B-meson charged current anomalies: the post-Moriond status

Debjyoti Bardhan\textsuperscript{1,} and Diptimoy Ghosh\textsuperscript{2,}\footnote{bardhan@post.bgu.ac.il} and \textsuperscript{3} diptimoy.ghosh@iiserpune.ac.in

\textsuperscript{1}Department of Physics, Ben-Gurion University, Beer-Sheva 8410501, Israel
\textsuperscript{2}Department of Physics, Indian Institute of Science Education and Research, Pune 411008, India

In this note, we discuss the impact of the recent Belle result on the various theoretical explanations of the $R_D$ and $R_{D^*}$ anomalies. The pure tensor explanation, which was strongly disfavoured by the measurements of $F_L^{D^*}$ and high-\textit{pt} $pp \rightarrow \tau\nu$ searches before Moriond, is now completely allowed because of reduction of the experimental world-average. Moreover, the pure right-chiral vector solution (involving right-chiral neutrinos) has now moved into the 2\textsigma{} allowed range of the LHC $pp \rightarrow \tau\nu$ searches. We also critically re-examine the bound on $B(B_c^+ \rightarrow \tau^-\nu_\tau)$ from LEP data and show that the bound is considerably weaker than the number 10\% often used in the recent literature.

The Belle collaboration has recently published results for $R_D$ and $R_{D^*}$ with a semileptonic tag [1, 2], and their result is consistent with the Standard Model (SM) expectation within 1.2\textsigma{}. Consequently, the experimental world average has moved towards the SM. However, the tension between the experimental world average and the SM expectation is still more than 3\textsigma{}, and thus, it is interesting to re-examine the status of the various New Physics (NP) explanations in view of the new world-average. In Table I below, we collect all the experimental results related to this anomaly.

\begin{tabular}{|c|c|c|}
\hline
 & SM prediction & Measurement \\
\hline
$R_D$ & $0.300\pm0.008$ [5] & $0.407\pm0.046$ (pre-Moriond) [4] \\
 & $0.299\pm0.011$ [5] & $0.334\pm0.031$ [1, 2, 4] \\
$R_{D^*}$ & $0.258\pm0.005$ [4, 6–8] & $0.306\pm0.015$ (pre-Moriond) [4] \\
 & & $0.297\pm0.015$ [1, 4] \\
$P_L^{D^*}$ & $-0.47\pm0.04$ [6] & $-0.38_{-0.05}^{+0.05}$ [9, 10] \\
$F_L^{D^*}$ & $0.46\pm0.04$ & $0.60\pm0.087$ [11] \\
$R_{D/s}$ & 0.290 & 0.71\pm0.25 [12] \\
\hline
\end{tabular}

\textbf{TABLE I.} Observables, their SM predictions and the experimentally measured values. The pre-Moriond experimental averages for $R_D$ and $R_{D^*}$ are based on [9, 10, 13–19].

The most general effective Lagrangian for the decay $b \rightarrow c\tau^-\nu_\tau$ involving mass dimension-6 operators and only left-chiral neutrinos can be written as

$$L_{\text{eff}}^{b \rightarrow c\tau\nu} = -\frac{4G_FV_{cb}}{\sqrt{2}} \left( C_{V}^{LL} [\bar{c} \gamma^\mu P_L b] [\bar{\tau} \gamma_\mu P_L \nu] + C_{V}^{SL} [\bar{c} \gamma^\mu P_R b] [\bar{\tau} \gamma_\mu P_L \nu] + C_{S}^{LL} [\bar{c} \gamma^\mu P_L b] [\bar{\tau} P_L \nu] + C_{S}^{SL} [\bar{c} \gamma^{\mu\nu} P_R b] [\bar{\tau} \sigma_{\mu\nu} P_L \nu] + \text{h.c.}\right)$$

If one uses power-counting rules arising from linearly-realised SU(2) $\times$ U(1) gauge invariance, it turns out that the Wilson Coefficient (WC) $C_{V}^{LL}$, with the possibility of lepton non-universality, is only generated at the mass dimension-8 level [20]. Thus, it is expected to be suppressed compared to the other WCs as long as the scale of NP is not too close to the Higgs vacuum expectation value, thus we will ignore it in this analysis.

