Exclusive semileptonic decays at Belle II

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Semileptonic decays

- **SM precision measurements**
  - Semileptonic decays used to measure the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$

- **Potential probes of new physics**
  - $\sim 3\sigma$ discrepancy from SM in measurements of ratios

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_{\tau})}{\mathcal{B}(B \to D^{(*)}\ell\nu_{\ell})} \ (\ell = \mu, e)$$

$$q^2 = (p_{\ell} + p_{\nu})^2$$
Status of $|V_{cb}|$ and $|V_{ub}|$

- **Exclusive**: Reconstruct specific final states
  - Measure all visible final state particles

- *i.e.*:
  - $|V_{cb}| : B \rightarrow D(*)\ell\nu$
  - $|V_{ub}| : B \rightarrow \pi\ell\nu$

- **Theoretical**: Lattice QCD
  - $\rightarrow$ covered today

- **Inclusive**: Measure general $X\ell\nu$ decay
  - Measure some particles in decay
  - Assign remaining unmeasured parts to $X$

- *i.e.*:
  - $|V_{cb}| : B \rightarrow X_c\ell\nu$
  - $|V_{ub}| : B \rightarrow X_u\ell\nu$

- **Theoretical**: HQET
  - $\rightarrow$ talk by Frank Meier on Tuesday
Status of $|V_{cb}|$ and $|V_{ub}|$

- $\sim 3.3\sigma$ discrepancy between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ measurements
SuperKEKB and Belle II

**SuperKEKB:**
- $e^+e^-$ collider at 10.58 GeV, the $\Upsilon(4S)$ resonance
- Peak luminosity reached: $4.71 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, June 22, 2022
  - World record!
  - > 100% increase over KEKB (Belle)

**Belle II:**
- Hermetic detector
  - 3-dimensional missing momentum measurements
  - Important for studying events with missing energy
- Particle identification
  - $\mu$ ID superior to Belle
  - $e$ and $K$ ID not at Belle level yet but improving
  - high $\gamma$ detection efficiency
Luminosity

- Data-taking since 2019
- With June 2022 went into Long Shutdown 1
- Recorded data up until LS1: 424 fb\(^{-1}\) (BaBar: 425 fb\(^{-1}\), Belle: 711 fb\(^{-1}\))
- Current results: 189 fb\(^{-1}\)
- Long term goal 50 ab\(^{-1}\) by > 2030
Untagged vs Tagged

**Untagged**
- Reconstruct only $B_{\text{sig}}$
- High efficiency, high backgrounds

**Tagged**
- $B_{\text{sig}}$ and $B_{\text{tag}}$ are reconstructed
- Tag can be hadronic or semileptonic
- Precisely determine missing neutrino momentum

**Terminology**
- **Untagged - Tagged**
  - Only one or both $B$ mesons reconstructed per event
- **Exclusive - Inclusive**
  - Reconstruction of $B_{\text{sig}} \rightarrow$ specific decay or $B_{\text{sig}} \rightarrow X\ell\nu$
Full Event Interpretation algorithm [Comput Softw Big Sci 3, 6 (2019)] to reconstruct $B_{tag}$

- Reconstruct $B$ candidate with all combination of daughters
- Calculate signal probability with multivariate classifiers

**Hadronic FEI**

- Over 200 BDTs to reconstruct $O(10000)$ distinct decay chains
- $\epsilon_{B^+} \approx 0.5\%$, $\epsilon_{B^0} \approx 0.3\%$ at $\sim 15\%$ purity
- $\sim 50\%$ increase over Belle tag

\[ M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{tag}}^{cm})^2} > 5.27 \text{ GeV/c}^2 \]
Featured analyses with 189 fb$^{-1}$

- **Exclusive CKM measurements**
  
  | Analyses covered | $|V_{ub}|$ | $|V_{cb}|$ |
  |------------------|----------|----------|
  | Unagged $B \rightarrow \pi \ell \nu$ (2022) | $B \rightarrow D \ell \nu$ (2022) |
  | Tagged $B \rightarrow \pi e \nu$ (2022) | $B \rightarrow D^* \ell \nu$ (2022) |

- **Branching ratio measurements**
  
  - Tagged $\mathcal{B}(B \rightarrow \rho \ell \nu)$ (2022)
Untagged $|V_{ub}|$ via $B \rightarrow \pi \ell \nu$

