Belle II status and prospects for flavor physics

Jing-Ge Shiu/NTU
On behalf of the Belle II collaboration
Belle II status and prospects for flavor physics

Outline

- SuperKEKB and Belle II
- Status and schedule
- Physics prospect
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SuperKEKB @ Tsukuba, ~ 1.5 hours away from Tokyo
lake Kasumigaura (霞ヶ浦)
famous Mt. Tsukuba
LHC
27 km circumference
~100m underground
7000 ~ 14000 GeV

table

Lake Geneva
famous Mt. Jura
They are similar!!
at least geographically and geometrically.

LHC
27 km circumference
~100m underground
7000 ~ 14000 GeV

SuperKEKB
~3 km circumference
10~11 GeV
(7 GeV e- / 4 GeV e+)
What is Belle II's role in this LHC era?
Why Belle II

Last generation B factories achieved a great success in B (charm, $\tau$) physics studies and explored possible new physics.

However, there are still remaining puzzles and open questions:
- How “standard” is the SM (where is the NP)?
- Those “dark” things …..
Why Belle II

**Energy frontier**
→ powerful in energy scale to search for new particles and physics. (LHC)

**Precision/intensity frontier**
→ focus on a certain energy range for precision measurements to search for anomalies from the SM and new physics from rare decays (SuperKEKB + Belle II)

complementary with each other
SuperKEKB: why not just keep running KEKB/Belle

founded in 2008, groundbreaking in 2011
peak luminosity $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$ (40 x KEKB)
→ nano beam with higher beam currents
Belle II: 50ab$^{-1}$ data (50 x Belle)
→ high precision measurements; rare decays
Belle II Collaboration

>700 members
101 institutions
Requirements for the Belle II detector
(critical issues at $L = 8 \times 10^{35}/\text{cm}^2/\text{s}$)

- Higher event rate
  ➔ higher trigger rate, DAQ, computing
- Higher background
  ➔ radiation damage ➔ BEAST2
  ➔ occupancy
  ➔ fake hits and pile-up noise
- $\beta\gamma$ reduced by a factor of 1.5

- Upgrade
  ➔ better vertexing/tracking
    ➢ pixel + silicon strip (VXD)
    ➢ new CDC larger volume smaller cell
  ➔ better particle identification
  ➔ faster readout electronics and computing
  ➔ faster and flexible trigger system
    ➢ z-vertex trigger to reduce background
Most sub-detectors will be ready in 2017.

**ECL**
- photon, electron
- CsI(Tl)
- waveform sampling

**VXD**
- vertexing
- PXD: 2 layers DEPFET
- SVD: 4 layers DSSD

**CDC**
- charged particle tracking
- track z-vertex trigger
- smaller cell size, long level arm
- He(50%)+C$_2$H$_6$ (50%)

**1.5T solenoid**

**KLM**
- Klong, muon
- RPC+scintillator (barrel)
- scintillator (end-caps)

**TOP/RICH**
- particle identification
- TOP(barrel): DIRC
- RICH(fwd): aerojel

**e^- (7 GeV)**

**e^+ (4 GeV)**

**trigger rate ~ 20 kHz**

**GRID computing**
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Belle II roll-in

Phase 1: beam practice
BEAST2 phase 1
no collision
no Belle II
background study

Phase 2: beam collision
BEAST2 phase 2
no VXVD

Phase 3: increasing lumi.
full Belle II
physics run 1

now

CDC in

VXVD installation
(SVD+PXD)

keep running,
and running,
and running,
…..

Schedule in the coming years
Schedule in the coming years

- **Phase 1: beam practice**
  - BEAST2 phase 1
  - No collision
  - No inner detector
  - No CDC
  - No magnetic field

- **Phase 2: beam collision**
  - BEAST2 phase 2
  - No VXD
  - VXD installation (SVD+PXD)

- **Phase 3: full Belle II**
  - Physics run 1
  - ~ 6 years to reach target data statistics

~ 6 years to reach target data statistics

MR startup

MR renovation for phase 2 including installation of QCS and Belle II

w/ QCS w/o Belle II

w/ Belle II (no VXD)

w/ full Belle II

HEN start LE start

VXD installation

Reoptimized schedule

Goal of Belle II/SuperKEKB

Integrated luminosity (ab$^{-1}$)

Peak luminosity (cm$^{-2}$s$^{-1}$)

PHASE 1

PHASE 2

PHASE 3

SuperKEKB Goal

~ 6 years to reach target data statistics

time to open the other eye.
SuperKEKB/BEAST2 phase 1 operation

Feb.~Jun., 2016: **target beam energies/ lower-currents** without collision

**Red:** total beam current  
**Purple:** vacuum pressure  
**Cyan:** beam lifetime

![Graph showing beam current and other metrics over time with specific events marked.](image-url)
Phase 1,

**Bea st 2**

has paved the road for the beauty.