If one also assumes the existence of light right-chiral neutrino(s), as was first done in [21] to solve the $R_{D}$ anomaly, five additional operators can be constructed by the replacement $P_L \rightarrow P_R$ in the leptonic currents of Eq. 1. In particular, a pure-right chiral vector current namely,

$$L_{\text{eff}}^{b \rightarrow c\tau\nu} \supset -\frac{4G_FV_{cb}}{\sqrt{2}} C_{V}^{RR} [\bar{c} \gamma^\mu P_R b][\bar{\tau} \gamma_\mu P_R \nu] + \text{h.c.}$$

was considered by several authors [22–24], and we will include it in our analysis.

As the experimental situation for $R_D$ and $R_{D^*}$ is far from clear, we do not try to perform a fit to the WCs; for an early global fit, see [25]. Instead, we show how $R_D$ and $R_{D^*}$ vary with respect to the WCs, and overlay the current 1\textsigma{} experimental world-average and the corresponding currently allowed values of the WCs.

In Fig. 1, we show this for two WCs $C_{V}^{LL}$ and $C_{V}^{RR}$ assuming them to be real. It can be seen from the left panel that $C_{V}^{LL} = C_{V}^{LL}_{(SM)} = 1$ is now at the edge of the 1\textsigma{} allowed region for $R_D$. This is due to the fact the the
new experimental world-average for $R_D$ is now consistent with the SM expectation at $\sim 1\sigma$ level. So the anomaly is mostly driven by $R_{D\ast}$. In order to be consistent with both $R_D$ and $R_{D\ast}$ simultaneously at the $1\sigma$ level, $C_{V}^{LL}$ has to be in the range $C_{V}^{LL} : [1.045, 1.107]$. So there has not been a qualitative change in the situation after the new Belle measurement. Similarly, the allowed range for $C_{V}^{RR}$ now is $|C_{V}^{RR}| : [0.305, 0.480]$. The lower edge of this range, $|C_{V}^{RR}| = 0.305$, is now consistent with the $2\sigma$ upper bound $|C_{V}^{RR}| = 0.32$ from the LHC $pp \to \tau \bar{\tau}$ searches [26] (bound from LHC $pp \to \tau \bar{\tau} + X$ searches was also studied in [27, 28]). Note that, both the WCs $C_{L}^{LL}$ and $C_{V}^{RR}$ can be generated by a single $U(3, 1, 1/3)$ Leptoquark mediator [24, 29–32].

Variations of $R_D$ and $R_{D\ast}$ with respect to $C_{L}^{LL}$ and $C_{S}^{LL} = -8C_{L}^{LL}$ are shown in Fig. 2. It can be seen from the left panel of Fig. 2 that a simultaneous solution of $R_D$ and $R_{D\ast}$ is possible for $C_{L}^{LL}$ in the range $C_{L}^{LL} : [-0.021, -0.013]$. We remind the readers that the corresponding value of $C_{L}^{LL}$ before the recent Belle result was $C_{L}^{LL} \sim 0.35$ [20, 33] which was strongly disfavoured both by the LHC $pp \to \tau \bar{\tau}$ searches [26, 34, 35] as well as the measurement of $F_{P}^{\nu}$ [36]. The new allowed range for $C_{L}^{LL}$, on the other hand, is completely safe. Thus, this has been a qualitative change after the new Belle measurement. The specific relation $C_{S}^{LL} \approx -8C_{L}^{LL}$ (at the $m_b$ scale) shown on the right panel is interesting because it is generated by a single $S(3, 1, 1/3)$ Leptoquark mediator [37]. The allowed range of the WC in this case is $[0.113, 0.170]$ which, as can be seen from Fig. 3, produces $B(B_{c}^{-} \to \tau^{-}\bar{\nu}_{\tau})$ less than its SM value, and thus is completely safe.

