CMS Physics Analysis Summary

Search for new physics in events with same-sign dileptons, b-tagged jets and missing energy

The CMS Collaboration

Abstract

A search for anomalous production in the same-sign dilepton final state with at least two b-jets and missing energy is performed. This analysis uses a data sample collected with the CMS detector of proton-proton collisions at a centre-of-mass energy of 7 TeV, corresponding to an integrated luminosity of 4.7 fb$^{-1}$. No excess above the standard model background expectation is observed. Upper limits at 95% confidence level are set on the number of events from non-standard model sources. These limits are used to set constraints on a number of new physics models. Information on acceptance and efficiencies are also provided so that the results can be used to confront additional models in an approximate way.
1 Introduction

In this note we present a search for anomalous production of events with two like-sign isolated leptons ($e$ or $\mu$), b-quark jets, and missing energy. In proton-proton collisions events from standard model (SM) sources with two isolated like-sign leptons, hadronic jets, and missing energy are rare. Anomalous production of such events would be an indication of new physics. While in general the hadronic jets in these anomalous processes can originate from light flavor, there is a range of well-established models predicting the presence of two to four b-quark jets in such events. These appear naturally in signatures of supersymmetry (SUSY) where bottom-and top- quark superpartners are lighter than other squarks [1–5], enhancing the fraction of strongly produced SUSY events with top and bottom quarks in the final states. Here, the signatures with two like-sign leptons, b-quark jets and missing energy most naturally correspond to strongly produced SUSY processes with multiple W bosons appearing in the decay chains, either from top quarks or from charginos. In addition to SUSY processes, an exchange of a $Z'$-boson with flavor violating ut-quark coupling [6, 7], proposed to explain the top-quark pair forward-backward production asymmetry observed at the Tevatron [8–10], leads naturally to like-sign top-quark pair production at the LHC. A similar topology is expected in models of maximal flavor violation (MaxFV) [11–13]. Experimentally, events with two isolated like-sign leptons, jets, and missing energy, selected without b-quark jet identification (b-tagging), are dominated by $tt$ production [14, 15] with one of the leptons originating from the semileptonic decay of a b-quark. (These leptons are usually accompanied by significant hadronic activity, but can be isolated due to fluctuations in the b-quark decay chain and fragmentation). The requirement of at least two b-tagged jets strongly suppresses the $tt$ background, since the two b-quarks in $tt$ are very unlikely to produce three distinct objects, i.e., two b-tagged jets and one isolated high transverse momentum ($p_T$) lepton.

The search was performed on a data set corresponding to an integrated luminosity of $4.7 \text{ fb}^{-1}$ collected by the CMS [16] collaboration in proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ delivered by the LHC in 2011. This work relies heavily on the event selections and background estimation methods of the previous CMS inclusive same sign dilepton search not requiring b-tagged jets in the final states [14, 15, 17]. Compared to the most recent analysis [15], a more stringent isolation requirement is applied to suppress backgrounds with misidentified leptons, and the lepton transverse momenta ($p_T$) are required to be above 20 GeV, as is typical for leptons from $W$ decay that are expected to be present in the signals of interest. The rest of the data analysis is unchanged.

A counting signature-based experiment is performed by comparing the event yield with the expected signal and backgrounds. A loose baseline selection is identified first, and selection regions with tighter requirements on the missing energy and on the sum of jet $p_T$ ($H_T$) are then added to provide better sensitivity to potential signal models. A recipe is provided to set limits on any model with same-sign dileptons, missing energy, and b-jets. The recipe relies on efficiency functions to be used to emulate the selection efficiencies for leptons, jets, and missing energy. These functions can then be applied to a signal simulated at the matrix-element level.

As a reference, we provide constraints on several models representative of a topology with two like-sign leptons, missing energy and b-jets. The signal topologies with only two b-quark jets in the final states are: like-sign top quarks production in the $Z'$ model [6] and in the MaxFV model [13]; production of two sbottoms each decaying as $\tilde{b}_1 \rightarrow t \tilde{\chi}^+_1$, where $\tilde{\chi}^+_1 \rightarrow W^- \tilde{\chi}^0_1$ and $\tilde{\chi}^0_1$ is the lightest supersymmetric particle (LSP). The topologies with more than two b-quark jets are: $\tilde{g}\tilde{g}$ or $\tilde{g}b$ production with $\tilde{g} \rightarrow b\tilde{b}$ and $\tilde{b}_1 \rightarrow t \tilde{\chi}^+_1$, where $\tilde{\chi}^+_1 \rightarrow W^- \tilde{\chi}^0_1$, $\tilde{g}\tilde{g}$ with both gluinos giving a $tt\tilde{\chi}^0_1$ final state with an intermediate virtual or on-shell stop.
2 CMS Detector

