Belle II Status and Prospects

Phillip Urquijo, The University of Melbourne
Flavour Physics and CP Violation 2020
Belle II detector

**Belle II @ Super-KEKB**

Intensity frontier flavour-factory experiment, Successor to Belle @KEKB (1999-2010)

- Belle II @ Super-KEKB
- Intensity frontier flavour-factory experiment
- Successor to Belle @KEKB (1999-2010)
- 7 GeV e⁻, 4 GeV e⁺
- $E_{CM}$ $Y(4S) = 10.58$ GeV + scans
- $Y(4S) \rightarrow B$ anti-$B$
- $B +$ Charm + $\tau + Y$ factory
- ~1050 researchers (355 grad students) from 23 countries.
- Inclusive:
  - KEDR
  - BES
- Exclusive:
  - Mark-I
  - Mark-I + LGW
  - Mark-II
  - PLUTO
  - Crystal Ball
  - BES
  - KEDR
- $J/\psi$, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$
- $\Upsilon$ factory

$R = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$

**Note:**
- CLEO data above $\Upsilon(4S)$ were not fully corrected for radiative effects, and we retain them on the plot only for illustrative purposes with a normalization factor of 0.8. The full list of references to the original data and the details of the $R$ ratio extraction from them can be found in [100]. The computer-readable data are available at [http://pdg.lbl.gov/current/xsect/](http://pdg.lbl.gov/current/xsect/). (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, August 2019.)

### 9.5 10 10.5 11
- MD-1
- ARGUS
- CLEO
- CUSB
- DASP
- DHHM
- MD-1
- Crystal Ball
- CLEO II
- CUSB
- DASP
- LENA

**PDG2019**

$\Upsilon$工厂区域

$Y(1S)$, $Y(2S)$, $Y(3S)$, $Y(4S)$, $Y(5S)$, $Y(6S)$

**off-resonance ($\Upsilon(4S)$-60 MeV): 10.52 GeV**

**BB threshold: 10.56 GeV**

$\Upsilon(4S)$: 10.58 GeV
Belle II Flavour Program

- Belle II plans to collect 50 ab\(^{-1}\) of collisions near Y(4S)
  - a (Super) B-factory (~1.1 \times 10^9\ BB pairs per ab\(^{-1}\))
  - a (Super) charm factory (~1.3 \times 10^9\ cc pairs per ab\(^{-1}\))
  - a (Super) τ factory (~0.9 \times 10^9\ ττ pairs per ab\(^{-1}\))

- Flavour program at Belle II
  - CKM precision metrology
  - Flavour BSM analyses with good “detection universality” (e.g. leptons). Ready to tackle “anomalies”.
  - Dark, missing energy: hidden portals, axiflavons etc.
  - Important, unexplained hierarchy among 10 of 19 params of SM m\(\nu\)=0
    - Mass (6 params, small ratios of scales)
    - CP violation (4 params, strong hierarchy between generations)
    - With phenomenological consequences for quark flavour dynamics
CKM and CPV SM Metrology: Belle II core program

\[ B \rightarrow \pi \pi, \rho \rho \quad \Phi_2 \quad \text{via Form factor / OPE} \]

\[ B \rightarrow D l \nu / b \rightarrow c l \nu \quad \Phi_3 \quad \text{via Form factor / OPE} \]

\[ B \rightarrow \pi l \nu / b \rightarrow u l \nu \quad \Phi_1 \quad \text{via Decay constant f}_M \]

\[ B_s \rightarrow J/\psi \Phi \quad \beta_s \quad \varepsilon_K \quad (\rho, \eta) \quad \text{via B}_K \]

\[ K \rightarrow \pi \nu \text{ anti-}\nu \quad \rho, \eta \quad \Delta m_d, \Delta m_s \quad \text{via Bag factor B}_B \]

\[ B(s) \rightarrow \mu^+ \mu^- \quad |V_{t[d,s]}| \quad \text{via Decay constant f}_B \]

\[ \text{Observables with very different properties} \]

Tree: e.g., \(|V_{ub}|, \Phi_3\)

Loop: e.g., \(\Delta m_d, \Delta m_s, \varepsilon_K, \sin(2\beta)\)

CP-conserving: e.g., \(|V_{ub}|, \Delta m_d, \Delta m_s\)

CP-violating: e.g., \(\gamma, \varepsilon_K, \sin(2\beta)\)

Exp. uncs.: e.g., \(\alpha, \sin(2\beta), \gamma\)

Syst. uncs.: e.g., \(|V_{ub}|, |V_{cb}|, \varepsilon_K, \Delta m_d, \Delta m_s\)
CKM and CPV SM Metrology: Belle II core program

\[ |V_{cb}| \text{ via Form factor / OPE} \]
\[ |V_{ub}| \text{ via Form factor / OPE} \]
\[ |V_{UD}| \text{ via Decay constant } f_M \]
\[ (\rho, \eta) \text{ via } B_K \]
\[ |V_{tb} V_{t[d,s]}| \text{ via Bag factor } B_B \]
\[ |V_{t[d,s]}| \text{ via Decay constant } f_B \]

