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Search for Supersymmetry in Four W and Multiple b-Quark Final States

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Abstract. In this talk, the latest results from CMS on searches for new physics in final states with four W bosons and multiple b-quarks are presented using up to 20 fb^{-1} of data from the 8 TeV LHC run of 2012. This final state is of special importance in the context of the search for third generation squarks in gluino or sbottom cascade decays. The four W final state is reconstructed in a variety of final states ranging from zero to four leptons, and including up to eight or more jets and E_T^{miss}.

1 Introduction

In proton-proton collisions, the production rate of events yielding four W bosons and multiple b-quarks is predicted to be very small by the Standard Model (SM), while several of the new physics models beyond the SM predict relatively large cross sections for this final state. Gluino and sbottom pair production in Supersymmetry (SUSY), for which the representative diagrams are shown in Figure 1, are the two examples that can lead to signatures with four W bosons and four or two b-quarks. If realized at the LHC the experimental signatures for such models would be spectacular and would include various multiplicities of leptons, jets, b jets and large missing transverse energy, E_T^{miss}.

The CMS collaboration [1] explored various final states to search for signatures with four W and multiple b-quarks using the LHC data collected in 2012 [2–5]. The SM backgrounds and the search strategies vary significantly depending on the required number of leptons (e, μ, τ) in these searches, therefore the searches are organized according to this number of leptons. About 20% of the four W events results in a zero-lepton final state, where 12 jets are expected, 4 or 2 of which are b-quark jets. The CMS search in this channel [5] is detailed in another contribution in this proceedings. Despite the large expected backgrounds from top pair and W+jets processes, the single-lepton channel is an excellent channel to search for this signature due to the largest branching ratio (BR), ~ 44%, to this channel. The same-sign dilepton and, in particular, multi-lepton final states, are also excellent channels to search for such models due to the much lower expected SM background.

2 Search in trilepton + b jet channel

Events with at least three leptons $(eee, ee\mu, e\mu\mu, \mu\mu\mu)$ with $p_T > 10/10/20$ GeV, at least two jets with $p_T > 30$

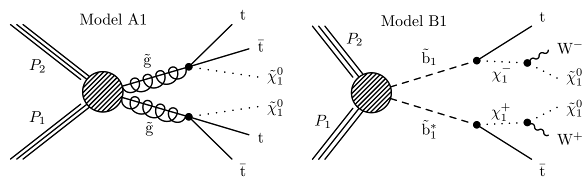

Figure 1. Representative diagrams for gluino-pair production with subsequent decay to four top quarks and two lightest SUSY particles (LSP) ($pp \rightarrow \tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}\chi_1^0\chi_1^0$) via off-shell top squark (left) and direct sbottom pair production with decay to two top quarks, two W and two LSP ($pp \rightarrow \tilde{b}_1\tilde{b}_1^* \rightarrow t\bar{t}WW\chi_1^0\chi_1^0$) (right).

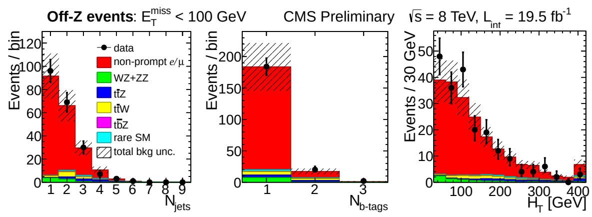

Figure 2. The kinematical distributions for the OFFZ data selected with $E_T^{miss} < 100$ GeV and $N_{b-tags} \geq 1$ requirements. The last bin in the histograms includes overflow. The shaded bands correspond to the estimated uncertainties on the background which are calculated on a bin-by-bin basis.

