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Javier Mauricio Duarte for the CMS Collaboration

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# Inclusive Searches for Supersymmetry with the CMS detector at $\sqrt{s} = 8$ TeV

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**Abstract**

We discuss two complementary searches for supersymmetry and their combination carried out on approximately 19 fb$^{-1}$ of data collected by CMS during the $\sqrt{s} = 8$ TeV LHC run. Results for a variety of final state signatures, including multi-bottom, multi-top, and mixed top-plus-bottom quark topologies, are presented. The combination of results yields an improved bound on the top-squark mass. For a neutralino mass of 100 GeV, the branching fraction dependent (independent) pair production of gluinos and top squarks is excluded for gluino masses up to 1310 (1175) GeV and for top squark masses up to 730 (645) GeV.

*Keywords:* particle physics, hadron collider, CMS, SUSY, supersymmetry, top squark, gluino, inclusive, razor, BDT, boosted decision tree

## 1. Introduction

R-parity conserving, weak-scale supersymmetry (SUSY) is a well-motivated theory, which provides a suitable dark matter candidate and predicts events at the Large Hadron Collider (LHC) with jets and large missing transverse momentum $E_T^{miss}$. Some SUSY models may contain a light chargino $\tilde{\chi}^{\pm}$ and a neutralino $\tilde{\chi}^0$ nearly degenerate in mass, a light top or a bottom squark ($\tilde{t}$ or $\tilde{b}$), and potentially a slightly heavier gluino $\tilde{g}$ in order to minimize the fine-tuning associated with the observed value of the Higgs boson mass [1].

We discuss two complementary methods to search for squarks and gluinos in the context of natural SUSY spectra, shown in Fig 1. One search, called herein the inclusive razor search, is performed on events with two or more jets, at least one of which is identified as originating from a bottom quark [2, 3]. This search extend a previous analysis by the Compact Muon Solenoid (CMS) Collaboration, performed with the same technique on the data collected at a center-of-mass energy of 7 TeV [4, 5] and utilizes the razor kinematic variables $R^2$ and $M_R$ [6, 7] to search for a broadly peaking signal on the smoothly falling standard model (SM) background. The other search, called herein the single-lepton boosted decision tree (BDT) search, is performed on events with one isolated electron or muon, four jets, at least one of which is identified as originating from a bottom quark, and missing transverse energy [8].

Both searches are carried out on the data collected by the CMS Collaboration in proton-proton collisions at $\sqrt{s} = 8$ TeV in 2012, corresponding to an integrated luminosity of 19.3-19.4 fb$^{-1}$. A complete description of the CMS detector is given in [9].

Together, these searches provide the strongest mass limit on the top squark in the case of one choice of decay mode, as well as a more universal mass limit on both the top squark and the gluino, independent of the choice of branching fractions.

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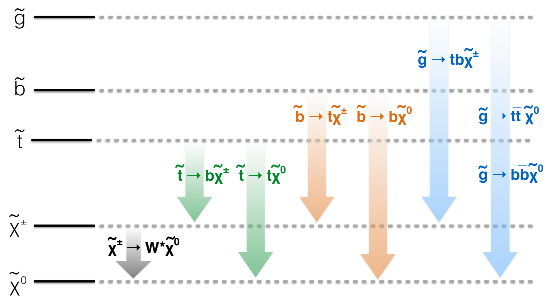



Figure 1: Simplified natural SUSY spectrum considered as a benchmark for result interpretations. The neutralino is forced to be the lightest SUSY particle. The difference in mass between the chargino and the neutralino is fixed at 5 GeV. Gluino and same-flavor squark pair production are considered in separate models, scanning the masses of the produced SUSY particle and the neutralino.

## 2. Inclusive Razor Search

This section provides a brief summary of a search for SUSY in hadronic events with b-jets. A more complete description can be found in [2] and [3]. The analysis is performed on the events collected by a set of dedicated triggers in the HLT, consisting of a loose selection on $\mathrm{M_R}$ and $\mathrm{R}^2$. The triggers are seeded from a L1 selection of two jets in the central part of the detector.

