Search for top squarks and dark matter particles in opposite-charge dilepton final states at CMS

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A search for new physics is presented in final states with two oppositely charged leptons, jets identified as originating from b quarks, and missing transverse momentum using 35.9/fb of CMS data recorded in 2016. Hypothetical signal events are efficiently separated from the dominant top quark pair background with requirements on missing transverse momentum and transverse mass variables, the latter reducing the background by four orders of magnitude. No significant deviation is observed from the expected background. The results are interpreted in terms of simplified models of pair produced scalar partners of top quarks (top squarks), as predicted by supersymmetric models. Exclusion limits reach up to top squark masses of 1.3 TeV for specific model assumptions. Additionally, pair production of dark matter particles via scalar or pseudoscalar mediators is tested, and the analysis provides exclusions of scalar mediators with masses below 100 GeV.

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1. Introduction

The standard model of particle physics (SM) successfully describes processes at very different energy scales, reaching up to the TeV scale which is probed at the Large Hadron Collider (LHC) at CERN. However, several shortcomings are present within the SM that give hints that physics beyond this theory exists. Supersymmetry (SUSY) is one of the most prominent theories that provides a solution to the hierarchy problem, and, if R-parity is conserved, a dark matter candidate in form of the lightest SUSY particle. The lightest SUSY particles are expected to have masses at the TeV scale, accessible with the LHC.

A search for top squark pair production in final states with two opposite-charge leptons, at least two hadronic jets with one of them being identified to originate from b quarks (b jet), and significant transverse momentum imbalance (p_T^{miss}), is performed [1]. The analysis is based on a dataset of proton-proton collisions at a center-of-mass energy of 13 TeV, recorded by the CMS experiment in 2016 [2]. Diagrams for processes leading to such final states are shown in Fig. 1. In the simplest SUSY model, shown in Fig. 1 (left), the pair produced top squarks each deacy to the stable lightest neutralino $\widetilde{\chi}_1^0$ (LSP) and a top quark. Following the conventions of [3], this model is called T2*tt*. In a second model, called T8*bbℓℓνν* and shown in Fig. 1 (center), top squarks decay via intermediate charginos to sleptons, which subsequently decay to a lepton and a neutralino $\widetilde{\chi}_1^0$. This decay is motivated by the 100% branching fraction into two leptons. In a simplified dark matter (DM) model shown in Fig. 1 (right) a scalar (ϕ) or pseudoscalar (a) mediator is produced in the $t\bar{t}$ t-channel that decays to two Dirac fermions χ, which are the stable DM particles.
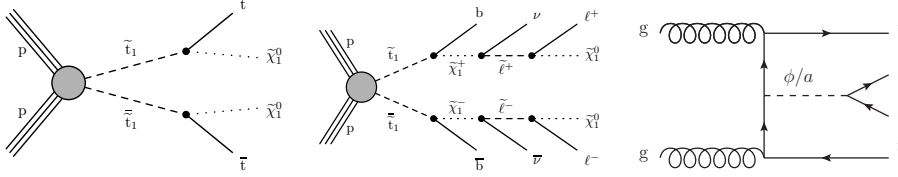

Figure 1: Diagrams for simplified SUSY and dark matter models: strong production of top squark pairs $\widetilde{t}_1\bar{\widetilde{t}}_1$, where each top squark decays to a top quark and a $\widetilde{\chi}_1^0$ (T2*tt* model, left), or to a neutrino and an intermediate slepton $\nu\widetilde{\ell}^\pm$ that yield $\nu\widetilde{\chi}_1^0$ and an $\ell^\pm$ from the virtual slepton decay (T8*bbℓℓνν* model, center). Direct DM production through scalar or pseudoscalar mediators in association with top quarks is shown at the right.

