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SEARCHES FOR SUPERSYMMETRY WITH THE CMS DETECTOR AT THE LHC*

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Results of the 2015 early searches for supersymmetric particles obtained by the CMS experiment with 13 TeV data are reviewed. With an integrated luminosity of 2.2 fb^{-1}, limits on the gluino mass have been lifted up to higher values with respect to previous limits from 19.5 fb^{-1} of 8 TeV data.

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1. Introduction

In 2015, the CMS [1] experiment has performed new searches for particles predicted by the supersymmetry (SUSY) [2], which is an interesting extension of the Standard Model. In general, the supersymmetry is in agreement with low-mass Higgs boson [3] and by foreseeing a stable lightest supersymmetric particle can provide a dark matter candidate. The phenomenology of supersymmetric theories is diverse, therefore the CMS experiment planned a broad range of generic searches, which have been performed in the LHC Run 1 at proton–proton collisions at the centre-of-mass energy of 8 TeV. In Run 1, any sign of supersymmetric particles has not been found. Therefore, the early searches of Run 2 were focused on processes, for which the production cross section has the largest increase for the collision's energy growth from 8 TeV to 13 TeV. Following the precise calculations, the gluino pair production is enhanced at 13 TeV as shown in Fig. 1. The main signature of the gluino production is an event with many hard jets from the hadronic decay of gluinos and a genuine missing transverse energy (MET) coming form neutralinos, which are assumed to be the lightest supersymmetric particles (LSP).

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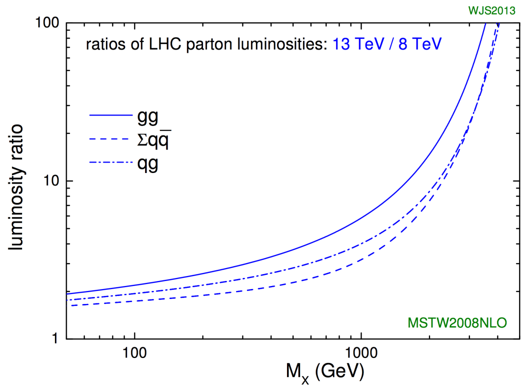

Fig. 1. The LHC luminosity ratios for energy increase from 8 TeV to 13 TeV as a function of supersymmetric particle mass. The figure is taken from [4].

In the context of the Simplified Model Spectra [5], it is assumed that gluinos decay with a 100% branching fraction to an LSP and a quark and anti-quark pair. In early Run 2 searches, three general final states of the three-body gluino decays are analysed as plotted in Fig. 2. In the topology T1qqqq ($\widetilde{g} \rightarrow q\bar{q}\,\widetilde{\chi}_1^0$), a small number of b-tagged jets is expected. The high number of b-tagged jets characterizes the signature of T1bbbb ($\widetilde{g} \rightarrow b\bar{b}\,\widetilde{\chi}_1^0$), whereas many non-$b$-tagged as well as b-tagged jets are expected for the T1tttt final state ($\widetilde{g} \rightarrow t\bar{t}\,\widetilde{\chi}_1^0$). Following the above characteristic, analyses increase their sensitivity by searches in bins of total numbers of jets and b-tagged jets, and discriminant variables such as HT, MHT, the razor variables, and alphaT, which will be described later. Searches for gluino are performed by the CMS in fully-hadronic, single-lepton, and di-lepton channels. In this article, a representative set of new results of theses searches with an integrated luminosity of 2.2 fb^{-1} 13 TeV data will be reviewed.

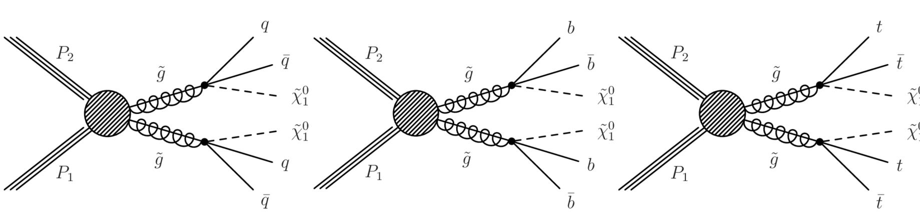

Fig. 2. Diagrams of gluino pair production in the proton–proton collisions with light or heavy quarks in the final state named as T1qqqq for light quarks (left), T1bbbb for bottom quarks (middle), T1tttt for top quarks (right).

2. Search for supersymmetry with HT and MHT variables

Assuming the largest potential cross section of the gluino pair production, which decay into four or more hadronic jets, it is expected that supersymmetric events have large jets multiplicity. It results in the large value of HT (H_{T}) variable, which is the scalar sum of the transverse momentum values (p_{T}) of jets in the event, and which can be used as a discriminant variable in the search, together with the MHT ($H_{\mathrm{T}}^{\mathrm{miss}}$) observable used to measure the missing transverse energy (MET) from the magnitude of the vector sum of the jet transverse momenta.

The CMS analysis [6] is sensitive to wide range of SUSY scenarios thanks to searches in subsamples of data defined by four observables: MHT, HT and numbers of jets N_{jet} and b-tagged jets $N_{b-\mathrm{jet}}$. Exclusive intervals of MHT and HT variables are illustrated schematically in Fig. 3 (left). Each of them is examined in three N_{jet} bins and four $N_{b-\mathrm{jet}}$ bins for a total of 72 search regions, where N_{jet} : 4–6, 7–8, ≥9; $N_{b-\mathrm{jet}}$: 0, 1, 2, ≥3.

