Unparticle effects on $B \rightarrow D^{(*)}\tau\nu$

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Abstract

We examine the possible unparticle effects on $R(D^{(*)})$ associated with $B \rightarrow D^{(*)}\tau\nu$ decays by minimum-$\chi^2$ fitting. Recent measurements from Belle and LHCb are included in this analysis. While it is true that the new experimental results of $R(D^{(*)})$ get closer to the standard model predictions, there are still rooms for new physics and unparticles are also one possibility. Our best-fit values are $R(D) = 0.456$ and $R(D^{*}) = 0.270$, which are still far from the standard model values by more than $(R(D))$ or almost $(R(D^{*}))$ 2$\sigma$. We also find that the unparticle effects are quite safe to render the branching ratio $\text{Br}(B_c \rightarrow \tau\nu)$ less than 10%.
The standard model (SM) is a very successful theory in particle physics. But there must be new physics (NP) beyond the SM for many reasons. Flavor physics is a good testing ground for NP. Recently, $B$ factories and LHCb observed an excess of the semileptonic $B$ decay, $B \to D^{(*)}\tau\nu$ \cite{1,8}. The anomaly is encoded in a ratio of the branching ratios

$$R(D^{(*)}) \equiv \frac{\text{Br}(B \to D^{(*)}\tau\nu)}{\text{Br}(B \to D^{(*)}\ell\nu)} ,$$

where $\ell = e, \mu$. The SM predicts that \cite{9,10}

$$R(D)_{\text{SM}} = 0.300 \pm 0.008 ,$$

$$R(D^*)_{\text{SM}} = 0.252 \pm 0.003 .$$

Both measurements from BABAR and Belle are larger than the SM predictions, Eq. (2). Results of BABAR are quite different from the SM prediction at the $3.4\sigma$ level ($R(D)$ by $2.0\sigma$ and $R(D^*)$ by $2.7\sigma$) \cite{1,2}. BABAR also excluded the type-II two-Higgs-doublet model (2HDM) where a charged Higgs could contribute to $R(D^{(*)})$ at the 99.8% confidence level. The Belle results are between Eq. (2) and the BABAR measurements, and compatible with the type-II 2HDM. Very recently, LHCb reported new measurements of $R(D^*)$ consistent with the SM \cite{8}. Previous results from LHCb are larger than the SM predictions by $2.1\sigma$ \cite{7}. In a recent analysis we showed that with an anomalous $\tau$ couplings, any types of 2HDM is as good as another to fit the $R(D^{(*)})$ data \cite{11}.

In this work we examine the unparticle effects on $R(D^{(*)})$. Unparticles are hypothetical things which behave like a fractional number of particles \cite{12}. In this scenario, a scale-invariant hidden sector at high energy couples to the SM particles weakly at some high scale $\Lambda_U$. The low-energy effective description of the scale-invariant sector is the unparticles. Unparticle effects on $B$ physics have been studied in many ways \cite{13-19}. As will be shown later, unparticles contribute quite differently from other NP particles. We check the compatibility of the unparticle scenario by global $\chi^2$ fitting to $R(D^{(*)})$.

The relevant Lagrangian involving scalar unparticles $O_{U\ell}$ coupled to the left-handed currents is given by

$$\mathcal{L}_U = \frac{c_{q'q}}{\Lambda^d_{U\ell}} \bar{q}' \gamma_\mu (1 - \gamma_5) q \partial^\mu O_{U\ell} + \frac{c_{\ell'\ell}}{\Lambda^d_{U\ell}} \bar{\ell}' \gamma_\mu (1 - \gamma_5) \ell \partial^\mu O_{U\ell} ,$$

where $c_{q'q,\ell'\ell}$ are dimensionless couplings, and $d_{U\ell}$ is the scaling dimension of $O_{U\ell}$. By the
unitarity constraints, \( d_U \geq 1 \) \cite{20}. The effective Hamiltonian for \( q \to q' \ell \ell' \) is then

