Probe of *CP* Violation in Top Quark Pair Production at Hadron Supercolliders

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We show that measurement of the difference in the transverse energy distribution of leptons and antileptons from $t\bar{t}$ events at hadron colliders provides an interesting probe of *CP* violation in the Higgs sector. We predict a *CP*-violating asymmetry at the 10^{-3} level.

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Twenty-five years after the discovery of *CP* violation, the origin of this phenomenon is still a mystery. Gauge theories with only gauge bosons and fermions have no useful *CP*-violating parameters. Thus, any *CP*-violating effects may be traced back to the scalar boson sector. The standard theory of Kobayashi and Maskawa [1] assumes that all *CP*-violating effects reside in the quark-Higgs-boson Yukawa couplings. However, if the Higgs sector contains several scalar fields, additional *CP*-violating parameters may appear in the Higgs boson self-couplings [2]. It is known that this second type of *CP* violation cannot itself account for the manifestations of *CP* violation in the neutral kaon system [3]. On the other hand, this second source of *CP* violation is quite a natural one. In addition, several groups [4] have recently invoked *CP* violation in the Higgs sector to drive models in which the cosmological baryon asymmetry is produced at the weak phase transition.

How can *CP* violation in the Higgs sector be observed? Weinberg [5] has recently suggested that this mechanism of *CP* violation may have an observable effect on the electric dipole moment of the neutron. Barr and Zee [6] have pointed out that it also contributes to the electric dipole moment of the electron. We will show here that this type of *CP* violation can also be probed effectively in high-energy hadron collider experiments. This is quite an unusual conclusion, since in the Kobayashi-Maskawa model, *CP*-violating amplitudes are typically suppressed in high-energy processes by a dimensionless factor of order 10^{-12} [7]. However, in top quark production one can expect *CP* asymmetries of order 10^{-3} which remain visible in inclusive experiments such as the measurement of lepton energy spectra. These are difficult experiments, but they are well matched to the large samples of top quarks which should be produced at the Superconducting Super Collider (SSC) and CERN Large Hadron Collider (LHC). Observation of this effect would provide direct evidence for the connection between *CP* violation and the mass-dependent couplings of heavy quarks.

We will analyze the effects of *CP* violation in the Higgs sector using a simplified model introduced by Weinberg [5]. We assume that the mass matrix of Higgs bosons mixes *CP*-even and -odd scalars. The lightest eigenstate of the Higgs boson mass matrix then corresponds to a neutral boson ϕ which couples to the top quark through

$$\delta\mathcal{L} = -(m_t/v)\phi\bar{t}[AP_L + A^*P_R]t\,, \tag{1}$$

where A is a complex combination of mixing angles. We assume that heavier Higgs bosons may be neglected. Then we find *CP*-violating amplitudes proportional to $\mathrm{Im}[A^2]$, which Weinberg calls $2\,\mathrm{Im}Z_2$. This *CP*-violating structure occurs naturally in models with two or more Higgs doublets. In that context, Weinberg shows that $|\mathrm{Im}[A^2]| \le \sqrt{2}$, for a reasonable choice of Higgs field vacuum expectation values. The experimental bounds on the neutron [8] and electron [9] electric dipole moments do not yet improve this purely theoretical constraint. Weinberg showed that the theoretical bound can be saturated. In our numerical estimates, we set the *CP*-violating parameter $\mathrm{Im}[A^2]$ to its maximum allowed value.

Exchange of the Higgs boson ϕ creates *CP*-violating final-state interactions in $t\bar{t}$ production by gluons or quarks, as shown in Fig. 1. The effect is easy to understand in intuitive terms: At high energy, helicity conservation insists that gluons dominantly produce left-handed top quarks (t_L) with right-handed top antiquarks ($\bar{t}_R$) or vice versa ($t_R\bar{t}_L$). However, near threshold, there is also substantial production of $t_L\bar{t}_L$ and $t_R\bar{t}_R$. These latter states go into each other under *CP*, so any asymmetry in their production rates is a signal of *CP* violation. We will show below that such an asymmetry is induced by ϕ exchange.

For light quarks, an asymmetry in the production of different helicity states would be unobservable. However, the top quark is known to be very heavy. This means that the lifetime of the top quark is very short: $\tau \sim ((1.1$

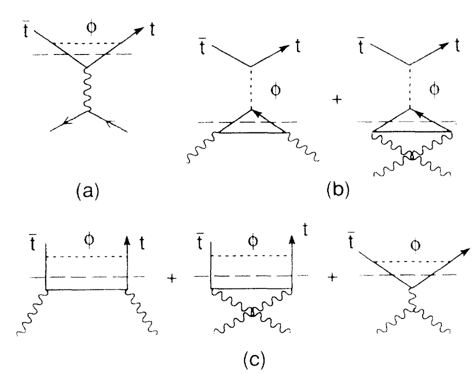

FIG. 1. Feynman graphs which produce *CP* violation in the processes $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$.

