PROCEEDINGS OF SCIENCE

Rare decays at CMS

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The latest CMS results are presented on the search for the neutrino-less $\tau^{\pm} \rightarrow \mu^{\pm}\mu^{\pm}\mu^{\mp}$ decay, the first observation of the $\eta \rightarrow \mu^{+}\mu^{-}\mu^{+}\mu^{-}$ decay, the measurement of the $B_s^0 \rightarrow \mu^{+}\mu^{-}$ branching fraction and effective lifetime, and the search for the $B^0 \rightarrow \mu^{+}\mu^{-}$ decay. 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

Since the discovery of the Higgs boson [1, 2], the experimental efforts at the LHC have been focused on the measurements of its characteristics. At the same time, many well-known problems remain, and call for new physics (NP) scenarios.
Rare decays are highly sensitive to contributions from NP, making them an ideal field for Beyond the Standard Model (BSM) studies. The Large Hadron Collider (LHC) allows to probe the effects of new mediators like leptoquarks or heavy bosons [3], which could manifest as an increase of the decay probability of SM processes. The study of Flavor Changing Neutral Currents (FCNC) decays, Lepton Flavor Violating (LFV) decays, and the precise measurement of SM properties offer a broad range for NP investigations [4, 5]. Specifically, decays with muons in the final state provide a clear experimental signature in the LHC environment and serve as an optimal mode for these analyses.
The $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp, \eta \to \mu^+\mu^-\mu^+\mu^-$ and $B^0_{(s)} \to \mu^+\mu^-$ searches on the CMS 13 TeV proton-proton collision data are described in this proceeding.

2. Search for the $\tau \to 3\mu$ decay

In the Standard Model (SM) lepton flavour numbers are exactly conserved. The observation of neutrino oscillations [6], however, proves that neutrinos are massive particles and allows for LFV processes, such as the neutrino-less $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ decay. These processes are predicted at very low branching ratios (BR) and are sensitive to new physics effects which could enhance their probability.
The neutrino-less $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ decay is predicted with a branching ratio of O(10^{-55}) [7] and represents 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 for at hadron and electron-positron asymmetric colliders. The most stringent value on its branching fraction is set by the Belle collaboration at 2.1×10^{-8} at 90% of confidence level (CL) [8]. 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 [9] and 3.76×10^{-7} at 90% CL [10], 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 [11]. The analysis presented in this section extends the CMS result to the full Run-2 data taking era (from 2016 to 2018) [12].

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 [13, 14] to be about 70% of the total τ lepton production. The final state is characterized by soft muons, a non negligible fake 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 spectra of the final state, the low hadron activity surrounding signal events and the large missing transverse momentum originated from the neutrino give a better handle for background rejection and make the sensitivity

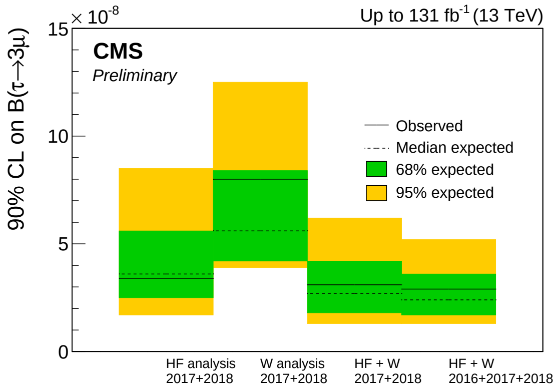

Figure 1: Observed (full black line) and expected (dashed black line) upper limits at 90% confidence level obtained for the 2017–2018 HF and W analyses, their combination and their combination with the 2016 analysis (Run-2). The 68% and 95% confidence intervals of the expected upper limits are shown with green and yellow bands, respectively [12].

of the W channel comparable to the HF one.
Different triggers are employed to select events either with three muons or two muons and one track, in order to recover low-momentum muons which could fail the trigger muon reconstruction. To reduce the fake-muon contamination due to pions and kaons, quality requirements are imposed on the muon tracks.
Multivariate techniques (Boosted Decision Trees, BDT) are used to mitigate the background contamination, mostly originated by the semileptonic decays of D mesons and from combinatorial three-muon events.
To increase the analysis sensitivity, events are categorized based on their invariant mass resolution and their signal-to-background ratio. The signal strength parameter is shared by the categories and is extracted with a simultaneous unbinned maximum likelihood fit to the three muon invariant mass distribution of the events selected by the BDT's. 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) $\times 10^{-8}$ 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.

