Lepton Flavour Universality in B Decays and Other Recent Results at Belle

- **$b \rightarrow c \tau \nu_{\tau}$**
  - Measurement of $R(D)$ and $R(D^*)$ with a semileptonic tagging method
    \[
    R(D^{(*)}) \equiv \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu)}, \quad \ell = e, \mu
    \]
  - Belle Collab., arXiv:1904.08794

- **$b \rightarrow s \ell^+ \ell^-$**
  - Measurement of the $D^{*-}$ polarization in the decay $B^0 \rightarrow D^{*-} \tau^+ \nu_{\tau}$
  - Belle Collab., arXiv:1903.03102

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  - Measurement of the $D^{*-}$ polarization in the decay $B^0 \rightarrow D^{*-} \tau^+ \nu_{\tau}$
  - Belle Collab., arXiv:1903.03102

- Test of lepton flavor universality in $B \rightarrow K^* \ell^+ \ell^-$ decays at Belle
  \[
  R(K^*) \equiv \frac{\mathcal{B}(B \rightarrow K^* \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^* e^+ e^-)}
  \]
  - Belle Collab., arXiv:1904.02440

Results (still preliminary), are based on the full data set recorded by the Belle detector at $\Upsilon(4S)$.

The 27th International Workshop on Weak Interactions and Neutrino,
Bari 3-8 June 2019

Maria Różańska, H. Niewodniczański Institute of Nuclear Physics, Kraków, on behalf of the Belle Collaboration
Belle detector: high-hermeticity (86% of solid angle), multi-purpose magnetic spectrometer operating (1999-2010) at KEKB collider, collected 772M $B\bar{B}$ pairs from $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

Unique tool to study experimentally challenging $B$- meson decays, e.g. to multiple neutrinos.

- employ $B_{tag}$ - reconstruction techniques to infer more information on $B_{sig}$
$B \rightarrow D^{(*)} \tau \nu_\tau$

**$b \rightarrow c \tau \nu_\tau$ transitions**

SM and NP contribute at the tree level

**Theoretically well-controlled observables, with complementary sensitivity to NP:**

- $R(D^{(*)}) = \frac{B(B \rightarrow D^{(*)} \tau \nu)}{B(B \rightarrow D^{(*)} \ell \nu)}$ ← signal
  - normalization
  - Common uncertainties (partly) cancel out:
    - Theoretical uncertainty of some form factors
    - Uncertainty of $|V_{cb}|$
    - Experimental uncertainty of efficiencies, partial BF's...
- Differential ($e.g. q^2$) distributions
- $\tau$ (and $D^*$) polarization

**Experimentally challenging!**

- B-factories exploit $B_{\text{tag}}$ reconstruction techniques
- Measurements of $R(D^{(*)})$ achieved sensitivity that challenges SM and some of its extensions.

**Experimental uncertainties larger than those of the SM predictions ⇒ call for improvements**

- Measurements of $R(D^{(*)})$ achieved sensitivity that challenges SM and some of its extensions.
- $B_{\text{tag}} \rightarrow \text{hadrons}$
- $B^0$ & $B^+$ combined

- Theoretically well-controlled observables, with complementary sensitivity to NP:
  - $R(D^{(*)}) = \frac{B(B \rightarrow D^{(*)} \tau \nu)}{B(B \rightarrow D^{(*)} \ell \nu)}$ ← signal
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**Experimentally challenging!**

- B-factories exploit $B_{\text{tag}}$ reconstruction techniques
- Measurements of $R(D^{(*)})$ achieved sensitivity that challenges SM and some of its extensions.

