Determination of the Cabibbo-Kobayashi-Maskawa matrix elements $V_{cb}$ and $V_{ub}$

Christoph Schwanda (Austrian Academy of Sciences)
On behalf of the Belle and Belle II collaborations
The Cabibbo-Kobayashi-Maskawa mechanism
The weak interaction down-type doublet partners are a mixture of the mass (flavour) eigenstates described by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix.

The CKM element magnitudes squared determine the rate of quark flavour transitions in charged current processes.

\(-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} \overline{u_L} i \gamma^\mu (V_{\text{CKM}})_{ij} d_L^j W^\mu_\mu + \text{h.c.}\)

\(V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\)

\(VV^\dagger = V^\dagger V = 1\)
**CP violation**

Wolfenstein parametrization of $V_{\text{CKM}}$

$$V_{\text{CKM}} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)$$

- However, $V_{\text{CKM}}$ also contains a complex phase, responsible for all CP-violating phenomena in the quark sector of the SM, and consistent with observations in $K, D$ and $B$ meson decays so far.
- New physics would typically disturb the SM pattern of CPV.
The CKM unitarity triangle

...and how to probe it with B mesons

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

CPV in \( B \rightarrow \pi\pi, \rho\rho, \rho\pi \)

CPV in \( B \rightarrow J/\psi K_s \)
**Semileptonic $B$ decays**

**Determination of the CKM elements** $|V_{cb}|$ and $|V_{ub}|$

- SL $B$ decays are studied to determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$
  
  - $|V_{xb}|$ are limiting the global constraining power of UT fits
  
  - Important inputs in predictions of SM rates for ultrarare decays such as $B_s \rightarrow \mu\nu$ and $K \rightarrow \pi\nu\nu$
  
- The determinations can be
  
  - *Exclusive* — from a single final state
  
  - *Inclusive* — sensitive to all SL final states

$$d\Gamma \propto G_F^2 |V_{qb}|^2 |L_\mu \langle X |\bar{q}\gamma_\mu P_L b |B\rangle|^2$$

<table>
<thead>
<tr>
<th></th>
<th>Experiment</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>**Exclusive $</td>
<td>V_{cb}</td>
<td>$**</td>
</tr>
<tr>
<td>**Inclusive $</td>
<td>V_{cb}</td>
<td>$**</td>
</tr>
</tbody>
</table>
Determinations of both $|V_{cb}|$ and $|V_{ub}|$ exhibit a discrepancy at the level of $\sim 3\sigma$ between exclusive and inclusive.

The current experimental focus is on understanding the origin of this discrepancy, as this inconsistency limits the power of precision flavour physics.

$$|V_{cb}|_{\text{excl}} = (39.10 \pm 0.50) \times 10^{-3}$$
$$|V_{ub}|_{\text{excl}} = (3.51 \pm 0.12) \times 10^{-3}$$
$$|V_{cb}|_{\text{incl}} = (42.19 \pm 0.78) \times 10^{-3}$$
$$|V_{ub}|_{\text{incl}} = (4.19 \pm 0.17) \times 10^{-3}$$

[PRD 107, 052008 (2023)]
The facilities
1999 – 2010: B factory at KEK (Japan)

KEKB double ring e+e- collider

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

Belle detector
The Belle detector

- SC solenoid
  - 1.5T
- CsI(Tl)
- $16X_0$
- TOF counter
- 8 GeV $e^-$
- Si vtx. det.
  - 3(4) lyr. DSSD
- Central Drift Chamber
- small cell +He/C$_2$H$_5$
- $\mu / K_L$ detection
  - 14/15 lyr. RPC+Fe
- Aerogel Cherenkov cnt.
  - n=1.015~1.030
  - 3.5 GeV $e^+$
Comparison of B factories (1999-2010)

> 1 ab$^{-1}$
On resonance:
$\Upsilon(5S): 121$ fb$^{-1}$
$\Upsilon(4S): 711$ fb$^{-1}$
$\Upsilon(3S): 3$ fb$^{-1}$
$\Upsilon(2S): 24$ fb$^{-1}$
$\Upsilon(1S): 6$ fb$^{-1}$
Off reson./scan: 
$\sim 100$ fb$^{-1}$

$\sim 550$ fb$^{-1}$
On resonance:
$\Upsilon(4S): 433$ fb$^{-1}$
$\Upsilon(3S): 30$ fb$^{-1}$
$\Upsilon(2S): 14$ fb$^{-1}$
Off resonance:
$\sim 54$ fb$^{-1}$
From KEKB to SuperKEKB