3. Observation of the $\eta \to 4\mu$ decay

Light mesons decays have been widely studied [15–19], but some of their properties and decays remain unmeasured. The determination of the $\eta \to \mu^+\mu^-\mu^+\mu^-$ decay branching fraction offers a precision test of the SM [20, 21] and allows to probe BSM theories [20, 22]. At CMS, the first observation of the $\eta \to \mu^+\mu^-\mu^+\mu^-$ decay has been achieved using Run-2 proton-proton collision data collected at a centre of mass energy of 13 TeV [23] and is described in this section.
The main limiting factors of a high-energy hadron collider experiment trigger are the stringent limits on the event processing time and on the data throughput. The CMS experiment [24] adopts a two-level trigger system. The first level (L1) is purely hardware and reduces the acquisition rate to about 100 kHz, seeding the reconstruction of the second trigger level. The second level (HLT,

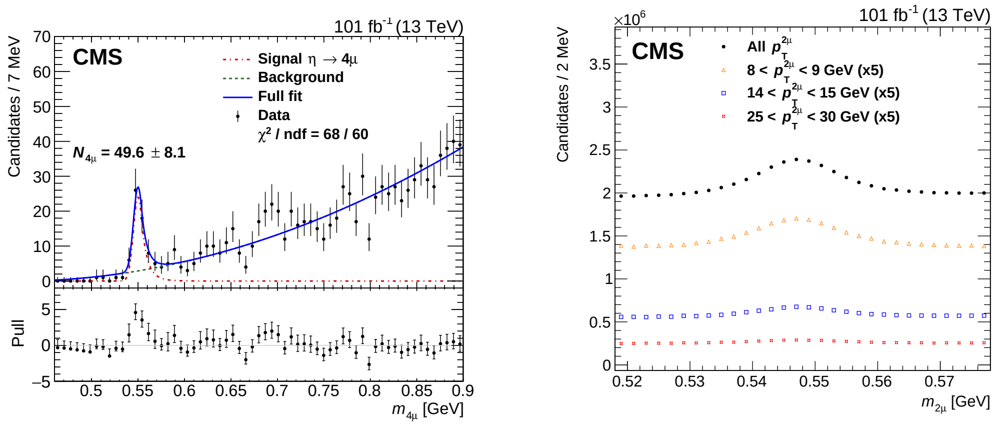

Figure 2: On the left, the invariant mass distribution of $\eta \to \mu^+\mu^-\mu^+\mu^-$ signal candidates is shown. Data points are shown in black, and the signal-plus-background fit is shown with a blue line. The signal component of the fit function is shown with a dashed red line, while the background component is shown with a dashed green line. On the right, the invariant mass distribution of $\eta \to \mu^+\mu^-$ events is shown for different ranges of transverse momentum [23].

High Level Trigger) is purely software and runs a high-level reconstruction of the physics objects. With an average event size of 1 MB, the HLT rate is limited to about 1 kHz for standard triggers. Already during Run-1, CMS developed a strategy to bypass these limitations known as data scouting [25]. This strategy consists in saving only the HLT information of an event, without the raw content coming from the sub-detectors, greatly reducing the event size and process time (in case of scouting data, no event reconstruction is run after the HLT).
The $\eta \to \mu^+\mu^-\mu^+\mu^-$ analysis is based on 2017 and 2018 double-muon scouting triggers, which collected a total integrated luminosity of 101 fb^{-1}. These triggers are based on double-muon L1 trigger seeds and select events with two low-p_T muons reconstructed by the HLT (starting from 3 GeV). The scouting strategy reduces the event size to few kB (4 kB in 2017 and 8 kB in 2018) and allows to reach an acquisition rate of 2 kHz, not possible with standard double-muon triggers for which the HLT rate is 30 Hz [26]. The invariant mass distribution of the signal candidates is shown in Fig. 2, where the η meson mass peak is clearly visible. The signal yield is extracted with an unbinned maximum likelihood fit and it is normalized to the $\eta \to \mu^+\mu^-$ channel yield, also shown in Fig. 2. The significance of the $\eta \to \mu^+\mu^-\mu^+\mu^-$ peak exceeds five standard deviations and the measured branching fraction is $\mathcal{B}_{\eta\to 4\mu} = 5.0 \pm 0.8\ (stat)\ \pm 0.7\ (syst)\ \pm 0.7\ (\mathcal{B}_{\eta\to 2\mu})\ \times 10^{-9}$. The measured value is compatible with the SM prediction of $\mathcal{B}_{\eta\to 4\mu} = 3.98 \pm 0.15\ \times 10^{-9}$ [27].

4. Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and effective lifetime and search for the $B^0 \to \mu^+\mu^-$ decay

Flavour changing neutral currents (FCNC) are strongly suppressed in the SM. Thanks to their precise theoretical prediction and their clean experimental signatures, the rare FCNC decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ represent an ideal probe for NP. The first observation of the $B_s^0 \to \mu^+\mu^-$ decay has been reported by a combination of LHCb and CMS data analyses [28], and has been later confirmed by the ATLAS [29], CMS [30] and LHCb [31, 32] experiments, individually. A combined analysis of the three experiments [33] has reported a deviation from the SM prediction of 2.5 standard deviations. This section describes the measurement of the $B_s^0 \to \mu^+\mu^-$ decay branching fraction, the effective B_s^0 lifetime measurement in the $B_s^0 \to \mu^+\mu^-$ decay, and the search for $B^0 \to \mu^+\mu^-$ decays in CMS Run-2 data [34], corresponding to an integrated luminosity of 140 fb^{-1}, collected during proton-proton collisions at the centre of mass energy of 13 TeV. This analysis represents the most precise measurement of the B_s^0 properties by a single experiment to date.

Di-muon signal candidates are collected using double-muon triggers, selecting high-quality oppositely charged muons in the central region of the detector, originating from the same vertex. Similar triggers are used to collect events for the normalization channels $B_s^0 \to J/\psi\ \phi$ and $B^+ \to J/\psi\ K^+$.
The sources of background contamination are two-body decays of B mesons, semileptonic decays of B mesons and combinatorial events (events where the two signal muons originate from independent sources). The first set is found to be negligible after a tight muon track quality selection. The second and third set of background events are instead reduced by mean of a Boosted Decision Tree (BDT). The BDT is trained using MC simulations of the signal process and real data events taken from the signal sidebands. Three main feature categories are used as input to the training: pointing angles and isolation properties help to reduce the semileptonic contamination, while the di-muon vertex information is used to reduce the combinatorial contamination. The number of signal events is extracted from data with a two-dimensional unbinned maximum-likelihood fit to the di-muon invariant mass of the signal candidates and its uncertainty. The branching fractions are obtained normalizing the observed number of signal events with respect to the $B^+ \to J/\psi\ K^+$ channel yield. In order to reduce the dependence from the external input f_s/f_u (the ratio between the B_s^0 and B^+ production, measured by LHCb to be 0.231±0.008 [35]) the $B_s^0 \to \mu^+\mu^-$ branching fraction is also measured with respect to the $B_s^0 \to J/\psi\ \phi$ channel yield.
The lifetime of the B_s^0 meson is extracted with a three-dimensional unbinned maximum likelihood fit to the signal candidates decay time, their decay time uncertainty and their invariant mass.
Events are categorized based on their pseudorapidity, the year of data-taking and their signal purity (BDT score), for a total of sixteen categories, and the parameters of interest of the analysis are correlated between the categories. Figure 3 shows the invariant mass distribution and decay time distribution of events falling into the high-purity categories.
A signal exceeding 12 standard deviations is found in the $B_s^0 \to \mu^+\mu^-$ channel and its branching fraction and lifetime are measured. No evidence for the $B^0 \to \mu^+\mu^-$ decay is found and an upper limit is set on its branching fraction at 95% confidence level.
The measured values of the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fractions, normalized with respect to $B^+ \to J/\psi\ K^+$ channel yield, and the upper limit on the $B^0 \to \mu^+\mu^-$ branching fraction are:

$$\mathcal{B}_{B_s^0 \to \mu^+\mu^-} = 3.83^{+0.38}_{-0.36}\ (stat)\ ^{+0.19}_{-0.16}\ (syst)\ ^{+0.14}_{-0.13}\ (f_s/f_u) \times 10^{-9},$$

$$\mathcal{B}_{B^0 \to \mu^+\mu^-} = 0.37^{+0.75}_{-0.67}\ (stat)\ ^{+0.08}_{-0.09}\ (syst) \times 10^{-10},$$