GeV)$[m_t/(150\text{ GeV})]^3)^{-1}$. This lifetime is comparable to the hadronization time, and much shorter than the time $t \sim [(2\text{ MeV})(150\text{ GeV})/m_t]^{-1}$ needed to flip the spin of the top quark [10,11]. In addition, the top quark decays through the parity-violating weak interaction, and this decay acts as a spin analyzer. Since $m_t > m_W$, the dominant decay of the t quark should be $t \to W^+ b$. For large top mass, the W will be predominantly longitudinal, while the b is always left handed [12]. Therefore, a t_L will decay to an energetic b_L, which must go forward to carry the quark spin, and to a less energetic W^+; for t_R, the relative energies of b and W are roughly reversed. By observing the energy distribution of the W's, or even of their decay leptons, one can effectively track the spin of the t.

In particular, note that $t_L\bar{t}_L$ produces a relatively slow W^+ with an energetic W^-, while $t_R\bar{t}_R$ produces a slow W^- with an energetic W^+. Thus, a difference in the production of $t_L\bar{t}_L$ and $t_R\bar{t}_R$ leads to a charge asymmetry in the energy distributions of W's or their decay leptons. This is observable *CP* violation [13].

$t\bar{t}$ asymmetry.— Let us now compute the underlying *CP* asymmetry

$$\Delta N_{LR} = [N(t_L\bar{t}_L) - N(t_R\bar{t}_R)]/(\text{all } t\bar{t}) \tag{2}$$

for production of $t\bar{t}$ from $q\bar{q}$ and from gluon fusion. For $q\bar{q}$, the asymmetry (2) arises because Fig. 1(a) produces a color electric dipole form factor $F_{2A}(q^2)$. Interfering its contribution with that of the lowest-order diagram, we find

$$\Delta N_{LR} = \frac{2\beta}{3-\beta^2}\,\mathrm{Re}F_{2A}, \tag{3}$$

where $\beta = (1-4m_t^2/s)^{1/2}$ is the center-of-mass velocity of the two quarks. The term in $\mathrm{Re}F_{2A}$ proportional to the imaginary factor $A^2 - A^{*2}$ involves the absorptive part of the Feynman integral:

$$\mathrm{Re}F_{2A} = \frac{1}{16\pi}\left(\frac{m_t}{v}\right)^2 \mathrm{Im}[A^2]\frac{4m_t^2}{s\beta} \times \left[1 - \frac{m_\phi^2}{s\beta^2}\ln\left(1+\frac{s\beta^2}{m_\phi^2}\right)\right], \tag{4}$$

with m_ϕ the mass of the ϕ. This generates the asymmetry shown in Fig. 2(a) for a top mass of 150 GeV. As promised, this asymmetry is of order 10^{-3} for values of m_ϕ in the few hundred GeV range.

It is straightforward to repeat this analysis for the process $gg \to t\bar{t}$ using the remaining diagrams of Fig. 1. We will present the precise formulas in a longer paper [14]. The result of this calculation is shown in Fig. 2(b), where we plot the asymmetry ΔN_{LR} from gluon fusion. Note that the diagrams with ϕ exchange in the s channel interfere constructively when $m_\phi < 2m_t$ and lead to a resonance effect when the ϕ is above $t\bar{t}$ threshold [15]. The magnitude of the asymmetry is again of order 10^{-3}.

Lepton asymmetry.— We now show how this *CP*-violating polarization asymmetry translates directly into an asymmetry in the energy spectra of charged leptons from top decay. At tree level in the top quark center of mass, the decay distribution of the charged lepton is simply

$$\frac{d^2\Gamma}{dE_l\,d\cos\psi} = \frac{d\Gamma}{dE_l}\frac{1+\cos\psi}{2}, \tag{5}$$

where ψ is the angle between the top spin and the lepton momentum, and $d\Gamma/dE_l$ is the unpolarized energy distribution [16]. When the top quark is boosted, (5) gives a correlation between the lepton energy and the top helicity. In Fig. 3 we show the energy spectra for t_L and t_R of mass 150 GeV and energy 200 GeV. For these typical values, we see that the lepton energy spectrum is a powerful t spin analyzer.

