Overview of $R(D)$ and $R(D^*)$

Flavour Physics and CP Violation Conference

Racha Cheaib
May 23, 2022

On behalf of the Belle, Belle II and LHCb collaborations
Lepton Flavour Universality

- **Lepton Flavour Universality**: gauge interactions of the three generations of leptons are identical once the mass difference is accounted for.

- **Violation of LFU is a clear signal of new physics** and hence the search for such signals in leading particle physics experiments.

- **Semileptonic $B$ decays**: an excellent probe for SM precision measurements ($|V_{cb}|$ and $|V_{ub}|$) and an invaluable portal for lepton flavour universality tests.

Discrepancies with the Standard Model have been observed in multiple LFU tests: $R(D)-R(D^*) : 3.1\sigma$  
$R(K)-R(K^*) : 3.1\sigma$  
eq etc..
R(D) and R(D*)

- R(D) and R(D*) are defined as the ratio of the semitauonic decay $B \to D^* \tau \bar{\nu}$ to the lighter lepton counterparts $B \to D^* \ell \bar{\nu}$, $\ell = e, \mu$.

$$R(D) = \frac{\mathcal{B}(\bar{B} \to D^{+} \tau^{-} \bar{\nu}_{\tau})}{\mathcal{B}(\bar{B} \to D^{+} \ell^{-} \bar{\nu}_{\ell})}, \quad R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^{*+} \tau^{-} \bar{\nu}_{\tau})}{\mathcal{B}(\bar{B} \to D^{*+} \ell^{-} \bar{\nu}_{\ell})}$$

- Determined to high precision in the SM:

$$R(D)^{\text{SM}} = 0.254 \pm 0.005 \quad R(D^*)^{\text{SM}} = 0.299 \pm 0.003$$

- Ratio allows for many uncertainties to cancel.

- Measurement has been performed by BaBar, Belle, and LHCb and showed a combined 3.1$\sigma$ deviation from the SM.

- Various new physics scenarios predict deviation from the SM.
**R(D) and R(D*)**

- Wide range of measurements at the $B$-factories and LHCb with hadronic and/or leptonic $\tau$ decays.
- Final state cannot be fully reconstructed due to lepton neutrinos.

**B-factories:** hadronic or semileptonic $B$ tagging to exploit the full event kinematics and identify missing energy components.

**LHCb:** excellent vertexing to suppress leading backgrounds and approximate $B_{\text{sig}}$ kinematics.
LHCb

$R(D^*)$ muonic with $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$


$R(D^*)$ hadronic with $\tau^+ \rightarrow \pi^+ \pi^- \pi^+(\pi^0)\bar{\nu}_\tau$

Measurement performed with 3.0 fb$^{-1}$ of LHCb data collected during 2011-2012.

Common reconstruction procedure for both the signal mode $\bar{B}^0 \to D^{*+}\tau^-\nu_\tau$ and normalization mode $\bar{B}^0 \to D^{*+}\mu^-\nu_\mu$.

$$R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

MVA algorithm developed to distinguish whether a charged track originated from the $B_{\text{sig}}$ or the rest of event.

- Based on track separation from PV, track angle, etc…

Separation of signal and normalization using: $E^*_\mu, m^2_{\text{miss}}, q^2$

in the $B$ rest frame:

$$q^2 = (p_B - p_D)^2 \text{ and } m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$$

$B$ rest frame determined using:

- the unit vector from the PV to the $B$ decay vertex

- $p_z$ of $B$ given by

$$p_{B,z} = (m_B/m_{\text{reco}})(p_{\text{reco},z})$$
• Challenging backgrounds:
  • Semileptonic decays to excited charm states: \( B \rightarrow D^{(*)}\ell\nu \)
  • Double charm \( B \) decays: \( B \rightarrow D^{(*)}H_cX, H_c \rightarrow \mu\nu X \)
  • \( B \) decays with hadrons misidentified muons
  • Maximum likelihood fit of \( m_{miss}^2, E_{\mu}^*, \) and \( q^2 \) to extract relative signal, normalization and background contributions.
Main systematic uncertainties from the limited size of the MC samples.  
Kinematic distribution for events with hadrons misidentified as muons are determined from control samples.  
Result is 1.7 sigma over the SM.  
First measurement of $R(D^*)$ at a hadronic collider.  
Improved modeling of background events can decrease systematic uncertainty in future results.  
Future simultaneous measurement of $R(D)$ and $R(D^*)$ at LHCb with Run1 data and Run 2 data, i.e. 4 times the available statistics.  
Full angular analysis of $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$ and $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$
LHCb

\[ R(D^*) \text{ muonic with } \tau^+ \to \mu^+ \nu \bar{\nu}_\tau \]


\[ R(D^*) \text{ hadronic with } \tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau \]

• Measure $\kappa(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} = \frac{N_{\text{sig}} \epsilon_{\text{sig}}}{N_{\text{norm}} \epsilon_{\text{norm}} \mathcal{B}(\tau^+ \to 3\pi\nu_\tau) + \mathcal{B}(\tau^+ \to 3\pi\pi^0\bar{\nu}_\tau)}$. 

• Convert it to $R(D^*)$ via $R(D^*) = \kappa(D^{*-}) \times \frac{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}$. 

• Large backgrounds originating from $B \to D^*3\pi X$ and $B \to DD(*)$ 
  • $\sim 100x$ the signal 
  • Reduced by requiring $\Delta z/\sigma_z > 4$

---

B vertex determined through a fit of all the reconstructed particles in the decay chain.

Momentum of $\tau$ can be determined up to two fold ambiguity using:

- Unit-vector between $B^0$ vertex and PV
- Unit vector between $3\pi$ vertex and $B^0$ vertex
R(D*) hadronic

- $B \to D^{(*)}D^{(*)}(X)$ backgrounds suppressed using MVA:
  - Different resonant structures of $\tau$ and $D_s^+$ decays
  - Neutral isolation
  - Kinematic properties: $m(\pi^+\pi^-)$, $m(D^{(*)}\pi^+\pi^-\pi^+)$, etc..

- Remaining backgrounds from:
  - $X_b \to D^{(*)}D_s^+(X)$
  - $X_b \to D^{(*)}D^+(X)$
  - $X_b \to D^{(*)}D^0X$
  - Combinatorial
  - $X_b \to D^{**}\tau\nu$

Related to the signal yield by a proportionality factor of: $0.110 \pm 0.044$

Main double charm background:
Corrections and Relative yields determined from control sample with $D_s^+ \to D^*\tau\nu$.

Template shapes, yield, or relative yield of remaining background contributions also examined via control mode samples.

**Signal region:** BDT > -0.075

**LHCb simulation**
- Signal
- Background

**R(D*) hadronic**

- Signal yield extracted via a 3 dimensional fit to $t_\tau$ decay time and $q^2$ in 4 bins of the BDT output.

- $N_{\text{sig}} = 1296 \pm 86$
- $N_{\text{norm}} = 17660 \pm 158$

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

\[ \mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau) = [1.42 \pm 0.094(\text{stat}) \pm 0.129(\text{syst}) \pm 0.054(\text{ext})] \times 10^{-2} \]

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

Limited knowledge of the external branching fraction
R(D*) hadronic

- Leading systematic uncertainties:
  - Simulated sample size.
  - Knowledge of the $D_s^+$ decay model.
  - Difference in trigger efficiency for signal and normalization modes.

- First result on R(D*) with hadronic tau at the LHC, 1.1$\sigma$ above the SM expectation.

Combined with R(D*) muonic from the LHC:

$$R(D^*) = 0.31 \pm 0.0160\text{(stat)} \pm 0.021\text{(sys)}$$

2.2$\sigma$ above the SM.

- External measurements of the double charm decays can decrease the systematic uncertainty.

