Письма в ЭЧАЯ. 2009. Т. 6, № 1(150). С. 37–40

ON LEPTONIC DECAY OF A HEAVY QUARKONIUM WITH A HIGGS-BOSON EMISSION

G. A. Kozlov

Joint Institute for Nuclear Research, Dubna

A leptonic ($\bar{l}l$) decay of a heavy quark–antiquark bound state $T(\bar{Q}Q)$ with a Higgs-boson H emission is investigated. The applying of the low-energy theorem to meson–Higgs coupling allows one to estimate the probability of the decay $T(\bar{Q}Q) \to \bar{l}lH$. Only a simple version of the Standard Model extension containing two-Higgs doublet is considered.

В работе исследуется лептонный ($\bar{l}l$) распад тяжелого кварк-антикваркового связанного состояния $T(\bar{Q}Q)$ с эмиссией бозона Хиггса H. Применение низкоэнергетической теоремы к константе связи кваркония с хиггсовским бозоном позволяет выполнить оценку распада $T(\bar{Q}Q) \to \bar{l}lH$. В статье рассматривается лишь простая версия расширения Стандартной модели, содержащая двуххиггсовский дублет.

PACS: 11.10.St, 12.60.Fr

It is well known that some extensions of the Standard Model (SM) admit the existence of new physical bound states (hadrons), composed of heavy quarks and antiquarks including the 4th generation quarks (Q_4) [1]. The question of the existence of 4th generation fermions (f_4) is among the most important, intriguing and not solved yet ones in the modern elementary particle physics. We know that, e. g., the heterotic string phenomenology in E_6 model leads to the 4th generation of leptons (l_4) and Q_4 with a relatively stable massive neutrino of 4th generation (ν_4) [2]. Possible virtual contributions of 4th generation particles have been advocated by recent analysis [3] of precision data on the SM parameters. The following question arises: what about the recent limits on the masses of f_4? It turns out that l_4 and Q_4 are not excluded under the condition that the Dirac ν_4 is a (quasi)stable particle and it has a mass around 50 GeV [3], and the rest of a spectrum of f_4 particles satisfies their direct experimental constraints on the 4th generation masses m_4 on the level above 80–220 GeV. The best result on the lower bound restriction on m_4 was given by the CDF collaboration at the Fermilab Tevatron, using the measurement of the energy loss dE/dx in a «calorimeter». For the up-type Q_4 (labeled as U) with the electric charge $e_U = +2/3$ this limit is $m_U > 220$ GeV [4], which, in principal, corresponds to the production cross section of the order of 1 pb at the Tevatron energy. It has already been reported [5] that in spite of the multi-fb^{-1} luminosity which one expects the Tevatron CDF and D0 to collect by the time the LHC will start, the rates for heavy quarks will allow their abundant production already with typical start-up luminosities of 1% of the design, namely 10^{-32} cm$^{-2}\cdot$ s^{-1}. The estimation leads to the fact that the production rate for pairs of heavy quarks at the LHC with the mass O(400 GeV) is more than that 100 times larger than at the Tevatron. In paper [6], we have already investigated the issues of production and decays of hadrons containing the so-called light Q_4 with the masses exceeding the top-quark mass, $m_4 > m_t$. We considered strongly bound states, made out of heavy quarks (including fourth family) and using Higgs fields to bind them. There is an important special feature, because unlike the exchange of gauge fields, the scalar particles attract both particles and antiparticles, and the attraction of quarks by Higgs exchange is independent of color. The scenario on the hypothesis that a bound state can be formed from six top quarks and six antitop quarks, held together mainly by Higgs particle exchange, has been considered in [7].

Since there is no direct indications of the existence of the stable f_4 fermions (that means their small lifetime compared with the lifetime of the Universe), it means, obviously, that one of the ways to explore these new particles is their search via the production and their identification through the decays at modern hadron colliders. We assume that hadrons composed of Q_4 quarks are unstable and effectively decay where one of the final states should be the Higgs boson. The reason of the Higgs emission is covered by the more probable and effective couplings between the Higgs boson and heavy quarks.