$^1$ Note, however, that for $|C_{V}^{RR}| = 0.305$, the value of $R_{D\ast}$ is at the lower edge of the experimental $1\sigma$ allowed region. Moreover, the sensitivity of the current high-$p_T$ measurements is not enough to constrain the left-handed scenario $C_{L}^{LL} \approx 1.05$. Thus, the right-handed scenario is statistically worse than the $C_{L}^{LL}$ solution.

FIG. 2. Variations of $R_D$ and $R_{D\ast}$ against $\text{Re}[C_{L}^{LL}]$ and $\text{Re}[C_{S}^{LL}] = -8\text{Re}[C_{L}^{LL}]$.

Another single mediator solution that has been discussed in the literature is the so-called $R_{S}(3, 2, 7/6)$ Leptoquark [38, 39]. which, contrary to the $S(3, 1, 1/3)$ Leptoquark mediator, generates $C_{S}^{LL} \approx +8C_{L}^{LL}$ (see the sign difference) at the $m_b$ scale$^2$. In the left panel of Fig. 4, we show this case assuming real values of the WCs. It can be seen that, the combination $\text{Re}[C_{S}^{LL}] = +8\text{Re}[C_{L}^{LL}]$ at most can produce $R_D$ and $R_{D\ast}$ at the lower edge of their $1\sigma$ experimental world-average if a simultaneous solution is desired (for $\text{Re}[C_{L}^{LL}] = +8\text{Re}[C_{L}^{LL}] \approx -0.12$). A much better description of the data is possible if imaginary WCs are assumed as shown in the right panel of Fig. 4. The case of imaginary WCs in this context was first discussed in [40], and later also in [39, 41–44]. In this case,

$^2$ Note that, the relation $C_{S}^{LL} = \pm 8C_{L}^{LL}$ are approximately true only at the $m_b$ scale. It is obtained by QCD renormalization group flow from the leptoquark matching scale ($\approx$ few TeV) where the actual relations are $C_{S}^{LL} = \pm 4C_{L}^{LL}$.

FIG. 3. Variation of $B(B_{c}^{-} \to \tau^{-}\bar{\nu}_{\tau})$ with respect to $\text{Re}[C_{S}^{LL}]$ and $\text{Im}[C_{S}^{LL}]$.

FIG. 4. Variations of $R_D$ and $R_{D\ast}$ against $\text{Re}[C_{S}^{LL}] = +8\text{Re}[C_{L}^{LL}]$ and $\text{Im}[C_{S}^{LL}] = +8\text{Im}[C_{L}^{LL}]$. One needs $\text{Im}[C_{S}^{LL}] = +8\text{Im}[C_{L}^{LL}]$ in the range $[0.480, 0.820]$ which gives $B(B_{c}^{-} \to \tau^{-}\bar{\nu}_{\tau}) > 10\%$, see Fig. 3. However, the authors of Ref. [45] claimed an upper bound of $10\%$ on this branching ratio, arising from the LEP data taken on the $Z$ peak. Thus, the $\text{Im}[C_{S}^{LL}] = +8\text{Im}[C_{L}^{LL}]$ solution seems to be in slight tension if the $10\%$ upper
bound is taken at face value. While some authors [41] expressed concerns about the validity of this bound, not much effort was made to estimate as to how much this bound can be relaxed. We will discuss this in detail in the next section.

As the operator $C_{S}^{RL}$ alone cannot explain $R_{D}$ and $R_{D}$ simultaneously, we do not discuss it anymore.

Before concluding this section, we would like to make a couple of comments on the impact of $P_{D}$ and $P_{S}$ on the various scenarios. In all the scenarios explaining the $R_{D}$ and $R_{D}$ anomalies, the variation of $P_{D}$ is less than $\sim 2.5\%$ from the SM prediction. Unfortunately, this is also true about $P_{D}^{LL}$, the only exception being the $\mathrm{Im}[C_{S}^{RL}] = 8\mathrm{Im}[C_{S}^{LL}]$ solution in which case the variation can be $5-10\%$ below the SM. Thus, distinguishing the various explanations by either $P_{D}^{LL}$ or $P_{D}^{LL}$ looks difficult at the moment.

