The Belle II experiment
Status and Prospects

Kunxian Huang¹
Behalf of the Belle II collaboration
¹National Taiwan Univ.
@NuFACT 2019, Daegu, Korea
Outline

- SuperKEKB accelerator and Belle II detector
  - Road to high Luminosity
    - Operation of Phase 3
  - Performance of Phase 2 and phase 3
- Physics Prospects
- Particle re-discovered @ Belle II
- Decay mode re-discovered @ Belle II
B factory experiment milestones

- Belle and Babar experiments operated until ~2010 used $e^-e^+$ accelerator with asymmetry energies to produce mass of B mesons. 1.5 ab$^{-1}$ data are recorded.
- Target of luminosity of SuperKEKB/Belle II is 50 ab$^{-1}$.  
- High luminosity, boosted B meson.  
  - CKM matrix unitary angles  
  - CP violation  
  - Rare B/D meson decays  
- LFV/LNV in tau decays  
- Search for tetraquark & pentaquark
### KEKB to SuperKEKB

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>$E_b$</td>
<td>3.5</td>
<td>8</td>
</tr>
<tr>
<td><strong>Beam crossing angle</strong></td>
<td>$\phi$</td>
<td>22</td>
<td>83</td>
</tr>
<tr>
<td><strong>$\beta$ function @ IP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_x^*/\beta_y$</td>
<td>1200/5.9</td>
<td>32/0.27</td>
<td>25/0.30</td>
</tr>
<tr>
<td><strong>Beam current</strong></td>
<td>$I_b$</td>
<td>1.64</td>
<td>1.19</td>
</tr>
<tr>
<td><strong>Peak Luminosity</strong></td>
<td>$L$</td>
<td>$2.1 \times 10^{34}$</td>
<td>$80 \times 10^{34}$</td>
</tr>
</tbody>
</table>

- **Lorentz factor**
- **Beam current**
- **Beam-beam factor**

- **Beam aspect ratio** (flat beam ~ 1-2%)
- **Vertical beta function at IP**
- **Geometrical corrections** (Hourglass effect...)

**New superconducting/permanent final focusing quads near the IP**
Phase 1: Background, Optics Commissioning, Feb–June 2016. No Collision. No Belle Detector.

Belle II Detector rolled-in to the beamline, Apr., 2017

Phase 2: Pilot run, Superconducting Final Focus, add positron damping ring, First Collisions (0.5 fb⁻¹). No VXD detector. April 27–July 17, 2018

Belle II collaboration

- Belle II now has grown to ~948 researchers from 26 countries.
- Youth and potential: There are 330 graduate students in the collaboration.

Korea institutes:
Chonnam, Gyeongsang, Hanyang, KISTI, Korea, Kyungpook, Seoul, Soongsil, Yonsei
Belle II detector

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

- Beryllium beam pipe
  - 2cm diameter

- Vertex Detector
  - 2 layers DEPFET + 4 layers DSSD

- Central Drift Chamber
  - He(50%):C_{2}H_{6}(50%), small cells, long lever arm, fast electronics (Core element)

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

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

- Electrons (7 GeV)

- Positrons (4 GeV)
VXD (PXD+SVD) detector installed in Phase 3

Installation work finished Nov. 2018.

- **PXD**: Two layers of DEPFET pixel sensors $r=14\text{mm}$, $r=22\text{mm}$.
  - Only inner layer and small part of outer layer installed, replacement with full system in 2021
- **SVD**: Four layers of double sided strip detectors $r=39\text{mm}$ to $r=140\text{mm}$
First Collisions in Phase 3
## Luminosity of SuperKEKB/Belle II phase 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved in phase 3</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{\text{LER}} ) (A)</td>
<td>0.880</td>
<td>2.6</td>
</tr>
<tr>
<td>( I_{\text{HER}} ) (A)</td>
<td>0.940</td>
<td>3.6</td>
</tr>
<tr>
<td>( \beta_y ) (mm)</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td># of bunches</td>
<td>1576</td>
<td>2364</td>
</tr>
<tr>
<td>( L_{\text{peak}} ) (cm(^{-2})s(^{-1}))</td>
<td>Det on 6.1 x 10(^{33})</td>
<td>8 x 10(^{35})</td>
</tr>
<tr>
<td></td>
<td>Det off 12 x 10(^{33})</td>
<td></td>
</tr>
</tbody>
</table>

Total \( \int L \, dt = 6.49 \text{ [fb}^{-1}\)\]

- Fire accident in Linac
- Restored in One month
Impact parameter resolution

$\sigma_y \sim 1.5 \mu m$

Beam-profile effect is subtracted at this plot.

