Belle II at SuperKEKB, Status and Prospects

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KEK
High Energy Accelerator Research Organization

Z. Dolezal, Epiphany 2020
Asymmetric energy Flavor factories

- $e^+e^-$ beams tuned at $Y(4S)$ resonance 10.6 GeV
- 50% decays: coherent production $B^0\overline{B}^0$
- Fully reconstruct one of the $B$'s
- Tag the flavor of the other $B$
First-generation Factories

- Success culminated in 2008 Nobel prize in Physics
- Rich legacy left for next generation experiments
Motivation for another $e^+e^-$
Flavor Factory

- Precision CKM metrology $\rightarrow$ Standard Model (SM) candle
- New CP violating phases $\rightarrow$ CP violation in $B$ and $D$ decays
- Any imprint of new physics in FCNC transitions? $\rightarrow$ radiative and electroweak penguin decays
- How about charged Higgs boson? $\rightarrow$ study tree-level decay $B \rightarrow \tau \nu$ or $B \rightarrow D(\ast)\tau \nu$
- New physics in $\tau$ sector $\rightarrow$ search for lepton flavor violating (LFV) $\tau$-decays
- Can we probe dark matter? $\rightarrow$ hidden dark sector

Belle II @ SuperKEKB will address these and other questions with almost two orders of magnitude larger dataset than Belle+BABAR
SuperKEKB

Beams at KEKB

Nanobeams at SuperKEKB

Interaction-point size: $6 \times 0.06 \times 150 \ \mu\text{m}^3$
Nanobeam Scheme

\[ L = \frac{N^2 f_b}{4\pi \sigma_x \sigma_y} = \frac{\gamma_{e\pm}}{2e \tau} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{I_{e\pm} \xi_{e\pm}^*}{\beta_y^*} \right) \left( \frac{R_L}{R_{\xi_y}} \right) \]

<table>
<thead>
<tr>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>E_b</td>
<td></td>
</tr>
<tr>
<td>LER</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>HER</td>
<td>8</td>
<td>7.007</td>
</tr>
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<td>8</td>
<td>7.007</td>
</tr>
<tr>
<td>Beam crossing angle</td>
<td>( \varphi )</td>
<td>( \varphi )</td>
</tr>
<tr>
<td>LER</td>
<td>22</td>
<td>83</td>
</tr>
<tr>
<td>HER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta ) function @ IP</td>
<td>( \beta_x^*/\beta_y )</td>
<td>( \beta_x^*/\beta_y )</td>
</tr>
<tr>
<td>LER</td>
<td>1200/5.9</td>
<td>32/0.27</td>
</tr>
<tr>
<td>HER</td>
<td>25/0.30</td>
<td></td>
</tr>
<tr>
<td>Beam current</td>
<td>I_b</td>
<td></td>
</tr>
<tr>
<td>LER</td>
<td>1.64</td>
<td>3.6</td>
</tr>
<tr>
<td>HER</td>
<td>1.19</td>
<td>2.6</td>
</tr>
<tr>
<td>Luminosity</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>LER</td>
<td>(2.1 \times 10^{34})</td>
<td>(8 \times 10^{35})</td>
</tr>
<tr>
<td>HER</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Z. Dolezal Epiphany 2020
Luminosity vs Physics

E. Kou et al. PTEP 2019(123C01)
Belle II Collaboration

26 countries, 113 institutions, close to 1000 collaborators
Belle II Detector

- Designed to operate with a performance similar or better than Belle, but in a harsh beam background condition.

EM Calorimeter (ECL):
CsI(Tl) crystals, waveform sampling readout

K_\text{L} and muon detector (KLM):
Resistive plate counter (barrel outer); plastic scintillator + WLS fiber + SiPM (barrel inner two layers and endcap)

Particle identification:
Time-of-Propagation counter (barrel); Proximity focusing Aerogel RICH (forward)

Beryllium beam-pipe (10 mm radius)

e^- (7 GeV)

Central Drift Chamber (CDC):
He(50%)+C_2H_6(50%), small cells, long lever arm, fast electronics

Vertex Detector (VXD):
2-layer pixel (PXD) + 4-layer micro-strip (SVD)

e^+ (4 GeV)
Vertex Detector (VXD)

2 layers of DEPFET active pixels 75 µm thick (currently 2 modules in L2 only)

4 layers of double-sided strip sensors

Factor 2 or better impact parameter resolution in spite of the lowered Lorentz boost
Central Drift Chamber (CDC)

Bulky particle ID system

Stringing 51456 wires

Outer radius almost ~20% larger than at BABAR/Belle:
Improved momentum resolution

A. Soffer, Taipei 2019
Particle ID (Time of Propagation)

MCP-PMTs
512 channels
50 ps resolution

$K/\pi$ track

Cherenkov angle:
$\cos \theta_C = 1/n\beta$

Photon from $\pi^+$
Photon from $K^+$

Bar length = 2600 mm, width = 450 mm, thickness = 20 mm

16 quartz-bar modules:

<table>
<thead>
<tr>
<th>Quartz Property</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flatness</td>
<td>&lt;6.3µm</td>
</tr>
<tr>
<td>Perpendicularity</td>
<td>&lt;20 arcsec</td>
</tr>
<tr>
<td>Parallelism</td>
<td>&lt;4 arcsec</td>
</tr>
<tr>
<td>Roughness</td>
<td>&lt;0.5 nm (RMS)</td>
</tr>
<tr>
<td>Bulk transmittance</td>
<td>&gt; 98%/m</td>
</tr>
<tr>
<td>Surface reflectance</td>
<td>&gt;99.9%/reflection</td>
</tr>
</tbody>
</table>
How far have we gone?

