Heavy Flavors at Belle II
Status and Plans

Akimasa Ishikawa
(KEK)

On behalf of the Belle II Collaboration

DIS2019@Torino, Italia
Belle II @ SuperKEKB

- Belle II at SuperKEKB is the successor of the Belle experiment at KEKB
  - Main mission of the Belle II is to search for beyond the SM via studies of heavy flavors: B, charm and $\tau$
- The target luminosity for SuperKEKB is $8 \times 10^{35}$ /cm$^2$/s which is the world’s highest and 40 times larger than that for KEKB.
SuperKEKB

- Sitting on Y(4S)
  - To produce B meson pairs efficiently
- Asymmetric $e^+e^-$ Collision
  - Electron: 7GeV, Positron 4GeV
  - To boost B meson to study time dependent CP Violation
    - Difference of two B meson decay vertices $\Delta z \approx 140 \mu m$
- 40 times larger luminosity
  - Adopted nano-beam scheme by P. Raimondi
  - Beam size in vertical plain $1/20$
    - $\sigma_y^*=940nm \rightarrow 48/62nm$ (positron/electron)
  - Beam current $\times 2$
    - 1.7A/1.2A $\rightarrow$ 3.6A/2.6A

20190410
Belle II Detector

• All subdetectors had been upgraded
  – Work under 40 times larger instantaneous luminosity.

• General purpose $4\pi$ detector
  – Excellent momentum and energy resolution
  – Good PID capability to separate $\pi/K/p$

• Accumulate $50\text{ab}^{-1}$ data in 2027
  – Containing $10^{11}$ B mesons, $3\times10^{11}$ charm hadrons, $0.8\times10^{11}$ tau leptons
Belle II Collaboration

- Worldwide collaboration
  - ~800 researchers (including ~320 graduate students) from 113 institutions and 26 countries.
    - 10 Italian institutions: Frascati, INFN, Napoli, Padova, Perugia, Pisa, Roma Uno, Roma Tre, Torino, and Trieste
Phase1: Commissioning Run

- 2016: Phase 1 Commissioning Run
  - First SuperKEKB operation
  - No final focus, no collisions, Belle II detector roll out from the beam line
  - Special beam background monitor detector called BEAST II was installed

https://doi.org/10.1016/j.nima.2018.05.071
Rolling in Belle II Detector

- April 2017: After Phase 1, Belle II detector was rolled into the beam line
  - Only 1 ladder of vertex detector
Final Focus Magnet Moving in

• January 2018: The superconducting magnets for final focusing of the beams were moved to the core of the Belle II detector
Phase 2 Commissioning Run

- 2018 March-July
- First $e^+e^-$ collisions were achieved
- Data taking with Belle II minus VXD (vertex detector)
  - To avoid serious damage of VXD
- Beam backgrounds are high but tolerable
  - Synchrotron radiation (VXD background) observed for first time

→ All goals achieved. Safe to proceed and install full VXD
Phase 2 Commissioning Run

- 2018 March-July
- First $e^+e^-$ collisions were achieved
- Data taking with Belle II minus VXD (vertex detector)
  - To avoid serious damage of VXD
- Beam backgrounds are high but tolerable
  - Synchrotron radiation (VXD background) observed for first time

⇒ All goals achieved. Safe to proceed and install full VXD
SuperKEKB in Phase2

Ramping up the beam currents

- Achieved
  - $L_{\text{peak}} = 5.55 \times 10^{33} / \text{cm}^2 / \text{s}$
  - Belle II recorded $\sim 500 \text{ pb}^{-1}$
  - Confirmed the nano-beam scheme
  - Reduced $\beta_y^* \text{ to } 3 \text{ mm, } \sigma_y^* \sim 400 \text{ nm (Final target } \beta_y^* = 0.3 \text{ mm)}$

Squeezing the beams at the interaction point
Rediscovery of B mesons

• Clearly observed an excess of BB events
• Detector and full reconstruction analysis chain working well.
Vertex Detector Installed

• Nov 2018 : After phase2, vertex detector was installed
  – Layer 2 of Pixel detector partially, full SVD 3-6 layers.
• Ready for time dependent measurements
2019 March : Phase 3 started

Machine Tuning

- Reached $1 \times 10^{33} / \text{cm}^2/\text{s}$
- Additional beam collimators work fine to reduce beam background which limited the beam current in phase 2
Belle II Physics

• As Super B-factory
  – B physics: CPV beyond CKM picture, LFV in B decays, and more.

