Measurement of the CKM matrix element \( |V_{cb}| \) via \( B^- \rightarrow D^0 \ell^- \bar{\nu}_\ell \) at Belle II

Philipp Horak

HEPHY
Österreichische Akademie der Wissenschaft

OEPG Jahrestagung 2021

September 1, 2021
Overview

- Theoretical background
- Belle II experiment
- Current analysis status
- Outlook
Standard model

- Weak coupling strength differs between quark flavors
- Unitary CKM matrix
- $|V_{cb}| \approx 0.04$ with 2% uncertainty
- Measure $|V_{cb}|$ using semileptonic decays
**$|V_{xb}|$ with semileptonic decays**

### Inclusive
- Reconstruction of the generic decay $B \rightarrow X_{u/c} \ell \nu_{\ell}$ (*Manca Mrvar*)
- Calculation of $|V_{xb}|$ with Heavy Quark Expansion
- Series expansion in terms of $m_b$ and $\alpha_s$

### Exclusive
- Reconstruction of a specific decay, e.g. $|V_{ub}|$: $B \rightarrow \pi \ell \nu_{\ell}$
- $|V_{cb}|$: $B \rightarrow D^* \ell \nu_{\ell}$ (*Daniel Dorner*) or $B \rightarrow D \ell \nu_{\ell}$
- Calculation of $|V_{xb}|$ using Lattice QCD results

---

**Graphical Representation:**
- Plot showing the values of $|V_{ub}|$ and $|V_{cb}|$ with $\chi^2$ contours.
- The HFLAV Average is indicated in the plot.

---

**Philipp Horak (HEPHY)**
**$|V_{cb}|$ exclusive**

- Differential decay rates:
  \[
  \frac{d\Gamma}{dw}(B \to D\ell\nu_\ell) = \frac{G_F^2}{48\pi^3}(m_B + m_D)^2 m_D^3 \eta_{EW} |V_{cb}|^2 (w^2 - 1)^{3/2} G(w)^2
  \]

  - with the form factor $G(w)$
  - with the kinematic variable $w = v_B \cdot v_D = \frac{p_B \cdot p_D}{m_B m_D}$
  - $w_{\text{min}} = 1$: zero-recoil point, $D$ at rest in $B$ rest frame
  - Form factor at zero-recoil point from lattice QCD
    $G(w = 1) = 1.074 \pm 0.018 \pm 0.016$
### $D\ell\nu_\ell$ vs $D^*\ell\nu_\ell$

<table>
<thead>
<tr>
<th>Theory</th>
<th>$D\ell\nu_\ell$</th>
<th>$[D^* \rightarrow D\pi]\ell\nu_\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory</td>
<td>Scalar meson</td>
<td>Vector meson</td>
</tr>
<tr>
<td></td>
<td>$1^\dagger$ form factor free parameter $\rho^2$</td>
<td>$3^\dagger$ form factor parameters $\rho^2$, $R_1(1)$, $R_2(2)$</td>
</tr>
<tr>
<td></td>
<td>1 kinematic variable $w$</td>
<td>4 kinematic variables $w$, $\theta_\ell$, $\theta_V$, $\chi$</td>
</tr>
<tr>
<td>Experiment</td>
<td>Large downfeed from $D^*\ell\nu$</td>
<td>Clean sample by cutting on $m_D^* - m_D$</td>
</tr>
<tr>
<td></td>
<td>Smaller branching fraction</td>
<td>Pion from $D^*$ decay restricted to low $p$</td>
</tr>
<tr>
<td></td>
<td>No slow pion</td>
<td>Large systematic error from slow pion</td>
</tr>
</tbody>
</table>

$^\dagger$ for small lepton masses
The Belle II experiment

- Electron - positron collider in Tsukuba, Japan, in operation since 2018
- Collisions at $\sqrt{s} = 10.58$ GeV produce large amounts of $B$ mesons
- 7 sub detectors measure momenta, energies and identify particles resulting from $B$ decays

Total data sample: 50 ab$^{-1}$ until 2030s, currently 213 fb$^{-1}$ recorded
Analysis overview

