PROBING LIGHT DARK PARTICLES WITH η AND η' DECAYS*

Sergi González-Solís

Departament de Física Quàntica i Astrofísica, Universitat de Barcelona
Martí i Franquès, 1, 08028 Barcelona, Spain
and
Institut de Ciències del Cosmos, Universitat de Barcelona
Martí i Franquès, 1, 08028 Barcelona, Spain

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We analyze the sensitivity of the $\eta \to \pi^0\gamma\gamma$ decays to a leptophobic B boson in the sub-GeV mass range and provide branching ratio predictions for the single ALP $\eta/\eta' \to \pi\pi a$ decays as a function of the ALP mass.

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1. Introduction

Decays of the η and η' mesons offer a particularly suited playground to look for physics beyond the Standard Model (BSM) [1]. This is because all their decays are flavor-conserving and most of their strong and electromagnetic decays are either anomalous or forbidden at lowest order due to the conservation of fundamental discrete symmetries, namely C, P, CP, I, G-parity or angular momentum, which enhances the relative importance of potential new physics signals. Alternatively, the η and η' mesons also offer a place to search for new feebly-coupled light particles in the MeV–GeV mass range, such as dark photons or axion-like particles. In the BSM context, such particles are produced on-shell in meson decays and when they subsequently decay to Standard Model, particles appear as resonances in invariant mass distributions. The possible signals in η/η' decays typically mimic rare decays that are often highly suppressed in the SM. For example, the doubly-radiative $\eta \to \pi^0\gamma\gamma$ decay offers an experimental opportunity to look for a signature of a new hypothetical leptophobic gauge boson, named B boson, via $\eta \to B\gamma \to \pi^0\gamma\gamma$. On the other hand, ALP emission in η/η' decays can yield to exotic four- and five-body final-state channels. For example, the

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single ALP production in the $\eta/\eta' \to \pi\pi a$ decays is an ideal choice to search for an ALP signal via its decay into visible final states, such as $a \to \gamma\gamma, \ell^+\ell^-$ or $\pi\pi\pi$.

On the experimental side, upcomig η/η' factories, such as the approved JLab Eta Factory experiment [2] or the proposed REDTOP experiment [3], the super τ-charm facility [4] or the η factory at HIAF [5], will determine rare η and η' decays with precision several orders of magnitude higher than present measurements. These promising future prospects further motivate the investigation of η and η' decays as probes of BSM physics.

In this contribution, we highlight the main results of our study of the sensitivity of the $\eta \to \pi^0\gamma\gamma$ decay to a leptophobic B boson from Ref. [6] and of our predictions for the branching ratios of the $\eta/\eta' \to \pi\pi a$ decays with the strong $\pi\pi$ final-state interactions taken into account [7]. The theoretical framework is briefly given in Section 2 and our results are presented in Section 3. We close with an outlook in Section 4.

2. Theoretical framework

2.1. $\eta \to \pi^0\gamma\gamma$ decay: VMD and leptophobic B boson model

To calculate the vector meson exchange contributions, we use VMD. In this framework, the $\eta \to \pi^0\gamma\gamma$ decay proceeds through the $\eta \to V\gamma$ transition followed by $V \to \pi^0\gamma$ with $V = \rho^0, \omega$, and ϕ in the t and u channels. The amplitude reads [8]

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

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

$$\{a\} = (\epsilon_1\cdot\epsilon_2)(q_1\cdot q_2) - (\epsilon_1\cdot q_2)(\epsilon_2\cdot q_1)\,, \tag{2}$$

$$\begin{aligned}\{b\} = {}& (\epsilon_1\cdot q_2)(\epsilon_2\cdot P)(P\cdot q_1) + (\epsilon_2\cdot q_1)(\epsilon_1\cdot P)(P\cdot q_2) \\ & -(\epsilon_1\cdot\epsilon_2)(P\cdot q_1)(P\cdot q_2) - (\epsilon_1\cdot P)(\epsilon_2\cdot P)(q_1\cdot q_2)\end{aligned} \tag{3}$$

with P being the four-momentum of the η, and $\epsilon_{1,2}$ and $q_{1,2}$, the polarisation and four-momentum vectors of the photons, respectively. For our analysis, we fix the $g_{VP\gamma}$ couplings in Eq. (1) from the comparison of the calculated decay widths for the radiative $V \to \pi^0(\eta)\gamma$ transitions with their empirical values from the PDG. For the scalar meson exchange contributions, we use the Linear Sigma Model; these are small and are given in [8].

