CP-VIOLATION IN THE TOP SECTOR

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We discuss the prospects–within several models–for the observation of CP-violation (CP̸) in top decays and production. The outlook looks best for $t \to bW$ at the LHC (MSSM CP̸), $t \to b\tau\nu$ at TeV3, LHC and NLC ($H^+ CP̸$), $p\bar{p} \to t\bar{b} + X$ at TeV3 (MSSM CP̸), $pp \to t\bar{t} + X$ at the LHC (MSSM CP̸ & neutral Higgs CP̸) and for $e^+e^- \to t\bar{t}h$, $t\bar{t}Z$, where $h$ is the lowest mass neutral Higgs boson, at an NLC with energy $\geq 1$ TeV (neutral Higgs CP̸).

1 Introduction or: Why Do CP̸ in the Top Sector?

Just one experimental number for $Br(K_L \to 2\pi)$, and a few more that followed, but all in the neutral $K$ system, induced much activity. One can describe in broad terms most of the work as trying to answer the following questions:

- Regarding the $K$ sector: Is mixing the only source of the small CP̸ observed?
- For the $B$ sector: Is the SM the only source of the large CP̸ expected?
- In the $t$ sector: What extension of the SM causes the typically small CP̸ expected and in what observables is it best manifested?

Trying to answer the last question, there are already $O(100)$ papers on CP̸ for the top sector.

The advantages for studying CP̸ in $t$ (CP̸ |t) are:

1. The SM causes vanishingly small CP̸ |t. This is due to its very small mixing with the other generations and to the fact that $m_t >> m_{other quarks}$, causing extremely effective GIM cancellations.

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人寿的注脚： enhances the reading experience and emphasizes key points.
2. The top at $\sim 175$ GeV is among the so far observed particles—the closest to New Physics which may well be the cause for CP. Indeed, $m_t$ drives large CP in extensions of the SM.

3. If $m_t > m_{\text{new particles}}$, where this “window” may close pretty soon, CP-odd $T_N$-even observables which require absorptive cuts, may be measurable.

4. Since the top is that heavy, it decays before it has time to bind into hadrons. CP is therefore direct, there are no hadronic complications and the information carried by top spins is not diluted by hadronization. $\vec{s}_t$ is then as good as any four momentum $p$.

5. Last, but not least, future colliders will provide a large number of tops. In fact, the expected number of $t\bar{t}$ events/year is $10^4 - 10^5$ at the Tevatron runs 2 - 3, $10^7 - 10^8$ at the LHC and $10^5 - 10^6$ at an NLC.

Convinced of the importance of CP, we proceed as follows: In Sec. 2 we present models with non-standard CP. CP in top decays and CP-violating top dipole moments are discussed in Secs. 3 and 4, respectively. In Sec. 5 we discuss CP in future collider experiments resulting from: $ff \to t\bar{t}$ at TEV3, LHC and NLC, $ud \to t\bar{b}$ at TeV3, and $e^+e^- \to t\bar{t}h$, $t\bar{t}Z$ (tree-level CP) at an NLC. Finally, Sec. 6 includes summary and outlook.

2 Models With Non-Standard CP (MHDM\footnote{HDM, with *\footnote{2, 3, or Multi, denotes * Higgs Doublet Models.} denotes * Higgs Doublet Models.} and Supersymmetry)\footnote{The “naive” time reversal operator $T_N$, operates the same way as $T$ does, but without flipping between initial and final states.}

2.1 CP in the Neutral Higgs Sector in MHDM

Generically, CP in the neutral Higgs sector of any MHDM, can be expressed by the presence of both scalar and pseudoscalar couplings to fermions:

$$L_{hff} = \frac{g_W m_f}{\sqrt{2} m_W} h \bar{f} (a_f + i b_f \gamma_5) f,$$

therefore, CP in $ht\bar{t}$ is proportional to $m_t b_t$. In type II 2HDM $b_t$ is proportional to $1/\tan \beta$, where $\tan \beta \equiv v_u/v_d$ ($v_u$, $v_d$ are the vacuum expectation values of $H_u$, $H_d$, respectively; $H_q$ endows quark $q$ with a mass). Note that such a coupling does not exist in the Minimal SuperSymmetric Model (MSSM).
2.2 \( CP \) in the Charged Higgs Sector in MHDM

