CP VIOLATION IN TOP PHYSICS AT THE NLC*

David Atwood
Theory Group, National Jefferson Lab

and

Amarjit Soni
Theory Group, Brookhaven National Laboratory, Upton, NY 11973

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

* Invited talk presented by A. Soni at the International High Energy Physics Conference, Warsaw, Poland, 7/15/96-8/1/96

This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
CP VIOLATION IN TOP PHYSICS AT THE NLC

D. ATWOOD

Theory Group, National Jefferson Lab,

A. SONI

Theory Group, Brookhaven National Laboratory, Upton, NY 11973

Top quark is extremely sensitive to non-standard CP violating phases. General strategies for exposing different types of phases at the NLC are outlined. SUSY phase(s) cause PRA in $t \rightarrow Wb$. The transverse polarization of the $\tau$ in the reaction $t \rightarrow b\tau\nu$ is extremely sensitive to a phase from the charged Higgs sector. Phase(s) from the neutral Higgs sector cause appreciable dipole moment effects and lead to sizable asymmetries in $e^+e^- \rightarrow t\bar{t}H^0$ and $e^+e^- \rightarrow t\bar{t}\nu_e\bar{\nu}_e$.

1 Introduction

The standard model (SM) with three families and the CKM phase gives a natural explanation for the size of the observed CP asymmetry in the neutral kaon complex. It also strongly suggests the presence of large CP asymmetries in $B$-decays making $B$-physics very suitable for precision extraction of the CKM phase and a quantitative check of the unitarity triangle. Furthermore, the minimum SM with $m_t \sim 175$ GeV $> m_b, m_d, m_s$ also leads to the conclusion that CP violation effects in top production and decays have to be extremely small. However, extensions of the SM, invariably lead to new CP violating phase(s). Indeed in most extensions new CP violating phases appear rather naturally. In fact getting rid of non-standard phases in extensions of the SM may be as unnatural as it is to get rid of the CKM phase from the three generation SM. Since it is widely believed that the SM cannot account for baryogenesis CP violation from new physics is very likely a necessity. Therefore, it is important for us to seek optimal strategies to expose different types of non-standard CP violating phases. Based on studies that are so far available the prominent effects of different types of phases appears to be the following:

1. Dipole moment of the top quark could be large enough, most effectively due to phase(s) from the neutral Higgs sector, to be experimentally accessible.\footnote{Presenter}

2. SUSY phase(s) cause interesting partial rate asymmetry (PRA) effects in decays of the type $t \rightarrow Wb$.\footnote{\textsuperscript{5-6}}

3. The transverse polarization of the $\tau$ in the decay $t \rightarrow b\tau\nu$ is very sensitive to phase(s) originating from the charged Higgs sector.\footnote{\textsuperscript{7}}

4. CP violating phase(s) due to $H^0$ exchanges cause large asymmetries\footnote{\textsuperscript{8-9}} in $e^+e^- \rightarrow t\bar{t}H^0$ and in $e^+e^- \rightarrow t\bar{t}\nu_e\bar{\nu}_e$.\footnote{\textsuperscript{10,11}}

2 Top Polarimetry

The fact that the top is so heavy has the important consequence that the top quark does not bind into hadrons. All CP violation in the top quark is therefore direct CP. Spin of the top quark becomes a very important observable and its decays become very effective analyzers of its spin.\footnote{\textsuperscript{12}} The polarization of the top-quark is strongly correlated to the directions of the momentum of the charged lepton in $t \rightarrow b\ell\nu$, or to the $W$-momentum in $t \rightarrow bW$, or to the direction of the most energetic jet in $t \rightarrow b + 2\text{jets}$.\footnote{\textsuperscript{13,14}} The ability to track the top spin thus plays a crucial role in CP violation tests involving the top quark.

3 Dipole Moment of the Top-Quark

In many extensions of the SM the top quark can acquire dipole moment at one loop order. For example, CP violation phase from a neutral Higgs sector can cause top dipole moment of order $10^{-20}e\text{--cm}$ i.e. about ten orders of magnitude.
more than in the SM wherein one needs to go to at least two loop order and it is expected to be \( \lesssim 10^{-30} \text{e-} \cdot \text{cm} \). Much attention has recently been given to detection of the dipole moment form factor.\(^1\) It should be clear that the form factor has not only a real part but there is also an imaginary part arising at \( q^2 \gtrsim 4m_t^2 \). Since the life-time of the top quark is so short form factor extraction requires simultaneous studies of production and subsequent decay. A multitude of (CP Violating) observables that are \( \epsilon' \)-odd given to detection of the dipole moment form factor of the top quark is so short form factor extraction requires simultaneous studies of production and subsequent decay. Under these circumstances it is natural to search for an optimal observable\(^3\) namely, one that is the most efficient for determination of (e.g.) the real or the imaginary part of the dipole moment form factor for a fixed value of \( q^2 \). Separating the differential cross-section into a CP conserving \((\Sigma_0)\) and a CP violating \((\Sigma_1)\) piece\(^4\)

\[
\sigma (\phi) = \Sigma_0 (\phi) + \lambda \Sigma_1 (\phi) \tag{1}
\]

then the optimal observable, for determination of the dipole moment \( \lambda \) is given by\(^4\)

\[
0_{\text{opt}} = \Sigma_1 (\phi) / \Sigma_0 (\phi) \tag{2}
\]

