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CP VIOLATION TESTS FOR TOP/TAU PROCESSES

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Abstract

This paper reviews the following topics: (i) Tests for CP violation in top-quark production and decay processes. In particular, $m_t = 174 \pm 17 GeV$ implies good top-quark polarimetry because the W bosons in t-quark decays must be predominantly longitudinally polarized ($\Gamma_L/\Gamma_T = 2.4$). (ii) Tests for CP violation in tau lepton decays by the $\tau \to \rho\nu$ decay mode by usage of ρ polarimetry signatures. (iii) Tests for complete measurement of the $Z^0, \gamma^* \to \tau^-\tau^+$ vertex, including tests for CP violation in tau production processes.

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Motivations

There are three good reasons for searching for possible CP and/or T violations in t-quark (τ-lepton) processes.[1,2] (i) We do not know fundamentally the origin or significance of the "CKM mixing matrix." While it is very important to continue to test its parameters and formulation at B factories and in kaon decays, the CKM matrix itself is probably not truly basic either physically or mathematically, from the viewpoint of spontaneous symmetry violations in local quantum field theory. (ii) Most astrophysics investigations show that additional sources of CP violation, beyond CKM, are necessary to account for the observed baryon-to-photon ratio of the universe. (iii) We can use new collider data to rigorously and systematically test for CP and/or T violations in top/tau processes. In particular, it is very "good news" that the t-quark mass is large[4] ($m_t = 174 \pm 17$ GeV) for this implies[1] good t-quark polarimetry (see below). For tests of τ-lepton couplings, it is good that the branching ratio[5] $B(\tau \to \rho\nu) \approx 25\%$ is large. For instance, this means that there are two tests[3] for "non-CKM-type" leptonic CP violation in $\tau \to \rho\nu$ decay.

CP Violation Tests for Tau Decays

The essential idea is to search for leptonic CP violation by including ρ polarimetry observables in order to generalize the τ-spin-correlation function[6] $I(E_\rho, E_B)$ for the process

$$Z^0, \gamma^* /_{\text{Unpolarized}} \to \tau^-\tau^+ \to (\rho^- \nu_\tau)(B^+X) \tag{1}$$

where $B = \rho, \pi, \mu, e$ with $X = \bar{\nu}_\tau$ or $\bar{\nu}_\tau \nu_\ell$. ALEPH has recently used[7] the simpler energy-correlation function $I(E_\rho, E_B)$ to measure the "chiral polarization parameter"

$$\xi_\rho \equiv \frac{|g_L|^2 - |g_R|^2}{|g_L|^2 + |g_R|^2} = 1.03 \pm 0.11 \pm 0.05 \tag{2}$$

which tests that the $\tau^- \to \rho^- \nu_\tau$ coupling is indeed pure V-A (to at least the 10% level).

By ρ polarimetry, there are two tests for "non-CKM-type" leptonic CP violation in $\tau \to \rho\nu$ decay: This fact is easily seen because by rotational invariance there are two independent helicity amplitudes for $\tau^- \to \rho^- \nu_\tau$ decay

$$A(-1,-1/2) = |A(-1,-1/2)| e^{\iota \phi_{-1}^{a}}, \quad A(0,-1/2) = |A(0,-1/2)| e^{\iota \phi_{0}^{a}} \tag{3}$$

assuming a L-handed ν_τ. The CP-conjugate decay $\tau^+ \to \rho^+ \bar{\nu}_\tau$ depends on

$$B(1,1/2) = |B(1,1/2)| e^{\iota \phi_{1}^{b}}, \quad B(0,1/2) = |B(0,1/2)| e^{\iota \phi_{0}^{b}} \tag{4}$$

assuming a R-handed $\bar{\nu}_\tau$. By CP invariance $B(\lambda_{\bar{\rho}}, \lambda_{\bar{\nu}}) = A(-\lambda_{\bar{\rho}}, -\lambda_{\bar{\nu}})$. The two tests are that the phase difference and moduli ratio for the two amplitudes for $\tau^- \to \rho^- \nu_\tau$ decay must equal those for the CP-conjugate decay. That is,

