

# Doubly radiative $\eta^{(\prime)}$ decays: interplay of vector, scalar, and tensor contributions

*Phys.Rev.D* 102 (2020) 3, 034026

*Phys.Rev.D* 112 (2025) 11, 114009

Emilio Royo ([emilio.royocarratala@uchceu.es](mailto:emilio.royocarratala@uchceu.es))

Universidad Cardenal Herrera-CEU

Kraków, June 25<sup>th</sup>, 2026



**18<sup>th</sup> International Workshop  
on Meson Physics**  
25<sup>th</sup> - 30<sup>th</sup> June 2026, Kraków, Poland

Organized by Jagiellonian University,  
GSI Helmholtz Centre for Heavy Ion Research,  
INFN-LNF Frascati, Institute of Nuclear Physics PAS

**Organizers:**  
Catalina Curceanu INFN-INFN Frascati (Chair)  
James Stenar GSI Darmstadt / JY-Fochum (Chair)  
Piotr Sobotka Jagiellonian University (Chair)  
Sean Dobbs Florida State University  
Andreas Krieger Uppsala University  
Joachim Stroh GSI / Goethe University Frankfurt  
Arturo Sanchez Institute of Nuclear Physics PAS  
Damian G. Sorensen Jagiellonian University (Scientific Secretary)  
Rafal Lalk Jagiellonian University (Scientific Secretary)

**Advisory Committee:**  
Marco Battaglia INFN Genova  
Andrea Danese INFN Padova  
Adam Doni University of Mainz  
Alessandro Drago University of Ferrara  
Laura Fabbietti Technical University of Munich  
Christian Fischer University of Gießen  
Avraham Gal Hebrew University of Jerusalem  
Tania Horn The Catholic University of America  
Daisuke Ido Tokyo Institute of Technology  
Takashi Inakubo Osaka University  
Hiroyuki Nakanishi Osaka University  
Eulogio Oset University of Valencia  
Angel Ramos University of Barcelona, ICCUB  
Sebastian Steininger IPN Orsay  
Craig D. Roberts Argonne National Laboratory  
Harmut Schmedden University of Bonn  
Karin Schwaninger Uppsala University  
Xiaoyan Shen Institute of High Energy Physics CAS Beijing  
Holt Thiesler Indiana University  
Adam Szczepaniak Indiana University  
Ulrike Thoma Osaka University  
Eberhard Weidmann Austrian Academy of Sciences Vienna  
Song Song Zhou Tsinghua University

**Mailing address:**  
MESON2026 Workshop, Uniwersytet Jagielloński,  
Instytut Fizyki, ul. Sokołowska 11, 30-348 Kraków, Poland  
phone: +48 12 664 45 87, +48 12 664 47 11  
e-mail: meson@fjz.uj.edu.pl



<https://meson.if.uj.edu.pl>



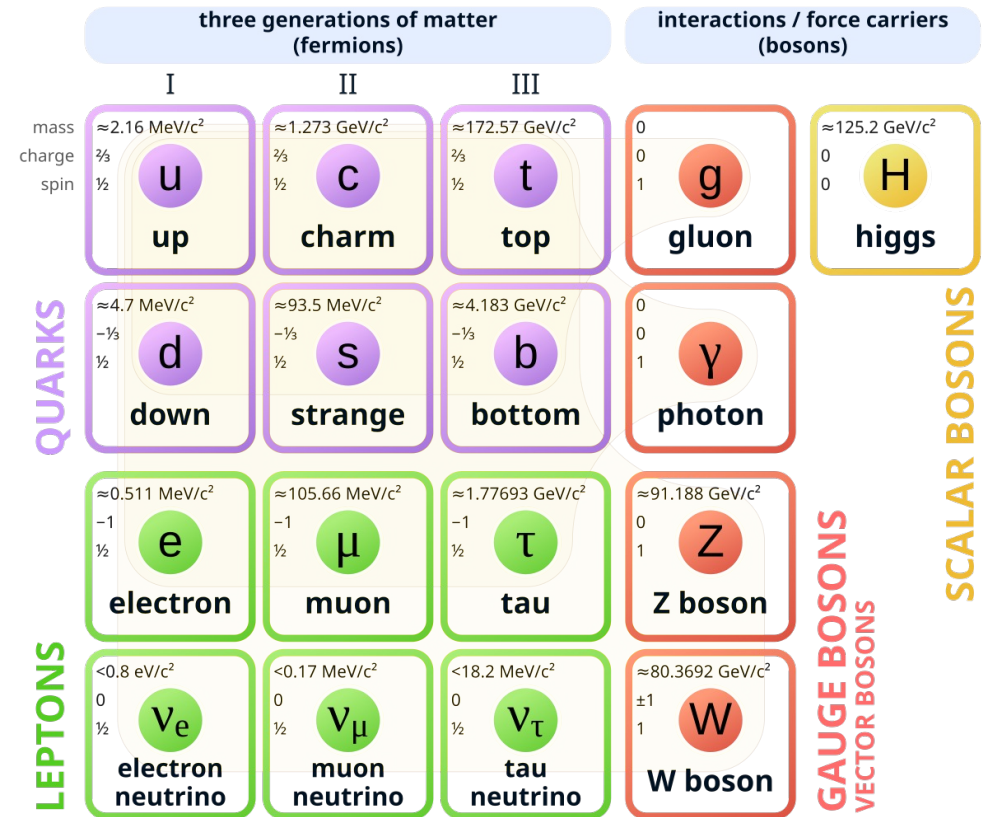
# Table of contents

- Introduction
- Doubly radiative  $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$  decays in the Standard Model
- Conclusions

# Introduction

- The Standard Model (SM) of particle physics is one of the most successful scientific theories to date
  - Its current formulation was established in the 1970s
- The SM has received extensive experimental support
  - So far, no experimental result has conclusively contradicted the SM at the  $5\sigma$  level
- Yet, we know the SM is incomplete, as it leaves several observed phenomena unexplained
  - It does not incorporate gravity
  - It does not provide a viable dark matter candidate
  - It does not fully explain the observed matter-antimatter asymmetry
  - ...

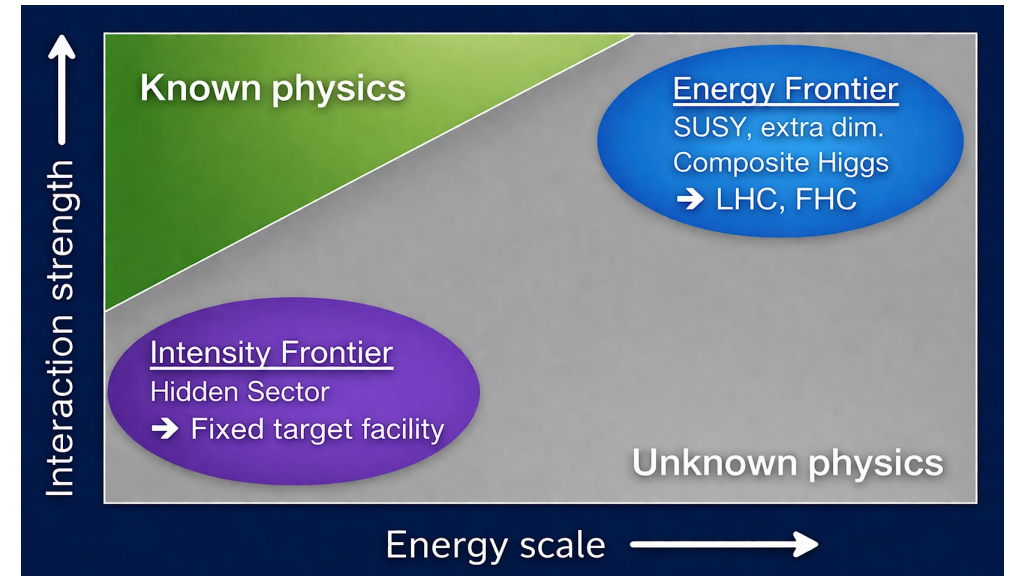
## Standard Model of Elementary Particles



[https://en.wikipedia.org/wiki/Standard\\_Model](https://en.wikipedia.org/wiki/Standard_Model)

# Introduction

- Experimental strategies to search for BSM physics
  - Energy frontier: direct searches at high-energy colliders
    - Limited by cost and construction timescales of large facilities
    - Examples: LHC, FCC, ILC, CEPC
  - Intensity frontier: indirect searches via high-precision, high-intensity experiments
    - Provides sensitivity to small deviations from Standard Model predictions
    - Particularly powerful when SM predictions are precise or backgrounds are suppressed
    - Examples: Belle II, BESIII, KLOE-2, etc.



