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Searches for LFV with CMS: leptoquarks with couplings to quarks of the 3rd generation

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Leptoquarks (LQ) with couplings to the third generation of Standard Model (SM) quarks have been proposed as possible explanations of the flavour anomalies indicating the violation of lepton flavour universality (LFV). The CMS collaboration has initiated an extensive search programme for these new states in the LHC run-2 data recorded at $\sqrt{s} = 13$ TeV. In this article, the CMS search results in the LQ pair-production final states $\tau b\,\tau b$, $\nu t\,\nu t$, $\nu b\,\nu b$, $\tau t\,\tau t$, and $\mu t\,\mu t$, as well as in the LQ single-production final state $\tau\,\tau b$ are discussed. No significant deviation from the SM is observed in any of these channels. For a broad range of LQ decay modes, exclusion limits on the LQ masses are determined at 95% confidence level reaching from 1.0 TeV to 1.8 TeV.

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1. Introduction

While direct searches for new physics at the LHC have not seen any significant deviation from the Standard Model (SM) prediction so far, anomalies in the flavour sector have been reported pointing towards a violation of lepton flavour universality (see e.g. [1, 2, 3] and references therein). In particular, the measurements of rare decays of B mesons by the BABAR, BELLE and LHCb collaborations feature several interesting observations. Among these, the ratios R_D and R_{D^*}, defined as ratios of the branching fractions for $\overline{B} \to D^{(*)}\tau\overline{\nu}$ to those for $\overline{B} \to D^{(*)}\mu\overline{\nu}$ show a deviation with a combined significance of about four standard deviations from the SM prediction (see [3] and references therein). The ratio R_K of the branching fractions for $B \to K^{(*)}\mu\mu$ to those for $B \to K^{(*)}ee$ shows a deviation of 2.6 standard deviations [4].

As a possible explanation for these deviations, leptoquarks (LQ) with couplings to SM quarks of the third generation (b,t) have been proposed (see e.g. [1] and references therein). LQs are hypothetical new scalar (spin $J = 0$) or vector ($J = 1$) particles which decay to a lepton and a quark and carry strong and fractional electromagnetic charges. They appear in many extensions of the SM, like GUT-inspired models, technicolour, compositeness or R-parity violating supersymmetry. Classification of different LQ types is usually performed within the Buchmüller-Rückl-Wyler model [5] depending on their quantum numbers. Often the existence of only three categories of LQs is assumed, each featuring couplings to leptons and quarks of the same SM generation. However, relaxing these coupling restrictions within the constraints on flavour changing neutral currents and other rare processes, would lead to final states with leptons and quarks from different SM generations.

At the LHC, processes of the strong interaction (gluon-gluon fusion or quark-antiquark annihilation) lead to a copious pair-production of LQs resulting in $l^{\pm}ql^{\mp}q$, $l^{\pm}q\nu q'$ and $\nu q'\nu q'$ final states depending on the LQ branching fraction to a quark and a charged lepton, β, or to a quark and a neutrino, $1 - \beta$. The cross-sections of the strong pair-production only depend on the LQ mass M_{LQ} and are independent of the Yukawa coupling λ of the LQ-lepton-quark vertex. Calculations at leading order (LO) and next-to-leading order (NLO) accuracy are available for this production mode for vector and scalar leptoquarks [6, 7], respectively. In general, the single-production of LQs via quark-gluon scattering is suppressed at the LHC for LQs with couplings to third generation quarks, since it requires a heavy quark in the initial state. However, for high values of λ and M_{LQ} the single-production could be sizeable for LQs with couplings to bottom quarks leading to $l^{\pm}l^{\pm}b$, $l^{\pm}\nu b$ and $\nu\nu b$ final states. The cross-section for LQ single-production is dependent on both M_{LQ} and λ.

The CMS collaboration has initiated a broad range of direct searches for the pair-production of LQs with couplings to quarks of the third generation. CMS results based on the LHC run-2 dataset recorded at a centre-of-mass energy of $\sqrt{s} = 13$ TeV are available in the $\tau b \tau b$ [8, 9, 10], $\nu t \nu t$ [11, 12], $\nu b \nu b$ [11, 12], $\tau t \tau t$ [13] and $\mu t \mu t$ [14] final states. In addition, a first search for the single-production of LQs has been performed in the $\tau \tau b$ final state [15]. Results of searches for third generation LQs from LHC run-2 data by the ATLAS collaboration are not yet available.

