Search for production of SUSY partners of the top quark with the CMS detector

Grégory Hammad on behalf of the CMS Collaboration
Groupe de Physique des Particules, Université de Mons, Belgium
E-mail: gregory.hammad@umons.ac.be

Abstract. The results of a search for production of supersymmetric partners of the top quark in proton-proton collisions at $\sqrt{s} = 7$ TeV at the LHC are presented. These results are based on a data sample, collected by the CMS detector in 2011, corresponding to 5 fb$^{-1}$ of integrated luminosity. No sign of new physics is observed and exclusion limits on masses of supersymmetric particles are derived in the context of simplified models.

1. Introduction
In many supersymmetric extensions (SUSY) of the Standard Model, SUSY partners of the 3rd quark generation (stop, sbottom) are lighter than the partners of the 1st and 2nd generations, allowing production rates high enough to be observed at the LHC. Moreover, recent results on Higgs boson searches favour light stop particles [1]. As these 3rd generation SUSY partners should decay to heavy quarks (t, b), evidence for the existence of such SUSY partners may be observed by studying events with top quark pairs in the final state.

2. Experimental signature
In the context of R-parity conserving SUSY models, supersymmetric particles, which have an odd R-parity, are produced in pairs and lead to final states containing lightest SUSY particles (LSP) via cascade decays. The LSP are stable and are assumed to be weakly interacting massive particles. Experimentally, the non-detection of the LSP causes to an energy imbalance in the transverse plane with respect to the direction of the colliding particles. This imbalance, called missing transverse energy (MET), is a distinctive SUSY signature.

At the Large Hadron Collider, the CMS Collaboration [2] searched for the production of stop quark pairs either via gluino decay ($pp \rightarrow \tilde{g} \tilde{g} \rightarrow \tilde{t}^* \tilde{t}^*$) or via direct production ($pp \rightarrow \tilde{t} \tilde{t}^*$). As the top quark decays almost exclusively into a b quark and a W boson, the final state topology depends on the subsequent decay of the W boson ($W \rightarrow l\nu$ or $W \rightarrow q\bar{q}$). Experimental signatures of stop quark production are thus characterised by:

- isolated leptons with high transverse momentum ($p_T$) in leptonic decay channels,
- large missing transverse energy (MET),
- jets from b-quarks.

The main algorithms used by the CMS Collaboration to identify b-jets are the simple secondary vertex tagger (SSV), the track counting tagger (TC) and the combined secondary vertex tagger (CSV) [3].

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3. Search strategies

3.1. Search with same-sign dileptons (SS+b)
In the context of Supersymmetry, final states with two same-sign leptons may correspond to the production of gluino pairs decaying into $tt\tilde{\chi}_0$ via an intermediate virtual or on-shell stop with subsequent decays of two same-sign top quarks via the leptonic channel $t \rightarrow bW \rightarrow bl\nu$. In this analysis [4], the event selection requires at least two isolated same-sign leptons with $p_T > 20$ GeV/c. In addition, at least two jets with $p_T > 40$ GeV/c are required, among which at least two are tagged as b-jets by the SSV tagger. To suppress background events from $Z$+jets production, events with any third isolated lepton forming an opposite-sign, same-flavour lepton pair with a mass compatible with the $Z$ boson mass are rejected. Remaining background events containing one or more fake leptons (i.e., mis-identified hadrons, electrons from photon conversion, etc.) are estimated from data using events with one or more leptons failing tight identification and isolation requirements but not looser ones. These events are then corrected for the probability for a fake lepton to pass the selection, obtained from events with a lepton candidate and a separated jet. The background contribution from opposite-sign dilepton events with one lepton having a mis-reconstructed charge is estimated using a control sample with opposite-sign dilepton events corrected for the charge misidentification probability derived from simulation and validated with a data sample containing lepton pairs whose invariant mass is compatible with the $Z$ boson mass. Finally, events with genuine same-sign leptons from rare SM processes (e.g., $ttW$ or $ttZ$) are estimated using simulation.