Analysis strategy

- Reconstruction of $B^- \to D^0 \ell^- \bar{\nu}_\ell$ and $D^0 \to K^- \pi^+$ with $\ell = (e, \mu)$
- *Untagged*, i.e., no requirements for second $B$ meson

Current status:

- First results with 62.8 fb$^{-1}$
- Reconstruction and measurement of the branching ratio
- Measurement of lepton universality $R(e/\mu)$

Detector data $\rightarrow$ Decay reconstruction $\rightarrow$ Signal extraction (Likelihood Fit) $\rightarrow$ Branching ratio
Decay reconstruction

- Cuts on variables include $m_{K\pi}$, particle identification, event shape to maximize statistical significance
- Suppression of $D^* \ell \nu_\ell$ downfeed by applying vetos:
  - If slow pion can be found that cleanly reconstructs $D^*$, discard candidate
- Selection optimized on simulated Monte-Carlo (MC) data
Decay reconstruction

- $\theta_{BY}$: Angle between nominal $B$ meson and combined $D^0 \ell^-$ system ($Y$)

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

- $\cos \theta_{BY}$ only restricted between -1 and 1 for signal events

Pre-fit
Fit

- $N_{\text{sig}}$ in the sample via binned Maximum Likelihood Fit
- Shapes of distributions from MC rescaled to match real data
- 4 components: Signal, $D^*\ell\nu$, other $B\bar{B}$ background and continuum ($e^+e^- \rightarrow q\bar{q}, q \in [u, d, s, c]$)

**Post-fit**

![Plot showing the fit results for $B^- \rightarrow D^0 e^- \bar{\nu}_e$]
Branching ratio

\[ \text{Br} \left( B^- \to D^0 \ell^- \bar{\nu}_\ell \right) = \frac{N_{\text{sig}}}{\epsilon N_{B^\pm} \text{Br} \left( D^0 \to K^- \pi^+ \right)} \]

- with amount of signal events \( N_{\text{sig}} \), \( \epsilon = \frac{n_{\text{reco,MC}}}{n_{\text{true,MC}}} \) and number of \( B^\pm \) mesons in the data sample \( N_{B^\pm} \)
- Statistical error from fit
- Systematic errors evaluated individually and added in quadrature

<table>
<thead>
<tr>
<th>( D \ell \nu_\ell )</th>
<th>Branching ratio [%]</th>
<th>Relative stat. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D \ell \nu_\ell ) (World average)</td>
<td>2.29 ± 0.05\text{stat} ± 0.08\text{syst}</td>
<td>2.3%</td>
</tr>
</tbody>
</table>

\[ R(e/\mu) = \frac{\text{Br} \left( B^- \to D^0 e^- \bar{\nu}_e \right)}{\text{Br} \left( B^- \to D^0 \mu^- \bar{\nu}_\mu \right)} \]

\[ R(e/\mu) = 1.04 \pm 0.05\text{stat} \pm 0.03\text{syst} \]
Reconstruction of $B^- \rightarrow D^0 \ell^- \bar{\nu}_\ell$ and $D^0 \rightarrow K^- \pi^+ \ell$ with $\ell = (e, \mu)$

- 62.8 fb$^{-1}$ Belle II data
- Branching ratio in agreement with world average
- $R(e/\mu)$ in agreement with lepton universality

**Next steps**

- Reconstruction of kinematic variable $w$
- Differential decay rate
- Extrapolation to $w = 1$ for $|V_{cb}|$ measurement
- $\approx 500$ fb$^{-1}$ until shutdown in 2022
Backup
$V_{xb}$ with $B$ mesons

**Hadronic decays**

- Large branching fractions
- Easy to reconstruct
- Dependent on hadronic currents
- Difficult to compute

**Leptonic decays**

- No hadronic contributions
- Theoretically clean
- Very low branching ratios ($\approx 10^{-7}\%$)
- $B \rightarrow \mu \nu$ measured with $3\sigma$ at Belle

**Semileptonic decays**

- Large branching ratios ($B^{-} \rightarrow D^{0} \ell^{-}\bar{\nu_{\ell}} \approx 2.3\%$)
- Theory side computable
- Compromise between theory and experiment
# Selection criteria