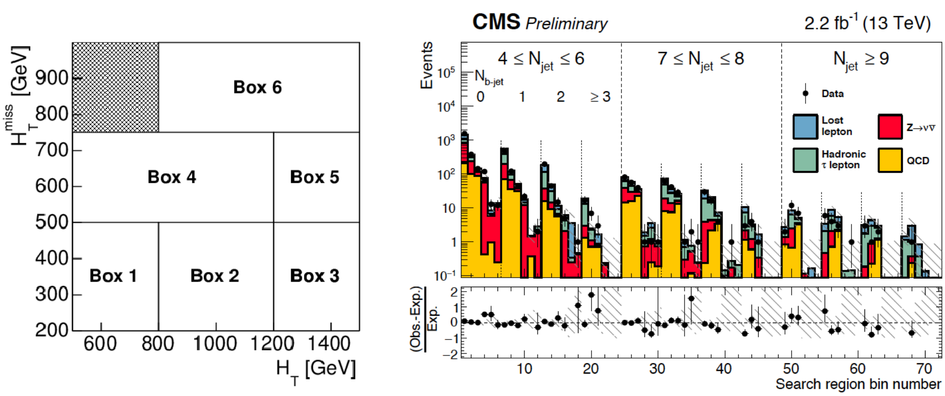

Fig. 3. Schematic illustration of the search intervals in the MHT *versus* HT plane (left). Observed numbers of events and corresponding SM background predictions in all search regions of the analysis with fractional differences are shown in the lower panel. The hatched regions indicate the total uncertainties in the background predictions (right). The plots are taken from [6].

The main sources of background come from the SM production of top quarks produced in pairs or form single-top quark processes, W or Z bosons in association with jets, where neutralino in the final state gives rise to the MET measurement. An important irreducible background is generated by multiple jets produced through the strong interaction (quantum chromodynamics (QCD) multijet production), where the large MET has a source in mismeasurement of the jet transverse momentum. The data-driven methods are used to evaluate the SM contributions. A single-lepton (single-muon) control sample is used to estimate the lost-lepton (hadronically decaying τ lepton) background from top and W+jets backgrounds. Invisible decays of Z boson are determined from γ+jets and $Z \to \mu\mu$ events. In the baseline selection, at least 4 jets with $p_{\mathrm{T}} > 30$ GeV are required. The QCD background is suppressed by targeting under-measured jets using $\Delta\phi(p_{\mathrm{T}}^{i=1-4}, H_{\mathrm{T}}^{\mathrm{miss}}) > (0.5, 0.5, 0.3, 03)$ between vectors of transverse jet momentum and MHT. The veto on the electron and muon (with $p_{\mathrm{T}} > 10$ GeV) in the event suppresses top/$W \to l\nu$ events.

The final data events in the 72 search regions are shown in Fig. 3 (right). Observed numbers of events are compared to the predictions for the SM background in the lower panel of the plot. Statistically, in all regions, predicted background is compatible with the data. Results are interpreted as the gluino mass limits in three SMS scenarios by selecting the particularly sensitive search-region phase space. Figure 4 (left) presents the projection of MHT sensitive to the T1bbbb topology, for which $N_{b-\mathrm{jet}} \geq 3$ is required. In the corresponding Fig. 4 (right), the 95% confidence level (C.L.) NLO+NLL upper limits on the gluino production cross sections is shown as a function of the gluino and LSP masses.

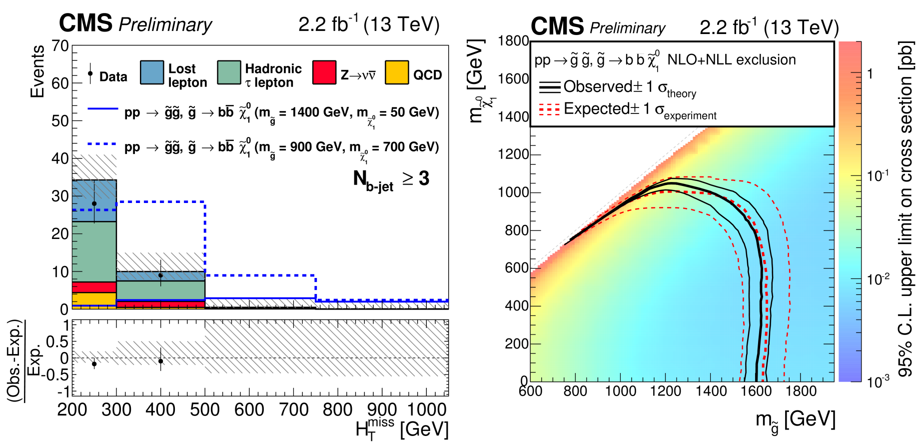

Fig. 4. Observed numbers of events and SM background predictions for the T1bbbb scenario (left). The corresponding 95% confidence level upper limits on the production cross sections as a function of the gluino and LSP masses. The solid (dashed) curves show the observed exclusion contours assuming the NLO+NLL cross sections, with the ± 1 standard (experimental) deviation uncertainties (right). The plots are taken from [6].

The CMS analysis [6] of the Run 2 data significantly extends limits obtained in previous searches. Gluinos with masses below 1600, 1530, and 1440 GeV are excluded for T1bbbb, T1tttt, T1qqqq scenarios, respectively.

