Abstract

The dominant theoretical uncertainty in extracting $|V_{td}/V_{ts}|$ from the ratio of branching ratios $R_{\rho/\omega} \equiv \mathcal{B}(B \to (\rho, \omega)\gamma)/\mathcal{B}(B \to K^*\gamma)$ is given by the ratio of form factors $\xi_\rho \equiv T^{B \to K^*}(0)/T^{B \to \rho}(0)$. We find $\xi_\rho = 1.17 \pm 0.09$ from QCD sum rules on the light-cone. Using QCD factorisation for the branching ratios, including the most dominant power-suppressed effects beyond QCD factorisation, and the current experimental results for $R_{\rho/\omega}$, this translates into $|V_{td}/V_{ts}|_{\text{BaBar}} = 0.199^{+0.023}_{-0.025}\text{(exp)} \pm 0.014\text{(th)}$, which corresponds to $\gamma_{\text{BaBar}} = (61.0^{+13.5}_{-16.0}\text{(th)}^{+8.9}_{-9.3}\text{(th)})$, and $|V_{td}/V_{ts}|_{\text{Belle}} = 0.207^{+0.028}_{-0.033}\text{(exp)}^{+0.014}_{-0.015}\text{(th)}$, $\gamma_{\text{Belle}} = (65.7^{+17.3}_{-20.7}\text{(exp)}^{+8.9}_{-9.2}\text{(th)})$. 

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Both BaBar and Belle have seen the $b \to d$ penguin-dominated decays $B \to (\rho, \omega)\gamma$. Assuming the Standard Model (SM) to be valid, these processes offer the possibility to extract the CKM matrix element $|V_{td}|$, in complementarity to the determination from $B_d$ mixing and the SM unitarity triangle based on $|V_{ub}/V_{cb}|$ and the angle $\gamma$. In order to extract $|V_{td}|$ from the measured rate, one needs to know both short-distance weak and strong interaction effects and long-distance QCD effects. Whereas the former can, at least in principle, be calculated to any desired precision in the framework of effective field theories, and actually are currently known to (almost) NNLO in QCD [3], the assessment of long-distance QCD effects has been notoriously difficult. A solution to this problem is provided by QCD factorisation (QCDF) [4, 5], a consistent framework allowing one to write the relevant hadronic matrix elements as

$$\langle V | Q_i | B \rangle \equiv \left[ T_{B \to V 1}^{B \to V}(0) T_i^I + \int_0^1 d\xi \, du \, T_{II}^I(\xi, u) \, \phi_B(\xi) \, \phi_{V;\perp}(v) \right] \cdot \epsilon . \tag{1}$$

Here $\epsilon$ is the photon polarisation 4-vector, $Q_i$ is one of the operators in the effective Hamiltonian, $T_{B \to V 1}^{B \to V}$ is a $B \to V$ transition form factor, and $\phi_B, \phi_{V;\perp}$ are leading-twist light-cone distribution amplitudes (DAs) of the $B$ meson and the vector meson $V$, respectively. These quantities are universal non-perturbative objects and describe the long-distance dynamics of the matrix elements, which is factorised from the perturbative short-distance interactions included in the hard-scattering kernels $T_i^I$ and $T_{II}^I$. The above QCDF formula is valid in the heavy-quark limit $m_b \to \infty$ and is subject to corrections of order $\Lambda_{QCD}/m_b$.

Although it is possible to determine $|V_{td}|$ from the branching ratio of $B \to (\rho, \omega)\gamma$ itself, the associated theoretical uncertainties get greatly reduced when one considers the ratio of branching ratios for $B \to K^*\gamma$ and $B \to (\rho, \omega)\gamma$ instead. One then can extract $|V_{td}|/|V_{ts}|$ from

$$\frac{\mathcal{B}(B \to (\rho, \omega)\gamma)}{\mathcal{B}(B \to K^*\gamma)} = \frac{|V_{td}|^2}{|V_{ts}|^2} \left( \frac{1 - m_{\rho,\omega}^2/m_B^2}{1 - m_{K^*}^2/m_B^2} \right)^3 \left( \frac{T_{\rho,\omega}^{K^*}(0)}{T_{\rho,\omega}^{K^*}(0)} \right)^2 \left[ 1 + \Delta R \right] ; \tag{2}$$

$\Delta R$ contains all non-factorisable effects induced by $T_i^{I,II}$ in (1). The theoretical uncertainty of this determination is governed by both the ratio of form factors $T_{\rho,\omega}^{K^*}(0)/T_{\rho,\omega}^{K^*}(0)$ and the value of $\Delta R$, which parametrises not only SU(3)-breaking effects, but also power-suppressed corrections to QCDF. In this talk, I report the results of a recent calculation of both the form factor ratios and the $\Delta R$ term, including effects beyond QCDF, see Refs. [6, 7, 8].