**LEP bound on $\mathcal{B}(B_{c}^{-} \rightarrow \tau^{-}\bar{\nu}_{\tau})$:**

As mentioned in the previous section, the authors of [45] used the LEP data [46] collected at the $Z$ peak to put an upper bound on the branching fraction of $B_{c}^{-} \rightarrow \tau^{-}\bar{\nu}_{\tau}$. As this constraint has potentially interesting consequences for the $R_{D}$ and $R_{D}$ anomalies, in this section we will revisit it in detail.

In Ref. [46], the L3 collaboration obtained an upper bound on the number of $B^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau}$ events, $\mathcal{N}(B^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau}) < 3.8$. Based on this, they provided an upper bound

$$\mathcal{B}(B^{-}\rightarrow \tau\bar{\nu}_{\tau}) < 5.7 \times 10^{-4} \text{ at 90\% C.L.} \quad (3)$$

As $\mathcal{N}(B^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau}) \propto f_{b\rightarrow B^{-}} \times \mathcal{B}(B^{-}\rightarrow \tau\bar{\nu}_{\tau})$ where, $f_{b\rightarrow B^{-}}$ is the inclusive probability that a $b$ quark hadronizes into a $B_{c}^{-}$ or a $B_{c}^{-}$ meson, and Ref. [46] uses a value $f_{b\rightarrow B^{-}} = 0.382 \pm 0.025$, the bound in Eq. 3 can be translated into the following bound

$$f_{b\rightarrow B^{-}} \times \mathcal{B}(B^{-}\rightarrow \tau\bar{\nu}_{\tau}) < 2.035 \times 10^{-4} \quad (4)$$

Separating the total number of events into those coming from $B_{u}^{-}$ and $B_{c}^{-}$ decays, we get

$$f_{b\rightarrow B_{u}^{-}} \mathcal{B}(B_{u}^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau}) + f_{b\rightarrow B_{c}^{-}} \mathcal{B}(B_{c}^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau}) < 2.035 \times 10^{-4} \quad (5)$$

This gives,

$$\mathcal{B}(B_{c}^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau}) < \left(\frac{2.035 \times 10^{-4}}{f_{b\rightarrow B_{c}^{-}} \mathcal{B}(B_{c}^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau}) - 1}\right) \times \frac{f_{b\rightarrow B_{c}^{-}}}{f_{b\rightarrow B_{u}^{-}}} \mathcal{B}(B_{c}^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau}) \quad (6)$$

The quantities $\mathcal{B}(B_{u}^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau})$ and $f_{b\rightarrow B_{c}^{-}}$ are known experimentally:

$$\mathcal{B}(B_{u}^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau}) = (1.06 \pm 0.20) \times 10^{-4} \quad [4, 47] \quad (7)$$

$$f_{b\rightarrow B_{c}^{-}} = 0.412 \pm 0.008 \quad [4, 47] \quad \text{(LEP)} \quad (8)$$

$$f_{b\rightarrow B_{c}^{-}} = 0.340 \pm 0.021 \quad [4, 47] \quad \text{(Tevatron)} \quad (9)$$

Note that, the hadronization fractions in $Z$ decays do not necessarily need to be identical to those in $p\bar{p}$ collisions because of the different momentum distributions of the $b$-quark in these processes; in $p\bar{p}$ collisions, the $b$ quarks have momenta close to $m_{b}$, rather than $\sim m_{Z}/2$ in $Z$ decays. In fact, CDF and LHCb collaborations have reported evidence for a strong $p_{T}$ dependence of the $A_{LL}$ fraction [48–51]. The LHCb and the ATLAS collaborations have also studied the $p_{T}$ dependence of $B_{c}^{-}\rightarrow B_{c}^{+}$, but the results are not conclusive yet.

Therefore, we use the measurement of $f_{b\rightarrow B_{c}^{-}}$ from LEP only and plot the upper bound on $\mathcal{B}(B_{c}^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau})$ as a function of $f_{b\rightarrow B_{c}^{-}}/f_{b\rightarrow B_{c}^{-}}$ in Fig. 8. The upper bound $\mathcal{B}(B_{c}^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau}) = 10\%$ corresponds to $f_{b\rightarrow B_{c}^{-}}/f_{b\rightarrow B_{c}^{-}}$ $\sim 4 \times 10^{-3}$.

