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Searches for strong production of supersymmetric particles

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Supersymmetry (SUSY) provides elegant solutions to several problems in the Standard Model, and searches for SUSY particles are an important component of the LHC physics program. Naturalness arguments favour supersymmetric partners of the gluons and third-generation quarks with masses light enough to be produced at the LHC. This proceeding will present the latest results of searches conducted by the ATLAS experiment which target gluino and squark production, including stop and sbottom, in a variety of decay modes.

1 Introduction

The Standard Model (SM) is the theory describing the elementary particles and their interactions. Despite the many experimental results precisely confirming the predictions of this theory, there are still some open questions within the model. SUperSYmmetry (SUSY) is a Beyond Standard Model (BSM) physics theory, predicting the existence of fermionic (bosonic) supersymmetric partners (also known as *sparticles*) for the bosons (fermions) in the SM, differing by 1/2 unit in spin. A new quantum number is introduced to distinguish between SM and BSM particles, R-parity, $R = (-1)^{3(B-L)+2s}$ with B, L being the baryon and lepton numbers, while s is the spin of the particle. According to the violation of this quantum number or not, two scenarios are introduced: R-parity-violating (RPV) and R-parity-conserving (RPC) models.
The charged and neutral superpartners of the SM Higgs (called *higgsinos*) and electroweak (EWK) gauge bosons (collectively referred to as *electroweakinos*) mix to form *chargino* ($\tilde{\chi}_i^{\pm}$, $i = 1, 2$) and *neutralino* ($\tilde{\chi}_j^0$, $j = 1, \ldots, 4$) mass eigenstates, respectively. R-parity conservation requires SUSY particles to be produced in pairs, and the $\tilde{\chi}_1^0$ is assumed to be the lightest supersymmetric particle (LSP) and to be stable. As a consequence, it may be identified as a potential Dark Matter (DM) candidate.
The latest searches for strong production of supersymmetric particles are highlighted, exploiting the full LHC Run 2 proton-proton collision dataset collected with the ATLAS [1] experiment at $\sqrt{s} = 13$ TeV and corresponding to an integrated luminosity of 139 fb^{-1}.

2 SUSY Strong searches

2.1 A search for R-parity violating decays of the top squark to b-quark and a lepton

A search for direct pair production of the top squark (or *stop*), the supersymmetric partner of the top quark, in a decay through a R-parity violating coupling to a charged lepton and a b-quark [2], is presented. Results on partial Run 2 dataset were previously published [3].
The experimental signature requires two oppositely charged leptons, not necessarily of the same flavor, and two b-jets. For this analysis, only events with electrons or muons are selected, and final states are split by flavor into ee, $e\mu$, and $\mu\mu$ channels. Sensitivity for a stop decaying to a b-jet and a τ-lepton (through leptonic τ decay) is obtained through investigation of these electron and muon channels. Events are required to have at least two leptons and two jets: from each stop decay, the lepton-jet pair is used to reconstruct the invariant mass m_{bl} of the original stop. Having two leptons and two jets in the final state, two pairings are possible: the pairing that minimizes the mass asymmetry $m_{bl}^{asym} = (m_{bl}^0 - m_{bl}^1)/(m_{bl}^0 + m_{bl}^1)$ between the two possible options is chosen. Events are further selected to have small mass asymmetry $m_{bl}^{asym} < 0.2$ in order to reduce the contamination from background processes with a more uniform m_{bl}^{asym} distribution. Several other kinematic selections are defined to reduce the contribution from the dominant backgrounds, identified in the $t\bar{t}$, single-top and $Z+$jets processes. The expected background yield in the signal regions (SRs) is estimated by scaling each MC prediction by a normalization factor derived from three dedicated control regions (CRs), one for each background process, defined by inverting or relaxing some specific signal selections. Four different validation regions (VRs), kinematically close to the SRs, are defined to test the extrapolation of the background fit from the CRs to the SRs. No significant excess above the Standard Model expectation is observed in any SR and, for model dependent results, two exclusion fits are performed for each lepton branching ratio point probed: one inclusive 15-bin fit, which is agnostic to lepton final state, and one 45-bin fit simultaneously across all three lepton flavor channels as separate SRs. For each stop mass and branching ratio, the configuration providing the strongest expected limit on the signal strength is used. The flavor-agnostic configuration typically has the stronger expected sensitivity when $\mathcal{B}(\tilde{t} \to b\ell)$, $\ell = e, \mu, \tau$ are similar in size, while the flavor-aware configuration is more sensitive in the corners of the branching ratio plane, corresponding to 100% branching ratios. Exclusion limits are derived at 95% confidence level (CL) for stop pair production. In addition to using the aforementioned SR definitions for model-dependent results, a second set of regions is defined to produce model-independent limits and upper limits are set on the cross-section of BSM processes in the three channels.