VXD resolution in impact parameter $\sim 14 \ \mu m$

Impact parameter distributions in two-track events. Alignment and calibration are working well.
K/π identification by TOP detector

K and π tracks are tagged from the charge of the slow π (daughter of D∗+) in the decay of D∗+ → D⁰[K−π+]π⁺.

A kaon track consist with the kaon-hypothesis PDF.
Physic Prospect
Rich Physics in Belle II

Leptonic/Semi-leptonic

<table>
<thead>
<tr>
<th>Process</th>
<th>Observable</th>
<th>Theory</th>
<th>Sys limit (Disco.)</th>
<th>vs LHCb</th>
<th>vs Belle</th>
<th>Anomaly</th>
<th>NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow \pi \ell \nu$</td>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
<td>***</td>
<td>10-20</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>$B \rightarrow X_c \ell \nu$</td>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
<td>**</td>
<td>2-10</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>$B \rightarrow \tau \nu$</td>
<td>Br.</td>
<td>***</td>
<td>&gt;50 (2)</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \rightarrow \mu \nu$</td>
<td>Br.</td>
<td>***</td>
<td>&gt;50 (5)</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \rightarrow D^{(*)} \ell \nu$</td>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
<td>***</td>
<td>1-10</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>$B \rightarrow X_u \ell \nu$</td>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
<td>***</td>
<td>1-5</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>$B \rightarrow D^{(*)} \tau \nu$</td>
<td>$R(D^{(*)})$</td>
<td>***</td>
<td>5-10</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \rightarrow D^{(*)} \tau \nu$</td>
<td>$P_\tau$</td>
<td>***</td>
<td>15-20</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \rightarrow D^{(*)} \tau \nu$</td>
<td>Br.</td>
<td>*</td>
<td>-</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>-</td>
</tr>
</tbody>
</table>

Radiative/EWP

| Process | $|V_{ud}|$ | Theory | Sys limit (Disco.) | vs LHCb | vs Belle | Anomaly | NP |
|---------|------------|--------|-------------------|---------|---------|---------|-----|
| $B \rightarrow K^{(*)} \nu \nu$ | $R_{\nu
u}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow X_{s+d} \gamma$ | $A_{CP}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow X_{d} \gamma$ | $A_{CP}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow K^{(*)}\pi^0\gamma$ | $S_{K^{(*)}\gamma}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow \phi \gamma$ | $S_{\phi \gamma}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow X_s l^+ l^-$ | Br. | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow X_s l^+ l^-$ | $R_{X_s}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow K^{(*)} e^+ e^-$ | $R(K^{(*)})$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow X_{s} \gamma$ | Br. | *** | 1-5 | *** | *** | *** | ** |
| $B \rightarrow K_{L,\phi} \rightarrow \gamma\gamma$ | Br. | $A_{CP}$ | ** | > | *** | ** | - |
| $B \rightarrow K^{*} e^+ e^-$ | $P_{K^{*}}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow K_{L}$ | Br. | *** | >50 | *** | *** | *** | ** |

