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Search for pair production of third-generation scalar leptoquarks and top squarks in proton–proton collisions at $\sqrt{s} = 8$ TeV

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ABSTRACT

A search for pair production of third-generation scalar leptoquarks and supersymmetric top quark partners, top squarks, in final states involving tau leptons and bottom quarks is presented. The search uses events from a data sample of proton–proton collisions corresponding to an integrated luminosity of 19.7 fb^{-1}, collected with the CMS detector at the LHC with $\sqrt{s} = 8$ TeV. The number of observed events is found to be in agreement with the expected standard model background. Third-generation scalar leptoquarks with masses below 740 GeV are excluded at 95% confidence level, assuming a 100% branching fraction for the leptoquark decay to a tau lepton and a bottom quark. In addition, this mass limit applies directly to top squarks decaying via an R-parity violating coupling λ'_{333}. The search also considers a similar signature from top squarks undergoing a chargino-mediated decay involving the R-parity violating coupling λ'_{3jk}. Each top squark decays to a tau lepton, a bottom quark, and two light quarks. Top squarks in this model with masses below 580 GeV are excluded at 95% confidence level. The constraint on the leptoquark mass is the most stringent to date, and this is the first search for top squarks decaying via λ'_{3jk}.

1. Introduction

Many extensions of the standard model (SM) predict new scalar or vector bosons, called leptoquarks (LQ), which carry non-zero lepton and baryon numbers, as well as color and fractional electric charge. Examples of such SM extensions include SU(5) grand unification [1], Pati–Salam SU(4) [2], composite models [3], superstrings [4], and technicolor models [5]. Leptoquarks decay into a quark and a lepton, with a model-dependent branching fraction for each possible decay. Experimental limits on flavor-changing neutral currents and other rare processes suggest that searches should focus on leptoquarks that couple to quarks and leptons within the same SM generation, for leptoquark masses accessible to current colliders [3,6].

The dominant pair production mechanisms for leptoquarks at the CERN LHC would be gluon–gluon fusion and quark–antiquark annihilation via quantum chromodynamic (QCD) couplings. The cross sections for these processes depend only on the leptoquark mass for scalar leptoquarks. In this Letter, a search with the CMS detector for third-generation scalar leptoquarks, each decaying to a tau lepton and a bottom quark, is presented.

Similar signatures arising from supersymmetric models are also covered by this search. Supersymmetry (SUSY) [7,8] is an attractive extension of the SM because it can resolve the hierarchy problem without unnatural fine-tuning, if the masses of the supersymmetric partner of the top quark (top squark) and the supersymmetric partners of the Higgs boson (higgsinos) are not too large [9,10]. In many natural SUSY models the top squark and the higgsinos are substantially lighter than the other scalar SUSY particles. This light top squark scenario can be realized in both R-parity conserving (RPC) and R-parity violating (RPV) SUSY models, where R-parity is a new quantum number [11] that distinguishes SM and SUSY particles. In the context of an RPC decay of the top squark, the presence of an undetected particle (the lightest SUSY particle) is expected to generate a signature with large missing transverse momentum. If R-parity is violated, however, SUSY particles can decay into final states containing only SM particles. The RPV terms in the superpotential are:

$$W \ni \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k + \mu_i L_i H_u \qquad (1)$$

where W is the superpotential; L is the lepton doublet superfield; E is the lepton singlet superfield; Q is the quark doublet superfield; U and D are the quark singlet superfields; H_u is the Higgs

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doublet superfield that couples to up-type quarks; λ, λ', and λ'' are coupling constants; and i, j, and k are generation indices.

At the LHC, top squarks ($\tilde{\mathrm{t}}$) would be directly pair-produced via strong interactions. In this search, two different decay channels of directly produced top squarks are considered. Both scenarios relate to simplified models in which all of the other SUSY particles have masses too large to participate in the interactions. In the first case we study the two-body lepton number violating decay $\tilde{\mathrm{t}} \to \tau \mathrm{b}$ [11] with a coupling constant λ'_{333} allowed by the trilinear RPV operators. The final-state signature and kinematic distributions of such a signal are identical to those from the pair production of third-generation scalar leptoquarks. When the masses of the supersymmetric partners of the gluon and quarks, excluding the top squark, are large, the top squark pair production cross section is the same as that of the third generation LQ. Thus, the results of the leptoquark search can be directly interpreted in the context of RPV top squarks.

