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IMPORTANCE OF TESTS FOR THE COMPLETE LORENTZ STRUCTURE OF THE $t \rightarrow W^+b$ VERTEX AT HADRON COLLIDERS

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Abstract

The most general Lorentz-invariant decay-density-matrix for $t \rightarrow W^+b \rightarrow (l^+\nu)b$, or for $t \rightarrow W^+b \rightarrow (j_{\bar{d}}j_u)b$, is expressed in terms of eight helicity parameters. The parameters are physically defined in terms of partial-width-intensities for polarized-final-states in $t \rightarrow W^+b$ decay. The parameters are the partial width, the b quark's chirality parameter ξ, the W^+ polarimetry parameter σ, a "pre-SSB" test parameter ζ, and four W_L-W_T interference parameters η, $\eta^{'}$, ω, $\omega^{'}$ which test for $\tilde{T}_{FS}$ violation. They can be used to test for non-CKM-type CP violation, anomalous $\Gamma_{L,T}$'s, top weak magnetism, weak electricity, and second-class currents. By stage-two spin-correlation techniques, percent level statistical uncertainites are typical for measurements at the Tevatron, and several mill level uncertainites are typical at the LHC.

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Historically in the study of the weak charged-current in muonic and in hadronic processes, it has been important to determine the "complete Lorentz structure" directly from experiment. Here, we exploit the fact that the high mass, $\sim 175\ GeV$, of the newly discovered top quark [1,2,3] implies that $t \rightarrow W^+ b$ decay allows for probes of new physics beyond the standard model because this decay is essentially free of complicating hadronization effects, and that[4] approximately 70% of the final W's will be longitudinally polarized, i.e. $\Gamma_L/\Gamma_T = 2.43$ if the standard model(SM) is indeed correct.

In the t rest frame, the matrix element for $t \rightarrow W^+ b$ is

$$\langle \theta_1^t, \phi_1^t, \lambda_{W^+}, \lambda_b | \frac{1}{2}, \lambda_1 \rangle = D^{(1/2)*}_{\lambda_1, \mu}(\phi_1^t, \theta_1^t, 0) A\left(\lambda_{W^+}, \lambda_b\right) \tag{1}$$

where $\mu = \lambda_{W^+} - \lambda_b$ and λ_1 is the t helicity. The final W^+ momentum is in the θ_1^t, ϕ_1^t direction, see Fig. 1. For the CP-conjugate process, $\bar{t} \rightarrow W^- \bar{b}$, in the $\bar{t}$ rest frame

$$\langle \theta_2^t, \phi_2^t, \lambda_{W^-}, \lambda_{\bar{b}} | \frac{1}{2}, \lambda_2 \rangle = D^{(1/2)*}_{\lambda_2, \bar{\mu}}(\phi_2^t, \theta_2^t, 0) B\left(\lambda_{W^-}, \lambda_{\bar{b}}\right) \tag{2}$$

with $\bar{\mu} = \lambda_{W^-} - \lambda_{\bar{b}}$, λ_2 is the $\bar{t}$ helicity. So, by Lorentz invariance there are only 2 amplitudes $A(0, -1/2), A(-1, -1/2)$ for b_L, etc.

Such formulas[2] only assume Lorentz invariance and do not assume any discrete symmetry properties. Therefore, it is easy to test for the consequences of addtional symmetries[6]. As shown in Table 1 a specific discrete symmetry implies a specific relation among the associated helicity

[2]To modularize the analysis, we consistently use the standard helicity formalism and phase conventions[5]. Previous analyzes of the helicity properties of $t \rightarrow W + b$ include [4,7]; studies of CP violation in t reactions include [4,8,9]. Input numbers: $m_t = 175 GeV, m_W = 80.35 GeV, m_b = 4.5 GeV$.

amplitudes. In particular[6,10], measurement of a non-real helicity amplitude implies a violation of $\tilde{T}_{FS}$ invariance when a first-order perturbation in an "effective" hermitian Hamiltonian is reliable. $\tilde{T}_{FS}$ invariance is to be distinguished from canonical T invariance which requires interchanging "final" and "initial" states. So $\tilde{T}_{FS}$ invariance will be violated when either there is a violation of canonical T invariance or when there are absorptive final- state interactions. Actual time-reversed reactions are required for a direct test of T invariance.

Similarly in the W^+ rest frame, the matrix element for $W^+ \to l^+\nu$ or for $W^+ \to j_{\bar{d}} j_u$ is

$$\langle \tilde{\theta}_a, \tilde{\phi}_a, \lambda_l^+, \lambda_\nu | 1, \lambda_{W^+} \rangle = D^{1*}_{\lambda_{W^+},1}(\tilde{\phi}_a, \tilde{\theta}_a, 0) c \tag{3}$$

since $\lambda_\nu = -\frac{1}{2}, \lambda_{l^+} = \frac{1}{2}$, neglecting $(\frac{m_l}{m_W})$ corrections. This equation also describes the $W^+ \to j_{\bar{d}} j_u$ decay mode, neglecting $(\frac{m_{jet}}{m_W})$ corrections.

The associated composite decay density matrix for $t \to W^+ b \to (l^+\nu)b$, or for $t \to W^+ b \to (j_{\bar{d}} j_u)b$, is

$$R_{\lambda_1 \lambda_1'} = \sum_{\lambda_W, \lambda_W'} \rho_{\lambda_1 \lambda_1'; \lambda_W \lambda_W'}(t \to W^+ b) \rho_{\lambda_W \lambda_W'}(W^+ \to l^+ \nu) \tag{4}$$

where $\lambda_W, \lambda_W' = 0, \pm 1$ with

$$\rho_{\lambda_1 \lambda_1'; \lambda_W \lambda_W'}(t \to W^+ b) = \sum_{\lambda_b = \mp 1/2} D^{(1/2)*}_{\lambda_1, \mu}(\phi_1^t, \theta_1^t, 0) D^{(1/2)}_{\lambda_1', \mu'}(\phi_1^t, \theta_1^t, 0) A(\lambda_W, \lambda_b) A(\lambda_W', \lambda_b)^*$$

$$\rho_{\lambda_W \lambda_W'}(W^+ \to l^+ \nu) = D^{1*}_{\lambda_W, 1}(\widetilde{\phi_a}, \widetilde{\theta_a}, 0) D^{1}_{\lambda_W', 1}(\widetilde{\phi_a}, \widetilde{\theta_a}, 0) |c|^2$$