\[
\mathcal{H}_{\text{eff}}^{UL} = -\frac{A_{d_U} \epsilon^{-\phi_{d_U}}}{2 \sin d_U \pi} \frac{m_{\ell} c_{\ell \ell'}}{s^{2-d_U} \Lambda_U^{2d_U}} \left[ (q')(\bar{\ell} \ell') c_{q'} q (m_{q'} - m_q) + (q' \gamma_5 q)(\bar{\ell} \ell') c_{q'} q (-m_{q'} - m_q) + (q' \bar{\ell} \gamma_5 \ell) c_{q'} q (-m_{q'} + m_q) + (q' \gamma_5 q)(\bar{\ell} \gamma_5 \ell) c_{q'} q (m_{q'} + m_q) \right] ,
\]

where

\[
A_{d_U} = \frac{16\pi^{5/2}}{(2\pi)^{2d_U}} \frac{\Gamma(d_U + 1/2)}{\Gamma(d_U - 1) \Gamma(2d_U)} ,
\]

\[
\phi_{d_U} = (d_U - 2)\pi ,
\]

and \( s \equiv (p_\ell + p_{\ell'})^2 \).

As discussed in \cite{21}, operators \( \mathcal{O}_{VL} \) and \( \mathcal{O}_{SL} \) contribute to \( R(D) \) while operators \( \mathcal{O}_{VL}, \mathcal{O}_{AL}, \) and \( \mathcal{O}_{PL} \) do to \( R(D^*) \), where

\[
\mathcal{O}_{VL} = (q' \gamma^\mu q) (\bar{\ell} \gamma^\mu P_L \ell) , \quad \mathcal{O}_{AL} = (q' \gamma^\mu \gamma_5 q) (\bar{\ell} \gamma^\mu P_L \ell) ,
\]

\[
\mathcal{O}_{SL} = (q' q) (\bar{\ell} P_L \ell) , \quad \mathcal{O}_{PL} = (q' \gamma_5 q) (\bar{\ell} P_L \ell) ,
\]

with \( P_L = (1 - \gamma_5)/2 \). While \( \mathcal{O}_{VL} \) affects both \( R(D) \) and \( R(D^*) \), \( \mathcal{O}_{VL} \) alone cannot provide satisfactory explanations for the experimental data \cite{21}. We expect the scalar unparticles can do the job and check the possibility.

In this analysis we do not consider the vector unparticles. Vector unparticles contribute through

\[
\frac{c_V}{\Lambda_U^{d_V-1}} q' \gamma^\mu (1 - \gamma_5) q \mathcal{O}_{UL} ,
\]

where \( d_V \) is the scaling dimension of the vector unparticle operator \( \mathcal{O}_{UL} \). The unitarity constraint requires that \( d_V \geq 3 \) \cite{20}. Typically the contribution amounts to \( \sim (m_B^2/\Lambda_U^2)^{d_V-1} \) while that of scalar unparticles is \( \sim (m_B^2/\Lambda_U^2)^{d_U} \). One can expect that effects of vector unparticles are very suppressed compared to those of scalar ones due to the unitarity constraints \cite{17}.

The decay rates of \( B \to D^{(*)} \ell \nu \) mediated by \( \mathcal{O}_U \) are given by

\[
\Gamma^{D^{(*)}} = \Gamma_{\text{SM}}^{D^{(*)}} + \Gamma_{\text{mix}}^{D^{(*)}} + \Gamma_{U}^{D^{(*)}} .
\]
The differential decay rates for \( B \to D\ell\nu \) are given by

\[
\frac{d\Gamma_{SM}^D}{ds} = \frac{G_F^2|V_{cb}|^2}{96\pi^3m_B^2}\left\{4m_B^2P_D^2\left(1 + \frac{m_D^2}{2s}\right)|F_1|^2
\right. \\
\left. + m_B^4\left(1 - \frac{m_D^2}{m_B^2}\right)^2\frac{3m_D^2}{2s}|F_0|^2\right\}(1 - \frac{m_D^2}{s})^2P_D,
\]

(10)

\[
\frac{d\Gamma_{\text{mix}}^D}{ds} = \frac{G_FV_{cb}^*}{\sqrt{2}16\pi^3}(\kappa U_c c_{\ell}\cos\phi_d) m_B^2 m_D
\times \left(1 - \frac{m_D^2}{m_B^2}\right)|F_0|^2\left(1 - \frac{m_D^2}{s}\right)^2P_D,
\]

