Charmed-Meson Physics at Belle II

Guanda Gong  gonggd@mail.ustc.edu.cn
University of Science and Technology of China
on behalf of the Belle II collaboration
Sep 22, 2020 – Beauty 2020, online
Outline

- SuperKEKB and Belle II Detector
- Status and Prospects of Charmed-Meson Physics
  - Time-Integrated Measurements
    - Time-integrated $CP$ violation
  - Time-Dependent Measurements
    - $D^0$ lifetime measurement
    - $D^0-\bar{D}^0$ mixing
  - Full Charm Event Reconstruction
    - Leptonic, rare decays
- Conclusions
SuperKEKB and Belle II Detector

SuperKEKB

- Designed peak luminosity
  \[ = 6.5 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1} \]
  \[ = 6.5 \times 10^2 \text{ nb}^{-1} \text{s}^{-1} \]
- \( e e \rightarrow c \bar{c} \) cross section
  \[ \approx 1.3 \text{ nb} @10.58 \text{ GeV} \]
- Nano beams technique
  beam size ↓ 20 times
  currents ↑ 2 times

KEK Laboratory - Tsukuba, Japan

\( e^+ 4 \text{ GeV} 3.6 \text{ A} \)
\( e^- 7 \text{ GeV} 2.6 \text{ A} \)

KEKB \( e^+/e^- \)
E (GeV): 3.5/8.0
I (A): ~ 1.6/1.2
\( \beta^* \) (mm): ~5.9/5.9
Crossing angle (mrad): 22

SuperKEKB \( e^+/e^- \)
E (GeV): 4.0/7.0
I (A): ~ 3.6/2.6
\( \beta^* \) (mm): ~0.27/0.3
Crossing angle (mrad): 83
SuperKEKB and Belle II Detector

Belle II Detector

**Vertex Detector**
- **PXD:** 2 layers **DEPFET** pixels detector
  - Beampipe  \( r = 10 \text{ mm} \)
  - Layer 1  \( r = 14 \text{ mm} \)
  - Layer 2  \( r = 22 \text{ mm} \)

**SVD:** 4 layers double side Si strips detector (DSSD)

**Central Drift Chamber**
- He(50%): \( \text{C}_2\text{H}_6(50\%) \), small cell size, long lever arm, fast electronics

**EM Calorimeter**
- CsI(Tl), **waveform sampling** (barrel)

**Particle Identification**
- Time-of-Propagation counter (barrel)
- Proximity focusing
- Aerogel RICH (fwd)

**\( K_L \& \mu \) detector**
- Resistive Plate Chambers (barrel outer layers)
- Scintillator
  + WaveLength Shifting Fibers
  + Multi-Pixel Photon Counter (end-caps, inner 2 barrel layers)

7.4 m

7.1 m
SuperKEKB and Belle II Detector

- Target dataset: 50 ab\(^{-1}\) (50×Belle)
- Current integrated luminosity (2019-2020) ≈ 74 fb\(^{-1}\)
- New world record luminosity (June 2020) ≈ 2.4 × 10\(^{34}\) cm\(^{-2}\) s\(^{-1}\)

\[\int L_{\text{Recorded}} \, dt = 74.10 \text{[fb}^{-1}]\]

\[L_{\text{peak}} = 2.4 \times 10^{34}/\text{cm}^2/\text{sec}\]

> 2.11 × 10\(^{34}\) cm\(^{-2}\) s\(^{-1}\) (Belle, June 2009)
Efficient Measurements

- Time-integrated $CP$ violation: Prospect@50 ab$^{-1}$

- $CP$ violation is a sensitive probe to physics beyond SM

- Time-integrated $CP$ violation could be measured by:

  $A_{CP} = \frac{N_{D^0 \rightarrow f^-N_{\bar{D}^0 \rightarrow \bar{f}}}}{N_{D^0 \rightarrow f^+N_{\bar{D}^0 \rightarrow \bar{f}}}}$

- Belle II would produce important measurement especially for channels containing neutral final states

- Measured $A_{CP}$ will reach a precision of $o(10^{-4})$, also in channels with neutrals in the final state

