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Rare decays at CMS and Run 3 perspectives(*)

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Summary. — A summary of the recent results obtained by the CMS experiment regarding the search for rare decays in proton-proton collisions at a center-of-mass energy of 13 TeV is presented. These results include the search for the decay $\tau \to \mu\mu\mu$ and the first observation of the decay $\eta \to \mu\mu\mu\mu$. Additionally, improvements to the trigger system for Run 3 and their implications for this type of research will be discussed.

1. – Introduction

Rare decays are those processes particularly suppressed in the Standard Model (SM). In this proceeding we are interested in decays with precisely known theoretical predictions, which are sensitive to New Physics (NP), whose branching ratio (BR) can be affected by NP. In addition, these decays can be experimentally accessible at CMS, if the predicted BR by theory is at least 10^{-9}. Such small BRs are accessible due to the remarkable trigger system of CMS [6] (particularly for muon system).

This contribution focuses on rare decays, specifically highlighting two main categories:

- Multi-muonic decays of neutral mesons. In particular, we will focus on $\eta \to 4\mu$ [11] and $J/\psi \to 4\mu$ [10];
- Decays forbidden by accidental symmetries of the SM, namely processes involving lepton universality violation (LUV), lepton number violation (LNV), and lepton flavor violation (LFV). We will focus on the LFV $\tau \to 3\mu$ decay [4].

Analyzing these rare phenomena requires a significant amount of data, constrained by the trigger rate. To address this issue, the three analysis we selected adopted three different approaches: Scouting, B-Parking, and Standard [12].

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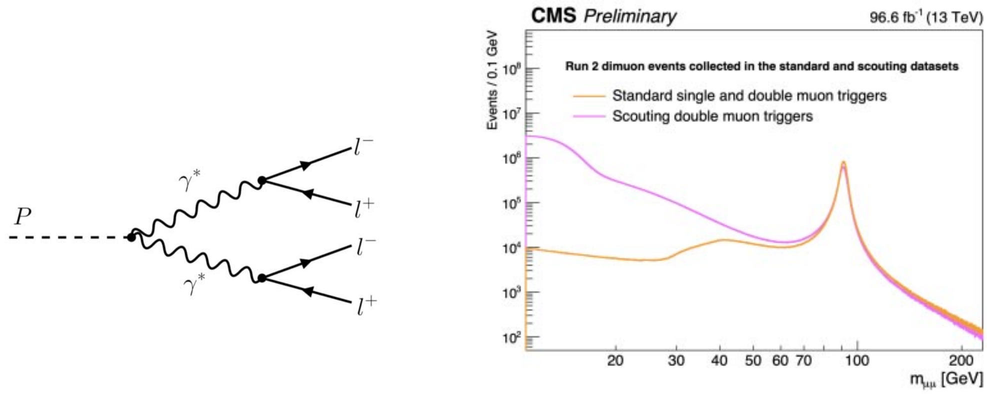

Fig. 1. – Feynman diagram of $\eta \to 4\mu$ in the SM via double-Dalitz decays [11] (left); Run 2 di-muon events collected by the standard and scouting triggers [2] (right).

2. – Observation of the rare $\eta \to 4\mu$ decay

The leptonic radiative decays of η mesons are strongly suppressed in the SM because they can only occur as electromagnetic transitions. For this reason, their exploration can serve as a test of the SM and an investigation on NP dynamics.

Regarding specifically the decay $\eta \to 4\mu$, the SM predicts a BR of $(3.98 \pm 0.15) \times 10^{-9}$ [7], depicted by a Feynman diagram similar to that shown in fig. 1 (left). However, this limit can be altered by the introduction of new theories predicting hidden photons, light scalar Higgs bosons, axions, or by the violation of some discrete symmetry.

2·1. *Data and Trigger Strategy*. – The $\eta \to 4\mu$ search is performed with data collected by CMS during 2017 and 2018 in proton-proton collisions at a center-of-mass energy of $\sqrt{s}$= 13 TeV, corresponding to an integrated luminosity of 101 fb^{-1}.