The central feature of the Compact Muon Solenoid (CMS) apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the $x$-axis pointing to the center of the LHC, the $y$-axis pointing up (perpendicular to the LHC plane), and the $z$-axis along the counterclockwise-beam direction. The polar angle, $\theta$, is measured from the positive $z$-axis and the azimuthal angle, $\phi$, is measured in the $x$-$y$ (transverse) plane. The pseudorapidity $\eta$ is defined as $\eta = -\ln \tan \theta/2$. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). 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 detectors covering $|\eta| < 3$, CMS has extensive forward calorimetry reaching $|\eta| \lesssim 5$. A more detailed description can be found in Ref. [16].

3 Datasets and Event Selection

Dilepton events used in the analysis are selected by the CMS trigger system if there are at least two leptons (electrons or muons) reconstructed online. The trigger selects dielectron events with at least one electron with energy measured in the ECAL projected on the transverse plane ($E_T$) above 17 GeV, as well as a second electron with $E_T > 8$ GeV. Electron-muon events are required to have at least one electron with $E_T > 17$ (8) GeV and one muon with $p_T > 8$ (17) GeV. For dimuon events the requirements on $p_T$ for the higher (lower) threshold changed as the luminosity increased during data taking from 7 (7) GeV, to 13 (8) GeV, and then finally 17 (8) GeV.

Electron candidates are reconstructed for analysis using a combination of measurements provided by the tracker and the ECAL [18]. Muon candidates are reconstructed using a combination of measurements in the silicon tracker and the muon detectors [19]. Two leptons of the same-sign, $p_T > 20$ GeV, and $|\eta| < 2.4$, are required in each event. Electron candidates that shower in the transition region between the barrel and endcap calorimeters ($1.442 < |\eta| < 1.566$) are not considered in the analysis. The two leptons must be consistent with originating from the same collision vertex. Additional identification requirements are applied to suppress backgrounds in the same way as in the inclusive same-sign dilepton analysis [15]. The isolation requirement is applied on a scalar sum of the track $p_T$ and calorimeter $E_T$ measurements, computed in a cone of $\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.3$ relative to the lepton candidate momentum. This sum must be less than 0.1$p_T$ of the candidate itself. The two lepton candidates are required to have an invariant mass $m_{\ell \ell}$ above 8 GeV to suppress backgrounds from b-hadron decays. Events with any third lepton with $p_T > 10$ GeV and isolation sum below 0.2$p_T$ are rejected if this lepton forms an opposite-sign same-flavor pair having $76 < m_{\ell \ell} < 106$ GeV with either of the selected leptons. This requirement suppresses the WZ background.

Jets and missing transverse energy ($E_T^{\text{miss}}$) are reconstructed by the particle flow algorithm [20–22]. Jets are clustered using the anti-$k_T$ algorithm [23] with a parameter $R = 0.5$. Jet energies are corrected by subtracting the average contribution from particles from other proton-proton collisions (pileup) and by scaling the measured jet momentum to correspond on average to that expected in simulation [21]. At least two jets with $p_T > 40$ GeV and $|\eta| < 2.5$ are required in each event. The magnitude of the $E_T^{\text{miss}}$-vector, computed as the negative of the vector sum of all particle flow candidate momenta in the transverse plane, is required to be above 30 GeV.

At least two of the selected jets are required to be b-tagged using the simple secondary vertex tagger at a medium operating point (SSVHEM) [24]. This b-jet tagging algorithm requires the
reconstruction of a secondary vertex with at least two associated tracks. The secondary vertex must be significantly displaced from the primary collision vertex.

Events passing the selections described above comprise the baseline sample. There are 7 events observed in data, 2\(ee\), 2\(\mu\mu\), and 3\(e\mu\).

