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Design and commissioning with first Run 3 data of new triggers to search for the CLFV $\tau \to 3\mu$ decay at the CMS experiment

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A search for the charged lepton flavor violating $\tau \to 3\mu$ decay was performed by the CMS experiment at the LHC, using data collected in 2017–2018 during proton-proton collisions. This data sample corresponds to an integrated luminosity of 97.7 fb^{-1}, recorded at a center-of-mass energy of 13 TeV. Tau leptons produced by the decays of heavy flavor mesons (B and D) or W bosons are exploited in the analysis, with a tailored strategy designed for the two different cases, and combined for the final result. No significant excess was observed, and an upper limit on the branching fraction $\mathcal{B}(\tau \to 3\mu)$ of 3.1×10^{-8} at 90% confidence level was set. Finally, this result was combined with the earlier CMS search based on 2016 data, resulting in a final observed (expected) upper limit on $\mathcal{B}(\tau \to 3\mu)$ of 2.9×10^{-8} (2.4×10^{-8}) at 90% confidence level.

To complement this search, a description of the improved version of the trigger designed for this analysis for the next LHC data taking period, started in 2022, is presented.

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1. Introduction

In the Standard Model (SM) there are no symmetries that would forbid lepton flavor violating (LFV) processes, which have been observed for the first time in the form of neutrino oscillations. However, to date no evidence for this kind of decays was found in the charged lepton sector. Although in principle possible, charged LFV (CLFV) decays, such as the $\tau \to 3\mu$ decay, are expected to have, in the SM with neutrino oscillations, a vanishingly small branching ratio (BR) ($O(10^{-54})$) [1]. Therefore, any observation by the ongoing experiments of these kind of decays would be an unambiguous sign of new physics, since many Beyond the Standard Model (BSM) theories predict an enhancements of several order of magnitude for this BR: up to 10^{-10}–10^{-8} is expected in the context of the Minimal Supersymmetric SM with the See-Saw mechanism [2] or in the R-parity violation [3] framework.

The search for this decay has been carried out by several experiments, and no evidence for its existence has been observed up to now. The current best experimental upper limit on $\mathcal{B}(\tau \to 3\mu)$, set by the Belle collaboration, is 2.1×10^{-8} at 90% confidence level (CL) [4], followed by the ones set by the LHC experiments: LHCb (2011–2012 data, 3 fb^{-1}), CMS (2016 data, 33.2 fb^{-1}), and ATLAS (2012 data, 20.3 fb^{-1}), which have set, respectively, upper limits of 4.6×10^{-8} [5], 8.0×10^{-8} [6], and 38×10^{-8} [7], at 90% CL. It is worth noting that, while LHCb targeted only the tau production from heavy-flavor (HF) hadron decays, and ATLAS exploited tau leptons coming from W bosons, CMS used both channels in its search, reaching a higher analysis sensitivity.

2. The CMS experiment

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Additional forward calorimetry complements the coverage provided by the barrel and endcap detectors. 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 [8].

Events of interest are selected using a two-tiered trigger system [9]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

In CMS, muons are identified by matching tracks in the silicon tracker with tracks in the muon detector and verifying the energy deposited in the calorimeters is consistent with that expected for them. The muon momentum is obtained from the curvature observed in the silicon tracker and the relative p_T resolution for muons with $p_T < 100$ GeV is 1% in the barrel and 3% in the endcaps [10].

3. Event selection and categorization

The first selection, performed by dedicated L1 trigger algorithms, requires either three muons, two muons or one muon with some conditions on the p_T, ΔR or on the dimuon mass. Then, an event passes the HLT if it contains two muons with $p_T > 3$ GeV and a track with $p_T > 1.2$ GeV, forming a common vertex, and having an invariant mass value (assuming the track to be a muon) compatible with the tau mass, i.e. in a range of 1.60-2.02 GeV. In the offline selections, the known di-muon resonances below the tau mass are vetoed: $\omega(783)$, $\phi(1020)$.

To enhance the analysis sensitivity, the selected events are split into separate categories based on the calculated 3-muon mass resolution: $\sigma_m/m \leq 0.7\%$, $0.7\% < \sigma_m/m < 1.05\%$, and $\sigma_m/m \geq 1.05\%$ (labeled A, B, and C). The signal region (SR) for each category includes candidates with 3-muon invariant masses within twice the average mass resolution. A further categorization is then performed based on the reconstruction algorithm used for the third muon.

