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Searches for new physics that couple with third generation fermions

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Abstract

The τ lepton, with a mass of 1776.86 ± 0.12 MeV, is unique in its ability to decay into hadrons and a neutrino. Approximately one-third of τ decays produce an electron or a muon and two neutrinos, denoted as τ_e and τ_μ. The remaining decays, mainly involving hadrons and a tau neutrino, are denoted as τ_h. At the CERN LHC, searches involving τ leptons are crucial for studying the decay of Higgs bosons to τ pairs, probing Yukawa couplings, and CP properties of the Higgs. These measurements support Standard Model (SM) tests and searches for Beyond Standard Model (BSM) physics, including new or heavy Higgs bosons, leptoquarks, supersymmetric particles, or gauge bosons. The τ lepton polarization in Z boson decays is also significant for probing the SM. Despite its potential as a portal to new physics, the τ lepton's decay products, especially neutrinos and hadrons, make its reconstruction and identification challenging at the LHC. At the CMS experiment, neutrinos contribute to Missing Transverse Energy (MET), and hadronically decaying τ leptons are often misidentified as jets, complicating the separation of τ -involved processes from background processes.

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1 The CMS experiment

The CMS experiment is a general-purpose detector with cylindrical symmetry and a layered structure, located at one of the LHC collision points (IP5) in Cessy, France. The detector is 21.6 m long, has a diameter of 14.6 m, and weighs 12.500 t. It is designed to study proton-proton and lead-lead collisions at center-of-mass energies up to 14 TeV and 5.5 TeV, respectively, with luminosities up to $10^{34}\text{cm}^{-2}\text{s}^{-1}$ (proton-proton) and $10^{27}\text{cm}^{-2}\text{s}^{-1}$ (lead-lead). The CMS detector features a high-magnetic-field, large-bore superconducting solenoid, and includes an all-silicon pixel and strip tracker, a lead-tungstate scintillating-crystals electromagnetic calorimeter, a brass-scintillator sampling hadron calorimeter, and muon detectors covering most of the 4π solid angle. Forward sampling calorimeters ensure hermeticity. The CMS detector features a two-layered trigger system, which, together with the Data Acquisition System (DAQ), manages the collision rate of 40 MHz and balances it with storage capabilities. It reduces approximately 1 billion interactions per second to about 1000 events per second for storage and analysis. The CMS Trigger has two levels: **L1 Trigger**: implemented in customized hardware boards, it selects events using information from calorimeters and muon systems to identify particle candidates lowering the rate from 40 MHz to 100 kHz ; the **High Level Trigger (HLT)**: implemented in software, it further refines the event selection, lowering the rate to $\sim$ 1 kHz for offline storage.

2 Search for new physics in the τ lepton plus missing transverse momentum final state

A search for new physics in the τ and neutrino[1] final states performed using proton-proton collision data collected by the CMS experiment during Run 2, at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, for a total integrated luminosity of 138 fb^{-1}. The analysis employs a binned-likelihood method to analyze the shape of the distribution of transverse mass (m_T), the mass of the visible tau lepton and the missing momentum in the transverse plane with respect to the beam, for different model scenarios. Upper exclusion limits are determined for the cross section times branching fraction ($\sigma \times B$) for the production of sequential SM-like heavy charged vector boson (W') within the Sequential Standard Model (SSM) theory, a Quantum Black Hole (QBH) models, a LeptoQuark (LQ) and on the values of Wilson coefficients in the Effective Field Theory (EFT) description. Furthermore, a model-independent approach to limit-setting is examined and deliberated. All the considered signals have a similar structure in terms of final state: considering a signature $X \to \tau + \nu_\tau \to \tau$ +MET, the final state will contain one (hadronic) tau and missing transverse momentum, expecting back-to-back kinematics and balanced in p_T. Therefore a relevant observable is the transverse mass, m_T, which is used for the final fit. The primary background contribution originates from off-shell W boson production, which is irreducible, having the same signature as signal, followed by events featuring misidentified τ originating by different mechanisms as the production of $t\bar{t}$ pairs, single top, di-boson and QCD with many jets in the final state. Backgrounds from misidentified jets are calculated with a data driven method. The Full Run 2 distribution of hadronically decaying τ lepton events with missing transverse momentum considering the is shown in Fig. 1.

2.1 Results

In Fig. 2 exclusion limits at the 95% confidence level are shown for different model-dependent and for model-independent interpretations, and they are summarized in Tab. 1. No significant deviation from the SM expectations is observed. In particular, for the first time, upper limits are placed on the cross section of the $pp \to \tau\nu$ process mediated by t-channel LQ exchange. The limits obtained for the various interpretations presented are the most stringent to date [1].

