Semileptonic B decays at Belle and Belle II

Uwe Gebauer

II. Physikalisches Institut, Universität Göttingen

Brookhaven Forum 2019
Particle Physics and Cosmology in the 2020’s
Why semileptonic decays?

- Easier to describe theoretically due to less QCD influence compared to fully hadronic decays.
- Higher branching fractions (e.g. $10.33 \pm 0.28\%$ of $B^0$ decays), and easier to reconstruct than fully leptonic decays.
- Well suited for determining CKM matrix elements and probing new physics.

Standard Model $B^0 \rightarrow D^{*-} \ell^+ \nu_\ell$

Same decay via a BSM charged Higgs
Collected $772 \times 10^6 B\bar{B}$ at the $\Upsilon(4S)$ resonance

Belle Detector

- SC solenoid 1.5T
- CsI(Tl) 16$\lambda_0$
- TOF counter
- 8 GeV e
- Si vxt. det. 3/4 lyr. DSSD
- $\mu / K_l$ detection 14/15 lyr. RPC+Fe
- Central Drift Chamber
- Aerogel Cherenkov cnt. $n=1.015-1.030$
- $3.5 \text{ GeV} e^+$

Belle II Detector

- EM Calorimeter CsI(Tl), waveform sampling electronics
- Particle Identification Time-of-Propagation counter (barrel)
- Prox. focusing Aerogel RICH (forward)
- KL and muon detector
  - Resistive Plate Counter (barrel outer layers)
  - Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)
- Vertex Detector
  - 2 layers Si Pixels (DEPFET) + 4 layers Si double sided strip DSSD
- Central Drift Chamber
  - Smaller cell size, long lever arm
- Prox. focusing Aerogel RICH (forward)
- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

Belle II

- Upgraded in combination with accelerator to achieve $40\times$ the luminosity
- Data taking started in March this year
Full Event Interpretation (FEI)

- $\Upsilon(4S)$ always decays to $B\bar{B}$ pairs, reconstruct one called $B_{\text{tag}}$ in over 1000 channels with boosted decision trees (BDTs)
- Choice between hadronic and semileptonic $B$ decay modes
- Known initial state allows to use the other $B$-meson ($B_{\text{sig}}$) in signal analysis

 Comes at a price of low efficiency for high purity
- Untagged analyses not considering second $B$-meson have higher efficiency, but also higher backgrounds

Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method

Semitauonic B decays are an important probe towards BSM processes, due to the high masses involved. The ratio with lighter mesons

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

has been both experimentally and theoretically determined and is a source of tension in the Standard Model.

- $B_{\text{tag}}$ reconstructed semileptonically using FEI
- Reconstruct $B_{\text{sig}}$ in $D^{+/0(*)} \ell^-$
  - $D^* \rightarrow D\pi$ and $D$ to a number of $K$ and $\pi$
- Many $\nu$ in event: One from $B_{\text{tag}}$, one($\ell = e, \mu$) or three($\ell = \tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau$) from $B_{\text{sig}}$
  - Extra energy left in the calorimeter strongly hints at background event with additional particles

Caria, G. et al. (Belle Collaboration) arxiv:1904.08794
Combined results

- Data contains three components:
  - $\bar{B} \to D(\ast) \tau^\pm \bar{\nu}_\tau$,
  - $\bar{B} \to D(\ast) \ell^\pm \bar{\nu}_\ell$ and
  - background

- To distinguish $\tau$ from $e, \mu$ events, train a BDT sensitive to the additional $\nu$

- Fit to BDT output and $E_{ECL}$ to determine event numbers

Results

**First measurement of $R(D)$ with semileptonic tag**

<table>
<thead>
<tr>
<th></th>
<th>This analysis</th>
<th>Updated HFLAV average</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(D)$</td>
<td>$0.307 \pm 0.037 \pm 0.016$</td>
<td>$0.340 \pm 0.027 \pm 0.013$</td>
<td>$0.299 \pm 0.003$</td>
</tr>
<tr>
<td>$R(D^\ast)$</td>
<td>$0.283 \pm 0.018 \pm 0.014$</td>
<td>$0.295 \pm 0.011 \pm 0.008$</td>
<td>$0.258 \pm 0.005$</td>
</tr>
</tbody>
</table>

Belle results combined now agree with the SM within $1.8\sigma$, closer than before.
There has been a long-standing tension between inclusive and exclusive measurements of $|V_{cb}|$.