This composite decay density matrix can be elegantly expressed in terms of eight helicity parameters $(\xi, \zeta, \sigma, \ldots)$:

$$\mathbf{R} = \begin{pmatrix} \mathbf{R}_{++} & e^{\iota \phi_1^t} \mathbf{r}_{+-} \\ e^{-\iota \phi_1^t} \mathbf{r}_{-+} & \mathbf{R}_{--} \end{pmatrix} \tag{5}$$

The diagonal elements are

$$\mathbf{R}_{\pm\pm} = \mathbf{n}_a[1 \pm \mathbf{f}_a \cos\theta_1^t] \pm (1/\sqrt{2}) \sin\theta_1^t \{\sin 2\tilde{\theta}_a \ [\omega \cos\tilde{\phi}_a + \eta' \sin\tilde{\phi}_a] - 2 \sin\tilde{\theta}_a \ [\eta \cos\tilde{\phi}_a + \omega' \sin\tilde{\phi}_a]\} \tag{6}$$

In (5), $\mathbf{R}_{\pm\pm}$ are simply the angular distributions $\frac{dN}{d(\cos\theta_1^t)d(\cos\tilde{\theta}_a)d\tilde{\phi}_a}$ for the polarized t decay chain, $t \to W^+b \to (l^+\nu)b$, or $t \to W^+b \to (j_{\bar{d}}j_u)b$. The off-diagonal elements depend on

$$\begin{aligned} \mathbf{r}_{+-} &= (\mathbf{r}_{-+})^* \\ &= \mathbf{n}_a\mathbf{f}_a \sin\theta_1^t + 2\sqrt{2} \sin\tilde{\theta}_a \sin^2\tfrac{\tilde{\theta}_a}{2} \{\cos\theta_1^t[\eta \cos\tilde{\phi}_a + \omega' \sin\tilde{\phi}_a] + \iota[\eta \sin\tilde{\phi}_a - \omega' \cos\tilde{\phi}_a]\} \end{aligned} \tag{7}$$

In (6,7),

$$\begin{aligned} \mathbf{n}_a &= \tfrac{1}{8}(5 - \cos 2\tilde{\theta}_a - \sigma[1 + 3\cos 2\tilde{\theta}_a] - 4[\xi - \zeta]\cos\tilde{\theta}_a) \\ \mathbf{n}_a\mathbf{f}_a &= \tfrac{1}{8}(4[1 - \sigma]\cos\tilde{\theta}_a - \xi[1 + 3\cos 2\tilde{\theta}_a] + \zeta[5 - \cos 2\tilde{\theta}_a]) \end{aligned} \tag{8}$$

or equivalently

$$\begin{pmatrix} \mathbf{n}_a \\ \\ \mathbf{n}_a\mathbf{f}_a \end{pmatrix} = \sin^2\tilde{\theta}_a \frac{\Gamma_L^{\pm}}{\Gamma} \pm \frac{1}{4}(3 + \cos 2\tilde{\theta}_a)\frac{\Gamma_T^{\pm}}{\Gamma} \mp \cos\tilde{\theta}_a \frac{\Gamma_T^{\mp}}{\Gamma} \tag{9}$$

The subscripts on the Γ's denote the polarization of the final W^+, either "L=longitudinal" or "T=transverse"; superscripts denote "$\pm$ for sum/difference of the b_L versus b_R contributions".

Similarly, for the CP-conjugate process $\bar{t} \to W^-\bar{b} \to (l^-\bar{\nu})\bar{b}$ or $\bar{t} \to W^-\bar{b} \to (j_d j_{\bar{u}})\bar{b}$

$$\bar{\mathbf{R}} = \begin{pmatrix} \bar{\mathbf{R}}_{++} & e^{\iota\phi_2^t}\bar{\mathbf{r}}_{+-} \\ \\ e^{-\iota\phi_2^t}\bar{\mathbf{r}}_{-+} & \bar{\mathbf{R}}_{--} \end{pmatrix} \tag{10}$$

$$\bar{\mathbf{R}}_{\pm\pm} = \mathbf{n}_b[1 \mp \mathbf{f}_b \cos\theta_2^t] \mp (1/\sqrt{2}) \sin\theta_2^t \{\sin 2\tilde{\theta}_b[\bar{\omega} \cos\tilde{\phi}_b - \bar{\eta}' \sin\tilde{\phi}_b] - \sin\tilde{\theta}_b[\bar{\eta} \cos\tilde{\phi}_b - \bar{\omega}' \sin\tilde{\phi}_b]\} \tag{11}$$

$$\begin{aligned} \bar{\mathbf{r}}_{+-} &= (\bar{\mathbf{r}}_{-+})^* \\ &= -\mathbf{n}_b\mathbf{f}_b \sin\theta_2^t - 2\sqrt{2} \sin\tilde{\theta}_b \sin^2\tfrac{\tilde{\theta}_b}{2} \{\cos\theta_2^t[\bar{\eta} \cos\tilde{\phi}_b - \bar{\omega}' \sin\tilde{\phi}_b] + \iota[\bar{\eta} \sin\tilde{\phi}_b + \bar{\omega}' \cos\tilde{\phi}_b]\} \end{aligned} \tag{12}$$

$$\mathbf{n}_b = \tfrac{1}{8}(5 - \cos 2\tilde{\theta}_b - \bar{\sigma}[1 + 3\cos 2\tilde{\theta}_b] - 4[\bar{\xi} - \bar{\zeta}]\cos\tilde{\theta}_b)$$
$$\mathbf{n}_b\mathbf{f}_b = \tfrac{1}{8}(4[1 - \bar{\sigma}]\cos\tilde{\theta}_b - \bar{\xi}[1 + 3\cos 2\tilde{\theta}_b] + \bar{\zeta}[5 - \cos 2\tilde{\theta}_b]) \tag{13}$$

$$\begin{pmatrix} \mathbf{n}_b \\ \\ \mathbf{n}_b\mathbf{f}_b \end{pmatrix} = \sin^2\tilde{\theta}_b \frac{\bar{\Gamma}_L^{\pm}}{\bar{\Gamma}} \pm \frac{1}{4}(3 + \cos 2\tilde{\theta}_b)\frac{\bar{\Gamma}_T^{\pm}}{\bar{\Gamma}} \mp \cos\tilde{\theta}_b \frac{\bar{\Gamma}_T^{\mp}}{\bar{\Gamma}} \tag{14}$$

