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# Search for pair production of top squarks and for dark matter in final states with two leptons using data collected by the ATLAS experiment during the LHC Run 2

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**Summary.** — A search for the direct pair production of top squarks ($\tilde{t}$) and for dark matter in events with two opposite-charge leptons, jets and missing transverse momentum is presented. The analysis is based on 139 fb$^{-1}$ of proton-proton collision data recorded by the ATLAS experiment at the Large Hadron Collider (LHC) at $\sqrt{s} = 13\,\text{TeV}$. Concerning the pair production of top squarks, current results extend previous exclusion limits with sensitivity across a wide range of mass differences between the $\tilde{t}$ and the lightest neutralino $\tilde{\chi}_1^0$. Furthermore, spin-0 mediator dark matter models are considered, with the mediator being produced in association with a pair of top squarks. No significant deviations from the Standard Model expectations are observed and limits at 95%confidence level (CL) are set on the masses of $\tilde{t}$, $\tilde{\chi}_1^0$ and dark matter mediators.

## 1. – Introduction

Supersymmetry (SUSY) [1] is one of the most promising theoretical extensions of the Standard Model (SM). It is a space-time simmetry postulating the existence of a SM partner particle whose spin differs by one-half unit. In the most simple SUSY model, the Minimal Supersymmetric Standard Model (MSSM), since the conservation of leptonic (L) and barionic (B) numbers is not a natural consequence of the theory, the $R$-parity quantum number is introduced, being defined as $R = (-1)^{3(B-L)+2S}$, with $S$ being the spin of the particle. If $R$-parity is conserved, as is assumed in this proceeding, SUSY particles are always produced in pairs in a collider and the Lightest Supersymmetric Particle (LSP) is stable and a promising Dark Matter (DM) candidate.

The scalar partners of right-handed and left-handed quarks (squarks) can mix to form two eigenstates ($\tilde{q}_i$, $i = 1, 2$), in order of increasing masses. In the case of the SUSY partner of the top quark, the *top squark*, large mixing effects can lead to one mass eigenstate, $\tilde{t}_1$, significantly lighter than other squarks, therefore easier to be produced in a collider.

The superpartners of the SM Higgs boson and the electroweak gauge bosons mix to form chargino ($\tilde{\chi}_i^{\pm}$) and neutralino ($\tilde{\chi}_j^0$, $j = 1, 2, 3, 4$) mass eigenstates, ordered by increasing mass. The LSP is identified as the lightest neutralino $\tilde{\chi}_1^0$.

A potential DM candidate is a weakly interacting massive particle $\chi$ (WIMP) [2], implying a signature with missing transverse momentum at the LHC. Some simplified models for DM production assume the existence of a mediator particle, coupling both to the SM and to the dark sector; this coupling relies on the Minimal Flavour Violation ansatz [3]. As a consequence, color-neutral mediators would be largely produced through loop-induced gluon fusion or in association with third-generation (heavy) quarks.

The results shown in this proceeding are based on [4], which presents the searches for the direct pair production of top squarks and DM particles in final states with two opposite electric charged leptons, jets and missing transverse momentum $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$ ($E_{\mathrm{T}}^{\mathrm{miss}}$ is its magnitude) using 139 fb$^{-1}$ of proton-proton collision data recorded by the ATLAS detector [5] during the entire LHC Run 2 at $\sqrt{s} = 13$ TeV. Concerning DM production in association with top quarks, the DM particles are pair produced through the exchange of a spin-0, scalar ($\phi$) or pseudoscalar ($a$), mediator, following the decay chain: $pp \to \chi\bar{\chi}t\bar{t}$. On the other hand, according to the mass difference between the top squark and the LSP, different decay modes are identified, based on simplified models [6]:

- For $m(W) + m(b) < m(\tilde{t}_1) - m(\tilde{\chi}_1^0) < m(t)$, the *three-body* decay is identified, through an off-shell top quark: $\tilde{t}_1 \to bW\tilde{\chi}_1^0$.
- For $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) < m(W) + m(b)$ the *four-body* decay is allowed, $\tilde{t}_1 \to bff'\tilde{\chi}_1^0$, where $f$ and $f'$ are the two fermions (lepton and neutrino) coming from an off-shell $W^*$ decay.
- For $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) > m(t)$, being a similar final state to DM production, results are thus interpreted in the scenario of the *two-body* decay, $\tilde{t}_1 \to t\tilde{\chi}_1^0$.

