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

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Abstract: A search for new physics is performed based on events with jets and a pair of isolated, same-sign leptons. The results are obtained using a sample of proton-proton collision data collected by the CMS experiment at a centre-of-mass energy of 8 TeV at the LHC, corresponding to an integrated luminosity of 19.5 fb^{-1}. In order to be sensitive to a wide variety of possible signals beyond the standard model, multiple search regions defined by the missing transverse energy, the hadronic energy, the number of jets and b-quark jets, and the transverse momenta of the leptons in the events are considered. No excess above the standard model background expectation is observed and constraints are set on a number of models for new physics, as well as on the same-sign top-quark pair and quadruple-top-quark production cross sections. Information on event selection efficiencies is also provided, so that the results can be used to confront an even broader class of new physics models.

Keywords: Supersymmetry, Hadron-Hadron Scattering

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1 Introduction

In the standard model (SM), proton-proton collision events having a final state with isolated leptons of the same sign are extremely rare. Searches for anomalous production of same-sign dileptons can therefore be very sensitive to new physics processes that produce this signature copiously. 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-quark pair production [7, 8]. In SUSY, for example, same-sign dileptons occur naturally with the production of gluino pairs, when each gluino decays to a top quark and a top anti-squark, with the anti-squark further decaying into a top anti-quark and a neutralino.

In this paper we describe searches for new physics with same-sign dileptons (ee, eμ, and $\mu\mu$) and hadronic jets, with or without accompanying missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). Our choice of signatures is driven by the following considerations. New physics signals with large cross sections are likely to be produced by strong interactions, and we thus expect significant hadronic activity in conjunction with the two leptons. Astrophysical evidence for dark matter [9] suggests considering SUSY models with R-parity conservation, which provides an excellent dark matter candidate — a stable lightest supersymmetric particle

(LSP) that escapes detection. Therefore, a search for this signature involves sizable $E_{\mathrm{T}}^{\mathrm{miss}}$ due to undetected LSPs. Nevertheless, we also consider signatures without significant $E_{\mathrm{T}}^{\mathrm{miss}}$ in order to be sensitive to SUSY models with R-parity violation (RPV) [10] which imply an unstable LSP. Beyond these general guiding principles, the choice of signatures is made independently of any particular physics model and, as a result, these signatures can be applied also to probe non-supersymmetric extensions of the SM.

The results reported in this document expand upon a previous search [11] and are based on the proton-proton collision dataset at $\sqrt{s} = 8\,\mathrm{TeV}$ collected with the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) during 2012, corresponding to an integrated luminosity of $19.5\,\mathrm{fb}^{-1}$. We consider several final states, characterized by the scalar sum (H_{T}) of the transverse momenta (p_{T}) of jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, the number of jets, and the number of jets identified as originating from b quarks (b-tagged jets). Additionally, in order to provide coverage for a wide range of generic signatures, we perform the analysis with two different requirements on the lepton p_{T}: the high-p_{T} analysis, where the leptons are selected with a p_{T} requirement of at least 20 GeV, and the low-p_{T} analysis, where the p_{T} threshold is lowered to 10 GeV. While the low-p_{T} leptons extend the sensitivity to scenarios with a compressed spectrum of SUSY particle masses, the high-p_{T} analysis targets models where the leptons are produced via on-shell W or Z bosons, and is less subject to backgrounds with leptons originating from jets. The use of a lower threshold on lepton p_{T} for the low-p_{T} analysis is compensated by a tighter H_{T} requirement. In this respect, the two searches are complementary, even if partially overlapping.

In contrast to the previous analysis [11], the signal regions within each of the low- and high-p_{T} analyses are defined to be exclusive. Furthermore, we increase the number of search regions in order to improve the sensitivity to a wider class of beyond-standard-model (BSM) processes. The selection criteria for the analysis objects and the methods used to estimate the SM backgrounds are largely unchanged from those of our previous same-sign dilepton studies [11–14].

Tables of observed yields and estimated SM backgrounds are provided for both the high-p_{T} and low-p_{T} analyses in each exclusive signal region. Having found no evidence for a BSM contribution to the event counts, limits are set on a variety of SUSY-inspired models by performing a counting experiment in each exclusive search region. Additionally, results for the high-p_{T} analysis are used to set upper limits on the cross sections of the same-sign top-quark pair production and quadruple top-quark production, which can arise from new physics or as rare processes in the SM.

Finally, we include additional information on the event selection efficiencies to facilitate the interpretation of these results within models not considered in this paper.

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 experiment uses a right-handed coordinate system, with the origin defined to be the nominal interaction point, the x axis pointing to the centre of the LHC ring, the y axis pointing up, and the z axis pointing in

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the anticlockwise-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 magnetic 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 flux-return yoke. Full coverage is provided by the tracker, calorimeters, and muon detectors within $|\eta| < 2.4$. In addition to the barrel and endcap calorimeters up to $|\eta| = 3$, CMS has extensive forward calorimetry reaching $|\eta| \lesssim 5$. Events are selected by a two-stage trigger system: a hardware-based trigger (L1) followed by a software-based high-level trigger (HLT) running on the data acquisition computer farm. A more detailed description of the CMS apparatus can be found in ref. [15].

3 Event selection and Monte Carlo simulation

Events used in this search are selected using two complementary online algorithms. The high-p_{T} analysis uses a set of dilepton triggers, requiring the first (second) highest-p_{T} lepton to have $p_{\mathrm{T}} > 17$ (8) GeV at the HLT. The low-p_{T} analysis uses high-level triggers that employ a reduced p_{T} threshold on leptons, of 8 GeV, and looser lepton identification requirements, but apply an additional online selection of $H_{\mathrm{T}} > 175$ GeV. The minimum lepton p_{T}, the lepton identification requirements, and the H_{T} selections that are imposed offline for these two analyses are driven by the trigger selections. The selection efficiencies of these triggers for events used in this analysis vary between 81% and 96% and are discussed in detail in section 6.

Offline, events with at least two isolated same-sign leptons (ee, eμ or $\mu\mu$) and at least two jets are selected. The lepton pairs are required to have an invariant mass above 8 GeV and to be consistent with originating from the same collision vertex. The requirement on the transverse impact parameter, calculated with respect to the primary vertex, has been tightened to 100 (50) μm for electrons (muons) compared to the previous versions of this analysis. This selection further suppresses the backgrounds from two sources: non-prompt leptons from semi-leptonic decays of heavy-flavour quarks and lepton charge misidentification. The algorithms used to calculate the isolation of the leptons, reconstruct jets, identify b-tagged jets, as well as the jet-lepton separation requirements are identical to the ones described in refs. [11, 12]. For the identification of b-quark jets we continue to use the medium operating point of the combined secondary vertex (CSV) algorithm [16], which is based on the combination of secondary-vertex reconstruction and track-based lifetime information. The treatment of the effects of multiple proton-proton interactions within the same LHC bunch-crossing (pileup) on jet energies [17] also remains unchanged. Unlike the previous analysis, there is no requirement on the number of b-tagged jets when selecting events. This number is, however, used in the categorization of events into various signal regions.

Kinematic selections for jets, leptons, and b-tagged jets are summarized in table 1. Events with a third lepton are rejected if the lepton forms an opposite-sign same-flavour pair with one of the first two leptons for which the invariant mass of the pair ($m_{\ell\ell}$) satisfies

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Object	p_T (GeV)	$\lvert\eta\rvert$
Electrons	>10(20)	< 2.4 and $\notin [1.4442, 1.566]$
Muons	>10(20)	<2.4
Jets	>40	<2.4
b-tagged jets	>40	<2.4

Table 1. Kinematic and fiducial requirements on leptons and jets that are used to define the low-p_T (high-p_T) analysis.

$m_{\ell\ell} < 12\,\text{GeV}$ ($p_T > 5\,\text{GeV}$) or $76 < m_{\ell\ell} < 106\,\text{GeV}$ ($p_T > 10\,\text{GeV}$). These requirements are designed to minimize backgrounds from processes with a low-mass bound state or $\gamma^* \to \ell^+\ell^-$ in the final state, as well as multiboson (WZ, ZZ, and triboson) production.

Monte Carlo (MC) simulations, which include pileup effects, are used to estimate some of the SM backgrounds (see section 5), as well as to calculate the efficiency for various new physics scenarios. All SM background samples are generated with the MadGraph 5 [18] program and simulated using a Geant4-based model [19] of the CMS detector. Signal samples are produced with MadGraph 5 using the CTEQ6L1 [20] parton distribution functions (PDF); up to two additional partons are present in the matrix element calculations. Version 6.424 of pythia [21] is used to simulate parton showering and hadronization, as well as the decay of SUSY particles. A signal sample for an RPV model is produced with pythia 6.424. For signal samples, the detector simulation is performed using the CMS fast simulation package [22]. Detailed cross checks are performed to ensure that the results obtained with fast simulation are in agreement with the ones obtained with geant-based detector simulation. Simulated events are processed with the same chain of reconstruction programs that is used for data.

4 Search strategy

The search is based on comparing the number of observed events with the expectation from SM processes in several signal regions (SR) that have different requirements on four discriminating variables: E_T^{miss}, H_T, the number of jets, and the number of b-tagged jets. We define two sets of signal regions: *baseline* and *final* SRs. The former set imposes looser selection requirements, thereby forming a sample of events where the contributions of signal events are expected to be negligible, that is used to validate methods that are employed to predict the background in the final SRs; the latter set is based on tighter selection requirements, making it sensitive to many BSM processes. The interpretation of the results, discussed in section 8, is primarily based on the final SRs.