Definitions of helicity parameters by partial-width intensities for polarized-final-states:

There are eight $t \to W^+ b$ decay parameters since there are the four $W_{L,T}$ $b_{L,R}$ final-state combinations: The first parameter is simply $\Gamma \equiv \Gamma_L^+ + \Gamma_T^+$, i.e. the partial width for $t \to W^+ b$, and

$$\Gamma_L^{\pm} = \left|A(0, -\tfrac{1}{2})\right|^2 \pm \left|A(0, \tfrac{1}{2})\right|^2$$
$$\Gamma_T^{\pm} = \left|A(-1, -\tfrac{1}{2})\right|^2 \pm \left|A(1, \tfrac{1}{2})\right|^2. \tag{15}$$

The second is the b quark's chirality parameter $\xi \equiv \frac{1}{\Gamma}(\Gamma_L^- + \Gamma_T^-)$. Equivalently,

$\xi \equiv (\text{Prob } b \text{ is } b_L) - (\text{Prob } b \text{ is } b_R)$,

$$\xi \equiv |<b_L|b>|^2 - |<b_R|b>|^2 \tag{16}$$

So a value $\xi = 1$ means the coupled b quark is pure b_L, i.e. $\lambda_b = -1/2$. The remaining two partial-width parameters are defined by

$$\zeta \equiv (\Gamma_L^- - \Gamma_T^-)/\Gamma, \quad \sigma \equiv (\Gamma_L^+ - \Gamma_T^+)/\Gamma. \tag{17}$$

This implies for W^+ polarimetry that

$\sigma = (\text{Prob } W^+ \text{ is } W_L) - (\text{Prob } W^+ \text{ is } W_T)$,

is the analogue of the b quark's chirality parameter in (16). Thus, the parameter σ measures the degree of polarization, "L minus T", of the emitted W^+. For a pure $(V-A)$, or $(V+A)$, coupling $\sigma = 0.41$, see Table 1.

The interference between these W_L and W_R amplitudes can also be determined by measuring the four normalized parameters,

$$\begin{aligned} \omega &\equiv I^-_{\mathcal{R}}\ /\Gamma, \qquad \eta \equiv I^+_{\mathcal{R}}\ /\Gamma \\ \omega' &\equiv I^-_{\mathcal{I}}\ /\Gamma, \qquad \eta' \equiv I^+_{\mathcal{I}}\ /\Gamma \end{aligned} \tag{18}$$

The associated $W_L - W_T$ interference intensities are

$$\begin{aligned} I^{\pm}_{\mathcal{R}} &= \left|A(0,-\tfrac{1}{2})\right| \left|A(-1,-\tfrac{1}{2})\right| \cos\beta_a \\ &\pm \left|A(0,\tfrac{1}{2})\right| \left|A(1,\tfrac{1}{2})\right| \cos\beta_a^R \\ I^{\pm}_{\mathcal{I}} &= \left|A(0,-\tfrac{1}{2})\right| \left|A(-1,-\tfrac{1}{2})\right| \sin\beta_a \\ &\pm \left|A(0,\tfrac{1}{2})\right| \left|A(1,\tfrac{1}{2})\right| \sin\beta_a^R \end{aligned} \tag{19}$$

Here, $\beta_a \equiv \phi^a_{-1} - \phi^a_0$, and $\beta^R_a \equiv \phi^a_1 - \phi^{aR}_0$ are the measurable phase differences of of the associated helicity amplitudes $A(\lambda_{W+}, \lambda_b) = |A| \exp \iota\phi$ in the standard helicity amplitude phase convention[5].

When there is only a $(V-A)$ coupling and $m_b = 0$ these parameters have the values[3] shown in Table 2. Note that the "pre-SSB case" of a mixture of only V and A couplings and $m_b = 0$ implies that the two parameters directly sensitive to $\tilde{T}_{FS}$ violation vanish, $\omega' = \eta' = 0$. Also in the pre-SSB case, the b quark's chirality parameter $\xi \to \frac{|g_L|^2 - |g_R|^2}{|g_L|^2 + |g_R|^2}$ so that the "stage-one spin correlation" parameter $\frac{\zeta}{\mathcal{S}_W} \to \xi$. So, in this special case ζ also measures the b quark's helicity and $\frac{\zeta}{\mathcal{S}_W} = \xi$, but for more general couplings and/or $m_b \neq 0$ neither is true. Also in the pre-SSB case, the interference parameter $\frac{\omega}{\mathcal{R}_W} = \xi$. Therefore, precision measurements with ξ and ζ distinct, and

[3]If one factors out "W-polarimetry factors" ,see footnote below, via $\sigma = \mathcal{S}_W \tilde{\sigma}$, $\omega = \mathcal{R}_W \tilde{\omega}$, ... these parameters all equal one or zero for pure $(V-A)$ and $m_b = 0$. Systematic effects will cancel by considering the ratios ζ/ξ versus $\mathcal{S}_W$, and ω/ξ versus $\mathcal{R}_W$ in the two pre-SSB tests.

with ξ and ω distinct, will be two useful probes of the dynamics of EW spontaneous symmetry breaking, see (26) and (27) below for instance.