Events with at least two muons in the final state and an invariant mass below 40 GeV are being searched for. However, in this region the efficiency of the standard trigger used at CMS is poor. For this reason, a dedicated di-muon trigger based on the data scouting technique has been developed. This technique allows for the acquisition of more events while maintaining the same bandwidth as the standard stream. To achieve this, a high-rate trigger ($\sim$ 2 kHz) is used, but only a limited amount of information per event is saved ($\sim$ 8 kB/event). The comparison between the two triggers, shown in fig. 1 (right), clearly demonstrates the advantage of using this strategy in the invariant mass region below 40 GeV.

2·2. *Analysis Strategy and Results*. – Events that pass the trigger are further filtered by requiring four muons that form a good common vertex and have a total charge of zero. Then, the BR of $\eta \to 4\mu$ is evaluated relative to the BR of $\eta \to 2\mu$ using:

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}} , \tag{1}$$

where:

- i and j refer to p_T and η bins;
- $A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$ are the efficiencies of the two decays measured in MC simulations in each i,j bin, shown in fig. 2 (left);
- $N_{4\mu}$ and $N_{2\mu}^{i,j}$ are the yields of the two decays measured in data;
- $\mathcal{B}_{2\mu} = (5.8 \pm 0.8) \times 10^{-6}$ [14] is the BR of $\eta \to 2\mu$.

A peak is observed in the invariant mass spectrum of the four muons (fig. 2 (right)) with a statistical significance greater than 5 sigma, corresponding to $N_{4\mu} = 49.6 \pm 8.1$. By inserting this value into eq. (1), a result of $(5.0 \pm 0.8(stat) \pm 0.7(syst) \pm 0.7(\mathcal{B}_{2\mu})) \times 10^{-9}$ is obtained, which is compatible with the expected value from the SM.

3. – Observation of the $J/\psi \to 4\mu$ decay

The leptonic decay $J/\psi \to 4\mu$ is suppressed in the SM and can occur only with a virtual Z or γ, as shown in fig. 3 (left). The BR expected from the SM is $(9.74 \pm 0.05) \times 10^{-7}$ [1]. However, this decay is sensitive to the presence of NP because new particles could replace the γ^* or Z^* in the decay, altering its branching ratio [9].

3˙1. *Data and Trigger Strategy.* – The $J/\psi \to 4\mu$ search is performed with data collected by CMS during 2018 in proton-proton collisions at a center-of-mass energy of $\sqrt{s}$= 13 TeV for an integrated luminosity of 33.6 fb^{-1}.

In this analysis, the B-Parching technique [12] was used. This dataset consists of events collected by single muon triggers with a variable rate that increases stepwise as the rate of the Physics Stream decreases (as shown in fig. 3 (center)). The idea is to trigger on a muon originating from the decay of a b quark without making assumptions about the other b quark in the event. This approach produces an unbiased sample of decays of hadrons containing b quarks. With this approach the trigger rate is very high. So, the data are "parked" and analyzed only when computational resources are available.

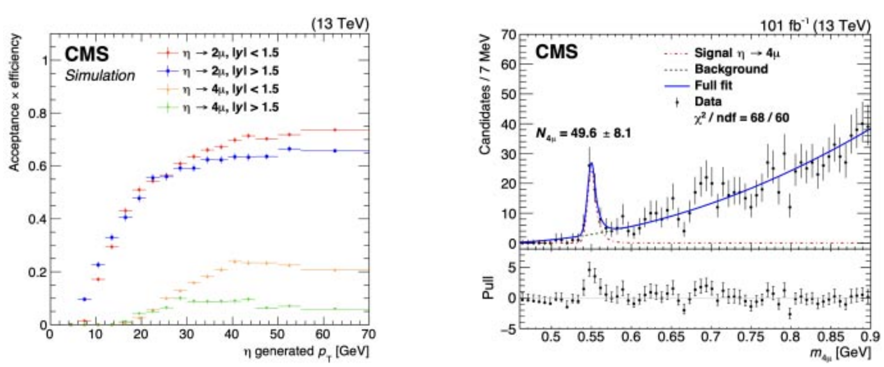

Fig. 2. – $\eta \to 2\mu$ and $\eta \to 4\mu$ efficiencies measured with MC simulations (left) [11]; 4μ invariant mass fit (right) [11].