4 Background Estimation

There are three distinct background contributions to this search: events with one or two “fake” leptons, rare SM processes that yield events with two isolated same-sign leptons, and events with opposite-sign lepton pairs with a lepton charge misreconstructed (“q-flips”). Here we use the term “fake lepton” to refer to a lepton from heavy flavour decay, or an electron from unidentified photon conversion, or a muon from meson decays in flight, or a hadron misidentified as a lepton. The backgrounds, which are further discussed below, are estimated using the same techniques as in the inclusive analysis [14, 15]: the fake and q-flip backgrounds are estimated from control data samples, while the rare SM backgrounds are taken from simulation.

The background from fakes is estimated based on events with one or both leptons failing the isolation and identification selection, but still passing a looser selection. Counts of events in this control sample are weighted by the expected ratio (“tight-to-loose” or TL ratio) of the rate of fake leptons passing the selection to that of those failing it. This TL ratio is measured as a function of lepton type, lepton \(p_T\) and lepton \(\eta\) in a data sample of events with a single lepton candidate and a well separated jet (“away-jet”). After suitable suppression of W and Z processes, this sample is dominated by fakes. The systematic effects on the method to estimate events with fake leptons arise from differences in kinematics and sample composition between the sample where the TL ratio is measured and the sample where it is applied. The systematic uncertainty on the method is taken to be 50%. This uncertainty is based on tests of the ability of this method to predict the same-sign dilepton background in simulated \(t\bar{t}\) events as well as on the observed variations of the TL ratio as a function of the \(p_T\) threshold of the away jet and the addition of a btag requirement on that jet.

The baseline sample is estimated to have 1.2 ± 0.9, 0.3 ± 0.3, and 2.0 ± 1.2 events with fake leptons in the \(ee\), \(\mu\mu\), and \(e\mu\) final states, respectively. These uncertainties include the statistical uncertainties on the number of events passing the loose lepton selection, as well as the 50% systematical uncertainty.

As mentioned above, the contribution to the event yield from rare SM processes yielding isolated high \(p_T\) same-sign dileptons, jets, and missing energy, is estimated from simulation. Events are generated with the MADGRAPH [25] event generator and then passed on to the PYTHIA [26] program for parton showering. The generated events are processed by the CMS event simulation and the same chain of reconstruction programs used for collision data. We find that background events from \(t\bar{t}\) W and \(t\bar{t}\) Z production represent more than 90% of all the genuine same-sign dilepton backgrounds considered in simulation. Other processes considered include production of diboson (ZW, ZZ, same-sign WW) and triboson (combinations of W and Z) final states. Compared to the inclusive analysis [15], these backgrounds are strongly suppressed by the b-tagging requirement. Backgrounds like (W/Z)\(\gamma\) and \(t\bar{t}\)\(\gamma\) are included as well to simulate events with a photon converting in the tracker material and misidentified as an electron. Their contribution is negligibly small. A conservative systematic uncertainty of 50% is assigned to the total number of expected simulated events. The production cross-sections used to normalize the dominant \(t\bar{t}\) W and \(t\bar{t}\) Z contributions are 0.16 pb and 0.14 pb [27], respectively. In the baseline sample the simulated rare SM backgrounds are expected to contribute
$0.7 \pm 0.4, 0.9 \pm 0.5,$ and $1.6 \pm 0.8$ events in the $ee$, $\mu\mu$, and $e\mu$ final states, respectively.

Events with opposite-sign lepton pairs where one of the leptons has incorrectly measured charge (q-flip) contribute to the same-sign dilepton sample. The q-flip probability for muons is of order $10^{-5}$ and can be neglected. In contrast, this probability for electrons with kinematics typical to that of a W or Z decay is estimated in simulation to be of the order of $10^{-3}$. The number of same sign events due to q-flips is given by the number of opposite sign events passing the same selections with a weight applied to each electron corresponding to its charge misidentification probability. This probability is measured in simulation as a function of electron $p_T$ and $\eta$. The method was tested in data by using the $Z \to e^+e^-$ sample and the probability mentioned above to predict the number of $e^\pm e^\pm$ events with invariant mass consistent with the $Z$ mass. This prediction was found to be in good agreement with the number of events of this type in the CMS data sample. A systematic uncertainty of 20% is estimated for this method based on variation in the average charge misidentification rate between typical lepton momenta in $Z$ and $t\bar{t}$ events. In the baseline sample the q-flip contribution is estimated to be $0.5 \pm 0.1$ in each of the $ee$ and $e\mu$ final states.