We can now calculate the observable asymmetry due to *CP* violation in the Higgs sector. To remove some effects of the longitudinal boost of the parton-parton collision, we present the asymmetry in the distribution of lepton transverse energy. To compute this, we fold the production cross sections for $t\bar{t}$ pairs of each helicity combination, including the effects of ϕ exchange from Fig. 1, with the decay distribution (5). In Fig. 4(a), we plot the average lepton transverse energy distribution at the SSC. We use a top mass of 150 GeV, $\sqrt{s} = 40$ TeV, and the "average" parton density functions of Diemoz *et al.* [17]. The

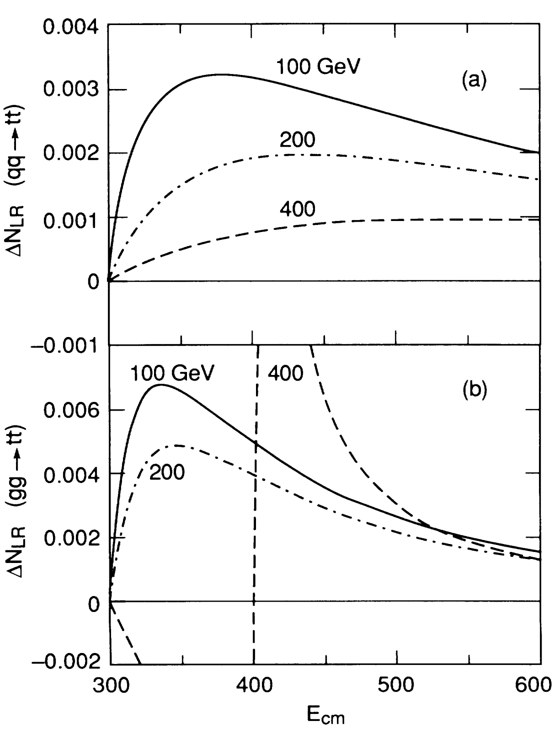

FIG. 2. The *CP*-violating asymmetry ΔN_{LR} (a) in $q\bar{q} \to t\bar{t}$ and (b) in $gg \to t\bar{t}$. The asymmetry is computed for a top mass of 150 GeV, $\mathrm{Im}[A^2] = \sqrt{2}$, and $m_\phi = 100$, 200, and 400 GeV.

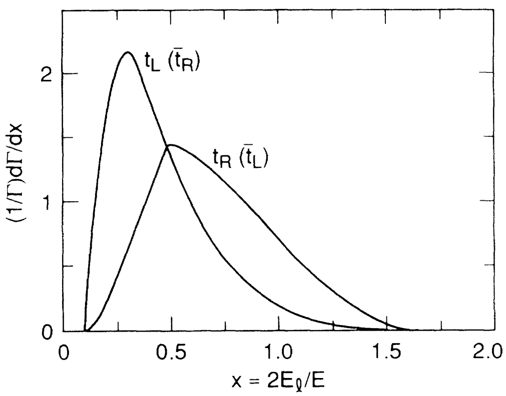

FIG. 3. Lepton energy spectra for t_L ($\bar{t}_R$) and t_R ($\bar{t}_L$) for top quarks of mass 150 GeV and energy 200 GeV.

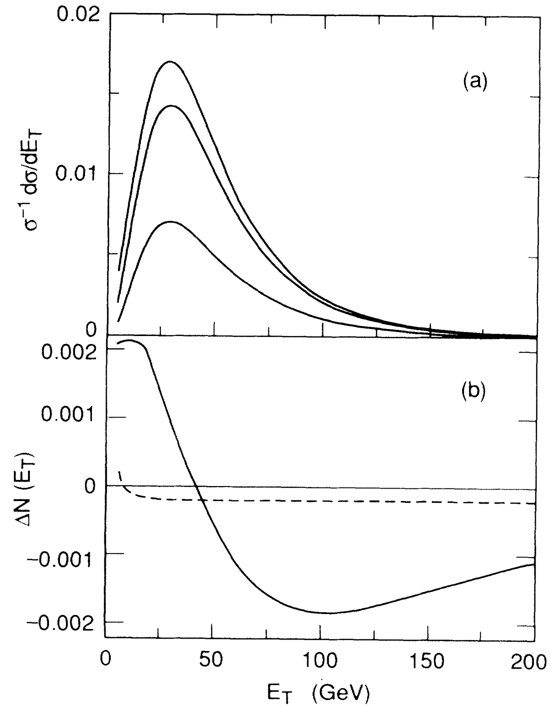

FIG. 4. (a) The transverse energy distribution (in GeV^{-1}) for leptons from the decay of top quark pairs produced at the SSC; (b) the charge asymmetry in this energy distribution due to CP violation (solid line), and due to non-CP-violating effects (dashed line). In this calculation, $m_t = 150$ GeV, $\mathrm{Im}[A^2] = \sqrt{2}$, and $m_\phi = 100$ GeV. In (a), the top curve contains all leptons, and the lower curves show the effects of cuts on the lepton rapidity, $|y| < 2.5$ and $|y| < 1$; (b) is computed with a rapidity cut $|y| < 2.5$.

bulk of the top decay leptons have transverse energy (and also total energy) below 100 GeV and rapidity $|y| < 2.5$.