2. Search strategy

We select events with two leptons, electrons or muons, with a transverse momentum (p_T) of at least 20 GeV and no additional leptons with p_T >15 GeV. At least two jets, out of which at least one has to be classified as b jet, are required. In order to suppress contributions from Drell-Yan (DY) production we require the invariant mass of same-flavor lepton pairs to be more than 15 GeV off the Z boson mass. By requiring p_T^{miss} >80 GeV and a minimum value for a measure of the significance of p_T^{miss}, DY and multiboson processes are reduced further. Requirements on the angular separation of p_T^{miss} with the leading and subleading jets suppress events that pass the aforementioned selection due to jet mismeasurements and the p_T^{miss} resolution.

$M_{T2}(b\ell b\ell)$ (GeV)	p_T^{miss} (GeV)	$100 \leq M_{T2}(\ell\ell) < 140$ GeV	$140 \leq M_{T2}(\ell\ell) < 240$ GeV	$M_{T2}(\ell\ell) \geq 240$ GeV
$0 - 100$	$80 - 200$	SR0	SR6	
	≥ 200	SR1	SR7	
$100 - 200$	$80 - 200$	SR2	SR8	
	≥ 200	SR3	SR9	SR12
≥ 200	$80 - 200$	SR4	SR10	
	≥ 200	SR5	SR11	

Table 1: Definition of the signal regions, which are further split into opposite-flavor and same-flavor regions.

After applying the above selection criteria the majority of background events contain two leptons from top quark pair production (t$\bar{\text{t}}$), where both the top quark and antiquark decay leptonically. A variable called $M_{T2}(\ell\ell)$ based on the transverse mass (M_T) is constructed in order to separate potential signal events from the dominant background,

$$M_{T2}(\ell\ell) = \min_{\vec{p}_{T,1}^{miss} + \vec{p}_{T,2}^{miss} = \vec{p}_T^{miss}} \left(\max \left[M_T(\vec{p}_{T,1}^{vis}, \vec{p}_{T,1}^{miss}), M_T(\vec{p}_{T,2}^{vis}, \vec{p}_{T,2}^{miss}) \right] \right). \tag{2.1}$$

For well reconstructed t$\bar{\text{t}}$ events $M_{T2}(\ell\ell)$ has a kinematic endpoint at the mass of the W boson, while signal events would also populate the tails of the distributions due to the additional contribution of the LSPs to p_T^{miss}. One can furthermore add the momentum of the b jets to the visible momentum component in the computation of $M_{T2}(\ell\ell)$, resulting in a variable called $M_{T2}(b\ell b\ell)$ with a kinematic endpoint at the top quark mass for t$\bar{\text{t}}$ events.
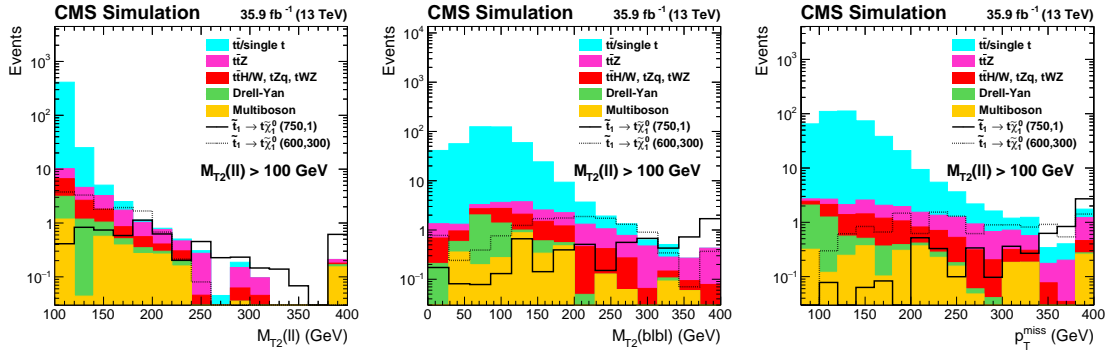

Figure 2: Simulated distributions of $M_{T2}(\ell\ell)$ (left), $M_{T2}(b\ell b\ell)$ (center), and p_T^{miss} (right) for the SM processes (stacked filled histograms) and a SUSY signal with a top squark mass of 750 (600) GeV and the LSP mass of 1 (300) GeV shown as solid (dashed) black line [1].