A generic parameterization for any MHDM is (for each generation):

\[ L_{H^{+ud}} = \frac{g_W}{\sqrt{2}m_W} V_{ud}^{CKM} \times H^{+u}(m_u U_u P_L + m_d U_d P_R) d, \]

(2)

where \( P_L, P_R \equiv (1 \mp \gamma_5)/2 \), and a similar equation for \( L_{H^{+\nu\ell}} \) with \( u \to \nu \ell \) and \( d \to \ell \). \( U_u, U_d, U_\ell \) depend on the mixing parameters in the charged Higgs sector, and are in general complex with at least 3 Higgs doublets. \( H^+ \) CP \( \neq t \) is then proportional to \( \Im (U^*_u U_d) \), or to \( \Im (U^*_u U_\ell) \).

2.3 \( CP \) in the MSSM

\( CP \) can originate in the MSSM from various sources, as discussed below. Again, the top sector is the best one for studying such effects.

\( CP \) in \( \tilde{f}_L - \tilde{f}_R \) mixing:

One can parametrize \( \tilde{f}_L - \tilde{f}_R \) mixing as follows:

\[
\tilde{f}_L = \cos \alpha_f \tilde{f}_1 - e^{i\beta_f} \sin \alpha_f \tilde{f}_2 \\
\tilde{f}_R = e^{-i\beta_f} \sin \alpha_f \tilde{f}_1 + \cos \alpha_f \tilde{f}_2,
\]

(3)

causing \( CP \) to be proportional to \( \xi_{CP}^f \equiv \frac{1}{2} \sin(2\alpha_f) \sin \beta_f \). Now, since \( \sin(2\alpha_f) \) goes as \( (m_f/M_{\text{Supersymmetry}}) \), this mechanism is most useful for \( f = t \). Furthermore, \( \beta_t \) is proportional to \( \arg(A_t) \) is the coefficient of \( QH_2U \) in \( L_{\text{soft}} \). arg(\( A_t \)) is expected to be small in the case of complete universality of the soft breaking parameters at the GUT scale, i.e., \( N=1 \) minimal supergravity. However, \( \arg(A_t) \sim O(1) \) is consistent with non-universal \( A \) terms. Consequently, we can have maximal \( CP \) i.e., \( \xi_{CP}^t = \frac{1}{2} \).

\( CP \) via \( \arg(\mu) \):

One can, in principle, have a non-vanishing \( \arg(\mu) = -\arg(B) \) (\( \mu B \) is the coefficient of \( H_1 H_2 \) in \( L_{\text{soft}} \)). However, since \( d_n < 0.97 \times 10^{-25} \text{ e-cm} \), where \( d_n \) is the neutron Electric Dipole Moment (EDM), \( \arg(\mu) \lesssim 10^{-2} - 10^{-3} \) is practically inevitable for \( m_{\text{squark}} \lesssim 1 \text{ TeV} \).

3 \( CP \) in Top Decays

Let us now discuss \( CP \) for top decays to \( d_k W \) and in particular to \( b\tau\nu \).
3.1 Partial Rate asymmetry (PRA)

If a PRA is \( \neq 0 \) then CP is violated. Since from CPT invariance \( \Gamma_{\text{total}}^t = \Gamma_{\bar{t}}^t \), once a PRA is non-vanishing, there should be a compensating PRA from another available decay channel. This CP-CPT connection generally dictates a small PRA.|\( t \).

PRA in the SM:
PRA\((t \rightarrow d_kW)\) is proportional to \( \Im (\text{self-energy-like}) \times \Re (\text{tree}) \). At best it is around \( 10^{-9} \) for the small \( t \rightarrow d W (k = 1) \) process. \[ 10^{-9}, \]

PRA\((t \rightarrow ud_k \bar{d}_k, cd_k \bar{d}_k)\), results from \( \Im (\text{tree''}) \times \Re (\text{strong penguin}) \) and despite \( W \) resonance enhancement in the \( W \) exchange “tree” diagram, is \( \sim 10^{-5} \) at best for the small \( t \rightarrow d d \) decay. \( \therefore \) Therefore, within the SM, CP \( t \) is too small to be measurable.

PRA in 2HDM:
For PRA\((t \rightarrow d_kW)\), \( H^+ \) was added to SM \( W^+ \); \( \square \) no enhancement over the SM was found. Furthermore, there is no contribution from the neutral Higgs \( h \) in 2HDM with natural flavor conservation, e.g., type II.