- Future R(D*) measurement using Run 2 data, increased statistics will allow for higher statistics in the control samples.

- Planned measurement of longitudinal D* polarisation in $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta R(D^<em>)/R(D^{</em>-})$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>4.7</td>
</tr>
<tr>
<td>Empty bins in templates</td>
<td>1.3</td>
</tr>
<tr>
<td>Signal decay model</td>
<td>1.8</td>
</tr>
<tr>
<td>$D^{<strong>}\tau\nu$ and $D_s^{</strong>}\tau\nu$ feeddowns</td>
<td>2.7</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow 3\pi X$ decay model</td>
<td>2.5</td>
</tr>
<tr>
<td>$B \rightarrow D^{<em>-}D_s^{+} X$, $B \rightarrow D^{</em>-}D^{+} X$, $B \rightarrow D^{*-}D^{0} X$ backgrounds</td>
<td>3.9</td>
</tr>
<tr>
<td>Combinatorial background</td>
<td>0.7</td>
</tr>
<tr>
<td>$B \rightarrow D^{*-}3\pi X$ background</td>
<td>2.8</td>
</tr>
<tr>
<td>Efficiency ratio</td>
<td>3.9</td>
</tr>
<tr>
<td>Normalization channel efficiency (modeling of $B^0 \rightarrow D^{*-}3\pi$)</td>
<td>2.0</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>9.1</td>
</tr>
</tbody>
</table>
More LFU tests: $R(J/\psi)$ and $R(\Lambda_c)$

- LHCb has also measured $R(J/\psi) = \frac{\mathcal{B}(B_c \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c \to J/\psi \mu^+ \nu_\mu)}$, with $\tau \to \mu^+ \nu_\mu \nu_\tau$
  
  $$R(J/\psi) = 0.71 \pm 0.17\text{(stat)} \pm 0.18\text{(sys)}$$

- First observation of $\mathcal{B}(B_c \to J/\psi \tau^+ \nu_\tau)$ with 3.1σ significance.
- The result is 2σ above the SM.
- Large uncertainty from unknown form factors of $B_c$ decay.

PRL 120, 121801 (2018)
More LFU tests: $R(J/\psi)$ and $R(\Lambda_c)$

- LHCb has also measured $R(J/\psi) = \frac{\mathcal{B}(B_c \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c \to J/\psi\mu^+\nu_\mu)}$, with $\tau \to \mu^+\nu_\mu\nu_\tau$

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

- First observation of $\mathcal{B}(B_c \to J/\psi\tau^+\nu_\tau)$ with 3.1$\sigma$ significance.
- The result is 2$\sigma$ above the SM.
- Large uncertainty from unknown form factors of $B_c$ decay.

NEW:

- \[ R(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c\tau^+\nu_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^+\nu_\mu)}, \text{ with } \tau \to \pi^+\pi^-\pi^+\nu_\tau \]

- First observation of $\mathcal{B}(\Lambda_b \to \Lambda_c\tau^+\nu_\tau)$ with 6.1$\sigma$ significance.

\[ R(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059 \]

agrees with the SM prediction of $R(\Lambda_c^+) = 0.324 \pm 0.004$.

- Largest systematic uncertainty from the template shapes of background modes.
- Additional systematic uncertainty from external branching fractions.
- Constrains NP models that predicts high values of $R(\Lambda_c^+)$.
R(D) and R(D*) at Belle

Hadronic tagging with leptonic tau decays

Hadronic tagging with hadronic tau decays

Semileptonic tagging with leptonic tau decays
Phys. Rev. Lett. 124, 161803, 2020
R(D) and R(D*) at Belle

Hadronic tagging with leptonic tau decays

Hadronic tagging with hadronic tau decays

Semileptonic tagging with leptonic tau decays
Phys. Rev. Lett. 124, 161803, 2020
The B-factories employ $B$-tagging to measure $R(D)$ and $R(D^*)$.

