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Search for new physics in events with same-sign dileptons and b jets in pp collisions at $\sqrt{s} = 8$ TeV



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ABSTRACT: A search for new physics is performed using events with isolated same-sign leptons and at least two bottom-quark jets in the final state. Results are based on a sample of proton-proton collisions collected at a center-of-mass energy of 8 TeV with the CMS detector and corresponding to an integrated luminosity of 10.5 fb^{-1} . No excess above the standard model background is observed. Upper limits are set on the number of events from non-standard-model sources and are used to constrain a number of new physics models. Information on acceptance and efficiencies is also provided so that the results can be used to confront an even broader class of new physics models.

KEYWORDS: Hadron-Hadron Scattering

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1 Introduction

Events with same-sign, isolated leptons (e or μ) from standard model (SM) processes in proton-proton collisions are extremely rare. As a result, searches for anomalous production of same-sign dileptons can be very sensitive to new physics contributions. These include supersymmetry (SUSY) [1–3], universal extra dimensions [4], pair production of $T_{5/3}$ particles (fermionic partners of the top quark) [5], heavy Majorana neutrinos [6], and same-sign top-pair production [7, 8]. More specifically, the signature of same-sign dileptons accompanied by bottom quarks can arise from SUSY processes where third-generation quark superpartners are lighter than other squarks [9–13], resulting in an abundance of top and bottom quarks produced in cascade decays. These scenarios are particularly interesting for two reasons. First, because they have not been excluded by early SUSY searches at the Large Hadron Collider (LHC); second, because relatively light bottom and top squarks are necessary if SUSY is to be the “natural”, (i.e., not fine-tuned), solution to the gauge hierarchy problem (see for example the discussion in ref. [12]).

In this Paper we present the result of a search for new physics in events with same-sign isolated dileptons and two or more bottom-quark jets (b jets). The search was performed on a dataset corresponding to an integrated luminosity of 10.5 fb^{-1} of proton-proton (pp) collisions collected at a center-of-mass energy of 8 TeV with the Compact Muon Solenoid

(CMS) [14] detector at the LHC. This search is an extension of the search at 7 TeV described in ref. [15].

In the analysis, we select events with two isolated, high transverse momentum (p_T), same-sign leptons (e or μ), and at least two jets identified as b jets (b-tagged jets). The numbers of observed events in signal regions defined by additional requirements on missing transverse energy (E_T^{miss}), the number of b-tagged jets, and the scalar sum of jet p_T (H_T), are compared with SM expectations. Having found no evidence for a beyond-the-SM contribution to the event counts, we set limits on the number of events from new physics in the event sample. These limits are then translated into a limit on the same-sign top-pair production cross section and are used to bound the parameters of other new physics models. Finally, we include additional information on the event selection efficiencies so that our results can be used to test models of new physics not explicitly considered here.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. The CMS experiment uses a right-handed coordinate system, with the origin defined to be the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the LHC plane), and the z axis pointing in the counterclockwise beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x - y (transverse) plane. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$. Within the field volume are a silicon pixel and strip tracker, a crystal electromagnetic calorimeter, and a brass-scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. Full coverage is provided by the tracker, calorimeters, and the muon detectors within $|\eta| < 2.4$. In addition to the barrel and endcap calorimeters up to $|\eta| = 3$, CMS has extensive forward calorimetry reaching $|\eta| \lesssim 5$. A more detailed description of the CMS apparatus can be found in ref. [14].

3 Event selection and Monte Carlo simulation

The event selection is essentially the same as for the 7 TeV analysis [15]. We require two isolated same-sign leptons (e or μ), consistent with originating from the same vertex and with pair invariant mass above 8 GeV, and at least two b-tagged jets. Events are collected with dilepton triggers. The kinematic requirements on leptons and jets are summarized in table 1. Events with a third lepton are rejected if the lepton forms an opposite-sign same-flavor pair with one of the first two leptons, and if the invariant mass $m_{\ell\ell}$ of the pair satisfies $m_{\ell\ell} < 12$ GeV ($p_T > 5$ GeV) or $76 < m_{\ell\ell} < 106$ GeV ($p_T > 10$ GeV), where the conditions in parentheses show the respective p_T requirement on the third lepton. These requirements are designed to minimize backgrounds from events with $\gamma^* \rightarrow \ell^+\ell^-$, low-mass bound-state, and multi-boson (WZ and ZZ, as well as tribosons) production.