We have calculated $T_1$ previously, in Refs. [9], using the method of QCD sum rules on the light-cone. Here, we focus on the ratios

$$\xi_\rho \equiv \frac{T_{1}^{B \to K^*}(0)}{T_{1}^{B \to \rho}(0)} , \quad \xi_\omega \equiv \frac{T_{1}^{B \to K^*}(0)}{T_{1}^{B \to \omega}(0)} , \tag{3}$$

which govern the extraction of $|V_{ts}/V_{td}|$ from $B \to V\gamma$ decays. Compared with our previous results of Ref. [9], we implement the following improvements:

- updated values of SU(3)-breaking in twist-2 parameters [10, 11];
- complete account of SU(3)-breaking in twist-3 and -4 DAs [12];
NLO evolution for twist-2 parameters.

The sum rules can of course be used to determine each form factor separately, but it turns out that the ratio is more accurate, because $\xi_{\rho,\omega}$ is independent of the $B$-meson decay constant $f_B$ and also, to very good accuracy, of $m_b$ and the sum rule parameters $M^2$ and $s_0$, i.e. a good part of the systematic uncertainties of the method cancel. However, $\xi_{\rho,\omega}$ is very sensitive to SU(3)-breaking effects in the DAs, and it is precisely these effects we shall focus on in this paper. A similar analysis for the ratio of the $D \to K$ and $D \to \pi$ form factors was carried out in Ref. [13].

Let us now discuss the results for $\xi_{\rho}$ and their uncertainty. The light-cone sum rule for $\xi_{\rho}$, Ref. [6], depends on sum-rule specific parameters, the Borel parameter $M^2$ and the continuum threshold $s_0$, and on hadronic input parameters, i.e. decay constants $f_{\rho, K^*}$, Gegenbauer moments of twist-2 light-cone DAs of the $\rho$ and $K^*$, $a_{1,2}^{\parallel,\perp} (\rho, K^*)$, and parameters describing twist-3 and 4 DAs. In Fig. 1 we plot the dependence of $\xi_{\rho}$ on the Borel parameter and the continuum threshold. The curves are very flat, which indicates that the systematic uncertainties of the light-cone sum rule approach cancel to a large extent in the ratio of SU(3)-related form factors. In Fig. 2 we plot $\xi_{\rho}$ as a function of $f_{\perp}^{K^*}$, for various values of $f_{\perp}^{\rho}$. The uncertainty in both parameters causes an uncertainty in $\xi_{\rho}$ of $\pm 0.08$. In Fig. 3 left panel, we show the dependence of $\xi_{\rho}$ on $a_1(K^*)$, which induces a change in $\xi_{\rho}$ by $\pm 0.03$. The right panel shows the dependence on $a_2$ which is rather mild and causes $\xi_{\rho}$ to change by $\pm 0.02$. The variation of the remaining parameters within their respective limits causes another $\pm 0.02$ shift in $\xi_{\rho}$, so that we arrive at the following result [6]:

$$\xi_{\rho} = \frac{T_{1}^{B\to K^*}(0)}{T_{1}^{B\to \rho}(0)} = 1.17 \pm 0.08(f_{\perp}^{K^*}) \pm 0.03(a_1) \pm 0.02(a_2) \pm 0.02(\text{twist-3 and -4})$$

$$\pm 0.01(\text{sum-rule parameters, } m_b \text{ and twist-2 and -4 models})$$

$$= 1.17 \pm 0.09 .$$

The total uncertainty of $\pm 0.09$ is obtained by adding the individual terms in quadrature. $\xi_{\rho}$ was also obtained from a quenched lattice calculation [16]: $\xi_{\rho,\text{latt}} = 1.2 \pm 0.1$, which agrees with our result. An analogous calculation of $\xi_{\omega}$ yields [8]:

$$\xi_{\omega} = \frac{T_{1}^{B\to K^*}(0)}{T_{1}^{B\to \omega}(0)} = 1.30 \pm 0.10 .$$