$$\beta_a = \beta_b \quad \text{(1st test)} \tag{5}$$

where $\beta_a \equiv \phi^a_{-1} - \phi^a_o$, $\beta_b \equiv \phi^b_1 - \phi^b_o$; and

$$r_a = r_b \quad \text{(2nd test)} \tag{6}$$

in terms of the moduli ratios

$$r_a \equiv \frac{|A(-1,-1/2)|}{|A(0,-1/2)|}, \quad r_b \equiv \frac{|B\,(1, 1/2)|}{|B\,(0, 1/2)|} \tag{7}$$

[R-handed ν_τ amplitudes for a pure V-A coupling are order $A(1, 1/2) / A(-1, -1/2) \approx m_\nu/m_\tau$ and order $A(0, 1/2) / A(0, -1/2) \approx m_\rho m_\nu/(m_\tau)^2$.]

It is important to distinguish between (a) the exact time-reversal-invariance operation, T, which relates the amplitudes for the process and the fully time-reversed process, e.g. $\mathcal{M}(\tau^- \to \rho^- \nu_\tau) = \mathcal{N}(\tau^- \leftarrow \rho^- \nu_\tau)$, and (b) the approximate time-reversal-operation, $\tilde{T}_{FS}$, which holds only if possible final-state-interactions are neglected. By $\tilde{T}_{FS}$ invariance, the amplitude $\mathcal{M}$ is purely real, i.e. $\mathcal{M} = \mathcal{M}^*$. So there is the simple comparison shown in "Table 1":

Table 1: Comparison of discrete symmetry predictions.

$CP\,\tilde{T}_{FS}$	CP	$\tilde{T}_{FS}$
$r_a = r_b$	$r_a = r_b$	no prediction
$\beta' \equiv \beta_a + \beta_b = 0, 2\pi$	$\tilde{\beta} \equiv \beta_a - \beta_b = 0$	all β's vanish

Note the opposite predictions for the phase-difference relations in the case of CP versus $CP\,\tilde{T}_{FS}$ invariance.

Notice that for the decay chain

$$Z^o, \gamma^*|_{\text{Unpolarized}} \to \tau^-\tau^+ \to (\rho^- \nu_\tau)(\rho^+ \bar{\nu}_\tau), \tag{8}$$

we cannot learn more about CP invariance: Any τ spin-correlation function $I(\ldots) \approx A^*A\,B^*B$ where the amplitude A describes $\tau^- \to \rho^- \nu_\tau$, and B describes $\tau^+ \to \rho^+ \bar{\nu}_\tau$. Therefore, we can't measure $|A(0,-1/2)|$ versus $|B(0, 1/2)|$ for they appear in the overall norm of "I" as a common factor. Likewise, we can't measure ϕ_o^a versus ϕ_o^b since the possible net phase from the A^*A factor is 0 or $\pm\beta_a$.

In the standard lepton model (pure V–A and no CP violation), $\beta_a = \beta_b = 0$ and the moduli ratio $r_a = r_b \approx \sqrt{2}\, m_\rho/m_\tau = 0.613$. Also, the above two tests should be compared with the classic CP test for partial width asymmetry of CP-conjugate reactions:

$$A_\Gamma \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \tag{9}$$

where, e.g. $\Gamma = \Gamma(\tau^- \to \rho^- \nu_\tau)$ and $\bar{\Gamma} = \bar{\Gamma}(\tau^+ \to \rho^+ \bar{\nu}_\tau)$. For τ two-body decay modes, the denominator of (9) is known to (1 to 4)%, so (at best) we know $A_\Gamma \sim$ (1 to 4)% whereas we find (see below) that the fractional uncertainty of the moduli can be measured to the $(\delta r_a)/r_a \sim$ (0.1 to 1)% level from data, respectively, at γ^* energies (at the Z^o).

