7

ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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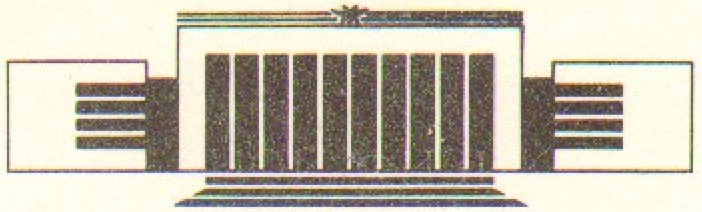

НОВОСИБИРСК

On the Higgs Boson Contribution to the $t\bar{t}$ Production Threshold Cross-Section

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ABSTRACT

The correction to the $e^+e^-\to t\bar{t}$ cross-section near the threshold which is due to the standard model Higgs exchange is calculated at $m_{\text{Higgs}} \gtrsim m_t$.

The existing limitations on the mass of the t-quark [1] indicate that it decays in a half-weak way by the $t\to W^+ + b$ channel and is of a large width ($\Gamma_t \sim 180(m_t/m_W)^3$ MeV [2]). The large width of the quark makes the $e^+e^-\to tt$ cross-section in the near-threshold region a calculable «alive» function of the t-quark mass m_t, its width Γ_t and the QCD coupling constant α_S [3—5].

In a number of the recent papers (see, e.g. [6—8]) the $e^+e^-\to t\bar{t}$ cross-section near the threshold was calculated in detail in terms of the nonrelativistic approximation suggested in [3]. These calculations take into account not only the chromodynamic (QCD) interaction, but also the interaction with the Higgs boson which gives a noticeable contribution to the cross-section for a heavy enough t-quark. The latter is incorporated as an addition to the chromodynamic potential of the Higgs boson:

$$V_{\text{Higgs}}(r) = \frac{m_t^2}{4\pi v^2}\frac{1}{r}e^{-m_H r}, \qquad (1)$$

where m_H is the mass of the Higgs boson, m_t is the quark mass and $v = 246$ GeV is the Higgs field vacuum expectation value. However, no mention is made of the applicability of such an approach and the derived result is used at arbitrary large m_H.

In the present note we would like to pay attention to the inapplicability of the potential approximation at $m_H \gtrsim m_t$ and to have a correct result for this range. Indeed, for the potential approximation to be applicable, it is necessary that t-quarks be nonrelativistic in all intermediate states. There is no difficulty in seeing that the momenta of the order of m_H are characteristic in the exchange by the Higgs boson. Therefore we may use this approximation only under the condition $m_H \ll m_t$. For heavier Higgs bosons, that is when $m_H \gtrsim m_t$, the interaction becomes essentially nonpotential. It is convenient in this case that at these masses the interaction with the Higgs boson involved and the QCD interaction are separated in space. Indeed, in the exchange by the Higgs boson the characteristic distances between t- and $\bar{t}$-quarks are of the order m_H^{-1}, while in the case of the QCD-interaction the distances

$$\sim |p|^{-1} = [m_t(\sqrt{S} - 2m_t + i\Gamma_t)]^{-1/2}$$

are typical, where $\sqrt{S}$ is the invariant mass of the produced pair. For this reason, the contributions of the QCD and Higgs interactions to the $t\bar{t}$ production cross-section near the threshold factorize, i.e. this cross-section may be represented as

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{QCD}(1 + \Delta^{(H)}), \qquad (2)$$

where $\sigma_{t\bar{t}}^{CDD}$ is the cross-section of the process with only the involvement of the QCD interaction in final state, and the correction $\Delta^{(H)}$ is calculated with the QCD interaction switched off. Factorization (2) has an accuracy of $\sim |p|/m_H$. The $\Delta^{(H)}$ may be calculated with the same accuracy just at the $t\bar{t}$ production threshold, i.e. at $S = 4m_t^2$. Finally, the width of the t-quark may be neglected in $\Delta^{(H)}$ calculation up to the terms having the order $\Gamma_t/m_{H,t}$. It should be noted that the said above may concern not only the $t\bar{t}$ production in e^+e^- annihilation, but also any other mechanisms of $t\bar{t}$ production near the threshold.