GeV where one of them is identified to be b-quark jet and $E_T^{miss} > 50$ GeV are selected. In order to reduce the background from SM processes with a Z boson (like WZ, ZZ, ttZ), events are classified into two categories: events with an opposite-sign same-flavor dilepton pair forming an invariant mass consistent with Z boson, ONZ, and the rest with no Z boson candidate, OFFZ. In this talk, the analysis of the second category is included. The main background for this analysis in the OFFZ category is from top-pair production where the third lepton arises from semi-leptonic decays of the b-quarks. This background is sig-

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nificantly reduced by the isolation requirement on the leptons as well as by removing lepton candidates that overlap with identified b-jet candidates. The residual background from this source is estimated using a well established data-driven method, so called “Btag-and-Probe”. We measure the probability for a b jet to yield an isolated lepton that satisfies the full lepton selection using a $b\bar{b}$ di-jet control sample. The performance of the technique was studied in simulation as well as in a data sample where the SM processes are expected to be dominant. In Figure 2, the predictions obtained using this method, labeled as “non-prompt e/μ”, are compared to the observed data events as a function of various variables; a good agreement can be seen. Based on these performance studies of the technique we estimate a systematic uncertainty of 30% for this background determination. This incorporates the uncertainty arising from the fact that this probability is measured in a QCD-dominated control sample but applied to a different environment ($t\bar{t}$) where the spectrum of the b-jets is harder. A second category of backgrounds arises from some rare SM processes that are irreducible in this analysis. These processes are the top (pair) production in association with W, Z or Higgs boson ($t\bar{t}W$, $t\bar{t}Z$, tbZ, $t\bar{t}H$), diboson production (WZ, ZZ) and other processes leading to multibosons in the final state. These backgrounds are predicted using leading-order MC event generators and the most accurate calculations of the cross sections available, mostly with the next-to-leading order (NLO) or the next-to-next-to-leading order (NNLO) precision. A 50% systematic uncertainty is assigned to account for the limited experimental cross-checks possible for these processes in the phase-space regions of the search.

In Figure 3, the E_T^{miss} spectrum is presented in bins of jet and b-jet multiplicity for events with $H_T > 200$ GeV, where H_T is the scalar sum of the transverse momenta of the selected jets. Additional to the predicted total SM background and observed data events, we also show the expected signal yields in each bin for two benchmark points. The data agrees with the expected SM background in all considered signal regions considered. The predicted backgrounds and observed data events in each jet, b-jet multiplicity and E_T^{miss} are used to obtain 95% confidence level (C.L.) upper limit (UL) on the production cross section for various signal models that produce four W bosons and multiple b-quark jets in the final state.

3 Search in same-sign dilepton + b jet channel

Same-sign dilepton events in general provide great potential for new physics searches at the LHC. They are rarely produced in the SM and can naturally be produced in various new physics scenarios. In the context of searches for SUSY, additional requirements of a large hadronic activity and large E_T^{miss} further reduce the SM contribution to this final state, making it even more attractive for such searches.

CMS has performed a search with same-sign dileptons using 10.5 fb^{-1} of LHC data collected in 2012 [3]. Events

