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Observation of the Rare Decay of the η Meson to Four Muons

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A search for the rare $\eta \to \mu^+\mu^-\mu^+\mu^-$ double-Dalitz decay is performed using a sample of proton-proton collisions, collected by the CMS experiment at the CERN LHC with high-rate muon triggers during 2017 and 2018 and corresponding to an integrated luminosity of 101 fb^{-1}. A signal having a statistical significance well in excess of 5 standard deviations is observed. Using the $\eta \to \mu^+\mu^-$ decay as normalization, the branching fraction $\mathcal{B}(\eta \to \mu^+\mu^-\mu^+\mu^-) = [5.0 \pm 0.8(\mathrm{stat}) \pm 0.7(\mathrm{syst}) \pm 0.7(\mathcal{B}_{2\mu})] \times 10^{-9}$ is measured, where the last term is the uncertainty in the normalization channel branching fraction. This work achieves an improved precision of over 5 orders of magnitude compared to previous results, leading to the first measurement of this branching fraction, which is found to agree with theoretical predictions.

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The η and $\eta\prime$ mesons are $J^{PC} = 0^{-+}$ particles with masses of 547.9 and 957.8 MeV, respectively, comprising admixtures of up, down, and strange quarks [1]. Despite a comprehensive experimental campaign [2–6] to study these light mesons, several properties of the η and $\eta\prime$ remain unmeasured. Their leptonic radiative decays, also known as Dalitz decays, constitute such an example. They proceed via the electromagnetic coupling of pseudoscalar mesons to the photon, where one or more of the photons internally convert into a pair of leptons, as shown in Fig. 1. Such decays are typically highly suppressed because they can only occur through these electromagnetic interactions instead of the comparatively stronger nuclear interactions. To date, the only observed leptonic radiative decays are $\eta \to \mu^+\mu^-$, $\eta \to e^+e^-e^+e^-$, and, more recently, $\eta\prime \to e^+e^-e^+e^-$ [3–5]. The decays $\eta \to e^+e^-$, $\eta \to \mu^+\mu^-\mu^+\mu^-$, $\eta \to e^+e^-\mu^+\mu^-$, and most $\eta\prime$ decays have so far eluded discovery. Observing these rare decays is important because they can serve as precision tests of the standard model, they offer sensitivity to an array of new physics scenarios [7,8], and the interaction between pseudoscalars and photons contributes to the hadronic light-by-light component of the anomalous magnetic moment of the muon [7,9]. A thorough description of radiative decays and their impact on several relevant standard model observables, as well as their sensitivity to new physics, can be found in Ref. [8].

In this Letter, we report the first observation of the muon double-Dalitz decay of the η meson, $\eta \to \mu^+\mu^-\mu^+\mu^-$, using $\sqrt{s} = 13$ TeV proton-proton (pp) collision data collected by the CMS experiment during 2017 and 2018 at the LHC. The predicted branching fraction for this decay channel is extremely small, $\mathcal{B}(\eta \to 4\mu) = (3.98 \pm 0.15) \times 10^{-9}$ [10], making its observation particularly challenging. The analysis measures the rate of $\eta \to 4\mu$ events compared to the normalization channel $\eta \to 2\mu$ [3], for which the branching fraction is known with a precision of 14% [1]. The product of the CMS detector acceptance and signal efficiency, as well as systematic uncertainties, is evaluated with simulation studies for both channels. Tabulated results are provided in the HEPData record for this analysis [11]. The defining feature of the measurement is the use of high-rate triggers, which extends the sensitivity of CMS to dimuon and four-muon resonances of masses lower than what is achievable with the standard muon triggers [12], leading to an improved precision of 5 orders of magnitude compared to previous works [13].

The CMS apparatus is a multipurpose detector designed to trigger on and identify electrons, muons, photons, and (charged and neutral) hadrons [14–16]. A superconducting solenoid of 6 m internal diameter provides a magnetic field

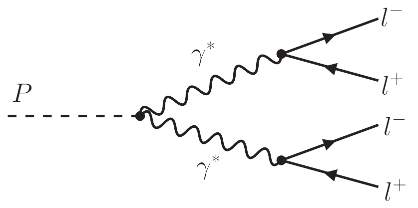

FIG. 1. Feynman diagram of pseudoscalar decays into four leptons, known as double-Dalitz decays.

