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Search for a leptophobic $U(1)_B$ boson using $\eta \to \pi^0\gamma\gamma$ and $\phi \to \pi^0\eta\gamma$ decays

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The possibility for the existence of a leptophobic $U(1)$ gauge boson associated to baryon symmetry is scrutinized in the MeV–GeV mass range by means of an exhaustive analysis of the corresponding golden channels $\eta \to \pi^0\gamma\gamma$ and $\phi \to \pi^0\eta\gamma$. Using the latest experimental data on these two processes and taken also into account the Standard Model contributions from scalar and vector meson exchanges, we are able to obtain the best 95% exclusion limits up-to-date of the mass m_B and coupling α_B to known particles of this hypothetical B boson.

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1. Introduction

A leptophobic $U(1)_B$ boson is a hypothetical gauge boson associated to baryon symmetry, which couples predominantly to quarks and only radiatively induced to leptons. This vector mediator mainly coupled to hadrons can be missed in dark-photon searches looking for l^+l^- resonances. The way one searches for this $U(1)_B$ boson depends on its mass. In the intermediate MeV–GeV mass range, the doubly radiative decays of η and η' mesons, with special emphasis on the process $\eta \to \pi^0\gamma\gamma$, together with the very well measured $\phi \to \pi^0\eta\gamma$ channel, are a perfect laboratory for testing its properties and extracting the mass m_B and coupling to Standard Model particles α_B.

The minimal $U(1)_B$ model has an interaction Lagrangian [1, 2]

$$\mathcal{L}_{\rm int} = \left(\frac{1}{3}g_B + \varepsilon Q_q e\right)\bar{q}\gamma^\mu q B_\mu - \varepsilon e \bar{\ell}\gamma^\mu \ell B_\mu \,, \tag{1}$$

where B_μ is the new gauge boson field and g_B is its gauge coupling, with $\alpha_B = g_B^2/4\pi$ being the fine structure constant associated to the baryonic force. B-boson interactions preserve the low-energy symmetries of QCD, namely $C-$, $P-$, and $T-$invariance, as well as isospin and SU(3) flavor symmetry at zeroth order in ε. The quantum numbers of the B boson are those of the ω boson. As such, if kinematically allowed, they share the same electromagnetic and hadronic decays.

In 2014, S. Tulin calculated for the first time in Ref. [1] the effects of B-boson exchange contributions in decays such as $\eta^{(\prime)} \to \pi^0\gamma\gamma$ or $\phi \to \pi^0\eta\gamma$ using the hidden local symmetry (HLS) framework for vector meson dominance (VMD) supplemented with the conventional $V\gamma$ interaction and the new similar $B\gamma$ one. The calculations were performed under the following simplifications: i) the use of the narrow width approximation (NWA) for the intermediate B-boson exchange, ii) the branching ratio of $B \to \pi^0\gamma$ is set to 1, and, most notably, iii) the QCD contribution is off. These simplified predictions were confronted with the experimental data for these reactions at the time and first exclusion limits for the mass m_B and coupling α_B were obtained, with the result of being the $\eta \to \pi^0\gamma\gamma$ reaction the most limiting one. Nowadays, recent high-precision experimental analyses, particularly for $\eta \to \pi^0\gamma\gamma$ or $\phi \to \pi^0\eta\gamma$ decays, coming from the KLOE and KLOE-II collaborations, demand a reevaluation of the theory contributions to these processes without simplifications.

In this respect, a first new analysis was carried out in Ref. [3] for the $\eta^{(\prime)} \to \pi^0\gamma\gamma$ decays, and a second is now in progress for the $\phi \to \pi^0\eta\gamma$ decay [4]. In this contribution, a summary of the previous two works is presented and the outline of the presentation is the following. In section 2, the Standard Model (SM) contributions from scalar and vector meson exchanges are briefly sketched, while in section 3, B-boson contributions are given in more detail. In section 4, the best up-to-date 95% exclusion limits for the mass m_B and the coupling α_B to SM particles from $\eta \to \pi^0\gamma\gamma$ and $\phi \to \pi^0\eta\gamma$ decays are obtained. Finally, a summary of our results and the conclusions are submitted in section 5.

2. Standard Model contributions

The main SM contribution to the process $\eta \to \pi^0\gamma\gamma$ is due to the exchange of the lightest vector mesons (ρ and ω), while that of the a_0 scalar meson is negligible. The detailed amplitudes

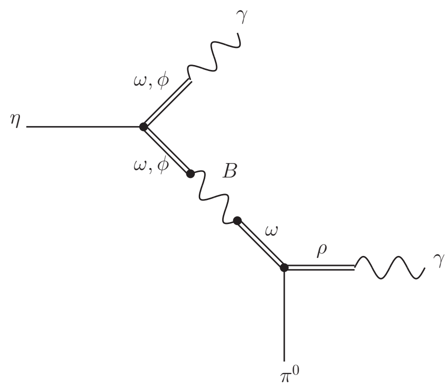

Figure 1: Schematic diagram of the B-boson exchange mechanism for the decay $\eta \to \pi^0\gamma\gamma$.

can be found in Ref. [5]. Instead, for the $\phi \to \pi^0\eta\gamma$ decay, the dominant contribution is the a_0 scalar exchange, while vector exchanges are less important. In this case, a detailed version of the amplitudes can be found in Ref. [6].