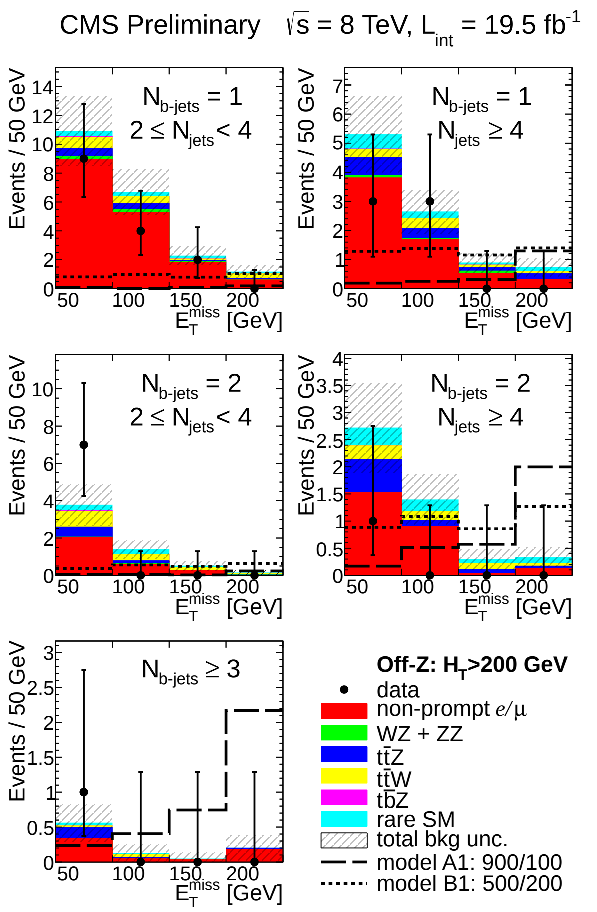

Figure 3. Predicted total background and observed data yields as a function of MET for events that do not contain an opposite-sign-same-flavour pair that is a Z boson candidate (OFFZ) with $H_T > 200$ GeV. The shaded bands correspond to the estimated total uncertainties on the background. The dashed histograms show an expected yield for the A1 (B1) model with particle masses $m_{\tilde{g}} = 900$ GeV and $m_{\chi_1^0} = 100$ GeV ($m_{\tilde{b}_1} = 500$ GeV and $m_{\tilde{\chi}^\pm} = 200$ GeV).

with same-charge dileptons ($ee, \mu\mu, e\mu$) with $p_T > 20$ GeV, at least two b jets with $p_T > 40$ GeV, $E_T^{miss} > 50$ GeV and $H_T > 200$ GeV are selected. By altering the lower bounds on number of jets, E_T^{miss} and H_T, various signal regions that could increase the sensitivity to different SUSY particle mass spectra are formed. The main backgrounds to this search are similar to those in the trilepton search discussed in Section 2. The requirement of at least two b jets, where these b jets are well separated from same-sign dilepton candidates in the $\eta-\phi$ plane, rejects $t\bar{t}$ background significantly. The remaining background from this source is predicted using the same technique as in the trilepton search. Irreducible backgrounds from rare SM processes like $t\bar{t}W$, $t\bar{t}Z$, tbZ, $t\bar{t}H$ and multiboson production are estimated using MC simulations.

An additional background to the same-sign dilepton final state comes from events with opposite-sign leptons where the charge of one of the leptons is mismeasured because of severe bremsstrahlung in the tracker material.

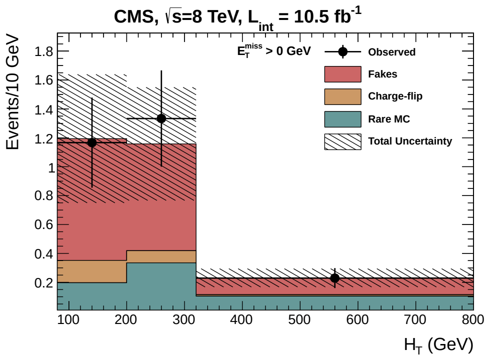

Figure 4. Predicted SM background from each source compared to the observed data events, as a function of E_T^{miss} and H_T, in the same-sign dilepton final state.

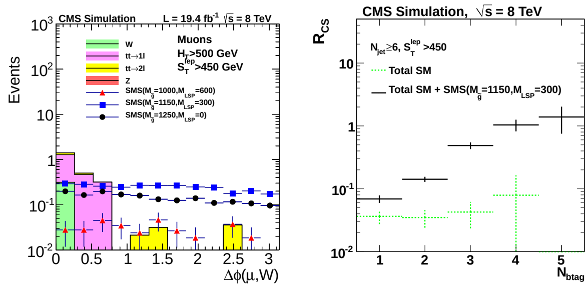

Figure 5. Left: the $\Delta\phi(W, \ell)$ distribution for muon events with $N_{bjet} \geq 3$, $N_{jet} \geq 6$, and $S_T^{lep} > 450$ GeV. The single lepton $t\bar{t}$ background is strongly suppressed in the $\Delta\phi(W, \ell) > 1$ signal region. Right: the transfer factor, R_{CS}, as a function of number of b jets for events with $N_{jet} > 6$, for electrons and muons combined in the $S_T^{lep} > 450$ GeV bin.