The razor variables $\mathrm{M_R}$ and $\mathrm{R}^2$ are defined to describe the two-jet topology resulting from the production of two squarks, each decaying to a quark and the lightest SUSY particle (LSP), assumed to be a stable neutralino $\tilde{\chi}^0_1$. The four-momenta of the two jets are used to compute $\mathrm{M_R}$ and $\mathrm{R}^2$, defined as

$$\mathrm{M_R} \equiv \sqrt{(|\vec{p}_{\mathrm{j}_1}| + |\vec{p}_{\mathrm{j}_2}|)^2 - (p_z^{\mathrm{j}_1} + p_z^{\mathrm{j}_2})^2} \quad (1)$$

$$\mathrm{R}^2 \equiv \frac{\mathrm{E_T^{miss}}(p_\mathrm{T}^{\mathrm{j}_1} + p_\mathrm{T}^{\mathrm{j}_2}) - \vec{\mathrm{E}}_\mathrm{T}^{\mathrm{miss}} \cdot (\vec{p}_\mathrm{T}^{\,\mathrm{j}_1} + \vec{p}_\mathrm{T}^{\,\mathrm{j}_2})}{4M_R^2} \quad (2)$$

where $\vec{p}_{\mathrm{j}_i}$, $\vec{p}_\mathrm{T}^{\,\mathrm{j}_i}$, and $p_z^{\mathrm{j}_i}$ are the momentum of the ith-jet, its transverse component, its longitudinal component, respectively, while $\mathrm{E_T^{miss}}$ and $p_\mathrm{T}^{\mathrm{j}_i}$ are the magnitude of $\vec{\mathrm{E}}_\mathrm{T}^{\mathrm{miss}}$ and $\vec{p}_\mathrm{T}^{\,\mathrm{j}_i}$, respectively.

Each event is reduced to a two-jet topology by clustering the selected jets into two “megajets” [7, 4, 5]. “Boxes” are used to classify events, as given in Table 1.

The two-dimensional probability density function $\mathrm{P_{SM}(M_R, R^2)}$ of each SM process is found to be well described by the function [4, 5]:

$$f(\mathrm{M_R}, \mathrm{R}^2) = [b(\mathrm{M_R} - \mathrm{M_R^0})^{1/n}(\mathrm{R}^2 - \mathrm{R}_0^2)^{1/n} - 1] \times e^{-bn(\mathrm{M_R}-\mathrm{M_R^0})^{1/n}(\mathrm{R}^2-\mathrm{R}_0^2)^{1/n}}. \quad (3)$$

where $b$, $n$, $\mathrm{M_R^0}$, and $\mathrm{R}_0^2$ are free parameters of the background model. The SM background-only likelihood function for the each box and each b-tagged jet multiplicity is written as:

$$\mathcal{L}(\mathrm{data}|\vec{\theta}) = \frac{e^{-\mathrm{N_{SM}}}}{\mathrm{N}!} \prod_{i=1}^{\mathrm{N}} \mathrm{N_{SM}} \mathrm{P_{SM}}(\mathrm{M}_{\mathrm{R}(i)}, \mathrm{R}^2{}_{(i)}) , \quad (4)$$

where $\mathrm{P_{SM}(M_R, R^2)}$ is the function in Eq. (3) normalized to unity, $\vec{\theta}$ is the set of background shape and normalization parameters, and the product runs over the N events in that dataset. The total likelihood in these boxes is computed as the product of the likelihood functions for each b-tagged jet multiplicity.

Different parameters are used for each box and b-tagged jet multiplicity bin, with the exception of the 2b-tag and ≥3b-tag bins, in which common background shape parameters are used. The background shape and normalization parameters are derived from a maximum likelihood fit to the events in low-$\mathrm{M_R}$ and low-$\mathrm{R}^2$ sidebands. The data in the signal-sensitive region are found to be consistent with expectation from the sideband fits in all boxes.

## 3. Single-Lepton BDT Search

This section presents a summary of the search for the pair production of top squarks in events with a single isolated electron or muon, jets, large missing transverse energy, and large transverse mass. A full description of the analysis can be found in [8].

