Belle II Highlights

Doris Yangsoo Kim
on behalf of the Belle II collaboration

August 8, 2023
30th Anniversary of the Rencontres du Vietnam:
Windows on the Universe
ICESE, Quy Nhon, Vietnam
HEP experiments have seen huge accomplishments during the last decades.
  – CPV/CKM, discovery of XYZ/tetra/penta particles, discovery of Higgs, etc.
  – Next major theme: New Physics, requiring more precision and larger samples.
• Belle II/SuperKEKB is the upgrade of Belle/KEK.
• Upsilon(4S) decays into $B \bar{B}$ meson pairs, coherently with no additional fragments.
  – Full event reconstruction tagging possible
• Direct detection of neutrals such as $\gamma$, $\pi^0$, $K_L$.
• A hermetic detector:
  – Detection of neutrinos or invisibles as missing energy/momentum.
• Large continuum charm and $\tau$ samples in addition to $B$ samples.
  – Detect both $e$ and $\mu$ with similar performance.
  – For example, search for LFV $\tau$ decays at $O(10^{-9})$ possible.
Belle II Physics Prospects

- Charm decays
- Next precision CKM matrix
  - Semileptonic B decays (CKM elements)
  - Hadronic B decays (angles and CPV)
  - Time dependent CP violation
- $\tau$ physics
- Hadron spectroscopy
- Rare decays, FCNC
- New physics
  - Lepton flavor violation
  - Dark sector, long lived particles

https://confluence.desy.de/display/BI/Snowmass+2021
The Belle II Detector

Pixelated photo sensors in TOP/ARICH/KLM
Front-end ASICs in many subsystems.

**Electrons (7GeV)**

**Positrons (4GeV)**

**Vertex Detector**
1 to 2 layers Si Pixels (DEPFET)
4 layers Si double sided strip DSSD

**Beryllium beam pipe**
2cm diameter

**Central Drift Chamber**
(He + C2H6) small cells, long lever arm

**EM Calorimeter:**
CsI(Tl), waveform sampling

**Particle Identification**
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

**KL and muon detector:**
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

With respect to Belle,
Vertexing and Tracking Improved
Particle ID improved, and
Better background insensitivity.
Note: higher event rate

**Doris Yangsoo Kim @ Rencontres du Vietnam, August 8, 2023**
The Belle II Collaboration

- As of July 2023, approximately 1,100 members, 120 institutes, 27 countries
SuperKEKB Luminosity: Current Status

- After the SupepKEKB commission phases, physics runs started spring 2019.
- Spring/summer 2022 run ended June.
  - Peak luminosity at $L_{peak} = 4.7 \times 10^{34} cm^{-2}s^{-1}$, the current world record on June 22nd.
  - Current integrated luminosity at $\int L_{recorded} dt = 424 fb^{-1}$.
    (~ Babar, ~ ½ Belle)
- Long shutdown 1 (LS1) started 2022 summer for upgrades (see later slides).
- Run 2 starts coming fall/winter.

https://confluence.desy.de/display/BI/Belle+II+Luminosity
Charm Particle Lifetime

- Charm particles @ low-energy QCD calculation (non-perturbative and high order correction). The effective models do have uncertainties.
- Measurements of charm lifetimes can test the models.
- At SuperKEKB, \( \sigma_{c\bar{c}} \sim \sigma_{b\bar{b}} \). Large charm sample.
- \( e^+ e^- \) collision gives clean environment. Less bias.
- Small interaction region and the new Belle II vertex detector give strong constraints and better resolutions.
  - Amount of \( t < 0 \): detector resolution
- A great opportunity to measure the world best charm lifetimes.

