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, the measurement of the B_s^0 lifetime, the search for the $B^0 \rightarrow \mu^{+}\mu^{-}$ decay, and the measurement of the angular observables of the $B^0 \rightarrow K^{*0}\mu^{+}\mu^{-}$ decay. The results are based on data collected in proton-proton collisions at the centre of mass energy of 8 TeV and 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 and open questions remain [3], and call for new physics (NP) scenarios.
Given their sensitivity to NP contributions, rare processes represent a thriving ground for NP searches and Beyond Standard Model (BSM) studies. The $\tau^{\pm} \to \mu^{\pm}\mu^{\pm}\mu^{\mp}$, $\eta \to \mu^{+}\mu^{-}\mu^{+}\mu^{-}$ and $B^0_{(s)} \to \mu^{+}\mu^{-}$ searches in the CMS 13 TeV proton-proton collision data, and the angular analysis of the $B^0 \to K^{*0}\mu^{+}\mu^{-}$ decay on CMS 8 TeV proton-proton collision data are described in this report.

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 [4], however, proves that neutrinos are massive particles and allows for lepton flavour violating (LFV) processes, such as the neutrino-less $\tau^{\pm} \to \mu^{\pm}\mu^{\pm}\mu^{\mp}$ decay. Nevertheless, these processes are predicted at very low branching ratios (BR) and are sensitive to new physics effects, which could manifest as an enhancement in the decay probability. The neutrino-less $\tau^{\pm} \to \mu^{\pm}\mu^{\pm}\mu^{\mp}$ decay, predicted with a probability of $O(10^{-55})$ [5], represent a golden channel for LFV searches at CMS due to its clear final state and the abundance of τ lepton produced in proton-proton collisions.
The $\tau^{\pm} \to \mu^{\pm}\mu^{\pm}\mu^{\mp}$ decay has been searched at 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% of confidence level (CL) [6]. 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 [7] and 3.76×10^{-7} at 90% CL [8], 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 [9]. The analysis presented in this section extends the CMS result to the full Run-2 data taking era (from 2016 to 2018) [10].

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 [11, 12] 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 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 spectrum 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 of the W channel comparable to the HF one.
Different triggers are employed to select events either with two muons and one track or events with three muons. Signal candidates are identified among events with three muons with a displaced secondary vertex, reconstructed offline. To reduce the fake-muon contamination due to pions and

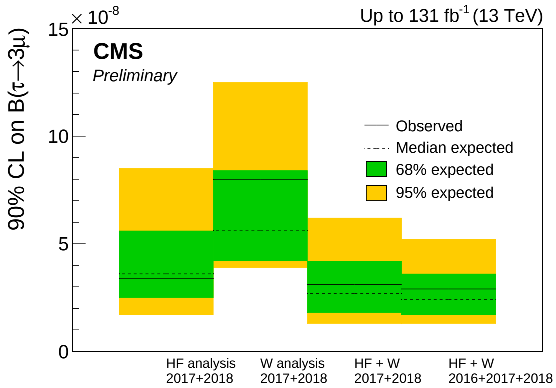

Figure 1: Observed (full black line) and expected (dashed black line) upper limits at 90% of confidence level obtained for the 2017-2018 HF and W analyses, their combination and their combination with the 2016 analysis (Run-2). The 68% and 95% confidence intervals of the expected upper limits are shown with green and yellow bands, respectively. The figure is taken from [10].

kaons, quality requirements are imposed to 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 and the results are combined with the 2016 data analysis by means of likelihood product. The HF signal is normalized to the $D_s \to \phi\pi$ production and the W signal is normalized to the W boson production cross section measurement [13].
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. Search for the $\eta \to 4\mu$ decay

Although light mesons decays have been widely studied [14–18], 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 [19, 20] and allows to probe BSM theories [19, 21]. 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 [22] and is described in this section.