It is important to realize that any leptonic-CKM-type phases will equally affect the $A(-1, -1/2)$ and $A(0, -1/2)$ amplitudes. Therefore, they will cancel out in β_a and in r_a. Hence, $\beta_a = \beta_b$ and $r_a = r_b$ test for a non-CKM-type leptonic CP violation. In comparison, A_Γ is not sensitive to $\beta_a \neq \beta_b$.

The quantities β_a and r_a can be[3] measured from the full angular distribution for process (1), including the $\pi^\mp$ momentum direction versus that of the $\rho^\mp$ momentum. Since this adds on spin-correlation information from the next stage of decays in the decay sequence, we call such an energy-angular distribution a "Stage 2 Spin-Correlation" function (S2SC). Table 2 lists the associated[3] ideal statistical errors for $\tau \to \rho\nu$ decay for possible application of S2SC functions at the Z^o, at a B factory, or at the τ-charm threshold:

Table 2: Statistical errors for the corresponding discrete symmetry tests.

Error Tests	$\sigma(r_a)$ $CP\,\tilde{T}_{FS}$, CP	$\sigma(\tilde{\beta}) \approx \sigma(\beta_a)$ CP $\tilde{T}_{FS}$	$\sigma(\beta')$ $CP\,\tilde{T}_{FS}$
M_Z	0.6%	~ 1.9°	~ 3°
10 GeV	0.1%	~ 0.4°	~ 0.7°
4 GeV	0.1%	~ 0.9°	~ 1.1°

At the Z^o, 10^7 Z^o's are assumed, and at each γ^* energy we assume 10^7 $\tau^-\tau^+$ pairs. Notice that the measurement of the phase differences at γ^* energies, versus at the Z^o, does not improve as much as expected through the increase in statistics because in using ρ-polarimetry a Wigner-rotation is involved in the going from the center of mass frame's ρ-observables to the respective τ rest frame's ρ-observables. We find that τ spin correlations are necessary to measure β_a at γ^* energies; and we find that at the Z^o, without using spin-correlations there would be an extra suppression factor of $\langle P_\tau \rangle \approx -0.138$.

DISCLAIMER

Since the direction of the initial e^- beam has been integrated out, there is no obvious source for a violation of $\tilde{T}_{FS}$ invariance for process (8). For instance, unlike in $K_{\ell 3}$ decays, since ν_τ is only weakly interacting there is no simple electromagnetic rescattering of the ν_τ and ρ^-.

CP Violation Tests for $\tau^-\tau^+$ Production

In general, there are 4 independent (complex) helicity amplitudes $T(\mp\pm)$, $T(\mp\mp)$ for

$$Z^o, \text{ or } \gamma^* \rightarrow \tau_1^- \tau_2^+ \tag{10}$$

where $\lambda_{1,2}$ label respectively the τ^- (τ^+) helicities in $T(\lambda_1, \lambda_2)$. The consequences of imposing discrete symmetries is shown in Table 3.

Table 3: Symmetry constraints for production amplitudes

If Invariance	Then	
CP		$T(++) = T(--)$
P	$T(+-) = T(-+)$,	$T(++) = T(--)$
C	$T(+-) = T(-+)$	
$\tilde{T}_{FS}$	$T(\lambda_1, \lambda_2)$ is purely real	

Here, in generalizing $I(E_A, E_B)$ we include the additional information that's available from knowing the initial e^- beam direction. That is, for the process

$$e^-e^+ \rightarrow Z^o,\ \gamma^* \rightarrow \tau^-\tau^+ \rightarrow (A^- X)\,(B^+ X') \tag{11}$$

(where $A, B = \mu, e, \pi, \rho, k^*, a_1$) we include[8] the angles θ_e and ϕ_e of initial e^- beam relative to the final hadronic A^- and B^+ momenta in the c.m. frame. This <u>beam-reference τ spin-correlation</u> function (BRSC) gives the full angular distribution for process (11).