Take advantage of existing items (KEKB tunnel, KEKB components)

- New beam pipe & bellows
  TiN-coated beam pipe with antechambers

- Main ring arc and straight section:
  Redesign the lattices of both rings to reduce the emittance

- Main ring arc section:
  LER: Replace all main dipoles
  HER: Preserve the present cells

- KEKB
- Super KEKB

- New design for Near-IR

- Add / modify RF systems for higher beam current

- New beam line Tsukuba section

- New QCS magnet for Nano-beam scheme
  New superconducting / permanent final focusing quads near the IP

- New low emittance e⁻ gun

- Positron damping ring

- New e⁺ source

- New and re-use wiggler magnets are mixed:
  Oho section (LER & HER)
  Nikko section (LER)

$L = 8 \times 10^{-35} \left[ \frac{cm^2 s^{-1}}{s} \right] \times \frac{f_{\delta \xi \eta}}{\beta_y}$. 

[Equation Image]
<table>
<thead>
<tr>
<th>parameters</th>
<th>KEKB LER</th>
<th>KEKB HER</th>
<th>SuperKEKB LER</th>
<th>SuperKEKB HER</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy $E_b$</td>
<td>3.5</td>
<td>8</td>
<td>4</td>
<td>7</td>
<td>GeV</td>
</tr>
<tr>
<td>Half crossing angle $\phi$</td>
<td>11</td>
<td></td>
<td>41.5</td>
<td></td>
<td>mrad</td>
</tr>
<tr>
<td>Horizontal emittance $\varepsilon_x$</td>
<td>18</td>
<td>24</td>
<td>3.2</td>
<td>4.3-4.6</td>
<td>nm</td>
</tr>
<tr>
<td>Emittance ratio $\kappa$</td>
<td>0.88</td>
<td>0.66</td>
<td>0.27</td>
<td>0.25</td>
<td>%</td>
</tr>
<tr>
<td>Beta functions at IP $\beta_x^<em>/\beta_y^</em>$</td>
<td>1200/5.9</td>
<td></td>
<td>32/0.27</td>
<td>25/0.31</td>
<td>mm</td>
</tr>
<tr>
<td>Beam currents $I_b$</td>
<td>1.64</td>
<td>1.19</td>
<td>3.60</td>
<td>2.60</td>
<td>A</td>
</tr>
<tr>
<td>beam-beam parameter $\xi_y$</td>
<td>0.129</td>
<td>0.090</td>
<td>0.0886</td>
<td>0.0830</td>
<td></td>
</tr>
<tr>
<td>Luminosity $L$</td>
<td>$2.1 \times 10^{34}$</td>
<td></td>
<td>$8 \times 10^{35}$</td>
<td></td>
<td>cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>

- **Small beam size & high current** to increase luminosity
- **Large crossing angle**
- **Change beam energies** to solve the problem of LER short lifetime
The Belle II detector

**Central drift chamber**
Spatial resolution ~100µm
\(dE/dx\) resolution: 5%
\(p_T\) resolution: 0.4%

**Vertex detector**
2 layers of DEPFET pixels (PXD) and 4 layers of silicon strips (SVD)
Vertex resolution ~15µm

**Electromagnetic Calorimeter**
Energy resolution: 1.6 - 4%

**KLM**
Instrumented flux return

\(E_{cm} = 10.58\text{ GeV} \) (\(\Upsilon(4S)\) resonance)

KEK
Tsukuba, Japan

4 GeV \(e^+\)
Belle II timeline

Luminosity projection

- Super-KEKB already delivered the world highest instantaneous luminosity at an $e^+e^-$ machine ($4.71 \times 10^{34}$ cm$^{-2}$s$^{-1}$ in June 2022)

We are here
$\mathcal{L}_{\text{recorded}} = 428/fb$

LS1 (2022-23):
PXD2 installation and other maintenance/upgrade of detector & machine

LS2 (2026-27):
SKB IR upgrade VTX installation?

