SUSY searches in the context of R-parity violation with CMS data

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Several searches for supersymmetric particles are presented using data collected by the CMS experiment during Run 2 of the LHC. With rather stringent limits placed on R-parity conserving models, we explore three different scenarios where R-parity is not conserved. In these cases the lightest supersymmetric particle is not required to be stable, and can decay exclusively into known standard model particles. Different coupling scenarios and coupling strengths are possible, however, the focus here lies on prompt hadronic R-parity violating decays.

1 Introduction

Despite the huge success of the standard model (SM) of particle physics, proven to withstand several decades of ever more precise measurements, there are still unanswered questions that encourage the presence of physics beyond the standard model (BSM). One of these scenarios is supersymmetry (SUSY), where each SM particle has a supersymmetric partner that differs in spin from its SM counterpart. Both ATLAS and CMS Collaborations have extensive search programs to find these new, up to now elusive particles. One cornerstone of these searches is the presence of a lightest supersymmetric particle (LSP) that typically escapes detection. A quantum number is introduced that distinguishes SM from SUSY particles, so called R-parity with $R = (-1)^{3B+L+2s}$, where B is the baryon number, L the lepton number, and s the spin of the particle. If R-parity is a conserved quantity then SUSY particles are produced in pairs and each decay chain ends with the LSP, which is stable and escapes detection. However, if R-parity is not conserved, several new possibilities for LSP decays open up. In these proceedings we will focus on hadronic RPV decays, where the SUSY particles exclusively decay into quarks. The data were collected by the CMS experiment [1] during Run 2 of the LHC at $\sqrt{s} = 13$ TeV and integrated luminosities of the analyzed data range from 2.6 fb^{-1} to 38.2 fb^{-1}.

2 Search for high mass gluinos

Under the assumption of minimal flavor violation (MFV) the flavor structure of the new physics scenario follows the one already realized in the SM. In this specific model the coupling to third

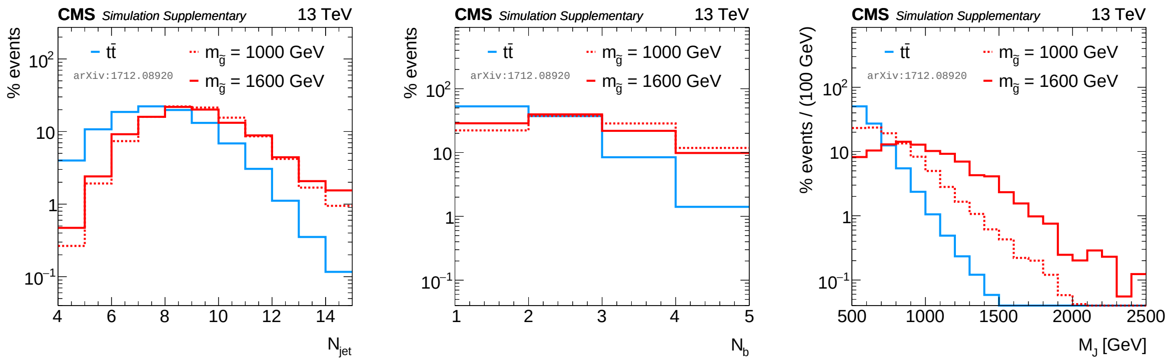

Figure 1 – High mass gluino search [2]: The figure shows the normalized distributions of the $\tilde{g} \rightarrow$ tbs signal for gluino masses of $\tilde{g}$ = 1600 GeV and 1000 GeV in comparison with the main SM background of $t\bar{t}$+jets production.