PRA in 3HDM:
PRA\((t \rightarrow b \tau \nu)\) goes like \( \Im (W \text{–tree''}) \times \Re (H \text{–tree}) \) and is proportional to \( \Im G_L^W \lesssim 10^{-8} \) where \( G_L \) is the longitudinal part of the \( W \) propagator. To overcome this small value, it was suggested \( \square \) that the above PRA gets a larger contribution proportional to \( \Im G_T^W \times \Re (\text{tree \times loops}) \), where \( G_T \) is the transverse part of the \( W \) propagator; indeed this contribution was found to be \( \sim 10^{-5} \), which is still too small to be of experimental interest.

PRA in MSSM:
PRA\((t \rightarrow bW)\) is proportional to tree \( \times \) loops with supersymmetric partners in loops. In one limit, \( \square \) a \( \tilde{t} \tilde{b} \tilde{g} \)-loop is considered. Such a contribution requires the already excluded condition \( m_t > m_{\tilde{t}} + m_{\tilde{g}} \). In another limit, \( \square \) a \( \tilde{t} \tilde{g} \tilde{g} \)-loop was suggested. Such a term, which is proportional to \( \arg(\mu) \), leads to a PRA \( \sim 2\% \), for \( m_{\tilde{g}} = 100 \) GeV. However this requires \( \arg(\mu) \sim \mathcal{O}(1) \), which seems to be excluded by \( d_n \). In another limit it was assumed \( \square \) that \( \arg(\mu) = 0 \) and that \( b \) squarks are degenerate. The PRA arising from a \( \tilde{t} \tilde{g} \)-loop, which is proportional to \( \xi_{CP} \), is at best \( \lesssim 0.3\% \) for \( m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 300 \) GeV and requires \( m_t > m_{\tilde{t}} + m_{\tilde{g}} \).

3.2 Beyond PRA for \( t \rightarrow b \tau \nu \) in 3HDM

There are ways to utilize \( W \text{–tree''} \times H \text{–tree} \) and bypass the small \( G_L^W \) factor and the CP-CPT connection, to obtain CP-violating asymmetries much larger than PRA. \( \square \) To this end one defines, for example, the energy asymmetry:
\[ A_E = \frac{\langle E_{\tau^+} \rangle - \langle E_{\tau^-} \rangle}{\langle E_{\tau^+} \rangle + \langle E_{\tau^-} \rangle}. \]  

(4)

It was found that \( A_E \approx 10^{-3} \gg PRA. \)

Furthermore, one can define various \( \tau \) polarization asymmetries, such as the transverse one:

\[ A_z = \frac{\tau^+ (\uparrow) - \tau^+ (\downarrow) - \tau^- (\uparrow) + \tau^- (\downarrow)}{\tau^+ (\uparrow) + \tau^+ (\downarrow) + \tau^- (\uparrow) + \tau^- (\downarrow)}, \]

(5)

where in the \( \tau \) rest frame \( \vec{p}_t \) is on the \(-x\) axis and \( x-y \) is the decay plane. Since \( A_z \) is CP-odd and \( T_N \)-odd, there is no need for an absorptive phase. Note that, by avoiding \( \tau \)-spin summation, there is no \( m_\tau \) suppression in \( A_z \).

Indeed, \( A_z \sim (m_t/m_\tau)A_E \sim \text{few} \times 10^{-1} \) requiring \( \gtrsim 10^3 t \) quarks, which is a gratifying result.

4 CP-Violating Top Dipole Moments

There are three top dipole moments that may signify the presence of CP-violation. They can be considered as CP-odd form factors in the \( \gamma t \bar{t}, Zt \bar{t}, \) or the \( gt \bar{t} \) vertices that measure the effective coupling between the spin of a short-lived top quark and an external gauge field:

\[ \Gamma_{\gamma,Z,g} = id_{\gamma,Z,g}^t(s)\bar{u}_t(p_t)\sigma_{\mu\nu}(g_5)\gamma^\mu p^\nu (p_t); \ p = p_t + p_\bar{t}. \]

(6)

In the SM \( d_t \) is a 3-loops effect, \( \approx 10^{-30} \) e-cm, is unmeasurable. We therefore present below results for extensions of the SM. The numerical values for \( d_t \), for typical parameters as described below, are displayed in Table 1. The corresponding values for \( d_Z \) are slightly smaller.