**Observables with very different properties**

**Tree:** e.g., \(|V_{ub}|\), \(\Phi_3\)

**Loop:** e.g., \(\Delta m_d, \Delta m_s, \varkappa, \sin(2\beta)\)

**CP-conserving:** e.g., \(|V_{ub}|, \Delta m_d, \Delta m_s\)

**CP-violating:** e.g., \(\gamma, \varkappa, \sin(2\beta)\)

**Exp. uncs.:** e.g., \(\alpha, \sin(2\beta), \gamma\)

**Syst. uncs.:** e.g., \(|V_{ub}|, |V_{cb}|, \varkappa, \Delta m_d, \Delta m_s\)
CKM and CPV SM Metrology: Belle II core program

$B \rightarrow \pi \pi, \rho \rho$

$B \rightarrow D^(*) K^(*)$

$B \rightarrow J/\psi K_s$

$B_s \rightarrow J/\psi \Phi$

$K \rightarrow \pi \nu \text{anti-}\nu$

$B_s \rightarrow \mu^+ \mu^-$

$B \rightarrow D \ell / b \rightarrow c \ell / b$

$B \rightarrow D_0 \ell / b \rightarrow c \ell / b$

$B \rightarrow D_0^0 \ell / b \rightarrow c \ell / b$

$B \rightarrow J/\psi K\beta\epsilon_K$

$B_s \rightarrow J/\psi K\beta\epsilon_K$

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$B_s \rightarrow J/\psi K\beta\epsilon_K$
SuperKEKB

Achievements

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>Achievements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^*_{\gamma}$(mm)</td>
<td>5.9/5.9</td>
<td>0.3/0.27</td>
<td>1/1</td>
</tr>
<tr>
<td>$I_{\text{beam}}$(A)</td>
<td>1.19/1.65</td>
<td>2.6/3.6</td>
<td><strong>0.70/0.88</strong></td>
</tr>
<tr>
<td>$L$(cm$^{-2}$s$^{-1}$)</td>
<td>2.11x10$^{34}$</td>
<td>80x10$^{34}$</td>
<td>1.88x10$^{34}$</td>
</tr>
</tbody>
</table>

1) New e$^+$ damping ring (commissioned 2018).
2) New 3 km e$^+$ ring vacuum chamber (commissioned in 2016). Optics and vacuum scrubbing in 2018.
3) New superconducting final focus (commissioned 2018).

20× smaller beam spot ($\sigma_y=50$ nm) but generally higher beam background

SuperKEKB, 1/6/2020

SuperKEKB Accelerator

Damping ring: reduces the beam emittance

New RF system: increases the beam current

New focusing magnets: reduces the beam size

KEKB $\rightarrow$ SuperKEKB

**Nano-beam scheme**

1 $\mu$m

400 $\mu$m

83 mrad

10 mm

Reduces the beam size in the interaction region to 50 nm.
Belle II Detector, 2020 Full Operations

K-Long and muon detector:
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM’s (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel + endcap)

Particle Identification
iTOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd)

Central Drift Chamber
He(50%):C$_2$H$_6$(50%), small cells, long lever arm, fast electronics (Core element)

Vertex Detector
1→2 layers DEPFET + 4 layers DSSD

Beryllium beam pipe
2cm diameter

~90% data taking efficiency

VXD:
Another key element is now ready in global cosmic since Jan 2019
VXD installed to Belle II (Nov 2018)

PXD: L1+1/6 of L2 (rest will be added in 2020)

One half of VXD

Large improvement in vertex resolution
~90% data taking efficiency
Nano-beams and the vertex detector

SuperKEKB

The vertex distribution is constrained in the nano-beam scheme.

\[ \sigma = 550 \, \mu m \]

Effective bunch length reduced x 1/10
And vertex resolution 2x better than Belle

Belle II

Belle II MC Vs Belle

D^0 lifetime:
Accepted value 410 fs

\[ \tau_{D^0} = 370 \pm 40 (stat) \, fs \]

Talk by R. Briere

Phillip URQUIJO
Tracking - tag and probe

$$\text{ee} \rightarrow \tau\tau(\gamma)$$

Used for early trigger & track efficiency measurements. Ratio of 3 and 4 track events, with e or µ tag.

More techniques being explored with > 10 fb⁻¹ datasets.

$$\epsilon_{\text{track}} \cdot A = \frac{N_4}{N_3 + N_4}$$

$$\delta = 1 - \frac{\epsilon_{\text{Data}}}{\epsilon_{\text{MC}}}$$

Talk by M. Villanueva

Systematic error on tracking based on averaging over subsets.

$$\delta_{\text{overall}} = 0.19 \pm 0.14 \text{ (stat)}\%$$
Hadron Identification

- $dE/dx$ (CDC, SVD) & Time of propagation Cherenkov patterns (TOP), and Cherenkov rings (ARICH).
- Performance with $D^*$ sample.
- FCNC $b \rightarrow d$ and $b \rightarrow s$ transitions are key are for flavour studies, requiring better $K/\pi$ ID performance than Belle.

