Semileptonic and leptonic $B$ decay results from early Belle II data

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on behalf of the Belle II collaboration

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SuperKEKB project

KEKB machine heavily upgraded:
- New positron damping ring
- New 3 km positron ring vacuum chamber
- New superconducting final focus

Aim to deliver 50 ab$^{-1}$ in 6 years!

<table>
<thead>
<tr>
<th>parameter</th>
<th>LER (e$^+$)</th>
<th>HER (e$^-$)</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>4.000</td>
<td>7.007</td>
<td>GeV</td>
</tr>
<tr>
<td>Half crossing angle</td>
<td></td>
<td>41.5</td>
<td>mrad</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>3.2</td>
<td>4.6</td>
<td>nm</td>
</tr>
<tr>
<td>Emittance ratio</td>
<td>0.27</td>
<td>0.25</td>
<td>%</td>
</tr>
<tr>
<td>Beta functions at IP (x/y)</td>
<td>32 / 0.27</td>
<td>25 / 0.30</td>
<td>mm</td>
</tr>
<tr>
<td>Beam currents</td>
<td>3.6</td>
<td>2.6</td>
<td>A</td>
</tr>
<tr>
<td>Beam-beam parameter</td>
<td>0.0881</td>
<td>0.0807</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>$8 \times 10^{35}$</td>
<td></td>
<td>cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>

Semileptonic and Leptonic B decay from early Belle II data
SuperKEKB operations

Phase 1: Single beam commissioning, without final focus, performed in 2016

Phase 2: Collision commissioning, with final focus, nanobeam scheme, and Belle II detector in place (without vertex detector), from April to July 2018.

Belle II managed to collect 0.5 fb\(^{-1}\) in the time left from machine tuning, very useful sample for commissioning and first physics !!!

Phase 3: stable data taking with full Belle II detector in place started in March 2019.

See talk by Manfred Berger
The Belle II detector

Upgrades with respect to Belle detector:

- **EM Calorimeter**: CsI(Tl), waveform sampling electronics
- **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

07/06/2019

Semileptonic and Leptonic B decay from early Belle II data
Belle II event displays in Phase2 run

All subdetectors operational. Collisions mostly used for commissioning
Belle II detector shows already good performance in phase 2 data: all anticipated particles have been re-discovered. B mesons mass peak is well reconstructed.

Good test bench for physics analysis tools!
FEI: Full event interpretation, enhances by a factor of 2 the event tagging efficiency

A dedicated boosted decision tree for each step
More than 1000 B decay modes are reconstructed


Very powerful tool for all tagged analyses: high purity but usually low statistics
Untagged analyses by converse have high statistics, high background, and less kinematical constraints (Rest of the Event)
FEI performances on phase 2 data

- Only hadronic tags
- Continuum suppressed by cut on $R_2$
- Fit $m_{bc} = \sqrt{\frac{s}{4} + p_{Btag}^2}$

Efficiency = $\frac{N_B^{\text{correct}}}{N_Y(4s)^{\text{total}}}$

Purity = $\frac{N_B^{\text{correct}}}{N_B^{\text{all}}}$

<table>
<thead>
<tr>
<th>Candidates</th>
<th>Efficiency</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FEI Signal Probability $\mathcal{P} &gt; 0.01$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charged Candidates</td>
<td>$937 \pm 126$</td>
<td>$0.17%$</td>
</tr>
<tr>
<td>Neutral Candidates</td>
<td>$394 \pm 59$</td>
<td>$0.09%$</td>
</tr>
<tr>
<td><strong>FEI Signal Probability $\mathcal{P} &gt; 0.2$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charged Candidates</td>
<td>$389 \pm 43$</td>
<td>$0.07%$</td>
</tr>
<tr>
<td>Neutral Candidates</td>
<td>$182 \pm 24$</td>
<td>$0.03%$</td>
</tr>
</tbody>
</table>
Inclusive analysis of $B \rightarrow Xe\nu$ in phase 2 data

Data sample of 0.4915 fb$^{-1}$

electrons identified by cutting on $E_{ECL}/P_{track}$

$J/\psi$ candidates rejected

Fox-Wolfram moments ratio $R2<0.4$ to suppress continuum background

$p_e < 1$ GeV

$p_e > 1$ GeV
Inclusive analysis of $B \to Xe\nu$ in phase 2 data

Good data – Monte Carlo agreement for electron momentum $> 1$ GeV

Fitting momentum distribution in the range $0.6 < p_e (\text{cms}) < 2.4$ GeV yields:

- $42191 \pm 304$ signal events (40209 ± 200 expected from MC)

Still a lot of work to do to measure $|V_{cb}|$ and $|V_{ub}|$....