Let us now turn to the calculation of the ratio of branching ratios and the determination of $|V_{td}/V_{ts}|$. BaBar and Belle have measured the quantity

$$R_{\rho/\omega} \equiv \frac{\overline{B}(B \to (\rho, \omega)\gamma)}{\overline{B}(B \to K\gamma)} ,$$

where $\overline{B}(B \to (\rho, \omega)\gamma)$ is defined as the CP-average $\frac{1}{2} [\mathcal{B}(B \to (\rho, \omega)\gamma) + \mathcal{B}(\bar{B} \to (\bar{\rho}, \omega)\gamma)]$ of

$$\mathcal{B}(B \to (\rho, \omega)\gamma) = \frac{1}{2} \left\{ \mathcal{B}(B^+ \to \rho^+\gamma) + \frac{T_{B^0}^{\rho^+}}{T_{B^0}^{\rho^0}} \left[ \mathcal{B}(B^0 \to \rho^0\gamma) + \mathcal{B}(B^0 \to \omega\gamma) \right] \right\} ,$$

$\mathcal{B}(\bar{B} \to (\bar{\rho}, \omega)\gamma)$...
Figure 1: Left panel: $\xi_\rho$ as a function of the Borel parameter $M^2$ for $s_0 = 35$ GeV$^2$ and central values of the input parameters. Right panel: $\xi_\rho$ as a function of the continuum threshold $s_0$ for $M^2 = 8$ GeV$^2$ and central values of the input parameters. Solid lines: DAs in conformal expansion; long dashes: BT model [14] for twist-2 DAs; short dashes: BT model for twist-2 DAs and renormalon model for twist-4 DAs [15].

Figure 2: $\xi_\rho$ as a function of $f_{K^*}^\perp(1$ GeV$)$. Solid line: $f_{\rho}^\perp(1$ GeV$) = 0.165$ GeV, dashed lines: $f_{\rho}^\perp$ shifted by $\pm 0.009$ GeV.

Figure 3: Left panel: $\xi_\rho$ as a function of $a_1(K^*)$ at 1 GeV. Right panel: $\xi_\rho$ as a function of $a_2(\rho)$ at 1 GeV. Solid line: $a_2(K^*) = a_2(\rho) - 0.04$; dashed lines: $a_2(K^*)$ shifted by $\pm 0.02$. Longitudinal and transverse parameters $a_i^\parallel$ and $a_i^\perp$ are set equal.
and \( \mathcal{B}(B \to K^*\gamma) \) is the isospin- and CP-averaged branching ratio of the \( B \to K^*\gamma \) channels. The experimental results are [1] [2]

\[
R_{\text{exp}}^{\text{BaBar}} = 0.030 \pm 0.006, \quad R_{\text{exp}}^{\text{Belle}} = 0.032 \pm 0.008.
\]

As for the theoretical prediction of \( R_{\rho,\omega} \), it turns out that the exclusive \( B \to V\gamma \) process is actually described by two physical amplitudes, one for each polarisation of the photon:

\[
\mathcal{A}_{L(R)} = \mathcal{A}(B \to V\gamma_{L(R)}), \quad \mathcal{A}_{L(R)} = \mathcal{A}(B \to \bar{V}\gamma_{L(R)}),
\]

where \( \bar{B} \) denotes a \((b\bar{q})\) and \( V \) a \((D\bar{q})\) bound state. In the notation introduced in Ref. [5] in the context of QCDF, the decay amplitudes can be written as

\[
\mathcal{A}_{L(R)} = \frac{G_F}{\sqrt{2}} \left( \lambda_q^D a_{7L(R)}^u V\gamma_{L(R)} + \lambda_q^D a_{7L(R)}^c V\gamma_{L(R)} \right) \langle V\gamma_{L(R)} | Q_7^{L(R)} | \bar{B} \rangle
\]

\[
= \frac{G_F}{\sqrt{2}} \left( \lambda_q^D a_{7L(R)}^u (V) + \lambda_q^D a_{7L(R)}^c (V) \right) \langle V\gamma_{L(R)} | Q_7^{L(R)} | \bar{B} \rangle,
\]

and analoguously for \( \mathcal{A}_{L(R)} \). The \( \lambda_q^D, D = s, d \) are products of CKM matrix elements. The \( a_{7L(R)}^c \) calculated in Refs. [5], coincide, to leading order in \( 1/m_b \), with our \( a_{7L}^U \), whereas \( a_{7R}^U \) are set zero in [5]. Our expression (8) is purely formal and does not imply that the \( a_{7R(L)}^U \) factorise at order \( 1/m_b \). As a matter of fact, they don’t. The operators \( Q_7^{L(R)} \) are given by