This search focuses on two decay modes of the top squark: $\tilde{t} \to t\tilde{\chi}^0_1$ and $\tilde{t} \to b\tilde{\chi}^\pm_1 \to bW^\pm\tilde{\chi}^0_1$, which are expected to have large branching fractions if kinematically accessible. The signature of the signal process includes high transverse momentum jets, including two b-jets, and $\mathrm{E_T^{miss}}$. We require exactly one isolated, high $p_\mathrm{T}$ electron or muon, at least 4 jets, at least one b-tagged jet, and large $\mathrm{E_T^{miss}}$ and transverse mass $\mathrm{M_T} = \sqrt{2\mathrm{E_T^{miss}} p_\mathrm{T}^\ell (1 - \cos(\Delta\phi))}$, where $p_\mathrm{T}^\ell$ is the transverse momentum of the lepton and $\delta\phi$ is the difference in azimuthal angles between the lepton and $\mathrm{E_T^{miss}}$ directions. The requirement of large $\mathrm{M_T}$ strongly suppresses backgrounds from semi-leptonic decays of top quark pairs, and from $W$+jets. The dominant background in this kinematic region is dilepton decays of top quark pairs, where one of the leptons is not identified. The primary results of the search use boosted decision tree (BDT) techniques, and a cut-based analysis is pursued as a cross-check. Several BDT and cut-based signal regions are defined, in order to be sensitive to a range of

Table 1: Kinematic and multiplicity requirements defining the nine razor boxes. Boxes are listed in order of event filling priority. The ranking is introduced to unambiguously associate an event to the first box it fills.

| Requirements | | | | |
|---|---|---|---|---|
| Box | Lepton | b-tag | Kinematic | Jet |
| Two-lepton boxes | | | | |
| MuEle | ≥ 1 tight electron and ≥ 1 loose muon | ≥ 1 b-tag | ($M_R$ > 300 GeV and $R^2$ > 0.15) and ($M_R$ > 350 GeV or $R^2$ > 0.2) | ≥ 2 jets |
| MuMu | ≥ 1 tight muon and ≥ 1 loose muon | | | |
| EleEle | ≥ 1 tight electron and ≥ 1 loose electron | | | |
| Single-lepton boxes | | | | |
| MuMultiJet | 1 tight muon | ≥ 1 b-tag | ($M_R$ > 300 GeV and $R^2$ > 0.15) and ($M_R$ > 350 GeV or $R^2$ > 0.2) | ≥ 4 jets |
| EleMultiJet | 1 tight electron | | | |
| MuJet | 1 tight muon | | | 2 or 3 jets |
| EleJet | 1 tight electron | | | |
| Hadronic boxes | | | | |
| MultiJet | none | ≥ 1 b-tag | ($M_R$ > 400 GeV and $R^2$ > 0.25) and ($M_R$ > 450 GeV or $R^2$ > 0.3) | ≥ 4 jets |
| ≥ 2 b-tagged jet | none | ≥ 2 b-tag | | 2 or 3 jets |

signal kinematics, which depend on the masses of the supersymmetric particles produced in the signal events.

Backgrounds are estimated from simulation, with scale factors (where necessary) and uncertainties derived from data control regions. The data is consistent with the expected backgrounds in the signal regions. The results are interpreted in the context of models of top squark pair production where the top squark decays either to a top quark and a neutralino or to a bottom quark and a chargino. These results probe top squarks up to about 650 GeV.

## 4. Interpretation of Results

For this set of interpretations, a simplified natural SUSY spectrum [1] is taken as a reference. The LSP is assumed to be a neutralino $\tilde{\chi}^0_1$, 5 GeV lighter than a chargino $\tilde{\chi}^\pm_1$. The chargino is forced to be the NLSP, with 100% branching fraction for the decay involving a virtual $W$ ($W^*$), $\tilde{\chi}^\pm_1 \rightarrow W^* \chi^0_1$. Three other SUSY partners are assumed to be accessible at the LHC, namely the gluino and the lightest top and bottom squarks. The rest of the SUSY spectrum is assumed to be decoupled, with masses large enough to be inaccessible at the LHC. The SUSY partners composing this natural SUSY spectrum are summarized in Fig. 1, together with the possible decay modes.