Search regions defined in bins of the number of jets and b-tagged jets provide broad coverage of strongly produced SUSY particles, including signatures with low hadronic activity as well as signatures involving third-generation squarks. Additionally, as SUSY models with a small mass splitting between the parent sparticle and the LSP may result in low E_T^{miss}, we also define search regions with a looser requirement on E_T^{miss}. The high-

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H_T (GeV)	E_T^{miss} (GeV)	N_{jets}	$N_{b\text{-jets}}$	SR name
>250 (80)	>30 if $H_T < 500$ else >0	≥2	=0	BSR0
>250 (80)	>30 if $H_T < 500$ else >0	≥2	=1	BSR1
>250 (80)	>30 if $H_T < 500$ else >0	≥2	≥2	BSR2

Table 2. Definition of the baseline signal regions for the three different requirements on the number of b-tagged jets ($N_{b\text{-jets}}$). N_{jets} refers to the number of jets in the event. The same naming scheme is used for both the low- and high-p_T analyses, which differ only in a looser requirement on H_T (in parentheses) for the high-p_T analysis.

$N_{b\text{-jets}}$	E_T^{miss} (GeV)	N_{jets}	$H_T \in [200, 400]$ (GeV)	$H_T > 400$ (GeV)
= 0	50–120	2–3	SR01	SR02
		≥4	SR03	SR04
	>120	2–3	SR05	SR06
		≥4	SR07	SR08
= 1	50–120	2–3	SR11	SR12
		≥4	SR13	SR14
	>120	2–3	SR15	SR16
		≥4	SR17	SR18
≥ 2	50–120	2–3	SR21	SR22
		≥4	SR23	SR24
	>120	2–3	SR25	SR26
		≥4	SR27	SR28

Table 3. Definition of the signal regions for the high-p_T analysis. The low-p_T analysis employs a tighter requirement $H_T > 250$ GeV and uses the same numbering scheme, in which the first digit in the name represents the requirement on the number of b-tagged jets for that search region, e.g. SR01, SR11, and SR21 correspond to SRs with $N_{b\text{-jets}}$ 0, 1, and ≥2, respectively.

p_T search is ideal for BSM models with an on-shell W boson produced in a new-physics particle decay, but events with an off-shell W boson can produce low-p_T leptons, which is why leptons with transverse momenta as low as 10 GeV are included in this study.

We define the three baseline signal regions (BSR0, BSR1, and BSR2) for both the low- and high-p_T analyses, as described in table 2. The event selection criteria are tightened and the granularity of the regions is increased to define the 24 final SRs described in table 3 for the high-p_T analysis. For the low-p_T signal regions, the categories are equivalent to those of the high-p_T analysis, but the selection differs in the requirement on H_T and lepton p_T. The threshold on H_T is increased from 200 to 250 GeV in order to ensure 100% efficiency for the triggers used by the low-p_T event selection. All 24 signal regions are mutually exclusive and may therefore be statistically combined within either high-p_T or low-p_T analysis.

Additional (overlapping) signal regions, listed in table 4, are defined with no or loose E_T^{miss} requirements in order to provide better sensitivity to scenarios such as RPV SUSY

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N_{jets}	$N_{\text{b-jets}}$	$E_{\text{T}}^{\text{miss}}$ (GeV)	H_{T} (GeV)	Lepton charge	SR name
$\geq$2	$\geq$0	>0	>500	++/−−	RPV0
$\geq$2	$\geq$2	>0	>500	++/−−	RPV2
$\geq$2	=1	>30	>80	++/−−	SStop1
$\geq$2	=1	>30	>80	++ only	SStop1++
$\geq$2	$\geq$2	>30	>80	++/−−	SStop2
$\geq$2	$\geq$2	>30	>80	++ only	SStop2++

Table 4. Signal regions that are used in the search for same-sign top-quark pair production and RPV SUSY processes.

models and same-sign top-quark pair production. These search regions are formed using events that satisfy high-p_{T} lepton selection and contain at least two jets. Because in RPV SUSY scenarios the LSP decays, mainly into detectable leptons and quarks, such events are not expected to have large $E_{\text{T}}^{\text{miss}}$, but they usually have substantial H_{T}. Thus, in search regions designed for such models, the $E_{\text{T}}^{\text{miss}}$ requirement is removed completely, while a relatively high $H_{\text{T}} > 500\,\text{GeV}$ requirement is applied to reduce the level of SM background. These search regions are labelled as RPV0 and RPV2 for $N_{\text{b-jets}} \geq 0$ and $\geq$2, respectively.

Same-sign top quark pair events in which the W bosons decay leptonically generally contain moderate $E_{\text{T}}^{\text{miss}}$, due to the accompanying neutrinos. Using events with $E_{\text{T}}^{\text{miss}} > 30\,\text{GeV}$, we form four signal regions, denoted SStop1, SStop2, SStop1++, and SStop2++, where "++" refers to the selection of only positively charged dilepton pairs. Note that in most new physics scenarios, $\text{pp} \to \overline{\text{tt}}$ is suppressed with respect to $\text{pp} \to \text{tt}$ because the PDF of the proton is dominated by quarks, rather than anti-quarks. For such scenarios, the SStop1++ and SStop2++ signal regions are expected to provide higher sensitivity.

5 Backgrounds

There are three main sources of SM background in this analysis, which are described below. More details on the methods used to estimate these backgrounds can be found in refs. [12, 14].

- "Non-Prompt leptons", i.e. leptons from heavy-flavour decays, misidentified hadrons, muons from light-meson decays in flight, or electrons from unidentified photon conversions. The background caused by these non-prompt leptons, which is dominated by $\text{t}\bar{\text{t}}$ and W + jets processes, is 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 described in section 3. The background rate is obtained by scaling the number of events in this sample by a "tight-to-loose" ratio, i.e. the probability that a loosely identified non-prompt lepton also passes the full set of requirements. Various definitions of the loose lepton selection criteria are studied in

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detail, and combination of relaxed isolation and lepton-identification requirements is used. These probabilities are measured as a function of lepton p_{T} and η, as well as event kinematics, in control samples of QCD multijet events that are enriched in non-prompt leptons.

- Rare SM processes that yield same-sign leptons, mostly from $\mathrm{t\bar{t}W}$, $\mathrm{t\bar{t}Z}$, and diboson production. We also include the contribution from the SM Higgs boson produced in association with a vector boson or a pair of top quarks in this category of background. All these backgrounds are estimated from MC simulation. The event yields are corrected for several effects, summarized in section 6, to account for the differences between object selection efficiencies in data and simulation.

- Charge misidentification, i.e. events with opposite-sign isolated leptons where the charge of one of the leptons is misidentified because of severe bremsstrahlung in the tracker material. This background, which is relevant only for electrons and is negligible for muons, is estimated by selecting opposite-sign ee or eμ events passing the full kinematic selection and then weighting them by the p_{T}- and η-dependent probability of electron charge misassignment. This probability, which varies between 10^{-4} and 10^{-5}, is obtained from simulation and is then validated with a control data sample of $\mathrm{Z} \to \mathrm{ee}$ events.

Backgrounds stemming from non-prompt leptons constitute the major contribution to the total background in most search regions. The rare SM processes dominate in the search regions with large numbers of b-tagged jets or high $E_{\mathrm{T}}^{\mathrm{miss}}$ requirements. The contribution from charge misidentification is generally much smaller and stays below the few-percent level in all search regions.

The primary origin of the systematic uncertainty for the non-prompt lepton background estimate is differences between the QCD multijet sample, where the "tight-to-loose" ratio is determined, and the signal regions, where the method is applied, both for the event kinematics and for the relative rates of the various sources of non-prompt leptons. A systematic uncertainty also arises because $\mathrm{t\bar{t}}$ and W+jets events, the two dominant components of the non-prompt background, differ themselves in the event kinematics and relative importance of the various sources, making it difficult to define a "tight-to-loose" ratio that is equally appropriate for both components. Based on the variation between true and predicted background yields when the background estimation method is applied to simulation, the systematic uncertainty of the estimate is assessed at 50%. This systematic part is the dominant uncertainty in the non-prompt lepton background estimate in most signal regions. The statistical uncertainty in the method is driven by the number of events in the sideband regions, defined with relaxed lepton requirements, that are used to estimate the non-prompt lepton background. As the kinematic selections are tightened, the statistical uncertainty becomes more important, becoming comparable in size to the systematic uncertainty in the search regions with the tightest selections.

For the rare SM processes, the next-to-leading-order (NLO) production cross sections are used to normalize the MC predictions. The cross section values used for the most rele-

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Channel	Low-p_{T}	High-p_{T}
ee, $p_{\mathrm{T}} < 30\,\mathrm{GeV}$	0.93 ± 0.06	0.92 ± 0.05
ee, $p_{\mathrm{T}} > 30\,\mathrm{GeV}$	0.93 ± 0.06	0.96 ± 0.06
eμ	0.93 ± 0.06	0.93 ± 0.06
$\mu\mu$, $\lvert\eta\rvert < 1.0$	0.94 ± 0.06	0.90 ± 0.05
$\mu\mu$, $1.0 < \lvert\eta\rvert < 2.4$	0.90 ± 0.05	0.81 ± 0.05

Table 5. Summary of the trigger selection efficiencies for low- and high-p_{T} analyses in each channel. The thresholds on $|\eta|$ and p_{T} correspond to the lower p_{T} lepton of the dilepton pair.

vant processes, $\mathrm{t\bar{t}W}$ and $\mathrm{t\bar{t}Z}$, are 232 fb [23] and 208 fb [24, 25], respectively. Because these and other rare processes are simulated using leading order (LO) generators, the systematic uncertainty for the rare SM background accounts both for the theoretical uncertainty in the cross sections and for the non-uniformity of the ratio between the LO and NLO cross sections as a function of jet multiplicity, H_{T}, and $E_{\mathrm{T}}^{\mathrm{miss}}$ [23]. The systematic uncertainties for each SM process that contributes to this background are assigned to be 50% and are considered to be 100% correlated across all signal regions.

