b → cτν overview and Belle II prospects

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On behalf of the Belle II collaboration

Anomalies and Precision in the Belle II era
Vienna, 6-8.9. 2021
Introduction

- semi-tauonic $b \rightarrow c\tau\nu$ decays provide powerful probes of the Standard Model (SM)

→ NP contributions typically less constrained than in $b \rightarrow c\ell\nu$ ($\ell = e, \mu$)

→ rich spectrum of kinematic observables accessible

→ complementary sensitivities of different modes to various SM extensions

→ far from fully explored, experimentally very challenging

→ in the last decade several measurements indicating enhanced rates of $b \rightarrow c\tau\nu$
compared with the SM predictions.
Observables

Lepton flavor universality tests: \[
\mathcal{R}(H_c) = \frac{\mathcal{B}(B \rightarrow H_c \tau \bar{\nu}_\tau)}{\mathcal{B}(B \rightarrow H_c \ell \bar{\nu}_\ell)} \quad H_C = D^{(*)}, J/\psi \\
\text{normalization}
\]

→ experimentally and theoretically convenient due to cancellation of several uncertainties in the ratio

Kinematic variables: e.g. \[q^2 = (p_B - p_{D^*})^2\] distributions

Polarization fractions: \(\tau\) polarization, \(D^{*-}\) longitudinal polarization

Uncertainties of the SM predictions for \(\mathcal{R}(H_c)\) range from 1% to 3%

→ sensitivity to NP contributions
Measurement basics

- relatively large branching fractions

- but multiple neutrinos in the final state → challenging decay reconstruction

→ determination of initial B momentum allows for evaluation of

\[ q^2 = (p_B - p_{D^*})^2 \]
(momentum transfer to leptons)

\[ m_{\text{miss}}^2 = (p_B - p_{D^*(\ast)} - p_\ell)^2 \]
(missing mass)

\[ E_l^* = (p_\ell \cdot p_B)/m_B \]
(charged lepton energy in B frame)

→ basis for signal / normalization mode separation

- accessible to B factories and LHCb
Measurement basics - B factories

- $e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B \bar{B}$

- fully known initial state + hermetic detector ($4\pi$) → tagging techniques

→ in signal/normalization events all particles in an event assigned (to $B_{\text{sig}}$ or $B_{\text{tag}}$)

background events: larger $E_{\text{ECL}}$  
signal vs. normalization: $m_{\text{miss}}^2 + \text{kinematics}$
Measurement basics - LHCb

- tagging not available

- but very large sample of b-hadrons +
  large Lorentz boost +
  excellent vertexing

  → well separated vertices in the decay chain

- if \( \tau \) decay vertex can be reconstructed (e.g. \( \tau \rightarrow (3\pi)\nu \))

  → \( B \) momentum determined up to discrete ambiguity

- for \( \tau \rightarrow \mu\nu\bar{\nu} \) vertex not available

  → rest frame approximation:

\[
(p_B)_z = \frac{m_B}{m_{reco}} (p_{reco})_z
\]
Summary of existing B-factory measurements

<table>
<thead>
<tr>
<th>Hadronic tag with $\tau \rightarrow \ell \nu \bar{\nu}$</th>
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<tr>
<th>Semi-leptonic tag with $\tau \rightarrow \ell \nu \bar{\nu}$</th>
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<thead>
<tr>
<th>Hadronic tag with $\tau \rightarrow \pi \nu$, $\tau \rightarrow \rho \nu$</th>
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<tbody>
<tr>
<td>Belle $\tau$ polarization measurement</td>
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<tr>
<th>Inclusive tag with $\tau \rightarrow \pi \nu$, $\tau \rightarrow \ell \nu \bar{\nu}$</th>
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<tbody>
<tr>
<td>Belle $D^{*-}$ polarization measurement</td>
</tr>
<tr>
<td>arXiv:1903.03102</td>
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<thead>
<tr>
<th>Result</th>
<th>BABAR</th>
<th>Belle</th>
</tr>
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<tbody>
<tr>
<td>$R(D)$</td>
<td>$0.440 \pm 0.058 \pm 0.042$</td>
<td>$0.375 \pm 0.064 \pm 0.026$</td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>$0.332 \pm 0.024 \pm 0.018$</td>
<td>$0.293 \pm 0.038 \pm 0.015$</td>
</tr>
</tbody>
</table>