Together with p_T^{miss}, $M_{T2}(\ell\ell)$ and $M_{T2}(b\ell b\ell)$ are the main search variables in this analysis. Several signal regions are constructed using various thresholds of those observables which are introduced in Table 1. Simulated distributions of the variables are shown in Fig. 2.

3. Background prediction

The main contributions to backgrounds from SM processes come from t$\bar{\text{t}}$, DY, and multiboson production. Additionally, events from t$\bar{\text{t}}$ production in association with Z, W, or H bosons are significantly contributing in the signal regions.

Well reconstructed $t\bar{t}$ events are contained in regions of low $M_{T2}(\ell\ell)$ and $M_{T2}(b\ell b\ell)$. Mismeasurements of p_T^{miss} or misidentification of leptons can promote events to regions with higher values of $M_{T2}(\ell\ell)$ and $M_{T2}(b\ell b\ell)$. Simulated events are used to predict the $t\bar{t}$ background in the signal regions. The modeling of these events is validated in dedicated control regions and their normalization is extracted by inverting the requirements on $M_{T2}(\ell\ell)$. A systematic uncertainty is assigned to the prediction based on the agreement of data and simulation in the control regions.
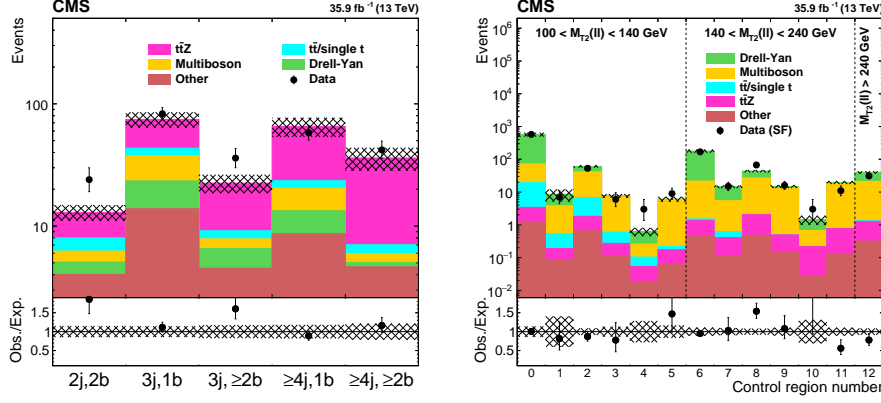

Figure 3: Event yields in the $t\bar{t}Z$ (left) and Drell-Yan and multiboson control regions (right) with the relevant SM processes scaled to data via a maximum likelihood fit. The hatched band shows the uncertainties from the fit as well as uncertainties from experimental effects [1].

The overall normalization of events from $t\bar{t}$ production in association with a Z boson, which constitutes an irreducible background if the Z boson decays to neutrinos, is measured in final states with three leptons. We obtain sample of $t\bar{t}Z$ events with high purity by requiring at least one b jet and a same-flavor dilepton pair with an invariant mass close to the Z boson mass. Event yields in the dedicated control regions are shown in Fig. 3 (left). The measured data-tp-prediction scale factor which is applied to simulated distributions is compatible with unity.

We measure the data-to-prediction scale factor simultaneously for DY and multiboson production in events that do not contain a b jet but a same-flavor lepton pair with an invariant mass that lies within 15 GeV around the Z boson mass. The measured scale factors are close to unity for both DY and multiboson events, and the resulting event yields are shown in Fig. 3 (right).

4. Results

The observed $M_{T2}(\ell\ell)$ and $M_{T2}(b\ell b\ell)$ distributions are well described by the expected SM backgrounds as shown in Fig. 4. No significant excess over predicted SM background is seen in the signal regions, as shown in Fig. 5.

