

Relativistic corrections to the Higgs boson decay into a pair of vector quarkonia

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• The aim of the work is to calculate decay width of Higgs boson into pair of vector quarkonia ($J/\psi, \Upsilon$) and investigate the influence of relativistic correction, connected with the relative motion of quarks both in relativistic wave function of bound quarks and in production amplitude.

• The upper limits on the branching fractions of such processes are obtained by CMS collaboration (arXiv:0906.1926 [hep-ex], 2022):

$$B(H \rightarrow J/\psi + J/\psi) < 3.8 * 10^{-4}, \quad B(H \rightarrow \Upsilon + \Upsilon) < 1.7 * 10^{-3}, \quad \Gamma_H = 3.2_{-2.2}^{+2.8} \text{ MeV}$$

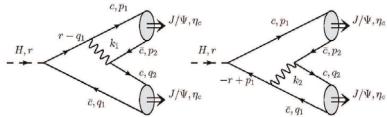
• The calculation has performed within the framework of relativistic quark model and standard model. General structure of pair production amplitude has the form of a convolution of a production amplitude of two quark – antiquark pairs and the relativistic wave functions

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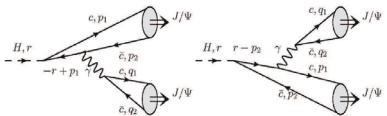
$$\frac{d\Gamma_{1 \rightarrow 2}}{d\Omega} = \frac{|\mathbf{P}|}{32\pi^2 M_H^2} |M_{fi}|^2, \quad M_{fi} = -ig_H \int \frac{d\mathbf{p}}{(2\pi)^3} \int \frac{d\mathbf{q}}{(2\pi)^3} \text{Tr} \left\{ \Psi_{B_c}^{P,V}(p, P) \Gamma(p, q, P, Q) \Psi_{B_c}^{P,V}(q, Q) \gamma_V \right\}$$

$$p_1 = \eta_1 P + p, \quad p_2 = \eta_2 P - p, \quad q_1 = \rho_1 Q + q, \quad q_2 = \rho_2 Q - q, \quad \eta_{1,2} = \frac{M_{Q\bar{Q}}^2 \pm m_Q^2 \mp m_{\bar{Q}}^2}{2M_{Q\bar{Q}}^2}, \quad \rho_{1,2} = \frac{M_{Q\bar{Q}}^2 \pm m_Q^2 \mp m_{\bar{Q}}^2}{2M_{Q\bar{Q}}^2}$$

There are number of decay mechanisms with pair vector meson production:



Pic. 1. Quark-gluon mechanism of the pair charmonium production

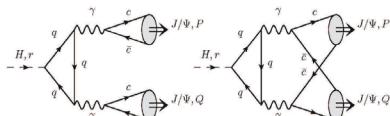


Pic. 2. Quark-photon mechanism of the pair charmonium production

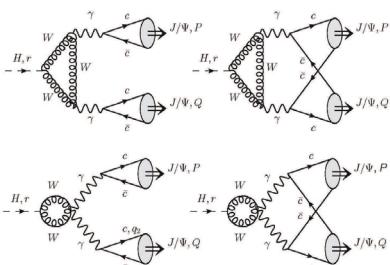
Accounting for the small ratio of relative quark momenta p and q to the mass of the Higgs boson M_H , we can simplify the denominators of quark and gluon propagators:

$$\frac{1}{(p_1 + q_1)^2} \approx \frac{1}{(p_2 + q_2)^2} \approx \frac{4}{M_H^2},$$

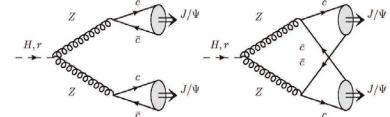
$$\frac{1}{(r - q_1)^2 - m_1^2} \approx \frac{1}{(r - p_1)^2 - m_1^2} \approx \frac{1}{(r - q_2)^2 - m_1^2} \approx \frac{1}{(r - p_2)^2 - m_1^2} \approx \frac{2}{M_H^2}$$



Pic. 3. Quark loop mechanism of the pair charmonium production



Pic. 4. W-boson loop mechanism of the pair charmonium production



Pic. 5. Z-boson mechanism of the pair charmonium production

The tensor corresponding to the quark or W-boson loops in indirect production mechanism has the structure:

$$T_{Q,W}^{\mu\nu} = A_{Q,W}(t)(g^{\mu\nu}(v_1 v_2) - v_1^\mu v_2^\nu) + B_{Q,W}(t)(v_1^\mu - v_1^\nu(v_1 v_2))(v_1^\nu - v_2^\nu(v_1 v_2))$$

where $t = \frac{M_H^2}{4m_{Q,W}^2}$. The structure functions $A_{Q,W}(t), B_{Q,W}(t)$ can be obtained using

an explicit expression for a loop integrals and Mandelstam – Cutkosky rules.

