CMS Physics Analysis Summary

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Search for Multijet Resonances in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration

Abstract

A model-independent search for three-jet hadronic resonance production in pp collisions at a center-of-mass energy of 7 TeV has been conducted by the CMS Collaboration at the LHC, using a data sample corresponding to an integrated luminosity of 35 pb^{-1}. Events with high jet multiplicities and a large scalar sum of jet transverse momenta are analyzed. Good agreement is found between the expected Standard Model QCD background and all selected events, and limits are set on a model used to describe the production of RPV SUSY gluino pairs. These are the most stringent limits set to date on the production of three-jet hadronic resonances and the first limits from pp collisions.

Jet production dominates the overall cross section in high energy proton-proton collisions, offering a rich environment to search for new physics in the form of strongly-coupled heavy resonances. Although multijet final states are experimentally challenging because they do not necessarily contain distinctive features such as leptons or large missing transverse energy to distinguish them from Standard Model (SM) background events, they are central to the phenomenology for many extensions of the SM. Variations of technicolor models, resulting in heavy colored fermions that transform as octets under $SU(3)_{\text{color}}$, have been proposed in a variety of forms [1–4]. Other more recent models incorporate R-parity violating (RPV) decays of supersymmetric gluinos to three-quark final states, where the gluino represents a colored adjoint Majorana fermion [5–7]. In all cases, these heavy quark resonances can be pair-produced, yielding a six-jet final state.

This Letter presents the results of a search for three-jet hadronic resonances using jet ensembles, the first such search in pp collisions. The results are based on a data sample of 35.1 ± 1.4 pb^{-1} [8, 9] of proton-proton collisions at $\sqrt{s} = 7$ TeV collected with the Compact Muon Solenoid (CMS) detector [10] at the CERN Large Hadron Collider (LHC) in the running period from March through November 2010. Events with at least six jets, each with transverse momentum (p_T) greater than 45 GeV/c and absolute pseudorapidity (η) [11] less than 3.0, are selected and investigated for evidence of three-jet resonances consistent with strongly-coupled supersymmetric particle decays. The event selection criteria are optimized in the context of the gluino model mentioned above. However, the generic features of the selection criteria provide a strong model-independent basis that can be applied to many extensions of the SM.

CMS is a multi-purpose detector. Here, we briefly describe the subdetectors most relevant to this analysis. The high resolution pixel and silicon strip systems provide charged tracking coverage for $|\eta| < 2.4$. Together with the 3.8 T magnetic solenoid that encompasses them, they provide transverse track momentum resolution of about 1% for $p_T = 100$ GeV/c and the reconstruction of tracks with momentum as low as 100 MeV/c. Energy deposits of the jets are measured using electromagnetic (ECAL) and hadronic (HCAL) calorimeters. The ECAL is composed of finely segmented crystals with an energy resolution on the order of $3\%/\sqrt{E(\text{GeV})}$. The ECAL covers the barrel region ($|\eta| < 1.4$) with a granularity of $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$ and the endcap region ($1.4 < |\eta| < 3.0$) with a granularity that increases up to 0.05×0.05 for $|\eta| \approx 3.0$. The HCAL is a brass/scintillator sampling calorimeter that covers $|\eta| < 3.0$ with a granularity of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$. The region $3.0 < |\eta| < 5.0$ is instrumented with a forward calorimeter.

Events are recorded using a two-tier trigger system. Objects satisfying the requirements at the first level (L1) are passed to the High Level Trigger (HLT) where the total recorded rate is restricted to ~ 0.5 kHz. The triggers of interest for this analysis are based on the sum of all uncorrected transverse energy from jets (H_T), reconstructed using calorimeter information only. The H_T triggers are used to select recorded events. For the L1 trigger, the effective H_T threshold is 80 GeV. The corresponding threshold for the HLT varies between 100 and 150 GeV depending on the run period.

The CMS particle-flow algorithm [12] uses calorimeter information and combines it with reconstructed tracks to identify individual particles such as photons, leptons, and both neutral and charged hadrons within the jets. The particle-flow objects serve as input for jet reconstruction, performed using the anti-k_T algorithm [13] with a cone radius 0.5.

Jet energy-scale corrections derived from Monte Carlo (MC) simulation [14] are applied to account for the non-linear and non-uniform response of the calorimeter. In data, a small residual correction factor is used to correct for differences in jet response between data and simulation.

