PROCEEDINGS OF SCIENCE

Status and prospects of rare decays at ATLAS and CMS

Federica M. Simone[a,b,*] **for the ATLAS and CMS collaborations**

[a] *Physics Department, Polytechnic of Bari, via Orabona 4, I-70125, Bari, Italy*

[b] *INFN, Section of Bari, via Orabona 4, I-70125, Bari, Italy*

E-mail: federica.maria.simone@cern.ch

Recent results from rare flavour decays searches achieved using proton-proton collision data at $\sqrt{s}$ = 13 TeV by ATLAS and CMS are presented. They include the studies of $B^0_{(s)} \to \mu^+\mu^-$ decays carried out by both experiments and the first observation of the $\eta \to 4\mu$ double Dalitz decay by CMS using Run 2 data. The trigger strategies allowing for rare decays searches involving soft muons in Run 3 are also discussed.

Workshop Italiano sulla Fisica ad Alta Intensità (WIFAI2023)
8-10 November 2023
Dipartimento di Architettura dell'Università Roma Tre, Rome, Italy

*Speaker

PoS(WIFAI2023)028

1. Introduction

The search for rare flavour transitions is motivated by suppressed decay amplitudes, ideally predicted with good precision in the Standard Model (SM), similar or smaller to the decay probabilities in some new physics scenarios. Experimental precision allowing disentangling the SM contribution from other contributions is of course a crucial aspect.

The ATLAS [1] and CMS [2] experiments achieved excellent performance during the Run 2 of the LHC [3], allowing for rare decays studies. A dedicated trigger strategy extended the physics program of both experiments, enhancing the sensitivity to flavour decays with low transverse momentum (p_{T}) muons in the final state.

In this contribution, recent results in the field of rare transitions by ATLAS and CMS are discussed, together with the perspectives for the Run 3 of the LHC.

2. Studies of $B^0_{(\mathrm{s})} \to \mu^+\mu^-$ decays

The leptonic decays of B hadrons such as the $B^0_{\mathrm{s}} \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays provide a very clear experimental signature, given by the fully reconstructed dimuon final state. In the SM, both decays are described by penguin and box diagrams thus being strongly suppressed. Furthermore, these decays are helicity suppressed, with $B^0 \to \mu^+\mu^-$ decays being also Cabibbo–Kobayashi–Maskawa suppressed, thus constituting a sensitive probe for Beyond the Standard Model (BSM) physics.

The $B^0_{\mathrm{s}} \to \mu^+\mu^-$ lifetime provides an independent test for the SM. The two B^0_{s} mass eigenstates are characterised by two different and precisely known lifetimes, $\tau_{\mathrm{H}} = 1.624 \pm 0.009$ ps and $\tau_{\mathrm{L}} = 1.429 \pm 0.007$ ps for the heavy and light eigenstate respectively [7]. In the SM, only the CP-odd heavy-mass B^0_{s} eigenstate can decay to two muons. Therefore, new physics introducing CP violation would cause a deviation from the expected lifetime.

While $B^0_{\mathrm{s}} \to \mu^+\mu^-$ decays have been observed in a combined analysis by the CMS and LHCb Collaborations [6], no evidence for $B^0 \to \mu^+\mu^-$ has been found so far. In this contribution, recent studies on $B^0_{(\mathrm{s})} \to \mu^+\mu^-$ BR and lifetime by the CMS and ATLAS Collaborations are reported.

2.1 Measurement of $B^0_{(\mathrm{s})} \to \mu^+\mu^-$ branching ratios and $B^0_{\mathrm{s}} \to \mu^+\mu^-$ lifetime at CMS

The measurement of the $B^0_{\mathrm{s}} \to \mu^+\mu^-$ effective lifetime and $B^0_{(\mathrm{s})} \to \mu^+\mu^-$ branching ratios has been carried out by CMS using the full Run 2 dataset, accounting for an integrated luminosity of 140 fb^{-1}[8]. Events collected by low-p_{T} dimuon triggers are selected to reconstruct the signal $B^0_{(\mathrm{s})} \to \mu^+\mu^-$ decays as well as $B^+ \to J/\psi K^+$ and $B^0_{\mathrm{s}} \to J/\psi\phi$ channels used for normalisation. A Boosted Decision Tree (BDT) is trained for suppressing the large combinatorial background, using simulated signal events and data events in the mass sidebands.