[1]Neutrinos escape undetected from the CMS detector, and their kinematics can be related to the missing part of energy balance in the transverse plane (MET), or, equivalently, the missing momentum in the transverse plane

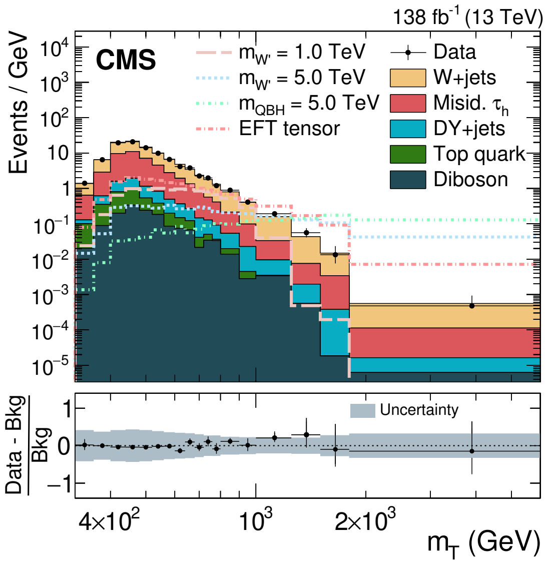

Figure 1: Transverse mass distribution of the τ_h+p_T^{miss} system. The p_T^{miss} is the missing momentum for the energy balance in the transverse plane with respect to the beam. Data are represented by black dots with statistical uncertainty, the expectation from SM processes are the stacked full histograms. The horizontal lines of the data points reflect the varying bin sizes. Signal samples are illustrated as dashed lines for exemplary SSM W' boson, QBH, and EFT signal hypotheses and are normalized to 10 fb. The ratios of the background-subtracted data yield to the expected background yield are presented in the lower panel. The combined statistical and systematic uncertainties in the background are represented by the grey shaded band in the ratio panel. This caption has been adapted from [1].

Table 1: Summary of 95% CL exclusion limits (expected and observed) derived from 2016–2018 data, for the physics models studied in this analysis: sequential standard model (SSM), nonuniversal gauge interaction model (NUGIM), a quantum black hole (QBH) interpretation, t-channel leptoquark (LQ), and effective field interpretation (EFT). This caption has been adapted from [1].

Model	Parameter	Expected Limit	Observed Limit
SSM W' $\rightarrow \tau + \nu$	$m_{W'}$	4.8 TeV	4.8 TeV
NUGIM $\cot(\theta_E) = 1$	$m_{W'}$	4.8 TeV	4.8 TeV
NUGIM $\cot(\theta_E) = 5.5$	$m_{W'}$	2.2 TeV	2.2 TeV
QBH	m_{QBH}	6.6 TeV	6.6 TeV
LQ democratic, $g_U = 1.0$	m_{LQ}	6.7 TeV	5.9 TeV
LQ best fit LH, $_U = 1.0$	m_{LQ}	145 TeV	205 TeV
LQ best fit LH, $g_U = 2.5$	m_{LQ}	1.8 TeV	1.5 TeV
LQ best fit LH+RH, $g_U = 1.0$	m_{LQ}	645 TeV	515 TeV
LQ best fit LH+RH, $g_U = 2.5$	m_{LQ}	3.0 TeV	2.5 TeV
EFT	ϵ_L^{cb}	0.27	0.32
EFT	ϵ_{SL}^{cb}	0.41	0.51
EFT	ϵ_T^{cb}	0.22	0.27