With respect to ref. [15], there have been a few modifications in the lepton identification and isolation requirements. The main difference is that lepton isolation is now computed

	p_T	η
electrons	$p_T > 20 \text{ GeV}$	$ \eta < 1.442$ or $1.566 < \eta < 2.4$
muons	$p_T > 20 \text{ GeV}$	$ \eta < 2.4$
jets	$p_T > 40 \text{ GeV}$	$ \eta < 2.4$
b-tagged jets	$p_T > 40 \text{ GeV}$	$ \eta < 2.4$

Table 1. Kinematic requirements for leptons and jets in this analysis.

with particle-flow information [16] rather than with charged tracks and calorimeter deposits, and an event-by-event correction is made to account for the effect of multiple pp interactions in the same bunch crossing (pileup); the mean number of interactions in the same crossing is 15. This correction consists of subtracting from the measured sum- P_T in the isolation cone the estimated contribution from pileup. This contribution is of order 1 GeV, and it is calculated based on a measurement of the hadronic event activity not associated with the pp interaction that produced the leptons. As a result of this correction, the efficiency of the isolation requirement for leptons from W and Z decays is almost independent of pileup.

The jet reconstruction is the same as in ref. [15], but the b-tagging algorithm has been changed slightly. We now use the CSV method of ref. [17], which is based on the combination of secondary-vertex reconstruction and track-based lifetime information. Efficiencies for lepton identification, trigger efficiency, and b-tagging are summarized in sections 6 and 7.

Monte Carlo (MC) simulations including pileup are used to estimate some of the SM backgrounds (see section 4), as well as to calculate the efficiency for various new physics scenarios. In this analysis, SM background samples and new physics signal samples are generated with the MADGRAPH V5 [18] and PYTHIA V6.4 [19] programs, respectively. Standard model processes are simulated using a GEANT4-based model [20] of the CMS detector; the simulation of new physics signals is performed using the CMS fast simulation package [21]. All simulated events are processed with the same chain of reconstruction programs used for collision data.

4 Backgrounds

There are three sources of SM background to potential new physics signals:

- “fake leptons”, i.e., leptons from heavy-flavor decay, misidentified hadrons, muons from light-meson decay in flight, or electrons from unidentified photon conversions. These are estimated from a sample of events with at least one lepton that passes a loose selection but fails the full set of tight identification and isolation requirements. The background estimation uses the “tight-to-loose” ratio, i.e., the probability for a loosely identified fake lepton to also pass the full set of requirements, as determined from studies of fake leptons in multijet events.

- “charge flips”, i.e., events with opposite-sign isolated leptons where one of the leptons is an electron and its charge is misreconstructed due to severe bremsstrahlung in the tracker material (this effect is negligible for muons). Charge flips are estimated by selecting opposite-sign ee or $e\mu$ events passing the full kinematic selection, weighted by the p_T - and η -dependent probability of electron charge misassignment. This probability is obtained from MC simulation and is validated on a sample of $Z \rightarrow ee$ events.
- rare SM processes that yield same-sign high- p_T leptons and b jets, mostly from $t\bar{t}W$ and $t\bar{t}Z$ production. This background contribution is obtained from Monte Carlo simulation.

More details on the background estimation can be found in refs. [15, 22]. The systematic uncertainties are 20% for charge flips, and 50% for both fake and rare SM backgrounds. The next-to-leading order $t\bar{t}W$ and $t\bar{t}Z$ production cross sections used to normalize the MC predictions are 232 fb [23] and 208 fb [24, 25], respectively.