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of 3.8 T. Within the solenoid volume are the silicon pixel and strip tracker, a crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid, covering the pseudorapidity range $|\eta| < 2.4$. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [17].

Events are first selected by the two-tiered trigger system [12]. The first tier (level-1, or L1) is a hardware-based trigger that uses information from the calorimeters and the muon detectors to select events at a rate of roughly 100 kHz. The second tier (high-level trigger, or HLT) consists of a farm of processors running the CMS reconstruction software optimized for fast online processing. The HLT processes events at an output rate of about 1 kHz with approximately 1 MB/event, a limit imposed by the total available data transfer bandwidth. These are the "standard triggers" [18]. The standard dimuon triggers require one muon with transverse momentum p_T larger than 12(15) GeV at L1 in 2017(2018) and 17 GeV at HLT, and a second muon with p_T at least 5(7) GeV at L1 in 2017 (2018) and 8 GeV at HLT. These triggers collect data at a rate of about 30 Hz at a peak instantaneous luminosity of $2 \times 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [18].

For dimuon resonance masses below about 40 GeV, the performance of the standard muon triggers deteriorates. To improve efficiency for those masses, a dedicated set of high-rate dimuon triggers was developed. These triggers allow considerably lower muon p_T thresholds but store only a limited amount of information per event, ensuring that the total data transfer bandwidth remains affordable. The information stored in the event includes only muons reconstructed at the HLT, apart from additional limited event-level information, leading to an event size of around 4 kB in 2017 and 8 kB in 2018 [18]. This strategy, first introduced by the CMS Collaboration in 2012, is referred to as "data scouting" [18–20].

The high-rate triggers include several requirements at L1, described in Table I. The fraction of events passing the full four-muon selection that is accepted by each path is shown in the last column. The first L1 path (#1) collects most of the events of interest for the dimuon invariant mass ($m_{2\mu}$) region below about 1 GeV; the decay products of the η meson are generally collimated, given the small mass of the η meson and its comparatively high p_T distribution. At the HLT, each of the two muons is further required to have a p_T of at least 3 GeV. These high-rate triggers were commissioned in 2017 and found to provide a rate of about 2 kHz at the peak instantaneous luminosity of $2 \times 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [18], more than 60 times the rate of the standard muon triggers. The data were collected in 2017 and 2018, corresponding to an integrated luminosity of 101 fb^{-1} [21–23].

TABLE I. Set of dimuon L1 requirements applied in the high-rate triggers. The angular separation between muons in the η-ϕ plane is defined as $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where ϕ is the azimuthal angle. The first L1 path requires, for each muon, $p_T >$ 4.0(4.5) GeV in 2017 (2018). The third path imposes separate requirements on each muon p_T. The $m_{2\mu}$ column denotes a range of allowed dimuon invariant masses. The charge column indicates if an opposite-sign (OS) requirement exists between muons. The last column reports the fraction of selected events accepted by each path.

L1 path	p_T [GeV]	$\lvert\eta\rvert$	ΔR	$m_{2\mu}$ [GeV]	Charge	Fraction
#1	> 4.0 (4.5)	…	< 1.2	…	OS	90%
#2	…	< 1.5	< 1.4	…	OS	48%
#3	> 15, > 7	…	…	…	…	46%
#4	> 4.5	< 2.0	…	7–18	OS	9%

Events passing the high-rate trigger requirements are further selected to improve the signal-to-background discrimination. The $\eta \to 2\mu$ selection requires two oppositely charged muons consistent with production at a common origin (i.e., vertex). The vertex reconstruction is based on a Kalman filtering algorithm [24] and performed pairwise, regardless of the decay channel. The $\eta \to 4\mu$ selection requires four muons with a net charge of zero, which are also consistent with a common origin. In this case, the full set of six dimuon vertices must be reconstructed and compatible in position. In both two- and four-muon selections, more than one combination of muons ("candidates") per event is allowed if all muons satisfy the listed requirements, but in both cases, more than 98% of events in the signal mass window 0.53–0.57 GeV feature only one passing combination. To maximize the signal efficiency for reconstructing and identifying candidate η meson decays, no additional selection is applied.