**Belle II CDC $dE/dx$**
2018 Preliminary

Kinematically identified kaon from $D^*$ in TOP; $x$ vs $t$ pattern (mapping of Cherenkov ring)

$D^* \rightarrow D^0\pi^+$; $D^0 \rightarrow K^{-}\pi^+$

### Belle II 2019 Preliminary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$ (GeV/c)</td>
<td>1.73</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.84</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.94</td>
</tr>
<tr>
<td>$K$ decay</td>
<td>$\pi^-\pi^+$</td>
</tr>
<tr>
<td>$\pi$ decay</td>
<td>$\pi^0\pi^0$</td>
</tr>
<tr>
<td>Pixel column</td>
<td>15</td>
</tr>
<tr>
<td>Hit time [ns]</td>
<td>20</td>
</tr>
<tr>
<td>z</td>
<td>-69.1 cm</td>
</tr>
<tr>
<td>$dip$</td>
<td>8.5°</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>-21.5°</td>
</tr>
<tr>
<td>Prism side</td>
<td>Mirror side</td>
</tr>
</tbody>
</table>

### Belle II 2020 Preliminary

$D^*$ kinematically tagged kaon

- $p$ = 1.73 GeV/c
- $\beta$ = 0.84
- K efficiency (data)
- Kaon PDF
- log $L(K) = 236.38$

### Belle II 2018 Preliminary

- $p$ = 1.73 GeV/c
- $\beta$ = 0.84
- K efficiency (MC)
- Kaon PDF
- log $L(K) = 257.51$

**Pion PDF X**

**Kaon PDF ✓**
Lepton Reconstruction & Identification

- Targeting precision in LFUV tests. Challenge: $B \rightarrow \tau \rightarrow l$ have $<p> \sim 500$ MeV/c.
- Driven by ECL, KLM, + $dE/dx$ (CDC, SVD)
- $\mu$ Little to no radiation (heavy), Stable within Belle II but need $> 700$ MeV/c to reach KLM.
- $e$ Final state radiation, Brems. in material (less material than LHC detectors).
- Good universality between $e$ and $\mu$: efficiencies and resolution (after Brems. recovery).

![Diagram of Belle II and Belle-II simulation](image)

**FIG. 18**

$\int L \, dt = 5.2$ fb$^{-1}$

$N_{ee} = 3913 \pm 82$

$N_{\mu\mu} = 4053 \pm 75$

**FIG. 19**

Lepton identification $e$ vs $\bar{e}$ in barrel region. The cut on the classifier is arbitrarily chosen to result in a flat 95% average efficiency for correctly identifying $e$ with $\bar{e}$ in each of the three momentum categories. The mis-ID probability as a function of $\delta$ difference in probability of the BDT method with respect to the likelihood method.

M. Milesi, CHEP 2019

Fakes near 1% or lower.

Bellev II 2019 Preliminary

 Phillip URQUIJO
Stable photon efficiencies, resolution and pointing information for invariant masses from the calorimeter.

- Efficiencies: $ee \rightarrow \mu \mu \gamma$
- Resolution: $\pi^0$, $\eta$, $\mu \mu \gamma$
- Calibration and material effects under constant development and improvement.
- $K_L$-ID under development too.

$\pi^0 \rightarrow \gamma \gamma$

$\eta \rightarrow \gamma \gamma$

$\eta \rightarrow \pi \pi \eta(\gamma \gamma)$

Photon Efficiencies

Single Photon Lines
Counting

**Luminosity**

Measured with $\text{ee} \rightarrow \text{ee}(\gamma)$, $\gamma\gamma$ in ECL

**Integrated luminosity in phase 2**

$= 496.3 \pm 0.3 \pm 3.0 \text{ pb}^{-1}$

→ better than 1% precision.

**Belle II**

![Belle II Data, ee, γγ, Bkg, Tot](image)

**ECL clusters**

$\left| \phi_{cm}^{\max1} - \phi_{cm}^{\max2} \right| - 180^\circ$ [degrees]

**B-counting**

We are on the $\Upsilon(4S)$ resonance and recording $B$-anti $B$ pairs with ~99% efficiency. c.f. $\sigma(\Upsilon(4S))$-1.05 nb at 10.58 GeV

+ ~6 fb\(^{-1}\) of data taken 60 MeV below $\Upsilon(4S)$ to date.
2020 — Towards the first flavour publications

- (59) fb\(^{-1}\) on disk, ready to reach several hundred by the end of the year.
- Already 1 publication on dark sector searches - more soon to come.
- Flavour publications likely to start with 2019+2020 data - **several ideas for new \(\tau\) results.**

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Talk by M. Villanueva

2019: 10 fb\(^{-1}\) (November)

2020: ~80 fb\(^{-1}\) (End of run in June)

2020: ~200-400 fb\(^{-1}\) (December, **Babar 500 fb\(^{-1}\)**)

**Run resumes October.**

2021-2022: ~1 ab\(^{-1}\) (**Belle**) [arXiv: 1808.10567 / PTEP]

