PROCEEDINGS OF SCIENCE

Rare decays in CMS

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Studies of rare decays play an important role in the search for physics beyond the standard model. Recent results from the CMS experiment on the decays of B and τ particles to final states containing muons, based on 8 and 13 TeV data, are presented. In addition, the perspectives for the measurements of the $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fractions and $B^0_s \to \mu^+\mu^-$ effective lifetime at the High-Luminosity LHC are reported, together with the projections for the sensitivity of the P'_5 parameter in the $B^0 \to K^{0*}\mu^+\mu^-$ angular analysis.

European Physical Society Conference on High Energy Physics - EPS-HEP2019 -
10-17 July, 2019
Ghent, Belgium

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Rare decays of flavoured particles offer a complementary approach to direct measurements in the search for New Physics (NP) phenomena, providing sensitivity to higher mass scales. The impact of NP could become manifest via enhancements or suppressions in the branching fractions, or in modifications to the angular distributions of the decay final state particles. Recent results on this topic from the CMS experiment [1] will be described, together with the perspectives for selected rare decay measurements at the High Luminosity LHC (HL-LHC).

1. Angular analysis of the $B^+ \to K^+\mu^+\mu^-$ decay

The $B^+ \to K^+\mu^+\mu^-$ decay, being a Flavour Changing Neutral Current process, is forbidden at tree level in the Standard Model (SM) and occurs through higher-order processes, resulting in a branching fraction (BF) of 4.4×10^{-7}. New heavy particles from NP could appear in competing diagrams, affecting the differential angular distributions of the final state particles. The decay has been already studied in various experiments [2, 3, 4, 5] and no hint of beyond SM physics has been found.

The analysis from CMS presented here is based on data collected in 2012 at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.5 fb^{-1} [6]. Events are selected by a low p_T dimuon trigger, which requires two oppositely charged muons to be compatible with a common vertex, displaced from the interaction point. The offline selection requires two muons and an additional track, assumed to be a kaon, to originate from a single point. Kinematical and topological selections are applied to further suppress background from combinatorial and partially reconstructed b hadron decays.

The decay rate is described in Eq. 1.1 as a function of the two variables q^2 and $\cos\theta_\ell$, where q^2 is the dimuon invariant mass squared, θ_ℓ is the angle between the negative-charged muon and the kaon in the dimuon rest frame, F_H represents the contribution from the pseudoscalar, scalar, and tensor amplitudes to the decay width, and A_{FB} is the forward-backward asymmetry of the dimuon system:

$$\frac{1}{\Gamma_\ell}\frac{d\Gamma_\ell}{d\cos\theta_\ell} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_\ell) + \frac{1}{2}F_H + A_{FB}\cos\theta_\ell \tag{1.1}$$

In the q^2 range from 1 to 22 GeV^2, 2286 $\pm$ 73 signal events are identified. The F_H and A_{FB} parameters are extracted from a 2-dimensional extended unbinned maximum likelihood fit to the angular distribution of the selected B^+ meson candidates, in various q^2 intervals. The main sources of systematic uncertainties include the parametrisation of the background distribution, the fitting procedure and the description of the reconstruction efficiency. A detailed table is available in Ref. [6].

The results for F_H and A_{FB} are shown in Fig.1 as a function of q^2. The measured values of A_{FB} are consistent with the SM expectation of no asymmetry. A good agreement is also found between F_H results and SM theoretical predictions, as well as with previous measurements.

2. Search for $\tau \to \mu^+\mu^-\mu^+$ decays

The $\tau \to \mu^+\mu^-\mu^+$ decay is a charge lepton flavour violating process, without missing neutri-