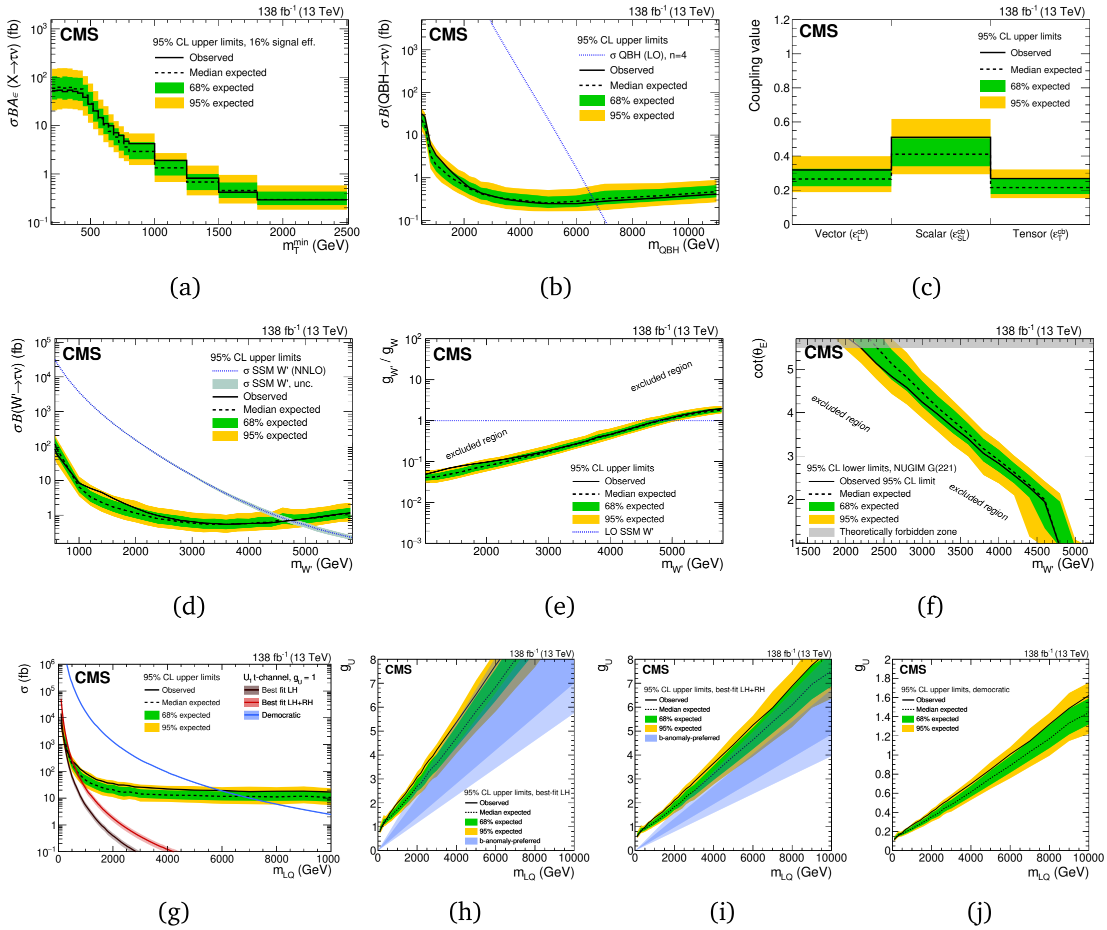

Figure 2: Bayesian 95% CL upper exclusion limits on: product of signal cross section and branching fraction for the model independent scenario for the $\tau + \nu$ decay in a back-to-back configurations as a function ofm_T^{min}, without making any assumption on the signal shapes, considering a signal selection efficiency of 16% (Fig. 2a), QBH $\rightarrow \tau + \nu$ process as a function of m_{QBH} (Fig. 2b), on Wilson coefficients described by the EFT model (Fig. 2c), $W' \rightarrow \tau + \nu$ process (Fig. 2d) in SSM, $g_{W'}/g_W$ under the same hypothesis (Fig. 2e). Lower exclusion limits on the NUGIM G(221) mixing angle $\cot(\theta_E)$ (Fig. 2f). In the SSM assumptions, exclusion limits are shown as a function of $m_{W'}$. Figures in the last row represent LQ expected and observed upper limits of the LQ cross section(Fig. 2g) and couplings as a function of the LQ mass in the LH (Fig. 2h), LH+RH (Fig. 2i), and democratic (Fig. 2j) scenarios. Theoretical expectations are represented by the blue dashed lines. The 68% and 95% quantiles of the limits are represented by the green and yellow bands, respectively. This caption has been adapted from [1].

3 The Tau Lepton reconstruction

The tau lepton reconstruction in CMS involves several steps:

- The **L1 Tau reconstruction:**, which involves calibration of trigger towers to mimic true offline response, clustering is performed around a central seed, and merging of clusters to form L1 Tau Objects for the next steps;
- The **HLT Tau reconstruction,** where calorimeter jets built around L1 seeds and also pixel track based isolation (only for diτ triggers) are exploited to build hadronic tau

