TTP09-24

Effects of right-handed charged currents on the determinations of $|V_{ub}|$ and $|V_{cb}|$

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(Dated: July 14, 2009)

We study the effect of a right-handed coupling of quarks to the W-boson on the measurements of $|V_{ub}|$ and $|V_{cb}|$. It is shown that such a coupling can remove the discrepancies between the determinations of $|V_{ub}|$ from $B \to \pi\ell\nu$, $B^+ \to \tau^+\nu$ and $B \to X_u\ell\nu$. Further the measurements of $|V_{cb}|$ from $B \to D^*\ell\nu$, $B \to D\ell\nu$ and inclusive $B \to X_c\ell\nu$ decays can be brought into better agreement. We demonstrate that a right-handed coupling can be generated within the MSSM by a finite gluino-squark loop. The effect involves the parameters ${\delta^u_{23}}^{RL}$ and ${\delta^u_{13}}^{RL}$ of the squark mass matrices, which are poorly constrained from other processes. On the other hand, all gluino-squark corrections to the regular left-handed coupling of the W-boson are found to be too small to be relevant.

PACS numbers: 10.10.Gh, 12.60.Jv, 14.40.Nd, 14.70.Fm, 14.80.Ly

I. INTRODUCTION

In the Standard Model (SM) with its gauge group $\mathrm{SU(3)_C} \times \mathrm{SU(2)_L} \times \mathrm{U(1)}$ the tree-level W coupling has a pure $V - A$ structure meaning that all charged currents are left-handed. Right-handed charged currents were first studied in the context of left-right symmetric models [1] which enlarge the gauge group by an additional $SU(2)_R$ symmetry between right-handed doublets. In these models new right-handed gauge bosons W_R, Z_R appear and the physical SM-like W-boson has a dominant left-handed component with a small admixture of W_R. The latter will generically lead to small right-handed couplings to both quarks and leptons. The right-handed mass scale inferred from today's knowledge on neutrino masses is so large that all right-handed gauge couplings are undetectable. Most of these couplings are further experimentally strongly constrained [2]. A different source of right-handed couplings of quarks to the W-boson can be loop effects, which generate a dimension-6 quark-quark-W vertex. In this case no right-handed lepton couplings occur, as long as the neutrinos are assumed left-handed. A generic analysis of such higher-dimensional right-handed couplings has been studied in Ref. [3] aiming at a better understanding of $K \to \pi\mu\nu$ data.

We will investigate the effect of a right-handed W-coupling on the extraction of $|V_{ub}|$ and $|V_{cb}|$ in section II and show that current tensions between SM and data can be removed. In section III we will calculate the loop-corrected W-coupling in the generic Minimal Supersymmetric Standard Model (MSSM). We find that the right-handed W-coupling can be as large as 20% and brings the different determinations of $|V_{ub}|$ into perfect agreement. The effect on $|V_{cb}|$ is at most around 2%, which alleviates the tension studied in Sect. II. Finally we conclude.

II. RIGHT-HANDED W COUPLINGS

An appropriate framework for our analysis is an effective Lagrangian. Following the notation of Ref. [4], we write

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_i C_i^{(5)} Q_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} Q_i^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right), \tag{1}$$

here $\mathcal{L}_{\rm SM}$ is the Standard Model (SM) Lagrangian, while $Q_i^{(n)}$ stand for dimension-n operators built out of the SM fields and are invariant under the SM gauge symmetries. Such an effective theory approach is appropriate for any SM extension in which all new particles are sufficiently heavy ($M_{\rm new} \sim \Lambda \gg m_t$). As long as only processes with momentum scales $\mu \ll \Lambda$ are considered, all heavy degrees of freedom can be eliminated [5], leading to the effective theory defined in (1). The operators $Q_i^{(5)}$ and $Q_i^{(6)}$ have been completely classified in Ref. [6]. Since $Q_i^{(5)}$ involve no quark fields, they are not needed for our further discussion, and we skip the superscripts "(6)" at the dimension-six operators and the associated Wilson coefficients C_i. In this article, we need the following dimension-six operator describing anomalous right-handed W-couplings to quarks:

$$Q_{RR} = \bar{u}_f \gamma^\mu P_R d_i \left(\tilde{\phi}^\dagger i D^\mu \phi\right) + h.c. \tag{2}$$

where ϕ denotes the Higgs doublet and $\widetilde{\phi} = i\tau^2\phi^*$. The Feynman rule for the W-u_f-d_i interaction vertex,

$$\frac{-ig_2\gamma^\mu}{\sqrt{2}}\left(V^L_{fi}P_L + V^R_{fi}P_R\right), \tag{3}$$

is found by combining the usual SM interaction with the extra contributions that are obtained by setting the Higgs field in Eq. (2) to its vacuum expectation value. In Eq. (3) V^L_{fi} and V^R_{fi} denote elements of the effective