5 Search results

After the basic selection described in Section 3, we define several “signal regions” (SR) with increasing requirements on $H_T$ and $E_T$ with respect to the baseline selection. These requirements improve the sensitivity to new physics models with high $\sqrt{s}$ and/or high $E_T$ from, e.g., high $p_T$ non interacting particles, such as LSPs in SUSY models. We also define a SR with minimal requirements on $H_T$ and $E_T$ but allowing only for positive leptons. This region is designed to be sensitive to $pp \to t\bar{t}$ production (in these models $pp \to t\bar{t}$ would be further suppressed due to the parton distribution functions of the proton). Finally, we have also defined a SR with moderate $H_T$ and $E_T$ requirements and three or more $b$-tagged jets (SR7). This region can improve the sensitivity to models of new physics with several ($\geq 4$) $b$-quarks in the final state. However for the models considered here (Section 8) we find that SR7 does not improve the sensitivity. This is because the increase in efficiency due to the looser $H_T$ and $E_T$ requirements does not compensate for the efficiency loss associated with the requirement of a third $b$-tag.

The definition of the signal regions, the data event yields, and the expected backgrounds are summarized in Table 1. Distributions of $H_T$ and $E_T$ are also displayed in Fig. 1. Note that SR1 corresponds to the baseline event selection of Section 3. The event yields are consistent with the background predictions, and there is no evidence for physics beyond the SM in this search. In Table 1 we also show the observed upper limit on the number of non-SM events calculated using the CLs method [28, 29] under three different assumptions for the signal efficiency uncertainty. This uncertainty will be discussed in Section 6.

6 Efficiencies and associated uncertainties

Events in this analysis are collected with dilepton triggers. The efficiency of the trigger has been measured to be $99 \pm 1\%$ ($96 \pm 3\%$) per electron (muon) in the range $|\eta| < 2.4$. The efficiency of the lepton identification and isolation requirements, as measured on a sample of simulated events from a typical SUSY scenario, is displayed in Figure 2. Studies of large data samples of $Z \to ee$ and $Z \to \mu\mu$ events indicate that the simulation reproduces the efficiencies of the identification requirements to better than $2\%$ [18, 19]. The efficiency of the isolation requirement on leptons in $Z$ events is also well reproduced by the simulation. However, this efficiency depends on the hadronic activity in the event, and is typically $10\%$ lower in SUSY events with hadronic...
Figure 1: Top plot: distribution of $E_T$ vs. $H_T$ for the seven events in SR1; $ee$ events: circles; $e\mu$ events: squares; $\mu\mu$ events: triangles. Bottom left plot: projection of the scatter plot on the $H_T$ axis. Bottom right plot: projection of the scatter plot on the $E_T$ axis. For the one-dimensional distributions we also show the result of the background predictions, with their uncertainties.
6 Efficiencies and associated uncertainties

Table 1: A summary of the results of this search. For each signal region (SR), we show its most distinguishing kinematical requirements, the prediction for the three background (BG) components as well as the total, the event yield, and the observed 95% CL upper limit on the number of non-SM events in each region calculated under three different assumptions for the event efficiency uncertainty (see text for details).