.....but very good starting point given the small available sample, the new detector and the changing conditions in which it was collected!
A data sample of 366 pb\(^{-1}\) is used

\[ \bar{B}^0 \rightarrow D^{*+} e^- \bar{\nu}_e \] is reconstructed in the channel where \( D^* \rightarrow D^0 (\rightarrow K \pi) \pi_{\text{slow}} \)

Events Selections:

- electrons identified by cutting on \( E_{\text{ECL}}/P_{\text{track}} \)
- \( R2 < 0.25 \) to suppress continuum
- Slow \( \pi \) cms momentum < 0.4 GeV/c
- Selection around \( M_D \) and \( (M_{D^*} - M_D) \) expected values
Exclusive reconstruction of $\bar{B}^0 \rightarrow D^{*+} e^- \bar{\nu}_e$ in phase 2 data

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

22 signal events observed
15 events in the range (-1, 1 )
13 predicted by MC

$Y =$ visible final system ($D^*$, $e$)
Belle II perspectives with semileptonic B decays

Exclusive measurements:
reconstruct final states: $B \rightarrow D \ell \nu$, $B \rightarrow \pi \ell \nu$

$BR \propto |V_{qb}|^2 F(w)$ (F form factor)
need input from lattice QCD

Inclusive measurements:
Include all $B \rightarrow X_q \ell \nu$.
via optical theorem:
$BR \propto |V_{qb}|^2 \left( \Gamma(b \rightarrow q \ell \nu) + \ldots \right)$
HQE needed to determine total rate

Inclusive vs exclusive measurements used to show some discrepancies, but recent averages and model independent FF parametrization recovered agreement:
Belle II will improve both statistical and systematical uncertainties and in most cases it will allow to fit the FF shape thus reducing theory error:

- \(|V_{cb}|\) exclusive: from \(B \rightarrow D^* \ell \nu\) and \(B \rightarrow D \ell \nu\)
  compatible results, but \(V_{cb}\) value depends on FF parametrization:
  CLN vs BGL i.e. discrepancy or not with inclusive determination.
  Currently systematics dominated mainly coming from hadronic tag calibration.
  Powerful FEI technique and high statistical sample will allow FF fit from differential \(B \rightarrow D \ell \nu\) decay rates and help reducing theory error on parametrization.

- \(|V_{cb}|\) inclusive: simultaneous fit to the semileptonic inclusive width, the moments of the lepton energy spectrum and the moments of the hadronic mass spectrum squared.
  currently theory error dominated. High statistical sample will allow accurate measurement of the \(E_\ell\) spectrum and of other momenta, and to test the validity of the OPE description at low energy, thus reducing theory errors.
B→π ℓ ν both tagged and untagged.
B_s→K ℓ ν untagged only, at Y(5s), less precise.

Extract $V_{ub}$ from a combined fit to the measured $q^2$ spectrum and Lattice QCD predictions. Higher Belle II selection efficiencies and improved resolutions will allow to pin down the $V_{ub}$ error by a ~2 already with 5 ab$^{-1}$. Lattice QCD improvements may gain another factor of 2.
Inclusive $V_{ub}$

Can be obtained both from untagged and hadronic tagged analyses, where neutrino momentum is reconstructed or constrained.
Soft pions used to identify $D^*$ and reduce $B \rightarrow X_c \ell \nu$ background.

$V_{ub}$ is extracted from a model independent combined fit to:

$$B \rightarrow X_u \ell \nu, B \rightarrow X_c \ell \nu, B \rightarrow X_s \gamma$$

together with the parameters of the same shape function $F(k)$ taking into account b quark momentum distribution inside $B$ meson (SIMBA technique).

Belle II precise measurements of differential distributions will further constrain the fit.
Large statistical sample and improved Belle II particle reconstruction will allow to reach \( \sim 1\% \) experimental error on \( V_{ub} \), both in the tagged and untagged exclusive channels, systematics dominated, and comparable with expected theory errors. Inclusive channel has slightly higher systematics and larger theory error.
**Belle II expectations for $V_{ub}$ from $B \to \tau \nu$**

$$\text{BR} \propto |V_{ub}|^2 F_B^2 m_\tau^2$$

- Both leptonic and hadronic tag
- Fully reconstruct tag side and lepton on signal side. $> 1 \nu$ in final state.
- $E_{ECL}$ = energy sum of all neutral clusters not used for reconstruction
- Signal shows up as a low energy excess in $E_{ECL}$ spectrum