CPV

<table>
<thead>
<tr>
<th>Process</th>
<th>$\phi$</th>
<th>Theory</th>
<th>Sys limit (Disco.)</th>
<th>vs LHCb</th>
<th>vs Belle</th>
<th>Anomaly</th>
<th>NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow J/\psi K_S^0$</td>
<td>$\phi_1$</td>
<td>***</td>
<td>&gt;10</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \rightarrow J/\psi K_S^0$</td>
<td>$\phi_1$</td>
<td>***</td>
<td>&gt;10</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \rightarrow \eta K_S^0$</td>
<td>$\phi_1$</td>
<td>***</td>
<td>&gt;10</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \rightarrow J/\psi \pi^0$</td>
<td>$\phi_1$</td>
<td>***</td>
<td>&gt;10</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \rightarrow \rho^0 \pi^0$</td>
<td>$\phi_2$</td>
<td>***</td>
<td>&gt;10</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \rightarrow \eta \eta^*$</td>
<td>$\phi_2$</td>
<td>***</td>
<td>&gt;10</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \rightarrow \phi \phi$</td>
<td>$\phi_3$</td>
<td>***</td>
<td>&gt;10</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
</tbody>
</table>

Integrated Luminosity target: 50 ab$^{-1}$

| $B \rightarrow \phi \gamma$ | $A_{CP}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow \phi \gamma$ | $A_{CP}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow \phi \gamma$ | $A_{CP}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow \phi \gamma$ | $A_{CP}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow \phi \gamma$ | $A_{CP}$ | *** | >50 | *** | *** | *** | ** |
| $B \rightarrow \phi \gamma$ | $A_{CP}$ | *** | >50 | *** | *** | *** | ** |

<table>
<thead>
<tr>
<th>Golden mode</th>
<th>Hadronic</th>
<th>Silver mode</th>
<th>Charm</th>
<th>Tau</th>
</tr>
</thead>
</table>

Quarkonium and Dark sectors.

Few selected topics are mentioned later. “The Belle II Physics Book” has more exciting topics.
CKM unitarity triangle global fit

2016

CKM global fit with Belle II 50 ab$^{-1}$

Error depress much
Leptonic Decays of $B^+ \rightarrow \mu^+ \nu$ & $B^+ \rightarrow \tau^+ \nu$

- Leptonic decay: Tree process. Branching fractions of $B^+ \rightarrow l^+ \nu$ in SM is proportional to $m_l^2$ as below function.

$$B(B^+ \rightarrow l^+ \nu)_{SM} = \frac{G_F^2 M_B M_l^2}{8\pi} \left(1 - \frac{M_l^2}{M_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B$$

- Clean processes with accurate theoretical BF.
- Small theoretic uncertainties in SM
  - Good probe for new physics in tree process.
- The effect of two Higgs doublet models (2HDM II) to branching ratio of $\mu^+ \nu$ is as below:

$$B_{2HDM II} = r_H B_{SM}, r_H \sim (1 - t^2 \frac{m_B^2}{m_H^2})^2$$

- If NP affects only on $\tau^+ \nu$ mode, to eliminate uncertainties of $f_B$ and $|V_{ub}|$. The below ratios are used to prove NP.

$$R_{pl} = \frac{\tau_{B^0}}{\tau_{B^+}} \frac{B(B^+ \rightarrow \tau^+ \nu_\tau)}{B(B^0 \rightarrow \pi^+ l^+ \nu_l)} \quad R_{pl} = \frac{B(B^+ \rightarrow \tau^+ \nu_\tau)}{B(B^+ \rightarrow \mu^+ \nu_\mu)}$$

<table>
<thead>
<tr>
<th>Lepton</th>
<th>$B_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>$(8.89\pm0.73) \times 10^{-12}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$(3.80\pm0.31) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$(8.45\pm0.70) \times 10^{-5}$</td>
</tr>
</tbody>
</table>
\[ B^+ \rightarrow \tau^+ \nu \]

**Belle result:**

- **Semileptonic tag (PRD 92(5),051102,2015)**
  \[ BF = [1.25 \pm 0.28 \text{(stat.)} \pm 0.27 \text{(syst.)}] \times 10^{-4}. \]

- **Hadronic tag (PRL 110,131801,2013)**
  \[ BF = [0.72 + 0.27 - 0.25 \text{(stat.)} \pm 0.11 \text{(syst.)}] \times 10^{-4}. \]

- **\(|V_{ub}|\) measurement**

- Exploit new method of Full Event Interpretation (FEI) to select correct reconstruction of \( B_{\text{sig}} \) & \( B_{\text{tag}} \):
  - \( B_{\text{tag}} \) can be hadronic tag or semileptonic
  - Efficiency (total few \( 10^{-3} \)) is higher than the method used in Belle.