The decay widths of the Higgs boson into a pair of vector quarkonia with accounting of all production mechanisms have the form (The common factor corresponds to the amplitudes of the quark – gluon decay mechanism):

$$\Gamma_{VV} = \frac{2^{14} \sqrt{2} \pi \alpha_s^2 m^2 G_F |\tilde{R}_V(0)|^4 \sqrt{\frac{r_1^2}{4} - 1}}{9M_H^5 r_1^5} \sum_{\lambda\sigma} |\epsilon_1^\lambda \epsilon_2^\sigma F_{VV}^{\lambda\sigma}|^2$$

$$F_{VV}^{\lambda\sigma} = \tilde{F}_1 \nu_1^\sigma \nu_2^\lambda + \tilde{F}_2 g^{\lambda\sigma}$$

In function \tilde{F}_i we separate the relative contributions of different decay mechanisms with respect to the quark – gluon mechanism:

$$\tilde{F}_i = g_i^{(1)} + \frac{9}{16} r_1^2 \frac{e_q \alpha}{\alpha_s} g_i^{(2)} + \sum_0 \frac{27\pi}{8} r_1^4 \frac{e_q^2 e_q^2 \alpha^2 m_Q^2}{\alpha_s s m_{Q\bar{Q}}} g_i^{(3)}, \quad g_i^{(4)} = \frac{9\pi e_q^2 \alpha^2 r_1^4 M_Z M_W}{64\alpha_s s m_{Q\bar{Q}}} g_i^{(4)}$$

$$+ \frac{9M_H^4 \alpha}{16M_Z^2 s m_{Q\bar{Q}} \alpha_s} \frac{(\frac{1}{2} - a_z)^2}{\sin^2 2\theta_W} g_i^{(5)},$$

Functions $g_i^{(j)}$ are carried out using FORM package:

$$g_1^{(1)} = -2 + \frac{2}{9} \omega_1^2, \quad g_2^{(1)} = -1 + 2r_2 + r_1^2 + \frac{4}{3} r_2 \omega_1 + \frac{1}{9} \omega_1^2 + \frac{2}{3} r_2 \omega_1^2 - \frac{1}{9} r_1^2 \omega_1^2,$$

$$g_1^{(2)} = 4 - \frac{4}{9} \omega_1^2, \quad g_2^{(2)} = 2 + 4r_2 - 2r_1^2 - \frac{2}{3} r_2 \omega_1 - \frac{2}{9} \omega_1^2 - \frac{2}{3} r_2 \omega_1^2 + \frac{1}{9} r_1^2 \omega_1^2,$$

$$g_1^{(3)} = -A_Q(t) \left(1 + \frac{2}{3} \omega_1 + \frac{1}{9} \omega_1^2 \right) + B_Q(t) \left(1 + \frac{2}{3} \omega_1 + \frac{1}{9} \omega_1^2 \right),$$

$$g_2^{(3)} = A_Q(t) \left(-1 - \frac{2}{3} \omega_1 - \frac{1}{9} \omega_1^2 + \frac{1}{2} r_1^2 + \frac{1}{3} \omega_1 r_1^2 + \frac{1}{18} \omega_1^2 r_1^2 \right),$$

$$g_1^{(4)} = -A_W(t) \left(1 + \frac{2}{3} \omega_1 + \frac{1}{9} \omega_1^2 \right) + B_W(t) \left(1 + \frac{2}{3} \omega_1 + \frac{1}{9} \omega_1^2 \right),$$

$$g_2^{(4)} = A_W(t) \left(-1 - \frac{2}{3} \omega_1 - \frac{1}{9} \omega_1^2 + \frac{1}{2} r_1^2 + \frac{1}{3} \omega_1 r_1^2 + \frac{1}{18} \omega_1^2 r_1^2 \right),$$

$$g_1^{(5)} = 0, \quad g_2^{(5)} = \left(1 + \frac{1}{3} \omega_1 \right)^2 \left(\frac{1}{2} - a_z \right)^2 - \frac{M_Z^4}{3 \left(\frac{M_Z^2}{4} - M_W^2 \right)} \times$$

$$\left(-\frac{1}{4} - \frac{1}{6} \omega_1 - \frac{1}{36} \omega_1^2 + \frac{1}{2} a_z + \frac{1}{3} \omega_1 a_z + \frac{1}{18} \omega_1^2 a_z - \frac{1}{2} a_z^2 - \frac{1}{3} \omega_1 a_z^2 - \frac{1}{18} \omega_1^2 a_z^2 \right)$$

$a_z = 2|e_Q| \sin^2 \theta_W, \quad r_1 = M_H/M_{Q\bar{Q}}, \quad r_2 = m_Q/M_{Q\bar{Q}}$

The relativistic parameters are carried out in the quark model as a result of calculating integrals with wave functions of quark bound states in the momentum representation.

$$I_n = \int_0^\infty p^2 R(p) dp \frac{\varepsilon(p) + m}{2\varepsilon(p)} \left(\frac{\varepsilon(p) - m}{\varepsilon(p) + m} \right)^n, \quad \tilde{R}(0) = \frac{\sqrt{2}}{\sqrt{\pi}} \int_0^\infty p^2 R(p) dp \frac{\varepsilon(p) + m}{2\varepsilon(p)},$$

$$\omega_1 = \frac{I_1}{I_0}, \quad \omega_2 = \frac{I_2}{I_0}$$

Numerical results for the decay widths in the nonrelativistic approximation and with the account for relativistic corrections (in GeV)

Final states	Nonrelativistic value	Relativistic value
$J/\psi + J/\psi$	3.29×10^{-12}	0.69×10^{-12}
$\Upsilon + \Upsilon$	0.63×10^{-12}	0.74×10^{-12}

The contributions of different mechanisms to the Higgs boson decay widths in GeV.

Contribution	$H \rightarrow J/\psi + J/\psi$	$H \rightarrow \Upsilon + \Upsilon$
Quark – gluon	0.36×10^{-15}	0.10×10^{-12}
Quark – photon	0.80×10^{-12}	0.16×10^{-12}
Quark loop	0.70×10^{-13}	0.37×10^{-12}
W-boson loop	0.74×10^{-13}	0.68×10^{-13}
$H \rightarrow ZZ$	0.22×10^{-12}	1.45×10^{-12}
Total	0.69×10^{-12}	0.74×10^{-12}