The uncertainty associated with the charge-misidentification background estimate, which is estimated to be 30%, accounts for differences between data and simulation, and the limited momentum range of electrons probed in the control sample.

The total background in each search region is obtained by summing the yields from each of these background sources, and the total uncertainty is calculated by considering the individual uncertainties to be uncorrelated.

6 Efficiencies and associated uncertainties

The trigger efficiency is measured with data, using triggers that are orthogonal to those described in section 3. The measured efficiencies are summarized in table 5. Correction factors to take the trigger inefficiencies into account are applied to all acceptances calculated from MC simulation, for both signal and background samples. We assign a 6% uncertainty to these efficiencies, based on the statistical uncertainty of the measurement and deviations from the quoted numbers in table 5 as a function of $|\eta|$ and p_{T}.

The offline lepton selection efficiencies in data and simulation are measured using Z-boson events to derive simulation-to-data correction factors. The correction factors applied to simulation are 90 (96)% for $p_{\mathrm{T}} < 20\,\mathrm{GeV}$ and 94 (98)% for $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ for electrons (muons). The uncertainty of the total efficiency is 5% (3%) for electrons (muons) with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$, increasing to 10% (5%) for lower transverse momentum. An additional systematic uncertainty is assigned to account for potential mismodelling of the lepton isolation efficiency due to varying hadronic activity in signal events. This uncertainty is 3% for all leptons except muons with $p_{\mathrm{T}} < 30\,\mathrm{GeV}$, for which it is 5%.

Another source of systematic uncertainty is associated with the jet energy scale correction. This systematic uncertainty varies between 5% and 2% in the p_{T} range 40–100 GeV

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for jets with $|\eta| < 2.4$ [26]. It is evaluated on a single-jet basis, and its effect is propagated to H_{T}, $E_{\mathrm{T}}^{\mathrm{miss}}$, the number of jets, and the number of b-tagged jets. 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ are less affected by the uncertainty in the jet energy scale. In addition, there is a contribution to the total uncertainty arising from limited knowledge of the resolution of the jet energy, but this effect is generally of less importance than the contribution from the jet energy scale.

The b-tagging efficiency for b-quark jets with $|\eta| < 2.4$, measured in data using samples enriched in $\mathrm{t\bar{t}}$ and muon-jet events, has a p_{T}-averaged value of 0.72. The false positive b-tagging probability for charm-quark jets is approximately 20%, while for jets originating from light-flavour quarks or gluons it is of the order of 1%. Correction factors, dependent on jet flavour and kinematics, are applied to simulated jets to account for the differences in the tagging efficiency in simulation with respect to data. The total uncertainty of the b-tagging efficiency is determined by simultaneously varying the efficiencies to tag a bottom, charm, or light quark up and down by their uncertainties [16]. The importance of this effect depends on the signal region and the model of new physics. In general, models with more than two b quarks in the final state are less affected by this uncertainty.

Additional uncertainties due to possible mismodelling of the pileup conditions or initial-state radiation (ISR) [27] are evaluated and found to be 5% and 3–15%, respectively. The uncertainty of the signal acceptance due to the PDF choice is found to be less than a few percent. Finally, there is a 2.6% uncertainty in the yield of events because of the uncertainty in the luminosity normalization [28].

A summary of the systematic uncertainties associated with the acceptance and signal efficiency for this analysis is provided in table 6. While the uncertainties associated with the integrated luminosity, modelling of lepton selection, trigger efficiency, and pileup are taken to be constant across the parameter space of the new physics models considered in this paper, uncertainties arising from the remaining observables are estimated for each model separately on an event-by-event basis by varying those observables within their uncertainties. The total uncertainty in the computed acceptance is in the 13–25% range. The figures in table 6 are representative values for these uncertainties and do not characterize the results for extreme kinematic regions, such as those near the diagonal of the parameter space of the SUSY simplified models discussed in section 8, where the particle mass spectra are compressed.

7 Results

The distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$ versus H_{T} for events in the three baseline signal regions are shown in figure 1. The results are shown separately for the low- and high-p_{T} samples. The corresponding results for the four selection variables H_{T}, $E_{\mathrm{T}}^{\mathrm{miss}}$, N_{jets}, and $N_{\text{b-jets}}$ are shown in figure 2. For these latter results, the SM background prediction is also shown. There are no significant discrepancies observed between the observations and background predictions for any region.

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Source	%
Luminosity	2.6
Modelling of lepton selection (ID and isolation)	10
Modelling of trigger efficiency	6
Pileup modelling	5
Jet energy scale	1–10
Jet energy resolution	0–3
b-jet identification	2–10
ISR modelling	3–15
Total	13–25

Table 6. Summary of representative systematic uncertainties for the considered signal models.

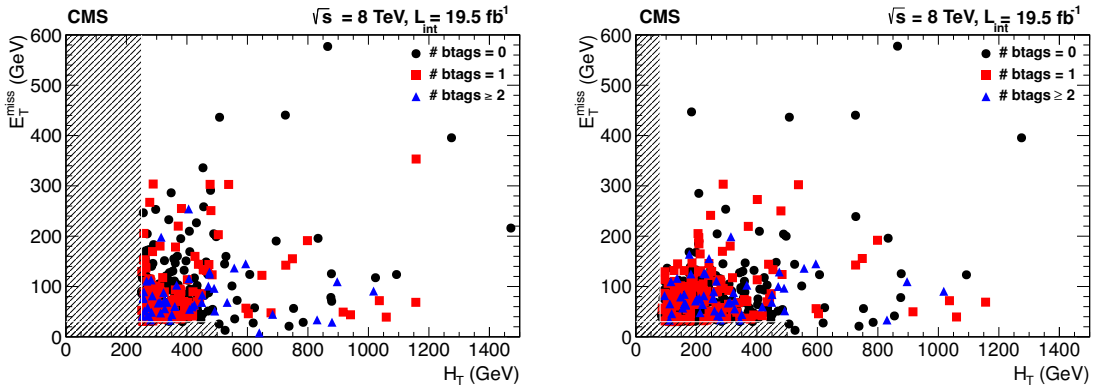

Figure 1. Distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$ versus H_{T} for the baseline signal regions BSR0, BSR1, and BSR2 for the low-p_{T} (left) and the high-p_{T} (right) analyses. The regions indicated with the hatched area are not included in the analyses.

The observations in each of the final signal regions are presented in tables 7 and 8 and in figure 3 along with the corresponding SM background prediction. The contributions of rare SM processes and non-prompt leptons vary among the signal regions between 40% and 60%, while the charge misidentification background is almost negligible for all signal regions. The observations are consistent with the background expectations within their uncertainties. The p-values [29] for each signal region in the low- and high-p_{T} analyses are studied, and are found to be consistent with a uniform distribution between 0 and 1.

8 Limits on models of new physics and on rare SM processes

Given the lack of a significant excess over the expected SM background, the results of the search are used to derive limits on the parameters of various models of new physics and to derive limits on the cross sections of rare SM processes. The 95% confidence level (CL) upper limits on the signal yields are calculated using the LHC-type $\mathrm{CL_s}$ method [30–32].

