Exclusive Semi-leptonic Decays at Belle II

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(on behalf of the Belle II Collaboration)

CKM2021
25.11.21
SuperKEKB

- $e^+e^-$ collider with $\sqrt{s} = 10.58$ GeV, the $\Upsilon(4S)$ resonance
- Peak luminosity of $3.1 \times 10^{34}/\text{cm}^2/\text{sec}$ reached in June of this year – new world record!
  - ~50% increase from KEKB record luminosity
- Record luminosity largely due to new nano-beam scheme and doubling of beam currents
The Belle II Detector

- **EM Calorimeter**: Cs(Tl), waveform sampling electronics
  - Electrons (7 GeV)

- **Vertex Detector**: 2 layers Si Pixels (DEPFET) + 4 layers Si double sided strip DSSD

- **Central Drift Chamber**: Smaller cell size, long lever arm

- **KL and muon detector**: Resistive Plate Counter (barrel outer layers) + Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

- **Particle Identification**: Time-of-Propagation counter (barrel) + Prox. focusing Aerogel RICH (forward)
  - Positrons (4 GeV)

Belle II TDR, arXiv:1011.0352
Belle II Data-taking: Status and Outlook

- Collected over 231 fb\(^{-1}\) of data thus far
  - Dataset size comparable to Belle targeted for end of 2022, of order 800 fb\(^{-1}\)
  - Long-term: 50 ab\(^{-1}\) (50 x Belle dataset) by end of experiment
Belle II Data-taking: Status and Outlook

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LS1 = Long Shutdown 1
Motivation: Exclusive Semi-leptonic Decays

- Precision measurements of CKM matrix elements key for testing unitarity condition, particularly for $|V_{ub}|$, which forms dominant uncertainty
- Exclusive semi-leptonic decays golden modes for measurements of $|V_{ub}|$ and $|V_{cb}|$, e.g. $B \rightarrow \pi \ell \nu_\ell$, $B \rightarrow D^{(*)}\ell \nu_\ell$
- Existing tension between $|V_{ub}|$ and $|V_{cb}|$ from inclusive vs. exclusive approaches, each of order $\sim 3\sigma$
- Projected Belle II dataset will be significant in resolving this tension and improving precision
Reconstruction Methods for Exclusive Semi-leptonic Decays at Belle II

- **Untagged (inclusive tagged) approaches:**
  - Reconstruct signal decay of interest
  - All remaining particles in event assigned to inclusive tag
  - Highly efficient but low purity, selection optimisation key

- **Tagged approaches:**
  - Reconstruct both signal $B$ decay and other $B$-meson in event (tag)
  - Tag can be hadronic or semi-leptonic
  - Unique advantage of hadronic tagging for semi-leptonic signal decays → missing neutrino momentum can be determined
Untagged $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$

- Here, $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K \pi^+$, with $\Delta m_{(D^*,D)} \in [0.144, 0.148]$ GeV/c$^2$
- Signal extraction via distribution of $\cos(\theta_{BY})$: cosine of angle between flight directions of $B$-meson and combined $D^{*-}\ell$ system ($Y$)
- Branching fraction consistent with PDG, but large systematic uncertainty due to slow pion tracking
- Next steps: Extract $|V_{cb}|$ from fits to $\cos(\theta_{BY})$ in bins of hadronic recoil parameter, $w$

$$\cos \theta_{BY} = \frac{2 E_B^* E_Y^* - m_B^2 - m_Y^2}{2 |p_B^*||p_Y^*|}$$

$\mathcal{B} (\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell) = (4.60 \pm 0.05_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.45_{\pi s})\%$

PDG: $(5.05 \pm 0.14)\%$
Untagged $B^- \to D^0 \ell^- \bar{\nu}_\ell$

- Signal extraction via distribution of $\cos(\theta_{BY})$: cosine of angle between flight directions of $B$-meson and combined $D$-$\ell$ system ($Y$)
- Large backgrounds from $B \to D^* \ell \nu_\ell$ decays reduced via dedicated veto
- Competitive branching fraction measurement, consistent with PDG
- Next steps: Extract $|V_{cb}|$ from fits to $\cos(\theta_{BY})$ in bins of hadronic recoil parameter, $w$

$$\cos \theta_{BY} = \frac{2E_B^*E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|}$$

$B(B^- \to D^0 \ell^- \bar{\nu}_\ell) = (2.29 \pm 0.05_{stat} \pm 0.08_{syst})\%$

PDG: $(2.35 \pm 0.03_{stat} \pm 0.09_{syst})\%$
Tagged Analysis at Belle II: Full Event Interpretation

- Multi-variate analysis technique for reconstructing $B$-tags via over 4000 unique decay chains
- Includes both hadronic and semi-leptonic tagging functionality

![Graphs and data](image)

- Selection on final classifier output $P_{\text{tag}}$ provides good signal-background discrimination

\[ M_{bc} = \sqrt{E_{\text{CM}}^2 - \left| p_{B_{\text{tag}}} \right|^2} \]
Hadronic Tagged $\bar{B}^0 \rightarrow D^*+\ell^-\bar{\nu}_\ell$

- Here, $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K\pi^+$, with $\Delta m_{(D^*,D)} \in [0.143, 0.148]$ GeV/$c^2$
- Hadronic tag reconstructed recoiling against signal $B$-meson, whilst satisfying an optimal selection on the FEI classifier output
- Events with tracks remaining after $\Upsilon(4S)$ reconstruction excluded
- Signal extraction via distribution of $m^2_{miss}$, the square of the missing four-momentum in the event
- Branching fraction consistent with PDG, with dominant systematic uncertainty due to slow pion tracking

\[
m^2_{miss} = \left(p_e^+ e^- - p_{B_{tag}} - p_{D^*} - p_\ell\right)^2
\]