The $B^0_{\mathrm{s}} \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ BRs are extracted from a simultaneous unbinned maximum likelihood (ML) fit on the dimuon invariant mass and its uncertainty. The BR is measured relative to the $B^+ \to J/\psi K^+$ yield, while the $B^0_{\mathrm{s}} \to J/\psi\phi$ channel is used as an alternative normalisation channel for cross-check. Figure 1 (left) shows the dimuon mass fit for one high-purity category based on the BDT selection. A $B^0_{\mathrm{s}} \to \mu^+\mu^-$ signal significance exceeding 12 standard deviations is found and the $B_s^0 \to \mu^+\mu^-$ BR is measured to be:

$$\mathcal{B}_{B_s^0\to\mu^+\mu^-} = 3.38^{+0.38}_{-0.36}(\text{stat})^{+0.19}_{-0.16}(\text{syst})^{+0.14}_{-0.13}(f_s/f_d) \times 10^{-9} \tag{1}$$

where f_s/f_d indicates the uncertainty related to the p_T-dependent measurement of the ratio of the fragmentation fractions by LHCb used in the measurement [9]. Figure 2 (left) compares this result to the most recent results at the LHC and to the SM predictions, showing good agreement with the SM and best precision ever achieved by a single experiment.

No evidence for $B^0 \to \mu^+\mu^-$ decays is found and an upper limit on the $B^0 \to \mu^+\mu^-$ BR is set at 95% confidence level:

$$\mathcal{B}_{B^0\to\mu^+\mu^-} < 1.9 \times 10^{-10} \tag{2}$$

compatible with the SM prediction as shown in Figure 2 (right).

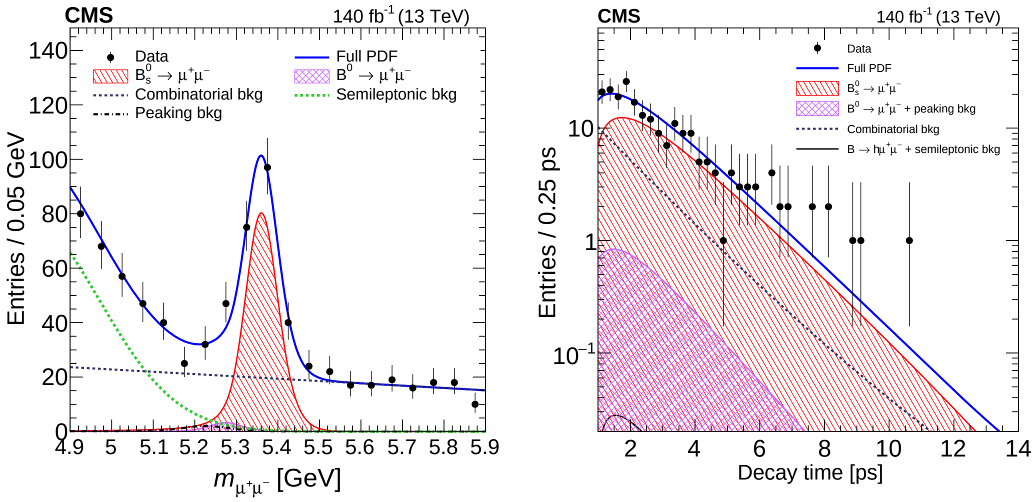

Figure 1: Left: projection on the dimuon mass axis of the fit to the branching fraction for BDT score above 0.99. Right: projection on the signal candidate decay time of the ML fit for the dimuon invariant mass region $5.28 < \mathrm{m}(\mu^+\mu^-) < 5.48$ GeV [8].

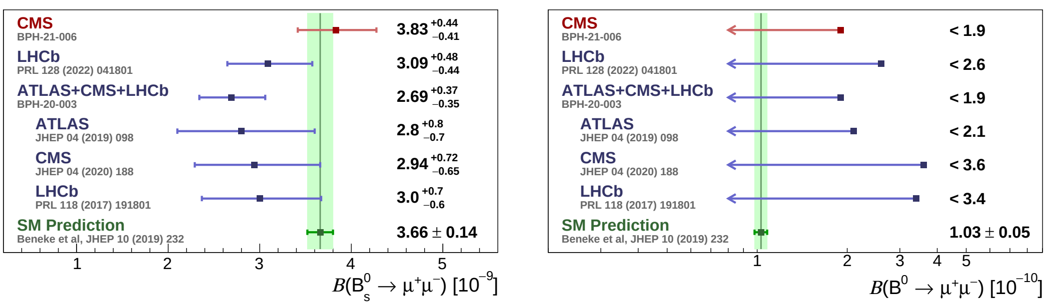

Figure 2: Comparison of the $B_s^0 \to \mu^+\mu^-$ (left) and $B^0 \to \mu^+\mu^-$ (right) branching fraction measurements with the most recent results and the Standard Model [8].

