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$\eta^{(\prime)} \to \pi^0\gamma\gamma$ decays: Test of meson exchange models and searches of leptophobic B bosons

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Summary. — We analyze the vector and scalar meson exchange contributions to the doubly radiative decays $\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$, and study the sensitivity of these decays to a leptophobic B boson in the sub-GeV mass range. Our results are relevant for studies of these decays at existing (A2, BESIII, KLOE-2) and forthcoming η/η'-factories, such as the JEF and REDTOP experiments.

1. – Introduction

The rare doubly radiative decays $\eta/\eta' \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$ have attracted a lot of attention recently(1), both from the experimental and theoretical sides, since the preliminary experimental measurement of the $\eta \to \pi^0\gamma\gamma$ decay by the KLOE-2 Collaboration(2). While our theoretical predictions of the branching ratios (BR) for the decays of the η' meson, $\mathrm{BR}(\eta' \to \pi^0\gamma\gamma) = 2.91(21) \times 10^{-3}$ and $\mathrm{BR}(\eta' \to \eta\gamma\gamma) = 1.17(8) \times 10^{-4}$ [3], are compatible with the experimental results from the BESIII Collaboration, $\mathrm{BR}(\eta' \to \pi^0\gamma\gamma) = 3.20(7)(23) \times 10^{-3}$ [4] and $\mathrm{BR}(\eta' \to \eta\gamma\gamma) = 8.25(3.41)(0.72) \times 10^{-5}$ [5], the situation for $\eta \to \pi^0\gamma\gamma$ is presently inconclusive. For this decay, the new measurement from KLOE-2, $\mathrm{BR}(\eta \to \pi^0\gamma\gamma) = 0.99(11)(24) \times 10^{-4}$ [2], is in agreement with our calculation, $\mathrm{BR}(\eta \to \pi^0\gamma\gamma) = 1.35(8) \times 10^{-4}$ [3], but in tension with the PDG average, $\mathrm{BR}(\eta \to \pi^0\gamma\gamma) = 2.55(22) \times 10^{-4}$ [6]; the main input being $\mathrm{BR}(\eta \to \pi^0\gamma\gamma) = 2.54(27) \times 10^{-4}$ from the A2 Collaboration at MAMI [7].

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(1) See, *e.g.*, talks at ECT* workshop, *Precision test of fundamental physics with light mesons*, June 12–16, 2023 [1].

(2) See talk by G. Mandaglio at this workshop [2].

On the other hand, these decays have been put forward as powerful probes to search for MeV–GeV signals of a new hypothetical gauge boson, named B boson, that emerges from a new $U(1)_B$ gauge symmetry and couples predominantly to quarks over leptons [8].

The aim of this contribution is to highlight the results for the three decays that we have obtained in ref. [3] based on meson exchange ideas and show the updated constraints on the B boson parameters, mass m_B and coupling to Standard Model particles α_B, that we have recently placed in ref. [9]. The theoretical framework is detailed in sect. **2** and our results presented in sect. **3**. We close with an outlook in sect. **4**.

2. – Theoretical framework

2˙1. *Standard Model: Vector and scalar meson exchange contributions.* – To calculate the vector meson exchange contributions we use VMD. In this framework, $\eta \to \pi^0\gamma\gamma$ proceeds through the transition $\eta \to V\gamma$ followed by $V \to \pi^0\gamma$, resulting in a total of six diagrams contributing to the amplitude, which correspond to the exchange of the three neutral vector mesons $V = \rho^0, \omega$ and ϕ in the t and u channels. Combining the participating $V\eta\gamma$ and $V\pi^0\gamma$ interacting terms from the effective $VP\gamma$ Lagrangian from ref. [10] with the propagator of the corresponding vector meson, we find the vector meson contributions to $\eta \to \pi^0\gamma\gamma$ [3]

$$\mathcal{A}^{\mathrm{VMD}}_{\eta\to\pi^0\gamma\gamma} = \sum_{V=\rho^0,\omega,\phi} g_{V\eta\gamma}\, g_{V\pi^0\gamma} \left[\frac{(P\cdot q_2 - m_\eta^2)\{a\} - \{b\}}{D_V(t)} + \left\{ \begin{array}{c} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array} \right\} \right], \tag{1}$$

