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Search for lepton flavour violating decays involving tau leptons in the final state at CMS

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Abstract

In the Standard Model (SM) lepton flavour numbers are approximately conserved at energies accessible to current experiments, where lepton flavour violation is extremely suppressed. The observation of neutrino oscillations, however, proves that neutrinos are massive particles and allows for additional Lepton Flavour Violating (LFV) processes also at low energies. Nevertheless, these processes are predicted with very low branching ratios and are sensitive to new physics effects, which could manifest as an enhancement in the decay probability. Similarly, Lepton Flavour Universality Violating (LFUV) observables allows for the test of the SM and the study of beyond the SM theories. The latest CMS results from the Higgs, B-physics and exotica groups are presented on the search for LFV and LFUV with tau leptons in the final state. The results are based on data collected in proton-proton collisions at the centre-of-mass energy of 13 TeV.

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1 Introduction

This proceeding outlines the searches for Lepton Flavour Violating (LFV) and Lepton Flavour Universality (LFU) violating decays involving tau leptons in the final state, made by the CMS [1] Collaboration with proton-proton collision data collected at the centre-of-mass energy of 13 TeV, covering a wide range of the experiment acceptance region.

2 Search for the lepton flavour violating $\tau \to 3\mu$ decay

The neutrino-less $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ decay, predicted with a probability of $O(10^{-55})$ [2], represent a golden channel for LFV searches at CMS due to its clear final state and the abundance of τ leptons produced in proton-proton collisions. The $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ decay has been searched at

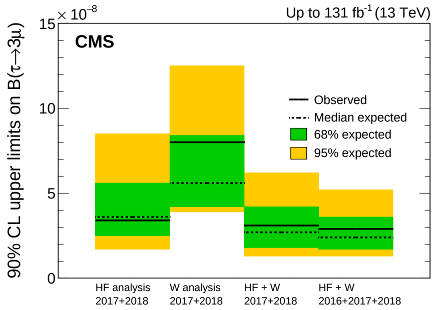

Figure 1: Observed (full black line) and expected (dashed black line) upper limits at 90% of confidence level obtained for the 2017-2018 HF and W analyses, their combination and their combination with the 2016 analysis. The 68% and 95% confidence intervals of the expected upper limits are shown with green and yellow bands, respectively [7].

hadron and electron-positron asymmetric colliders and the most stringent value on its branching fraction is set by the Belle collaboration at 2.1×10^{-8} at 90% confidence level (CL) [3]. At the LHC, the decay has been searched by the LHCb and ATLAS experiments, which obtained an upper limit of 4.6×10^{-8} at 90% CL [4] and 3.76×10^{-7} at 90% CL [5], respectively. The CMS experiment has searched for $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ events in proton-proton collisions at the centre-of-mass energy of 13 TeV using 2016 data (33 fb^{-1}), obtaining an upper limit on the $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ branching fraction equal to 8.0×10^{-8} at 90% CL [6]. The analysis presented in this section extends the CMS result to the full Run-2 data taking era (from 2016 to 2018, corresponding to 131 fb^{-1}) [7].

In proton proton collisions, τ leptons are mostly produced via heavy hadron decays, where the D_s channel is dominant and is estimated by simulations [8,9] to be about 70% of the total τ lepton production. The final state of $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ events produced in heavy flavour (HF) decays is characterized by soft muons, a non negligible misidentified muon contamination, and a large hadron activity surrounding the outgoing muon tracks. Instead, τ leptons produced via W boson decays contribute only to a small part of the τ production, more than a factor 1000 lower with respect to HF. However, the central production, the harder spectrum of the final state, the low hadron activity surrounding signal events and the large missing transverse momentum originated from the neutrino offer a better handle for background rejection and make the sensitivity of the W channel comparable to the HF one. Signal candidates are identified among events with three muons with a displaced secondary vertex. To reduce the contamination from pions and kaons misidentified as muons, quality requirements are imposed on the signal muon tracks. The background contamination, mostly originated by the semileptonic decays of D mesons and from combinatorial three-muon events, is mitigated using Boosted Decision Tree (BDT) discriminators, trained separately for each τ production channel using data events lying outside the signal region and simulated signal events. The signal strength is extracted with an unbinned maximum likelihood fit to the three muon invariant mass distribution of the events selected by the BDT's. Data from the 2016 analysis are included in the fit. No evidence of signal is found and an observed (expected) upper limit is set on the $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ branching fraction to 2.9 (2.4) $\times10^{-8}$ at 90% CL. Figure 1 shows the observed and expected upper limits for the 2017 and 2018 data analysis in the HF and W channels, and their combination with the 2016 data analysis.