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Phys. Rev. Lett. 127 (2021), 211801
D⁰, D⁺, Dˢ⁺, Λᶜ⁺, Ωᶜ⁰ Lifetimes

**D⁰ → K⁻π⁺**

**D⁺ → K⁻π⁺π⁺**

**Mode** | **Belle II (fs)** | **Size** | **Previous WA (fs)** | **Ref.**
---|---|---|---|---
D⁰ | 410.5 ± 1.1 ± 0.8 | 72 fb⁻¹ | 410.1 ± 1.5 | Phys. Rev. Lett. 127 (2021), 211801
D⁺ | 1030.4 ± 4.7 ± 3.1 | 1040 ± 7 | | |
Dˢ⁺ | 498.7 ± 1.7⁺1.1⁻0.8 | 504 ± 4 | | arXiv: 2306.00365
Λᶜ⁺ | 203.2 ± 0.9 ± 0.8 | 202.4 ± 3.1 | | Phys. Rev. Lett. 130 (2023), 071802
Ωᶜ⁰ | 243 ± 48 ± 11 | 268 ± 24 ± 10 LHCb, 69 ± 12 pre-LHCb | | Phys. Rev. D 127 (2023), L031103

Belle II Ωᶜ⁰ lifetime measurement confirms the LHCb result.

Hierarchical reconstruction is performed to obtain B (tag) meson exclusively. Then use the Upsilon(4S) constraint to get the B (sig) meson.

• Traditionally, at Upsilon(4s), one B (tag) is reconstructed first. The rest of the event is considered as a signal B.
  – B flavor tagging (page 11)

• An improved tool (FEI) was developed based on Boosted Decision Tree.
  – MVA based. O(10^4) decay channels.
  – Max. tag side efficiency: \( \varepsilon_{\text{had}} \approx 0.5\% \) and \( \varepsilon_{\text{SL}} \approx 2\% \)
  – ex) Paolo Rocchetti’s talk. This talk page 13.
Why CKM Matrix?

• Unitary triangle constraints are powerful test of the SM.
  – Precision on $\alpha$ and $\gamma$ angles are much less than $\beta$.
• Predicting rare decays involves $V_{qq'}$. Needed for New Physics searches.
  – Use semi-leptonic, leptonic decays of mesons.

Prog. Theor. Exp. Phys. 2022 083C01 (2022) aka PDG 2022
Time Dependent CPV and Mixing in B physics

- Belle II flavor tagging $\varepsilon_{\text{eff}} = (30.0 \pm 1.2 \pm 0.4)\%$
  

- The 190 $fb^{-1}$ sample was studied to extract $B^0$ lifetime and mixing frequency.

- 30k $B^0 \to D^{(*)-}h^+$ decays are used for this result.

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Belle II: $\tau_{B^0} = 1.499 \pm 0.013 \text{(stat)} \pm 0.008 \text{(syst)} \text{ ps}$

Belle II: $\Delta m_{d} = 0.516 \pm 0.008 \text{(stat)} \pm 0.005 \text{(syst)} \text{ ps}^{-1}$

W. A.: $1.510 \pm 0.004 \text{ ps}$

W. A.: $0.50665 \pm 0.0018 \pm 0.005 \text{ ps}^{-1}$

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Phy. Rev. D 127 (2023), L091102

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Next, sin 2β

Proper time differences

\[ B^0 \rightarrow J / \psi K_S^0 \]
\[ B^0 \rightarrow \phi K_S^0 \]
\[ B^0 \rightarrow K_S^0 \pi^0 \]
\[ B^0 \rightarrow K_S^0 K_S^0 K_S^0 \]