2023 5 ab\(^{-1}\) B2TiP Milestone
Search for an invisibly decaying $Z'$

- Search for vector boson $Z'$ that couples to 2nd and 3rd generation only.
- $ee \rightarrow \mu\mu Z'$ or $e\mu Z'$
- Invisible decays to Dark Matter or neutrinos.
- Possible explanation for g-2 anomaly.
- First physics publication.

limits on the $Z$ coupling constant at the level of $5 \times 10^{-2}$–1 for $M(Z') \leq 6$ GeV/$c^2$

**Belle II**

**Phillip URQUIJO**
Dark Sector - results to come

- Vector portal \( e F_{\gamma}^\mu v F_{\gamma}^\nu \mu (\text{dark photon } A') , \sum_i \theta g' I \gamma' Z' \mu ! (\text{dark } Z') \)
- Axion portal \( \frac{G_{agg}}{4} a G_\mu \gamma v + \frac{G_{agg}}{4} a F_{\gamma}^\mu v (\text{axion, alps}) \)
- Scalar portal \( \lambda H^2 S^2 + \mu H^2 S (\text{dark Higgs}) \)

Often with low multiplicity signatures, not explored at Belle. But the trigger/data volume is a challenge.

O(10 nb) acceptance / suppress QED events (100s nb), keeping B & D > 99% efficiency.

More to come, e.g.

- \( e^+ e^- \rightarrow \gamma X \)
- \( e^+ e^- \rightarrow \gamma \text{ ALP } (\rightarrow \gamma \gamma) \)
- \( e^+ e^- \rightarrow \gamma A' (\text{dark photon}) \)

Dark \( Z' \), Magn. Monopoles

Can also access through heavy flavour transitions.

Belle II

Phillip URQUIJO 15
Time dependent CP Violation / Overview

- $\Phi_1$ & New physics TDCPV in $b \to qqs$ transitions ($q = u,d,s$) are major targets
- $\Delta t$ resolution $\sim 0.77$ ps (30% to a factor 2 better than Belle);
- **PXD + nano-beam spot in Belle II, +30% $K_S$ acceptance**
- Effective flavour tagging efficiency $\sim 36\%$ (MC estimate, 30\% at Belle)

<table>
<thead>
<tr>
<th>Channel</th>
<th>WA (2017)</th>
<th>5 ab$^{-1}$</th>
<th>50 ab$^{-1}$</th>
<th>PTEP 2019 (2019) 12, 123C01</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K^0$</td>
<td>0.022</td>
<td>0.012</td>
<td>0.0052</td>
<td>SM</td>
</tr>
<tr>
<td>$\phi K^0$</td>
<td>0.12</td>
<td>0.048</td>
<td>0.020</td>
<td>NP</td>
</tr>
<tr>
<td>$\eta' K^0$</td>
<td>0.06</td>
<td>0.032</td>
<td>0.015</td>
<td>NP</td>
</tr>
<tr>
<td>$\omega K_S^0$</td>
<td>0.21</td>
<td>0.08</td>
<td>0.024</td>
<td>NP</td>
</tr>
<tr>
<td>$K_S^0 \pi^0 \gamma$</td>
<td>0.20</td>
<td>0.10</td>
<td>0.031</td>
<td>NP</td>
</tr>
<tr>
<td>$K_S^0 \pi^0$</td>
<td>0.17</td>
<td>0.09</td>
<td>0.028</td>
<td>NP</td>
</tr>
</tbody>
</table>

**Belle II**

**Phillip URQUIJO**

**Constrains penguin pollution**

**Expect Belle II to dominate all these channels within 2 years**
- Good understanding of basic tools and performance for TDCPV.
- B-decay vertices reconstructed using VXD hit information.
- ~1 ps $\Delta t$ resolution achieved - dominated by tag-side.

**Systematic Errors [ps]**

<table>
<thead>
<tr>
<th>Source</th>
<th>[ps]</th>
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<tbody>
<tr>
<td>Fit bias</td>
<td>0.05</td>
</tr>
<tr>
<td>$\tau_{\text{eff}}$</td>
<td>0.01</td>
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<tr>
<td>Calibration</td>
<td>0.03</td>
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</tbody>
</table>

- $\tau_{B^0} = 1.48 \pm 0.28 \pm 0.06$ ps compatible with world average $1.519 \pm 0.004$ ps
**B mixing**

- Fraction \( N_{OF}/(N_{OF}+N_{SF}) \) calculated for each \( \Delta t \) bin and compared with MC-expected value \( P_{OF}(\Delta t) \times R(\Delta t) \)
- \( P_{OF}(\Delta t) = [1 - \cos(\Delta m t)] \)
- Flavour specific final states: \( |+\pm|, |\pm| \)

\[
\chi_d = (17.2 \pm 5.6)\% \quad (WA = 18.6)\%
\]
**B reconstruction towards \( \Phi_1 \)**

- \( \sin 2\Phi_1 \) from \( B \rightarrow ccK^0 \) - a few x 1000 recorded by Belle II to date.
- With the full dataset “systematic” uncertainties will be larger, but data driven. Balance stat-power with good vertex fitted events.
- Searches for NP in \( B \rightarrow \eta'K_S \) etc. are stat limited through to 50 ab\(^{-1}\).
- For theory: often neglected the contributions from suppressed amplitudes carrying a different phase - need to work together on modes like \( B \rightarrow J/\psi \pi^0 \).