In some natural SUSY models [12], if the higgsinos ($\tilde{\chi}^0$, $\tilde{\chi}^\pm$) are lighter than the top squark, or if the RPV couplings that allow direct decays to SM particles are sufficiently small, the top squark decay may preferentially proceed via superpartners. In the second part of the search we focus on a scenario in which the dominant RPC decay of the top squark is $\tilde{\mathrm{t}} \to \tilde{\chi}^\pm \mathrm{b}$. This requires the mass splitting between the top squark and the chargino to be less than the mass of the top quark, so it is chosen to be 100 GeV. The chargino is assumed to be a pure higgsino and to be nearly degenerate in mass with the neutralino. We consider the case when $\tilde{\chi}^\pm \to \tilde{\nu}\tau^\pm \to \mathrm{qq}\tau^\pm$. The decay of the sneutrino occurs according to an RPV operator with a coupling constant λ'_{3jk}, where the cases $j, k = 1, 2$ are considered. Such signal models can only be probed by searches that do not require large missing transverse momentum, as the other decay of the chargino, $\tilde{\chi}^\pm \to \nu\tilde{\tau}$, does not contribute to scenarios involving the λ'_{3jk} coupling because of chiral suppression. From such a signal process, we expect events with two tau leptons, two jets originating from hadronization of the bottom quarks, and at least four additional jets.

In this Letter, the search for scalar leptoquarks and top squarks decaying through the coupling λ'_{333} is referred to as the leptoquark search. The search for the chargino-mediated decay of top squarks involving the λ'_{3jk} coupling is referred to as the top squark search. The data sample used in this search has been recorded with the CMS detector in proton–proton collisions at a center-of-mass energy of 8 TeV and corresponds to an integrated luminosity of 19.7 fb^{-1}. One of the tau leptons in the final state is required to decay leptonically: $\tau \to \ell\bar{\nu}_\ell\nu_\tau$, where ℓ can be either an electron or a muon, denoted as a light lepton. The other tau lepton is required to decay to hadrons (τ_h): $\tau \to \mathrm{hadrons} + \nu_\tau$. These decays result in two possible final states labeled below as $\mathrm{e}\tau_\mathrm{h}$ and $\mu\tau_\mathrm{h}$, or collectively $\ell\tau_\mathrm{h}$ when the lepton flavor is unimportant. The leptoquark search is performed in a mass range from 200 to 1000 GeV using a sample of events containing one light lepton, a hadronically decaying tau lepton, and at least two jets, with at least one of the jets identified as originating from bottom quark hadronization (b-tagged). The top squark search is performed in a mass range from 200 to 800 GeV using a sample of events containing one light lepton, a hadronically decaying tau lepton, and at least five jets, with at least one of the jets b-tagged.

No evidence for third-generation leptoquarks or top squarks decaying to tau leptons and bottom quarks has been found in previous searches [13,14]. The most stringent lower limit to date on the mass of a scalar third generation leptoquark decaying to a tau lepton and a bottom quark with a 100% branching fraction is about 530 GeV from both the CMS and ATLAS experiments. This Letter also presents the first search for the chargino-mediated decay of the top squark through the RPV coupling λ'_{3jk}.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are several subdetectors. A silicon pixel and strip tracker allows the reconstruction of the trajectories of charged particles within the pseudorapidity range $|\eta| < 2.5$. The calorimetry system consists of a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass and scintillator hadron calorimeter, and measures particle energy depositions for $|\eta| < 3$. The CMS detector also has extensive forward calorimetry ($2.8 < |\eta| < 5.2$). Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke of the magnet. Collision events are selected using a two-tiered trigger system [15]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [16].

3. Object and event selection

Candidate LQ or top squark events were collected using a set of triggers requiring the presence of either an electron or a muon with transverse momentum (p_T) above a threshold of 27 or 24 GeV, respectively.