where $t, u = (P - q_{2,1})^2 = m_\eta^2 - 2P\cdot q_{2,1}$ are the Mandelstam variables, $\{a\}$ and $\{b\}$ are the Lorentz structures, which are defined as

$$\begin{aligned} \{a\} &= (\epsilon_1\cdot\epsilon_2)(q_1\cdot q_2) - (\epsilon_1\cdot q_2)(\epsilon_2\cdot q_1), \\ \{b\} &= (\epsilon_1\cdot q_2)(\epsilon_2\cdot P)(P\cdot q_1) + (\epsilon_2\cdot q_1)(\epsilon_1\cdot P)(P\cdot q_2) \\ &\quad - (\epsilon_1\cdot\epsilon_2)(P\cdot q_1)(P\cdot q_2) - (\epsilon_1\cdot P)(\epsilon_2\cdot P)(q_1\cdot q_2), \end{aligned} \tag{2}$$

where P is the four-momentum of the η meson, and $\epsilon_{1,2}$ and $q_{1,2}$ are, respectively, the polarisation and four-momentum vectors of the photons. The denominator $D_V(t) = m_V^2 - t - i\, m_V\Gamma_V$ is the vector meson propagator; for the ρ^0 propagator, we use an energy-dependent decay width $\Gamma_{\rho^0}(t) = \Gamma_{\rho^0} \times [(t - 4m_\pi^2)/(m_{\rho^0}^2 - 4m_\pi^2)]^{3/2} \times \theta(t - 4m_\pi^2)$. The amplitudes for the partner reactions $\eta' \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$ have a similar structure to that of eq. (1), with the replacements $m_\eta^2 \to m_{\eta'}^2$, and $g_{V\eta\gamma}g_{V\pi^0\gamma} \to g_{V\eta'\gamma}g_{V\pi^0\gamma}$ for the $\eta' \to \pi^0\gamma\gamma$ and $g_{V\eta\gamma}g_{V\pi^0\gamma} \to g_{V\eta'\gamma}g_{V\eta\gamma}$ for the $\eta' \to \eta\gamma\gamma$. For our analysis, we fix the $g_{VP\gamma}$ couplings in eq. (1) from the comparison of the calculated decay widths for the radiative transitions $V \to P\gamma$ and $P \to V\gamma$ with their empirical values from the PDG [6].

We use the Linear Sigma Model to calculate the scalar meson exchange contributions to the amplitude. These are small and are given in ref. [3].

2˙2. *Beyond the Standard Model: Leptophobic B-boson contribution.* – In analogy to the VMD contributions, we next define the framework to include intermediate B-boson exchanges to the decay amplitude. This contribution proceeds via the transition $\eta \to B\gamma \to \pi^0\gamma\gamma$ and can be assessed from the conventional VMD VVP and $V\gamma$ Lagrangians [11] supplemented by an effective Lagrangian that describes the VB interaction. The latter is formally identical to the $V\gamma$ Lagrangian with the substitutions

$A^\mu \to B^\mu$, $e \to g_B$ and $Q \to \mathrm{diag}\{1/3, 1/3, 1/3\}$. From the VVP and VB Lagrangians along with the corresponding V-meson propagators, it is straightforward to obtain expressions for the $g_{BP\gamma}$ couplings in terms of the generic B-boson coupling g_B. The $g_{BP\gamma}$ couplings are energy dependent and read [9]

$$\begin{aligned} & g_{B\pi^0\gamma}(q^2) = \frac{e g_B}{4\pi^2 f_\pi} F_\omega(q^2),\ g_{B\eta\gamma}(q^2) = \frac{e g_B}{12\pi^2 f_\pi}\left[\cos\varphi_P F_\omega(q^2) + \sqrt{2}\sin\varphi_P F_\phi(q^2)\right], \\ & g_{B\eta'\gamma}(q^2) = \frac{e g_B}{12\pi^2 f_\pi}\left[\sin\varphi_P F_\omega(q^2) - \sqrt{2}\cos\varphi_P F_\phi(q^2)\right], \end{aligned} \tag{3}$$

where φ_P is the η-η' mixing angle in the quark-flavour basis [10]. The functions $F_V(q^2)$ in the previous equations are form factors that account for the ω and ϕ propagation, and are given by $F_V(q^2) = m_V^2/(m_V^2 - q^2 - i m_V \Gamma_V)$.