**HFLAV**

Summer 2018

- $R(D) = 0.407 \pm 0.039 \pm 0.024 \text{ ~2.3}\sigma$ above the SM (0.299 $\pm$ 0.003)
- $R(D^*) = 0.306 \pm 0.013 \pm 0.007 \text{ ~3.0}\sigma$ above the SM (0.258 $\pm$ 0.05)
- $R(D^*)$ & $R(D)$ $\sim$3.8$\sigma$ away from the SM

- $B(B^0 \rightarrow D^{*-} e^+ \nu) = 1.01 \pm 0.01 (\text{stat}) \pm 0.03 (\text{ syst})$

Belle, arXiv:1809.03290

- one of the most precise results is obtained with $B_{\text{tag}} \rightarrow D^* \ell \nu$, only $B^0 \rightarrow D^{*-} \tau^+ \nu$ measured
  ⇒ very promising approach
Measurement of $R(D)$ and $R(D^*)$ with semileptonic tagging

- **Reconstruct $B_{\text{tag}}$ decay:** $B \rightarrow D^{(*)} \ell \nu$ (BDT-based hierarchical algorithm)
  - BDT classifier output, $-2 < \cos\theta_{B,Y}^{\text{tag}} < 1$
    \[
    \cos\theta_{B,Y}^{\text{tag}} = \frac{2E_{\text{beam}}E_Y - m_B^2 - M_Y^2}{2|p_B||p_Y|}
    \]
    $Y = D^{(*)}\ell$

- **Search for $D^{(*)} \ell$ among remaining tracks and clusters**
  - No extra charged tracks, or $\pi^0$s...
  - $\cos\theta_{B,Y}^{\text{sig}} < 1$, $|p_{D^{(*)}}| < 2$ GeV
  - 4 disjoint data samples: $D^{*+} \ell^-, D^{*0} \ell^-, D^+ \ell^-, D^0 \ell^-$

- **Distinguish $B \rightarrow D^{(*)}\ell(\tau)\nu$ from background**
  - $E_{\text{ECL}}$ – sum of the energies of remaining neutral clusters, $E_{\text{ECL}} \approx 0$ for signal, tends to be higher for background

- **Distinguish $B \rightarrow D^{(*)}\tau\nu$ from $B \rightarrow D^{(*)}\ell\nu$**
  - BDT classifier with input variables:
    \[
    \cos\theta_{B,Y}^{\text{sig}} , E_{\text{vis}} = \sum E_i , M_{\text{miss}}^2 = (E_{\text{beam}} - E_{D^{(*)}\ell})^2 - (p_{D^{(*)}\ell})^2
    \]

- **Extract $R(D)$ and $R(D^*)$**
  - Extended maximum likelihood 2-D fit to the BDT classifier output and $E_{\text{ECL}}$
  - Fit simultaneously 4 $D^{(*)}\ell$ samples
Measurement of $R(D)$ and $R(D^*)$ with sl tagging - fit

**Fit components**

- **Floating**
  - norm: $B \to D(*)\ell\nu$
  - signal: $B \to D(*)\tau\nu$
  - feed-down
    - $B^+ \to D^*\ell\nu \Rightarrow D\ell\nu$
    - $B^0 \to D^*\ell\nu \Rightarrow D\ell\nu$
  - background
    - $B \to D^{**}\ell\nu$

- **Correlated**
  - feed-down
    - $B^+ \to D^*\tau\nu \Rightarrow D\tau\nu$
    - $B^0 \to D^*\tau\nu \Rightarrow D\tau\nu$

- **Fixed**
  - fake $D(*)$
    - calibrated from data
  - other bkgds
    - fixed from MC

**$E_{ECL}$ fit projections; insets show signal enhanced region (class $> 0.9$)**

- $D^+\ell^-$
  - $N_{\text{sig}} = 307 \pm 65$

- $D^0\ell^-$
  - $N_{\text{sig}} = 1471 \pm 193$

- $D^{*+}\ell^-$
  - $N_{\text{sig}} = 376 \pm 36$

- $D^{*0}\ell^-$
  - $N_{\text{sig}} = 275 \pm 29$
Measurement of $R(D)$ and $R(D^*)$ with sl tagging - results

$$R(D^*) = \frac{1}{2B(\tau \to \ell \nu \nu)} \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{norm}}}$$

$$R(D) = 0.307 \pm 0.037 \text{(stat)} \pm 0.016 \text{(syst)}$$
compatible within 0.2$\sigma$ with SM

$$R(D^*) = 0.283 \pm 0.018 \text{(stat)} \pm 0.014 \text{(syst)}$$
compatible within 1.1$\sigma$ with SM