Figure 2 shows the $m_{2\mu}$ spectrum in the region around the η meson mass, 0.518–0.578 GeV, obtained with data collected using the high-rate triggers after applying the two-muon selection. The distributions are shown for the inclusive dimuon p_T ($p_T^{2\mu}$) range and additionally for three slices, 8–9, 14–15, and 25–30 GeV, highlighting the rapid decrease of the production cross section with $p_T^{2\mu}$. A binned maximum likelihood fit to the total spectrum with a sum of two Gaussian functions and a third-order Chebychev polynomial reveals approximately 4.5 million $\eta \to 2\mu$ decays. Given the branching fraction $\mathcal{B}(\eta \to 2\mu) = (5.8 \pm 0.8) \times 10^{-6}$ [1], the total number of η mesons produced in the sensitive kinematic region of the CMS detector is about 10^{12}, neglecting reconstruction inefficiencies. This huge η production rate is critical for the study of its rare decay channels.

Figure 3 shows the four-muon invariant mass ($m_{4\mu}$) distribution in the range 0.46–0.90 GeV, obtained with data collected using the high-rate triggers after applying the

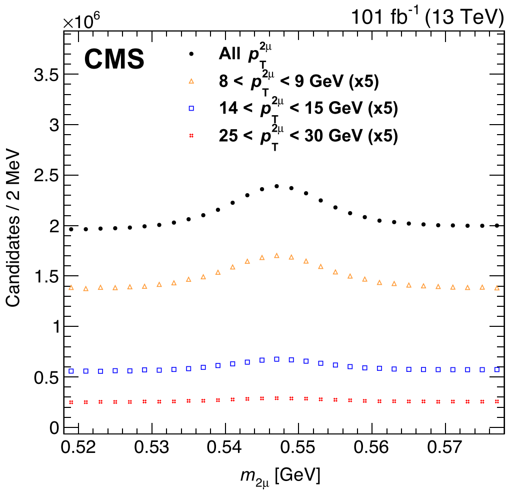

FIG. 2. Distribution of $m_{2\mu}$ obtained with the dimuon selection integrated in dimuon p_T and in three p_T ranges as indicated in the legend, with the number of events in the selected p_T ranges multiplied by 5 for better visibility.

four-muon selection. A clear peak is observed in the signal mass window 0.53–0.57 GeV, corresponding to the η meson mass. A binned maximum likelihood fit of the spectrum to the sum of a single-sided Crystal-Ball function [25] for the signal and a threshold function proportional to $(m_{4\mu} - 4m_\mu)^\beta$ for the background, where m_μ is the muon mass and β is a free parameter of the fit, yields $N_{4\mu} = 49.6 \pm 8.1$ signal events and 16.6 ± 0.6 background events (in the signal mass window). The parameters of the signal function, except for the normalization, are fixed from simulation. This corresponds to a statistical significance in excess of 5 standard deviations, determined by means of a log-likelihood ratio test with a saturated model [26], under a signal-plus-background (S + B) hypothesis compared to the background-only assumption.

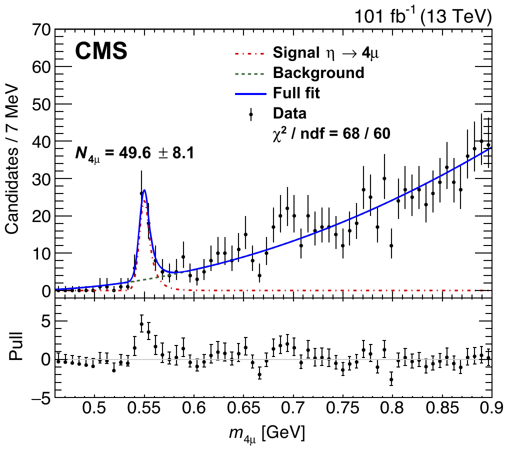

FIG. 3. Measured $m_{4\mu}$ distribution, with the fit result overlaid. The pull distribution in the lower panel is shown relative to the background component of the fit model and defined as (Data−FitBkg)/$\sqrt{\sigma^2_{\text{Data}} - \sigma^2_{\text{FitBkg}}}$. Uncertainties are statistical only.