Both electrons and muons are required to be reconstructed within the range $|\eta| < 2.1$ and to have $p_\mathrm{T} > 30$ GeV. Electrons, reconstructed using information from the ECAL and the tracker, are required to have an electromagnetic shower shape consistent with that of an electron, and an energy deposition in ECAL that is compatible with the track reconstructed in the tracker. Muons are required to be reconstructed by both the tracker and the muon spectrometer. A particle-flow (PF) technique [17–19] is used for the reconstruction of hadronically decaying tau lepton candidates. In the PF approach, information from all subdetectors is combined to reconstruct and identify all final-state particles produced in the collision. The particles are classified as either charged hadrons, neutral hadrons, electrons, muons, or photons. These particles are used with the "hadron plus strips" algorithm [20] to identify τ_h objects. Hadronically decaying tau leptons with one or three charged pions and up to two neutral pions are reconstructed. The reconstructed τ_h is required to have visible $p_\mathrm{T} > 50$ GeV and $|\eta| < 2.3$. Electrons, muons, and tau leptons are required to be isolated from other reconstructed particles. The identified electron (muon) and τ_h are required to originate from the same vertex and be separated by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.5$. The light lepton and the τ_h are also required to have opposite electric charge. Events are vetoed if another light lepton is found, passing the kinematic, identification, and isolation criteria described above, that has an opposite electric charge from the selected light lepton.

Jets are reconstructed using the anti-k_T algorithm [21,22] with a size parameter 0.5 using particle candidates reconstructed with the PF technique. Jet energies are corrected by subtracting the average contribution from particles coming from other proton–proton collisions in the same beam crossing (pileup) and by applying a jet energy calibration, determined empirically [23]. Jets are required to be within $|\eta| < 2.4$, have $p_\mathrm{T} > 30$ GeV, and be separated from both the light lepton and the τ_h by $\Delta R > 0.5$. The minimum jet p_T requirement eliminates most jets from pileup interactions. Jets are b-tagged using the combined secondary vertex algorithm with the loose operating point [24]. In the leptoquark search, the b-tagged jet with the highest p_T is selected, and then the remaining jet with the highest p_T is selected whether or not it is b-tagged. In the top squark search, the b-tagged jet with the highest p_T is selected, and then the remaining four jets with the highest p_T are selected whether or not they are b-tagged.

To discriminate between signal and background in the leptoquark search, the mass of the τ_h and a jet, denoted $M(\tau_h, \text{jet})$, is required to be greater than 250 GeV. There are two possible pairings of the τ_h with the two required jets. The pairing is chosen to minimize the difference between the mass of the τ_h and one jet and the mass of the light lepton and another jet. According to a simulation, the correct pairing is selected in approximately 70% of events.

The S_T distribution after the final selection is used to extract the limits on both the leptoquark and top squark signal scenarios, where S_T is defined as the scalar sum of the p_T of the light lepton, the τ_h, and the two jets (five jets) for the leptoquark search (top squark search).

4. Background and signal models

Several SM processes can mimic the final-state signatures expected from leptoquark or top squark pair production and decay. For this analysis, the backgrounds are divided into three groups, which are denoted as $t\bar{t}$ irreducible, major reducible, and other. The $t\bar{t}$ irreducible background comes from the pair production of top quarks ($t\bar{t}$) when both the light lepton and τ_h are genuine, each produced from the decay of a W boson. In this case, the light lepton can originate either directly from the W boson decay or from a decay chain $W \to \tau\nu_\tau \to \ell\nu_\ell\nu_\tau\nu_\tau$. The major reducible background consists of events in which a quark or gluon jet is misidentified as a τ_h. The processes contributing to the major reducible background are associated production of a W or Z boson with jets, and $t\bar{t}$. Additionally, a small contribution from the QCD multijet process is included, in which both the light lepton and the τ_h are misidentified jets. The third group, other backgrounds, consists of processes that make small contributions and may contain either genuine or misidentified tau leptons. This includes the diboson and single-top-quark processes, the $t\bar{t}$ and Z + jets processes when a light lepton is misidentified as a τ_h, and the Z + jets process when the Z boson decays to a pair of tau leptons. The other backgrounds are estimated from the simulation described below, while the $t\bar{t}$ irreducible and major reducible backgrounds are estimated using observed data. The major reducible and other backgrounds include events with both genuine and misidentified light leptons.