Combined $R(D)$&$R(D^*)$ compatible within ~1.2$\sigma$ with SM

**Systematic uncertainties (%)**

<table>
<thead>
<tr>
<th>source</th>
<th>$\Delta R(D)$</th>
<th>$\Delta R(D^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{**}$ composition</td>
<td>0.76</td>
<td>1.41</td>
</tr>
<tr>
<td>Fake $D^{(*)}$ calibr.</td>
<td>0.19</td>
<td>0.11</td>
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<td>$B_{\text{tag}}$ calibr.</td>
<td>0.07</td>
<td>0.05</td>
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<tr>
<td>Feed-down factors</td>
<td>1.69</td>
<td>0.44</td>
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<tr>
<td>Efficiency factors</td>
<td>1.93</td>
<td>4.12</td>
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<tr>
<td>Lepton eff. &amp; fake rate</td>
<td>0.36</td>
<td>0.33</td>
</tr>
<tr>
<td>Slow $\pi$ efficiency</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>PDF shapes</td>
<td>4.39</td>
<td>2.25</td>
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<td>$B$ decay form fact.</td>
<td>0.55</td>
<td>0.28</td>
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<tr>
<td>$\mathcal{B}(B \to D^{(*)}\ell \nu)$</td>
<td>0.05</td>
<td>0.02</td>
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<tr>
<td>$\mathcal{B}(D)$</td>
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<td>0.13</td>
</tr>
<tr>
<td>$\mathcal{B}(D^*)$</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \to \ell \nu \nu)$</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>$BF$s of $\Upsilon(4S)$</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td>Total</td>
<td>5.21</td>
<td>4.94</td>
</tr>
</tbody>
</table>

**Preliminary Belle average**

$$R(D) = 0.326 \pm 0.034$$

$$R(D^*) = 0.284 \pm 0.018$$
correlation: $\rho = -0.47$
compatible within ~2$\sigma$ with SM

*New SM prediction: $R(D^*) = 0.253 \pm 0.006 \sim 1.3\sigma$

$R(D)$ and $R(D^*)$ – 2019

$R(D) = 0.340 \pm 0.027 \pm 0.013$

$R(D^*) = 0.295 \pm 0.011 \pm 0.008$

$\sim 1.4\sigma$ above the SM

$\sim 2.5\sigma$ above the SM

Tension reduced to $3.1\sigma$, but central values consistently above the SM predictions
Other observables in $B \rightarrow D^{(*)}\tau\nu$ decays

- (Inconclusive) hints of a deviation from the Standard Model in $b \rightarrow c\tau\nu_\tau$ transitions
  - $R(D^{(*)})$ systematically above the SM expectations, surprisingly larger effect for $R(D^*)$;
  - Angular observables in $B \rightarrow D^{(*)}\tau\nu$ decays, basically, not explored yet

$\cos \theta_{hel} \Rightarrow \tau$ polarization ($P^D_{\tau} (\alpha=1)$), $\tau \rightarrow \rho \nu_\tau \ (\alpha=0.45)$

$\cos \theta_V \Rightarrow D^*$ polarization ($F^D_L$)

$\cos \theta_{hel}$ and $\cos \theta_V$ can be reconstructed at B-factories using hadronic decays of $B_{tag}$

\[ \tilde{p}_{sig} = - \tilde{p}_{tag} \]
Need efficient reconstruction of $B_{\text{tag}}$ in hadronic modes

⇒ do it inclusively

Find $B_{\text{sig}}$ candidates $D^{*-} d^+_\tau \tau^+ \rightarrow d^+_\tau \nu_\tau (\nu_\ell)$, $d_\tau = \ell, \pi$