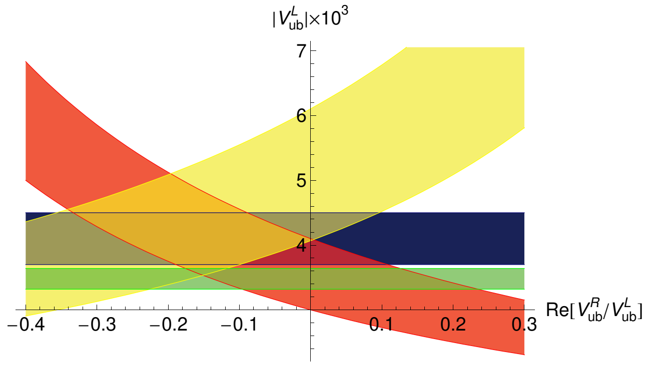

FIG. 1: $\left|V_{ub}^L\right|$ as a function of $\mathrm{Re}\left[\mathrm{V}_{\mathrm{ub}}^{\mathrm{R}}/\mathrm{V}_{\mathrm{ub}}^{\mathrm{L}}\right]$ extracted from different processes. Blue(darkest): inclusive decays. Red(gray): $B \to \pi l \nu$. Yellow(lightest gray): $B \to \tau\nu$. Green(light gray): V_{ub}^L determined from CKM unitarity.

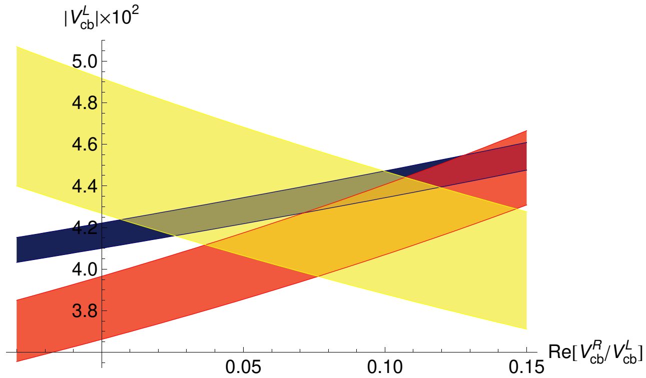

FIG. 2: $\left|V_{cb}^L\right|$ as a function of $\mathrm{Re}\left[\mathrm{V}_{\mathrm{cb}}^{\mathrm{R}}/\mathrm{V}_{\mathrm{cb}}^{\mathrm{L}}\right]$ extracted from different processes. Blue(darkest): inclusive decays. Red(gray): $B \to D^* l\nu$. Yellow(light gray): $B \to Dl\nu$.

CKM matrices, which are not necessarily unitary. V_{fi}^R is related to the Wilson coefficient in Eq. (1) via

$$V_{fi}^R = \frac{C_{RR}}{2\sqrt{2}G_F\Lambda^2}. \tag{4}$$

V_{fi}^L receives contributions from the tree-level CKM matrix and the LL analogue of Q_{RR} in Eq. (2).

Right-handed couplings to light quarks have been studied in Ref. [3]. Ref. [7] examines such couplings in inclusive b→c transitions. In Ref. [4] it was pointed out that very strong constraints can be obtained on V_{tb}^R from $b \to s\gamma$, because the usual helicity suppression factor of m_b/M_W is absent in the right-handed contribution. By the same argument V_{ts}^R (or V_{td}^R if one considers $b \to d\gamma$) is tightly constrained. Large effects concerning transitions between the first two generations are unlikely, because V_{us}^L and V_{cd}^L are larger than other off-diagonal CKM elements. Further deviations from Minimal Flavour Violation (MFV), i.e. deviations from Yukawa-driven flavour transitions, are unlikely in the first two generations, but plausible with respect to transitions involving the third generation [8]. We therefore focus our attention on the remaining two elements V_{ub}^R and V_{cb}^R.

