Top, Polarization, LHC and New Physics

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Polarization observables in top quark decays are sensitive probes of possible new physics contributions to the interactions of the heavy third generation quarks. Within an effective theory approach such new physics contributions can be classified in terms of several higher dimensional operators. We investigate the interplay between indirect constraints on such operators, coming mainly from rare B physics processes, and direct measurements of top polarization observables at the LHC.

1 Introduction

The extensive production of top quarks at the LHC and Tevatron colliders offers the possibility to study tWb interactions with high accuracy. Within the Standard Model (SM) the partial $t \to bW$ decay width and the branching fraction

$$\Gamma(t \to bW)^{\rm SM} \simeq \frac{\alpha |V_{tb}|^2}{16 s_W^2} \frac{m_t^3}{m_W^2}\,, \qquad \mathcal{B}(t \to bW)^{\rm SM} \simeq \frac{|V_{tb}^2|}{|V_{tb}^2| + |V_{ts}^2| + |V_{td}^2|}\,, \tag{1}$$

are sensitive to the value of the CKM matrix element V_{tb}, related to the top-bottom charged current.[1] However, present indirect constraints on V_{tb} within the SM employing CKM unitarity[2] are already much stronger compared to the present[3] and projected[4] experimental direct sensitivity.

Fortunately, helicity fractions of the final state W in this decay provide additional information on the structure of the tWb interaction. Considering leptonically decaying W's, one can define the angle between the charged lepton momentum in the W rest frame and the W momentum in the t-quark rest frame (θ_ℓ^*). Then the normalized differential decay rate for unpolarized top quarks can be written as

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^*} = \frac{3}{8}(1+\cos\theta_\ell^*)^2\mathcal{F}_+ + \frac{3}{8}(1-\cos\theta_\ell^*)^2\mathcal{F}_- + \frac{3}{4}\sin^2\theta_\ell^*\mathcal{F}_L\,, \tag{2}$$

with $\mathcal{F}_i = \Gamma_i/\Gamma$ being the W-boson helicity fractions.[5,6 a] There has been a continuing interest in the measurement of $\mathcal{F}_i$ by the CDF and DØ collaborations at the Tevatron. Their most recent

[a] Note that by definition $\sum_i \mathcal{F}_i = 1$ so that only two of the helicity fractions represent independent observables.

analyses yield [7,8]

$$\mathcal{F}_L^{\rm CDF} = 0.88(13)\,, \qquad \mathcal{F}_L^{\rm D\O} = 0.669(102)\,,$$
$$\mathcal{F}_+^{\rm CDF} = -0.15(9)\,, \qquad \mathcal{F}_+^{\rm D\O} = 0.023(53)\,, \tag{3}$$

where the statistical and systematic uncertainties have been combined in quadrature. Compared to these values, an order of magnitude improvement in precision is expected from the LHC experiments in the coming years. [5,9]

In the SM, simple helicity considerations show that $\mathcal{F}_+$ vanishes at the Born level in the $m_b = 0$ limit. A non-vanishing $\mathcal{F}_+$ could arise from i) $m_b \neq 0$ effects, ii) $\mathcal{O}(\alpha_s)$ radiative corrections due to gluon emission [b], or from iii) non-SM tWb interactions. The $\mathcal{O}(\alpha_s)$ and the $m_b \neq 0$ corrections to $\mathcal{F}_+$ have been shown to occur only at the per-mille level in the SM. [11] Specifically, they yield

$$\mathcal{F}_L^{\rm SM} = 0.687(5)\,, \qquad \mathcal{F}_+^{\rm SM} = 0.0017(1)\,. \tag{4}$$

One could therefore conclude that measured values of $\mathcal{F}_+$ exceeding 0.2% level, would signal the presence of new physics (NP) beyond the SM.

2 Effective theory analysis

The structure of NP contributions possibly affecting $t \to bW$ transitions can be analyzed using effective field theory methods – by introducing the effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i C_i \mathcal{Q}_i + \text{h.c.} + \mathcal{O}(1/\Lambda^3)\,, \tag{5}$$

where $\mathcal{L}_{\rm SM}$ is the SM part, Λ is the scale of NP and $\mathcal{Q}_i$ are dimension-six operators, invariant under SM gauge transformations and consisting of SM fields. In order to exhibit observable effects in the $t \to bW$ decays $\mathcal{Q}_i$ should also not mediate flavor changing neutral currents (FCNCs) in the down sector at the tree-level.[12] Since the SM electroweak symmetry breaking induces misalignment between the up and down quark mass eigenbases via the CKM mechanism, isolating NP effects in tWd_j interactions to a particular single flavor transition in the physical (mass) basis in general requires a large degree of fine-tuning in the flavor structure of the effective operators at the high scale, where they are generated. One possible solution is to require the operators to be flavor aligned with either the up or the down Yukawas of the SM resulting effectively in minimal flavor violating (MFV) scenarios.[13] A systematic analysis of all MFV allowed flavor structures even in the presence of large bottom Yukawa effects yields a total of seven dimension-six effective operators which can significantly affect the tWb interaction [14]