generation quarks, i.e., top and bottom quarks, would be enhanced. Specifically, in this search [2] we consider gluino ($\tilde{g}$) pair production where each of the gluinos decays through an intermediate mass-decoupled top squark to a top, a bottom, and a strange quark, i.e., $\tilde{g} \rightarrow$ tbs. This striking final state contains many jets, b jets, but little to no missing transverse momentum. For this search the semileptonic decay of the $t\bar{t}$ system is used, which reduces the background from QCD multijet production significantly. Events are selected if they contain exactly one isolated lepton (e or μ) with $p_T > 20$ GeV, at least 4 jets clustered with a distance parameter R = 0.4 with p_T > 30 GeV, whose scalar sum H_T is above 1200 GeV. For events satisfying these criteria, all jets and the lepton are clustered into "large" radius jets using the anti-k_T clustering algorithm with a distance parameter of R = 1.2. The sum of the masses of these large R jets M_J is then used to further separate the new physics signal from the main background of $t\bar{t}$+jets production by requiring a minimum M_J threshold of 500 GeV. Given the nature of the signal, we expect an excess of events with many jets and b jets. The N_{jet} and N_b distributions can be seen in the first two plots in Figure 1. Jets originating from the fragmentation of b quarks are identified with the combined secondary vertex algorithm in CMS, using secondary vertex as well as track-based information. With this signal topology in mind, events are categorized into different exclusive regions of jet multiplicity N_{jet} and M_J. An examples of the M_J distribution is shown in Figure 1 as well. A binned maximum likelihood fit to the N_b distribution is carried out in each category to identify a potential excess at high N_b. Event categories with lower number of jets, low M_J, or low N_b act as control regions to constrain the main SM backgrounds. Figure 2 shows one of these fit results, accompanied by the data distribution in one of the most sensitive search regions. We observe good agreement between the SM prediction and the data, and proceed to set limits on this new physics scenario for different gluino masses. This is shown in the right-hand plot in Figure 2, where the expected and observed 95% confidence level (CL) limits on the pair production cross section for this RPV gluino model are given. Masses between 1 TeV and 1.6 TeV are excluded in this analysis.

3 Search for pair-produced dijet resonances - low mass top squarks

In order for SUSY to solve known issues of the SM, such as the stabilization of the Higgs mass at 125 GeV, the expectation is that SUSY particles should not be too heavy. In particular the partner of the top quark, the top squark ($\tilde{t}$), is expected to be relatively light. Recent searches for these particles, however, yield exclusions up to about 1 TeV. If we assume R-parity violating decays, where each top squark decays into two SM quarks, light top squarks with masses of 80 to 240 GeV could still be hiding in the data behind copious amounts of QCD multijet background. Especially for low masses, these new particles could be highly boosted, which is the target of the search discussed in this section [3]. Under the assumption of a boosted final state, events are

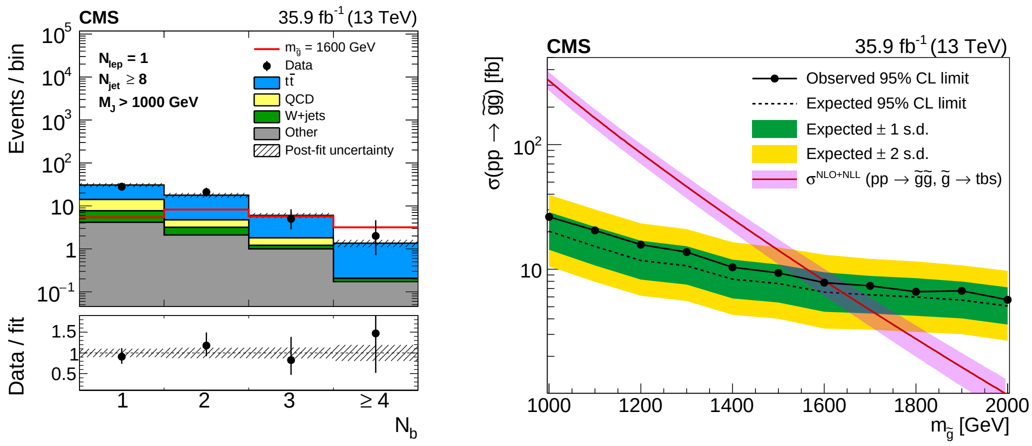

Figure 2 – High mass gluino search[2]: The left figure shows the post-fit N_b distributions in one of the most sensitive search regions. The figure on the right shows the expected (black dashed line with $\pm$ 1 and 2 σ uncertainty bands in green and yellow) and observed limit on the gluino pair production cross section as a function of the gluino mass. For this scenario we exclude masses between 1 TeV and 1.6 TeV.