5 Event yields

The search is based on comparing the event yields and background predictions in nine signal regions (SRs) with different requirements on E_T^{miss} , H_T , and the number of b-tagged jets. In order to improve the sensitivity to $pp \rightarrow tt$ production, we also define a SR with positive leptons only. The requirements for the SRs are loosely motivated by possible new physics scenarios. For example, signal regions with high E_T^{miss} are most sensitive to R-parity-conserving SUSY models with relatively light neutralinos; requiring larger H_T reduces the SM background while generally maintaining good efficiency to detect new heavy particles that are produced via the strong interaction; the signal region with three or more b-tagged jets is sensitive to final states that include several b quarks.

The definition of the signal regions and the observations of the search are summarized in table 2. The basic kinematic properties of the selected events are shown in figure 1. The results are consistent with the background predictions.

Table 2 also shows the 95% confidence level (CL) observed upper limit (N_{UL}) on the number of non-SM events, calculated using the CL_s method [26–28] under three different assumptions for the signal efficiency uncertainty. As can be seen from table 2, the limits are only weakly dependent on this uncertainty. The uncertainty on the signal efficiency is discussed in section 6.

6 Efficiencies and associated uncertainties

The dilepton triggers require one lepton to have $p_T > 17$ GeV and the other $p_T > 8$ GeV. The trigger efficiency, measured using events collected with hadronic triggers, is $96 \pm 5\%$ for ee , $93 \pm 5\%$ for $e\mu$, and $88 \pm 4\%$ for $\mu\mu$. All acceptances, which are calculated from MC simulation, include a correction factor for the trigger efficiency.

	SR0	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8
No. of jets	≥ 2	≥ 2	≥ 2	≥ 4	≥ 4	≥ 4	≥ 4	≥ 3	≥ 4
No. of btags	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 3	≥ 2
Lepton charges	++/--	++/--	++	++/--	++/--	++/--	++/--	++/--	++/--
E_T^{miss}	>0 GeV	>30 GeV	>30 GeV	>120 GeV	>50 GeV	>50 GeV	>120 GeV	>50 GeV	>0 GeV
H_T	>80 GeV	>80 GeV	>80 GeV	>200 GeV	>200 GeV	>320 GeV	>320 GeV	>200 GeV	>320 GeV
Fake BG	25 ± 13	19 ± 10	9.6 ± 5.0	0.99 ± 0.69	4.5 ± 2.9	2.9 ± 1.7	0.7 ± 0.5	0.71 ± 0.47	4.4 ± 2.6
Charge-flip BG	3.4 ± 0.7	2.7 ± 0.5	1.4 ± 0.3	0.04 ± 0.01	0.21 ± 0.05	0.14 ± 0.03	0.04 ± 0.01	0.03 ± 0.01	0.21 ± 0.05
Rare SM BG	11.8 ± 5.9	10.5 ± 5.3	6.7 ± 3.4	1.2 ± 0.7	3.4 ± 1.8	2.7 ± 1.5	1.0 ± 0.6	0.44 ± 0.39	3.5 ± 1.9
Total BG	40 ± 14	32 ± 11	17.7 ± 6.1	2.2 ± 1.0	8.1 ± 3.4	5.7 ± 2.4	1.7 ± 0.7	1.2 ± 0.6	8.1 ± 3.3
Event yield	43	38	14	1	10	7	1	1	9
N_{UL} (13% unc.)	27.2	26.0	9.9	3.6	10.8	8.6	3.6	3.7	9.6
N_{UL} (20% unc.)	28.2	27.2	10.2	3.6	11.2	8.9	3.7	3.8	9.9
N_{UL} (30% unc.)	30.4	29.6	10.7	3.8	12.0	9.6	3.9	4.0	10.5

Table 2. A summary of the results of this search. For each signal region (SR), we show its distinguishing kinematic requirements, the prediction for the three background (BG) components, as well as their total, and the observed number of events. We also show the 95% CL upper limit on the number of new physics events (N_{UL}) under different assumptions on the signal efficiency uncertainty. Note that the number of jets on the first line of the table includes both b-tagged and non b-tagged jets.