$$\begin{aligned}
\mathcal{Q}_{LL} &= [\bar{Q}'_3 \tau^a \gamma^\mu Q'_3]\big(\phi_d^\dagger \tau^a \mathrm{i} D_\mu \phi_d\big) - [\bar{Q}'_3 \gamma^\mu Q'_3]\big(\phi_d^\dagger \mathrm{i} D_\mu \phi_d\big),\\
\mathcal{Q}_{LRt} &= [\bar{Q}'_3 \sigma^{\mu\nu} \tau^a t_R]\phi_u W^a_{\mu\nu}\,,\\
\mathcal{Q}_{RR} &= V_{tb}[\bar{t}_R \gamma^\mu b_R]\big(\phi_u^\dagger \mathrm{i} D_\mu \phi_d\big)\,,\\
\mathcal{Q}_{LRb} &= [\bar{Q}_3 \sigma^{\mu\nu} \tau^a b_R]\phi_d W^a_{\mu\nu}\,,\\
\mathcal{Q}'_{LL} &= [\bar{Q}_3 \tau^a \gamma^\mu Q_3]\big(\phi_d^\dagger \tau^a \mathrm{i} D_\mu \phi_d\big) - [\bar{Q}_3 \gamma^\mu Q_3]\big(\phi_d^\dagger \mathrm{i} D_\mu \phi_d\big),\\
\mathcal{Q}''_{LL} &= [\bar{Q}'_3 \tau^a \gamma^\mu Q_3]\big(\phi_d^\dagger \tau^a \mathrm{i} D_\mu \phi_d\big) - [\bar{Q}'_3 \gamma^\mu Q_3]\big(\phi_d^\dagger \mathrm{i} D_\mu \phi_d\big),\\
\mathcal{Q}'_{LRt} &= [\bar{Q}_3 \sigma^{\mu\nu} \tau^a t_R]\phi_u W^a_{\mu\nu}\,,
\end{aligned} \tag{6}$$

where we have introduced $Q_3 = (V^*_{kb} u_{Lk}, b_L)$, $Q'_3 = (t_L, V_{ti} d_{iL})$, $\sigma^{\mu\nu} = \mathrm{i}[\gamma^\mu, \gamma^\nu]/2$ and $W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g\epsilon_{abc} W^b_\mu W^c_\nu$. Furthermore, $q_{L(R)} = P_{L(R)} q$ denote the left- and right-handed

[b] Electroweak corrections also contribute, but turn out to be much smaller. [10]

quark fields ($q = u_i, d_i$), where $P_{L(R)} = (1 \mp \gamma_5)/2$, while $\phi_{u,d}$ are the up- and down-type Higgs fields (in the SM $\phi_u = \mathrm{i}\tau^2\phi_d^*$) and g is the weak coupling constant. The first two operators in (6) appear already at zeroth order in the down-type Yukawa insertions, the following two would be linear in a bottom Yukawa expansion, while the remaining three necessarily require the insertion of at least two down-type Yukawa matrices.

In the mass basis all of these operators contribute to the four possible helicity structures of the tWb vertex

$$\mathcal{O}_{L(R)} = \frac{g}{\sqrt{2}} W_\mu^- \left[\bar{b}\gamma^\mu P_{L(R)} t\right] , \qquad \mathcal{O}_{LR(RL)} = \frac{g}{\sqrt{2}} W_{\mu\nu}^- \left[\bar{b}\sigma^{\mu\nu} P_{L(R)} t\right] . \tag{7}$$

However, at the same time they also enter FCNCs in the B meson sector at one-loop resulting in severe constraints from $B \to X_s\gamma$ branching ratio measurements[12] and $B_{s,d}$ meson oscillation observables.[14] Presently, the operator $\mathcal{O}_{LR}$ is least affected by these indirect constraints and thus has the potential to modify the $t \to bW$ decay characteristics in an observable way. However its contributions to $\mathcal{F}_+$ exhibit the same helicity suppression as the SM, mandating the evaluation of $t \to bW$ decay in presence of such NP contributions at next-to-leading order (NLO) in QCD.[15] After taking into account the existing indirect bounds on the operators in (7), contributions of $\mathcal{O}_{LR}$ indeed allow for largest enhancement in $\mathcal{F}_+$, but are still necessarily below 2‰. Turning to $\mathcal{F}_L$, observable effects due to most operators in (7) are again suppressed due to indirect constraints from B FCNCs, with the exception of $\mathcal{O}_{LR}$ where direct measurements at the Tevatron[7,8] are already providing competitive constraints (see figure 1).