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>$A_{CP}$ (%)</th>
<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^+K^-$</td>
<td>976</td>
<td>$-0.32 \pm 0.21 \pm 0.09$</td>
<td>$\pm 0.03$</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>976</td>
<td>$+0.55 \pm 0.36 \pm 0.09$</td>
<td>$\pm 0.05$</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^0\pi^0$</td>
<td>966</td>
<td>$-0.03 \pm 0.64 \pm 0.10$</td>
<td>$\pm 0.09$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_S^0\pi^0$</td>
<td>966</td>
<td>$-0.21 \pm 0.16 \pm 0.07$</td>
<td>$\pm 0.02$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_S^0K_S^0$</td>
<td>921</td>
<td>$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$</td>
<td>$\pm 0.23$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_S^0\eta$</td>
<td>791</td>
<td>$+0.54 \pm 0.51 \pm 0.16$</td>
<td>$\pm 0.07$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_S^0\eta'$</td>
<td>791</td>
<td>$+0.98 \pm 0.67 \pm 0.14$</td>
<td>$\pm 0.09$</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^+\pi^-\pi^0$</td>
<td>532</td>
<td>$+0.43 \pm 1.30$</td>
<td>$\pm 0.13$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^+\pi^-\pi^0$</td>
<td>281</td>
<td>$-0.60 \pm 5.30$</td>
<td>$\pm 0.40$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^+\pi^-\pi^+\pi^-$</td>
<td>281</td>
<td>$-1.80 \pm 4.40$</td>
<td>$\pm 0.33$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \phi\pi^+$</td>
<td>955</td>
<td>$+0.51 \pm 0.28 \pm 0.05$</td>
<td>$\pm 0.04$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^+\pi^0$</td>
<td>921</td>
<td>$+2.31 \pm 1.24 \pm 0.23$</td>
<td>$\pm 0.17$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \eta\pi^+$</td>
<td>791</td>
<td>$+1.74 \pm 1.13 \pm 0.19$</td>
<td>$\pm 0.14$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \eta'\pi^+$</td>
<td>791</td>
<td>$-0.12 \pm 1.12 \pm 0.17$</td>
<td>$\pm 0.14$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K_S^0\pi^+$</td>
<td>977</td>
<td>$-0.36 \pm 0.09 \pm 0.07$</td>
<td>$\pm 0.02$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K_S^0K^+$</td>
<td>977</td>
<td>$-0.25 \pm 0.28 \pm 0.14$</td>
<td>$\pm 0.04$</td>
</tr>
<tr>
<td>$D^+_s \rightarrow K_S^0\pi^+$</td>
<td>673</td>
<td>$+5.45 \pm 2.50 \pm 0.33$</td>
<td>$\pm 0.29$</td>
</tr>
<tr>
<td>$D^+_s \rightarrow K_S^0K^+$</td>
<td>673</td>
<td>$+0.12 \pm 0.36 \pm 0.22$</td>
<td>$\pm 0.05$</td>
</tr>
</tbody>
</table>

Belle II Physics Book; PETP 2019, 123C01 (2019)

$$\sigma_{Belle \ II} = \sqrt{(\sigma_{stat}^2 + \sigma_{syst}^2) \cdot (\mathcal{L}_{Belle}/50 \, ab^{-1}) + \sigma_{irred}^2}$$
The following $D^0$ channels are rediscovered:

- $D^{*+} \rightarrow D^0 \pi^+_S$, $D^0 \rightarrow K_SK_S$
  SCS decay, sensitive for CPV

- $D^{*+} \rightarrow D^0 \pi^+_S$, $D^0 \rightarrow K_S \pi^0$
  CF decay, used to be normalization model for
  $D^0 \rightarrow K_SK_S/\pi^0\pi^0/\gamma\gamma$

The resolution and background level is comparable with Belle, with only 1.5 years of data taking

**Time-Integrated Measurements**

---

**Time-integrated $CP$ Violation: Current Status**

- $D^{*+} \rightarrow D^0 \pi^+_S$, $D^0 \rightarrow K_S K_S$
- $D^0 \rightarrow K_S K_S$