In Fig. 4(b) we present the CP-violating lepton asymmetry,

$$\Delta N(E_T) = \frac{d\sigma/dE_{T,l^+} - d\sigma/dE_{T,l^-}}{d\sigma/dE_{T,l^+} + d\sigma/dE_{T,l^-}}, \tag{6}$$

at the SSC for a top mass of 150 GeV, a Higgs boson mass of $m_\phi = 100$ GeV [18], and $\mathrm{Im}[A^2] = \sqrt{2}$. As anticipated, the asymmetry is of the order 10^{-3}. A similar asymmetry is present in the lepton total-energy distributions.

The shape of the asymmetry is quite similar to the derivative of the averaged transverse energy distribution shown in Fig. 4(a). Thus, it is important to ensure that the event selection and energy measurement is unbiased by the charge of the lepton. For muons, a misalignment of the tracking system can produce such a bias [19]. Fortunately, the energy measurement in a calorimeter depends negligibly on the charge, so this important systematic error cancels if one measures the asymmetry in the calorimeter response for electrons versus positrons.

Non-CP-violating sources of the asymmetry.— If the future TeV-energy hadron colliders were proton-antiproton colliders, any asymmetry of the lepton energy distributions would necessarily be a consequence of CP violation. However, the SSC and LHC are planned to be proton-proton colliders, and these give other sources of the lepton asymmetry unrelated to CP violation. Most of these are eliminated if one carefully selects $t\bar{t}$ production events. However, there is one irreducible background: Since quarks in general carry more of the proton's energy than antiquarks, and since the reaction $q\bar{q} \to t\bar{t}$ has a small forward-backward asymmetry induced by α_s corrections, t's produced by this reaction tend to have a slightly higher energy than $\bar{t}$'s. This leads to a lepton energy asymmetry. The effect is small for three reasons: First, $q\bar{q}$ annihilation is a subdominant process for producing $t\bar{t}$ at the SSC. Second, the asymmetry arises from a QCD radiative correction. Third, the forward-backward asymmetry mainly affects longitudinal variables; its effect on the transverse energy asymmetry would cancel out if there were no lepton acceptance cut. Nevertheless, we must show that this effect does not overwhelm the small CP-violating signal.

The electromagnetic analog of this forward-backward asymmetry has been calculated for the process $e^+e^- \to \mu^+\mu^-$ [20]. The QCD asymmetry can be obtained from this result by the replacement $\alpha \to [(d^{abc})^2/32]\alpha_s = \frac{5}{12}\alpha_s$. To obtain a crude estimate, we use the approximate formulas of Brown *et al.*, which set the top mass to zero and use the soft limit for the real gluons. This overestimates the asymmetry in the production of a heavy quark. We set the cutoff on gluon energy at $\Delta E/E = 0.3$. This gives the background asymmetry shown as the dashed curve in Fig. 4(b). Note that it is smaller than the CP-violating effect and essentially independent of lepton energy.

In conclusion, we have shown that multiple Higgs models with CP-violating couplings can produce an asymmetry in the charged lepton energy spectra occurring in $t\bar{t}$ production. This asymmetry can be of the order 10^{-3}, and well above backgrounds. Thus, this *CP*-violating effect might be observable in hadron supercolliders, which are expected to produce of order 10^8 top quark pairs per year. All of our plots have been for SSC energies, but the effect is comparable for the LHC.

Much more detailed investigations are needed to predict precise limits on the *CP*-violating parameters at these colliders. Presumably, a lepton isolation cut and a cut on the total transverse mass of jets can remove the backgrounds from $gg \rightarrow b\bar{b}$, $q\bar{q} \rightarrow W+\text{jets}$, and $Wg \rightarrow t\bar{b}/b\bar{t}$ without seriously biasing the $t\bar{t}$ sample.

We believe that it is possible to study the charge-dependent energy asymmetry of leptons at a level below 10^{-3} with the detectors now being contemplated for the next generation of hadron colliders. We encourage those designing these experiments to explore this new window into the physics of *CP* violation.

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