3 Interplay with new CP violating contributions in $B_{d,s} - \bar{B}_{d,s}$ oscillations

Recently, possible NP effects in the $B_{d,s} - \bar{B}_{d,s}$, mixing amplitudes have received considerable attention. In particular within the SM, the $B^0 - \bar{B}^0$ mass difference and the time-dependent CP asymmetry in $B \to J/\psi K_s$ are strongly correlated with the branching ratio $\mathrm{Br}(B^+ \to \tau^+\nu)$.[17] The most recent global analyses point to a disagreement of this correlation with direct measurements at the level of 2.9 standard deviations.[16] Similarly in the B_s sector the recently measured CP-asymmetries by the Tevatron experiments, namely in $B_s \to J/\psi\phi$[18] and in dimuonic inclusive decays[19] when combined, deviate from the SM prediction for the CP violating phase in $B_s - \bar{B}_s$ mixing by 3.3 standard deviations.[16]

Anomalous tWd_j interactions offer a possible solution of these anomalies via their contributions to $B_{d,s} - \bar{B}_{d,s}$ oscillation observables at the one-loop level. Within the MFV approach they contribute universally to B_d and B_s mixing amplitudes.[14] Such case has been analyzed in general[16,20] and found consistent with present data. Among the operators in (6), contributions of $\mathcal{Q}_{RR}$ and $\mathcal{Q}_{LRb}$ to $B_{s,d}$ oscillations are severely suppressed by constraints coming from the $B \to X_s\gamma$ decay.[12] On the other hand, contributions of operators $\mathcal{Q}_{LL}$ and $\mathcal{Q}_{LRt}$ cannot introduce new CP violating phases. Namely as shown recently,[21] a necessary condition for new flavor violating structures $\mathcal{Y}_x$ to introduce new sources of CP violation in quark transitions is that $\mathrm{Tr}(\mathcal{Y}_x[Y_u Y_u^\dagger, Y_d Y_d^\dagger]) \neq 0$, where $Y_{u,d}$ are the SM up- and down-quark Yukawa matrices. In MFV models (where $\mathcal{Y}_x$ is built out of Y_u and Y_d) this condition can only be met if $\mathcal{Y}_x$ contains products of both Y_u and Y_d. In (6) this is true for all operators except $\mathcal{Q}_{LL}$ and $\mathcal{Q}_{LRt}$. One can still use the present oscillation data to put bounds on contributions of these two operators. In particular, the resulting indirect constraint on the $\mathcal{O}_{LR}$ structure contributing to $t \to bW$ decay is comparable to both, the indirect $B \to X_s\gamma$ bound due to the same $\mathcal{Q}_{LRt}$ operator, as well the present direct $\mathcal{F}_L$ measurements as shown in figure 1. The remaining three operators in (6), $\mathcal{Q}_{LL}^{\prime(\prime\prime)}$ and $\mathcal{Q}'_{LRt}$ can contribute with new CP violating phases and are not overly constrained by the $B \to X_s\gamma$ decay rate measurement.[14] As such they can account for the recently observed anomalies in the CP violating observables related to $B_{s,d} - \bar{B}_{s,d}$ mixing.