In principle, such a BRSC enables a complete measurement[8] of the off-shell photon and Z^o couplings of the tau lepton. But at the Z^o, the helicity-changing neutral-current amplitudes $T(++)$ and $T(--)$ will remain unmeasured by a BRSC (assuming no experimental surprises) since the fractional ideal statistical error $\delta/T(--)| / |T(--)| \sim 6$ for 10^7 Z^o's. But experimentally, "Is there something where the Standard Model says there is nothing?" Perhaps the tau is the place to look since

$$\frac{|\,\text{Helicity-changing Neutral Current}|}{|\,\text{Helicity-changing Neutral Current}|} = \frac{|T(--)|}{|T(++)|}$$

$$\approx \sqrt{2}\ \frac{v_f}{a_f}\ \frac{m_\ell}{M_Z} \quad (\text{in SM}) \tag{12}$$

equals 10^{-3} for τ, 10^{-4} for μ, and 10^{-6} for e. There should be a better test by using a BRSC function with a polarized initial e^- beam.

The other general result is that BRSC functions provide 4 distinct tests for $CP/\tilde{T}_{FS}$ violation[8,9] in $Z^o, \gamma^* \rightarrow \tau^-\tau^+$ production: As easily seen from "Table 3" there are 3 relative phases

$$\beta_{++} \equiv \phi_{++} - \phi_{--} \tag{12a}$$
$$\beta_{+-} \equiv \phi_{+-} - \phi_{-+} \tag{12b}$$
$$\beta_o \equiv 1/2\,(\phi_{++} + \phi_{--}) - 1/2\,(\phi_{+-} + \phi_{-+}) \tag{12c}$$

and the CP-asymmetry (moduli) parameter

$$\lambda \equiv \frac{|T(++)| - |T(--)|}{|T(++)| + |T(--)|} \tag{13}$$

By CP invariance, $\beta_{++} = \lambda = 0$. By $\tilde{T}_{FS}$ invariance, $\beta_{++} = \beta_{+-} = \beta_o = 0$. Interference between the γ^* and indirect quarkonium amplitudes does not simulate $\tilde{T}_{FS}$ violation; SM contributions to $\tilde{T}_{FS}$ violation from the 1-loop electroweak (τ - Z^o - τ) vertex correction and from γ^* - Z^o interference are both small [versus the calculated statistical errors at the Z^o for (12) and (13)].[8,9]

In practice, for 10^7 Z^o's the moduli $|T(-+)|$ and $|T(+-)|$ can be measured to 1%, and β_{+-} $<(\sim 3^o)$. For 10^7 $\tau^-\tau^+$ pairs at 10GeV, the P and C equalities for the moduli displayed in "Table 3" can be tested to 1%, [β_{+-} and β_o] $<(\sim 1^o)$ and $\beta_{++} < (\sim 4^o)$.

Both OPAL and ALEPH have bounded a possible tensor, CP-violating contribution from a weak-dipole coupling[9] to the Z^o:

$$\mathcal{L}\,\Big|_{\text{CP violating}} = -1/2\, i\, \bar{\tau}\, \sigma^{\mu\nu}\, \gamma_5\, \tau\ \{\tilde{d}_\tau(q^2)\, Z_{\mu\nu}\,\} \tag{14}$$

with $|d_\tau(M_Z^2)| \leq 7 \times 10^{-17}$ e-cm (3.7×10^{-17} e-cm) respectively.[10]

CP Violation Tests[2] for Top Quark Processes

There is a close analogy[1] between applications of t-quark polarimetry and of $t\bar{t}$ spin-correlation tests and the ones discussed above for the τ-lepton. The situation is particularly simple if viewed from the $t\bar{t}$ center of mass frame, i.e. the "X" rest frame of Fig. 1. At an e^-e^+