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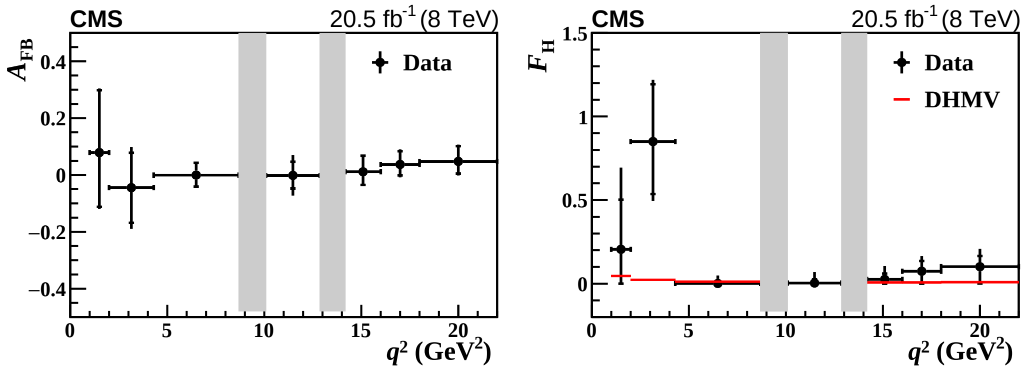

Figure 1: Results of the A_{FB} (left) and F_H (right) measurements in ranges of q^2 [6]. The statistical uncertainties are shown by the inner vertical bars, while the outer vertical bars give the total uncertainties. The vertical shaded regions correspond to the J/ψ and $\psi(2S)$ dominated control regions. The horizontal lines in the right plot show the DHMV SM theoretical predictions [7, 8].

nos in the final state. In the SM, this process is allowed by neutrino oscillations, but its branching fraction is beyond current experimental accessibility (BF $\sim 10^{-14}$ [9]). However, the decay rate results strongly enhanced in various NP scenarios [10, 11]. The three muon final state is experimentally accessible and clean, and previous searches from Belle [12], BaBar [13], LHCb [14] and ATLAS [15] have not found any hint of signal. The current world best limit, from the Belle experiment, is BF $< 2.1 \times 10^{-8}$ at 90% CL.

The CMS experiment has performed a search for this decay on 2016 data at 13 TeV (33 fb^{-1}) using τ leptons produced in D and B hadron decays [16]. The analysis strategy is based on the reconstruction of three offline muons with total charge equal to ± 1. Events are previously selected by an online algorithm which demands two muons and a generic track, originating from a common vertex. A Boosted Decision Tree (BDT) discriminator is used to reduce the background contamination. Discriminating variables include quantities related to the goodness of the muon reconstruction and identification, and to the three-muon candidate properties. The BDT is trained on a simulated signal sample and on backgrounds from data sidebands.

Selected events are divided into three categories based on the three-muon mass resolution, which, in turn, depends on the muon rapidity; three other categories are established based on the per-event BDT score, but in this case only the two with the highest signal-to-background ratio are retained. This procedure results in 6 categories, to be included in the final fit.

$D_s \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ events are used as a normalisation channel, as in Eq. 2.1,

$$N_{sig} = N_{D_s} \frac{\mathscr{B}(D_s \to \tau\nu)}{\mathscr{B}(D_s \to \phi\pi)} \frac{\varepsilon_{sig}}{\varepsilon_{\phi\pi}} \mathscr{B}(\tau \to 3\mu), \tag{2.1}$$

where ε_{sig} and $\varepsilon_{\phi\pi}$ are the acceptance times reconstruction efficiencies for the signal and normalisation modes, respectively. The fraction of non-prompt D_s is estimated from a fit to the proper decay leght distribution using template shapes from the simulation.

The final limit on $\tau \to \mu^+\mu^-\mu^+$ branching fraction is extracted through a simultaneous maximum likelihood fit to the 6 categories mentioned above. Fig. 2 shows the three-muon invariant mass distribution per each category, with the results of the background only fit (blue) and expected signal shape (red) superimposed. The dominant systematic uncertainties derive from uncertainties on the D_s normalisation ($\sim$10%) and on the $D_s \to \phi\pi$ branching fraction ($\sim$8%). The observed (expected) limit at 90% CL on $\mathscr{B}(\tau \to \mu^+\mu^-\mu^+)$ is 8.8 (9.9) $\times$ 10^{-8}.

