In order to observe a signal of possible $CP$ violation in top-quark couplings, we study top-quark production and decay under the conditions of the Tevatron upgrade. Transverse energy asymmetries sensitive to $CP$ violation are defined. Applying the recently proposed optimal method, we calculate the statistical significance for the direct observation of $CP$ violation in the production and subsequent decay of top quarks.
1. Introduction

The top quark, thanks to its huge mass, is expected to provide a good opportunity to study physics beyond the Standard Model (SM). Indeed, as many authors have pointed out [1 – 8], CP violation in the combined process of top-quark production and decay could be a useful signal for possible non-standard interactions. This is because (i) the CP violation in the top-quark couplings induced within the SM is negligible and (ii) a lot of information on the top quark is transferred to the secondary leptons without getting obscured by the hadronization effects.

In this letter we will consider two types of semi-inclusive processes: first, the process in which both top-quarks decay semileptonically,

\[ p\bar{p} \rightarrow t\bar{t} \rightarrow l^+l^-X , \]  

and secondly those processes in which only one of them decays semileptonically,

\[ p\bar{p} \rightarrow t\bar{t} \rightarrow l^+X \quad p\bar{p} \rightarrow l^-X . \]  

The latter processes (2) are particularly interesting because they have a better statistics and give the best signature for the top-quark identification.

The main production mechanism for the top-quark production at the Tevatron is q\bar{q}–annihilation to top quarks where the quark and the anti-quark stem from a high energy proton and anti-proton, respectively. In principle there are also gluon processes to consider but at Tevatron energies they give only a small contribution to the cross section of the order of 10%, and less than 1% to the CP sensitive observables considered here. Therefore they will be neglected in the calculations.

We will apply the usual CDF cuts in our analysis [9]. For example, a \( p_T \)-cut of 5 GeV for all leptons and a rapidity cut of 3 for all particles will be introduced. It was checked that these cuts do not induce fake effects in the CP-sensitive observables. We will adopt the Tevatron upgrade energy \( \sqrt{s} = 2.0 \) TeV. Two options for the luminosity will be considered here; so called “TeV-33” defined as \( L = 30 \text{ fb}^{-1} \) and the Tevatron Run II with \( L = 2 \text{ fb}^{-1} \) at the same energy.
2. The optimal method

In order to be as sensitive as possible to CP-violating couplings we will adopt here the recently proposed optimal procedure [10] for the data analysis. Let us briefly summarize the main points of this method. Suppose we have a cross section

\[ \frac{1}{\sigma} \frac{d\sigma}{d\phi} = \sum_i c_i f_i(\phi) \]  

(3)

where the \( f_i(\phi) \) are known functions of the location in final-state phase space \( \phi \) and the \( c_i \) are model-dependent coefficients. \( \sigma \) is the integrated cross section \( \sigma = \int \frac{d\sigma}{d\phi} d\phi \). In this paper we will restrict ourselves to a case for which all of the \( c_i \) are small except for \( c_1 = 1 \) (\( f_1(\phi) \) will be the SM contribution, the other \( c_i \) will parameterize beyond the SM physics). The ultimate goal would be to determine the \( c_i \)'s. It can be done by using appropriate weighting functions \( w_i(\phi) \) such that

\[ \int w_i(\phi) \frac{1}{\sigma} \frac{d\sigma}{d\phi} (\phi) d\phi = c_i. \]  

Generally, different choices for \( w_i(\phi) \) are possible, but there is a unique choice such that the resultant statistical error is minimized. Such functions are given by

\[ w_i(\phi) = \sum_j X_{ij} f_j(\phi), \]  

(4)

where \( X_{ij} \) is the inverse matrix of \( M_{ij} \) which is defined as

\[ M_{ij} \equiv \int \frac{f_i(\phi) f_j(\phi)}{\sigma} \frac{d\sigma}{d\phi} (\phi) d\phi. \]  

(5)

When we take these weighting functions, the statistical uncertainty of \( c_i \) becomes

\[ \Delta c_i = \sqrt{V_{ii}}, \]  

(6)

for the covariance matrix \( V \) defined as

\[ V_{ij} = \frac{1}{N} \int w_i(\phi) w_j(\phi) \frac{1}{\sigma} \frac{d\sigma}{d\phi} d\phi, \]  

(7)

where \( \sigma \) and \( N \) stand for the total cross section and the total number of observed events, respectively.
Since we assume that non-standard interactions do not alter the SM pattern radically, we will keep only linear terms in the $c_i$ (those which arise from an interference with SM contributions). Within this approximation, the expression $\frac{1}{\sigma} \frac{d\sigma}{d\phi}$ in Eqs. (4-7) can be replaced by the SM contribution $f_1$.