2.2 Search for new phenomena with top-quark pairs and large missing transverse momentum

A BSM search is conducted for new phenomena in events with a top quark pair and large missing transverse momentum, where the top quark pair is reconstructed in final states with one isolated electron or muon and multiple jets [4]. Two different searches are considered, targeting the same final state: the direct pair production of squark top, $\tilde{t}_1$, and the search for a spin-0 mediator produced in association with top squarks decaying into a pair of DM particles. With respect to the previous publication [5], this analysis employs improved object reconstruction, identification algorithms and background simulations, new neural-network-based classifiers for the reconstruction of the hadronically decaying top quark and for the event discrimination. All events are required to have exactly one (for SRs) or three (for the ttZ VR) signal leptons. Then, events are classified into two mutually exclusive categories: resolved high-$E_{\mathrm{T}}^{\mathrm{miss}}$ and boosted topologies, with the presence of a large-R jet. Events are further classified according to the number of b-tagged jets (1 or 2) and the presence of a *top*-tagged large-R jet. For high-$E_{\mathrm{T}}^{\mathrm{miss}}$ events, a minimum number of light jets is required as input to a Neural Network (NN) jet algorithm, for *top*-tagging purposes. The hadronic top quark candidate is reconstructed by the combination of jets that give the highest top-NN output value, while the leptonic top quark candidate comprises the lepton and the b-tagged

leading-p_{T} jet that is not associated with the hadronic top quark candidate.
Boosted events are first categorised according to whether the large-R jet is *top*-tagged or not and six cathegories are defined according to the numbers of b-tagged jets inside and outside the large-R jet. Overall, eight orthogonal categories in different kinematic regimes and with different reconstructed objects are used to maximise the signal acceptance. Finally, two NN-based event classifiers, one for the $\tilde{t}_1\tilde{t}_1$ search and one for the DM search, are employed to discriminate signal from background events. Moreover, the stop and DM-NN output values are used to split each event category into SRs, CRs and VRs. The dominant sources of background events are $t\bar{t}$, single-top and $W+$jets. All these backgrounds are estimated from simulation and corrected based on a fit to data in CRs. Despite its small cross-section, $t\bar{t}Z(\rightarrow \nu\bar{\nu})$ production constitutes another important background as it yields events with signal-like kinematic properties, although not fitted in a dedicated CR: the validation for this irreducible background is done using events enhanced in $t\bar{t}Z(\rightarrow \ell\ell)$. To select events with kinematic properties similar to those of the $t\bar{t}Z(\rightarrow \nu\bar{\nu})$, the three-lepton events are categorised and classified as one-lepton events using a modified missing transverse momentum which incorporates the vectorial sum of the two leptons from the Z-boson decay. No statistically significant deviations from the SM expectation are observed and exclusion limits are calculated at 95% CL, by combining current results with previous searches in similar final states but with different lepton multiplicities. Results from this analysis are also interpreted in the context of a search for effective vector contact interactions between top quarks and all three generations of left-handed neutrinos.