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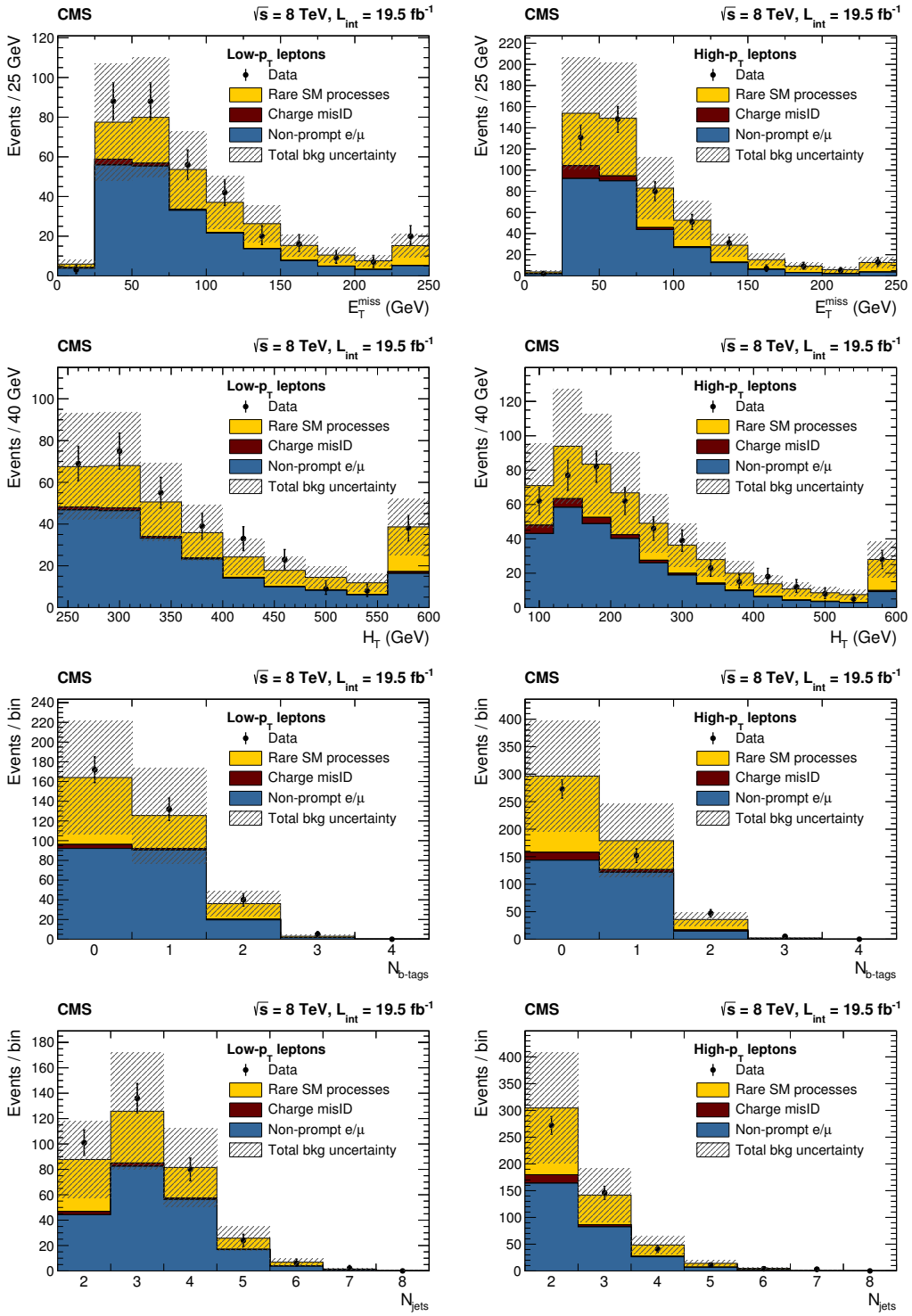

Figure 2. Distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$, H_{T}, number of b-tagged jets, and number of jets for the events in the low-p_{T} (high-p_{T}) baseline region with no $N_{\text{b-jets}}$ requirement (events selected in BSR0, BSR1, and BSR2) are shown on the left (right). Also shown as a histogram is the background prediction. The shaded region represents the total background uncertainty.

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Region	Low-p_{T}		High-p_{T}	
	Expected	Observed	Expected	Observed
SR01	44 ± 16	50	51 ± 18	48
SR02	12 ± 4	17	9.0 ± 3.5	11
SR03	12 ± 5	13	8.0 ± 3.1	5
SR04	9.1 ± 3.4	4	5.6 ± 2.1	2
SR05	21 ± 8	22	20 ± 7	12
SR06	13 ± 5	18	9 ± 4	11
SR07	3.5 ± 1.4	2	2.4 ± 1.0	1
SR08	5.8 ± 2.1	4	3.6 ± 1.5	3
SR11	32 ± 13	40	36 ± 14	29
SR12	6.0 ± 2.2	5	3.8 ± 1.4	5
SR13	17 ± 7	15	10 ± 4	6
SR14	10 ± 4	6	5.9 ± 2.2	2
SR15	13 ± 5	9	11 ± 4	11
SR16	5.5 ± 2.0	5	3.9 ± 1.5	2
SR17	4.2 ± 1.6	3	2.8 ± 1.1	3
SR18	6.8 ± 2.5	11	4.0 ± 1.5	7
SR21	7.6 ± 2.8	10	7.1 ± 2.5	12
SR22	1.5 ± 0.7	1	1.0 ± 0.5	1
SR23	7.1 ± 2.7	6	3.8 ± 1.4	3
SR24	4.4 ± 1.7	11	2.8 ± 1.2	7
SR25	2.8 ± 1.1	1	2.9 ± 1.1	4
SR26	1.3 ± 0.6	2	0.8 ± 0.5	1
SR27	1.8 ± 0.8	0	1.2 ± 0.6	0
SR28	3.4 ± 1.3	3	2.2 ± 1.0	2

Table 7. Predicted and observed event yields for the low-p_{T} and high-p_{T} signal regions.

SR	Expected	Observed
RPV0	38 ± 14	35
RPV2	5.3 ± 2.1	5
SStop1	160 ± 59	152
SStop1++	90 ± 32	92
SStop2	40 ± 13	52
SStop2++	22 ± 8	25

Table 8. Predicted and observed event yields in the signal regions designed for same-sign top-quark pair production and RPV SUSY models.

Lognormal nuisance parameters are used for the signal (table 6) and background estimate (tables 7 and 8) uncertainties. For each model considered, limits are obtained by performing a statistical combination of the most sensitive signal regions.

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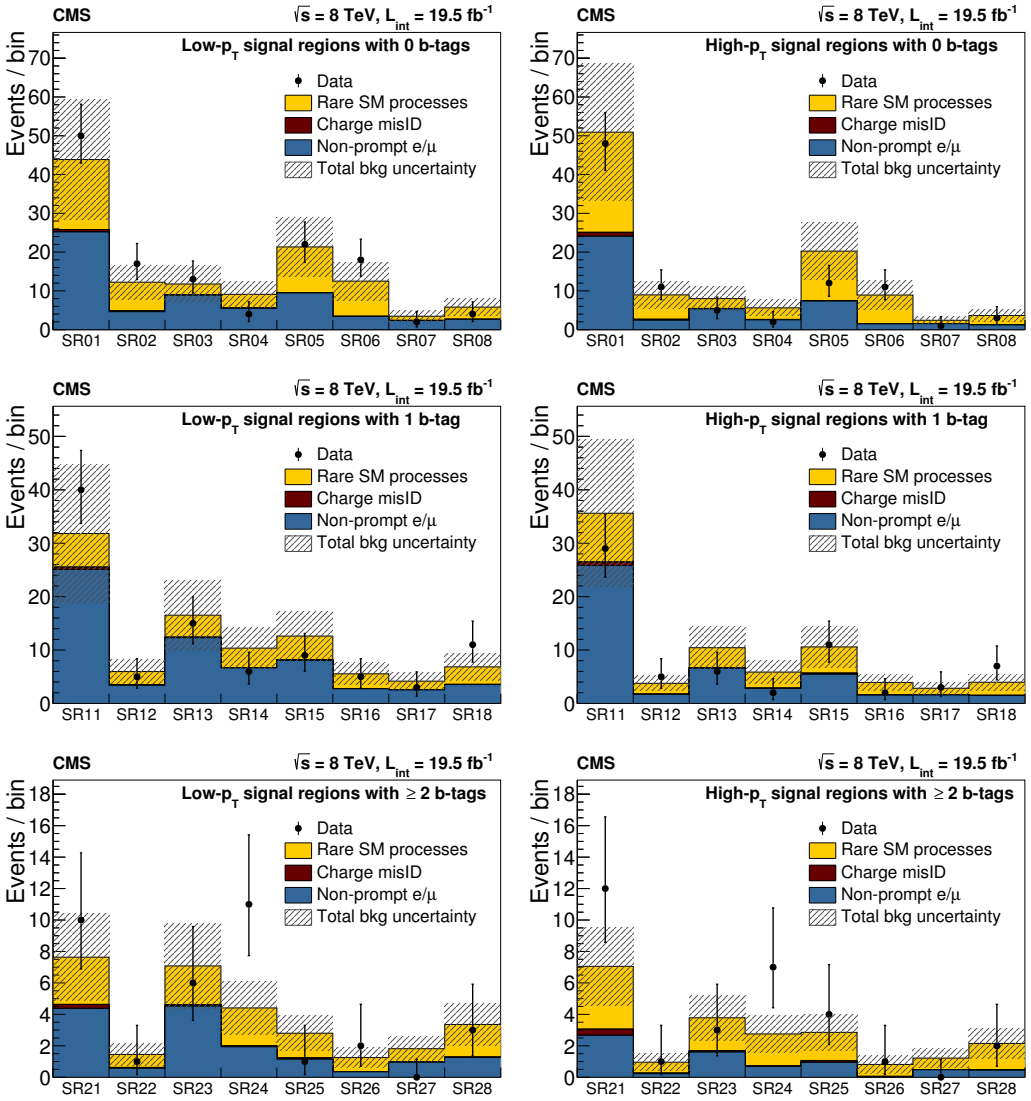

Figure 3. Summary plots showing the predicted background from each source and observed event yields as a function of the SRs in the low-p_{T} (high-p_{T}) analysis on left (right).

The signal regions used to set limits on the new physics models explored in this paper are given in table 9.

The number of events that are expected to satisfy the selection for a given signal model is obtained from MC simulation. The uncertainties for the event yields are computed as described in section 6. For a given signal region, the different sources of uncertainties in the signal acceptance are considered to be uncorrelated, with correlations across signal regions taken into account. The uncertainties in the total background across the signal regions are considered to be fully correlated.