S. Alekhin et al. - arXiv:1504.04855

# Introduction

- The  $\eta$  and  $\eta'$  decays as an intensity frontier laboratory
  - The  $\eta$  is a pseudo-Goldstone boson of the spontaneously broken chiral symmetry of QCD
  - The  $\eta'$  is strongly affected by the  $U(1)_A$  anomaly
  - The  $\eta$  and  $\eta'$  are eigenstates of  $C$ ,  $P$ ,  $CP$ , and  $G$ :  $I^G J^{PC} = 0^+ 0^{-+}$
  - All their additive quantum numbers are zero  $\Rightarrow$  flavour conserving decays
  - Many strong and electromagnetic decays are suppressed at leading order by symmetries
  - Their decays are largely free from SM background



**Perfect laboratory for stress-testing the SM in search of BSM physics**

# Introduction

## Rich physics program at $\eta, \eta'$ factories

### Standard Model highlights

- Theory input for light-by-light scattering for  $(g-2)_\mu$
- Extraction of light quark masses
- QCD scalar dynamics

### Fundamental symmetry tests

- P,CP violation
- C,CP violation

[Kobzarev & Okun (1964), Prentki & Veltman (1965), Lee (1965), Lee & Wolfenstein (1965), Bernstein et al (1965)]

### Dark sectors (MeV—GeV)

- Vector bosons (dark photon, B boson, X boson)
- Scalars
- Pseudoscalars (ALPs)

(Plus other channels that have not been searched for to date)

Channel	Expt. branching ratio	Discussion
$\eta \rightarrow 2\gamma$	39.41(20)%	chiral anomaly, $\eta$ - $\eta'$ mixing
$\eta \rightarrow 3\pi^0$	32.68(23)%	$m_d - m_u$
$\eta \rightarrow \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	$\chi$ PT at $O(p^6)$ , leptophobic B boson, light Higgs scalars
$\eta \rightarrow \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	$\chi$ PT, axion-like particles (ALPs)
$\eta \rightarrow 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [52]
$\eta \rightarrow \pi^+\pi^-\pi^0$	22.92(28)%	$m_d - m_u$ , C/CP violation, light Higgs scalars
$\eta \rightarrow \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$ , P/CP violation
$\eta \rightarrow \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	$\chi$ PT, ALPs
$\eta \rightarrow e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$ , dark photon, protophobic X boson
$\eta \rightarrow \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$ , dark photon
$\eta \rightarrow e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$ , BSM weak decays.
$\eta \rightarrow \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$ , BSM weak decays, P/CP violation
$\eta \rightarrow \pi^0\mu^+t^-t^-$	$2.68(11) \times 10^{-4}$	C/CP violation, ALPs
$\eta \rightarrow \pi^+\pi^-e^+e^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$ , P/CP violation, ALPs
$\eta \rightarrow \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$ , P/CP violation, ALPs
$\eta \rightarrow e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \rightarrow e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \rightarrow \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \rightarrow \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \rightarrow \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	P/CP violation
$\eta \rightarrow 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \rightarrow 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Gan, Kubis, Passemar, Tulin (2020)

# Introduction

- $\eta / \eta'$  factories



Wasa-at-COSY

$\sim 3 \times 10^7$




KLOE-2 (Frascati)

$\sim 10^9$



BESIII

$\sim 4 \times 10^7$




HADES

$\sim 4.5 \times 10^8$



CB@MAMI

$\sim 3 \times 10^8$



CMS

$\eta \sim 10^{12}$

Experiment	Technique	Total $\eta$ production
<i>GlueX@JLAB</i> (running)	$\gamma_{12 \text{ GeV}} \text{ p} \rightarrow \eta \text{ X} \rightarrow \text{neutrals}$	$5.5 \times 10^7 / \text{yr}$
<i>JEF@JLAB</i> (approved)	$\gamma_{12 \text{ GeV}} \text{ p} \rightarrow \eta \text{ X} \rightarrow \text{neutrals}$	$1.5 \times 10^8 / \text{yr}$
<i>HIAF</i> (approved)		$\sim 10^{13} / \text{yr}$
<i>REDTOP</i> (proposed)	$p_{1.8 \text{ GeV}} \text{ Li} \rightarrow \eta \text{ X}$	$3.4 \times 10^{13} / \text{yr}$

# Table of contents

- Introduction
- Doubly radiative  $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$  decays in the Standard Model
- Conclusions

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- SM motivation
  - To probe the non-perturbative regime of QCD and test  $\chi PT$  and related chiral effective theories
- BSM motivation
  - Searching for BSM particles requires precise control of the SM background

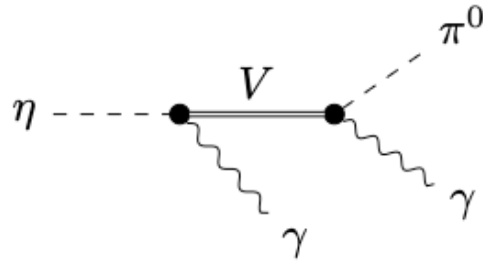
# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- Our approach: beyond  $\chi PT$  via resonance dynamics
  - Inspired by the resonance saturation hypothesis, we model the resonance exchanges at amplitude level
    - Captures de physics encoded in LECs
    - Avoids relying on a fixed-order chiral truncation, effectively resumming resonance contributions
  - Vector resonances ( $V$ ) [*Phys.Rev.D* 102 (2020) 3, 034026]
    - Vector Meson Dominance (VMD)
    - Dominant contribution, well-established phenomenology
  - Scalar resonances ( $S$ ) [*Phys.Rev.D* 102 (2020) 3, 034026]
    - Linear Sigma Model
    - Full one-loop propagators for  $\sigma$ ,  $f_0$  and  $a_0$  (Breit–Wigner inadequate for broad/near-threshold states)
  - Tensor resonances ( $T$ ) [*Phys.Rev.D* 112 (2025) 11, 114009]
    - Chiral-inspired framework for  $a_2$  exchange
    - Consistent with symmetry constraints

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- VMD to assess vector exchange contributions

- Six diagrams corresponding to the exchange of  $V = \rho^0, \omega, \phi$



with Lorentz structures

$$\mathcal{A}_{\eta \rightarrow \pi^0 \gamma \gamma}^{\text{VMD}} = \sum_{V=\rho^0, \omega, \phi} g_{V\eta\gamma} g_{V\pi^0\gamma} \left[ \frac{(P \cdot q_2 - M_\eta^2) \{a\} - \{b\}}{D_V(t)} + \left\{ \begin{array}{l} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array} \right\} \right]$$

Energy-dependent width  
in  $\rho^0$  propagator

$$\{a\} = (\epsilon_1 \cdot \epsilon_2)(q_1 \cdot q_2) - (\epsilon_1 \cdot q_2)(\epsilon_2 \cdot q_1),$$

$$\{b\} = (\epsilon_1 \cdot q_2)(\epsilon_2 \cdot P)(P \cdot q_1) + (\epsilon_2 \cdot q_1)(\epsilon_1 \cdot P)(P \cdot q_2) - (\epsilon_1 \cdot \epsilon_2)(P \cdot q_1)(P \cdot q_2) - (\epsilon_1 \cdot P)(\epsilon_2 \cdot P)(q_1 \cdot q_2)$$

- The decays  $\eta' \rightarrow \pi^0(\eta)\gamma\gamma$  are formally identical with

$$M_\eta^2 \rightarrow M_{\eta'}^2, \text{ and } g_{V\eta\gamma} g_{V\pi^0\gamma} \rightarrow g_{V\eta'\gamma} g_{V\pi^0(\eta)\gamma}$$

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- VMD to assess vector exchange contributions
  - $g_{VP\gamma}$  extracted directly from experiment (**empirical couplings**)

$$\Gamma_{V \rightarrow P\gamma} = \frac{1}{3} \frac{g_{VP\gamma}^2}{32\pi} \left( \frac{M_V^2 - M_P^2}{M_V} \right)^3$$

$$\Gamma_{P \rightarrow V\gamma} = \frac{g_{VP\gamma}^2}{32\pi} \left( \frac{M_P^2 - M_V^2}{M_P} \right)^3$$



Decay	BR	$ g_{VP\gamma} $ GeV <sup>-1</sup>
$\rho^0 \rightarrow \pi^0\gamma$	$(4.7 \pm 0.6) \times 10^{-4}$	0.22(1)
$\rho^0 \rightarrow \eta\gamma$	$(3.00 \pm 0.21) \times 10^{-4}$	0.48(2)
$\eta' \rightarrow \rho^0\gamma$	$(28.9 \pm 0.5)\%$	0.40(1)
$\omega \rightarrow \pi^0\gamma$	$(8.40 \pm 0.22)\%$	0.70(1)
$\omega \rightarrow \eta\gamma$	$(4.5 \pm 0.4) \times 10^{-4}$	0.135(6)
$\eta' \rightarrow \omega\gamma$	$(2.62 \pm 0.13)\%$	0.127(4)
$\phi \rightarrow \pi^0\gamma$	$(1.30 \pm 0.05) \times 10^{-3}$	0.041(1)
$\phi \rightarrow \eta\gamma$	$(1.303 \pm 0.025)\%$	0.2093(20)
$\phi \rightarrow \eta'\gamma$	$(6.22 \pm 0.21) \times 10^{-5}$	0.216(4)

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- VMD to assess vector exchange contributions

- $g_{VP\gamma}$  determined from a phenomenological model and a statistical fit to experimental data from  $VP\gamma$  decays (**model-based couplings**)

*Phys.Lett.B 807 (2020)*

$$g_{\rho^0\pi^0\gamma} = \frac{1}{3}g, \quad g_{\omega\pi^0\gamma} = g \cos\phi_V, \quad g_{\phi\pi^0\gamma} = g \sin\phi_V,$$

$$g_{\rho^0\eta\gamma} = gz_{\text{NS}} \cos\phi_P, \quad g_{\rho^0\eta'\gamma} = gz_{\text{NS}} \sin\phi_P,$$

$$g_{\omega\eta\gamma} = \frac{1}{3}g \left( z_{\text{NS}} \cos\phi_P \cos\phi_V - 2 \frac{\bar{m}}{m_s} z_{\text{S}} \sin\phi_P \sin\phi_V \right),$$

$$g_{\omega\eta'\gamma} = \frac{1}{3}g \left( z_{\text{NS}} \sin\phi_P \cos\phi_V + 2 \frac{\bar{m}}{m_s} z_{\text{S}} \cos\phi_P \sin\phi_V \right),$$

$$g_{\phi\eta\gamma} = \frac{1}{3}g \left( z_{\text{NS}} \cos\phi_P \sin\phi_V + 2 \frac{\bar{m}}{m_s} z_{\text{S}} \sin\phi_P \cos\phi_V \right),$$

$$g_{\phi\eta'\gamma} = \frac{1}{3}g \left( z_{\text{NS}} \sin\phi_P \sin\phi_V - 2 \frac{\bar{m}}{m_s} z_{\text{S}} \cos\phi_P \cos\phi_V \right),$$



$$g = 0.70 \pm 0.01 \text{ GeV}^{-1}, \quad z_{\text{S}}\bar{m}/m_s = 0.65 \pm 0.01,$$