3. Search for supersymmetry with razor variables

The razor variables [7] are used to separate well the SUSY signal from the SM background. Their discriminant power comes from the change of the standard search for the SUSY excess in tail of the MET distribution to the search for a peak occurring in razor variables.

The razor variables are define for the sparticle pair production event. Each of sparticle creates a hemisphere of their decay products which can be simplified as a decay to a SM particle and the LSP. In the experiment, jets and selected leptons can be clustered into two distinct hemispheres, called megajets. The first razor variable estimates a mass-invariant-like variable defined as: $M_R = \sqrt{(|\vec{p}^{\,j_1}| + |\vec{p}^{\,j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$, where $|\vec{p}^{\,j_i}|$ and $p_z^{j_i}$ are the absolute and the longitudinal values of the i^{th} megajet momentum. The second razor variable is a transverse mass of two megajet system including missing transverse energy: $M_{\mathrm{T}}^R = \sqrt{\frac{1}{2}[E_{\mathrm{T}}^{\mathrm{miss}}(p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2}) - \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}(\vec{p}_{\mathrm{T}}^{\,j_1} + \vec{p}_{\mathrm{T}}^{\,j_2})]}$, where the vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is defined as the projection of the negative vector sum of the momenta of all reconstructed particles in an event on the plane perpendicular to the beam axis, and its magnitude is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$. The ratio of two razor estimator defines a transverse shape of event in a following way: $R^2 = (M_{\mathrm{T}}^R/M_R)^2$. The variable M_R has a peak at the characteristic scale related to the decay of the initially produced sparticle: $M_R = M_\Delta = (M_S^2 - M_{\mathrm{LSP}}^2)/M_S$, whereas for the SM background, the distribution of M_R has an exponentially decaying shape. This behaviour is illustrated in Fig. 5. In the plot for the hypothetical SUSY model, a broad peak in M_R and a long tail in R^2 is observed, well-separated from the background. The variable R^2 is related to MET and, therefore, is also used to suppress QCD background.

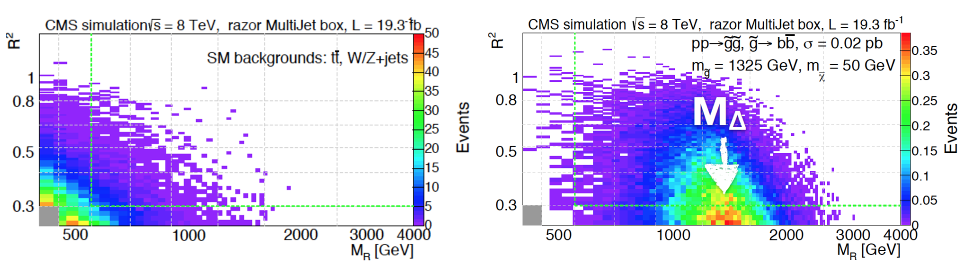

Fig. 5. Distributions of razor variables M_R *versus* R^2 for SM processes (left) and SUSY signal (right). The CMS simulation for Run 1 data at $\sqrt{s} = 8$ TeV of the integrated luminosity 19.5 fb^{-1}.

The CMS analysis [8] with razor variables maximize sensitivity of various possible types of signal processes by search in the leptonic and hadronic final states. All events are divided into different categories based on presence or absence of jets and leptons. All event categories are required to have at least four jets with $p_{\rm T} > 40$ GeV. The *MultiJet* category has additionally no electrons or muons and $M_R > 500$ GeV, $R^2 > 0.25$. The *Muon MultiJet* requires one tight muon with $p_{\rm T} > 20$ GeV and $M_R > 400$ GeV, $R^2 > 0.15$ and similarly *Electron MultiJet* has one tight electron with $p_{\rm T} > 25$ GeV and $M_R > 400$ GeV, $R^2 > 0.15$. Events with two or more tight electrons or muons are rejected. Each event category is separated into b-tag bins with $N_{b-\rm jet} = 1, 2, 3, \geq 4$ b-tagged jets. The search is performed in two-dimensional (2D) planes of razor variables M_R and R^2, which are divided into many bins (34 or 55 bins for hadronic and leptonic categories, respectively). The SM background is modelled by a parametric 2D function in M_R

