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New Interactions in Top Quark Production and Decay at the Tevatron Upgrade

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Abstract

New interactions in top-quark production and decay are studied under the conditions of the Tevatron upgrade. Studying the process $q\bar{q} \to t\bar{t} \to b\mu^+\nu\bar{t}$, it is shown how the lepton rapidity and transverse energy distribution are modified by nonstandard modifications of the $gt\bar{t}$– and the tbW–vertex.

Heavy particles like the top–quark provide an interesting opportunity to study physics beyond the Standard Model because it is conceivable that nonstandard effects appear first in interactions of the known heavy particles (the top quark and the heavy gauge bosons).

In this letter the process $q\bar{q} \to t\bar{t} \to bW^+\bar{t} \to b\mu^+\nu\bar{t}$ will be studied assuming that it proceeds as in the Standard Model ($t\bar{t}$ production by s–channel gluon exchange and subsequent decay to bW). We shall assume that all nonstandard effects in the production process $q\bar{q} \to t\bar{t}$ can be represented by modifying the $gt\bar{t}$ vertex. Similarly, nonstandard effects in the decay of top quarks will be parametrized by modifying the Standard Model tbW vertex. Note that the $\bar{t}$ state is assumed to decay hadronically and its decay products are averaged over. Among all top quark events, these processes are particularly interesting because they show the best compromise between statistics and event signature. In fact, for a hadronic decay the $\bar{t}$ momentum can be fully reconstructed to fulfill $p_{\bar{t}}^2 = m_t^2$. This together with a hard lepton used as a trigger is a rather unique signature of top quarks in proton collisions. Furthermore, a refined analysis of production and decay dynamics is possible, because the b, the l^+ and the $\bar{t}$ momentum can be experimentally determined.

The most general effective $gt\bar{t}$ vertex can be parametrized as follows

$$\Gamma^{\mu a}(g^* \to t\bar{t}) = ig_s\bar{u}(p_t)\Big[\gamma^\mu(1+\delta A_P-\delta B_P\gamma_5)+\frac{p_t^\mu - p_{\bar{t}}^\mu}{2m_t}(\delta C_P-\delta D_P\gamma_5)\Big]\frac{\lambda^a}{2}v(p_{\bar{t}}) \tag{1}$$

where g_s is the strong coupling constant and λ^a the Gell–Man λ–matrices. The SM vertex is given by $\delta A_P = \delta B_P = \delta C_P = \delta D_P = 0$. Note that there is an equivalent parametrization of the vertex by

$$\Gamma^{\mu a}(g^* \to t\bar{t}) = ig_s\bar{u}(p_t)\Big[\gamma^\mu(F_1^L P_L+F_1^R P_R)-\frac{i\sigma^{\mu\nu}(p_t + p_{\bar{t}})_\nu}{m_t}(F_2^L P_L+F_2^R P_R)\Big]\frac{\lambda^a}{2}v(p_{\bar{t}}) \tag{2}$$

where $P_{L/R} = (1 \mp \gamma_5)/2$. Using the Gordon decomposition one can indeed show that $\delta A_P = \frac{1}{2}(F_1^L + F_1^R) - 1 - F_2^L - F_2^R$, $\delta B_P = \frac{1}{2}(F_1^L - F_1^R)$, $\delta C_P = F_2^L + F_2^R$ and $\delta D_P = F_2^L - F_2^R$.

