Measurements of lepton flavor non-universality in B decays at Belle

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for the Belle Collaboration

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25th Anniversary of the Rencontres du Vietnam
Outline

- R(D) and R(D*) measurement with $B \xrightarrow{} D(*)\tau\nu$
- Test of lepton universality in $B \xrightarrow{} K^\ast\pi$
- Search for Lepton flavor violating decay $B \xrightarrow{} K^\ast\mu\nu$
Belle and KEKB

- **KEKB**
  - Achieved World Highest Luminosity (as of 2009)
    - $L = 2.1 \times 10^{34} \text{ /cm}^2 \text{/sec} \approx 20 \text{ BB pairs / sec}$
  - Asymmetric energy to boost B mesons
    - $8.0 \text{GeV} \ e^- \times 3.5 \text{GeV} \ e^+$

- **Belle**
  - Multi-purpose $4\pi$ detector
  - Vertexing, tracking, EM calorimeter, PID

- Data taking for 1999-2010
Belle Integrated Luminosity

- The world largest integrated luminosity of $>1 \text{ab}^{-1}$
- $711 \text{ fb}^{-1}$ on $Y(4S)$ resonance $\rightarrow 772 \times 10^{6}$ BB pairs

On resonance:
- $Y(5S): 121 \text{ fb}^{-1}$
- $Y(4S): 711 \text{ fb}^{-1}$
- $Y(3S): 3 \text{ fb}^{-1}$
- $Y(2S): 25 \text{ fb}^{-1}$
- $Y(1S): 6 \text{ fb}^{-1}$

Off res. / scan:
- $\sim 100 \text{ fb}^{-1}$
Semi-tauonic B decay: $B \rightarrow D^{(*)} \tau \nu$

- Sensitive to new physics

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

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

Polarization of tau could probe the NP model

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

NP model (vector, scalar, tensor) dependence

[M. Tanaka and R. Watanabe PRD 87, 034028 (2013)]
**B → D(*)τν Analysis at Belle**

Utilize the B factory specific feature: only one B-meson pair is produced

**Tag Side**

- Tag B pair event by reconstructing one B meson in hadronic or semileptonic B Decay
- Provide pure single B event

**Signal Side**

- Final state has two or more neutrinos
- Remaining energy in the calorimeter (E_{ECL})

**Diagram**

\[ B^- \rightarrow X \]

\[ B^+ \rightarrow D \tau^+ \nu_\tau \]

Require no particle remains after removing products of tagging B and the particle(s) from signal decays

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Tagging Methods

- **Hadronic Tag**
  - Fully reconstruct in $B \rightarrow D X$ decays
  - $\sim 1100$ exclusive decay channels
    - [NIM A 654, 432 (2011)]
  - Tagging efficiency $\sim 0.2\%$
  - Less background

- **Semileptonic Tag**
  - Reconstruct $B \rightarrow D^{(*)} l \nu$
    - $E_B = E_{\text{beam}}$
    - Undetected neutrino mass $\sim 0$
  - Tagging efficiency $\sim 0.5\%$
  - More background

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

\[ \cos \theta_{B,D^{(*)} l} = \frac{2E_{\text{beam}}E_{D^{(*)} l} - m_B^2 - M_{D^{(*)} l}^2}{2P_B^*P_{D^{(*)} l}^*} \]
Results with leptonic tau decays

Hadronic Tag [PRD92,072014(2015)]

Semileptonic Tag [PRD94,072007(2016)]

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

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

$$R(D^*) = 0.302 \pm 0.030 \pm 0.011$$

Consistent with, but higher than the SM predictions:

R(D) = 0.299 +/- 0.003
R(D^*) = 0.258 +/- 0.005

[SM average of HFLAV Summer 2018]
Results of Polarization Measurement

- Hadronic tag
- Two body tau decays: \( \tau \to \pi \nu, \rho \nu \)
  - Helicity angle sensitive to the tau polarization

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

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

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

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

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Current $B \rightarrow D(*)\tau\nu$ Situation

$3.8\sigma$ deviation from the SM prediction!

