise from perturbative QCD processes of order \(O(\alpha_s^2)\) and higher. The invariant mass shape of incorrectly combined signal triplets is found to be similar to that of the background from SM multijet processes, such that the combined distribution is consistent with that of SM multijets alone. Moreover, because the normalisation of the background component \((P_0)\) in Eq. (2) is unconstrained, any incorrectly combined signal triplets, if present, would be absorbed into the background estimate. The triplet invariant mass distribution for the background decreases smoothly with increasing mass, and we model this background using a four-parameter function (Eq. (2)) fitted directly to the data, except in the case of the low-mass, heavy-flavour search.

For the low-mass, heavy-flavour search, there is an additional background contribution from all-hadronic \(t\bar{t}\) events. These events are modelled using the MadGraph [27] generator, and the expected number of \(t\bar{t}\) events is determined from the next-to-next-to-leading-order (NNLO) cross section of 245.8 \(\pm 8.7_{\text{theo}}\) pb [28]. The shape of the contribution from SM multijet processes is modelled with a statistically independent data sample, constructed by imposing a veto on b-tagged jets while retaining all other selection requirements. This sample is referred to as the b-jet control region, and the combination of simulated \(t\bar{t}\) events and the background from SM multijet processes, modelled by this control region, gives the total SM background estimate for the low-mass, heavy-flavour analysis.

A comparison of the background estimate to the data is performed, in which the data are fit using a binned maximum likelihood method with either the four-parameter function of Eq. (2) for the inclusive analysis and the high-mass, heavy-flavour analysis, or...
the background shape described above for the low-mass, heavy-flavour analysis. Fig. 4 shows a comparison between the three-jet invariant mass distribution in data and the background estimate for the inclusive analysis. Fig. 5 shows the comparisons between data and background estimates for the low- and high-mass heavy-flavour analyses. In all three cases, no statistically significant deviations from the data are observed.

As a validation of the analysis technique, we consider the $t\bar{t}$ triplets as a signal with the background solely composed of triplets from SM multijet processes, whose shape is modelled by the b-jet control region, with the small amount of simulated $t\bar{t}$ events without b tags subtracted. The $t\bar{t}$ cross section is extracted based on the contribution of its signal triplets and is compared with the theoretical prediction for the cross section of $245^{+8}_{-7}\text{pb}$. The measurement yields a result of $205\pm28\text{pb}$ (combined statistical and systematic uncertainties), which is within less than two standard deviations from the theoretical value, thereby showing our technique can successfully reconstruct hadronically decaying $t\bar{t}$ events.

To obtain an estimate of the number of signal triplets expected after all selection criteria are applied, the sum of a Gaussian function that represents the signal and a four-parameter function (Eq. (2)) that models the incorrectly combined signal triplets is fit to the simulated $M_{jjj}$ distribution for each gluino mass. The Gaussian component of the fit provides the estimate for the expected number of signal triplets. The factors in this overall triplet signal efficiency ($A \times \epsilon$) are both parametrised as functions of gluino mass, as shown in Fig. 6. The width of the Gaussian function modelling the signal varies according to the detector resolution, ranging from 17 to 70 GeV for gluino masses from 200 to 1500 GeV. The $A \times \epsilon$ ranges from about 0.003 to 0.033 for the inclusive search for gluino masses from 400–1500 GeV, and, for the heavy-flavour search, from 0.005 to 0.04 for masses from 200–600 GeV, and from 0.008 to 0.015 for masses from 600–1500 GeV. For high-mass gluinos, the $A \times \epsilon$ flattens slightly because of the decreased efficiency to reconstruct triplets in the Gaussian signal peak.