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cuts</th>
</tr>
</thead>
</table>
| Tracking & event level    | \(|d_0| < 0.5 \text{ cm}\)  
|                           | \(|z_0| < 2 \text{ cm}\)                                            |
|                           | thetainCDCAcceptance                                               |
|                           | nCDCHits > 0                                                       |
|                           | nTracks > 3                                                        |
|                           | \(R_2 < 0.3\)                                                      |
|                           | \(E_{\text{vis}} > 4 \text{ GeV}\)                               |
| Lepton                    | \(p^* > 0.6 \text{ GeV}\)                                         |
|                           | e/\(\mu\) \(\text{ID} > 0.9\)                                    |
| \(D^0\)                   | \(M \in [1.857 \text{ GeV}, 1.872 \text{ GeV}]\)                 |
| \(Y(\text{combined } D^0 - \ell)\) | \(M > 3.15 \text{ GeV}\)                                      |

### Brems correction

- **correctBremsBelle module**
- Angle < 0.05  
  0.05 GeV < \(E\) < 0.15 GeV
To suppress $D^*$ downfeed, implement 2 vetos:

- $B^0 \rightarrow [D^{*+} \rightarrow D^0 \pi^+] \ell^- \nu_\ell$
  - Slow $\pi$: $p < 0.35$ GeV
  - $144$ MeV $< m_{D^*} - m_D < 148$ MeV

- $B^+ \rightarrow [D^{*0} \rightarrow D^0 [\pi^0 \rightarrow \gamma \gamma]] \ell^+ \nu_\ell$
  - $\pi^0 \rightarrow \gamma \gamma$ selection criteria from recommendations
  - $141$ MeV $< m_{D^*} - m_D < 145$ MeV
  - Opening angle of $D^0 \pi^0 < 17^\circ$

*eff40 lists are chosen*
MC corrections

- Lepton ID corrections
  - Apply a weight to each $B$ candidate based on lepton $p$ and $\theta$
  - Recommended tables from the Lepton ID group for the Moriond 2021 dataset
  - Efficiency, $\ell - \pi$ fake rate, $\ell - K$ fake rate
  - To assign weights PIDvar module by Will Sutcliffe

- Momentum correction
  - To account for $B$ field map, apply global scale factor
  - Recommended scale factor: 1.00056 to data
Angle between $Y(D^0 - \ell)$ and nominal $B \cos \theta_{BY}$

- Scaled using luminosities

**Belle II**

$\int \mathcal{L} dt = 62.8 \text{ fb}^{-1}$

$B \rightarrow D^0 e^- \bar{\nu}_e$

- Signal
- $D^*$
- Other $B\bar{B}$
- Continuum
- MC stat. unc.
- Data

**Belle II**

$\int \mathcal{L} dt = 9.2 \text{ fb}^{-1}$

$B \rightarrow D^0 e^- \bar{\nu}_e$

- Signal
- $D^*$
- Other $B\bar{B}$
- Continuum
- MC stat. unc.
- Data

**e mode, continuum data**

**e mode, off-resonance data**
MC agreement - $\mu$

- Angle between $Y(D^0 - \ell)$ and nominal $B \cos \theta_{BY}$
- Scaled using luminosities

**Belle II**

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

- Signal
- $D^*$
- Other $B\bar{B}$
- Continuum
- MC stat. unc.
- Data

**Belle II**

\[ \int \mathcal{L} \, dt = 9.2 \text{ fb}^{-1} \]

- Signal
- $D^*$
- Other $B\bar{B}$
- Continuum
- MC stat. unc.
- Data

$\mu$ mode, continuum data

$\mu$ mode, off-resonance data
Fit

- Binned likelihood fit ROOT's TFractionFitter
- fit range: $|\cos \theta_{BY}| < 4$, 30 bins
- 4 floating templates:
  - signal: selected with BASF2 variable isSignal including missing neutrinos and brems-photons
  - $D^*$: all events where the $B$ mother of selected lepton decays like $B \to D^*(0,\pm)\ell\nu(\gamma)$
  - other $B\bar{B}$: Candidates from mixed and charged MC that are neither signal nor $D^*$
  - Continuum: Candidates from continuum MC*

---

*due to sample size we use continuum MC rather than off-resonance data*
Post-fit distributions