3.2. Search with single lepton final states
Two different analyses searched for stop production with a single lepton in the final state. Their search sensitivity was found to be enhanced by requiring a high b-tag jet multiplicity.

(e/\mu, \geq 2b, MET) analysis [5] : event selection requires one isolated lepton with $p_T > 20$ GeV/c, at least three jets with $p_T > 40$ GeV/c and MET > 100 GeV. In addition, the scalar sum of the selected jet transverse momenta, $H_T$, is required to be higher than 350 GeV/c. Identification of b-jets is made with the SSV algorithm. The main background sources after event selection are $tt$ and W+jets production and are estimated separately by fitting the MET distribution with distinct exponential templates parametrized as a function of $H_T$. The free parameters of these templates are determined from data in a control region defined by $350 < H_T < 700$ GeV and $100 < \text{MET} < 400$ GeV where the fraction of $tt$ to W+jets events is derived using template fits to the observed b-tagged jet multiplicity. The fitted MET templates are then extrapolated at high value of $H_T$.

(e/\mu, \geq 3b, Y_{\text{MET}}) analysis [5] : events are selected by requiring one isolated lepton with $p_T > 20$ GeV/c, at least four jets with $p_T > 40$ GeV/c, MET > 60 GeV and $H_T > 375$ GeV/c. In addition, selected events are required to have at least one b-tagged jet, using the TC tagger. Background events, mainly $tt$ and W+jets events, are estimated using a factorisation method in the $H_T$-$Y_{\text{MET}}$ plane, with $Y_{\text{MET}} = \text{MET}/\sqrt{H_T}$. The signal region is defined by $H_T > 650$ GeV and $Y_{\text{MET}} > 5.5 \sqrt{\text{GeV}}$. Correlation factors between $H_T$ and $Y_{\text{MET}}$ for the different background processes are derived from simulation. Background estimations are calculated per b-tagged jet multiplicity.

3.3. Search with fully hadronic final states
Three different analyses searched for stop production with multi-jet final states.

$\alpha_T$ analysis [6] : selected jets are combined into two pseudo-jets in such a way that their $E_T$ difference, $\Delta H_T$, is minimum. The $\alpha_T$ variable is then defined as $\alpha_T = 1/2((H_T - \Delta H_T)/(H_T^2 - \tilde{H}_T^2))^{1/2}$ with $\tilde{H}_T$ the magnitude of the vector sum of all the jet transverse momenta. For perfectly balanced dijet events with jets back-to-back in $\phi$, $\alpha_T$ is equal to 0.5. For imbalanced events, this
value becomes smaller. In principle, only dijet systems, with jets not back-to-back in $\phi$, recolling against genuine MET can have values greater than 0.5. Jets are required to have $E_T > 50 \text{ GeV}$ and events are selected if they have at least two jets with $E_T > 100 \text{ GeV}$, the highest one in $E_T$ being within the tracker acceptance. Events with forward jets (|$\eta$| > 3) are vetoed. The signal region is defined by $H_T > 275 \text{ GeV}$ and $\sigma_T > 0.55$. This region is then divided into eight variable-size bins in $H_T$ and b-tagged jet multiplicity bins. For each bin, background event estimations are derived from control samples using transfer functions calculated with simulation.