## 2. CMS searches for leptoquarks with couplings to 3rd generation quarks

In the following subsections a short introduction to the CMS results of direct searches for LQs with couplings to 3rd generation quarks is given. For more details on the physics background, on the data analysis, on the results, on the physics interpretation, as well as for a more complete list of references, the reader is referred to the original CMS publications. Unless stated otherwise, all results discussed in this review are based on a dataset of LHC pp collisions at $\sqrt{s} = 13$ TeV recorded by the CMS experiment [16] in 2016, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$.

2.1 LQ pair-production in $\nu j \,\nu j$, $\nu b \,\nu b$ and $\nu t \,\nu t$ final states

For the study of LQ pair-production in $\nu j \,\nu j$, $\nu b \,\nu b$, and $\nu t \,\nu t$ final states, the CMS collaboration uses the results of an analysis [11] searching for the SUSY pair-production of squarks in the decay channel $\tilde{q}\tilde{q} \to \chi_1^0 q \chi_1^0 q$ using events with jets and significant transverse momentum imbalance, as inferred through the M_{T2} variable. The analysis makes use of 213 exclusive search regions to cover a broad range of new physics scenarios and masses. Recently, the search results have been reinterpreted [12] for the study of LQ pair-production scenarios ($\text{LQ}\overline{\text{LQ}} \to \nu q \,\nu q$). In Fig. 1 (left) the distribution of the M_{T_2} variable is shown in a signal region with particular strong sensitivity for the LQ signal. The analysis does not show any significant deviation from the SM expectation which has been estimated from dedicated data control regions. Exclusion limits at 95% confidence level (CL) on the LQ pair-production cross-section have been determined for LQ decays to all quark flavours. The kinematic differences of the pair-production between scalar and vector LQs have been found to be within the assumed uncertainties. The exclusion limits on the production cross-section as observed and expected for the LQ decay into νt are shown in Fig. 1 (right) compared to three signal models of scalar and vector LQs. For $\beta = 0$, i.e. for LQs decaying exclusively into the νq channel, scalar (vector) LQs are excluded up to $M_{\text{LQ}} = 980/1100/1020$ GeV (1790/1810/1780 GeV) for $q = udsc/b/t$ respectively.