From Table 2, one easily sees that the numerical values of "$\xi, \zeta, \sigma, \ldots$" are very different for unique Lorentz couplings. This is indicative of the analyzing power of polarization techniques in two-body t decay modes. Both the real and the imaginary parts of the associated helicity amplitudes can be directly measured, c.f. (19).

Tests for anomalous Γ_L, Γ_T polarized-partial-widths:

The contribution of the longitudinal(L) and transverse(T) W-amplitudes in the decay process is projected out by the simple formulas:

$$I_{\mathcal{R}}^{b_L,b_R} \equiv \frac{1}{2}(I_{\mathcal{R}}^{+} \pm I_{\mathcal{R}}^{-}) = |A(0,\mp\frac{1}{2})||A(\mp 1,\mp\frac{1}{2})| \cos\beta_a^{L,R} = \frac{\Gamma}{2}(\eta \pm \omega)$$

$$I_{\mathcal{I}}^{b_L,b_R} \equiv \frac{1}{2}(I_{\mathcal{I}}^{+} \pm I_{\mathcal{I}}^{-}) = |A(0,\mp\frac{1}{2})||A(\mp 1,\mp\frac{1}{2})| \sin\beta_a^{L,R} = \frac{\Gamma}{2}(\eta' \pm \omega')$$

$$\Gamma_L^{b_L,b_R} \equiv \frac{1}{2}(I_L^{+} \pm I_L^{-}) = |A(0,\mp\frac{1}{2})|^2 = \frac{\Gamma}{4}(1+\sigma \pm \xi \pm \zeta)$$

$$\Gamma_T^{b_L,b_R} \equiv \frac{1}{2}(I_T^{+} \pm I_T^{-}) = |A(\mp 1,\mp\frac{1}{2})|^2 = \frac{\Gamma}{4}(1-\sigma \pm \xi \mp \zeta) \tag{20}$$

In the first line, $\beta_a^L = \beta_a$. Unitarity, requires the two right-triangle relations

$$(I_{\mathcal{R}}^{b_L})^2 + (I_{\mathcal{I}}^{b_L})^2 = \Gamma_L^{b_L}\Gamma_T^{b_L} \tag{21}$$

$$(I_{\mathcal{R}}^{b_R})^2 + (I_{\mathcal{I}}^{b_R})^2 = \Gamma_L^{b_R}\Gamma_T^{b_R}. \tag{22}$$

It is important to determine directly from experiment whether or not these partial widths are anomalous in nature versus the standard $(V-A)$ predictions because the W_L and W_T partial widths might have distinct dynamical differences versus the SM predictions if electroweak dynamical symmetry breaking(DSB) occurs in nature, e.g. associated with a t quark compositeness and/or a $(t\bar{t})$ condensate and/or anomalous $W_{L,T}$-$W_{L,T}$ interactions. In areas of physics in which DSB does occur, the on-shell and off-mass-shell values of such polarized-partial-widths reveal important dynamical information.

Tests for non-CKM-type CP, and $\tilde{T}_{FS}$ violations:

A violation of $\tilde{T}_{FS}$-invariance could occur for a dynamical reason, e.g. because of the exchange of an unknown Z' boson between the final $W^+$and the final b in which the Z' couples differently to the W_L versus the W_T. Or $\tilde{T}_{FS}$-violation could occur because of a fundamental violation of canonical T-invariance. Whatever the cause might turn out to be, the experimental discovery of a violation of $\tilde{T}_{FS}$-invariance in $t \to W^+ b$ would be very significant.

- If the primed parameters $\omega' \neq 0$ and/or $\eta' \neq 0 \Longrightarrow \tilde{T}_{FS}$ **is violated:**

Only two of the four parameters $\eta, \eta', \omega, \omega'$ are needed to test for $\tilde{T}_{FS}$ violation because the two-right-triangle relations imply

$$(\eta \pm \omega)^2 + (\eta' \pm \omega')^2 = \frac{1}{4}[(1 \pm \xi)^2 - (\sigma \pm \zeta)^2]. \tag{23}$$

The barred parameters $\bar{\xi}, \bar{\zeta}, \ldots$ have the analogous definitions for the CP conjugate modes, for instance, $\bar{\xi} =$ (Prob $\bar{b}$ is $\bar{b}_R$) $-$ (Prob $\bar{b}$ is $\bar{b}_L$) ,

$$\bar{\Gamma}^{\pm}_{L} = |B(0, \frac{1}{2})|^2 \pm |B(0, -\frac{1}{2})|^2. \tag{24}$$

Therefore,

- If any $\bar{\xi} \neq \xi, \bar{\zeta} \neq \zeta, \ldots \Longrightarrow$ **CP is violated:**

With precisions forseeable in the near future, since $m_b/m_t \sim m_b/m_W \sim 0$, there are two simple tests for "non-CKM-type" CP violation in $t \to Wb$ decay. The two tests are: $\beta_a = \beta_b$, where $\beta_a = \phi^a_{-1} - \phi^a_0$, $\beta_b = \phi^b_1 - \phi^b_0$, and $r_a = r_b$, where $r_a = \frac{|A(-1,-\frac{1}{2})|}{|A(0,-\frac{1}{2})|}$, $r_b = \frac{|B(1,\frac{1}{2})|}{|B(0,\frac{1}{2})|}$. Normally[10] a CKM-phase will contribute equally at tree level to both the $t \to W^+ b_L$ decay amplitudes and so will cancel out in the ratio of their moduli and in their relative phase. With improved precision there are the two additional tests: $\beta^R_a = \beta^L_b$ and $r^R_a = r^L_b$, see [6,10].

