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CP nonconservation in $p\bar{p}\rightarrow t\bar{b}X$ at the Fermilab Tevatron

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The reaction $p\bar{p}\rightarrow t\bar{b}X$ is found to be rather rich in exhibiting several different types of CP asymmetries. The spin of the top quark plays an important role. Asymmetries are related to form factors arising from radiative corrections of the tbW production vertex due to nonstandard physics. As illustrations, effects are studied in two Higgs doublet models and in supersymmetric models; asymmetries up to a few percent may be possible. [S0556-2821(96)01921-2]

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The origin of CP violation remains a pressing issue in particle physics. The standard model (SM), with three generations of quarks, can accommodate a CP-violating phase, the Cabibbo-Kobayashi-Maskawa (CKM) phase [1]. However it is widely believed that this phase cannot account for baryogenesis [2]. Additional CP-violating phases due to new physics are therefore a necessity. In addition, in extensions of the SM, new phase(s) appear rather readily. It is therefore quite unlikely that the CKM phase is the only CP-violating phase in nature. In particular, in top physics the SM causes negligible CP-violation effects [3] whereas, in sharp contrast, nonstandard sources often give rise to appreciable effects [4,5]. Searching for CP violation in top-quark production and/or decay is, therefore, one of the best ways to look for signals for new physics.

In this paper we examine CP-violation asymmetries in top-quark production via the basic quark-level reaction

$$u+\bar{d}\rightarrow t+\bar{b},\quad \bar{u}+d\rightarrow \bar{t}+b. \tag{1}$$

Indeed the reaction is very rich for CP-violation studies as it exhibits many different types of asymmetries. Some of these involve the top spin. Therefore the ability to track the top spin through its decays becomes important and top decays have to be examined as well.

In the SM these effects are extremely small since they are severely suppressed by the Glashow-Iliopoulos-Maiani (GIM) mechanism [3]. As an illustration of the possibilities with nonstandard sources of CP violation we consider two extensions of the SM: a two Higgs doublet model (2HDM) with natural flavor conservation (NFC), often called a type-II model and a supersymmetric standard model (SSM). We find that CP asymmetries can be sizable, in some cases at the level of a few percent. Thus the asymmetries in tb production can be appreciably larger than those in tt pair production [6,7] wherein they tend to be about a few tenths of percents. Since the number of events needed for observation scales as (asymmetry)$^{-2}$ the enhanced CP-violation effects in $t\bar{b}(\bar{t}b)$ may make up for the reduced production rates for tb compared to $t\bar{t}$. In fact larger asymmetries are not just gratifying but can also be essential as detector systematics can be a serious limitation for asymmetries $\lesssim$0.1%.

Let us first discuss the asymmetries in the $u\bar{d}(\bar{u}d)$ subprocess. We consider four types of asymmetries that may be present. First is the CP-violating asymmetry in the cross section:

$$A_0=(\sigma_q-\sigma_{\bar{q}})/(\sigma_q+\sigma_{\bar{q}}), \tag{2}$$

where σ_q and $\sigma_{\bar{q}}$ are the cross sections for $u\bar{d}\rightarrow t\bar{b}$ and $\bar{u}d\rightarrow \bar{t}b$, respectively, at $\hat{s}=(p_t+p_{\bar{b}})^2$. The CPT theorem of quantum field theory implies that the total cross sections for $u\bar{d}$ and $d\bar{u}$ are identical. If a cross-section asymmetry A_0 in the tb final state is present, then to maintain the balance of total cross sections, another mode must have a compensating asymmetry.

