Belle II news on charm and $B$ to charm

56th Rencontres de Moriond 2022
Electroweak Interactions & Unified Theories
March 17, 2022

Riccardo Manfredi (University and INFN Trieste)
on behalf of the Belle II collaboration

riccardo.manfredi@ts.infn.it
Beauty and charm factory

Energy-asymmetric $e^+e^-$ collisions at the $\Upsilon(4S)$. CM boosted with $\beta\gamma \sim 0.28$.
Final focus magnets to
- squeeze vertical size to $\sim 50$ nm
- large crossing angle of $\sim 83$ mrad
$\Rightarrow$ design 30x intensity wrt previous $B$-factories

Compared to Belle
- much improved vertexing
- greater acceptance
$\Rightarrow$ similar performance with expected 20x bkg

Large clean samples of $B$ and $D$ mesons. Current dataset of $\sim 265$ fb$^{-1}$.

Today:
- $\Lambda_{c^+}$ (new for Moriond), $D^0$, $D^+$ lifetimes
- CKM $\gamma$ from Belle + Belle II combined data (first combined measurement)
Charm physics at Belle II

Program: CPV measurements, searches for rare and forbidden decays. Focus on final states with neutrals or missing $E$.

Lifetimes: high-precision measurements probe vertexing capabilities and give insight of systematic effects for future time-dependent analyses.

Belle II/SuperKEKB
- small interaction region allows stringent constraints on production vertex position
- new vertex detector improves 2x resolution wrt Belle and BaBar
Measuring decay time

Compute decay time $t$ and its uncertainty $\sigma_t$ from the production and decay vertices and momentum:

$$ t = \frac{m}{p^2 \cdot c} \overrightarrow{d} \cdot \overrightarrow{p} $$

Selection explicitly checked to be unbiased. Controlling systematics is crucial.

$\sim 171k \ D^+ \rightarrow (D^0 \rightarrow K^-\pi^+)\pi^+$

$\sim 59k \ D^+ \rightarrow (D^+ \rightarrow K^-\pi^+\pi^+)\pi^0$

$\sim 152k \ \Lambda_c^+ \rightarrow pK^-\pi^+$

New for Moriond
Decay-time fits

2D fit of unbinned $t - \sigma_t$ distributions.

Signal: exponential convoluted with resolution (single or double Gaussian) determined directly in data.

Background: fit sidebands simultaneously.

All shape parameters free.

Blind analyses.
Misalignment: affects decay-length scale. Estimated using simulations of various misaligned configurations.

Background: account for simulation not well reproducing decay-time distributions.

Resolution: account for neglected correlations between $t$ and $\sigma_t$.

$\Xi_c \rightarrow \Lambda_c \pi$ background can introduce biases. Unaccounted for in previous measurement. Significant uncertainty based on pheno expectations of $\Xi_c$ rate. May reduce with dedicated data-driven studies.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (fs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D^0 \rightarrow K^- \pi^+$</td>
</tr>
<tr>
<td>Statistical</td>
<td>1.1</td>
</tr>
<tr>
<td>Resolution model</td>
<td>0.16</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.24</td>
</tr>
<tr>
<td>Detector alignment</td>
<td>0.72</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>0.19</td>
</tr>
<tr>
<td>Total systematic</td>
<td>0.8</td>
</tr>
</tbody>
</table>

$\Lambda_c^+ \rightarrow pK^- \pi^+$ (preliminary)

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (fs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution model</td>
<td>0.46</td>
</tr>
<tr>
<td>Background contamination</td>
<td>0.20</td>
</tr>
<tr>
<td>Imperfect alignments</td>
<td>0.46</td>
</tr>
<tr>
<td>Momentum scale correction</td>
<td>0.09</td>
</tr>
<tr>
<td>Input charm masses</td>
<td>0.01</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.69</td>
</tr>
<tr>
<td>Contamination from $\Xi_c \rightarrow \Lambda_c \pi$</td>
<td>- 1.4</td>
</tr>
</tbody>
</table>
World-leading charm lifetimes

\[ \tau(D^0) = (410.5 \pm 1.1 \pm 0.8) \text{ fs} \]
\[ \tau(D^+) = (1030.4 \pm 4.7 \pm 3.1) \text{ fs} \]
\[ \tau(\Lambda_c^+) = (204.1 \pm 0.8 \pm 0.7 - 1.4) \text{ fs} \]

Belle II

World average

\[ \tau(D^0) = (410.1 \pm 1.5) \text{ fs} \]
\[ \tau(D^+) = (1040 \pm 7) \text{ fs} \]
\[ \tau(\Lambda_c^+) = (202.4 \pm 3.1) \text{ fs} \]

World’s best. Establish excellent detector performances (see Thibaud’s talk for more on vertexing). \( \Lambda_c \) benchmarks future baryon lifetime measurements.

PRL 127, 211801 (2021)
Measurement of $\gamma$
\( \gamma \) from \( B \to DK \) decays

Phase between \( b \to c \) and \( b \to u \).

Tree-dominated: precise SM reference.

