

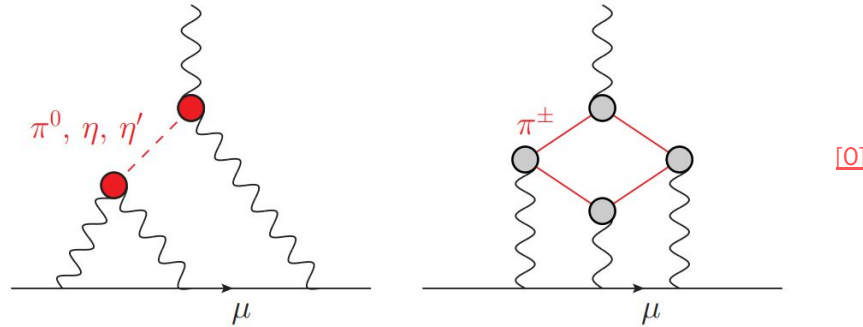
First Observation of the Rare Decay $\eta \rightarrow \mu^+ \mu^- e^+ e^-$ with the CMS Experiment

Bennett Greenberg*, CMS Collaboration

*Princeton University, Princeton, NJ, USA

XXXIX Rencontres de Physique de La Vallée d'Aoste, 4 Mar 2026, La Thuile (Italy)

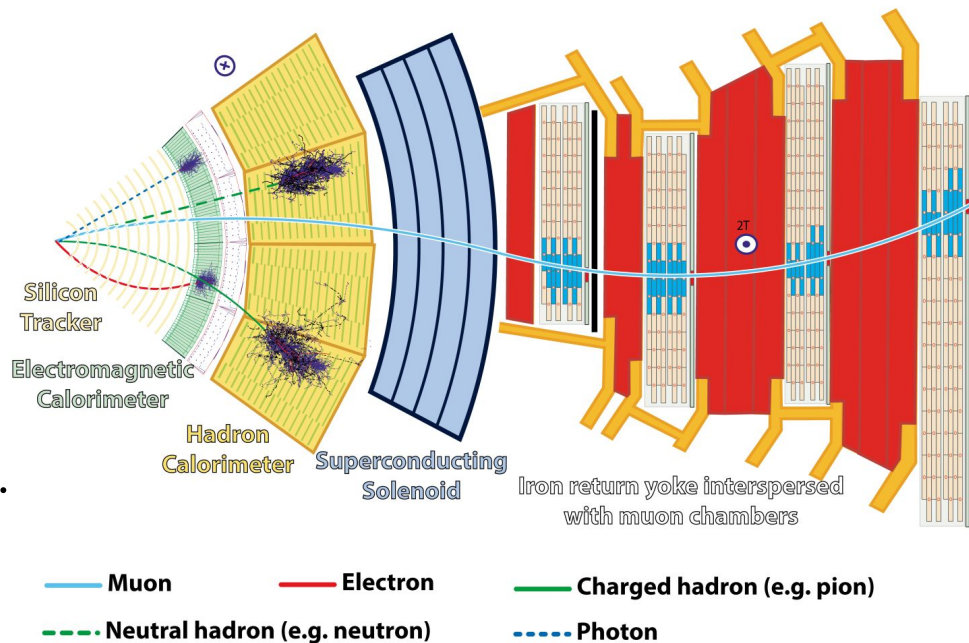
Introduction



- The muon anomalous magnetic moment ($g-2$) theory calculation (and other computations involving hadronic light-by-light scattering) are affected by transition form factors (TFFs) related to the various decay modes of light mesons.
- In this analysis, we observe one contributing decay mode for the first time:
 $\eta \rightarrow \mu^+ \mu^- e^+ e^-$ [\[CMS-PAS-BPH-24-001\]](#)
 - We also measure branching fraction (BF) to compare to theory predictions.
 - This is possible with CMS thanks to data parking.