		S_T^{lep} [GeV]	control reg. data	prediction	observation
$N_{btag}=2$	Muons	[250,350]	141	$6.00 \pm 2.23 \pm 2.40$	9
		[350,450]	24	$1.37 \pm 1.12 \pm 1.19$	2
		>450	9	$0.0 \pm 0.66 \pm 0.66$	0
	Electr.	[250,350]	112	$3.83 \pm 1.75 \pm 1.84$	9
		[350,450]	28	$2.74 \pm 1.86 \pm 2.02$	2
		>450	9	$0.0 \pm 0.42 \pm 0.42$	0
$N_{btag} \geq 3$	Muons	[250,350]	28	$1.92 \pm 0.84 \pm 0.95$	0
		[350,450]	13	$0.57 \pm 0.52 \pm 0.58$	0
		>450	2	$0.0 \pm 0.22 \pm 0.22$	0
	Electr.	[250,350]	45	$1.89 \pm 0.94 \pm 1.03$	4
		[350,450]	7	$0.85 \pm 0.70 \pm 0.80$	0
		>450	0	$0.0 \pm 0.08 \pm 0.08$	0

Figure 6. Predicted SM background in each signal region compared to observed events in data in the single lepton analysis. "Control reg. data" corresponds to the number of events in $\Delta\phi(W, \ell) < 1$ which are used to determine the background in $\Delta\phi(W, \ell) > 1$. The statistical uncertainty on the predicted background is also shown in parenthesis.

This background is negligible for muons. The charge mismeasurement probability for electrons is measured using $Z \rightarrow ee$ events. The number of same-sign and opposite-sign dielectron events where dilectrons form an invariant mass consistent with the Z mass are compared. The background in this category is estimated using this measured probability together with the number of opposite-sign ee or $e\mu$ events passing the full kinematic selection of the search. This background accounts only for less than 10% of the total background.

In Figure 4, the H_T distribution is shown for the predicted SM background from each source mentioned above, after the full event selection. No excess over expected SM background is observed.

4 Search in single-lepton + b jet channel

The branching fraction from four-W final states to a single lepton is the largest, about 44%. CMS has performed a search in this channel with multijets and b-jets, with a data sample corresponding to 19.4 fb^{-1} of integrated luminosity. The events containing exactly one lepton (e, μ) with $p_T > 20$ GeV, $H_T > 500$ GeV, at least six jets and two b jets are selected. At this stage of the selection the main SM backgrounds are $t\bar{t}$, V+jets, single top quark and diboson production. The backgrounds other than top-pair production are strongly suppressed by requiring that a number of jets are identified as having arisen from b quarks.

In this search, the angle between the lepton and W momentum vectors, $\Delta\phi(W, \ell)$, and the leptonic mass scale of the event, $S_T^{lep} = \sqrt{p_T(W)^2 + M_T(W)^2}$, are used to further suppress the $t\bar{t}$ background. For events with a single leptonically-decaying W boson, large values of S_T^{lep} arise when the W boson is highly boosted. For such events, $\Delta\phi(W, \ell)$ is expected to be small, therefore requiring $\Delta\phi(W, \ell) > 1$ and large S_T^{lep} strongly suppresses the single-lepton $t\bar{t}$ background and leaves the dileptonic $t\bar{t}$ background as dominant. On the other hand, in signal events no such correlation is expected. In Figure 5 (left) the $\Delta\phi(W, \ell)$ distribution for the background processes as well as for three benchmark points in Model A is shown to illustrate the discrimination power of the $\Delta\phi(W, \ell)$ variable. The events that remain in $\Delta\phi(W, \ell) < 1$ are used to estimate the residual $t\bar{t}$ background at $\Delta\phi(W, \ell) > 1$. The ratio of the events with $\Delta\phi(W, \ell) > 1$ to $\Delta\phi(W, \ell) < 1$, here referred to as R_{CS}, is shown to be uniform as a function of number of b jets for the background-only hypothesis. This is shown in Figure 5 (right) for both background only and signal-plus-background hypotheses. We therefore measure R_{CS} in a sample with fewer b-tagged jets than the final signal sample and use it together with events at $\Delta\phi(W, \ell) < 1$ at each search region to predict the residual background.

In Table 6 the predicted total background and number of observed events in each signal selection region is shown. The uncertainty on the predicted background is dominantly due to the low statistics for $\Delta\phi(W, \ell) < 1$, which is used to determine the background in $\Delta\phi(W, \ell) > 1$. The observed data agrees with the expected SM background.