(11)

\[
\frac{d\Gamma_{U_d}^D}{ds} = \frac{m_B^2}{32\pi^3}|\kappa U_c c_{\ell}|^2|F_0|^2s\left(1 - \frac{m_D^2}{s}\right)^2P_D,
\]

(12)

where

\[
\kappa_U = \frac{A_{dU}}{2\sin d_U \pi - \sin^2 d_U \Lambda_U^2},
\]

(13)

is the unparticle factor and

\[
P_D \equiv \sqrt{\frac{s^2 + m_B^4 + m_D^4 - 2(sm_B^2 + sm_D^2 + m_B^2 m_D^2)}{2m_B}},
\]

(14)

is the momentum of \( D \) in the \( B \) rest frame. The form factors \( F_0 \) and \( F_1 \) are given by

\[
F_0 = \frac{\sqrt{m_B m_D}}{m_B + m_D}(w + 1)S_1,
\]

(15)

\[
F_1 = \frac{\sqrt{m_B m_D(m_B + m_D)}}{2m_B P_D}\sqrt{w^2 - 1}V_1,
\]

(16)

where

\[
V_1(w) = V(1)\left[1 - 8\rho_D^2 z(w) + (51\rho_D^2 - 10)z(w)^2 - (252\rho_D^2 - 84)z(w)^3\right],
\]

(17)

\[
S_1(w) = V_1(w)\left\{1 + \Delta \left[-0.019 + 0.041(w - 1) - 0.015(w - 1)^2\right]\right\},
\]

(18)

with

\[
w = \frac{m_B^2 + m_D^2 - s}{2m_B m_D}, \quad z(w) = \frac{\sqrt{w + 1} - \sqrt{2}}{\sqrt{w + 1} + \sqrt{2}},
\]

(19)

\[
\rho_D^2 = 1.186 \pm 0.055, \quad \Delta = 1 \pm 1.
\]

(20)
For $B \to D^* \ell \nu$ decay,

$$\frac{d\Gamma_{\text{SM}}^{D^*}}{ds} = \frac{G_F^2 |V_{cb}|^2}{96 \pi^3 m_B^2} \left[ (|H_+|^2 + |H_-|^2 + |H_0|^2) \left( 1 + \frac{m_\ell^2}{2s} \right) + 3 \frac{m_\ell^2}{2s} |H_s|^2 \right] (21)$$

$$\times s \left( 1 - \frac{m_\ell^2}{s} \right)^2 P_{D^*},$$

$$d\Gamma_{\text{mix}}^{D^*}/ds = \frac{G_F V_{cb}^*}{\sqrt{2} 4 \pi^3} (\kappa_u c_b c_{c\ell} \cos \phi_u) m_{\ell} A_0^2 \left( 1 - \frac{m_\ell^2}{s} \right)^2 P_{D^*}^3,$$ (22)

$$d\Gamma_{d}^{D^*}/ds = \frac{1}{8 \pi^3} |\kappa_u c_b c_{c\ell}|^2 A_0^2 s \left( 1 - \frac{m_\ell^2}{s} \right)^2 P_{D^*}^3,$$ (23)

where $P_{D^*} = P_D (m_D \to m_{D^*})$. The form factors are given by

$$H_\pm(s) = (m_B + m_{D^*}) A_1(s) \mp \frac{2m_B}{m_B + m_{D^*}} P_{D^*} V(s),$$ (24)

$$H_0(s) = -\frac{1}{2 m_{D^*} \sqrt{s}} \left[ \frac{4 m_B^2 P_{D^*}^2}{m_B + m_{D^*}} A_2(s) - (m_B^2 - m_{D^*}^2 - s)(m_B + m_{D^*}) A_1(s) \right],$$ (25)

$$H_s(s) = \frac{2m_B P_{D^*}}{\sqrt{s}} A_0(s),$$ (26)