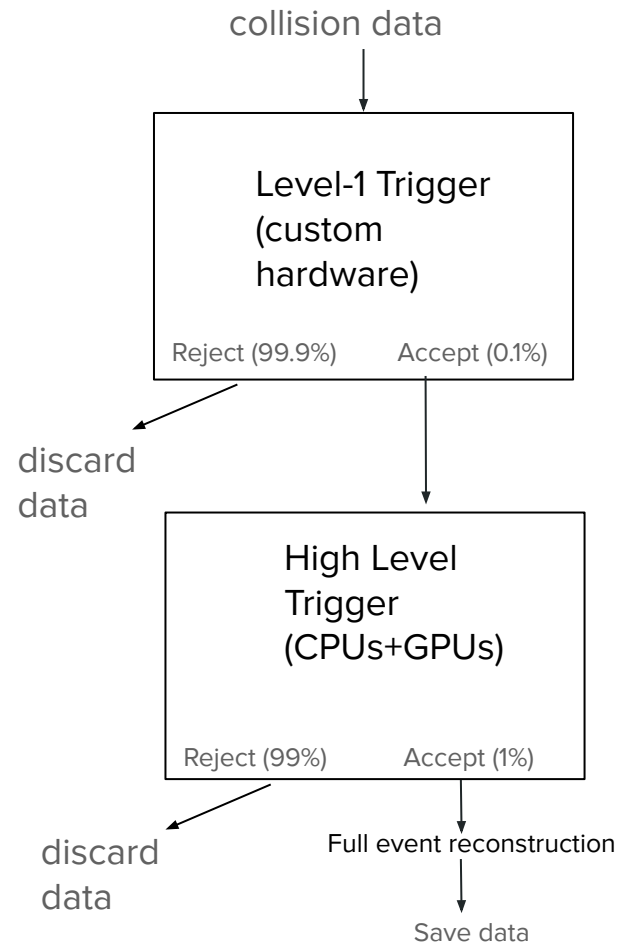
The CMS Detector

- Multi-purpose detector
 - 15 meter-tall, 21 meter-long cylindrical detector.
- All-silicon inner tracker.
- Electromagnetic and hadronic calorimeters both within interior of powerful superconducting magnet.
- Gas-based muon detectors interspersed with return yokes of the magnet.



Data scouting and parking

- CMS 2-level trigger system shown at right
 - Level-1 trigger (L1T): custom hardware trigger to reject 99.9% of events.
 - High-level trigger (HLT): software trigger to select the most interesting $\sim 1\%$ of events that pass the L1T.
- Data scouting: To get around memory storage and online processing power limitation
 - Simplified event reconstruction, only saves small part of event information.
- **Data parking:** To get around online processing power limitation
 - Raw data from the detectors is "parked" offline until computing resources are available to run full event reconstruction.
 - This stream is used for this analysis.



The η and η' Mesons

- Flavor eigenstates:

- $\eta_0 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$

- $\eta_8 = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$

- Mixed according to: $\begin{pmatrix} \cos \theta_M & -\sin \theta_M \\ \sin \theta_M & \cos \theta_M \end{pmatrix} \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix} = \begin{pmatrix} \eta \\ \eta' \end{pmatrix}$

- Mixing angle $\theta_M \cong -15^\circ$

- Small(ish) angle \rightarrow

$$\begin{aligned} \eta' &\approx \eta_0 \\ \eta &\approx \eta_8 \end{aligned}$$

- Mass eigenvalues:

- η : **547.9 MeV**

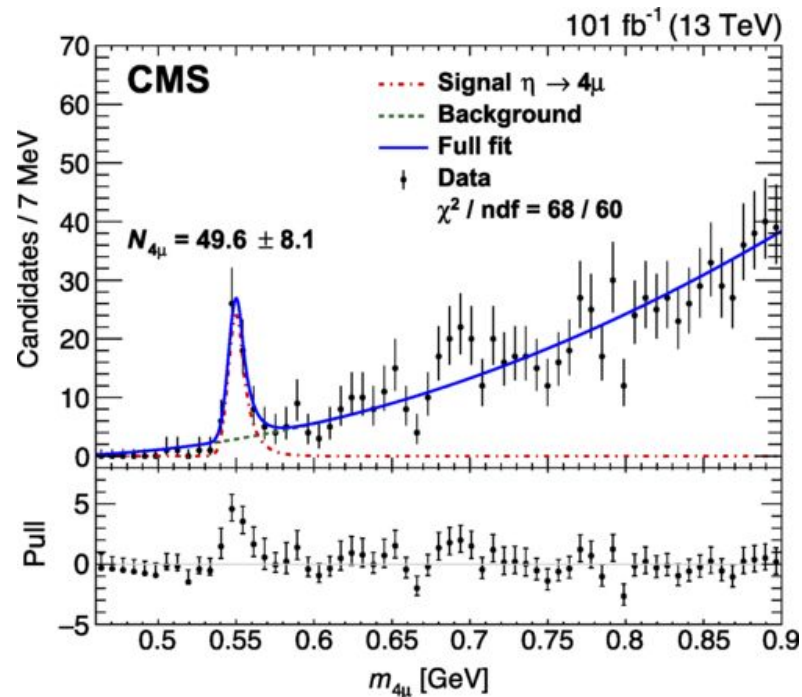
- η' : 957.8 MeV

Decay mode	Exp. BF or CL 90% upper bound
$\gamma\gamma$	$(39.36 \pm 0.18) \%$
$3\pi^0$	$(32.57 \pm 0.21) \%$
$\pi^+\pi^-\pi^0$	$(23.02 \pm 0.25) \%$
$\pi^+\pi^-\gamma$	$(4.28 \pm 0.07) \%$
$e^+e^-\gamma$	$(0.69 \pm 0.04) \%$
$\mu^+\mu^-\gamma$	$(3.1 \pm 0.4) \times 10^{-4}$
$\pi^+\pi^-e^+e^-(\gamma)$	$(2.68 \pm 0.11) \times 10^{-4}$
$\pi^0\gamma\gamma$	$(2.55 \pm 0.22) \times 10^{-4}$
$2e^+2e^-$	$(2.40 \pm 0.22) \times 10^{-5}$
$\mu^+\mu^-$	$(5.8 \pm 0.8) \times 10^{-6}$
$2\mu^+2\mu^-$	$(5.0 \pm 1.3) \times 10^{-9}$
$\pi^+\pi^-\gamma\gamma$	$< 0.21 \%$
$2\pi^02\gamma$	$< 0.12 \%$
$\pi^+\pi^-\pi^0\gamma$	$< 6 \times 10^{-4}$
$\mu^+\mu^-\pi^+\pi^-$	$< 3.6 \times 10^{-4}$
4γ	$< 2.8 \times 10^{-4}$
$\pi^+e^-\bar{\nu}_e + \text{c.c.}$	$< 1.7 \times 10^{-4}$
$\mu^+\mu^-e^+e^-$	$< 1.6 \times 10^{-4}$
invisible	$< 1.0 \times 10^{-4}$
$\pi^0\mu^+\mu^-\gamma$	$< 3 \times 10^{-6}$
e^+e^-	$< 7 \times 10^{-7}$

η meson decays [2]

$\eta \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ Observation at CMS

- Using data scouting technique during LHC Run 2, CMS was able to observe the very rare decay $\eta \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ for the first time [3], and measure a BF of $(5.0 \pm 1.3) \times 10^{-9}$.
- Improvement in sensitivity by more than 5 orders of magnitude over previous upper limit [4]!



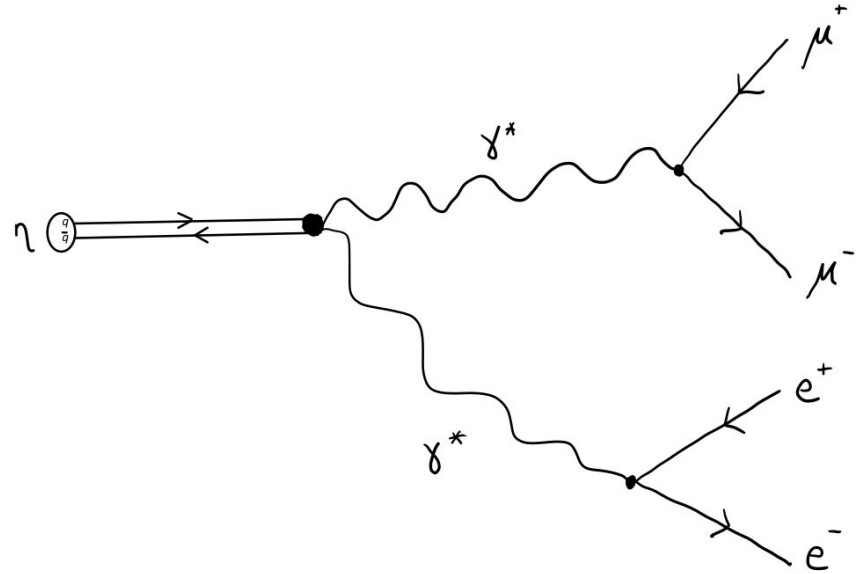
$\eta \rightarrow \mu^+ \mu^- e^+ e^-$ Decay