<table>
<thead>
<tr>
<th>No. of jets</th>
<th>SR1</th>
<th>SR2</th>
<th>SR3</th>
<th>SR4</th>
<th>SR5</th>
<th>SR6</th>
<th>SR7</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
</tr>
<tr>
<td>No. of btags</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td>≥ 2</td>
</tr>
<tr>
<td>Lepton charges</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>$E_T$</td>
<td>≥ 30 GeV</td>
<td>≥ 30 GeV</td>
<td>≥ 120 GeV</td>
<td>≥ 50 GeV</td>
<td>≥ 50 GeV</td>
<td>≥ 120 GeV</td>
<td>≥ 50 GeV</td>
</tr>
<tr>
<td>$H_T$</td>
<td>≥ 80 GeV</td>
<td>≥ 80 GeV</td>
<td>≥ 200 GeV</td>
<td>≥ 200 GeV</td>
<td>≥ 320 GeV</td>
<td>≥ 320 GeV</td>
<td>≥ 320 GeV</td>
</tr>
<tr>
<td>q-Flip BG</td>
<td>1.1 ± 0.2</td>
<td>0.5 ± 0.1</td>
<td>0.05 ± 0.01</td>
<td>0.3 ± 0.1</td>
<td>0.12 ± 0.03</td>
<td>0.026 ± 0.009</td>
<td>0.008 ± 0.004</td>
</tr>
<tr>
<td>Fake BG</td>
<td>3.4 ± 2.0</td>
<td>1.8 ± 1.2</td>
<td>0.32 ± 0.50</td>
<td>1.5 ± 1.1</td>
<td>0.81 ± 0.78</td>
<td>0.15 ± 0.45</td>
<td>0.15 ± 0.45</td>
</tr>
<tr>
<td>Rare SM BG</td>
<td>3.2 ± 1.6</td>
<td>2.1 ± 1.1</td>
<td>0.56 ± 0.28</td>
<td>2.0 ± 1.0</td>
<td>1.04 ± 0.52</td>
<td>0.39 ± 0.20</td>
<td>0.11 ± 0.06</td>
</tr>
<tr>
<td>Total BG</td>
<td>7.7 ± 2.6</td>
<td>4.4 ± 1.6</td>
<td>0.9 ± 0.6</td>
<td>3.7 ± 1.5</td>
<td>2.0 ± 0.9</td>
<td>0.6 ± 0.5</td>
<td>0.3 ± 0.5</td>
</tr>
<tr>
<td>Event yield</td>
<td>7</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$N_{UL}$ (12% unc.)</td>
<td>7.4</td>
<td>6.9</td>
<td>5.2</td>
<td>7.3</td>
<td>4.7</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>$N_{UL}$ (20% unc.)</td>
<td>7.7</td>
<td>7.2</td>
<td>5.4</td>
<td>7.6</td>
<td>4.8</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>$N_{UL}$ (30% unc.)</td>
<td>8.1</td>
<td>7.6</td>
<td>5.8</td>
<td>8.2</td>
<td>5.1</td>
<td>2.8</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Cascades than in Z events. To account for this variation, we take a 5% systematic uncertainty per lepton in the acceptance to events from new physics.

Figure 2: Lepton selection efficiency as a function of $p_T$ (left); b-tagging efficiency as a function of b-quark $p_T$ (right). See text for details.

The b-tagging efficiency on simulated data is also shown in Figure 2 for b-jets of $|\eta| < 2.5$. Study of a variety of data control samples indicate that this efficiency needs to be degraded by a factor of 0.96, independent of $p_T$. This factor of 0.96 is applied to the simulation of possible new physics signals, e.g., all the models of Section 8. The systematic uncertainty on the b-tagging efficiency is 4% (15%) for jets of $p_T < 240$ GeV ($p_T > 240$ GeV).

The energies of jets in this analysis are known to 7.5% (not all the corrections described in Ref. [21] were applied). The uncertainty on the jet energy scale has an effect on the efficiencies of the jet multiplicity, $H_T$, and $E_T$ requirements. The importance of these effects depends on the signal region and the model of new physics. For example, for the $Z'$ model of Section 8.1, the uncertainty on the acceptance of the SR2 requirements due to the imperfect knowledge of the jet energy scale is 8%. In general, models with high hadronic activity and high $E_T$ are less affected by this uncertainty.

Finally, there is a 4.5% uncertainty on the yield of events from any new physics model due to
the uncertainty in the luminosity normalization. The total uncertainty on the acceptance is then in the 12-30% range.

7 Information for Model Testing

The search described in this letter is a signature-based search that finds no evidence for physics beyond the SM. In Section 8 we use our results to put bounds on the parameter space of a few interesting new physics models. Here we present additional information that can be used to confront other models of new physics in an approximate way by generator level studies that compare the expected number of events in 4.7 fb$^{-1}$ with the upper limits from Table 1.

The values of $N_{UL}$ in Table 1 are given under different assumptions for the efficiency uncertainty. This is because, as discussed in Section 6, this uncertainty depends on the model under test. Fortunately, the dependence of $N_{UL}$ on the acceptance uncertainty is not very strong.

The kinematical requirements on jets and leptons given in Section 3 are the first ingredients of the acceptance calculation for a new model. Leptons at the hard-scatter level passing the kinematical selection can be counted, and this count can be corrected for the finite lepton efficiencies shown in Fig. 2. Similarly, the number of jets in the event can be approximated by counting the number of colored final state partons of $p_T > 40$ GeV and $|\eta| < 2.5$ at the hard scatter level. A generator level $H_T$ variable, $H_T^{gen}$, can be calculated by summing the $p_T$ of all the colored partons from the previous step; isolated photons and additional leptons of $p_T > 40$ GeV and and $|\eta| < 2.5$ should also be included in the $H_T^{gen}$ calculation. Similarly, a generator level $E_T$ variable, $E_T^{gen}$, can be defined from the vector sum of transverse momenta of all non interacting particles. Finally, the number of reconstructed $b$-jets can be obtained by counting the number of jets associated to $b$-quarks and applying the efficiency parametrization of Fig. 2. The efficiencies of the $H_T$ and $E_T$ requirement after hadronization and detector simulation as a function of $H_T^{gen}$ and $E_T^{gen}$ for a typical SUSY scenario are shown in Fig. 3.