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

PDG: $(5.05 \pm 0.14)\%$

25.11.2021 Nadia Toutounji: Exclusive semi-leptonic decays at Belle II The University of Sydney
Hadronic Tagged $B \rightarrow \pi \ell \nu_\ell$

- Hadronic tag selected satisfying minimum threshold on FEI classifier output
- Events with tracks remaining after $\Upsilon(4S)$ reconstruction excluded
- Signal extraction via distribution of $m^2_{\text{miss}}$
- $B^+ \rightarrow \pi^0 \ell \nu_\ell$: Branching fraction consistent with PDG, dominant systematic uncertainties from calibration of FEI algorithm and $\pi^0$ reconstruction efficiency

$$m^2_{\text{miss}} = (p_{e^+} - p_{B_{\text{tag}}} - p_{\pi} - p_\ell)^2$$

PDG: $(7.80 \pm 0.27) \times 10^{-5}$

Belle II Preliminary $\int \mathcal{L} \, dt = 62.8 \, \text{fb}^{-1}$
Hadronic Tagged $B \to \pi \ell \nu_\ell$

- For $B^0 \to \pi \ell \nu_\ell$, signal extraction via 3 bins of the square of the 4-momentum transfer to the leptonic system, $q^2$
- Branching fraction consistent with PDG, dominant systematic uncertainty due to calibration of FEI algorithm

- Next steps: $|V_{ub}|$ extraction
- Semi-leptonic tagged and untagged $B \to \pi \ell \nu_\ell$ in progress

$$m_{\text{miss}}^2 = \left( p_{e^+} - p_{B_{\text{tag}}} - p_\pi - p_\ell \right)^2$$

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = \left(1.47 \pm 0.29\text{(stat)} \pm 0.05\text{(syst)}\right) \times 10^{-4}$$

(from sum of partial branching fractions in 3 $q^2$ bins)

PDG: $(1.50 \pm 0.06) \times 10^{-4}$
First Results: Hadronic Tagged $B \rightarrow \rho \ell \nu_{\ell}$

- Hadronic tag selected satisfying minimum threshold on FEI classifier output
- $\rho$-meson selected within mass window $M_{\pi\pi} \in [0.333, 1.217]$ GeV/c$^2$
- Events with tracks remaining after $\Upsilon(4S)$ reconstruction excluded
- Signal extraction via distribution of $m_{miss}^2$
- Next steps: 2-dimensional signal extraction via $m_{miss}^2$ and $M_{\pi\pi}$ to constrain backgrounds

Due to low signal significance at this sample size (< 2$\sigma$), 95% CL upper limits on branching fractions quoted at present:

\[ B(B^0 \rightarrow \rho^- \ell^+ \nu_{\ell}) < 3.37 \times 10^{-4} \]
\[ B(B^+ \rightarrow \rho^0 \ell^+ \nu_{\ell}) < 1.97 \times 10^{-4} \]

PDG:

- $(2.94 \pm 0.11 \pm 0.18) \times 10^{-4}$
- $(1.58 \pm 0.11) \times 10^{-4}$
Prospects for $|V_{ub}|$ and $|V_{cb}|$ with Exclusive Semi-leptonic Decays

- Dominant uncertainty in unitarity triangle fits due to $|V_{ub}|$
- Belle II simulation: potential to reduce uncertainty on $|V_{ub}|$ by a factor of 2 (untagged) at target integrated luminosity
- Improved precision on exclusive $|V_{cb}|$ also anticipated

arXiv:1808.10567
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<table>
<thead>
<tr>
<th>Observables</th>
<th>Expected the. accuracy</th>
<th>Expected exp. uncertainty</th>
<th>Facility (2025)</th>
</tr>
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<tbody>
<tr>
<td>UT angles &amp; sides</td>
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<tr>
<td>$\phi_1$ deg</td>
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<td>$\phi_2$ deg</td>
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<td>$ incl.</td>
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<td>$</td>
<td>V_{cb}</td>
<td>$ excl.</td>
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The Belle II Physics Book (for target 50 ab$^{-1}$)
Summary

• Exclusive semi-leptonic $B$-meson decays are golden modes for extractions of CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$

• With large projected dataset and improved detector, Belle II aims to increase precision of these measurements and resolve tension between inclusive and exclusive results

• Multiple studies of exclusive semi-leptonic decays underway using various analysis approaches, with first $|V_{ub}|$ and $|V_{cb}|$ measurements planned for 2022

• Related topics: - Inclusive semi-leptonic decays (Raynette van Tonder)
  - Exclusive semi-leptonic decays involving $\tau$ leptons (Racha Cheaib)
Back-up
First Results: Hadronic Tagged $B \rightarrow \rho \ell \nu_{\ell}$

<table>
<thead>
<tr>
<th></th>
<th>$B^0 \rightarrow \rho^- \ell^+ \nu_{\ell}$</th>
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</thead>
<tbody>
<tr>
<td>$N^{\text{data}}_{\text{sig}}$</td>
<td>$11.0 \pm 8.3$</td>
<td>$13.7 \pm 9.4$</td>
</tr>
<tr>
<td>$\mathcal{B}$</td>
<td>$(1.51 \pm 1.13\text{(stat)} \pm 0.09\text{(syst)}) \times 10^{-4}$</td>
<td>$(9.26 \pm 6.33\text{(stat)} \pm 0.38\text{(syst)}) \times 10^{-5}$</td>
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<tr>
<td>95% CL limit</td>
<td>$&lt; 3.37 \times 10^{-4}$</td>
<td>$&lt; 19.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\mathcal{B}_{\text{PDG}}$</td>
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