The spin of the top allows three additional types of CP-violating polarization asymmetries. To define these let us introduce the coordinate system in the *top-quark* (or top *antiquark*) *rest frame* where the unit vectors are $\vec{e}_z\propto-\vec{P}_b$, $\vec{e}_y\propto\vec{P}_u\times\vec{P}_b$, and $\vec{e}_x=\vec{e}_y\times\vec{e}_z$. Here $\vec{P}_b$ and $\vec{P}_u$ are the three-momenta of the b antiquark and the initial u quark in that frame. With respect to each of the coordinate directions we can define the polarization asymmetry $A(\lambda)=[\Pi(\lambda)\pm\bar{\Pi}(\lambda)]/2$ where λ is one of $\{\hat{x},\hat{y},\hat{z}\}$; $\Pi(\lambda)$ $[\bar{\Pi}(\lambda)]$ is the polarization of the $t(\bar{t})$ in the direction λ. Thus $\Pi(\lambda)=[N_t(+\lambda)-N_t(-\lambda)]/=[N_t(+\lambda)+N_t(-\lambda)]$ where $N_t(\pm\lambda)$ is the number of tops polarized in the direction $\pm\lambda$. The sign is chosen to make the quantity CP odd: + if $\lambda=\hat{x}$ or $\hat{z}$,—if $\lambda=\hat{y}$.

While all these four asymmetries are manifestly CP violating, A_0, $A(\hat{z})$, and $A(\hat{x})$ are even under naive time reversal (T_N) whereas $A(\hat{y})$ is T_N odd. So the first three require a complex Feynman amplitude whereas $A(\hat{y})$ needs a real amplitude. Of course, all four do need a CP-violating phase in the underlying theory. In the limit of massless u and d quarks the CP-violating contribution to the Wtb vertex may be represented by the effective interaction

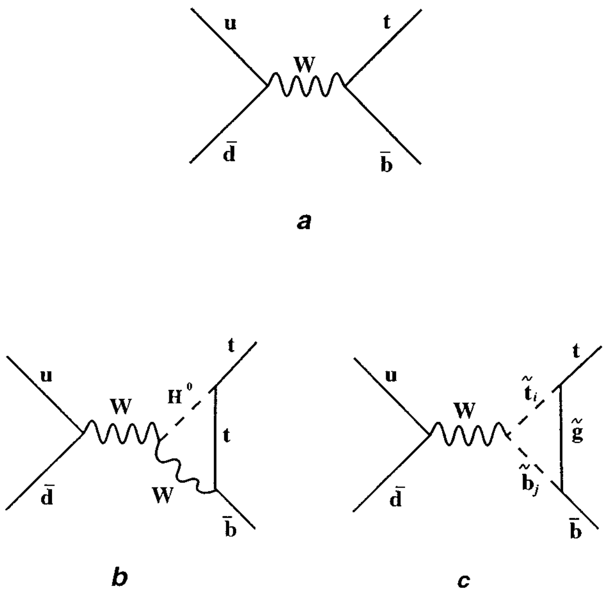

FIG. 1. Feynman diagrams for contributions to $u\overline{d}\rightarrow t\overline{b}$: (a) the standard model process, (b) one-loop graph in the two Higgs doublet models (2HDM), and (c) an example of one-loop graph that could occur in SUSY models.

$$\mathcal{L}=i2^{-1/2}g_W W^+_\mu \overline{t}[F\gamma^\mu + i m_t^{-1} G\sigma^{\alpha\mu}q_\alpha]Lb$$
$$-i2^{-1/2}g_W W^-_\mu \overline{b}R[F\gamma^\mu + i m_t^{-1} G\sigma^{\alpha\mu}q_\alpha]t, \qquad (3)$$

where $L=(1-\gamma_5)/2$, $R=(1+\gamma_5)/2$, we have taken the b quark to be massless and consider only the left-handed component which will interfere with the standard-model (tree-level) contribution. Let us denote the real and imaginary parts of these form factors by $F=F_R+iF_I$ and $G=G_R+iG_I$. Note that the terms proportional to F_R and G_R are Hermitian while the terms proportional to F_I and G_I are not and thus related to final-state interaction effects. In terms of these form factors, the three T_N even asymmetries are

$$A_0=-2F_I+\frac{6}{2+x}G_I, \quad A(\hat{z})=2\frac{2-x}{2+x}F_I-\frac{2}{2+x}G_I,$$
$$A(\hat{x})=-3\pi x^{-1/2}[(2+x)A_0+(2-x)A(\hat{z})]/32, \qquad (4)$$

where $x=m_t^2/\hat{s}$. The dependence of A_0 on F_I and G_I provides a clue as to how the balance of the total cross section required by CPT is achieved. In order for these imaginary parts to exist in perturbation theory, there must be a contribution from a loop graph which has an intermediate state J that can be kinematically on shell. J is therefore another component of the cross section, and in fact it is the cross-section asymmetry of J that compensates for that of tb.