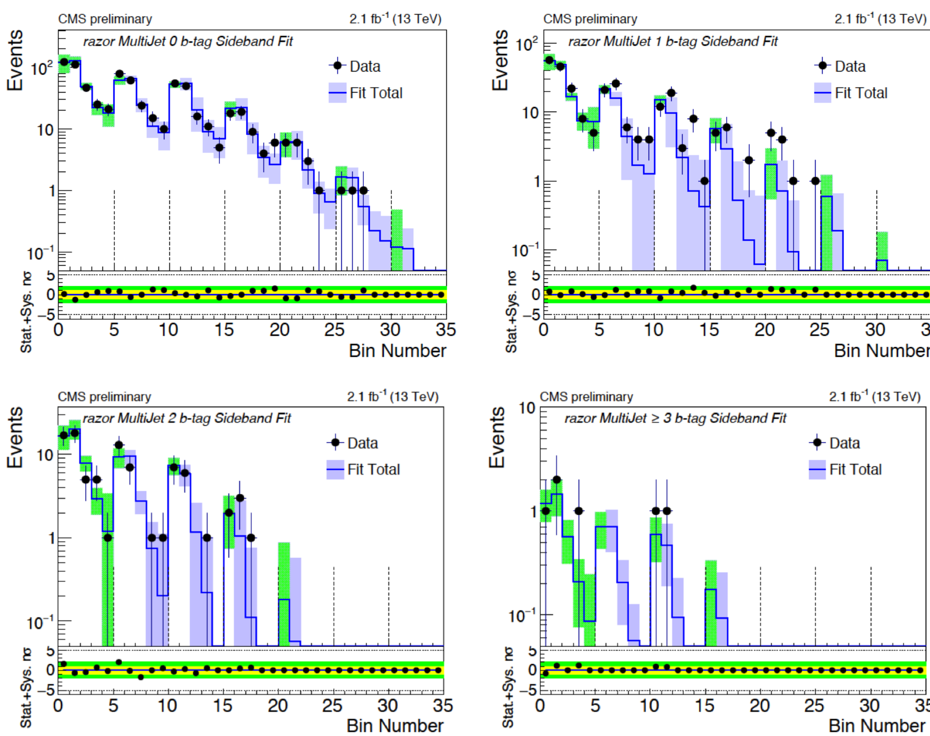

Fig. 6. Results for the razor *MultiJet* category separately for four b-tag bins. The observed data and predicted background in all bins of M_R and R^2 variable. The lower panel shows the deviation between the observed data and the background in units of standard deviation with statistical and systematic uncertainties. The plots are taken from [8].

and R^2 in sidebands define for low values of razor variables above preselection cuts. Next, the fit is extrapolated to the full plane of M_R and R^2. The SM predictions are made separately for all categories and b-tag bins. The search is preformed in a signal-sensitive regions, which is $M_R > 600$ (450) GeV, $R^2 > 0.3$ (0.2) for the hadronic (leptonic) category. The results for *MultiJet* category are shown in Fig. 6. No significant deviations are found in the data.

In spite of that, a toy study is done to test what would happen when a signal was present. Events corresponding to the T1bbbb signal at the normal signal strength are injected to the data and the background-only sideband fit is performed. In Fig. 7, characteristic patterns of excesses in two adjacent bins in the M_R dimension are clearly visible. However, the signal also flows into a sideband region, which may make a hypothetical discovery more difficult.

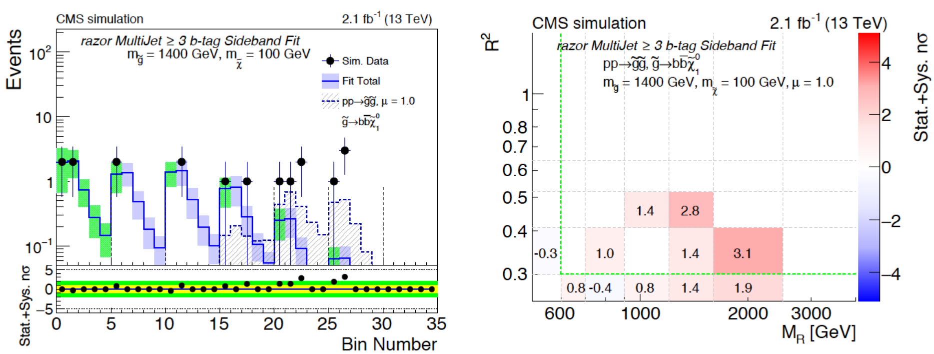

Fig. 7. The result of the background-only fit performed in the sideband on a signal-plus-background toy dataset using gluino pair-production in T1bbbb scenario (left). The corresponding distributions of deviations (in standard units) in the R^2–M_R plane (right). The plots are taken from [8].

Since the data are comparable with predicted SM backgrounds, results are interpreted as 95% C.L. upper limits on the production cross section for simplified models T1bbbb, T1tttt and T1qqqq. In Fig. 8, observed and expected exclusion limits on various simplified models for 2.1 fb^{-1} of 13 TeV data can be compared. Assuming, the LSP mass of 100 GeV, the pair production of gluinos in multi-bottom-quark and multi-top-quark final states is excluded for gluino masses up to 1650 GeV and 1600 GeV, respectively. For the case of final states with light quarks, gluinos up to 1350 GeV in mass are excluded.

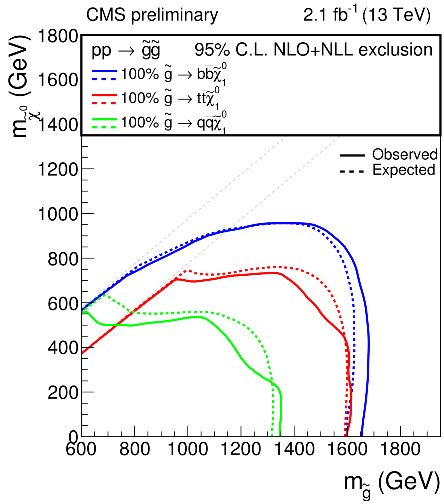

Fig. 8. The razor search summary of the exclusion contours at 95% C.L. in the context of gluino pair-production in simplified model scenarios T1bbbb, T1tttt and T1qqqq. The dashed and solid lines represent the expected and observed exclusion contours at 95% C.L., respectively. The figure is taken from [8].