---

**Preliminary Belle II**

\[ \int L = 8.7 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal</th>
<th>Background</th>
<th>Expected signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^0 \rightarrow J/\psi K_S^0 ) ( J/\psi \rightarrow e^+e^- )</td>
<td>38.4 ( \pm 6.3 )</td>
<td>1.9 ( \pm 0.5 )</td>
<td>38.5 ( \pm 3.1 )</td>
</tr>
<tr>
<td>( B^0 \rightarrow J/\psi K_S^0 ) ( J/\psi \rightarrow \mu^+\mu^- )</td>
<td>74.8 ( \pm 8.5 )</td>
<td>0.5 ( \pm 0.2 )</td>
<td>64.6 ( \pm 4.5 )</td>
</tr>
<tr>
<td>( B^0 \rightarrow J/\psi K_S^0 ) ( J/\psi \rightarrow \ell^+\ell^- )</td>
<td>113.9 ( \pm 11.1 )</td>
<td>1.3 ( \pm 0.3 )</td>
<td>103.1 ( \pm 5.5 )</td>
</tr>
</tbody>
</table>

**Philipp URQUIJO**

**Talk by F. Abudinen**

---

<table>
<thead>
<tr>
<th>( \Phi_1 )</th>
<th>Current</th>
<th>50 ab(^{-1}) projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.7(^\circ)</td>
<td>0.2(^\circ)</td>
</tr>
<tr>
<td>Theoretical - QCDF &amp; pQCD</td>
<td>0.1(^\circ)</td>
<td>0.1(^\circ)</td>
</tr>
<tr>
<td>Theoretical - SU(3)</td>
<td>1.7(^\circ)</td>
<td>0.8(^\circ)</td>
</tr>
</tbody>
</table>

---

**Preliminary Belle II**

\[ \int L = 50 \text{ ab}^{-1} \]
B reconstruction towards $\Phi_2$ & Direct CPV

**Complement of B→Kπ isospin rotations required to test for new sources of CPV, $I_{K\pi} = 0$ in SM**

<table>
<thead>
<tr>
<th>Decay</th>
<th>MC Yield</th>
<th>Data Yield</th>
<th>MC Yield/fb⁻¹</th>
<th>Data Yield/fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K^+\pi^-$</td>
<td>371 ± 24</td>
<td>79 ± 11</td>
<td>7.4 ± 0.5</td>
<td>9.1 ± 1.3</td>
</tr>
<tr>
<td>$B^0 \to \pi^+\pi^-$</td>
<td>78 ± 11</td>
<td>16 ± 5</td>
<td>1.6 ± 0.2</td>
<td>1.8 ± 0.6</td>
</tr>
<tr>
<td>$B^+ \to K^0\pi^+$</td>
<td>83 ± 10</td>
<td>18 ± 5</td>
<td>1.7 ± 0.2</td>
<td>2.1 ± 0.6</td>
</tr>
<tr>
<td>$B^+ \to K^+\pi^0$</td>
<td>191 ± 20</td>
<td>27 ± 8</td>
<td>3.8 ± 0.4</td>
<td>3.1 ± 0.9</td>
</tr>
<tr>
<td>$B^+ \to K^+K^+K^-$</td>
<td>559 ± 28</td>
<td>92 ± 12</td>
<td>11.2 ± 0.6</td>
<td>10.6 ± 1.4</td>
</tr>
<tr>
<td>$B^+ \to K^+\pi^+\pi^-$</td>
<td>1008 ± 44</td>
<td>160 ± 19</td>
<td>20.2 ± 0.9</td>
<td>18.4 ± 2.2</td>
</tr>
</tbody>
</table>

$\int L \, dt = 8.7 \, fb^{-1}$

$\int L \, dt = 50 \, fb^{-1}$
B reconstruction towards $\Phi_3$

• Demonstration of Belle II high momentum PID on a decay mode to be used for future determinations of the UT angle $\Phi_3$. Improved $\Delta E$ resolution in Belle II - better DK/D$\pi$ separation than Belle.

• Ultimate reach of $\sim 1.5^\circ$ precision on $\Phi_3$ predominantly from GGSZ $D \to K_S^0\pi^+\pi^-$.

• Requires us to use neutral modes with significant BRs: CP even ($\pi^0\pi^0$, $K_L^0\pi^0$, $K_S^0\pi^0\pi^0$...), CP odd ($K_S^0K_S^0K_L^0$, $\eta\pi^0\pi^0$, ...), Self-conjugate ($K_L\pi\pi$, $K_LKK$...).