2.2 LQ pair-production in $\tau t \tau t$ final states

In the CMS search for the pair-production of LQs with decays into top quarks and τ leptons in the LHC run-2 dataset [13] events are selected with at least one electron or muon (denoted as l), at least one hadronically decaying τ lepton (denoted as τ_h), and additional hadronic jets. The first analysis of this LQ decay channel has been performed by the CMS collaboration using LHC data recorded at $\sqrt{s} = 8$ TeV [17] leading to a 95% CL exclusion limit on the leptoquark mass of 685 GeV assuming unit branching fraction into τt. For the data recorded at $\sqrt{s} = 13$ GeV, the analysis had to be changed significantly due to different background contributions and relative impact of systematic uncertainties. For a maximum expected significance for a hypothetical LQ signal, the run-2 analysis splits the event sample into 10 exclusive categories according to the number of τ_h candidates, $N(\tau_\text{h})$, the relative l/τ_h charges (OS, SS) and the value of S_T, defined as the scalar sum of the transverse momenta of all selected leptons, jets and missing transverse momentum. In all categories a considerable fraction of events is selected in which jets are misidentified as τ_h candidates. For the estimation of this contribution in $t\bar{t}$ and W+jets events, a sophisticated data-driven method is employed depending on the category.
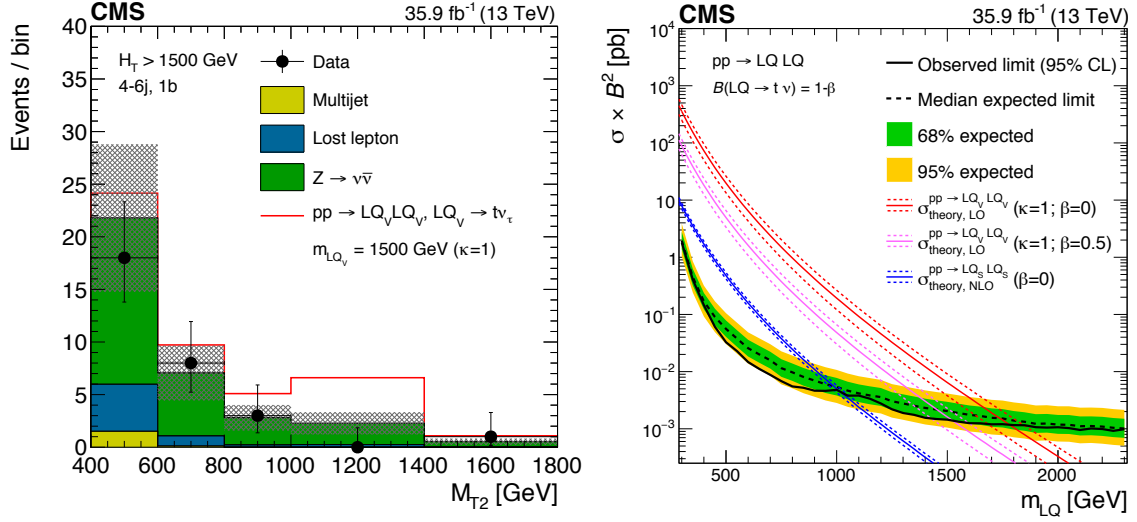
Figure 1: Reinterpretation of a CMS search for squarks and gluinos to constrain LQ modes [11, 12]: (left) observed distribution of the M_{T_2} variable compared to the expectation from SM background processes and a hypothetical LQ signal (stacked on top of the background expectation) assuming a mass of $M_{LQ} = 1500$ GeV; (right) exclusion limits at 95% CL on the production cross section as a function of the LQ mass for pair-production of LQs decaying with unit branching fraction to a neutrino and a top quark.

Since only a small number of events is selected with $N(\tau_h) \geq 2$, simple counting experiments are performed for the corresponding two (e or μ) signal categories. In the electron channel 9 events are observed in the data, while $7.9^{+2.4}_{-2.5}$ are expected from SM background processes. In the muon channel 11 events are observed in the data, while $8.4^{+2.6}_{-2.3}$ are expected. In the eight remaining signal categories with $N(\tau_h) = 1$, the four-momentum of an hadronically decaying top quark is reconstructed and the distribution of its transverse momentum (p_T^t) is used in a statistical analysis of the shape observed in the data and expected for the SM backgrounds and the LQ signal. An example p_T^t distribution in one of the most sensitive categories is shown in Fig. 2 (left).

No significant deviation from the background expectation is found in any of the 10 signal categories and exclusion limits at 95% CL have been obtained from a binned maximum likelihood (ML) fit. Assuming a unit braching fraction of the LQs into τt, masses of scalar leptoquarks are excluded up to 900 GeV. The results of this search have been combined with a CMS search for the SUSY pair-production of scalar sbottom quarks in the decay mode $\tilde{b}\tilde{b} \rightarrow \chi_1^0 b \chi_1^0 b$ ([11], see Sect. 2.1) which can be interpreted as a search for LQ pair-production in the decay mode $LQ\overline{LQ} \rightarrow \nu b \nu b$ representing the complementary LQ decay channel which opens for branching fractions smaller than 1. In Fig. 2 (right) the upper exclusion limits on the pair-production cross-section for scalar LQs obtained from this combination is shown in the (mass, branching fraction)-plane. For all values of the branching fraction, masses of scalar LQs are excluded up to 800 GeV.