3. CP-violating transverse energy asymmetries

We will assume that all non-standard effects in the production process $q\bar{q} \rightarrow t\bar{t}$ can be represented by the gluon exchange in the $s$-channel with the following effective coupling:

$$\Gamma^\mu(g^* \rightarrow t\bar{t}) = g_s u(p_t) \left[ \gamma^\mu (F^L_1 P_L + F^R_1 P_R) - \frac{i\sigma^{\mu\nu}(p_t + p_{\bar{t}})\nu}{m_t} (F^L_2 P_L + F^R_2 P_R) \right] v(p_\bar{t}),$$

(8)

where $g_s$ is the strong coupling constant, $P_{L/R} \equiv (1 \mp \gamma_5)/2$ and colour degrees of freedom have been omitted. The SM vertex is given by $F^R_1 = F^L_1 = 1$ and $F^R_2 = F^L_2 = 0$. A non-zero value of $F^L_1 - F^R_2$ is a signal of CP violation.

For the on-shell $W$, we will adopt the following parameterization of the $tbW$ vertex suitable for the decays $t \rightarrow W^+ b$ and $\bar{t} \rightarrow W^- \bar{b}$:

$$\Gamma^\mu(t \rightarrow W^+ b) = -\frac{g}{\sqrt{2}} V_{tb} u(p_b) \left[ \gamma^\mu (f^L_1 P_L + f^R_1 P_R) - \frac{i\sigma^{\mu\nu} k^{\nu}}{M_W} (f^L_2 P_L + f^R_2 P_R) \right] u(p_t),$$

(9)

$$\Gamma^\mu(\bar{t} \rightarrow W^- \bar{b}) = -\frac{g}{\sqrt{2}} V_{\bar{b}t} v(p_t) \left[ \gamma^\mu (\bar{f}^L_1 P_L + \bar{f}^R_1 P_R) - \frac{i\sigma^{\mu\nu} k^{\nu}}{M_W} (\bar{f}^L_2 P_L + \bar{f}^R_2 P_R) \right] v(p_\bar{b}),$$

(10)

where $g$ is the SU(2) gauge-coupling constant, $V_{tb}$ is the $(tb)$ element of the Kobayashi-Maskawa matrix and $k$ is momentum of the $W$. For the SM tree-level interactions has $f^L_1 = \bar{f}^L_1 = 1$ and $f^R_1 = f^L_2 = f^R_2 = \bar{f}^L_1 = \bar{f}^L_2 = \bar{f}^R_1 = \bar{f}^R_2 = 0$. Again, because $W$ is on shell, there are two additional form factors which do not contribute. One can show that $[2]$

$$f^L_{1,2} = \pm \bar{f}^L_{1,2}, \quad f^R_{1,2} = \pm \bar{f}^R_{1,2},$$

(11)

Two other possible form factors do not contribute in the limit of zero parton mass.
where upper (lower) signs are those for CP-conserving (-violating) contributions. Therefore any observable sensitive to CP-violation in the top-quark decay must be proportional to $f_1^{L,R} - \bar{f}_1^{L,R}$ or $f_2^{L,R} - \bar{f}_2^{R,L}$.2

The matrix element for the combined production and decay of top quarks via $q\bar{q}$-annihilation, $q\bar{q} \rightarrow t\bar{t} \rightarrow l^+l^- + \ldots$ has been obtained by the algebraic computer program FORM [11]. For the massless $b$ quark the resulting expression consists of a CP-conserving SM piece plus two terms linear in the CP-violating couplings $c_P$ and $c_D$ corresponding to CP violation in the production and in the decay process, respectively:

$$
c_{SM} = 1 \quad c_P = \frac{1}{2} \text{Re}(F_2^L - F_2^R) \quad c_D = \frac{1}{2} \text{Re}(f_2^R - \bar{f}_2^L).
$$

The notation of Sect. 2 has been used here with the indices 1 = SM, 2 = P(roduction) and 3 = D(ecay). Hereafter we assume that $m_b = 0$ and all non-standard interactions violate $CP$, i.e. $F_2^L = -F_2^R$ and $f_2^R = -\bar{f}_2^L$. The matrix element squared will be then convoluted with the Morfin and Tung [12] parton distributions (the 'leading order' set from the 'fit sl'). Numerical results will be obtained using the Monte Carlo package RAMBO [13].