<table>
<thead>
<tr>
<th>Type</th>
<th>Mode</th>
<th>[\sin 2\beta = S]</th>
<th>[A_{CP} = -C]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b \rightarrow c\bar{c}s)</td>
<td>(B^0 \rightarrow J/\psi K_S^0)</td>
<td>(0.720 \pm 0.062 \pm 0.016)</td>
<td>(0.094 \pm 0.044^{+0.042}_{-0.017})</td>
<td>arXiv:2302.12898</td>
</tr>
<tr>
<td>(b \rightarrow s\bar{s}s)</td>
<td>(B^0 \rightarrow \phi K_S^0)</td>
<td>(0.54 \pm 0.25^{+0.06}_{-0.08})</td>
<td>(0.31 \pm 0.20 \pm 0.05)</td>
<td>arXiv:2307.02802</td>
</tr>
<tr>
<td>(b \rightarrow d\bar{d}s)</td>
<td>(B^0 \rightarrow K_S^0 \pi^0)</td>
<td>(0.75^{+0.20}_{-0.23} \pm 0.04)</td>
<td>(0.04^{+0.15}_{-0.14} \pm 0.05)</td>
<td>arXiv:2305.07555</td>
</tr>
<tr>
<td>(b \rightarrow d\bar{d}s)</td>
<td>(B^0 \rightarrow K_S^0 K_S^0 K_S^0)</td>
<td>(-1.37^{+0.35}_{-0.45} \pm 0.03)</td>
<td>(0.07^{+0.15}_{-0.20} \pm 0.02)</td>
<td>Moriond 2023, arXiv:2209.09547</td>
</tr>
</tbody>
</table>

\(\beta = \phi_1\)
Fully Inclusive $B \to X_s\gamma$

- An effective way to search for NP in $b \to s\gamma$ channel. FCNC forbidden at tree level SM.
- 189 $fb^{-1}$ sample fitted in bins of $E^B_{\gamma}$ (photon energy in $B_{\text{sig}}$ rest frame) simultaneous with $B_{\text{tag}}$ mass.
- FEI used. Tag side is $B$ hadronic decays.
- Signal photon background veto from $\pi^0$ and $\eta$. Further suppression by a BDT classifier. $X_s$ candidate is isolated.
- Though efficiency is low at < 1%.

### Table

<table>
<thead>
<tr>
<th>$E^B_{\gamma}$ threshold (GeV)</th>
<th>$\mathcal{B}(B \to X_s\gamma) \times 10^{-4}$</th>
</tr>
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<tbody>
<tr>
<td>1.8</td>
<td>3.54 ± 0.78 ± 0.83</td>
</tr>
<tr>
<td>2.0</td>
<td>3.06 ± 0.56 ± 0.47</td>
</tr>
<tr>
<td>2.1</td>
<td>2.49 ± 0.46 ± 0.35</td>
</tr>
</tbody>
</table>
SuperKEKB Upgrade during LS1

- The sudden beam loss mitigation strategy.
- Reducing beamline neutrons by additional shielding around final-focus magnets and endcaps.
- Collimators: harder material, non-linear to decrease beam halo.
- For stability and increase in currents, RF cavity being replaced.
- Injector area: faster kicker magnet, new focusing magnet, new large-aperture beam pipe.

For LS2 plan, LP 2023 talk by L. Piilonen.
Belle II Upgrade during LS1

- One layer → two layer pixel detector (PXD)
- TOP PMT replaced for increased lifespan and robustness
- DAQ upgrade to PCIe40
- Improved gas distribution, gain stability, and monitoring for drift chamber
Summary

• SuperKEKB has achieved $L_{peak} = 4.7 \times 10^{34} cm^{-2}s^{-1}$, the world record on June 22nd, 2022.
  – It is a super B factory now.
• Belle II published world leading results in charm lifetime. D lifetime full set!
  – More updates are coming with the 424 $fb^{-1}$ sample.
• Belle II started producing results on many interesting physics from B and other sectors.
  – Only a few selected topics are shown here.
  – Detailed reports at Moriond 2023, LP 2023
• This is a very exciting time to do flavor physics, looking for physics beyond the Standard Model.
**τ Mass Measurement**

- τ mass needed for lepton flavor universality test, BF measurements, and strong coupling measurements at τ mass.
- Belle II studied $190 \text{fb}^{-1}$ of $e^+e^- \rightarrow \tau^+\tau^-, \tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$.
- Fit the threshold of $M_{\text{min}} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*) (E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$.
- Precision info of beam energy and track momentum scale is needed.