The results are interpreted in the context of several simplified SUSY and DM models. For the T2tt model results are combined with other CMS searches for top squark pair production in final states with a single lepton [4] and the all-hadronic final states [5]. In the combined result top squarks with masses of up to 1050 GeV for a massless LSP are excluded at 95% confidence level, as shown in Fig. 6 (left). The sensitivity to the T8$bb\ell\ell\nu\nu$ model is highly dependent on the masses of the intermediate chargino and slepton. In all considered configurations the chargino
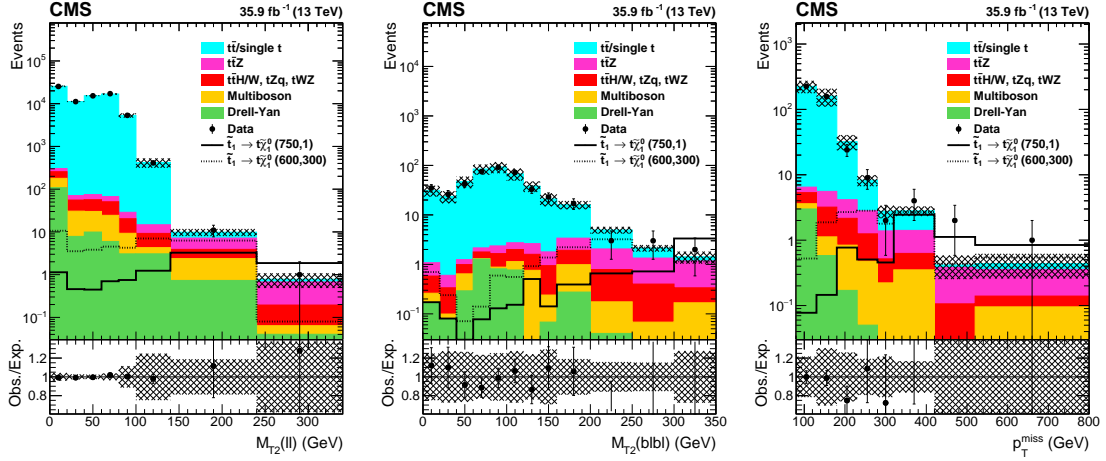
Figure 4: Distributions of $M_{T2}(\ell\ell)$ (left), $M_{T2}(b\ell b\ell)$ (center) and p_T^{miss} (right). For the $M_{T2}(b\ell b\ell)$ and p_T^{miss} distributions, events must satisfy $M_{T2}(\ell\ell) > 100$ GeV. The hatched band shows the total uncertainty on the expected SM background [1].
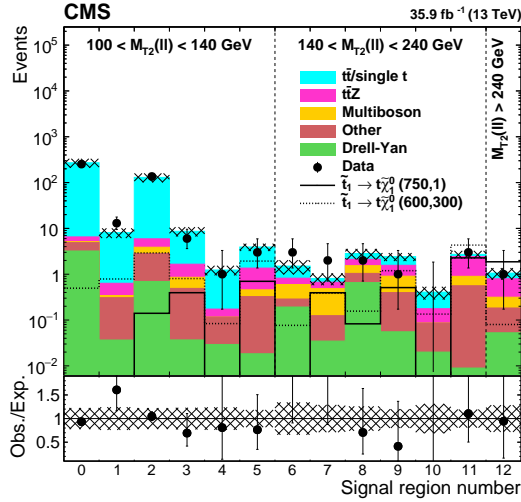

Figure 5: Predicted and observed event yields in the signal regions. The hatched band shows the total uncertainty on the expected SM background [1].

mass is set to the average of the top squark and the LSP mass. The slepton mass is parametrized by $m_{\tilde{\ell}} = x(m_{\tilde{t}_1} + m_{\tilde{\chi}_1^0}) + m_{\tilde{\chi}_1^0}$. If the masses of the slepton and the LSP are close, corresponding to low values of x, the sensitivity decreases due to the softer lepton p_T spectrum. For $x = 0.95$, top squarks are excluded up to a mass of 1300 GeV for an almost massless LSP, shown in Fig. 6 (right).