The framework to include intermediate B-boson exchanges to the decay amplitude is similar in spirit to the VMD contributions. This contribution proceeds via the $\eta \to B\gamma \to \pi^0\gamma\gamma$ transition and the amplitude reads [6]

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

where the $g_{BP\gamma}$ couplings are energy-dependent

$$g_{B\pi^0\gamma}\left(q^2\right) = \frac{eg_B}{4\pi^2 f_\pi}F_\omega\left(q^2\right), \tag{5}$$

$$g_{B\eta\gamma}\left(q^2\right) = \frac{eg_B}{12\pi^2 f_\pi}\left[\cos\varphi_P F_\omega\left(q^2\right) + \sqrt{2}\sin\varphi_P F_\phi\left(q^2\right)\right], \tag{6}$$

$$g_{B\eta'\gamma}\left(q^2\right) = \frac{eg_B}{12\pi^2 f_\pi}\left[\sin\varphi_P F_\omega\left(q^2\right) - \sqrt{2}\cos\varphi_P F_\phi\left(q^2\right)\right], \tag{7}$$

with φ_P the η–η' mixing angle in the quark–flavor basis, and where $D_B(q^2) = m_B^2 - q^2 - im_B\Gamma_B(q^2)$ 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.

2.2. ALP-ChPT Lagrangian and $\eta^{(\prime)} \to \pi\pi a$ leading order decay amplitudes

To describe the ALP interactions with mesons, we use the ALP-χPT Lagrangian given by [7]

$$\begin{aligned}\mathcal{L}^{\chi\mathrm{PT@LO}}_{\mathrm{ALP}} &= \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}M_a^2a^2 - \frac{1}{2}m_0^2\left(\eta_0 - \frac{Q_G}{\sqrt{6}}\frac{f_\pi}{f_a}a\right)^2 \\ &\quad + \frac{f_\pi^2}{4}\mathrm{Tr}\left[\partial_\mu U^\dagger\partial^\mu U\right] + \frac{f_\pi^2}{4}\mathrm{Tr}\left[2B_0\Big(M_q(a)U + M_q(a)^\dagger U^\dagger\Big)\right], \end{aligned}\tag{8}$$

where f_π MeV is the pion decay constant, B_0 is a low-energy constant related to the quark condensate, $\delta^{ij}B_0 = -\langle q^i\bar{q}^j\rangle/f_\pi^2$, m_0 parametrizes the $\mathrm{U}(1)_A$ anomaly contribution to the mass of the chiral singlet η_0, and $M_q(a)$ is the ALP-dependent quark mass matrix

$$M_q(a) \equiv \begin{pmatrix} m_u\,\mathrm{e}^{iQ_u a/f_a} & & \\ & m_d\,\mathrm{e}^{iQ_d a/f_a} & \\ & & m_s\,\mathrm{e}^{iQ_s a/f_a}\end{pmatrix}, \tag{9}$$

and $U \equiv \exp\left(\frac{i\sqrt{2}\Phi}{f_\pi}\right)$ is the usual nonlinear representation of the pseudo-Nambu–Goldstone boson chiral meson nonet. The quadratic mass term in Eq. (8) mixes the ALP field a with the neutral, strangeness-zero chiral mesons fields π_3, η_8, and η_0. In order to obtain the physical ALP state $a_{\rm phys}$ and meson states π^0, η, and η', the mass matrix needs to be diagonalized. The resulting relations between the original Lagrangian and physical states is given in detail Ref. [7]. The leading order amplitudes for the $\eta \to \pi^0\pi^0 a$ decay read

$$\mathcal{A}\left(\eta \to \pi^0\pi^0 a\right) = \frac{m_\pi^2}{f_\pi^2}\left[C_\eta \frac{(m_u A_u + m_d A_d)}{m_u + m_d} + \left(2\theta_{\pi\eta'} C_\eta C_{\eta'} + \theta_{\pi\eta}\left(C_\eta^2 - C_{\eta'}^2\right)\right) \frac{(m_u A_u - m_d A_d)}{m_u + m_d}\right], \quad (10)$$