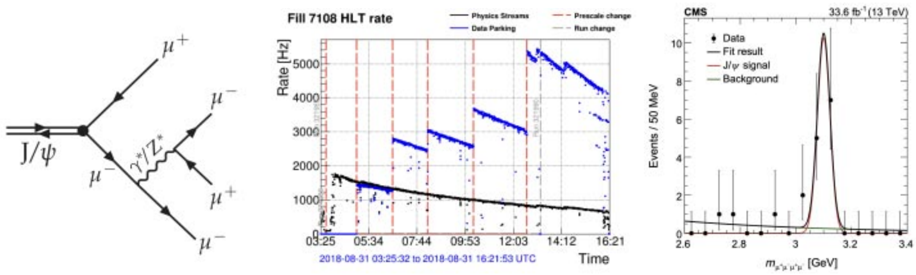

Fig. 3. – Feynman diagram of $J/\psi \to 4\mu$ decay in the SM (left) [10]; Example of B-Parking trigger rate during a fill (center) [3]; Invariant mass spectrum of the 4μ with fit (right) [10].

3˙2. *Analysis Strategy and Results.* – Events that pass the trigger are further filtered by requiring four muons with $|\eta| < 1.5$ and $p_T > 3.5$ GeV, total charge zero, 2.6 GeV $< m_{4\mu} < 3.4$ GeV and forming a good common vertex. Then the BR of $J/\psi \to 4\mu$ is evaluated relative to the BR of $J/\psi \to 2\mu$ using eq. (2)

$$\frac{\mathcal{B}_{J/\psi\to 4\mu}}{\mathcal{B}_{J/\psi\to 2\mu}} = \frac{N_{J/\psi\to 4\mu}}{N_{J/\psi\to 2\mu}} \frac{\epsilon_{J/\psi\to 2\mu}}{\epsilon_{J/\psi\to 4\mu}} \, , \tag{2}$$

where:

- $\epsilon_{J/\psi\to 2\mu}$ and $\epsilon_{J/\psi\to 4\mu}$ are the efficiencies obtained from the MC.
- $N_{J/\psi\to 2\mu}$ and $N_{J/\psi\to 4\mu}$ are the yields of the two decays measured in data;
- $\mathcal{B}_{J/\psi\to 2\mu} = (5.961 \pm 0.033) \times 10^{-2}$ [14] is the BR of $J/\psi \to 2\mu$.

A peak is observed in the invariant mass spectrum of the four muons, fig. 3 (right), with a statistical significance greater than 5 sigma, corresponding to $N_{J/\psi\to 4\mu} = 11.6^{+3.8}_{-3.1}$. Using eq. (2), a result of $(11.1^{+3.3}_{-2.7}(stat) \pm 0.4(syst)) \times 10^{-7}$ is obtained, which is compatible with the SM prediction.

4. – Search for the $\tau \to 3\mu$ decay

The SM allows LFV decays, like the $\tau \to 3\mu$ one, through neutrino oscillation, but with small BRs. In the $\tau \to 3\mu$ case the expected BR is $\mathcal{O}(10^{-54})$ [13]. However, NP theories can predict significantly higher BRs, even at the level of $O(10^{-8})$, which are experimentally observable. Therefore, the $\tau \to 3\mu$ decay serves as a testing ground to probe these theories.

4˙1. *Analysis Strategy and Results.* – The $\tau \to 3\mu$ search is performed with data collected by CMS during 2017 and 2018 in proton-proton collisions at a center-of-mass energy of $\sqrt{s}$= 13 TeV for an integrated luminosity of 97.7 fb^{-1}. The analysis consists of two independent channels: Heavy flavour (HF) (τ from decays of B and D mesons) and W (τ from decay of the W boson). For each of those a dedicated trigger has been developed. The trigger selects three muons with a total charge of ± 1, referred to as a "triplet". Offline selections are then applied based on the expected final state, namely three muons that form a good common vertex, with an invariant mass of the triplet between 1.6 and 2 GeV, and selections are applied to the muon quality reconstruction.