- **Feature:** 2 or 3 neutrinos in final state.
  \( M_{\text{miss}}^2 \): large in \( \tau \) leptonic, small in \( \tau \) hadronic

- Due high rate of beam background, cluster timing, crystal energy \( E_9/E_{25} \) → select \( \pi^0 \).
$B^+ \rightarrow \mu^+ \nu$

**Belle result:** (PRL 121,031801,2018)
$BF = [6.46 \pm 2.22 \text{ (stat.)} \pm 1.60 \text{ (syst.)}] \times 10^{-7}. @ 2.4\sigma$

- As the tag efficiency is low, better not to use tag method.
- Background: continuum, $\pi \ell \nu$, $\rho \ell \nu$, and BB generic.
- Neural Network/GBDT is used to suppress background.
  - 14 input parameters that is uncorrected with $|P_\mu|$. Output: $O_{nn}$
- $P_\mu^*$ in CM frame
- Feature: $P_\mu^{B} \sim M_B/2$ in B rest frame.
  - Convert $P_\mu^*$ to $P_\mu^B$
- Likely to claim observation at 5 $ab^{-1}$. 

<table>
<thead>
<tr>
<th>$\ell$</th>
<th>$B_{SM}$</th>
<th>711 fb$^{-1}$</th>
<th>5 $ab^{-1}$</th>
<th>50 $ab^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>$(7.71 \pm 0.62) \times 10^{-5}$</td>
<td>$61200 \pm 5000$</td>
<td>$430000 \pm 35000$</td>
<td>$430000 \pm 350000$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$(3.46 \pm 0.28) \times 10^{-7}$</td>
<td>$275 \pm 23$</td>
<td>$1930 \pm 160$</td>
<td>$1930 \pm 160$</td>
</tr>
<tr>
<td>$e$</td>
<td>$(0.811 \pm 0.065) \times 10^{-11}$</td>
<td>$0.0064 \pm 0.0005$</td>
<td>$0.0453 \pm 0.0037$</td>
<td>$0.453 \pm 0.037$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>$R_{ps}$</th>
<th>$R_{pl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 $ab^{-1}$</td>
<td>$[-0.22, 0.20]$</td>
<td>$[-0.42, 0.29]$</td>
</tr>
<tr>
<td>50 $ab^{-1}$</td>
<td>$[-0.11, 0.12]$</td>
<td>$[-0.12, 0.11]$</td>
</tr>
</tbody>
</table>
$B^0 \rightarrow \pi^0 \pi^0$ decay

- Color suppressed tree process. Experimental result is $BF = [1.31 \pm 0.19 \text{(stat.)} \pm 0.18 \text{ (syst.)}] \times 10^{-6}$

Belle 2017
  - Theory paper for this enhancement: PRD 73, 114014 (2006), PRD 83, 034023 (2011)
  - More data and lower sys error are needed.

- $\Phi_2$ angle measurement by direct CP violation. $A_{CP} = 0.14 \pm 0.36 \pm 0.10$

- Due to high rate of beam background, timing and $E_9/E_{25}$ selection of $\gamma$ are important.

- Flavor tag of $B_{tag}$

- Spreaded signal shape in $\Delta E$
$B^0 \rightarrow \pi^0 \pi^0$ decay

- Color suppressed tree process. Experimental result is $BF = [1.31\pm0.19\text{(stat.)}\pm0.18 \text{ (syst.)}] \times 10^{-6}$

Belle 2017

- Theory paper for this enhancement: PRD 73, 114014 (2006), PRD 83, 034023 (2011)
- More data and lower sys error are needed.

- $\Phi_2$ angle measurement by direct CP violation. $A_{CP} = 0.14 \pm 0.36 \pm 0.10$

- Due to high rate of beam background, timing and $E_9/E_{25}$ selection of $\gamma$ are important.