$B \rightarrow \pi\pi$ Br and $A_{CP}$ Studies

- Belle II measures $B \rightarrow \rho\rho, \pi\pi$ properties with isospin analysis: $Br$ and $A_{CP}$ used to reduce hadron uncertainties in CKM $\alpha$ (loop process).
- $B \rightarrow \rho\rho$: arXiv: 2206.12362, 2208.03554
- $B \rightarrow \pi\pi$: Moriond 2023, Phys. Rev. D 107, 112009 (2023)

<table>
<thead>
<tr>
<th>$Br(B^0 \rightarrow \pi^+\pi^-)$</th>
<th>$(5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Br(B^+ \rightarrow \pi^+\pi^0)$</td>
<td>$(5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$</td>
</tr>
<tr>
<td>$A_{CP}(B^+ \rightarrow \pi^+\pi^0)$</td>
<td>$-0.081 \pm 0.54 \pm 0.008$</td>
</tr>
<tr>
<td>$Br(B^0 \rightarrow \pi^0\pi^0)$</td>
<td>$(1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$</td>
</tr>
<tr>
<td>$A_{CP}(B^0 \rightarrow \pi^0\pi^0)$</td>
<td>$0.14 \pm 0.46 \pm 0.07$</td>
</tr>
</tbody>
</table>

$\alpha = \phi_2$
Belle II & Related LP 2023 Physics Subjects

- Michele Veronesi "Recent Belle II results on time-dependent CP violation and charm physics"
- Xiaodong Shi "Recent Belle II results on hadronic B decays"
- Niharika Rout "Recent Belle II results on radiative and electroweak penguin decays"
- Kazuki Kojima "Recent Belle II results on semileptonic B-decays and tests of lepton-flavor universality"
- Savino Longo "Recent dark-sector and tau physics results at Belle II"
- Yang Li "Recent quarkonium results at Belle II"
- Petar Rados "Belle II and LHCb Upgrade I performance"
- Yuehong Xie (Belle II & LHCb) "CP violation on heavy flavor physics"
- Chunhui Chen "Semileptonic b-hadron decays (Belle II / LHCb)"
- Changzheng Yuan (BESIII, Belle/Belle II, LHC exps.) "Heavy flavour spectroscopy"
Belle II and LHCb

• Belle II and LHCb have different systematics
  – Two experiments are required to establish NP.
  – LHCb: large $b\bar{b}$ cross-section (LHCb 1 fb$^{-1}$ ~ Belle II 1 ab$^{-1}$). Good sensitivity and S/N with di-muon modes and charged tracks with a vertex.
KEKB to SuperKEKB: Accomplished

- Nano beam scheme + Crab waist optics
- Target: vertical beta function $\beta^*_y$ 5.9 mm (KEKB) to 0.3 mm (SuperKEKB)
- Increase beam currents $I_{e\pm}$
- Increase beam-beam interaction $\xi_y$
$D_s, \Lambda_c^+, \Omega_c^0$, Lifetimes

$D_s^+ \rightarrow \phi\pi^+$

$\Lambda_c^+ \rightarrow pK^-\pi^+$

$\Omega_c^0 \rightarrow \Omega^-\pi^+$,

$\Omega^- \rightarrow \Lambda^0 K^-$, $\Lambda^0 \rightarrow p\pi^-$
Meanwhile, Validate sin 2β Method

- Apply the strategy to the golden mode: \( B^0 \to J/\psi K_S^0 \). This tree mode should be precisely measured, to compare with the penguin decays.
- NP can appear in the penguin decays such as \( B^0 \to K_S^0 K_S^0 K_S^0 \).

\[ \sin 2\beta \] validation from \( B^0 \to J/\psi K^+ \)

\( \sin 2\beta \) results from \( B^0 \to J/\psi K_S^0 \)

\[
S_{CP} \approx \sin 2\beta = 0.720 \pm 0.062 \text{ (stat)} \pm 0.016 \text{ (syst)}
\]

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A_{CP} = 0.094 \pm 0.044 \text{ (stat)}^{+0.042}_{-0.017} \text{ (syst)}
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