Talk by M. Merola
B → D(*) τ⁻ ν analysis / Converted Belle→Belle II Data

- Semileptonic tag / FEI BDT, B→D τ ν and B→D* τ ν Simultaneously
- Employed Belle II analysis framework. Stat. limited!

\[ R(D) = 0.307 \pm 0.037 \pm 0.016 \]
\[ R(D^*) = 0.283 \pm 0.018 \pm 0.014 \]

2D fit \( E_{\text{ECL}} + \text{BDT}_{XGBoost} \) [\( M^2_{\text{miss}}, E_{\text{vis}}, \cos \theta_{B-D^*} \)]
B → D*(*)τ−ν analysis / Converted Belle→Belle II Data

- Semileptonic tag / FEI BDT, B→D τ ν and B→D* τ ν Simultaneously
- Employed Belle II analysis framework. Stat. limited!

\[ \mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016 \]
\[ \mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014 \]
Untagged $B \rightarrow D^* 1 \nu$

- Signals for $B \rightarrow D^+ l^{-} \nu$, $D^* \rightarrow D^{0} \pi^{+}$ using $\cos \theta_{BD^{*}}$
- Clear signals are found in both $e$ and $\mu$ modes.
- BRs consistent with WA. Performance corrections applied.

$$B(\bar{B}^{0} \rightarrow D^{*+} e^{-} \bar{\nu}_{e}) = (4.42 \pm 0.14 ({\text{stat}}) \pm 0.33 ({\text{sys}}))\%$$

$$B(\bar{B}^{0} \rightarrow D^{*+} \mu^{-} \bar{\nu}_{\mu}) = (4.70 \pm 0.13 ({\text{stat}}) \pm 0.35 ({\text{sys}}))\%$$

$$\cos \theta_{BY} = \frac{2E_{B}^{*}E_{Y}^{*} - M_{B}^{2} - m_{Y}^{2}}{2p_{B}^{*}p_{Y}^{*}}$$


Talk by M. Merola
B full reconstruction algorithms

- Belle (II) analyses use semileptonic and hadronic “tagging” for flavour, charge, kinematics.

**MC tag-side efficiency @10% purity**

<table>
<thead>
<tr>
<th></th>
<th>Had. $B^+/B^{0}$ [%]</th>
<th>SL. $B^+/B^{0}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Reconstruction Belle</td>
<td>0.28/0.18</td>
<td>0.67/0.63</td>
</tr>
<tr>
<td>FEI Belle</td>
<td>0.76/0.46</td>
<td>1.80/2.04</td>
</tr>
</tbody>
</table>

N of correct $B_{tag}$ per 1 fb$^{-1}$ in Belle (FEI)

8350/5060

19800/22440

650k Hadronic B-tags for physics analysis already (50 fb$^{-1}$)!
- Enough for tagged measurements of many modes.

Belle II

Phillip URQUIJO

Talk by S. Stekova
Semileptonic and leptonic B decays / Targets

- History of anomalies in |V_{ub}|, |V_{cb}|, B→D(∗) τ ν — key to identify bias.
- CKM precision tests are challenging, but more data will help overcome over most systematic errors.
- Improvements to K_L reconstruction, beam background mitigation for SE_ECL, B→D** l ν background, tag efficiency, tag calibration.
- Purely leptonic modes are a Belle II focus for > 1 ab⁻¹.

<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⋅10⁻³ ⋅ (1 ± 1.8%)</td>
</tr>
<tr>
<td></td>
<td>V_{cb}</td>
<td>excl.</td>
<td>39.0⋅10⁻³ ⋅ (1 ± 3.0%<em>{ex} ± 1.4%</em>{th.})</td>
</tr>
<tr>
<td></td>
<td>V_{ub}</td>
<td>incl.</td>
<td>4.47⋅10⁻³ ⋅ (1 ± 6.0%<em>{ex} ± 2.5%</em>{th.})</td>
</tr>
<tr>
<td></td>
<td>V_{ub}</td>
<td>excl. (WA)</td>
<td>3.65⋅10⁻³ ⋅ (1 ± 2.5%<em>{ex} ± 3.0%</em>{th.})</td>
</tr>
<tr>
<td>B(B → τν) [10⁻⁶]</td>
<td>91 ⋅ (1 ± 24%)</td>
<td>9%</td>
<td>4%</td>
</tr>
<tr>
<td>B(B → μν) [10⁻⁶]</td>
<td>&lt; 1.7</td>
<td>20%</td>
<td>7%</td>
</tr>
<tr>
<td>R(B → Dτν) (Had. tag)</td>
<td>0.374 ⋅ (1 ± 16.5%)</td>
<td>6%</td>
<td>3%</td>
</tr>
<tr>
<td>R(B → D∗τν) (Had. tag)</td>
<td>0.296 ⋅ (1 ± 7.4%)</td>
<td>3%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Belle II  
Phillip URQUIJO
**b → s γ Reconstruction**

- Large program of radiative decays CP violation - New sources of CP violation in B→K⁺γ, pγ could reveal right handed currents.
- B→K⁺π⁰γ is a near term target for TDCPV analysis.
- b→d currents not well explored yet.
- Reconstructed yields (2.6 fb⁻¹) consistent with WA branching fraction.