4. Multivariate analysis

A two step multivariate analysis is carried out to further suppress the background. As a first step, a boosted decision tree (BDT) is trained based on muon reconstruction quality, which is motivated by the expectation that the background is dominated by events with at least one of the muons coming from a pion or kaon decay, or random matching between hadron tracks in the tracker and stubs in the muon detectors. The score of this classifier is then used as input to a second BDT, trained separately for each mass resolution category, and using also information about the 3-muon vertex quality, its isolation, the angle between the 3-muon momentum vector and the vector connecting the primary and 3-muon vertices, and the missing energy (in case of the W channel), computed as the negative vector sum of the transverse momenta of all other particles in the event. The training is performed by using simulated signal events (with properly mixed D and B meson decays) and background events from data sideband regions.

Based on the BDT score, events are further split into 4 bins, and, for each category, the bin with the lowest BDT score is discarded, ending up with a total of 36 categories. The bin boundaries are optimized to give the largest expected signal significance (before unblinding the SR).

5. Signal extraction and results

The BR $\mathcal{B}(\tau \to 3\mu)$ is obtained from a maximum likelihood fit performed simultaneously on the 3-muon invariant mass distribution in all the categories of the two channels. Data points in the sidebands are fitted with an exponential function, while the simulated signal is fitted with the sum of a Gaussian and a Crystal Ball function in the HF case, and with a Gaussian function for the W channel, as shown in Fig.1 for the most sensitive categories. Both signal models have fixed mean and width, as determined from fitting the simulated events in the corresponding category. The background normalizations are free parameters in the fit. No significant excess is seen, and an observed (expected) upper limit of 3.1×10^{-8} (2.7×10^{-8}) have been set at 90% CL [12], by using a frequentist method [11] based on modified profile likelihood test statistics and the CLs criterion [13, 14]. Events in common among the two channels are removed from the HF one in the combined fit.

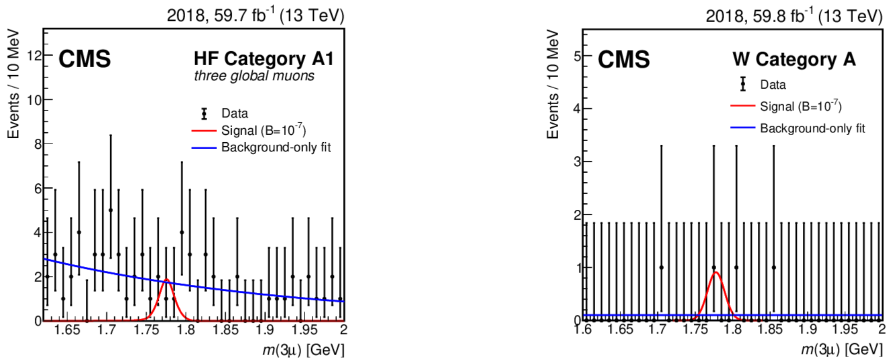

Figure 1: Three-muon invariant mass distributions in the highest sensitivity category of both channels (HF on the left, W on the right). Data are shown with filled circles and the vertical bars represent the statistical uncertainty. The solid and dashed lines represent respectively the background-only fit and the expected signal assuming $\mathcal{B}(\tau \to 3\mu) = 10^{-7}$ [12].

This result is combined with the earlier result with 2016 data [6] by performing a simultaneous unbinned maximum likelihood fit to the 3-muon mass distributions, resulting in an observed (expected) upper limit at 90% CL on $\mathcal{B}(\tau \to 3\mu)$ of 2.9×10^{-8} (2.4×10^{-8}), as shown in Fig.2.

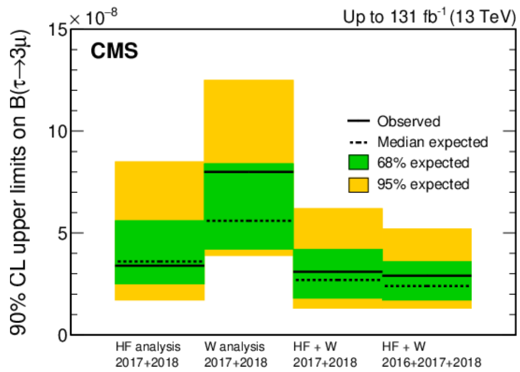

Figure 2: Observed and expected upper limits on $\mathcal{B}(\tau \to 3\mu)$ at 90% CL, from the HF analysis, the W boson analysis, the combination of the two analyses, as well as their combination with the previously published result using 2016 data [12].

6. New triggers for the next data taking

For the LHC Run 3 data taking, started in summer 2022, new triggers have been developed to increase the acceptance of the experiment for this process. The trigger improvement is twofold: on one hand, the newly introduced possibility to compute the 3-muon invariant mass already at the first level of trigger allows us to lower the p_T requirements, retrieving the low momentum muons from the HF channels; on the other hand, an improved version of the muon reconstruction algorithm at the HLT, tailored for very low-p_T muons, largely increases the muon efficiency in the phase space of interest for this analysis.

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