A. Determination of V_{ub}^L and V_{cb}^L

The experimental determination of $|V_{ub}|$ and $|V_{cb}|$ from both inclusive and exclusive B decays is a mature field by now [2]. More recently, also the leptonic decay $B \to \tau\nu_\tau$ is studied in the context of V_{ub}. To discuss the impact of right-handed currents we denote the CKM element extracted from data with SM formula by V_{qb}, where $q = u$ or $q = c$. If the matrix element of a considered exclusive process is proportional to the vector current, V_{qb}^L and V_{qb}^R enter with the same sign and the "true" value of V_{qb}^L in the presence of V_{qb}^R is given by:

$$V_{qb}^L = V_{qb} - V_{qb}^R \tag{5}$$

For processes proportional to the axial-vector current V_{qb}^R enters with the opposite sign as V_{qb}^L, so that

$$V_{qb}^L = V_{qb} + V_{qb}^R. \tag{6}$$

In inclusive decays the interference term between the left-handed and right-handed contributions is suppressed by a factor of m_q/m_b, so that it is irrelevant in the case of V_{ub} and somewhat suppressed in the case of V_{cb}. The remaining dependence on V_{qb}^R is quadratic and therefore negligible.

Starting with $|V_{ub}|$, we note that the determinations from inclusive and exclusive semileptonic decays agree within their errors, but the agreement is not perfect [2, 9]. The analysis of $B \to \tau\nu$ is affected by the uncertainty in the decay constant f_B. Within errors the three determination of $|V_{ub}|$ are compatible, as one can read off from Fig. 1. The picture looks very different once the information from a global fit to the unitarity triangle (UT) is included: As pointed out first by the CKMFitter group, the measured value of $B \to \tau\nu$ suffers from a tension with the SM of 2.4–2.7σ [9]. First, the global UT fit gives a much smaller error on $|V_{ub}|$ (as a consequence of the well-measured UT angle β); the corresponding value is also shown in Fig. 1. Second, the data on $B_d - \overline{B}_d$ mixing exclude very large values for f_B, which in turn cut out the lower part of the yellow (light gray) region in Fig. 1. Essentially we realise from Fig. 1 that we can remove this tension while simultaneously bringing the determinations of $|V_{ub}|$ from inclusive and exclusive semileptonic decays into even better agreement. For this the right-handed component must be around $\mathrm{Re}\,(V_{ub}^R/V_{ub}^L) \approx -0.15$. Since new physics may as well affect the other quantities entering the UT, a more quantitative statement requires the consideration of a definite model.

Next we turn to $|V_{cb}|$: The relative uncertainties in the exclusive decays $B \to D^* l\nu$ and $B \to Dl\nu$ and in the inclusive $B \to X_c\ell\nu$ analyses are much smaller than in the $b \to u$ decays considered above. We remark here that $B \to Dl\nu$ only involves the vector current so that Eq. (5) applies. $B \to D^* l\nu$ receives contributions from

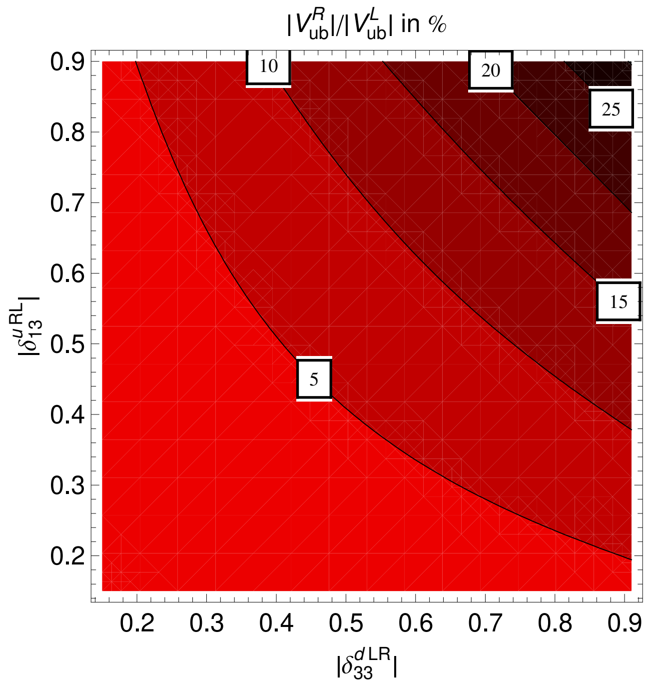

FIG. 3: Relative strength of the induced right-handed coupling $|V^R_{ub}|$ with respect to $|V^L_{ub}|$ for $M_{\rm SUSY} = 1\,{\rm TeV}$. $|V^L_{ub}|$ is determined from CKM unitarity.