• Heavy flavors
  – Not only B but charm and τ can be studied

• Light dark matter searches
  – Vector portal, scalar portal

• Others
  – EW measurements at low energy
    • Hadronic vacuum polarization
  – Hadron physics
Early Physics Target: Dark Sector

- Belle did not have single photon trigger required for this search
- BaBar sensitivity reduced due to lack of hermiticity of projective crystals in calorimeter

FIG. 4. Projected Belle II sensitivity to $e^+e^- \rightarrow \gamma A', A' \rightarrow$ invisible (left), and to production of axion-like particles that couple to photons (right). In both cases Belle II has world-leading sensitivity with only 20 fb$^{-1}$ of data, which should be collected within the first year of running. (Figures are taken from the Belle II Physics Book and Ref. [73].)
Recent LHCb results on $R_{K^*}$ have tensions with the SM:

$$R_{K^*}(q^2) = \frac{BF(B \rightarrow K^{(*)}\mu^+\mu^-)}{BF(B \rightarrow K^{(*)}e^+e^-)}$$

- $\sim 2.6\sigma$ each
- Simple combination $\sim 4\sigma$
- Can be explained by Leptoquark or flavorful $Z'$

New Belle results have large uncertainty.
$R_K, \ R_{K^*} \ and \ R_{\chi s}$

- Ideal measurements at $e^+e^-$ B-factory: Belle II
  - Efficiency for electron and muon similar
    - No problem on bremsstrahlung recovery
  - Both low and high $q^2$ can be accessible
    - Low $1<q^2<6\text{GeV}^2$
    - High $q^2>14.4\text{GeV}^2$
  - Inclusive mode $R_{\chi s}$ possible
- In 2022, we can reach the sensitivity of LHCb with $3/fb$ for low $q^2$

\[
R_H = \frac{B(B \rightarrow H\mu^+\mu^-)}{B(B \rightarrow He^+e^-)}
\]
$B \rightarrow D(\ast) \tau \nu$

- $B \rightarrow D \tau \nu$ and $B \rightarrow D^* \tau \nu$ are tree-level SM decays containing 3rd generation quarks and leptons

- Ratio of heavy-to-light lepton modes provides robust theoretical prediction

\[
R = \frac{\mathcal{B}(b \rightarrow q \tau \bar{\nu}_\tau)}{\mathcal{B}(b \rightarrow q \ell \bar{\nu}_\ell)}
\]

- Measurements from BaBar, Belle and LHCb deviate from SM (combined 3.1σ)
  - Can be explained by leptoquark, flavorful W’ or extension of Higgs sector

- Belle II can precisely measure $R(D)$ and $R(D^*)$ to constrain or identify BSM physics
- Both charged and neutral $B$ and various final states
**CKM Matrix and Unitarity Triangle**

- **Product of** $V_{id}$ and $V_{ib}^*$ **of CKM matrix**
  \[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]
  - Triangle can be drawn in the complex plane
  - To test new physics in $B^0$-$\bar{B}^0$ mixing $\Delta B=2$
    - Three observable from tree, another three from loop

**Mass eigenstate**

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} = 
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix} 
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

**Flavor eigenstate**

\[
\begin{pmatrix}
  1 - \frac{\lambda^2}{2} \\
  -\lambda \\
  A\lambda^3(1 - \rho - i\eta)
\end{pmatrix} + O(\lambda^4)
\]

- **$B^0$-$\bar{B}^0$ mixing**
  - $B_d^{0}$ mixing
  - $b \rightarrow u\nu\bar{v}$
  - $B \rightarrow \pi\pi, \rho\pi, \rho\rho$

- **$B \rightarrow DK$**
  - $b \rightarrow c\nu\bar{l}$

- **$B \rightarrow J/\psi Ks$**

**Diagram notes**

- **Tree loop** side angle
- **CPV phase**

---

*Figure: Uehara, Sumner*
Unitarity Triangle Measurements

- Precision will be limited by theory or lattice QCD except $\phi_3$
  - Uncertainties of all the sides $\sim1\%$
  - Uncertainties of all the angles $\sim1\text{deg}$
- 200TeV NP scale can be accessible with EFT analysis
- $>10\text{ TeV}$ in SUSY

Tanimoto and Yamamoto (2014)

\[
M_{12}^{d,s} = (M_{12}^{d,s})_{\text{SM}} \times (1 + h_{d,s} e^{2i\sigma_{d,s}})
\]

\[
\frac{C_{ij}^2}{\Lambda^2} \left( \bar{q}_i L \gamma^\mu q_j L \right)^2
\]

<table>
<thead>
<tr>
<th>Couplings</th>
<th>NP loop order</th>
<th>Scales (in TeV) probed by $B_{d}$ mixing</th>
<th>$B_{s}$ mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>C_{ij}</td>
<td>=</td>
<td>V_{ti}V_{tj}^*</td>
</tr>
<tr>
<td></td>
<td>one loop</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>$</td>
<td>C_{ij}</td>
<td>= 1$ (no hierarchy)</td>
<td>tree level</td>
</tr>
<tr>
<td></td>
<td>one loop</td>
<td>$2 \times 10^2$</td>
<td>40</td>
</tr>
</tbody>
</table>
Summary

• Belle II recorded first data without vertex detector in Phase2
  – Instantaneous luminosity of $5.5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
  – Integrated luminosity of 0.5 fb$^{-1}$

• Phase 3 Physics run is just started in March 2019
  – Early physics target: dark sector search
  – Some rediscoveries in this summer
    • $B \rightarrow K^*\gamma$ etc
  – Aim to supersede existing B factory data set by ~2021

• Stay tuned
Backup