Neutral Higgs CP \( \not \equiv \) in MHDM:

From Eq. 1 we see that \( d_t \) goes like \( m_t^2 a_t \times b_t \). The results in the table are for \( a_t = b_t = 1, m_{H^0} \sim \mathcal{O}(1) \) TeV, \( i > 1 \) (note that \( h \equiv H_1^0 \)).

\( H^+ \) CP \( \not \equiv \) in MHDM:

From Eq. 3 we find that \( d_t \) goes like \( m_t m_b \Im (U_t U_b^*) \). The numbers in Table 3 are for \( \Im (U_t U_b^*) = 5, m_{H^+} \sim \mathcal{O}(1) \) TeV, \( i > 1 \).

MSSM CP \( \not \equiv \) from \( \tilde{t}_L - \tilde{t}_R \) mixing:

From Subsec. 2.3 we see that \( d_t \sim \xi_{CP}^t \) which we take to be 0.5 and \( m_{\tilde{t}_{1,2}} = 50, 400 \) GeV.

We observe that all the values in Table 3 are at least 7 orders of magnitude larger than \( d_t^{\text{SM}} \). Unfortunately, as we see in the next section, only few of the
Table 1: CP-violating top EDMs, taken at 500, 1000 GeV, in three models (for more details see text). Masses are in GeV.

| $d^\gamma_t$ (e−cm) | neutral Higgs $m_h = 100 - 300$ | charged Higgs $m_{H^+} = 200 - 500$ | Supersymmetry $m_{\tilde{g}} = 200 - 500$ |
|---------------------|---------------------------------|---------------------------------|---------------------------------|
| 500 GeV             | $(4.1 - 2.0) \times 10^{-19}$   | $(29.1 - 2.1) \times 10^{-22}$  | $(3.3 - 0.9) \times 10^{-19}$   |
| 1000 GeV            | $(0.9 - 0.8) \times 10^{-19}$   | $(15.7 - 1.0) \times 10^{-22}$  | $(1.2 - 0.8) \times 10^{-19}$   |
| 500 GeV             | $(0.3 - 0.8) \times 10^{-19}$   | $(33.4 - 1.5) \times 10^{-22}$  | $(0.3 - 0.9) \times 10^{-19}$   |
| 1000 GeV            | $(0.7 - 0.2) \times 10^{-19}$   | $(0.3 - 2.7) \times 10^{-22}$   | $(1.1 - 0.3) \times 10^{-19}$   |

predictions are (marginally) measurable.$^d$

5 CP in Future Collider Experiments

In this section, we discuss CP for top pair production, and for single top production in future experiments.

5.1 Model Independent Studies of $e^+e^−$, $q\bar{q} \rightarrow t\bar{t}$

Let $\Sigma$ be a differential cross-section, and $d\phi$ a phase space element. Then the contribution of $d^\gamma_t$, $V = \gamma$, $Z$ through $V$ s-channel exchange, is added to the SM ($d_t = 0$):

$$
\Sigma(\phi) d\phi = \Sigma_0(\phi) d\phi + \sum_{V=\gamma, Z} \left[ \Re d^V_t(s) \Sigma \Re(d^V_t)(\phi) + \Im m d^V_t(s) \Sigma \Im m(d^V_t)(\phi) \right] d\phi, \quad (7)
$$

for $e^+e^−$, $q\bar{q} \rightarrow t\bar{t}$ (for $q\bar{q}$, $g$ exchange should be added). In Eq. $^d$ the usually smaller, CP in $t$ decays is neglected. Note also, that in MSSM $d_t$ is not the whole story due to new box diagrams.

To minimize the statistical error, optimal observables:

$$
O_{\Re} = \Sigma \Re (d^V_t)/\Sigma_0, \quad O_{\Im} = \Sigma \Im m (d^V_t)/\Sigma_0, \quad (8)
$$

$^d$Also note that for MHDM $d^t_g$ in $g_g c_m = (3/2)d^t_g$ in $e$−cm; this does not hold for MSSM due to an additional $g\tilde{g}\tilde{g}$ loop.
were introduced. Then \( \Re, \Im m \Delta t \sim 10^{-17} \text{ e-cm} \), can be reached–at a 1\( \sigma \) level–with \( 10^4 \bar{t}t \) and \( \sqrt{s} = 500 \text{ GeV} \) (NLC). Optimal observables are by now extensively used.