Combining the couplings from eq. (3) with the propagator of the B boson, we get the B-boson exchange contribution to the amplitude of the $\eta^{(\prime)} \to \pi^0\gamma\gamma$ decays:

$$\mathcal{A}^{B\,\mathrm{boson}}_{\eta^{(\prime)}\to\pi^0\gamma\gamma} = g_{B\eta^{(\prime)}\gamma}(t) g_{B\pi^0\gamma}(t)\left[\frac{(P\cdot q_2 - m^2_{\eta^{(\prime)}})\{a\} - \{b\}}{D_B(t)} + \left\{\begin{matrix} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{matrix}\right\}\right], \tag{4}$$

where $\mathcal{D}_B(q^2) = m_B^2 - q^2 - i\sqrt{q^2}\,\Gamma_B(q^2)$ is the B-boson propagator, with $\Gamma_B(q^2) = \sum_i \Gamma_B^i(q^2)$ the energy-dependent width of the B boson, with the sum running over the partial widths of the various decay channels the B boson can decay into. For our study, we include the partial widths of the channels $B \to \pi^0\gamma$, e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, and $\pi^0\pi^+\pi^-$ [9].

3. – Standard Model predictions and limits on the B-boson parameters

In fig. 1 we present our Standard Model predictions for the diphoton invariant-mass distribution for $\eta \to \pi^0\gamma\gamma$ (left) and $\eta' \to \pi^0\gamma\gamma$ (right) as compared to experimental data, while in table I we show the resulting branching ratios; the uncertainties in our predictions come from the errors of the $g_{VP\gamma}$ couplings. For the decay $\eta \to \pi^0\gamma\gamma$, whereas our theoretical treatment shows a good agreement with the preliminary measurements of the spectrum by KLOE-2 [2], it appears to present a normalization offset with respect to the data from the A2 [7] and Crystal Ball [12] Collaborations, with a BR that is found to be approximately half of the averaged PDG one (see table I). On the other hand, using the exact same treatment our predictions for the decays of the η' meson are compatible with the experimental results from BESIII [4, 5].

Next, we calculate the constraints on the B-boson parameters, coupling $\alpha_B (\equiv g_B^2/4\pi)$ and mass m_B, set by experiment. For that, we write the amplitude for these decays as the coherent sum of the vector, scalar and B-boson exchange contributions, $\mathcal{A} = \mathcal{A}_{\mathrm{VMD}} + \mathcal{A}_{\mathrm{L}\sigma\mathrm{M}} + \mathcal{A}_{B\,\mathrm{boson}}$. We start with the $\eta \to \pi^0\gamma\gamma$ decay using the BR measurements by KLOE-2 (preliminary) and the PDG value. In fig. 2, we show the limits in the α_B-m_B plane, which are found by requiring our predictions to not exceed the corresponding BR at 2σ. The grey area is excluded by KLOE-2, which yields a more stringent limit than the resulting one from the PDG (solid red line). The dashed lines in the figure are found setting the SM (or, equivalently, QCD) contributions to zero. Clearly, these contributions are not negligible as the limits on α_B could be up to an order of magnitude weaker when their effects are turned off (labelled QCD off in the plots).