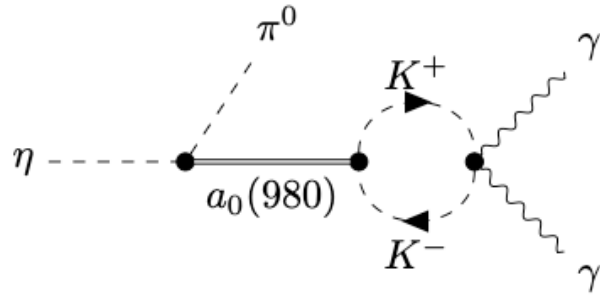
$$\phi_P = (41.4 \pm 0.5)^\circ, \quad \phi_V = (3.3 \pm 0.1)^\circ,$$

$$z_{\text{NS}} = 0.83 \pm 0.02.$$

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- $\mathcal{L}\sigma\text{M}$  to assess scalar exchange contributions

- $\chi\text{PT}$  loops complemented with scalar meson poles. For the  $\eta \rightarrow \pi^0\gamma\gamma$  decay, one obtains



$$\mathcal{A}_{\eta \rightarrow \pi^0 \gamma \gamma}^{\text{L}\sigma\text{M}} = \frac{2\alpha}{\pi} \frac{1}{M_{K^+}^2} L(s_K) \{a\} \times \mathcal{A}_{K^+ K^- \rightarrow \pi^0 \eta}^{\text{L}\sigma\text{M}}$$

where

$$\mathcal{A}_{K^+ K^- \rightarrow \pi^0 \eta}^{\text{L}\sigma\text{M}} = \frac{1}{2f_\pi f_K} \left\{ (s - M_\eta^2) \frac{M_K^2 - M_{a_0}^2}{D_{a_0}(s)} \cos \phi_P + \frac{1}{6} \left[ (5M_\eta^2 + M_\pi^2 - 3s) \cos \phi_P - \sqrt{2}(M_\eta^2 + 4M_K^2 + M_\pi^2 - 3s) \sin \phi_P \right] \right\}$$

$$L(z) = -\frac{1}{2z} - \frac{2}{z^2} f\left(\frac{1}{z}\right), \quad f(z) = \begin{cases} \frac{1}{4} \left( \log \frac{1+\sqrt{1-4z}}{1-\sqrt{1-4z}} - i\pi \right)^2 & \text{for } z < \frac{1}{4} \\ -\left[ \arcsin\left(\frac{1}{2\sqrt{z}}\right) \right]^2 & \text{for } z > \frac{1}{4} \end{cases}$$

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- L $\sigma$ M to assess scalar exchange contributions

- The complete one-loop propagator is used to parameterise the propagation of the  $\sigma$ ,  $f_0$  and  $a_0$  scalar resonances

$$D(s) = s - M_R^2 + \text{Re}\Pi(s) - \text{Re}\Pi(M_R^2) + i\text{Im}\Pi(s)$$

where  $M_R$  is the renormalised mass of the scalar meson and  $\Pi(s)$  is the 1PI two-point function

- The amplitude for the  $\eta' \rightarrow \pi^0\gamma\gamma$  decay gets contribution from the exchange of an  $a_0$
- The amplitude for the  $\eta' \rightarrow \eta\gamma\gamma$  decay receives contributions from the exchange of a  $\sigma$  and an  $f_0$

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- Theoretical predictions vs. measurements

- The square amplitude with vector and scalar exchange contributions is

$$|\mathcal{A}|^2 = |\mathcal{A}^{\text{VMD}}|^2 + |\mathcal{A}^{\text{L}\sigma\text{M}}|^2 + 2\text{Re}\mathcal{A}^{*\text{VMD}}\mathcal{A}^{\text{L}\sigma\text{M}}$$

- Summary of predictions and contributions

Results from  
*Phys.Rev.D 102 (2020)*

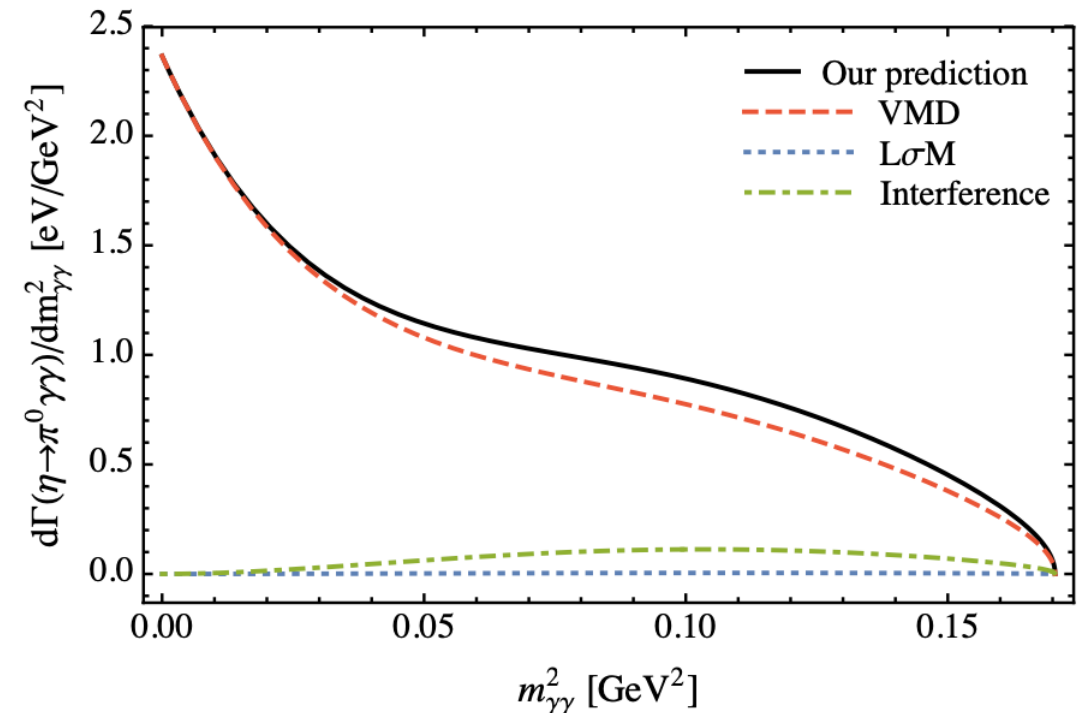
Decay	Couplings	Chiral-loop	L $\sigma$ M	VMD	$\Gamma$	BR <sub>th</sub>	BR <sub>exp</sub>
$\eta \rightarrow \pi^0\gamma\gamma$ (eV)	Empirical	$1.87 \times 10^{-3}$	$5.0 \times 10^{-4}$	0.16(1)	0.18(1)	$1.35(8) \times 10^{-4}$	$2.56(22) \times 10^{-4}$ <i>[Particle Data Group]</i>
	M-B	$1.87 \times 10^{-3}$	$5.0 \times 10^{-4}$	0.16(1)	0.17(1)	$1.30(1) \times 10^{-4}$	
$\eta' \rightarrow \pi^0\gamma\gamma$ (keV)	Empirical	$1.1 \times 10^{-4}$	$1.3 \times 10^{-4}$	0.57(3)	0.57(3)	$2.91(21) \times 10^{-3}$	$3.20(7)(23) \times 10^{-3}$ <i>[Phys.Rev.D 96 (2017) 1, 012005]</i>
	M-B	$1.1 \times 10^{-4}$	$1.3 \times 10^{-4}$	0.70(4)	0.70(4)	$3.57(25) \times 10^{-3}$	
$\eta' \rightarrow \eta\gamma\gamma$ (eV)	Empirical	$1.4 \times 10^{-2}$	3.15	21.2(1.2)	21.7(1.2)	$1.17(8) \times 10^{-4}$	$8.25(3.41)(0.72) \times 10^{-5}$ <i>[Phys.Rev.D 100 (2019) 5, 052015]</i>
	M-B	$1.4 \times 10^{-2}$	3.15	19.1(1.0)	19.8(1.0)	$1.07(7) \times 10^{-4}$	

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

## ■ Theoretical predictions vs. measurements for $\eta \rightarrow \pi^0\gamma\gamma$

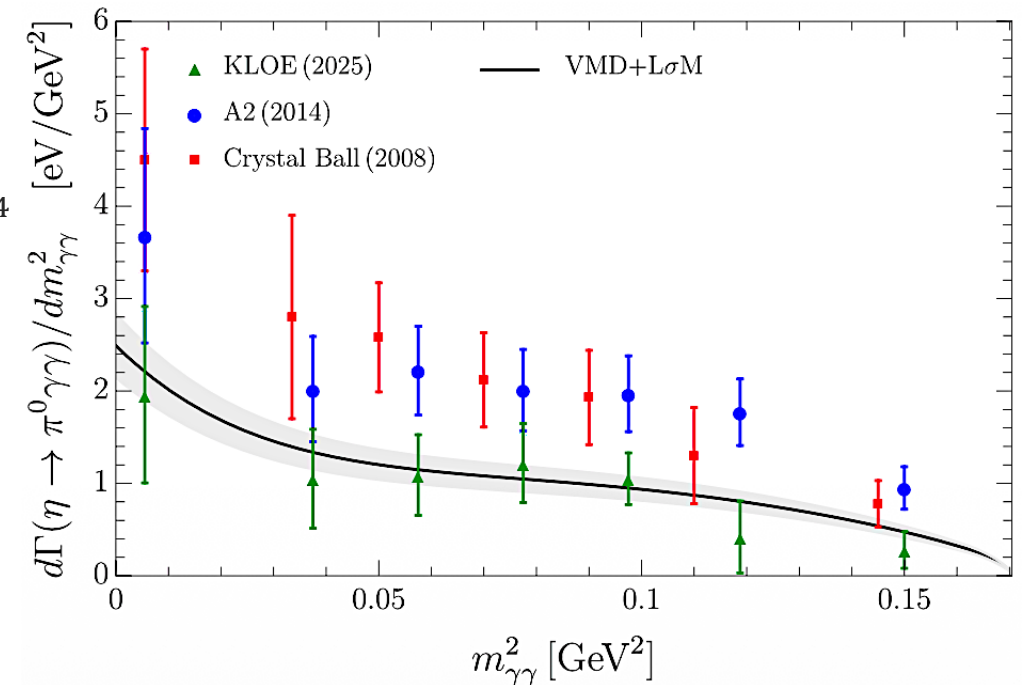
- Updated prediction BR =  $1.36(18) \times 10^{-4}$
- Vector exchanges dominate: 93%
  - $\rho$ : 27% of the signal
  - $\omega$ : 21% of the signal
  - $\phi$ : 0% of the signal
  - $\rho$ - $\omega$ - $\phi$  interference: 52% of the signal
- Scalar exchanges negligible:  $\sim 0\%$
- Vector-scalar interference: 7%