- Proceeds via a pair of virtual photons.
- With virtual photons, the matrix elements depend on a Transition Form Factor (TFF).
 - *This mode is especially interesting because there is no quantum exchange diagram (as there would be if both lepton pairs were identical).
- Latest theoretical predictions^[5-6]:

$$2.3 \times 10^{-6}$$

- Latest experimental upper limit^[4]:

$$1.6 \times 10^{-4}$$



Analysis Strategy

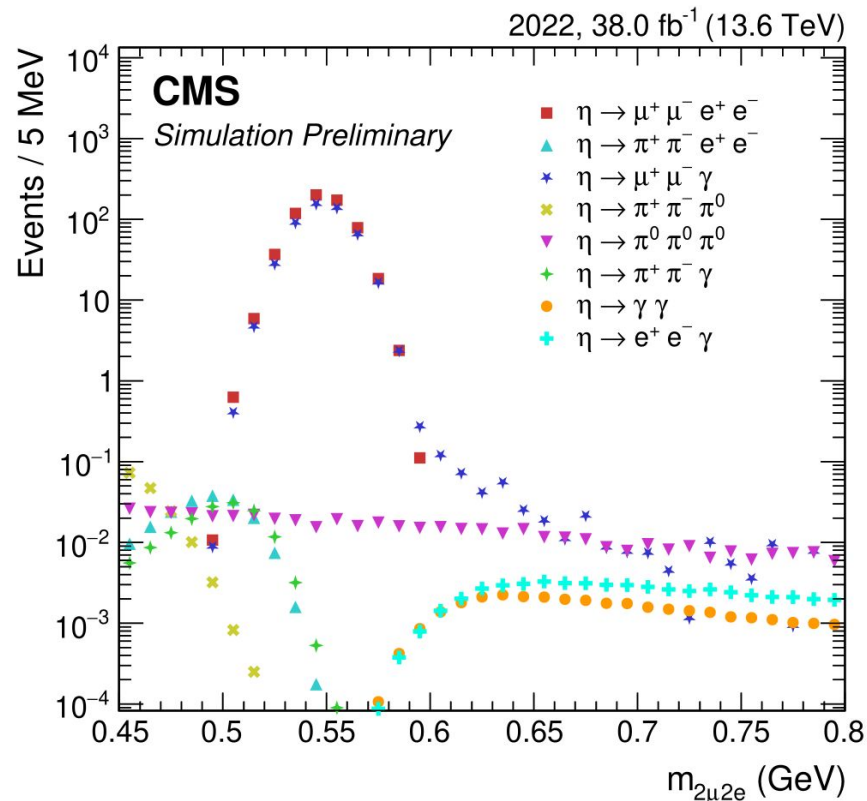
- Goal: perform first measurement of $\eta \rightarrow \mu^+ \mu^- e^+ e^-$ branching fraction, $B_{2\mu 2e}$.
- Use $\eta \rightarrow \mu^+ \mu^- \gamma$ channel as normalization (photon converts to $e^+ e^-$).
 - Known branching fraction: $B_{2\mu\gamma} = (3.1 \pm 0.4) \times 10^{-4}$.
 - Several large uncertainties cancel out thanks to ratio.
- Use equation:
$$\frac{B_{2\mu 2e}}{B_{2\mu\gamma}} = \frac{N_{2\mu 2e}}{N_{2\mu\gamma}} \frac{\epsilon_{2\mu\gamma}}{\epsilon_{2\mu 2e}}$$
 - Measure number of $\eta \rightarrow \mu^+ \mu^- e^+ e^-$ events $N_{2\mu 2e}$ in 2022 **parking** data invariant mass spectrum.
 - Measure $N_{2\mu\gamma}$ in same parking data, with an inverted conversion veto to get electrons from photon conversions.
 - Measure efficiencies $\epsilon_{2\mu 2e}$ and $\epsilon_{2\mu\gamma}$ in Monte Carlo (MC) simulation.
- Blinding strategy: multiply BF by unknown blinding factor in range [0.1, 9.0].

