# Consequences of the symmetry breaking in the *t*-quark electromagnetic vertex for *t*-quark production in $\bar{p}p$ collisions

B. A. Arbuzov and S. A. Shichanin
*Institute for High Energy Physics, 142284 Protvino, Moscow Region, Russia*

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In the framework of a model of dynamical breaking of the electroweak symmetry the possibility of obtaining a large $t$-quark mass due to chiral symmetry breaking in the electromagnetic vertex of the $t$ quark is considered. The self-consistent set of equations is considered for a value of an anomalous magnetic moment. The essential part of the set is connected with the due appearance of a Goldstone pseudoscalar. Solution of the set gives values of the anomalous moment $\kappa$ and the coupling constant of the pseudoscalar with the $t$ quark, depending on the high-energy cutoff. The main consequences of a large $\kappa$, $\kappa \simeq 1$, especially for the $t$-quark production in the Tevatron experiments are discussed. The mechanism results in additional contribution to the $t$-quark production cross section, which gives, e.g., $\simeq 10$ pb for $M_t = 170$ GeV, $\kappa = 1$, consistent with the existing data. The cross section for the process $\bar{p}p \to \bar{t}t\gamma$ and the $p_t$ distribution of $\gamma$ are also calculated. The results can be assumed to provide the best restrictions for the value of $\kappa$ of the anomalous magnetic moment of $t$. On the other hand, this approach gives definite predictions for the $t$-quark quest, which could be compared with the existing and forthcoming data.

In the present paper we look at the possibility that the $t$ quark has peculiar properties and corresponding experimental consequences. The $t$ quark differs from other quarks by its very large mass. It could be that the large $t$-quark mass is due to an additional interaction. This conjecture could be realized on the basis of a model for the dynamic breaking of the electroweak symmetry.[1,2] The approach in Ref. 1 does not assume the existence of elementary Higgs scalars as the starting point of the electroweak theory. As a substitute for the standard Higgs mechanism we analyze a set of dynamical equations for a three-$W$ vertex and for mass operators of $W$ and $Z$. The main point of this approach consists in the appearance of a new gauge-invariant vertex in the region of "small" momenta, which corresponds to the effective Lagrangian $L_{\text{eff}} \sim \epsilon^{abc} W^a_{\mu\nu} W^b_{\nu\rho} W^c_{\rho\mu}$. The presence of the vertex in the region of small momenta only is provided by a form-factor which decreases sufficiently rapidly for large momentum variables. The region of action of the new interaction is bounded by a cutoff $\Lambda$. The model defines a self-consistent set of equations for the new vertex and for $W$ and $Z$ masses. The analysis of this set of equations leads to the conclusion that the dynamical breaking of the symmetry is quite possible,[1] and we obtain the $W$ and $Z$ masses with the value of the cutoff $\Lambda$ of TeV order of magnitude. There must also be scalars; these scalars, however, are not elementary states, but rather bound states that consist of $W$s and $Z$s. The order of magnitude of their mass must also be $\simeq$TeV.

Analogous considerations are applied to the problem of the $t$-mass origin.[2] Here we look at the possibility of the breaking of the chiral symmetry which is connected with the $t$ quark via the appearance of an anomalous magnetic moment in the $t$ electromagnetic vertex. Note that a possible anomalous magnetic moment of the $t$ quark is discussed from different points of view in several papers, e.g., Ref. 3. The additional term is

$$\Gamma_\mu(p,q)=iF(p^2,q^2,k^2)\,\frac{e\kappa}{2M}\,\sigma_{\mu\nu}k_\nu, \tag{1}$$

where $k=q-p$ is the photon momentum, $p$ and $q$ are, respectively, the momenta of $t$ and $\bar{t}$, $M$ is the $t$ mass, and $F(p^2,\,q^2,\,k^2)$ is a form factor which can be chosen, e.g., in the form[1]

$$F(p^2,q^2,k^2)=\frac{\Lambda^6}{(\Lambda^2-p^2)(\Lambda^2-q^2)(\Lambda^2-k^2)}, \tag{2}$$

where $\Lambda$ is the cutoff mass parameter.

There are processes which are sensitive to the value of $\kappa$ when $\kappa$ is sufficiently large, e.g., the transition $b\to s+\gamma$. In Ref. 4 the corresponding calculations are shown to give the upper bounds for $\kappa$, which depend on the $t$ mass. For example, $\kappa\leqslant 6$ for $m=150$ GeV and $\kappa\leqslant 7$ for $M=170$ GeV. As we shall see below, the most sensitive test for $\kappa$ provides the process of $\bar{t}t$ production. The value of $\kappa$ on the order of unity changes the predictions for the cross sections substantially. The problem therefore is whether the values $\kappa\simeq 1$ are natural. The approximation which is used in Ref. 2 leads to values $\kappa\simeq 10$. We see, however, that this value is too large. Let us now take into account the well-known important effect.