Reconstruct $B_{\text{tag}}$ from remaining tracks and clusters

- $M_{\text{tag}} = \sqrt{E_{\text{beam}}^2 - |p_{\text{tag}}|^2}$; $\Delta E_{\text{tag}} = E_{\text{tag}} - E_{\text{beam}}$; $E_{\text{tag}} = \Sigma_i E_i$, $p_{\text{tag}} = \Sigma_i p_i$
- $M_{\text{tag}} > 5.2 \text{ GeV}$, $-0.30 < \Delta E_{\text{tag}} < 0.05 \text{ GeV}$
- Suppress incorrectly reconstructed $B_{\text{tag}}$'s:
  - total charge=0, no extra $\ell^\pm$, $N_{\pi^0} + N_Y < 5$, $N_{K_L^0} = 0$ ($d_\tau = \pi$)
- >80%(60%) signal events for $d_\tau = \ell (\pi)$ contained at $M_{\text{tag}} > 5.26 \text{ GeV}$

Calibrate background using side-bands

- $M_{\text{tag}} < 5.26 \text{ GeV}$, $X_{\text{mis}} < 0.75$ (0.5) $d_\tau = \ell (\pi)$
- $X_{\text{mis}} = \frac{E_{\text{beam}} - E_{D^*+d_\tau} - |p_{D^*d_\tau}|}{|p_B|}$

Suppress background

- $X_{\text{mis}} > 1.5$ (1.0), $E_{\text{vis}} < 8.7$ (8.8) GeV, $d_\tau = \ell (\pi)$
- $M_{\text{tag}}$ distributions flat for most bkgd
  - can be used to extract signal yields
Measure \( \cos \theta_V \) distribution

- Extract signal yields in 3 equidistant bins of \( \cos \theta_V \): 
  - \( I [-1, -0.67) \)
  - \( II [-0.67, -0.33) \)
  - \( III [-0.33, 0) \)
- \( \cos \theta_V > 0 \) excluded because of low reconstruction efficiency of slow \( \pi \) from \( D^* \) decay
- Signal yields extracted from UEML fit to \( M_{\text{tag}} \) distributions; simultaneous fit to all decay chains

Fit projections in bins of \( \cos \theta_V \):

- \( \tau \rightarrow \pi \)
- \( \tau \rightarrow e \)
- \( \tau \rightarrow \mu \)

\[ N_{\text{sig}}^I = 151 \pm 21 \quad N_{\text{sig}}^{II} = 125 \pm 19 \quad N_{\text{sig}}^{III} = 55 \pm 15 \]

Acceptance correction factors: \( s_I = 0.98 \), \( s_{II} = 0.96 \), \( s_{III} = 1.08 \) \((\text{SM dynamics assumed})\)
Measurement of the $D^{*-}$ polarization in the decay $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$

- Extract fraction of the longitudinal $D^{*-}$ polarization from the angular distribution:

$$\frac{dN_{\text{sig}}}{d\cos\theta_V} = N_{\text{sig}} \frac{3}{4} [2 F^D_L \cos^2 \theta_V + (1 - F^D_L) \sin^2 \theta_V]$$

- Result (preliminary):

$$F^D_L = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$$

- Can be reduced by adding $B^+ \rightarrow D^{*0}\tau^+\nu_\tau$

<table>
<thead>
<tr>
<th>Systematic uncertainties evaluated assuming SM dynamics</th>
<th>$\Delta F^D_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>source</td>
<td></td>
</tr>
<tr>
<td>MC statistics</td>
<td>±0.032</td>
</tr>
<tr>
<td>bkgd combinatorial and peaking</td>
<td>±0.010</td>
</tr>
<tr>
<td>signal shape</td>
<td>±0.010</td>
</tr>
<tr>
<td>bkgd calibr.</td>
<td>±0.001</td>
</tr>
<tr>
<td>Background modelling</td>
<td>±0.003</td>
</tr>
<tr>
<td>$D^{**}$ composition</td>
<td>±0.011</td>
</tr>
<tr>
<td>$B \rightarrow D^{**}\tau\nu$</td>
<td>±0.005</td>
</tr>
<tr>
<td>$B \rightarrow$ hadrons</td>
<td>±0.005</td>
</tr>
<tr>
<td>2-body $B \rightarrow D^{*}M$</td>
<td>±0.004</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>±0.002</td>
</tr>
<tr>
<td>Form factors</td>
<td>±0.003</td>
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<tr>
<td>$\cos\theta_V$ resol.</td>
<td>±0.003</td>
</tr>
<tr>
<td>Acceptance non-uniformity</td>
<td>±0.015</td>
</tr>
<tr>
<td>-0.005</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>±0.039</td>
</tr>
<tr>
<td>-0.037</td>
<td></td>
</tr>
</tbody>
</table>