Similarly, the following parameterization of the tbW vertex suitable for the decay $t \to bW^+$ will be adopted

$$\Gamma^\mu(t \to bW^+) = -i\frac{g}{\sqrt{2}}V_{tb}\bar{u}(p_b)\Big[\gamma^\mu(P_L+\frac{\delta A_D}{2}-\frac{\delta B_D}{2}\gamma_5)+\frac{p_b^\mu+p_t^\mu}{2m_t}(\delta C_D-\delta D_D\gamma_5)\Big]u(p_t) \quad (3)$$

where g is the SU(2) gauge-coupling constant and V_{tb} the (tb) element of the CKM matrix. The SM vertex is given by $\delta A_D = \delta B_D = \delta C_D = \delta D_D = 0$. A Gordon decomposition similar to the above leads to an equivalent description

$$\Gamma^\mu(t \to bW^+) = -i\frac{g}{\sqrt{2}}V_{tb}\bar{u}(p_b)\Big[\gamma^\mu(G_1^L P_L+G_1^R P_R)-\frac{i\sigma^{\mu\nu}(p_t-p_b)_\nu}{m_t}(G_2^L P_L+G_2^R P_R)\Big]u(p_t) \quad (4)$$

Indeed, one has $\delta A_D = G_1^L+G_1^R-1+G_2^L+G_2^R$, $\delta B_D = G_1^L-G_1^R-1-G_2^L+G_2^R$, $\delta C_D = -G_2^L - G_2^R$ and $\delta D_D = -G_2^L + G_2^R$. Note the factor m_t appearing in Eq. (4) whereas in Refs. [1, 2] the W–mass was used to normalize the nonstandard couplings G_1^L and G_1^R.

In Eqs. (1)–(4) all terms have been neglected, which in the cross section give contributions proportional to the light fermion masses or to the off-shellness of the W–boson. Apart from such terms, Eqs. (1) and (3) comprise the most general interactions of top quarks with gluons and W–bosons, respectively.

Using Eqs. (1) and (3), the matrix elements M_P for $t\bar{t}$ production as well as M_D for the decay process $t \to bl^+\nu$ and for the combined production and decay process $q\bar{q} \to t\bar{t} \to \bar{t}bl^+\nu$ were calculated. Only contributions linear in the nonstandard couplings were kept. One finds

$$\begin{aligned} M_P &= [s^2+2m_t^2 s-4s(p_t\cdot p_q)+8(p_t\cdot p_q)^2](1+2\delta A_P) \\ &\quad +4\delta C_P[m_t^2 s-2s(p_t\cdot p_q)+4(p_t\cdot p_q)^2] \end{aligned} \quad (5)$$

where $s = (p_q+p_{\bar{q}})^2$ is the total partonic energy and $p_t\cdot p_q$ is related to the top quark production angle θ in the parton–cms : $2p_t\cdot p_q = \frac{s}{2}(1-\sqrt{1-\frac{4m_t^2}{s}}\cos\theta)$.

The notation of Ref. [3] was used and a factor $\frac{64\pi^2\alpha_s^2}{9s^2}$ has been left out. As is obvious from this equation, the coupling δA_P renormalizes the total cross section whereas δC_P modifies the angular distribution and δB_P and δD_P do not contribute at all. Note, however, that δB_P and δD_P will strongly contribute – via spin terms – to the combined process $q\bar{q} \to t\bar{t} \to \bar{t}bl^+\nu$ (see below)!

For the decay matrix element one finds

$$\begin{aligned} M_D &= (p_t \cdot p_l)[\frac{m_t^2}{2} - (p_t \cdot p_l)](1 + \delta A_D + \delta B_D) \\ &\quad +(\delta C_D - \delta D_D)[-(p_t \cdot p_l)^2 + \frac{1}{2}(p_t \cdot p_l)(m_t^2 + m_W^2) - \frac{1}{4}m_t^2 m_W^2] \end{aligned} \quad (6)$$

where $p_t{\cdot}p_l$ can be related to the lepton energy E_l in the rest system of the top quark : $p_t \cdot p_l = m_t E_l$. The notation and normalization of Ref. [4] was used. Obviously, the couplings δA_D and δB_D just renormalize the Standard Model cross section whereas $\delta C_D - \delta D_D$ really modifies the lepton distributions.