4. Search for supersymmetry with the $\alpha_{\rm T}$ variable

The next complementary search [9] in the CMS detector is performed with a kinematical variable $\alpha_{\rm T}$ [10], which is a powerful discriminator between events with misreconstructed and genuine MET. As for razor variables described in Sec. 3, $\alpha_{\rm T}$ is calculated for two megajet events. The variable $\alpha_{\rm T} = E_{\rm T}^{j_2}/M_{\rm T}$ is defined as a ratio of an energy of less energetic jet, $E_{\rm T}^{j_2}$, and transverse mass of di-jet system, $M_{\rm T} = \sqrt{(H_{\rm T})^2 - (H_{\rm T}^{\rm miss})^2}$. The variable is sensitive to the topology of di-jet event. In the case of the QCD background, jets are back-to-back in the ϕ plane and $\alpha_{\rm T}$ is equal to 0.5 for a perfectly measured di-jet event with $E_{\rm T}^{j_1} = E_{\rm T}^{j_2}$ in the limit of large jet momenta compared to jet masses. $\alpha_{\rm T}$ is smaller than 0.5 in the case of an imbalance in the measured energies of back-to-back jets. When the two jets are not back-to-back and balancing genuine MET, which is the case of the signal (SUSY) topology, $\alpha_{\rm T}$ is greater than 0.5. The discriminant power of $\alpha_{\rm T}$ is presented in Fig. 9 (left). With the cut on $\alpha_{\rm T}$, the QCD background is significantly suppressed. Further variables are also employed to discriminate against multijet production and suppress this background process to a negligible level. The $\Delta\phi^\star$ variable, which is a minimum angle between a given jet and the MHT vector computed without that jet, has a peak in low values for jets with neutrinos, due to semileptonic decays of heavy-flavour mesons, as illustrated in Fig. 9 (right). The signal region is selected with following cuts: $\alpha_{\rm T} > 0.65$ to 0.52 ($H_{\rm T}$ dependent, for the region of $H_{\rm T} < 800$ GeV), $\Delta\phi^{\star} > 0.5$ and $H_{\rm T}^{\rm miss}/E_{\rm T}^{\rm miss} < 1.25$. The remaining background consists mainly of: tt+jets, W+jets, $Z \to \nu\nu$ and is predicted in the signal region from observed counts in control regions.

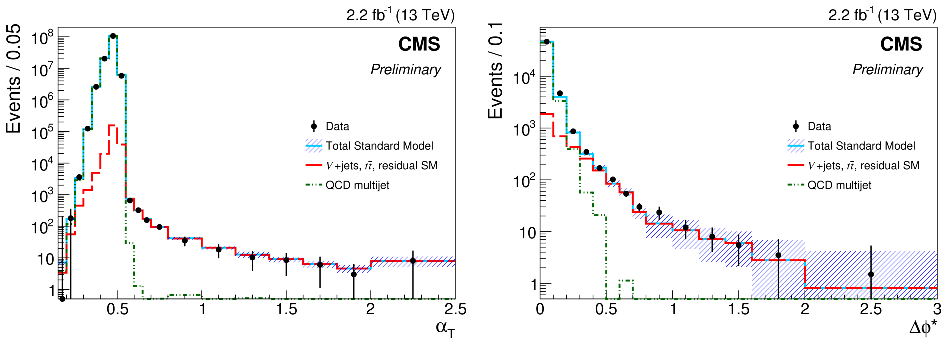

Fig. 9. The $\alpha_{\rm T}$ distribution observed in data for events that satisfy the pre-selection (left). The $\Delta\phi^{\star}$ distribution observed in data for events that satisfy the full signal region selection criteria and $H_{\rm T} > 800$ GeV. The QCD backgrounds are determined from simulation, while all other SM backgrounds are estimated using a $\mu+$jets data control sample (right). The plots are taken from [9].

The CMS $\alpha_{\rm T}$ analysis [9] gives sensitivity to wide variety of the signal topologies, including monojet-like events. The event categorization is defined by numbers of $N_{\rm jet} = 1, 2, 3, 4, \geq 5$ and $N_{\rm b-jet} = 0, 1, 2, \geq 3$ ($N_{\rm b-jet} \leq N_{\rm jet}$). The searches are performed in bins of $H_{\rm T} > 200$, 250, 300, 350, 400, 500, 600, > 800 GeV. Around 200 bins are considered in the analysis. The preselection includes requirements on presence of at least one jet with $p_{\rm T} > 40$ GeV and the forward jet veto, and lepton/photon jet vetoes, and energy sums $H_{\rm T} > 200$ GeV and $H_{\rm T}^{\rm miss} > 130$ GeV.

The final search for the excess is performed in the distribution of MHT. In all categories, no significant tension between the predictions and data in the signal region is observed, which is well-described by the SM-only hypothesis. For two simplified models T1bbbb and T1qqqq, the upper limits in the gluino pair production are set. Figure 10 presents results for T1bbbb scenario, where gluino and neutralino masses are excluded below 1550 GeV and 950 GeV, respectively.