---

The selection criteria are different in the left plots (Belle II) and right plots (Belle)
Three $D_S^+$ channels are also rediscovered in the data:
- $D_S^+ \rightarrow \phi \pi^+$
- $D_S^+ \rightarrow K^*0 \pi^+$
- $D_S^+ \rightarrow K_S^0 \pi^+$

Rediscoveries of other channels are in progress.
Time-Dependent Measurements

- $D^0$ lifetime measurement

- fit the proper time distributions of three $D^*$-tagged $D^0$ decays channels.
  - unbinned ML fit
  - per-candidate flight time errors
Time-Dependent Measurements

- $D^0$ lifetime measurement
  
  Proper time resolution at Belle II is a factor of 2 better than Belle & BaBar, thanks to the improved vertex detector and the "nano-beams" technique

  - Belle SVD2 = 4 layers DSSD
  - BaBar SVT = 5 layers DSSD
  - Belle II VXD = 2 layers DEPFET pixels + 4 layers DSSD

  Sensitivity for mixing parameters would benefit from such resolution improvement. An example of Toy MC study for $D^0 \rightarrow K\pi$:

<table>
<thead>
<tr>
<th>estimated error on</th>
<th>current HFLAV</th>
<th>Belle scaled to 50/ab</th>
<th>Toy MC 50/ab, CPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x'$ (%)</td>
<td>–</td>
<td>(*) 0.45</td>
<td>0.15</td>
</tr>
<tr>
<td>$x'^2$ (%)</td>
<td>–</td>
<td>0.009</td>
<td>–</td>
</tr>
<tr>
<td>$y'$ (%)</td>
<td>–</td>
<td>0.16</td>
<td>0.10</td>
</tr>
<tr>
<td>$</td>
<td>q/p</td>
<td>$</td>
<td>~ 0.09</td>
</tr>
<tr>
<td>$\phi$ (°)</td>
<td>~ 9</td>
<td>–</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Resolution improvement visible at $t < 0$
Time-Dependent Measurements

- $D^0 - \bar{D}^0$ mixing: brief introduction
  - Mass eigenstates and flavor eigenstates
    \[ |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \]
  - Definition of mixing parameters
    \[ x = \frac{m_1 - m_2}{\Gamma} \text{ and } y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2} \]
  - SM prediction mixing via short and long distance interaction

- $CP$ violation in mixing
  - Direct $CP$ violation
    \[ \left| \frac{\bar{A}_f}{A_f} \right| \neq 1 \]
  - $CP$ violation in pure mixing
    \[ \left| \frac{q}{p} \right|^2 \neq 1, \quad \phi = \text{Arg} \left( \frac{q}{p} \right) \neq 0 \]
  - $CP$ violation in interference of decay amplitudes with and without mixing
    \[ \frac{q \bar{A}_f}{p A_f} \neq 1 \]
Time-Dependent Measurements

$D^0-\bar{D}^0$ mixing: $D^0$ wrong sign decays

- $R_{WS}(t) = N_{WS}(t)/N_{RS}(t)$, could be used to measure mixing parameters and CPV

- $R_{WS}$ (time integrated) in the Belle II data
  - Reconstruct RS & WS decays, extract PDF from RS and use it to fit the WS distributions

\[ R_{WS}(t) = N_{WS}(t)/N_{RS}(t) \]

\[ R_{WS}(\text{time integrated}) \text{ in the Belle II data} \]

\[ \text{Reconstruct RS & WS decays, extract PDF from RS and use it to fit the WS distributions} \]
Time-Dependent Measurements

$D^0 - \bar{D}^0$ mixing: $D^0 \rightarrow K_S \pi^+ \pi^-$ time-dependent Dalitz analysis

- Time-dependent amplitude fit
  - In self-conjugate channels like $D^0 \rightarrow K_S \pi^+ \pi^-$, $x$ and $y$ parameters could be easily disentangle from the strong phase.