Updated with latest empirical couplings



# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- Theoretical predictions vs. measurements for  $\eta \rightarrow \pi^0\gamma\gamma$ 
  - Shape of the spectrum is well captured
    - Normalisation offset with respect to
      - A2 [BR =  $2.54(27) \times 10^{-4}$ ]
      - Crystall Ball [BR =  $2.21(24)(47) \times 10^{-4}$ ]
    - Good agreement with KLOE-2, BR =  $0.98(11)(13) \times 10^{-4}$  [JHEP 01 (2026) 091]
  - **Discrepancy between measurements** from different experimental collaborations
    - Experimental situation needs to be settled (e.g., JEF, REDTOP)



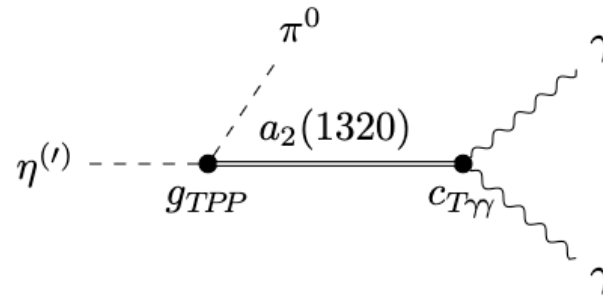
# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- Motivation for including the  $a_2(1320)$  tensor meson
  - The  $a_2(1320)$  couples strongly to  $\gamma\gamma$  and  $\pi\eta$ , making the tensor exchange a natural contribution to  $\eta \rightarrow \pi^0\gamma\gamma$
  - It is observed in the crossed channel  $\gamma\gamma \rightarrow \pi^0\eta$  (Belle), so a consistent description of both processes requires its inclusion
  - Scalar contributions have been shown by multiple independent analyses to be subdominant and insufficient to explain discrepancies. The tensor meson is the next natural candidate to explore
  - The KLOE-2 vs A2/Crystal Ball tension and the subleading role of scalars motivate including tensor exchange

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- $a_2(1320)$  tensor exchange contribution

- The Feynman diagram contributing to the process is



- The chiral Lagrangians for the tensor mesons required in the calculations are

$$\mathcal{L}_{TPP} = g_{TPP} \langle T_{\mu\nu} \{u^\mu, u^\nu\} \rangle, \quad \mathcal{L}_{T\gamma\gamma} = c_{T\gamma\gamma} \langle T_{\mu\nu} \Theta_\gamma^{\mu\nu} \rangle$$

where

$$u_\mu = i(u^\dagger \partial_\mu u - u \partial_\mu u^\dagger), \quad u = e^{i \frac{\Phi}{\sqrt{2}F_\pi}}$$

$$\Theta_\gamma^{\mu\nu} = f_{+\alpha}^\mu f_+^{\alpha\nu} + \frac{1}{4} g^{\mu\nu} f_+^{\rho\sigma} f_{+\rho\sigma},$$

Careful with order of indices!

$$f_+^{\mu\nu} = e(u Q u^\dagger + u^\dagger Q u) F^{\mu\nu}, \quad F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- The  $g_{TTP}$  and  $c_{T\gamma\gamma}$  couplings are determined experimentally through

$$\Gamma(a_2 \rightarrow \pi\eta) = \frac{8p^5(m_{a_2}, m_\pi, m_\eta)}{15\pi m_{a_2}^2} \frac{|g_{TTP}|^2}{F_\pi^4} \cos^2 \phi_P \quad \Longrightarrow \quad |g_{TTP}| = 21.5(1.0) \text{ MeV}$$

$$\Gamma(a_2 \rightarrow \pi\eta') = \frac{8p^5(m_{a_2}, m_\pi, m_{\eta'})}{15\pi m_{a_2}^2} \frac{|g_{TTP}|^2}{F_\pi^4} \sin^2 \phi_P \quad \Longrightarrow \quad |g_{TTP}| = 22.4(1.9) \text{ MeV}$$

and

$$\Gamma(a_2 \rightarrow \gamma\gamma) = \frac{8\pi}{45} \alpha^2 m_{a_2}^3 |c_{T\gamma\gamma}|^2 \quad \Longrightarrow \quad |c_{T\gamma\gamma}| = 1.2 \times 10^{-4} \text{ MeV}^{-1}$$

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- The amplitude for  $\eta \rightarrow \pi^0$  ( $a_2 \rightarrow \gamma\gamma$ ) is

$$\mathcal{A}_{\eta \rightarrow \pi^0 \gamma\gamma}^{a_2} = \frac{32e^2}{3F_\pi^2} g_{TPP} c_{T\gamma\gamma} \cos \phi_P P^\mu p^\nu \frac{P_{\mu\nu,\rho\sigma}(s)}{m_{a_2}^2 - s - im_{a_2}\Gamma_{a_2}(s)} \\ \times \left\{ g^{\rho\alpha} q_1^\beta q_2^\sigma + g^{\sigma\beta} q_1^\rho q_2^\alpha - g^{\rho\alpha} g^{\sigma\beta} (q_1 \cdot q_2) - g^{\alpha\beta} q_1^\rho q_2^\sigma + \frac{1}{2} g^{\rho\sigma} [g^{\alpha\beta} (q_1 \cdot q_2) - q_1^\beta q_2^\alpha] \right\} \epsilon_\alpha^*(q_1) \epsilon_\beta^*(q_2)$$

where

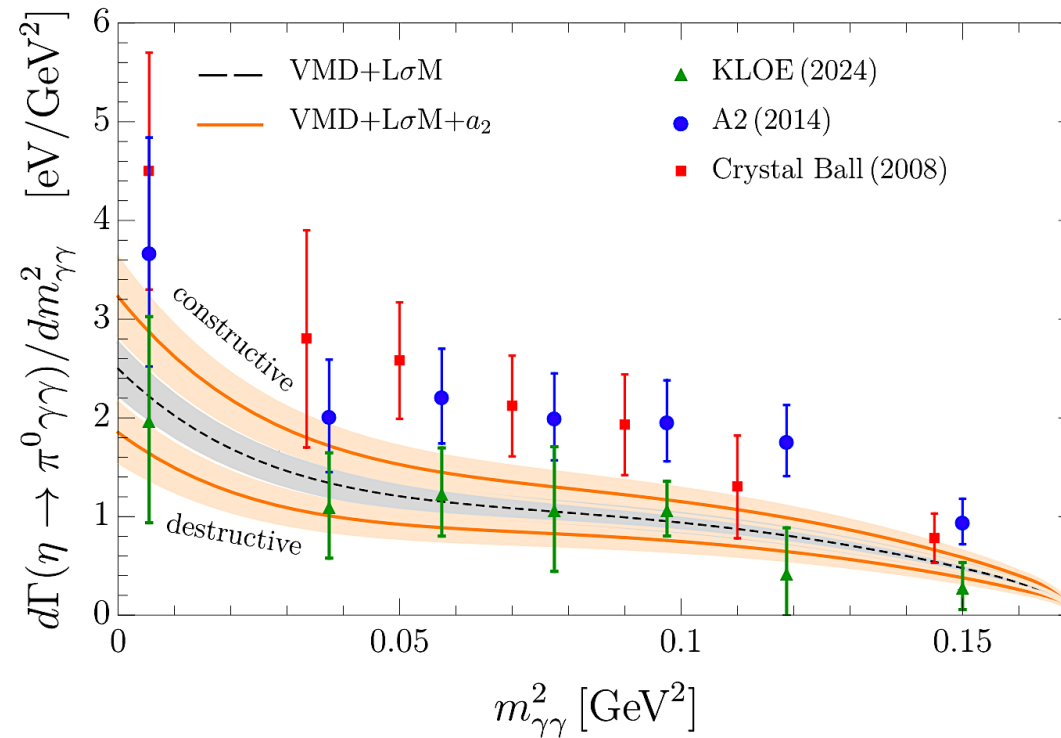
$$P_{\mu\nu,\rho\sigma}(q) = \frac{1}{2} (P_{\mu\rho} P_{\nu\sigma} + P_{\nu\rho} P_{\mu\sigma}) - \frac{1}{3} P_{\mu\nu} P_{\rho\sigma}, \quad P_{\mu\nu} = g_{\mu\nu} - \frac{q_\mu q_\nu}{m_{a_2}^2}$$

and  $P(p)$  is the four-momentum of the  $\eta(\pi^0)$

- Likewise, the amplitude for  $\eta' \rightarrow \pi^0$  ( $a_2 \rightarrow \gamma\gamma$ ) is obtained by making the replacements  $m_\eta \rightarrow m_{\eta'}$  and  $\cos \phi_P \rightarrow \sin \phi_P$