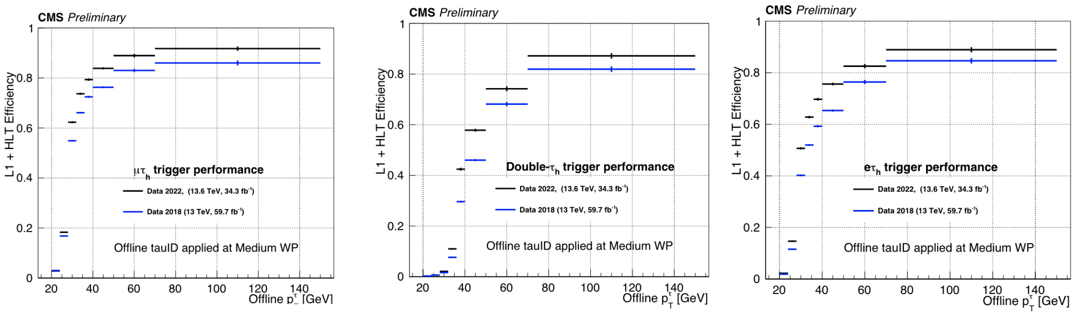

Figure 3: Performance of HLT tau lepton at 2018 (in blue) and 2022 (black dots) for the $\mu\tau_\mathrm{h}$ (left), $\tau_\mathrm{h}\tau_\mathrm{h}$ (center), and $e\tau_\mathrm{h}$ (right) triggers. In both eras the same HLT $\mathrm{p_T}(\tau)$ threshold and offline tau ID working point are used. Copyrights are held by the CMS Collaboration.

candidates at "Level 2" (L2), the first stage of HLT; on top of L2 there are Particle-Flow event reconstruction (PFTau) and a more detailed, L3, tau reconstruction, exploiting PF candidates and further cuts on higher level observables;

- Finally, the **Offline Tau reconstruction,** where the AK4 jets are considered as seed, the decay mode are reconstructed via the Hadron+Plus+Strips (HPS) algorithm [2]. Finally, the **offline tau identification** is performed via the Machine Learning based DeepTauID algorithm [3].

3.1 Tau reconstruction during Run 3

In July 2022, the Run 3 of LHC started, with 13.6 TeV p-p collisions. It is expected to end in 2025. Between the Run 2 and Run 3 data takings many improvements in all the tau reconstruction and identification steps have been developed. At the HLT level, the plans for the Run 3 are to: maintain successful HLT triggers from Run2, while removing under-performing ones; introduce Machine Learning based techniques for τ identification; add new trigger paths optimized for different physics processes, such as boosted or displaced diτ triggers, which will improve many BSM searches, and new final state topologies as diτ +jets or VBF+one or 2 τ leptons triggers. There are three machine learning algorithms introduced at HLT for the tau reconstruction and identification: *L2TauNNTag*, *deepTau@HLT* and *particleNet@HLT*. The first is a brand new Convolutional Neural Network (CNN) for hadronically decaying taus identification against its main background, QCD processes with many jets in the final state, at the L2. It exploits information coming from calorimeters and tracks to produce its output. For the Run 3, the well-proven DeepTau [3] exploited for offline taus was adapted in order to be placed at HLT after the PF candidates building; during the second half of the Run 3 data taking, deepTau@HLT was replaced by another algorithm exploited for offline particle reconstruction, the particleNet [4] readapted for HLT.

In figure Fig. 3, the cumulative L1+HLT efficiencies for 2018 and 2022 data, respectively in black and blue, for three different triggers (eτ_h, $\mu\tau_h$, diτ $_h$) are displayed. In general, the efficiencies are higher in 2022 data in all τ p_T range [5]. Furthermore, currently new performance plots for 2023 are available and soon also the inclusion of ParticleNet@HLT will be finalised and compared with early Run 3 triggers with deepTau and Run 2 paths. Moreover, a retraining of L2TauNNTag is ongoing in order to correctly identify very high p_T taus, which were not considered during the first training.

4 Conclusion

Tau leptons are crucial to probe the Standard Model (SM) and to search for Beyond Standard Model (BSM) physics involving leptons. Therefore, good performance in reconstruction and identification of the hadronic tau decays is crucial for many important physics analyses in CMS, both SM and BSM. In order to correctly identify hadronic τ decays and discriminate them against jets coming from different physical processes mimicking their signature, especially QCD multi-jet events, many strategies have been explored at CMS: for the offline reconstruction during Run 2 the two algorithms HPS and deepTau have been introduced; the HPS algorithm was exploited also at the latest stages of the HLT identification and reconstruction. During Run 2, there was limited optimization at the trigger level in this area, but in Run 3 new machine-learning based algorithms have been improved for the online (trigger) reconstruction: L2NNTag + deepTau/ParticleNet. Many improvements have been made for Run 3 and future LHC runs to maximize efficiency while maintaining an affordable acquisition rate. These improvements are expected to have important impact on all analyses that include τ leptons.

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