Tests for additional Lorentz structures:

A chiral classification of additional Lorentz structure is a natural phenomenological extension of the symmetries of the SM, but this formalism easily allows searches for non-chiral couplings[6,10]. For $t \to W^+ b$, the most general Lorentz coupling is

$$W^*_\mu \bar{u}_b(p)\, \Gamma^\mu u_t(k) \tag{25}$$

where $k_t = q_W + p_b$. In (25)

$$\begin{aligned}\Gamma^\mu_V = g_V \gamma^\mu + \frac{f_M}{2\Lambda} \iota\sigma^{\mu\nu}(k-p)_\nu + \frac{g_{S^-}}{2\Lambda}(k-p)^\mu \\ + \frac{g_S}{2\Lambda}(k+p)^\mu + \frac{g_{T^+}}{2\Lambda}\iota\sigma^{\mu\nu}(k+p)_\nu\end{aligned}$$

$$\begin{aligned}\Gamma^\mu_A = g_A \gamma^\mu \gamma_5 + \frac{f_E}{2\Lambda} \iota\sigma^{\mu\nu}(k-p)_\nu \gamma_5 + \frac{g_{P^-}}{2\Lambda}(k-p)^\mu \gamma_5 \\ + \frac{g_P}{2\Lambda}(k+p)^\mu \gamma_5 + \frac{g_{T_5^+}}{2\Lambda}\iota\sigma^{\mu\nu}(k+p)_\nu \gamma_5\end{aligned}$$

The parameter $\Lambda =$ "the effective-mass scale of new physics". In effective field theory this is the scale at which new particle thresholds are expected to occur or where the theory becomes non-perturbatively strongly-interacting so as to overcome perturbative inconsistencies. It can also be interpreted as a measure of a new compositeness scale. In old-fashioned renormalization theory Λ is the scale at which the calculational methods and/or the principles of "renormalization" breakdown.

Without additional theoretical or experimental inputs, it is not possible to select what is the "best" minimal set of couplings for analyzing the structure of the $(\bar{b}t)$ charged current. For instance, there are the equivalence theorems that for the vector current, $S \approx V + f_M, T^+ \approx -V + S^-$, and for the axial-vector current, $P \approx -A + f_E, T_5^+ \approx A + P^-$. So, from the perspective of searching for fundamental dynamics, it is important to investigate what limits can be set for a variety of Lorentz structures (including $S^\pm$, $P^\pm$, $T^\pm$, and ${T_5}^\pm$) and not just for a kinematically minimal, but theoretically prejudiced, set.

DSB or compositeness considerations motivate searching for an additional tensorial $g_+ = f_M + f_E$ coupling which would preserve the three logically independent $m_b = 0$ signatures for only b_L couplings: $\xi = 1, \sigma = \zeta, \eta = \omega$, and also $\omega' = \eta'$ if $\tilde{T}_{FS}$ violation occurs. But g_+ would give non-$(V-A)$-values, $\sigma = \zeta \neq 0.41$ and $\eta = \omega \neq 0.46$. For Λ large, there are the predictions for purely real g_+ that[4]

$$(\frac{\zeta}{\mathcal{S}_W} - \xi) = (\xi - \frac{\omega}{\mathcal{R}_W})\frac{g}{l} = 0.076(\xi - \frac{\omega}{\mathcal{R}_W}) \tag{26}$$

[4]In the presence of additional Lorentz structures, W-polarimetry factors $\mathcal{S}_W = \frac{1-2\frac{m_W^2}{m_t^2}}{1+2\frac{m_W^2}{m_t^2}} = 0.4068$, and $\mathcal{R}_W = \frac{\sqrt{2}\frac{m_W}{m_t}}{1+2\frac{m_W^2}{m_t^2}} = 0.4567$ naturally appear because of the referencing of "new physics" to the $(V-A)$ structure of the SM, see [6]. See also, footnote 3 above.

and for purely imaginary g_+ that

$$(\frac{\zeta}{\mathcal{S}_W} - \xi) = (\xi - \frac{\omega}{\mathcal{R}_W})\frac{2u}{o} = 8.4(\xi - \frac{\omega}{\mathcal{R}_W}) \tag{27}$$

The ratios "g/l" and $2u/o$" are given functions [6] of $m_{t,W}$.

While some terms of the above form do occur as higher-order perturbative-corrections in the standard model, such SM contributions are expected to be less than the precision of planned Tevatron and LHC experiments. A systematic analysis of the higher-order EW corrections versus the sensitivities of S2SC parameters should be performed. The $S^- \pm P^-$ couplings do not contribute when the final W^+ is on the mass-shell. Both the weak magnetism $\frac{f_M}{2\Lambda}$ and the weak electricty $\frac{f_E}{2\Lambda}$ terms are divergenceless. On the other hand, since $q^2 = m_W{}^2$, even when $m_b = m_t$ the couplings S^-, T^+, A, P^-, T_5^+ contribute to the divergences.

To study the reality structure of $J_{\bar{b}t}$, we assume[11,10] that it is Hermitian and has an SU(2) symmetry $t \leftrightarrow b$. Then for real form factors, the "Class I" couplings are V, A, f_M, P^-, and "Class II" couplings are f_E, S^-. We define $J^\mu_{\bar{b}t} = J^\mu_I + J^\mu_{II}$ where for $U = \exp(\iota\pi I_2)$,

$$(J^\mu_I)^\dagger = -U J^\mu_I U^{-1} \quad First Class$$

$$(J^\mu_{II})^\dagger = U J^\mu_{II} U^{-1} \quad Second Class$$

There is a "clash" between the "Class I and Class II" structures and the consequences of time-reversal invariance. Useful theorems are that (a) ($t \leftrightarrow b$ symmetry) + (T invariance) $\Longrightarrow$ Class II currents are absent, (b) ($t \leftrightarrow b$ symmetry) + (existence of J^μ_I and J^μ_{II}) $\Longrightarrow$ violation of T invariance, and (c) (existence of J^μ_{II}) + (T invariance) $\Longrightarrow$($t \leftrightarrow b$ symmetry) in $J_{\bar{b}t}$ is broken.

