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Reply to "Comment on 'Two-photon decay width of the sigma meson' "

Francesco Giacosa,[1] Thomas Gutsche,[2] and Valery E. Lyubovitskij[2,*]

[1]*Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, Max von Laue-Strasse 1, 60438 Frankfurt, Germany*
[2]*Institut für Theoretische Physik, Universität Tübingen, Kepler Center for Astro and Particle Physics, Auf der Morgenstelle 14, D-72076 Tübingen, Germany*

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We reply to the preceding comment by E. van Beveren *et al.* [E. van Beveren, F. Kleefeld, G. Rupp, and M. D. Scadron, Phys. Rev. D **79**, 098501 (2009)].

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In Ref. [1] we evaluated the radiative decay width $\sigma/f_0(600) \to \gamma\gamma$ under the assumption that σ is described as a quark-antiquark state with flavor configuration $\bar{n}n \equiv (\bar{u}u + \bar{d}d)/\sqrt{2}$. For this purpose we utilized both local and nonlocal interaction Lagrangians describing the coupling of constituent quarks to the scalar field and which also allows a consistent, gauge-invariant inclusion of the electromagnetic interaction. Since a nonlocal model description of a quark-antiquark bound state is in our view unavoidable, we demonstrated in a pure quarkonium description that $\Gamma_{\sigma\to\gamma\gamma} < 1$ keV for a mass of $M_\sigma \lesssim 800$ MeV. In Ref. [1] we also stress that a further inclusion of meson loops will enhance the value of $\Gamma_{\sigma\to\gamma\gamma}$, but an explicit calculation was not performed. Our main conclusion in Ref. [1] was therefore that a dominant or pure quarkonia interpretation of the σ does not allow for a full explanation of currently available data [2] on $\Gamma_{\sigma\to\gamma\gamma}$.

The preceding comment by E. van Beveren *et al.* [3] claims that in [1] we were mistaken on essentially three points on which we briefly elaborate in the following.

Evaluation of the quark triangle diagram: In Ref. [1] we stress that an accurate evaluation of the quark triangle diagram for $\sigma \to \gamma\gamma$ generates a term which in general causes destructive interference when compared to the corresponding $\pi^0 \to \gamma\gamma$ amplitude. This additional term vanishes under the peculiar condition $M_\sigma = 2m_q$, where m_q is the constituent quark mass. The original citation in Ref. [1] of the authors of preceding comment with respect to this technical issue referred to this peculiarity. The analytical results both deduced in Refs. [1,3] for $\Gamma_{\sigma\to\gamma\gamma}$ now completely agree in the case of a local Lagrangian formulation.

Nonlocal description of quark-antiquark bound states: To further illustrate the need for a nonlocal Lagrangian formulation we first refer to the Nambu Jona-Lasinio (NJL) model, which originally is given in local form (see e.g. Refs. [4–6]). Regularization of loop integrals requires the introduction of a sharp cutoff Λ or a cutoff function. Independent of the precise form of the cutoff function the important point is that the cutoff $\Lambda \sim 1$ GeV has a well-defined physical meaning: it is related to the nonperturbative nature of the underlying and fundamental theory of quarks and gluons, QCD, and it sets the corresponding low-energy scale. Note however that the cutoff Λ, together with the precise form of the cutoff procedure is not included in the original NJL Lagrangian. Once a physical cutoff of the order $\Lambda \sim 1$ GeV has been introduced in an effective theory, it should be consistently included in all diagrams, including those that are ultraviolet (UV) convergent. A simple way to introduce this cutoff function already at the level of the starting Lagrangian is to render it nonlocal. This is explicitly done, for instance, in Refs. [7–10]. On a quantitative level NJL models with a proper introduction of the regularization procedure deliver an upper bound with $\Gamma_{\sigma\to\gamma\gamma} < 1$ keV in a pure quarkonium interpretation [11]. This finding is consistent with the results of Ref. [1], although explicit numbers will depend on dynamical details and, for example, the explicit values for the σ and constituent quark masses.

Even on more general grounds, the QCD Bethe-Salpeter approach or QCD motived quark models based on bosonization of the QCD generating functional (for a review see [7,8,12]) show that a nonlocal interaction of a meson with its constituents—the quarks—naturally emerges out of quark-gluon-dynamics. One might argue about the precise form of vertex functions and quark propagators, but the very fact that a nonlocal interaction arises seems undisputable.

We therefore still argue that a nonlocal description of quark-antiquark bound states with a typical intrinsic scale of about 1 GeV will result in values for $\Gamma_{\sigma\to\gamma\gamma}$ below 1 keV, with explicit quantitative numbers depending on dynamical details and, trivially, on the mass of the σ. Please note that most of the analyses now agree on a pole position of the σ near (500-i 250) MeV (see also note on scalar mesons [2]).

Meson loops: Because of the large width of the σ the coupling to $\pi\pi$ and $K\bar{K}$ followed by final state interaction will have a strong impact on the radiative decay width. In the comment [3] the authors deduce a net effect due to meson loops of about 40% of their total two-gamma width $\Gamma_{\sigma\to\gamma\gamma} \approx 3.5$ keV. In Ref. [11] meson loops also contribute by about 50% but resulting only in $\Gamma_{\sigma\to\gamma\gamma} \approx 1.03$ keV

[*]On leave of absence from the Department of Physics, Tomsk State University, 634050 Tomsk, Russia.

in total. A recent model dependent analysis of $\pi\pi$ and $\gamma\gamma$ scattering data [13] deduces a total 2γ decay width of $\Gamma^{\rm tot}_{\sigma\to\gamma\gamma} \approx (3.9 \pm 0.6)$ keV, where the bulk part can be explained by rescattering. The direct or bare σ-pole contribution results in only $\Gamma^{\rm dir}_{\sigma\to\gamma\gamma} \approx (0.13 \pm 0.05)$ keV, actually in line with our results of Ref. [1]. Again, a model-independent estimate of meson-loop contributions to the 2γ decay width of the σ seems presently not available. An analysis by Pennington [14] confirms the large value for the $\gamma\gamma$ decay width with $\Gamma_{\sigma\to\gamma\gamma} = (4.1 \pm 0.3)$ keV, although Oller *et al.* [15] or Bernabeu *et al.* [16] deduce in their analyses smaller values of 1.8 ± 0.4 keV and 1.2 ± 0.4 keV, respectively.

If a large $\gamma\gamma$ decay width of the $f_0(600)$ will be confirmed in future, our theoretical analysis shows that this result cannot be explained by the quark-loop contribution alone. Then we have two options: (i) Discard a dominant quark-antiquark interpretation of the $f_0(600)$, in agreement with many recent works [17]; (ii) Argue that the meson loops generate the—by far—dominant contribution. In this case, however, it will be rather difficult to extract precise information about the nature of scalar states from $\gamma\gamma$ decays.

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