- Mixing parameters sensitivity @50 ab$^{-1}$
  - $\sigma_{Belle II} = \sqrt{(\sigma_{stat}^2 + \sigma_{syst}^2) \cdot (L_{Belle}/50 \text{ ab}^{-1}) + \sigma_{irred}^2}$.
  - The improved proper time resolution is not considered

<table>
<thead>
<tr>
<th>Data</th>
<th>stat.</th>
<th>syst.</th>
<th>Total</th>
<th>stat.</th>
<th>syst.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>976 fb$^{-1}$</td>
<td>0.19</td>
<td>0.06</td>
<td>0.11</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 ab$^{-1}$</td>
<td>0.08</td>
<td>0.03</td>
<td>0.11</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 ab$^{-1}$</td>
<td>0.03</td>
<td>0.01</td>
<td>0.11</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>976 fb$^{-1}$</td>
<td>15.5</td>
<td>5.2-5.6</td>
<td>7.0-6.7</td>
<td>17.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 ab$^{-1}$</td>
<td>6.9</td>
<td>2.3-2.5</td>
<td>7.0-6.7</td>
<td>9.9-10.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 ab$^{-1}$</td>
<td>2.2</td>
<td>0.7-0.8</td>
<td>7.0-6.7</td>
<td>7.0-7.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The resolution of release energy, $Q$, is a factor of 2 better than Belle

Belle II Physics Book; PETP 2019, 123C01 (2019)
**Time-Dependent Measurements**

- $D^0$-$\bar{D}^0$ mixing: $D^0 \rightarrow K_S \pi^+ \pi^-$ time-dependent Dalitz analysis

![Graph showing $t$ vs. Candidates (60 fs) with Data and Fit lines, and Belle II 2019 Preliminary integral $\int L \, dt = 9.6 \, fb^{-1}$]

- Proper time resolution comparable to the ones observed in lifetime analysis

- Sensitivity study for mixing and CPV parameters measurements, with the consideration of resolution of Belle II detector, is ongoing.

- Proper time resolution comparable to the ones observed in lifetime analysis (410.1 ± 1.5 fs)

- $\rho(770)^0$ and $K^*(892)^-$ compatible with world average (410.1 ± 1.5 fs)
Full Charm Event Reconstruction

- Method: Tag the D meson in the rest of event, deduce the kinematic information of desired final state by information of other particles

- Light mesons ($K, \pi, \ldots$)

$$e^+ e^- \rightarrow c\bar{c} \rightarrow D_{\text{tag}} X_{\text{frag}} D_{\text{sig}}$$

- Reconstructed in several channels ($D^0, D^*, D_s \ldots$)

- Useful in: inclusive branching fraction measurement, (semi-)leptonic study, rare/forbidden decays search

- Example: recoiled method for $D_s$ leptonic decays

$$e^+ e^- \rightarrow c\bar{c} \rightarrow D_{\text{tag}} X_{\text{frag}} K D_s^{*+}, \quad D_s^{*+} \rightarrow D_s^+ \gamma, \quad D_s^+ \rightarrow \mu^+ \nu$$

$$P_{\text{miss}} = P_{\text{cms}} - P(D_{\text{tag}} X_{\text{frag}} K \gamma \mu)$$

- Expected signal yields @50 ab$^{-1}$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Belle</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(0.91, 0.92 ab$^{-1}$)</td>
<td>(50 ab$^{-1}$)</td>
</tr>
<tr>
<td>$D_s^- \rightarrow \mu^- \bar{\nu}$</td>
<td>492 ± 26</td>
<td>27 000</td>
</tr>
<tr>
<td>$D^- \rightarrow \mu^- \bar{\nu}$</td>
<td>—</td>
<td>1 250</td>
</tr>
<tr>
<td>Inclusive $D^0 \rightarrow$ anything</td>
<td>$(695 \pm 2) \times 10^3$</td>
<td>$38 \times 10^6$</td>
</tr>
</tbody>
</table>

---

Belle II Physics Book; PETP 2019, 123C01 (2019)
Conclusions

- **Belle II** is expected to have important contribution for many charm measurements, and we are moving forward with the newly collected data.
  - Designed peak luminosity of **SuperKEKB**: $6.5 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$
  - Target dataset: $50\times$Belle

- The resolution for proper time and release energy Q are better than Belle, owing to the new vertex detector and “nano beams” technique.
  - Proper time resolution improves a factor of ~2
  - In $D^0 \rightarrow K_S\pi^+\pi^-$ channel, the resolution of Q improves a factor of ~2

- Some nice works are ongoing and there will be more exciting results in the coming years.

Thank you!