\[
Q_7^{L(R)} = \frac{e}{8\pi^2} m_b \bar{D} \sigma_{\mu\nu} (1 \pm \gamma_5) b F^{\mu\nu}
\]

and generate left- (right-) handed photons in the decay \( b \to D\gamma \). We split the factorisation coefficients into three separate contributions:

\[
a_{7L}^U (V) = a_{7L}^{U,\text{QCDF}} (V) + a_{7L}^{U,\text{ann}} (V) + a_{7L}^{U,\text{soft}} (V) + \ldots,
\]

\[
a_{7R}^U (V) = a_{7R}^{U,\text{QCDF}} (V) + a_{7R}^{U,\text{ann}} (V) + a_{7R}^{U,\text{soft}} (V) + \ldots,
\]

where \( a_{7L}^{U,\text{QCDF}} \) is the leading term in the \( 1/m_b \) expansion; all other terms are suppressed by at least one power of \( m_b \). We only include those power-suppressed terms that are either numerically large or relevant for certain observables. The dots denote terms of higher order in \( \alpha_s \) and further \( 1/m_b \) corrections to QCDF, most of which are uncalculable. The superscript “ann” denotes the contributions from weak annihilation diagrams which are particularly relevant for \( B \to (\rho, \omega)\gamma \). At order \( 1/m_b \), they can be calculated in QCDF themselves, but there are additional large corrections of \( O(1/m_b^2) \) induced by long-distance photon emission from soft quarks, see Refs. [17] [18]. We have included these corrections in Ref. [8], as well as the “soft” contributions induced by soft-gluon emission from quark loops.

In terms of these coefficients, and the appropriate CKM parameters, the non-factorisable correction in Eq. (2) can be expressed as

\[
1 + \Delta R = \left| \frac{a_{7L}^c (\rho)}{a_{7L}^c (K^*)} \right|^2 \left( 1 + \text{Re} (\delta a_+ + \delta a_0) \left[ \frac{R_b^2 - R_b \cos \gamma}{1 - 2R_b \cos \gamma + R_b^2} \right] \right)
\]
\[ R = \frac{\rho}{\omega} \]
\[ |V_{td}/V_{ts}|^2 \]

Figure 4: Left panel: $|V_{td}/V_{ts}|^2$ as function of $R_{\rho/\omega}$. Solid line: central values. Dash-dotted lines: theoretical uncertainty induced by $\xi_{\rho} = 1.17 \pm 0.09$. Dashed lines: other theoretical uncertainties. Right panel: $\Delta R$ from Eq. (11) as function of $|V_{td}/V_{ts}|$. Solid line: central values. Dashed lines: theoretical uncertainty.

Figure 5: The UTangle $\gamma$ as function of $R_{\rho/\omega}$. Solid lines: central values of input parameters. Dash-dotted lines: theoretical uncertainty induced by $\xi_{\rho} = 1.17 \pm 0.09$. Dashed lines: other theoretical uncertainties.

\[ + \frac{1}{2} \left( |\delta a_{\pm}|^2 + |\delta a_0|^2 \right) \left\{ \frac{R_b^2}{1 - 2 R_b \cos \gamma + R_b^2} \right\} \]

(10)

with $\delta a_{0,\pm} = a_{+}^{\tau L}(\rho^{0,\pm})/a_{c}^{\tau L}(\rho^{0,\pm}) - 1$. Here $\gamma$ is one of the angles of the UT ($\gamma = \arg V_{ub}^* \text{ in the standard Wolfenstein parametrisation of the CKM matrix}$) and $R_b$ one of its sides:

\[ R_b = \left( 1 - \frac{\lambda^2}{2} \right) \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right|. \]

In Figs. 4 and 5 we plot the values of $|V_{td}/V_{ts}|^2$ and $\gamma$, respectively, determined from (2) as a function of $R_{\rho/\omega}$. Although the curve in Fig. 4(a) looks like a straight line, as naively expected from (2), this is not exactly the case, because of the dependence of $\Delta R$ on $|V_{td}/V_{ts}|$. In Fig. 4(b) we plot $\Delta R$ as a function of $|V_{td}/V_{ts}|$. The dependence of $\Delta R$ on $|V_{td}/V_{ts}|$ is rather strong.