The PYTHIA v6.4.24 generator [25] is used to model the signal and diboson processes. The leptoquark signal samples are generated with masses ranging from 200 to 1000 GeV, and the top squark signal samples are generated with masses ranging from 200 to 800 GeV and the sneutrino mass set to 2000 GeV. The MADGRAPH v5.1.3.30 generator [26] is used to model the $t\bar{t}$, W + jets, and Z + jets processes. This generation includes contributions from heavy-flavor and extra jets. The single top-quark production is modeled with the POWHEG 1.0 r138 [27–29] generator. Both the MADGRAPH and POWHEG generators are interfaced with PYTHIA for hadronization and showering. The TAUOLA program [30] is used for tau lepton decays in the leptoquark, $t\bar{t}$, W + jets, Z + jets, diboson, and single top-quark samples. Each sample is passed through a full simulation of the CMS detector based on GEANT4 [31] and the complete set of reconstruction algorithms is used to analyze collision data. Cross sections for the leptoquark signal and diboson processes are calculated to next-to-leading order (NLO) [32,33]. The cross sections for the top squark signal are calculated at NLO in the strong coupling constant, including the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO + NLL) [34–38]. The next-to-next-to-leading-order or approximate next-to-next-to-leading-order [39,40] cross sections are used for the rest of the background processes.

The efficiencies of the trigger and final selection criteria for signal processes are estimated from the simulation. The efficiencies for light leptons and b jets are calculated from data and used where necessary to correct the event selection efficiency estimations from the simulation. No correction is required for hadronically decaying tau leptons.

The $t\bar{t}$ irreducible background is estimated from an $e\mu$ sample that is 87% pure in $t\bar{t}$ events according to the simulation. The contributions from other processes are simulated and subtracted from the observed data. This sample comprises events with one electron and one muon that satisfy the remaining final selection criteria, except that a τ_h is not required. The potential signal contamination of this sample has been found to be negligible for any signal mass hypothesis. The final yield of the $e\mu$ sample is scaled by the relative difference in the selection efficiencies between the $\ell\tau_h$ and $e\mu$ samples. The selection efficiencies are measured in the simulation and are corrected to match those from collision data. The estimation of the final yield based on the observed data agrees with both the direct prediction from the simulation and the yield obtained after applying the same method to the Monte Carlo (MC) samples. The S_T distribution for the $t\bar{t}$ irreducible background is obtained from a simulated $t\bar{t}$ sample that consists exclusively of fully leptonic decays of top quarks.

The major reducible background from $t\bar{t}$, W + jets, and Z + jets events in which a jet is misidentified as a hadronically decaying tau lepton is estimated from observed data. The probability of misidentification is measured using events recorded with a Z boson produced in association with jets and decaying to a pair of muons ($Z \to \mu\mu$). The invariant mass of the muon pair is required to be greater than 50 GeV and events are required to contain at least one jet that is incorrectly identified as a τ_h and may or may not pass the isolation requirement. The misidentification probability $f(p_T(\tau))$ is calculated as the fraction of these τ_h candidates that pass the isolation requirement and depends on the p_T of the candidates. The background yield is estimated from a sample of events satisfying the final selection criteria, except that all τ_h candidates in the events must fail the isolation requirement. Eq. (2) relates the yield of these “anti-isolated” events to the yield of events passing the final selection, using the misidentification probability:

$$N_{\text{misID}\ \tau} = \sum_{\text{events}}^{\text{(anti-iso)}} \frac{1 - \prod_\tau [1 - f(p_T(\tau))]}{\prod_\tau [1 - f(p_T(\tau))]}. \tag{2}$$

The estimation of the final yield based on the observed data agrees with both the direct prediction from the simulation and the estimation performed using the same approach on simulated samples. The S_T distribution for the major reducible background is obtained using simulated samples for the W + jets and Z + jets processes and the $t\bar{t}$ process with exclusively semi-leptonic decays.

The QCD multijet process contributes only in the $e\tau_h$ channel in the leptoquark search and corresponds to 16% of the reducible background. The contribution from multijet events is estimated from a sample of observed events satisfying the final selection criteria for the $e\tau_h$ channel except that the electron and τ_h must have the same electric charge. The QCD component is included in the distribution of the rest of the major reducible background, described above.

5. Systematic uncertainties

There are a number of systematic uncertainties associated with both the background estimation and the signal efficiency. The uncertainty in the total integrated luminosity is 2.6% [41]. The uncertainty in the trigger and lepton efficiencies is 2%, while the

Table 1
The estimated backgrounds, observed event yields, and expected number of signal events for the leptoquark search. For the simulation-based entries, the statistical and systematic uncertainties are shown separately, in that order.

