Latest *Belle II* results on beauty and charm decays

Saurabh Sandilya
(on behalf of the Belle II Collaboration)

Indian Institute of Technology Hyderabad

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SuperKEKB+Belle II : beauty and charm factory

- SuperKEKB collides $e^+$ and $e^-$, with CM energy at $\Upsilon(4S)$ resonance.
- $e^+e^- \rightarrow \Upsilon(4S) : 1.1 \text{ nb}$, $e^+e^- \rightarrow c\bar{c} : 1.3 \text{ nb}$, $e^+e^- \rightarrow \tau^+\tau^- : 0.92 \text{nb}$
- Large and clean samples of B mesons, D mesons and $\tau$ leptons.
- Total data set about 105 fb^{-1}. Today’s results based on up to $63 \text{ fb}^{-1} (9 \text{ fb}^{-1})$ on (off) resonance

$\mathcal{L}_{\text{goal}} = 6.5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

$\mathcal{L}_{\text{achieved}} = 2.4 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
on June 2020, world record

As compared to Belle:
- Better vertex resolution
- Better Ks efficiency
- Similar K/$\pi$ separation.
- Similar or better performance than Belle even under 20 times higher backgrounds.

Gianluca Inguglia (Mar 31st)
Study of $B^- \rightarrow D(\ast)h^-$

- Decays $B^- \rightarrow D(\ast)K^-$ are important for precise determination CKM angle $\gamma/\phi_3$.
- Dominant and clean decay $B^- \rightarrow D(\ast)\pi^-$ provide good control sample.
- PID to $K/\pi$ from $B$, signal enhanced with $M_{bc} = \sqrt{E_{beam}^2 - (\vec{P}_{BC})^2} > 5.27$ GeV/c^2;
- Unbinned ML fit in $\Delta E (= E_B - E_{beam})$ and MVA output (with event shape variables).

\[
\frac{\Gamma(B^- \rightarrow D^0 (K_S^0 \pi^- \pi^+)K^-)}{\Gamma(B^- \rightarrow D^0 (K_S^0 \pi^- \pi^+)\pi^-)} = (6.32 \pm 0.81^{+0.09}_{-0.11}) \times 10^{-2}
\]

In all the 5 reconstructed modes results agree with the PDG within $2\sigma$
First Belle II reconstruction of $B^0 \rightarrow \pi^0\pi^0$

- $B^0 \rightarrow \pi^0\pi^0$ limits precision of isospin relations to determine $\alpha/\phi_2$.
- Unique to Belle II: final state are just four photons.
- $B \rightarrow D(K\pi\pi^0)\pi^0$ as control channel.
- Dedicated MVA for optimized photon selection.
- Dominant bkg from continuum $\pi^0$. Suppressed with another MVA.

Signal yield $14.0^{+6.8}_{-5.6}$ events, and $\text{BF}(B^0 \rightarrow \pi^0\pi^0) = 0.98^{+0.48}_{-0.39} \pm 0.27 \times 10^{-6}$
First Belle II analysis of $B^+ \rightarrow \rho^+\rho^0$

- pion-only ($\pi^+\pi^0)(\pi^+\pi^-)$ final state and broad $\rho$ peak $\Rightarrow$ large bkg
- Spin-0 $\rightarrow$ spin1 + spin-1 $\Rightarrow$ angular analysis.
- 6D fit including $\Delta E$, CS, and $\rho$ masses to extract signal, and helicity angles to measure fraction $f_L$ of decays with longitudinal polarization.

$N = 104 \pm 16$

$\mathcal{B} = [20.6 \pm 3.2(stat) \pm 4.0(syst)] \times 10^{-6}$

$f_L = 0.936^{+0.049}_{-0.041}(stat) \pm 0.021(syst)$

20% better precision than Belle on 78 fb$^{-1}$ (PRL 91, 221801 (2003)).
First Belle II measurements of $B^0 \rightarrow K^0\pi^0$


$$I_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^+} \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^+\pi^0} \frac{B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^0\pi^0} \frac{B(K^0\pi^0)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}}$$

Precision on $A_{K^0\pi^0}$ is the most limiting input

**Challenges:**
- $\pi^0$ final state $\Rightarrow$ $\Delta E$ tails
- CP-eigenstate $\Rightarrow$ need flavor tagging

$$N(B^0 \rightarrow K^0_S\pi^0) = 45^{+9}_{-8}$$

$$B = [8.5^{+1.7}_{-1.6} \text{(stat)} \pm 1.2 \text{(syst)}] \times 10^{-6}$$

$$A_{K^0\pi^0} = -0.40^{+0.46}_{-0.44} \text{(stat)} \pm 0.04 \text{(syst)}$$

First Belle II DCPV in $K^0\pi^0$, the single most limiting input of isospin-sum-rule probing power
\( B^0 \rightarrow J/\psi K_L^0 \)