$M_{T2}$ analysis [7]: originally developed to measure the mass of the primary pair-produced sparticles, the $M_{T2}$ variable is used in this analysis to discriminate SUSY events against SM background events. First, two event hemispheres are formed by merging the selected jets. Then the transverse mass $m_T$ of each hemisphere $i$ is calculated as a function of $m_\chi$, the mass of the LSP and $p_T^{\chi(i)}$, the unknown LSP transverse momentum in hemisphere $i$. Finally, $M_{T2}$ is defined as $M_{T2}(m_\chi) = \min\left(\frac{\max(m^{(1)}_{T}, m^{(2)}_{T})}{p_T^{\chi(1)}+p_T^{\chi(2)}-p_T^{miss}}\right)$. A maximum difference of 70 GeV is imposed between MET and the magnitude of the vector sum of all the selected jet transverse momenta in order to reject events with large contributions from soft and/or forward jets to the momentum imbalance. Events with hard jets falling identification criteria in the central detector acceptance are also rejected. In order to reject further events with non back-to-back hemispheres, as expected in SUSY events, a minimum in azimuth $\phi$ between any selected jets and the MET, $\Delta \phi_{min.}(\text{jets,MET}) > 0.3$ is required. Events are selected by requiring at least four jets with $p_T > 150/100/40/40 \text{ GeV/c}$, $H_T > 750 \text{ GeV}$ and MET > 30 GeV/c. In addition, events are required to have at least one b-tagged jet, using the SSVHE tagger. After event selection, the number of remaining multi-jet events is estimated from a side-band region defined with $\Delta \phi_{min.}(\text{jets,MET}) < 0.2$. The level of events with lost leptons are determined from single lepton data set corrected for the probability to loose a lepton, derived from simulation. Finally, the number of events with genuine MET from $Z(\rightarrow \nu \nu)+$jets processes is estimated from a control sample with an isolated photon and corrected for the $M_{T2}$-dependent ratio of $Z(\rightarrow \nu \nu)+$jets to $\gamma+jets$ events obtained from simulation. The signal region is divided in several $H_T$ and $M_{T2}$ bins.

(MET+$b$) analysis [8]: events are selected by requiring at least three jets with $p_T > 50 \text{ GeV}$ and at least one identified $b$-jet using the CSV tagger. Events with at least one isolated lepton with $p_T > 10 \text{ GeV/c}$ are vetoed. The multi-jet background is estimated from a control sample defined by a cut on the minimum azimuthal opening angle between MET and the three jets with the highest $p_T$. Background from $tt$ and $W+jets$ processes are estimated using a MET template derived from a single lepton sample. Five signal regions are then defined based on the number of required b-tagged jets, using different minimum requirement on $H_T$ and MET.

3.4. Inclusive search
A search for stop production was performed using the so-called razor variable $R$ which is related to MET and to $M_R$, an event-by-event indicator of the sparticle mass [9]. It is observed that distributions of $R$ and $M_R$ for SM background events can be modelled by simple exponentials in the $R^2 - M_R$ plane. A dedicated control sample is then defined for each SM background process in order to get a data-driven estimation of the parameters of these exponential shapes. A complete model for the SM background processes is then built and used to fit a background dominated region in the $R^2 - M_R$ plane in order to derive the SM background yield from data. Finally, this background model is extrapolated to the signal region, at large $R^2$ and high $M_R$ and the expected yields are then compared to the observed yields in different non overlapping signal regions. Events are classified according to the number of isolated lepton (0,1,2) and according to lepton flavours. Results are obtained for each category and then combined to test the compatibility of the background-only hypothesis with the data. In order to enhance the
Figure 1. Exclusion limits at 95% C.L. on the mass parameters for simplified models of stop production, via gluino decay (left) and via direct production (right).

sensitivity to stop production, a second razor analysis, razor+b [10], used only events with at least one b-tagged jet (TCHE). Motivated by models predicting low mass stop decaying via $\tilde{t}_1 \rightarrow t + \tilde{\chi}_0$, and thus producing low to moderate MET, a third complementary analysis was developed (razor multi-jet [11]) for which the signal region is defined with a lower cut on $R^2$ compared to the other razor analyses. Only events with at least 6 jets ($p_T > 30 \text{ GeV/c}$) are considered and at least one b-tagged jet (TCHE) is required for events in the signal region.

4. Results and conclusion

Using proton-proton collision data collected during 2011 at $\sqrt{s} = 7$ TeV, the CMS Collaboration searched for stop pair production in all decay channels. No significant excess of data was observed over the SM expectations. Exclusion limits on SUSY particle masses were then derived in several models, particularly on the gluino and stop masses in the context of simplified models [12]. As illustrated in Figure 1, simplified models for stop production via gluino decay are excluded at 95% C.L. for a gluino mass up to 1 TeV, assuming a LSP mass below 200 GeV. Simplified models for direct stop production are excluded at 95% C.L. for a stop mass comprised between 310 GeV and 420 GeV for a LSP mass below 100 GeV.

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