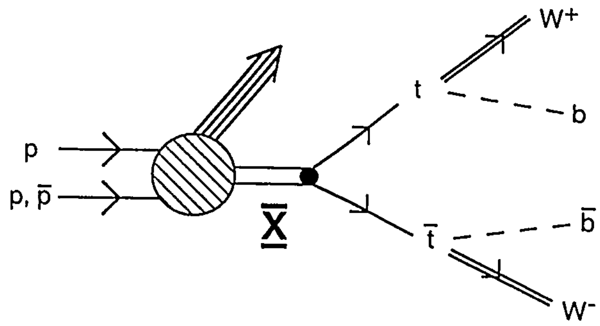

Fig. 1: The process $X \to t\bar{t} \to (W^+ b)(W^- \bar{b})$

collider when the decay $X \to \bar{f}_1 f_2$ occurs, the X frame is often known kinematically; at a hadronic collider for $t\bar{t}$ production it may be known (or partially constrained) depending on the chosen t, and $\bar{t}$, decay channels.[1,11] CP invariance relates the helicity amplitudes, $t_{\lambda_1 \lambda_2}$, for the decay of a spin-J system, X, into a pair of spin-1/2 particles. For γ_{CP} the CP quantum number of X, $t_{++} = \gamma_{CP}\, t_{--}$. For $\gamma_{CP} = +1$, the other two amplitudes are self-conjugate ($t_{+-} = t_{-+}$); and for $\gamma_{CP} = -1$, or $J = 0$, they vanish ($t_{+-} = t_{-+} = 0$).

For[4] $m_t = 174 \pm 17$ GeV, there is good t-polarimetry because the ratio of longitudinally (L) polarized W's to transversely (T) polarized W's is[1]

$$\frac{\Gamma_L}{\Gamma_T} = \frac{m_t^2}{2\, m_2^2} = 2.35 \tag{15}$$

For example, the W^+ energy distribution goes as

$$I(E_{w^+}) = 1 - \alpha\, \xi_{W^+}\, \mathscr{S}_t \cos\theta_1{}^t \tag{16}$$

in which there is an important suppression factor[1]

$$\mathscr{S}_t = \frac{m_t^2 - 2m_w^2}{m_t^2 + 2m_w^2} \tag{17}$$

$$\mathscr{S}_t = \frac{\Gamma_L - \Gamma_T}{\Gamma_L + \Gamma_T} \tag{18}$$

$$= \begin{cases} 0.403 & \text{for } m_t = 174 \text{ GeV} \\ \text{zero} & \text{if } m_t = 113 \text{ GeV} \end{cases}$$

When m_t was thought by some physicists to be less massive, the zero at $m_t = \sqrt{2}\, m_w = 113$ GeV was considered to be "discouraging". For comparison, the analogous factor in $\tau \to \rho\nu$ decay has the value $\mathscr{S}_\rho = 0.46$, so $m_t = 174 \pm 17$ GeV is very "good news" considering the many uses that are now being made of $\tau \to \rho\nu$ polarimetry. [Here also, W polarimetry can be used[3] to improve the $\tau \to \rho\nu$ polarimetry signature, just as ρ polarimetry is being used[3,6,7] for $\tau \to \rho\nu$.]

In (16), the "chiral polarization parameter"

$$\xi_{W^+} = \frac{|g_L|^2 - |g_R|^2}{|g_L|^2 + |g_R|^2} \tag{19}$$

again tests for a V-A, versus V+A, coupling in $t \to W^+ b$ decay. By the spin-correlation function $I(E_{W^+}, E_{W^-})$, the ξ_{W^+} decay parameter can be separated from the $X \to \bar{t}t$ production parameter

$$\alpha \equiv \frac{|t_{-+}|^2 - |t_{+-}|^2}{\mathscr{N}}, \quad \mathscr{N} \equiv \sum_{\lambda_1, \lambda_2} |t_{\lambda_1, \lambda_2}|^2 \tag{20}$$