The results improve by considering \( \Sigma(t\bar{t}) \rightarrow \Sigma(t\bar{t} \rightarrow b\ell\nu + bW_{\text{had}}) + \text{beam} \) polarization. One can then go down to \( \Re, \Im m \Delta t \sim \text{few} \times 10^{-19} - 10^{-18} \text{ e-cm} \) (at 1\( \sigma \)). Many more observables were suggested, but none is doing better than the above. In view of the models results (see Table 1), this is rather discouraging.

### 5.2 CP\( \overset{\sim}{\neq} \) in pp \( \rightarrow t\bar{t} + X \)

Gluon fusion dominates at the LHC. In a seminal work, \( \Sigma(t\bar{t}) \rightarrow \Sigma(t\bar{t} \rightarrow bW^+ + bW^- \rightarrow b\ell\nu_\ell + \bar{b}\ell\bar{\nu}_\ell) \) the energy asymmetry \( A_E \), defined in Eq. 4 (with \( \tau \rightarrow e \)), requires an absorptive part, which in a 2HDM with neutral Higgs CP\( \overset{\sim}{\neq} \) (with box and triangle diagrams), is already there as \( s > 4m_t^2 \). A non-vanishing \( A_E \) is due to a different number of \( t_L\bar{t}_L \) from \( t_R\bar{t}_R \). \( A_E \sim O(10^{-3}) \) is possible, requiring \( \gtrsim 10^7 \bar{t}t \), which is about the number expected at the LHC. This work was subsequently extended (e.g. to MSSM) but the results are again at most of \( O(10^{-3}) \). Since the \( gg \) luminosity is so much larger than the \( q\bar{q} \) luminosity at the LHC, the fact that there are more quarks than anti-quarks in the proton, cannot fake–through \( q\bar{q} \rightarrow t\bar{t} \)–the CP-violating signal as long as it is \( \gtrsim O(10^{-3}) \). Furthermore, the effect of QCD can be neglected. It still remains to be seen whether detector systematics can be overcome for such a signal.

### 5.3 CP\( \overset{\sim}{\neq} \) for Single Top Production in Tevatron Run 3

The subprocess here is \( u\bar{d} \rightarrow t\bar{b} \rightarrow bW^+ + \bar{b} \), in 2HDM and MSSM; it is obviously irrelevant for the LHC. For both models CP\( \overset{\sim}{\neq} \) is a loop effect, with only a triangle contribution for 2HDM and both triangle and box for MSSM. For the latter case, the box-loops are negligible. Thus for both models CP\( \overset{\sim}{\neq} \) stems from the effective \( tbW \) production vertex, which in turn is much larger than CP\( \overset{\sim}{\neq} \) from \( t \) decays. In the 2HDM the basic vertex from which CP\( \overset{\sim}{\neq} \) originates is the \( ib_3\gamma_5 \) part in \( \mathcal{L}_{\text{Higgs}} \) (see Eq. 1), while in MSSM it is generated from \( t_L \rightarrow t_R \) mixing (see Subsec. 2.3). As we discuss below, CP\( \overset{\sim}{\neq} \) in \( tb \) production can reach a few percents (CP\( \overset{\sim}{\neq} \) in top pair production is at most a few tenths of a percent), which is good news for TeV3.

Consider the CP-violating top polarization asymmetries:

\[
A_i = \frac{N(\uparrow_i) - N(\downarrow_i) + \bar{N}(\uparrow_i) - \bar{N}(\downarrow_i)}{N(\uparrow_i) + N(\downarrow_i) + \bar{N}(\uparrow_i) + \bar{N}(\downarrow_i)} \quad i = x, y, z, \quad (9)
\]
where the event plane is the $x - z$ plane. While $A_0$ (the cross-section asymmetry), $A_x$ and $A_z$ are $T_N$-even, $A_y$ is $T_N$-odd. Next, we present numerical results for some sets of the unknown parameters (for detailed studies, see the original papers).

