RD and RD*
Theoretical Developments

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are tree level processes

• Precise prediction on the Ratio has been done

\[ R_D = \frac{\Gamma(\bar{B} \to D\tau\bar{\nu})}{\Gamma(\bar{B} \to D\ell\bar{\nu})} = 0.299 \pm 0.003 \]

\[ R_{D^*} = \frac{\Gamma(\bar{B} \to D^*\tau\bar{\nu})}{\Gamma(\bar{B} \to D^*\ell\bar{\nu})} = 0.257 \pm 0.003 \]

\[ \sim 1\% \]

Nevertheless,

• the SM values are NOT in agreement with data
$R_D$ vs $R_{D^*}$

$\Delta \chi^2 = 1.0$ contours

$R(D) = 0.300(8)$ HPQCD (2015)
$R(D) = 0.299(11)$ FNAL/MILC (2015)
$R(D^*) = 0.252(3)$ S. Fajfer et al. (2012)

Approximate significance:
$\sim 4.1 \sigma$

References:
LHCb: PRL 115, 111803 (2015), arXiv 1708.08856
Topics

• SM predictions
• NP explanations
• Relevant observables
SM predictions

[1] Form Factor

Main uncertainty in RD(*) comes from Form Factors

\[ \langle D(v')|\bar{c}\gamma_\mu b|B(v)\rangle = \sqrt{m_Bm_D}\left[ h_+(q^2)(v + v')_\mu + h_-(q^2)(v - v')_\mu \right] \]

\[ \frac{d\Gamma(B \to D\ell\nu)}{dw} = \frac{G_F^2|V_{cb}|^2\eta^2 m_B^5}{48\pi^3} (w(q^2)^2 - 1)^{3/2} r_D^3 (1 + r_D)^2 \mathcal{G}(q^2)^2 \]

Using Heavy Quark Effective Theory, \( q^2 \) dependence can be described

\[ \mathcal{G} = h_+ - \frac{1 - r_D}{1 + r_D} h_- = \xi_{IW}(q^2) + \frac{\alpha_s}{\pi} \chi_1(q^2) + \frac{\Lambda_{QCD}}{m_{c,b}} \chi_2(q^2) + \cdots \]

The functions are then determined with QCD sum-rule / lattice + fit to data of the light lepton mode.
QCDSR + lattice QCD + Fit to Belle data of $B \to D(\ast)\ell\nu$ ($\ell = e, \mu$) up to the NLO, i.e. $O(\alpha_s), O(1/m_Q)$

Ligeti et al., 1703.05330

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$R(D)$</th>
<th>$R(D^\ast)$</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{w=1}$</td>
<td>0.292 ± 0.005</td>
<td>0.255 ± 0.005</td>
<td>41%</td>
</tr>
<tr>
<td>$L_{w=1}+SR$</td>
<td>0.291 ± 0.005</td>
<td>0.255 ± 0.003</td>
<td>57%</td>
</tr>
<tr>
<td>NoL</td>
<td>0.273 ± 0.016</td>
<td>0.250 ± 0.006</td>
<td>49%</td>
</tr>
<tr>
<td>NoL+SR</td>
<td>0.295 ± 0.007</td>
<td>0.255 ± 0.004</td>
<td>43%</td>
</tr>
<tr>
<td>$L_{w\geq1}$</td>
<td>0.298 ± 0.003</td>
<td>0.261 ± 0.004</td>
<td>19%</td>
</tr>
<tr>
<td>$L_{w\geq1}+SR$</td>
<td><strong>0.299 ± 0.003</strong></td>
<td><strong>0.257 ± 0.003</strong></td>
<td><strong>44%</strong></td>
</tr>
<tr>
<td>th:$L_{w\geq1}+SR$</td>
<td>0.306 ± 0.005</td>
<td>0.256 ± 0.004</td>
<td>33%</td>
</tr>
<tr>
<td>Data [9]</td>
<td>0.403 ± 0.047</td>
<td>0.310 ± 0.017</td>
<td>−23%</td>
</tr>
<tr>
<td>Refs. [53, 57, 59]</td>
<td>0.300 ± 0.008</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Ref. [58]</td>
<td>0.299 ± 0.003</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Ref. [34]</td>
<td>—</td>
<td>0.252 ± 0.003</td>
<td>—</td>
</tr>
</tbody>
</table>
Another development. Soft-photon effects depend on lepton mass, which leads to corrections even in RD(*)