The B_s^0 meson lifetime is extracted from a three-dimensional simultaneous unbinned ML fit on the dimuon invariant mass, the decay time and its uncertainty. Figure 1 (right) shows the decay time distribution for one dimuon invariant mass bin as an example. The measured B_s^0 meson lifetime is:

$$\tau = 1.83^{+0.23}_{-0.20}(\text{stat})^{+0.04}_{-0.04}(\text{syst})\ \text{ps}. \tag{3}$$

The result, in good agreement with the SM, is the most precise measurement to date.

2.2 Measurement of $B_s^0 \to \mu^+\mu^-$ lifetime at ATLAS

The measurement of the B_s^0 effective lifetime by ATLAS is based on data collected in 2015 and 2016 at $\sqrt{s} = 13$ TeV center-of-mass energy, accounting for an integrated luminosity of 36.2 fb^{-1}[10]. Data collected by a set of dimuon triggers are selected using the same strategy as in the BR measurement published by the ATLAS Collaboration in 2019 [11]. A BDT is trained for background rejection and the optimal working point is set based on the signal significance.

Figure 3 (left) shows the dimuon invariant mass of the selected data candidates, where the fit is the same employed for the BR measurement [11]. The proper decay time distribution of the data candidates is displayed in Figure 3 (right), where the sPlot [12] technique is used for background subtraction based on the mass fit. Signal simulated samples parameterised as a function of the B_s^0 lifetime hypothesis are used to build MC templates. The lifetime measurement is obtained by minimising the binned χ^2 between the data histogram and lifetime-dependent signal MC templates. The red histogram in Figure 3 (right) shows the simulated proper decay time distribution corresponding to the lifetime fit, which gives as a result:

$$\tau = 0.99^{+0.42}_{-0.07}(\text{stat}) \pm 0.17(\text{syst})\ \text{ps}. \tag{4}$$

The measurement is in agreement with the SM prediction within uncertainties.

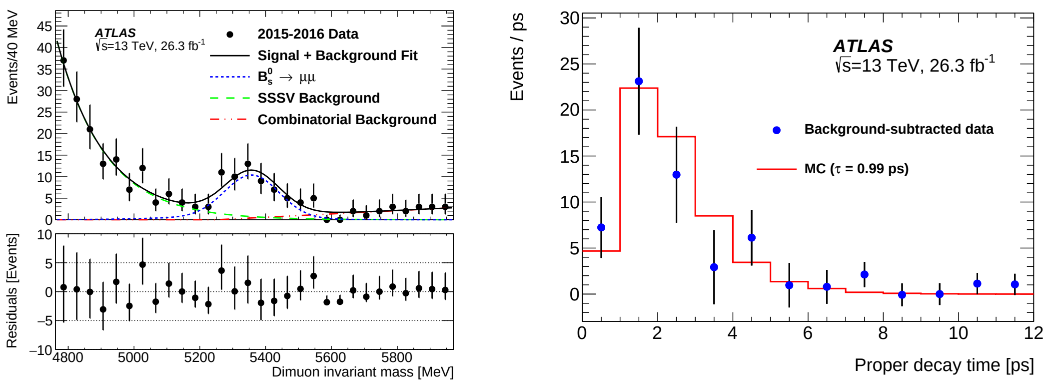

Figure 3: Left: invariant mass distribution of dimuon candidates passing the optimised BDT selection in the 2015-2016 dataset. Right: signal proper decay time distribution extracted with the *sPlot* background subtraction procedure applied to the invariant mass fit. The superimposed signal MC template is the result of the lifetime fit [10].

3. First observation of the rare $\eta \to 4\mu$ decay at CMS

The leptonic radiative decays of the neutral pseudoscalars η and η' are an important test of the SM. They occur through the electromagnetic coupling of the η to the photon which then converts into a lepton pair, thus being typically suppressed. The properties of these decays constitute a sensitive probe to new physics [13, 14]. They also connect to the hadronic contributions to the anomalous magnetic moment of the muon [13]. The rare decay of the η meson to four muons is predicted in the SM with BR $\mathcal{B}(\eta \to 4\mu) = (3.98 \pm 0.15) \times 10^{-9}$. Here we report on the first observation of this decay mode at CMS, using data collected in 2017 and 2018 at $\sqrt{s} = 13$ TeV center-of-mass energy, accounting for an integrated luminosity of 101 fb^{-1}[15]. The data were collected by a special set of high-rate muon triggers, also called *scouting* triggers, which collected events with loose selections, notably with no constraints on the dimuon mass, while storing only a limited amount of the event information to keep a manageable total data bandwidth [16]. As displayed in Figure 4 (left), this strategy allowed to extend the sensitivity of CMS to muon resonances at very low mass.

