Recent results of B decays from Belle

Martin Heck for the Belle Collaboration | 01. September 2017
Overview

- key characteristics of Belle

- $B \rightarrow D^* \tau \nu$ - new measurement of $\tau$ polarization and $R(D^*)$

- $B \rightarrow K^* l^+ l^-$ - lepton-flavour-dependent angular analysis

- other recent results on rare $B$ decays
  - $B \rightarrow h(\ast) \nu \nu$
  - $B^+ \rightarrow \mu^+ \nu$

- summary & outlook
Key Characteristics of Belle

- asymmetric electron-positron collider at Y(4S)-energy
- 772 million $B\bar{B}$ pairs
- Running: 1999 - 2010
$B \rightarrow D^* \tau \nu$ - Polarization and $R(D^*)$

**Phys. Rev. Lett. 118, 211801**

- **strategy:**
  - recombine one of the $B$ mesons of the $Y(4S)$ - for this analysis, hadronic tagging is used, as it delivers a better resolution for $p(B_{signal})$, which is $\sim 331$ (326) MeV/c in the (~known) Y(4S)-cms for $B^+$ ($B^0$) mesons.
  - recombine signal side in all reasonable $D^*$ channels and $\pi/\rho$, light leptons instead of $\pi/\rho$ for normalisation channels
  - Require kinematics of signal events to be consistent with the signal as well as no additional tracks, no additional good $\pi^0$, less than 1.5 GeV of energy in the ECL left.
Due to our knowledge of $B_{\text{signal}}$ momentum, we can calculate the helicity angle $\cos \theta_{\text{hel}}$:

- angle between the $\tau$-daughter momentum and the opposite of the momentum of the $\tau \nu$ system in the $\tau$ rest frame

Only $\cos \theta_{\text{hel}}$ between -1 and 0.8 is used, for further analysis, sample is divided into two categories:

- $\cos \theta_{\text{hel}}$ larger or smaller than zero

Simulation with SM-like signal
$B \rightarrow D^* \tau \nu$ - Results

$P_\tau(D^*) = \frac{[2(N_{\text{sig}}^F - N_{\text{sig}}^B)]}{[\alpha(N_{\text{sig}}^F + N_{\text{sig}}^B)]}$

- F(oward) denotes events with $\cos \theta_{\text{hel}} > 0$
- B(ackward) denotes events with $\cos \theta_{\text{hel}} < 0$
- $\alpha$ denotes a factor for the sensitivity of the respective final state
  - $\alpha = 1$ for $\pi$, $\alpha = 0.45$ for $\rho$
- SM prediction for polarization:
  (Tanaka et al., PRD 87. 0.4028)

$P_\tau(D^*) = -0.497 \pm 0.013$

$R(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}\text{(stat.)}$
$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}\text{(syst.)}$
$B \rightarrow D^* \tau \nu$ - BR Overview

- world average differs by $\sim 4 \sigma$ from theory predictions
- when thinking about New Physics solutions to the discrepancy, take into account, that we might not actually see $\tau$s, but perhaps light leptons + missing mass/energy
\[ B \rightarrow K^* \ l^+ \ l^- \] - angular analysis for \( \mu/e \)

Phys. Rev. Lett. 118, 111801

- strategy:
  - reconstruct \( B \) mesons (\( B^+ / B^0 \)) in \( K^*[K^+ \pi / K^+ \pi^0 / K_{S^0} \pi^+] \ l^+ \ l^- \) (\( l = \mu/e \))
  - Extract observables \( P'_{i} \) (explanation see later)
\[ B \rightarrow K^* l^+ l^- - m_{bc} \] signal extraction

- Most backgrounds don’t peak in the beam constraint mass \( M_{bc} = \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}_B|^2/c^2} \)
- background distributions in the observables estimated from sideband
- Small peaking backgrounds are evaluated on MC to be very small
\[ \frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2\theta_K + F_L \cos^2\theta_K + \frac{1}{4} (1 - F_L) \sin^2\theta_K \cos 2\theta_\ell 
\right.
\]

\[ - F_L \cos^2\theta_K \cos 2\theta_\ell + S_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi 
\]

\[ + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6 \sin^2\theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi 
\]

\[ + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \right] , \]

\[ F_L, S_i \text{ functions only dependent on } q^2 \]

Believed to be largely free from Form Factor uncertainties:

\[ P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}} \]
B → K* l⁺ l⁻ - Results

- Fit results for P'₄ and P'₅ for all decay channels and separately for the electron and muon modes. The first uncertainties are statistical and the second systematic.
$B \to K^* \ell^+ \ell^-$ - Results in Numbers