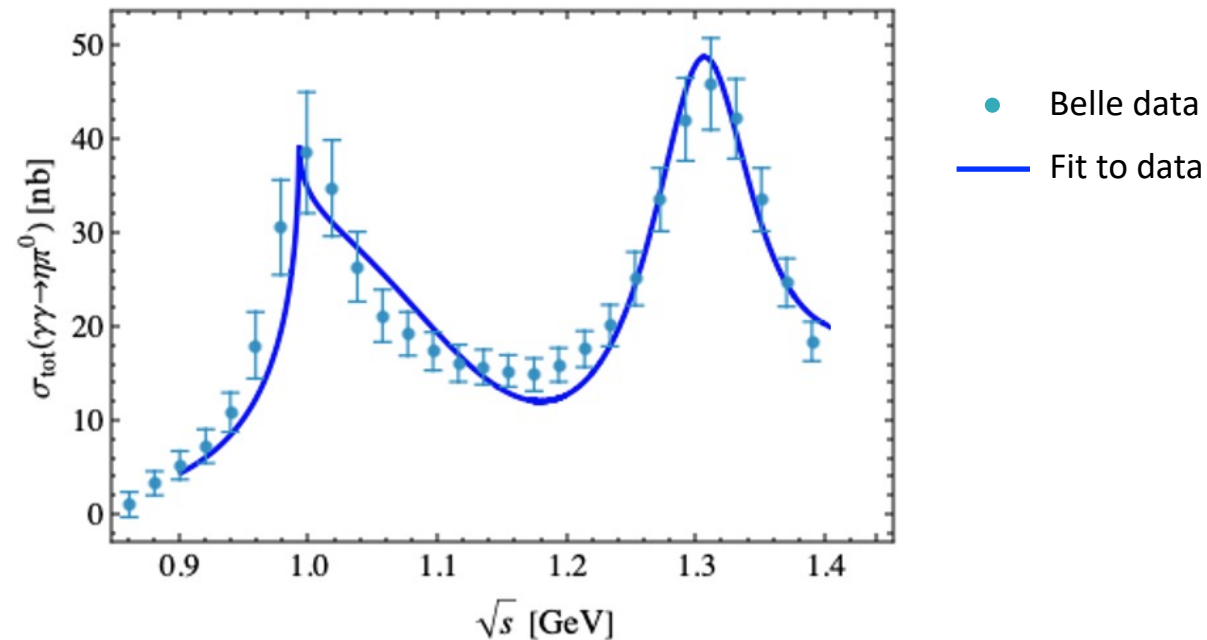
# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- Diphoton invariant mass distribution for  $\eta \rightarrow \pi^0\gamma\gamma$



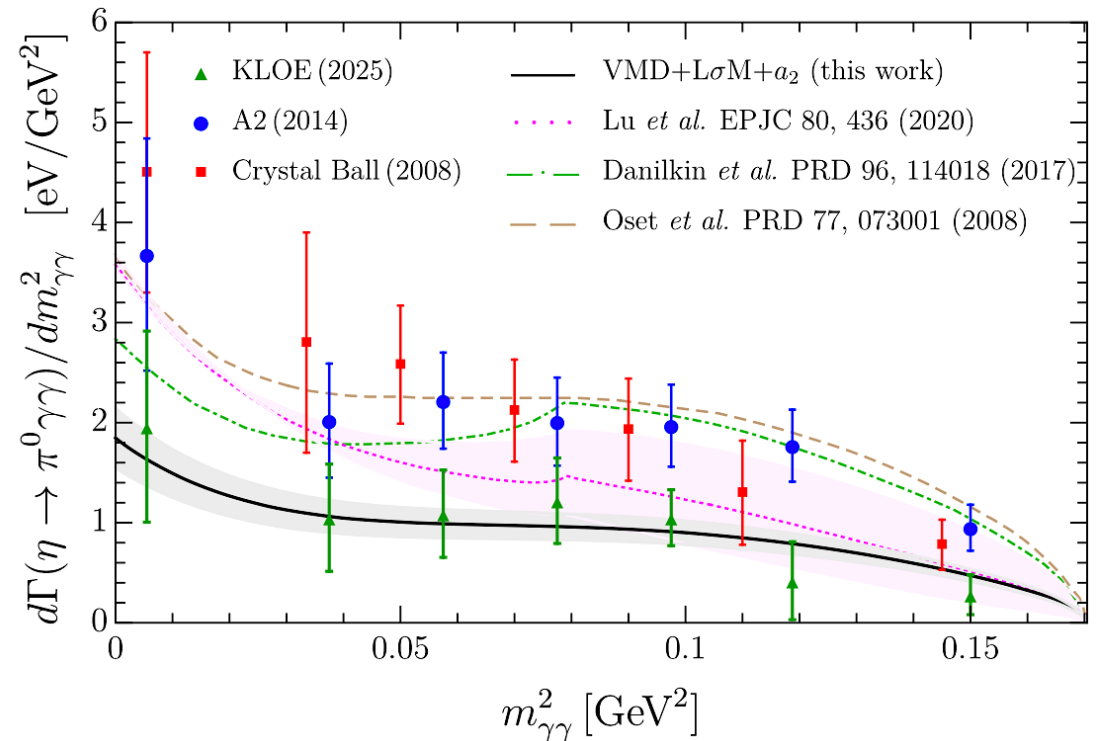
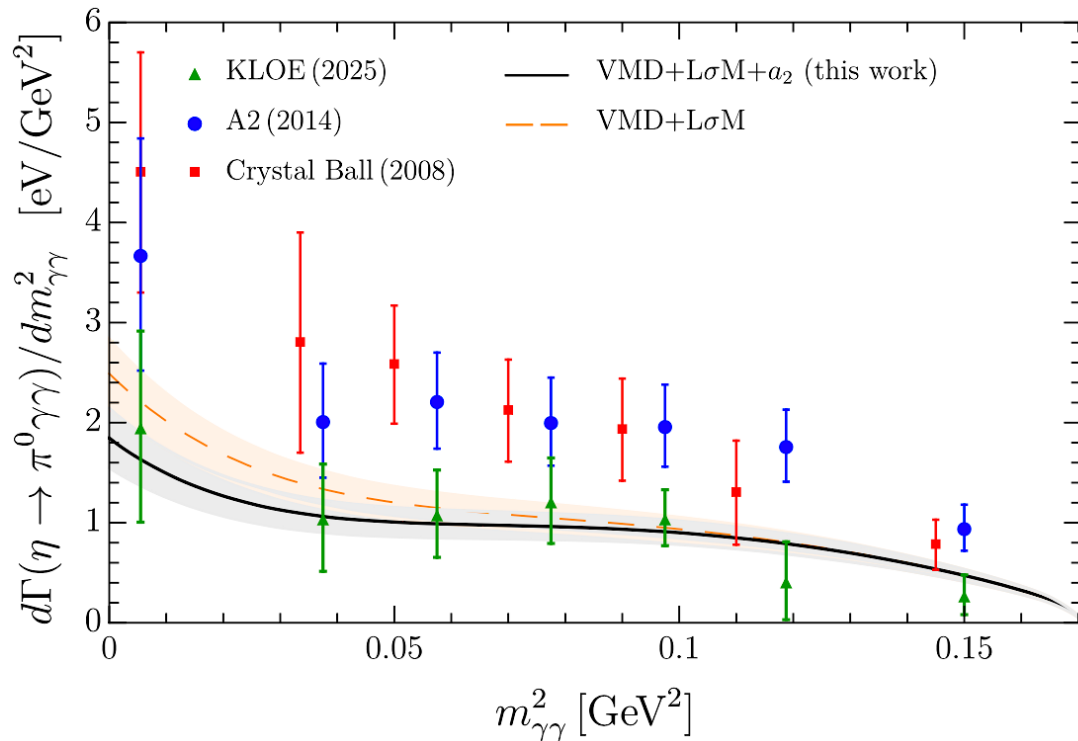
# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- Unlike  $\eta \rightarrow \pi^0\gamma\gamma$ ,  $\gamma\gamma \rightarrow \eta\pi^0$  scattering data fix the sign of the vector-tensor interference, which is found to be destructive



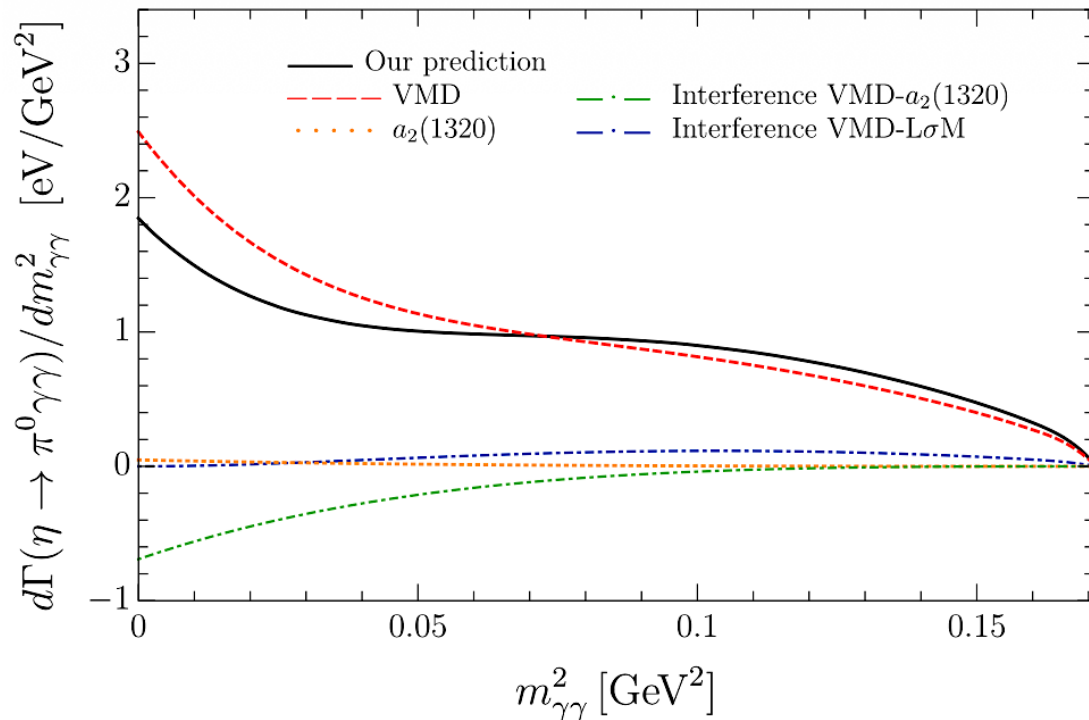
# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- Our prediction for  $\eta \rightarrow \pi^0\gamma\gamma$ : BR =  $1.17(17) \times 10^{-4}$



# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

- Our prediction for  $\eta \rightarrow \pi^0\gamma\gamma$ : BR =  $1.17(17) \times 10^{-4}$



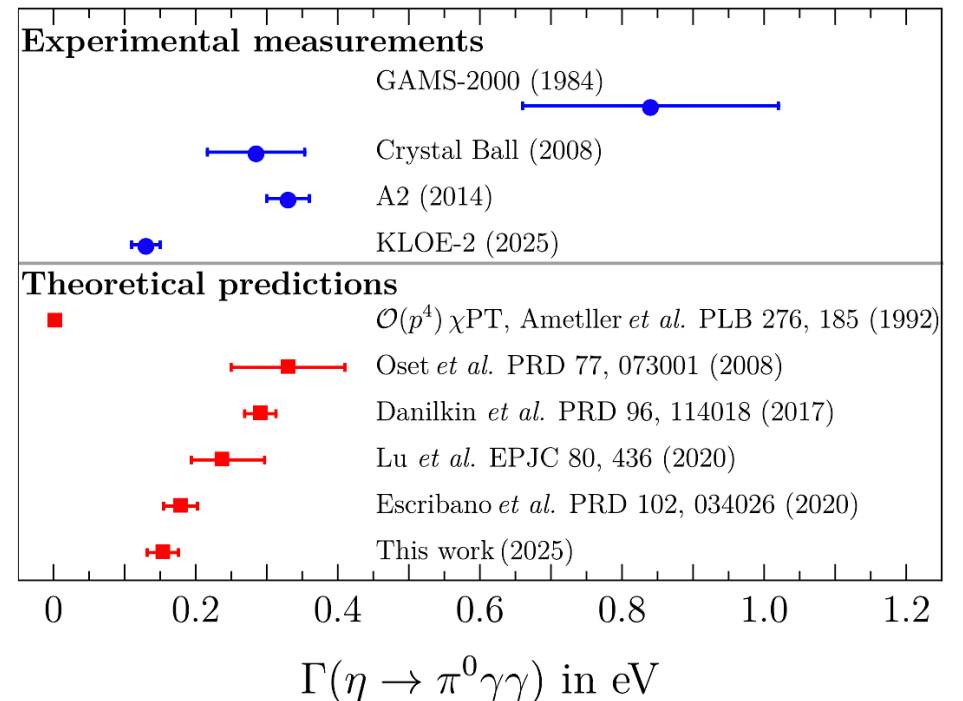
Term	Value (in eV)
Vectors (V)	0.1661
Scalars (S)	0.0005
$a_2$	0.0020
V-S interference	0.0121
V- $a_2$ interference	-0.0270
$\Gamma_{\text{th}}$	0.1538
BR <sub>th</sub>	$1.17(17) \times 10^{-4}$
BR <sub>exp</sub> (PDG)	$2.55(22) \times 10^{-4}$
BR <sub>exp</sub> (KLOE-2)	$0.98(11_{\text{stat}})(14_{\text{syst}}) \times 10^{-4}$

Using updated  $g_{VP\gamma}$  values

# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

## ■ $\eta \rightarrow \pi^0\gamma\gamma$ : Experimental and Theoretical Status

- Our final prediction, including vector, scalar, and tensor resonance exchanges, is  $\text{BR} = 1.17(17) \times 10^{-4}$   
[*Phys.Rev.D* 112 (2025) 11, 114009]
- In very good agreement with KLOE-2 experiment  
 $\text{BR} = 0.98(11)(14) \times 10^{-4}$   
[*JHEP* 01 (2026) 091]
- In tension ( $\sim 4.3\sigma$ ) with A2 Collaboration measurement  
 $\text{BR} = 2.54(27) \times 10^{-4}$   
[*Phys.Rev.C* 90 (2014) 2, 025206]
- **Both theoretical predictions and experimental measurements show significant spread**



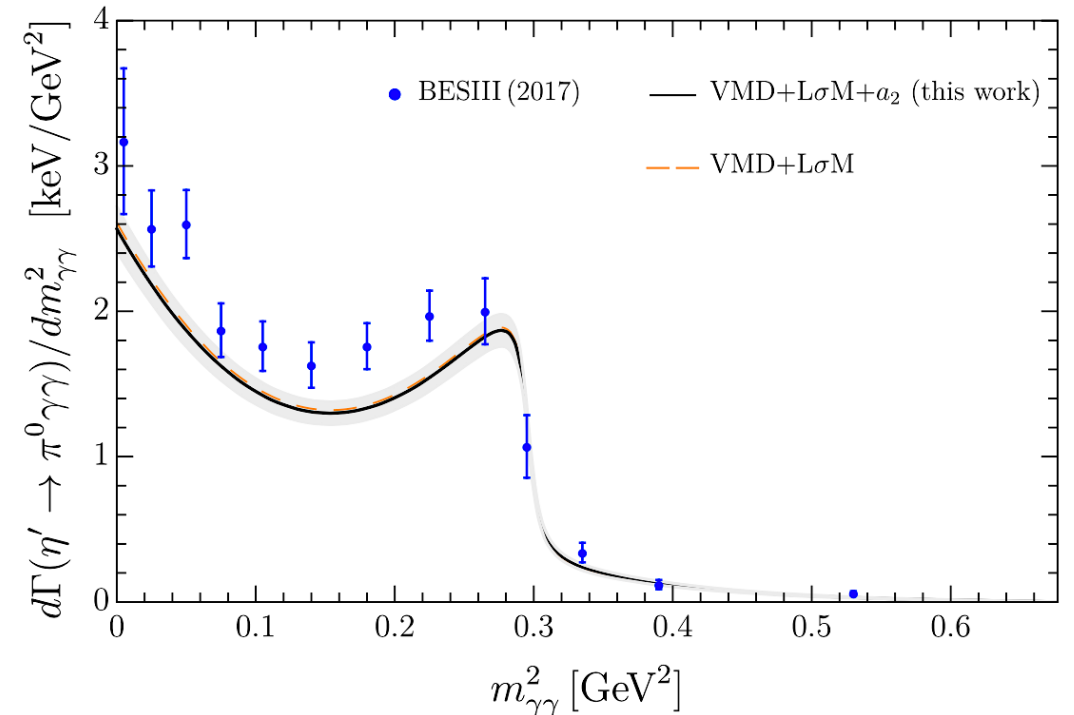
# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

## ■ Theoretical predictions vs. measurements for $\eta' \rightarrow \pi^0\gamma\gamma$

- Updated prediction BR =  $2.78(21) \times 10^{-3}$
- Vector exchanges dominate: 100%
  - $\rho$ : 5% of the signal
  - $\omega$ : 78% of the signal
  - $\phi$ : ~0% of the signal
  - $\rho$ - $\omega$ - $\phi$  interference: 17% of the signal
- Scalar exchanges negligible: ~0%
- Vector-scalar interference: ~0%
- Tensor contribution negligible: ~0%
- Prediction compatible with BESIII measurement,  
BR =  $3.10(7)(23) \times 10^{-3}$

[*Phys.Rev.D* 96 (2017) 1, 012005]

Updated result  
*Phys.Rev.D* 112 (2025)



# Rare $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ decays in the SM

## ■ Theoretical predictions vs. measurements for $\eta' \rightarrow \eta\gamma\gamma$

- Updated prediction BR =  $1.17(8) \times 10^{-4}$

Corrected complete propagators

- Vector exchanges dominate: 96%

- $\rho$ : 57% of the signal
- $\omega$ : 15% of the signal
- $\phi$ : 1% of the signal
- $\rho$ - $\omega$ - $\phi$  interference: 23% of the signal

- Scalar exchanges NOT negligible: 16%

- Vector-scalar interference: -12%

- Prediction compatible with BESIII

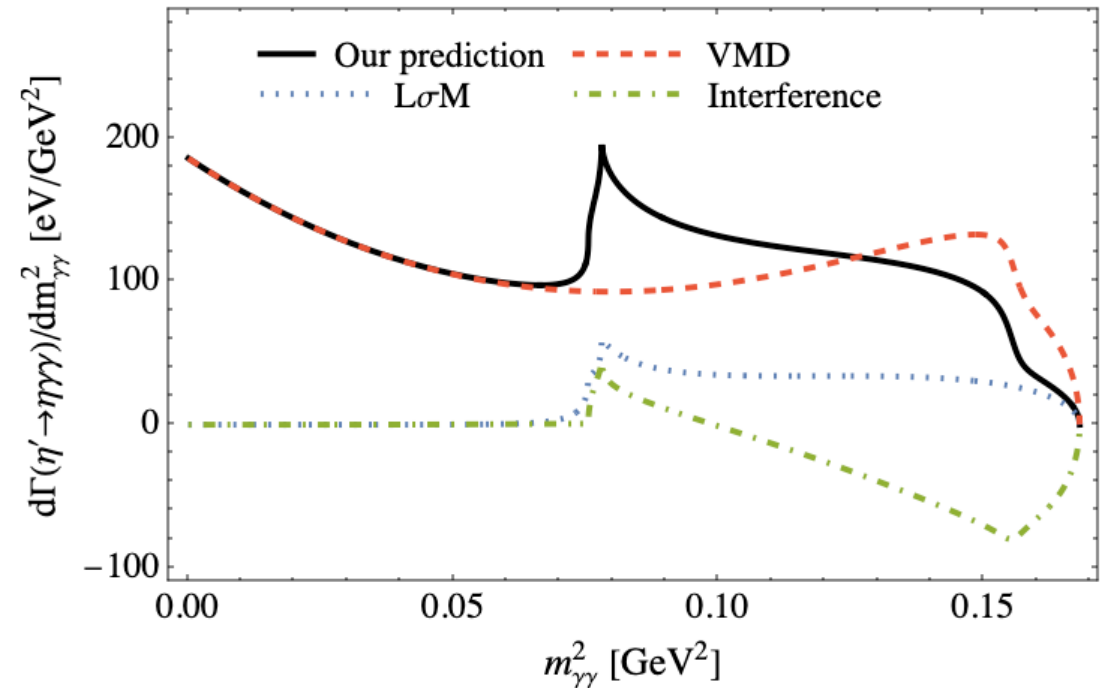
- BR =  $8.25(3.41)(0.72) \times 10^{-5}$

[Phys.Rev.D 100 (2019) 5, 052015]

- BR <  $1.33 \times 10^{-4}$  at 90% C.L.