- Reconstruct $B^0 \rightarrow \pi^\pm \ell \nu$ with $\ell = (e, \mu)$
- Main challenge: large backgrounds from continuum and other semileptonic decays
- Separate boosted decision trees to suppress background
- Signal extraction via binned 2D fit using $\Delta E$ and $M_{bc}$

$$\Delta E = E^*_B - E^*_\text{beam}$$
$$M_{bc} = \sqrt{(E^*_\text{beam})^2 - (p^*_B)^2}$$
Untagged $|V_{ub}|$ via $B \rightarrow \pi \ell \nu$

- Momentum transfer $q^2 = (p_B - p_\pi)^2 = (p_\ell + p_\nu)^2$
  - important parameter for $|V_{ub}|$ extraction

- Untagged analysis: $p_B$ not known, estimated with new method (extension of BABAR’s diamond frame [Phys. Rev. D 74, 092004]):
  - Calculate angle between $B$ meson and combined $\pi \ell = Y$
    $$\cos \theta_{BY} = \frac{2 E^*_B E^*_Y - m^2_B - m^2_Y}{2 |p^*_B||p^*_Y|}$$
  - Calculate Rest of Event (ROE) momentum $p_{ROE}$
  - Likely direction on $\cos \theta_{BY}$ cone: close to back-to-back of $p_{ROE}$
  - Build weighted average over 10 uniformly distributed vectors on cone with weights

$$\frac{1}{2} (1 - \hat{p}_{ROE} \cdot \hat{p}_B) \sin^2 \theta_B$$
Untagged $|V_{ub}|$ via $B \to \pi \ell \nu$

- Differential branching ratios dependent on $|V_{ub}|$ and $q^2$

$$
\frac{d\mathcal{B}(B \to \pi \ell \nu)}{dq^2} \propto |V_{ub}|^2 \times f_+(q^2)
$$

- To extract $|V_{ub}|$ partial branching fractions measured with independent fits in 6 $q^2$ bins

**Post-Fit**

<table>
<thead>
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<th>Bin</th>
<th>$[q_{min}^2, q_{max}^2]$ [GeV$^2$]</th>
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<td>4</td>
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<td>5</td>
<td>[16,20]</td>
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<tr>
<td>6</td>
<td>[20,\infty]</td>
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</table>
Untagged $|V_{ub}|$ via $B \to \pi \ell \nu$

- Combine $e$ and $\mu$ spectra in weighted average
- Fit partial branching ratios to BCL expansion [Phys. Rev. D 79, 013008] to determine $|V_{ub}|$
- FNAL/MILC [Phys. Rev. D 92, 014024] Lattice QCD constraints included as nuisance parameters

![Graph showing $B(B^0 \to \pi^- \ell^+ \nu_\ell)$ distribution with error bands and fit curve.]

$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.42 \pm 0.06_{\text{stat}} \pm 0.13_{\text{sys}}) \times 10^{-4}$,

PDG: $(1.50 \pm 0.06) \times 10^{-4}$

$|V_{ub}| = (3.54 \pm 0.12_{\text{stat}} \pm 0.15_{\text{sys}} \pm 0.16_{\text{theo}}) \times 10^{-3}$

World-average exclusive $\pi \ell \nu$: $(3.67 \pm 0.15) \times 10^{-3}$ [arXiv:2206.07501]
Reconstruct $B^0 \rightarrow \pi^\pm e^+\nu_e$ and $B^\pm \rightarrow \pi^0 e^+\nu_e$

Hadronic FEI

Clean $q^2$ reconstruction thanks to tag: $q^2 = (p_{e^+e^-} - p_{B_{tag}} - p_{\pi})^2$

Fit $M_{miss}^2 = (p_{e^+e^-} - p_{B_{tag}} - p_e - p_{\pi})^2$ in 3 $q^2$ bins
Tagged $|V_{ub}|$ via $B \to \pi e\nu$

- Fit partial branching ratios to BCL expansion [Phys. Rev. D 79, 013008] to determine $|V_{ub}|$
- FNAL/MILC [Phys. Rev. D 92, 014024] Lattice QCD constraints included as nuisance parameters

$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$$

World-average exclusive $\pi \ell \nu$: [arXiv:2206.07501]

$$(3.67 \pm 0.15) \times 10^{-3}$$

- Leading systematic: Tag calibration factor
Tagged $B(B \to \rho \ell \nu)$

- Tagged measurement of $B^0 \to \rho^{\pm} \ell \nu$ and $B^\pm \to \rho^0 \ell \nu$ with $\rho \to \pi \pi$
  - Potential new avenue to measure $|V_{ub}|$ with independent sample
  - Previously observed tensions in both $\rho^{\pm}$ and $\rho^0$ modes

