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Universal form factor for exclusive production of heavy meson pairs in photon-photon collisions

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Abstract

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In the leading order over the inverse heavy quark mass, one finds heavy flavour-independent relations for the photonic production form factors of vector and pseudoscalar states at moderate energies.

Аннотация

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В ведущем приближении по обратной массе тяжелого кварка найдены независящие от аромата тяжелого кварка соотношения, связывающие формфакторы рождения векторных и псевдоскалярных состояний при умеренных энергиях.

Photon-photon collisions open new interesting possibilities in researches of properties of fundamental interactions at both high and moderate energies. In the latter case, these collisions can just now be practically studied at LEP in processes with equivalent photons [1]. Moreover, one consideres some prospects in a creation of photon-photon colliders.

In the present paper we study the exclusive production of heavy meson pairs (pseudoscalar and vector states) $\gamma\gamma \to H_Q H_{\bar{Q}}$ in the limit of infinitely heavy quark $m_Q \gg \Lambda_{QCD}$, where Λ_{QCD} determines the energetic scale of confinement. In this limit the effective action of heavy quarks possesses the spin-flavour symmetry [2], so that a heavy quark, moving with a velocity $\boldsymbol{v}$, can be replaced by any other heavy quark, moving with the same velocity $\boldsymbol{v}$ and having any flavour and an arbitrary orientation of its spin.

Using the covariant representation of pseudoscalar (P) and vector (V) states of the ($Q\bar{q}$) system [3], in the leading order over $\alpha_S(m_Q)$ one can write down the following expressions for the t-channel amplitudes of the exclusive production of heavy meson pairs in the photon-photon collisions

$$\begin{aligned} M_{PP}(t) &= 2m_Q\,\mathrm{Sp}\left\{\gamma_5\frac{1-\hat{v}}{2}\hat{\epsilon}_1\,S(k-q)\,\hat{\epsilon}_2\frac{1+\hat{v}'}{2}\gamma_5\right\}\bar{\omega}(y)\,4\pi\alpha_{em}e_Q^2\,, \\ M_{PV}(t) &= 2m_Q\,\mathrm{Sp}\left\{\gamma_5\frac{1-\hat{v}}{2}\hat{\epsilon}_1\,S(k-q)\,\hat{\epsilon}_2\frac{1+\hat{v}'}{2}\hat{\epsilon}_V\right\}\bar{\omega}(y)\,4\pi\alpha_{em}e_Q^2\,, \qquad (1) \\ M_{VV}(t) &= 2m_Q\,\mathrm{Sp}\left\{\hat{\epsilon}_V\frac{1-\hat{v}}{2}\hat{\epsilon}_1\,S(k-q)\,\hat{\epsilon}_2\frac{1+\hat{v}'}{2}\hat{\epsilon}_{V'}\right\}\bar{\omega}(y)\,4\pi\alpha_{em}e_Q^2\,, \end{aligned}$$

where the factor $(\sqrt{2m_Q})^2$ appears from the normalization of mesonic fields, e_Q is the heavy quark charge. The meson momenta p, p', directed into the meson-photon vertex, are determined by the four-velocities of heavy quarks v, v'

$$p_\mu = m_Q\cdot v_\mu, \quad p'_\mu = m_Q\cdot v'_\mu.$$

$\epsilon_{1,2}$ and $\epsilon_{V,V'}$ are the polarization vectors of photons and vector mesons, respectively.

$$k = \frac{1}{2}(p_1-p_2), \quad q = \frac{m_Q}{2}(v-v'),$$

where $p_{1,2}$ are the photon momenta, directed from the vertex. $S(p)$ is the heavy quark propagator at the large virtuality $|p^2-m_Q^2| \geq m_Q^2$. In the considered order over hard corrections in QCD, $S(p)$ is given by the expression for the free quark

$$S(p) = \frac{\hat{p}+m_Q}{p^2-m_Q^2}\,.$$

In the leading approximation over the inverse heavy quark mass, the scalar form factor $\bar{\omega}(y = v \cdot v')$ is universal, i.e. it does not depend on the heavy quark flavour and spin orientation.

The u-channel amplitudes can be obtained from the t-channel expressions by the substitution $k \to -k$ and the replacement $\epsilon_1 \leftrightarrow \epsilon_2$.

As is noted in ref.[4], the expressions for the amplitudes of heavy quark production are valid in the region of the soft emission of light quarks, entering the mesons, and those relations get essential corrections at $s \to \infty$, where the additional parameter $\sqrt{s}\Lambda_{QCD}/m_Q^2$ appears. It becomes of the order of unit. Thus, expressions (1) are valid at moderate energies (for the $B\bar{B}$-pair production one has $\sqrt{s} < 50$ GeV).

Further, one can easily find

$$t = (k-q)^2 = -m_Q^2(y + \sqrt{y^2-1}\cos\theta),$$

where θ is the angle between the photon momentum p_1 and the meson velocity v. Then

$$S(k-q) = \frac{1}{2m_Q}\,\frac{\hat{n} - \hat{v} + \hat{v}' + 2}{1 + y + \sqrt{y^2-1}\cos\theta},$$

where $n = 2k/m_Q$, $n^2 = -2(y+1)$.