Studies have shown that the anticipated luminosity at the NLC\(^5\) of \( 5 \times 10^{33} \text{cm}^{-2} \text{s}^{-1} \) should be able to give limits on \( \lambda \) to the level of \( \sim 10^{-19} \text{e} \cdot \text{cm} \) at one sigma.\(^4\) Thus observation of the top dipole moments that are expected in the Higgs sector. The effects are large as they originate from tree level interferences and also the \( W \) propagator is on-shell and causes a “resonance” enhancement. There is a CP-odd, \( T_N \)-odd transverse polarization asymmetry sensitive to the real part of the \( W \)-propagator and a CP-odd, \( T_N \)-even transverse polarization asymmetry that is driven by the imaginary part of the resonant \( W \)-propagator. The second type of asymmetry does not occur in \( K \to \pi \mu \nu \) or \( B \to D(D^*) \tau \nu \) in top decays both types of asymmetries are quite large. For \( m_H \sim 200 \text{GeV} \) they can be as big as 50% and for \( m_H \sim 400 \text{GeV} \) they can be in the range 5–20%. At the NLC, \( \sqrt{s} = 500 \text{GeV} \), with a luminosity of \( 5 \times 10^{33} \text{cm}^{-2} \text{s}^{-1} \) we may be able to probe asymmetries larger than about 6% with three sigma sensitivity. Clearly, the ability to measure the polarization of the \( \tau \) would be a very important feature in experiments at the NLC.

5 Transverse Polarization of the \( \tau \) due to a Charged Higgs Phase\(^7\)

The transverse polarization of the \( \tau \) in the decay \( t \to Wb \) is extremely sensitive to the presence of a CP violating phase from the charged Higgs sector. The effects are large as they originate from tree level interferences and also the \( W \)-propagator is on-shell and causes a “resonance” enhancement. There is a CP-odd, \( T_N \)-odd transverse polarization asymmetry sensitive to the real part of the \( W \)-propagator and a CP-odd, \( T_N \)-even transverse polarization asymmetry that is driven by the imaginary part of the resonant \( W \)-propagator. The second type of asymmetry does not occur in \( K \to \pi \mu \nu \) or \( B \to D(D^*) \tau \nu \) \( \ldots \) in top decays both types of asymmetries are quite large. For \( m_H \sim 200 \text{GeV} \) they can be as big as 50% and for \( m_H \sim 400 \text{GeV} \) they can be in the range 5–20%. At the NLC, \( \sqrt{s} = 500 \text{GeV} \), with a luminosity of \( 5 \times 10^{33} \text{cm}^{-2} \text{s}^{-1} \) we may be able to probe asymmetries larger than about 6% with three sigma sensitivity. Clearly, the ability to measure the polarization of the \( \tau \) would be a very important feature in experiments at the NLC.

6 Neutral Higgs CP in \( e^+ e^- \to t \bar{t} H^0 \). \( \tag{3} \)

CP violation phase due to a neutral Higgs sector leads to very interesting effects that occur through the interference of two tree graphs (see Fig.1)\(^8\) Without using beam polarization and/or \( t, \bar{t} \) spin, there is only one triple correlation that is possible, i.e. \( (\vec{p}_+ - \vec{p}_- ) \cdot ( \vec{p}_t \times \vec{p}_{\bar{t}} ) \). The resulting, \( T_N \)-odd, \( \sum_{\text{all sources}} \left| V_{t\bar{t}} \right|^2 \neq 1 - |V_{t\bar{b}}|^2 \)
111
So $A_2$ and $A_3$ are $T_N$-even requiring absorptive parts whereas $A_y$ is $T_N$-odd requiring real Feynman amplitude. Therefore $A_y$ arises from interference among the tree level graphs in Fig. 2. Near resonance $A_x$ also arises primarily from these tree graphs; the Higgs width provides the necessary absorptive parts. $A_3$, though, receives additional contributions from loop graphs.

In addition to CP violating polarization asymmetries there is also an interesting CP-even, $T_N$-odd asymmetry that is quite sizable. We should be able to use it to determine the Higgs width in SM as well as in its extensions.

The works of Ref. 10,11 on the reaction $e^+e^- \rightarrow t\bar{t}H^0$, are complementary. Ref. 10 deals with interference of a neutral Higgs exchange with the other SM graphs of Fig. 2. Ref. 11 ignores that contribution to CP violation and focuses primarily on interference between two neutral Higgs occurring in a 2HDM.

8 Summary

SM causes negligible CP violating effects in top physics whereas many types of extensions lead to large effects therein. The top can receive a large dipole moment from neutral Higgs CP. The latter can also cause significant asymmetries in $e^+e^- \rightarrow t\bar{t}H^0$ and $e^+e^- \rightarrow t\bar{t}\nu_e\nu_e$ arising at tree level. SUSY phase(s) can cause PRA in $t \rightarrow Wb$. Phase(s) from the charged Higgs sector result in large transverse polarization of $\tau$ in $t \rightarrow b\tau\nu$.

There is thus the exciting possibility that the parameters needed for understanding of baryogenesis could be extracted or verified through CP

\[ A_x = \frac{1}{2}(p_x + \bar{p}_x); \quad A_y = \frac{1}{2}(p_y + \bar{p}_y) \]
\[ A_z = \frac{1}{2}(p_z + \bar{p}_z) \]
Figure 2: The Feynman diagrams that participate in the subprocess $W^+W^- \rightarrow t\bar{t}$. The blob in Fig.2a represents the width of the Higgs resonance and the cut across the blob is to indicate the imaginary part.

violation studies of the top quark in accelerator experiments.

Acknowledgments

This research was supported in part by the US-DOE contracts DC-AC05-84ER40150 (CEBAF) and DE-AC-76CH00016 (BNL).

References