Additional Belle results will come soon

Belle II has started $\Rightarrow$ Significant improvement in near future
Lepton Universality in $B\to K^{*}\mu\mu$

- LHCb reported 2.6 $\sigma$ tension in
  \[ R_K \equiv \frac{\mathcal{B}(B\to K^+\mu^+\mu^-)}{\mathcal{B}(B\to K^+e^+e^-)} \quad R^*_K \equiv \frac{\mathcal{B}(B\to K^{*}\mu^+\mu^-)}{\mathcal{B}(B\to K^{*}e^+e^-)} \]
- also in angular observable
  \[ P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}} \quad \frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_L d\cos\theta_K d\phi dq^2} : \theta_K, \theta_L, \phi, F_L, S_i \]

- [PRL 113, 151601(2014), JHEP 08(2017), 055]
- [JHEP 02(2016), 104]
B$\rightarrow$K*ll Angular Analysis Results

- B$\rightarrow$K*$\mu\mu$, K*ee reconstructed with Belle full data
- Angular analysis performed in four bins to obtain angular observables
  - $P'_i$
  - the difference between the lepton flavors
    \[ Q_i = P^\mu_i - P^e_i \]

Largest deviation in $P'_5$ of muon mode with $2.6\sigma$

[N_{sig} = 127 \pm 15]

[N_{sig} = 185 \pm 17]

[PRL118, 111801 (2017)]
Comparison with other measurements

- Measurements are compatible with the SM
- Similar central values for the $P'_5$ anomaly with 2.5s tension
Search for lepton flavor violating decay $B^0 \rightarrow K^{*0}\mu e$

- 2018 New Belle Result with 772M $B\bar{B}$

[arXiv:1807.03267 submitted to PRD]

No signal observed
Set most stringent limit of these decays

$\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+e^-) < 1.2 \times 10^{-7}$

$\mathcal{B}(B^0 \rightarrow K^{*0}\mu^-e^+) < 1.6 \times 10^{-7}$

$\mathcal{B}(B^0 \rightarrow K^{*0}\mu^\pm e^\mp) < 1.8 \times 10^{-7}$
Summary

• Belle measured lepton universality using the data sample of the world largest luminosity

• **Tensions from the SM** exist in the measurements of $B \rightarrow D(*)\tau\nu$ and $B \rightarrow K^{*}\mu\mu$

• New search for the LFV decay $B \rightarrow K^{*}\mu\epsilon$ has been performed and set the most stringent limits

• Still need more results to be conclusive
  - Still some more analyses on going at Belle
  - Significant improvement from Belle II in near future
B→D(*)τν Systematic Errors

Hadronic Tag

### TABLE IV. Overview of relative systematic uncertainties in percent. The last column gives the correlation between $R(D)$ and $R(D^*)$.

<table>
<thead>
<tr>
<th>Source</th>
<th>$R(D)$ [%]</th>
<th>$R(D^*)$ [%]</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{(*)}\nu$ shapes</td>
<td>4.2</td>
<td>1.5</td>
<td>0.04</td>
</tr>
<tr>
<td>$D^{**}$ composition</td>
<td>1.3</td>
<td>3.0</td>
<td>-0.63</td>
</tr>
<tr>
<td>Fake $D$ yield</td>
<td>0.5</td>
<td>0.3</td>
<td>0.13</td>
</tr>
<tr>
<td>Fake $\ell$ yield</td>
<td>0.5</td>
<td>0.6</td>
<td>-0.66</td>
</tr>
<tr>
<td>$D_\ell$ 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 $f_{D^+}$</td>
<td>2.5</td>
<td>0.7</td>
<td>-0.98</td>
</tr>
<tr>
<td>Efficiency ratio $f_{D^{*0}}$</td>
<td>1.8</td>
<td>0.4</td>
<td>0.86</td>
</tr>
<tr>
<td>Efficiency ratio $f_{\pi^+}$</td>
<td>1.3</td>
<td>2.5</td>
<td>-0.99</td>
</tr>
<tr>
<td>Efficiency ratio $f_{\pi^0}$</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 $g_-$</td>
<td>1.7</td>
<td>1.0</td>
<td>-1.00</td>
</tr>
<tr>
<td>Efficiency ratio $f_{\eta}$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.84</td>
</tr>
<tr>
<td>$M_{\pi\pi}$ shape</td>
<td>0.6</td>
<td>1.0</td>
<td>0.00</td>
</tr>
<tr>
<td>$\omega$ 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>
<tr>
<td>Total</td>
<td>7.1</td>
<td>5.2</td>
<td>-0.32</td>
</tr>
</tbody>
</table>

Semileptonic Tag

### TABLE I. Summary of the systematic uncertainties on $R(D^*)$ for electron and muon modes combined and separated. The uncertainties are relative and are given in percent.