The lepton efficiency curves of Figure 2 are parametrized as

$$
\epsilon = \epsilon_\infty \text{erf} \left( \frac{p_T - 20 \text{ GeV}}{\sigma} \right) + \epsilon_20 \left( 1 - \text{erf} \left( \frac{p_T - 20 \text{ GeV}}{\sigma} \right) \right),
$$

with $\epsilon_\infty = 0.66 (0.67)$, $\epsilon_20 = 0.33 (0.44)$, $\sigma = 32$ GeV (23 GeV) for electrons (muons).
The Monte Carlo $b$-tagging efficiency parametrization, also shown in Figure 2, is $\epsilon = 0.62$ for $90 < p_T (\text{GeV}) < 170$; at higher (lower) $p_T$ it decreases linearly with a slope of $0.0012$ ($0.0051$) GeV$^{-1}$.

The $H_T$ and $E_T$ turn-on curves as a function of the respective generator version shown in Figure 3 are parametrized as $0.5 \{ \text{erf}(x - x_{1/2})/\sigma + 1 \}$. The parameters of the function are summarized in Table 2.

Table 2: Parameters used in describing the turn-on curves for $H_T$ and $E_T$ as a function of their generator values. See text for details.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$H_T$</th>
<th>$E_T$</th>
</tr>
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</table>
| $x_{1/2}$ | > 200 GeV | > 30 GeV
| $\sigma$  | > 320 GeV | > 50 GeV
|           | 13 GeV | 43 GeV
|           | 188 GeV | 123 GeV
|           | 308 GeV | 37 GeV
|           | 88 GeV  | 39 GeV
|           | 102 GeV | 37 GeV

For a few of the Monte Carlo models of new physics described in Section 8, we have compared the acceptance from the full simulation with the result of the simple acceptance model described above. Typically the two calculations agree at the $\approx 30\%$ level or better in the case of FCNC based $Z'$ model or MxFV, where we expect same sign top final state; performance may vary more for other models.

8 Models of new physics

We use the search results to constrain several specific models of new physics. For each model considered, we use the Monte Carlo yields and the background estimations corresponding to the signal region that is expected to give the most stringent limit on the cross-section at a given point in model parameter space. Cross-section limits are computed including systematic uncertainties on lepton efficiency (5% per lepton), luminosity (4.5%), jet energy scale, and $b$-tagging efficiency. These last two uncertainties are evaluated at each point in parameter space, as they depend on the underlying kinematics of the events. In addition, the Monte Carlo event yields are corrected for “signal contamination”, i.e., the over-subtraction of the fake background that would occur in the presence of a real signal. This over-subtraction would be caused by same-sign dilepton events with one lepton passing the loose selection but failing the final identification or isolation requirements. The cross-section limits are then used to exclude regions of model parameter space.

8.1 Models of $pp \rightarrow tt$

We consider two models that result in same-sign top pairs without significant additional hadronic activity or missing energy. Limits are set based on the results from SR2. The kinematical requirements in this region are modest, and are comparable to those used in measurements of the $pp \rightarrow t\bar{t}$ cross-section in the opposite sign dilepton channel [30]. We require only positively charged dileptons, since in the two models considered $t\bar{t}$ production dominates over $t\bar{t}$.