The matrix element for the combined production and decay process is not just the product of Eqs. (5) and (6), but contains additional terms $\sim \delta B_P$ and $\sim \delta D_P$, i.e. one has $M = M_P M_D + \Delta$, with

$$\begin{aligned} \Delta &= 4\delta B_P(p_\nu \cdot p_b)\Big\{[(p_l \cdot p_t)(p_q \cdot p_t)(p_{\bar{q}} \cdot p_{\bar{t}}) - m_t^2(p_l \cdot p_{\bar{q}})(p_q \cdot p_{\bar{t}})] + [q \leftrightarrow \bar{q}]\Big\} \\ &\quad +\delta D_P(p_\nu \cdot p_b)\Big\{[(p_q \cdot p_{\bar{q}})(p_l \cdot p_t)(p_t \cdot p_{\bar{t}}) - m_t^2(p_q \cdot p_{\bar{q}})(p_l \cdot p_{\bar{t}}) + (p_l \cdot (p_t + p_{\bar{t}})) \\ &\quad \times(p_q \cdot p_t)(p_{\bar{q}} \cdot (p_t - p_{\bar{t}})) - (p_q \cdot p_{\bar{q}})(p_l \cdot p_{\bar{q}})(p_1 \cdot (p_t - p_{\bar{t}}))] + [q \leftrightarrow \bar{q}]\Big\}. \end{aligned} \quad (7)$$

These latter terms arise when the 'spin contributions' $\sim s_t$ of the amplitude $A(q\bar{q} \to t\bar{t})$ (i.e. the terms proportional to the spin vector s_t of the top quark) are 'contracted' with the 'spin contributions' of the decay amplitude $A(t \to bl^+\nu)$ using $s_t^2 = -1$. Note that such term are not present in the Standard Model. Spin terms arise in the Standard Model if correlations of t *and* $\bar{t}$ decay are considered [5], or if there is an axialvector component of the Standard Model coupling on the production side, like in $e^+e^- \to t\bar{t}$ via Z–exchange [6, 2]. Note further that the terms $\sim \delta D_P$ and $\sim \delta D_D$ in the above expressions give rise to CP violating effects when the behavior of top and antitop quark is compared [1, 7].

Using the matrix elements Eqs. (5), (6) and (7) one can determine the lepton rapidity and transverse energy distribution under the conditions of the Tevatron upgrade. The Tevatron upgrade is defined by a total energy of $\sqrt{S} = 2$ TeV and two options for the luminosity, the so called 'TeV-33' defined as $L = 30$ fmbarn^{-1} and the Tevatron Run II with $L = 2$ fmbarn^{-1} [8]. The expected number of single-leptonic events (1 b-quark tagged) [8] is 1300 and $20,000$ for $L = 2,\ 30$ fmbarn^{-1}, respectively. Numerical results were obtained using the Monte Carlo package RAMBO [9]. Standard CDF and D0 cuts were applied. The matrix element squared were convoluted with the Morfin and Tung [10] parton distributions (the 'leading order' set from the 'fit sl'). Finally the ratio of the results to the Standard Model predictions were taken. Figures 1 and 2 show these ratios for coupling values $\delta B_P = 0.1$, $\delta C_P = 0.1$, $\delta D_P = 0.1$ and $\delta C_D = 0.1$, respectively. Figure 1 shows the dependence on the lepton–p_T and figure 2 on the lepton rapidity.

As one would expect, nonstandard effects are roughly of the order of 5–10 %. Effects are larger for the transverse energy than for the rapidity distribution. The most pronounced effects come from δB_P and δD_P at intermediate and high lepton E_T. From Figs. 1 and 2 it is apparent that the contribution $\sim \delta C_D$ is relatively smaller than the other ones. This proves that effects from the decay vertex are harder to find than nonstandard effects at the production vertex. The figures also include the shape of the Standard Model predictions (in arbitrary units). The short–dashed curves in Fig. 1 are