In this letter, we consider the process of the Higgs-boson emission in decays $T(\bar{Q}Q) \to V^{\star}H \to \bar{l}lH$, where $T(\bar{Q}Q)$ is the spin-1 heavy particle and $V^{\star}$ is a set of intermediate neutral vector bosons including new generations of gauge bosons (e.g., from E_6 model, Little Higgs model [8]). Assuming an infinitely small momentum of the Higgs boson when the Higgs field is considered as the external one and does not carry the dependence on the coordinates (the low-energy theorem [9]), the probability of the decay $T(\bar{Q}Q) \to \bar{l}lH$ normalized to the Drell–Yan process $T(\bar{Q}Q) \to \bar{l}l$ is given by the formula (see [6, 10])

$$R_{T(\bar{Q}Q)\to\bar{l}lH/\bar{l}l} \equiv \frac{\Gamma(T(\bar{Q}Q) \to \bar{l}lH)}{\Gamma(T(\bar{Q}Q) \to \bar{l}l)} = \int\limits_0^{s_l^{\max}} ds_l \frac{\lambda^{1/2}(m_T^2, m_H^2, s_l)}{24\pi^2 v^2 s_l} \eta_{HQ}^2 \times$$
$$\times \left(1 - \frac{4m_l^2}{s_l}\right)^{1/2} \left(1 + \frac{2m_l^2}{s_l}\right) \frac{\lambda(m_T^2, m_H^2, s_l) + 6m_T^2 s_l}{(m_T^2 - s_l)^2 + \Gamma_T^2 m_T^2}, \quad (1)$$

where $s_l = (p_l + p_{\bar{l}})^2 = 2(m_l^2 + p_l \cdot p_{\bar{l}})$ is the invariant mass of $\bar{l}l$ pair; Γ_T is the total width of $T(\bar{Q}Q)$ heavy particle and m_T is its mass; $\lambda(x, y, z) = (z - y - x)^2 - 4xy$ is the usual triangle function. The couplings η_{HQ} of neutral Higgs bosons H to $Q\bar{Q}$ relative to the SM-like value $g\, m_Q/2m_W$ [1] are given for up (U) and down (D) types of quarks in the form [11]

$$\eta_{HU} = \frac{\cos\alpha}{\sin\beta} = \sin(\beta - \alpha) + \cot\beta \cos(\beta - \alpha), \quad (2)$$

$$\eta_{HD} = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta - \alpha) - \tan\beta \cos(\beta - \alpha). \quad (3)$$

In the decoupling regime reflecting the special ratio between the masses of Z boson (m_Z) and CP-odd Higgs boson A (m_A), $z = (m_Z/m_A)^2 \ll 1$, the relations (2) and (3) transform in the following distributions on the angle $\tan\beta = v_U/v_D$ for two vacuum expectation values

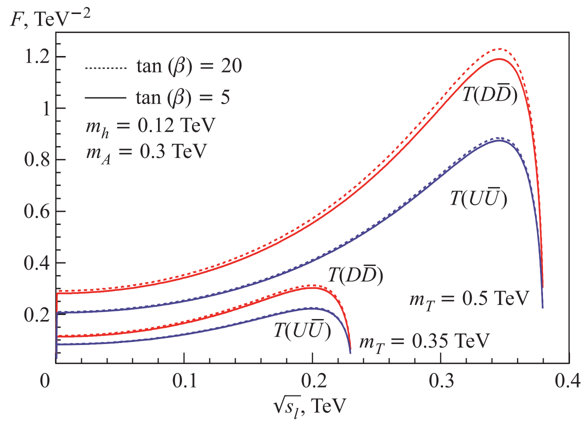

Fig. 1. The differential distribution $F = \Gamma^{-1}(T(\bar{Q}Q) \to \bar{l}l)d\Gamma(T(\bar{Q}Q) \to \bar{l}lH)/ds_l$ over invariant mass of the lepton pair s_l for $T(U\bar{U})$ and $T(D\bar{D})$ bound states with different $\tan\beta = 5$ and $\tan\beta = 20$ at fixed $m_h = 120$ GeV and $m_A = 300$ GeV as a function of $\sqrt{s_l}$

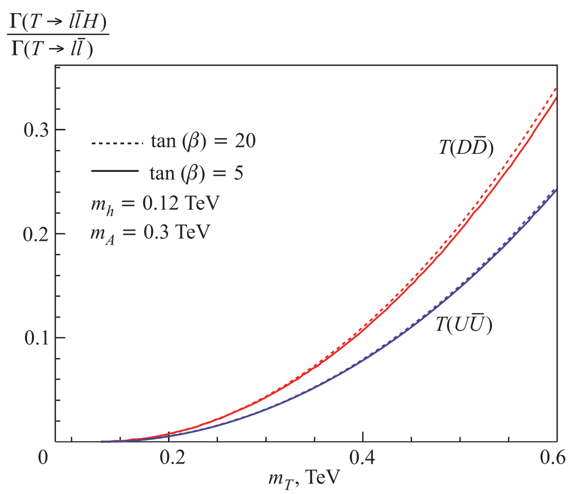

Fig. 2. The relative decay width R (1) for $T(U\bar{U})$ and $T(D\bar{D})$ bound states for different $\tan\beta = 5$ and $\tan\beta = 20$ at fixed $m_h = 120$ GeV and $m_A = 300$ GeV as a function of $m_T \simeq 2m_Q$