The first model is the $Z'$ model of Ref. [6], which was proposed as a possible explanation of the anomalous forward-backward asymmetry observed at the Tevatron [8–10]. This model introduces a new neutral boson that couples chirally to up and top quarks. The relevant term in the lagrangian is $\mathcal{L} = \frac{1}{2} g_W f_R \bar{u} \gamma^\mu (1 + \gamma^5) t Z'_\mu + \text{h.c.}$, and the model parameters are $f_R$ and the mass of the $Z'$, $m(Z')$. In this model same sign top pairs are produced dominantly through $t$-channel $Z'$ exchange in $uu \rightarrow tt$. 
8.2 Models with four top quarks and 2 LSPs from gluino pair production and decay via real or virtual stop quarks

The efficiency for \( pp \to tt \) events in the \( Z' \) model was calculated from simulated Monte Carlo events, first generated with MADGRAPH and then processed by Pythia for parton showering. We find an efficiency, including branching ratios, of \((0.23 \pm 0.04)\%\), largely independent of \( m(Z') \). The resulting cross-section upper limit is 0.67 \( \text{pb} \) at 95% CL. This improves the previous CMS limit \([17]\) by a factor of 25. This improvement is due to the factor 130 increase in the integrated luminosity between the two analyses. The limit scales faster than the inverse of the square root of the luminosity since the addition of the b-tag requirement has reduced the background level by a large factor. Our limit is also a factor of 5.5 more stringent than that reported by the ATLAS collaboration \([31]\).

The second model \([11–13]\) has a new scalar SU(2) doublet \( \Phi = (\eta^0, \eta^+) \) that couples the first and third generation quarks \( (q_1, q_3) \) via a Lagrangian term \( \mathcal{L} = \xi \Phi q_1 q_3 \). Remarkably, this model is largely consistent with constraints from flavor physics. The parameters of this ”Maximally Flavor Violating” (MxFV) model are the mass of the \( \eta^0 \) boson and the value of the coupling \( \xi \). In the MxFV model, same sign top pairs are produced dominantly in \( uu \to tt \) through \( t \)-channel \( \eta^0 \) exchange. At small values of \( \xi \) and \( \eta^0 \) mass \( ug \to t\eta^0 \to ttu \) becomes important; the third production mechanism, \( uu \to \eta^0\eta^0 \to uu\bar{t}, \bar{u}u\bar{t}, uu\bar{t} \) is also considered in our analysis. In the MxFV case, Monte Carlo events were generated using LHE files interfaced with MADGRAPH, followed by PYTHIA for parton showering. The decay widths are computed using BRIDGE \([32]\).

The limits on the parameter spaces of the \( Z' \) and MxFV models are shown in Figure 4. These limits are based on the lowest order (LO) cross-section calculation. Our bounds disfavor the \( Z' \) model as an explanation of the Tevatron \( tt \) forward-backward asymmetry; the MxFV limits are significantly more stringent than those of the CDF experiment \([13]\).

8.2 Models with four top quarks and 2 LSPs from gluino pair production and decay via real or virtual stop quarks

In this Section we consider two SUSY models of gluino pair production \((pp \to \tilde{g}\tilde{g})\) with stop quarks playing a dominant role in the decay of the gluino. The gluino decays under consideration are (see also Fig. 5)

- Model A1, three-body gluino decay mediated by virtual stop: \( \tilde{g} \to t\bar{t}\chi_1^0 \) \([33–35]\);

\footnote{Model A1 is also referred to as “T1tttt” within the CMS Collaboration.}
• Model A2, two-body gluino decay to a top-stop pair: $\tilde{g} \to \tilde{t}_1 \tilde{t}_1$, $\tilde{t}_1 \to t \tilde{\chi}_0^0$ [4, 36].

The assumption of Model A1 is that the stop is the lightest squark, but all squarks are heavier than the stop. The dominant gluino decay channel would then be $\tilde{g} \to t \tilde{\chi}_1^0$, mediated by virtual stop quarks. Model A2 is the same as Model A1 but with stop quarks light enough to be on-shell. Both models result in $t\bar{t}\tilde{\chi}_0^1$ final states, i.e., final states with as many as four isolated high $p_T$ leptons, four $b$-quarks, several light quark jets, and significant missing energy from the neutrinos in $W$ decay and the LSPs. For Model A1, the parameters are the gluino mass, $m(\tilde{g})$, and the LSP mass, $m(\tilde{\chi}_0^1)$. Model A2 has the stop mass, $m(\tilde{t}_1)$, as an additional parameter.

SUSY events for models A1 and A2 were generated with PYTHIA. We find that for a large range of parameter space the most sensitive signal region is SR6. This is because these new physics scenarios result in many jets and significant $E_T$. Near the kinematical boundaries, where the $\tilde{\chi}_1^0$ has low momentum, SR4 and SR5 tend to be the most sensitive.