<table>
<thead>
<tr>
<th>$q^2$ in GeV$^2$/cm$^2$</th>
<th>$P'_4$</th>
<th>$P''_4$</th>
<th>$P'''_4$</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>$-0.22^{+0.36}_{-0.34} \pm 0.15$</td>
<td>$0.23^{+0.21}_{-0.22} \pm 0.07$</td>
<td>$-0.22^{+0.39}_{-0.41} \pm 0.03$</td>
<td>$0.43^{+0.26}_{-0.28} \pm 0.10$</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>$-0.38^{+0.50}_{-0.48} \pm 0.12$</td>
<td>$0.47^{+0.27}_{-0.28} \pm 0.05$</td>
<td>$0.51^{+0.39}_{-0.46} \pm 0.09$</td>
<td>$0.42^{+0.39}_{-0.39} \pm 0.14$</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>$-0.07^{+0.31}_{-0.31} \pm 0.07$</td>
<td>$-0.30^{+0.19}_{-0.19} \pm 0.09$</td>
<td>$-0.52^{+0.26}_{-0.26} \pm 0.03$</td>
<td>$-0.03^{+0.31}_{-0.30} \pm 0.09$</td>
</tr>
<tr>
<td>[10.09, 12.90]</td>
<td>$-0.18^{+0.28}_{-0.27} \pm 0.06$</td>
<td>-</td>
<td>$-0.40^{+0.33}_{-0.29} \pm 0.09$</td>
<td>$-0.17^{+0.25}_{-0.25} \pm 0.01$</td>
<td>-</td>
<td>$0.09^{+0.29}_{-0.29} \pm 0.02$</td>
</tr>
<tr>
<td>[14.18, 19.00]</td>
<td>$-0.14^{+0.26}_{-0.26} \pm 0.05$</td>
<td>$-0.15^{+0.41}_{-0.40} \pm 0.04$</td>
<td>$-0.10^{+0.39}_{-0.39} \pm 0.07$</td>
<td>$-0.51^{+0.24}_{-0.22} \pm 0.01$</td>
<td>$-0.91^{+0.36}_{-0.39} \pm 0.03$</td>
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$B \to K^* \, l^+ \, l^-$ - Lepton Universality Test

$Q = P^\mu - P^e$
Good agreement with measurements from LHC experiments.

Note: This is the combined $e/\mu$ value from Belle. Discrepancy with SM is bigger when taking $P'_{5\mu}$. 

$q^2 \ [\text{GeV}^2/c^4]$
\[ B \rightarrow h^{(*)} \nu \nu \]


- could be an alternative way to see the same kind of New Physics, that might be in \( B \rightarrow K^* l^+ l^- \)

- basic strategy similar to \( B \rightarrow D^* \tau \nu \):
  - recombine one of the \( B \) mesons of the \( Y(4S) \) - using *semileptonic tag-side decays* in the most recent measurement
  - select the \( h^{(*)} \)
  - veto any additional tracks, neutral pions/kaons
  - fit the amount of energy remaining in the calorimeter for the remaining events
$B \rightarrow h^{(*)} \nu \nu$ - Limits Overview

- Better sensitivity than hadronically tagged analysis
$B \to h(\ast) \nu \nu$ - Limits Overview

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<th>Channel</th>
<th>Observed signal yield</th>
<th>Significance</th>
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<tr>
<td>$K^+ \nu \bar{\nu}$</td>
<td>$17.7 \pm 9.1 \pm 3.4$</td>
<td>$1.9 \sigma$</td>
</tr>
<tr>
<td>$K_S^0 \nu \bar{\nu}$</td>
<td>$0.6 \pm 4.2 \pm 1.4$</td>
<td>$0.0 \sigma$</td>
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$B \rightarrow h^{(*)} \nu \nu$ - Limits Overview

### Channel

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<tr>
<td>$K^{*+} \nu \bar{\nu}$</td>
<td>$16.2 \pm 7.4 \pm 1.8$</td>
<td>$2.3\sigma$</td>
</tr>
<tr>
<td>$K^{*0} \nu \bar{\nu}$</td>
<td>$-2.0 \pm 3.6 \pm 1.8$</td>
<td>$0.0\sigma$</td>
</tr>
</tbody>
</table>
$B \rightarrow h^{(*)} \nu \nu$ - Limits Overview

For comparison: Hadronically tagged analysis (Phys. Rev. D 87 (2013) 111103)

→ Both are worth doing
$B^+ \rightarrow \mu^+ \nu$

publication in preparation

- strategy:
  - Identify a muon
  - Fit the muon momentum in the Y(4S) rest frame and the output of an multivariate classifier
\[ B^+ \rightarrow \mu^+ \nu \]

- 2.4 \( \sigma \) significance.
- \( B(B^- \rightarrow \mu^- \bar{\nu}_\mu) \in [2.9, 10.7] \times 10^{-7} \) at the 90\% C.L.

- Two sided limit compatible with SM value of \((3.80 \pm 0.31) \times 10^{-7}\)
  (value debatable due to \( V_{ub} \) situation)

- Extensive studies of u l \( \nu \) backgrounds
Summary & Outlook

- Polarisation & R(D*) in yet another Belle analysis of $B \to D^* \tau \nu$ using hadronic final states for $\tau$s is well compatible with the Standard Model.

- Belle’s analysis of $K^* l^+ l^-$ confirms, there is reason for excitement.

- $B \to h^{(*)} \nu \nu$ limits are less than an order of magnitude away from the Standard Model, future experiments will likely observe strange final states.

- $B^+ \to \mu^+ \nu$ is almost within reach and will be seen either by Belle or very early in future flavour experiments.