![FIG. 5. $\mathcal{B}(B_{c}^{-}\rightarrow \tau^{-}\bar{\nu}_{\tau})$ as a function of $f_{b\rightarrow B_{c}^{-}}/f_{b\rightarrow B_{c}^{-}}$. The width of the plot corresponds to the uncertainties in Eq. (7) and (8).](image)
Using
\[ R_{\pi^+ / \mu^+} = 0.0469 \pm 0.0054 \] \[ (14) \]
\[ R_{\pi^+ / K^+}^{\text{LHCb}} = (0.683 \pm 0.02) \times 10^{-2} \] \[ (15) \]
\[ R_{\pi^+ / K^+}^{\text{CMS}} = (0.48 \pm 0.08) \times 10^{-2} \] \[ (16) \]
we get,
\[ \frac{f_{b \to B_c^+}}{f_{b \to B_u^+}} = \frac{\left( 1.22 - 1.75 \right) \times 10^{-4}}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_{\mu})} \text{(using [55])} \] \[ (18) \]
\[ \frac{f_{b \to B_c^+}}{f_{b \to B_u^+}} = \frac{\left( 0.74 - 1.40 \right) \times 10^{-4}}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_{\mu})} \text{(using [56])} \] \[ (19) \]
As the LHCb and CMS measurements of \( R_{\pi^+ / K^+} \) are about 2.5\% away from each other, we consider them separately and do not use their average. Moreover, while the LHCb Collaboration uses the cuts \( 0 < p_T(B_c^+) < 20 \text{ GeV} \) and \( 2.0 < \eta < 4.5 \) in their analysis (at \( \sqrt{s} = 8 \text{ TeV} \)), the CMS Collaboration uses \( p_T(B_c^+) > 15 \text{ GeV} \) and \( |\eta| < 1.6 \) (at \( \sqrt{s} = 7 \text{ TeV} \)). Thus the discrepancy could be due to the dependence of \( f_{b \to B_c^+} / f_{b \to B_u^+} \) on kinematics.

Plugging Eqs. (18) and (19) into Eq. 6, one can obtain a bound on \( \mathcal{B}(B_c^+ \to \tau^- \bar{\nu}_{\tau}) \) directly as a function of \( \mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_{\mu}) \). This is shown in the right panel of Fig. 6.

Using \( \mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_{\mu}) \leq 2.5 \times 10^{-2} \), as used in [45], we get \( f_{b \to B_c^+} / f_{b \to B_u^+} \geq 3 \times 10^{-3} \) and \( \mathcal{B}(B_c^- \to \tau^- \bar{\nu}_{\tau}) \leq 14\% \) from the CMS data, the latter being similar but slightly weaker than [45].

We would like to make two comments at this stage:

- The bound on \( \mathcal{B}(B_c^- \to \tau^- \bar{\nu}_{\tau}) \) depends linearly on \( \mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_{\mu}) \). As \( \mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_{\mu}) \) has not yet been measured, a model independent bound is not possible. Moreover, even the SM calculation, and in particular the uncertainty, is not fully under control at the moment. Thus, a precise bound on \( \mathcal{B}(B_c^- \to \tau^- \bar{\nu}_{\tau}) \) cannot be obtained currently.

- Even in the presence of better information on \( \mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_{\mu}) \), Eqs. (18) and (19) provide values of \( f_{b \to B_c^+} / f_{b \to B_u^+} \) at the LHC and for the specific kinematic regions used in [55] and [56]. As discussed before, the value of \( f_{b \to B_c^+} / f_{b \to B_u^+} \) at LEP may be different from the above because of 1) larger average \( p_T \) of the b-mesons produced at LEP 2) \( b \bar{b} \) pairs produced at LEP are in the colour singlet state contrary to most of the \( b \bar{b} \) pairs produced at the LHC which are in the colour octet state.