Background modeling with Toy MC

[CMS-PAS-BPH-24-001]

- To get an idea of the general shapes of the possible backgrounds, we generated toy events with a simple model of the underlying physics.
 - Charged pions can be misidentified as muons.
 - Photons can convert to muons or electrons in the beam pipe or innermost layer of the tracker.
- Only one resonant background has potential to mimic our signal:

$$\eta \rightarrow \mu^+ \mu^- \gamma.$$



Event Selections

Signal Selections:

- $\mu^+\mu^-e^+e^-$ Vertex χ^2 probability > 10%
- double-muon Parking trigger
- Loose muon ID
- muon $p_T > 3, 4$ GeV
- muon $|\eta| < 2.4$
- electron $p_T > 2$ GeV
- electron 0 missing inner tracker hits
- electron $|\eta| < 2.5$; NOT $1.44 < |\eta| < 1.57$
- electron ID

These selections chosen to optimize resonant background rejection and maximize signal acceptance, according to MC.

Reference channel selections

- $\mu^+\mu^-e^+e^-$ Vertex χ^2 probability > 10%
- double-muon Parking trigger
- Loose muon ID
- muon $p_T > 3, 4$ GeV
- muon $|\eta| < 2.4$
- electron $p_T > 2$ GeV
- electron 0 missing inner tracker hits
- electron $|\eta| < 2.5$; NOT $1.44 < |\eta| < 1.57$
- electron FAILS photon conversion veto

These selections chosen to optimize *signal* rejection and maximize reference channel acceptance according to MC, while keeping as many selections as possible the same as in the signal channel.

Fit to data: signal channel

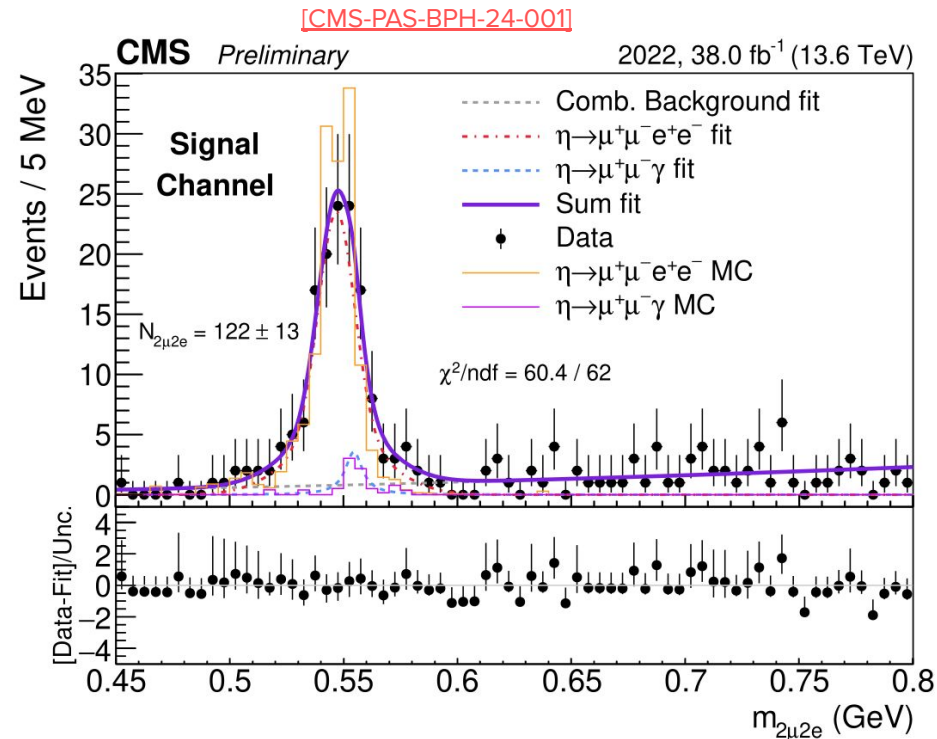
- Fit performed to **data** with starting parameters taken from fits to MC.