We know from the beginning of the study of chiral symmetry breaking[5] that the appearance of the Goldstone zero-mass pseudoscalar is inevitable in the case of symmetry breaking. Here this means that there exists a $\bar{t}t$ bound state $\Phi$ which interacts with $t$, $\bar{t}$ according to

$$L_{\rm int}=g\bar{\psi}\gamma_5\psi\Phi, \tag{3}$$

where $\psi$ is the spinor which describes $t$.

The equations for the $t$-quark magnetic vertex (1) and for its mass are shown schematically in Fig. 1. The calculations give the following set of equations:

$$\begin{aligned} &e\kappa Z^2=e\kappa\,\frac{g^2}{16\pi^2}, \\ &MZ^2=M\,\frac{\alpha\kappa^2}{16\pi}\,y-M\,\frac{g^2}{16\pi^2}\left(\ln y-\frac{11}{6}\right), \\ &Z^2=Z-\frac{\alpha\kappa^2}{32\pi}\,y-\frac{g^2}{32\pi^2}\left(\ln y-\frac{11}{6}\right), \end{aligned} \tag{4}$$

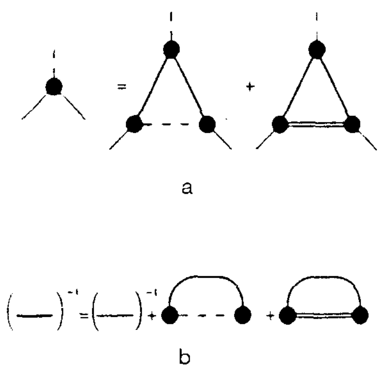

FIG. 1. Graphical equations for $\bar{t}t\gamma$ vertex (a) and for the $t$-quark mass operator (b). The solid line represents the $t$ quark, the dashed line denotes the photon, and the double line is the $\bar{t}t$ bound pseudoscalar. Circles correspond to the vertices (1) and (3).

$$y=\frac{\Lambda^2}{M^2}.$$

Here $Z$ is the $t$-quark renormalization constant, based on the following definition of its full propagator (the heavy line in Fig. 1):

$$G(p)=\frac{Z^{-1}}{i(M-\hat{p})}.$$

Note that the first term in the vertex equation of Fig. 1, which contains the photon exchange with the vertices (1), is zero. The set (4) has, of course, a trivial solution $M=0$; $\kappa=0$, which corresponds to the requirement that the original symmetry be maintained. However, there is also a nontrivial solution,

$$\frac{g^2}{4\pi}=\frac{4\pi}{(\ln y-1/3)^2},\quad \kappa=\sqrt{\frac{16\pi(\ln y-5/6)}{\alpha y[\ln(y)-1/3]^2}}. \tag{5}$$

We see that $\kappa$ depends on the value of the cutoff. For example, for $y=700$ we have $\Lambda=4.5$ TeV, $\kappa=1.03$ and for $y=220$ we have, $\Lambda=2.5$ TeV, $\kappa=2$. The values of $\Lambda$ correspond to the $t$-quark mass $M=170$ GeV. Thus, when the cutoff is on the order of magnitude $\simeq$TeV, $\kappa$ is on the order of unity. In this sense, the values $\kappa\simeq1$ are natural in our approach.

Now let us consider the $\bar{t}t$ production cross section. We calculate it for proton–antiproton collisions at two c.m. energies: 1800 and 2000 GeV, using the current data on the structure functions. For the electromagnetic vertex we use only expression (1) and obtain the results in the leading order. The additional term in the cross section which we deal with is proportional to $\kappa^2$. The results for $\kappa=1$ are presented in Table I. We see that for $M=170$ GeV and $E=1800$ GeV we have $\Delta\sigma=9.8$ pb. For another value of $\kappa$ the numbers in Table I must be multiplied by $\kappa^2$.

