# Chapter 1

# CMS-SUS-17-001: a CMS search for stops and dark matter with opposite-sign dileptons

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**Abstract**
We present the MADANALYSIS 5 implementation and validation of the CMS-SUS-17-001 analysis, which documents a search for the production of top squarks decaying into a dileptonic system and missing transverse energy. The results are based on a dataset of proton-proton collisions recorded by CMS with a center-of-mass energy of 13 TeV and an integrated luminosity of 35.9 fb$^{-1}$. The validation of our reimplementation is based on a comparison of the expected number of signal event counts in the signal regions with information provided by the CMS collaboration, with signal events corresponding to a simplified scenario in which the Standard Model is extended by a stop and a neutralino.

## 1 Introduction

In this contribution, we present the MADANALYSIS 5 [1–3] implementation of the CMS-SUS-17-001 search [4] for the superpartners of the top quark, together with its validation. The CMS analysis targets the production of a pair of top squarks that decay into a final-state system comprising at least two jets with one of them being $b$-tagged, one pair of leptons of opposite electric charge, and a significant amount of missing transverse momentum. The main search variable consists of the $m_{T2}$ stransverse mass [5, 6] that has a kinematic endpoint for the dominant contributions to the Standard Model background.

In order to validate our reimplementation, we have reinterpreted the results of the CMS collaboration in the context of a class of simplified models where the Standard Model is supplemented by a top squark and a neutralino, where the neutralino is stable and thus gives rise to missing transverse momentum. We have compared, for two benchmark configurations, predictions obtained with our MADANALYSIS 5 reimplementation with the official CMS results at different level of the selection strategy. Although the analysis is also sensitive to generic dark matter simplified models, the information provided by CMS has not allowed us to generate events to perform a comparison in this case.

## 2 Description of the analysis

The CMS-SUS-17-001 analysis relies on a final-state signature made of two top quarks and missing transverse energy $\not{E}_T$ as could arise from stop-pair production and decay,

$$pp \to \tilde{t}\tilde{t}^* \to t\bar{t} + \not{E}_T \;, \qquad (1.1)$$

and illustrated in Fig. 1.1 The analysis focuses on the dileptonic decay of the top-antitop system and the preselection is implemented accordingly.

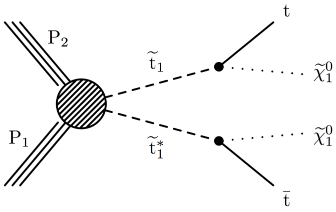


**Fig. 1.1:** Representative Feynman diagram for the production of a pair of top squarks that each decays into a neutralino and a top quark.

### 2.1 Object definitions and preselection

The signal region definitions rely on the presence of two lepton candidates $\ell_1$ and $\ell_2$ whose transverse momentum $p_T$ and pseudorapidity $\eta$ satisfy

$$\begin{aligned} p_T^{\ell_1} > 25 \text{ GeV} \qquad \text{and} \qquad |\eta^{\ell_1}| < 2.4 \,, \\ p_T^{\ell_2} > 20 \text{ GeV} \qquad \text{and} \qquad |\eta^{\ell_2}| < 2.4 \,, \end{aligned} \tag{1.2}$$

for the leading and next-to-leading lepton, respectively. Lepton isolation is enforced by requiring that the sum of the transverse momentum of the particles present in a cone of radius $R = 0.3$ centered on the lepton is smaller that $0.12$ times the lepton $p_T$,

$$\frac{1}{p_T^\ell} \sum_i (p_T)_i < 0.12 \,. \tag{1.3}$$

Jets are recontructed by means of the anti-$k_T$ algorithm [7] with a radius parameter set to $R = 0.4$, and their transverse momentum $p_T^j$ and pseudorapidity $\eta^j$ are required to fulfill

$$p_T^j > 30 \text{ GeV} \qquad \text{and} \qquad |\eta| < 2.45 \,. \tag{1.4}$$

Moreover, any jet found within a cone of radius $R = 0.4$ centered on an isolated lepton is removed from the jet collection. Jets are tagged as $b$-jets according to the medium working point of the CSVv2 CMS algorithm [8], which corresponds to a tagging efficiency of about 55%–65% for a percent-level mistagging rate. The missing transverse momentum $\mathbf{E}_T^{\text{miss}}$ is defined as the negative of the vector sum of the transverse momenta of all reconstructed objects, and the missing transverse energy is then defined by its norm,

$$E_T^{\text{miss}} = |\mathbf{E}_T^{\text{miss}}| \,. \tag{1.5}$$

Event preselection starts by requiring an opposite-charge pair of leptons (electrons or muons) with a dilepton invariant mass $m_{\ell\ell}$ satisfying