- Threshold function for **combinatorial background**:

$$y = (x - x_0)^\alpha, x_0 = 2(m_\mu + m_e)$$

- Breit-Wigner for **resonant background**.
- Double-Gaussian for **signal peak**.
- Result:

$$N_{2\mu 2e} = 122.2 \pm 13.0 \text{ (10.6\% stat.)}$$



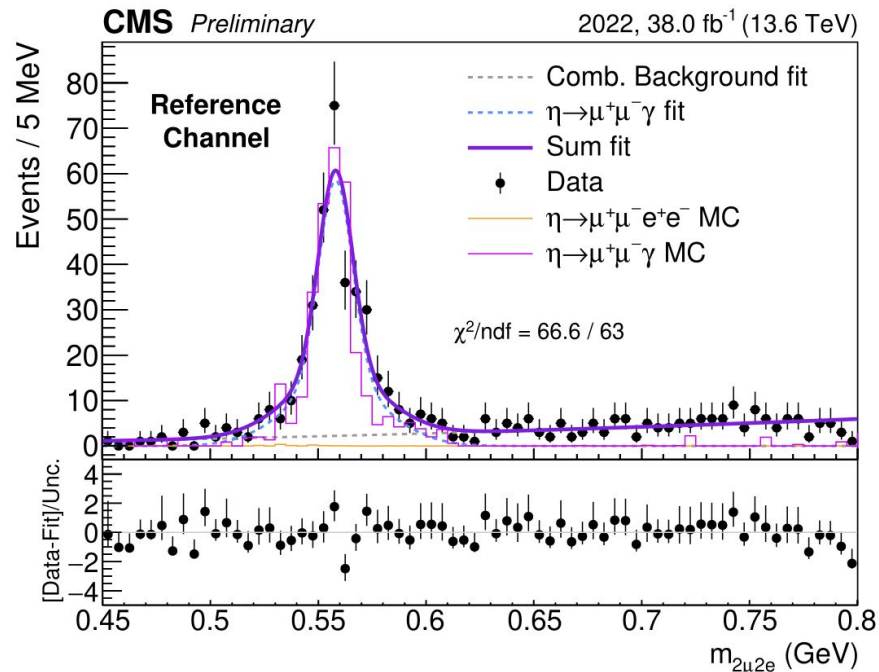
muon $p_T > 3,4$ GeV; electron $p_T > 2$ GeV;

electron ID variable required;

other event selections

Reference channel: fit to data

- Reference channel: electrons required to **fail** a photon conversion candidate veto
 - $\eta \rightarrow \mu^+ \mu^- e^+ e^-$ signal nearly completely rejected in this channel.
 - This data peak entirely from $\eta \rightarrow \mu^+ \mu^- \gamma$.
- Fit performed to **data** with starting parameters taken from fits to MC.
- Threshold function for **combinatorial background**.
- Double-Gaussian for $\eta \rightarrow \mu^+ \mu^- \gamma$ peak.
- Result: $N_{2\mu\gamma} = 328.1 \pm 22.3$ (6.8% stat.)



muon $p_T > 3,4$ GeV; electron $p_T > 2$ GeV;

electron failed conversion veto;

other event selections

Uncertainties

Line	Source	Value (%)
1	Electron ID efficiency SF	13.6
2	Photon conversion probability	15.1
3	Reference channel kinematic model	3.3
4	Signal channel kinematic model	11.0
5	Fit signal model, $N_{2\mu 2e}$	4.6
6	Fit resonant background model, $N_{2\mu 2e}$	3.3
7	Fit combinatorial background model, $N_{2\mu 2e}$	1.8
8	Fit signal and background models, $N_{2\mu\gamma}$	10.9
9	Total systematic uncertainty	26.4
10	Statistical uncertainty	12.6
11	Total relative uncertainty	29.3
12	Uncertainty in $B(\eta \rightarrow \mu^+ \mu^- \gamma)$	12.9
13	Total absolute uncertainty	32.0