Uncertainties corresponding to the entire suite of corrections range from 3 to 5%, depending on the measured jet's pseudorapidity and uncorrected energy. Jet quality criteria are applied to both data and simulation to remove particles mis-identified as jets. For simulated signal events, more than 99.9% of all selected jets satisfy these criteria.

To optimize the event selection, the pair-production of gluinos, where each gluino decays to three jets through the uds RPV coupling, is used to model the signal. Gluino production and decay are simulated using the PYTHIA [15] MC program. The gluino mass is varied between 200 and 500 GeV/c^2 in 50 GeV/c^2 steps. The leading order cross section from PYTHIA is 325 pb for a gluino mass of 200 GeV/c^2, falling to $\sim$1 pb for a gluino mass of 500 GeV/c^2. For the generation of this signal all superpartners except the gluino are taken to be decoupled [5]. The next-to-leading order (NLO) correction factors (k-factors), with values ranging from 1.7 to 2.2, are calculated with the PROSPINO [16] program and are applied to the leading order cross sections. Simulation of the CMS detector is performed using GEANT4 [17].

Events in data are pre-selected using the lowest unprescaled H_T trigger. The selected events are required to contain at least one primary vertex, constructed from at least five tracks with small impact parameters. The vertex must lie within 24 cm of the geometric center of the detector along the direction of the beam axis, and within 2 cm in the direction perpendicular to this axis.

Pair-produced three-jet resonances naturally yield events with high jet multiplicities and large transverse energy. Thus, we require there to be at least six jets in the event whose total scalar sum of jet p_T is at least 425 GeV/c. The latter requirement ensures a 100% trigger efficiency in these events. Jets are required to have $p_T > 45$ GeV/c and $|\eta| < 3.0$, which also minimizes effects from multiple interactions.

The leading six jets in p_T are associated into triplet combinations such that each unique combination of jets is represented, resulting in 20 combinations of jet triplets. For signal events, each of the pair-produced gluinos corresponds to one of these 20 jet triplets, assuming an optimistic scenario in which all six jets come solely from these particles' decay, leaving 18 jet triplets as additional background. Thus, the overall background arises not only from SM events, described by quantum chromodynamics (QCD), but also from uncorrelated triplets in signal events themselves. It is necessary then to make additional requirements on each triplet to increase the signal sensitivity. The invariant mass of background triplets scales with the respective scalar sum of jet p_T, while for signal triplets the mass is constant. To reduce background, we therefore require each jet triplet to satisfy the following relation:

$$M_{jjj} < \sum_{i=1}^{3} |p_T^{\text{jet}}|_i - \Delta, \qquad (1)$$

where M_{jjj} is the triplet invariant mass, $\sum_{i=1}^{3} |p_T^{\text{jet}}|_i$ the scalar sum p_T of the jets in the triplet, and Δ an offset adjusted to optimize signal sensitivity. All triplets in the event that satisfy this requirement are included in the M_{jjj} distribution, which is sensitive to the presence of three-jet resonances. The value of Δ is determined by maximizing the ratio of the number of signal triplets to the sum of the number of signal plus background triplets in a $\pm 1\sigma$ window around the center of the gluino mass peak. The value of Δ is taken as 130 GeV/c^2 for all gluino masses considered.

Even after the final selection, background remains from both QCD multijet events and uncorrelated triplets in signal events. The latter only contribute minimally, and the shape of their distribution is found to be consistent with that of the dominant background, from QCD multijet events. These QCD multijet events arise from hard dijet interactions combined with initialand final-state radiation in the form of gluon jets. Because the underlying kinematical distributions are fundamentally the same among events with high jet multiplicity (N_{jet}), we use a rescaled mass distribution of triplets in events with $N_{\text{jet}} = 4$ to estimate the shape of the background. Specifically, we select events with $N_{\text{jet}} = 4$ that satisfy all other selection criteria, form jet triplets, and require each to pass Eqn. 1. The M_{jjj} distribution of these triplets is multiplied by the ratio of the average triplet scalar p_T in data for the $N_{\text{jet}} \geq 6$ to the $N_{\text{jet}} = 4$ region, to account for expected minor kinematical differences between the two regions. The resulting M_{jjj} distribution is then parameterized with a background function, which we choose to be an exponential distribution [18]. The parameters of the background function in the $N_{\text{jet}} \geq 6$ region are constrained to equal those found for the scaled sideband distribution to within their uncertainties, aside from an overall normalization constant. As a cross-check, we apply this sideband procedure to predict the shape of the M_{jjj} distribution for an $N_{\text{jet}} = 5$ sample, where QCD background is also expected to dominate, and find good agreement.

