CKM measurements at the Belle II experiment

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On behalf of Belle II Collaboration

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CKM matrix and unitarity triangle (UT)

\[
V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A^2 \lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

Complex phase cause CP violation

\[V^\dagger V = 1 \rightarrow \textbf{b row \ d column}\]

- \[\phi_1 = \arg \left( \frac{V_{ub} V_{ud}^*}{V_{ud} V_{ub}^*} \right)\]
- \[\phi_2 = \arg \left( \frac{V_{td} V_{tb}^*}{V_{tb} V_{td}^*} \right)\]
- \[\phi_3 = \arg \left( \frac{V_{cd} V_{cb}^*}{V_{cb} V_{cd}^*} \right)\]

Search for NP with different processes (tree, loop diagrams) by precise measurement of UT

- Comprehensive test (only Belle II)
  - Measure all sides and angles

- \[V_{ub} V_{ud} + V_{cb} V_{cd} + V_{tb} V_{td} = 0\]

- \[\lambda^3 \cdot 1 \quad \lambda^2 \cdot \lambda \quad 1 \cdot \lambda^3\]
The Belle II detector

**Level-1 trigger system**
CDC+ECL+TOP+KLM
L1 trigger latency 5 μsec

**Data acquisition (DAQ) system**
Maximum 30 kHz L1 trigger
1MB/event

**Computing system**
GRID
Tens of PB / year

**Vertex detector (VXD)**
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)

**Central Drift Chamber (CDC)**
He (50%), C₂H₆ (50%), small cells, long lever arm

**ElectroMagnetic Calorimeter (ECL)**
Barrel: CsI(Tl) + waveform sampling
Endcap: pure CsI + waveform sampling

**Particle Identification**
Barrel: Time-Of-Propagation counters (TOP)
Forward: Aerogel RICH (ARICH)

**K_π/μ detector (KLM)**
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator
This talk focuses on: measurements of $|V_{cb}|$, $|V_{ub}|$ and $\phi_1, \phi_3$.

Data-set used for the analyses present in this talk:
- 34.6 fb$^{-1}$ ($|V_{cb}|$, $|V_{ub}|$, $\phi_1$)
- 62.8 fb$^{-1}$ ($\phi_3$)

$\phi_1$: details in Radek Zlebcik’s talk “Rediscovery of the decays for the CP violation measurements at Belle II” on 10 June

$\phi_2$: Ching-hua Li’s talk “Charmless B decays at Belle II” on 10 June
**B decay reconstruction at Belle II**

### Data

\[ \int \mathcal{L} dt = 34.6 \text{ fb}^{-1} \]

- **Untag**: only reconstruct signal B decay
- **Tag**: reconstruct signal B decay, also the other side B

### Belle II preliminary

![Graph showing candidates](image)

- Baryonic
- \( \psi \)
- \( D^0 \)
- \( D^{*} \)
- \( D^+ \pi^- \)
- \( D^- n \pi^- \)
- \( D^- \pi^+ \)
- \( D^0 m \pi^- \)
- \( D^+ \pi^- \)
- \( K_S \)
- \( K^- \)
- \( \pi^+ \)
- \( \pi^- \)
- \( \tau^- \)
- \( \nu_{\tau} \)

### Reconstruction

- **Signal side reconstruction**
- **Tag side reconstruction**

**Reconstruct ~100 hadronic decay channels, ~10000 decay chains**

- \( \varepsilon = 0.47\% \) for \( B^\pm \) @ purity ~30\%
- \( \varepsilon = 0.29\% \) for \( B^0 \) @ purity ~20\%

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**arXiv: 1807.08680**

**arXiv:2008.06096**

**BELLE2-CONF-PH-2020-005**

**BELLE2-CONF-PH-2021-005**

**BELLE2-CONF-PH-2021-009**

\[ M_{bc} = \sqrt{(E^*_{beam})^2 - (p_B^*)^2} \]
BF$(B \rightarrow D^* l \nu)$ for $|V_{cb}|$

\[ \mathcal{B}(B \rightarrow D^* l \nu) \]

hadronic tag

untagged

PLAN:
Form factor determination rely heavily on $w = 1$ (zero recoil)

Unfolded $w$ spectrum to compare with BGL parameterization

Similar plots for the $B \rightarrow D^* \nu$ channel
BF($B^0 \to \pi l \nu$) and BF($B \to X_u l \nu$) for $|V_{ub}|$

$|V_{ub}|$ determination from exclusive and inclusive measurements differ by $\sim 2\sigma$

**Measurement of $B(\bar{B}^0 \to \pi l \nu)$ based on hadronic tag**


BELLE2-CONF-PH-2020-007

**Untagged Inclusive $B \to X_u l \nu$ measurement**

- lepton momentum endpoint
- less $B \to X_c l \nu$ (dominant background)