The asymmetry $A(\hat{y})$ is expressible in terms of the real parts of the form factor G: $A(\hat{y})=(3\pi/4)(1-x)G_R/[(2+x)\sqrt{x}]$. This may be obtained from the imaginary parts through the use of dispersion relations.

Figure 1(a) shows the SM tree-level production process. The necessary absorptive parts require radiative corrections, involving a CP-violating phase, at least to one-loop order. Figure 1(b) shows the only graph relevant to a type-II 2HDM with a CP phase residing in neutral Higgs boson exchanges. Figure 1(c) shows an example of a one-loop graph that pertains to a SSM which can involve new CP-violating phase(s) as well as the needed absorptive parts.

As is well known, in a 2HDM with NFC, CP violation emanates from soft symmetry-breaking complex parameters in the Higgs potential [8,9]. These induce mixing between real and imaginary parts of the Higgs fields in their mass matrix. Consequently the mass eigenstates do not have a definite CP property. Therefore, an important feature of the 2HDM is that CP violation may result from the neutral Higgs sector even when there is none in the charged Higgs sector. This CP-violating phase from neutral Higgs boson exchanges is much more difficult to look for compared to that from the charged Higgs boson exchanges. The top quark can play a special role with regard to the neutral Higgs CP as due to its large mass its coupling with the Higgs boson are significantly enhanced compared to all the other quarks.

In this model the neutral Higgs boson mass eigenstates couple to fermions with both scalar and pseudoscalar couplings. Thus, the part of the Lagrangian involving ffH_j^0 and the WWH_j^0 couplings is

$$\mathcal{L}_{H_j^0}=H_j^0\overline{f}(a_{fj}+ib_{fj}\gamma_5)f+c_{Wj}m_W H_j^0 g_{\mu\nu}W^\mu W^\nu, \qquad (5)$$

where $j=1,2,3$ for the three neutral spin-0 fields. The coupling constants, a_{fj}, b_{fj}, and c_{Wj} are functions of $\tan\beta$, which is the ratio between the two vacuum expectation values (VEV's) in this model, i.e., $\tan\beta=v_2/v_1$, and of the three mixing angles $\alpha_{1\cdots 3}$ which diagonalize the 3×3 Higgs mass matrix.

For simplicity we assume that two of the three neutral Higgs particles are much heavier compared to the third one. The effects we are seeking are therefore likely to be dominated by the lightest neutral Higgs boson. We thus omit the index j in Eq. (5) and denote the couplings of the lightest Higgs boson with the top and the W as a_t, b_t, and c_W.

From Fig. 1 we see that the imaginary part of the loop is provided by the WH intermediate state and hence the cross-section asymmetry A_0 is compensated by an asymmetry in $ud\rightarrow W^+H$ versus $\overline{ud}\rightarrow W^-H$. Clearly this imaginary part can only exist above the WH threshold at $\hat{s}=(m_W+m_H)^2$. So below this A_0, $A(\hat{z})$, and $A(x)$ will be identically 0, though, $A(\hat{y})$ need not be since it depends only on virtual effects.