In view of the above, we try to estimate the ratio \( f_{b \to B_c^+} / f_{b \to B_u^+} \) at LEP using the event generator Pythia8 [57, 58] which has Hadronization model tuned to provide a good description of the available experimental data. The results are shown in Table. II. In each of the cases presented in Table. II, we have generated 1 million events in order to reduce the statistical uncertainty. In Case-I, we have used the same \( p_T \) and \( \eta \) cuts as in [56], and get a value \( f_{b \to B_c^+} / f_{b \to B_u^+} = 1.06 \times 10^{-3} \) which is much smaller than \( f_{b \to B_c^-} / f_{b \to B_u^-} = 3 \times 10^{-3} \) which was used to obtain a bound \( \mathcal{B}(B_c^- \to \tau^- \bar{\nu}_{\tau}) \leq 10\% \). Note that, from Eq. 19, \( f_{b \to B_c^-} / f_{b \to B_u^-} = 1.06 \times 10^{-3} \) would correspond to \( \mathcal{B}(B_c^- \to J/\psi \mu^+ \nu_{\mu}) \approx 6 \times 10^{-2} \) (see the left panel of Fig. 6) which is much larger than the values considered in [45]. In the third row of Table. II, we

| \( p_T(B_c^+) \) | \( f_{b \to B_c^+} / f_{b \to B_u^+} \) |
|---|---|
| \( > 15 \text{ GeV} \) \( |\eta| < 1.6 \) | 0.255 \( \times 10^{-4} \) 1.06 \( \times 10^{-3} \) |
| \( < 15 \text{ GeV} \) \( |\eta| < 1.6 \) | 0.301 \( \times 10^{-4} \) 1.89 \( \times 10^{-3} \) |
| \( > 15 \text{ GeV} \) \( |\eta| < 1.6 \) | 0.374 \( \times 10^{-4} \) 1.09 \( \times 10^{-3} \) |
| \( > 15 \text{ GeV} \) \( |\eta| < 1.6 \) | 0.255 \( \times 10^{-4} \) 0.98 \( \times 10^{-3} \) |
| LEP (at the \( Z \) peak) \( |\eta| < 1.6 \) | 0.42 \( \times 10^{-4} \) 1.07 \( \times 10^{-4} \) |

TABLE II. Hadronization fractions calculated from Pythia8.
\[ f_{b \to B^-} = 0.094 \] (not shown in the table), and
\[ f_{b \to B^-}/f_{b \to B^0} = 1.07 \times 10^{-3}, \] the first two numbers being consistent with their experimental measurements \[4, 47\]. Using the number \( f_{b \to B^-}/f_{b \to B^0} = 1.07 \times 10^{-3} \), from Fig. 5, we get
\[
\mathcal{B}(B_c^- \to \tau^- \bar{\nu}_\tau) \leq 39\%.
\] (20)

We warn the readers that this bound should only be taken as an estimate because, after all, Pythia only uses a Hadronization model adjusted to describe a large amount of available experimental data well (as we saw, indeed it reproduced the correct values for \( f_{b \to B^-} \) and \( f_{b \to B^0} \)), and the value of \( f_{b \to B^-} \) obtained from Pythia is neither based on any first principle calculation nor on direct experimental data.

To summarise, in this short note, we have shown that

- the recent Belle results on \( R_D \) and \( R_{D^*} \) have interesting implications on the various possible EFT explanations of the data. The most important being that the pure tensor explanation is now completely allowed both by the measurement of \( F_D^P \) and the high-\( p_T \ p p \to \tau \nu \) searches by ATLAS and CMS.

- the solution in terms of a pure right-chiral vector current (involving right-chiral neutrinos) has now moved into the 2\( \sigma \) allowed range of the LHC \( p p \to \tau \nu \) searches.

- the upper bound on the branching fraction of \( B_c^- \to \tau^- \bar{\nu}_\tau \) from the LEP data is much weaker than the bound 10\% used in the recent literature. Our estimate of this bound, based on the Hadronization model implemented in Pythia8, is approximately 40\%. This bound, while being independently important, may also have interesting implications on the various scalar-pseudoscalar explanations of the \( R_D \) and \( R_{D^*} \) data.

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