It is now basically a matter of choice whether to use $R_{\rho/\omega}$ to determine $|V_{td}/V_{ts}|$ or $\gamma$. Once one of these parameters is known, the other one follows from

\[ \left| \frac{V_{td}}{V_{ts}} \right| = \lambda \sqrt{1 - 2 R_b \cos \gamma + R_b^2} \left[ 1 + \frac{1}{2} (1 - 2 R_b \cos \gamma) \lambda^2 + O(\lambda^4) \right]. \]
Table 1: Central values and uncertainties of $|V_{td}/V_{ts}|$ and $\gamma$ extracted from representative values of $R_{\rho/\omega}$. $\Delta_{\xi_{\rho}}$ is the uncertainty induced by $\xi_{\rho}$ and $\Delta_{\text{other th}}$ that by other input parameters, including $\xi_{\omega}$ and $|V_{ub}|$.

| $R_{\rho/\omega}$ | $|V_{td}/V_{ts}|$ | $\Delta_{\xi_{\rho}}$ | $\Delta_{\text{other th}}$ | $\gamma$ | $\Delta_{\xi_{\rho}}$ | $\Delta_{\text{other th}}$ |
|-----------------|----------------|----------------|----------------|--------|----------------|----------------|
| 0.026           | 0.183          | $\pm 0.012$   | $\pm 0.007$   | 50.8   | $^{+7.5}_{-8.2}$ | $\pm 5.8$   |
| 0.028           | 0.191          | $^{+0.012}_{-0.013}$ | $\pm 0.006$   | 56.0   | $^{+7.7}_{-8.3}$ | $\pm 4.7$   |
| 0.030           | 0.199          | $\pm 0.013$   | $\pm 0.006$   | 61.0   | $^{+7.9}_{-8.4}$ | $\pm 4.0$   |
| 0.032           | 0.207          | $^{+0.013}_{-0.014}$ | $\pm 0.006$   | 65.7   | $^{+8.1}_{-8.5}$ | $\pm 3.6$   |
| 0.034           | 0.214          | $\pm 0.014$   | $\pm 0.006$   | 70.2   | $^{+8.4}_{-8.8}$ | $\pm 3.5$   |
| 0.036           | 0.221          | $^{+0.014}_{-0.015}$ | $\pm 0.006$   | 74.5   | $^{+8.8}_{-9.0}$ | $\pm 3.7$   |

In Fig. 5 we plot $\gamma$ as a function of $R_{\rho/\omega}$, together with the theoretical uncertainties. In order to facilitate the extraction of $|V_{td}/V_{ts}|$ (or $\gamma$) from measurements of $R_{\rho/\omega}$, Tab. 1 contains explicit values for the theoretical uncertainties for representative values of $R_{\rho/\omega}$. The uncertainty induced by $\xi_{\rho}$ is dominant. As discussed in Ref. [6], a reduction of this uncertainty would require a reduction of the uncertainty of the transverse decay constants $f_V (\rho)$ and $K^*$. With the most recent results from BaBar, $R_{\rho/\omega} = 0.030 \pm 0.006 \ [1]$, and from Belle, $R_{\rho/\omega} = 0.032 \pm 0.008 \ [2]$, we then find

BaBar: $\frac{|V_{td}|}{|V_{ts}|} = 0.199^{+0.022}_{-0.025} (\exp) \pm 0.014 (\th) \leftrightarrow \gamma = (61.0^{+13.5}_{-16.0} (\exp) +^{8.9}_{-9.3} (\th)) \degree$,

Belle: $\frac{|V_{td}|}{|V_{ts}|} = 0.207^{+0.028}_{-0.033} (\exp) +^{0.014}_{-0.015} (\th) \leftrightarrow \gamma = (65.7^{+17.3}_{-20.7} (\exp) +^{8.9}_{-9.2} (\th)) \degree$. (12)

These numbers compare well with the Belle result [19] from tree-level processes, $\gamma = (53 \pm 20) \degree$ and results from global fits. We also would like to point out that the above determination of $\gamma$ is actually a determination of $\cos \gamma$, via Eq. (11), and implies, in principle, a twofold degeneracy $\gamma \leftrightarrow 2\pi - \gamma$. This is in contrast to the determination from $B \rightarrow D^{(*)}K^{(*)}$ in [19], which carries a twofold degeneracy $\gamma \leftrightarrow \pi + \gamma$. Obviously these two determinations taken together remove the degeneracy and select $\gamma \approx 55 \degree < 180 \degree$. If $\gamma \approx 55 \degree + 180 \degree$ instead, one would have $|V_{td}/V_{ts}| \approx 0.29$ from (11), which is definitely ruled out by data. Hence, the result (12) confirms the SM interpretation of $\gamma$ from the tree-level CP asymmetries in $B \rightarrow D^{(*)}K^{(*)}$.

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