2.3 LQ pair-production in $\mu t \mu t$ final states

The CMS search for LQ pair-production in the decay mode $\mu t \mu t$ in the run-2 dataset [14] represents the first search for this LQ type which could provide a simultaneous explanation of deviations in $R_{D^{(*)}}$, R_K, and the anomalous magnetic moment of the muon (see list of references in
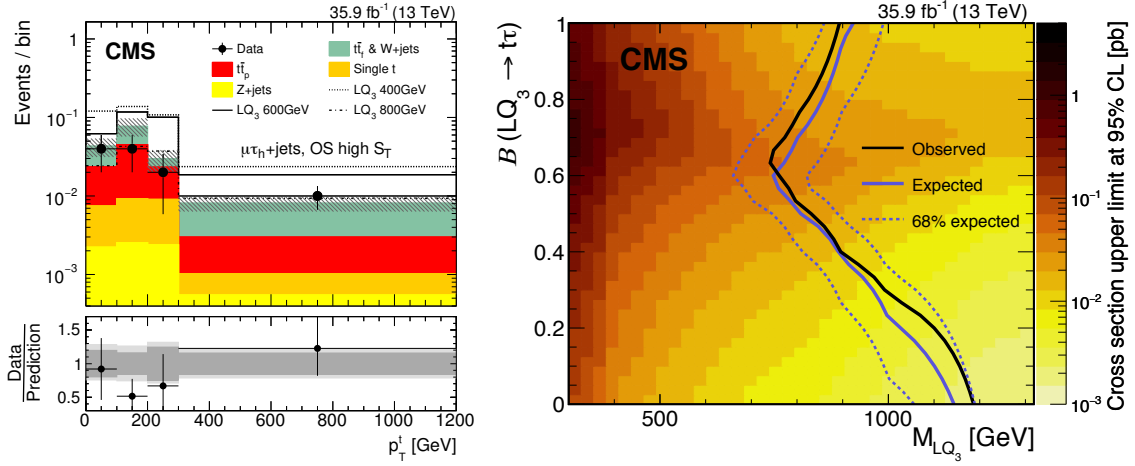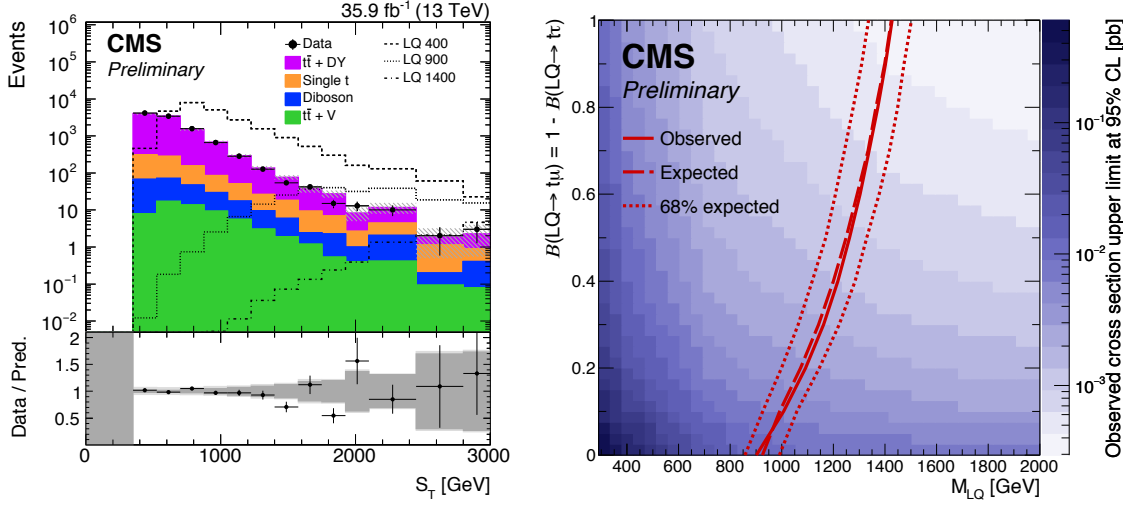
Figure 2: Search for pair-produced LQs with decays to a top quark and a τ lepton [13]: (left) distribution of the transverse momentum of the top quark candidate in one of the 10 categories considered in the analysis; (right) upper exclusion limits at 95% CL on the production cross section for pair-production of scalar LQs decaying into a top quark and a τ lepton ($B = 1$) or a bottom quark and a neutrino ($B = 0$) in the (M_{LQ}, B)-plane. The solid black (blue) line shows the observed (expected) mass exclusion limits. The plot additionally includes results from a search for pair-produced bottom squarks [11].