Measurement of relative phase of b_L and b_R amplitudes:

If only b_L coupling's existed, there would be only 2 amplitudes, so 3 measurements, of r_a, β_a,and $|A(0,-\frac{1}{2})|$ would provide a "complete measurement" of $t \to W^+ b$. However, since $m_b \neq 0$, there are 2 more amplitudes, $A(0,\frac{1}{2})$ and $A(1,\frac{1}{2})$, so to achieve an "almost" complete measurement, 3 additional quantities must be determined, e.g. r_a^R, β_a^R and $\lambda_R \equiv \frac{|A(0,\frac{1}{2})|}{|A(0,-\frac{1}{2})|}$. However, a further measurement is necessary to determine the relative phase of the b_L and b_R amplitudes, $\beta_a^o \equiv \phi_o^{aR} - \phi_o^a$ or $\beta_a^1 \equiv \phi_1^a - \phi_{-1}^a$. This would be possible by development of b quark-polarimetry techniques. It might be possible to obtain this missing phase through a measurement of the interference between the b_L and b_R amplitudes in $t \to W^+ b$ with $b \to c l^- \bar{\nu}$ where the b quark is required to occur in a bound state in a $J \neq 0$ mass region, e.g. B^*. Existing LEP data on the angular distributions in B^* decays could be analyzed to see if such b quark-polarimetry is feasible.

Sensitivities of measurements at hadronic colliders:

The simplest kinematic measurement of the above helicity parameters at the Tevatron and at the LHC would be through purely hadronic top decay modes. CDF has reported[12] observation of such decays. In this case the $(t\bar{t})_{cm}$ frame is accessible and the four-variable, stage-two spin-correlation function, I_4,

$$I(E_{W^+}, E_{W^-}, \tilde{\theta}_1, \tilde{\theta}_2) = \sum_i \{\rho_{+-}(q_i\bar{q}_i \to t\bar{t})^{prod}[\rho_{++}\bar{\rho}_{--} + \rho_{--}\bar{\rho}_{++}] \\ + \rho_{++}(q_i\bar{q}_i \to t\bar{t})^{prod}[\rho_{++}\bar{\rho}_{++} + \rho_{--}\bar{\rho}_{--}]\} \quad (28)$$

can be used. The "i" summation is over the incident quarks and gluons in the $p\bar{p}$, or pp. If one thinks in terms of probabilities, the quantum-mechanical structure of this expression is obvious.

The kinematic variables in I_4 are the $(t\bar{t})$ center-of-mass energies E_{W^+} and E_{W^-}, the polar angle $\tilde{\theta}_1$ which specifies the $j_{\bar{d}}$ jet (or the l^+) momentum in the W^+rest frame when the boost is directly from the $(t\bar{t})_{cm}$ frame[6], and $\tilde{\theta}_2$ for the j_d jet (or the l^-) momentum in the W^-rest frame.

Such "$S2SC$" functions may turn out to be very useful for probing for unexpected $t\bar{t}$ production mechanisms since, by CP invariance, I_4 only depends on two diagonal production-density-matrix-elements[6] in the $q\bar{q} \to t\bar{t}$ channel and also in the $gg \to t\bar{t}$ channel. CP can also be tested in production [4,8,6].

In (28), the composite decay density matrix elements are simply the decay probability for a t_1 with helicity $\frac{h}{2}$ to decay $t \to W^+ b$ followed by $W^+ \to j_{\bar{d}} j_u$, or $W^+ \to l^+ \nu$ since $dN/d\left(\cos\theta_1^t\right) d\left(\cos\tilde{\theta}_1\right) = \rho_{hh}\left(\theta_1^t, \tilde{\theta}_1\right)$ and for the decay of the $\bar{t}_2$, $\bar{\rho}_{hh} = \rho_{-h,-h}\left(1 \to 2, addbars\right)$. For t_1 with helicity $\frac{h}{2}$

$$\rho_{hh} = \rho_o + h\rho_c \cos\theta_1^t + h\rho_s \sin\theta_1^t \tag{29}$$

where

$$\begin{aligned} \rho_o = \frac{1}{8}\{ & 6 - 2\cos^2\omega_1 \cos^2\tilde{\theta}_1 - \sin^2\omega_1 \sin^2\tilde{\theta}_1 \\ & +\sigma[2 - 6\cos^2\omega_1\cos^2\tilde{\theta}_1 - 3\sin^2\omega_1\sin^2\tilde{\theta}_1] - 4(\xi - \zeta)\cos\omega_1\cos\tilde{\theta}_1\} \end{aligned} \tag{30}$$

$$\begin{aligned} \rho_c = \frac{1}{8}\{ & \zeta[6 - 2\cos^2\omega_1\cos^2\tilde{\theta}_1 - \sin^2\omega_1\sin^2\tilde{\theta}_1] \\ & +\xi[2 - 6\cos^2\omega_1\cos^2\tilde{\theta}_1 - 3\sin^2\omega_1\sin^2\tilde{\theta}_1] + 4(1-\sigma)\cos\omega_1\cos\tilde{\theta}_1\} \end{aligned} \tag{31}$$

$$\rho_s = \frac{1}{\sqrt{2}}\{\frac{1}{2}\omega\sin 2\omega_1[\sin^2\tilde{\theta}_1 - 2\cos^2\tilde{\theta}_1] + 2\eta\sin\omega_1\cos\tilde{\theta}_1\} \tag{32}$$

with[5] the Wigner rotation angle $\omega_1 = \omega_1(E_{W^+})$. Note that the ρ_s term depends only on the $W_L - W_T$ interference intensities, whereas the ρ_o and ρ_c terms only depend on the polarized-

[5] The rotation by ω_1 about the implicit y_a axis in Fig. 1 is given by $\sin\omega_1 = m_W\beta\gamma\sin\theta_1^t/p_1$, $\cos\omega_1 = \frac{E_{cm}(m_t^2 - m_W^2 + [m_t^2 + m_W^2]\beta\cos\theta_1^t)}{4m_t^2 p_1}$ where p_1 = the magnitude of the W^+ momentum in the $(t\bar{t})_{cm}$ frame and γ, β

partial-widths, specifically

$$\rho_{o,c} = \frac{1}{2}[2 - 2\cos^2\omega_1\cos^2\tilde{\theta}_1 - \sin^2\omega_1\sin^2\tilde{\theta}_1]\frac{\Gamma_L^{\pm}}{\Gamma}$$
$$\pm\frac{1}{4}[2 + 2\cos^2\omega_1\cos^2\tilde{\theta}_1 + \sin^2\omega_1\sin^2\tilde{\theta}_1]\frac{\Gamma_T^{\pm}}{\Gamma} \mp \cos\omega_1\cos\tilde{\theta}_1\frac{\Gamma_T^{\mp}}{\Gamma} \tag{33}$$

with $\bar{\rho}_{o,c} = \rho_{o,c}\ (1 \to 2, addbars)$.