- 2-dimensional fit in $M_{\pi \pi}$ and $M_{miss}^2$ to measure branching fractions

- BDT to suppress continuum background

\[ B(B^0 \to \rho^- \ell^+ \nu_\ell) = (4.12 ± 0.64^{\text{stat}} ± 1.16^{\text{sys}}) \times 10^{-4}, \]
PDG: $(2.94 ± 0.11 ± 0.18) \times 10^{-4}$

\[ B(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.77 ± 0.23^{\text{stat}} ± 0.36^{\text{sys}}) \times 10^{-4} \]
PDG: $(1.58 ± 0.11) \times 10^{-4}$

- Large systematic from $B \to \pi \pi \ell \nu$ background
Untagged $|V_{cb}|$ via $B \to D \ell \nu$

- Reconstruct $B^\pm \to D^0 \ell \nu$ and $B^0 \to D^\pm \ell \nu$ with $\ell = (e, \mu)$ and $D \to K\pi(\pi)$
- Main challenge: large backgrounds from $D^* \ell \nu$
- Signal extraction via 1 dimensional fit of angle between $B$ and $Y(D\ell)$
  - Only between -1 and 1 for signal
  $$\cos \theta_{BY} = \frac{2 E_B^* E_Y^* - m_B^2 - m_Y^2}{2 |p_B^*||p_Y^*|}$$
- $D^*$ veto to reduce $B \to D^* \ell \nu$ candidates
  - Reconstruct slow pion $\pi_s$ with $p < 0.35$ GeV
  - If $\pi_s$ and $D$ candidate can be combined to $D^*$ with $m_{D^*} - m_D \in [140, 150]$ MeV $\to$ veto event

Belle II Preliminary $\int L \, dt = 189.2$ fb$^{-1}$
Untagged $|V_{cb}|$ via $B \to D\ell\nu$

- Differential decay width proportional to $V_{cb}$ and hadronic recoil $w$
  \[
  \frac{d\Gamma}{dw}(B \to D\ell\nu) = \frac{G_F^2}{48\pi^3}(m_B + m_D)^2 m_D^3 \eta_{EW} |V_{cb}|^2 (w^2 - 1)^{3/2} G(w)^2,
  \]
  
- with $w = \frac{P_B \cdot P_D}{m_B m_D} = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}$ and form factor $G(w)$
- Fit form factor to differential decay rates in 10 bins of $w$
- BGL ($N=3$) parametrization [Phys. Rev. D 56, 6895 (1997)]

\[
|V_{cb}| = (38.3 \pm 1.2) \times 10^{-3}
\]
World-average exclusive $D\ell\nu$: [arXiv:2206.07501]

\[
(39.14 \pm 0.92_{\text{exp}} \pm 0.36_{\text{th}}) \times 10^{-3}
\]

- Consistent with the exclusive world average
- $\sim 3\%$ error, comparable to the past measurements
Tagged $|V_{cb}|$ via $B \rightarrow D^* \ell \nu$

- Tagged measurement of $B^0 \rightarrow D^{*\pm} \ell \nu$ with $\ell = (e, \mu)$, $D^{*-} \rightarrow D^0 \pi_-^-$ and $D^0 \rightarrow K^- \pi^+$
- High signal purity thanks to tagging and clean signature of $D^* \ell \nu$ mode
- Fit $m_{miss}^2$ in 10 bins of $w$
Tagged $|V_{cb}|$ via $B \rightarrow D^* \ell \nu$

- Fit CLN parametrized form factor [NPB530, 153 (1998)] to differential decay rates

![Graph showing differential decay rates vs. $w$]

$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$

World-average exclusive $D^* \ell \nu$: [arXiv:2206.07501]

$(38.46 \pm 0.40_{\text{exp}} \pm 0.55_{\text{th}}) \times 10^{-3}$

- Major systematic errors: slow $\pi$ efficiency and tag calibration
Improved measurements of $|V_{cb}|$ and $|V_{ub}|$ are essential to increase the constraining power of the Unitarity triangle fit

First exclusive measurements of $|V_{cb}|$ and $|V_{ub}|$ at Belle II with 189 fb$^{-1}$

Results are in agreement with previous results and approaching their precision

Soon: $|V_{cb}|$ from untagged $D^*\ell\nu$, $A_{fb}$ in $D^*\ell\nu$, first $R(D^*)$ results and many more!

Related talks:
- Frank Meier: Belle II results on inclusive $B \to X\ell\nu$
- Koji Hara: LFU measurements in semileptonic $b \to c\ell\nu$ decays