## 2. – Analysis strategy

Different event selection strategies are inspired by previous published strategies [7, 8] and re-optimised to exploit Run 2 dataset. Commonly to all selections, an improvent in the sensitivity is obtained by introducing the $E_{\mathrm{T}}^{\mathrm{miss}}$ significance variable. Moreover, the four-body sensitivity also benefits from a reduction in the lepton $p_T$ threshold, being lowered for electron (muons) from 7 GeV to 4.5 (4) GeV.

Events are required to have exactly two signal leptons (electrons and/or muons) with opposite electric charge. In the two-body and three-body selections, a dilepton invariant mass $m_{\ell\ell} > 20$ GeV is required to remove leptons from Drell-Yan and low-mass resonances; in the four-body selection, given the softer $p_T$ threshold, this requirement is reduced to 10 GeV. Events with the Same lepton Flavour (SF, $e^{\pm}e^{\mp}$ and $\mu^{\pm}\mu^{\mp}$) are required to have $|m_{\ell\ell} - m_Z| < 20$ GeV to reject events from the $Z$ boson decay. This condition is not applied in the four-body selection. No additional selection is applied to the Different Flavour (DF, $e^{\pm}\mu^{\mp}$) events. Different jet and $b$-jet multiplicities are required in the three selections.

The separation between signal and SM background events is obtained using suitable variables, which involve key features of the event final state, *i.e.*, $E_{\mathrm{T}}^{\mathrm{miss}}$ and lepton $p_T$, and possible combinations. The lepton-based stransverse mass $m_{\mathrm{T2}}^{\ell\ell}$ [9, 10] is a kinematic variable used to bound the masses of a pair of identical particles, decaying in turn into a visibile and an invisible particle. The three-body selection uses some *super-razor* variables [11], derived under some assumption in order to approximate the center-of-mass energy frame (Razor Frame) of two parent particles and the decay frames.

The two-body selection requires cuts on the transverse momentum of the two leptons, *i.e.* $p_T(\ell_1) > 25$ GeV and $p_T(\ell_2) > 20$ GeV, and, among other variables, on the stransverse mass, $m_{\mathrm{T2}}^{\ell\ell} > 110$ GeV. Two sets of Signal Regions (SRs) are defined: a set of *exclusive* SRs, binned in the $m_{\mathrm{T2}}^{\ell\ell}$ variable (shape fit) to maximise model-dependent sensitivity, and a set of *inclusive* ones, for model-independent results, keeping the lower limit of $m_{\mathrm{T2}}^{\ell\ell}$ variable and combining DF and SF events together.

The three-body selection is characterised by two different signal kinematics: similar to $WW$ production when $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m(W)$ and similar to $t\bar{t}$ when $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m(t)$. Two SRs are thus defined and kept orthogonal, according to $b$-jet multiplicities. Separation between SF and DF events is kept to optimise model-dependent search sensitivity.

The four-body selection requires soft leptons, efficiently selected by imposing a lower and a upper bound on lepton $p_T$. Two SRs are defined, kept orthogonal thanks to the sub-leading lepton $p_T$ being smaller or larger than 10 GeV. The presence of an energetic Initial State Radiation jet is required, introducing an unbalance in the event kinematics with large $E_{\mathrm{T}}^{\mathrm{miss}}$.

## 3. – Background estimation

The Monte Carlo (MC) predictions for the dominant and irreducible SM backgrounds are corrected using a data-driven normalisation procedure, while non-dominant processes are estimated directly using MC only. A simultaneous profile likelihood fit is used to constraint MC yields to observed data in dedicated Control Regions (CRs), extracting specific normalisation factors. Systematic uncertainties are taken into account in the fit through nuisance parameters. The SM background thus corrected is verified in dedicated Validation Regions (VRs), orthogonal to both SRs and CRs, and not used to constraint the fit. The accuracy of the modelling is assessed in regions of the parameter space kinematically close to the SRs.