To verify that the choice of the background model does not bias the derived limit, the exponential function is tested on a $N_{\text{jet}} \geq 6$ control region, defined by the standard selection criteria except without the constraint of Eqn. 1. The exponential function is found to have good agreement with the data in the fitted region, corresponding to $M_{jjj} > 350$ GeV/c^2. Its fit to the control region is shown in Fig. 1.

To estimate the number of signal events expected after all selection criteria are applied, the simulated M_{jjj} distribution for each gluino mass is fit to the sum of a Gaussian function that represents the signal and the exponential function that models the background. The fitted range is $170 < M_{jjj} < 800$ GeV/c^2. The integral of the Gaussian component provides the estimate for the expected number of signal triplets produced, and the value of this integral is used to determine the acceptance for each gluino mass. The acceptance is parameterized using a second degree polynomial as a function of gluino mass and ranges from 0.4 to 5%.

We evaluate a systematic uncertainty on the event acceptance as follows. An uncertainty related to the jet energy scale is evaluated by varying each jet's energy correction factor within its uncertainties, applying it to the jet's uncorrected energy, and then re-evaluating 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 7% to 16%. A similar procedure is used to quantify the uncertainty related to initial- and final-state radiation. The difference of 2% to 4% with respect to the nominal acceptance is taken as the systematic uncertainty. To determine the effects of multiple interactions on the signal acceptance, signal samples are generated with the number of interactions per crossing in the simulation set to the average of their distribution in the data. Applying the acceptance calculation on this sample leads to differences of 1% to 6% compared to the nominal fit, which is taken as the uncertainty. These contributions, combined with those from the luminosity measurement (4%) and choice of parton distribution function set (4%), yield a total systematic uncertainty on the signal acceptance between 10 and 19%, depending on the value of the gluino mass.

Figure 2 shows the three-jet invariant mass distribution for the $N_{\text{jet}} \geq 6$ region with all selection criteria applied, with the background exponential shape super-imposed. The simulated signal distribution for a gluino mass of 250 GeV/c^2, normalized to the luminosity of the data, is also shown. To quantify the agreement observed between the data and expected QCD background, a limit-setting procedure is performed.

Upper limits are placed on the cross section for the production of three-jet resonances in the

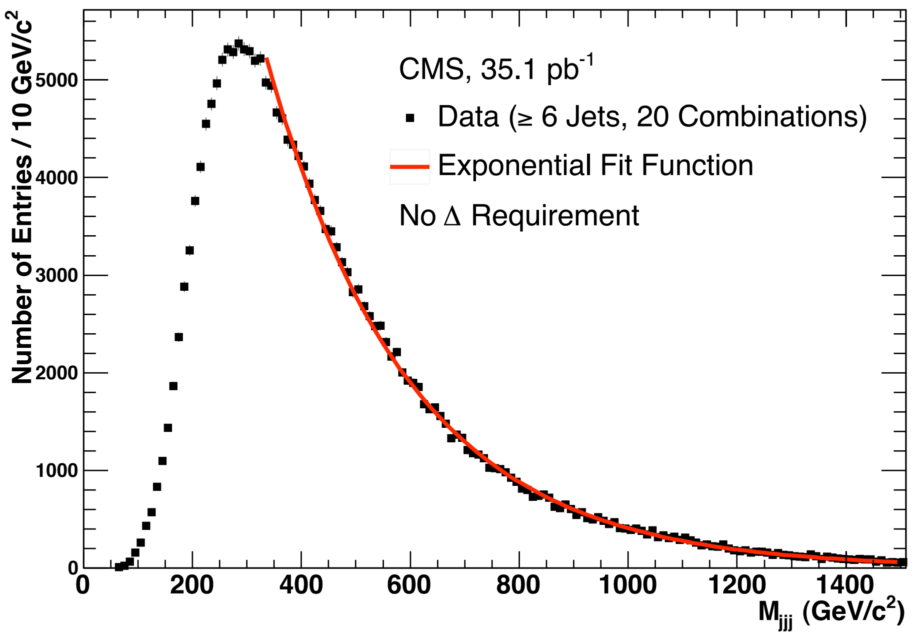

Figure 1: Three-jet invariant mass distribution for the $N_{\text{jet}} \geq 6$ data for the control region, without the requirement from Eqn. 1 applied.