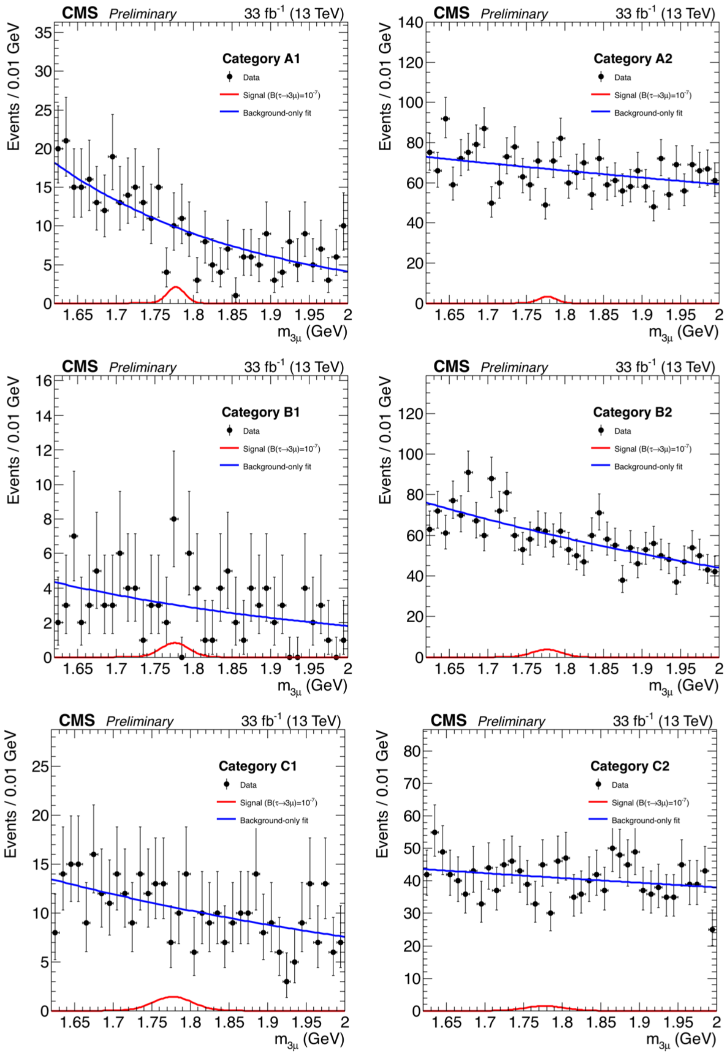

Figure 2: Three-muon invariant mass distributions in the six independent event categories used in the analysis [16]. Data are shown with points, the background-only fit and the expected signal for $\mathscr{B}(\tau \to \mu^+\mu^-\mu^+) = 10^{-7}$ are shown with the blue and red lines, respectively.

3. Prospects for selected measurements at the HL-LHC

The HL-LHC run, which is due to start in 2026, is expected to deliver an integrated luminosity of approximately 3000 fb^{-1} at a pp center of mass value of 14 TeV [17]. Significant upgrades of the CMS detector are foreseen [18] to withstand the highly-demanding operating conditions and to fully exploit the delivered luminosity. In particular, a new silicon tracker with finer granularity, extended coverage, and better radiation tolerance will be installed, which, together with the planned improvements in the muon system, will allow to significantly improve the mass resolution measurement. The perspectives for the measurements of the $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fractions and the B^0_s effective lifetime are reported in the following, together with projections for the CMS sensitivity to the P'_5 parameter in the $B^0 \to K^{0*}\mu^+\mu^-$ decay.

The decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are highly suppressed in the SM, since they can only proceed through Flavour Changing Neutral Current processes, forbidden at tree level. The SM predictions are $(3.56 \pm 0.30) \times 10^{-9}$ and $(1.07 \pm 0.10) \times 10^{-10}$ for the B^0_s and B^0 decays respectively [19]. The branching fractions are enhanced or further suppressed by many extensions of the SM [20, 21, 22, 23], making these decays an excellent probe for physics beyond the SM. The current experimental results from the ATLAS, LHCb, and CMS Collaborations [24, 25, 26, 27] are all in agreement with the SM expectations, though still statistically limited.

The high statistics available at the HL-LHC will allow to perform precise measurements of the branching fractions and of the effective lifetime of the $B^0_s \to \mu^+\mu^-$ decay.

The analysis performance with the upgraded CMS detector is estimated. The predictions [28] are based on the CMS analysis of the 2016 dataset, described in [29]. The sensitivity to the effective lifetime and branching fraction measurements is evaluated on pseudo-experiments based on the PDF for the signal and background components as from the reference analysis. Improvements in the dimuon invariant mass resolution, which will be provided by the new tracking system, are included in the prediction. In particular, the mass resolution in the barrel region is estimated to improve by ∼40-50% with respect to the Run 2 scenario, resulting both in a substantial reduction of the semileptonic background contribution within the signal regions and in an improved separation of the B^0_s and B^0 signals.