Goal in the mid 2030ies:
$\mathcal{L}_{\text{recorded}} \approx 50/ab$
Untagged vs. Tagged

**Untagged:**
- only $B_{\text{sig}}$ is reconstructed
- high signal yield (+)
- high backgrounds (-)
- poor neutrino reconstruction (-)

**Tagged:**
- $B_{\text{sig}}$ and $B_{\text{tag}}$ are reconstructed
- signal yield $O(10^3)$ lower (-)
- low backgrounds (+)
- good neutrino reconstruction (+)
- tag calibration (-)
Hadronic tagging at Belle II

The hadronic FEI employs over 200 boosted decision trees to reconstruct 10000 B decay chains at low purity (about 50% increase with respect to the Belle tag)

- $\epsilon_{B^+} \approx 0.5\%$, $\epsilon_{B^0} \approx 0.3\%$ at low purity (about 50% increase with respect to the Belle tag)

$$M_{bc} = \sqrt{E_{beam}^2 / 4 - (p_{B_{tag}}^{cm})^2} > 5.27 \text{ GeV}/c^2$$
Exclusive measurements
preliminary [to be submitted to Phys. Rev. D]
Parameterisation of $B \to D^* \ell \nu$

- Three form-factors as function of $w = V_B \cdot V_{D^*}$ parameterise the non-perturbative physics

$$\frac{d^4\Gamma}{dw \cos \theta_\ell d \cos \theta_V d\chi} \propto |V_{cb}|^2 F^2(w, \cos \theta_\ell, \cos \theta_V, \chi)$$

- Form factor parameterisations
    $$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{n_g-1} a_n z^n,$$
    $$f(z) = \frac{1}{P_f(z)\phi_f(z)} \sum_{n=0}^{n_f-1} b_n z^n,$$
    $$F_1(z) = \frac{1}{P_F(z)\phi_F(z)} \sum_{n=0}^{n_F-1} c_n z^n,$$
    $$z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

  $$h_{A_1}(z) = h_{A_1}(w = 1) \left( 1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3 \right)$$
  $$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$
  $$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$
Measurement

- $D^*+ \rightarrow D^0(\rightarrow K^−π^+)π^+$ is reconstructed and combined with an appropriately charged lepton ($e$ or $\mu$)

- The neutrino direction is reconstructed inclusively using the known angle $\cos \theta_{BY}$ between the $B$ and the $Y = D^* + \ell$ direction

  $$\cos \theta_{BY} = \frac{2E_B^{CM}E_Y^{CM} - m_B^2c^4 - m_Y^2c^4}{2|p_B^{CM}||p_Y^{CM}|c^2}$$

- The yield in 10 (8) bins of $w$, $\cos \theta_\ell$, $\cos \theta_V$ and $\chi$ is extracted by fitting $\cos \theta_{BY}$ and $\Delta M = M(Kππ) - M(Kπ)$

- Bin-to-bin migration is corrected with SVD unfolding [arXiv:hep-ph/9509307]

- Main challenges: accurate background model, slow pion tracking and statistical correlations between bins
BGL fit result

BGL truncation order determined by Nested Hypothesis Test [Phys. Rev. D100, 013005]

<table>
<thead>
<tr>
<th>Values</th>
<th>Correlations</th>
<th>$\chi^2$/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{a}_0 \times 10^3$</td>
<td>0.89±0.05</td>
<td>1.00</td>
</tr>
<tr>
<td>$\bar{b}_0 \times 10^3$</td>
<td>0.54±0.01</td>
<td>0.26</td>
</tr>
<tr>
<td>$\bar{b}_1 \times 10^3$</td>
<td>-0.44±0.34</td>
<td>-0.34</td>
</tr>
<tr>
<td>$\bar{c}_1 \times 10^3$</td>
<td>-0.05±0.03</td>
<td>0.07</td>
</tr>
</tbody>
</table>

LQCD used only for normalisation at zero recoil ($w = 1$)

$|V_{cb}|_{BGL} = (40.9 \pm 0.3_{\text{stat}} \pm 1.0_{\text{syst}} \pm 0.6_{\text{theo}}) \times 10^{-3}$

![Belle II plots](image)
Adding LQCD at \( w > 1 \)

LQCD constraints on \( h_A(w) \) at \( w = 1.03, 1.10, 1.17 \)

\[ \text{[Eur. Phys. J. C 82, 1141 (2022)]} \]

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>V_{cb}</td>
</tr>
<tr>
<td>( a_0 \times 10^3 )</td>
<td>22.0 ± 1.4</td>
</tr>
<tr>
<td>( b_0 \times 10^3 )</td>
<td>13.2 ± 0.2</td>
</tr>
<tr>
<td>( b_1 \times 10^3 )</td>
<td>9.0 ± 14.5</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>-0.5 ± 0.4</td>
</tr>
<tr>
<td>( c_1 \times 10^3 )</td>
<td>-0.7 ± 0.8</td>
</tr>
</tbody>
</table>