3. Leptophobic $U(1)_B$ boson contribution

The diagrammatic representation of the decay process is depicted in Fig. 1 for the $\eta \to \pi^0\gamma\gamma$ case. The B-boson exchange contribution to the amplitude of the $\eta \to \pi^0\gamma\gamma$ decay is given by

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

where $D_B(q^2) = m_B^2 - q^2 - i m_B \Gamma_B$ is the B-boson propagator and $g_{B(\eta,\pi^0)\gamma}(t)$ are energy-dependent couplings, which are found in Ref. [3].

For the $\phi \to \pi^0\eta\gamma$ case, a preliminary version of the amplitude will be given in Ref. [4].

4. m_B and α_B exclusion limits

In this section, we make use of the theoretical expressions presented in Refs. [3, 4], along with the available experimental data, to place limits on the B-boson parameters α_B and m_B. We start with the $\eta \to \pi^0\gamma\gamma$ decay using the PDG reported value, BR $= (2.56 \pm 0.22) \times 10^{-4}$ [7], as well as the (preliminary) value from the KLOE collaboration, BR $= (1.23 \pm 0.14) \times 10^{-4}$ [8]. 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 branching ratios at 2σ. The grey area is excluded by the data from KLOE, which yield a more stringent limit than the resulting one from the PDG (solid red line). This is as expected given that the BR from KLOE is found to be in good agreement with our SM prediction from Ref. [5], BR $= (1.35 \pm 0.08) \times 10^{-4}$, and, thus, the KLOE constraints on the B boson turn out to be stronger. The dashed black line in the figure is found using the data from KLOE but with the SM (or, equivalently, QCD) contributions set to zero. Clearly, these contributions are not negligible, as the limits on α_B become an order of magnitude weaker when their effects are turned off (labelled QCD off in the plots).

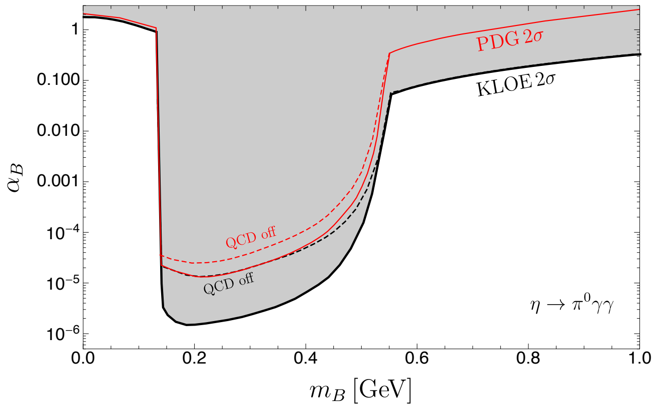

Figure 2: Limits on the leptophobic B-boson coupling α_B for different m_B masses from the $\eta \to \pi^0\gamma\gamma$ BR measurements by KLOE [8] (black line) and the PDG [7] (red line). The grey shaded region is excluded by KLOE and the dashed lines correspond to the limits with the QCD contributions turned off.

The shape and size of the excluded region in Fig. 2 contains key physical information. In this figure, three different regions are observed. The first one corresponds to $m_B \lesssim m_{\pi^0}$, where $\alpha_B \sim \mathcal{O}(1)$. At $m_B \sim m_{\pi^0}$, the limit placed on the coupling plummets by almost six orders of magnitude down to $\alpha_B \sim 10^{-6}$; it then moderately increases, to finally take a steep rise when m_B approaches m_η, reaching $\alpha_B \sim 10^{-2}$. Finally, for $m_B \gtrsim m_\eta$, the constraint on the coupling grows very smoothly as m_B increases. Out of the three, the $m_{\pi^0} \lesssim m_B \lesssim m_\eta$ region deserves special attention and raises the question as to why α_B is constrained so strongly there. The answer to this is related to the fact that the B-boson width is tiny in this region of parameter space.

The smoking gun signature of a B boson in the $m_{\pi^0} \lesssim m_B \lesssim m_\eta$ region would be the observation of a peak at around m_B in the $\pi^0\gamma$ invariant mass distribution. In Fig. 3, we show the quantitative effect of a B boson on the $\eta \to \pi^0\gamma\gamma$ decay using two sets of representative values for α_B and m_B from the not-excluded region of parameter space

$$\alpha_B = 10^{-6}, \quad m_B = 250\,\text{MeV}\,; \qquad \text{and} \qquad \alpha_\text{B} = 10^{-2}, \quad \text{m}_\text{B} = 540\,\text{MeV}\,. \tag{3}$$

In this figure, the solid black line corresponds to our SM prediction from Ref. [5], whereas the effect of including the B boson is shown by the dashed red and dotted green lines for the two sets of α_B and m_B values from Eq. (3), respectively. As it can be seen, the differences in the distribution introduced by the B-boson contribution are very small, and it is very difficult to distinguish the associated lines from the SM prediction. That is, the allowed values for α_B in the $m_{\pi^0} \lesssim m_B \lesssim m_\eta$ region are so small that it makes the B-boson signal strongly suppressed, rendering the task of experimentally identifying it nearly impossible.