selected if they contain two jets with a cone size of R = 0.8 and a p_T of at least 150 GeV in a data set corresponding to 2.7 fb^{-1}. The sum of the p_T of all of these jets has to be greater than 900 GeV in order to pass the trigger threshold and be collected by the CMS experiment. At the event level further topological selection criteria are applied to the $\Delta\eta(j_1, j_2)$ between the two leading jets and the mass asymmetry $M_{asym} = |M_{j_1} - M_{j_2}|/(M_{j_1} + M_{j_2})$. The normalized distribution for two signal scenarios of $m_{\tilde{t}} = 80$ GeV (red) and $m_{\tilde{t}} = 170$ GeV (pink) and the main QCD multijet background (in blue) are shown in the top two plots of Figure 3. Events are selected where $\Delta\eta(j_1, j_2) < 1.5$ and $M_{asym} < 0.1$. Additionally, we expect each jet to exhibit a two prong substructure. The n-subjettines variable τ_{21} is used to select jets that are likely to contain a two prong decay, as can be seen in the bottom plot of Figure 3, where the signal peaks at lower values of τ_{21}, when compared to QCD multijet events. The leading and subleading jets have to satisfy $\tau_{21} < 0.45$. After these selections the analysis is carried out as a so-called "bump hunt" by searching for a localized excess of events in the average jet mass spectrum of the dijet events. A potential new physics signal would be visible as a peak structure around the respective top squark mass. The final average mass spectrum is shown in the left-hand plot of Figure 4. The main background of QCD multijet production shown in blue is estimated using an ABCD approach, where orthogonal (BCD) regions are defined by inverting the selections on $\Delta\eta(j_1, j_2)$ and M_{asym}, which are uncorrelated variables for this background. A binned maximum likelihood fit is performed using this QCD estimate and additional but minor background contributions (such as $t\bar{t}$+jets and W+jets events) are taken from simulation. As can be seen in the ratio panel of the left-hand plot in Figure 4, we observed good agreement between the SM background and the data. Limits can be set at the 95% CL on the production cross section of RPV top squarks decaying into two quarks, as shown in the right-hand plot of the same figure. Here RPV top squarks with masses between 80 and 240 GeV are excluded. The sensitivity decreases significantly above a mass of 250 GeV due to the fact that these particles are less boosted and therefore less likely to be clustered into one of the R = 0.8 jets.

4 Search for light pair-produced resonances decaying into at least four quarks - low mass squarks and gluinos

Another possible way that light SUSY particles could be hiding behind large amounts of background is, if their decays involve intermediate sparticles, leading to many light flavor quarks in the final state. Two of these types of scenarios are considered for the search discussed in