both vector and axial vector currents, but the contribution from the vector current is kinematically suppressed in the kinematic endpoint region used for the extraction of $|V_{cb}|$. Therefore Eq. (6) applies to $B \to D^* l\nu$. The impact of a right-handed current on $B \to X_c \ell\nu$ has been calculated in Ref. [7]. Fig. 2 shows that the agreement among the three values of $|V_{cb}|$ obtained from these decay modes is not totally satisfactory within the SM. One further realises that we can reduce the discrepancy to less than 1σ if a right-handed coupling in the range $0.07 \leq {\rm Re}\,[V^R_{cb}/V^L_{cb}] \leq 0.12$ is present.

III. MSSM RENORMALIZATION OF THE QUARK-QUARK-W VERTEX

In Ref. [8] the renormalization of the quark-quark-W vertex by chirally enhanced supersymmetric self-energies has been computed. The results imply new bounds on the off-diagonal elements of the squark mass matrices if t'Hooft's naturalness criterion is invoked. In this section we extend the analysis of [8] and calculate the leading contributions to the quark-quark-W vertex which decouple for $M_{\rm SUSY} \to \infty$. Using the conventions of Ref. [8] we expand to first oder in the external momenta and decompose the self-energies as

$$\Sigma^q_{fi} = \left(\Sigma^{q\,LR}_{fi} + \not p\,\Sigma^{q\,RR}_{fi}\right) P_R + \left(\Sigma^{q\,RL}_{fi} + \not p\,\Sigma^{q\,LL}_{fi}\right) P_L . \tag{7}$$

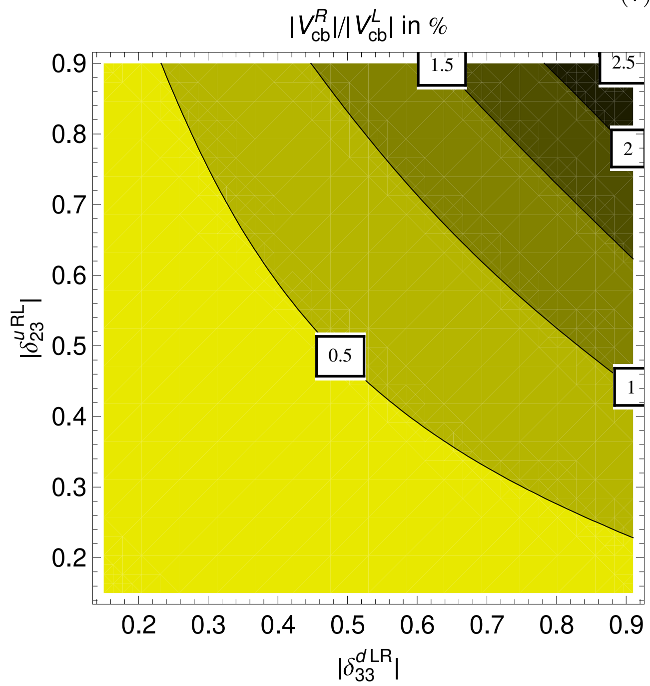

FIG. 4: Same as Fig. 3 for V^R_{cb}.

These self-energies lead to a flavour-valued wave-function renormalization $\Delta U^{q\,L,R}_{fi}$ for all external left and right-handed fields. It is useful to decompose these factors further in to a unphysical anti-hermitian part $\Delta U^{q\,L\,A}_{fi}$, which can be absorbed into the renormalization of the CKM matrix, and a hermitian part $\Delta U^{q\,L\,H}_{fi}$ which constitutes a physical effect appearing as a deviation from CKM unitarity.

$$\begin{aligned}
\Delta U^{q\,L\,A}_{fi} &= \frac{\Delta U^{q\,L}_{fi} - \Delta U^{q\,l\dagger}_{fi}}{2} = \frac{1}{m^2_{q_i} - m^2_{q_f}} \left(m_{q_i} m_{q_f} \Sigma^{q\,RR}_{fi} + \frac{m^2_{q_i} + m^2_{q_f}}{2} \Sigma^{q\,LL}_{fi} + m_{q_i} \Sigma^{d\,LR}_{fi} + m_{q_f} \Sigma^{d\,RL}_{fi} \right) \\
\Delta U^{q\,L\,H}_{fi} &= \frac{\Delta U^{q\,L}_{fi} + \Delta U^{q\,L\dagger}_{fi}}{2} = \frac{\Sigma^{q\,LL}_{fi}}{2}
\end{aligned} \tag{8}$$