where

$$A_1(w^*) = \frac{w^* + \frac{1}{2}}{2} r_{D^*} h_{A_1}(w^*),$$ (27)

$$A_0(w^*) = \frac{R_0(w^*)}{r_{D^*}} h_{A_1}(w^*),$$ (28)

$$A_2(w^*) = \frac{R_2(w^*)}{r_{D^*}} h_{A_1}(w^*),$$ (29)

$$V(w^*) = \frac{R_1(w^*)}{r_{D^*}} h_{A_1}(w^*),$$ (30)

$$h_{A_1}(w^*) = h_{A_1}(1) \left[ 1 - 8 \rho_{D^*}^2 z(w^*) + (53 \rho_{D^*}^2 - 15) z(w^*)^2 - (231 \rho_{D^*}^4 - 91) z(w^*)^3 \right],$$ (33)

$$R_0(w^*) = R_0(1) - 0.11(w^* - 1) + 0.01(w^* - 1)^2,$$ (34)

$$R_1(w^*) = R_1(1) - 0.12(w^* - 1) + 0.05(w^* - 1)^2,$$ (35)

$$R_2(w^*) = R_2(1) + 0.11(w^* - 1) - 0.01(w^* - 1)^2.$$ (36)

with

$$w^* = \frac{m_B^2 + m_{D^*}^2 - s}{2m_B m_{D^*}}, \quad r_{D^*} = \frac{2 \sqrt{m_B m_{D^*}}}{m_B + m_{D^*}},$$ (32)
|        | $R(D)$        | $R(D^*)$       |
|--------|--------------|---------------|
| BABAR  | $0.440 \pm 0.058 \pm 0.042$ | $0.332 \pm 0.024 \pm 0.018$ |
| Belle(2015) | $0.375 \pm 0.064 \pm 0.026$ | $0.293 \pm 0.038 \pm 0.015$ |
| Belle(2016) | $-$ | $0.302 \pm 0.030 \pm 0.011$ |
| Belle(1703) | $-$ | $0.276 \pm 0.034^{+0.029}_{-0.026}$ |
| Belle(1709) | $-$ | $0.270 \pm 0.035^{+0.028}_{-0.025}$ |
| LHCb(1506) | $-$ | $0.336 \pm 0.027 \pm 0.030$ |
| LHCb(1711) | $-$ | $0.286 \pm 0.019 \pm 0.025 \pm 0.021$ |

TABLE I. Experimental data for $R(D^*)$. The uncertainties are ±(statistical)±(systematic). For the third uncertainty of LHCb(1711), see [8] for details.

Here [22]

$$\rho_{D^*}^2 = 1.207 \pm 0.028, \quad R_0(1) = 1.14 \pm 0.07, \quad (37)$$

$$R_1(1) = 1.401 \pm 0.033, \quad R_2(1) = 0.854 \pm 0.020. \quad (38)$$

The experimental data for our fits are given in Table I. The $R(D^*)$ values from the Belle get slightly closer to the SM predictions. As can be seen in Eqs. (11), (12), (22), (23), the unparticle couplings appear only in the form of $c_{cb} c_{\nu \ell}$. In our analysis $c_{cb} c_{\nu \ell}$, $d_U$, and $\Lambda_U$ are fitting parameters to minimize $\chi^2$, which is defined by

$$\chi^2 = \sum_i \frac{(x_i - \mu_i)^2}{(\delta \mu_i)^2}, \quad (39)$$

where the $x_i$’s are model predictions and the $(\mu_i \pm \delta \mu_i)$’s are experimental data. New physics effects in $R(D^{(*)})$ could affect the $B_c \to \tau \nu$ decay [23, 24]. Scalar unparticles contribute to the branching ratio of $B_c \to \tau \nu$ as

$$\text{Br}(B_c \to \tau \nu) = \text{Br}(B_c \to \tau \nu)_{SM} |1 + r_U|^2, \quad (40)$$

where

$$\text{Br}(B_c \to \tau \nu)_{SM} = \frac{\tau_{B_c} G_F^2 |V_{cb}|^2}{8\pi} m_{B_c} m_{\tau} f_{B_c}^2 \left(1 - \frac{m_{\tau}^2}{m_{B_c}^2}\right)^2, \quad (41)$$

$$r_U = \frac{c_{cb} c_{\nu \ell}}{\sqrt{2} G_F m_{B_c}^2 V_{cb}} \frac{A_{d_U} e^{-i \phi_U}}{\sin d_U \pi} \left(\frac{m_{B_c}}{\Lambda_U}\right)^{2d_U}. \quad (42)$$
Here $\tau_{B_c}$ and $f_{B_c}$ are the lifetime and the decay constant of $B_c$, respectively.