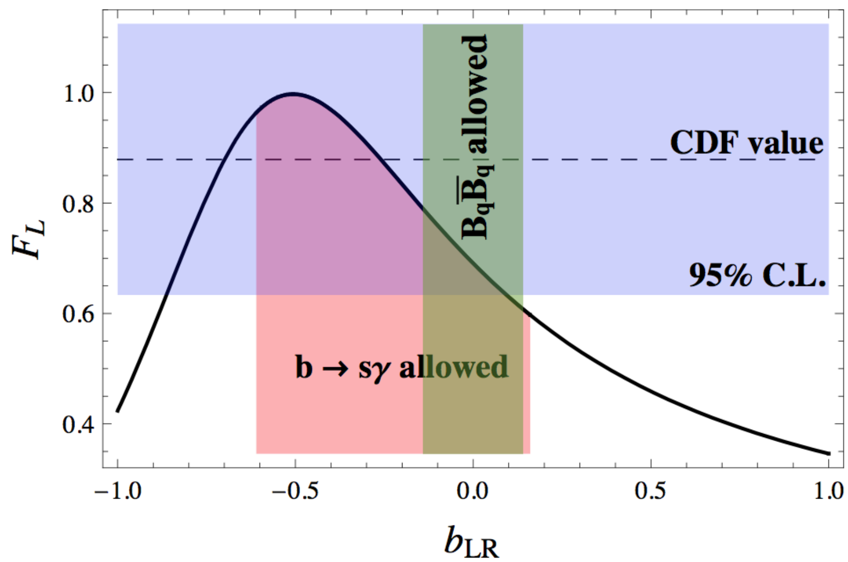

Figure 1: Prediction of $\mathcal{F}_L$ as a function of the normalized Wilson coefficient $b_{LR} = C_{LRt} v m_t/\Lambda^2$, where $v =$ 246 GeV corresponding to the effective operator $\mathcal{Q}_{LRt}$ in (6) (other possible NP contributions being set to zero). Red band below the full curve shows the allowed interval for b_{LR} as given by the $B \to X_s\gamma$ analysis while the vertical green band denotes values allowed $B_{s,d}$ oscillation data, both at 95% C.L.. For comparison, we also show the recent CDF measurement of $\mathcal{F}_L$ given in eq. (3) (horizontal blue shaded region).

Finally, one can try to predict the effects of effective operators in (6) on the helicity fractions of the W boson in the $t \to bW$ decay channel, provided these same operators are responsible for new CP violating contributions in $B_{d,s}$ meson mixing. Both $\mathcal{Q}_{LL}^{\prime(\prime\prime)}$ have the same chiral structure as the SM contribution and thus cannot affect the helicity fractions. They only yield small corrections to the total $t \to bW$ decay rate. On the other hand $\mathcal{Q}'_{LRt}$ contributes to the helicity structure $\mathcal{O}_{LR}$. Under its influence, $\mathcal{F}_{L,+}$ can deviate by as much as 15% and 30% respectively compared to the SM predictions, although much smaller deviations are perfectly consistent with the ranges for the relevant Wilson coefficient of $\mathcal{Q}'_{LRt}$ preferred by the $B_{d,s}$ mixing analysis. A robust prediction that can be made however is that at least one of the two independent helicity fractions ($\mathcal{F}_{L,+}$) needs to deviate by at least 5% from the corresponding SM prediction. While this is clearly beyond the reach of the LHC experiments for the $\mathcal{F}_+$, it is comparable to the expected precision for $\mathcal{F}_L$.[9]

4 Conclusions

Polarization observables in $t \to bW$ decay as represented by the W helicity fractions $\mathcal{F}_i$ can probe the structure of the tWb vertex and are thus sensitive probes of possible new contributions to top quark interactions beyond the SM. Such effects can be analyzed using effective theory methods in terms of contributions of higher dimensional effective operators. Within the paradigm of MFV they can also be correlated with other observables, sensitive to new flavor violating contributions, in particular FCNC processes in the down sector. Then, indirect bounds from $B \to X_s\gamma$ disfavor significant deviations in the $\mathcal{F}_+$ helicity fraction for individual contributions of dimension-six effective operators, even after taking into account possible significant enhancements due to QCD corrections. On the other hand, the current measurements of $\mathcal{F}_L$ are already competitive with B physics observables in constraining the effective tWb dipole interactions.

Anomalous tWd_j interactions can also affect $B_{s,d} - \bar{B}_{s,d}$ mixing phenomenology at one loop.

The associated CP violating observables are particularly interesting to consider in light of recently reported anomalies in both $B_{s,d}$ sectors. Within MFV and up to $\mathcal{O}(m_s/m_b)$ suppressed effects, contributions induced via new tWd_j interactions to $B_{s,d}$ mixing amplitudes are universal. Upon single insertions of individual dimension-six effective operators contributing to tWb interactions, they yield constraints comparable in some cases to $B \to X_s\gamma$ and current direct measurements of $\mathcal{F}_i$. On the other hand, taking into account possible large bottom Yukawa effects, several of the MFV allowed effective operators can accommodate the CP violating anomalies and be consistent with constraints from $B \to X_s\gamma$ decay rate measurements. Unfortunately among these possibilities, only one operator predicts observable effects in $t \to bW$ decay. In particular, at least one of the two independent W helicity fractions $\mathcal{F}_{L,+}$ needs to deviate by at least 5% if this (dipole) operator is solely responsible for the new CP violating effects in $B_{s,d}$ oscillations. In the future, such CP violating contributions might nonetheless be probed more directly in decays of polarized top quarks, where it is possible to define sensitive CP violating helicity observables.[22] Such effects could possibly be measured in single top production at the LHC.

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