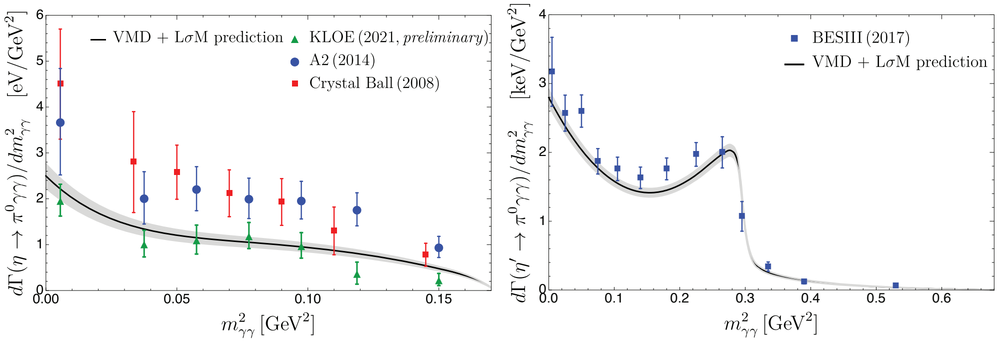

Fig. 1. – Experimental diphoton energy spectra for $\eta \to \pi^0\gamma\gamma$ (left) and $\eta' \to \pi^0\gamma\gamma$ (right) compared to our theoretical predictions from ref. [3] APS copyright. The data is taken from ref. [7] (A2), ref. [12] (Crystal Ball), ref. [2] (KLOE-2, preliminary) and ref. [4] (BESIII).

4. – Outlook

In this work, we have presented predictions for the decays $\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$ using the VMD and LσM frameworks to account for the vector and scalar meson exchange contributions, respectively. On the one hand, our predictions for the decays of the η' meson are compatible with the experimental measurements from BESIII. On the other hand, our prediction for $\eta \to \pi^0\gamma\gamma$ is in agreement with the new (preliminary) measurement from KLOE-2, but in tension with the previous measurement from the A2 and Crystal Ball Collaborations. There is a growing interest in resolving this discrepancy. On the theory side, ref. [13] suggests that contributions from the $a_2(1320)$ tensor resonance could be relevant at low diphoton invariant mass, while on the experimental side future analysis with improved statistics, *e.g.*, from A2 or the Jefferson Lab Eta Factory (JEF) experiment, could help clarify the experimental situation.

We have also studied the sensitivity of these decays to a leptophobic B boson. Adding the explicit B-boson exchange contribution to the SM amplitude has allowed us to place stringent limits on the B-boson parameters α_B and m_B by comparing with current experimental data. In particular, from the analysis of the decay $\eta \to \pi^0\gamma\gamma$, we have strengthened by one order of magnitude the current constraints.

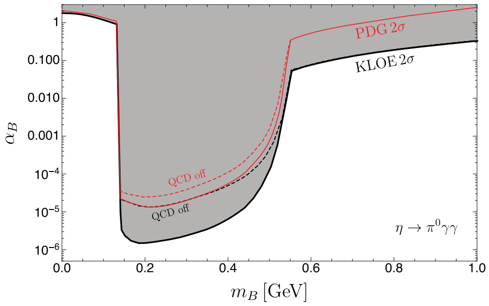

Fig. 2. – Limits on the leptophobic B-boson coupling α_B for different m_B masses from the $\eta \to \pi^0\gamma\gamma$ BR measurements by KLOE-2 [14] (black line) and the PDG [6] (red line). Figure taken from ref. [9] (APS copyright).

Table I. – *Our predictions for the* BR *from ref.* [3] *compared to the experimental measurements.*

Decay	$\mathrm{BR}_{\mathrm{th}}$ [3]	$\mathrm{BR}_{\mathrm{exp}}$
$\eta \to \pi^0\gamma\gamma$	$1.35(8) \times 10^{-4}$	$0.99(11)(24) \times 10^{-4}$ (KLOE-2 [2]) $2.56(22) \times 10^{-4}$ (PDG [6])
$\eta' \to \pi^0\gamma\gamma$	$2.91(21) \times 10^{-3}$	$3.20(7)(23) \times 10^{-3}$ (BESIII [4])
$\eta' \to \eta\gamma\gamma$	$1.17(8) \times 10^{-4}$	$8.25(3.41)(0.72) \times 10^{-5}$ (BESIII [5])

Our results are relevant for studies of these decays at existing (A2, BESIII, KLOE-2) and forthcoming η/η'-factories, such as the JEF and REDTOP experiments.

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