<table>
<thead>
<tr>
<th>Signal Yield (stat. error only)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>B⁰ → K⁺⁰[K⁺π⁻]γ</td>
<td>19.1 ± 5.2</td>
</tr>
<tr>
<td>B⁺ → K⁺⁺[K⁺π⁰]γ</td>
<td>9.8 ± 3.4</td>
</tr>
<tr>
<td>B⁺ → K⁺⁺[K⁺π⁻]γ</td>
<td>6.6 ± 3.1</td>
</tr>
</tbody>
</table>

- Any right-handed currents from NP?
- SM favored
- SM disfavored, enhanced with RH current

**Talk by S. Halder**

**Belle II**

**Phillip URQUIJO**
EW penguin B decay prospects

- Belle II should refute/confirm deviations observed by LHCb within 4 years. Expect first signals by ICHEP.
- Electron channels (low X/X₀) good resolution & τ channels
- Inclusive B→X l⁺ l⁻ (initially sum over exclusives with M(Xₜ) < 1.8 GeV/c², eventually: explore fully inclusive recoil).

Expect to see first clear signals in data collected to date!

Rare: e.g. BR(B⁰→K⁺π⁻)=(9.9±1.2) x 10⁻⁷

Talk by S. Halder

Belle Preliminary 2019,
R(K*) arXiv:1904.02440
R(K) arXiv:1908.01848

Belle II 2019
Projections for R(K*)

Pull

Events / (0.0025 GeV/c²)

M_{bc} (GeV/c²)

Pull

Events / (0.0025 GeV/c²)

M_{bc} (GeV/c²)

R(K)

0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8

q² (GeV²/c⁴)

0 5 10 15 20

Data
LHCb
BaBar
SM prediction
• Except for $B \rightarrow X_{s+d} \gamma$ inclusive, all channels are highly statistics limited.
• Expect systematics to be subdominant beyond 50 ab$^{-1}$
• Key to understand beam background induced efficiency loss and $E_{ECL}$ degradation in $B \rightarrow K\nu\nu$.
• SM level (5 $\sigma$) in $B \rightarrow X\nu\nu$. Novel ALPs/Scalars/LLPs searches in $B$ decays.

<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>$B(B \rightarrow K^{+}\nu\bar{\nu})$</td>
<td>$&lt; 40 \times 10^{-6}$</td>
<td>25%</td>
<td>9%</td>
</tr>
<tr>
<td>$B(B \rightarrow K^{+}\nu\bar{\nu})$</td>
<td>$&lt; 19 \times 10^{-6}$</td>
<td>30%</td>
<td>11%</td>
</tr>
<tr>
<td>$A_{CP}(B \rightarrow X_{s+d}\gamma)$ [10$^{-2}$]</td>
<td>$2.2 \pm 4.0 \pm 0.8$</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$S(B \rightarrow K^{0}_{S}\pi^{0}\gamma)$</td>
<td>$-0.10 \pm 0.31 \pm 0.07$</td>
<td>0.11</td>
<td>0.035</td>
</tr>
<tr>
<td>$S(B \rightarrow \rho\gamma)$</td>
<td>$-0.83 \pm 0.65 \pm 0.18$</td>
<td>0.23</td>
<td>0.07</td>
</tr>
<tr>
<td>$A_{FB}(B \rightarrow X_{s}\ell^{+}\ell^{-})$ (1 &lt; $q^{2}$ &lt; 3.5 GeV$^2$/c$^4$)</td>
<td>26%</td>
<td>10%</td>
<td>3%</td>
</tr>
<tr>
<td>$Br(B \rightarrow K^{+}\mu^{+}\mu^{-})/Br(B \rightarrow K^{+}e^{+}e^{-})$ (1 &lt; $q^{2}$ &lt; 6 GeV$^2$/c$^4$)</td>
<td>28%</td>
<td>11%</td>
<td>4%</td>
</tr>
<tr>
<td>$Br(B \rightarrow K^{+}(892)\mu^{+}\mu^{-})/Br(B \rightarrow K^{+}(892)e^{+}e^{-})$ (1 &lt; $q^{2}$ &lt; 6 GeV$^2$/c$^4$)</td>
<td>24%</td>
<td>9%</td>
<td>3%</td>
</tr>
<tr>
<td>$B(B \rightarrow \gamma\gamma)$</td>
<td>$&lt; 8.7 \times 10^{-6}$</td>
<td>23%</td>
<td>–</td>
</tr>
<tr>
<td>$B(B \rightarrow \tau\tau)$ [10$^{-3}$]</td>
<td>–</td>
<td>$&lt; 0.8$</td>
<td>–</td>
</tr>
</tbody>
</table>

\[
\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{td} V_{ts}^{*} \frac{e^2}{16\pi^2} \sum (C_1 O_1 + C_2 O_2') + \text{h.c.}
\]
Expected (Integrated) Luminosity