- The decay \( B^0 \rightarrow J/\psi K_L^0 \) provides an independent measurement of \( \sin(2\phi_1) \).
- \( J/\psi \rightarrow e^+e^- \) or \( \mu^+\mu^- \) and \( K_L^0 \) is reconstructed as a hadronic neutral cluster in \( K_L \) and \( \mu \) detector (KLM).
- \( p(K_L^0) \) is calculated from the direction of the cluster in KLM and reconstructed momentum of \( J/\psi \) with \( B^0 \) mass constraint.

The yield is observed with the same purity as in predecessor Belle.
Work in progress to include neutral clusters in ECL in the path of TDCPV and \( \sin(2\phi_1) \) measurements.
Inclusive photon spectrum from \( b \to s \gamma \) transition

- **B-decays with \( b \to s \gamma \) transitions**: FCNCs, suppressed at tree level and sensitive to many SM extensions.

\[
\begin{align*}
  & b & \to & W^- & t & \to & s \\
  & BF \sim 10^{-5}
\end{align*}
\]

- Monochromatic (smeared) photon energy from the two-body decay \( b \to s \gamma \).

- High energy photon \( E_\gamma^* > 1.4 \) GeV
- The \( \gamma \) should not be arising from a \( \pi^0 \) decay
- Continuum Suppression with event shape variables.
- Data driven (from off-resonance and side-bands) scaling of MC.
- Excess around expected region is clearly visible.

\[
\begin{align*}
  & \text{Belle II preliminary} \\
  & \int L dt = 62.8 \text{ fb}^{-1}
\end{align*}
\]
**B$^+ \rightarrow K^+ \ell\ell$ decays at Belle II**

- **B-decays with b$\rightarrow$s$\ell\ell$ transitions:** FCNCs, suppressed at tree level and sensitive to many SM extension.

  - These decays have raised a lot of interest in the study of the LFU ratio.
  - The rare decays B$^+ \rightarrow K^+ \ell\ell$ ($\ell = e, \mu$) are seen at Belle II with just 62.8 fb$^{-1}$
  - Signal yield: $8.6^{+4.3}_{-3.9} \pm 0.4 \ (2.7\sigma)$

![Diagram of B-decay processes involving W$^-$, b, s, and l transitions](image)

![Graphs showing B$^+ \rightarrow K^+ \ell\ell$ candidates and distributions](graphs)
B$^+ \rightarrow K^+\nu\nu$ decays at Belle II

- Transition mediates by a virtual $Z$-boson.
- SM prediction for the $\text{BF}[B \rightarrow K^+\nu\nu]_{SM}$ is $(4.6 \pm 0.5) \times 10^{-6}$ [B2TIP, PTEP 2019, 123C01].

- **Inclusive tagging approach** : nested statistical-learning discriminators exploits efficiently topology allowing for sizeable signal (4%) while controlling large backgrounds.

- Validate with $B^+ \rightarrow K^+ J/\psi [\rightarrow \mu^+\mu^-]$

- $\mu^+\mu^-$ ignored
- $K^+$ momentum modified
- 2-body $\rightarrow$ 3-body
B$^+ \to K^+ \nu\nu$ decays at Belle II

- Measured signal strength $\mu = 4.2^{+2.9}_{-2.9}^{+1.8}_{-1.6} = 4.2^{+3.4}_{-3.2}$.
- Consistent with the bkg-only (SM) hypothesis at CL 1.3 $\sigma$ (1 $\sigma$)
- Observed (expected) UL @90% CL $4.1 \times 10^{-5}$ ($2.6 \times 10^{-5}$)
- $\mathcal{B}[B \to K^+\nu\nu] = 1.9^{+1.3}_{-1.3}^{+0.8}_{-0.7} \times 10^{-5}$

Data and post-fit predictions in the signal and control region bins

Sensitivity with just 63 fb$^{-1}$ data is already close to previous searches with significantly large data-set.
D⁰ lifetime measurement

- Reconstructed \( D⁰ \to K^−\pi^+ \), \( D⁰ \to K^−\pi^+\pi^0 \), and \( D⁰ \to K^−\pi^+\pi^+\pi^- \) from \( D^{*+} \to D⁰\pi^+ \) in 9.6 fb\(^{-1}\) data collected in 2019.
- \( D^{*+} \) should not be originating from a B decay (\( P_{D^*}^* > 2.5\) GeV).