Simulated samples of rare η decays are generated at leading order with a custom workflow. The first step employs the PLUTO v6 generator [27] to simulate the two- and four-muon decays of the η meson in its rest frame, using the vector meson dominance model [28]. Subsequently, the η meson and its decay products are boosted to the laboratory frame by sampling from uniform p_T and rapidity distributions in the 5–70 GeV and $|y| < 2.4$ ranges, respectively. The decay products are then embedded into complete CMS events, which also include the simulation of fragmentation, parton shower, and hadronization processes in the initial and final states with the PYTHIA 8.230 package [29], and simulation of the underlying event with the CP5 tune [30]. The location of the decay products in the detector is sampled from the distribution of the beam envelope. Finally, the interaction of final-state particles with the CMS detector is simulated using the GEANT4 toolkit [31]. Simulated events include the contribution of additional particles produced in time within the same or nearby bunch crossings. The multiplicity of vertices is matched to the one observed in the data.

To check whether the observed peak is indeed compatible with the $\eta \to 4\mu$ decay, the signal simulation was used to predict the four-muon p_T ($p_T^{4\mu}$) spectrum for the experimentally measured branching fraction $\mathcal{B}(\eta \to 4\mu)$ of 5×10^{-9} (described later). The signal $p_T^{4\mu}$ distribution was reweighted based on the η meson p_T differential production rate measured with the two-muon channel. Figure 4 compares the predicted distribution to the measured spectrum and to the expected background, obtained from events with $m_{4\mu}$ within the 0.6–0.9 GeV sideband, where no signal is expected. The shape is then normalized such that the total background yield is fixed to the one extracted from the $m_{4\mu}$ fit. The correlation between $p_T^{4\mu}$ and $m_{4\mu}$ for background events was verified to be weak by comparing the $m_{4\mu}$ spectrum across several $p_T^{4\mu}$ ranges. The sum of the predicted signal and background contributions agrees with the observation. An additional check was performed by applying a tight muon selection to muons in the signal mass window and in the sideband, and by comparing the fraction of muons surviving the selection between the two regions. This selection requires at least six energy deposits per muon track in the silicon tracker, of which at least one is in the pixel layers, and a track $\chi^2/\text{ndf} < 10$, where ndf is the number of degrees of freedom. About 99% of four-muon combinations passed this selection in the signal mass window, compared to only 84% in the sideband. Since the sidebands presumably contain more hadrons misidentified as muons, this indicates a negligible contamination of such hadrons in the signal region.

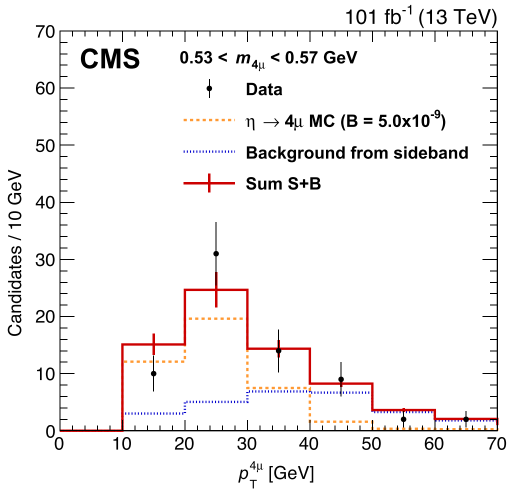

FIG. 4. Comparison of the four-muon p_T spectrum observed in data with $0.53 < m_{4\mu} < 0.57$ GeV (black points) and the signal prediction from simulation assuming the observed branching fraction (orange dashed line). Also shown is the predicted background shape, extracted from the mass sideband, normalized to the background fit yield (dotted blue line), and the sum of signal and background predictions (solid red line).

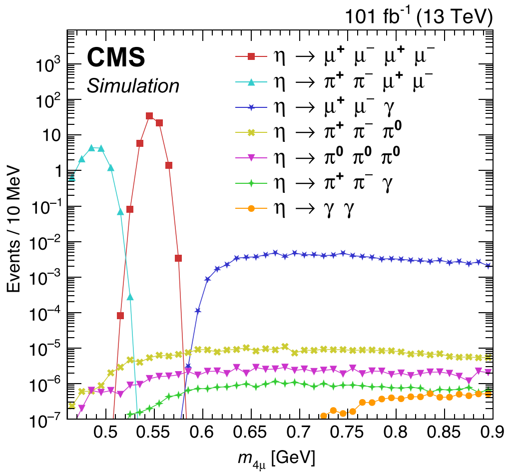

FIG. 5. Predicted background contributions to the signal mass window, estimated with simplified MC simulations. The $\eta \to \mu^+\mu^-\mu^+\mu^-$ signal is displayed as a benchmark (red squares), followed by various other decay modes of the η meson. The curves are normalized to an integrated luminosity of 101 fb^{-1}. For unobserved decay modes, the current experimental upper limits are conservatively taken as the reference branching fractions in the estimations, with the exception of the signal channel, where the branching fraction measured in this work is used.