Since $\Delta^{(H)} \lesssim 0.1$ at the existing limitations on m_t [1], this quantity may be calculated in the one-loop approximation. In the case of the $t\bar{t}$ production in e^+e^- annihilation, the problem reduces to the calculation of the one-loop correction to the $t\bar{t}$ vertex of the vector current in the mass shell renormalization scheme, at

$$p_\pm^2 = m_t^2, \quad (p_+ + p_-)^2 = 4m_t^2. \qquad (3)$$

Here $p_\pm$ — the momenta of the quark and of the antiquark. Calculations are performed in the standard way and give

$$\Delta^{(H)} = \frac{m_t^2}{2\pi^2 v^2}\left(1 - \frac{\rho^2}{3} + \left(2 - \frac{3}{2}\rho^2 + \frac{\rho^4}{3}\right)\ln\rho + \right.$$

$$\left. + \left(4 - \frac{13}{3}\rho^2 + \frac{13}{6}\rho^4 - \frac{\rho^6}{3}\right)f(\rho)\right), \qquad (4)$$

where $\rho = m_H/m_t$ and the function $f(\rho)$ if of the form

$$f(\rho) = \begin{cases} \dfrac{1}{\sqrt{\rho^2(\rho^2-4)}} \ln\left(\dfrac{\rho}{2} + \sqrt{(\rho^2/4) - 1}\right), & \rho > 2; \\ \dfrac{1}{\sqrt{\rho^2(4-\rho^2)}} \operatorname{arctg}\dfrac{\sqrt{4-\rho^2}}{\rho}, & \rho < 2; \end{cases} \qquad (5)$$

We will present the asymptotics of $\Delta^{(H)}$. At $m_H \gg m_t$

$$\Delta^{(H)} = \frac{5m_t^4}{12\pi^2 v^2 m_H^2}\left(\ln\frac{m_H^2}{m_t^2} + \frac{31}{30}\right), \qquad (6)$$

And at $m_H \ll m_t$ $\Delta^{(H)} = \Delta_p^{(H)}$, where

$$\Delta_p^{(H)} = \frac{m_t^3}{2\pi m_H v^2}. \qquad (7)$$

We would like now to compare, at $m_H \gtrsim m_t$, the correction to the cross-section, which was obtained when using potential (1), with the correct correction (4). For this purpose, note that formula (7) gives the first correction to the cross-section on account of the potential (1), which is easily checked by the direct calculation. As $\Delta_p^{(H)} \lesssim 0.1$ within $m_H \gtrsim m_t$, formula (7) is true for the full correction in the potential approximation.

Figure 1 shows the values of the ratio $\Delta^{(H)}/\Delta_p^{(H)}$ depending on $\rho = m_H/m_t$. As it is seen, at $\rho \gtrsim 1$ its value differs strongly from unit, i.e. the potential approximation gives incorrect results at $m_H \gtrsim m_t$. Note that the potential approach, which has been applied in Refs [6—8], and the approach which is being developed here, have formally a common range of applicability

$$|p| \ll m_H \ll m_t. \qquad (8)$$

Really, with the existing limitations on $m_{t,H}$ taking into account, the inequality (8) cannot be very strong. Nevertheless, it is easy to see that if they are fulfilled, there is good agreement between the results of [6] and our result (7).

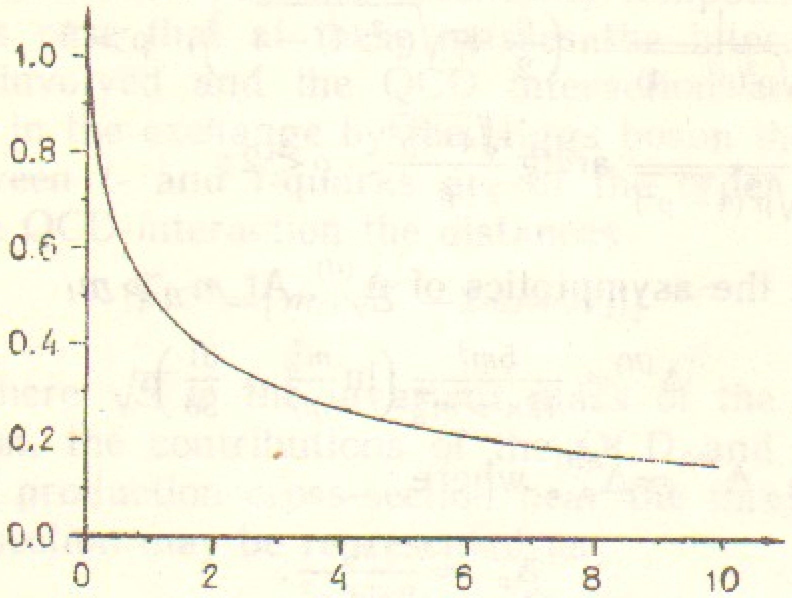

Fig. 1.

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