Exp vs SM

$$\begin{cases} F^D_L = 0.46 \pm 0.04 & [1] \\ F^D_L = 0.441 \pm 0.006 & [2] \\ F^D_L = 0.457 \pm 0.010 & [3] \\ F^D_L = 0.47 \pm 0.01 & [4] \\ F^D_L = 0.455 \pm 0.009 & [5] \end{cases}$$

1.42σ, 1.76σ, 1.58σ, 1.44σ, 1.60σ

Several tensions (~3σ from SM) in $b \to s \ell^+ \ell^-$ transitions (angular observables in $\to K^* \mu^+ \mu^-$, $BF$'s of some $b \to s \ell^+ \ell^-$ decays - theoretical uncertainties are still subject of debate) can be fit with NP models that predict $R(K^*) < 1$.

$R\left(K^{(*)}\right) = \frac{\mathbb{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathbb{B}(B \to K^{(*)}e^+e^-)} \cong 1 \pm \mathcal{O}(10^{-4}(10^{-3})) \quad \text{robust SM prediction}$

Precise test of LFU in FCNC

- $R(K) \equiv \frac{\mathbb{B}(B \to K\mu^+\mu^-)}{\mathbb{B}(B \to Ke^+e^-)} = 0.846^{+0.060+0.016}_{-0.054-0.014} \quad 1.1 < q^2 < 6 \text{ GeV}^2 \quad q^2 = (M_{\ell^+\ell^-})^2$
  
  compatibility with SM: $2.5\sigma$

- $R(K^{*0}) = 0.66^{+0.11}_{-0.07} \pm 0.03 \quad 0.45 < q^2 < 1.1 \text{ GeV}^2$
  $R(K^{*0}) = 0.69^{+0.11}_{-0.07} \pm 0.05 \quad 1.10 < q^2 < 6 \text{ GeV}^2$
  compatibility with SM: $2.2$–$2.3\sigma$ (low $q^2$), $2.4$–$2.5\sigma$ (central $q^2$)

**Belle:** 😞 lower statistics, 😊 good performance for $e^\pm$ modes
Measurement of $R(K^*)$

- **Reconstruction & selection of $B \rightarrow K^* \ell^+ \ell^-$**
  
  $B^0 \rightarrow K^*0 \ell^+ \ell^-$, $K^*0 \rightarrow K^+\pi^-, K_S^0\pi^0$
  
  $B^+ \rightarrow K^+\ell^+ \ell^-$, $K^+ \rightarrow K^+\pi^0, K_S^0\pi^+$

  - hierarchical NN reconstruction
  
  - \( P_{e/\mu} \equiv \frac{L_{e/\mu}}{L_{e/\mu}+L_\pi} > 0.9 \)

- **Background suppression**
  
  - Multivariate method utilizing event topology and NN outputs
  
  - Irreducible background from $B \rightarrow J/\psi K^*$ and $B \rightarrow \psi(2S)K^*$ reduced by rejecting events in the relevant $M_{\ell^+\ell^-}$ windows

- **Signal extraction**
  
  - UEML fit to $M_{bc} \equiv \sqrt{E_{beam}^2 - |p_B|^2}$

  in several bins of $q^2$: [0.045, 1.1], [1.1, 6], [0.1, 8], [15, 19], [0.045, ] GeV$^2$

- **Control sample: data in the veto region of $J/\psi$**

  \[
  \frac{B(B \rightarrow J/\psi(\rightarrow\mu^+\mu^-)K^*)}{B(B \rightarrow J/\psi(\rightarrow e^+e^-)K^*)} = 1.015 \pm 0.025 \pm 0.038
  \]
Measurement of $R(K^*)$