A BDT discriminator, based on various properties of events, is used to separate signal events from backgrounds. The signal yields are extracted via an unbinned maximum likelihood fit to the dimuon invariant mass distribution in bins of the BDT discriminant variable, and the branching fractions are then extracted exploiting the normalisation channel $B^+ \to J/\psi K^+$, which has a well measured branching fraction and similar topology/kinematics as the signal. The left and middle plots of Fig. 3 show the invariant mass fit projections corresponding to an integrated luminosity of 3000 fb^{-1} for both $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ channels in two pseudorapidity regions.

The $B^0_s \to \mu^+\mu^-$ effective lifetime is measured by a two-step procedure: first, an unbinned maximum likelihood fit to the dimuon invariant mass distribution is performed, and the proper decay time distribution of B^0_s signal events is projected with the sPlot [30] technique. Hence, a binned maximum likelihood fit to the obtained signal proper time distribution, shown in the right plot of Fig. 3, is carried out to extract the measurement of the effective lifetime of the $B^0_s \to \mu^+\mu^-$.

The results for the estimated analysis sensitivity for different integrated luminosities are summarised in Tab. 1 for the total uncertainties on the $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fractions, the range of the significance of the B^0 observation and the statistical uncertainty on the $B^0_s \to \mu^+\mu^-$ effective lifetime. With an integrated luminosity of 3000 fb^{-1}, CMS will have the capability to measure the $B^0_s \to \mu^+\mu^-$ effective lifetime with an error of about 0.05 ps, and to observe the $B^0 \to \mu^+\mu^-$ decay with more than 5 standard deviation significance.

Table 1: Estimated analysis sensitivity for integrated luminosities of 300 and 3000 fb^{-1}. Columns report the total integrated luminosity, the total uncertainties on the $\mathrm{B_s^0} \to \mu^+\mu^-$ and $\mathrm{B^0} \to \mu^+\mu^-$ branching fractions, the range of the significance of the $\mathrm{B^0}$ observation (the range indicates the $\pm 1\sigma$ of the distribution of the significance) and the statistical uncertainty on the $\mathrm{B_s^0} \to \mu^+\mu^-$ effective lifetime

$\mathscr{L}$ [fb^{-1}]	$\delta\mathscr{B}(\mathrm{B_s^0} \to \mu^+\mu^-)$	$\delta\mathscr{B}(\mathrm{B^0} \to \mu^+\mu^-)$	$\sigma(\mathrm{B^0} \to \mu^+\mu^-)$	$\delta[\tau(B_s)]$ (stat-only)
300	12%	46%	1.4-3.5σ	0.15 ps
3000	7%	16%	6.3-8.3σ	0.05 ps

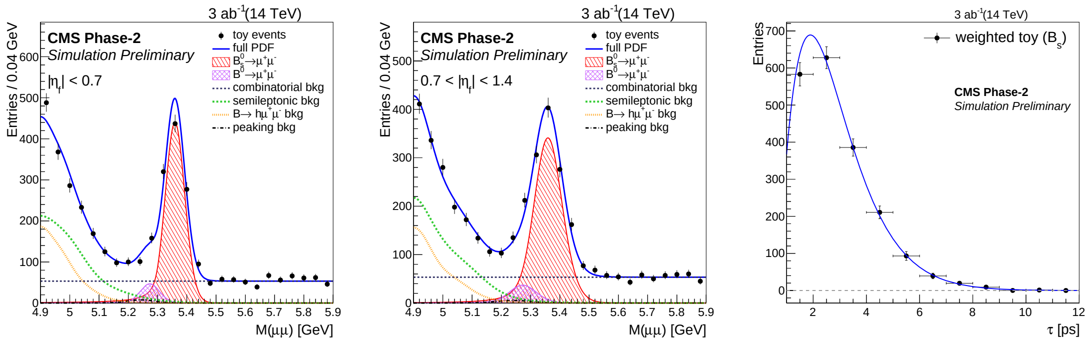

Figure 3: Dimuon invariant mass distributions from simulated events for the Phase-2 scenario, in the central barrel region (left) and in a more forward region (center). The results of the fit are superimposed. The right plot shows the binned maximum likelihood fit to the background-subtracted decay time distribution [28].