| $R(D^*)$ | $0.307 \pm 0.037 \text{(stat)} \pm 0.016 \text{(syst)}$ |
| $P_{\tau}(D^*)$ | $-0.38 \pm 0.51 \text{(stat)}^{+0.21}_{-0.16} \text{(syst)}$ |

| $F_{L,\tau}(D^*)$ | $0.60 \pm 0.08 \text{(stat)} \pm 0.04 \text{(sys)}$ |
Example: Latest $\mathcal{R}(D^{(*)})$ from Belle – Semi-leptonic tag


- using FEI (full event interpretation) for the tag-side $B \to D^{(*)} l \bar{\nu}_l$ reconstruction
- reconstructed signal modes: $D^+ \ell^-, D^0 \ell^-, D^{*+} \ell^-, D^{*0} \ell^- \quad (\ell = e, \mu)$
- combine kinematic variables using BDT: $(\cos \theta_{B,D^{(*)}l}, m^2_{\text{miss}}, E_{\text{vis}}) \to \mathcal{O}_{\text{sig}}$
- $E_{\text{ECL}} - \mathcal{O}_{\text{sig}}$ distributions of all samples are fit simultaneously, constraining $\mathcal{R}(D(\ast)^0) = \mathcal{R}(D(\ast)^+)$. 

- Free parameters: signal yields, normalization yields, $B \rightarrow D^{**} l\nu$ yield, feed-down $D(\ast)$.

$$\mathcal{R}(D) = 0.307 \pm 0.037 \text{ (stat)} \pm 0.016 \text{ (syst)}$$

$$\mathcal{R}(D^{\ast}) = 0.283 \pm 0.018 \text{ (stat)} \pm 0.014 \text{ (syst)}$$

Most precise values to date!

Main systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta \mathcal{R}(D)$ (%)</th>
<th>$\Delta \mathcal{R}(D^{\ast})$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{**}$ composition</td>
<td>0.76</td>
<td>1.41</td>
</tr>
<tr>
<td>PDF shapes</td>
<td>4.39</td>
<td>2.25</td>
</tr>
<tr>
<td>Feed-down factors</td>
<td>1.69</td>
<td>0.44</td>
</tr>
<tr>
<td>Efficiency factors</td>
<td>1.93</td>
<td>4.12</td>
</tr>
</tbody>
</table>
Summary of existing LHCb measurements

\[ \mathcal{R}(D^{*-}) \text{ with } \tau \rightarrow \mu \nu \bar{\nu} \]


\[ \mathcal{R}(D^{*-}) = 0.336 \pm 0.027 \text{ (stat)} \pm 0.030 \text{ (syst)} \]

\[ \mathcal{R}(D^{*-}) \text{ with } \tau \rightarrow \pi^- \pi^+ \pi^- \nu \]


\[ \mathcal{R}(D^{*-}) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013 \]

\[ \mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c \rightarrow J/\psi \tau \bar{\nu}_\tau)}{\mathcal{B}(B_c \rightarrow J/\psi l \bar{\nu}_l)} \]


\[ \mathcal{R}(J/\psi) = 0.71 \pm 0.17 \text{ (stat)} \pm 0.18 \text{ (syst)} \]

\[ \mathcal{R}(J/\psi)^{SM} = 0.2582 \pm 0.0038 \quad \sim 2\sigma \text{ deviation} \]

- so far \[ \mathcal{R}(D) \] not measured: lower \( B \), no \( D^* \) mass constraint, significant \( D^* \) feed-down
Consistency with the SM predictions

\[ R(D) - R(D^*) \]

\[ \Delta \chi^2 = 1.0 \text{ contours} \]

