PROCEEDINGS OF SCIENCE

Search for Supersymmetry with a Highly Compressed Mass Spectrum in the Single Soft Lepton Channel with the CMS Experiment at the LHC

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Models with compressed mass spectra target a very interesting region of the SUSY parameter space and are very well motivated by theoretical considerations, such as dark matter constraints and naturalness. The presented analysis focuses on signal events containing a single low-momentum lepton and moderate missing transverse energy. The search targets a simplified model in which the signal consists of stop (supersymmetric partner of the top quark) pair-production, followed by 4-body decays into a lepton-neutrino (quark-antiquark) pair, a b-quark and a neutralino, which is considered the lightest supersymmetric particle (LSP), and with a mass gap between the stop and the LSP that is smaller than the W-boson mass. The LSPs and the neutrino escape the detector, leading to a missing transverse energy signature. Compressed regions are challenging to study, as the visible decay products have low momentum and generally do not pass detector acceptance thresholds. This difficulty can be mitigated by requiring the presence of an initial-state radiation jet, which boosts the system. The results are based on data from Run II of the Large Hadron Collider, recorded with the CMS detector at a centre-of-mass energy of 13 TeV.

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1. Introduction

A focus of the Physics Programme at the Large Hadron Collider (LHC), CERN, is the search for physics Beyond the Standard Model (BSM), which includes the search for Supersymmetry (SUSY). SUSY postulates that for every elementary SM particle, there exists a corresponding superpartner state, differing by half-integer spin, such as the stop, which is the superpartner of the top quark. Many SUSY models require R-parity (+1 for SM, -1 for SUSY) conservation, meaning that the sparticles are pair-produced, and the models that are considered in this analysis describe stop pair-production. The SUSY particles are predicted to have decay chains to SM particles that can be detected with the Compact Muon Solenoid (CMS) detector [1].

Even though wide regions of the SUSY parameter space have already been excluded with LHC Run I and recent Run II results, there are several 'crevasses' of compressed mass parameter space, which are targeted by several dedicated analyses. Among these scenarios there are models where the mass splitting Δm between the next-to-LSP and LSP is small. There are several theoretical considerations which motivate SUSY models with such compressed spectra; while natural SUSY favours low masses of the stop, the process of co-annihilation of light stops and LSPs can reproduce the correct cosmological DM relic density [2].

The specific case where the mass difference between the stop and LSP $\Delta m = m_{\tilde{t}} - m_{\mathrm{LSP}} < m_{\mathrm{W}}$, where m_{W} is the mass of the W-boson, with stop decays via an off-shell top t^* and W^*, is considered. For such small mass differences, the available energy for the decay products is small, resulting in low momenta of the visible decay products, which typically do not pass detector acceptance thresholds. The LSPs and the neutrino escape the detector, leading to a missing transverse momentum $p_{\mathrm{T}}^{\mathrm{miss}}$ signature, which is also low. In the presence of initial state radiation (ISR), the system is boosted and the visible decay products become detectable and the $p_{\mathrm{T}}^{\mathrm{miss}}$ increases. Therefore, the signal signature investigated contains a high momentum ISR jet, moderate $p_{\mathrm{T}}^{\mathrm{miss}}$ and a low momentum lepton.

The Simplified Models (SMS) used for interpretations of this analysis describe stop pair-production with four-body stop decay or the chargino-mediated stop decay as shown in Figure 1, where the neutralino ($\tilde{\chi}_1^0$) is the LSP, while the only free parameters are the stop and LSP masses. The analysis targets the single-lepton final state.

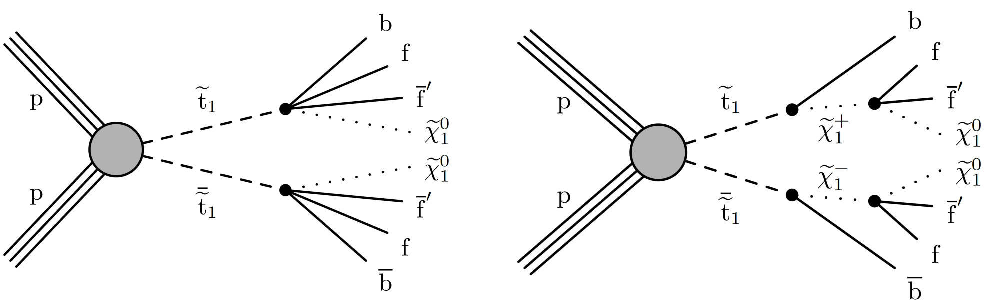

Figure 1: Simplified signal models for top squark pair-production with subsequent four-body (left) and chargino-mediated (right) decays into a lepton and neutrino (quark-antiquark) pair, b-quark jet and LSP. The chargino ($\tilde{\chi}_1^{\pm}$) mass is assumed to be halfway between the stop and LSP. [3]