The large integrated luminosity that will be collected at the HL-LHC will also allow to perform more precise studies of the angular distributions of the $\mathrm{B^0} \to \mathrm{K^{0*}}\mu^+\mu^-$ decay, whose branching fraction is at the level of 10^{-7}. This decay gives access to NP-sensitive observables, as the P_5' parameter, for which a deviation from SM expectation has been observed by LHCb [31] and Belle [32], while CMS analysis of Run 1 data [33] shows consistency of the parameter with the SM prediction.

The expected precision on the P_5' parameter is extrapolated to the integrated lumi of 3000 fb^{-1} [34], starting from CMS Run 1 results. Effects of improvements in the analysis strategy have not been considered to perform the extrapolation, and it is assumed that trigger thresholds and efficiencies will remain the same. The extrapolation also assumes that the signal-to-background ratio will not change, despite the improved mass resolution (of about 20%) with the Phase-2 detector should ameliorate the signal-to-background ratio with respect to the Run 1 result.

Simulated samples of signal events generated with the Phase-2 conditions, including an average of 200 pileup, are used. For each q^2 bin, the expected $\mathrm{B^0} \to \mathrm{K^{0*}}\mu^+\mu^-$ signal yield is extracted from an extended unbinned maximum likelihood fit to the $\mathrm{K}^+\pi^-\mu^+\mu^-$ invariant mass, and rescaled to the luminosity of 3000 fb^{-1}. The estimated statistical uncertainty on the P_5' parameter is obtained by scaling the statistical uncertainty measured in Run 1 by the square root of the ratio between the yields observed in the Run 1 data and the expected yields for Phase-2. Systematic uncertainties are scaled by a factor 2, or according to the increase of statistics of the control samples. Overall, the uncertainties are estimated to improve up to a factor of 15 compared to the Run 1 result, as shown in Fig. 4. The plot also shows that, with the increased amount of collected data foreseen for Phase-2, the angular analysis could be performed in narrower q^2 bins, allowing to measure the P'_5 shape with finer granularity. For this study, only the q^2 region below the J/ψ mass squared, which is more sensitive to possible new physics effects, is considered.

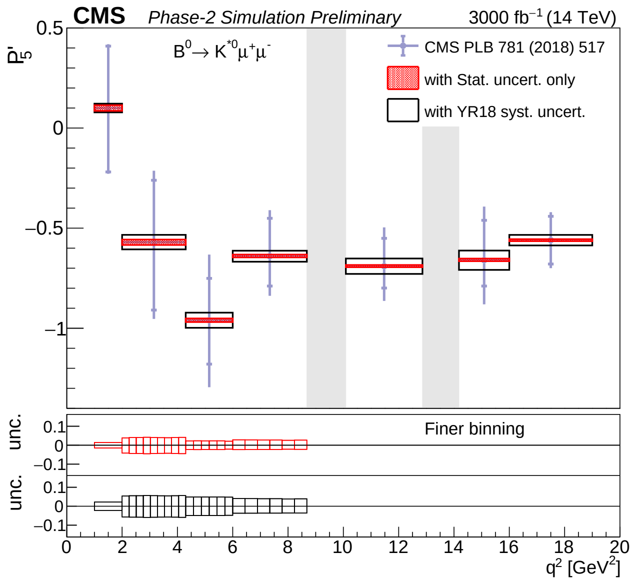

Figure 4: Projected statistical (hatched regions) and total (open boxes) uncertainties on the P'_5 parameter versus q^2 in the Phase-2 scenario with an integrated luminosity of 3000 fb^{-1} [34]. The CMS Run 1 measurement of P'_5 is shown by circles with inner vertical bars representing the statistical uncertainties and outer vertical bars representing the total uncertainties. The vertical shaded regions correspond to the J/ψ and ψ resonances. The two lower pads represent the statistical (upper pad) and total (lower pad) uncertainties with the finer q^2 binning.

References

[1] S. Chatrchyan *et al.* [CMS Collaboration], *"The CMS Experiment at the CERN LHC"*, JINST **3** (2008) S08004.