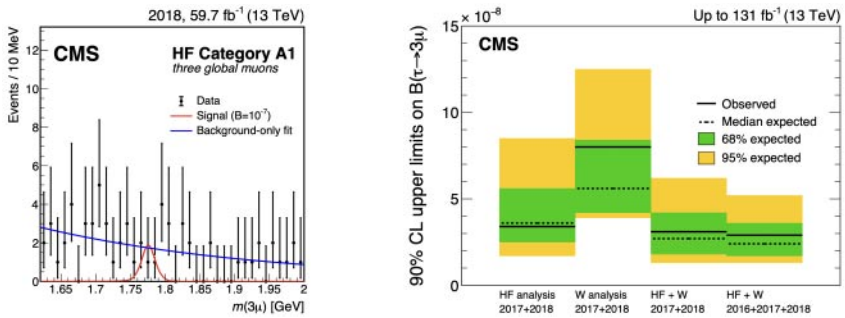

Fig. 4. – Invariant mass fit with Gaussian + Crystal Ball and an exponential for one of the HF categories (left) [4]; Observed and expected upper limits on BR the BR at 90% C.L. for the two channels and their combination (right) [4].

Background suppression is further applied by vetoing resonances like $\varphi \to \mu\mu$ and $\omega \to \mu\mu$, and by removing K or π mesons misidentified as muons using a multivariate analysis (MVA) specifically developed for the HF channel. Finally, to suppress combinatorial background, a boosted decision tree (BDT) is trained to discriminate it (extracted from data in the mass sidebands) from the signal (obtained via Monte Carlo simulations).

The events are then categorized based on the invariant mass resolution and the BDT score, and for each category, a maximum likelihood fit is performed as shown in fig. 4 (left). Observed (Expected) upper limits (UL) on the BR are determined using the CL$_s$ criterion, and the obtained result is $3.1(2.7) \times 10^{-8}$ at 90% C.L.. Combining this result with the one by CMS in 2016 [5] we obtain the full Run 2 result for CMS: $2.9(2.4) \times 10^{-8}$ at 90% C.L..

5. – Run 3 Perspectives

The extensive dataset collected by CMS during Run 2 provides significant opportunities for exploring rare decays. However, greater expectations are now focused on the data being collected in Run 3 due to the changes in the trigger strategy.

In particular, Run 3 introduces a new inclusive di-muon trigger suitable for various studies including $b \to s\ell\ell$, charmonium spectroscopy, beauty hadron spectroscopy, LFV $\tau \to 3\mu$, exotic searches, and $\eta \to \mu^+\mu^-e^+e^-$.

Additionally, a di-electron trigger was included in 2022 for probing LUV [8]. Furthermore, improvements to the scouting trigger have been implemented, resulting in increased rate and enhanced muon reconstruction performance that now closely matches the offline one [12].

6. – Conclusion

In this contribution, we have described three analyses with muons in the final state, made possible by three different trigger strategies (Scouting, B-Parking, and Standard): $\eta \to 4\mu$ and $J/\psi \to 4\mu$ both observed for the first time; $\tau \to 3\mu$ for which we set the best UL achieved at a hadron collider. Additionally, we have described the improvements to the trigger that will enable even better results with the Run 3 data.

REFERENCES

[1] Chen W. *et al.*, *Phys. Rev. D*, **104** (2021) 094023.
[2] CMS Collaboration, CMS-DP-2023-070 (2023).
[3] CMS Collaboration, CMS-DP-2019-043 (2019).
[4] CMS Collaboration, *Phys. Lett. B*, **853** (2024) 138633.
[5] CMS Collaboration, *J. High Energy Phys.*, **2021** (2021) 163.
[6] CMS Collaboration, *JINST*, **3** (2008) S08004.
[7] Escribano R. and Gonzàlez-Solís S., *Chin. Phys. C*, **42** (2018) 023109.
[8] Fontanesi E., *PoS*, **ICHEP2022** (2022) 681.
[9] Gütschow C. and Schönherr M., *Eur. Phys. J. C*, **81** (2021) 48.
[10] CMS Collaboration, *Phys. Rev. D*, **109** (2024) L111101.
[11] CMS Collaboration, *Phys. Rev. Lett.*, **131** (2023) 091903.
[12] CMS Collaboration, CERN-EP-2024-068 (2024).
[13] G. Hernández-Tomé, G. López Castro and P. Roig, *Eur. Phys. J. C*, **80** (2020) 438.
[14] Particle Data Group (Navas S. *et al.*), *Phys. Rev. D*, **110** (2024) 030001.