where $m_\pi^2 \equiv B_0(m_u + m_d)$ is the leading order pion mass in the isospin limit, and

$$C_\eta \equiv \frac{\cos\theta_{\eta\eta'}}{\sqrt{3}} - \frac{\sin\theta_{\eta\eta'}}{\sqrt{3/2}}, \quad (11)$$

$$C_{\eta'} \equiv \frac{\cos\theta_{\eta\eta'}}{\sqrt{3/2}} + \frac{\sin\theta_{\eta\eta'}}{\sqrt{3}}, \quad (12)$$

$$A_u \equiv \frac{f_\pi}{f_a} Q_u + \theta_{a\pi} + \frac{\theta_{a\eta_8}}{\sqrt{3}} + \frac{\theta_{a\eta_0}}{\sqrt{3/2}}, \quad (13)$$

$$A_d \equiv \frac{f_\pi}{f_a} Q_d - \theta_{a\pi} + \frac{\theta_{a\eta_8}}{\sqrt{3}} + \frac{\theta_{a\eta_0}}{\sqrt{3/2}} \quad (14)$$

$\theta_{aP}(P = \pi, \eta_8, \eta_0)$ and $\theta_{\eta\eta'}$ are, respectively, the ALP-meson and the η–η' mixing angles. The amplitudes for the partner $\eta^{(\prime)} \to \pi^+\pi^- a$, and $\eta' \to \eta\pi^0 a$ decays have a similar structure and are given in Ref. [7].

2.3. Pion–pion rescattering effects

In any decay with hadrons in the final state, final-state rescattering effects shall be taken into account for making predictions with a reasonably degree of accuracy. Here, we go beyond leading order calculations and include the strong pion–pion final-state interaction effects via dispersion relations. In practice, we multiply the amplitude in Eq. (10) by the Omnès function [7]

$$\Omega_0^0(s) = \exp\left[\frac{s}{\pi}\int_{4m_\pi^2}^{\infty} \frac{ds'}{s'}\frac{\delta_0^0(s')}{s' - s}\right], \quad (15)$$

where $\delta_0^0(s)$ is the $I = 0$ $\pi\pi$ S-wave scattering phase.

3. Results

3.1. Limits on the leptophobic B-boson parameters α_B and m_B

In this section, we use of the expressions for the amplitudes presented in Section 2.1, along with available experimental data, to set limits on the B-boson parameters α_B and m_B. In particular, we write the amplitude for $\eta^{(\prime)} \to \pi^0\gamma\gamma$ as the sum of the vector, scalar, and B-boson exchange contributions $\mathcal{A} = \mathcal{A}_{\rm VMD} + \mathcal{A}_{{\rm L}\sigma{\rm M}} + \mathcal{A}_{B\,\rm boson}$ and require that the branching ratio with B-boson contribution does not exceed the measured branching ratios at 2σ. The resulting limits in the α_B–m_B plane are shown in Fig. 1. As seen, the $\eta \to \pi^0\gamma\gamma$ channel yields more stringent limits than the η' decays.

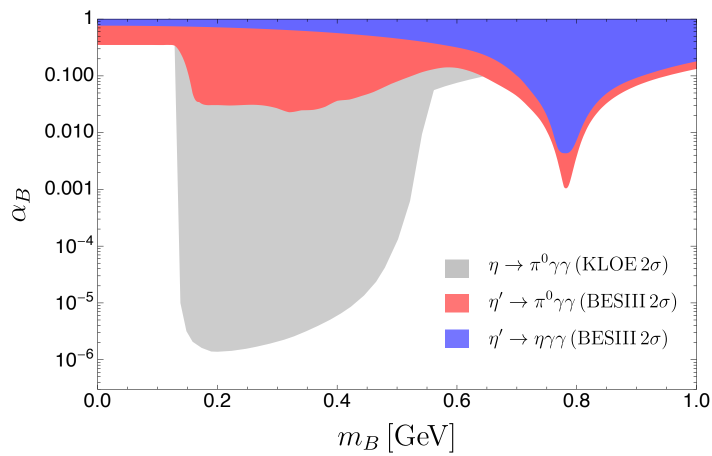

Fig. 1. Limits on the leptophobic B-boson mass m_B and coupling α_B from the BR measurements of the decays $\eta \to \pi^0\gamma\gamma$ (grey) by KLOE [9], $\eta' \to \pi^0\gamma\gamma$ (red) [10], and $\eta' \to \eta\gamma\gamma$ (blue) [11] by BESIII.