[2] B. Aubert *et al.* [BaBar Collaboration], *"Measurements of branching fractions, rate asymmetries, and angular distributions in the rare decays $B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$"*, Phys. Rev. D **73** (2006) 092001 [hep-ex/0604007].

[3] J.-T. Wei *et al.* [Belle Collaboration], *"Measurement of the Differential Branching Fraction and Forward-Backword Asymmetry for $B \to K^{(*)}\ell^+\ell^-$"*, Phys. Rev. Lett. **103** (2009) 171801 [arXiv:0904.0770 [hep-ex]].

[4] T. Aaltonen *et al.* [CDF Collaboration], *"Measurements of the Angular Distributions in the Decays $B \to K^{(*)}\mu^+\mu^-$ at CDF"*, Phys. Rev. Lett. **108** (2012) 081807 [arXiv:1108.0695 [hep-ex]].

[5] R. Aaij *et al.* [LHCb Collaboration], *"Angular analysis of charged and neutral $B \to K\mu^+\mu^-$ decays"*, JHEP **1405** (2014) 082 [arXiv:1403.8045 [hep-ex]].

[6] A. M. Sirunyan *et al.* [CMS Collaboration], *"Angular analysis of the decay $B^+ \to K^+\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV"*, Phys. Rev. D **98** (2018) 112011 [arXiv:1806.00636 [hep-ex]].

[7] S. Descotes-Genon, L. Hofer, J. Matias and J. Virto, *"On the impact of power corrections in the prediction of $B \to K^*\mu^+\mu^-$ observables"*, JHEP **1412** (2014) 125 [arXiv:1407.8526 [hep-ph]].

[8] S. Descotes-Genon, L. Hofer, J. Matias and J. Virto, *"Global analysis of $b \to s\ell\ell$ anomalies"*, JHEP **1606** (2016) 092 [arXiv:1510.04239 [hep-ph]].

[9] X. Y. Pham, *"Lepton flavor changing in neutrinoless tau decays"*, Eur. Phys. J. C **8** (1999) 513 [hep-ph/9810484].

[10] E. Arganda and M. J. Herrero, *"Testing supersymmetry with lepton flavor violating tau and mu decays"*, Phys. Rev. D **73** (2006) 055003 [hep-ph/0510405].

[11] M. Raidal *et al.*, *"Flavour physics of leptons and dipole moments"*, Eur. Phys. J. C **57** (2008) 13 [arXiv:0801.1826 [hep-ph]].

[12] K. Hayasaka *et al.* [Belle Collaboration], *"Search for Lepton Flavor Violating Tau Decays into Three Leptons with 719 Million Produced Tau+Tau- Pairs"*, Phys. Lett. B **687** (2010) 139 [arXiv:1001.3221 [hep-ex]].

[13] J. P. Lees *et al.* [BaBar Collaboration], *"Limits on tau Lepton-Flavor Violating Decays in three charged leptons"*, Phys. Rev. D **81** (2010) 111101 [arXiv:1002.4550 [hep-ex]].

[14] R. Aaij *et al.* [LHCb Collaboration], *"Search for the lepton flavour violating decay $?^? \; ? \; ?^? \; ?^+ \; ?^?$"*, JHEP **1502** (2015) 121 [arXiv:1409.8548 [hep-ex]].

[15] G. Aad *et al.* [ATLAS Collaboration], *"Probing lepton flavour violation via neutrinoless $\tau \longrightarrow 3\mu$ decays with the ATLAS detector"*, Eur. Phys. J. C **76** (2016) no.5, 232 [arXiv:1601.03567 [hep-ex]].

[16] CMS Collaboration, *"Search for $\tau \to 3\mu$ decays using τ leptons produced in D and B meson decays"*, [CMS-PAS-BPH-17-004].

[17] G. Apollinari, I. Béjar Alonso, O. Brüning, P. Fessia, M. Lamont, L. Rossi and L. Tavian, *High-Luminosity Large Hadron Collider (HL-LHC) : Technical Design Report V. 0.1*, CERN Yellow Report CERN 2017-007-M [doi:10.23731/CYRM-2017-004].