In the context of this natural spectrum, five simplified models [10, 11, 12, 13, 14] are considered for gluino pair production, based on three-body gluino decays [15]:

- **T1bbbb**: pair-produced gluinos, each decaying with a 100% branching fraction to a pair of bottom quarks and the LSP.
- **T1tbbb**: pair-produced gluinos, each decaying with a 50% branching fraction to a pair of bottom quarks and the LSP or a top quark, a bottom quark, and the NLSP.
- **T1ttbb**: pair-produced gluinos, each decaying with a 50% branching fraction to a pair of bottom quarks and the LSP or a pair of top quarks and the LSP.
- **T1tttb**: pair-produced gluinos, each decaying with a 50% branching fraction to a pair of top quarks and the LSP or a top quark, a bottom quark, and the NLSP.
- **T1tttt**: pair-produced gluinos, each decaying with a 100% branching fraction to a pair of top quarks and the LSP.

The corresponding Feynman diagrams are shown in Fig. 2. Similar models were not considered, for which the same final states are obtained from two-body gluino decays to squark and quark and the consequent cascade.

In addition, the following three simplified models are considered for the production of top-squark pairs:

- **T2bW***: pair-produced top squarks, each decaying with a 100% branching fraction to a bottom quark and the NLSP.

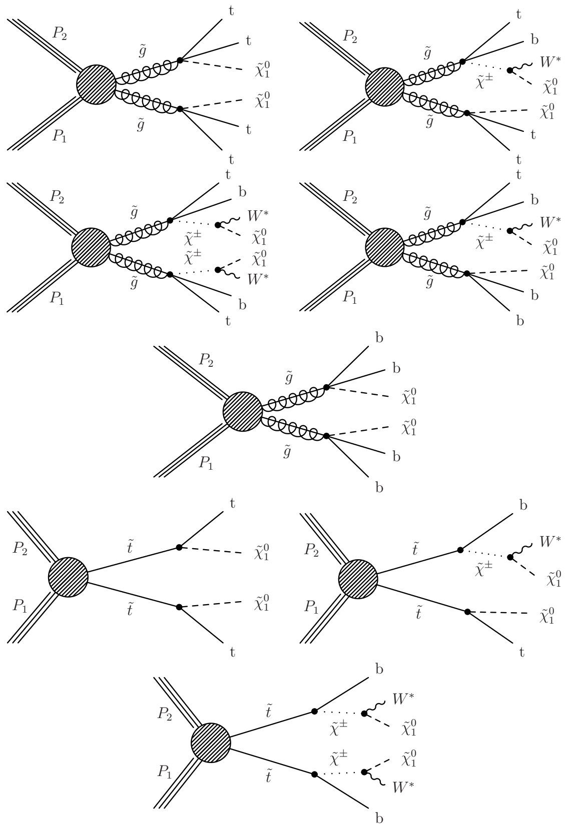



Figure 2: Diagrams displaying the event topologies of gluino (upper 5 diagrams) and top-squark (lower 3 diagrams) pair production considered in this paper.

- **T2tb**: pair-produced top squarks, each decaying with a 50% branching fraction to a top quark and the LSP or a bottom quark and the NLSP.
- **T2tt**: pair-produced top squarks, each decaying with a 100% branching fraction to a top quark and the LSP.

The corresponding Feynman diagrams are shown in Fig. 2.

Events for these simplified models are generated with the MadGraph v5 simulation [16, 17], in association with up to two partons. The SUSY particle decays are treated with Pythia v6.4.26 assuming a constant matrix element (phase space decay). The event is showered in Pythia and matched to the matrix element kinematic configuration using the MLM algorithm [18], before being processed through a fast simulation of the CMS detector [19]. The SUSY particle production cross sections are calculated to next-to-leading order (NLO) and next-to-leading-logarithm (NLL) accuracy [20, 21, 22, 23, 24], assuming the decoupling of the other SUSY partners. The NLO+NLL cross section and the associated theoretical uncertainty [25] are taken as a reference to derive the exclusion limit on the SUSY particle masses.

We interpret the results of the searches by determining the 95% confidence level (CL) limit on SUSY models using the LHC $CL_S$ procedure [26], combining the likelihoods of different searches in a global likelihood. The 95% CL upper limit on the SUSY signal cross section (corresponding to the $\sigma$ value at which $CL_S = 0.05$) is computed for each point of a given model's two-dimensional SUSY mass plane. The 95% CL mass exclusion contour is derived by intersecting this surface with the NLO+NLL cross section value surface.

### *4.1. Razor Search Results for Gluino and Squark Pair Production*

A comparison of the results in the representative SUSY simplified models are shown in Fig. 3.