First, we present limits on the parameter spaces of various R-parity-conserving simplified SUSY models [33]. The exclusion contours are obtained with the gluino or bottom-squark pair production cross sections at the NLO+NLL (i.e. next-to-leading-logarithm)

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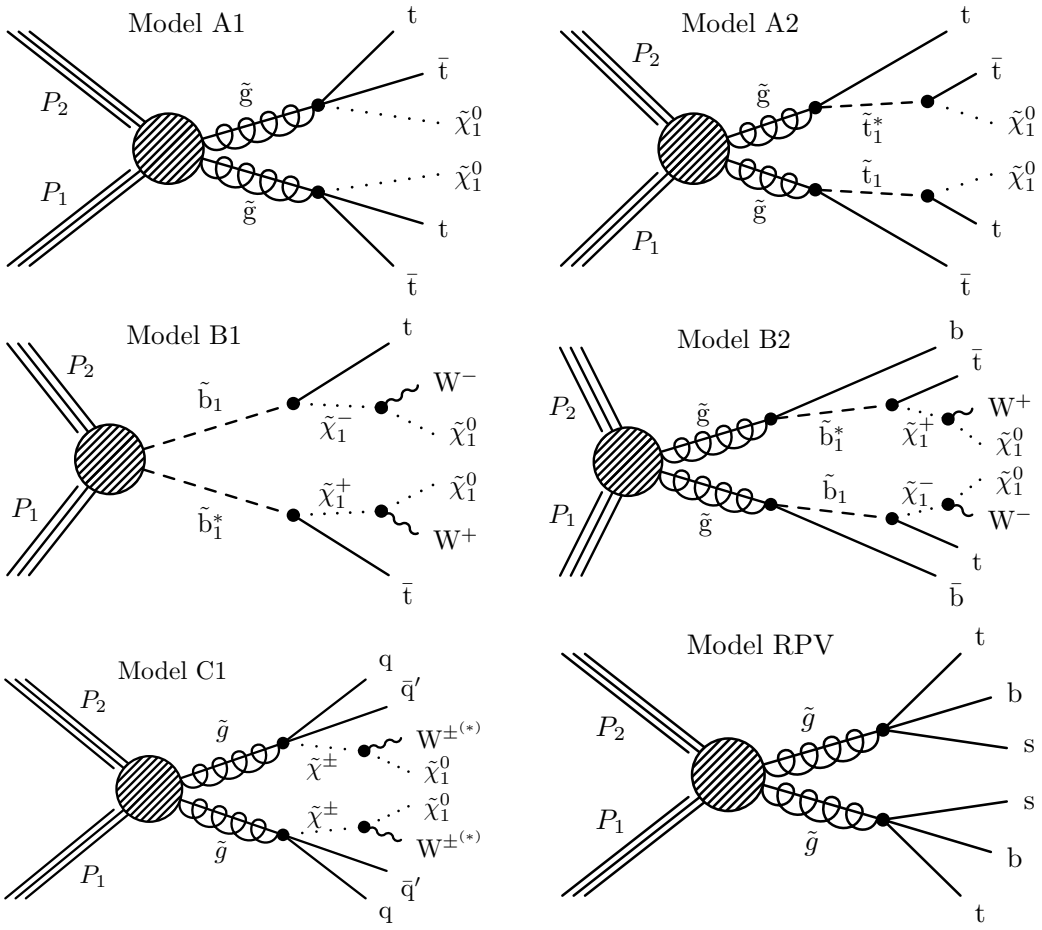

Figure 4. Diagrams for the six SUSY models considered (A1, A2, B1, B2, C1, and RPV).

accuracy that are calculated in the limit where other sparticles are heavy enough to be decoupled [34–39]. The production of SUSY particles and the decay chains under consideration are shown schematically in figure 4.

Scenarios A1 and A2 represent models of gluino pair production resulting in the $t\bar{t}t\bar{t}\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ final state, where $\widetilde{\chi}_1^0$ is the lightest neutralino [33, 40–43]. In model A1, the gluino undergoes a three-body decay $\widetilde{g} \to t\bar{t}\widetilde{\chi}_1^0$ mediated by an off-shell top squark. In model A2, the gluino decays to a top quark and a top anti-squark, with the on-shell anti-squark further decaying into a top anti-quark and a neutralino. Both of these models produce four on-shell W bosons and four b quarks. Therefore, search regions SR21-SR28, which require at least two b-tagged jets and high-p_{T} leptons, are used to derive the limits on the parameters of these models; the region with the best sensitivity is SR28. The 95% CL upper limits on the cross section times branching fraction, as well as the exclusion contours, are shown in figure 5. For model A1, the results are presented as a function of gluino mass and $\widetilde{\chi}_1^0$ mass, and for model A2 as a function of gluino mass and top squark mass with the $\widetilde{\chi}_1^0$ mass set to 50 GeV. In model A2, the limits do not depend on the top squark or $\widetilde{\chi}_1^0$ masses provided that there is sufficient phase space to produce on-shell top

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Model	Constraints on parameters	Analysis	Signal regions used
A1		high-p_{T}	21–28
A2	$\mathrm{m}_{\widetilde{\chi}_1^0} = 50\,\mathrm{GeV}$	high-p_{T}	21–28
B1	$\mathrm{m}_{\widetilde{\chi}_1^0} = 50\,\mathrm{GeV}$	high-p_{T}	11–18, 21–28
B1	$m_{\widetilde{\chi}_1^0}/\mathrm{m}_{\widetilde{\chi}_1^\pm} = 0.5$	high-p_{T}	11–18, 21–28
B1	$m_{\widetilde{\chi}_1^0}/\mathrm{m}_{\widetilde{\chi}_1^\pm} = 0.8$	low-p_{T}	11–18, 21–28
B2	$\mathrm{m}_{\widetilde{\chi}_1^0} = 50\,\mathrm{GeV}$, $\mathrm{m}_{\widetilde{\chi}_1^\pm} = 150\,\mathrm{GeV}$	high-p_{T}	21–28
B2	$\mathrm{m}_{\widetilde{\chi}_1^0} = 50\,\mathrm{GeV}$, $\mathrm{m}_{\widetilde{\chi}_1^\pm} = 300\,\mathrm{GeV}$	high-p_{T}	21–28
C1	$m_{\widetilde{\chi}_1^\pm} = 0.5m_{\widetilde{\chi}_1^0} + 0.5m_{\widetilde{\mathrm{g}}}$	high-p_{T}	01–08
C1	$m_{\widetilde{\chi}_1^\pm} = 0.8m_{\widetilde{\chi}_1^0} + 0.2m_{\widetilde{\mathrm{g}}}$	low-p_{T}	01–08
RPV		high-p_{T}	RPV2
$\mathrm{pp} \to \mathrm{tt},\ \overline{\mathrm{tt}}$		high-p_{T}	SStop1, SStop2
$\mathrm{pp} \to \mathrm{tt}$		high-p_{T}	SStop1++, SStop2++
$\mathrm{pp} \to \mathrm{tt}\overline{\mathrm{tt}}$		high-p_{T}	21–28

Table 9. Signal regions used for limit setting for the new physics models considered in this analysis.

quarks with a moderate boost in the decay of both the gluino and the top squark. This range extends to approximately 600 GeV for the $\widetilde{\chi}_1^0$ mass.

Model B1 is a model of bottom-squark pair production, followed by one of the most likely decay modes of the bottom squark, $\widetilde{\mathrm{b}}_1 \to \mathrm{t}\widetilde{\chi}_1^-$ with $\widetilde{\chi}_1^- \to \mathrm{W}^-\widetilde{\chi}_1^0$, where $\widetilde{\mathrm{b}}_1$ and $\widetilde{\chi}_1^-$ represent the lightest bottom squark and lightest chargino, respectively. We consider three cases in this decay mode. We either set the $\widetilde{\chi}_1^0$ mass to 50 GeV and present the limits in the ($m_{\widetilde{\chi}_1^\pm}$, $m_{\widetilde{\mathrm{b}}_1}$) plane, or consider the ($m_{\widetilde{\chi}_1^0}$, $m_{\widetilde{\mathrm{b}}_1}$) plane with the mass of the chargino set according to $m_{\widetilde{\chi}^0}/m_{\widetilde{\chi}_1^\pm} = 0.5$ or $m_{\widetilde{\chi}^0}/m_{\widetilde{\chi}_1^\pm} = 0.8$. The values 0.5 and 0.8 are representative choices that determine whether the top quark and W boson are on-shell or off-shell, which has a direct impact on the sensitivity of the analysis in this model. The limits for this model, obtained using search regions SR11 to SR28, are presented in figure 6. For $m_{\widetilde{\chi}^0}/m_{\widetilde{\chi}_1^\pm} = 0.8$, the low-$p_{\mathrm{T}}$ lepton selection is used, while high-p_{T} leptons are used for the other two scenarios. SR28 is again the most sensitive signal region, followed by the regions requiring one b-tagged jet: SR18, SR15, and SR13.

Model B2 consists of gluino pair production followed by $\widetilde{\mathrm{g}} \to \widetilde{\mathrm{b}}_1\overline{\mathrm{b}}$. The gluino decay modes in models A1 and A2 are expected to be dominant if the top squark is the lightest squark. Conversely, if the bottom squark is the lightest, the decay mode in model B2 would be the most probable. The limits on this model, calculated using search regions SR21-SR28 and the high-p_{T} lepton selection, are presented in figure 6 as a function of $m(\widetilde{\mathrm{b}}_1)$ and $m(\widetilde{\mathrm{g}})$ for two fixed masses of $m_{\widetilde{\chi}_1^\pm}$, 150 and 300 GeV. The region with the largest sensitivity to this model is SR28.