v_U and v_D [6]:

$$\eta_{HU} \simeq 1 + z\,\sin(2\beta)\,\cos(2\beta)\,\tan^{-1}(\beta), \tag{4}$$

$$\eta_{HD} = 1 - z\,\sin(2\beta)\,\cos(2\beta)\,\tan(\beta). \tag{5}$$

The production rate for a light CP-even Higgs boson is estimated. For illustration we plotted in Fig. 1 in detail the $\sqrt{s_l}$-dependence of $F_{T(\bar{Q}Q)\to\bar{l}lH/\bar{l}l} = \Gamma^{-1}(T(\bar{Q}Q) \to \bar{l}l)d\Gamma(T(\bar{Q}Q) \to$ $\to \bar{l}lH)/ds_l$ on different values of $T(Q_4\bar{Q}_4)$ heavy quarkonia masses for $\tan\beta = 5$ and

$\tan\beta = 20$ at fixed values of the lightest CP-even Higgs boson mass $m_H = m_h = 120$ GeV and $m_A = 300$ GeV, obeying the decoupling regime mentioned above.

We found that for $T(\bar{U}U)$ bound state the changing of $F_{T(\bar{Q}Q)\to\bar{l}lH/\bar{l}l}$ is very small with increasing of m_A from 200 up to 300 GeV at $5 \leqslant \tan\beta \leqslant 20$. However, the situation changes drastically if one considers the bound state composed of D quarks. The amplitude $F_{T(\bar{Q}Q)\to\bar{l}lH/\bar{l}l}$ falls down with increasing m_A.

In Fig. 2 we plotted the relative decay width $R_{T(\bar{Q}Q)\to\bar{l}lH/\bar{l}l}$ (1) versus the T bound state mass $m_T \simeq 2m_Q$ for $T(\bar{U}U)$ and $T(\bar{D}D)$ bound states, respectively at different $\tan\beta$.

No essential difference is found with increasing of $\tan\beta$ from 5 to 20. In conclusion, the decays of heavy quarkonia are very good place to search for a Higgs boson in the light sector (e.g., CP-even h boson). The decays we have discussed, $T(\bar{Q}Q) \to \bar{l}lH$, have branching ratios which could potentially be probed by precision measurements at hadron colliders. On the other hand, since there are three-body decays, the measurements of the invariant mass spectra of leptons recoiling against a Higgs boson may give valuable insight into the dynamics of heavy quark–antiquark bound state involved.

REFERENCES

1. *Hewett J., Rizzo T.* // Phys. Rep. 1989. V. 183. P. 193.
2. *Fargion D. et al.* // Astropart. Phys. 2000. V. 12. P. 307;
   Belotsky K. M., Khlopov M. Yu. // Gravitation and Cosmology. 2001. V. 7. P. 189; 2002. V. 8 (Suppl.). P. 112.
3. *Maltoni M. et al.* // Phys. Lett. B. 2000. V. 476. P. 107;
   Ilyin V. A. et al. // Phys. Lett. B. 2001. V. 503. P. 126;
   Novikov V. A. et al. // Phys. Lett. B. 2002. V. 529. P. 111.
4. *Acosta D. et al.* (*CDF Collab.*) // Phys. Rev. Lett. 2003. V.90. P.131801.
5. *Gianotti F., Mangano M.* hep-ph/0504221.
6. *Kozlov G.A. et al.* // J. Phys. G: Nucl. Part. Phys. 2004. V. 30. P. 1201.
7. *Froggatt C. D., Nielsen H. B.* hep-ph/0312218.
8. *Arkani-Hamed N., Cohen A. G., Georgi H.* // Phys. Lett. B. 2001. V. 513. P. 232.
9. *Vainstein A. I., Zakharov V. I., Shifman M. A.* // Usp. Fiz. Nauk. 1980. V. 131. P. 537.
10. *Bergstrem L., Dawson S.* // Phys. Lett. B. 1989. V. 232. P. 387.
11. *Carena M., Haber H. E.* // Prog. Part. Nucl. Phys. 2003. V. 50. P. 63.

Received on January 10, 2008.