Using the Lagrangian (5) the CP asymmetries, A_0 and $A(\hat{z})$, resulting from the interference of Figs. 1(a) and 1(b) can be readily calculated:

$$A_0=-\frac{b_t c_W m_W R_0}{16\pi m_t}\{(1-3y-z)\phi-2(1-y)$$
$$\times(x+xy-xz-4y)\tau\}, \qquad (6)$$

$$A(\hat{z})=\frac{b_t c_W m_W R_0}{16\pi m_t(1-x)}\{(1+3x-7y-z+3xy+xz)\phi$$
$$-2\tau[(x-2y)^2+(3x-4y)(1-z+xz)$$
$$+x(1-x)y(y-z)]\}, \qquad (7)$$

where $x=m_t^2/\hat{s}$, $y=m_W^2/\hat{s}$, $z=m_H^2/\hat{s}$, $\phi=\sqrt{1+y^2+z^2-2y-2z-2yz}$, $R_0=x/[y(2+x)(1-x)]$, $\tau=(1-x)^{-1}\tanh^{-1}[(1-x)\phi\Delta]$, and $\Delta=(1+x-y-z+xz-xy)^{-1}$.

It is clear from Eq. (5) that all the *CP* asymmetries are proportional to the product $b_t c_W$. We choose the angles in the Higgs mixing matrix as $\alpha_1=\alpha_2=\pi/2$ and $\alpha_3=0$ which gives maximal effects [10,11]. It follows that $b_t c_W m_W \simeq 0.2 m_t \cos\beta \cot\beta$ so the asymmetries are now a function of $\tan\beta$ and m_H only.

We present our numerical results for $\tan\beta=0.3$ [12]. Numbers for other values of $\tan\beta$ can then be obtained from the above relation. Figure 2 shows the asymmetries as a function of $\hat{s}$ for $m_H=100$ GeV. The asymmetries A_0, $A(\hat{z})$, and $A(\hat{x})$ are in the range of about 1/2–3 %.

Since the real part of the graph in Fig. 1(b) does not need a physical threshold, it may receive contributions from Higgs masses boson of arbitrary mass. In the limit of degenerate Higgs boson masses, *CP*-violating effects should vanish. Hence, in calculating F_R, G_R, it is not valid to ignore the contributions of more massive Higgs bosons. We will assume therefore that the other Higgs bosons of the theory have a mass m_H' and, for our numerical estimates we will take $m_H'=1$ TeV. Recall that if $\hat{s}<(m_H'+m_W)^2$ then the existence of the heavier Higgs bosons does not effect the values of A_0, $A(\hat{x})$, or $A(\hat{z})$ since these depend on F_I and G_I. In Fig. 2 we also show the value of $A(\hat{y})$; it tends to be smaller than the other asymmetries.

To search for the effects of these three types of spin asymmetries that occur at the production vertex, decays of the top will obviously need to be examined [13,14]. In particular when considering $A(\hat{y})$ one must keep in mind that it is dependent on the real part of the loop amplitude of Fig. 1(b). One complication that this could lead to is that a similar asymmetry may also enter into the decay $t\to bW$ when similar radiative corrections to that vertex are also included [15]. This is not a concern in the case of the other observables since if we assume that the Higgs is above the threshold, i.e., $(m_W+m_H)>m_t$, the necessary condition that there be an imaginary part in the decay amplitude is not satisfied.

As it turns out, the observed value of $A(\hat{y})$ is not affected by *CP* violation in the decay process. The key point is that the measurement of $A(\hat{y})$ through the decay chain $u(p_u)d(p_d)\to b(p_{b1})t(p_t)$ followed by $t(p_t)\to b(p_{b2})e^+(p_e)\nu(p_\nu)$ is equivalent to measurement of the term proportional to $\epsilon(p_e,p_d,p_t,p_1)$. On the other hand, *CP* violation arising from the decay process is proportional to $\epsilon(p_e,p_d,p_t,p_{b2})$. It is easy to see that an observable related to the first of these will be insensitive to the second [10].