<table>
<thead>
<tr>
<th>Sources</th>
<th>$R(D^*)$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC size for each PDF shape</td>
<td>$\pm1.2%$</td>
</tr>
<tr>
<td>PDF shape of the normalization in $\cos\theta_{B,D\ell}$</td>
<td>$\pm0.0%$</td>
</tr>
<tr>
<td>PDF shape of $B \to D^{**}\ell \bar{\nu}_\ell$</td>
<td>$\pm0.7%$</td>
</tr>
<tr>
<td>PDF shape of $B \to D\ell \bar{\nu}_\ell$</td>
<td>$\pm1.2%$</td>
</tr>
<tr>
<td>PDF shape of $B \to X_c D^*$</td>
<td>$\pm1.1%$</td>
</tr>
<tr>
<td>Reconstruction efficiency ratio $\epsilon_{norm}/\epsilon_{sig}$</td>
<td>$\pm0.0%$</td>
</tr>
<tr>
<td>Modeling of semileptonic decay</td>
<td>$\pm0.0%$</td>
</tr>
<tr>
<td>$B(\tau^- \to \ell^- \nu_\ell \bar{\nu}_\ell)$</td>
<td>$\pm0.0%$</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>$\pm4.1%$</td>
</tr>
</tbody>
</table>

Hadronic Tag, hadronic tau decay

### TABLE II. The systematic uncertainties in $R(D^*)$ and $P_+(D^*)$, 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>$P_+(D^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic $B$ composition</td>
<td>$\pm7.7%$</td>
<td>$\pm0.134$</td>
</tr>
<tr>
<td>MC statistics for PDF shape</td>
<td>$\pm0.9%$</td>
<td>$\pm0.103$</td>
</tr>
<tr>
<td>Fake $D^*$</td>
<td>$\pm2.8%$</td>
<td>$\pm0.18$</td>
</tr>
<tr>
<td>$B \to D^{**}\ell^- \bar{\nu}_\ell$</td>
<td>$\pm2.4%$</td>
<td>$\pm0.048$</td>
</tr>
<tr>
<td>$B \to D^{*+}\tau^- \bar{\nu}_\tau$</td>
<td>$\pm1.1%$</td>
<td>$\pm0.001$</td>
</tr>
<tr>
<td>$B \to D'^+\ell^- \bar{\nu}_\ell$</td>
<td>$\pm2.3%$</td>
<td>$\pm0.007$</td>
</tr>
<tr>
<td>$\tau$ daughter and $\ell^-\ell^+$ efficiency</td>
<td>$\pm1.9%$</td>
<td>$\pm0.019$</td>
</tr>
<tr>
<td>MC statistics for efficiency estimation</td>
<td>$\pm1.0%$</td>
<td>$\pm0.019$</td>
</tr>
<tr>
<td>$B(\tau^- \to \pi^- \nu_\tau \rho^- \bar{\nu}_\tau)$</td>
<td>$\pm0.3%$</td>
<td>$\pm0.002$</td>
</tr>
<tr>
<td>$P_+(D^*)$ correction function</td>
<td>$\pm0.0%$</td>
<td>$\pm0.010$</td>
</tr>
</tbody>
</table>

### Common sources

<table>
<thead>
<tr>
<th>Source</th>
<th>$R(D^*)$</th>
<th>$P_+(D^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tagging efficiency correction</td>
<td>$\pm1.6%$</td>
<td>$\pm0.018$</td>
</tr>
<tr>
<td>$D^*$ reconstruction</td>
<td>$\pm1.4%$</td>
<td>$\pm0.006$</td>
</tr>
<tr>
<td>Branching fractions of the $D$ meson</td>
<td>$\pm0.8%$</td>
<td>$\pm0.007$</td>
</tr>
<tr>
<td>Number of $BB$ and $B(\Upsilon(4S) \to B^+ B^-)$</td>
<td>$\pm0.5%$</td>
<td>$\pm0.006$</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>$\pm4.0%$</td>
<td>$\pm0.21$</td>
</tr>
</tbody>
</table>
R(D) and R(D*) Measurements

BaBar had. tag
0.440 ± 0.058 ± 0.042

Belle had. tag
0.375 ± 0.064 ± 0.026

Average
0.407 ± 0.039 ± 0.024

PRD94,094008(2016)
0.299 ± 0.003

FNAL/MILC (2015)
0.299 ± 0.011

HPQCD (2015)
0.300 ± 0.008

BaBar had. tag
0.332 ± 0.024 ± 0.018

Belle had. tag
0.293 ± 0.038 ± 0.015

Belle sl.tag
0.302 ± 0.030 ± 0.011

Belle hadronic tau
0.270 ± 0.035 ± 0.027

LHCb muonic tau
0.336 ± 0.027 ± 0.030

LHCb hadronic tau
0.291 ± 0.019 ± 0.029

Average
0.306 ± 0.013 ± 0.007

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
\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_\ell \ d\cos\theta_K \ d\phi \ dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2\theta_K + F_L \cos^2\theta_K + \frac{1}{4} (1 - F_L) \sin^2\theta_K \cos 2\theta_\ell \\
- F_L \cos^2\theta_K \cos 2\theta_\ell + S_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi \\
+ S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6 \sin^2\theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \right],
\]

\[
P_{i=4,5,6,8}^{r} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}
\]
**B → K*ll Results and Syst. Errors.**

**TABLE I.** Fit results for $P'$ and $P''$ for all decay channels and separately for the electron and muon modes. The first uncertainties are statistical and the second systematic.