$Y(4S)$ produced almost at rest, and instantly decays into a pair of $B$ mesons.

Exclusive reconstruction of one of the $B$ mesons, $B_{\text{tag}}$, using hadronic and semi-leptonic modes.

Infer momentum and direction of signal $B$ candidate:

$$p_{B_{\text{sig}}} = \left( E_{B_{\text{sig}}}, \vec{p}_{B_{\text{sig}}} \right) = \left( \frac{m_{Y(4S)}}{2}, -\vec{p}_{B_{\text{tag}}} \right)$$

Ideal for decays with neutrinos, missing energy signatures!
R(D) and R(D*) with Hadronic Tagging

- Measured using 711 fb$^{-1}$ of Belle data
- Reconstruct first $B$ exclusively via 1149 hadronic modes in a hierarchal approach.
  - Efficiency of 0.3% for $B^+$ and 0.2% for $B^0$.
- Remaining information, tracks and cluster, are used for signal and normalisation reconstruction.
- Reconstruct $D^0$, $D^+$ $D^*$, $D^{*+}$ via multiple modes.
- Combine with lepton and determine $m_{\text{miss}}^2$.
- Exact determination of $q^2$ and $m_{\text{miss}}^2$.
- Region below $m_{\text{miss}}^2 < 0.85$ GeV$^2$/c$^4$ is dominated by normalisation mode.
R(D) and R(D*) with Hadronic Tagging

- Large crossfeed from $D^*\ell$ to $D\ell$ samples, added to the total signal and normalisation yields.
- Challenging $B \to D^{(*)}\ell\nu$ with the same signature in the higher $m_{miss}^2$ region as the signal.
- Train BDT $O'_{NB}$ for 4 samples $D^*+\ell, D^*0\ell, D^+\ell, D^0\ell$, with main discriminating variable is $E_{ECL}$.

$E_{ECL}$ the sum energy of all neutral clusters in the event after the full signal selection is applied: $B_{sig} \cdot B_{tag}$.

Simultaneous fit to:

- $m_{miss}^2$ in $m_{miss}^2<0.85 \text{ GeV}^2/c^4$ to extract normalisation yield
- $O'_{NB}$ in $m_{miss}^2>0.85 \text{ GeV}^2/c^4$ to extract signal and background yields.
R(D) and R(D*) with Hadronic Tagging

- Leading systematic uncertainties:
- Final result:
  - modelling and composition of the $B \rightarrow D^{(*)} \ell \nu$ background.
  - Shape of the BDT output
  - Fixed factors in the fit, determined from simulation.

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

$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

<table>
<thead>
<tr>
<th>$D^{(<em>)</em>} \ell \nu$ shapes</th>
<th>R(D) [%]</th>
<th>R(D*) [%]</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{(<em>)</em>}$ composition</td>
<td>4.2</td>
<td>1.5</td>
<td>0.04</td>
</tr>
<tr>
<td>Fake D yield</td>
<td>1.3</td>
<td>3.0</td>
<td>-0.63</td>
</tr>
<tr>
<td>Fake $\ell$ yield</td>
<td>0.5</td>
<td>0.3</td>
<td>0.13</td>
</tr>
<tr>
<td>$D_s$ yield</td>
<td>0.1</td>
<td>0.1</td>
<td>-0.85</td>
</tr>
<tr>
<td>Rest yield</td>
<td>0.1</td>
<td>0.0</td>
<td>-0.70</td>
</tr>
<tr>
<td>Efficiency ratio $f^D_D$</td>
<td>2.5</td>
<td>0.7</td>
<td>-0.98</td>
</tr>
<tr>
<td>Efficiency ratio $f^{D^0}_D$</td>
<td>1.8</td>
<td>0.4</td>
<td>0.86</td>
</tr>
<tr>
<td>Efficiency ratio $f^{D_\pi^+}_D$</td>
<td>1.3</td>
<td>2.5</td>
<td>-0.99</td>
</tr>
<tr>
<td>Efficiency ratio $f^{D^*_D}$</td>
<td>0.7</td>
<td>1.1</td>
<td>0.94</td>
</tr>
<tr>
<td>CF double ratio $g^+$</td>
<td>2.2</td>
<td>2.0</td>
<td>-1.00</td>
</tr>
<tr>
<td>CF double ratio $g^0$</td>
<td>1.7</td>
<td>1.0</td>
<td>-1.00</td>
</tr>
<tr>
<td>Efficiency ratio $f^{\nu\ell}_\nu$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.84</td>
</tr>
<tr>
<td>$M_{\text{miss}}^2$ shape</td>
<td>0.6</td>
<td>1.0</td>
<td>0.00</td>
</tr>
<tr>
<td>$\delta_{\text{NB}}$ shape</td>
<td>3.2</td>
<td>0.8</td>
<td>0.00</td>
</tr>
<tr>
<td>Lepton PID efficiency</td>
<td>0.5</td>
<td>0.5</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Total: 7.1 5.2 -0.32

