Status and outlook for $R(D(\ast))$

Koji Hara (KEK)

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Anomalies 2020
Semi-tauonic B decay: $B \to D(\ast)\tau\nu$

- Sensitive to new physics

  **Ratio of $\tau$ to $\mu,e$ could be reduced/enhanced**

  $$R(D(\ast)) = \frac{\mathcal{B}(B \to D(\ast)\tau\nu)}{\mathcal{B}(B \to D(\ast)\ell\nu)} \quad \text{L} = e,\mu$$

  SM $R(D) = 0.299 \pm 0.003$, $R(D^\ast) = 0.258 \pm 0.005$ [HFLAV2019]

- Polarizations of $\tau$ and $D^\ast$ can probe the NP model

  $$P_{\tau}(D(\ast)) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \quad F_{L,D^\ast}^D = \frac{\Gamma(D_L^\ast)}{\Gamma(D_L^\ast) + \Gamma(D_T^\ast)}$$

NP type (vector, scalar, tensor) dependence

[M. Tanaka and R. Watanabe PRD 87, 034028 (2013)]

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Anomalies 2020
B factory experiments
- Produce BB pairs via $e^+e^- \rightarrow Y(4s)$
- Only one BB pair in an event
- $4\pi$ detector surrounding the IP
  - Belle + BaBar have accumulated $> \sim 1\text{ab}^{-1}$
  - Belle II started physics data taking in 2019 and will accumulate $50\text{ab}^{-1}$

LHCb
- Experiment dedicated to B physics at LHC
- Many b hadrons produced in pp collisions
- Single arm detector covering the forward region
- Large boost $\rightarrow$ good separation of vertices: primary vertex, B, D, $\tau$
- Collected Run 1 + Run 2 $\sim 9\text{fb}^{-1}$
- Now in long shutdown for upgrade

These experiments are complementary
Utilize the B factory specific feature: only one B-meson pair is produced

**Tag B** pair event by reconstructing one B meson in hadronic or semileptonic B Decay

→ Provide pure single B event

- Require no particle remains after removing tagging B and signal B candidates

→ Remaining energy in the calorimeter ($E_{ECL}$)

- Multiple missing neutrinos → (Missing mass)² > 0

**Anomalies 2020**
Tagging Methods

- **Hadronic Tag**
  - **Exclusive tag**
    - Fully reconstruct in \( B \to D X \) decays
      - \( \sim 1100 \) exclusive decay channels (Belle) [NIM A 654, 432 (2011)]
    - Tagging efficiency \( \sim 0.2 \% \)
    - Less background
  - **Inclusive tag**
    - Reconstruct tag-side \( B \) with all particles except signal-side
    - Higher efficiency than exclusive tag
    - Need clean signal-side final state
    - Used for first observation of \( B \to D^* \tau \nu \) by Belle
      - [PRL99, 191807(2007)]

- **Semileptonic Tag**
  - **Reconstruct** \( B \to D^{(*)}\ell \nu \)
    - Partial reconstruction with
      - \( E_B = E_{\text{beam}} \)
      - Undetected neutrino mass \( \sim 0 \)
  - Tagging efficiency \( \sim 0.5\% \)
  - More background

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Belle \( B \to \tau \nu \) analysis [PRD 82, 071101(R) (2010)]

Beam energy

Constrained mass

\[ m_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2} \]

Events (100 GeV/c$^2$)

\( \times 10^3 \)
Results with Hadronic Tag by BaBar

- 471 M $\bar{B}B$ sample
- Leptonic tau decays are used

$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042$$

$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018$$

Both are larger than SM expectations
Results with Hadronic Tag by Belle (leptonic $\tau$ decays)

[PRD92,072014(2015)]

- 772 M $BB$ sample
- Leptonic tau decays are used

$R(D) = 0.375 \pm 0.064 \pm 0.026$

$R(D^*) = 0.293 \pm 0.038 \pm 0.015$
Belle R(D(*)) Measurement with Semileptonic Tag

- Previous Analysis [PRD94,072007(2016)]
  Measure $R(D^*)$ with $B^0 \to D^*\tau^+\nu$ (and charge conjugate) decays
  - Good signal purity by using clean $D^*\to D^0\pi^-$ decays