[Phys.Rev.D 100 (2019) 5, 052015]

- We await the experimental release of the  $m_{\gamma\gamma}^2$  spectrum



# Table of contents

- Introduction
- Doubly radiative  $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$  decays in the Standard Model
- **Conclusions**

# Conclusions

- SM results for  $\eta^{(\prime)} \rightarrow \pi^0(\eta)\gamma\gamma$ : vector/scalar exchanges (VMD,  $L\sigma M$ ) and tensor  $a_2(1320)$  included via a chiral model
- $\eta \rightarrow \pi^0\gamma\gamma$ 
  - In excellent agreement with latest KLOE-2 measurement
  - Vector-tensor interference relevant at low  $m_{\gamma\gamma}^2$ , identified as destructive from scattering data (Belle)
  - Experimental tension among CB, A2, KLOE-2 calls for more precise measurements
- $\eta' \rightarrow \pi^0\gamma\gamma$ 
  - In good agreement with BESIII measurement
  - Tensor contribution negligible
- $\eta' \rightarrow \eta\gamma\gamma$ 
  - In good agreement with BESIII measurement

Backup slides

# Backup slides

- Many of the strong and EM  $\eta$  and  $\eta'$  decays are suppressed at leading order due to symmetries
  - Strong decays at lowest order
    - $\eta^{(\prime)} \rightarrow 2\pi$  and  $\eta \rightarrow 4\pi$  violate  $P$  and  $CP$  invariance
    - $\eta^{(\prime)} \rightarrow 3\pi$  are suppressed by  $G$ -parity conservation
  - First order EM decays
    - $\eta^{(\prime)} \rightarrow 2\gamma$  are suppressed because they proceed through the anomaly
    - $\eta^{(\prime)} \rightarrow 3\gamma$  violate  $C$  invariance
    - $\eta \rightarrow \pi^0\gamma$  violates  $C$  invariance and angular momentum conservation
    - $\eta \rightarrow 2\pi^0\gamma$  and  $\eta \rightarrow 3\pi^0\gamma$  violate  $C$  invariance
    - $\eta \rightarrow \pi^+\pi^-\gamma$  is suppressed because it proceeds through the anomaly
    - $\eta^{(\prime)} \rightarrow \pi^0 l^+ l^-$  violate  $C$  as single- $\gamma$  process
    - $\eta' \rightarrow \eta l^+ l^-$  violate  $C$  as single- $\gamma$  process

# Backup slides

- Updated  $g_{VP\gamma}$  values from  $V \rightarrow P\gamma$  and  $P \rightarrow V\gamma$  decays

[Phys.Rev.D 102 (2020) 3, 034026]

Decay	BR	$ g_{VP\gamma} $ GeV <sup>-1</sup>
$\rho^0 \rightarrow \pi^0\gamma$	$(4.7 \pm 0.6) \times 10^{-4}$	0.22(1)
$\rho^0 \rightarrow \eta\gamma$	$(3.00 \pm 0.21) \times 10^{-4}$	0.48(2)
$\eta' \rightarrow \rho^0\gamma$	$(28.9 \pm 0.5)\%$	0.40(1)
$\omega \rightarrow \pi^0\gamma$	$(8.40 \pm 0.22)\%$	0.70(1)
$\omega \rightarrow \eta\gamma$	$(4.5 \pm 0.4) \times 10^{-4}$	0.135(6)
$\eta' \rightarrow \omega\gamma$	$(2.62 \pm 0.13)\%$	0.127(4)
$\phi \rightarrow \pi^0\gamma$	$(1.30 \pm 0.05) \times 10^{-3}$	0.041(1)
$\phi \rightarrow \eta\gamma$	$(1.303 \pm 0.025)\%$	0.2093(20)
$\phi \rightarrow \eta'\gamma$	$(6.22 \pm 0.21) \times 10^{-5}$	0.216(4)



[Phys.Rev.D 112 (2025) 11, 114009]

Decay	BR	$ g_{VP\gamma} $ GeV <sup>-1</sup>
$\rho^0 \rightarrow \pi^0\gamma$	$(4.7 \pm 0.8) \times 10^{-4}$	0.22(2)
$\rho^0 \rightarrow \eta\gamma$	$(3.00 \pm 0.21) \times 10^{-4}$	0.48(2)
$\eta' \rightarrow \rho^0\gamma$	$(29.48 \pm 0.35)\%$	0.393(7)
$\omega \rightarrow \pi^0\gamma$	$(8.33 \pm 0.25)\%$	0.71(1)
$\omega \rightarrow \eta\gamma$	$(4.5 \pm 0.4) \times 10^{-4}$	0.136(6)
$\eta' \rightarrow \omega\gamma$	$(2.52 \pm 0.07)\%$	0.122(2)
$\phi \rightarrow \pi^0\gamma$	$(1.33 \pm 0.05) \times 10^{-3}$	0.041(1)
$\phi \rightarrow \eta\gamma$	$(1.306 \pm 0.024)\%$	0.2096(20)
$\phi \rightarrow \eta'\gamma$	$(6.23 \pm 0.21) \times 10^{-5}$	0.216(4)

# Backup slides

- Complete one-loop propagator

$$D(s) = \frac{i}{s - M_0^2 + \Pi(s)} = \frac{i}{s - M_R^2 + \text{Re}\Pi(s) - \text{Re}\Pi(M_R^2) + i\text{Im}\Pi(s)}, \quad \text{with } M_R^2 \equiv M_0^2 - \text{Re}\Pi(M_R^2)$$

- The pole mass and pole width of the resonance,  $M_p$  and  $\Gamma_p$ , are found from the pole equation on the second Riemann sheet

$$\Delta(s_p) = s_p - M_R^2 + \text{Re}\Pi_+(s_p) - \text{Re}\Pi_+(M_R^2) + i\text{Im}\Pi_+(s_p) = 0,$$

with

$$\Pi_+(s) = \text{Re}R(s) - \text{Im}I(s) + i[\text{Im}R(s) + \text{Re}I(s)] \quad \text{and} \quad s_p \equiv \left(M_p - \frac{i}{2}\Gamma_p\right)^2$$

where  $\Pi_+(s)$  denotes the self-energy analytically continued to the second Riemann sheet