- Flavor tag of $B_{tag}$

- Spreaded signal shape in $\Delta E$
Charmless Baryonic B decays

Baryonic B decay is B meson decay to two baryons + etc.

\[ B \rightarrow B\bar{B}' + m \]

Threshold enhancement:

- \( M_{BB'} \) peak at low mass region: \( M_{BB'} \sim m_B + m_{B'} \)

First found rare baryonic decay in Belle, 2002

Through \( b \rightarrow s\gamma \) process, Belle 2005

- Threshold enhancement is an universal feature in baryonic B decay.

- Possible Theory
  - Baryon form factor
    - Cheng & Yang PRD 66 014020 ('02)
    - Chua, Hou, Tsai PRD 66 054004 ('02)
  - Quasi 2-body decay
    - Chua, Hou, Tsai PLB 544 139 ('02)

- Direct CP violation is also shown in \( B^+ \rightarrow p\bar{p}K^+ \) at \( M_{pp} < 2.85 \) GeV by LHCb
Angular asymmetries of Baryonic B decays

$\Theta_p$: angle between p direction and the meson/photon direction in BB-bar rest frame.

- Angle asymmetries are large and unexpected.
- LHCb found that angle asymmetries is function of $M_{pp}$ in $B^+\rightarrow p\bar{p}K^+$ and $B^+\rightarrow p\bar{p}\pi^+$ (PRL 113, 141801 (2014))
- This issue is still a puzzle.
  - Need more data for search asym. in more modes.
Possible topics

- $B^+ \rightarrow p \bar{p} \rho^+$
- $B^0 \rightarrow p \Sigma^0 \pi^-$
- $B^0 \rightarrow p \bar{p} \pi^0$
- $B^- \rightarrow p \bar{p} \ell \nu$
- $B^- \rightarrow p \bar{n} K^-$
- $B^0 \rightarrow n \Lambda^0 \gamma$
- etc.
Lepton Flavor Violation $\tau$ Decays at Belle II

- Super B-Factor, and $\tau$ factory too!
  $\sigma(e^+e^- \rightarrow \gamma(4s)) = 1.05$ nb
  $\sigma(e^+e^- \rightarrow \tau\tau) = 0.92$ nb
- Charged LPV process occur oscillations in loops. In SM, small rate is immeasurable ($10^{-49}$~$10^{-54}$) for all LFV decays.

$$B(l_1 \rightarrow l_2 \gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{l_1,i}^* U_{l_2,i} \frac{\Delta m^2_{l_1}}{M_{WW}^2} \right|^2$$

- Charged LFV enhanced in many NP models ($10^{-7}$~$10^{-10}$)
  
  Thrust and visible energy are useful variables in analysis.
LFV $\tau$ Decays at Belle II

- Observation of LFV is a clear signature of New Physics.
- Lower the upper limit by two order of magnitude.
Particle re-discover
Mass peaks

- \( \pi^0 \rightarrow \gamma \gamma \)
- \( \eta \rightarrow \gamma \gamma \)
- \( J/\psi \rightarrow e^+ e^- \)
- \( J/\psi \rightarrow \mu^+ \mu^- \)

Impact parameter
Vertex fitting

\( E_9 / E_{21} \) selection
Mass peaks

Impact parameter $E_9/E_{21}$ selection

$K_s$ optimization selection

$D^0 \rightarrow K^+ \pi^-$

$D^0 \rightarrow K^+ \pi^- \pi^0$

$D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$

$D^0 \rightarrow K^+ K^-$

$D^0 \rightarrow K^- K^+$
Topology of final states of B meson

---

Fox-Wolfram moments

$$R_2 = \frac{H_2}{H_0}$$

FW moments variables are used to separate BB pair event from qq-bar events.
Re-discover B meson

Demonstration of Capabilities: Modes with neutrals, and $K_s$ mesons are efficiently reconstructed along with all-charged final states containing kaons and pions.
B decay mode re-discover
FEI: BDT (boosted decision trees) and a large number of B decay modes. Increase yields by $O(X^8)$ than FR of Belle.