For the analogous expression for the right-handed fields exchange L and R in Eq. (8). Neglecting external momenta, the genuine vertex-correction originating from a squark-gluino loop is given by

$$-i\Lambda^{W\,\tilde{g}}_{u_f d_i} = \frac{g_2}{\sqrt{2}}\frac{i\alpha_s}{3\pi}\gamma^\mu \sum_{s,t=1}^{6}\sum_{j,k=1}^{3}\Big(W^{\tilde{u}}_{fs}W^{\tilde{u}*}_{ks}V^L_{kj}W^{\tilde{d}}_{jt}W^{\tilde{d}*}_{it}P_L + W^{\tilde{u}}_{f+3,s}W^{\tilde{u}*}_{ks}V^L_{kj}W^{\tilde{d}}_{jt}W^{\tilde{d}*}_{i+3,t}P_R\Big)C_2\left(m_{\tilde{u}_s}, m_{\tilde{d}_t}, m_{\tilde{g}}\right). \quad (9)$$

The matrices $W^{\tilde{q}}_{st}$ diagonalize the squark mass matrices [8]. There are several important properties of Eq. (9):

- The part proportional to the left-handed projector P_L cancels with the anti-hermitian part of the wave-function renormalization because of the SU(2) relation between the left-handed up and down squarks for $M_{\rm SUSY} \to \infty$, in accordance with the decoupling theorem [5]. Since the loop functions depend only weakly on $M_{\rm SUSY}$, the cancellation is very efficient, even for light squarks around 300 GeV.

- A right-handed coupling of quarks to the W boson is induced if left-right mixing of squarks is present. The effective coupling corresponds to Q_{RR} in Eq. (2) and vanishes in the decoupling limit. There is no wave-function renormalization for right-handed (massless) quark fields and no gauge cancellations occur.

We show the relative size of the right-handed coupling involving u and b (c and b) in Fig. 3 (Fig. 4) plotting ${\delta^u_{13}}^{RL}$ (${\delta^u_{23}}^{RL}$) vs. ${\delta^d_{33}}^{LR}$. Note that the flavour-changing mass insertion ${\delta^u_{13}}^{RL}$ (${\delta^u_{23}}^{RL}$) is neither constrained from the fine-tuning argument imposed in [8] nor severely restricted by FCNC processes [10]. For this reason the possible size of V^R_{ub} (V^R_{cb}) can be large enough to explain (attenuate) the apparent discrepancies among the various determinations of $|V_{ub}|$ ($|V_{cb}|$).

IV. CONCLUSIONS

In this article we have first examined the effect of an effective right-handed coupling of quarks to the W boson on the determination of $|V_{ub}|$ and $|V_{cb}|$ from different decay modes. In both cases a right-handed coupling can improve the agreement among these determinations (Figs. 1 and 2). In particular, one can simultaneously remove the disturbing problem with $B \to \tau\nu_\tau$ [9] and improve the agreement among inclusive and exclusive determinations of $|V_{ub}|$. Second, we have shown that a loop-induced right-handed coupling is generated within the MSSM if left-right mixing of squarks is present. This coupling has the right size needed to resolve the tensions in $|V_{ub}|$. Such a scenario involves a large left-right mixing between sbottoms (as present in e.g. the popular large-$\tan\beta$ scenarios) and a large A^u_{31}-term which might be observable at the LHC [10]. In $b \to c$ transitions the loop-induced supersymmetric right-handed coupling can alleviate, but cannot fully remove, the discrepancies among the three methods to determine $|V_{cb}|$. To probe $b \to u$ transitions we propose to look for right-handed couplings in the differential decay distributions of $B \to \rho\ell\nu_\ell$. The smaller right-handed component in $b \to c$ transitions can be probably better studied in $B \to X_c\ell\nu$ [7] than in $B \to D^*\ell\nu$ decays, because a theoretical control of form factors to percent accuracy is challenging.

Acknowledgments

I like to thank Lars Hofer, Mikolaj Misiak, and Ulrich Nierste for helpful discussions and proofreading the article. This work is supported by BMBF grants 05HT6VKB and 05H09VKF and by the EU Contract No. MRTN-CT-2006-035482, "FLAVIAnet".

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