- Parameters for the scalar resonances

$$M_{\sigma R} = 498 \text{ MeV}$$

$$M_{f_0 R} = 990 \text{ MeV}$$

$$M_{a_0 R} = 980 \text{ MeV}$$

$$M_{\sigma p} = 550 \text{ MeV}$$

$$M_{f_0 p} = 990 \text{ MeV}$$

$$M_{a_0 p} = 980 \text{ MeV}$$

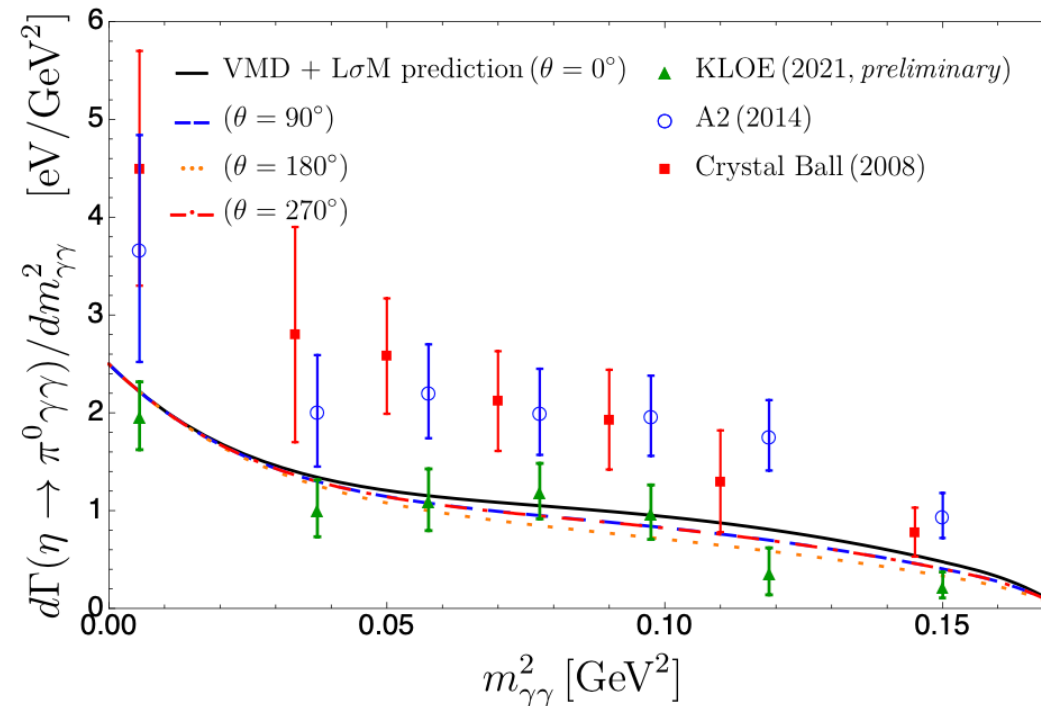
$$\Gamma_{\sigma p} = 400 \text{ MeV}$$

$$\Gamma_{f_0 p} = 15 \text{ MeV}$$

$$\Gamma_{a_0 p} = 100 \text{ MeV}$$

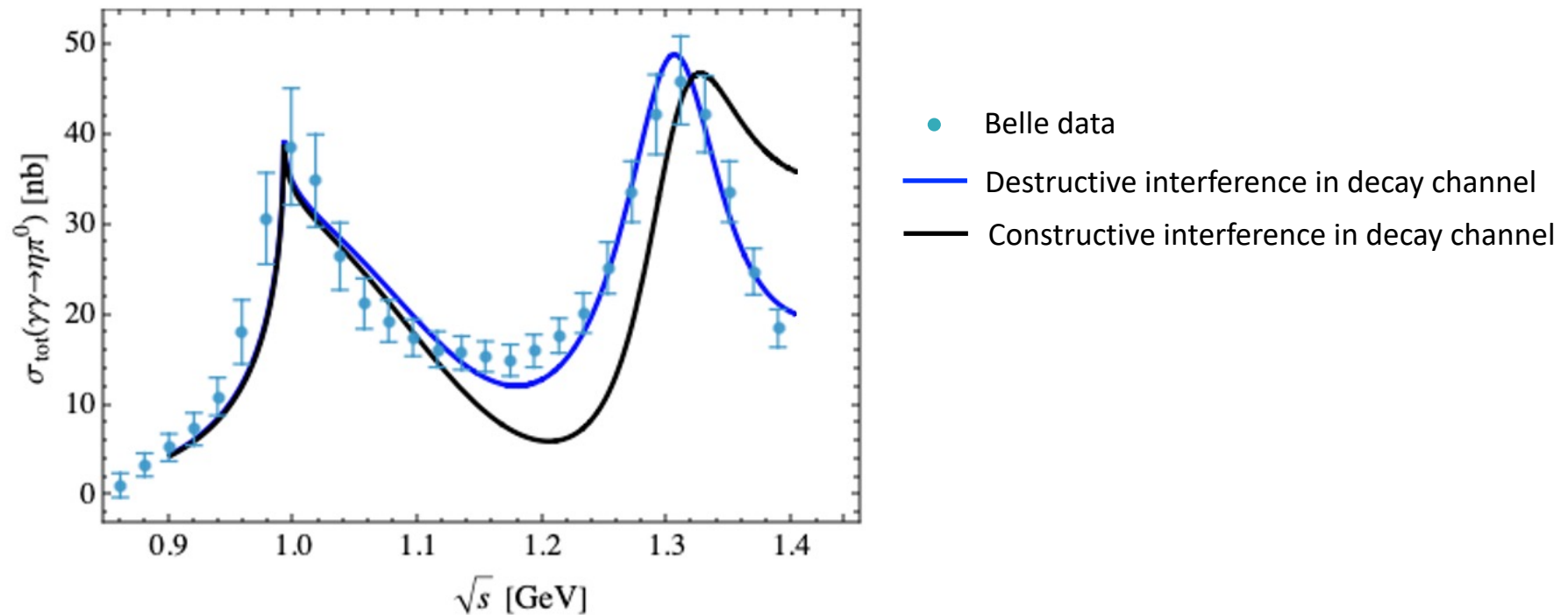
# Backup slides

- Relative phase between the VMD and  $L\sigma M$  amplitudes in  $\eta \rightarrow \pi^0\gamma\gamma$



# Backup slides

- Probing the relative phase of the tensor-exchange contribution via  $\gamma\gamma \rightarrow \eta\pi^0$



# Backup slides

## ■ Comparison of theoretical approaches for $\eta \rightarrow \pi^0 \gamma \gamma$ in the SM

	This work (2025)	Oset et al. (2008)	Danilkin et al. (2017)	Lu & Moussallam (2020)
<b>Approach</b>	VMD + $L\sigma M$ + chiral tensor Lagrangian; amplitude computed directly in the decay region	Chiral unitary (Bethe–Salpeter) + VMD loops + anomalous terms	Dispersion theory on $\gamma\gamma \rightarrow \eta\pi^0$ , continued by crossing symmetry to the decay region	Muskhelishvili–Omnès on $\gamma\gamma \rightarrow \eta\pi^0/K_S K_S$ + analytic continuation
<b>Vectors</b>	VMD $\rho, \omega, \phi$ ; empirical PDG 2024 couplings; energy-dependent width for the $\rho$ resonance	VMD $\rho, \omega$ (no $\phi$ ); universal $SU(3)$ couplings normalized to 2007 BRs	VMD $\rho, \omega$ (no $\phi$ ); universal or individual coupling; no full propagator	VMD $\rho, \omega, \phi$ in $d$ -wave; couplings fitted to Belle $\gamma\gamma \rightarrow \eta\pi^0$ and $K_S K_S$ data
<b>Scalar (<math>a_0</math>)</b>	$L\sigma M$ (subdominant, minimal effect)	Dynamically generated (Bethe–Salpeter, $\pi\eta/K\bar{K}$ ); sign of $a_0$ fixed for first time	Coupled-channel Omnès for scattering; scalars not retained in decay region; decay prediction: $\chi$ PT NLO loops + VMD only	Muskhelishvili–Omnès two-channel; soft-photon/soft-pion theorems imposed; simultaneous $\pi\eta$ and $K_S K_S$ fit
<b>Tensor (<math>a_2</math>)</b>	Included with chiral Lagrangians; sign fixed by $\gamma\gamma \rightarrow \pi^0 \eta \Rightarrow$ <b>destructive interference</b>	<b>Not included</b>	BW in scattering amplitude; Blatt–Weisskopf factors omitted; $a_2$ not continued to the decay region	BW in $d$ -wave with fitted couplings; <b>interference sign</b> not discussed in decay region
<b>Additional contributions</b>	None (resonance exchanges provide all-order estimates)	$\chi$ PT loops + VMD loop diagrams + anomalous terms – potential <b>overcounting</b> of vector contributions	$\chi$ PT kaon loops included, yielding $\sim 0.010$ eV - larger than found by others; added in positive interference with VMD to reproduce decay data	Isospin-violating $\pi^+ \pi^-$ cusp included
<b>Main strength</b>	Simplicity, all-order resonances; updated couplings; tensor phase determined by $\gamma\gamma \rightarrow \pi^0 \eta$	First dynamical generation of $a_0$ – fixes scalar sign unambiguously	Rigorous $s$ -wave (analyticity, unitarity); no free hadronic parameters	State-of-the-art dispersive $s$ -wave; constrained by $\pi\eta$ and $K_S K_S$ data
<b>Main weakness</b>	Scalar sector treated with $L\sigma M$ (less sophisticated than dispersive methods) – but scalar contribution is subdominant	Mix of VMD, loops, and anomalous terms without a clear organising principle; uses older radiative BRs	Crude $d$ -wave treatment relative to $s$ -wave; vector $\phi$ missing; continuation to the decay region not fully validated; uses older radiative BRs	Hadronic cutoff $\Lambda_S$ governing left-hand cut; $d$ -wave treatment crude relative to $s$ -wave; two degenerate fit solutions – one argued to be unphysical
<b>Predicted <math>\Gamma</math> (eV)</b>	<b><math>0.154 \pm 0.022</math></b>	$0.33 \pm 0.08$	$0.291 \pm 0.022$	$0.237^{+0.060}_{-0.043}$
<b>Predicted BR</b>	<b><math>(1.17 \pm 0.17) \times 10^{-4}</math></b>	$(2.52 \pm 0.61) \times 10^{-4}$	$(2.22 \pm 0.19) \times 10^{-4}$	$(1.81^{+0.46}_{-0.33}) \times 10^{-4}$
<b>Agreement with KLOE-2 (2026)</b>	<b>Excellent</b> ( $\sim 0.8\sigma$ )	Disfavoured ( $\sim 8\sigma$ above)	Disfavoured ( $\sim 7\sigma$ above)	High (factor $\sim 2.4$ , $\sim 4\sigma$ , above KLOE-2 central value)

Table 1: Comparison of theoretical approaches for  $\eta \rightarrow \pi^0 \gamma \gamma$ . Experimental BRs: KLOE-2 (2025) BR =  $0.98(11_{\text{stat}})(14_{\text{syst}}) \times 10^{-4}$ ; PDG (2024) BR =  $2.55(22) \times 10^{-4}$ .

# Backup slides

## ■ The REDTOP experiment

- Concept: low-energy fixed-target meson factory operating in the high-intensity precision frontier
- Setup: 1.8 GeV proton beam on a target of 10 Li/Be foils, producing  $\sim 10^{14}$   $\eta$  mesons in three years
- Production:  $\eta/\eta'$  production via intranuclear baryonic resonances [ $\Delta$ , N(1440), N(1535), ...] in nucleon-nucleon collisions
- Detection principle: Prompt Cherenkov light from charged decay products, while most background particles remain below Cherenkov threshold
- Physics opportunities :
  - New particle searches (BSM vectors, scalars, heavy neutral leptons, ALPs, ...)
  - Test of conservation laws ( $C/CP$  symmetries, lepton flavour universality)
  - Non-perturbative QCD (light-quark masses, form factors, ...)
  - Muon polarimetry (polarisation in decays,  $CP$  violation, ...)