2. Samples and Event Selection

The sample of events under consideration come from proton-proton (p-p) data from Run II of the Large Hadron Collider, recorded with the CMS detector at a centre-of-mass energy $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}. Simulated Monte Carlo (MC) samples of SM background and signal events are produced by using several generators and reconstructed with the same algorithms as data.

The events are required to have been triggered by an online selection on $p_{\mathrm{T}}^{\mathrm{miss}}$ and preselection cuts are applied to focus on the relevant parameter space. These include kinematic cuts requiring high $p_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV and hadronic energy $H_{\mathrm{T}} > 300$ GeV, defined as the scalar sum of the p_{T} of all jets with $p_{\mathrm{T}} > 30$ GeV and pseudorapidity $|\eta| < 2.4$. The leading jet is considered as ISR given that its $p_{\mathrm{T}}(\mathrm{ISR}) > 100$ GeV. Additional cuts limiting to maximum two jets with $p_{\mathrm{T}} > 60$ GeV, while requiring the angle $\Delta\phi$ between them to be less than 2.5 rad, are applied to fight the remainder of QCD-multijet background, which predominantly has a back-to-back topology. Concerning the leptonic selection, at least a muon with $p_{\mathrm{T}} > 3.5$ GeV and $|\eta| < 2.4$ or an electron $p_{\mathrm{T}} > 5$ GeV and $|\eta| < 2.5$ is required. Taus and extra light leptons with $p_{\mathrm{T}} > 20$ GeV are vetoed. The distributions of the key variables used in the analysis, lepton p_{T} and transverse mass m_{T}, are shown in Figure 2 at the level of preselection.

To enhance the signal-to-background ratio, two sets of signal regions (SRs) are chosen, SR1 and SR2, targeting a range of values of Δm. The leptons are required to have $p_{\mathrm{T}} < 30$ GeV and for SR1 $|\eta| < 1.5$. SR1 targets very low Δms where the b-jets are expected to be too soft to detect, and are therefore vetoed, whereas SR2 requires at least a soft b-jet with $30 < p_{\mathrm{T}} < 60$ GeV, thereby, targeting higher mass splittings. To further increase the sensitivity of the analysis to the signal, both SRs are binned in lepton p_{T} : L: $5-12$ GeV, M: $12-20$ GeV, H: $20-30$ GeV. In the muon channel, there is an additional very low (VL) bin with $3.5 < p_{\mathrm{T}} < 5$ GeV. The transverse mass m_{T} is calculated between lepton p_{T} and $p_{\mathrm{T}}^{\mathrm{miss}}$: $m_{\mathrm{T}} \equiv \sqrt{2 p_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}(1-\cos(\Delta\Phi))}$. It has a characteristic shape for both W+jets and $\mathrm{t\bar{t}}$, which are the dominant backgrounds of the analysis, forming a peak around the W-boson mass. A splitting in m_{T} (a: $m_{\mathrm{T}} < 60$ GeV, b: $60 < m_{\mathrm{T}} < 95$ GeV, c: $m_{\mathrm{T}} > 95$ GeV) isolates this W-peak, providing further sensitivity. In order to avoid strange topologies with high $p_{\mathrm{T}}^{\mathrm{miss}}$ and low H_{T}, and vice-versa, a simultaneous selection on both quantities is possible by defining: $C_{\mathrm{T1}} \equiv \min(p_{\mathrm{T}}^{\mathrm{miss}}, H_{\mathrm{T}} - 100\,\mathrm{GeV})$ and $C_{\mathrm{T2}} \equiv \min(p_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}(\mathrm{ISR}) - 25\,\mathrm{GeV})$, where the subscript number corresponds to the SR the cut is applied in. For SR2, a selection on ISR jet p_{T} is more effective than H_{T}. Both SRs are split into two bins of C_{T}: $300 < C_{\mathrm{T}} < 400$ GeV and $C_{\mathrm{T}} > 400$ GeV.