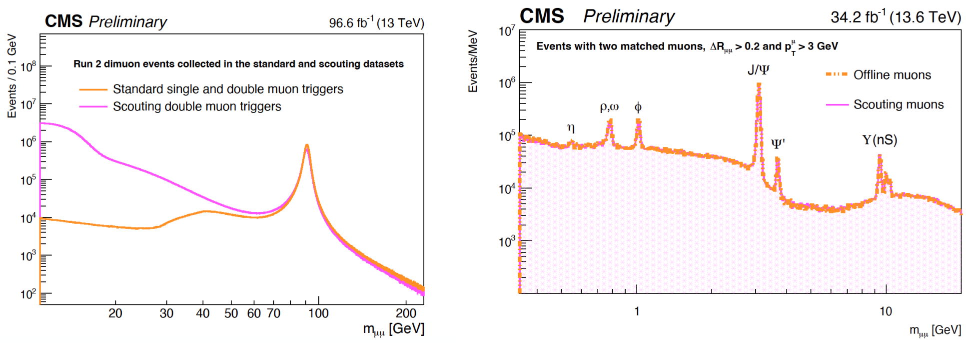

Figure 4: Left: Dimuon invariant mass spectrum reconstructed using events collected in Run 2 by standard (orange) and scouting (magenta) triggers at the CMS experiment. Right: Dimuon invariant mass spectrum obtained using events collected in 2022 by scouting triggers, reconstructed by the offline reconstruction (orange) and at trigger level (magenta) [16].

3.1 $\eta \to 4\mu$ BR measurement

Events collected by the scouting triggers in 2017 and 2018 were selected to reconstruct the $\eta \to 4\mu$ and $\eta \to 2\mu$, the latter used as a normalisation channel for the $\eta \to 4\mu$ BR measurement as described by the following equation:

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{\mathrm{i,j}} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}} \tag{5}$$

where $\mathcal{B}_{2\mu} = (5.8 \pm 0.8) \times 10^{-6}$ [7], $N_{4\mu}$ and $N_{2\mu}$ are the $\eta \to 4\mu$ and $\eta \to 2\mu$ measured yield respectively, and $A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$ are the detector acceptance and reconstruction efficiencies for the two channels, estimated from simulated samples in bins of pseudorapidity and p_{T} of the η meson. Figure 5 (left) shows the dimuon invariant mass distribution used for the $\eta \to 2\mu$ yield measurement, while the four-muons invariant mass distribution of the selected signal candidates is reported in Figure 5 (right), together with the background and signal fit for the yield extraction. The peak at the η mass exceeds 5 standard deviations statistical significance and the $\eta \to 4\mu$ BR is measured to be:

$$\mathcal{B}_{4\mu} = [5.0 \pm 0.8(\mathrm{stat}) \pm 0.7(\mathrm{syst}) \pm 0.7(\mathcal{B}_{2\mu})] \times 10^{-9} \tag{6}$$

where the uncertainty realative to the $\mathcal{B}_{2\mu}$ value has been factorised out. The measurement, compatible with the SM prediction, constitutes the first observation of this rare decay mode.

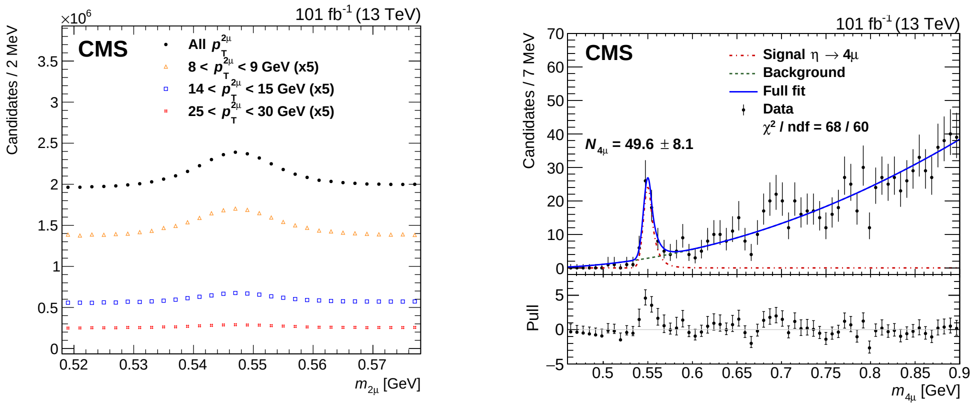

Figure 5: Left: dimuon invariant mass distribution around the η meson mass obtained with data collected using the scouting triggers. Right: m(4μ) invariant mass distribution with the fit result overlaid [15].