LQCD constraints on \( h_A(w), R_1(w) \) and \( R_2(w) \) at \( w = 1.03, 1.10, 1.17 \)

\[ \text{[Eur. Phys. J. C 82, 1141 (2022)]} \]

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<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>V_{cb}</td>
</tr>
<tr>
<td>( a_0 \times 10^3 )</td>
<td>28.3 ± 1.0</td>
</tr>
<tr>
<td>( a_1 \times 10^3 )</td>
<td>-31.5 ± 66.6</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>-5.8 ± 2.5</td>
</tr>
<tr>
<td>( b_0 \times 10^3 )</td>
<td>13.3 ± 0.2</td>
</tr>
<tr>
<td>( c_1 \times 10^3 )</td>
<td>-3.2 ± 1.4</td>
</tr>
<tr>
<td>( c_2 \times 10^3 )</td>
<td>59.1 ± 31.1</td>
</tr>
</tbody>
</table>
Summary of the measurement

• Branching fraction

\[ \mathcal{B}(\mathbf{B}^0 \rightarrow \mathbf{D}^{**}\ell^ {-}\nu) = (4.94 \pm 0.02_{\text{stat}} \pm 0.22_{\text{syst}})\% \]

• Value of \( |V_{cb}| \)

\[ |V_{cb}|_{\text{BGL}} = (40.9 \pm 0.3_{\text{stat}} \pm 1.0_{\text{syst}} \pm 0.6_{\text{theo}}) \times 10^{-3} \]

\[ |V_{cb}|_{\text{CLN}} = (40.4 \pm 0.3_{\text{stat}} \pm 1.0_{\text{syst}} \pm 0.6_{\text{theo}}) \times 10^{-3} \]

• Lepton flavour universality tests

\[ R_{e/\mu} = 1.001 \pm 0.009_{\text{stat}} \pm 0.021_{\text{syst}} \]

\[ \Delta AFB = (-4 \pm 16_{\text{stat}} \pm 18_{\text{syst}}) \times 10^{-3} \]

\[ \Delta FL = 0.013 \pm 0.007_{\text{stat}} \pm 0.007_{\text{syst}} \]
$B \rightarrow D \ell^+ \nu$ untagged (189/fb)
preliminary [arXiv:2210.13143]
Measurement

- $D\ell\nu$ kinematics are described by $w$ only and the decay form factor contains a single function $f_+(w)$
- $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ are reconstructed and combined with an appropriately charged lepton ($e$ or $\mu$)
- Yields are extracted in 10 bins of $w$ by fitting the $\cos \theta_{BY}$ distributions
- Main challenges: background model, in particular $B \to D^{*}\ell\nu$ downfeed (significant despite active $D^*$ veto)
BGL fit


$|V_{cb}|_{\text{BGL}} = (38.28 \pm 1.16) \times 10^{-3}$

Average over $B^0$ and $B^+$, and $e$ and $\mu$
$B^0 \to \pi^- \ell^+ \nu$ untagged (189/fb)

preliminary [arXiv:2210.04224]
$B \rightarrow \pi \ell \nu$

**The golden mode for $|V_{ub}|$ exclusive**

- Differential rate in terms of $q^2 = (p_{\ell} + p_\nu)^2$

$$\frac{d\Gamma(B^0 \rightarrow \pi^- \ell^+\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |p_\pi|^3 |f_+(q^2)|^2$$

- BCL extraction of $|V_{ub}|$ [Phys.Rev.D79, 013008; Erratum-ibid. D82, 099902]
- Measure the differential rate in bins of $q^2$
- Theory calculates $f_+(q^2)$ at values of $q^2$
- Combined fit to the BCL expansion to determine $|V_{ub}|$ and $b_k$ ($z$ is a map of $q^2$)

$$f_+(q^2) = \frac{1}{1 - q^2/m_B^2} \sum_{k=0}^{K-1} b_k \left[ z^k - (-1)^{k-K} \frac{k}{K} z^K \right]$$
Measurement

- Charged $\pi$ mesons are combined with $e$ or $\mu$, the neutrino direction is reconstructed inclusively.

- The yield in 6 bins of $q^2$ is determined from a fit to $M_{bc} = \sqrt{E_{\text{beam}}^* - |\vec{p}_B^*|^2}$ vs. $\Delta E = E_B^* - E_{\text{beam}}^*$.