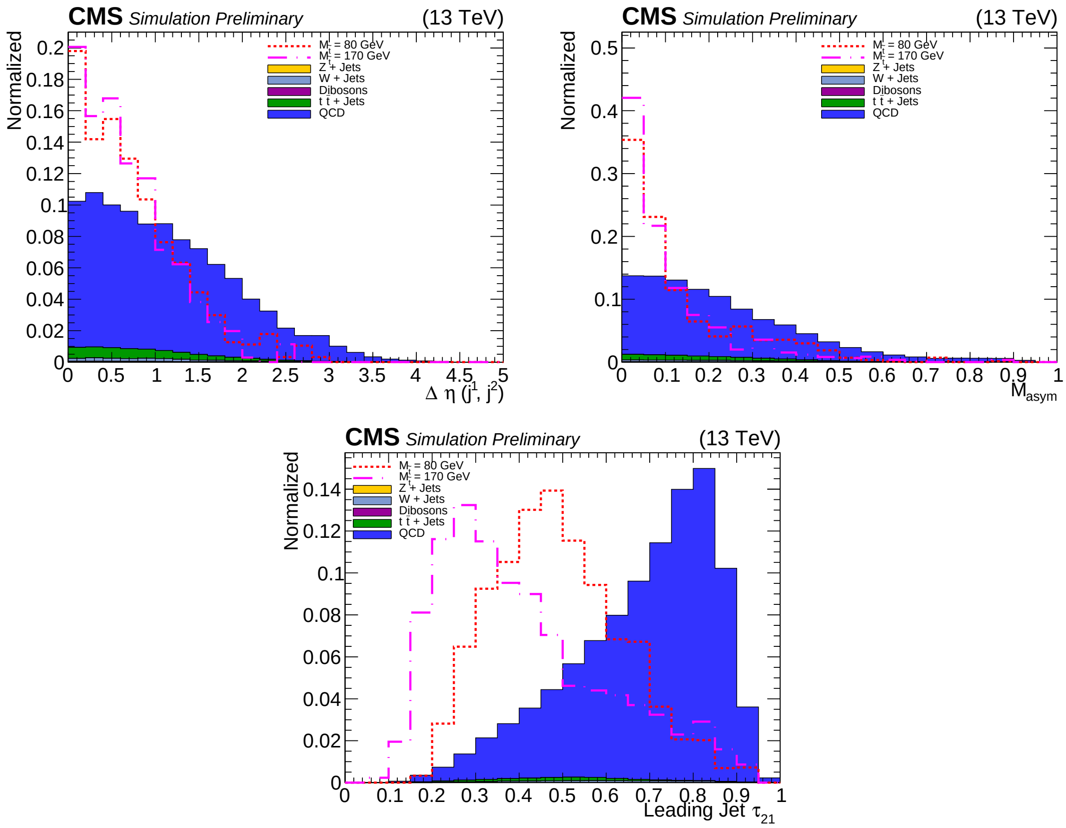

Figure 3 – Low mass top squark search [3]: The figures show the normalized distributions of the main SM backgrounds from QCD multijet events (blue solid histograms) and two signal scenarios with masses of 80 GeV (red, dotted) and 170 GeV (pink, dash-dotted). The plots show from left to right: the $\Delta\eta$ between the two leading jets, the mass asymmetry M_{asym}, and the τ_{21} variable for the leading jet in the event.