The main limiting factors of a high-energy experiment trigger are the stringent limits on the event processing time and on the data throughput. The CMS experiment [23] 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, High Level Trigger) is purely software and runs a high-level reconstruction of the physics objects. With an average event

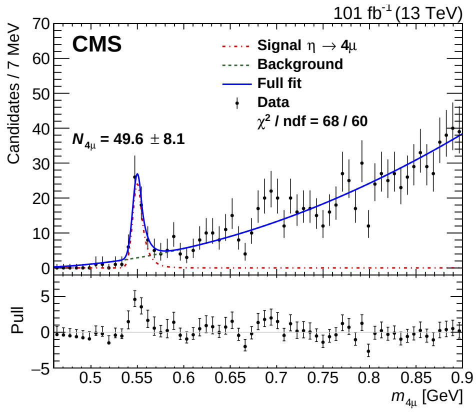

Figure 2: Invariant mass distribution of $\eta \to \mu^+\mu^-\mu^+\mu^-$ signal candidates (left). Data points are shown in black, and the signal-plus-background fit is shown with a blue line. The signal component of the fit function is shown with a dashed red line, while the background component is shown with a dashed green line. The figure is taken from [22].

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 [24]. This strategy consists in saving only the HLT information of an event, deleting 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 low-mass (below 1 GeV) double-muon L1 trigger seeds and select events with two low-p_T muons reconstructed at 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 [25]. 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. The significance of the $\eta \to \mu^+\mu^-\mu^+\mu^-$ peak exceeds five sigmas and the measured branching fraction is

$$\mathcal{B}_{\eta\to\mu^+\mu^-\mu^+\mu^-} = 5.0 \pm 0.8\ (stat)\ \pm 0.7\ (syst)\ \pm 0.7\ (\mathcal{B}_{\eta\to 2\mu})\ \times 10^{-9}$$

The measured value is compatible with the SM prediction $\mathcal{B}_{\eta\to\mu^+\mu^-\mu^+\mu^-} = 3.98 \pm 0.15 \times 10^{-9}$ [26].

4. Measurement of the $B^0_s \to \mu\mu$ and $B^0 \to \mu\mu$ branching fractions and B^0_s lifetime

Flavour changing neutral currents (FCNC) are strongly suppressed in the SM. Thanks to their precise theoretical predictions and their clean experimental signatures, the rare FCNC decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ represent an ideal field for new physics searches. The first observation of the $B^0_s \to \mu^+\mu^-$ decay has been reported by a combination of LHCb and CMS data analyses [27], and has been later confirmed by the ATLAS [28], CMS [29] and LHCb [30, 31] experiments, individually. A combined analysis of the three experiments [32] has reported a deviation from the

SM prediction of 2.5 sigmas.
This section describes the measurement of the $B_s^0 \to \mu^+\mu^-$ decay branching fraction, the lifetime measurement of the B_s^0 meson, and the search for $B^0 \to \mu^+\mu^-$ decays in CMS Run-2 data, corresponding to an integrated luminosity of 140 fb^{-1}, collected in proton-proton collisions at the centre of mass energy of 13 TeV [33]. This analysis supersedes the result by CMS on 2016 data [29] and 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 opposite 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 $B^+ \to J/\psi K^+$, with additional requirements on the J/ψ displacement from the primary vertex.
The sources of background contamination are charmless two-body decays of B mesons peaking in the signal region, 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 means of a BDT. The BDT is trained using MC simulations of the signal process and real data events taken from the di-muon invariant mass 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. Events are categorized based on their pseudorapidity, the year of data-taking and their signal purity (BDT score) for a total of sixteen categories. The parameters of interest are extracted with simultaneous maximum likelihood fits.
The number of signal events is extracted 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 to the $B^+ \to J/\psi K^+$ channel. 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 [34]) the $B_s^0 \to \mu^+\mu^-$ branching fraction is also measured with respect to the normalization to the $B_s^0 \to J/\psi\phi$ channel.
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.
Figure 3 shows the invariant mass distribution and decay time distribution of events falling into the high-purity categories.
An evidence exceeding 12 sigmas is found for the $B_s^0 \to \mu^+\mu^-$ channel and its branching fraction and lifetime are measured. No evidence of the $B^0 \to \mu^+\mu^-$ decay is found and an upper limit is set on its branching fraction at 95% of confidence level.
The measured values of the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fractions, normalized to $B^+ \to J/\psi K^+$ channel, and the upper limit on the $B^0 \to \mu^+\mu^-$ branching fraction are:

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

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

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

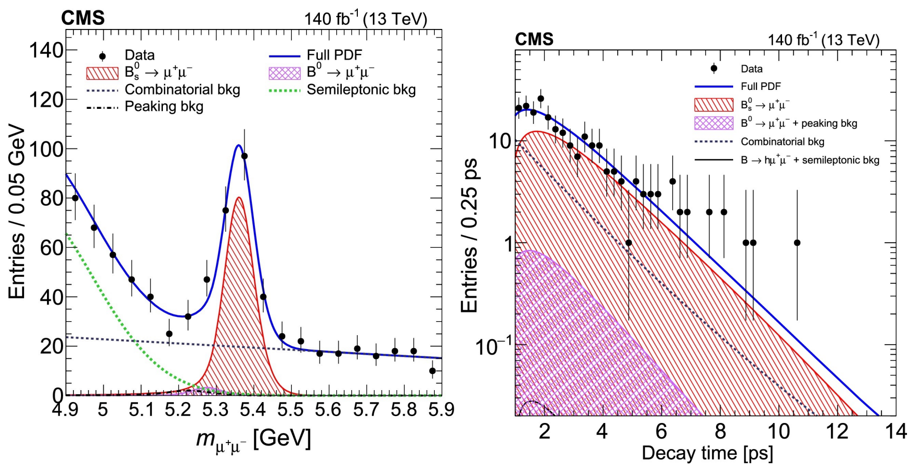

Figure 3: Invariant mass distribution (left) and proper decay time distribution (right) of signal candidates of events falling into the high-purity categories. The projection of the fit function is shown with a blue line. The semileptonic background component is shown with a green line, the combinatorial 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. The figures are taken from [33].

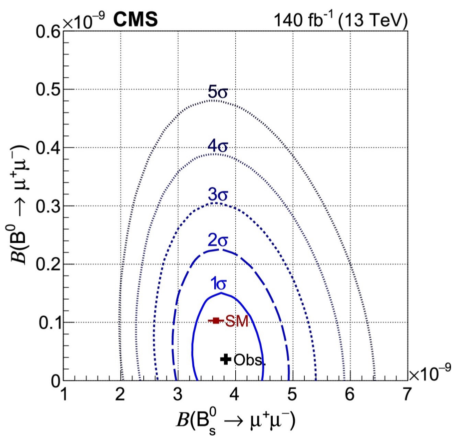

Figure 4: The measured values of $\mathcal{B}_{B^0\to\mu\mu}$ and $\mathcal{B}_{B^0_s\to\mu\mu}$ are shown with a black cross, and their confidence regions, at different confidence levels, are shown with dashed lines. The SM prediction is shown with a red marker. The figures are taken from [33].

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

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

The measured decay time of the B_s^0 meson is:

$$\tau_{B^0_s} \;=\; 1.83^{+0.23}_{-0.20}\ (stat)\ ^{+0.04}_{-0.04}\ (syst)\ \text{ps}$$

The measured values are compatible with the standard model predictions [35] $\mathcal{B}_{B^0_s\to\mu\mu} = (3.66 \pm 0.14) \times 10^{-9}$, as shown in Fig. 4, and with the world average value [36] $\tau_{B^0_{s,H}} = 1.624 \pm 0.009$ ps.