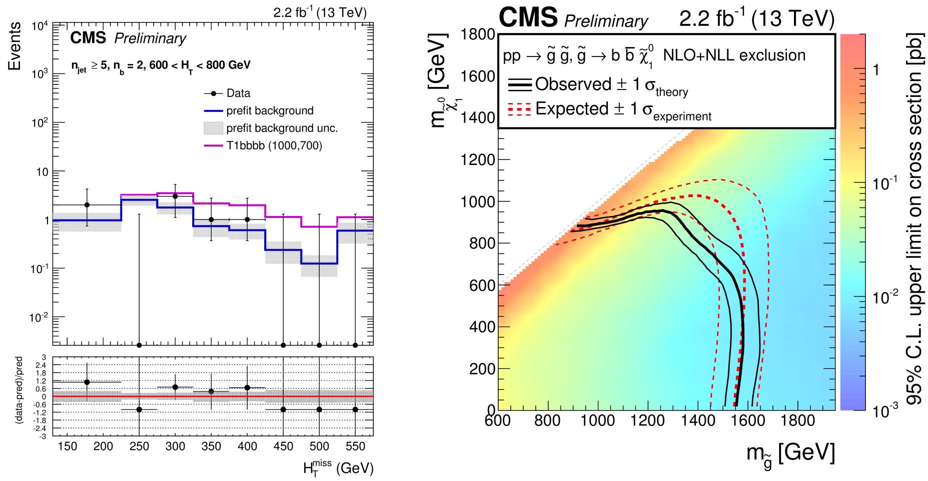

Fig. 10. The α_{T} results. The MHT distribution observed in data and the expected distribution for the sum of all SM background processes in T1bbbb scenario (left). The corresponding observed upper limit in cross section at 95% C.L. as a function of the gluino and neutralino masses (right). The plots are taken from [9].

5. Search for supersymmetry with opposite-sign di-leptons

An especially exiting search [11] has been performed with two opposite-sign (OS) the same-flavour (SF) leptons, jets, and missing transverse momentum. In Run 1, ATLAS and CMS experiments observed excesses in 8 TeV data. The new CMS analysis focuses on the invariant mass distribution of the lepton pair, searching for a resonant-like excess compatible with the Z boson mass (on-Z-peak) or a kinematic edge (off-Z-peak). The excess for the on-Z channel at the level of 3.0σ was reported by ALTAS, as shown in Fig. 11 (left), but was not confirmed by CMS. Instead, CMS observed 2.6σ excess as an edge in the mass invariant distribution of OSSF leptons. Details are shown in Fig. 11 (right).

The search is performed in the context of two supersymmetric model. The first one targets Gauge Mediated Supersymmetry Breaking (GMSB) model, where the lightest neutralino is the next-to the LSP. It is assumed that this neutralino decays into an on-shell Z boson and a massless gravitino, as illustrated in Fig. 12 (left). The Z boson decays into a pair of leptons producing the signature targeted by the on-Z search. The second approach is referred to the edge search. The Feynman diagram is shown in Fig. 12 (right). It assumes the production of a pair of sbottom–squarks $\tilde{b}\tilde{b}^{\star}$, which decay to the next-to-lightest neutralino $\tilde{\chi}^0_2$ and a b-quark. Two decay modes of the $\tilde{\chi}^0_2$ are considered. In the first one, the $\tilde{\chi}^0_2$ decays to a Z boson (on-shell or off-shell) and the lightest neutralino $\tilde{\chi}^0_1$. The second one features subsequent two-body decays with an intermediate slepton, $\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \ell\ell\tilde{\chi}_1^0$, and generates a characteristic edge in the mass invariant distribution of OSSF leptons.

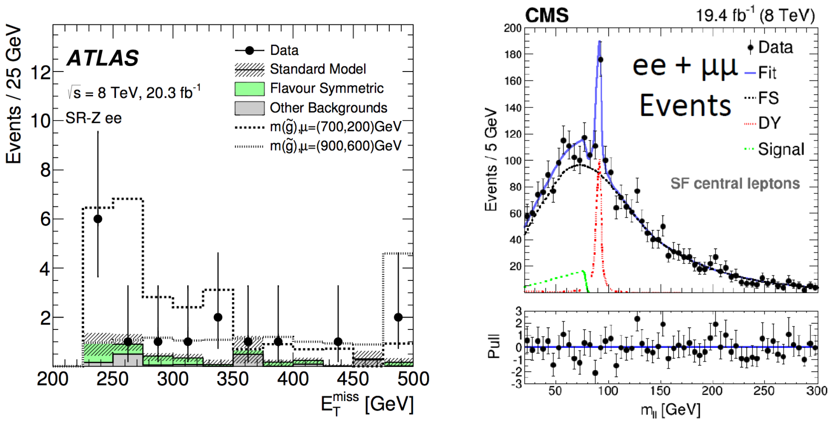

Fig. 11. The ALTAS 8 TeV result in the MET distribution [12] of the on-Z search with 3.0σ excess in the electron channel. In muon channel, the excess was estimated at the level of 1.7σ (left). The CMS 8 TeV result [13] of the slepton-edge search with the 2.6σ excess. Fit results for the signal-plus-background hypothesis in comparison with the measured di-lepton mass distributions in the central region, projected on the same-flavour (SF) event samples. The combined fit shape is shown as a solid line. The individual fit components and the extracted signal component are indicated by dashed lines. The lower plots show the pull distributions, defined as $(N_{\text{data}} - N_{\text{fit}})/\sigma_{\text{data}}$ (right).