- Bin-by-bin unfolding to correct migration.
BCL fit result

- LQCD input from FNAL/MILC [Phys. Rev. D92, 014024]

\[ B(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.426 \pm 0.056({\text{stat}}) \pm 0.125({\text{syst}})) \times 10^{-4} \]

\[ |V_{ub}|_{B^0 \to \pi^- \ell^+ \nu_\ell} = (3.55 \pm 0.12({\text{stat}}) \pm 0.13({\text{syst}}) \pm 0.17({\text{theo}})) \times 10^{-3} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>( B^0 \to \pi^- e^+ \nu_e )</th>
<th>( B^0 \to \pi^- \mu^+ \nu_\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector</td>
<td>q1</td>
<td>q2</td>
</tr>
<tr>
<td>MC sample size</td>
<td>4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Continuum</td>
<td>13.1</td>
<td>5.5</td>
</tr>
<tr>
<td>( B \to p\ell\nu )</td>
<td>9.5</td>
<td>12.5</td>
</tr>
<tr>
<td>( B \to X_{c,0} \ell\nu )</td>
<td>3.3</td>
<td>1.9</td>
</tr>
<tr>
<td>( B \to X_{s} \ell\nu )</td>
<td>2.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Total syst.</td>
<td>17.2</td>
<td>14.3</td>
</tr>
<tr>
<td>Stat.</td>
<td>10.2</td>
<td>6.01</td>
</tr>
<tr>
<td>Total</td>
<td>20.2</td>
<td>15.5</td>
</tr>
</tbody>
</table>
**Belle II | $V_{cb}$ | and | $V_{ub}$**

- Recent Belle II results on exclusive decays

|       | $|V_{cb}| \times 10^3$ | Reference                     |
|-------|-------------------------|--------------------------------|
| Belle II $B^0 \to D^{*-}\ell^+\nu$ untagged | $40.9 \pm 1.2$ (BGL) Preliminary | To be submitted to PRD        |
| Belle II $B^0 \to D^{*-}\ell^+\nu$ tagged    | $37.9 \pm 2.7$ (CLN) Preliminary | [arXiv:2301.04716]            |
| Belle II $B \to D\ell\nu$ untagged           | $38.28 \pm 1.16$ (BGL) Preliminary | [arXiv:2210.13143]            |

|       | $|V_{ub}| \times 10^3$ | Reference                     |
|-------|-------------------------|--------------------------------|
| Belle II $B \to \pi\ell\nu$ tagged           | $3.88 \pm 0.45$ Preliminary   | [arXiv:2206.08102]            |
| Belle II $B \to \pi\ell\nu$ untagged        | $3.55 \pm 0.25$ Preliminary   | [arXiv:2210.04224]            |

WA values [HFLAV 2021]

$|V_{cb}|_{\text{excl}} = (39.10 \pm 0.50) \times 10^{-3}$

$|V_{ub}|_{\text{excl}} = (3.51 \pm 0.12) \times 10^{-3}$
Inclusive measurements
| $V_{cb}$ | from inclusive decays |

\[ \Gamma = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \left( 1 + \frac{c_5(\mu) \langle O_5(\mu) \rangle}{m_b^2} + \frac{c_6(\mu) \langle O_6(\mu) \rangle}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right) \right) \]

- Based on the Operator Product Expansion (OPE)
- $\langle O_i \rangle$: hadronic matrix elements (non-perturbative)
- $c_i$: coefficients (perturbative)
- Parton-hadron duality $\rightarrow$ the hadronic ME depend only on the initial state

<table>
<thead>
<tr>
<th></th>
<th>Kinetic</th>
<th>1S</th>
</tr>
</thead>
<tbody>
<tr>
<td>[JHEP 1109 (2011) 055]</td>
<td>[PRD70, 094017 (2004)]</td>
<td></td>
</tr>
<tr>
<td>$O(1)$</td>
<td>$m_b, m_c$</td>
<td>$m_b$</td>
</tr>
<tr>
<td>$O(1/m_b^2)$</td>
<td>$\mu^2_{\pi}, \mu^2_G$</td>
<td>$\lambda_1, \lambda_2$</td>
</tr>
<tr>
<td>$O(1/m_b^3)$</td>
<td>$\rho^3_D, \rho^3_{LS}$</td>
<td>$\rho_1, \tau_{1-3}$</td>
</tr>
</tbody>
</table>
HFLAV fit (kinetic scheme)

| $|V_{cb}|$ [$10^{-3}$] | $m_b^{\text{kin}}$ [GeV] | $m_c^{\text{MS}}$ [GeV] | $\mu^2_\pi$ [GeV]$^2$ | $\rho_D^3$ [GeV]$^3$ | $\rho_G^3$ [GeV]$^3$ | $\rho_{LS}^3$ [GeV]$^3$ |
|----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| value 42.19          | 4.554           | 0.987           | 0.464           | 0.169           | 0.333           | −0.153          |
| error 0.78           | 0.018           | 0.015           | 0.076           | 0.043           | 0.053           | 0.096           |