Figure 1 shows the allowed region in the $c_{cb} c_{\nu \ell} - d_U$ plane at the 1$\sigma$ (red) and 2$\sigma$ (blue) levels. Note that the unparticle contribution comes as

$$
\frac{d\Gamma^{D(\ast)}_{\text{mix}}}{ds} + \frac{d\Gamma^{D(\ast)}_U}{ds} \sim c_{cb} c_{\nu \ell} \left( \frac{s}{\Lambda_U^2} \right)^{d_U} \left| c_{cb} c_{\nu \ell} \left( \frac{s}{\Lambda_U^2} \right)^{d_U} \right|^2 .
$$

(43)

Here $s = (p_\tau + p_\nu)^2 \leq (m_B - m_{D(s)})^2$ while $\Lambda_U \sim \mathcal{O}(\text{TeV})$, thus suppression of $(s/\Lambda_U^2)$ gets stronger as $d_U$ gets larger. Thus for small values of $|c_{cb} c_{\nu \ell}|$, large $d_U$ is not allowed because in this case the unparticle contribution becomes very small. In Fig. 2, $c_{cb} c_{\nu \ell}$ and $\Lambda_U$ are shown at the 1$\sigma$ (red) and 2$\sigma$ (blue) levels. Usually new physics (NP) effects appear as

$$
\sim \lambda_{\text{NP}}^\alpha \left( \frac{M_{\text{EW}}}{M_{\text{NP}}} \right)^\beta ,
$$

(44)

where $\lambda_{\text{NP}}$ is a new coupling, $M_{\text{EW}}$ is the electroweak scale, and $M_{\text{NP}}$ is the NP scale, with some fixed powers of $\alpha$ and $\beta$. Typically at lowest order $\alpha = \beta = 2$. In this case for large values of $\lambda_{\text{NP}}$, small values of $M_{\text{NP}}$ are not allowed because the value of Eq. (44) could be very large. In the unparticle scenario as in this analysis, $\beta = 2d_U$ is a model parameter.
FIG. 2. Allowed region for $c_{cb}c_{\nu L}$ vs $\Lambda_U$ at the $1\sigma$ (red) and the $2\sigma$ (blue) levels. $\Lambda_U$ is scanned over $1 \leq \Lambda_U \leq 10$ TeV.

which varies freely. The result is that the suppression of Eq. (44) for large $\lambda_{NP}$ is possible because $(M_{EW}/M_{NP})^{2d_U}$ can be small enough for large $d_U$. This feature is shown in Fig. 3. Figure 3 shows the allowed region in the $\Lambda_U$-$d_U$ plane. Note that for small values of $\Lambda_U$ around $\sim 1$ TeV (and for large $c_{cb}c_{\nu L}$) large values of $d_U$ are allowed. On the other hand, the NP effects of Eq. (44) should not be too small to account for anomalies well beyond the SM predictions. Roughly speaking, $\beta$ and $M_{NP}$ can not be large simultaneously. As expected from Eq. (43), for large values of $\Lambda_U$ only small values of $d_U$ are permitted. In Fig. 4 allowed ranges of $R(D)$ vs $R(D^*)$ (panel (a)) and $R(D)$ vs $\text{Br}(B_c \to \tau \nu)$ (panel (b)) are shown. The SM predictions of $R(D)$ and $R(D^*)$ are slightly off the 2$\sigma$ region. As shown in Fig. 4(b), the branching ratio of $B_c \to \tau \nu$ is mostly below $\sim 10\%$. Our result for $\text{Br}(B_c \to \tau \nu)$ is safe enough to satisfy a stronger constraint of [24] where the branching ratio should not exceed $10\%$. The best-fit values are summarized in Table II. Note that $\chi^2_{\text{min}}$/d.o.f is not far from 1, thus it can be said that unparticles fit the data well.