We see from Table I that for $\kappa\simeq1$ the additional term in the $\bar{t}t$ cross section is even larger than that calculated in the standard model. For example, for $M=170$ and $E=1800$ we have $\sigma_{SM}\simeq5$ pb. The experiments which look for the $t$ quark at the Tevatron imply a stringent limitation on $\kappa$. Indeed, the last CDF result,[6] $\sigma=13.9^{+6.1}_{-4.8}$ with $M=174\pm10^{+13}_{-12}$, implies that there is a place for an additional contribution to the cross section. Using

TABLE I. Cross section $\Delta\sigma$ (in pb) of the process $\bar{p}p \to \bar{t}+t+X$, $\kappa=1$.

| $M$, GeV | $E=1800$ GeV | $E=2000$ GeV |
|---|---|---|
| 130 | 34.4 | 41.7 |
| 140 | 24.8 | 30.6 |
| 150 | 18.1 | 22.7 |
| 160 | 13.3 | 17.0 |
| 170 | 9.8 | 12.8 |
| 180 | 7.3 | 9.7 |
| 190 | 5.5 | 7.4 |

information from Table I and attributing the difference between the measured cross section and the standard one to the magnetic term (1), we obtain an estimate $|\kappa|=1\pm0.5$. In fact, this means that $0\leqslant|\kappa|\leqslant2$. This limitation is much better than that of Ref. 4. Bearing in mind that the authors of Ref. 6 do not insist on decisive detection of the $t$-production, we should consider our result as the upper bound on $\kappa$. However, a refinement of the $t$-production cross-section measurements will make it possible either to confirm the existence of the magnetic term (1) or to reject it.

We study also the process $\bar{p}p \to \bar{t}+t+\gamma+X$. Its cross section again for $\kappa=1$ and Tevatron options is presented in Table II. For another value of $\kappa$ we multiply the numbers by $\kappa^4$.

Since the cross sections are not large, there is no contradiction with the data. However, the process under discussion gives photons with very high $p_t$. The calculation shows that for $M=170$ GeV and $E=2000$ GeV the maximum of the $p_t$ distribution is situated at $\simeq30$ GeV. This distribution is shown in Fig. 2. We see that the distribution extends toward higher values of $p_t$. For example, 40% of the events have $p_t\geqslant100$ GeV and 23% have $p_t\geqslant150$ GeV.

The results of Ref. 6 hint that there is an extra contribution to the $\bar{t}t$ production cross section. If this assumption is confirmed, we must look for a new mechanism for this contribution. Here we have seen that an anomalous magnetic moment of $t$ provides such mechanism. However, we could propose another additional interaction of the $t$ quark, which would explain these data. Our results show that a study of the process $\bar{p}p \to \bar{t}+t+\gamma+X$ can discriminate between different possibilities. To look for such a process we could use events tagged by $b$ particles from $t$ decays.

TABLE II. Cross section $\Delta\sigma$ (in pb) of the process $\bar{p}p \to \bar{t}+t+\gamma+X$, $\kappa=1$.

| $M$, GeV | $E=1800$ GeV | $E=2000$ GeV |
|---|---|---|
| 130 | 0.20 | 0.35 |
| 140 | 0.16 | 0.23 |
| 150 | 0.10 | 0.15 |
| 160 | 0.06 | 0.10 |
| 170 | 0.04 | 0.07 |
| 180 | 0.03 | 0.05 |
| 190 | 0.02 | 0.03 |

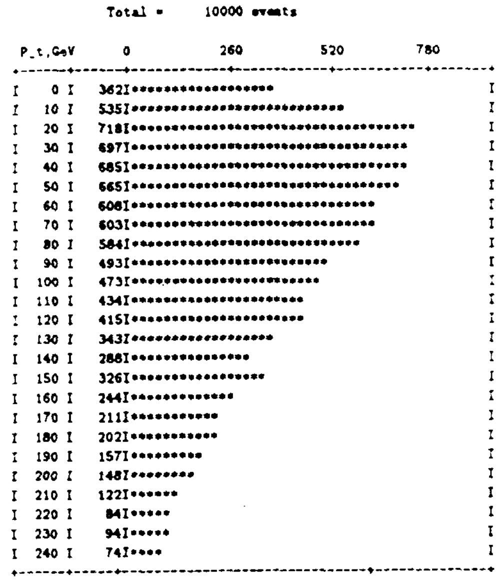


FIG. 2. Photon $p_t$ distribution for the process $\bar{p}+p\rightarrow\bar{t}+t+\gamma+X$, $E=2000$ GeV, and $M=170$ GeV.

In summary, we have proposed a self-consistent description of the $t$-quark properties. This description, of course, is approximate and we cannot guarantee that $\kappa\simeq1$ is correct. For the moment, the best way to check this approach is to compare it with the experiments on the $t$ production. There is also an important question concerning the Goldstone pseudoscalar. Its existence is essential for all points under discussion. Does it exist? Indeed, it must exist if we are to account for the observable effects. In this sense, it could be the 60-GeV $2\gamma$ cluster.[7] This possibility is discussed in Ref. 2. Taking into account the arguments of the present note, we conclude that this variant does not contradict the data on the $2\gamma$'s in the $Z$ decays. The BR of the $Z\rightarrow\gamma\gamma e^+e^-$ decay is estimated to be $\leqslant10^{-7}$.


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