| $|V_{ub}|$ | $B \to \tau \nu$ (had. tagged) | Statistical | Systematic (reducible, irreducible) | Total Exp | Theory | Total |
|----------|-------------------------------|-------------|-------------------------------------|-----------|--------|-------|
| 711 fb$^{-1}$ | 18.0 | (7.1, 2.2) | 19.5 | 2.5 | 19.6 |
| 5 ab$^{-1}$ | 6.5 | (2.7, 2.2) | 7.3 | 1.5 | 7.5 |
| 50 ab$^{-1}$ | 2.1 | (0.8, 2.2) | 3.1 | 1.0 | 3.2 |

| $|V_{ub}|$ | $B \to \tau \nu$ (SL tagged) | Statistical | Systematic (reducible, irreducible) | Total Exp | Theory | Total |
|----------|-------------------------------|-------------|-------------------------------------|-----------|--------|-------|
| 711 fb$^{-1}$ | 11.3 | (10.4, 1.9) | 15.4 | 2.5 | 15.6 |
| 5 ab$^{-1}$ | 4.2 | (4.4, 1.9) | 6.1 | 1.5 | 6.3 |
| 50 ab$^{-1}$ | 1.3 | (2.3, 1.9) | 2.6 | 1.0 | 2.8 |

Conclusions

• SuperKEKB machine has been commissioned and is starting stable run

• Belle II detector is fully installed and commissioned.

• 0.5 fb\(^{-1}\) collected in 2018 during commissioning allow some first physics

• FEI techniques tested on data and very powerful

• First semileptonic B decays reconstructed with inclusive and exclusive analysis.

• Stay tuned for future results!
... x40 luminosity means also much higher background...!

...but Belle II is equipped with upgraded detectors capable to rescue rare signals and reject garbage!

• A new and larger drift chamber: longer lever arm, smaller cells in the inner region, fast readout.

• An imaging Time of Propagation detector to perform PID in the barrel region

• A PID detector in the forward region (ARICH)

• An improved z resolution in the interaction region, thanks to Pixel (2 layers) + strip (4 layers) vertex detector.

• Fast ECL readout to reduce pile-up

• KLM 2 inner layers replaced with scintillators
Both measurements are systematics limited!

$V_{cb}$ determination from the 2 channels gives compatible results, but depends on FF parametrization: CLN vs BGL i.e. discrepancy or not with inclusive determination.

Belle II will reduce systematic uncertainty, mainly coming from hadronic tag calibration. Its large dataset can afford FF fit from differential $B \rightarrow D \ell \nu$ decay rates and help reducing theory error on parametrization.
Perform a simultaneous fit of $V_{cb}$, the b and c quark masses and other OPE parameters, to the semileptonic inclusive width, the moments of the lepton energy spectrum and the moments of the hadronic mass spectrum squared.

$$|V_{cb}|_{\text{incl}} = (42.19 \pm 0.78) \times 10^{-3}$$

HFLAV 2016 fit

actually dominated by theoretical uncertainties

Belle II large data set will allow accurate measurement of the $E_l$ spectrum and of other momenta, and to test the validity of the OPE description at low energy, thus helping theorists to reduce errors.
**Flavour tag at Belle II**

\[
\begin{align*}
\bar{B}^0 & \rightarrow D^{*+} \bar{\nu}_\ell \ell^- \\
& \quad \downarrow D^0 \pi^+ \\
& \quad \downarrow X K^- \\
\bar{B}^0 & \rightarrow D^+ \pi^- (K^-) \\
& \quad \downarrow K^0 \nu_\ell \ell^+ \\
\bar{B}^0 & \rightarrow \Lambda_c^+ X^- \\
& \quad \downarrow \Lambda \pi^+ \\
& \quad \downarrow p \pi^-
\end{align*}
\]

Charged leptons, kaons, pions and \(\Lambda\)'s allow to tag the B flavour without reconstructing it, thanks to quantum correlation of the two B mesons.

**Multivariate discriminating algorithm provides optimized tagging, already tested on Belle data:**

\[\varepsilon_{\text{eff}} = \sum_i \varepsilon_i (1-2w_i)^2, \ w_i \text{ mistag probability}\]

Tagging efficiency improved by 10% already on Belle data. Belle II will profit of its improved PID.

Old FT Belle data: \(\varepsilon_{\text{eff}} = (30.1\pm0.4)\%\)

New FT Belle data: \(\varepsilon_{\text{eff}} = (33.6\pm0.5)\%\)

New FT Belle MC: \(\varepsilon_{\text{eff}} = (34.18\pm0.03)\%\)

New FT Belle II MC: \(\varepsilon_{\text{eff}} = (37.16\pm0.03)\%\)
Long Term prospects for $R(D^*)$

$$R_{D^{(\ast)}} = \frac{\text{Br} \left( B \rightarrow D^{(*)}\tau\nu_\tau \right)}{\text{Br} \left( B \rightarrow D^{(*)}\ell\nu_\ell \right)} \quad (\ell = e, \mu)$$