( ~1 year ago)


beam BG/machine study
Phase 2, ring a Bell for a new era to come.

Beast2 with partial Belle II, some measurements possible.


early 2018 collision tuning partial Belle II (no vertexing)

➔ achieve $10^{34}$ /cm$^2$/s (KEKB/Belle peak)
➔ stable run close to $\gamma$(4S) preferred
➔ PID not fully reliable
➔ Integrated luminosity $\sim$(20±20 fb$^{-1}$)

Important milestone for Belle II

early 2018 collision tuning partial Belle II (no vertexing)

2019 ~ full Belle II commissioning

50 ab$^{-1}$

8x10$^{35}$/cm$^2$/s

➔ high flavor tagging eff.  
➔ good PID  
➔ clean detector environment

full power of Belle II physics

beam bg/machine study

possible early measurements
Belle II roll-in (April 11, 2017)

Belle II in position now (VXD)
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Belle II physics prospect

- **B physics**
  - precision measurements of CKM elements
  - rare B decays
  - other B decay physics, ...

- **Charm physics (Mixing, CPV in charm, rare charm decays, ...)**

- **τ physics (LFV, CPV, ...)**

- **Others**
  - bottomonium spectrum
  - exotics state (tetraquark, ...)
  - other new physics searching (Higgs BSM, dark sector, leptoquark, ...)

- advantage on decays with neutral particles in the final states.

more about Beyond the standard Model @Belle II and B2TiP, Y. Okada, May 3.
Belle II physics prospect – CKM

- does the unitary triangle really a triangle?
  current $\alpha + \beta + \gamma = (175 \pm 9)^\circ$ (PDG)
  $\rightarrow$ Belle II expects to improve the precision
  $\beta \sim 0.3^\circ$, $\alpha \sim 1.0^\circ$, $\gamma \sim 1.5^\circ$
  (precision 5~10% $\rightarrow$ 1~3%)

- precision measurements of $\sin(2\beta) = \sin(2\phi_1)$
  remains an important topic to check the consistency of the Unitary triangle and to search for new source of CPV
  e.g. $\Delta S = \sin(2\beta_{\phi K_s^0}) - \sin(2\beta_{J/\psi K_s^0})$
  $\rightarrow$ with 50ab$^{-1}$ data, Belle II can reach 5$\sigma$
  even with a small deviation $\Delta S \sim 0.02$
Belle II physics prospect \( B \rightarrow D(\ast) \tau\nu \)

\[
R(D(\ast)) = \frac{\Gamma(B^0 \rightarrow D(\ast) \tau\nu)}{\Gamma(B^0 \rightarrow D(\ast) l\nu)}_{l=\mu,e}
\]

sensitive to H-b-c coupling
larger BF in the SM (~1%)
smaller theoretical uncertainty of R(D)
discrimination of W and H by differential distribution

new Belle measurement [hep-ex 1603.06711]
\[ R(D^*) = 0.302 \pm 0.030 \text{(stat)} \pm 0.011 \text{(syst)} \ (13.8 \sigma) \]
Belle II physics prospect – charm physics

- B factories discovered the $D^0 - \overline{D}^0$ mixing.
  - Belle II will improve the measurements of the mixing parameters and look for CPV.
  - proper time resolution for $D^0$ decays $\sim 0.14$ ps

- Rare charm decays, e.g.
  - $D^0 \rightarrow \gamma\gamma$
  - predicted BF a few $x 10^{-8}$
  - Belle result $8.5x10^{-7} @ 90\%$CL  
    (PRD 93, 051102(R), 2016; 832 fb$^{-1}$ data)
  - expected to reach $10^{-7} - 10^{-8}$  
    (with full Belle II data)
Belle II physics prospect – tau LFV

LFV is suppressed in SM → a few models predict enhancements within Belle II's reach.

\[ \tau \rightarrow \mu \gamma \]
main background from \( \text{ee} \rightarrow \mu \mu \gamma_{\text{ISR}} \)
reduce sensitivity by a factor \( \sim 7 \)

\[ \tau \rightarrow \mu \mu \mu \]
very clean mode
reduce sensitivity by a factor of 50

possible reach by Belle II (50 ab\(^{-1}\))  \(< 10^{-9} < 10^{-10} \) → good to test NP