- Recent Update [PRL124,161803 (2020)]
  - Full Event Interpretation (FEI) tool developed in BelleII software framework
  - Multivariate analysis with Boosted-Decision Tree classifier
    - Better efficiency and enable to use more signal decay modes
  - Both $R(D)$ and $R(D^*)$ with both $B^0$ and $B^\to D^*\tau\nu$
  - 2D extended maximum-likelihood fit on “classifier” and $E_{ECL}$

**Classifier**: Boosted decision tree output of $\cos\theta_{B,D[*]l}$, $M_{miss2}$, $E_{vis}$

**Graph**:
- $y$ (signal vs normalization classifier)
  - $B \to D(*)\tau\nu$
  - $B \to D(*)\ell\nu$
  - Background events

**Figure**: MC $\cos\theta_{B,D[*]l}$, $B \to D^*l\nu$
Belle $R(D^*)$ Semileptonic Tag Result

**D*+1 mode**

<table>
<thead>
<tr>
<th>Signal</th>
<th>$B \rightarrow D_l \nu$</th>
<th>$B \rightarrow D \tau \nu$</th>
</tr>
</thead>
</table>

**D*01 mode**

$R(D^*) = 0.283 \pm 0.018 \pm 0.014$

Anomalies 2020
Belle R(D) Semileptonic Tag Result

First R(D) measurement with Semileptonic tag

\[ R(D) = 0.307 \pm 0.037 \pm 0.016 \]
Belle $R(D^*)$ Results

[S. Sandilya, talk at FPCP2020]

Belle combined result at about $1.6 \sigma$ from SM
R(D*) with $\tau \rightarrow \mu \nu \nu$ by LHCb

**[PRL 115, 111803 (2015)]**

- 3.0 fb$^{-1}$ Data
- $B^0 \rightarrow D^* \tau \nu$, $\tau \rightarrow \mu \nu \nu$
- 3D Fit to (Missing mass)$^2$, $E_\mu^*$, $q^2$
- Primary and B vertices $\rightarrow P_B$ direction
- $|P_B|$ is approximated by $(P_B)_z = m_B/m_{D^*\mu}(P_{D^*\mu})_z$

$$R(D^*) = 0.336 \pm 0.027 \text{(stat)} \pm 0.030 \text{(syst)}$$
R(D*) with $\tau \rightarrow 3\pi \nu$ by LHCb

[PRD97, 072013 (2018)]

- 3.0 fb$^{-1}$ Data
- Obtain Ratio $K(D^*) = \frac{Br(B^0 \rightarrow D^*\tau\nu)}{Br(B^0 \rightarrow D^*3\pi)}$
- **Reconstruct P$\tau$ Direction**

- 3D fit to $\tau$ decay time, $q^2$, BDT output

\[ K(D^{*-}) = 1.97 \pm 0.13\text{(stat)} \pm 0.18\text{(syst)} \]

Multiply $Br(B \rightarrow D^*3\pi)/Br(B \rightarrow D^*l\nu)$

\[ R(D^*) = 0.280 \pm 0.018\text{(stat)} \pm 0.029\text{(syst)} \]

(Update of $Br(B \rightarrow D^*l\nu)$ by HFLAV2019)
Latest R(D) and R(D*) Situation

BaBar (2012), had. tag
0.440 ± 0.058 ± 0.042
Belle (2015), had. tag
0.375 ± 0.064 ± 0.026
Belle (2019), sl. tag
0.307 ± 0.037 ± 0.016
Average
0.340 ± 0.027 ± 0.013
SM pred. average
0.299 ± 0.003
PRD 94 (2016) 094008
0.299 ± 0.003
PRD 95 (2017) 115008
0.299 ± 0.003
JHEP 1712 (2017) 060
0.299 ± 0.004
FNAL/MILC (2015)
0.299 ± 0.011
HPQCD (2015)
0.300 ± 0.008

1.4σ above SM

BaBar (2012), had. tag
0.332 ± 0.024 ± 0.018
Belle (2015), had. tag
0.293 ± 0.038 ± 0.015
Belle (2017), (had. tau)
0.270 ± 0.035 ± 0.027
Belle (2019), sl. tag
0.283 ± 0.018 ± 0.014
LHCb (2015), (muonic tau)
0.336 ± 0.027 ± 0.030
LHCb (2018), (had. tau)
0.280 ± 0.018 ± 0.029
Average
0.295 ± 0.011 ± 0.008
SM pred. average
0.258 ± 0.005
PRD 95 (2017) 115008
0.257 ± 0.003
JHEP 1711 (2017) 061
0.260 ± 0.008
JHEP 1712 (2017) 060
0.257 ± 0.005