Table 1: Expected (observed) upper limits at 95% confidence level on BSM particle masses for tau sneutrinos [19], Z' [20] and QBH [21–24] models. For sneutrinos, two reference values are assumed for the production (via quark-quark interaction) and decay couplings (λ =λ'=0.1 or λ =λ'=0.01). For the Z', a LFV branching fraction of 0.1 is assumed. For QBH, the ADD model with dimension 4 is assumed and the value reported is intended as a lower limit on the QBH threshold mass [10].

Channel	RPV SUSY $\tilde{\nu}_\tau$ (TeV)		LFV Z' (TeV)	QBH (TeV)
	λ=λ'=0.1	λ=λ'=0.01	B=0.1	n=4
eμ	2.2 (2.2)	4.2 (4.2)	5.0 (4.9)	5.6 (5.6)
eτ	1.6 (1.6)	3.7 (3.7)	4.3 (4.3)	5.2 (5.2)
$\mu\tau$	1.6 (1.6)	3.6 (3.7)	4.1 (4.2)	5.0 (5.0)

3 Search for heavy resonances and quantum black holes in the eμ, eτ and $\mu\tau$ final stastes

New physics may introduce LFV couplings to Standard Model (SM) particles, providing a clear and strong signature for experimental detection. This section describes the search for Beyond the SM (BSM) heavy resonances performed by the CMS Collaboration using proton-proton collision data collected at the centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1} [10]. Similar searches have been performed by the CDF [11] and D0 experiments [12] at the Fermilab Tevatron and by the ATLAS [13–15] and CMS [16,17] experiments at the CERN LHC. The analysis selects final states composed of two isolated leptons, eμ, eτ and $\mu\tau$. Only hadronic decays of the τ lepton are considered and the misidentified τ lepton rate, originating from jets, electrons and muons, is reduced by mean of a convolutional neural network [18]. Background events are mostly originated from $t\bar{t}$ events and multi-jet events, whose abbundance is estimated from simulation and data control regions, respectively. The signal strength is extracted from a fit to the invariant mass distribution of the final state leptons, computed under the hypothesis of collinearity between the τ lepton and its decay products for the eτ and $\mu\tau$ channels. The result is interpreted under different BSM models, including tau sneutrinos from R-violating supersymmetric models [19], LFV couplings of heavy Z' gauge bosons [20] and quantum black holes (QBH) from the dimension-4 ADD model [21–24]. No signal evidence is observed and upper limits are computed as a function of the BSM particle mass. Figure 2 shows the results for the $\mu\tau$ final state as an example. Table 1 shows the lower limits on the BSM candidate masses computed assuming reference values for the corresponding production and decay models. The analysis also offers a model-independent interpretation of the experimental data, obtained reducing the final state mass distribution to a single-bin distribution (above a threshold m_{min}) and assuming a flat acceptance above the threshold mass. Figure 3 shows the upper limit obtained as a function of the threshold mass m^{min} for the three different final states. Model dependent results can be obtained dividing the model-independent result by the fraction of events above m_{min} for the BSM model under test.

4 Search for lepton flavour violating decays of the Higgs boson in the eτ and $\mu\tau$ final states

Searches for LFV decays of the Higgs boson provide a good testing ground for BSM models, including models with more than one Higgs boson [25], supersymmetric models [26], composite Higgs models [27] or the Randall-Sundrum model of extra spatial dimensions [28].

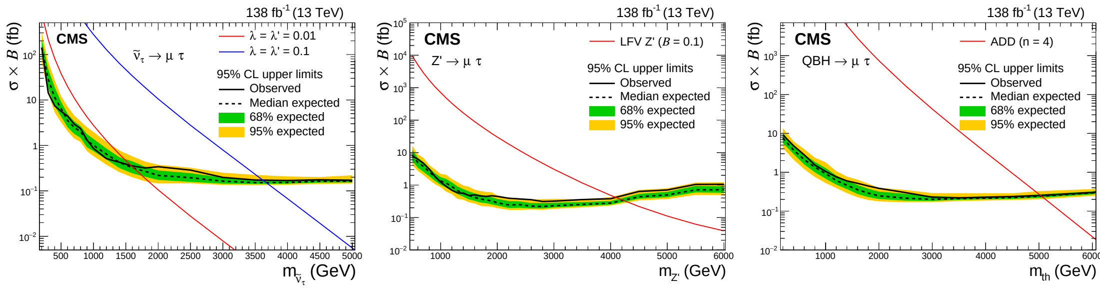

Figure 2: Expected and observed upper limits for $\mu\tau$ production via sneutrinos (left), Z' (center) and QBH (right) decay as a function of the BSM particle mass. Red and blue lines shows the value predicted by the BSM models assuming the reference values also listed in Tab. 1 [10].