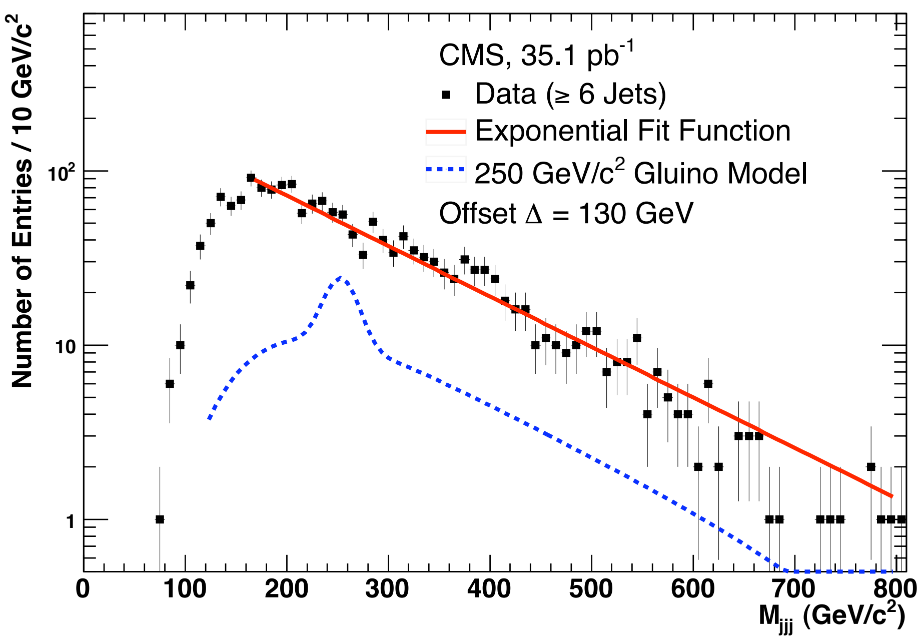

Figure 2: Three-jet invariant mass distribution for the $N_{\text{jet}} \geq 6$ data of triplets passing all selection criteria. The 250 GeV$/c^2$ gluino mass distribution, normalized to the data luminosity, is also shown.

$N_{\text{jet}} \geq 6$ region using a Bayesian technique. The binned likelihood L is defined as

$$L = \prod_i \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!},$$

where n_i is the measured number of events in the i-th bin and μ_i is the expected value. The quantity μ_i can be expressed as $\mu_i = \mu_S + \mu_B$, where μ_S and μ_B are the expected signal and background yields, respectively. The number of signal events is defined as $\mu_S = \sigma_S \cdot BR \cdot \mathcal{L} \cdot A$, where BR is the branching ratio to the uds quark final-state, $\mathcal{L}$ the integrated luminosity and A the signal acceptance. The parameter of interest is the cross section σ_S, which is given a uniform prior for values above zero.

The background model parameters and their corresponding uncertainties are taken from the constrained fit of the exponential function to the $N_{\text{jet}} \geq 6$ distribution with all selection criteria applied. Each uncertainty on the two parameters that describe the background shape, namely the exponential slope and normalization, is included as a Gaussian prior. The central value corresponds to the best fit value, with a width corresponding to one standard deviation, and a range truncated to be within $\pm 3\sigma$. Each prior π can be written as

$$\pi(P) \sim \exp\left[-\frac{(P - P_0)^2}{2 \cdot (f_P \cdot P_0)^2}\right],$$

where P_0 is the central value and f_P is the fractional uncertainty. In addition to the background parameters, priors are included for the acceptance and luminosity.

The signal is modeled by a Gaussian whose width is allowed to freely float in a range defined for each tested mass, based on detector resolution. For gluinos of mass from 200 to 500 GeV$/c^2$, this corresponds to widths from 10 to 25 GeV$/c^2$. The signal width, luminosity, acceptance, and the two parameters of the exponential background distribution are all treated as nuisance parameters. The likelihood is combined with the prior and nuisance parameters, and then marginalized to give the posterior density for σ_S. Integrating the posterior density to 0.95 of the total gives the 95% confidence level (C.L.) limit for σ_S. Marginalization and integration of the posterior density are performed using the RooStats MCMCCalculator [19].