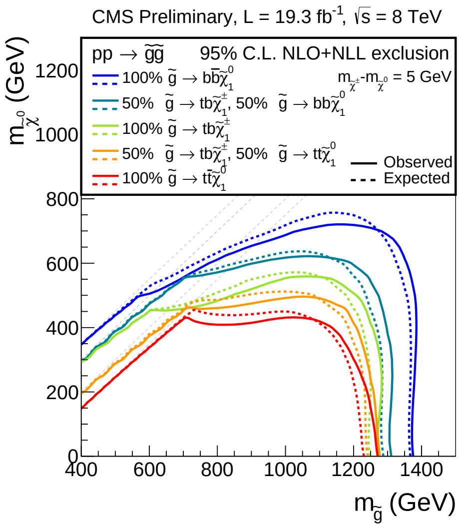
The limits corresponding to gluino-gluino topologies with mixed branching fractions lie within the band outlined by the T1bbbb and the T1tttt contours. As an example, gluino masses smaller than 1175 GeV for T1tttt and 1310 GeV for T1bbbb are excluded, depending on the gluino branching fractions, for an LSP mass of 100 GeV. Given this fact and the inclusive nature of the razor analysis, the T1tttt limit can be considered a conservative estimate of a branching-fraction-independent limit, generically valid for gluino-gluino production within the context of the simplified SUSY spectrum shown in Fig. 1.

For an LSP mass of 100 GeV, top-squark mass values larger than 375 GeV and smaller than 660 GeV are excluded in all three top-squark branching fraction scenarios considered in the inclusive razor search.

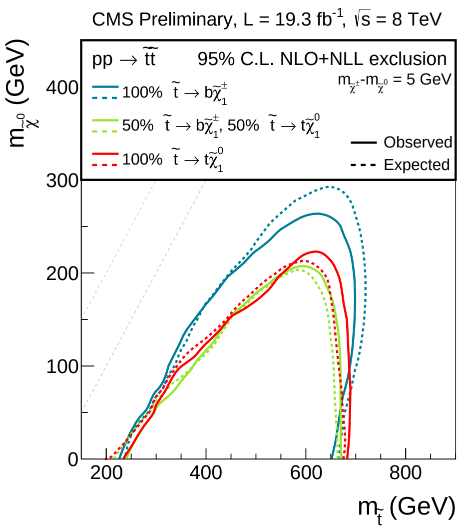
### *4.2. Combination of Results for Top-Squark Pair Production*

The individual results of the zero-lepton razor search and the single-lepton BDT search for a top squark decaying to a top quark and a neutralino are shown in Fig. 4.

A stronger limit on top-squark pair production is derived by combining the hadronic boxes of the razor search with the results of the exclusive single-lepton analysis. Fig. 5 shows the combined result obtained for the scenario where the top squark only decays to a top quark and the lightest neutralino. For an LSP mass of 100 GeV, the combination improves the constraint on the top-squark mass from 660 to 730 GeV. This result




(a)




(b)

Figure 3: Gluino mass limit (a) and top-squark mass limit (b) at a 95% CL, obtained for different models with the inclusive razor analysis in the context of the benchmark natural SUSY spectrum of Fig. 1.

provides the most stringent limit on these specific simplified models.

Fig. 5 (c) shows a more generic limit on the top-squark mass. We consider two decay modes for the top squark, already introduced when discussing the simplified natural SUSY spectrum of Fig. 1 . We scan the relative branching fractions, assuming that no other decay mode is allowed. The largest excluded cross section (that is, the worst upper limit) is found for each top-squark and neutralino mass. A branching fraction in-