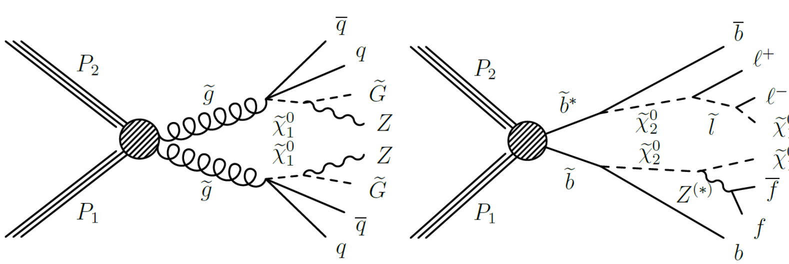

Fig. 12. The schematic diagram for gluino pair production with an on-Z decay for a simplified GMSB model (left). The diagram for sbottom quark pair production and a decay with the edge (right). The plots are taken from [11].

The analysis is designed to provide sensitivity to a range of new physics models, including the simplified models defined above and regions of 8 TeV excesses. The search is performed in signal regions binned in N_{jet}, $N_{b-\text{jet}}$ and $E_{\text{T}}^{\text{miss}}$ or $m_{\ell\ell}$ variables as described below.

The preselection requires tight cuts on leptons with $p_{\rm T}^{e/\mu} > 20$ GeV and loose selection for jets with $p_{\rm T} > 35$ GeV. The on-Z search is divided in three signal region (SR) categories with low (2–3 jets and $H_{\rm T} > 400$ GeV) and high jet multiplicity (≥ 4 jets), and ATLAS-like SR ($E_{\rm T}^{\rm miss} > 225$ GeV and $H_{\rm T} + p_{\rm T}^{\ell_1} + p_{\rm T}^{\ell_2} > 600$ GeV). The search is performed in bins of $N_{b-{\rm jet}} = 0, \geq 1$ and $E_{\rm T}^{\rm miss} > 100, 150, 225, 300$ GeV. In total, the on-Z search is done in 17 bins. For the edge search, all signal regions require $E_{\rm T}^{\rm miss} > 150$ GeV if $N_{\rm jet} \geq 2$ or $E_{\rm T}^{\rm miss} > 100$ GeV if $N_{\rm jet} \geq 3$. Signal regions are binned in three $N_{b-{\rm jet}} \geq 0, = 0, \geq 1$ and the mass invariant of two leptons, $m_{\ell\ell} = 20, 70, 81, 101, 120$ GeV.

Backgrounds from SM processes are divided into two categories. Backgrounds that produce the opposite flavour pairs ($e^{\pm}\mu^{\mp}$) as often as the same flavour pairs ($\mu^+\mu^-, e^+e^-$) are referred to as flavour-symmetric (FS) backgrounds. Among them, the dominant contribution arises from top production, but also WW, $Z/\gamma^\star(\to \tau\tau)$ or tW. The second category arises from Drell–Yan production in association with jets, where the MET arises from mismeasurement of the jets. These backgrounds are estimated from the data. Other contributions are small and derived from simulations.

For all signal regions for on-Z and edge searches, predicted SM backgrounds are consistent with the observed data in 13 TeV sample of an integrated luminosity of 2.2 fb^{-1}. The conclusion refers also to signal regions, where in Run 1 excesses were observed. The results for the on-Z search are shown in Fig. 13. On the left plot, the MET distribution for the ATLAS-like

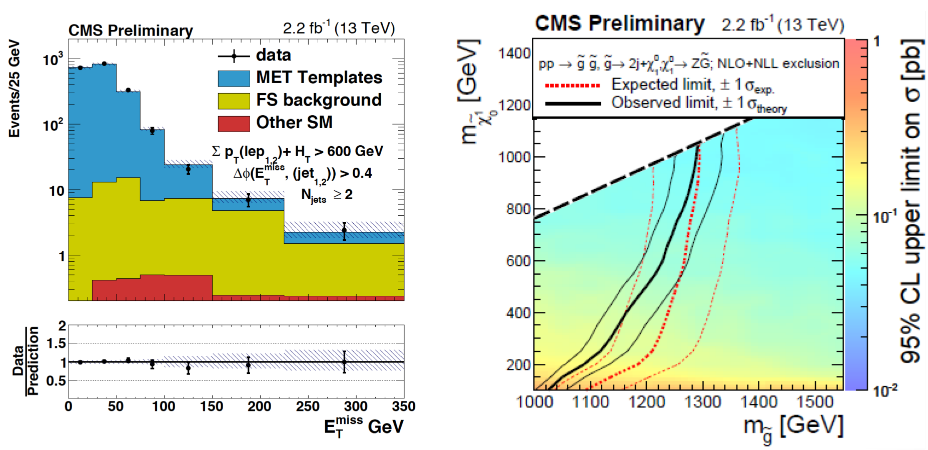

Fig. 13. The MET distribution for data and the data-driven predictions in on-Z ATLAS-like signal regions. SM background processes indicated as "Other SM" taken from MC simulations (right). The 95% C.L. exclusion contours for an upper limit of gluino pair production within the GMSB model (right). The plots are taken from [11].

region is shown. No evidence for a statistically significant signal is observed. On the right plot, results are interpreted in a model of GMSB, in which the Z bosons are produced in decay chains initiated through gluino pair production (Fig. 12 (left)). Gluino masses below 1300 GeV for high neutralino masses and 1100 TeV for low neutralino masses are excluded, extending the previous exclusion limits derived from the same analysis at 8 TeV by almost 200 GeV. Results in signal regions of the edge search are shown in Fig. 14. The second plot shows the mass invariant distribution of OSSF leptons. With Run 2 data, 8 TeV excesses are not confirmed.