Compared with previous BaBar measurement using hadronic tagging and leptonic tau decays.

PRL 100, 101802 (2012), PRD 88, 072012 (2013)
R(D) and R(D*) with Hadronic Tagging

- Leading systematic uncertainties:
- Final result:
  - modelling and composition of the $B \rightarrow D^{(*\bar{\nu})} \ell \nu$ background.
  - Shape of the BDT output
  - Fixed factors in the fit, determined from simulation.

R(D) = 0.375 ± 0.064 ± 0.026
R(D*) = 0.293 ± 0.038 ± 0.015

Compatible with type II 2HDM in the region $\tan\beta/m_{H^+} = 0.45(c^2/\text{GeV})$
R(D) and R(D*) at Belle

Hadronic tagging with leptonic tau decays

Hadronic tagging with hadronic tau decays

Semileptonic tagging with leptonic tau decays
Phys. Rev. Lett. 124, 161803, 2020
• Measure $\tau$ polarisation with $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to \rho^- \nu_\tau$ using the full Belle dataset.

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

• Sensitive to new physics contributions.

• SM predicts:
  
  $P_\tau(D) = 0.325 \pm 0.009$
  $P_\tau(D^{*}) = -0.497 \pm 0.013$

• Can be measured via:

  \[
  \frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_{hel}} = 1 + \alpha P_\tau \cos\theta_{hel}
  \]

  • $\alpha = 1$ for $\tau^- \to \pi^- \nu_\tau$
  • $\alpha = 0.45$ for $\tau^- \to \rho^- \nu_\tau$

Employ a hadronic tag analysis to determine the $B_{\text{sig}}$ 4-vector and the $\tau \nu_\tau$ frame

\[
\cos\theta_{hel}(\tau) = 1 - \frac{2m_\tau^2M_W^2}{(M_W^2-m_\tau^2)(m_\tau^2-m_h^2)}
\]
Divide signal sample into 2 regions:
- $\cos \theta_{\text{hel}}>0$ forward
- $\cos \theta_{\text{hel}}<0$ backward

Extract signal and background yields in a simultaneous fit to $E_{\text{ECL}}$ in 8 samples:

$$(B^-, B^0) \times (\pi^- \nu_\tau, \rho \nu_\tau) \times \text{(backward, forward)}$$

$$P_\tau(D^*) = \frac{[2(N^F_{\text{sig}} - N^B_{\text{sig}})]}{[\alpha(N^F_{\text{sig}} + N^B_{\text{sig}})]} \quad \text{and} \quad R(D^*) = \frac{\epsilon_{\text{norm}}N_{\text{sig}}}{\mathcal{B}_\tau \epsilon_{\text{sig}}N_{\text{norm}}}$$

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

$$P_\tau(D^*) = -0.38 \pm 0.51\text{(stat)}^{+0.21}_{-0.16}\text{(syst)}$$
R(D*) & Tau Polarization

Leading systematic uncertainties:

- Hadronic B decay decomposition
- Limited size of MC sample
- Fake D* component shape and yield

\[ R(D^*) = 0.270 \pm 0.035 \text{(stat)}^{+0.028}_{-0.025} \text{(syst)} \]
\[ P_{\tau}(D^*) = -0.38 \pm 0.51 \text{(stat)}^{+0.21}_{-0.16} \text{(syst)} \]

Result agrees with the SM and with previous Belle measurements.