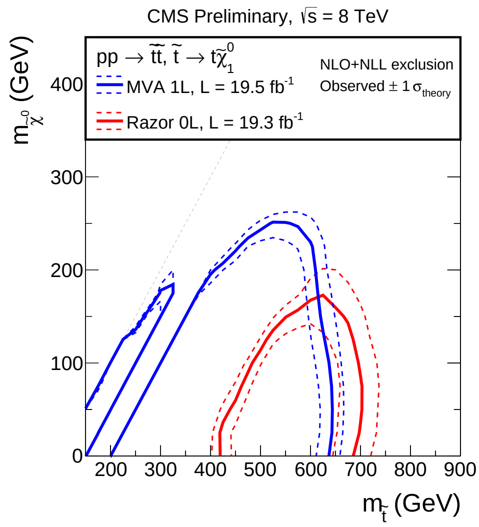


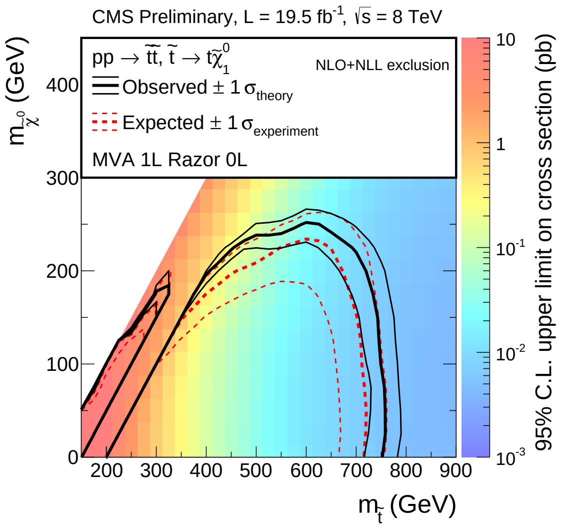

Figure 4: Top-squark mass limit at a 95% CL, obtained separately for the zero-lepton razor search and the single-lepton BDT search.

dependent limit is derived by comparing the worst-case exclusion to the corresponding top-squark pair production cross section. This way, top squarks decaying to the two considered decay modes are excluded at 95% confidence level for mass values > 400 GeV and < 645 GeV, assuming a neutralino mass of 100 GeV. Unlike other simplified model interpretations, this interpretation is not based on a specific choice of branching fractions. While a residual model dependence is introduced when only two decay modes are considered, this result is more general than previous constraints.

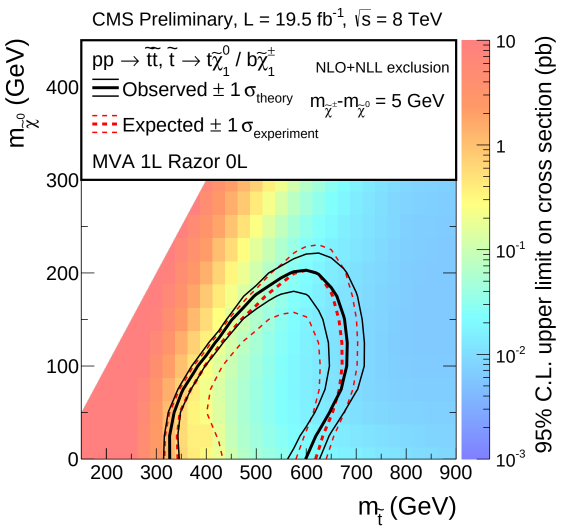
## 5. Conclusions

Two complementary SUSY searches, the inclusive razor search and the single-lepton BDT search, were performed on collision data collected by CMS at $\sqrt{s}$ = 8 TeV. The dataset size corresponds to an integrated luminosity of 19.3-19.4 fb$^{-1}$. No significant excess is observed over the SM background expectations is found in either search.

The inclusive razor search is translated into a 95% confidence level exclusion limit on the masses of the gluino and the top squark, in the context of simplified natural SUSY models. For a neutralino mass of 100 GeV and depending on the branching fractions, the pair production of gluinos and top squarks in multi-bottom, multi-top, and mixed top-plus-bottom quark topologies is excluded for gluino masses up to 1310 GeV and squark masses up to 660 GeV.




(a)




(b)

Figure 5: Top-squark mass limit at a 95% CL, obtained combining the result of the zero-lepton razor search with the result of the single-lepton BDT search [8] for (a) T2tt and (b) independent of the branching fraction choice.

Furthermore, using the combined likelihood of the zero-lepton razor search and the single-lepton BDT search, the exclusion bound on the top-squark mass is extended to 730 (640) GeV for a branching fraction BR($\tilde{t} \to t\tilde{\chi}^0_1$) = 100% (50%) and for a neutralino mass of 100 GeV. For the same neutralino mass, top squarks decaying to the two considered decay modes are excluded at a 95% confidence level for mass values > 400 GeV and < 645 GeV, independent of the branching fractions.

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