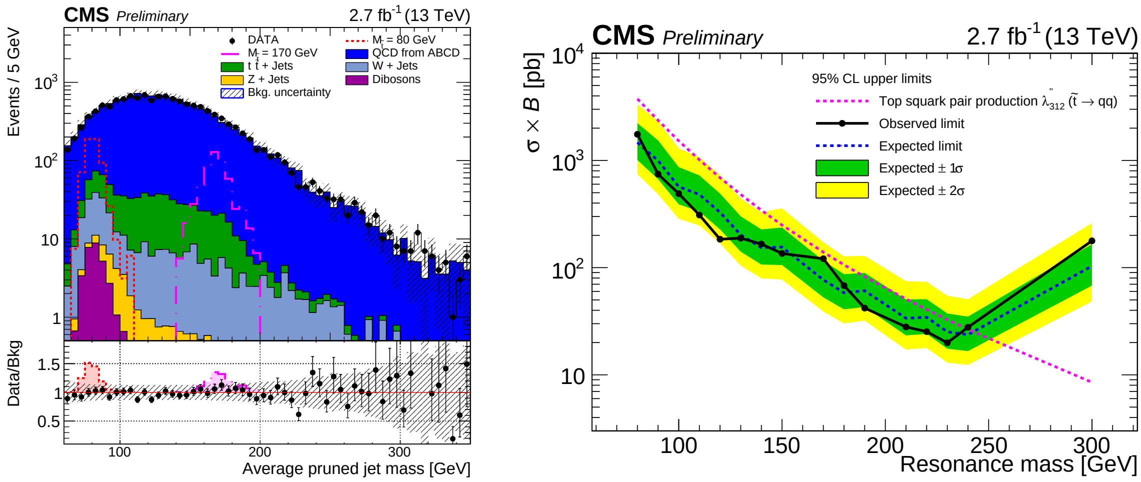

Figure 4 – Low mass top squark search [3]: The left figure shows the final average mass distribution with the main backgrounds depicted by the solid histograms and the data in black. Two signal models with masses of 80 GeV (red, dotted) and 170 GeV (pink, dash-dotted) are shown as well, which would be visible as a peak structure on top of the SM background. The right-hand plot shows the 95% CL expected and observed exclusion limits on the top squark pair production cross section, where each top squark decays to two light flavor quarks. Masses between 80 and 240 GeV can be excluded for this final state.

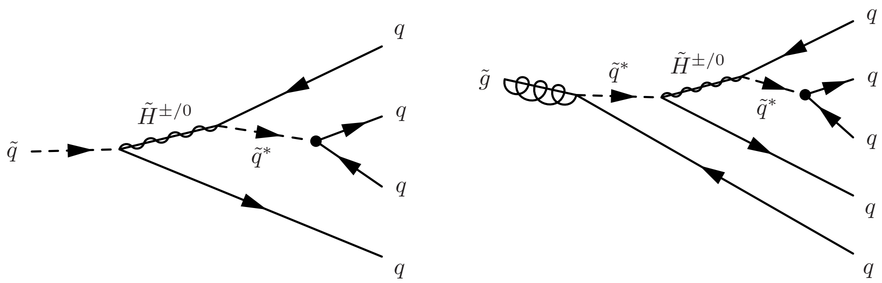

Figure 5 – Low mass squark and gluino search [4]: The figure shows the decay diagrams for squarks (left, 4-jet resonance), where the squark decays into a SM quark and a higgsino, which subsequently decays into three quarks. An additional quark is present in the decay of gluinos (right, 5-jet resonance), followed by the same squark decay as shown on the left.

this section. Figure 5 shows the diagrams of either a squark decaying through an intermediate higgsino into four light-flavor quarks, or on the right-hand side, a gluino decaying into five light-flavor quarks. If the parent particles are light, they could be boosted and the final state quarks could be very close together such that high multiplicity searches would not be sensitive. This particular final state scenario is explored for the first time with CMS data [4]. Events are selected if they contain at at least two jets with R = 1.2 and $p_T > 400$ GeV. The data set corresponds to 38.2 fb^{-1} collected during the 2015 and 2016 runs of the LHC. Similar to the search discussed in the previous section, the two leading jets are required to have $\Delta\eta(j_1, j_2) < 1.0$ and $M_{asym} < 0.1$. The substructure variables τ_{42} and τ_{43} are used to reduce backgrounds from QCD multijet (4-prong decay versus 2-prong decay) events and hadronically decaying top quarks (4-prong decay versus 3-prong decay), respectively. For the final search region, the leading and subleading jets are required to satisfy $\tau_{42} \leq 0.50$ and $\tau_{43} \leq 0.80$. After these selections are applied, we are inspecting the average mass distribution of the two jets for localized deviations that would appear if a hadronically decaying particle would be reconstructed. The main SM backgrounds in this search are QCD multijet production and all-hadronic $\mathrm{t\bar{t}}$ events. The QCD multijet mass template is generated entirely from data by first selecting events where at least one jet satisfies the substructure criteria. The distribution of the masses of selected jets are treated as a probability distribution $P(m)$ from which two jets are sampled, taking into account the constraints on $\Delta\eta(j_1, j_2)$ and M_{asym}, to form an average mass distribution:

$$P_{avg}(\bar{m}) = \int_0^{2\bar{m}} P(x) \cdot P(2\bar{m} - x) \cdot \theta\left(0.1 - \left|\frac{x - \bar{m}}{\bar{m}}\right|\right) dx, \tag{1}$$