Model C1 is based on the production of a gluino pair where each gluino decays to light quarks and a chargino via heavy virtual squarks: $\widetilde{\mathrm{g}} \to \mathrm{q}\overline{\mathrm{q}}'\widetilde{\chi}_1^\pm$, $\widetilde{\chi}_1^\pm \to \mathrm{W}^{(*)}\widetilde{\chi}_1^0$. The decay is charge-symmetric, resulting in an equal fraction of same-sign and opposite-sign

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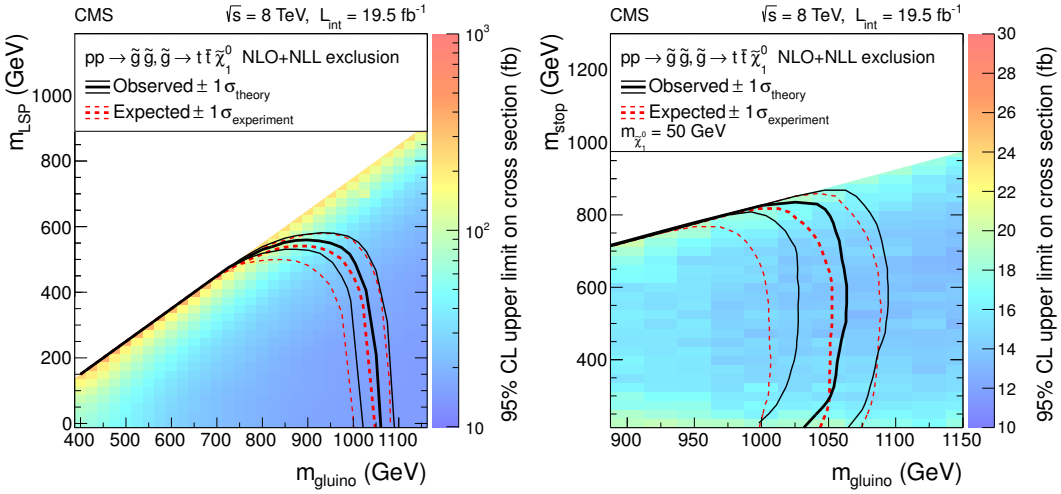

Figure 5. Exclusion regions at 95% CL in the planes of (left) $m(\widetilde{\chi}_1^0)$ versus $m(\widetilde{\mathrm{g}})$ (model A1), and (right) $m(\widetilde{\mathrm{t}}_1)$ versus $m(\widetilde{\mathrm{g}})$ (model A2). The excluded regions are those within the kinematic boundaries and to the left of the curves. The effects of the theoretical uncertainties in the NLO+NLL calculations of the production cross sections [39] are indicated by the thin black curves; the expected limits and their ±1 standard-deviation variations are shown by the dashed red curves.

W boson pairs in the final state. In this model there are three parameters: $m_{\widetilde{\mathrm{g}}}$, $m_{\widetilde{\chi}_1^\pm}$, and $m_{\widetilde{\chi}_1^0}$. Signal samples are produced for each bin in the $(m_{\widetilde{\chi}_1^0}, m_{\widetilde{\mathrm{g}}})$ plane. Chargino mass is defined through a parameter x as $m_{\widetilde{\chi}_1^\pm} = x m_{\widetilde{\chi}_1^0} + (1-x) m_{\widetilde{\mathrm{g}}}$. In the limit $x \to 0$, there is no observable hadronic activity in the event. At the other extreme, $x \to 1$, the chargino and LSP are degenerate and the chargino decays through an off-shell W boson yielding very soft leptons. In either cases, the analysis loses sensitivity. For intermediate values of the parameter x, the W boson is either on- or off-shell depending on the values of $m_{\widetilde{\chi}_1^0}$ and $m_{\widetilde{\mathrm{g}}}$, giving rise to either high- or low-p_{T} leptons. We examine x values of 0.5 and 0.8. The former value ensures that the W boson is on-shell in the sparticle mass range considered, while the latter yields mostly off-shell W bosons. In this model, no enrichment of heavy-flavour jets is expected. Therefore, the search regions SR01-SR08, with both the low- and high-p_{T} lepton selection, are used for cross section upper limit calculation. The limits are presented in figure 7. In this model, gluino masses up to 900 GeV are probed. Most of the sensitivity to this model is obtained from signal region SR08.

These results extend the sensitivity obtained in the previous analysis [11] on gluino and sbottom masses. For the gluino-initiated models (A1, A2, B2, and C1), we probe gluinos with masses up to about 1050 GeV, with relatively 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 the direct bottom-squark pair production, model B1, our search shows sensitivity for bottom-squark masses up to about 500 GeV.

These models are also probed by other CMS new physics searches in different decay modes. Other searches are usually 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 searches presented in refs. [44–47]. In particular, they are less stringent at low $m(\widetilde{\chi}_1^0)$ but

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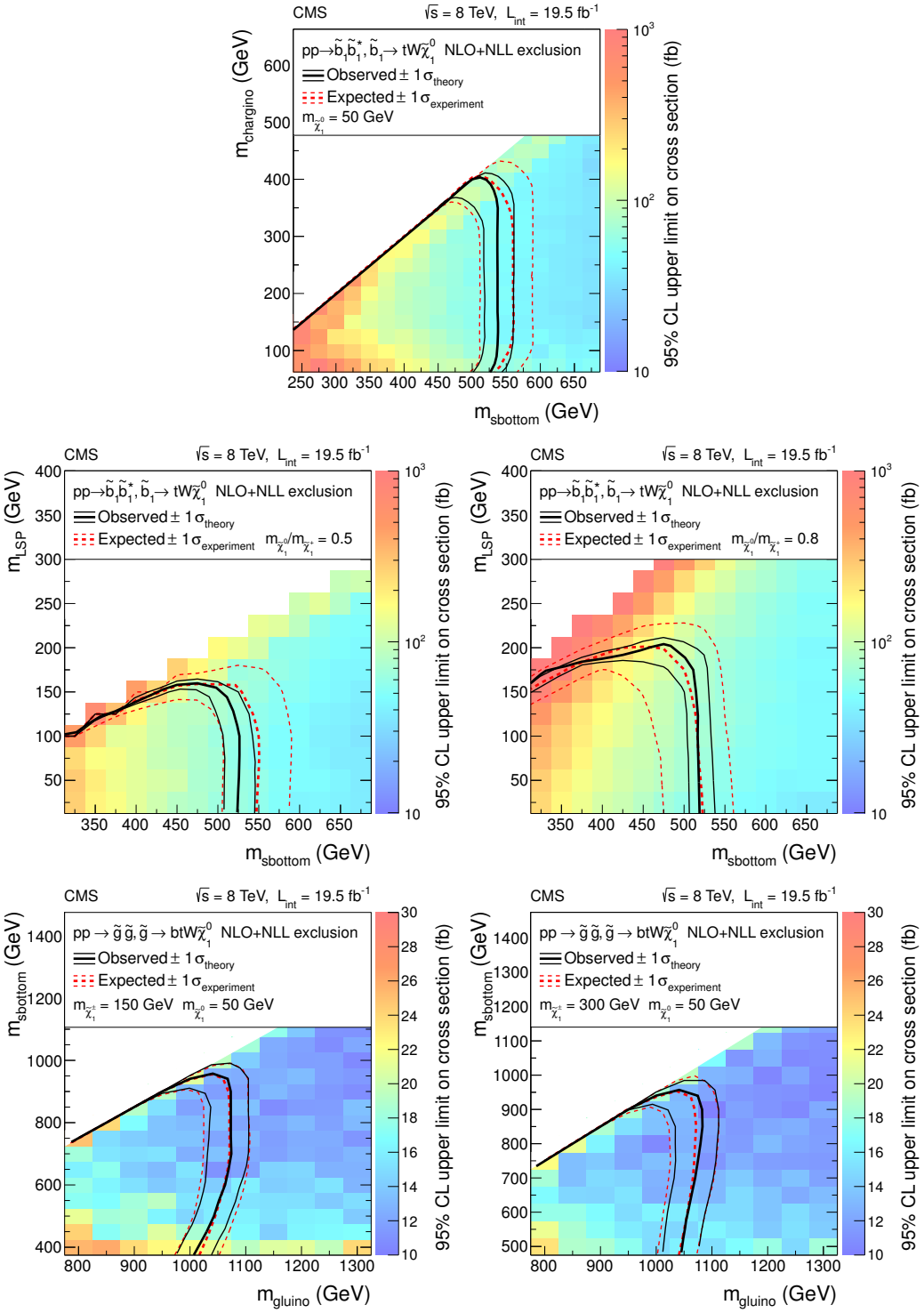

Figure 6. Exclusion regions at 95% CL in the planes of (top and center) $m(\widetilde{\chi}_1^{\pm})$ versus $m(\widetilde{\mathrm{b}}_1)$ and $m(\widetilde{\chi}_1^0)$ versus $m(\widetilde{\mathrm{b}}_1)$ (model B1), and (bottom) $m(\widetilde{\mathrm{b}}_1)$ versus $m(\widetilde{\mathrm{g}})$ (model B2). The convention for the exclusion curves is the same as in figure 5.