	$\mathrm{e}\tau_{\mathrm{h}}$	$\mu\tau_{\mathrm{h}}$
$\mathrm{t\bar{t}}$ irreducible	105.6 ± 18.1	66.7 ± 12.6
Major reducible	147.8 ± 33.0	117.3 ± 18.9
$\mathrm{Z}(\ell\ell/\tau\tau)+\text{jets}$	$21.4 \pm 7.4 \pm 4.9$	$7.5 \pm 4.6 \pm 0.2$
Single t	$16.0 \pm 2.8 \pm 4.4$	$17.3 \pm 2.8 \pm 4.7$
VV	$4.1 \pm 0.6 \pm 1.3$	$2.6 \pm 0.5 \pm 0.8$
Total exp. bkg.	$294.9 \pm 7.9 \pm 39.1$	$211.4 \pm 5.4 \pm 23.4$
Observed	289	216
$M_{\mathrm{LQ}} = 500$ GeV	$57.7 \pm 1.4 \pm 5.9$	$51.6 \pm 1.3 \pm 5.3$
$M_{\mathrm{LQ}} = 600$ GeV	$20.1 \pm 0.5 \pm 1.9$	$17.7 \pm 0.4 \pm 1.6$
$M_{\mathrm{LQ}} = 700$ GeV	$7.1 \pm 0.2 \pm 6.3$	$6.2 \pm 0.1 \pm 5.5$
$M_{\mathrm{LQ}} = 800$ GeV	$2.7 \pm 0.1 \pm 0.2$	$2.3 \pm 0.1 \pm 0.2$

Table 2
The estimated backgrounds, observed event yields, and expected number of signal events for the top squark search. For the simulation-based entries, the statistical and systematic uncertainties are shown separately, in that order.

	$\mathrm{e}\tau_{\mathrm{h}}$	$\mu\tau_{\mathrm{h}}$
$\mathrm{t\bar{t}}$ irreducible	88.3 ± 13.7	55.0 ± 9.5
Major reducible	65.7 ± 16.4	59.8 ± 13.8
$\mathrm{Z}(\ell\ell/\tau\tau)+\text{jets}$	$4.9 \pm 2.5 \pm 1.1$	$11.6 \pm 5.5 \pm 2.7$
Single t	$3.9 \pm 1.5 \pm 1.1$	$3.5 \pm 1.3 \pm 0.9$
VV	$0.6 \pm 0.2 \pm 0.2$	$0.4 \pm 0.2 \pm 0.1$
Total exp. bkg.	$163.4 \pm 2.9 \pm 21.5$	$130.3 \pm 5.6 \pm 17.1$
Observed	156	123
$M_{\tilde{\mathrm{t}}} = 300$ GeV	$94.3 \pm 8.5 \pm 13.2$	$82.8 \pm 8.0 \pm 11.7$
$M_{\tilde{\mathrm{t}}} = 400$ GeV	$43.9 \pm 2.6 \pm 4.3$	$38.3 \pm 2.3 \pm 3.8$
$M_{\tilde{\mathrm{t}}} = 500$ GeV	$19.4 \pm 0.8 \pm 1.8$	$15.4 \pm 0.7 \pm 1.5$
$M_{\tilde{\mathrm{t}}} = 600$ GeV	$6.9 \pm 0.9 \pm 0.7$	$5.7 \pm 0.3 \pm 0.5$

uncertainty assigned to the τ_{h} identification efficiency is 6%. The uncertainties in the b-tagging efficiency and mistagging probability depend on the η and p_{T} of the jet and are on average 4% and 10%, respectively [42].

Systematic uncertainties, totaling 19–22% depending on the channel and the search, are assigned to the normalization of the $\mathrm{t\bar{t}}$ irreducible background based on statistical uncertainty in the control samples and the propagation of the uncertainties in the acceptances, efficiencies, and subtraction of the contributions from other processes in the $\mathrm{e}\mu$ sample. Systematic uncertainties in the major reducible background are driven by statistical uncertainty in the measured misidentification probability and variation in the misidentification probability based on the event topology. These uncertainties amount to 16–24%, depending on the channel and the search.