$$\mathcal{B}_{B^0 \to \mu^+\mu^-} < 1.9 \times 10^{-10} \text{ at 95\% CL},$$

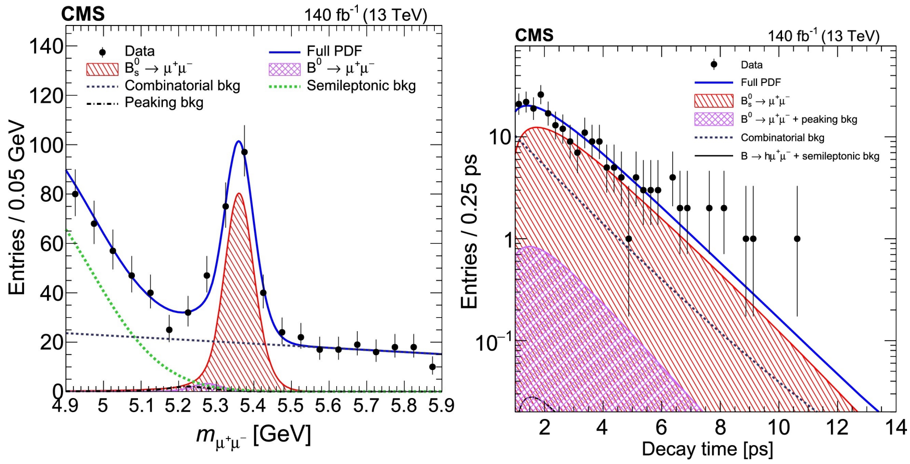

Figure 3: Invariant mass distribution (left) and proper decay time distribution (right) of signal candidates of events falling into the high-purity categories. The projection of the fit function is shown with a blue line. The semileptonic background component is shown with a green line, the combinatorial background component is shown with a black line, the peaking background component is shown with a purple area, and the signal component is shown with a red area [34].

while the measured $B_s^0 \to \mu^+\mu^-$ branching fraction normalized with respect to the $B_s^0 \to J/\psi\ \phi$ channel yield is:

$$\mathcal{B}_{B_s^0\to\mu\mu} = 4.02^{+0.40}_{-0.38}\ (stat)\ ^{+0.28}_{-0.23}\ (syst)\ ^{+0.18}_{-0.15}\ (\mathcal{B}_{B_s^0\to J/\psi\phi}) \times 10^{-9}.$$

The measured effective B_s^0 lifetime in the $B_s^0 \to \mu^+\mu^-$ decay is:

$$\tau_{B_s^0} = 1.83^{+0.23}_{-0.20}\ (stat)\ ^{+0.04}_{-0.04}\ (syst) \times 10^{-10}\ \text{ps}.$$

The measured branching fraction values are compatible with the standard model predictions [36] of $\mathcal{B}_{B_s^0\to\mu\mu} = (3.66 \pm 0.14) \times 10^{-9}$ and $\mathcal{B}_{B^0\to\mu\mu} = (1.03 \pm 0.05) \times 10^{-10}$, as shown in Fig. 4. The measured effective B_s^0 lifetime in the $B_s^0 \to \mu^+\mu^-$ decay is compatible with the SM prediction [37] of $\tau_{B^0_{s,H}} = 1.624 \pm 0.009$ ps.

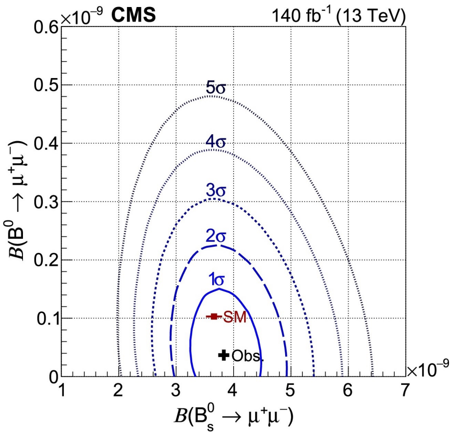

Figure 4: The measured values of $\mathcal{B}_{B^0\to\mu\mu}$ and $\mathcal{B}_{B_s^0\to\mu\mu}$ are shown with a black cross, and their confidence regions, at different confidence levels, are shown with dashed lines. The SM prediction is shown with a red marker [34].

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