5 Interpretation of the results

We have performed a suite of analyses in various final states to search for new physics models that lead to four W bosons, multiple b quarks and large E_T^{miss}. These searches are organized according to number of leptons in the final state and they cover phase-spaces from low to high jet and b-jet multiplicities as well as various E_T^{miss} regions, which maximizes the sensitivity to SUSY models with various sparticle mass spectra. In all these searches the observed data events are consistent with the expected SM background. We therefore use these results to constraint SUSY parameter space within the context of various simplified models. In most of the cases we perform simultaneous counting experiments in exclusively defined phase-space regions (signal regions).

In a scenario where the bottom squark is lighter than gluinos and other squarks, the direct sbottom production might become important. Searches for the sbottom quark at the LHC are important as the natural SUSY scenarios suggests relatively light masses for third generation squarks. One of the sbottom decay possibilities is shown in Figure 1 (right), leading to four W, two b-quarks and the lightest neutralinos in the final state. The results of the trilepton search are interpreted in this scenario. Figure 7 shows the 95% CL upper limits on the sbottom pair production cross sections as well as the exclusion contours where 100% BR for a decay chain discussed above is assumed . The experimental acceptance in this model can significantly vary depending on the masses $m_{\chi_1^0}$, $m_{\chi^\pm}$ and $m_{\tilde{b}}$. Two representative cases are considered; we scan various masses of the sbottom and neutralino where the chargino mass is fixed with the following relations: $m_{\chi_1^0}/m_{\chi^\pm} = 0.5$ and $m_{\chi_1^0}/m_{\chi^\pm} = 0.8$. As expected the cross section upper limits are relatively less stringent for the latter case due to the smaller phase-space allowed for the top to be produced on-shell and therefore it leads to soft b-quark jets, which reduces the signal selection acceptance. In these scenarios, the sbottom masses up to 550 and 600 GeV are probed. The same-sign dilepton results are also interpreted in this model, see Figure 8 (left), where the neutralino mass is fixed to 50 GeV. Masses of the sbottom up to 450 GeV are probed in this final state. In case gluinos are not too heavy, sbottom pair production via gluino production can become accessible at the LHC. Such a sbottom pair production can lead to four W, four b quarks, and neutralinos. The results of the search in the same-sign dilepton channel probe masses of the gluino up to 1 TeV in this scenario.

In the past few years, the searches for stop production at the LHC took considerable attention from both experimental and theoretical communities as they play an important role for the natural solution to the “hierarchy problem” within SUSY. Both ATLAS and CMS collaborations reported results on direct stop pair production. However, depending on the SUSY particle mass spectrum, for example, for not too large gluino masses combined with not too light stops, stop production via gluino pair production might be the only way to experimentally observe top squarks. In Figure 1 (left) a representative diagram is shown where the gluino undergoes a 3-body decay to a top-antitop pair and the lightest neutralino via a virtual stop. The results of the searches presented in this document are interpreted in the context of such a scenario and are presented in Figure 9. The search in the single lepton channel provides the best sensitivity extending the reach in gluino mass up to 1.3 TeV. However, it is important to note that the trilepton and same-sign dilepton channels can probe scenarios where the difference between gluino and neutralino mass is small. In such cases, the top quarks are produced almost at rest and therefore the final state products, b jets and leptons, are softer and accompanied by relatively small E_T^{miss}. Due to their low SM background these two searches can be performed with looser selections compared to the single lepton search, where large hadronic activity and E_T^{miss} requirements are necessary to reduce the background. Also note that the signal sample produced for this study contains always four on-shell top quarks. However, if nature exhibits smaller mass differ-

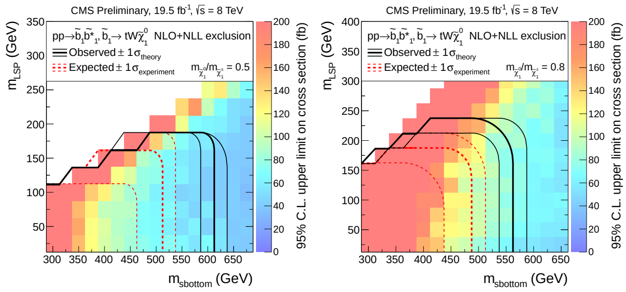

Figure 7. The 95% CL upper limits on the model B1 scenario cross sections (in fb) derived using the CLs method. The limits are computed for the following scenarios within the model B1: (left) $m_{\chi_1^0}/m_{\chi^\pm} = 0.5$ or (right) $m_{\chi_1^0}/m_{\chi^\pm} = 0.8$. The solid (black) contours show the observed exclusions assuming the NLO+NLL cross sections, along with the one standard deviation theory uncertainties. The dashed (red) contours present the corresponding expected results, along with the one standard deviation experimental uncertainties. The deviation of the observed limit from the expected one is evaluated to be at the level of two standard deviations in experimental uncertainty.