To determine the expected limits, a large set of pseudo-experiments (PEs) is generated using the background-only model. For every PE, each of the two parameters associated with the exponential is varied by generating a random number distributed according to a Gaussian probability distribution function centered at the central value, with a width corresponding to its associated uncertainty. The total number of events in a given PE is distributed according to the Poisson distribution given the number events seen in data in the fitted range. The same upper limit calculation performed on data is repeated for each PE at each mass, and the median of the upper limit distribution for all PEs is the expected limit.

The expected and observed limits as a function of mass are presented in Table 1 and in Fig. 3. The 95% C.L. upper limit on gluino pair-production is set to the value at which the 95% C.L. limit line crosses that of the NLO gluino cross section. These results can been seen in Fig. 3. From comparison with NLO production cross sections, we set a 95% C.L. upper limit on gluino pair-production corresponding to a gluino of mass of 280 GeV$/c^2$, with an expected limit of 270 GeV$/c^2$. The most significant excess, corresponding to a significance of 1.9 standard deviations, occurs for a mass around 390 GeV$/c^2$, incorporating factors such as the look-elsewhere effect [20].

In summary, a search for three-jet hadronic resonance production in pp collisions at a center-of-mass energy of 7 TeV has been conducted by the CMS Collaboration, using a data sample

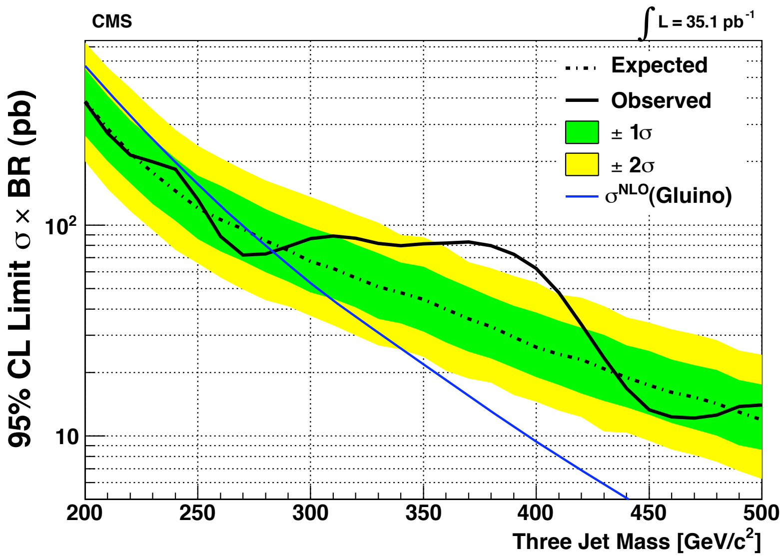

Figure 3: Expected and observed cross section limits at 95% C.L for gluino-pair production through RPV decays. Also shown are the $\pm 1\sigma$ and $\pm 2\sigma$ bands on the expected limit, as well as the theoretical cross section for gluino production.

M_{jjj}	Expected (pb)	Observed (pb)	M_{jjj}	Expected (pb)	Observed (pb)
200	387	383	360	40	82
210	287	273	370	36	83
220	219	214	380	33	80
230	178	200	390	29	73
240	146	184	400	26	62
250	120	132	410	24	48
260	106	88	420	23	34
270	96	72	430	21	24
280	84	73	440	19	17
290	76	79	450	17	13
300	67	86	460	16	12
310	62	89	470	15	12
320	56	87	480	14	13
330	51	82	490	13	14
340	48	80	500	12	14
350	45	82			

Table 1: Expected and observed 95% C.L. limits for gluino masses ranging from 200 to 500 GeV/c^2.

corresponding to an integrated luminosity of 35 pb^{-1}. Events with high jet multiplicities and large scalar sum of all jet p_T, expected signatures for hadronic resonances, are analyzed for the presence of signal events. The approach used is model-independent, but with event selection criteria optimized and acceptance calculated using the RPV SUSY model with gluino pair-production and decay into a six-jet final state. Good agreement is found between the data and the expected QCD background, and the production of gluinos decaying through the uds RPV coupling is excluded for masses between 200 and 280 GeV/c^2 at 95% C.L. These limits are complementary to recent results from the Tevatron, which exhibit sensitivity to gluinos of much lower mass [21]. The limits from this search are the highest on gluino production in the RPV scenario to date, and represent the first limits from pp collisions.

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