Results consistent with SM

Systematic uncertainties for $B^+/0$ modes and $q^2 > 0.045$ GeV$^2$

<table>
<thead>
<tr>
<th>source</th>
<th>$\Delta R(K^*)$</th>
</tr>
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<tbody>
<tr>
<td>$e, \mu$ efficiency</td>
<td>0.061</td>
</tr>
<tr>
<td>MC size</td>
<td>0.004</td>
</tr>
<tr>
<td>Classifier</td>
<td>0.013</td>
</tr>
<tr>
<td>Signal shape</td>
<td>0.008</td>
</tr>
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<td>Tracking eff.</td>
<td>0.016</td>
</tr>
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<td>0.023</td>
</tr>
<tr>
<td>total</td>
<td>0.075</td>
</tr>
</tbody>
</table>

$q^2$ in GeV$^2/c^4$

<table>
<thead>
<tr>
<th>$q^2$ range</th>
<th>All modes</th>
<th>$B^0$ modes</th>
<th>$B^+$ modes</th>
</tr>
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<tbody>
<tr>
<td>[0.045, 1.1]</td>
<td>0.52$\pm$0.36$\pm$0.05</td>
<td>0.46$\pm$0.55$\pm$0.07</td>
<td>0.62$\pm$0.60$\pm$0.10</td>
</tr>
<tr>
<td>[1.1, 6]</td>
<td>0.96$\pm$0.45$\pm$0.11</td>
<td>1.06$\pm$0.63$\pm$0.13</td>
<td>0.72$\pm$0.99$\pm$0.18</td>
</tr>
<tr>
<td>[0.1, 8]</td>
<td>0.90$\pm$0.27$\pm$0.10</td>
<td>0.86$\pm$0.33$\pm$0.08</td>
<td>0.96$\pm$0.35$\pm$0.14</td>
</tr>
<tr>
<td>[15, 19]</td>
<td>1.18$\pm$0.32$\pm$0.10</td>
<td>1.12$\pm$0.36$\pm$0.10</td>
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<tr>
<td>[0.045, ]</td>
<td>0.94$\pm$0.17$\pm$0.08</td>
<td>1.12$\pm$0.27$\pm$0.09</td>
<td>0.70$\pm$0.24$\pm$0.07</td>
</tr>
</tbody>
</table>

$\Rightarrow$ first measurements

References:
Belle Collab., arXiv:1904.02440

Results consistent with SM
Measurement of $R(K^*)$

Results consistent with SM and with other measurements

Systematic uncertainties for $B^+/0$ modes and $q^2 > 0.045 \text{ GeV}^2$

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</tr>
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$q^2$ in GeV$^2$/c$^4$:
- [0.045, 1.1]: $0.52_{-0.26}^{+0.36} \pm 0.05$ for all modes, $0.46_{-0.27}^{+0.55} \pm 0.07$ for $B^0$ modes
- [1.1, 6]: $0.96_{-0.29}^{+0.45} \pm 0.11$ for all modes, $1.06_{-0.38}^{+0.63} \pm 0.13$ for $B^0$ modes
- [0.1, 8]: $0.90_{-0.21}^{+0.27} \pm 0.10$ for all modes, $0.86_{-0.24}^{+0.33} \pm 0.08$ for $B^0$ modes
- [15, 19]: $1.18_{-0.32}^{+0.52} \pm 0.10$ for all modes, $1.12_{-0.36}^{+0.61} \pm 0.10$ for $B^0$ modes
- [0.045, ]: $0.94_{-0.14}^{+0.17} \pm 0.08$ for all modes, $1.12_{-0.21}^{+0.27} \pm 0.09$ for $B^0$ modes

$B^+$ modes:
- $0.62_{-0.36}^{+0.60} \pm 0.10$
- $0.72_{-0.44}^{+0.99} \pm 0.18$
- $0.96_{-0.35}^{+0.56} \pm 0.14$
- $1.40_{-0.68}^{+1.99} \pm 0.11$
- $0.70_{-0.24}^{+0.24} \pm 0.07$