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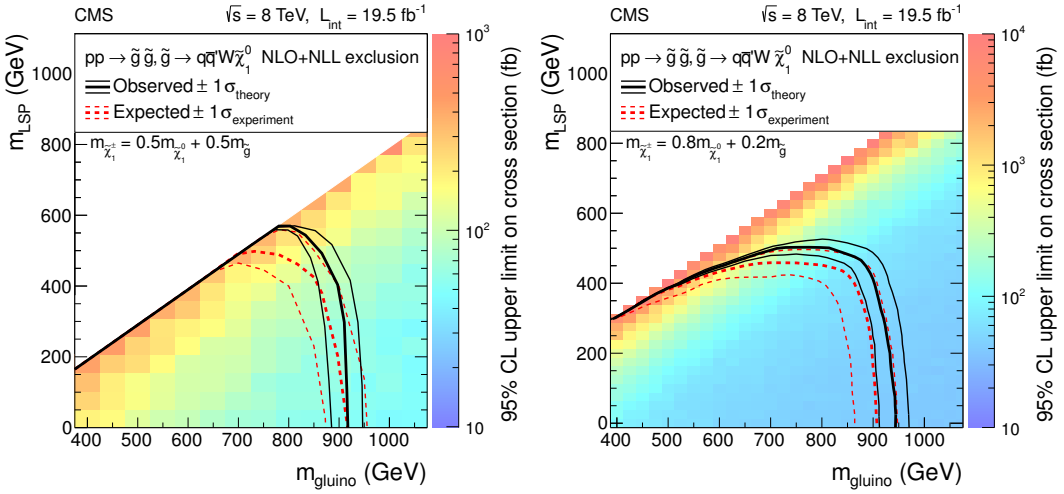

Figure 7. Exclusion regions at 95% CL in the planes of $m(\widetilde{\chi}_1^0)$ versus $m(\widetilde{\mathrm{g}})$ for two different values of chargino mass (model C1). The convention for the exclusion curves is the same as in figure 5.

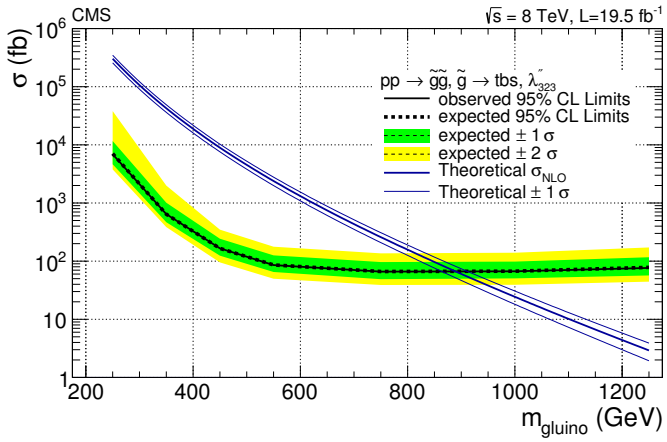

Figure 8. 95% CL upper limit on the gluino production cross section for an RPV simplified model, $\mathrm{pp} \to \widetilde{\mathrm{g}}\widetilde{\mathrm{g}}, \widetilde{\mathrm{g}} \to \mathrm{tbs}(\bar{\mathrm{t}}\bar{\mathrm{b}}\bar{\mathrm{s}})$.

more stringent at high $m(\widetilde{\chi}_1^0)$. A similar conclusion applies to model A2, since the final state is the same. For bottom-squark pair production, limits on $m(\widetilde{\mathrm{b}}_1)$ of about 600 GeV have been presented [46], but assuming the decay mode $\widetilde{\mathrm{b}}_1 \to \mathrm{b}\widetilde{\chi}_1^0$ instead of the model B1 mode $\widetilde{\mathrm{b}}_1 \to \mathrm{t}\widetilde{\chi}_1^-$ considered here. 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 [48–51].

A single RPV scenario is considered in this analysis, one in which gluino pair production is followed by the decay of each gluino to three quarks, as is favoured in the SUSY model with minimal flavour violation [52]: $\widetilde{\mathrm{g}} \to \mathrm{tbs}(\bar{\mathrm{t}}\bar{\mathrm{b}}\bar{\mathrm{s}})$ (model RPV). Such decays lead to same-sign W-boson pairs in the final state in 50% of the cases. Compared with the decays $\widetilde{\mathrm{g}} \to \mathrm{tsd}(\bar{\mathrm{t}}\bar{\mathrm{s}}\bar{\mathrm{d}})$, which also yield same-sign W-boson pairs, the mode considered profits from having two extra b quarks in the final state, resulting in a higher signal selection efficiency.

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The model is governed by one parameter ($m_{\tilde{g}}$), which dictates the production cross section and the final state kinematics. The dedicated search region RPV2 with the high-p_T lepton selection is used to place an upper limit on the production cross section. The result is shown in figure 8. In this scenario, the gluino mass is probed up to approximately 900 GeV.

The results for the signal regions SStop1, SStop1++, SStop2, and SStop2++ are used to set limits on the cross section for same-sign top-quark pair production, $\sigma(pp \to tt,\ \bar{t}\bar{t})$ from SStop1 and SStop2, and $\sigma(pp \to tt)$ from SStop1++ and SStop2++. Here $\sigma(pp \to tt,\ \bar{t}\bar{t})$ is shorthand for the sum $\sigma(pp \to tt) + \sigma(pp \to \bar{t}\bar{t})$. These limits are calculated using an acceptance obtained from simulated $pp \to t\bar{t}$ events and an opposite-sign selection. This acceptance, including branching fractions, is 0.43% (0.26%) for the SStop1 (SStop2) search region. The relative uncertainty in this acceptance is 14%. The observed upper limits are $\sigma(pp \to tt,\ \bar{t}\bar{t}) < 720\,\text{fb}$ and $\sigma(pp \to tt) < 370\,\text{fb}$ at 95% CL. The median expected limits are $470^{+180}_{-110}\,\text{fb}$ and $310^{+110}_{-80}\,\text{fb}$, respectively.

Similarly, the results from signal regions SR21-SR28 with the high-p_T lepton selection are used to set limits on the SM cross section for quadruple top-quark production. The observed upper limit is $\sigma(pp \to tt\bar{t}\bar{t}) < 49\,\text{fb}$ at 95% CL, compared to a median expected limit of $36^{+16}_{-9}\,\text{fb}$. The SM cross section as computed with the MC@NLO program [53] is $\sigma_{SM} = 0.914 \pm 0.005\,\text{fb}$. The most sensitive signal regions, SR24 and SR28, have a signal acceptance of 0.52% and 0.49%, respectively, with relative uncertainties of 13% and 17%.

9 Information for additional model testing

We have described a signature-based search that finds no evidence for physics beyond the SM. In section 8, the results are used to place bounds on the parameters of a number of models of new physics. Here, additional information is presented that can be used to confront other models of new physics in an approximate way through MC generator-level studies. The expected numbers of events can then be compared with an upper limit on the number of signal events that can be obtained using inputs from tables 7 and 8 and a signal acceptance uncertainty estimated from the generator-level studies.

The E_T^{miss} and H_T turn-on curves, shown in figure 9 as a function of the respective generator-level quantities, are parametrized as $0.5 \cdot \epsilon_\infty \cdot \{\text{erf}[(x - x_{1/2})/\sigma] + 1\}$, with $\text{erf}(z)$ the error function, and ϵ_∞, $x_{1/2}$, and σ the parameters of the fit. The generator H_T is calculated using generator jets, obtained by clustering all stable particles from the hard collision, after showering and hadronization, except for neutrinos and other non-interacting particles. The parameters of the fitted functions are summarized in tables 10 and 11 for E_T^{miss} and H_T, respectively. Analogously to the offline selection, only generator jets that are separated from generator electrons and muons by $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.4$ are considered in the derivation and application of the efficiency model. Only electrons and muons from the hard collision are considered. The separation between jets and leptons applies to the calculation of H_T as well as to the counting of jets and b-tagged jets. The generator-level E_T^{miss} is constructed as the vector sum p_T of all neutrinos, selected after showering and hadronization, and any other non-interacting particles from the hard collision.

An additional turn-on curve, introduced since the publication of ref. [11], has been added to parametrize the efficiency to reconstruct a jet with $p_T > 40\,\text{GeV}$. The curve,

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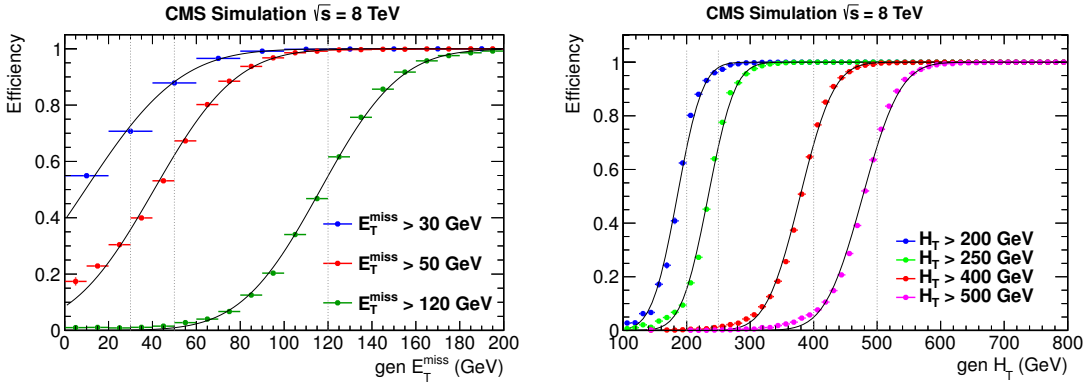

Figure 9. Efficiency for an event to satisfy a given reconstructed $E_{\mathrm{T}}^{\mathrm{miss}}$ (H_{T}) threshold as a function of generator-level $E_{\mathrm{T}}^{\mathrm{miss}}$ ($H_{\mathrm{T}}^{\mathrm{gen}}$). The curves are shown for $E_{\mathrm{T}}^{\mathrm{miss}}$ thresholds of 30, 50, and 120 GeV; the thresholds for H_{T} are 200, 250, 400, and 500 GeV.