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<table>
<thead>
<tr>
<th>Model</th>
<th>( B(\tau \rightarrow \mu \gamma) )</th>
<th>( B(\tau \rightarrow \mu \mu \mu) )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>mSUGRA+seesaw</td>
<td>( 10^{-7} )</td>
<td>( 10^{-9} )</td>
<td>PRD 66(2002) 115013</td>
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<tr>
<td>SUSY+SO(10)</td>
<td>( 10^{-8} )</td>
<td>( 10^{-10} )</td>
<td>PRD 68(2003) 033012</td>
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<tr>
<td>SM+seesaw</td>
<td>( 10^{-9} )</td>
<td>( 10^{-10} )</td>
<td>PRD 66(2002) 034008</td>
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<tr>
<td>Non-Universal Z'</td>
<td>( 10^{-9} )</td>
<td>( 10^{-8} )</td>
<td>PLB 547(2002) 252</td>
</tr>
<tr>
<td>SUSY+Higgs</td>
<td>( 10^{-10} )</td>
<td>( 10^{-7} )</td>
<td>PLB 566(2003) 217</td>
</tr>
</tbody>
</table>
Summary

● The SuperKEKB + Belle II will be ready for commissioning soon
  ➢ 40x higher instantaneous lumi.
  ➢ 50 ab$^{-1}$ data statistics.
  ➢ Belle → Belle II

● SuperKEKB first beam circulations in 2016
  ➢ Belle II roll-in in April
  ➢ prepare 1st collision in early 2018

● Physics commissioning with full Belle II in early 2019.
  ➢ precision measurements of CKM
  ➢ B, charm and $\tau$ physics
  ➢ exotics states, dark sector, light Higgs, ....

● A friendly competition and complementarity with other experiments
  (LHCb, BESIII), a new and exciting era to explore the physics frontier.
BACKUP
### Luminosity of KEKB and SuperKEKB

<table>
<thead>
<tr>
<th></th>
<th>KEKB achieved</th>
<th>SuperKEKB nano-beam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LER</td>
<td>HER</td>
</tr>
<tr>
<td>$E_{\text{beam}}$ (GeV)</td>
<td>3.5</td>
<td>8</td>
</tr>
<tr>
<td>$I_{\text{beam}}$ (A)</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>$\beta_y$ (mm)</td>
<td>5.9</td>
<td>5.9</td>
</tr>
<tr>
<td>luminosity ($cm^{-2}s^{-1}$)</td>
<td>$2.1\times10^{34}$</td>
<td>$8.0\times10^{35}$</td>
</tr>
</tbody>
</table>

$\beta y \sim 2/3$

factor 2

factor 20

factor 40

nano beams with high beam currents
low emittance 4.6 nm /3.2 nm

→ high intensity frontier
Belle II (top) compared with Belle (bottom)

SVD: 4 DSSD lyr → 2 DEPFET lyr + 4 DSSD lyr
CDC: small cell, long lever arm

ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)
VXD = PXD + SVD

SuperKEKB: Nano beam option, 1 cm radius of beam pipe. Final focus quadrupole "intergrated" into vertex detector.

- "PXD"
  - 2 layer Si pixel detector (DEPFET technology)
    - (R = 1.4, 2.2 cm)
    - Monolithic sensor
    - Thickness 75 μm (!), pixel size ≈50 x 50 μm²
    - L = 12 cm

- "SVD"
  - 4 layer Si strip detector (DSSD)
    - (R = 3.8, 8.0, 11.5, 14.0 cm)
    - L = 60 cm

Significant improvement in z-vertex resolution.
**Belle II PXD**

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>0.4 hits/μm²/s (3% max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>2 Mrad/year</td>
</tr>
<tr>
<td></td>
<td>$2 \cdot 10^{12} 1$ MeV n_{eq} per year</td>
</tr>
<tr>
<td>Integration time</td>
<td>20 μs</td>
</tr>
<tr>
<td>Momentum range</td>
<td>Low p (50 MeV - 3 GeV)</td>
</tr>
<tr>
<td>Acceptance</td>
<td>17°-155°</td>
</tr>
<tr>
<td>Material budget</td>
<td>0.21% $X_0$ per layer</td>
</tr>
<tr>
<td>Resolution</td>
<td>15 μm (50x75 μm²)</td>
</tr>
</tbody>
</table>

- Impact parameter resolution (15 μm), dominated by multiple scattering mainly in BP → Pixel size (50 x 75 μm²)
- Lowest possible material budget (0.21% $X_0$/layer)
  - Ultra-transparent detectors
  - Lightweight mechanics and minimal services in physics acceptance
**CDC**

*(central drift chamber)*

Three important roles:
- Track reconstruction and momentum determination
- Particle identification via $dE/dx$
- Trigger for background rejection