In general, both CP violating couplings $c_P$ and $c_D$ may be present. Therefore let us discuss how to observe a combined signal of CP violation emerging from these couplings. There are many, more or less efficient observables to be considered in the discussed process. In this letter only those related to the transverse energy of the muon, will be considered. A possible CP-sensitive asymmetry for the process [11] is for instance the transverse-energy ($E_T^\pm$) asymmetry for the muons:

$$
A_T^\mu = \frac{\sigma(E_T^- > E_T^+) - \sigma(E_T^+ > E_T^-)}{\sigma(E_T^+ > E_T^-) + \sigma(E_T^- > E_T^+)}.
$$

A non-zero observation of $A_T^\mu$ would prove CP violation in the production or in the decay of the top quarks.

\[2\] For $m_b = 0$ only $\bar{f}_2^L$ and $f_2^R$ interfere with the SM, therefore in the leading order in the nonstandard couplings, only terms proportional to $\bar{f}_2^L - f_2^R$ will appear in the cross section.
The asymmetry has been discussed in Ref. \cite{5, 14}. It is revisited here because we present a detailed numerical analysis applicable for the Tevatron upgrade conditions. Furthermore we are able to give results both for CP violation from the decay and from the production vertex whereas in Ref. \cite{5} only CP violation from the production side was considered. The result for the expected CP-violating effect is shown in Fig. 1 as a function of the couplings $c_P$ and $c_D$. It is seen that $c_P$ gives larger effects by about a factor of three. The effects may be remarkably large, however since we have neglected terms quadratic in $c_i$, one should not consider $c_i$'s greater than 0.2 in order to retain precision at the level of several per cent. In general, CP violation may be present both in the production and decay of top quarks. Therefore one should take an appropriately weighted sum of the two curves in Fig. 1. Unfortunately, lacking a real theory of CP violation the weights are not known.

It should be noted that among the transverse energy asymmetries the muon $E_T$–asymmetry is the most efficient to tag for CP-violating effects, not only because muons have much clearer signatures than other top-quark decay products but also due to the structure of the CP-violating matrix elements. For example, if one works out the matrix element for $c_P = c_D = 0.1$ one obtains a $A^\mu_T = +11.3\%$ (as seen in Fig. 1) whereas $A^W_T$, $A^\nu_T$, $A^b_T$, etc. are all smaller, $A^W_T = 5.3\%$, $A^\nu_T = -4.8\%$ and $A^b_T = -5.2\%$. This feature is independent of the values chosen for $c_P$ and $c_D$.

It is worth noting that the transverse-energy asymmetry $A^\mu_T$ is identical to the normalized expectation value $< w_E > = \int w_E \frac{1}{\sigma} \frac{d\sigma}{d\phi} d\phi$ of the following weighting function:

$$w_E(E^+_T, E^-_T) \equiv \frac{E^-_T - E^-_T}{|E^-_T - E^+_T|}. \quad (14)$$

$A^\mu_T$ can be decomposed according to

$$A^\mu_T = < w_E > = \int w_E \frac{1}{\sigma} \frac{d\sigma}{d\phi} d\phi = c_P \int w_E f_P d\phi + c_D \int w_E f_D d\phi \equiv c_P A_P + c_D A_D \quad (15)$$
Figure 1: Transverse energy asymmetry as defined in Eq. (13) for muons from semileptonic top-quark decays, as induced by $CP$ violating couplings $c_P$ and $c_D$ at the production and decay vertex, respectively.
with $A_P$ and $A_D$ calculated to be $A_P = 0.845$ and $A_D = 0.285$. Since $A_P > A_D$ we can conclude that it is easier to observe $CP$ violation in the production process. For the number of dilepton events denoted by $N_{ll}$, the statistical significance for $A_T^\mu$ determination is given by

$$N_{SD}^T \equiv |A_T^\mu|\sqrt{N_{ll}} = |c_P A_P + c_D A_D|\sqrt{N_{ll}}$$  \hspace{1cm} (16)$$

The expected number of events in the dilepton mode $N_{ll}$, at the integrated luminosity $L = 2$ and $30 \text{ fb}^{-1}$, respectively, allows an observation of the $3\sigma$ effect providing the following relations are satisfied:

$$|2.5c_P + 0.9c_D| \geq 1 \quad \text{for} \quad L = 2 \text{ fb}^{-1}$$  \hspace{1cm} (17)

$$|9.8c_P + 3.3c_D| \geq 1 \quad \text{for} \quad L = 30 \text{ fb}^{-1}$$  \hspace{1cm} (18)

So, we can observe that even $L = 2 \text{ fb}^{-1}$ allows for an observation of $c_P = c_D = .3$ at $\sqrt{s} = 2 \text{ TeV}$.