The lepton selection efficiencies, determined using a sample of simulated events from a typical signal scenario involving multiple top quarks in the final states arising from gluino decay [29, 30], are displayed in figure 2. Studies of large samples of $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events indicate that the lepton selection efficiencies are reproduced to better than 2% by the simulation. However, leptons in SUSY events have significantly lower isolation efficiency due to the large amount of hadronic activity that is expected in these scenarios. As a result, we conservatively assign an uncertainty of 5% per lepton to the lepton selection efficiency.

Figure 2 also shows the b-tagging efficiency, obtained from simulation, for b quarks with $|\eta| < 2.4$. The uncertainty on this efficiency is a function of b-jet p_T ; it is 4.4% at $p_T = 40$ GeV, 2.7% at $p_T = 100$ GeV, and 10% at $p_T = 500$ GeV [17].

The uncertainty on the energy scale of jets in this analysis is also a function of p_T [31]. It varies between 5% and 2% in the p_T range 40–100 GeV for jets with $|\eta| < 2.4$.

The importance of these effects depends on the signal region and the model of new physics. In general, models with high hadronic activity and large E_T^{miss} are less affected by the uncertainty on the jet energy scale.

The total uncertainty on the acceptance for the models described in section 8 is in the 13–20% range. Finally, there is a 4.4% uncertainty on the yield of events from any new physics model due to the uncertainty in the luminosity normalization [32].

7 Information for model testing

Our results can be used to confront models of new physics in an approximate way through generator-level studies that compare the expected numbers of events with the upper limits from table 2. The prescription to be used is given in ref. [15], section 7. The E_T^{miss} and H_T turn-on curves in this analysis are the same as those of ref. [15]. However the lepton