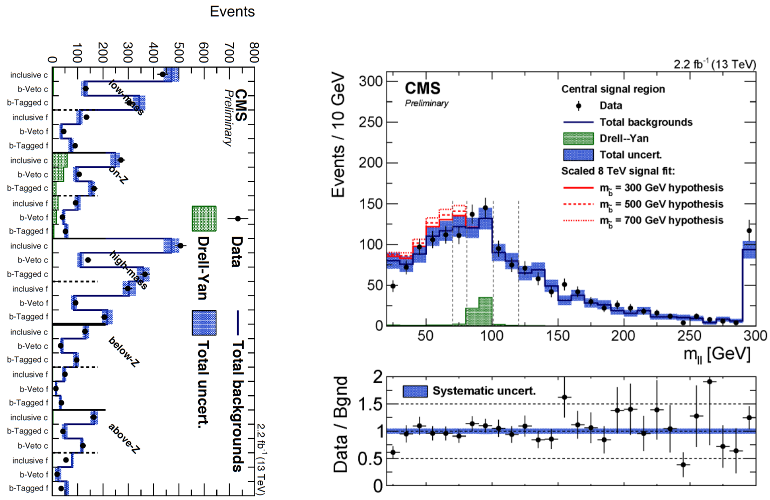

Fig. 14. Overview of results in all signal regions of the edge search (right). The corresponding di-lepton invariant mass spectra for central leptons. The signal shape measured by CMS with 8 TeV data has been overlaid on top of the background prediction and has been normalized to the size of the excess observed at 8 TeV scaled by the ratio of integrated luminosity and cross sections for 3 different sbottom mass hypothesis (left). The plots are taken from [11].

6. Early SUSY searches summary

New data (2.2 fb^{-1} of an integrated luminosity) from the highest ever achieved energy in proton–proton collisions at the LHC at a centre-of-mass energy 13 TeV allowed for extended searches for new physics. The CMS experiment completed seven analysis with new data. Four of these new CMS searches have been reviewed. Results are summarized in Fig. 15. Although no SUSY particles have been found, a significant progress for the exclusion limits was achieved. The gluino masses in several SUSY simplified models was excluded up to 1650 GeV. The new constrains are stronger by 300 GeV in comparison to limits obtained with 8 TeV data.

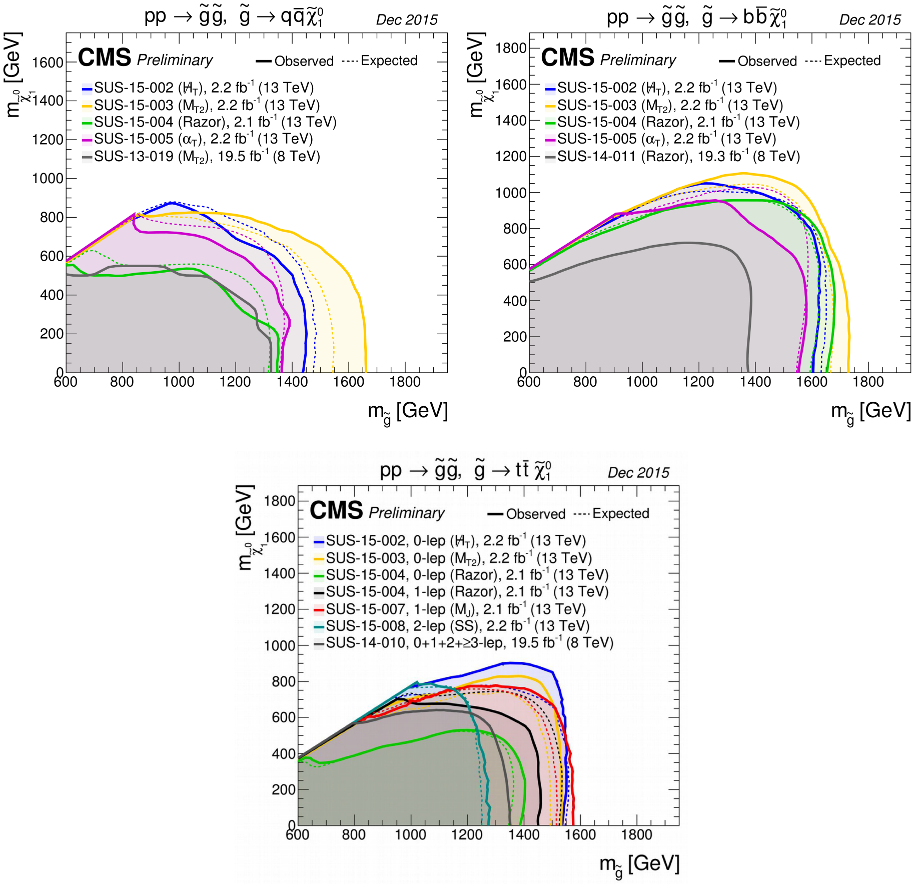

Fig. 15. The summary of the CMS early searches for supersymmetry with an integrated luminosity of 2.2 fb^{-1} of 13 TeV data. Exclusion regions are shown in the plane mass of the lightest neutralino *versus* mass of the gluino for three simplified models T1qqqq, T1bbbb and T1tttt.

In Run 1, ATLAS and CMS observed small excesses in the opposite-sign di-lepton channel. Results of Run 2 data have not revealed the same. Previous excesses have to be considered as statistical fluctuations.

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