5. Angular analysis of the $B^0 \to K^{*0}\mu\mu$ decay

FCNC are strongly suppressed in the SM and their properties are sensitive to NP contributions. The angular distribution of the $B^0 \to K^{*0}\mu^+\mu^-$ decay is described by the formula reported in [37], where the so-called P_1 and P_5' parameters are defined. These parameters have been measured by the ATLAS [38], Belle [39] and LHCb [40, 41] collaborations. The Belle and LHCb collaborations reported a deviation from the SM [37, 42–44] up to three sigmas in some regions of the decay phase space.

The CMS collaboration has measured the angular properties of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using proton-proton collision data collected at the centre of mass energy of 8 TeV, corresponding to an integrated luminosity of 20.5 fb^{-1} [45] and the data analysis is described in this section.

Signal candidates are reconstructed in the $\mu^+\mu^-K^\pm\pi^\mp$ final state and are collected at HLT selecting opposite charged double-muon events originating from a displaced vertex. The offline reconstruction is used to refine the event selection. A quality requirement is imposed to the muon tracks and to the displaced di-muon vertex. Two additional tracks, corresponding to the final-state pion and kaon, are identified in the event. The mass hypothesis (pion or kaon) which minimizes the distance from the K^{*0} meson mass value is assigned to them. The mis-tag rate (14%) is modeled in the angular decay function and is considered among the sources of systematic uncertainty of the analysis.

The P_1 and P_5' parameters are extracted with an unbinned maximum likelihood fit to the angular distribution described in [37] and the $K^\pm\pi^\mp\mu^+\mu^-$ invariant mass. The fit is performed in different bins of the di-muon invariant mass squared observable q^2, excluding the resonant regions of the J/ψ and $\psi(S)$ mesons.

To facilitate the fit convergence, a simplified version of the angular distribution is used [37], where the angular observables are folded to reduce the complexity of the problem.

The fit is done in two steps. In the first step, the background components are fit excluding the signal regions. In the second step, the parameters of interest are fit fixing the nuisance parameters to the result of the first fit. This procedure is validated using toy simulations and the systematic uncertainty derived from it is accounted for in the analysis.

The measured values of the P_1 and P_5' parameters, shown in Fig. 5, are compatible with the standard model prediction [37, 42–44] and with the LHCb results [41].

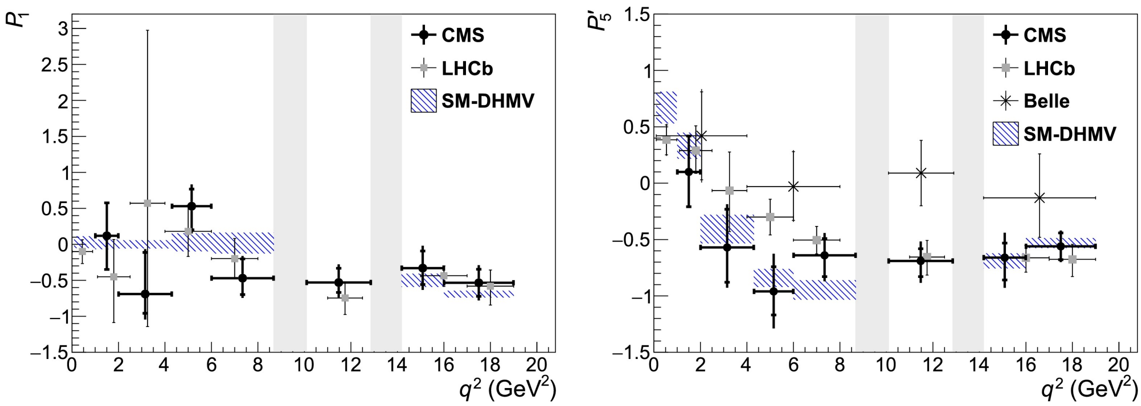

Figure 5: Values of the P_1 (left) and P'_5 parameters as a function of the di-muon invariant mass squared q^2. The CMS results are shown with black dots, the LHCb results [41] are shown with gray squares, the Belle results [39] are shown with black crosses and the SM predictions [37, 42–44] are shown with with blue areas. The J/ψ and $\psi(S)$ regions are excluded from the analysis. The figures are taken from [45].

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