2.5σ above SM
Latest $R(D)-R(D^*)$ vs SM

Deviation from SM is $3.1 \sigma$
More measurements in Addition to $R(D(\ast))$

- Polarizations
- Other $b \rightarrow c$ hadrons
**τ Polarization Measurement at Belle**

[PRL118, 211801 (2017) PRD97, 012004 (2018)]

- **Hadronic tag**
- **Two body tau decays**: $\tau \rightarrow \pi \nu$, $\rho \nu$
  - Helicity angle sensitive to the tau polarization
- $P_{\tau}(D^*)_{\text{SM}} = -0.497 \pm 0.013$
  [Tanaka, Watanabe, PRD 87, 034028 (2013)]

\[
\frac{1}{\Gamma d \cos \theta_{\text{hel}}} \frac{d\Gamma}{d \cos \theta_{\text{hel}}} = \frac{1}{2} \left(1 + \alpha \cdot P_{\tau} \cos \theta_{\text{hel}}\right)
\]

\[
\alpha = \begin{cases} 
1 & \text{for } \tau \rightarrow \pi^- \nu \\
0.45 & \text{for } \tau \rightarrow \rho^- \nu
\end{cases}
\]

**R(D*) world average**

HFLAV winter 2016

\[
R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst}),
\]

\[
P_{\tau}(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst}),
\]

(R(D*) included in the HFLAV avg)

Anomalies 2020
D* Polarization Measurement at Belle

- Reconstruct $B^0 \rightarrow D^* \tau \nu$
- Utilized **inclusive tag** method
- Extract signal yield in three $D^* \rightarrow D\pi$ helicity angle regions
- Fit the helicity angle distribution

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{\text{hel}}} = \frac{3}{4} \left[ 2 F_L^{D^*} \cos^2 \theta_{\text{hel}} + F_T^{D^*} \sin^2 \theta_{\text{hel}} \right]$$

**I**

$\tau \rightarrow \pi$

$\tau \rightarrow \nu$

$p \rightarrow \mu$

EVENTS/(0.333)

$F_L^{D^*} = 0.60 \pm 0.08\text{(stat)} \pm 0.04\text{(syst)}$

**II**

within 2 $\sigma$ of SM

preliminary
[arXiv:1903.03102]

$F_L^{D^*} = 0.46 \pm 0.03$ [PRD95, 115038(2017)]

$F_L^{D^*} = 0.441 \pm 0.006$ [arXiv:1808:03565]
R(\(J/\psi\)) Measurement at LHCb

\[ [\text{PRL120, 121801(2018)}] \]

- 3.0 fb\(^{-1}\) Data
- Measure

\[ R(J/\psi) = \frac{Br(B_c^+ \to J/\psi \tau \nu)}{Br(B_c^+ \to J/\psi \mu \nu)} \]

- Same method as muonic R(D\(^*\)) to estimate \( P_{Bc} \)
- 3D fit to (missing mass\(^2\), \( B_c \) decay time, category index \( Z \)) for (\( q^2 \), \( E_{\mu^*} \)) bins

\[ R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)} \]

\[ = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst}) \]

2\(\sigma\) from SM expectation 0.25-0.28

Anomalies 2020
Future prospects

- **New results** are expected from:
  - Run 2 updates with a total uncertainty reduction
  - Ongoing analyses:
    - \( R(D^0) : B^+ \rightarrow D^0 \tau \nu \)
    - \( R(D^+) : \bar{B}^0 \rightarrow D^+ \tau \nu \)
    - \( R(D_{s}^{(*)}) : B_s \rightarrow D_s^{(*)} \tau \nu \)
    - \( R(D^{**}) : B^+ \rightarrow D^{**}(2420)^0 \tau \nu \)
    - \( R(\Lambda_c^{(*)}) : \Lambda_b \rightarrow \Lambda_c^{(*)} \tau \nu \)
    - \( R(\psi) : B_{c}^{+} \rightarrow J/\psi \tau \nu \)
    - \( R(p) : \Lambda_b \rightarrow p \tau \nu \)
    - Combined measurement of \( R(D) \) and \( R(D^*) \)
  - Form factor measurements
    - \( \Lambda_b \rightarrow \Lambda_c l \nu \)
    - \( \Lambda_b \rightarrow \Lambda_{c}^{+} l \nu \)
    - \( B_s \rightarrow D_{s}^{(*)} l \nu \)
  - Angular analyses
    - In the **Upgrade I**, LHCb will collect ~50fb\(^{-1}\) (luminosity \(\times 5\))
Belle II Accumulating Physics Data