3. Background Estimation Methods

The estimation of the dominant backgrounds in the analysis is done with a combined approach, using both data and MC simulation. Control Regions (CRs) are chosen such that they are dominated by the relevant backgrounds, from which one can make a precise extrapolation to the SRs. The background estimation methods are split into estimating the prompt and nonprompt leptonic components separately.

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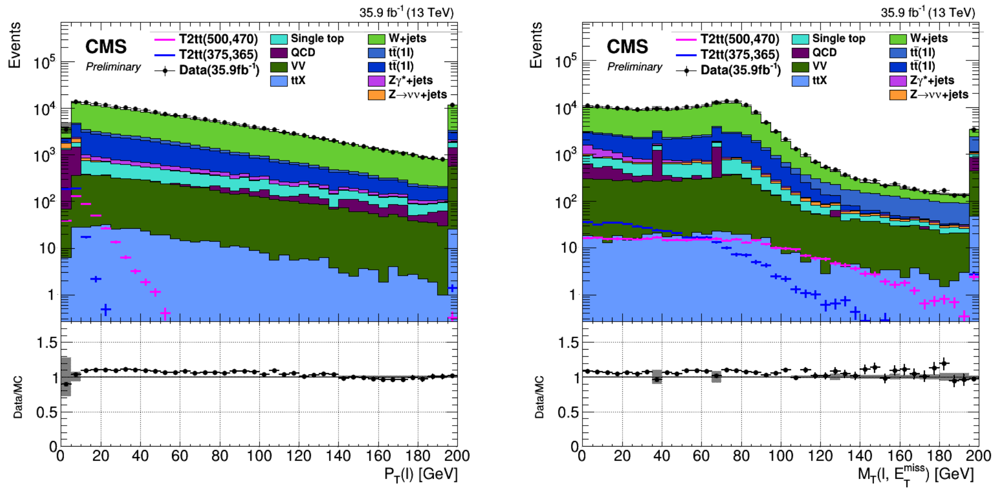

Figure 2: Distributions of lepton p_T (left) and transverse mass m_T (right) at the level of preselection. [3]

For the estimation of the dominant prompt backgrounds from W+jets and $t\bar{t}$, CRs are defined by simply inverting the lepton p_T selection ($p_T > 30$ GeV). Data/MC scale factors (SFs) are determined in these CRs, which are applied to the simulation in the SRs to find the expected background contribution. Thus, the data/MC scaling is extrapolated from a high p_T to a low p_T region. The method is successfully validated in adjacent Validation Regions (VRs), defined in terms of $200 < C_T < 300$ GeV, as well as a region where the b-tag requirement is tightened to $p_T > 60$ GeV.

The less-dominant nonprompt backgrounds, predominantly coming from QCD-multijet and Z decays to neutrinos ($Z(\rightarrow \nu\nu)$+jets), are estimated using the *Tight-to-Loose* method. This method requires a 'loose' object definition, for which there is an increased probability for a nonprompt lepton to pass the criteria. In the analysis it is defined by loosening the lepton isolation and impact parameter (d_{xy}, d_z) requirements. The 'tight' definition corresponds to the final object definition used in the analysis. The probability that a nonprompt lepton passes both the tight and loose criteria, namely, the *Tight-to-Loose* ratio ε_{TL}, is then determined in a QCD-enriched Measurement Region (MR), as a function of lepton p_T and η. This is done using events from a data set populated by jet and H_T triggers, which does not overlap with the final analysis data set. Apart from the requirement of high H_T, upper cuts on p_T^{miss} and m_T are applied to reduce the contamination from prompt leptons in this region. Application Regions (ARs) are defined by loosening the leptonic cuts in the SRs and the events in these regions are reweighted by the ε_{TL} ratio to determine the expected nonprompt contribution in the SRs. The remaining non-leading backgrounds are taken directly from simulation and a 50 % systematic uncertainty is assigned on the cross-sections.

4. Results and Interpretation

Several sources of background and signal systematic uncertainties are taken into account, such as the MC modelling of p_T and jet multiplicity distributions in W+jets and $t\bar{t}$ samples, pileup dependence, jet energy scale and resolution, object efficiencies or luminosity uncertainty. The predicted yields in the SRs are compared to observation, as shown at the top of Figure 3. No significant deviation from the SM is observed. Upper limits are set on the top squark pair-production cross section at 95 % CL in the plane of the top squark vs. LSP masses, assuming a 100 % branching ratio for the chosen decay channel; the decays are assumed to be prompt. The results are interpreted in terms of the 4-body and chargino-mediated decay SMS, as shown at the bottom of Figure 3.