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>Integrated luminosity &gt; 0.5 — 1.0 ab(^{-1})</td>
</tr>
<tr>
<td>2022</td>
<td>$\beta_y^* \to$ reach 0.3 mm (design value)</td>
</tr>
<tr>
<td>2023</td>
<td>Integrated luminosity 5 ab(^{-1})</td>
</tr>
<tr>
<td>2026</td>
<td>Peak luminosity to reach $\sim 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (design value)</td>
</tr>
<tr>
<td>2028</td>
<td>Integrated luminosity 50 ab(^{-1})</td>
</tr>
</tbody>
</table>
### Belle II - LHCb Comparison

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current Belle/ Babar</th>
<th>2019 LHCb</th>
<th>Belle II (5 ab⁻¹)</th>
<th>Belle II (50 ab⁻¹)</th>
<th>LHCb (23 fb⁻¹)</th>
<th>Belle II Upgrade (250 ab⁻¹)</th>
<th>LHCb upgrade II (300 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CKM precision, new physics in CP Violation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sin 2β/φ₁ (B→ J/ψ Kₛ)</td>
<td>0.03</td>
<td>0.04</td>
<td>0.012</td>
<td>0.005</td>
<td>0.011</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>γ/ψ₁</td>
<td>13°</td>
<td>5.4°</td>
<td>4.7°</td>
<td>1.5°</td>
<td>1.5°</td>
<td>0.4°</td>
<td>0.4°</td>
</tr>
<tr>
<td>α/ψ₂</td>
<td>4°</td>
<td>–</td>
<td>2</td>
<td>0.6°</td>
<td>–</td>
<td>0.3°</td>
<td>–</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>New physics in radiative &amp; EW Penguins, LFUV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_CP (B→η' Kₛ, gluonic penguin)</td>
<td>0.08</td>
<td>–</td>
<td>0.03</td>
<td>0.015</td>
<td>–</td>
<td>0.007</td>
<td>–</td>
</tr>
<tr>
<td>A_CP (B→K_Sπ⁰)</td>
<td>0.15</td>
<td>–</td>
<td>0.07</td>
<td>0.04</td>
<td>–</td>
<td>0.02</td>
<td>–</td>
</tr>
<tr>
<td><strong>Charm and τ</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔA_CP (KK-ππ)</td>
<td>–</td>
<td>8.5×10⁻⁴</td>
<td>–</td>
<td>5.4×10⁻⁴</td>
<td>1.7×10⁻⁴</td>
<td>2×10⁻⁴</td>
<td>0.3×10⁻⁴</td>
</tr>
<tr>
<td>A_CP (D→π/π⁰)</td>
<td>1.2%</td>
<td>–</td>
<td>0.5%</td>
<td>0.2%</td>
<td>–</td>
<td>0.1%</td>
<td>–</td>
</tr>
<tr>
<td>B_r(τ→e γ)</td>
<td>&lt;120×10⁻⁹</td>
<td>–</td>
<td>&lt;40×10⁻⁹</td>
<td>&lt;12×10⁻⁹</td>
<td>–</td>
<td>&lt;5×10⁻⁹</td>
<td>–</td>
</tr>
<tr>
<td>B_r(τ→μμμ)</td>
<td>&lt;21×10⁻⁹</td>
<td>&lt;46×10⁻⁹</td>
<td>&lt;3×10⁻⁹</td>
<td>&lt;3×10⁻⁹</td>
<td>&lt;16×10⁻⁹</td>
<td>&lt;0.3×10⁻⁹</td>
<td>&lt;5×10⁻⁹</td>
</tr>
</tbody>
</table>

*Possible in similar channels, lower precision – Not competitive.*

**Belle II**

Higher sensitivity to decays with photons and neutrinos (e.g. B→Kνν, νν), inclusive decays, time dependent CPV in B_d, τ physics.

**LHCb**

Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

**Overlaps in various key areas to verify discoveries.**

**Upgrades**

Most key channels will be stats. limited (not theory or syst.).

LHCb scheduled major upgrades during LS3 and LS4. Belle II formulating a 250 ab⁻¹ upgrade program post 2028.

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*arXiv: 1808.08865 (Physics case for LHCb upgrade II), PTEP 2019 (2019) 12, 123C01 (Belle II Physics Book)*
Conclusion

- **60 fb⁻¹ collected** (much of it during Covid19 travel restrictions): x10 or more each year since commencing in 2018.
- Enough to explore the power of Belle II with performance control channels, and to start the flavour physics program in earnest.
- Presented selected highlights with up to 10 fb⁻¹ with 2018+2019 data.
- **Dark sector publication on dark Z’,** with ALPs and dark photons to come soon.
- **First competitive flavour publications within reach.**

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**Belle II Presentations at FPCP**

- **F. Abudinen**, Belle II Highlights on first physics results
- **R. Briere**, Charm and Charmonium at Belle II
- **S. Halder**, Results and Prospects of Radiative and Electroweak Penguin Decays at Belle II
- **M. Merola**, CKM first measurements at Belle II
- **S. Stefkova**, Status and future development of the Full Event Interpretation algorithm at Belle II
- **M. H. Villanueva**, Tau physics highlights and prospects at Belle II