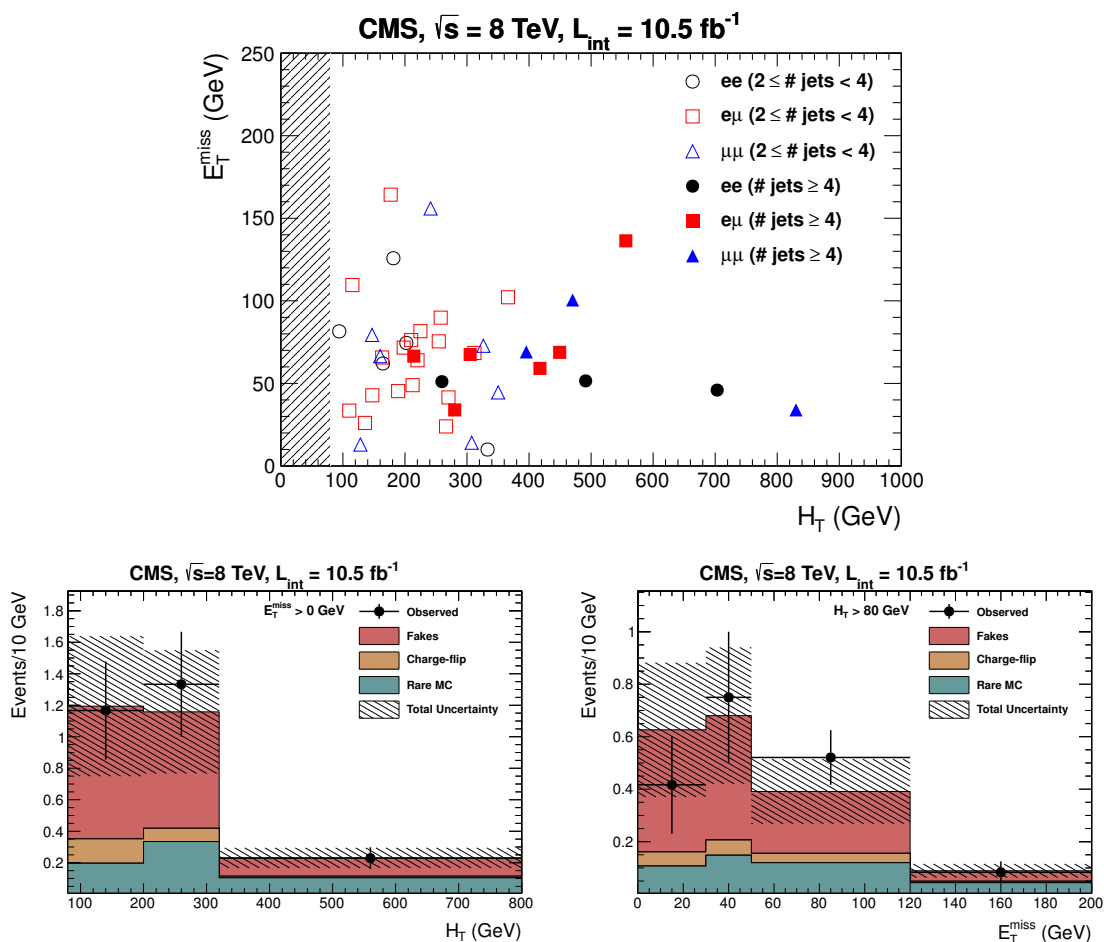


Figure 1. Top plot: distribution of E_T^{miss} versus H_T for the 43 events in the most inclusive signal region (SR0). Note that the ≥ 2 jets requirement in SR0 implies $H_T > 80$ GeV. Bottom-left plot: projection of the top plot on the H_T axis. Bottom-right plot: projection of the top plot on the E_T^{miss} axis. For the one-dimensional distributions, the number of events in each bin is scaled appropriately to reflect units of events per 10 GeV and is compared with the background predictions, with their uncertainties. The binning of the one-dimensional distributions is chosen to match the E_T^{miss} and H_T boundaries of the different signal regions.

and b-tagging efficiencies are slightly different because of the changes in the underlying selections. Their current parametrizations are given below.

The parametrization of the lepton efficiency, shown in figure 2 (left), is

$$\epsilon = \epsilon_\infty \operatorname{erf} \left(\frac{p_T - 20 \text{ GeV}}{\sigma} \right) + \epsilon_{20} \left[1 - \operatorname{erf} \left(\frac{p_T - 20 \text{ GeV}}{\sigma} \right) \right], \quad (7.1)$$

with $\epsilon_\infty = 0.65$ (0.69), $\epsilon_{20} = 0.35$ (0.48), and $\sigma = 42 \text{ GeV}$ (25 GeV) for electrons (muons). The parametrization of the simulated b-tagging efficiency, shown in figure 2 (right), is $\epsilon = 0.71$ for $90 < p_T < 170 \text{ GeV}$; at higher (lower) p_T it decreases linearly with a slope of -0.0004 (-0.0047) GeV^{-1} .

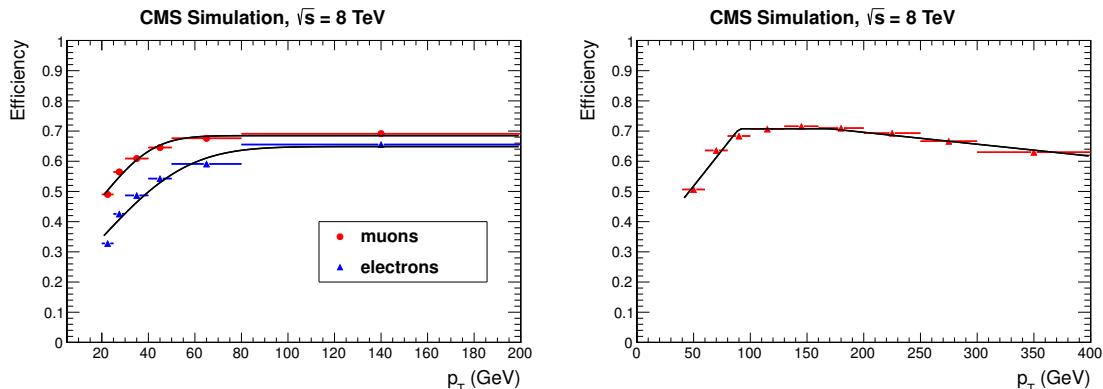


Figure 2. Lepton selection efficiency as a function of p_T (left); b-tagging efficiency as a function of the b-quark p_T (right). The superimposed curves represent the efficiency parametrizations discussed in section 7.