To ensure that the observed peak cannot be explained by other resonant backgrounds, such as additional decay modes of the η meson, we studied these modes using simplified Monte Carlo (MC) simulations. The decay chains are simulated via a series of two-body decays of the form $M \to m_1 m_2$. The results are reported in Fig. 5. Decays with final-state photons (or neutral pions) could mimic the four-muon signal if a photon converts to a pair of muons after interacting with detector material. However, in this case, the nearby nucleus imparts a momentum kick to the system and increases its total invariant mass. Therefore, as a general feature of this topology, backgrounds involving photons do not present a peak in the signal mass window. The only peaking background is $\eta \to \pi^+\pi^-\mu^+\mu^-$, where both pions are misidentified as muons. Here, however, the difference in mass between the two particles shifts the invariant mass peak down to about 0.48 GeV, sufficiently below the signal mass window. Furthermore, this decay mode has never been observed. The current experimental upper limit of $\mathcal{B}(\eta \to \pi^+\pi^-\mu^+\mu^-) < 1.6 \times 10^{-4}$ at the 90% confidence level [13], which is considerably higher than the theoretical prediction of 6.5×10^{-9} [32], is used in our estimate. Based on these studies, we conclude that other decay modes of the η meson provide a negligible contribution to the selected events.

The simulated samples of $\eta \to 4\mu$ and $\eta \to 2\mu$ events are used to evaluate the total signal efficiencies $A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$, respectively, given by the product of detector geometric acceptance and reconstruction and selection efficiencies, as functions of p_T for two rapidity regions: $|y| < 1.5$ and $1.5 < |y| < 2.4$. Figure 6 shows the total efficiencies vs p_T, split by rapidity range. In two-muon decays, $A_{2\mu}^{i,j}$ is limited by the trigger efficiency, reaching a plateau of about 70%. In contrast, in four-muon decays, the efficiency to reconstruct all four muons in the event has a maximum value of about 15%. The low-p_T behavior is understood to be correlated with the minimum p_T of about 3.5 GeV required

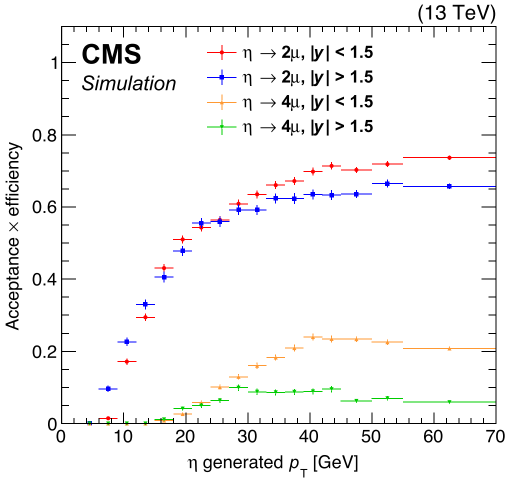

FIG. 6. Total efficiencies for the four-muon ($A_{4\mu}^{i,j}$, red and blue points) and two-muon ($A_{2\mu}^{i,j}$, orange and green points) decay channels, as functions of the generated meson's p_T and y, evaluated through MC simulation.

for a muon in the central region to reach the muon detectors. The high-$p_T^{4\mu}$ dropoff, in turn, comes from the difficulty of reconstructing four muons with very small angular separation, owing to the boost of the parent η meson.