Results consistent with SM and with other measurements.
Summary and outlook

- New measurement of $R(D(\ast))$ using semileptonic $B_{\text{tag}}$ decays
  
  $R(D) = 0.307 \pm 0.037\,(\text{stat}) \pm 0.016\,(\text{syst})$
  
  $R(D\ast) = 0.283 \pm 0.018\,(\text{stat}) \pm 0.014\,(\text{syst})$

  - first measurement of $R(D)$ with semileptonic tagging
  - most precise $R(D(\ast))$ measurements to date
  - results consistent with SM within $\sim 1.3\sigma$
  - tension between SM and experimental world averages reduced $3.8\sigma \Rightarrow \sim 3.1\sigma$

- Measurement of $D_{\ast}^{-}$ polarization in $B^{0} \rightarrow D_{\ast}^{-}\tau^{+}\nu_{\tau}$
  
  $F_{L}^{D_{\ast}} = 0.60 \pm 0.08\,(\text{stat}) \pm 0.04\,(\text{syst})$

  - first measurement of $D^{\ast}$ polarization in semitauonic decay
  - the measured value consistent with SM within $\sim 1.5\sigma$
  - experimental accuracy can be further improved with Belle data by including $B^{+} \rightarrow D^{\ast}\tau\nu_{\tau}$
  - $\frac{d^{2}\Gamma}{dq^{2}d\cos\theta_{V}}$ feasible at Belle II (enhanced sensitivity to NP, reduced acceptance effects)

- New measurements of $R(K^{\ast})$ in several bins of $q^{2}$: [0.045, 1.1], [1.1, 6], [0.1, 8], [15, 19], [0.045, ] GeV$^{2}$

  $R(K^{\ast}) = 0.94^{+0.17}_{-0.14}\,(\text{stat}) \pm 0.08\,(\text{syst})$, for $q^{2} > 0.045$ GeV$^{2}$

  - first measurement of $R(K^{\ast+})$
  - all results compatible with SM and other measurements

- Experimental accuracy limited by statistics $\Rightarrow$ good prospects for Belle II, with expected 50× larger data sample.
Backup slides
<table>
<thead>
<tr>
<th>Source</th>
<th>ΔR(D) (%)</th>
<th>ΔR(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>Fake D(s) calibration</td>
<td>0.19</td>
<td>0.11</td>
<td>-0.76</td>
</tr>
<tr>
<td>B_{tag} calibration</td>
<td>0.07</td>
<td>0.05</td>
<td>-0.76</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>Lepton efficiency and fake rate</td>
<td>0.36</td>
<td>0.33</td>
<td>-0.83</td>
</tr>
<tr>
<td>Slow pion efficiency</td>
<td>0.08</td>
<td>0.08</td>
<td>-0.98</td>
</tr>
<tr>
<td>MC statistics</td>
<td>4.39</td>
<td>2.25</td>
<td>-0.55</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</td>
<td>0.10</td>
<td>0.04</td>
<td>-0.58</td>
</tr>
<tr>
<td>B(B → D(s)ℓν)</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(τ̄ → ℓ−νμτ)</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>

**electron:**

\[ \mathcal{R}(D) = 0.281 \pm 0.042 \pm 0.017 \]
\[ \mathcal{R}(D^*) = 0.304 \pm 0.022 \pm 0.016 \]

**muon:**

\[ \mathcal{R}(D) = 0.373 \pm 0.068 \pm 0.030 \]
\[ \mathcal{R}(D^*) = 0.245 \pm 0.035 \pm 0.020 \]
### $R(K^*)$: Systematics