[14]). Events with at least two muons and at least two hadronic jets are split into two exclusive signal categories to obtain sensitivity for a broad range of LQ masses. For events with an additional electron or muon, the mass of the LQ can be reconstructed using permutations of jets and lepton candidates which best fit the decay hypothesis for the considered LQ mode. Since the reconstructed average LQ mass (M_{LQ}^{rec}) shows strong discrimination power between signal and SM background, its distribution has been used for the final statistical interpretation in this category. No significant deviation from the SM expectation has been observed in this category which features a particularly strong sensitivity for smaller LQ masses. An improved significance at higher LQ masses is expected for the remaining events (i.e. those without additional lepton). In this category, the spectrum of S_T, shown in Fig. 3 (left), was chosen for the statistical interpretation. Again, a significant deviation from the SM expectation has not been observed. In both categories, the contribution of SM background processes has been estimated using sophisticated data-driven methods.

Exclusion limits on the LQ pair-production cross-section have been obtained from simultaneous fits of the M_{LQ}^{rec} and S_T distributions. Assuming unit LQ branching fraction into μt, scalar LQs with masses up to 1420 GeV can be excluded. In addition, the analysis results have been combined with the analyses of the τt [13] and the νb [11] decay modes. An example for the resulting limits on the pair-production cross-section of scalar LQs in the (mass, branching fraction)-plane is shown in Fig. 3 (right). Scalar LQs with masses up to 900 GeV are excluded at the 95% CL for all values of the branching fractions into μt, τt and νb (not shown).

2.4 LQ pair-production in $\tau b \tau b$ final states

For the search for LQ pair-production in the $\tau b \tau b$ final state, several results have been published by the CMS collaboration based on different subsets of the LHC run-2 data at $\sqrt{s} = 13$ TeV. An analysis [8] of the dataset recorded in 2015 (2.1 fb^{-1}) in the $\tau_h b \tau_h b$ channel has found no sig-

Figure 3: Search for pair-produced LQs with decays to a top quark and a muon [13]: (left) observed S_T distribution compared to the post-fit expectations from SM background processes and hypothetical LQ signals assuming three different LQ masses; (right) upper exclusion limits at 95% CL on the production cross section for pair-production of scalar LQs decaying into a top quark and a muon ($B = 1$) or a top quark and a τ lepton ($B = 0$) in the (M_{LQ}, B)-plane. The solid (dashed) line shows the observed (expected) mass exclusion limits. The plot additionally includes results from the search for pair-produced LQs with decays to top quarks and τ leptons [13].

nificant deviation from the SM expectation and has resulted in an initial 95% CL mass exclusion limit for scalar LQs of 740 GeV for unit branching fraction of the LQ into τb.

A subset of the full 2016 CMS dataset, corresponding to a reduced integrated luminosity of only 12.9 fb^{-1}, has been analysed in the $\tau_l b \tau_h b$ channel [9]. The analysis relies on a binned ML fit of the S_T distributions in the $e\tau_h$ and $\mu\tau_h$ channels. The latter is shown in Fig. 4 (left) for illustration. No significant deviation from the SM expectation is observed and exclusion limits on the LQ pair-production cross-section are obtained as a function of M_{LQ} and β. A comparison with the theory cross-section [7] provides excluded regions in the (M_{LQ}, β)-plane as shown in Fig. 4 (right). The mass limit of 850 GeV for $\beta = 1$ is degraded for lower values of β since information in the complementary $\nu t \nu t$ channel has not been included in this analysis at the time of publication. However, the corresponding mass limit for $\beta = 0$ from the CMS analysis discussed in Sect. 2.1 has been determined to be $M_{LQ} = 1020$ GeV [12].

