Recent results on B and D decay from Belle II

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on behalf of the Belle II collaboration

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Max Planck Institute for Nuclear Physics, Heidelberg, Germany
Belle II Experiment in a Nutshell

- 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

[Link to Snowmass 2021]

Paul Feichtinger, July 26, Session A
Dark sector results from Belle II
The Belle II Detector

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

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

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

EM Calorimeter:
- CsI(Tl), waveform sampling

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

Beryllium beam pipe
- 2cm diameter

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

Doris Yangsoo Kim @ PASCOS
2022, July 27, 2022

Vertexing and Tracking Improved
- Particle ID improved
- Better background insensitivity
- Higher event rate
SuperKEKB Luminosity: Current Status

- After the commission phases, physics runs started spring 2019.
- Reclaimed the luminosity record June 2020! (Previously held by LHC.)
- Spring/summer 2022 run ended June.
  - Peak luminosity at $L_{\text{peak}} = 4.7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, the current world record on June 22nd.
  - Current integrated luminosity at $\int L_{\text{recorded}} \, dt = 424 \text{ fb}^{-1}$.
    (~ Babar, ~ ½ Belle)
- Long shutdown 1 (LS1) just started for upgrades (beam pipe, pixel, TOP MPT).

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 from continuum.
- $e^+ e^-$ collision gives clean environment. Less bias.
- Small interaction region and the new Belle II vertex detector give strong constraints and better resolutions.
- A great opportunity to measure the world best charm lifetimes.
### $D^0, D^+, \Lambda_c^+, \Omega_c^0$ Lifetimes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Belle II (fs)</th>
<th>Previous WA (fs)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$410.5 \pm 1.1 \pm 0.8$</td>
<td>$410.1 \pm 1.5$</td>
<td>Phys. Rev. Lett. 127 (2021), 211801</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$1030.4 \pm 4.7 \pm 3.1$</td>
<td>$1040 \pm 7$</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^+$</td>
<td>$203.2 \pm 0.9 \pm 0.8$</td>
<td>$202.4 \pm 3.1$</td>
<td>arXiv: 2206.15227v1, PRL accepted</td>
</tr>
<tr>
<td>$\Omega_c^0$</td>
<td>$243 \pm 48 \pm 11$</td>
<td>$268 \pm 24 \pm 10$ LHCb</td>
<td></td>
</tr>
</tbody>
</table>

#### Belle II Data

- $D^0 \to K^-\pi^+$
- $\Lambda_c^+ \to pK^-\pi^+$
- $\Omega_c^0 \to \Omega^-\pi^+$, $\Omega^- \to \Lambda^0K^-$, $\Lambda^0 \to p\pi^-$
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 NP searches.
  – Use semi-leptonic, leptonic decays of mesons.

To be published,
Prog. Theor. Exp. Phys. 2022 083C01 (2022) aka PDG 2022

Figure 12.1: Sketch of the unitarity triangle.
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. 
  arXiv.org: 2008.02707
- An improved tool (FEI) is developed based on Boosted Decision Tree. 
- MVA based. $O(10^4)$ decay channels.
- Max. tag side efficiency: $\varepsilon_{\text{had}} \approx 0.5\%$ and $\varepsilon_{\text{SL}} \approx 2\%$
The CKM Matrix elements

- The ~ 3σ tension between inclusive and exclusive measurements in $|V_{cb}|, |V_{ub}|$ is still going on.
- Preliminary Belle II results, based on 190 fb$^{-1}$ samples.

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</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
<td>$B \rightarrow Dl\nu$, $(l = e, \mu)$</td>
<td>Untagged</td>
</tr>
<tr>
<td></td>
<td>$B^0 \rightarrow D^*l\nu$, $(l = e, \mu)$</td>
<td>Hadronic</td>
<td>$(38.2 \pm 2.8 \text{ (stat. + sys. +theo.)}) \times 10^{-3}$</td>
<td>Moriond 2022</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
<td>$B^0 \rightarrow \pi l\nu$, $(l = e, \mu)$</td>
<td>Untagged</td>
</tr>
<tr>
<td></td>
<td>$B \rightarrow \pi e\nu$</td>
<td>hadronic</td>
<td>$(3.88 \pm 0.45\text{(stat. + sys. +theo.)}) \times 10^{-3}$</td>
<td>Moriond 2022</td>
</tr>
</tbody>
</table>
Signal Selection of SL modes.

\[ \cos \theta_{BY} \text{ (angle btw. } B \text{ and } DL) \]

\[ B^0 \rightarrow \pi^- e^+ \nu_e \text{ untagged} \]

\[ M_{\text{miss}}^2 = (P_{\text{beam}} - P_{\text{tag}} - P_{\bar{B}} - P_f)^2 \text{ [GeV}^2/c^4]\]

\[ \Delta E = E_B^* - E_{\text{beam}}^* \text{ [GeV]} \]
Time Dependent CPV and Mixing

- 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.