3.2. Branching ratio predictions for single ALP channels $\eta^{(\prime)} \to \pi\pi a$

With the parametrization of the leading order amplitudes and the rescattering corrections obtained in the previous section we can now extract the branching ratios for the single ALP $\eta^{(\prime)} \to \pi\pi a$ decays. We adopt two benchmark scenarios for the effective hadronic ALP couplings that have been commonly considered in the literature: the gluon- and quark-dominance scenarios. As a matter of example, in Fig. 2, we show the branching ratio for the decay $\eta \to \pi^+\pi^- a$ as a function of the ALP mass m_a for both the quark-dominance and gluon-dominance benchmark scenarios. See Ref. [7] for predictions for all $\eta^{(\prime)} \to \pi\pi a$ channels and for $\eta' \to \eta\pi^0 a$ as well as for multi-ALP final states, *e.g.* $\eta/\eta' \to \pi^0 aa$ and $\eta/\eta' \to aaa$.

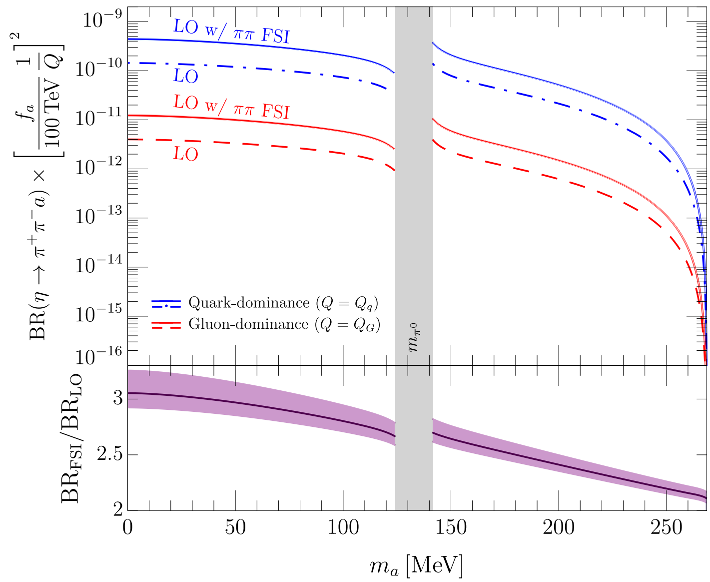

Fig. 2. (Branching ratios) × $(f_a/Q)^2$ for $\eta \to \pi^+\pi^- a$ as a function of the ALP mass m_a, for the quark-dominance (solid blue curve) and gluon-dominance (solid red curve) scenarios, including corrections from $\pi\pi$ final-state interactions (FSI). For comparison, the corresponding leading order (LO) predictions are indicated by the (dot-)dashed curves. The bottom panels indicate the overall enhancement of the branching ratios stemming from FSI corrections relative to the LO predictions. The curves' error bands reflect the uncertainties associated with the $\pi\pi$ rescattering phase shift $\delta_0^0(s)$ (see [7] for details). Since our small mixing approximations are not valid when $m_a \approx m_{\pi^0}$, this region is masked out in the plots. Note that the y-axes are normalized by an overall factor of $(100\ \text{TeV})^{-2}$.

Our theoretical predictions provide guidance to the ALP experimental searches in these channels at, *e.g.* BESIII [12] and HADES [13].

4. Outlook

Exploring dark sectors is an important and growing element of the BSM physics. In this contribution, we have seen that decays of the η and η' mesons are an interesting place to look for dark particles at the sub-GeV scale. In particular, we have presented limits on the leptophobic B-boson coupling α_B and mass m_B (see Fig. 1) and provided predictions for the single ALP production $\eta/\eta' \to \pi\pi a$ including $\pi\pi$ rescattering effects (see Fig. 2). Our results are relevant to guide the wealth of exciting ongoing and future experiments to search for dark particles signals in η/η' decays.

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