where θ is the Heaviside function that imposes the mass asymmetry requirement. For this procedure, corrections for the p_T and mass dependence of the jets are taken into account in order to reproduce the sum p_T spectrum (H_T) of the jets in data. The contribution from $\mathrm{t\bar{t}}$ events is estimated from simulation and both background components are validated in dedicated validation regions. Each of the templates is assigned three parameters for the overall normalization, the mean, and the stretch. The two validation regions in the corresponding template fits are shown in Figure 6, on the left for a QCD enriched region and on the right for a $\mathrm{t\bar{t}}$ enriched region. With the background templates validated we move to the fit of the average mass distribution in the signal region, which is shown in the top plot of Figure 7. Two potential signals for a squark mass of 100 and 500 GeV are shown as well. The SM background prediction agrees well with the observed data, and we proceed to set limits on the pair production cross section of squarks (bottom, left plot) and gluinos (bottom, right plot), respectively. Masses between 100 and 700 GeV are excluded for the squark scenario, while masses between 100 GeV and at least 1 TeV are excluded for the gluino case.

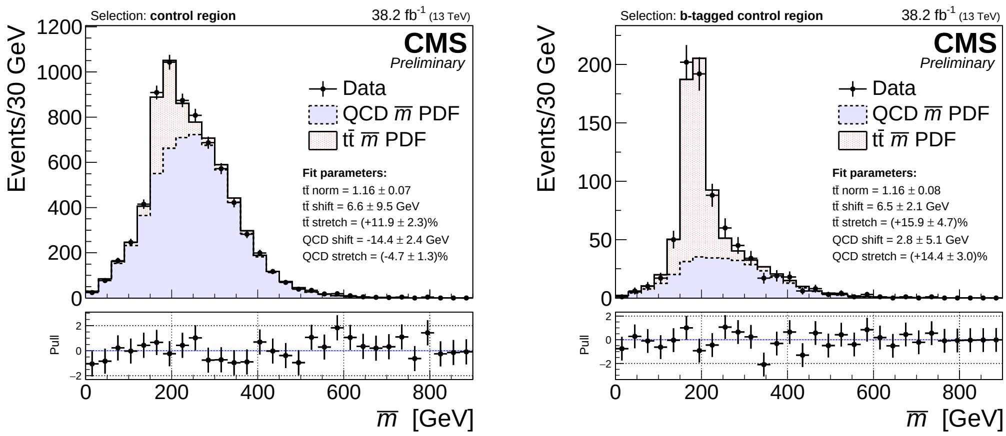

Figure 6 – Low mass squark and gluino search [4]: The figure shows the average mass distributions in the validation regions for a selection that enhances the contribution of QCD multijet events (left) or $t\bar{t}$ events (right).