BELLE2-NOTE-PL-2020-026

**Next target: $q^2$ distribution for $|V_{ub}|$ determination**

$\mathcal{B}(\bar{B}^0 \to \pi l^+ \nu) = (1.58 \pm 0.43 \text{(stat)} \pm 0.07 \text{ (sys)}) \times 10^{-4}$

$\mathcal{B}(\bar{B}^0 \to \pi l^+ \nu) = (1.50 \pm 0.06) \times 10^{-4}$ (PDG)

**Agreement**

Capable of measuring $|V_{ub}|$ with more data
### Prospects of $|V_{ub}|$ and $|V_{cb}|$

**Side** | **Observable** | **Dominant uncertainties**
--- | --- | ---
$|V_{td}|$ | $\Delta m_d$: $B\bar{B}$ mixing frequency | Lattice QCD ($|V_{td}|$ now is mainly limited by lattice QCD)
$|V_{cb}|$ | $Br(b \rightarrow cl\nu)$ | Exclusive: lattice QCD
**Inclusive: experiment vs. phenomenology**
$|V_{ub}|$ | $Br(b \rightarrow ul\nu)$ | Inclusive: experiment vs. phenomenology

### Table

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle (2017)</th>
<th>Belle II 5 ab(^{-1})</th>
<th>Belle II 50 ab(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ incl.</td>
<td>$42.2 \cdot 10^{-3}$ · (1 ± 1.8%)</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ excl.</td>
<td>$39.0 \cdot 10^{-3}$ · (1 ± 3.0%(<em>{\text{ex.}}) ± 1.4%(</em>{\text{th.}}))</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ incl.</td>
<td>$4.47 \cdot 10^{-3}$ · (1 ± 6.0%(<em>{\text{ex.}}) ± 2.5%(</em>{\text{th.}}))</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ excl. (WA)</td>
<td>$3.65 \cdot 10^{-3}$ · (1 ± 2.5%(<em>{\text{ex.}}) ± 3.0%(</em>{\text{th.}}))</td>
</tr>
</tbody>
</table>
Time dependent CPV - Flavor tagging

TDCPV measurement:
• Precise measurement of $\Delta t$
• $B$ flavor tagger

$\Delta t = \Delta z / \beta \gamma c$
$\Delta z \sim 130$ um

Effective flavor tagging efficiency:
• Belle II : (33.8 ± 3.9)%
• Belle : (30.1 ± 0.4)%
• Belle II MC : ~37%

Details in Radek Zlebcik’s “talk” on 10 June
Measurement of $\sin(2\phi_1)$

- $b \rightarrow c$: tree diagram dominated golden modes $B^0 \rightarrow J/\psi K^0, B^0 \rightarrow \psi(2S)K^0$…
- Theoretically and experimentally precise channel

\[
P(\Delta t, q) = \frac{e^{-|\Delta t|\tau_{B^0}}}{4\tau_{B^0}} (1 + (1 - 2\omega)q[S_f \sin(\Delta m \Delta t) + A_f \cos(\Delta m \Delta t)])
\]

$S_f$: indirect (time dependent) CPV parameter

$A_f$: direct CP violating asymmetry assumed zero

$\phi_1$: details with more new results in Radek Zlebcik’s “talk” on 10 June

Precision aimed at Belle II for $\sin(2\phi_1)$:
reduce uncertainty by factor ~5 to reach to 5%

$\sin(2\phi_1) \approx S_f = 0.55 \pm 0.21 \text{ (stat.)} \pm 0.04 \text{ (syst.)}$

$\sin(2\phi_1) = 0.699 \pm 0.017 \text{ (world average)}$
Foreseen precision of $\phi_3$ is expected to be $1.6^\circ$ with 50 ab$^{-1}$ dataset
Unitarity Triangle fit extrapolation at Belle II

Standard model (SM) scenario: the central values are chosen such that they satisfy the SM (closed UT)

- Tensions existed on $|V_{ub}|$ and $\phi_1$
- UT cannot close if keeping the central value for 50 ab$^{-1}$
- Differences between UT determined by tree ($|V_{ub}|$, $\phi_3$) and loop ($\phi_1$, $\phi_2$) can be discriminated with 50 ab$^{-1}$ data-set
Summary and prospects

- Super B-factory offers good probe for testing SM and searching for NP at luminosity frontier.

- Belle II will play a key role for CKM measurements.
  - First BF measurements of semileptonic B decays with had. tagged/untagged techniques for $|V_{cb}|$ and $|V_{ub}|$.
  - First sin$2\phi_1$ result has agreement with W.A, aim 5% precision at Belle II.
  - Decay rate ratio of $B\rightarrow DK/B\rightarrow D\pi$ was performed for determination of $\phi_3$.

- Looking forward for more interesting results from Belle II.