**Belle II**

$B^- \rightarrow D^0 e^- \bar{\nu}_e$

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

<table>
<thead>
<tr>
<th>Component</th>
<th>$e$ yield</th>
<th>$\mu$ yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>$19543.8 \pm 648.9$</td>
<td>$18869.3 \pm 636.3$</td>
</tr>
<tr>
<td>$D^*$</td>
<td>$65502.9 \pm 960.0$</td>
<td>$67595.0 \pm 843.7$</td>
</tr>
<tr>
<td>Other $B\bar{B}$</td>
<td>$59233.2 \pm 2450.2$</td>
<td>$64899.6 \pm 2101.0$</td>
</tr>
<tr>
<td>Continuum</td>
<td>$79697.7 \pm 1970.1$</td>
<td>$102308.1 \pm 1808.6$</td>
</tr>
</tbody>
</table>

Philipp Horak (HEPHY)
**Branching ratio**

\[ \text{Br}\left(B^+ \rightarrow D^0 \ell^+ \nu_\ell\right) = \frac{n_{\text{sig}}}{\epsilon \ n_{B^\pm} \ \text{Br}\left(D^0 \rightarrow K^- \pi^+\right)} \]

- \( n_{\text{sig}} \) from fit
- Selection efficiency \( \epsilon = \frac{n_{\text{reco,MC}}}{n_{\text{true,MC}}} \), \( \epsilon^e = 30.12\% \) \( \epsilon^\mu = 30.36\% \)
- \( n_{B^\pm} = 2 \times f^{+-} \times N_{B\bar{B}} = (68.21 \pm 0.06 \, \text{(stat.)} \pm 0.75 \, \text{(sys.)}) \times 10^6 \)
- \( \text{Br}\left(D^0 \rightarrow K^- \pi^+\right) = (3.950 \pm 0.031\%) \)

<table>
<thead>
<tr>
<th></th>
<th>Branching ratio [%]</th>
<th>Relative stat. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D \ e \ \nu_e )</td>
<td>2.343 ± 0.075(stat)</td>
<td>3.22%</td>
</tr>
<tr>
<td>( D \ \mu \ \nu_\mu )</td>
<td>2.244 ± 0.075(stat)</td>
<td>3.33%</td>
</tr>
<tr>
<td>( D \ \ell \ \nu_\ell )</td>
<td>2.293 ± 0.053(stat)</td>
<td>2.32%</td>
</tr>
</tbody>
</table>

\[ R(e/\mu) = 1.044 \pm 0.068(\text{stat.}) \]

---

*B2N-PH-2021-018*
## Results

<table>
<thead>
<tr>
<th>Source</th>
<th>electron sample</th>
<th>muon sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{B\bar{B}}$</td>
<td>1.61</td>
<td>1.61</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0 \to K^-\pi^+)$</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>Tracking</td>
<td>2.07</td>
<td>2.07</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>1.41</td>
<td>2.38</td>
</tr>
<tr>
<td>MC efficiency (statistical)</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>$D_{\ell\nu}$ form factor</td>
<td>0.15</td>
<td>0.11</td>
</tr>
<tr>
<td>$D^{*}_{\ell\nu}$ form factor</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td>Continuum shape</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Sum</td>
<td>3.14</td>
<td>3.68</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Branching ratio [%]</th>
<th>Relative stat. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D \ e \ \nu_e$</td>
<td>2.343 ± 0.075$<em>{\text{stat}}$ ± 0.073$</em>{\text{syst}}$</td>
<td>3.22%</td>
</tr>
<tr>
<td>$D \ \mu \ \nu_\mu$</td>
<td>2.244 ± 0.075$<em>{\text{stat}}$ ± 0.083$</em>{\text{syst}}$</td>
<td>3.33%</td>
</tr>
<tr>
<td>$D \ \ell \ \nu_\ell$</td>
<td>2.293 ± 0.053$<em>{\text{stat}}$ ± 0.084$</em>{\text{syst}}$</td>
<td>2.32%</td>
</tr>
<tr>
<td>$D \ \ell \ \nu_\ell$ (World average)</td>
<td>2.35 ± 0.03$<em>{\text{stat}}$ ± 0.09$</em>{\text{syst}}$</td>
<td></td>
</tr>
</tbody>
</table>