8 Limits on models of new physics

The results of the search are used to constrain specific models of new physics. For each model considered, limits are derived from the signal region expected to give the most stringent limit on the cross section at a given point in the parameter space of the model. The event selection efficiency for a given model is obtained from MC simulation, and the limits are calculated including systematic uncertainties on lepton efficiency, trigger efficiency, luminosity, jet energy scale, and b-tagging efficiency. The latter two uncertainties are evaluated at each point in the parameter space.

The results from SR1 and SR2 are used to set limits on the cross section for same-sign top-quark pair production, $\sigma(pp \rightarrow tt + \bar{t}\bar{t})$ from SR1, and $\sigma(pp \rightarrow tt)$ from SR2. Here $\sigma(pp \rightarrow tt + \bar{t}\bar{t})$ is shorthand for the sum $\sigma(pp \rightarrow tt) + \sigma(pp \rightarrow \bar{t}\bar{t})$. Note that in most new physics scenarios $pp \rightarrow \bar{t}\bar{t}$ is suppressed with respect to $pp \rightarrow tt$ because of the parton distribution functions of the proton. These limits are calculated using simulated $pp \rightarrow t\bar{t}$ events to model the acceptance. This acceptance, including branching fractions, is $0.29 \pm 0.04\%$. We find upper limits $\sigma(pp \rightarrow tt + \bar{t}\bar{t}) < 0.87$ pb and $\sigma(pp \rightarrow tt) < 0.30$ pb at the 95% CL; the median expected limits are 0.72 and 0.37 pb, respectively.

Next, we present limits on the parameter spaces of four R-parity-conserving SUSY models with third-generation squarks. The decay chains under consideration are shown schematically in figure 3.

Scenarios A1 and A2 represent models of gluino pair production resulting in the $t\bar{t}\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$ final state, where $\tilde{\chi}_1^0$ is the lightest neutralino [12, 29, 30, 33, 34]. In model A1, the gluino undergoes a three-body decay $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ mediated by an off-shell top squark. In model A2, the gluino decays to a top quark and an anti-top squark, with the on-shell anti-squark further decaying into an anti-top quark and a neutralino.

Models B1 and B2 have bottom squarks decaying as $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^-$ and $\tilde{\chi}_1^- \rightarrow W^- \tilde{\chi}_1^0$. Model B1 is a model of bottom-squark pair production, followed by one of the most likely

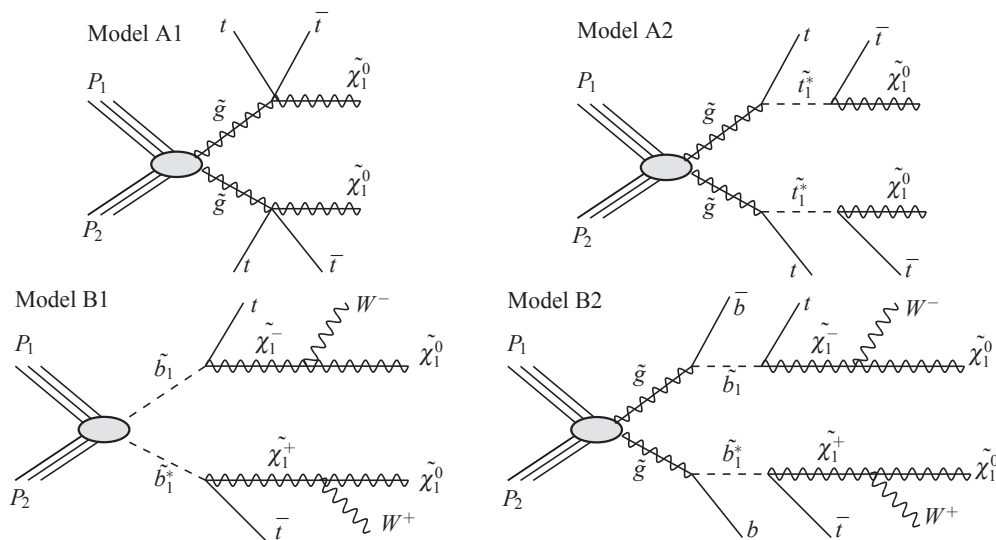


Figure 3. Diagrams for the four SUSY models considered (A1, A2, B1, and B2).