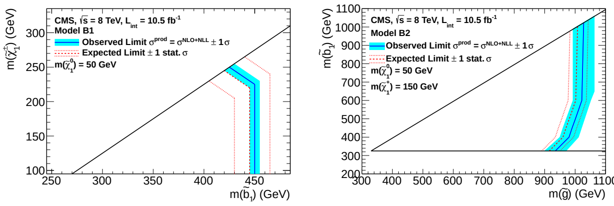

Figure 8. The 95% CL exclusion contours for two simplified models: model B1 scenario in a plane of $m_{\chi^\pm}$ and $m_{\tilde{g}}$ for $m_{\chi_1^0} = 50$ GeV on the left, and in a mass plane of $m_{\tilde{b}_1}$ and $m_{\tilde{g}}$ in a scenario where sbottom pairs are produced via gluinos ($pp \rightarrow \tilde{g}\tilde{g} \rightarrow b\bar{b}\tilde{b}_1\tilde{b}_1^* \rightarrow b\bar{b}WWt\bar{t}\chi_1^0\chi_1^0$) and chargino and the lightest neutralino masses are assumed to be 150 and 50 GeV respectively. The solid (black) contours show the observed exclusions assuming the NLO+NLL cross sections for the signal, along with the one standard deviation theory uncertainties shown in the blue shaded band. The dashed (red) contours present the corresponding expected results, along with the one standard deviation experimental uncertainties.

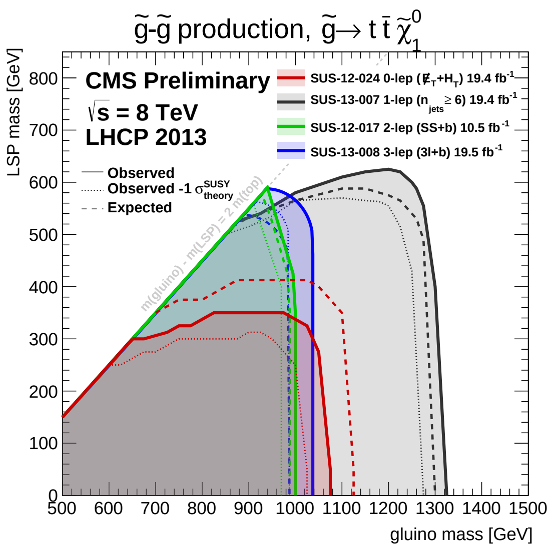

Figure 9. The summary of the expected (dashed curve) and observed (solid curve)95% CL exclusion contours obtained in various analyses as a function of $m_{\tilde{g}} - m_{\chi_1^0}$ in Model A1. Also in this case the NLO+NNL theory cross sections are used. The dotted curves represent the -1σ theory uncertainty.

ences for $m_{\tilde{g}} - m_{\chi_1^0}$, then the trilepton and same-sign dilepton channels become even more important to probe such scenarios.

6 Summary and Conclusion

We have presented the CMS searches for four-W and multiple-b-quark signatures in various final states with the LHC data collected in 2012 corresponding up to 20 fb^{-1} of integrated luminosity. No significant excess over expected SM background is observed. The results are used to constrain the parameters of various simplified models that lead to four-W and multiple-b-quark signatures. For the gluino pair production leading to this signature, the single lepton search gives the best sensitivity in a wide set of mass combinations of the gluino and the lightest neutralino, while for the cases where the mass differences between these two sparticles are small the same-sign dilepton and trilepton channels provide better sensitivity. A statistical combination of these searches in various lepton multiplicities can potentially give more stringent constraints in this model, in particular, hard-to-probe parameter regions, so-called "compressed sparticle spectra". The results are also interpreted in direct or gluino-mediated sbottom production. Sbottom masses up to 600 GeV are probed.

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