The results in the $\tau b \tau b$ final state have been updated during the course of this conference [10] using the full 2016 dataset of 35.9 fb^{-1}. The updated result provides an observed (expected) exclusion limit on the mass of scalar LQs of 1.02 (1.0) TeV, assuming a 100 % branching fraction for the leptoquark decay into τb. These results represent the most stringent limits in this decay channel to date.

2.5 Single LQ production in $\tau + \tau b$ final states

For LQs with couplings to third generation quarks, as considered in this article, the single LQ production mode via gluon-quark scattering is suppressed as it requires a bottom or top quark in
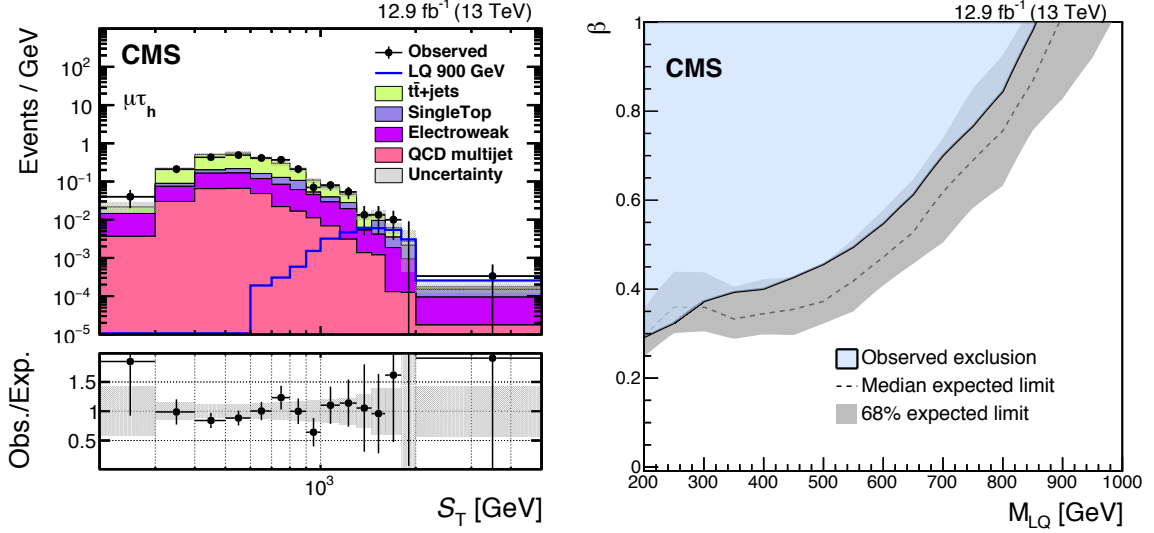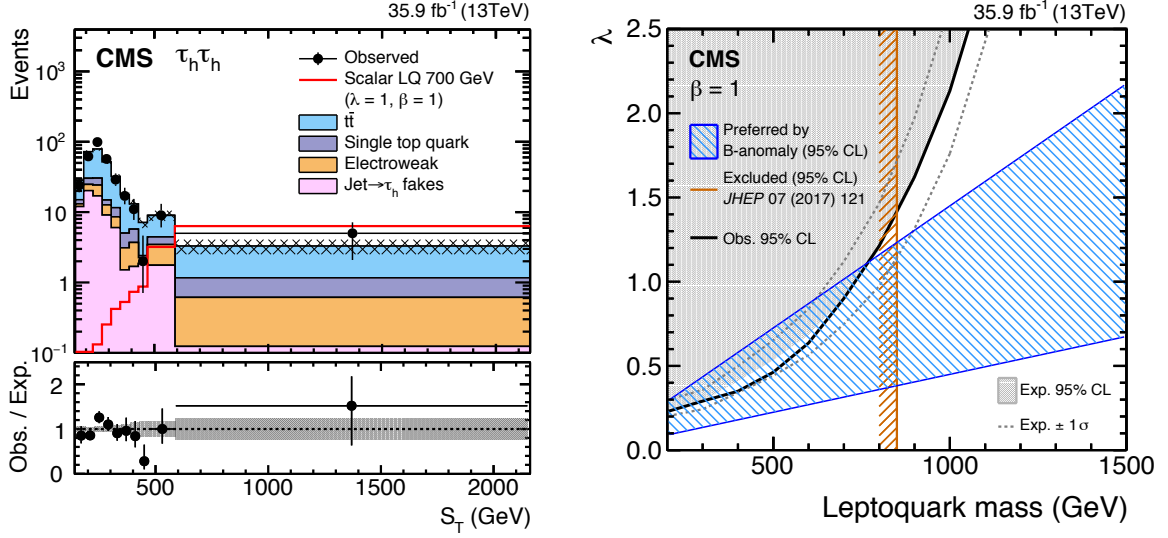
Figure 4: Search for pair-produced LQs with couplings to τ leptons and bottom quarks [9]: (left) observed S_T distribution in the $\mu\tau_h$ channel compared to the expectation from SM background processes and a hypothetical LQ signal assuming a mass of $M_{LQ} = 900$ GeV; (right) exclusion limits at 95% CL on the branching fraction β of the LQ to a τ lepton and a bottom quark as a function of the LQ mass.