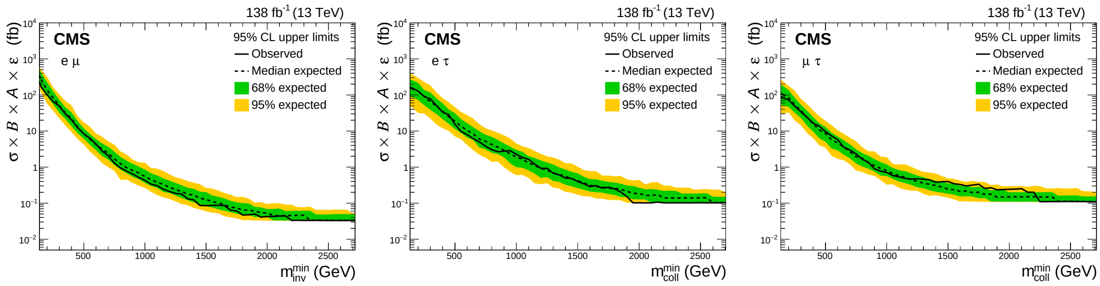

Figure 3: Expected and observed upper limits as a function of the mass threshold value m^{min} used to derive model-independent results for $e\mu$, $e\tau$, $\mu\tau$ production [10].

This section describes the search for LFV Higgs decays into leptons in CMS proton-proton collision data at 13 TeV (137 fb^{-1}) [29]. Similar searches have already been made by the ATLAS [30] and CMS [31] experiments. Events are selected in the $e\tau$ and $\mu\tau$ final states and tau leptons are only reconstructed in their hadronic decay modes and decaying into muons (for the eτ channel) or into electrons (for the $\mu\tau$ channel) to reduce the background from $Z \to l^+l^-$. The largest background contamination arises from W+jets and QCD mulit-jet events, where one or two jets are misidentified as leptons. The misidentified background is reduced imposing isolation requirements on the signal leptons and its magnitude is estimated using background-enriched data regions. Other background contributions (mostly $Z \to \tau^+\tau^-$, di-boson and $t\bar{t}$) are estimated from simulations or embedded techniques [32]. A BDT is trained for each analysis category using kinematic and topological observables and the signal strength is extracted with a binned maximum likelihood fit to the BDT score distributions. Figure 4 shows the distribution of the BDT score for the $\mu\tau_h$ 0-jet category of the analysis as an example. No significant excess of events is found and observed (expected) upper limits are set using the modified frequentist approach for CL_s [33] to $\mathcal{B}(H \to e\mu) <$ 0.15 (0.15)% and $\mathcal{B}(H \to \mu\tau) <$ 0.22 (0.16)%. The results are interpreted as exclusion limits on the Yukawa LFV couplings.

$$\sqrt{Y_{e\tau}^2 + Y_{\tau e}^2} < 1.35 \times 10^{-3}\,,$$
$$\sqrt{Y_{\mu\tau}^2 + Y_{\tau\mu}^2} < 1.11 \times 10^{-3}\,.$$

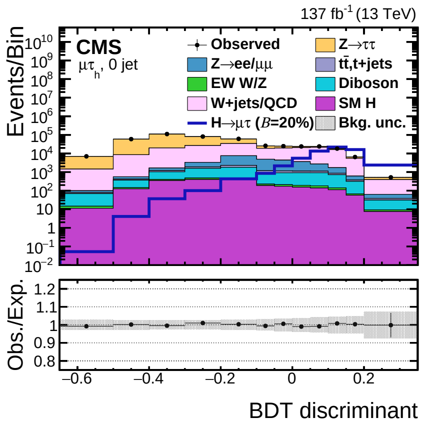

Figure 4: BDT score distribution for the $\mu\tau_h$ 0-jet category [29].

5 Test of lepton flavour universality violation in semileptonic B_c^+ meson decays

In the SM, lepton copuplings to electroweak bosons are identical. Semileptonic decays of B mesons are mediated by W bosons, and the difference of the leptonic final states probabilities is only due to the different lepton mass values. These ratios can be computed with high precision and a deviation from the predicted value would be an indication of new physics. Several models which allows for lepton flavour universality violation exists [34–37], but no significant evidence of such processes has been found by experiments. The semileptonic decays of B_c^+ mesons offer an unique opportunity for LFU tests at hadronic colliders, as B_c^+ mesons cannot be produced at B-factories operating at the Υ's energies. The so-called $R_{J/\psi}$ ratio, defined in Eq 1, has been measured by the LHCb Collaboration, which reported a deviation from the SM prediction of 2 standard deviations [38]

$$R_{J/\psi} = \frac{\mathcal{B}(B_c^+ \to J/\psi\ \tau^+\ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\ \mu^+\ \nu_\mu)} = 0.2582\ (\mathrm{SM})\,. \tag{1}$$