2.3 Search for top-quark pair production in final states with a top quark, a charm quark and missing transverse momentum

A BSM search for top squark pair production in final states with a top quark, a charm quark and missing transverse momentum is presented[6]. This is the first LHC result for top/charm quark final state without leptons. Due to the presence of a c-jet in the signature, a non-standard, analysis-specific c-tagging algorithm $DL1r_c$ is optimised, based on the $DL1r$ algorithm used for b-tagging[7]. The two tagging algorithms are run in sequence with the b-tagging algorithm taking precedence, and if a jet is classified as a b-jet, it is no longer considered as an input to the c-tagging algorithm. The parameter space is split into three main regions: the "bulk" region, with large $\Delta m(\tilde{t}_1, \tilde{\chi}^0_1)$; the "intermediate" region where the top squark and neutralino are relatively close in mass; and, finally, the "compressed" region, where the mass splitting is such that the top quark from the stop decay is produced just on-shell, i.e. $\Delta m(\tilde{t}_1, \tilde{\chi}^0_1) \sim m_t$. Many kinematic variables are employed in the definition of the SRs to isolate the SUSY signals and to reject events arising from the SM background and four orthogonal sets of SRs have been designed to target the different areas of parameter space. The largest background contribution originates from $Z+$jets events, followed by single-top or $W+$jets events, evaluated in dedicated CRs. As already explained beforehand, CRs requiring two leptons (2L) are used to extract a normalisation factor for the $Z+$jets background. A set of VRs is defined to validate the background predictions and good agreement is observed between data and post-fit background yields. A multi-bin profile likelihood fit is performed to assess the agreement of the signal and SM predictions against data and no significant deviations from the expected background prediction are observed in SRs. 95% CL exclusion limits are derived on the SUSY signal scenarios. Finally, an alternative interpretation is performed, where the neutralino mass is fixed to 1 GeV and the BR of the $\tilde{t}_1 \rightarrow t + \tilde{\chi}^0_1$ decay is allowed to vary between 0 and 1.

2.4 Search for supersymmetry in final states with missing transverse momentum and c-jets

The last presented BSM search is for top squark, charm squark, and leptoquark pair production decaying into final states with missing transverse momentum and jets originating from charm quarks [8]. A previous search, based on the identification of jets containing c-hadrons but no b-hadrons, used a partial Run 2 dataset [9]. In addition to a larger dataset, the search herein also benefits from improvements in c-tagging and from the Recursive Jigsaw Reconstruction (RJR) technique [10], which provides sensitivity to models with small mass splittings between the top squark and the LSP. To identify jets containing c-hadrons, the charm-tagging algorithm $DL1r_c$, optimized for the previously described search [6], is used with a dedicated tuning of the key parameters. The search uses two sets of SRs targeting two different set of kinematic regions: high-mass and compressed. The former SRs are sensitive to leptoquark models and SUSY models with large leptoquark or top squark masses and a large difference between the top squark and LSP masses; in these selections $E_{\mathrm{T}}^{\mathrm{miss}}$-based variables are relied upon to separate signal events from background events. The latter SRs are sensitive to SUSY models with both smaller top squark masses and compressed spectra; here the presence of high-momentum jets originating from initial-state radiation and RJR are used to suppress the SM background. The orthogonality between high-mass and compressed regions is guaranteed by the fact that the high-mass regions require the leading jet to be a c-tagged jet, while the compressed regions require the leading jet not to be c-tagged. The dominant backgrounds in all the SRs are from processes with W or Z bosons produced in association with jets, mainly from hadronic decays, and, in addition, the $Z \to \nu\bar{\nu}$ decay process, producing missing transverse momentum. These backgrounds are estimated, using the simulated samples, by extrapolating correction factors from dedicated CRs to the SRs. The contribution from the invisible decay is estimated through a CR with a 2L selection, treating the decay products as invisible, following the same procedure previously described. The VRs are used to test the accuracy of the procedure used to extrapolate the background from the CRs to the SRs. No significant excess of events over the expected SM background expectation is observed in SRs, and exclusion limits are set on the masses of the involved SUSY particles. Exclusion limits are also presented for an alternative interpretation in which top squarks are pair produced and each decays into a neutralino and either a top or a charm quark, with $\mathcal{B}(\tilde{t}_1 \to c + \tilde{\chi}_1^0)$ being varied between 0.1 and 1. The results are interpreted as upper limits at 95% CL on the production cross-section of selected SUSY and leptoquark models and as model-independent upper limits on the production cross-section for BSM particles.

3 Summary

The latest ATLAS searches for strongly produced supersymmetric particles are described. The searches use proton-proton collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 139 fb^{-1}. Observed data are found to be in agreement with SM background expectations and results are interpreted in terms of exclusion limits on the masses of the particles considered or on the branching ratios associated with the decays. Sensitity is improved with respect to the already published results in all the considered SUSY scenarios. Exclusion limits are set for the first time on some processes.

References

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