Because of the limited number of events in the simulation, uncertainties in the small backgrounds range between 20–50%. Uncertainty due to the effect of pileup modeling in the MC is estimated to be 3%. A 4% uncertainty, due to modeling of initial- and final-state radiation in the simulation, is assigned to the signal acceptance. The uncertainty in the initial- and final-state radiation was found to have a negligible effect on the simulated backgrounds. A 7–32% uncertainty from knowledge of parton distribution functions and a 14–80% uncertainty from QCD renormalization and factorization scales are assigned to the theoretical signal cross-section. Finally, jet energy scale uncertainties (2–4% depending on η and p_{T}) and energy resolution uncertainties (5–10% depending on η), as well as energy scale (3%) and resolution (10%) uncertainties for τ_{h}, affect both the S_{T} distributions and the expected yields from the signal and background processes.

6. Results

The numbers of observed events and expected signal and background events after the final selection for the leptoquark and top squark searches are listed in Tables 1 and 2, respectively, and the selection efficiencies for the two signals are listed in Tables 3 and 4. The S_{T} distributions of the selected events from the observed data and from the background predictions, combining $\mathrm{e}\tau_{\mathrm{h}}$ and $\mu\tau_{\mathrm{h}}$ channels, are shown in Fig. 1 for the leptoquark search and Fig. 2 for the top squark search. The distribution from the 500 GeV (300 GeV) signal hypothesis is added to the background in Fig. 1 (Fig. 2) to illustrate how a hypothetical signal would appear above the background prediction. The data agree well with the SM background prediction.

Table 3
Selection efficiencies in % for the signal in the leptoquark search, estimated from the simulation.

M_{LQ} (GeV)	$\mathrm{e}\tau_{\mathrm{h}}$	$\mu\tau_{\mathrm{h}}$
200	0.1	0.1
250	0.3	0.2
300	1.0	0.8
350	1.9	1.5
400	2.4	2.3
450	3.0	2.9
500	3.6	3.2
550	4.0	3.3
600	4.4	3.8
650	4.5	4.0
700	4.7	4.1
750	4.9	4.2
800	5.1	4.3
850	5.4	4.4
900	5.1	4.4
950	5.4	4.3
1000	5.5	4.4

Table 4
Selection efficiencies in % for the signal in the top squark search, estimated from the simulation.

$M_{\tilde{\mathrm{t}}}$ (GeV)	$\mathrm{e}\tau_{\mathrm{h}}$	$\mu\tau_{\mathrm{h}}$
200	0.02	0.02
300	0.3	0.2
400	0.7	0.6
500	1.2	1.0
600	1.5	1.2
700	1.8	1.4
800	1.8	1.3
900	1.5	1.1

An upper bound at 95% confidence level (CL) is set on $\sigma\mathcal{B}^2$, where σ is the cross section for pair production of third-generation LQs (top squarks) and $\mathcal{B}$ is the branching fraction for the LQ decay to a tau lepton and a bottom quark (the top squark decay to a $\tilde{\chi}^{\pm}$ and a bottom quark, with a subsequent decay of the chargino via $\tilde{\chi}^{\pm} \to \tilde{\nu}\tau^{\pm} \to \mathrm{qq}\tau^{\pm}$). The symbol M_{LQ} is used for the leptoquark mass and the symbol $M_{\tilde{\mathrm{t}}}$ is used for the top squark mass. The modified-frequentist construction $\mathrm{CL_s}$ [43–45] is used for the limit calculation. A maximum likelihood fit is performed to the S_{T} spectrum simultaneously for the $\mathrm{e}\tau_{\mathrm{h}}$ and $\mu\tau_{\mathrm{h}}$ channels, taking into account correlations between the systematic uncertainties. Expected and observed upper limits on $\sigma\mathcal{B}^2$ as a function of the signal mass are shown in Fig. 3 for the leptoquark search and Fig. 4 for the top squark search.