These quark-level asymmetries can be converted to the hadron (i.e., $p\bar{p}$) level by folding in the structure functions in the standard manner [16]. The results are shown in Fig. 3 where for the asymmetry $A(\hat{y})$ we apply a cut of $\hat{s}>(m_H+m_W)^2$. At the Tevatron ($E=2$ TeV) the expected number of events are 900–3000 with an integrated luminosity 3–10 fb^{-1}, respectively [17]. If the collider energy gets upgraded to 4 TeV and/or there are additional luminosity upgrades as have often been discussed, then the number of events can go up by another factor of about 2–10 [17]. Thus the asymmetries, in the range of a few percent, resulting from some extensions of the SM may well become within

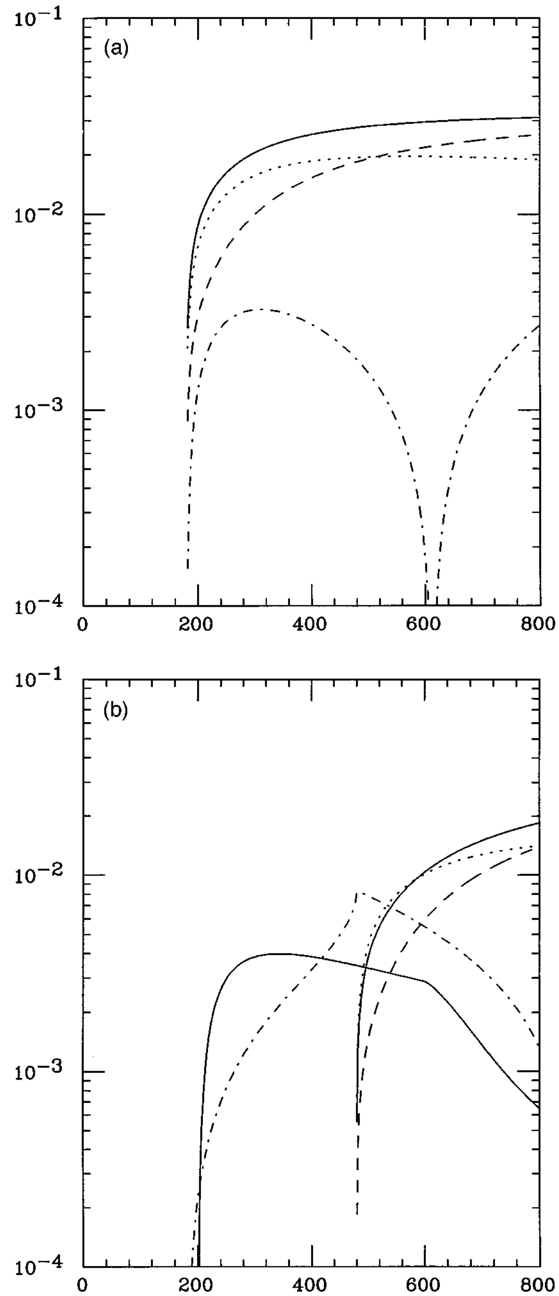

FIG. 2. The magnitudes of the quark-level asymmetries A_0 (solid), $A(\hat{z})$ (dashed), $A(\hat{x})$ (dotted), and $A(\hat{y})$ (dot-dashed) as a function of $\sqrt{\hat{s}}$ in the 2HDM with $\tan\beta=0.3$ and $m_H=100$ GeV. Note that $A(\hat{y})$ is computed keeping fixed the masses of the two heavier neutral H^0's to 1 TeV. Also shown with the lower solid line is the asymmetry A_0 in the SUSY model described in the text for parameters $\tilde{m}_{t1}=100$ GeV, $\tilde{m}_{t2}=500$ GeV, $\tilde{m}_q=100$ GeV, $\tilde{m}_g=100$ Gev, and $\mathrm{Im}(\mathcal{X}_{11}\mathcal{X}_{12}^*)=1/2$.

the reach of experiment provided that the signal for these single top events could be extracted from possible backgrounds [18].