$$m_{\ell\ell} > 20 \text{ GeV}. \tag{1.6}$$

Moreover, events featuring a third loosely isolated lepton with a transverse momentum larger than 15 GeV are vetoed. Loose lepton isolation is defined as in Eq. (1.3), but with a different threshold,

$$\frac{1}{p_T^\ell} \sum_i (p_T)_i < 0.40 \,. \tag{1.7}$$

In order to suppress the Drell-Yan background, the dilepton system cannot be compatible with a $Z$-boson and its invariant mass has to satisfy

$$\big|m_{\ell\ell} - m_Z\big| > 15 \text{ GeV}, \tag{1.8}$$

when the lepton flavors are identical. To further suppress boson production backgrounds, the analysis requires at least two jets, with at least one of them being $b$-tagged,

$$N_j \geq 2 \qquad \text{and} \qquad N_b \geq 1 \ , \tag{1.9}$$

where $N_j$ and $N_b$ respectively indicate the number of jets and $b$-tagged jets. Finally, the missing transverse momentum is imposed to fulfill

$$E_T^{\rm miss} > 80 \text{ GeV} \qquad \text{and} \qquad S \equiv \frac{E_T^{\rm miss}}{\sqrt{H_T}} > 5 \text{ GeV}^{1/2} \ , \tag{1.10}$$

the hadronic activity $H_T$ being defined as the scalar sum of the transverse momentum of all reconstructed jets. The missing momentum is finally enforced to be well separated in azimuth from the two leading jets $j_1$ and $j_2$,

$$c_1 \equiv \cos\Delta\phi\big(\mathbf{E}_T^{\rm miss}, j_1\big) < 0.80 \qquad \text{and} \qquad c_2 \equiv \cos\Delta\phi\big(\mathbf{E}_T^{\rm miss}, j_2\big) < 0.96 \ . \tag{1.11}$$

### 2.2 Event Selection

Our implementation includes all three aggregated signal regions defined in the CMS-SUS-17-001 analysis. Each signal region is defined by a different selection on the amount of missing transverse momentum $E_T^{\rm miss}$ and the value of the stransverse mass $m_{T2}(\ell_1\ell_2)$ evaluated by considering the visible branches of the event to be the two leptons,

$$m_{T2}(\ell_1\ell_2) = \min_{\mathbf{E}_{T1}^{\rm miss}+\mathbf{E}_{T2}^{\rm miss}=\mathbf{E}_T^{\rm miss}} \Big[\max\big[m_T(\mathbf{p}_T^{\ell_1}, \mathbf{E}_{T1}^{\rm miss}), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{E}_{T2}^{\rm miss})\big]\Big] \ . \tag{1.12}$$

Here, the minimization is made by considering all possible splittings of the missing momentum along the two decay chains. The three signal regions are then defined as

$$\begin{array}{lll} \text{SR A0} & E_T^{\rm miss} > 200 \text{ GeV} \ , & 100 \text{ GeV} < m_{T2}(\ell_1\ell_2) < 140 \text{ GeV} \ , \\ \text{SR A1} & E_T^{\rm miss} > 200 \text{ GeV} \ , & 140 \text{ GeV} < m_{T2}(\ell_1\ell_2) < 240 \text{ GeV} \ , \\ \text{SR A2} & E_T^{\rm miss} > 80 \text{ GeV} \ , & m_{T2}(\ell_1\ell_2) \geq 240 \text{ GeV} \ . \end{array} \tag{1.13}$$

## 3 Validation

### 3.1 Event generation

For our validation, we adopt two simplified model benchmarks inspired by the MSSM in which the Standard Model is extended by a stop and a neutralino, all other new physics states being decoupled. The two points respectively feature stop and neutralino masses of $(m_{\tilde{t}}, m_{\tilde{\chi}_1^0}) = (750, 1)$ GeV and $(600, 300)$ GeV. The top squark is imposed to decay into a top and a neutralino with a branching ratio of 100%.

Events have been generated with MadGraph5_ aMC@NLO [9] and Pythia 8 [10]. Samples featuring different final-state jet multiplicities have been merged through the MLM scheme [11, 12], the Pythia8 `qcut` parameter (*i.e.* the merging scale) being set to 187.5 GeV and the corresponding MadGraph `xqcut` parameter being set to 125 GeV. The simulation of the CMS detector is then achieved with the Delphes 3 program [13], that relies on FastJet [14] for object reconstruction, which we configure to include a $b$-tagging efficiency of 60% for a $p_T$-dependent mistagging rate equal to $0.1 + 0.000038 * p_T$. Our samples have been normalized to the NLO+NLL cross sections taken from Ref. [15], that respectively read 0.171 pb and 0.043 pb for 600 GeV and 750 GeV squarks.