Preliminary limits on the leptophobic B-boson coupling α_B for different m_B masses from the PDG average of the $\phi \to \eta\pi^0\gamma$ branching fraction [9] are shown in Fig. (4).

5. Conclusions

The sensitivity of the rare decays $\eta \to \pi^0\gamma\gamma$ and $\phi \to \pi^0\eta\gamma$ to a leptophobic $U(1)_B$ boson in the MeV–GeV mass range has been summarized in this contribution. Stringent limits on the B-boson

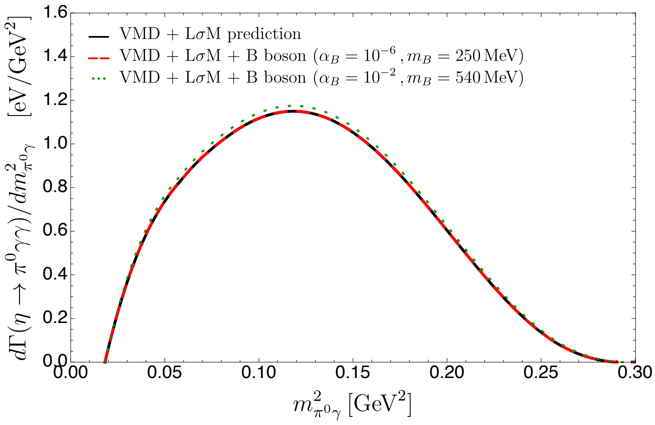

Figure 3: $m^2_{\pi^0\gamma}$ distribution for the $\eta \to \pi^0\gamma\gamma$ decay using our theoretical VMD and LσM prediction [5] (solid black line). Also shown are the spectra including the B-boson contribution using the two sets of representative values for α_B and m_B from the first set (dashed red line) and the second set (dotted green line) of Eq. (3).

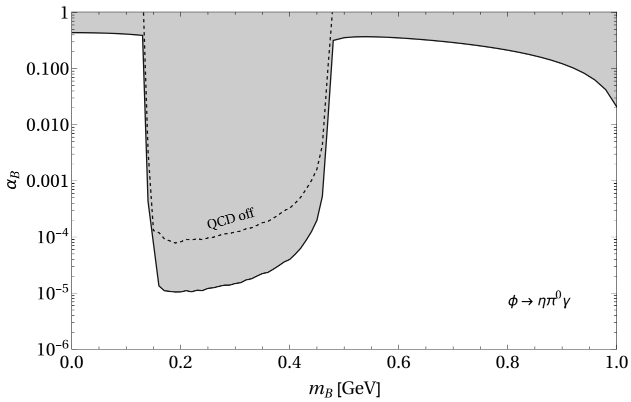

Figure 4: Limits on the leptophobic B-boson coupling α_B for different m_B masses from the PDG average of the $\phi \to \eta\pi^0\gamma$ branching fraction [9]. The gray shaded area is excluded, and the dashed line is the limit when the QCD contributions are set to zero.

parameters m_B and α_B have been found by comparing current experimental data with calculated theoretical predictions incorporating explicit B-boson exchange contributions, in addition to our SM (VMD and LσM) amplitudes. These limits are shown in Fig. 2 and Fig. 4 for $\eta \to \pi^0\gamma\gamma$ and $\phi \to \pi^0\eta\gamma$ reactions, respectively. From the individual analysis of the $\eta \to \pi^0\gamma\gamma$ decay, the current constraints have been strengthened by one order of magnitude in the resonant mass region $m_{\pi^0} \lesssim m_B \lesssim m_\eta$, reaching $\alpha_B \sim 10^{-6}$. These constraints would make a B-boson signature strongly suppressed, rendering the task of experimentally identifying this hypothetical gauge boson as a peak around m_B in the $\pi^0\gamma$ invariant mass distribution practically impossible. The $\phi \to \pi^0\eta\gamma$ decay is seen to be not as powerful as the $\eta \to \pi^0\gamma\gamma$ one at constraining B-boson parameters below m_η, reaching only $\alpha_B \sim 10^{-5}$, which would make the task of identifying a B boson in this channel also very challenging.

Our analysis of the most recent experimental $\gamma\gamma$ and $\pi^0\eta$ invariant mass distributions from the

KLOE Collaboration supports the description of the two reactions presented in these proceedings without contribution from a potential new leptophobic $U(1)_B$ boson, as our VMD and LσM treatment is capable of simultaneously predicting the $\eta \to \pi^0\gamma\gamma$ and $\phi \to \pi^0\eta\gamma$ decays with remarkable agreement with the experimental data.

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