decay modes of the bottom squark; model B2 consists of gluino pair production followed by $\tilde{g} \rightarrow \tilde{b}_1 \bar{b}$. The gluino decay modes in models A1 and A2 would be dominant if the top squark is the lightest supersymmetric quark. Conversely, if the bottom squark is lightest, the decay mode in model B2 would be the most probable.

Excluded regions in the parameter space of the four models are shown in figure 4. For the gluino-initiated models (A1, A2, and B2), we exclude gluinos with masses below around 1 TeV, with only a small dependence on the details of the models. This is because the limits are driven by the common gluino pair production cross section. In the case of bottom squark pair production (model B1) we set a limit $m(\tilde{b}_1) > 450$ GeV at 95% CL.

These models are also probed by other CMS new physics searches in different decay modes, although other searches have so far been interpreted in the context of model A1 but not A2, B1, or B2. For model A1 the limits given here are complementary to the limits from the single-lepton and “razor” searches [36]: less stringent at low $m(\tilde{\chi}_1^0)$ but more stringent at high $m(\tilde{\chi}_1^0)$. A similar conclusion applies to model A2, since the final state is the same. Comparable limits for model A1, as well as for similar models with top and bottom quarks from gluino decays, have been reported by the ATLAS collaboration [37–39]. In the case of bottom-squark pair production, the ATLAS collaboration has reported a limit $m(\tilde{b}_1) > 390$ GeV, but assuming the decay mode $\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$ instead of the model B1 mode $\tilde{b}_1 \rightarrow t \tilde{\chi}_1^-$ [40].

9 Summary

In summary, we have presented results of a search for same-sign dileptons with bottom-quark jets using the CMS detector at the LHC, based on a 10.5 fb^{-1} data sample of pp