Since the dilepton events are relatively rare and difficult to identify we shall discuss another observable here:

$$A_{cut}^\mu(E_{Tcut}) = \frac{\sigma^-(E_T^- > E_{Tcut}) - \sigma^+(E_T^+ > E_{Tcut})}{\sigma}$$  \hspace{1cm} (19)$$

which can be used for the processes Eq. (2). The $\sigma$ in (19) denotes the integrated cross section with no cuts except for the standard CDF cuts. Note that the transverse-energy-spectrum asymmetry $1/\sigma(d\sigma^+/dE_T - d\sigma^-/dE_T)$ may be obtained from $A_{cut}^\mu(E_{Tcut})$ just by differentiation with respect to $E_{Tcut}$. The dependence of $A_{cut}^\mu$ as a function of $E_{Tcut}$ is shown in Fig. 2 for two sets of the couplings, $(c_P = 0, \ c_D = 0.1)$ and $(c_P = 0.1, \ c_D = 0)$. From Fig. 2 one can read off the $E_{Tcut}$-region where the transverse-energy-spectrum asymmetry

\textsuperscript{23}The same phenomenon has been noticed for the process $e^+e^- \rightarrow t\bar{t} \rightarrow l^+ l^- X$ and $e^+e^- \rightarrow t\bar{t} \rightarrow l^\pm X$, see Ref. \textsuperscript{8}. It might have been anticipated as a consequence of the fact that the components of $(p_t + p_{\bar{t}})/m_t$ (production) are usually greater than those of $k/m_w$ (decay).
is maximal: $E_T = 50$ GeV and $E_T = 35$ GeV for CP violation in the production and decay, respectively.

Again, it is seen that effects of CP-violation in the production process are more pronounced.

As it is seen from our analysis it may happen that the values of $c_P$ and $c_D$ would conspire in such a way that the asymmetries discussed would be very small; CP violation in the production and decay would cancel each other. Therefore it would be very useful to be able to disentangle CP violation in the production and decay. The method of optimal observables introduced in the Chapter 2 provides the desired strategy. In the next chapter we present our numerical results for the separate determination of CP violation in the production and decay.

4. The optimal observables

It may be interesting to compare the statistical significance for the transverse-energy asymmetry with the one calculated for the optimal (for a detection of non-zero $c_P$ or $c_D$) observables defined in Sec.2. We shall consider the transverse-lepton-energy spectrum in the final state defined through the detection of high-$E_Tl^+$ + jets with appropriate cuts included. The spectrum is sensitive to $c_P$ and $\text{Re}(f_2^R)$:

$$\frac{1}{\sigma} \frac{d\sigma}{dE_T^+} = f_1^+(E_T^+) + c_P f_1^+(E_T^+) + \text{Re}(f_2^R) f_1^+(E_T^+),$$

where $\sigma$ denotes the cross section for the process $p\bar{p} \rightarrow l^+ + \text{jets}$ and $f^+$'s are known functions of $E_T^+$. We have assumed that all the non-standard interactions violate CP.

We have obtained the following relevant entries for the matrix $M_{ij}$:

$$M_{DP} = 0.17 \quad M_{PP} = 0.72 \quad M_{DD} = 0.048$$

Since the discussed form factors enter appropriate vertices multiplied by the $t\bar{t}$ or $W^+$ momentum, $M_{ij}$ depend on the proton energy. For example, with protons of energy 1.5 TeV one gets $M_{DP} = -0.125$, $M_{PP} = 0.33$ and $M_{DD} = 0.050$. It could be verified that the precision of $c_P$ and $f_2^R$ determination increases with the proton energy.
Figure 2: Transverse energy asymmetry as defined in Eq. (13) for muons from semileptonic top-quark decays, as induced by CP violating couplings $c_P$ and $c_D$ at the production and decay vertex, respectively.
Table 1: The minimal values for \( c_P \) and \( c_D \) necessary to observe \( CP \) violation in the single-lepton mode at the 3\( \sigma \) level for \( L = 2, 30 \text{ fb}^{-1} \).