$B_{\text{tag}}$ by Full Event Interpreter

$B_{\text{tag}}^{+}$

$B_{\text{tag}}^{0}$

$B_{\text{sig}}$ are reconstruct from $B \rightarrow Xlv$. 
Semi-leptonic B decays

Untagged of $B^0 \rightarrow D^{*+} \ell^- \nu$ candidates in $m_{\text{miss}}^2$ distribution. Clean signal can be seen in e and $\mu$ mode.

$$m_{\text{miss}}^2 = \left( \frac{P_{ee}}{2} - P_{D^*\ell}^* \right)$$
Observation of $B \to K^* \gamma$

First observation radiative penguin process ($b \to s \gamma$) @Belle II.

\[ B^0 \to K^{*0} \gamma \]

\[ B^+ \to K^{*+} \gamma \to K^+ \pi^{0} \gamma \]

\[ B^+ \to K^{*+} \gamma \to K_s^{0} \pi^+ \gamma \]

\[ \int L \, dt = 2.62 \, \text{fb}^{-1} \]

\[ 4.4\sigma \]

\[ 3.7\sigma \]

\[ 2.1\sigma \]
Observation of $B \rightarrow K^*\gamma$

First observation radiative penguin process ($b \rightarrow s\gamma$) @Belle II.

$B^0 \rightarrow K^*0\gamma$

$B^0 \rightarrow K^+\gamma \rightarrow K^+\pi^-\gamma$

$B^+ \rightarrow K^+\gamma \rightarrow K^0\pi^+\gamma$

$B^+ \rightarrow K^+\gamma \rightarrow K^0_s\pi^+\gamma$

Yields consistent with WA branching fraction
Time dependent $B^0\bar{B}^0$ mixing signature

Oscillation observed

$\bar{B}^0 \rightarrow D^* + l^- \nu$

Partial reconstruction and time determination uses only Lepton tagging.

No mixing fraction:

$$f_{\text{unmix}}(t) = K[1+\cos(\Delta m_d \Delta t)]$$

Use “diff” sign of two lepton in the final state. Verifies Belle II VXD capabilities for CP violation.
Summary

- Rich physics in Belle II experiment.
  - CP violation & rare decay of B/D decay, LFV/LNF in $\tau$ decay, pentaquark, dark sector and Quarkonium.
- The first physics run in the Super B factory mode (Phase 3) started in spring 2019. Integrated luminosity $\sim 6.5$ fb$^{-1}$.
- Time-dependent capabilities with VXD and particle ID with TOP are demonstrated. Many good results of re-discoveries are presented in phase 3 data.
- SuperKEKB are going through way to world’s highest luminosity accelerator. Belle II target at high efficiency data-taking rate to record more physics.
- Phase 3 resume in mid-October and continue until June 2020.
Stay tuned
Belle II will discover exciting physics soon.
backup
Replace short dipoles with longer ones (LER)

Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

Low emittance positrons to inject

Low emittance electrons to inject

Pasitron source

New positron target / capture section

Add / modify RF system for higher beam current
SuperKEKB/Belle II Luminosity Profile

- Luminosity is 40 times than KEKB.
  - Beam profile size: y-axis 50 nm, x-axis 100 μm. (nano beam)
  - Beam current is about 2 times of KEKB.
- Belle/KEKB recorded ~1000 fb⁻¹. Now we have to change units on the y-axis to ab⁻¹
**K_\ell** identification by ECL pulse shape discriminator

New PID approach: The pulse shape parameters of ECL (electromagnetic calorimeter) can be the inputs of BDT which works as an classifier of \( K_\ell/\gamma \).

---

**K_\ell^0** candidates selected from \( e^+e^- \rightarrow \phi \gamma \rightarrow K_S^0K_L^0\gamma \) control sample in Phase 2 Data and MC.