Full Belle II detector: Mar 2019

$L_{\text{peak}} = 1.2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

$L_{\text{int}} = 10.57$ fb$^{-1}$

Continuous beam injection started from 14th, May.
K/π Particle Identification

BELLE2-NOTE-PL-2019-022

Measured on a control sample

\[ D^{*+} \rightarrow D^0[K^-\pi^+]_s\pi^+ \]
Track Impact Parameter Resolution

Belle vs Belle II
Factor 2 better

Impact parameter resolution: 14 µm
D⁰ Lifetime

Good position resolution/alignment crucial!

Result with a small dataset

\[ \tau_{D^0} = (370 \pm 40_{\text{stat}}) \text{ fs} \]

Accepted value 410 fs

BELLE2-NOTE-PL-2019-003
J/ψ Reconstruction

Dilepton invariant mass

\[ e^+ e^- \]  \hspace{1cm} \[ \mu^+ \mu^- \]

BELLE2-NOTE-PL-2019-018

\[ \int L \, dt = 2.62 \text{ fb}^{-1} \]

\[ N_{\text{sig}} = 1608 \pm 54 \]

\[ \int L \, dt = 2.62 \text{ fb}^{-1} \]

\[ N_{\text{sig}} = 1684 \pm 48 \]
Rediscovery of B Mesons

Demonstration of Belle II’s B Physics Capabilities:
Modes with neutrals, and K mesons are efficiently reconstructed along with all-charged final states containing kaons and pions.

\[ M_{bc} = \sqrt{\left(\frac{E_{cm}}{2}\right)^2 - p_{\text{recon}}^2} \]
Full Event Interpretation Reconstruction (FEI)

This machine-learning technique (BDT) brings higher reconstruction efficiency.
First Belle II NP Search

A low-mass $Z'$ that couples to a $\mu\mu$ or $\mu e$ vertex is poorly constrained in the $Z' \rightarrow$ invisible channel. Could be responsible for the $g_\mu - 2$ anomaly.

$$e^+e^- \rightarrow \mu^+\mu^- + \text{inv.}$$

$$e^+e^- \rightarrow \mu^\pm e^\mp + \text{inv.}$$
Limits on $Z' \rightarrow \text{invisible}$

\[ e^+ e^- \rightarrow \mu^+ \mu^- + \text{inv.} \]

Limit on $Z' \mu \mu$ coupling for $Br(Z' \rightarrow \text{inv}) = 1$

\[ e^+ e^- \rightarrow \mu^\pm e^{\mp} + \text{inv.} \]

Limit on efficiency times cross section

References:
- Shuve & Yavin, PRD 89 (2014) 113004
- Galon & Zupan, JHEP 2017 (2017) 83
- Galon, Kwa, Tanedo, JHEP 2017 (2017) 64
- BABAR limits in $Z' \rightarrow \mu^+ \mu^-$ case: PRD 94 (2016) 011102

Some theory work on the MC needed in order to extract cross-section limits

arXiv:1912.11276
Submitted to PRL
Summary

- The Belle II experiment is a powerful tool to find signs of new physics by precision measurement of huge statistics of heavy flavor decays.
- From 2018, Belle II physics run has started.
- First physics results: re-discovery of B meson, Z’, B mixing.
- Full event interpretation.
- From February 2020 beam operation restarts.
- More info at student talks:

  - S. Bacher
  - J. Kandra
  - B. Knysh
  - R. Manfredi
Backup
New Constraints by the nano-beam scheme

LER (3.5 GeV -> 4 GeV):
- for longer Touschek lifetime $\propto E^3$

HER (8 GeV -> 7 GeV):
- Lower emittance beam $\propto 1/E^2$
- Lower Synchrotron radiation loss

● To realize nano-beam, Lorentz boost factor is decreased down to 2/3.
○ Thanks to Nano-beam scheme: diameter of IP beam pipe is reduced from 3cm to 2cm
<table>
<thead>
<tr>
<th>$e^+e^-$ has advantages in...</th>
<th>LHCb has advantages in...</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPV in $B \to \phi K_S, \eta' K_S,…$</td>
<td>CPV in $B \to J/\psi K_S$</td>
</tr>
<tr>
<td>CPV in $B \to K_S \pi^0 \gamma$</td>
<td>Most of $B$ decays not including $\nu$ or $\gamma$</td>
</tr>
<tr>
<td>$B \to K \nu \nu, \tau \nu, D(*) \tau \nu$</td>
<td>Time dependent measurements of $B_S$</td>
</tr>
<tr>
<td>Inclusive $b \to s \mu \mu$, see</td>
<td>$B_{(s,d)} \to \mu \mu$</td>
</tr>
<tr>
<td>$\tau \to \mu \gamma$ and other LFV</td>
<td>$B_c$ and bottomed baryons</td>
</tr>
<tr>
<td>$D^0 \overline{D^0}$ mixing</td>
<td></td>
</tr>
<tr>
<td>Observables</td>
<td>UT angles &amp; sites</td>
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<tr>
<td>-------------</td>
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<tr>
<td><strong>Search of LFV tau decays</strong></td>
<td><strong>Vibrant charm program</strong></td>
</tr>
</tbody>
</table>

**From Belle II book**

(to appear in PTEP)

Sub-detector installation

May 2016: TOP

Oct. 2016: CDC

Apr 2017
Belle II roll-in

Aug. 2017: ARICH

Jan. 2017 BWD ECL

2015 KLM

VXD: 2018