Preliminary result

$$\frac{\mathcal{B}_{2\mu 2e}}{\mathcal{B}_{2\mu\gamma}} = \frac{N_{2\mu 2e}}{N_{2\mu\gamma}} \frac{\epsilon_{2\mu\gamma}}{\epsilon_{2\mu 2e}}$$

- The *preliminary* branching fraction is found to be:

$$(2.15 \pm 0.27 \text{ (stat.)} \pm 0.57 \text{ (syst.)} \pm 0.28 \text{ (ref.)}) \times 10^{-6} = \mathbf{(2.15 \pm 0.69) \times 10^{-6}}$$

- Exact values could slightly change due to CMS-wide review.
- This preliminary result is consistent with the latest standard model predictions of $\sim 2.3 \times 10^{-6}$.

Summary

- The rare decay $\eta \rightarrow \mu^+ \mu^- e^+ e^-$ has been observed for the first time, with significance $\gg 5\sigma$, in CMS Run 3 2022 parking data.
- A *preliminary* unblinded branching fraction is obtained:

$$(2.2 \pm 0.7) \times 10^{-6}$$

- Consistent with the latest standard model predictions.
- Next steps:
 - Complete CMS internal review process.
 - Submit paper to Physics Review Letters (this month).

Future Directions

- Precision of this measurement could be improved by CMS in the future
 - Would require dedicated work to improve low- p_T electron algorithms
 - Such an analysis could be combined with an improvement to the $\eta \rightarrow 4\mu$ BF using Run 3 Parking data.
 - Could also potentially study Lepton Flavor Violation (LFV)!
- Related analyses on other η , η' meson rare decays are already in the works!
 - Many unobserved decay channels are accessible with the CMS Run 3 Parking dataset!

$\eta \rightarrow \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$
$\eta \rightarrow \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$
$\eta \rightarrow \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [56]
$\eta \rightarrow 2\pi^0$	$< 3.5 \times 10^{-4}$
$\eta \rightarrow 4\pi^0$	$< 6.9 \times 10^{-7}$

?

$\eta' \rightarrow e^+e^-$	$< 5.6 \times 10^{-9}$
$\eta' \rightarrow \mu^+\mu^-$	
$\eta' \rightarrow \ell^+\ell^-\ell^+\ell^-$	
$\eta' \rightarrow \pi^+\pi^-\pi^0\gamma$	
$\eta' \rightarrow \pi^+\pi^-$	$< 1.8 \times 10^{-5}$
$\eta' \rightarrow 2\pi^0$	$< 4 \times 10^{-4}$

(compiled by [0], source [2])

More Future Directions

- Extending further, many related searches could be performed involving η , η' meson decays into lepton, photon, and pion final states, with:
 - BSM physics like dark photons, axion-like particles (ALPs), C/CP violation
 - True muonium (standard model-predicted bound state of muon pair).
- REDTOP experiment at FNAL: proposed light meson factory
 - Goals: produce as many η , η' mesons as possible in a 3-year period, observe their rare decays to leptons, take precise measurements of the BFs, and search for light dark matter and true muonium
 - We can already get a jumpstart on many of these goals at the LHC!
 - We already have orders of magnitude more η , η' mesons than REDTOP plans to produce
 - Also much more background, though.