We extend the current limits and exclude scalar leptoquarks and top squarks decaying through the coupling λ'_{333} with masses below 740 GeV, in agreement with a limit at 750 GeV, expected in the absence of a signal. We exclude top squarks undergoing a

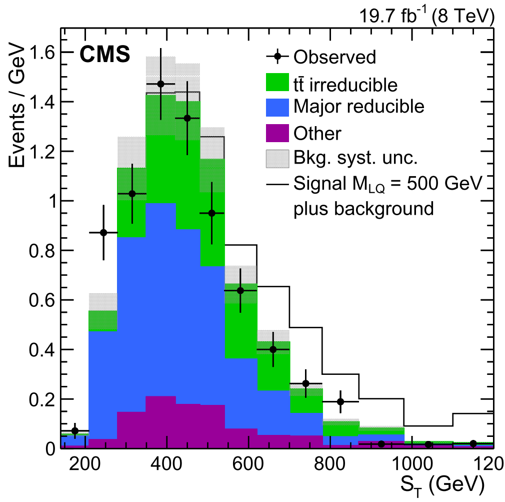

Fig. 1. The final S_T distribution for the leptoquark search with the $e\tau_h$ and $\mu\tau_h$ channels combined. A signal sample for leptoquarks with the mass of 500 GeV is added on top of the background prediction. The last bin contains the overflow events. The horizontal bar on each observed data point indicates the width of the bin in S_T.

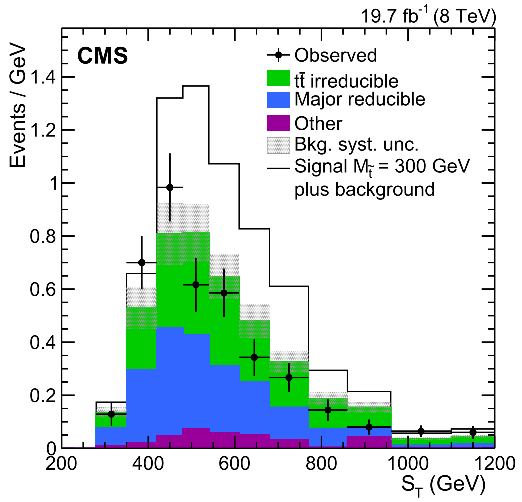

Fig. 2. The final S_T distribution for the top squark search with the $e\tau_h$ and $\mu\tau_h$ channels combined. A signal sample for top squarks with the mass of 300 GeV is added on top of the background prediction. The last bin contains the overflow events. The horizontal bar on each observed data point indicates the width of the bin in S_T.

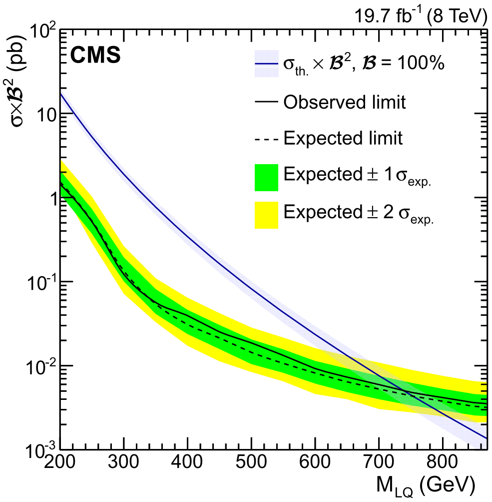

Fig. 3. The expected and observed combined upper limits on the third-generation LQ pair production cross section σ times the square of the branching fraction, $\mathcal{B}^2$, at 95% CL, as a function of the LQ mass. These limits also apply to top squarks decaying directly via the coupling λ'_{333}. The green (darker) and yellow (lighter) uncertainty bands represent 68% and 95% CL intervals on the expected limit. The dark blue curve and the hatched light blue band represent the theoretical LQ pair production cross section, assuming $\mathcal{B} = 100\%$, and the uncertainties due to the choice of PDF and renormalization/factorization scales. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

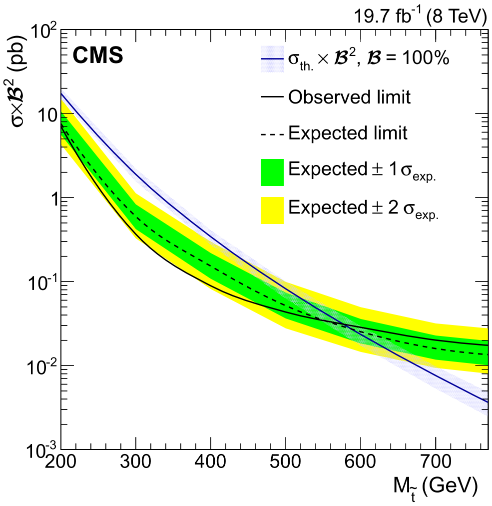

Fig. 4. The expected and observed combined upper limits on the top squark pair production cross section σ times the square of the branching fraction, $\mathcal{B}^2$, at 95% CL, as a function of the top squark mass. These limits apply to top squarks with a chargino-mediated decay through the coupling λ'_{3kj}. The green (darker) and yellow (lighter) uncertainty bands represent 68% and 95% CL intervals on the expected limit. The dark blue curve and the hatched light blue band represent the theoretical top squark pair production cross section, assuming $\mathcal{B} = 100\%$, and the uncertainties due to the choice of PDF and renormalization/factorization scales. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