Stay tuned!
Backup
Belle II - LHCb comparison

\[ R_\Delta(*) \]

\[ |V_{ub}| \]

\[ \sin(2\phi_1) \]

\[ \phi_3 \]
Hadronic mass moments of inclusive $B \to X_{c\ell}\nu$ with hadronic tag

BELLE2-CONF-PH-2020-011

$|V_{cb}|$ calculated based on the parameters extracted from $p^*l$ vs $\langle M_X^n \rangle$ distributions

A new method proposed in JHEP02 (2019)177 to extract $|V_{cb}|$ from $q^2$ vs $\langle q^2 \rangle_X$ distributions

Targeting a publication this summer

Moments dependence on the lepton momentum cut
$\sin(2\phi_1)$ with QCD penguin

- $b\to qqs$ : QCD penguin dominated contribution, sensitive to New Physics
  - Golden mode, e.g. $B\to \eta'K$ decays
- $\sin(2\phi_1)$ measured by $b\to s$ and $b\to c$ processes used to have $\sim 3.8\sigma$ tension, however now it was reduced to rather small
- Only rediscovery and BR measurement (CP measurement not done yet)

$B^\pm\to \eta'K^\pm$ with $\eta'\to \eta\pi^+\pi^-$ or $\eta'\to \rho\gamma$

$B^0\to \eta'K_S$ with $\eta'\to \eta\pi^+\pi^-$ or $\eta'\to \rho\gamma$

<table>
<thead>
<tr>
<th>Channel</th>
<th>This analysis</th>
<th>World average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to \eta'K$</td>
<td>$68.2^{+3.6}_{-3.5}(\text{stat}) \pm 3.4(\text{syst})$</td>
<td>$70.6 \pm 2.5$</td>
</tr>
<tr>
<td>$B^0 \to \eta'K^0$</td>
<td>$63.7^{+5.9}_{-5.5}(\text{stat}) \pm 5.8(\text{syst})$</td>
<td>$66 \pm 4$</td>
</tr>
</tbody>
</table>
**φ₂ measurement (B → πππ)**

### Diagrams

<table>
<thead>
<tr>
<th>Diagrams</th>
<th>B⁺ → π⁺π⁰</th>
<th>B⁰ → π⁺π⁻</th>
<th>B⁰ → π⁰π⁰</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree</td>
<td>✔</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Color Supp</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penguin</td>
<td></td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

### Constraint for φ₂
- TDCPV parameter S_f and A_f
- Branch fraction of all B → ππ (π⁺π⁻, π⁺π⁰, π⁰π⁰) modes

\[ S_f = \sqrt{1 - A_f^2 \sin(2\phi_2 + 2\Delta\phi_2)} \]

### Penguin pollution

- **Interference between tree and penguin**

### Results

- **Yield**
  - B⁺ → π⁺π⁰: \(43^{+19}_{-20}\)
  - B⁻ → π⁻π⁰: \(24^{+13}_{-14}\)

- **ACP**
  - \(-0.268^{+0.249}_{-0.322} ± 0.123\)
  - (PDG) \(0.03 ± 0.04\)

- **B⁻ → π⁰π⁰ analysis started at Belle II**
  - 8-fold ambiguity of φ₂ can be reduced to 2-fold with TDCPV in B⁰ → π⁰π⁰
**$\phi_2$ measurement ($B \to \rho \rho$)**

\[ \int L \, dt = 62.8 \, fb^{-1} \]

**BELLE2-CONF-DRAFT-2021-005**

![Graph showing $B^+ \to \rho^+ \rho^0$](image)

<table>
<thead>
<tr>
<th></th>
<th>$B^+ \to \rho^+ \rho^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yeild</td>
<td>$104 \pm 16$</td>
</tr>
<tr>
<td>$Br(10^{-6})$</td>
<td>$20.6 \pm 3.2 \pm 3.1$</td>
</tr>
<tr>
<td>PDG</td>
<td>$24.0 \pm 1.9$</td>
</tr>
<tr>
<td>$f_L$</td>
<td>$0.936^{+0.049}_{-0.041} \pm 0.021$</td>
</tr>
<tr>
<td>$f_L$(PDG)</td>
<td>$0.950 \pm 0.016$</td>
</tr>
</tbody>
</table>

$f_L =$ fraction of longitudinally polarized events

- Compatible with PDG value
- Performance superior to early Belle results

- $\Delta \phi_2 \sim 0.6^\circ$ (current 4.2°) with 50 fb$^{-1}$ data
- $B \to \pi \pi, B \to \rho \rho$ isospin analysis and $B \to \rho(\pi \pi) \pi$
  - Dalitz analysis of 3 body decays
- LHCb can not measure $\phi_2$
VXD position resolution

Detector resolution: difference between $d_0$ and beam profile

- $\sigma_x : 14.8 \, \mu m$
- $\sigma_y : 1.5 \, \mu m$

$d_0$ resolution:
- $14.2 \pm 0.1 \, \mu m$ (Data)
- $12.5 \pm 0.1 \, \mu m$ (Simulation)