References

- [0] L. Gan, B. Kubis, E. Passemar, S. Tulin, Precision tests of fundamental physics with η and η' mesons. Phys. Rept. 945, 1–105 (2022). <https://doi.org/10.1016/j.physrep.2021.11.001>
- [1] CMS Collaboration, “Enriching the physics program of the CMS experiment via data scouting and data parking”, Physics Reports (2024) [doi:https://doi.org/10.1016/j.physrep.2024.09.006](https://doi.org/10.1016/j.physrep.2024.09.006).
- [2] Particle Data Group, S. Navas et al., “Review of particle physics”, Phys. Rev. D 110 (2024) 030001, [doi:10.1103/PhysRevD.110.030001](https://doi.org/10.1103/PhysRevD.110.030001).
- [3] CMS Collaboration, “Observation of the rare decay of the η meson to four muons”, Phys. Rev. Lett. 131 (2023) 31, [doi:10.1103/PhysRevLett.131.091903](https://doi.org/10.1103/PhysRevLett.131.091903), arXiv:2305.04904.
- [4] CELSIUS/WASA Collaboration, “Measurement of eta meson decays into lepton-antilepton pairs”, Phys. Rev. D 77 (2008) 032004, [doi:10.1103/PhysRevD.77.032004](https://doi.org/10.1103/PhysRevD.77.032004), arXiv:0711.3531.
- [5] R. Escribano and S. González-Solís, “A data-driven approach to π^0 , η and η' single and double Dalitz decays”, Chinese Phys. C 42 (2018) 023109, [doi:10.1088/1674-1137/42/2/023109](https://doi.org/10.1088/1674-1137/42/2/023109), arXiv:1511.04916.
- [6] K. Kampf, J. c. v. Novotný, and P. Sanchez-Puertas, “Radiative corrections to double-dalitz decays revisited”, Phys. Rev. D 97 (Mar, 2018) 056010, [doi:10.1103/PhysRevD.97.056010](https://doi.org/10.1103/PhysRevD.97.056010).

Backup

slides

MC Production and Reweighting

- Full MC simulation required for signal channel ($\eta \rightarrow \mu^+ \mu^- e^+ e^-$); resonant background / reference channel ($\eta \rightarrow \mu^+ \mu^- \gamma$), and auxiliary channel ($\eta \rightarrow \mu^+ \mu^-$)
 - Signal channel: modified PLUTO to allow $\eta \rightarrow \mu^+ \mu^- e^+ e^-$ decays according to Vector Meson Dominance (VMD) model, interfaced with PYTHIA8.3 to make a particle gun.
 - Reference channel: used PYTHIA8.3 η particle gun, and forced decay to $\mu^+ \mu^- \gamma$.
 - Uses phase space model, which is not consistent with kinematic distributions observed by Ref. [8].
 - → We modify the MC event weights to make the kinematic distributions agree (→54% change in measured efficiency).
 - Auxiliary channel: used PYTHIA8.3 η particle gun, and forced decay to $\mu^+ \mu^-$.
 - Used only for differential η meson production cross section measurement (used in event weights for signal and reference channels)
 - → any uncertainties cancel out of final BF ratio.

Corrections to MC

- Several corrections to MC added from comparisons with data.
- Corrections whose effects cancel out of the final BF measurement:
 - Pileup
 - Trigger efficiency
 - Muon and electron p_T scale
 - Muon ID
- Non-canceling correction: electron ID
 - Scale factor derived from data/MC efficiency ratio, in signal channel with special selection:
 - Cut di-electron invariant mass from 0.04 – 0.09 GeV
 - Events with a photon conversion have di-electron invariant mass artificially forming peak between these values due to electron reconstruction algorithm incorrectly assuming the electrons come from the primary vertex.
 - → this completely removes resonant background
 - This cut cannot be used for the baseline analysis because it would cause non-trivial changes to efficiency distribution.

Photon conversion uncertainty

- Largest systematic uncertainty: photon conversion in the reference channel.
- Three components to this uncertainty:
 - Baseline data-MC comparison with and without requiring the photon conversion veto.
 - 9% from deviation from 1 in data/MC double-ratio.
 - Material budget uncertainty
 - 4%, found with data-MC comparisons of nuclear interaction vertices in the beam pipe and first pixel layer
 - Track cluster sharing effects
 - 11%, found by studying $K_S^0 \rightarrow \pi^+ \pi^-$ decays
 - Decay time constant of $\sim 10^{-10}$ seconds \rightarrow large number of decays at all radii of interest, so can compare data-MC agreement of tracking efficiency inside of the material.