the initial state. For this reason, the single-production cross-section for LQs with couplings to top quarks is negligibly small at the LHC. However, since the cross-section depends on the Yukawa coupling λ at the LQ-lepton-quark vertex, it could be sizable for high values of λ for LQs with couplings to bottom quarks. The CMS collaboration has performed a search for singly produced LQs decaying to a τ lepton and a bottom quark by studying the associated production of the LQ and a τ lepton [15] and compared the results with theory predictions designed to provide an explanation for the observed anomalies in the *B*-sector [18].

The analysis makes use of events with two τ candidates and at least one *b*-tagged hadronic jet. Three categories are studied: $\tau_h\tau_h$, $e\tau_h$, and $\mu\tau_h$, among which $\tau_h\tau_h$ provides the highest sensitivity. An additional $e\mu$ category is used to constrain the dominant $t\bar{t}$ background contribution in a binned ML fit of the S_T distributions which is performed as statistical test. An example S_T distribution of the most sensitive category is shown in Fig. 5 (left). No significant deviation from the SM expectation is observed in any of the categories and exclusion limits on the cross-section as a function of λ, β and M_{LQ} can be determined and compared to the theory prediction. The region excluded at 95% CL for scalar LQs and $\beta = 1$ is shown in Fig. 5 (right) in the (M_{LQ}, λ)-plane. The analysis is able to exclude the region of high values of λ at small M_{LQ}, while the CMS limit from LQ pair-production in the $\tau b \tau b$ mode [9] (see Sect. 2.4) excludes the region with $M_{LQ} < 850$ GeV for all values of λ as indicated in the figure. In the meantime, the $\tau b \tau b$ pair-production limit has been improved by CMS to $M_{LQ} < 1020$ GeV [10]. The CMS analyses exclude a significant part of the parameter space which has been identified as a possible explanation for the *B*-anomalies [18] shown by the hatched area.

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Figure 5: Search for singly produced LQs with couplings to τ leptons and bottom quarks [15]: (left) observed S_T distribution in the $\tau_h\tau_h$ signal region compared to the expectation from SM background processes and example signal contributions assuming a unit Yukawa coupling $\lambda = 1$ at the LQ-lepton-quark vertex and a unit branching fraction $\beta = 1$ of the LQ to a τ lepton and a bottom quark; (right) exclusion limits at 95% CL on the Yukawa coupling λ as a function of the LQ mass assuming $\beta = 1$.

3. Summary

Since models of leptoquarks with couplings to the third generation of SM quarks could provide a possible explanation of the anomalies observed in the flavour sector, the CMS collaboration has performed a broad range of different searches for the production of these states using the LHC run-2 dataset. The data are in agreement with the SM prediction. Certain parameter regions can be excluded which have been identified as a possible explanation for the flavour anomalies. Exclusion limits on masses of the leptoquark states in the region of 1.0 TeV and 1.8 TeV have been obtained. With future CMS datasets expected for the high-luminosity phase of the LHC (HL-LHC, $3000\,\mathrm{fb}^{-1}$), an increase of the accessible LQ mass range of about $500\,\mathrm{GeV}$ is expected.

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