- Belle II / SuperKEKB started physics data taking with full detectors in 2019
- Peak luminosity $2.4 \times 10^{34} \text{ cm}^2/\text{s} \ (\text{WR})$ exceeded KEKB
  - About half beam currents of KEKB, with $\beta_y^*$ squeezed to 1.0 mm ($\beta_y^*$=0.3mm is the final target)
  - Good achievement as a start up

More details in Gagan’s talk
Hadronic Tag in Early Belle II Data

• Belle II analysis software works very well.
• Hadronic tag (Full Event Interpretation) performance calibrated with data

Reconstructed variables:
$M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2}$

$P_{\text{tag}}$: classifier of purity

Purity dependent efficiency is calibrated
R(D(∗)) Belle II Prospect

[The Belle II Physics Book, PTEP 2019, 123C01]

→ Verify current deviation from the SM

Expected Precision at Belle II for R(D(∗)), τ polarization

<table>
<thead>
<tr>
<th></th>
<th>5 ab⁻¹</th>
<th>50 ab⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{D} )</td>
<td>(±6.0 ± 3.9)%</td>
<td>(±2.0 ± 2.5)%</td>
</tr>
<tr>
<td>( R_{D^*} )</td>
<td>(±3.0 ± 2.5)%</td>
<td>(±1.0 ± 2.0)%</td>
</tr>
<tr>
<td>( P_{\tau}(D^*) )</td>
<td>±0.18 ± 0.08</td>
<td>±0.06 ± 0.04</td>
</tr>
</tbody>
</table>

Note: latest Belle semileptonic tag is not included in the projection.

Belle II/SuperKEKB Luminosity Prospect

Correlations of variables → NP model

Verify current deviation from the SM
Summary

• $B \rightarrow D(*)\tau\nu$ decays are good probes for New Physics
• Belle, BaBar, LHCb have measured $R(D(*))$ with various methods and sub-decay modes
  o In addition to $R(D(*))$, other variables have been also measured
    • $\tau$, $D^*$ Polarizations
    • $R(J/\psi)$
• ‘Anomaly’ exists between measurements and SM
  o Little bit reduced but still there is 3.1 $\sigma$ difference
• LHCb and Belle II will provide more interesting results in future
  o Verify or reject the current ‘anomaly’
  o Determine the new physics model, if exists
# Belle Systematic Errors

<table>
<thead>
<tr>
<th>Source</th>
<th>Belle (Had, $\ell^-$)</th>
<th>Belle (Had, $\ell^-$)</th>
<th>Belle (SL, $\ell^-$)</th>
<th>Belle (Had, $h^-$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D$</td>
<td>$R_{D^*}$</td>
<td>$R_{D^*}$</td>
<td>$R_{D^*}$</td>
<td></td>
</tr>
<tr>
<td>MC statistics</td>
<td>4.4%</td>
<td>3.6%</td>
<td>2.5%</td>
<td>$\pm 4.0%$</td>
</tr>
<tr>
<td>$B \rightarrow D^{**} \ell \nu_\ell$</td>
<td>4.4%</td>
<td>3.4%</td>
<td>$+1.0%$</td>
<td>2.3%</td>
</tr>
<tr>
<td>Hadronic $B$</td>
<td>0.1%</td>
<td>0.1%</td>
<td>1.1%</td>
<td>$+7.3%$</td>
</tr>
<tr>
<td>Other sources</td>
<td>3.4%</td>
<td>1.6%</td>
<td>$+1.8%$</td>
<td>5.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>7.1%</td>
<td>5.2%</td>
<td>$+3.4%$</td>
<td>$+10.0%$</td>
</tr>
</tbody>
</table>
τ Hadronic decay: $R(D^*)$, τ Polarization

Systematic Errors

**TABLE II.** The systematic uncertainties in $R(D^*)$ and $P_\tau(D^*)$, where the values for $R(D^*)$ are relative errors. The group "common sources" identifies the common systematic uncertainty sources in the signal and the normalization modes, which cancel to a good extent in the ratio of these samples. The reason for the incomplete cancellation is described in the text.