<table>
<thead>
<tr>
<th>$q^2$ in GeV$^2 / c^4$</th>
<th>$e, \mu$ eff.</th>
<th>MC size</th>
<th>classifier</th>
<th>sig. shape</th>
<th>tracking</th>
<th>peaking bkg.</th>
<th>$c\bar{c}$ bkg.</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>all modes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- [0.045, None] -</td>
<td>0.061</td>
<td>0.004</td>
<td>0.013</td>
<td>0.008</td>
<td>0.016</td>
<td>0.031</td>
<td>0.023</td>
<td>0.075</td>
</tr>
<tr>
<td>- [0.1, 8] -</td>
<td>0.058</td>
<td>0.005</td>
<td>0.029</td>
<td>0.002</td>
<td>0.016</td>
<td>0.054</td>
<td>0.051</td>
<td>0.100</td>
</tr>
<tr>
<td>- [15, 19] -</td>
<td>0.090</td>
<td>0.012</td>
<td>0.012</td>
<td>0.014</td>
<td>0.020</td>
<td>0.003</td>
<td>0.003</td>
<td>0.095</td>
</tr>
<tr>
<td>- [0.045, 1.1] -</td>
<td>0.027</td>
<td>0.006</td>
<td>0.008</td>
<td>0.025</td>
<td>0.009</td>
<td>0.026</td>
<td>0.001</td>
<td>0.047</td>
</tr>
<tr>
<td>- [1.1, 6] -</td>
<td>0.065</td>
<td>0.008</td>
<td>0.048</td>
<td>0.033</td>
<td>0.017</td>
<td>0.070</td>
<td>0.013</td>
<td>0.114</td>
</tr>
<tr>
<td>$B^0$ modes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- [0.045, None] -</td>
<td>0.073</td>
<td>0.006</td>
<td>0.030</td>
<td>0.018</td>
<td>0.022</td>
<td>0.031</td>
<td>0.021</td>
<td>0.092</td>
</tr>
<tr>
<td>- [0.1, 8] -</td>
<td>0.058</td>
<td>0.006</td>
<td>0.040</td>
<td>0.019</td>
<td>0.017</td>
<td>0.033</td>
<td>0.018</td>
<td>0.084</td>
</tr>
<tr>
<td>- [15, 19] -</td>
<td>0.091</td>
<td>0.013</td>
<td>0.007</td>
<td>0.012</td>
<td>0.022</td>
<td>0.007</td>
<td>0.001</td>
<td>0.096</td>
</tr>
<tr>
<td>- [0.045, 1.1] -</td>
<td>0.024</td>
<td>0.007</td>
<td>0.044</td>
<td>0.005</td>
<td>0.009</td>
<td>0.049</td>
<td>0.001</td>
<td>0.071</td>
</tr>
<tr>
<td>- [1.1, 6] -</td>
<td>0.082</td>
<td>0.010</td>
<td>0.040</td>
<td>0.062</td>
<td>0.021</td>
<td>0.070</td>
<td>0.012</td>
<td>0.133</td>
</tr>
<tr>
<td>$B^+$ modes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- [0.045, None] -</td>
<td>0.044</td>
<td>0.005</td>
<td>0.032</td>
<td>0.018</td>
<td>0.010</td>
<td>0.025</td>
<td>0.023</td>
<td>0.068</td>
</tr>
<tr>
<td>- [0.1, 8] -</td>
<td>0.060</td>
<td>0.010</td>
<td>0.039</td>
<td>0.040</td>
<td>0.014</td>
<td>0.048</td>
<td>0.107</td>
<td>0.144</td>
</tr>
<tr>
<td>- [15, 19] -</td>
<td>0.089</td>
<td>0.028</td>
<td>0.016</td>
<td>0.041</td>
<td>0.021</td>
<td>0.008</td>
<td>0.002</td>
<td>0.106</td>
</tr>
<tr>
<td>- [0.045, 1.1] -</td>
<td>0.033</td>
<td>0.013</td>
<td>0.067</td>
<td>0.060</td>
<td>0.009</td>
<td>0.006</td>
<td>0.000</td>
<td>0.097</td>
</tr>
<tr>
<td>- [1.1, 6] -</td>
<td>0.045</td>
<td>0.010</td>
<td>0.137</td>
<td>0.060</td>
<td>0.011</td>
<td>0.086</td>
<td>0.009</td>
<td>0.179</td>
</tr>
</tbody>
</table>
Acceptance effects in $B \to D^* \tau \nu$

$$\theta_{hel}(D^*) \equiv \theta_V$$