chargino-mediated decay involving the coupling λ'_{3jk} with masses in the range 200–580 GeV, in agreement with the expected exclusion limit in the range 200–590 GeV. These upper limits assume $\mathcal{B} = 100\%$. Similar results are obtained when calculating upper bounds using a Bayesian method with a uniform positive prior for the cross section.

The upper bounds for the leptoquark search as a function of the leptoquark branching fraction and mass are shown in Fig. 5. Small $\mathcal{B}$ values are not constrained by this search. Results from the CMS experiment on a search for top squarks decaying to a top quark and a neutralino [46] are used to further constrain $\mathcal{B}$. If the neutralino is massless, the final state kinematic distributions for such a signal are the same as those for the pair production of leptoquarks decaying to a tau neutrino and a top quark. Limits can therefore be placed on this signal, which must have a branching fraction of $1 - \mathcal{B}$ if the leptoquark only decays to third-generation fermions. This reinterpretation is included in Fig. 5. The unexcluded region at $M_{LQ} = 200$–230 GeV corresponds to a portion of phase space where it is topologically very difficult to distinguish between the top squark signal and the $t\bar{t}$ process, owing to small missing transverse momentum. A top squark excess in this region would imply an excess in the measured $t\bar{t}$ cross section of $\sim 10\%$.

7. Summary

A search for pair production of third-generation scalar leptoquarks and top squarks has been presented. The search for

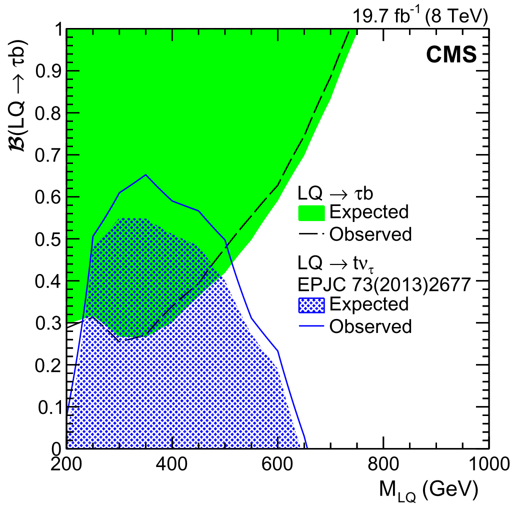

Fig. 5. The expected (dashed black) and observed (green solid) 95% CL upper limits on the branching fraction for the leptoquark decay to a tau lepton and a bottom quark, as a function of the leptoquark mass. A search for top squark pair production [46] has the same kinematic signature as the leptoquark decay to a tau neutrino and a top quark. This search is reinterpreted to provide the expected (blue hatched) and observed (blue open) 95% CL upper limits for low values of $\mathcal{B}$, assuming the leptoquark only decays to third-generation fermions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

leptoquarks and top squarks decaying through the R-parity violating coupling λ'_{333} is performed in final states that include an electron or a muon, a hadronically decaying tau lepton, and at least two jets, at least one of which is b-tagged. The search for top squarks undergoing a chargino-mediated decay involving the R-parity violating coupling λ'_{3jk} is performed in events containing an electron or a muon, a hadronically decaying tau lepton, and at least five jets, at least one of which is b-tagged. No excesses above the standard model background prediction are observed in the S_{T} distributions. Assuming a 100% branching fraction for the decay to a tau lepton and a bottom quark, scalar leptoquarks and top squarks decaying through λ'_{333} with masses below 740 GeV are excluded at 95% confidence level. Top squarks decaying through λ'_{3jk} with masses below 580 GeV are excluded at 95% confidence level, assuming a 100% branching fraction for the decay to a tau lepton, a bottom quark, and two light quarks. The constraint on the third-generation leptoquark mass is the most stringent to date, and this is the first search for top squarks decaying through λ'_{3jk}.

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