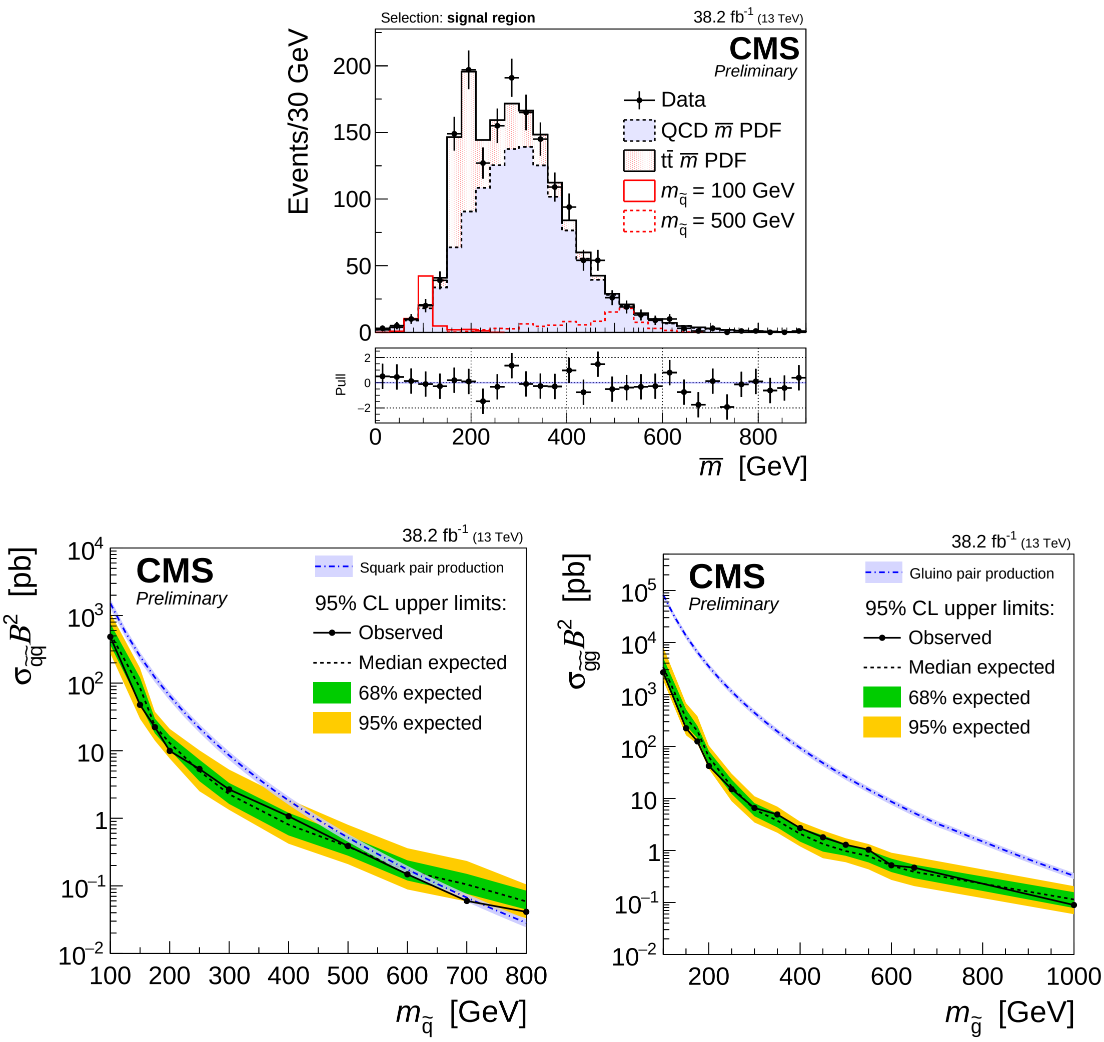

Figure 7 – Low mass squark and gluino search [4]: The left-hand plot shows the final average mass distribution in the signal region and the post-fit SM background shapes. Two signal points are shown as well, that would be visible as localized deviations from the SM background at the respective mass. The middle and right-hand plots show the 95% CL expected and observed limits as a function of mass for either squark pair production (middle) or gluino pair production (right) models.

5 Summary

We have discussed several searches for hadronic RPV scenarios conducted by the CMS experiment with data collected at 13 TeV during Run 2 of the LHC. Overall good agreement is observed between the SM predictions and the observed data for several different possible new physics scenarios, and limits are placed on the respective physics model cross sections. The discussed searches consider high mass scenarios, where the new physics signal would manifest itself at scales between 1 and 2 TeV, but also emphasize the importance of covering possible low mass scenarios that have been previously unexplored. New data driven techniques are employed in order to estimate the copious QCD multijet background that often arises in these kind of searches for hadronic RPV scenarios. Pair produced gluinos decaying to a top, bottom, and strange quark are excluded between 1 TeV and 1.6 TeV. The limits for pair produced top squarks decaying into two light flavor quarks range from 80 GeV to 240 GeV. Low mass squarks and gluinos with cascade decays to either four or five light flavor quarks are excluded between 100 GeV and 700 GeV, or at least 1 TeV, respectively.

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