First measurement of tau polarization:

\[ P_{\tau}(D^*) > +0.5 \text{ at 90\% CL} \]
R(D) and R(D*) at Belle

Hadronic tagging with leptonic tau decays

Hadronic tagging with hadronic tau decays

Semileptonic tagging with leptonic tau decays
Phys. Rev. Lett. 124, 161803, 2020
R(D) and R(D*) with Semileptonic Tagging

• Based on a data sample with $772 \times 10^6 \bar{B}B$ pairs

• Measure $R(D^*) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{(*)+}\ell^-\bar{\nu}_\ell)}$ with

  $\tau^+ \rightarrow \ell^+\nu_\ell\bar{\nu}_\tau$

• Use semileptonic tagging with a hierarchical based on a BDT classifier that reconstructs $D^{(*)}\ell\bar{\nu}_\ell$ and $D\ell\bar{\nu}_\ell$.

• Separate well reconstructed $B_{\text{tag}}$ candidates with $\cos \theta_{B,D^{(*)}\ell} = \frac{2E_{\text{beam}}E_D^{(*)}\ell - m_B^2 - m_D^{(*)}\ell}{2|p_B||p_{D^{(*)}\ell}|}$

• Reconstruct signal side $D^{(*)}\ell$ using a list of $D^0$ and $D^+$ modes

• Suppress background events using $E_{\text{ECL}} < 1.2$ GeV.

• Develop MVA to separate between signal and normalization from backgrounds based on variables such as $m_{\text{miss}}^2$ and $E_{\text{vis}}$.

Phys. Rev. Lett. 124, 161803, 2020
R(D) and R(D*) with Semileptonic Tagging

• Extra signal and normalization yields from a fit \(O_{\text{cls}}\) and \(E_{\text{ecl}}\) in four samples: \(D^{*+}\ell, D^{*0}\ell, D^{+}\ell, D^{0}\ell\)

• Feed down from \(D^*\) to \(D\) sample is large and left free in the fit.

• Background yield from \(B \to D^{(**)}\ell\nu\) is left free in the fit. Other backgrounds are fixed to their MC expectation.

• Fake \(D^*\): yield of fake or misreconstructed \(D^*\) mesons, determined using sideband data.

\[
R(D^{(*)}) = \frac{1}{2(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)} \frac{\epsilon_{\text{sig}}}{\epsilon_{\text{norm}}} \frac{N_{\text{sig}}}{N_{\text{norm}}}
\]
R(D) and R(D*) with Semileptonic Tagging

- Leading uncertainties
  - Limited MC sample size:
    - PDF shapes in the final fit
    - Efficiency ratio of signal to normalization events
    - Reconstruction efficiency of feed down yield.
  - Limited knowledge of $B \rightarrow D^{(*)}\ell \nu$ branching fractions

\[
R(D^*) = 0.283 \pm 0.018 \pm 0.014 \\
R(D) = 0.307 \pm 0.037 \pm 0.016
\]

- Most precise measurement performed to date!
- In agreement with the SM within 0.2\(\sigma\) and 1.1\(\sigma\).