4. Trigger strategies in Run 3

For both the ATLAS and CMS experiment the large statistics collected in Run 2 still brings large potential for rare decay searches. Nevertheless, this potential partially comes from the adoption of dedicated trigger strategies to enhance the detector sensitivity to decays involving low-p_T muons. At CMS, the *scouting* trigger strategy continues in Run 3 to explore low mass muon resonances as shown in Figure 4 (right). In parallel, the so-called "parking" strategy allows collecting events with soft dimuon triggers, where the resulting large datasets are fully reconstructed whenever the computing resources are available, thus allowing for rare decay searches as well as angular analyses with full precision [17].

5. Conclusions

In this contribution recent results by ATLAS and CMS in the field of rare flavour decays have been discussed. They include studies of $B^0_{(s)} \to \mu^+\mu^-$ decays properties by both experiments, and the recent observation of the rare $\eta \to 4\mu$ decay at CMS. The central role played by dedicated trigger strategies in these achievements have been highlighted, where further enhancement in the detector sensitivity to rare decays involving soft muons is expected in Run 3.

References

[1] ATLAS Collaboration, *"The ATLAS Experiment at the CERN Large Hadron Collider"*, *J. Instrum.* **3**, S08003 (2008). doi: 10.1088/1748-0221/3/08/S08003

[2] CMS Collaboration, *"The CMS experiment at the CERN LHC"*, *J. Instrum.* **3**, S08004 (2008). doi: 10.1088/1748-0221/3/08/S08004

[3] L. Evans and P. Bryant, *"LHC Machine"*, *J. Instrum.* **3**, S08001 (2008). doi: 10.1088/1748-0221/3/08/S08001

[4] CMS Collaboration, *"HLT Dimuon Invariant Mass Distributions In 2017 and 2018"*, CMS-DP-2018-055 (2018).

[5] ATLAS Collaboration, *"B-Physics trigger performance plots from 13 TeV data collected in 2018"*, ATL-COM-DAQ-2019-040 (2019).

[6] CMS and LHCb Collaborations, *"Observation of the rare $B^0_s \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data"*, Nature **522**, 68 (2015). doi: 10.1038/nature14474.

[7] Particle Data Group, R.L. Workman, et al., *"Review of particle physics"*, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022). doi: 10.1093/ptep/ptac097.

[8] CMS Collaboration, *"Measurement of the $B^0_s \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s}$ = 13 =13 TeV"*, *Phys. Lett.* B **842**, 2023 (137955). doi: 10.1016/j.physletb.2023.137955.

[9] LHCb Collaboration, *"Precise measurement of the f_s/f_d ratio of fragmentation fractions and of B^0_s decay branching fractions"*, Phys. Rev. D **104**, 2021 (032005). doi: 10.1103/PhysRevD.104.032005.

[10] ATLAS Collaboration, *"Measurement of the $B^0_s \to \mu^+\mu^-$ effective lifetime with the ATLAS detector"*, *J. High Energy Phys.* **2309**, 2023 (199). doi: 10.1007/JHEP09(2023)199.

[11] ATLAS Collaboration, *"Study of the rare decays of B^0_s and B^0 mesons into muon pairs using data collected during 2015 and 2016 with the ATLAS detector"*, *J. High Energy Phys.* **2019**, 2019 (098). doi: 0.1007/JHEP04(2019)098.

[12] M. Pivk and F.R. Le Diberder, *"SPlot: A Statistical tool to unfold data distributions"*, Nucl. Instrum. Meth. A **555**, 2019 (356). doi: 10.1016/j.nima.2005.08.106

[13] L. Gan et al., *"Precision tests of fundamental physics with η and η^0 mesons"*, Phys. Rep. **945**, 2022 (1). doi: 10.1016/j.physrep.2021.11.001.

[14] E. Goudzovski et al., *"New physics searches at kaon and hyperon factories"*, Rep. Prog. Phys. **86**, 2023 (016201). doi: 10.1088/1361-6633/ac9cee.

[15] CMS Collaboration, *"Observation of the Rare Decay of the η Meson to Four Muons"*, *Phys. Rev. Lett.* **131**, 2023 (091903). doi: 10.1103/PhysRevLett.131.091903.

[16] CMS Collaboration, *"Dimuon scouting at CMS"*, CMS-DP-2023-070 (2023).

[17] E. Fontanesi on behalf of the CMS Collaboration, *"New trigger strategies for CMS during Run 3"*, PoS(ICHEP2022) **414**, 2022 (681). doi: 10.22323/1.414.0681.