Recently the CMS collaboration announced the lower limits of $\Lambda_U$ with respect to $d_U$ at high energy collisions [25]. According to the Fig. 10 of [25], $\Lambda_U$ must be larger than
FIG. 3. Allowed region for $\Lambda_U$ vs $d_U$ at the 1$\sigma$ (red) and the 2$\sigma$ (blue) levels. $\Lambda_U$ is scanned over $1 \leq \Lambda_U \leq 10$ TeV.

FIG. 4. Allowed region in the $R(D)$-$R(D^*)$ plane (panel (a)) and the $R(D)$-$\text{Br}(B_c \to \tau\nu)$ plane (panel (b)) at the 1$\sigma$ (red) and the 2$\sigma$ (blue) levels. Green lines are the SM predictions while magenta ones are the best-fit points.
TABLE II. The best-fit values. $\chi^2_{\text{min}}/\text{d.o.f}$ is the minimum value of $\chi^2$ per degree of freedom.

| $R(D)$ | $R(D^*)$ | Br($B_c \to \tau \nu$) | $d\,U$ | $c_{cb}c_{\nu\ell}$ | $\Lambda_U$ (in TeV) | $\chi^2_{\text{min}}/\text{d.o.f}$ |
|--------|----------|-----------------------|------|------------------|-----------------|-------------------|
| 0.456  | 0.270    | $4.134 \times 10^{-2}$ | 1.000 | 2.306            | 4.326           | 1.671             |

$\sim 10^2$ TeV for $d\,U \lesssim 1.4$, and the lower limit of $\Lambda_U$ decreases for larger $d\,U$ until $\Lambda_U \gtrsim 0.3$ TeV for $d\,U = 2.2$. The results are for the fixed coupling, $\lambda = 1$. In our language, $\lambda = [(m_j - m_k)/\Lambda_U] c_{jk}$. Thus $\lambda = 1$ corresponds to very large values of $c_{jk} \gtrsim 10^3$. For such a large $c_{jk}$, $\Lambda_U$ must be large enough to keep the unparticle contribution moderate, as can be seen in Eq. (43). For example, if $c_{cb}c_{\nu\ell} \sim 10^6$ then $\Lambda_U^2 \gtrsim 10^6$ for $d\,U \sim 1$ because $\Lambda_U \sim (\text{a few}) \text{ TeV}$ for $c_{cb}c_{\nu\ell} \sim 1$ in Fig. 2. In this reason, our results are compatible with recent LHC data above TeV scale.

In conclusion, we have investigated the unparticle contributions to $R(D^{(*)})$. We only considered scalar unparticles because contributions from vector unparticles are expected to be very small. We fit the data by minimizing $\chi^2$ and found that $\chi^2_{\text{min}}/\text{d.o.f}$ is smaller than that of our previous work with 2HDM ($\sim 2.9$) [11]. At lowest order scalar unparticles contribute to $R(D^{(*)})$ as $\sim c_{cb}c_{\nu\ell}(s/\Lambda_U^2)^{d\,U}$. New physics scale $\Lambda_U$ could be around $\sim 1\text{TeV}$ thanks to $(s/\Lambda_U^2)^{d\,U}$ suppression. Our best-fit values of $R(D) = 0.456$ and $R(D^*) = 0.270$ are larger than the SM predictions by almost $(R(D^*))$ or more than $(R(D))$ $2\sigma$, as shown in Fig. 4. It is well known that the NP effects for $R(D^{(*)})$ would also affect $B_c \to \tau \nu$ decay, and $\text{Br}(B_c \to \tau \nu)$ could provide a strong constraint for NP. We found that scalar unparticles can render the branching ratio less than 10% (Fig. 4(b)). More data for $R(D^{(*)})$ and $\text{Br}(B_c \to \tau \nu)$ would check the plausibility of the unparticle scenario.

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