<table>
<thead>
<tr>
<th>Source</th>
<th>(\Delta R(D) (%))</th>
<th>(\Delta R(D^*) (%))</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{(*)}$ composition</td>
<td>0.76</td>
<td>1.41</td>
<td>-0.41</td>
</tr>
<tr>
<td>PDF shapes</td>
<td>4.39</td>
<td>2.25</td>
<td>-0.55</td>
</tr>
<tr>
<td>Feed-down factors</td>
<td>1.69</td>
<td>0.44</td>
<td>0.53</td>
</tr>
<tr>
<td>Efficiency factors</td>
<td>1.93</td>
<td>4.12</td>
<td>-0.57</td>
</tr>
<tr>
<td>Fake $D^{(*)}$ calibration</td>
<td>0.19</td>
<td>0.11</td>
<td>-0.76</td>
</tr>
<tr>
<td>$B_{\text{tag}}$ calibration</td>
<td>0.07</td>
<td>0.05</td>
<td>-0.76</td>
</tr>
<tr>
<td>Lepton efficiency</td>
<td>0.36</td>
<td>0.33</td>
<td>-0.83</td>
</tr>
<tr>
<td>and fake rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow pion efficiency</td>
<td>0.08</td>
<td>0.08</td>
<td>-0.98</td>
</tr>
<tr>
<td>$B$ decay form factors</td>
<td>0.55</td>
<td>0.28</td>
<td>-0.60</td>
</tr>
<tr>
<td>Luminosity, $f^{+-}, f^{00}$</td>
<td>0.10</td>
<td>0.04</td>
<td>-0.58</td>
</tr>
<tr>
<td>and $B(\Upsilon(4S))$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B \rightarrow D^{(*)}\ell \nu)$</td>
<td>0.05</td>
<td>0.02</td>
<td>-0.69</td>
</tr>
<tr>
<td>$B(D)$</td>
<td>0.35</td>
<td>0.13</td>
<td>-0.65</td>
</tr>
<tr>
<td>$B(D^*)$</td>
<td>0.04</td>
<td>0.02</td>
<td>-0.51</td>
</tr>
<tr>
<td>$B(\tau^- \rightarrow \ell^- \bar{\nu}<em>\ell \nu</em>\tau)$</td>
<td>0.15</td>
<td>0.14</td>
<td>-0.11</td>
</tr>
<tr>
<td>Total</td>
<td>5.21</td>
<td>4.94</td>
<td>-0.52</td>
</tr>
</tbody>
</table>
Belle II
Belle II experiment

- Luminosity projected to be 30x larger than that of Belle.
- 20x smaller vertical beam size.
- 1.5x beam current.

Improvements the Belle II detector:

Central beam pipe: decreased diameter from 3cm to 2cm (Beryllium)

Vertexing: new 2 layers of pixels, upgraded 4 double-sided layers of silicon strips

Tracking: drift chamber with smaller cells, longer lever arm, faster electronics

PID: new time-of-flight (barrel) and proximity focusing aerogel (endcap) Cherenkov detectors

EM calorimetry: upgrade of electronics and processing with legacy CsI(Tl) crystals

K₀ and μ: scintillators replace RPCs (endcap and inner two layers of barrel)
Belle II dataset

• Belle II started data-taking in March 2019 and has now collected ~380 fb⁻¹.

• Belle II will collect up to 510 fb⁻¹ before its first shutdown.

• Plan to confirm the current $B$-anomalies, $R(D)$ and $R(D^*)$, and to present first novel results $R(X)$. 
Preparing the toolkit
**B-tagging at Belle II**

- Exclusive reconstruction of $B$ mesons using hadronic and semi-leptonic modes.
- Achieved using the Full Event Interpretation (FEI), a multivariate algorithm based on a hierarchal approach.
- Employs over 200 Boosted Decision Trees to reconstruct ~10000 $B$ decay chains.
- Outputs a signal probability which separates correctly reconstructed $B$ mesons.
- 30-50% improvement in efficiency compared to Full Reconstruction at Belle.