Access with interfering decays to same final states. Direct determination WA: \textbf{HFLAV}

\[ \gamma[^{\circ}] = 65.9 \pm 3.3 \]

Self-conj. \( D^0 \) final states \( K_S^0 \pi \pi, K_S^0 K K \).

\( D \) Dalitz plot binning eliminates amplitude-model uncertainties.

\[ N_{i}^{\pm} = h_{B}^{\pm}\left[F_i + r_B^{2}\bar{F}_i + 2\sqrt{F_i\bar{F}_i}(c_i x_{\pm} + s_i y_{\pm})\right] \]

\( (x_{\pm}, y_{\pm}) = r_B \left( \cos(\gamma + \delta_B), \sin(\gamma + \delta_B) \right) \)

\( c_i, s_i: D^0 - \bar{D}^0 \) strong phase differences (inputs from BES III/CLEO)

\( F_i: \) fraction of \( D \) decays to \( i \)-th bin
Sample selection

128 fb\(^{-1}\) Belle II + 711 fb\(^{-1}\) Belle.

Improvements wrt previous Belle:
- \(K_S^0\) selection
- background suppression
- signal determination
- more statistics from \(D^0 \rightarrow K_S^0 KK\)
- new inputs from BESIII

Suppress “continuum” \((e^+e^- \rightarrow q\bar{q})\):
input event shape, angular distributions, 
\(B\) vertex and flavor tagging in MVA.

Additional discriminating variable for 2D \(\Delta E\) — MVA signal fit
Signal yield determination

\[ D^0 \rightarrow K_S^0 \pi^+ \pi^- \]

PID cut isolates \( B \rightarrow D K \) candidates: \( \sim 8\% \) mis-ID \( B \rightarrow D \pi \) contamination.

\( K^- \pi \) efficiencies and mis-ID rates directly from data with simultaneous fit of disjoint \( B \rightarrow D K \) and \( B \rightarrow D \pi \) samples.

Belle:
\[ K_S^0 \pi \pi: 1467 \pm 53 \]
\[ K_S^0 K K: 194 \pm 17 \]

Belle II:
\[ K_S^0 \pi \pi: 280 \pm 21 \]
\[ K_S^0 K K: 34 \pm 7 \]
Determination of CPV parameters

Simultaneous fit in each Dalitz bin to extract CP observables \((x_\pm, y_\pm)\). Mis-ID rate fixed from previous unbinned fit.

Extract \(F_i\) parameters directly in data to cancel the associated systematics and reduce reliance on simulation.

\[
x_+^{DK} = -0.113 \pm 0.032
\]
\[
y_+^{DK} = -0.046 \pm 0.042
\]
\[
x_-^{DK} = +0.092 \pm 0.033
\]
\[
y_-^{DK} = +0.100 \pm 0.042
\]
Results

\[ \delta_B[^\circ] = 124.8 \pm 12.9 \text{ (stat)} \pm 0.5 \text{ (syst)} \pm 1.7 \text{ (ext)} \]

\[ r_B^{DK} = 0.129 \pm 0.024 \text{ (stat)} \pm 0.001 \text{ (syst)} \pm 0.002 \text{ (ext)} \]

\[ \gamma[^\circ] = 78.4 \pm 11.4 \text{ (stat)} \pm 0.5 \text{ (syst)} \pm 1.0 \text{ (ext)} \]

Improvements wrt previous Belle equivalent to doubling statistics.

Latest inputs on strong-phase from BESIII highly reduces systematics.

Expect \(< 3[^\circ]\) uncertainty with 10 \(\text{ab}^{-1}\), including also more \(D\) final state. Uncertainty will still be dominated by the size of the data sample.
Exploit new improved detector: first high-precision ($O(10^{-3})$) results
- world’s best $D$ lifetimes, establishes excellent vertexing
- world’s best $\Lambda_c$ lifetime, benchmark for future baryon lifetimes (first Belle II)

Combine with Belle data to be impactful on flavor measurements with early data. Sensitivity improved in addition to larger data set:
- most precise CKM $\gamma$ determination from $B$-factories (first B + BII)

Competitive physics results even with initial data sets!
backup
Projections of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run.

• We start long shutdown I (LS I) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvements works of machine and detector. 
• We resume physics running from Fall 2023.
• A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
• An LS2 for machine improvements could happen on the time frame of 2026-2027.
Performance overview

Strong charged particle identification.  Good momentum resolution.  High $\gamma$ efficiency.

Flavor tagging efficiency comparable to Belle.
Fit of Belle data

\[ D^0 \rightarrow K_S^0 \pi^+ \pi^- \]

\[ D^0 \rightarrow K_S^0 K^+ K^- \]
CPV in $B \to D\pi$ decays

\[
\frac{N^+ - N^-}{N^+ + N^-} = \frac{N^+ - N^-}{N^+ + N^-} = \frac{N^+ - N^-}{N^+ + N^-}
\]

Belle II
\[
\int L \, dt = 128 \text{ fb}^{-1}
\]

Belle
\[
\int L \, dt = 711 \text{ fb}^{-1}
\]

$B^+ \to D\pi^+$

$K_S^0\pi\pi$

$K_S^0KK$