$R(e/\mu) \quad 1.044 \pm 0.046_{\text{stat}} \pm 0.034_{\text{syst}}$
Fit test

- Validate fit using toy MC test
- scale MC down to $62.8 \text{ fb}^{-1}$ and use as pseudodata
- resample pseudodata and templates with poisson weights
- perform fit for each toy and calculate pull $g = \frac{n_{\text{fitted}} - n_{\text{true}}}{\sigma_{\text{fitted}}}$
Systematic uncertainties

Number of $B$ mesons

- $N_{B\bar{B}} = (68.21 \pm 0.06 \text{ (stat.)} \pm 0.75 \text{ (sys.)}) \times 10^6$
- $f^{+-} = 0.514 \pm 0.006$
- add errors in quadrature
- resulting systematic: 1.61%

$\text{Br} \left( D^0 \rightarrow K^-\pi^+ \right)$

- $\text{Br} \left( D^0 \rightarrow K^-\pi^+ \right) = (3.950 \pm 0.031\%)$
- resulting systematic: 0.78%

Tracking

- Correct data-MC disagreement in track finding efficiency
- Recommended recipe: 0.69% systematic per charged track
- Three charged final state tracks: resulting systematic 2.07%
Lepton identification

- Provided tables have associated uncertainties for each $p, \theta$ bin
- Generate 300 resampled lepton ID tables (Will’s PIDvar module)
- For each resampled table, calculate amount of signal $n_{reco,MC}$
- Resulting systematic: 1.41% for $e$, 2.38% for $\mu$
Efficiency statistics

- Finite MC sample for calculating $\epsilon$
  \[ \sigma_{\text{binom}} = \sqrt{\frac{p(1-p)}{n}} \]
  
- Resulting systematic: 0.09%
**$D\ell\nu$ form factor uncertainty**

- MC13a generator: BGL form factor
- Reweight to CLN with 1 parameter $\rho^2$ by applying weights based on $w$
- Vary $\rho^2 \pm 1\sigma$, perform fit, deviation in branching ratio = systematic error

![form factor weights for signal candidates](image)

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Relative change $e$</th>
<th>Relative change $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^2 + \sigma$</td>
<td>+0.155%</td>
<td>+0.105%</td>
</tr>
<tr>
<td>$\rho^2 - \sigma$</td>
<td>-0.028%</td>
<td>-0.04%</td>
</tr>
</tbody>
</table>

- Resulting systematic errors 0.16% and 0.11%
$D^* \ell \nu$ form factor uncertainty

- MC13a generator: CLN form factor
- 3 parameters $\rho^2, R_1(1), R_2(1)$
- vary all $\pm 1\sigma$, perform fit, deviation in branching ratio $=$ systematic error

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Relative change $e$</th>
<th>Relative change $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^2 + \sigma$</td>
<td>-0.318%</td>
<td>-0.296%</td>
</tr>
<tr>
<td>$\rho^2 - \sigma$</td>
<td>+0.307%</td>
<td>0.306%</td>
</tr>
<tr>
<td>$R_1(1) + \sigma$</td>
<td>-0.002%</td>
<td>-0.005%</td>
</tr>
<tr>
<td>$R_1(1) - \sigma$</td>
<td>-0.005%</td>
<td>0.018%</td>
</tr>
<tr>
<td>$R_2(1) + \sigma$</td>
<td>-0.300%</td>
<td>-0.283%</td>
</tr>
<tr>
<td>$R_2(1) - \sigma$</td>
<td>0.291%</td>
<td>0.274%</td>
</tr>
</tbody>
</table>

- Resulting systematic error 0.44%
Continuum shape systematic

- To estimate effect of continuum MC mismatch on fitted branching ratio reweigh
- Divide offres content by continuum bin-by-bin to get ratios
- Fit ratios with a polynomial and apply weight to each continuum candidate based on $\cos \theta_{BY}$

**before reweighing**

**Belle II**

$\int Ldt = 9.2 \text{ fb}^{-1}$

- With reweighed continuum MC, fit for branching ratio
- Deviation in branching ratio 0.37%, used as systematic
Bin-by-bin efficiencies

- **V_{cb}** via $B^-$ → $D^0 \ell^- \bar{\nu}_\ell$