– present world average of \( R(D) - R(D^*) \) deviates from the SM with significance of \( \sim 3.1\sigma \)
Belle $\tau$ polarization measurement


$$P_\tau(D^{(*)}) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \quad \Gamma^\pm - \tau \text{ helicity}$$

SM expectation


Belle $D^\ast$ longitudinal polarization fraction

arXiv:1903.03102


consistent with the SM at $1.6\sigma$
Prospects @ Belle II

- uncertainty in existing B-factory measurements largely statistically dominated

- but increased luminosity at Belle II with higher beam background levels will provide very challenging environment → novel methods

- relevant input to $\mathcal{R}(D^{(*)})$ anomaly already with $\sim 0.5 \text{ ab}^{-1}$ (summer 2022)

fight beam backgrounds with ML methods

expected sensitivity $(\pm \text{stat} \pm \text{syst})$

\[
\begin{array}{ccc}
5 \text{ ab}^{-1} & 50 \text{ ab}^{-1} \\
R_D & (\pm 6.0 \pm 3.9)\% & (\pm 2.0 \pm 2.5)\% \\
R_D^{-} & (\pm 3.0 \pm 2.5)\% & (\pm 1.0 \pm 2.0)\%
\end{array}
\]

PTEP 2019 (12), 123C01, arXiv:1808.10567
### Systematic Uncertainty Considerations

#### Main Systematics in Existing Belle Measurements

<table>
<thead>
<tr>
<th>Source</th>
<th>Belle (Had, $\ell^-$) $R_D$</th>
<th>Belle (Had, $\ell^-$) $R_{D^*}$</th>
<th>Belle (SL, $\ell^-$) $R_{D^*}$</th>
<th>Belle (Had, $h^-$) $R_{D^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC statistics</td>
<td>4.4%</td>
<td>3.6%</td>
<td>2.5%</td>
<td>+4.0%</td>
</tr>
<tr>
<td>$B \rightarrow D^{**} \ell \bar{\nu}_\ell$</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>Total</td>
<td>7.1%</td>
<td>5.2%</td>
<td>+3.4%</td>
<td>+10.0%</td>
</tr>
</tbody>
</table>

- PDF templates, efficiencies → reducible with larger MC samples
- Dedicated measurements of $B \rightarrow D^{**} \ell \bar{\nu}_\ell$ and exclusive hadronic $B$ decays (e.g. $B \rightarrow D^{*+} \pi^+ X$)
- Improved modeling of $B \rightarrow D^{(*)} \ell/\tau \nu$ form factors, lepton id. efficiencies, etc.
- with hadronic tagging Belle II will also have access to $\mathcal{R}(X_c)$
  → hadronic model independent test of LFU

- with more data other observables will become increasingly important
  → angular correlations, polarizations, asymmetries
  → many of these much easier accessible at Belle II w.r.t LHCb
Prospects @ LHCb

- all existing LHCb measurements use Run 1 data only (3 fb-1)
- statistical uncertainties already at the level of systematic uncertainties
  → many contributions will get reduced with larger data samples
- many updates (+ 6 fb-1 of Run 2 data) + new analyses in progress

- $\mathcal{R}(D^+)$
- $\mathcal{R}(D^*)$ - (electron - muon)
- Combined measurement $\mathcal{R}(D^*) - \mathcal{R}(D^0)$
- $\mathcal{R}(D^{**})$
- $\mathcal{R}(D_s^*)$
- $\mathcal{R}(J/\Psi)$
- $\mathcal{R}(\Lambda^*_c)$
Summary

- semi-tauonic $b \rightarrow c\tau\nu$ decays provide powerful probes of the Standard Model (SM)

- many possible observables → but experimentally challenging

- in the last decade several measurements indicating enhanced rates of $b \rightarrow c\tau\nu$ compared with the SM predictions.

- complementary contributions from B factories and LHCb

- Belle II will provide important contributions to resolution of present anomalies already with $\sim 0.5 \text{ ab}^{-1}$ of collected data (summer 2022)