**Contribution from 2HDM (numerical results):**

If $\sqrt{s} = 2$ TeV, $\tan \beta = 0.3$, then for $m_h$ from approximately 200 to about 100 GeV $A_0 \approx 1\%$ reaching $\sim 1.5\%$, $A_z \approx 0.9\%$ increasing to about 1.2\%, $A_y \approx 0.5\%$ decreasing to approximately 0.2\% ($A_y$ reaches its maximal value of about 0.6\% around $m_h \sim 400$ GeV) and $A_x \approx 0.6\%$ rising to around 0.7\%.

**Contribution from MSSM (numerical results):**

Let us quote here some (optimistic) results for the cross-section asymmetry. If $m_{\tilde{g}} = 400$ GeV, $\tan \beta = 1.5$, $m_{\tilde{t}_1} = 50$ GeV, $m_{\tilde{t}_2} = 400$ GeV and $\xi_{CP} = 0.5$, then for $\mu \approx -70, -90$ GeV, $A_0$ is somewhat larger than 1.5\%, 2.5\% respectively. This is certainly an encouraging result.

### 5.4 Tree-level CP in 2HDM at an NLC with $\sqrt{s} \approx 1$ TeV

A search for tree-level CP originating from the $b_t$ term in $L_{htt}$ in 2HDM (see Eq. [3]), was suggested for $e^+e^- \to t\bar{t}h [25]$ and for $e^+e^- \to t\bar{t}Z [26]$. For both processes CP is proportional to $b_t c_t$, where $c_{g_{\mu \nu}}$ is the $hZZ$ coupling, which in our case is a function of $\tan \beta$ and of the mixing angles in the neutral Higgs sector $\alpha_i, i = 1, 2, 3$. None can be considered as a Higgs “discovery” channel, but once it is discovered its couplings can be studied in a clean environment.

Each process has two types of tree diagrams: The first process has real $h$ emission from the $Z$ propagator (which goes like $c$) and from an external $t$ (or $\bar{t}$) which includes $b_t$. The second reaction has real $Z$ emission from the initial and final fermions and another type of diagram where $Z$ is emitted from a $ZZh$ vertex with the virtual $h$ turning into $t\bar{t}$.

Consider $A_{\text{opt}} = \langle O \rangle / \sqrt{\langle O^2 \rangle}$, where $O = \vec{p}_e \cdot (\vec{p}_t \times \vec{p}_{\bar{t}})$. Due to the large mass of each of the outgoing particles, one has to go to a next NLC, with $\sqrt{s} > 800$ GeV, to obtain significant results. Furthermore, $\tan \beta$ has to be of $\mathcal{O}(1)$. As an example of the numerical results, we take $e^+e^- \to t\bar{t}h$ at $\sqrt{s} = 1$ TeV. The parameters of the model are taken as $\tan \beta = 0.5$ and $\{\alpha_i, i = 1, 2, 3\} = \{\pi/2, \pi/4, 0\}$. Then, when $m_h$ varies between 100 and 360 GeV, $A_{\text{opt}}$ increases from approximately 16\% to about 27\%. The expected statistical significance of the CP signal is $N_{SD} = \sqrt{\mathcal{L}} \times A_{\text{opt}}$. For the above range of $m_h$ and for $\mathcal{L} = 200$ fb$^{-1}$, $N_{SD}$ decreases from around 2 to 1. For $\sqrt{s} = 1.5$ TeV, $\mathcal{L} = 500$ fb$^{-1}$ and the same $m_h$ range, $N_{SD}$ varies between 4 and slightly above 3.
6 Summary and Outlook

Before getting into the summary, note that–for the sake of imposed brevity–we do not discuss here other interesting issues in CP

These include CP in $h \rightarrow t\bar{t}$, more coverage of $e^+ e^- \rightarrow t\bar{t}$, CP in $\mu^+ \mu^-$ colliders and $\gamma \gamma$ collisions. Hopefully, such omissions will be rectified elsewhere.

In summary, we can say that in view of the extremely small SM effect, any observation of $\text{CP} |_{t}$ will indicate the presence of New Physics. Due to its large mass, the top quark is very sensitive to beyond the SM scenarios, and it decays so fast that it evades hadronic complications.

Finally, in Table 2 we present our outlook regarding the prospects for observing $\text{CP} |_{t}$ in future accelerators.