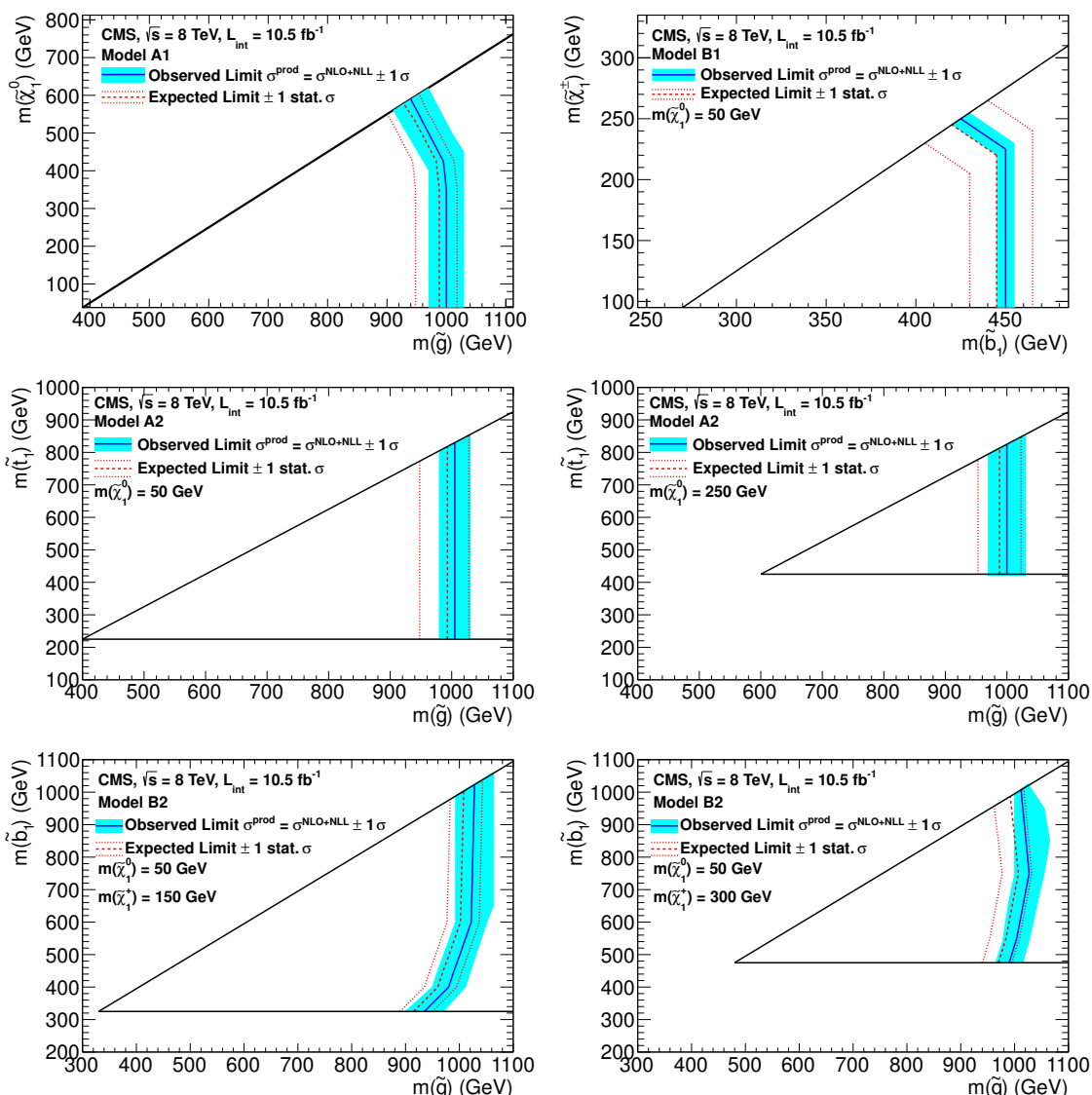


Figure 4. Exclusion regions at 95% CL in the planes of $m(\tilde{\chi}_1^0)$ vs. $m(\tilde{g})$ (model A1), $m(\tilde{\chi}_1^-)$ vs. $m(\tilde{b}_1)$ (model B1), $m(\tilde{t}_1)$ vs. $m(\tilde{g})$ (model A2), and $m(\tilde{b}_1)$ vs. $m(\tilde{g})$ (model B2). Models A2, B1, and B2 have more than two mass parameters, and cannot be fully represented in a two dimensional plot. The assumed values of the additional mass parameters are indicated in the plots. The black lines represent the kinematic boundaries of the models. The excluded regions are those within the kinematic boundaries and to the left of the bands. The effects of the theoretical uncertainties on the next-to-leading-order plus next-to-leading-log calculations of the production cross sections [35] are indicated by the shaded bands; the expected limits and their ± 1 standard-deviation variations are also shown.

collisions at $\sqrt{s} = 8$ TeV. No significant deviations from the standard model expectations are observed.

The results are used to set upper limits on the same-sign top-pair production cross

section $\sigma(\text{pp} \rightarrow \text{tt} + \bar{\text{t}}\bar{\text{t}}) < 0.87$ pb and $\sigma(\text{pp} \rightarrow \text{tt}) < 0.30$ pb at the 95% confidence level.

We also exclude gluinos with masses up to approximately 1 TeV if they decay exclusively into top or bottom squarks, and we place a lower limit on the bottom-squark mass of 450 GeV. Our results assume that the top and bottom squarks decay as $\tilde{\text{t}}_1 \rightarrow \text{t}\tilde{\chi}_1^0$ and $\tilde{\text{b}}_1 \rightarrow \text{b}\tilde{\chi}_1^-$, respectively. In the latter case we have also assumed $\tilde{\chi}_1^- \rightarrow \text{W}^- \tilde{\chi}_1^0$.

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