Belle II: $\tau_{B^0} = 1.499 \pm 0.013 \, (\text{stat}) \pm 0.008 \, (\text{syst}) \, \text{ps}$
W. A.: $1.510 \pm 0.004 \, \text{ps}$

Belle II: $\Delta m_{d} = 0.516 \pm 0.008 \, (\text{stat}) \pm 0.005 \, (\text{syst}) \, \text{ps}^{-1}$
W. A.: $0.50665 \pm 0.0019 \, \text{ps}^{-1}$
Next, Measure $\sin 2\beta$

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

**$\sin 2\beta$ validation from $B^0 \rightarrow J/\psi K^+$**

$\sin 2\beta$ results from $B^0 \rightarrow J/\psi K_S^0$

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

\[
A_{CP} = 0.094 \pm 0.044 \, \text{(stat)}^{+0.042}_{-0.017} \, \text{(syst)}
\]
Rare B decays: Overview

• FCNC $b \rightarrow s$ transitions are suppressed in the SM. A good place to look for NP.
  – The 10 to 30% uncertainty in the SM BR ($10^{-5}$ to $10^{-7}$) can be supplemented by ratios, asymmetries, and angular distributions.

• A decay channel involving leptons is an excellent place to test LFU or LFV.
  – Belle II have similar detector performances between electron and muon.

• The results from the initial physics sample are shown here.
$B^+ \rightarrow K^* l^+ l^-$

- $R_{K^*}$ measurements have a 2-3 $\sigma$ discrepancies between $e$ and $\mu$.
- The first Belle II report on 190 $fb^{-1}$ sample.
- Background suppressed by BDT, and veto on $J/\psi$, $\psi(2S)$ mass.
- 2D fit to $M_{bc}$ and $\Delta E$.

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<tr>
<th>Modes</th>
<th>Belle II</th>
<th>WA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow K^* \mu^+ \mu^-$</td>
<td>$(1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6}$</td>
<td>$(1.06 \pm 0.09) \times 10^{-6}$</td>
</tr>
<tr>
<td>$B \rightarrow K^* e^+ e^-$</td>
<td>$(1.42 \pm 0.48 \pm 0.09) \times 10^{-6}$</td>
<td>$(1.19 \pm 0.20) \times 10^{-6}$</td>
</tr>
<tr>
<td>$B \rightarrow K^* l^+ l^-$</td>
<td>$(1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$</td>
<td>$(1.05 \pm 0.10) \times 10^{-6}$</td>
</tr>
</tbody>
</table>
$B^+ \rightarrow K^+ \nu \nu$ with Inclusive Tagging

• The Belle II measurement at $63 fb^{-1}$ is comparable to the previous Babar/Belle measurements.
• Next step: 424 $fb^{-1}$ sample, hadronic/semileptonic taggings, more channels ($K^*$, $K_S$)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Limit on $\sin(2\theta_{CP})$ at 90% C.L.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babar</td>
<td>$&lt; 1.6 \times 10^{-5}$ (90% C.L.)</td>
<td>Phys. Rev. D87,112005 (2013)</td>
</tr>
<tr>
<td>Belle</td>
<td>$&lt; 1.9 \times 10^{-5}$ (90% C.L.)</td>
<td>Phys. Rev. D96,091101(R) (2017)</td>
</tr>
</tbody>
</table>
Summary

• SuperKEKB has achieved $L_{\text{peak}} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the world record on June 22nd, 2022.
  – It is a super B factory now.

• Belle II has started producing new results, including a world leading results in charm lifetime.
  – More updates are coming with the 424 $fb^{-1}$ sample!

• Belle II started producing results on many interesting B physics.
  – Only a few selected topics are shown here.
  – Further reports at ICHEP 2022, Moriond 2022.

• This is a very exciting time to do flavor physics, looking for physics beyond the Standard Model.
EXTRA
The Belle II Collaboration

- As of July 2022, approximately
- 1,100 members, 120 institutes, 27 countries
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 $\zeta_y$

KEKB beams

Beam crossing angle 22 mrad

SuperKEKB nanobeams

Beam crossing angle 83 mrad

$$L = \frac{\gamma_{e\pm}}{2e r_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \left(\frac{1}{\beta_y^*} \frac{I_{e\pm}}{\xi_{y,e\pm}} \right) \frac{R_L}{R_{\xi_y}}\right)$$