---

Photsons candidates selected from \( e^+e^- \rightarrow \mu^+\mu^- (\gamma) \) control sample in Phase 2 Data and MC.
<table>
<thead>
<tr>
<th>Input</th>
<th>2016</th>
<th>Belle II 2016</th>
<th>Belle II (+LHCb) 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ (semileptonic) [10^{-3}]</td>
<td>4.01 ± 0.08 ± 0.22</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ (semileptonic) [10^{-3}]</td>
<td>41.00 ± 0.33 ± 0.74</td>
</tr>
<tr>
<td>$\mathcal{B}(B \to \tau \nu)$</td>
<td>1.08 ± 0.21</td>
<td>±0.04</td>
<td>±0.03</td>
</tr>
<tr>
<td>$\sin 2\phi_1$</td>
<td>0.691 ± 0.017</td>
<td>±0.008</td>
<td>0.710 ± 0.008</td>
</tr>
<tr>
<td>$\phi_3 [^\circ]$</td>
<td>73.2^{+6.3}_{-7.0}</td>
<td>±1.5</td>
<td>67 ± 1.5 (±1.0)</td>
</tr>
<tr>
<td>$\phi_2 [^\circ]$</td>
<td>87.6^{+3.5}_{-3.3}</td>
<td>±1.0</td>
<td>90.4 ± 1.0</td>
</tr>
<tr>
<td>$\Delta m_d$</td>
<td>0.510 ± 0.003</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta m_s$</td>
<td>17.757 ± 0.021</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\mathcal{B}(B_s \to \mu \mu)$</td>
<td>2.8^{+0.7}_{-0.6} (±0.5)</td>
<td>±0.5</td>
<td>3.31^{+0.7}_{-0.6} (±0.5)</td>
</tr>
<tr>
<td>$f_{B_s}$</td>
<td>0.224 ± 0.001 ± 0.002</td>
<td>0.001</td>
<td>-</td>
</tr>
<tr>
<td>$B_{B_s}$</td>
<td>1.320 ± 0.016 ± 0.030</td>
<td>0.010</td>
<td>-</td>
</tr>
<tr>
<td>$f_{B_s}/f_{B_d}$</td>
<td>1.205 ± 0.003 ± 0.006</td>
<td>0.005</td>
<td>-</td>
</tr>
<tr>
<td>$B_{B_s}/B_{B_d}$</td>
<td>1.023 ± 0.013 ± 0.014</td>
<td>0.005</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>V_{cd}</td>
<td>/(\nu \bar{N})$</td>
<td>0.230 ± 0.011</td>
</tr>
<tr>
<td>$</td>
<td>V_{cs}</td>
<td>/(W \to c\bar{s})$</td>
<td>0.94^{+0.32}_{-0.26} ± 0.13</td>
</tr>
<tr>
<td>$f_{D_s}/f_{D_d}$</td>
<td>1.175^{+0.001}_{-0.004}</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\mathcal{B}(D \to \mu \nu)$</td>
<td>0.374 ± 0.017</td>
<td>±0.010</td>
<td>-</td>
</tr>
<tr>
<td>$\epsilon_K$</td>
<td>2.228 ± 0.011</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>V_{us}</td>
<td>f_K^{\to \pi}(0)$</td>
<td>0.2163 ± 0.0005</td>
</tr>
<tr>
<td>$\mathcal{B}(K \to \ell \nu)$</td>
<td>1.581 ± 0.008</td>
<td>-</td>
<td>1.5689 ± 0.008</td>
</tr>
<tr>
<td>$\mathcal{B}(K \to \mu \nu)$</td>
<td>0.6355 ± 0.0011</td>
<td>-</td>
<td>0.6357 ± 0.0011</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \to K\nu)$</td>
<td>0.6955 ± 0.0096</td>
<td>-</td>
<td>0.7170 ± 0.0096</td>
</tr>
<tr>
<td>$</td>
<td>V_{ud}</td>
<td>$</td>
<td>0.97425 ± 0.00022</td>
</tr>
</tbody>
</table>

- Error will depress much
Pentaquark search

From \( \Lambda_c^0 \rightarrow J/\psi K^- p \) decay, pentaquarks \( P_c(4380)^+ \) and \( P_c(4450)^+ \) are found in LHCb.