There are 3 particularly simple tests[1] for CP violation in the $X \to t\bar{t}$ production process: In terms of the azimuthal angle, Φ, between the $t \to W^+ b$ and $\bar{t} \to W^- \bar{b}$ decay planes, the spin-correlation function is [for the detailed expressions see Ref. 1]

$$I(E_W, E_{W^-}, \Phi) = I_o + I_X \tag{21a}$$

$$I_o = C_o + A_o \cos\Phi \tag{21b}$$

$$I_x = C_x + A_x \sin\Phi \tag{21c}$$

The I_x term is absent if CP invariance holds. The 3 tests are: (i) The $\sin\Phi$ term in (21) is absent[12] if CP is good. (ii) The energy-energy distribution will be asymmetric[1] if CP is violated since

$$\Delta(E_{W^+}, E_{W^-}) \equiv \frac{1}{2}\left[I(E_{W^+}, E_{W^-}) - I(E_{W^-}, E_{W^+})\right]$$

$$= \epsilon\, (\xi_{W^+} \cos\theta_1{}^t - \xi_{W^-} \cos\theta_2{}^t)\, \mathscr{S}_t \tag{22}$$

(iii) The W^+ energy distribution will be shifted[1] in α if CP is violated since

$$I(E_{W^+}) = 1 + (\alpha - \epsilon)\, \xi_{W^+} \mathscr{S}_t \cos\theta_1^{\,t} \tag{23}$$

Note that the "ϵ parameter" in (22) and (23) is[1]

$$\epsilon \equiv \frac{|t_{++}|^2 - |t_{--}|^2}{\mathcal{N}} \quad , \quad \mathcal{N} \equiv \sum_{\lambda_1\lambda_2} |t_{\lambda_1\lambda_2}|^2 \tag{24}$$

and that

$$\epsilon = \left\{ \begin{array}{l} \text{Excess of RR versus LL} \\ \text{(top-antitop) pairs} \end{array} \right\} \tag{25}$$

For proton-proton collisions, Schmidt and Peskin[13] have considered the observable

$$\Delta N_{LR} \equiv \frac{\text{Prod}\,(t_L \bar{t}_L) - \text{Prod}\,(t_R \bar{t}_R)}{\text{all}\,(t\,\bar{t})} \tag{26}$$

which is the same as the above "ϵ parameter." By using the lepton transverse energies as a helicity analyzer,

$$\Delta N(E_T) \equiv \left\{ \frac{d\sigma}{d\,E(\ell^+)_T} - \frac{d\sigma}{d\,E(\ell^-)_T} \right\} \Big/ \left\{ \text{Sum} \right\} \tag{27}$$

and perhaps optimistically an order $\{10^8\ (t\,\bar{t})\,/\,\text{year}\}$ production rate at a super-collider, they find that it is possible to probe CP violation in the Higgs sector at the interesting level of

$$\epsilon = \Delta N_{LR} = (\sim 10^{-3}) \tag{28}$$

The effects of T-odd correlations in $e^-e^+ \to t\,\bar{t}$ due to dipole form-factors has also been investigated.[14]

Tests for CP violation in top decays $(t \to W^+ b)$ include usage[15] of the classic CP partial-width asymmetry parameter

$$A_\Gamma \equiv \frac{\Gamma(t \to W^+ b) - \bar{\Gamma}(\bar{t} \to W^- \bar{b})}{\Gamma(t \to W^+ b) + \bar{\Gamma}(\bar{t} \to W^- \bar{b})} \tag{29}$$

Possible $\tilde{T}_{FS}$ asymmetry in $t \to W^+ b \to (\ell^+ \nu)\, b$ decay has been studied in terms of the asymmetry observable[16]

$$A \equiv \frac{\Gamma(e^+\,\text{out}) - \Gamma(e^+\,\text{into})}{\Gamma(e^+\,\text{out}) + \Gamma(e^+\,\text{into})} \tag{30}$$

where "out" ("into") denote the e^+ momentum direction versus the $\left(\vec{p}^{\,t}_{Lab} \times \vec{p}^{\,b} \right)$ direction.

Conclusions

(i) In searching for new phenomena with on-going experiments involving top, or tau, processes, we are fortunate to have 2 very powerful tools – (a) τ-lepton and t-quark polarimetry, and (b) $(\tau\,\bar{\tau})$ and $(t\,\bar{t})$ spin-correlations.

(ii) There are observables for testing for $CP\,/\,\tilde{T}_{FS}$ violation in $e^-e^+ \to \tau^-\tau^+$ completely, and in τ-lepton decays, and also in t-quark production and decay.

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