\[
t_{\text{flight}} = m_{D^0}(r_{\text{decay}} - r_{\text{prod}}) \cdot \frac{\hat{p}_{D^0}}{p_{D^0}}
\]

With 72 fb\(^{-1}\) Belle II life-time measurements expected to be competitive with world-averages!
In the path towards CPV in charm

- CPV in charm remains an important topic to study for the Belle II experiment.
- Preliminary study of the decay $D^{*+} \rightarrow D^0 [\pi^0 \pi^+ \pi^-] \pi^-$
- Ultimately to study time-averaged Dalitz analysis.

- Standard selection of $\pi^+$ and $\pi^0$
- $D^{*+}$ should not be originating from a $B$-decay ($P_{D^{*+}} > 2.5 \text{GeV}$)

- Unbinned ML fit to $\Delta M \approx M[D^{*+}] - M[D^0]$.
- Signal (two Gaussian) Background (Threshold function).
- Signal yield (estimated)/fb$^{-1} = 305 \pm 15$
• Upcoming large and clean samples of B, D (and τ) will allow Belle II to search for NP and to improve the measurements of SM parameters.

• Improved detector and analysis methods at Belle II leads to better sensitivity.

• Results using early data demonstrates the expected performances of all the sub-detectors.

• Belle II is running well amid CoViD-19 towards its ultimate goal to record 50 ab^{-1}.
Extra Slides
The exotic state $X(3872)$ is searched in the $B$-decay:

- The decay $B \rightarrow K\psi(2S)[\rightarrow J/\psi \pi\pi]$ serves as a good control sample.
- Simultaneous fit is performed to combine the distribution from $B^+$ and $B^0$ decays.

The $X(3872)$ signal yield is $14.4 \pm 4.6$ and the statistical significance is $4.6 \sigma$.
- First exotic state to be rediscovered in Belle II.
SuperKEKB Luminosity Plan

Operation plan proposed for MEXT 2020 Roadmap

- $L_{peak}$ Before IR upgrade
- $L_{peak}$ After IR upgrade

- Int. Luminosity

Peak luminosity [$10^{35}$ cm$^{-2}$s$^{-1}$]

Date

2019/1 2021/1 2023/1 2025/1 2027/1 2029/1 2031/1

RF [partial] IR (QCS) PXD

(PXD) (Tuning)
SuperKEKB Luminosity Plan

Belle II Online luminosity Exp: 7-8-10-12-14-16-17 - All runs

\[ \int L_{\text{Recorded}} \, dt = 101.67 \, [\text{fb}^{-1}] \]

Updated on 2021/03/26 22:11 JST
B^0 \rightarrow K^0\pi^0

- CP-eigenstate: flavor tagging to determine tag-side B’s flavor
- Probability density function of signal-side quark flavor q:

\[ P_{\text{sig}}(q) = \frac{1}{2}(1 - q \cdot \Delta w_r + q \cdot (1 - 2w_r) \cdot (1 - 2\chi_d) \cdot A_{K^0\pi^0}) \]

\[ \Delta t: P(q, \Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[ 1 + q(A_f \cos(\Delta m_d \Delta t) + S_f \sin(\Delta m_d \Delta t)) \right] \]

\( \chi_d \): time-integrated B^0 mixing probability (external input)
Assume null \( A_{CP} \) + continuum flavor symmetric

- Simultaneous fit over 7 flavor tagging r-bins

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta B(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking efficiency</td>
<td>1.8</td>
</tr>
<tr>
<td>( K_S^0 ) reconstruction efficiency</td>
<td>3.8</td>
</tr>
<tr>
<td>( \pi^0 ) reconstruction efficiency</td>
<td>3.2</td>
</tr>
<tr>
<td>Continuum-suppresion efficiency</td>
<td>2.4</td>
</tr>
<tr>
<td>N(( B\bar{B} )) (as written in Eq. 3)</td>
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<tr>
<td>Signal model</td>
<td>&lt;0.1</td>
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<tr>
<td>Continuum background model</td>
<td>1.2</td>
</tr>
<tr>
<td>Total</td>
<td>6.1</td>
</tr>
</tbody>
</table>

\[ B = (8.6^{+1.7}_{-1.6} \pm 0.5) \times 10^{-6} \]

\[ A_{K^0\pi^0} = -0.42^{+0.46}_{-0.44} \pm 0.04 \]