Important sources of reducible backgrounds come from jets, misidentified as leptons. The *fake/non-prompt* (FNP) lepton background comes from light and heavy flavour hadron decays and from photon conversions. This kind of background is particularly important in the four-body selection, accounting up to $\sim 80\%$ of the total SM background in the more compressed SR. The FNP background is mainly suppressed by the lepton isolation requirements, but a non-negligible contribution is expected and it is estimated using the *fake factor* method [12].

The main background sources for the two-body selection are $t\bar{t}$ and $t\bar{t}Z$ with invisible decay of the $Z$ boson, normalized in two different CRs. For $t\bar{t}Z$, a strategy with a three lepton final state is employed. The normalization is verified in three VRs: two for $t\bar{t}$ background, splitted by lepton flavour, and one for $t\bar{t}Z$, using events having a four lepton final states, in order to have two SF leptons compatible with the $Z$ boson decay.

The main background sources for the three-body selection are dibosons ($VV$, $V = W, Z$), $t\bar{t}$ and $t\bar{t}Z$. The CR for $t\bar{t}$ is enriched of this background by requiring two or more jets from a $b$-quark, while a $b$-jet veto suppress $t\bar{t}$ in the CR for $VV$. The normalization of $t\bar{t}Z$ is extracted using the same CR defined in the two-body selection. Validation is performed in three VRs: two for $t\bar{t}$, requiring a veto or only one $b$-jet, and one for $VV$.

The dominant background sources for the four-body selections are $VV$ and $t\bar{t}$. Some of the requirements defining the SRs are released in order to allow the presence of a bigger fraction of $t\bar{t}$ events. The VV contribution is selected by limiting the number of jets in the events and by requiring an additional veto on $b$-jets. The background predictions are tested in three VRs: one for $t\bar{t}$ and two for $VV$, selecting events with two and three leptons in the final state.

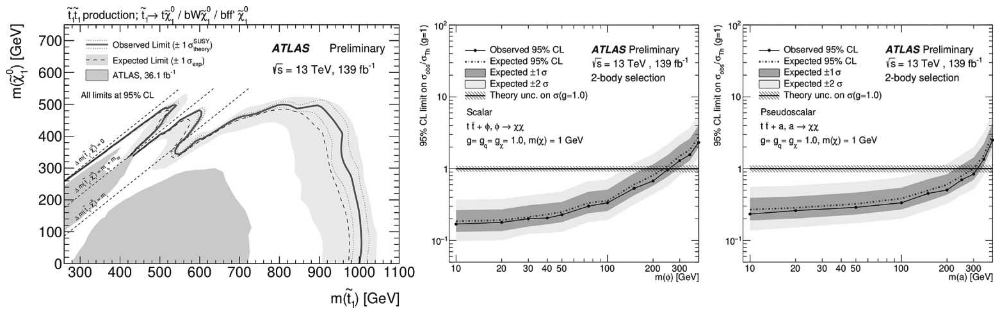


Fig. 1. – Observed and expected exclusion limits at 95%CL on SUSY simplified models for $\tilde{t}_1$ pair production, assuming $\tilde{t}_1 \to t^{(*)}\tilde{\chi}_1^0$ (left). Exclusion limits at 95%CL for $t\bar{t}+\phi$ scalar (center) and $t\bar{t}+a$ pseudoscalar (right) models as a function of the mediator mass for a DM particle of $m(\chi) = 1$ GeV [4].

## 4. – Results

No significant deviations from the SM expectations are observed in any of the selections considered. The analysis results are interpreted in terms of model-indipendent upper limits on the visible cross-section of new physics.

Exclusion limits at 95%CL for simplified models in which pair-produced $\tilde{t}_1$ decay with 100% branching ratio into a top quark and $\tilde{\chi}_1^0$ are shown in, fig. 1 (left); the exclusion contour is the overlap of the contours derived in each of the three selections separately. Figure 1 also reports exclusion limits on DM production in association with top quarks, upper limits at 95%CL are also set on the observed signal cross-section scaled to signal cross-section for unitary coupling $g = g_q = g_\chi = 1$ [13]. These limits are obtained as a function of the mediator mass, assuming a specific DM particle mass of 1 GeV, considering both the scalar (center) and pseudoscalar (right) mediator cases. The sensitivity is approximately constant for mediator masses below 100 GeV, excluding the $g = 1$ assumption for $\phi$ ($a$) mediator masses up to 200 (300) GeV.

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