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Emission of $q\bar{q}$ through virtual gluon exchange in massive-top-quark decay

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We have calculated the emissoin rate of $t \to Wbq\bar{q}$ through virtual gluon exchange in massive-top-quark decay. The two different kinds of methods lead to the same interesting result: the branching ratio is lowered an order of 2 more than that of the $t \to Wbg$ channel. It will be possible for future experiments to test this QCD effect.

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Considering that the top quark is one of the most important missing links of the standard model (SM), the search for it and the exploration of its properties have been a most important task at hadron colliders.

This paper is organized as follows. We first calculate the partial width for $t \to Wbq\bar{q}$, which is about 10^{-3} of the $t \to Wb$ decay width in the framework of the SM. Then we compare the $t \to Wbq\bar{q}$ partial width with the $t \to Wbg$ partial width [1,2].

In Figs. 1(a) and 1(b), we give the Feynman diagrams relevant to the process $t \to Wbq\bar{q}$.

First, we recall the $t \to Wb$ partial width [3] ("bare width") which is given by the diagram shown in Fig. 1(c):

$$\Gamma(t \to Wb) = \frac{G_F m_t^3}{8\sqrt{2}\pi} \lambda^{1/2}\left(1, \frac{m_b}{m_t}, \frac{m_W}{m_t}\right) \left[\left(1 - \frac{m_b^2}{m_t^2}\right)^2 + \left(1 + \frac{m_b^2}{m_t^2}\right) \frac{m_W^2}{m_t^2} - 2\frac{m_W^4}{m_t^4} \right] . \tag{1}$$

We use $|V_{tb}|^2 = 1$, and $\lambda(x,y,z) = (x^2 - y^2 - z^2)^2 - 4y^2z^2$. The first two Feynman diagrams of Fig. 1 lead to the matrix element

$$M = -\frac{g g_s^2}{\sqrt{2}} \epsilon_W^\mu \bar{u}(p_b) \left[\gamma_\mu \omega_- \frac{1}{\not{p}_b + \not{p}_W - m_t} \gamma_\rho + \gamma_\rho \frac{1}{\not{p}_t - \not{p}_W - m_b} \gamma_\mu \omega_- \right] u(p_t)$$
$$\times \frac{1}{k^2} \left[g^{\sigma\rho} - \frac{k^\sigma k^\rho}{(\hat{\mathrm{n}} \cdot k)^2} - \frac{k^\sigma n^\rho + k^\rho n^\sigma}{\hat{\mathrm{n}} \cdot k} \right] \bar{u}(p_q) \gamma_\sigma v(p_{\bar{q}}) , \tag{2}$$

where we choose the axial gauge and the ghost fields disappear. $\omega_\pm = (1 \pm \gamma_5)/2$ and $k = p_q + p_{\bar{q}}$. The spacelike Lorentz vector n satisfies $\hat{\mathrm{n}} \cdot \hat{\mathrm{n}} = -1$; we choose $\hat{\mathrm{n}} = (0,0,0,1)$ during our calculations. When k^2 goes to zero, we will meet on infrared divergence; we will come to this question later. For simplification in the computing, we also assume that the q and $\bar{q}$, which are produced by virtual gluon, are massless.

The differential decay rate for $t \to Wbq\bar{q}$ is expressed formally by

$$d\Gamma(t \to Wbq\bar{q}) = \frac{1}{2m_t} \frac{1}{3} \frac{1}{2} \bar{\Sigma} |M|^2 d\Omega , \tag{3}$$
$$d\Omega = \prod_{i=1}^{4} \frac{d^3 p_i}{2\omega_i} (2\pi)^4 \delta^{(4)} \left(m_t - \sum_{i=1}^{4} p_i \right) .$$

We use a commonly used technique to obtain the differential width: we average over the initial spin states and we sum over final spin states and quark colors. The tedious calculations are done by the computers, but the expression is too long to be shown here.

Because of the "size" of Eq. (3), the total width is impossible to be obtained analytically; we performed the integrations numerically. From now on, we use $\alpha_s = 0.1$, $m_W = 80$ GeV, $m_b = 4.7$ GeV. Certainly, when we let k^2 go to zero, we will meet the infrared divergence which would cancel the infrared divergence coming from the other set of Feynman diagrams of a complete radiative correction calculation. We choose $(k^2)_{\min} = 25$ GeV^2, which seems reasonable for perturbative QCD and also