The decay $B^0 \rightarrow D^{*-} \ell^+ \nu_\ell$ allows measuring both $|V_{cb}|$ and form factors describing the decay.

To achieve high statistics, use an untagged approach and only reconstruct the signal side.

Further decays considered are $D^{*-} \rightarrow \bar{D}^0 \pi^-$, $\bar{D}^0 \rightarrow K^- \pi^+$

Clean reconstruction channel, use vertex fits and momentum cuts to select particles

Signal $D^{*-}$ have a lower momentum than $D^{*-}$ directly from $e^+ e^- \rightarrow c \bar{c}$

**Background subtraction**

- Untagged analysis comes with large backgrounds
- Determine bkg yields by three-dim. fit to kinematic variables, use result to subtract bkg for

**CLN form factor fit**

- Parametrization used in the Monte Carlo and fits so far
- Fit three form factors plus normalization to projections of the three decay angles and the $D^*$ momentum

**BGL form factor fit**

- Model independent alternative parametrization
- Truncated to fit five parameters to the same variables as CLN

---

**Angles used to describe the decay**


Results

The results are for the CLN parametrization:

\[ |V_{cb}| = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3} \]

\[ B(B^0 \rightarrow D^*^- \ell^+ \nu_\ell) = (4.90 \pm 0.02 \pm 0.16)\% \]

And for BGL:

\[ |V_{cb}| = (38.3 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3} \]

\[ B(B^0 \rightarrow D^*^- \ell^+ \nu_\ell) = (4.90 \pm 0.02 \pm 0.16)\% \]

Compared with the world average for \( |V_{cb}| \), both agree well with other inclusive measurements, the tension with the exclusive measurements remains:

\[ |V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \text{ (inclusive)} \]

\[ |V_{cb}| = (39.1 \pm 0.4) \times 10^{-3} \text{ (CLN, exclusive)} \]

Lepton universality check

Separate fits to e and \( \mu \) allow a stringent bound on lepton universality violations:

\[ \frac{B(B^0 \rightarrow D^*^- e^+ \nu)}{B(B^0 \rightarrow D^*^- \mu^+ \nu)} = 1.01 \pm 0.01 \pm 0.03 \]
FEI reconstruction performance at Belle II

Use 0.41 fb$^{-1}$ of measured data and 10 fb$^{-1}$ of MC to evaluate the hadronic FEI performance in the Belle II setup.

- Output of the classifier shows good agreement with the expectation, and allows a high purity selection.
- However, signal extends over a wide range showing the trade-off between efficiency and purity to consider.

Beam-constrained mass $m_{bc} = \sqrt{(0.5 \times E_{Beam})^2 - \vec{p}_B^2}$ measures reconstruction quality.
To later calibrate the FEI, after making a selection on the classifier a signal mode is reconstructed by selecting a lepton and summing up the remaining particles.
Belle II untagged analysis of $\bar{B}^0 \to D^{*+} \ell^- \nu$

- Use $0.41 fb^{-1}$ of early data for a first analysis

- Reconstruct $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$

- Difference between initial state and sum of final states, needs precise knowledge of beam state:
  \[ m_{miss}^2 = \left( \frac{P_{Beam}}{2} - p_{D^* \ell} \right)^2 \]

- No particle ID requirements for hadrons

- The reconstruction and fit already show a clear signal peak to later extract the branching fraction
Conclusion

- Belle still produces new interesting results years after ending data taking.
- Belle II taking data and analyses on the way.

Thank you for your attention!