I_4 can also be written in terms of the variables useful for testing for non-CKM-type CP violation[the overall factor Γ_L^+/Γ is suppressed] :

$$\rho_{o,c} = \frac{1}{2}[2 - 2\cos^2\omega_1\cos^2\tilde{\theta}_1 - \sin^2\omega_1\sin^2\tilde{\theta}_1(1 \pm \lambda_R^2)]$$
$$\pm\frac{1}{4}[2 + 2\cos^2\omega_1\cos^2\tilde{\theta}_1 + \sin^2\omega_1\sin^2\tilde{\theta}_1](r_a^2 \pm [\lambda_R r_a^R]^2) \mp \cos\omega_1\cos\tilde{\theta}_1(r_a^2 \mp [\lambda_R r_a^R]^2) \tag{34}$$
$$\rho_s = \frac{1}{\sqrt{2}}\{\frac{1}{2}\sin 2\omega_1[\sin^2\tilde{\theta}_1 - 2\cos^2\tilde{\theta}_1][r_a\cos\beta_a - \lambda_R r_a^R\cos\beta_a^R]$$
$$+2\sin\omega_1\cos\tilde{\theta}_1[r_a\cos\beta_a + \lambda_R r_a^R\cos\beta_a^R]\} \tag{35}$$

with $\bar{\rho}_i = \rho_i(1 \to 2, a \to b)$, $\lambda_R \equiv \frac{|A(0,\frac{1}{2})|}{|A(0,-\frac{1}{2})|}$ [6,10].

In the framework of the parton model, we characterize the "sensitivity" for measurement of a parameter "a" appearing in a spin-correlation function $I(x,y) = Z_o(x,y) + aZ_1(x,y) + a^2 Z_2(x,y)$ by the fractional uncertainty "σ_a/a" where

$$\sigma_a \equiv \{\sum_{ij}\frac{1}{\sigma_{ij}^2}[Z_1(x_i,y_j) + 2aZ_2(x_i,y_j)]^2\}^{-1/2} \tag{36}$$

where $\sigma_{ij} = \sqrt{I(x_i,y_j)}$. "$x, y$" are event by event observables $E_{W^+}, \tilde{\theta}_1, \ldots$. The spin-correlation function $I(x_i,y_j)$ and the quantity $[Z_1(x_i,y_j) + 2aZ_2(x_i,y_j)]$ are smeared over the parton distribution functions for the p and $\bar{p}$ hadrons, just as in the evaluation of the $p\bar{p} \to t\bar{t}X$ cross section,.

describe the boost from this cm frame to the t_1 rest frame [$\gamma = E_{cm}/(2m_t)$ with E_{cm} = total energy of $t\bar{t}$, in $(t\bar{t})_{cm}$].

When “a” only appears linearly, set $Z_2 = 0$. This a simple and natural sensitivity criteria because for spin-correlation analyzes, a physical consequence of the QM-factorization structure of the parton model is that there are incident parton longitudinal beams characterized by the Feynman x_1 and x_2 momentum fractions instead of the known p and $\bar{p}$ momenta. If the parton momenta were known so that this momentum-smearing were not necessary, this procedure would correspond to the usual ideal statistical error procedure for characterizing least-squares measurements of fundamental parameters[13].

Using this criteria, for measurements at the Tevatron and the LHC we obtain the sensitivities listed in Table 3. Since these fractional uncertainties depend on $\sqrt{\frac{1}{\#events}}$, they can be scaled by the reader. The numbers listed assume $3 \cdot 10^4$ events in $p\bar{p}$ at $2TeV$, 10^6 events in pp at $14TeV$, and the MRS(A') parton distribution set[14].

At the Tevatron, percent level uncertainties are typical for measurements of the helicity parameters $\xi, \zeta, \sigma, \omega, \eta$. At the LHC, several mill level uncertainties are typical. These are also the sensitivity levels found for measurement of the polarized-partial-widths, $\Gamma^{\pm}_{L,T}$, and for the non-CKM-type CP violation parameter r_a. From I_4 the η parameter(ω parameter) can respectively best be measured at the Tevatron(LHC). However, by use of additional variables (all of $\tilde{\theta}_1, \tilde{\phi}_1, \tilde{\theta}_2, \tilde{\phi}_2$) in the stage-two step of the decay sequences where $W^{\pm} \rightarrow j_{\bar{d},d} j_{u,\bar{u}}$, and/or $l^{\pm}\nu$, we expect that these sensitivities would then be comparable to that for the other helicity parameters. Inclusion of additional variables should also improve the sensitivity to the CP violation parameter β_a which is at 33^o (Tevatron), 9.4^o (LHC). In regard to effective mass-scales for new physics exhibited by additional Lorentz couplings, we find $50 - 70TeV$ effective-mass scales can be probed at the Tevatron and $110 - 750TeV$ scales at the LHC. Associated sensitivities for measurements via other spin-correlation functions and with other top decay modes, in particular when $W^+ \to l^+ \nu$ and $W^- \to l^- \bar{\nu}$, will be reported in a later paper.

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Table Captions

Table 1: The helicity formalism is based on the assumption of Lorentz invariance but not on any specific discrete symmetry properites of the fundamental amplitudes, or couplings. For $t \to W^+ b$ and $\bar{t} \to W^- \bar{b}$ a specific discrete invariance implies a definite symmetry relation among the associated helicity amplitudes, such as shown.