6. Systematic uncertainties

Systematic uncertainties in the signal acceptance are assigned in the following manner. For uncertainties related to the jet energy scale (JES) [20], the jet energy corrections are varied within their uncertainties for each signal mass, and then the entire selection procedure is repeated to determine the parametrised values of the $A \times \epsilon$. The largest difference from the nominal values is taken as a systematic uncertainty. To evaluate the systematic uncertainty associated with the level of simulated ISR and FSR for signal events, i.e. the spontaneous emission of gluons from incoming or outgoing participants of the hard interaction, dedicated signal samples are generated where the relative amounts of ISR and FSR are coherently increased or decreased with respect to the nominal setting of the Pythia event generator [29]. The parameter controlling the amount of ISR (PARP(67)) is varied around its central value of 2.5 by ±0.5 and that for the FSR (PARP(71)) is varied from 2.5 to 8, with a nominal value of 4.0. For each sample, the rederived $A \times \epsilon$ is compared to the nominal value, and the difference is taken as the systematic uncertainty. Analogously, an uncertainty is assigned to account for the effects of multiple pp
collisions in an event (pileup) by reweighting all MC signal samples such that the distribution of the number of interactions per bunch crossing is shifted, high and low, by one standard deviation compared with that found in data [30]. For the analyses using b tagging, an uncertainty is assigned based on the scale factor that comprises the differences in b-tagging efficiencies in data compared with simulation [26]. The same procedure as outlined above is repeated, where the b-tagging scale factors are varied within their uncertainties, and the effect on $A \times \epsilon$ is evaluated. Uncertainties in the fit parameters of the Gaussian signal are used as an additional systematic uncertainty for each mass point. Finally, an overall systematic uncertainty of 2.6% is assigned to the integrated luminosity measurement [12]. The ranges in the values of these uncertainties are summarised in Table 2. Systematic uncertainties related to the signal and background shapes are discussed in Section 7.

7. Results and limits

The three-jet invariant mass distributions are examined for a Gaussian signal peak on top of the smoothly falling background distribution. As has been described, this analysis uses different selection criteria to search for resonances coupling to light-flavour and to heavy-flavour quarks, with the latter search done separately in low-mass and high-mass regions. In the analysis of each of the three selections, the background normalisation parameter is unconstrained and is therefore determined by the SM multijet component of the combined fit. For the function describing the background, the initial values of its parameters are taken from the background-only hypothesis fit to the data, while they are allowed to float in the background-plus-signal hypothesis fits for the limit calculation. The signal is modelled with Gaussians defined by the width and $A \times \epsilon$ curves shown in Fig. 6. The uncertainties in the expected number of signal triplets are included as log-normal constraints, where the uncertainty for the width of the Gaussian includes a 10% systematic uncertainty to account for jet resolution effects [20]. For the t background estimate, uncertainties in both the shape and normalisation are included. In addition to those already discussed in the previous section, uncertainties due to ambiguities in the parton shower matching procedure between the MadGraph and Pythia event generators, as well as those due to the dependence on the renormalisation and factorisation scale, are taken into account.

Upper limits are placed on the cross section times branching fraction for the production of three-jet resonances. A modified-frequentist approach, using the CLs [31,32] technique and a profile likelihood as the test statistic, is employed. Limits are calculated with the frequentist asymptotic calculator implemented in the RooStats [33,34] package. The full CLs calculations give similar limits within a few percent, and closure tests where a fixed signal is injected yield consistent coverage. The observed and expected 95% confidence level (CL) upper limits on the gluino pair-production cross section times branching fraction as a function of gluino mass are presented in Fig. 7. The solid red lines in the figure show the next-to-leading-order (NLO) plus next-to-leading-logarithm (NLL) cross sections for gluino pair production [35–39], and the dashed red lines indicate the corresponding one-standard-deviation ($\sigma$) uncertainties, which range between 15% and 43%. To quote final results, we use the points where the $-1\sigma$-uncertainty curve for the NLO + NLL cross section crosses the expected and observed-limit curves. We additionally quote the result where the central theoretical curve intersects the limit curves.

The production of gluinos undergoing RPV decays into light-flavour jets is excluded at 95% CL for gluino masses below 650 GeV, with a less conservative exclusion of 670 GeV based upon the theory value at the central scale. The respective expected limits are 755 and 795 GeV. These results extend the limit of 460 GeV [10] obtained with the 7 TeV CMS dataset. Gluinos whose decay includes a heavy-flavour jet are excluded for masses between 200 and 835 GeV, which is the most stringent mass limit to date for this model of RPV gluino decay, with the less conservative exclusion up to 855 GeV from the central theoretical value.

The respective expected limits are 825 and 860 GeV. While a smaller phase space is probed in the heavy-flavour search, the limits extend to higher masses because of the reduction of the background.
include a heavy-flavour jet in their decay have been excluded at 95% CL for masses between 200 and 835 GeV, which is the most stringent limit to date for this model of gluino decay.

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