Soft-photon corrections to RD result in

1. leading to $\text{RD}^+ \neq \text{RD}^0$
2. depending on photon energy cut
3. non-negligible constructive contribution to RD, at most $4\sim 6\%$
FIG. 3. The (leading) long-distance QED corrections to $R(D^+)_{\tau/\mu}$ and $R(D^0)_{\tau/\mu}$ as a function of $E_{\text{max}}$. 
NP explanations

There exist several solutions to the RD(*) anomaly. In terms of effective operators, possible NPs are given as follows

\[ L_{\text{eff}}^{\text{NP}} \equiv -2\sqrt{2}G_F V_{cb} C_{NP} O_{NP} \]

**V–A**: \[ O_{V_1} = (\bar{c}\gamma^{\mu} P_L b)(\bar{\tau}\gamma_{\mu} P_L \nu) \]

**Models**: (SM), W’ boson, Vector Leptoquark, ...

**Fit to data**: \[ C_{V_1} \sim +0.17 \]

- NP with 17% contribution of the SM value is required
- Assuming NP coupling =1, it implies \sim 2\text{TeV} NP scale
$V+A$ (quark sector): \[ \mathcal{O}_{V_2} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu) \]

Models: $W'$ boson, ...?

Fit to data: $C_{V_2} \sim 0.01 + 0.6i$

- Complex coupling is necessary

Scalar types: \[ \mathcal{O}_{S_{1(2)}} = (\bar{c} P_{R(L)} b)(\bar{\tau} P_L \nu) \]

Models: Charged Higgs, Scalar Leptoquark, ...

Fit to data: $C_{S_1} = $ no solution, $C_{S_2} \sim -1.5$

- 2HDM of typell is disfavored
- Large scalar contribution is needed

Tensor type: \[ \mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu) \]

Models: Doublet vector/scalar Leptoquark (in part)

Fit to data: $C_T \sim 0.3$
Relevant observables

[1] q^2 distribution  

Distributions for the case that $C_{\text{NP}}$ = best fit to the current results of $R_D(*)$

Some simple test with statistics was done and it turns out that

“5ab^-1 data for q^2 distributions enable us to distinguish the NP scenarios in case that the present anomalies still remain in the future”
has been observed at LHCb

\[ R_{J/\psi} = \frac{\Gamma(B_c \to J/\psi\tau\bar{\nu})}{\Gamma(B_c \to J/\psi\mu\bar{\nu})} \]

**data:** \( R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18 \)  
**LHCb, 1711.05623**

**SM:** \( R_{J/\psi} = 0.283 \pm 0.048 \)  
**RW, 1709.08644**

- Perturbative QCD analysis provides the form factor.
- Still large errors both in data (35%) and SM (17%)
- Deviation \( \sim 1.7\sigma \)

**NP:** Central value of the data cannot be reproduced
\( R_{D^*}^{SM} = 0.253 \pm 0.003 \)

\( R_{J/\psi}^{SM} = 0.283 \pm 0.048 \)
Not directly measured, but some limits have been estimated from Bc decay.

From Bc life time: uncertainty of theoretical evaluation implies

From LEP data: extracted from data at the Z boson peak

- Indirect bound is then given as \( \mathcal{B}(B_c \rightarrow \tau \nu) < 10 - 30\% \)
- This kills the Scalar NP explanation
Thank you!
FIG. 2. (a) The long-distance QED corrections to the branching ratios of $\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell$ and (b) $B^- \to D^0 \ell^- \bar{\nu}_\ell$, where $\ell = \mu, \tau$, as a function of $E_{\text{max}}$. The dotted lines show the corrections to $\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell$ without the Coulomb contributions, for the purpose of illustration.