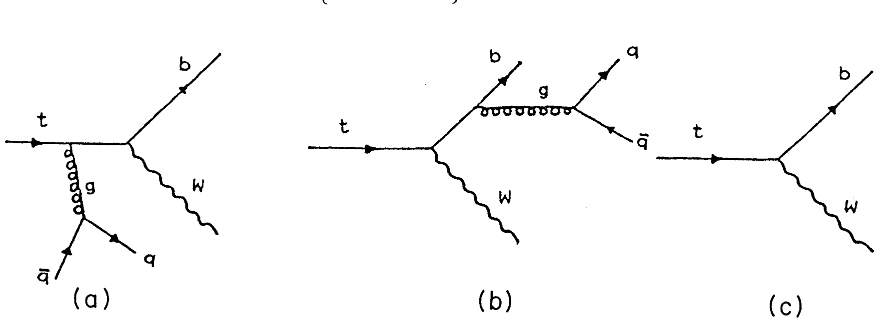

FIG. 1. Tree-level diagrams (a) and (b) relevant to the process $t \to Wbq\bar{q}$. (c) for $t \to Wb$.

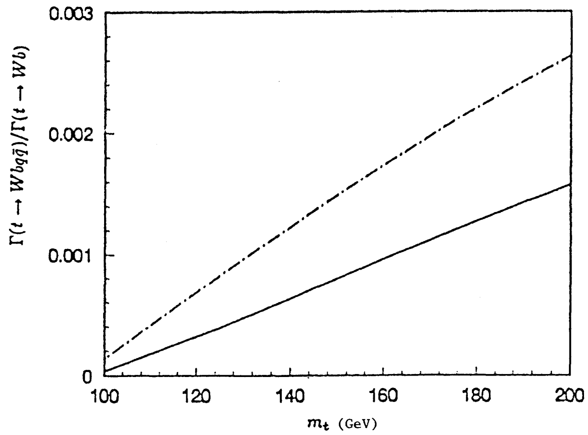

FIG. 2. $\Gamma(t \rightarrow Wbq\bar{q})/\Gamma(t \rightarrow Wb)$ vs m_t for different two values of $(k^2)_{\rm min}$. Dashed line, $(k^2)_{\rm min}=9$ GeV^2. Solid line, $(k^2)_{\rm min}=25$ GeV^2.

practical from an experimental point of view. The energy of q or $\bar{q}$ coming from the virtual gluon is several GeV, and it will not be difficult to observe quark jets. For completeness, we choose different values of $(k^2)_{\rm min}$ to repeat calculations; the results remain small as we will see below.

To obtain the partial width, we performed the Monte Carlo numerical integration. The independent integral variables were chosen according to Ref. [4]. We plot in Fig. 2 the ratio $\Gamma(t \rightarrow Wbq\bar{q})/\Gamma(t \rightarrow Wb)$ as a function of m_t for $(k^2)_{\rm min}=25$ GeV^2, 9 GeV^2. It increases with m_t and approaches 1.6×10^{-3} for $m_t \sim 200$ GeV. $(k^2)_{\rm min}=25$ GeV^2. Figure 2 in Ref. [2] also displays a similar kind of behavior. It is believed that the perturbative QCD radiative processes $t \rightarrow Wbg$ and $t \rightarrow Wbq\bar{q}$ will suppress the formation of nonperturbatively mesonic $(t\bar{q})$ and baryonic (tqq) bound states when the mass of the t quark increases.

Employing the spinor technique [5], we also calculate the partial width of the same process $t \rightarrow Wbq\bar{q}$. The spinor technique evaluates M instead of $|M|^2$ and is especially useful when both the number of the external lines and the number of diagrams involved become large. Choosing the same energy cut $(k^2)_{\rm min}$, the partial width we obtained this way is exactly the same as the results obtained by using the commonly used technique, as shown in Fig. 2. This means the partial width we derived is reliable.

We have seen that the emission of $q\bar{q}$ in the decay $t \rightarrow Wbq\bar{q}$ increases the width of the t quark by about 10^{-3} of the "bare width," while the hard-gluon bremsstrahlung corrections to $\Gamma(t \rightarrow Wb)$ can reach the range of 10^{-1}. The QCD gluonic corrections are well under control. The two processes are so different that it can be an important subject of the t quark. The final state of $t \rightarrow Wbq\bar{q}$ consists of three quark jets plus a lepton pair or two other jets from the W decay. The final state of $t \rightarrow Wbg$ consists of two quark jets plus a lepton pair or two other jets from the W decay. So, we can distinguish the former from the latter by the number of jets coming from the hadronization process of quarks. From the above perturbative QCD discussion, the ratio of $\Gamma(t \rightarrow Wbq\bar{q})/\Gamma(t \rightarrow Wbg)$ is rather small, in the range of 1%, which can be tested by the experiments at the Superconducting Super Collider (SSC), where one expects to be able to reconstruct about 10^8 top-quark decays per year. The experimental data will thus probe our knowledge of QCD and the complex hadronization process of quarks.

We conclude that the QCD correction calculated here can be interesting and should be included in considering new phenomena linked with a heavy top quark in the standard model (SM).

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