<table>
<thead>
<tr>
<th>Source</th>
<th>$R(D^*)$</th>
<th>$P_\tau(D^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic $B$ composition</td>
<td>+7.7%</td>
<td>+0.134</td>
</tr>
<tr>
<td></td>
<td>-6.9%</td>
<td>-0.103</td>
</tr>
<tr>
<td></td>
<td>+4.0%</td>
<td>+0.146</td>
</tr>
<tr>
<td></td>
<td>-2.8%</td>
<td>-0.108</td>
</tr>
<tr>
<td>Fake $D^*$</td>
<td>3.4%</td>
<td>0.018</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^{**} \ell^- \bar{\nu}_\ell$</td>
<td>2.4%</td>
<td>0.048</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^{**} \tau^- \bar{\nu}_\tau$</td>
<td>1.1%</td>
<td>0.001</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^* \ell^- \bar{\nu}_\ell$</td>
<td>2.3%</td>
<td>0.007</td>
</tr>
<tr>
<td>τ daughter and $\ell^-$ efficiency</td>
<td>1.9%</td>
<td>0.019</td>
</tr>
<tr>
<td>MC statistics for efficiency estimation</td>
<td>1.0%</td>
<td>0.019</td>
</tr>
<tr>
<td>$B(\tau^- \rightarrow \pi^- \nu_\tau, \rho^- \nu_\tau)$</td>
<td>0.3%</td>
<td>0.002</td>
</tr>
<tr>
<td>$P_\tau(D^*)$ correction function</td>
<td>0.0%</td>
<td>0.010</td>
</tr>
</tbody>
</table>

**Common sources**

<table>
<thead>
<tr>
<th>Source</th>
<th>$R(D^*)$</th>
<th>$P_\tau(D^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tagging efficiency correction</td>
<td>1.6%</td>
<td>0.018</td>
</tr>
<tr>
<td>$D^*$ reconstruction</td>
<td>1.4%</td>
<td>0.006</td>
</tr>
<tr>
<td>Branching fractions of the $D$ meson</td>
<td>0.8%</td>
<td>0.007</td>
</tr>
<tr>
<td>Number of $B\bar{B}$ and $\mathcal{B}(\Upsilon(4S) \rightarrow B^+B^- \text{ or } B^0\bar{B}^0)$</td>
<td>0.5%</td>
<td>0.006</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>+10.4%</td>
<td>+0.21</td>
</tr>
<tr>
<td></td>
<td>-9.4%</td>
<td>-0.16</td>
</tr>
</tbody>
</table>
# D* Polarization Systematic Errors

**TABLE I. Summary of systematic uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta F_{L}^{D*}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monte Carlo statistics</td>
<td></td>
</tr>
<tr>
<td>AR shape and peaking background</td>
<td>$\pm 0.032$</td>
</tr>
<tr>
<td>CB shape</td>
<td>$\pm 0.010$</td>
</tr>
<tr>
<td>Background scale factors</td>
<td>$\pm 0.001$</td>
</tr>
<tr>
<td>Background modeling</td>
<td></td>
</tr>
<tr>
<td>$B \to D^{**} \ell \nu$</td>
<td>$\pm 0.003$</td>
</tr>
<tr>
<td>$B \to D^{**} \tau \nu$</td>
<td>$\pm 0.011$</td>
</tr>
<tr>
<td>$B \to$ hadrons</td>
<td>$\pm 0.005$</td>
</tr>
<tr>
<td>$B \to D^* M$</td>
<td>$\pm 0.004$</td>
</tr>
<tr>
<td>Signal modeling</td>
<td></td>
</tr>
<tr>
<td>Form factors</td>
<td>$\pm 0.002$</td>
</tr>
<tr>
<td>$\cos \theta_{hel}$ resolution</td>
<td>$\pm 0.003$</td>
</tr>
<tr>
<td>Acceptance non-uniformity</td>
<td>$+0.015$ $-0.005$</td>
</tr>
<tr>
<td>Total</td>
<td>$+0.039$ $-0.037$</td>
</tr>
</tbody>
</table>