<table>
<thead>
<tr>
<th>$q^2$ in GeV$^2$/c$^2$</th>
<th>$P'_4$</th>
<th>$P''_4$</th>
<th>$P'_5$</th>
<th>$P'_5'$</th>
<th>$P''_5$</th>
<th>$P''_5'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1.00, 6.00]</td>
<td>$-0.45^{+0.23}_{-0.22} \pm 0.09$</td>
<td>$-0.72^{+0.40}_{-0.39} \pm 0.06$</td>
<td>$-0.22^{+0.35}_{-0.34} \pm 0.15$</td>
<td>$0.23^{+0.21}_{-0.22} \pm 0.07$</td>
<td>$-0.22^{+0.39}_{-0.41} \pm 0.03$</td>
<td>$0.43^{+0.25}_{-0.28} \pm 0.10$</td>
</tr>
<tr>
<td>[0.10, 4.00]</td>
<td>$0.11^{+0.32}_{-0.31} \pm 0.05$</td>
<td>$0.34^{+0.41}_{-0.45} \pm 0.11$</td>
<td>$-0.38^{+0.30}_{-0.46} \pm 0.12$</td>
<td>$0.47^{+0.27}_{-0.28} \pm 0.05$</td>
<td>$0.51^{+0.39}_{-0.46} \pm 0.09$</td>
<td>$0.42^{+0.39}_{-0.38} \pm 0.14$</td>
</tr>
<tr>
<td>[4.00, 8.00]</td>
<td>$-0.34^{+0.18}_{-0.17} \pm 0.05$</td>
<td>$-0.52^{+0.24}_{-0.22} \pm 0.03$</td>
<td>$-0.07^{+0.32}_{-0.31} \pm 0.07$</td>
<td>$-0.30^{+0.19}_{-0.19} \pm 0.09$</td>
<td>$-0.52^{+0.28}_{-0.26} \pm 0.03$</td>
<td>$-0.03^{+0.31}_{-0.30} \pm 0.09$</td>
</tr>
<tr>
<td>[10.09, 12.90]</td>
<td>$-0.18^{+0.28}_{-0.26} \pm 0.06$</td>
<td>$-0.52^{+0.17}_{-0.22} \pm 0.04$</td>
<td>$-0.10^{+0.39}_{-0.39} \pm 0.07$</td>
<td>$-0.51^{+0.36}_{-0.39} \pm 0.03$</td>
<td>$-0.91^{+0.36}_{-0.30} \pm 0.03$</td>
<td>$-0.13^{+0.35}_{-0.35} \pm 0.06$</td>
</tr>
</tbody>
</table>

**TABLE II.** Results for the lepton-flavor-universality-violating observables $Q_4$ and $Q_5$. The first uncertainty is statistical and the second systematic.

<table>
<thead>
<tr>
<th>$q^2$ in GeV$^2$/c$^2$</th>
<th>$Q_4$</th>
<th>$Q_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1.00, 6.00]</td>
<td>$0.498 \pm 0.527 \pm 0.166$</td>
<td>$0.056 \pm 0.485 \pm 0.163$</td>
</tr>
<tr>
<td>[0.10, 4.00]</td>
<td>$-0.723 \pm 0.676 \pm 0.163$</td>
<td>$-0.097 \pm 0.601 \pm 0.164$</td>
</tr>
<tr>
<td>[4.00, 8.00]</td>
<td>$0.448 \pm 0.392 \pm 0.076$</td>
<td>$0.498 \pm 0.410 \pm 0.095$</td>
</tr>
<tr>
<td>[14.18, 19.00]</td>
<td>$0.041 \pm 0.565 \pm 0.082$</td>
<td>$0.778 \pm 0.502 \pm 0.065$</td>
</tr>
</tbody>
</table>
B$\rightarrow$K*$\mu$e Upper Limits

Upper limit at 90% CL.


229M$B\bar{B}$

Belle (2017)

772M$B\bar{B}$

$K^{*0}\mu^{+}e^{-}$

$K^{*0}\mu^{-}e^{+}$

$K^{*0}\mu^{\pm}e^{\mp}$

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