Table 2: Comparison of helicity parameters' values for unique Lorentz couplings: The first 3 parameters (ξ, ζ, σ), plus the partial width $\Gamma(t \to W^+ b)$, give the polarized-final-state partial-widths, $\mathbf{\Gamma}$, for the four $W_{L,T} b_{L,R}$ final-state combinations. The latter 4 parameters $(\omega, \eta, \omega', \eta')$ give the complete W_L -W_T interference intensities, $\mathbf{\Gamma_{LT}}$. Numerical values are to two digits for $m_b = 0$. Only at three digits, do the standard model's $(V-A)$ values become sensitive to the m_b mass; see SM column in next table.

Table 3: At 2 TeV and at 14 TeV: First, sensitivities versus standard model values for measurements of the fundamental parameters $\xi, \zeta, \sigma, \omega$, and η by the stage-two spin- correlation function I_4 for the production-decay sequence $p\bar{p}$ or $pp \to t\bar{t}X$ with $t \to W^+ b$ and $\bar{t} \to W^- \bar{b}$. Sensitivities for measurements of the polarized-partial-widths $\Gamma^{\pm}_{L,T}$. Sensitivities for the two tests for "non-CKM-type" CP violation in $t \to W^+ b$ decay. Lastly, effective-mass scales Λ in TeV for "new physics" from additional Lorentz structures such as pure V or A, or from a chiral combination of tensorial couplings $g_+ \equiv f_M + f_E$ and $g_- \equiv f_M - f_E$ [limits are given for purely real and for purely imaginary g_i's].

Table 1:

Invariance	Symmetry Relation
P	$\mathrm{A}(-\lambda_{W^+}, -\lambda_b) = A\,(\lambda_{W^+}, \lambda_b)$
	$\mathrm{B}(-\lambda_{W^-}, -\lambda_{\bar{b}}) = B\,(\lambda_{W^-}, \lambda_{\bar{b}})$
C	$\mathrm{B}(\lambda_{W^-}, \lambda_{\bar{b}}) = A\,(\lambda_{W^-}, \lambda_{\bar{b}})$
CP	$\mathrm{B}(\lambda_{W^-}, \lambda_{\bar{b}}) = A\,(-\lambda_{W^-}, -\lambda_{\bar{b}})$
$\tilde{T}_{FS}$	$\mathrm{A}^*\,(\lambda_{W^+}, \lambda_b) = A\,(\lambda_{W^+}, \lambda_b)$
	$\mathrm{B}^*\,(\lambda_{W^-}, \lambda_{\bar{b}}) = B\,(\lambda_{W^-}, \lambda_{\bar{b}})$
CP$\tilde{T}_{FS}$	$\mathrm{B}^*\,(\lambda_{W^-}, \lambda_{\bar{b}}) = A\,(-\lambda_{W^-}, -\lambda_{\bar{b}})$

Figure Caption

FIG. 1: The two pairs of spherical angles θ_1^t, ϕ_1^t and $\tilde{\theta}_a$, $\tilde{\phi}_a$ describe the two stages in the sequential decay $t \to W^+ b$ followed by $W^+ \to j_{\bar{d}} j_u$, or $W^+ \to l^+ \nu$. The spherical angles $\tilde{\theta}_a$, $\tilde{\phi}_a$ specify the $j_{\bar{d}}$ jet (or the l^+) momentum in the W^+rest frame when the boost is from the t rest frame. For the hadronic W^+ decay mode, we use the notation that the momentum of the charge $\frac{1}{3}e$ jet is denoted by $j_{\bar{d}}$ and the momentum of the charge $\frac{2}{3}e$ jet by j_u. In this figure, ϕ_1^t is shown equal to zero for simplicity of illustration.

Table 2:

	$V \mp A$	$S \pm P$	$g_+ \equiv f_M + f_E$	$g_- \equiv f_M - f_E$
$\mathbf{\Gamma}$'s				
ξ	± 1	± 1	1	-1
ζ	± 0.41	± 1	-0.81	$1/3$
σ	0.41	1	-0.81	$-1/3$
$\mathbf{\Gamma_{LT}}$'s				
ω	± 0.46	0	0.10	-0.22
η	0.46	0	0.10	0.22
ω'	0	0	0	0
η'	0	0	0	0

Table 3:

	SM value	Sensitivity	
	($m_b = 4.5GeV$)	$p\bar{p}$ collider(Tevatron)	pp collider(LHC)
Helicity Parameters			
ξ	0.9993	0.89%	0.16%
ζ	0.4063	2.2%	0.39%
σ	0.4057	3.3%	0.62%
ω	0.4566	33%	2.5%
η	0.4568	7.9%	22%
$Polarized - Partial - Widths$			
Γ_L^+/Γ	0.7029	0.40%	0.070%
Γ_L^-/Γ	0.7028	13%	0.84%
Γ_T^+/Γ	0.2971	0.89%	0.16%
Γ_T^-/Γ	0.2965	1.5%	0.27%
$Non - CKM - type\ CP\ Violation\ Parameters$			
r_a	0.6499	0.84%	0.15%
β_a	0	33^o	9.4^o
$Effective - mass\ scales\ for$ "$New\ Physics$" $from\ Additional\ Lorentz\ Structures$			
ξ	0.9993	$\Lambda_{VorA} > 0.46TeV$	$\Lambda_{VorA} > 1.1TeV$
$Real(g_+)$	0	$\Lambda > 71TeV$	$\Lambda > 750TeV$
$Imag(g_+)$	0	$(\Lambda)^2 > (45TeV)^2$	$(\Lambda)^2 > (110TeV)^2$
$Real(g_-)$	0	$(\Lambda)^2 > (74TeV)^2$	$(\Lambda)^2 > (170TeV)^2$
$Imag(g_-)$	0	$(\Lambda)^2 > (74TeV)^2$	$(\Lambda)^2 > (170TeV)^2$