| Cut | $(m_{\tilde{t}}, m_{\tilde{\chi}}) = (750, 1)$ GeV | | $(m_{\tilde{t}}, m_{\tilde{\chi}}) = (600, 300)$ GeV | |
|---|---|---|---|---|
| | CMS | MA5 | CMS | MA5 |
| n(OS $\mu$ or $e$)= 2 | - | - | - | - |
| $m_{\ell\ell} > 20$ GeV | 0.99 | 0.99 | 0.99 | 0.97 |
| $\lvert m_Z - m_{\ell\ell}\rvert > 15$ GeV | 0.95 | 0.94) | 0.89 | 0.89 |
| $N_j \geq 2$ | 0.87 | 0.93) | 0.85 | 0.89 |
| $N_b \geq 1$ | 0.73 | 0.84) | 0.83 | 0.83 |
| $E_T^{\text{miss}} > 80$ GeV | 0.94 | 0.95 | 0.89 | 0.88 |
| $S > 5$ GeV$^{1/2}$ | 0.98 | 0.92 | 0.96 | 0.91 |
| $c_1 < 0.80$ | 0.9 | 0.97 | 0.92 | 0.97 |
| $c_2 < 0.96$ | 1.0 | 0.96 | 1.0 | 0.94 |
| $M_{T2}(\ell_1\ell_2) > 140$ GeV | 0.49 | 0.42 | 0.17 | 0.16 |
| All cuts | 0.24 | 0.25 | 0.083 | 0.075 |

**Table 1.1:** Comparison of the signal acceptance times efficiencies predictions made by MADANALYSIS 5 with the CMS official numbers for two benchmark scenarios and on a cut-by-cut basis.

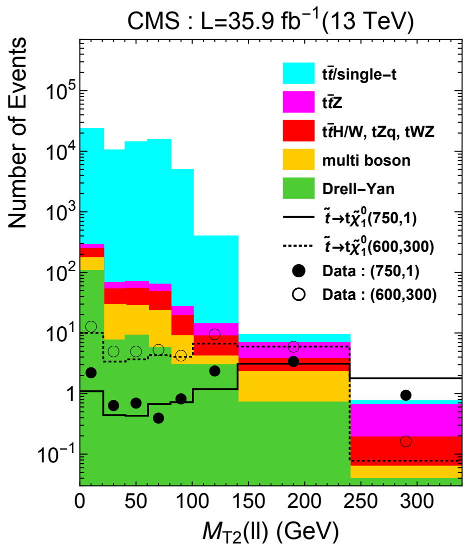


**Fig. 1.2:** Comparison of the $m_{T2}$ distributions predicted by MADANALYSIS 5 (circles) with the official results provided by CMS (lines). Results for the different background contributions are also included (as provided by the CMS collaboraiton). The distributions are given after the baseline selection.

### 3.2 Comparison with the official results

The cutflow for the analysis baseline selection is given in Table 1.1 for two supersymmetric model points of the simplified model above-described. In this case, the $m_{T2}$ variable is required to satisfy

$$m_{T2}(\ell_1\ell_2) \geq 140 \text{ GeV} . \quad (1.14)$$

A comparison of the $m_{T2}(\ell_1\ell_2)$ distribution for two considered supersymmetric scenarios is given in Fig. 1.2, where the lines refer to the official CMS results and the circulars markers to the MADANALYSIS 5 predictions.

The final event counts of both the CMS and MADANALYSIS 5 results appear to agree within 20%, similarly to the $m_{T2}$ spectra that are crucial for the final signal region selections.

## 4 Summary

The MADANALYSIS 5 reimplementation of the CMS search for new physics in events with two opposite-charge same-flavor leptons, at least one heavy-flavor tagged jet, and large missing transverse momentum, has been presented. All baseline event selection requirements have been incorporated, and simulated signal events for a set of benchmark mass points have been used to validate the analysis implementation. For the simulation, signal events corresponding to two different choices of top squark and neutralino masses were produced in the context of the so-called 'T2tt' supersymmetric simplified model (where the Standard Model is solely supplemented by a top squark and a neutralino) using a set of simulation parameters synchronized with the production recipe made available by CMS. A comparison has been made between the efficiencies of various event selection cuts reported by CMS and the corresponding efficiencies obtained in the MADANALYSIS 5 implementation, using the signal events of the supersymmetric benchmark model points. All individual cut efficiencies, as well as the signal efficiency after all event selection, agree within a deviation of about 20%. The implementation is considered to be validated, although recasters may benefit by performing additional studies to validate the selection efficiency in each signal region. CMS also provides correlation matrices for the estimated background counts in the three aggregate search regions, and it may be desirable to incorporate this information into the MADANALYSIS 5 implementation. The reimplemented analysis code is available from MADANALYSIS 5 version 1.6 onwards, its Public Analysis Database and from INSPIRE [16],

http://doi.org/10.7484/INSPIREHEP.DATA.MMM1.876Z.

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