Now, the optimal weighting functions can be obtained. The statistical errors \( \Delta c_i \) for the determination of \( c_P \) and \( \text{Re}(f_R^2) \) are the following:

\[
\Delta c_P = \sqrt{\frac{M_{DD}}{N_i \Delta}} = \frac{3.35}{\sqrt{N_i}} \quad \Delta \text{Re}(f_R^2) = \sqrt{\frac{M_{PP}}{N_i \Delta}} = \frac{13.04}{\sqrt{N_i}},
\]

where \( \Delta \equiv M_{DD}M_{PP} - M_{DP}^2 \) and \( N_i \) stands for the total number of single lepton events. An analogous procedure leads to \( \Delta c_P \) and \( \Delta \text{Re}(\bar{f}_L^2) \) from \( l^- \) energy spectrum. Since both distributions are statistically independent, we can combine them to receive \( \Delta c_P \) and \( \Delta c_D \)

\[
\Delta c_P = \frac{2.37}{\sqrt{N_i}} \quad \Delta c_D = \frac{18.43}{\sqrt{N_i}}
\]

In order to estimate the power of the optimal observables we need to calculate the statistical significance, \( N_{SD}^{P,D} \equiv |c_{P,D}|/\Delta c_{P,D} \) for their experimental determination:

\[
N_{SD}^P = \frac{|c_P|}{2.37\sqrt{N_i}} \quad N_{SD}^D = \frac{|c_D|}{18.43\sqrt{N_i}}.
\]

The expected number of single-leptonic events (1 b-quark tagged) \(^{[15]}\) is 1300 and 20,000 for \( L = 2 \) and 30 fb\(^{-1}\), respectively. In Table 1 we show the minimal values for \( c_P \) and \( c_D \) necessary to observe 3\( \sigma \) effects.

As it has already been noticed it will be much easier to observe \( CP \) violation in the production process; even at \( L = 2 \text{ fb}^{-1} \), \( c_P = 0.2 \) will be seen at the 3\( \sigma \) level.

The transverse-double-lepton-energy spectrum allows for independent \( c_{P,D} \)
Table 2: The minimal values for $c_P$ and $c_D$ necessary to observe $CP$ violation in the dilepton mode at the $3\sigma$ level for $L = 2$, $30$ fb$^{-1}$.

determination:

$$\frac{1}{\sigma} \frac{d^2\sigma}{dE_T^+ dE_T^-} = f_1^+(E_T^+, E_T^-) + c_P f_1^-(E_T^+, E_T^-) + c_D f_2^+(E_T^+, E_T^-),$$

(24)

where $\sigma$ stands for the cross section for the process $p\bar{p} \rightarrow l^+ l^- \text{ jets}$ and $f^\pm$’s are known functions of $E_T^+$ and $E_T^-$. In this case $M_{ij}$ are the following:

$$M_{DP} = \pm 0.57 \quad M_{PP} = 3.19 \quad M_{DD} = 0.13.$$  

(25)

The statistical significance for $c_{P,D}$ determination read:

$$N_{SD}^{P} = \frac{|c_P|}{1.17} \sqrt{N_l} \quad N_{SD}^{D} = \frac{|c_D|}{5.76} \sqrt{N_l}.$$  

(26)

Adopting the anticipated number of dileptonic events [13], $N_l = 80$ and 1200 for the luminosity $L = 2$ and $30$ fb$^{-1}$ we present in Table 2 the minimal values for $c_P$ and $c_D$ necessary to observe $3\sigma$ effects. It is seen from the table that single-leptonic modes are more promising as signals of non-standard and $CP$-violating physics than dilepton ones.

5. Summary

In this article we have calculated transverse energy asymmetries as well as optimal observables for $CP$ violating couplings in the production and decay of top quarks at the Tevatron upgrade. We have compared the physics potential of these observables and determined the regions in parameter space with the highest statistical significance. It has been found that it is considerable easier to observe $CP$ violation in the $t\bar{t}$ production process than in the semi-leptonic decays of
the top quarks produced at the Tevatron. It has been demonstrated that the single-leptonic modes are are more promising as signals of \( CP \) violation than the dilepton ones. A more general aim of this paper is to point out, that nonstandard \( CP \) violation in top-quark interactions may be found already before precision measurements at the LHC will be done.

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