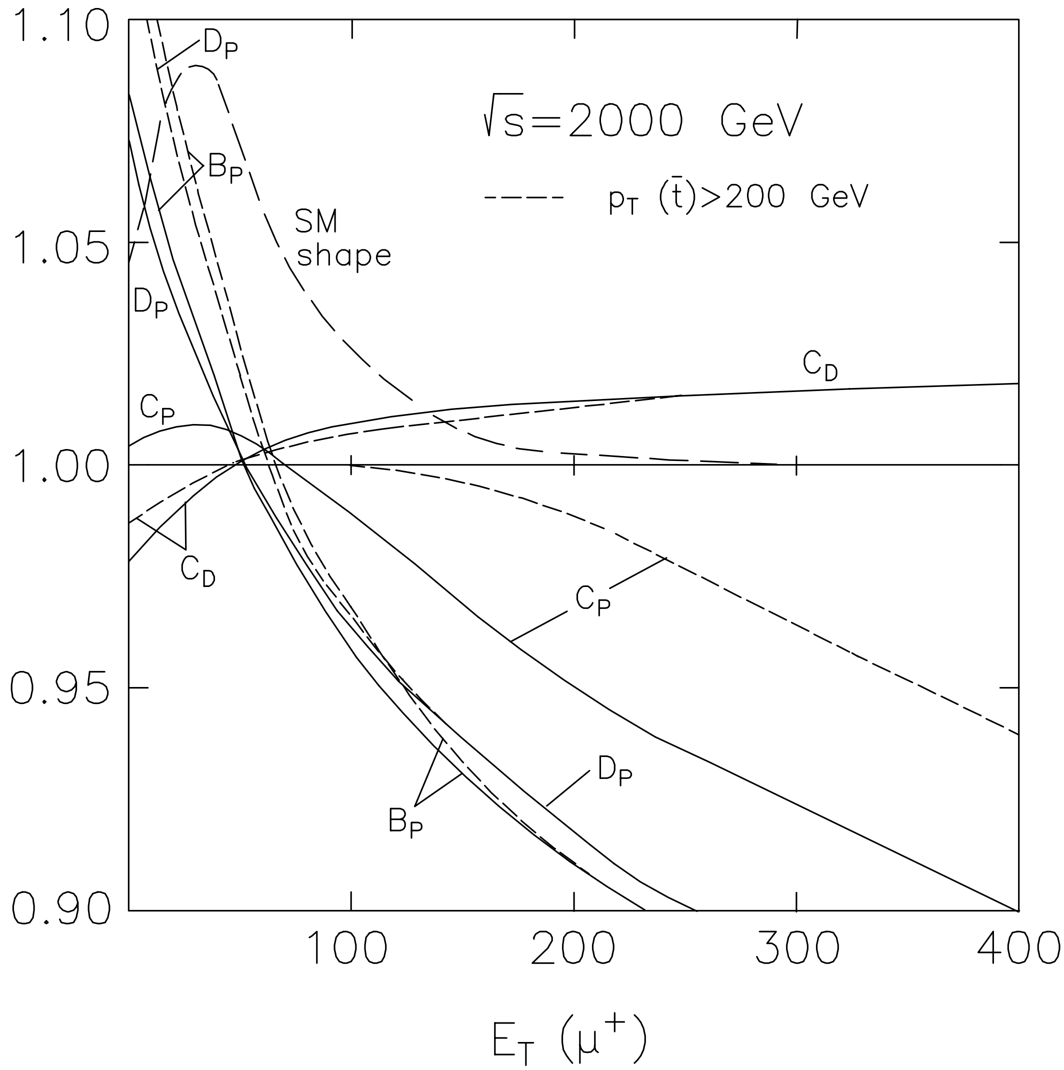

Figure 1: The ratio of nonstandard to SM contribution as a function of the lepton (l^+) transverse energy, for various nonstandard terms denoted by B_P, C_P, D_P and C_D, c.f. Eqs. (1) and (3). The values of the couplings were chosen to be $\delta B_P = 0.1$, $\delta C_P = 0.1$, $\delta D_P = 0.1$ and $\delta C_D = 0.1$. Also included is the shape of the SM contribution (in arbitrary units).