[18] D. Contardo, M. Klute, J. Mans, L. Silvestris and J. Butler, *Technical Proposal for the Phase-II Upgrade of the CMS Detector* CERN-LHCC-2015-010 [https://cds.cern.ch/record/2020886].

[19] A. J. Buras, J. Girrbach, D. Guadagnoli and G. Isidori, *On the Standard Model prediction for $\mathscr{B}(B_{s,d} \to \mu^+\mu^-)$*, Eur. Phys. J. C **72** (2012) 2172 [hep-ph/1208.0934].

[20] J. K. Parry, *Lepton flavor violating Higgs boson decays, $\tau \to \mu\gamma$ and $B_s \to \mu^+\mu^-$ in the constrained MSSM+NR with large tan beta*, Nucl. Phys. B **760** (2007) 38 [hep-ph/0510305].

[21] S. R. Choudhury, A. S. Cornell, N. Gaur and G. C. Joshi, *Signatures of new physics in dileptonic B-decays*, Int. J. Mod. Phys. A **21** (2006) 2617 [hep-ph/0504193].

[22] J. R. Ellis, J. S. Lee and A. Pilaftsis, *B-Meson Observables in the Maximally CP-Violating MSSM with Minimal Flavour Violation*, Phys. Rev. D **76** (2007) 115011 [hep-ph/0708.2079].

[23] J. R. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, *On $B_s \to \mu^+\mu^-$ and cold dark matter scattering in the MSSM with non-universal Higgs masses*, JHEP **0605** (2006) 063 [hep-ph/0603136].

[24] S. Chatrchyan *et al.* [CMS Collaboration], *Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and search for $B^0 \to \mu^+\mu^-$ with the CMS Experiment*, Phys. Rev. Lett. **111** (2013) 101804 [hep-ex/1307.5025].

[25] V. Khachatryan *et al.* [CMS and LHCb Collaborations], *Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data*, Nature **522** (2015) 68 [hep-ex/1411.4413].

[26] M. Aaboud *et al.* [ATLAS Collaboration], *Study of the rare decays of B_s^0 and B^0 into muon pairs from data collected during the LHC Run 1 with the ATLAS detector*, Eur. Phys. J. C **76**, no. 9, 513 (2016) [hep-ex/1604.04263].

[27] R. Aaij *et al.* [LHCb Collaboration], *Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and effective lifetime and search for $B^0 \to \mu^+\mu^-$ decay*, Phys. Rev. Lett. **118** (2017) 191801 [hep-ex/1703.05747].

[28] CMS Collaboration, *"Measurement of rare $B \to \mu^+\mu^-$ decays with the Phase-2 upgraded CMS detector at the HL-LHC",* [CMS-PAS-FTR-18-013].

[29] CMS Collaboration, *"Measurement of properties of* $\mathrm{B_s^0} \to \mu^+\mu^-$ *decays and search for* $\mathrm{B^0} \to \mu^+\mu^-$ *with the CMS experiment",* [CMS-PAS-BPH-16-004].

[30] M. Pivk and F. R. Le Diberder, *"SPlot: A Statistical tool to unfold data distributions",* Nucl. Instrum. Meth. A **555** (2005) 356 [physics/0402083 [physics.data-an]].

[31] R. Aaij *et al.* [LHCb Collaboration], *"Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity",* JHEP **1602** (2016) 104 [arXiv:1512.04442 [hep-ex]].

[32] S. Wehle *et al.* [Belle Collaboration], *"Lepton-Flavor-Dependent Angular Analysis of $B \to K^*\ell^+\ell^-$",* Phys. Rev. Lett. **118** (2017) no.11, 111801 [arXiv:1612.05014 [hep-ex]].

[33] A. M. Sirunyan *et al.* [CMS Collaboration], *"Measurement of angular parameters from the decay* $\mathrm{B^0} \to \mathrm{K^{*0}}\mu^+\mu^-$ *in proton-proton collisions at $\sqrt{s} = 8$ TeV",* Phys. Lett. B **781** (2018) 517 [arXiv:1710.02846 [hep-ex]].

[34] CMS Collaboration, *"Study of the expected sensitivity to the P_5' parameter in the* $\mathrm{B^0} \to \mathrm{K^{*0}}\mu^+\mu^-$ *decay at the HL-LHC",* [CMS-PAS-FTR-18-033].