The simplified DM models assume DM particle pair production via a mediator that couples to top quarks and DM particles with a strength of $g_q = g_{DM} = 1$. Scalar and pseudoscalar mediators with masses of up to 100 GeV and 50 GeV, respectively, are excluded for DM particle masses of 1 GeV, shown in Fig. 7.

In order to facilitate reinterpretation of the analysis, results in aggregate signal regions are provided, as well as correlation and covariance matrices for the full set of signal regions. The
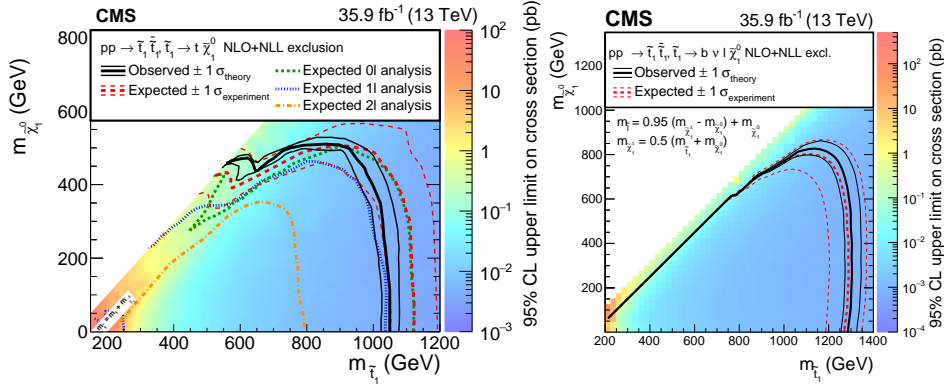
Figure 6: Expected and observed limits for the T2*tt* (left) and T8*bbℓℓνν* model (right) in the top squark and LSP mass plane. The color map indicates the 95% CL upper limit on the product of cross section and the square of the branching fraction. The area below the thick black line represents the observed exclusion limit at 95% CL. The red dashed line corresponds to the expected limits of the combined result for the T2*tt* model and for this analysis for the T8*bbℓℓνν* model. The green, orange, and blue dashed lines show the expected limits of the individual analyses (left) [1].

material can be accessed on HEPData [1], together with digitized versions of all figures and tables.
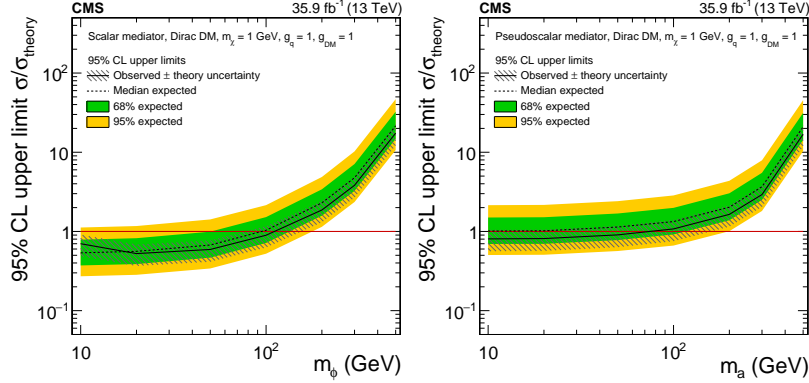

Figure 7: The 95% CL expected (dashed) and observed limits (solid line) on $\mu = \sigma/\sigma_{\text{theory}}$ for a DM particle with $m_\chi=1$ GeV. Different masses for the scalar (left) and pseudoscalar (right) mediators are assumed. The red horizontal line indicates $\mu = 1$. The hashed area around the observed limit corresponds to the 30% theory uncertainty in the inclusive signal cross section [1].

References

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