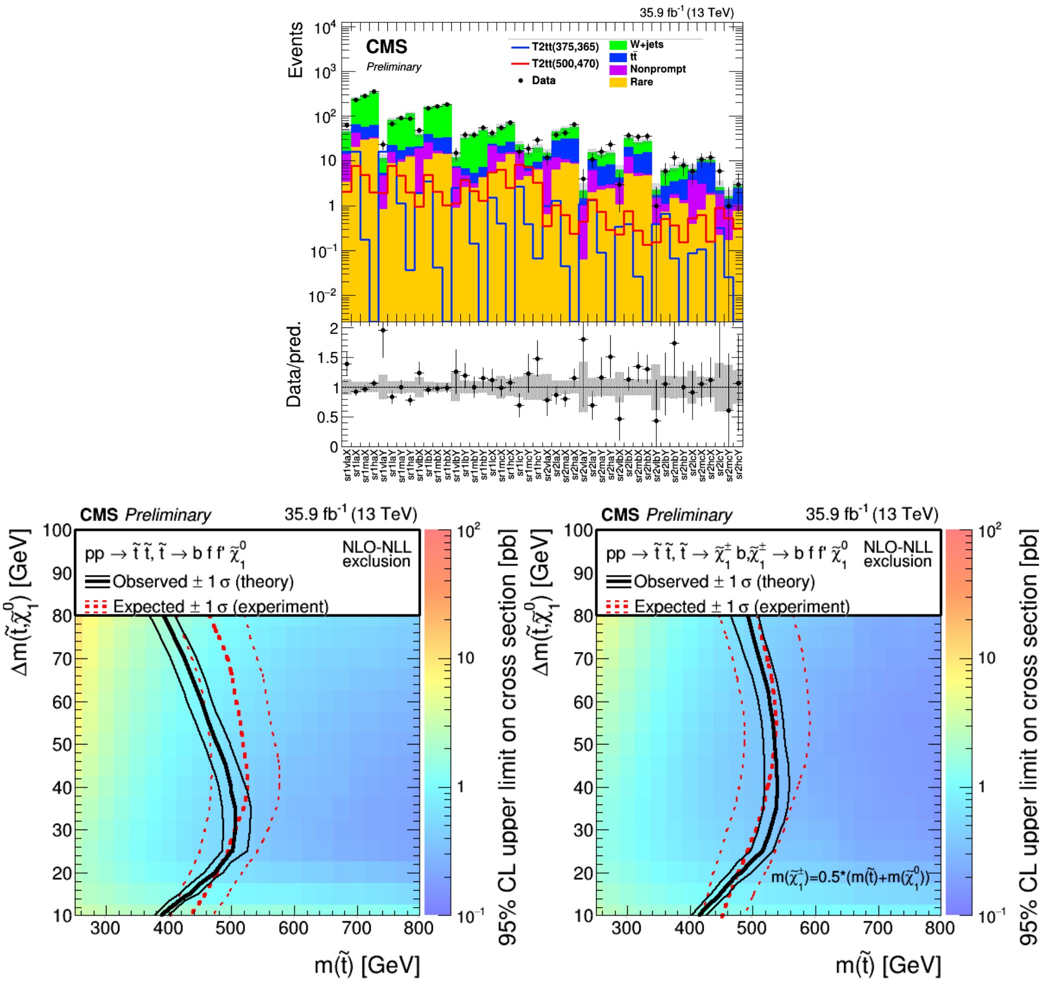

Figure 3: Top: Summary of observed data and expected background yields in the SRs. Bottom: Limits set on simplified signal models for top squark pair-production with subsequent four-body (left) and chargino-mediated (right) decays. A 100 % branching ratio to stop decays is assumed. [3]

References

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[2] C. Balázs, M. Carena and C. E. M. Wagner, *Dark matter, light stops and electroweak baryogenesis*, *Phys. Rev. D* **70** (2004) 015007, [hep-ph/0403224].

[3] CMS Collaboration, *Search for supersymmetry in events with at least one soft lepton, low jet multiplicity, and missing transverse momentum in proton-proton collisions at* $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-SUS-16-052, 2016. https://cds.cern.ch/record/2273394.