Thus, at the fixed velocities of mesons, the amplitudes for the exclusive production of heavy meson pairs do not depend on the heavy quark flavour and are determined by the universal function $\bar{\omega}(y)$. In the axial gauge $\epsilon_{1,2} \cdot n = 0$ the amplitudes take the form

$$\begin{aligned}
M_{PP}(t) &= -4\pi\alpha_{em}e_Q^2\frac{2\bar{\omega}(y)}{1+y+\sqrt{y^2-1}\cos\theta}\cdot \\
&\quad [4(\epsilon_1\cdot v)(\epsilon_2\cdot v) - (\epsilon_1\cdot\epsilon_2)\sqrt{y^2-1}\cos\theta]\,, \\
M_{PV}(t) &= 4\pi\alpha_{em}e_Q^2\frac{2\bar{\omega}(y)}{1+y+\sqrt{y^2-1}\cos\theta}\,\epsilon_{\mu\nu\alpha\beta}\cdot \\
&\quad [\epsilon_1^\mu\epsilon_2^\nu\epsilon_V^\alpha(v'(y-\sqrt{y^2-1}) - v - n)^\beta + (\epsilon_1\cdot v)\epsilon_2^\mu\epsilon_V^\nu v'^\alpha(n-3v)^\beta \\
&\quad +(\epsilon_2\cdot v)\epsilon_1^\mu\epsilon_V^\nu v^\alpha(n+v')^\beta + (\epsilon_2\cdot\epsilon_V)v^\mu v'^\nu n^\alpha\epsilon_1^\beta] \qquad (2)\\
M_{VV}(t) &= -4\pi\alpha_{em}e_Q^2\frac{2\bar{\omega}(y)}{1+y+\sqrt{y^2-1}\cos\theta}\cdot \\
&\quad [8(\epsilon_1\cdot v)(\epsilon_2\cdot v)(\epsilon_V\cdot\epsilon_{V'}) + \\
&\quad 2(\epsilon_1\cdot v)\{(\epsilon_2\cdot\epsilon_V)(\epsilon_{V'}\cdot(n-v)) + (\epsilon_2\cdot\epsilon_{V'})(\epsilon_V\cdot(v'-n))\} + \\
&\quad 2(\epsilon_2\cdot v)\{-(\epsilon_1\cdot\epsilon_V)(\epsilon_{V'}\cdot(n+v)) + (\epsilon_1\cdot\epsilon_{V'})(\epsilon_V\cdot(v'+n))\} + \\
&\quad (\epsilon_1\cdot\epsilon_2)\{(\epsilon_V\cdot v')(\epsilon_{V'}\cdot n) - (\epsilon_V\cdot n)(\epsilon_{V'}\cdot v)\} + \\
&\quad 2\sqrt{y^2-1}\cos\theta\{(\epsilon_1\cdot\epsilon_{V'})(\epsilon_2\cdot\epsilon_V) - \\
&\quad (\epsilon_1\cdot\epsilon_V)(\epsilon_2\cdot\epsilon_{V'}) - (\epsilon_1\cdot\epsilon_2)(\epsilon_V\cdot\epsilon_{V'})\}]\,.
\end{aligned}$$

Generally, relations (2) state connections between the cross sections for the production of the different spin states. The corresponding explicit expressions are bulky and we do not consider them here. Further, for the ratios of total cross sections for the pair production of mesons with different heavy quarks one has

$$\frac{\sigma_{PP}(s_1)}{\sigma_{PP}(s_2)} = \frac{\sigma_{PV}(s_1)}{\sigma_{PV}(s_2)} = \frac{\sigma_{VV}(s_1)}{\sigma_{VV}(s_2)} = \frac{m_{Q_2}^2}{m_{Q_1}^2}\,. \qquad (3)$$

at $s_{1,2} = 2m^2_{Q_{1,2}}(1+y)$, $y > 1$.

Next, considering the exclusive production of heavy meson pairs in the leading order of the QCD perturbative theory, we find that from 20 diagrams of $\gamma\gamma \to H_Q H_{\bar{Q}}$ process in the limit $\Lambda_{QCD}/m_Q \to 0$ and at fixed values of s the leading contributions are given by two t-channel and two u-channel diagrams with soft gluons, which are emitted by heavy quarks, entering the mesons, and the universal function is equal to

$$\bar{\omega}(y) = \frac{2\pi\alpha_s}{9}\,\frac{1}{(y+1)^2}\,\frac{f^2 M}{m_q^3}\,, \tag{4}$$

where α_s is determined by the running value at the scale $\mu^2 = s m_q^2/m_Q^2$. As is known [2], in the limit $m_Q \to \infty$ one has the scaling law for the leptonic constants of heavy mesons

$$f^2 \cdot M = \text{const}\,,$$

and the effective light quark mass m_q does not depend on the heavy quark flavour.

Thus, we have shown that in the leading approximation over the inverse heavy quark mass, the amplitudes for the exclusive production of heavy meson pairs are determined by the only universal form factor $\bar{\omega}(y)$, that does not depend on the heavy quark flavours, and in the QCD perturbation theory it is expressed by eq.(4).

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