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**Track Efficiency**

*Belie II Simulation (Preliminary)*

$\sigma_{t\phi} = 100 \mu m$

$\sigma_z = 2 \text{ mm}$

200 ns dead time

$$\frac{\sigma_{p_t}}{p_t} \sim 0.3\% / \beta \oplus 0.1\% \cdot p_t [GeV/c]$$

$$\sigma \left( \frac{dE}{dx} \right)_{\text{MIP}} \sim 5\%$$
EM calorimeter: upgrade needed because of higher rates (electronics → waveform sampling) and radiation load (endcap, replace some fraction of crystals CsI(Tl) → pure CsI)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

ECL cosmic ray test
(single high energy shower)
Particle Identification devices

**Barrel PID: TOP (Time Of Propagation)**

- MCP-PMT
- Focus mirror (sphere, r=7000)
- Backward Quartz radiator
- Forward Focusing mirror
- Small expansion block
- Hamamatsu MCP-PMT (measure t, x and y)

**EndCap PID: aerogel RICH**

- 200mm Cherenkov photon
- Aerogel radiator n~1.05
- Hamamatsu HAPD + new ASIC

First events in a partially instrumented sector of the ARICH.
Barrel PID: TOP (Time Of Propagation)

- Cherenkov ring imaging with **precise time measurement**.
- Uses internal reflection of Cherenkov ring images from quartz like the BaBar DIRC.
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm thick)
  - Photon detector (MCP-PMT)
    - Excellent time resolution $\sim 40$ ps
    - Single photon sensitivity in 1.5
EndCap PID: ARICH (aerogel RICH)

- Test Beam setup
- Aerogel
- Hamamatsu HAPDs
- Clear Cherenkov image observed
- Cherenkov angle distribution

6.6 $\sigma$ $\pi/K$ at 4GeV/$c$ !

Peter Križan, Ljubljana
KLM \( (K_L \text{ and muon detector}) \)

Interleaved with the iron plates of the flux return yoke

- **Barrel:**
  Belle RPCs reused
  Two inner layers replaced by scintillator strips
  Scintillator strips with WLS fibers
  Hamamatsu SiPM S10362

- **Endcap:**
  RPCs replaced with polystyrene scintillators
  99% geometrical acceptance. \( \sigma \sim 1 \text{ns} \)

(C. Marinas, DPG Münster 2017)
Belle II Level 1 trigger (CDC + ECL + TOP + KLM)

beam collision 254 MHz
nominal beam background rate ~10 MHz
interested physics event rate ~20 kHz
L1 max. latency 5 μs
L1 z-vertex trigger
L1 Global Reconstruction Logic

DAQ and analysis software
BASF2
(ROOT/C++/Python)
LHCb vs SuperKEKB

LHCb

- large samples (but low efficiencies)
- exclusive decays
- $B_s$ oscillations
- $B_c$, bottom baryons
- $B_{s,d}^0 \rightarrow \mu\mu$
- $B \rightarrow J/\psi K_S$
- $D^0 \rightarrow K^+\pi^-, K^+K^-$

SuperKEKB

- all final states measurable, esp. those with photons, neutrinos
  - + inclusive decays
  - rare decays, such as
    - $B^+ \rightarrow l^+\nu, B^+ \rightarrow K^+\nu\bar{\nu}$
    - $b \rightarrow s\gamma, b \rightarrow s\ell^+\ell^-$
    - $B \rightarrow J/\psi\phi, \pi\pi, \rho\pi, \rho\rho, \pi\pi\pi$
    - $D^0\bar{D}^0$ mixing
    - $e^+e^- \rightarrow \tau^+\tau^-$

LHCb and SuperKEKB will run concurrently. largely complementary

(Several working groups organized to assess the possible physics topics)
Potential early physics topics

Phase 2&3 possible to collect 300 fb$^{-1}$ data

- Bottomonium
  - Improving measurements (e.g. $\eta_b(nS), h_b(nP)$)
  - Searching for “missing” particles (e.g. $\Upsilon(1D, 2D)$)

- BSM physics: dark photon/light Higgs

$\Upsilon(3S)$ spectrum

$\Upsilon(3S) \rightarrow \gamma A', A' \rightarrow \text{invisible or } (e^+e^- \text{ or } \mu^+\mu^-)$ (dark photon)

cross section $\propto \varepsilon^2 \alpha^2 / E_{CM}^2$

$A' \rightarrow (e^+e^- \text{ or } \mu^+\mu^-)$

$A' \rightarrow \text{invisible}$

Exclusion regions (colored) for $\varepsilon$ as a function of $A'$ mass, for various experiments and projections of Belle II.

$\Upsilon(3S) \rightarrow \gamma A^0, A^0 \rightarrow \text{invisible}$

$\Upsilon(1D_2)$ has been measured by CLEO/BaBar.

$\Upsilon(1D_1), \Upsilon(1D_3), \Upsilon(2D)$ are not seen yet.