### Table: Efficiency Comparison

<table>
<thead>
<tr>
<th></th>
<th>$B^-$</th>
<th>$B^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hadronic</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEI with FR channels</td>
<td>0.53%</td>
<td>0.33%</td>
</tr>
<tr>
<td>FEI</td>
<td>0.76%</td>
<td>0.46%</td>
</tr>
<tr>
<td>FR</td>
<td>0.28%</td>
<td>0.18%</td>
</tr>
<tr>
<td>SER</td>
<td>0.4%</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Semileptonic</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEI</td>
<td>1.80%</td>
<td>2.04%</td>
</tr>
<tr>
<td>FR</td>
<td>0.31%</td>
<td>0.34%</td>
</tr>
<tr>
<td>SER</td>
<td>0.3%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>
Lepton Identification

- Belle II has global particle identification based on almost all detector subsystem inputs.
- PID performance and fake rate evaluated in bins of the polar angle using standard candle processes.

1.13 ≤ θ < 1.57 rad, electronID > 0.9

- Fake rates improved for low momenta using Boosted Decision Tree PID with ECL shower shape variables to separate between lepton and hadrons.

![Graph showing efficiency and mis-ID probability vs. p [GeV/c]]

- e.g. electron efficiency of 94% and pion misID at 2% for $\mathcal{L} > 0.9$

At p<1 GeV/c, electron fake rates reduced by a factor of 10.
**E_{ECL}**

- \( E_{ECL} \) is a key variable for many semi-leptonic and missing energy analyses, specifically \( B \to D^* \tau \nu_\tau \).

Belle II Simulation

Properly reconstructed events

\( E_{ECL} \) (GeV)

- Different contributions to \( E_{ECL} \):
  - Mis-reconstructed candidates
  - Hadronic split-offs
  - Beam background contributions

Develop a multi-variate algorithm (BDT) to suppress beam background and fake photon or hadronic shower split-off contributions.
**$R(D)$ and $R(D^*)$**

- One of the high priority analyses for Belle II.

$$R(D) = \frac{\mathcal{B}(\bar{B} \rightarrow D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^+ \ell^- \bar{\nu}_\ell)}$$

$$R(D^*) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{*+} \ell^- \bar{\nu}_\ell)}$$

Measure branching fraction of normalization mode to test Belle II data and analysis’s chain.

- 3 ongoing measurements planned before the long shut down of Belle II planned in 2022-2023:

**Hadronic Tagging**

**Leptonic tau:** $\tau \rightarrow e\nu_e$ and $\tau \rightarrow \mu\nu_\mu$

**Hadronic tau:** $\tau \rightarrow \rho, \pi\nu$

**Semi-leptonic Tagging**

**Leptonic tau:** $\tau \rightarrow e\nu_e$ and $\tau \rightarrow \mu\nu_\mu$

Initial plan: confirm anomaly with $\sim 0.5\text{ ab}^{-1}$ of Belle II data.
Tagged Exclusive $B^0 \rightarrow D^*+\ell \nu_{\ell}$

$m^2_{\text{miss}} = \left( p_{e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_{\ell} \right)^2$

$\mathcal{B}(B^0 \rightarrow D^*+\ell \nu_{\ell}) = (4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_3})\%$

In agreement with world average!

$\mathcal{B}(B^0 \rightarrow D^*+\ell \nu_{\ell}) = (5.05 \pm 0.14)\%$

$\int \mathcal{L} dt = 34.6 \text{ fb}^{-1}$
First results planned by Summer 2022.
Conclusion

• R(D) and R(D*) is a stringent test of Lepton Flavour Universality and a valuable portal for what lies beyond the SM.

• Future measurements planned:
  • LHCb: R(D), R(D*), R(J/ψ), R(Λ_c)
  • Belle II: R(D), R(D*), R(X)
  • BaBar: R(D) and R(D*) with semileptonic tagging (Talk by Yinxuan Li)
  • Combined with angular analyses measurements of \( B \to D^*\ell\nu \) and \( B \to D^*\tau\nu \) decays, we should be zooming in on the New Physics if it is there.