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**Figure 6:** Left plot: exclusion (95 % C.L.) in the $m(\tilde{\chi}_1^0) - m(\tilde{g})$ plane for model A1 (gluino decay via virtual stop quarks). The band represents the theoretical uncertainty on the gluino pair production cross-section. Right: exclusion (95 % C.L.) in the $m(\tilde{t}_1) - m(\tilde{g})$ plane for model A2 (gluino decay to on-shell top squarks) for different choices of the LSP mass.
The limits on the parameter space of the A1 and A2 models are displayed in Figure 6. These limits are based on the NLO+NLL [37, 38] calculations of the gluino pair production cross-section.

8.3 Models with multiple top quarks and W-bosons from decays of sbottom quarks

We now study possible SUSY signals with pairs of sbottom quarks decaying as $\tilde{b}_1 \rightarrow t\tilde{\chi}^-$ and $\tilde{\chi}^- \rightarrow W^-\chi^-_1$. The production mechanisms are (see also Fig. 7)

- Model B1, sbottom pair production: $pp \rightarrow \tilde{b}_1\tilde{b}_1^*$;
- Model B2, sbottom from gluino decay: $pp \rightarrow \tilde{g}\tilde{g}$ or $pp \rightarrow \tilde{g}\tilde{b}_1$ followed by $\tilde{g} \rightarrow \tilde{b}_1\tilde{b}$.

In scenarios where the sbottom is the lightest squark, the gluino decay mode of model B2 would have the highest branching fraction.

The final states are then $t\bar{t}W^+W^-\tilde{\chi}^+_1\tilde{\chi}^-_1$ for Model B1 and, for Model B2, a mixture of $t\bar{t}W^-W^-$, $t\bar{t}W^+W^-$, and $\tilde{t}\tilde{t}W^+W^+$, all with two $\chi^-_1$ and one or two $b$ or $\bar{b}$ quarks. For simplicity we consider only mass parameters where the chargino and the $W$ from chargino decay are on shell, except for model B1, where the chargino is allowed to be off shell.
Figure 9: Cross section limits on the sbottom pair-production cross-section compared with its expected value in Model B1. The cross-section limit is insensitive to the choice of LSP mass within the allowed kinematical range.

Figure 10: Gluino pair-production cross-section as a function of gluino mass compared with limits on the cross-section from the models A1, A2, and B2.

These final states yield up to four isolated high $p_T$ leptons, and between two and four bottom quarks. For Model B1 the parameters are the mass of the sbottom, $m(\tilde{b}_1)$, the mass of the chargino, $m(\tilde{\chi}^\pm)$, and the mass of the LSP, $m(\tilde{\chi}_1^0)$. Model B2 has $m(\tilde{g})$ as an additional parameter.

SUSY events for models B1 and B2 were also generated with Pythia. The most sensitive signal regions are SR1 and SR4 for Model B1, and SR5 and SR6 for Model B2. The exclusion region in parameter space are shown in Fig. 8 and are based on the NLO+NLL calculations of the production cross-sections.

In Fig. 9 we also show the limits on the sbottom pair-production cross-section from model B1 together with the expected cross-section for sbottom pair-production. The error band on the cross-section includes choice of the scale and associated PDF errors. Within the allowed kinematical range, we exclude $m(\tilde{b}_1)$ below 380 GeV for Model B1, and $m(\tilde{g})$ below 800 GeV for Model B2.

Finally, in Figure 10 we show the limits on $\sigma(pp \rightarrow \tilde{g}\tilde{g})$ for a few choices of the parameters of A1, A2, and B2. When compared with the expected gluino pair production cross-section, we find that the gluino mass limit is fairly insensitive to the details of the decay chain, since the limit is driven by the gluino cross-section.
9 Conclusion

We have presented results of a search for same-sign dileptons with $b$-jets and $E_T$ using the CMS detector at the LHC based on a 4.7 fb$^{-1}$ data sample of $pp$ collisions at $\sqrt{s} = 7$ TeV. We observe no significant deviations from the SM expectations.

The data are used to set 95% CL on the number of events for a number of plausible signal regions defined in terms of requirements in $E_T$ and $H_T$, the number of $b$-tagged jets (2 or 3), and also the sign of the leptons (only positive dileptons or both positive and negative dileptons).

We use these results to set limits on the parameter space of two models of same-sign top pair production, two models of gluino decay into virtual or real stop quarks, a model of sbottom pair production, and a model of sbottom production from gluino decay. In addition, we provide information to interpret our limits in other models of new physics.

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References