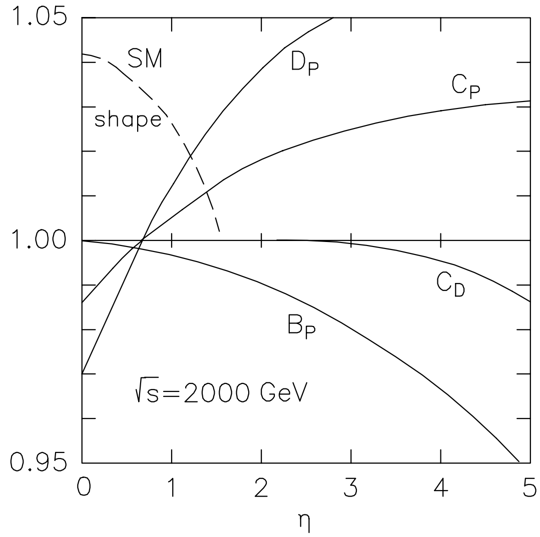

Figure 2: Same as Fig. 1 but as a function of the l^+ rapidity.

obtained if a p_T–cut on the $\bar{t}$ momentum is applied. Since the $\bar{t}$ momentum is experimentally known, the dependence on $p_T(\bar{t})$ may be analyzed in order to separate the different nonstandard effects. For example, the contribution $\sim \delta C_P$ depends strongly on $p_T(\bar{t})$ whereas the others do not.

Using the results Eqs. (5)–(7) it is also possible to calculate other distributions, like p_T– and η–distributions for $\bar{t}$ and b–quark, or more complicated 2–particle correlations. As an example, Fig. 3 shows the ratio of nonstandard to SM contribution as a function of the angle ϕ between the transverse momenta of $\bar{t}$ and l^+. One sees, for example, that in the high–statistics region ($\phi \sim \pi$) the interaction terms $\sim \delta B_P$ and $\sim \delta C_P$ can be clearly distinguished whereas the terms $\sim \delta B_P$ and $\sim \delta D_P$ give almost identical results.

In ref. [11] the lepton energy distribution in top quark decays was analyzed

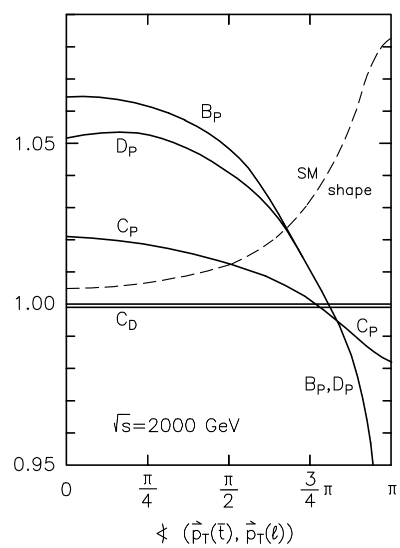

Figure 3: Same as Fig. 1 but as a function of the angle between the transverse momentum of l^+ and $\bar{t}$.

including the nonstandard interactions Eq. (4). Since this was done in the rest system of the top quark, results are not directly comparable with the present analysis.

To conclude, in this article I have calculated the full matrix elements as well as transverse energy and angular distributions for top quark production *and* decay under the conditions of the Tevatron upgrade. I have not included contributions from the process $gg \to t\bar{t}$ because they give less than 10 % of the top quark production cross section at Tevatron energies. Another approximation of the present letter is, that higher order QCD contributions have not been taken into account. These are in principle known because they are known for production and decay separately and spin terms do not contribute here. These contributions are also expected to be roughly of the order of 10 % and are also needed for a precision analysis of future Tevatron data. I did not include them here because I just wanted to elucidate the role of nonstandard interactions with reference to the leading order standard model process.

A more general aim of this paper is to point out, that nonstandard effects in top quark interactions may be found already before precision measurements at the LHC will be done.

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