The CMS Collaboration has meaured this ratio using proton-proton collision data at the centre-of-mass energy of 13 TeV, collected during 2018 (59.9 fb^{-1}) [39]. The measured value is compatible with the standard model within the experimental uncertainty, and the data analysis is described in this section. Only final states where the J/ψ meson decays into two muons and the τ lepton decays into a muon and two neutrinos are considered. The contribution of the two signal channels is decoupled with a binned maximum likelihood fit to the q^2 observable, defined as the square difference of the B_c^+ and J/ψ momenta (computed under the hypothesis of collinearity between the B_c^+ and the final state), and the distribution of the secondary vertex displacement significance from the primary vertex, computed in the plane transverse to the beam line (L_{xy}/σ_{xy}). The main background contamination comes from semileptonic decays of b-hadrons involving misidentified kaons or pions, reduced using muon track quality requirements and modeled from data control regions. Other background sources include feed-down decays of B_c^+ mesons and decays of other b-hadrons, both estimated using Monte Carlo simulations. Combinatorial events (events where the signal muons do not originate from a common process) are extrapolated from data control regions. Background-only control regions are used to constrain the background normalizations. The q^2 and $L_{xy}/\sigma_{L_{xy}}$ distribution for signal and background simulated events, as well as for collision data, is shown in Fig.5 for events in signal enriched regions. The fitted value of $R_{J/\psi}$ is $0.17^{+0.18}_{-0.17}(\mathrm{stat})^{+0.21}_{-0.22}(\mathrm{syst})^{+0.19}_{-0.18}(\mathrm{theo})$. The leading systematic uncertainties include the misidentified muon estimation (11.3%), the finite size

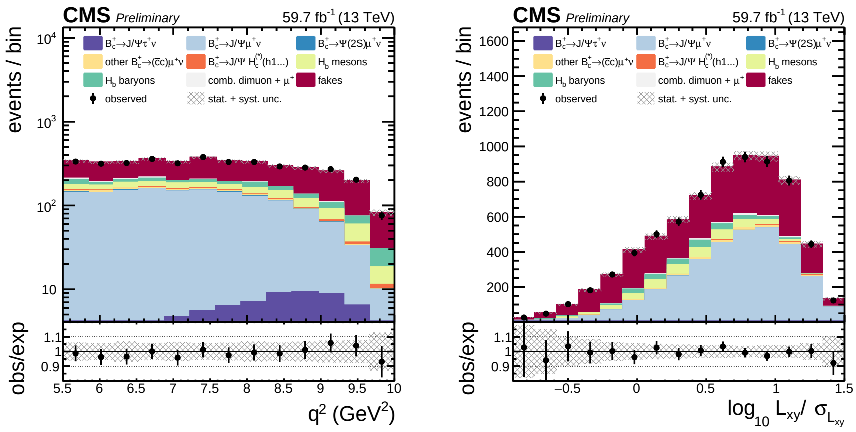

Figure 5: Left: distribution of the q^2 observable in the signal-enriched data region, defined by $m(3\mu) < m_{B_c^+}$, $q^2 > 5.5$ GeV ^{2} and IP3D/$\sigma_{IP3D} > 2$ (IP3D being the secondary vertex displacement from the primary vertex and σ_{IP3D} its uncertainty). Right: distribution the $L_{xy}/\sigma_{L_{xy}}$ observable in the signal-enriched data region, defined by $m(3\mu) < m_{B_c^+}$, $q^2 < 4.5$ GeV ^{2} and IP3D/$\sigma_{IP3D} > 0$. Data events are shown with black dots, different simulated contributions are shown with stacked histograms [39].

of the simulated samples (5.3%) and corrections to the simulated observables (4.4%). The theoretical uncertainty comes from the knowledge of B-hadron form factors.

6 Summary

This proceeding has highlighted the important role of the CMS experiment in exploring BSM physics, specifically in investigating lepton-flavour and lepton-universality violating decays with a focus on τ leptons. The CMS experiment has made significant contributions in studying high-mass observables of the Higgs boson [29] and exotic particles [10], as well as in analyzing low-momentum observables of heavy hadrons and lepton decays [7,39]. The results obtained from these searches are promising and point towards exciting possibilities for future research during the ongoing data collection and upcoming high-luminosity era.

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