Parameter	$E_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 120\,\mathrm{GeV}$
ϵ_∞	1.000 ± 0.001	1.000 ± 0.001	0.999 ± 0.001
$x_{1/2}$ (GeV)	13.87 ± 0.30	42.97 ± 0.14	117.85 ± 0.09
σ (GeV)	42.92 ± 0.34	37.47 ± 0.20	36.90 ± 0.14

Table 10. The resulting fit parameters for the efficiency curves presented in figure 9 left.

Parameter	$H_{\mathrm{T}} > 200\,\mathrm{GeV}$	$H_{\mathrm{T}} > 250\,\mathrm{GeV}$	$H_{\mathrm{T}} > 400\,\mathrm{GeV}$	$H_{\mathrm{T}} > 500\,\mathrm{GeV}$
ϵ_∞	0.999 ± 0.001	0.999 ± 0.001	0.999 ± 0.001	0.999 ± 0.001
$x_{1/2}$ (GeV)	185.2 ± 0.4	233.9 ± 0.3	378.69 ± 0.17	477.3 ± 0.2
σ (GeV)	44.5 ± 0.6	46.9 ± 0.4	59.41 ± 0.26	66.05 ± 0.25

Table 11. The resulting fit parameters for the efficiency curves presented in figure 9 right.

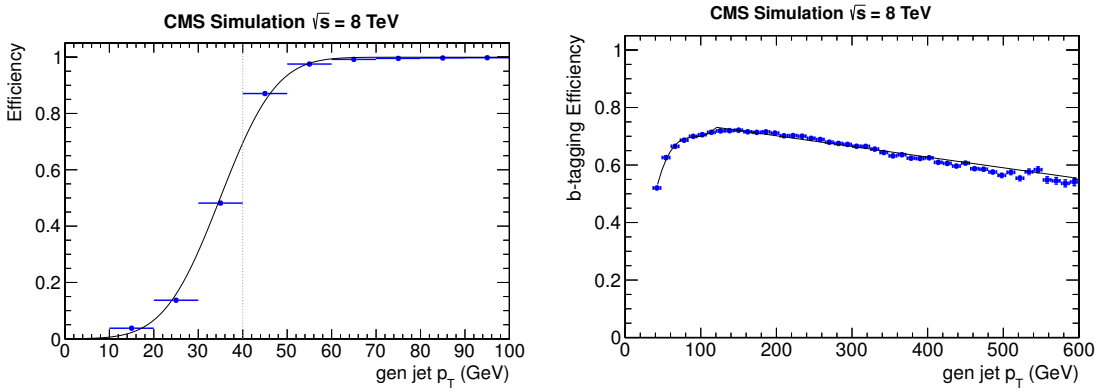

Figure 10. Efficiency for the reconstruction of jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ as a function of the generator jet p_{T} (left); b-tagging efficiency as a function of the p_{T} of the generator jet matched to a bottom quark from the hard collision (right).

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Parameter	Value
A	$(1.55 \pm 0.05) \times 10^{-6}$
B	$(-4.26 \pm 0.12) \times 10^{-4}$
C	0.0391 ± 0.0008
D	-0.496 ± 0.020
E	$(-3.26 \pm 0.01) \times 10^{-4}$
F	0.7681 ± 0.0016

Table 12. b-tagging efficiency parameters. A polynomial of form $Ax^3 + Bx^2 + Cx + D$ is used for $p_{\mathrm{T}} < 120\,\mathrm{GeV}$ while a linear fit, $Ex + F$, is performed above that threshold. Note that the parametrization is valid only for moderate range (i.e. [30–600] GeV) of b-quark jet p_{T}.

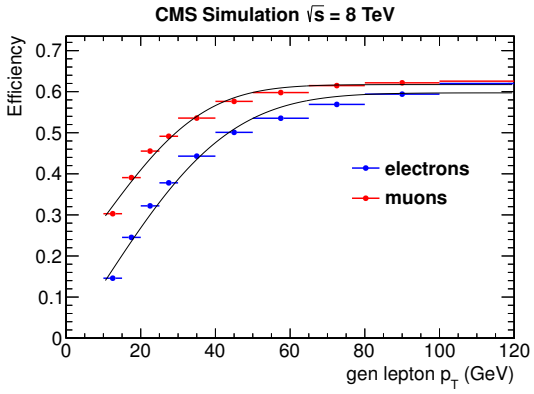

Figure 11. Electron and muon selection efficiency as a function of the generated lepton p_{T}.

Parameter	Electrons	Muons
ϵ_∞	0.640 ± 0.001	0.673 ± 0.001
ϵ_{10}	0.170 ± 0.002	0.332 ± 0.003
σ (GeV)	36.94 ± 0.320	29.65 ± 0.382

Table 13. The parameters of the fit performed in figure 11 for electron and muon selection efficiencies.

shown in figure 10 (left) as a function of the generator jet p_{T}, is described by the same functional form as the H_{T} turn-on. The parameters of the fit are (ϵ_∞, $x_{1/2}$, σ) = (1.0, 29.8 GeV, 18.8 GeV).

Figure 10 also shows the b-tagging efficiency, obtained from simulation, for b quarks with $|\eta| < 2.4$. The efficiency is fit with a third-order (first-order) polynomial for $p_{\mathrm{T}} < 120\,\mathrm{GeV}$ ($p_{\mathrm{T}} > 120\,\mathrm{GeV}$). The parameters of the fit are given in table 12.

The turn-on curves for the lepton selection are shown in figure 11. The lepton efficiency (ε) — including the effects of reconstruction, identification, and isolation as well as relevant data-to-simulation scale factors — is parametrized as $\varepsilon(p_{\mathrm{T}}) = \epsilon_\infty \cdot \mathrm{erf}\big[(p_{\mathrm{T}} - 10)/\sigma\big] + \epsilon_{10} \cdot \big\{1 - \mathrm{erf}\big[(p_{\mathrm{T}} - 10)/\sigma\big]\big\}$. The results of the fit are summarized in table 13.

The prescription to apply the efficiency model is similar to that described in ref. [14], with some modifications needed to accommodate the use of exclusive signal regions. The

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efficiencies for the H_T and E_T^{miss} selections in regions with upper and lower bounds are obtained by taking the difference between the relevant curves in figure 9. The jet reconstruction and b-tagging efficiencies are provided as per-jet quantities. Thus, one scale factor per jet should be obtained from the relevant curves. Additional combinatorial factors should be included, as dictated by the requirements of the signal region selection. The application of the lepton efficiency remains unchanged, with one factor per lepton obtained from the appropriate fit of figure 11. All the quoted efficiencies are multiplicative. The resulting signal yield, obtained by summing the contribution derived from the efficiency model over all events, is then compared to the calculated upper limit as described at the beginning of this section.

The efficiency model presented was applied to a variety of the signal models and search regions considered in this analysis. Results from the efficiency model were found to agree with those obtained using the detector simulation and reconstruction to within approximately 30%. It should be emphasized that the efficiency model is approximate and is not universally applicable. Lepton isolation efficiency, for example, depends on the hadronic activity in the event and in some extreme cases on the event topology. For instance, in models giving rise to top quarks with a significant boost, the lepton isolation efficiency in figure 11 overestimates the true value.

10 Summary

We have presented the results of a search for physics beyond the standard model with same-sign dilepton events using the CMS detector at the LHC. The study is based on a sample of pp collisions at $\sqrt{s} = 8\,\text{TeV}$ corresponding to an integrated luminosity of $19.5\,\text{fb}^{-1}$. The data are analyzed in exclusive signal regions formed by placing different requirements on the discriminating variables H_T, E_T^{miss}, number of jets, and number of b-tagged jets. The latter can assume values of 0, 1, and 2 or more, which allow us to probe signatures both with and without third-generation squarks. No significant deviation from standard model expectation is observed.

Using sparticle production cross sections calculated in the decoupling limit, and assuming that gluinos decay exclusively into top or bottom squarks and that the top and bottom squarks decay as $\widetilde{t}_1 \to t\widetilde{\chi}_1^0$ and $\widetilde{b}_1 \to t\widetilde{\chi}_1^-$ ($\widetilde{\chi}_1^- \to W^-\widetilde{\chi}_1^0$), lower limits on gluino and sbottom masses are calculated. Gluinos with masses up to approximately 1050 GeV and bottom squarks with masses up to about 500 GeV are probed. In models where gluinos do not decay to third-generation squarks, sensitivity for gluino masses up to approximately 900 GeV is obtained. A similar reach in the gluino masses is demonstrated in the scope of an R-parity violating model.

The results are used to set upper limits on the same-sign top-quark pair production cross section $\sigma(pp \to tt,\ \overline{t}\overline{t}) < 720\,\text{fb}$ and $\sigma(pp \to tt) < 370\,\text{fb}$ at 95% CL. An upper limit at 95% CL of $\sigma(pp \to tt\overline{t}\overline{t}) < 49\,\text{fb}$ is obtained for the cross section of quadruple top-quark production.

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