- Candidates for strange partners of charmed XYZ states e.g. \( Y(2175) \rightarrow \Phi \pi^+ \pi^- \) observed at BaBar and BESIII.
- LHCb search for strange partner \( P_s^+ \rightarrow \Phi p \) in \( \Lambda_c \rightarrow [\Phi p] \pi^0 \) at 915 fb\(^{-1}\)
  - No significant signal is found.

\[ M(P_c(4380)^+) = 4380 \pm 8 \pm 29 \text{ MeV} \]
\[ M(P_c(4450)^+) = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV} \]

Recently, \( P_c(4312)^+ \) and two peaks of \( P_c(4450)^+ \)

arXiv:1904.03947
Pentaquark search

From $\Lambda^0_b \rightarrow J/\psi K^- p$ decay, pentaquarks $P_c(4380)^+$ and $P_c(4450)^+$ are found in LHCb.

The LHCb collaboration

$M(P_c(4380)^+) = 4380 \pm 8 \pm 29$ MeV

$M(P_c(4450)^+) = 4449.8 \pm 1.7 \pm 2.5$ MeV

Recently, $P_c(4312)^+$ and two peaks of $P_c(4450)^+$

$B^0 \rightarrow J/\psi p\bar{p}$ of 5.2 fb$^{-1}$ data at LHCb

PRL 122, 191804 (2019)

arXiv:1507.03414

The LHCb collaboration

$B^0 \rightarrow J/\psi p\bar{p}$ of 5.2 fb$^{-1}$ data at LHCb

PRL 122, 191804 (2019)

arXiv:1507.03414

The LHCb collaboration

$M(P_c(4380)^+) = 4380 \pm 8 \pm 29$ MeV

$M(P_c(4450)^+) = 4449.8 \pm 1.7 \pm 2.5$ MeV

Recently, $P_c(4312)^+$ and two peaks of $P_c(4450)^+$

arXiv:1904.03947

B$^0 \rightarrow J/\psi p\bar{p}$

$B(B^0 \rightarrow J/\psi p\bar{p})$

$B(B^0 \rightarrow J/\psi p\bar{p})$

$= [4.51 \pm 0.40 \text{(stat)} \pm 0.44 \text{(syst)}] \times 10^{-7}$,

$B(B^0 \rightarrow J/\psi p\bar{p})$

$= [3.58 \pm 0.19 \text{(stat)} \pm 0.39 \text{(syst)}] \times 10^{-6}$,
Full Event Interpretation

- Fully reconstruct B decays in many many modes to reduce backgrounds and provide tagging
- Useful for channels with weak exp. signature
  - Missing momentum (many neutrinos in the final state)
  - Inclusive analyses
- Tag with semileptonic decays
  - PRO: Higher efficiency $\eta_{stag} \sim 1.5\%$
  - CON: more background, B momentum unmeasured
- Tag with hadronic decays
  - PRO: cleaner events, B momentum reconstructed
  - CON: smaller efficiency $\eta_{stag} \sim 0.3\%$

https://doi.org/10.1007/s41781-019-0021-8
$B^{±/0} \to X \ell^- \nu$

FEI is used to select $B_{\text{tag}}$
Flavor Tagger

MVA – based tagger:
many sub-taggers with many input variables

Total expected effective tagging efficiency:
37.2 % (Belle II MC)
to be compared with 30 – 33 % in BaBar and Belle
From the Belle to Belle II

- What has been changed?

- **PXD**, vertex resolution in z direction (beam direction) will be factor 2 better than before:
  \[50 \mu m \text{ (Belle)} \rightarrow 25 \mu m \text{ (Belle II)}\]

- **TOP**: no TOF (time-of-flight) detector anymore, but TOP (time-of-propagation) will do the timing of the Cerenkov light. Time resolution \(\sim 50\) ps. TOP detector surface is polished to nanometer precision for total reflection of Cerenkov light

- **KLM**: inner 2 layers of barrel + all layers in the endcap replaced by scintillators, because of large background

- **ECL** readout electronics exchanged, fast FADC sampling for identify pile-up of pulses

- Huge gain in **luminosity** in Belle II compared to Belle: factor \(x40\). How?
  - factor 2 by beam current: \(1.64/1.19\) A (Belle) \(\rightarrow 3.6/2.6\) A for \(e^+e^-\) beam in Belle II
  - factor 20 by "nano-beam" principle (collision point in vertical direction will be only 59 nm)
Time CP violation measurement

Ability to measure vertex precisely is needed in time CPV measurement