Table 2: An optimistic timetable–of topics discussed here– of CP $|_{t}$ versus time, where a $\checkmark$ stands for “likely”, $\times$ means “unlikely” and $\checkmark \times$ represents an “in-between” situation.

| Topic | $t \rightarrow bW$ (MSSM CP ) | $t \rightarrow b\tau\nu$ (H$^+$ CP ) | $p\bar{p} \rightarrow t\bar{b}$ (MSSM CP ) | $e^+ e^-, p \rightarrow t\bar{t}$ (MSSM CP & neutral Higgs CP ) | $e^+ e^- \rightarrow t\bar{t}h, Z$ (neutral Higgs CP ) |
|-------|-------------------|------------------|----------------|-------------------|----------------|
|       | $\times$          | $\checkmark$      | $\times$        | $\times$          | $\checkmark$     |
|       | $\sim 2005$ TeV3 | 2005 LHC          | $\sim 2010?$ 500 GeV NLC | $> 2010?$                | $\geq 1$ TeV NLC |

There are several check-marks, but no gold-plated reaction or observable.

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References

1. J.H. Christenson et al., Phys. Rev. Lett. 13, 138 (1964).
2. D. Atwood et al., Review on $Q\bar{P}$, in preparation.
3. See e.g.: G. Eilam, J.L. Hewett and A. Soni, Phys. Rev. Lett. 67, 1979 (1991) and ibid. 68, 2103 (1992); J.M. Soares, Phys. Rev. Lett. 68, 2102 (1992).
4. S.L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D 2, 1285 (1970).
5. I.I.Y. Bigi et al., Phys. Lett. B 181, 157 (1986).
6. R. Garisto and J.D. Wells, Phys. Rev. D 55, 1611 (1997).
7. S. Bar-Shalom, D. Atwood and A. Soni, Phys. Rev. D 57, 1495 (1998).
8. I.S. Altarev et al., Phys. Atom. Nucl. 59, 1152 (1996).
9. See e.g.: T. Falk, Nucl. Phys. Proc. Suppl. 52, 78 (1997); Y. Grossman, Y. Nir and R. Rattazzi in Heavy Flavors II, eds. A.J. Buras and M. Lindner (World Scientific, Singapore, 1998).
10. J.P. Ma and A. Brandenburg, Z. Phys. C 56, 97 (1992).
11. B. Grzδdkowski and W.Y. Keung, Phys. Lett. B 319, 526 (1993).
12. D. Atwood et al., Phys. Rev. D 57, 1495 (1993); T. Arens and L.M. Sehgal, Phys. Rev. D 51, 3525 (1995).
13. D. Atwood et al., Phys. Rev. Lett. 70, 1364 (1993); J. Papavassiliou, in Proc. of Standard Model IV, eds. J.F. Gunion, T. Han and J. Ohnemus (World Scientific, Singapore, 1995).
14. E. Christova and M. Fabbrichesi, Phys. Lett. B 320, 299 (1994).
15. D. Atwood, G. Eilam and A. Soni, Phys. Rev. Lett. 71, 492 (1993).
16. W. Bernreuther and M. Suzuki, Rev. Mod. Phys. 63, 313 (1991) and Erratum, ibid. 64, 633 (1992).
17. A. Soni and R.M. Xu, Phys. Rev. Lett. 69, 33 (1992); W. Bernreuther, T. Schröder and T.N. Pham, Phys. Lett. B 279, 389 (1992); D. Chang, W.Y. Keung and I. Phillips, Nucl. Phys. B 408, 286 (1994) and Erratum, ibid. 429, 255 (1994).
18. D. Atwood, S. Bar-Shalom and A. Soni, Phys. Rev. D 51, 1034 (1995), with $b \rightarrow t$.
19. See e.g.: A. Bartl et al., Nucl. Phys. Proc. Suppl. 66, 75 (1998).
20. D. Atwood and A. Soni, Phys. Rev. D 45, 2405 (1992).
21. W. Bernreuther, A. Brandenburg and P. Overmann, in $e^+e^-$ Collisions at TeV Energies: the Physics Potential, ed. P.M. Zerwas (DESY, 1996).
22. C.R. Schmidt and M.E. Peskin, Phys. Rev. Lett. 69, 410 (1992).
23. C. Schmidt, Phys. Lett. B 293, 111 (1992).
24. D. Atwood et al., Phys. Rev. D 54, 5412 (1996).
25. S. Bar-Shalom et al., Phys. Rev. D 53, 1162 (1996).
26. S. Bar-Shalom, D. Atwood and A. Soni, Phys. Lett. B 419, 340 (1998).