- Global fit to $\Gamma_{SL}$ and other inclusive observables
- At different lepton energy thresholds

[PRD 107, 052008 (2023)]
Motivated by JHEP 02 (2019) 177 [arXiv:1812.07472]

Semileptonic $B$ decays are reconstructed in 62.8/fb of hadronic tagged Belle II events

Signal weight $w$ as a function of $q^2$ determined from fitting the hadronic mass $M_X$

$q^2$ spectra are calculated as event-wise average

Leading systematics: background, moment calibration

$$q^2 = (p_\ell + p_\nu)^2$$

$q^2$ moments in $B \to X_c \ell \nu$

arXiv:2205.06372, submitted to PRD

$$\langle q^{2m} \rangle = \frac{C_{\text{cal}} \cdot C_{\text{acc}}}{\sum \text{events}} \cdot \sum \frac{w(q_i^2)}{\text{events}} \cdot \frac{w(q_i^2)}{q_i^{2m}} \cdot q_{\text{cal}}^{2m}$$
$q^2$ moments in $B \to X_c \ell \nu$

arXiv:2205.06372, submitted to PRD

- Belle II $q^2$ moments compared to Belle $q^2$ moments PRD 104, 112011 (2021) [arXiv:2109.01685]
- And fit by Bernlochner et al. [arXiv:2205.10274]
- This fit gives
  
  $|V_{cb}| = (41.69 \pm 0.63) \cdot 10^{-3}$
\( B \rightarrow X_u \ell \nu \) and \( |V_{ub}| \) inclusive

PRD 104, 012008 (2021), PRL 127, 261801 (2021)

4 predictions of the partial rate

BLNP
DGE
GGOU
ADFR

Our average

HFLAV \( B \rightarrow \pi \ell \nu \)

CKMfitter

Exclusive Average for \( B \rightarrow \pi \ell \nu \)

\[ |V_{ub}| = (3.67 \pm 0.09 \pm 0.12) \times 10^{-3} \]

CKM Unitarity:

\[ |V_{ub}| = (3.62^{+0.11}_{-0.08}) \times 10^{-3} \]

Arithmetic average:

\[ |V_{ub}| = (4.10 \pm 0.09 \pm 0.22 \pm 0.15) \times 10^{-3} \]

Can be used for future shape-function independent determination of Vub
Summary and conclusion

- The Cabibbo-Kobayashi-Maskawa magnitudes $|V_{cb}|$ and $|V_{ub}|$ are fundamental parameters of the Standard Model that play an important role in constraining the mechanism of quark-mixing/CP violation.

- $|V_{cb}|$ and $|V_{ub}|$ are currently known to the level of <2% and <4% (respectively) but there is a discrepancy at the level of 3σ between exclusive and inclusive determinations.

- The aim of ongoing measurements is to understand/identify the origin of this discrepancy.

\[
|V_{cb}|_{\text{excl}} = (39.10 \pm 0.50) \times 10^{-3} \quad |V_{cb}|_{\text{incl}} = (42.19 \pm 0.78) \times 10^{-3}
\]

\[
|V_{ub}|_{\text{excl}} = (3.51 \pm 0.12) \times 10^{-3} \quad |V_{ub}|_{\text{incl}} = (4.19 \pm 0.17) \times 10^{-3}
\]

[PRD 107, 052008 (2023)]
Backup
From Belle to Belle II

CsI(Tl) EM calorimeter: waveform sampling electronics, pure CsI for endcaps

4 layers DSSD vertex detector →
2 layers PXD (DEPFET) + 4 layers DSSD

Central Drift Chamber: smaller cell size, long lever arm

RPC $\mu$ & $K_L$ counter: scintillator + Si-PM for end-caps

Time-of-Flight, Aerogel Cherenkov Counter →
Time-of-Propagation (barrel), proximity focusing Aerogel RICH (forward)