Another extension of the standard model which can produce these kind of asymmetries is SSM. There are a number of possible graphs which could contribute [10,11]; here we will consider only the gluino exchange diagram given in Fig. 1(c). In this case *CP* violation arises through the mixing matrix between the fermion and the scalar states, in general a

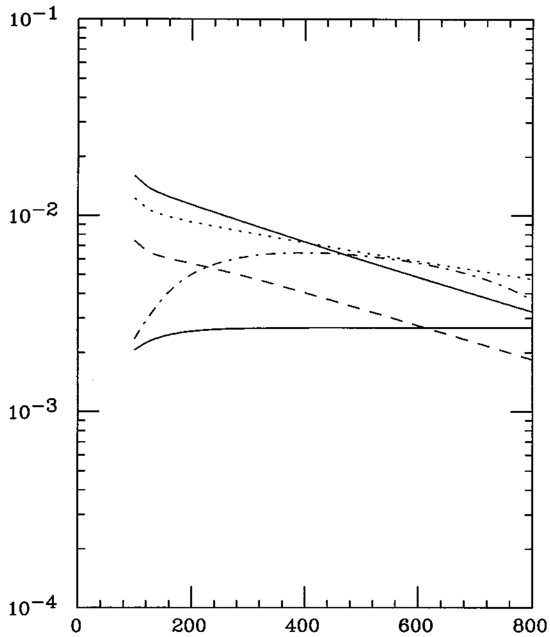

FIG. 3. The corresponding asymmetries in the $p\bar{p}$ c.m. frame as a function of m_H for the 2HDM and as a function of $\Delta\widetilde{m}_t(\equiv\widetilde{m}_{t2}-\widetilde{m}_{t1})$ for the SUSY case. See also caption to Fig. 2.

6×6 matrix. For simplicity, let us consider a scenario, motivated by supergravity models, where all the squarks are degenerate with a mass $\widetilde{m}_q$ except for the superpartner of the top quark, the stop. Furthermore, the two stop states mix with the left and right parts of the top quark with a general 2×2 unitary mixing matrix $\mathcal{X}$. In this case the helicity structure of the model is such that the form factor $F=G$. Thus $A(\hat{z})=A_0$, from which $A(\hat{x})$ can be obtained from Eq. (4) and $A(\hat{y})$ may be obtained through dispersion relations. In Fig. 2 we also show these asymmetries due to the SSM for $\widetilde{m}_{t1}=100$ GeV $\widetilde{m}_{t2}=500$ GeV, $\widetilde{m}_g=100$ GeV, and $\widetilde{m}_q=100$ GeV. We have also assumed that the quantity $\mathrm{Im}(\mathcal{X}_{11}\mathcal{X}_{12}^*)=1/2$ which is its maximum value. We can see that in this case the asymmetries are less than 1%. The small size of these asymmetries is, in part, due to the fact that the intermediate state [see Fig. 1(c)] consists of two scalars that must be in a P wave giving rise to an additional threshold suppression factor. However, in SSM many other types of loop corrections (e.g., box graphs) can also contribute giving rise to asymmetries on the order of several percents [10,11].

We close with a few remarks in brief. First, it is important to note that from the point of view of experimental detection these four asymmetries are independent. Thus, the sensitivity of a given detector to observing the combined CP-violation effects may be appreciably better than that for any one asymmetry [10,11].

Second, we have focused here on a $p\bar{p}$ machine (i.e., the Tevatron) as the self-conjugate nature of the initial state is rather important for CP studies. At the CERN Large Hadron Collider (LHC) (i.e., a pp machine), although the event rate is high, such CP studies are quite difficult. Note, for instance, that the cross sections for $pp\rightarrow tbX$ and to $\bar{t}\bar{b}X$ are expected to be different at the LHC even if CP was strictly conserved.

Finally we recall that the W-glue fusion subprocess, $W^++\text{gluon}\rightarrow t+b$, also contributes to the same final state [17]. While it will be useful to include its contribution to the asymmetries in a future study, for now we note that, at least in the 2HDM, CP-violating radiative corrections, to one-loop order, to Wg fusion do not yield absorptive parts (in the $m_b=0$ limit).

We will address to some of these issues in greater detail in future work [10].

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