The branching fraction $\mathcal{B}_{4\mu} \equiv \mathcal{B}(\eta \to 4\mu)$ is determined relative to $\mathcal{B}_{2\mu} \equiv \mathcal{B}(\eta \to 2\mu)$ using

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

where $N_{4\mu}$ is the total four-muon signal yield, $N_{2\mu}^{i,j}$ are the two-muon signal yields in bins i and j of the candidate η meson's p_T and rapidity, and $A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$ are the corresponding efficiencies. We define 32 bins in p_T in the range 7–70 GeV and two bins in $|y|$. Because of the relative nature of the measurement, several uncertainties cancel out when considering the ratio of quantities. Remaining uncertainties are assessed for each component of Eq. (1). The uncertainty on $\mathcal{B}_{2\mu}$ is 14% [1], while the statistical uncertainty on $N_{4\mu}$ is estimated to be 16% from the fit shown in Fig. 3. A similar source of uncertainty would arise from the measurement of $N_{2\mu}^{i,j}$, but it is negligible compared to the other uncertainties when considering the large sample of $\eta \to 2\mu$ decays.

The remaining dominant uncertainties are systematic in nature and arise from incomplete knowledge of the efficiencies evaluated by simulation. This type of uncertainty is subdivided into three parts: (i) on the track p_T threshold, 9.0%; (ii) on the trigger p_T threshold, 8.4%; and (iii) on the efficiency plateau, 3.2%. Parts (i) and (ii) are caused by imperfect modeling of the turn-on behavior of the single-muon reconstruction efficiency observed in data. They are estimated by varying the thresholds in simulation and measuring the corresponding variation of the relative $N_{4\mu}$ yield. A conservative but meaningful range of threshold variations is determined for part (i) by comparing the momentum scale variation that is required to shift the mass peak of the η meson by the width observed in the two-muon spectrum. For (ii), we assume a 10% uncertainty in the effective threshold of the trigger. The uncertainty on (iii) is determined by measuring the trigger efficiency in data with an unbiased sample of events collected with electron triggers. The discrepancy between this efficiency in data and simulation leads to a 3.2% correction to the branching fraction, which is also taken as the corresponding uncertainty. This uncertainty affects both decay channels in an unbalanced fashion owing to the different number of final-state muons, and hence it only partially cancels out in the ratio. A subdominant source of systematic uncertainty is attributed to the choice of fit model used to extract the signal yield in both channels. This uncertainty is assessed by testing several alternative signal and background models, and determining the variation in signal yield, resulting in a value of 6.6%. Overall, we estimate the total systematic uncertainty in the branching ratio measurement to be 14%, adding all contributions in quadrature.

The resulting $\mathcal{B}_{4\mu}/\mathcal{B}_{2\mu}$ ratio is

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = [0.86 \pm 0.14(\mathrm{stat}) \pm 0.12(\mathrm{syst})] \times 10^{-3}.$$

With $\mathcal{B}(\eta \to 2\mu) = (5.8 \pm 0.8) \times 10^{-6}$ [1], the branching fraction of the newly observed four-muon decay channel is measured to be

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

where the last term reflects the uncertainty in $\mathcal{B}(\eta \to 2\mu)$. The measurement is in agreement with the theoretical prediction of $(3.98 \pm 0.15) \times 10^{-9}$ [10].

In summary, the first observation of the η meson's rare double-Dalitz decay to four muons is reported. This is made possible by the use of CMS data collected with high-rate muon triggers at $\sqrt{s} = 13$ TeV in 2017 and 2018, corresponding to an integrated luminosity of 101 fb^{-1}. The branching fraction of the $\eta \to 4\mu$ decay is measured relative to the $\eta \to 2\mu$ decay, yielding a ratio of branching fractions of $(0.86 \pm 0.14(\mathrm{stat}) \pm 0.12(\mathrm{syst})) \times 10^{-3}$. Using the world average branching fraction value [1] for the normalization channel, the branching fraction of the four-muon decay channel is $\mathcal{B}(\eta \to \mu^+\mu^-\mu^+\mu^-) = (5.0 \pm 0.8(\mathrm{stat}) \pm 0.7(\mathrm{syst}) \pm 0.7(\mathcal{B}_{2\mu})) \times 10^{-9}$, where the last term is the uncertainty in the normalization channel branching fraction. This result is in agreement with theoretical predictions [10]. The augmented statistical power of data collected with high-rate triggers in future runs of the LHC will enable a detailed study of doubly virtual pseudoscalar transition form factors (TFFs) in the timelike region [33]. Measuring TFFs is crucial to understand the effects of the strong interaction in a range of relevant processes, such as the anomalous magnetic moment of the muon [7].

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering, so effectively, the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF

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