Latest results from Belle II

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INFN Padova
on behalf of the Belle II Collaboration

March 10th 2021
La Thuile 2021
Virtual mode
Outlook

- SuperKEKB collider
- Current integrated luminosity
- Luminosity plan

- Belle II Detector
- Detector performance
- Belle II Physics program
- Belle II Physics results:
  - Dark sector, $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$
  - $B\bar{B}$ mixing, TD CPV, $\tau$ mass

- Summary
SuperKEKB is a new $e^+e^-$ collider located at KEK (Tsukuba, Japan), it operates in the intensity frontier region with a target instantaneous luminosity of $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ which is 30 times larger than that of the previous KEKB collider.

<table>
<thead>
<tr>
<th></th>
<th>Instantaneous luminosity (cm$^{-2}$ s$^{-1}$)</th>
<th>Integrated recorded luminosity (ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babar</td>
<td>$1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>0.55</td>
</tr>
<tr>
<td>PEP-II</td>
<td></td>
<td>0.43 Y(4S)</td>
</tr>
<tr>
<td>Belle KEKB</td>
<td>$2.11 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>1</td>
</tr>
<tr>
<td>Belle II SuperKEKB</td>
<td>$6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>50</td>
</tr>
</tbody>
</table>

$\mathcal{L} \times 30 : \times 1.5$ current increase

$x 20 \ \beta_y^* \ \text{vertical beta function decrease}$

$\theta_x = 22 \ \text{mrad}$

$\theta_x = 83 \ \text{mrad}$

$\sigma_y = 1 \ \mu\text{m}$

$\sigma_y = 50 \ \text{nm}$
### SuperKEKB startup

<table>
<thead>
<tr>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019 - 2021</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phase 1</strong></td>
<td><strong>Phase 2</strong></td>
<td><strong>Phase 3</strong></td>
<td></td>
</tr>
<tr>
<td>1st Feb</td>
<td>Belle II installed except SVD &amp; PXD</td>
<td>19th Mar</td>
<td>from 11th Mar 2019 to now</td>
</tr>
<tr>
<td>1st July</td>
<td>Main Ring renovation Installation of QCS Dumping ring install.</td>
<td>7th July</td>
<td></td>
</tr>
<tr>
<td>Single Beam commissioning</td>
<td></td>
<td><strong>Beam collisions</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>( \mathcal{L}^{\text{MAX}} = 5.55 \times 10^{33} \text{cm}^{-2} \text{s}^{-1} )</strong></td>
<td><strong>( \mathcal{L}^{\text{MAX}} = 2.4 \times 10^{34} \text{cm}^{-2} \text{s}^{-1} )</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>( \int \mathcal{L} = 0.5 \text{ fb}^{-1} )</strong></td>
<td><strong>( \int \mathcal{L} = 94.5 \text{ fb}^{-1} )</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Beam collisions</strong></td>
</tr>
<tr>
<td>Summer STOP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter STOP</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**\( \mathcal{L}^{\text{MAX}} = 5.55 \times 10^{33} \text{cm}^{-2} \text{s}^{-1} \)**
\[ \int \mathcal{L} = 0.5 \text{ fb}^{-1} \]

**\( \mathcal{L}^{\text{MAX}} = 2.4 \times 10^{34} \text{cm}^{-2} \text{s}^{-1} \)**
\[ \int \mathcal{L} = 94.5 \text{ fb}^{-1} \]
We kept SuperKEKB and Belle II running in 2020 during the COVID-19 crisis, with extra effort from the local crew and the help of remote shifters.

**Luminosity world record**

- \(2.11 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
  (KEK June 2009)
- \(2.14 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
  (LHC May 2018)
- \(2.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
  (SuperKEKB June 2020)

**Current** \(\int \mathcal{L} = 94.5 \text{ fb}^{-1}\)

Results presented here used Run2019 + \(\sim 40\%\) Run2020a/b: \(\int \mathcal{L} = 34.6 \text{ fb}^{-1}\)

Next preliminary results will use Run2019 + 100\% Run2020a/b: \(\int \mathcal{L} = 62.8 \text{ fb}^{-1}\)
Luminosity plan

Submitted to MEXT roadmap 2020

\[ \int \mathcal{L} = 0.5 \div 1 \text{ ab}^{-1} \text{ in 2022} \]
\[ \int \mathcal{L} = 10 \text{ ab}^{-1} \text{ in 2026} \]
\[ \mathcal{L}_{\text{peak}} = 6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \text{ in 2029} \]
\[ \int \mathcal{L} = 50 \text{ ab}^{-1} \text{ in 2031} \]
Belle II detector

New trigger: for low multiplicity and dark sector searches

TOP: barrel PID
quartz bars + MCP-PMT
replaced aerogel threshold

Central Drift Chamber
He (50%) C₂H₆ (50%)
smaller cell size
n. wires = 14336 from 8400
longer lever arm
r_{ext}-r_{int} = 0.97 m from 0.8 m

Vertex detector (SVD + PXD)
Increased number of layers from 3 to 6
4 layers SVD DSSD N-type 50-75 μm / 160-240 μm
2 layers PXD DEPFET 50 μm / 55-85 μm

ARICH: endcap PID
focusing aerogel RICH + HAPD
replaced aerogel threshold

KLM: K_L and Muon scintillator + WLS + SiPM
replaced all 14 endcap RPC and 2 innermost barrel RPC

ECL: Calorimeter
CsI(Tl) crystals + PIN-PD electronics upgrade for waveform sampling

Magnet
1.5 Tesla

7 m height
7.5 m length

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Virtual mode
Subdetector installation

Barrel KLM: 2013
Endcap KLM: 2014
TOP: 2016
CDC: 2016
ARICH: 2017
ECL: 2017
SVD: 2018
PXD: 2018 Inner layer + 2 outer ladders
PXD: 2022 Full detector
Detector performance

**Particle Identification (K/π separation)**

\[ \varepsilon_{\text{effective}} = \sum_i \varepsilon_i (1 - 2w_i)^2 \]

- \( w_i \) = wrong-tag fractions
- \( \varepsilon_i \) = tag efficiency

**B flavor tagger**

- \( \varepsilon_{\text{effective}} \) (Belle II MC) = ~37%
- \( \varepsilon_{\text{effective}} \) (Belle II) = (33.8 ± 3.9)%
- \( \varepsilon_{\text{effective}} \) (Belle) = (30.1 ± 0.4)%

**Tracking efficiency (with \( \tau^+\tau^- \) events)**

**BELLE2-NOTE-PL-2020-024**

\[ \int L dt = 37.0 \text{ fb}^{-1} \]

**BELLE2-NOTE-PL-2020-014**

\[ \int L dt = 8.8 \text{ fb}^{-1} \]

Belle II physics program

Energy scan

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Y(1s)</th>
<th>Y(2s)</th>
<th>Y(3s)</th>
<th>Y(4s)</th>
<th>Y(5s)</th>
<th>Y(6s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.46</td>
<td>10.02</td>
<td>10.35</td>
<td>10.58</td>
<td>10.86</td>
<td>11.02</td>
</tr>
</tbody>
</table>

\[ \sigma [e^+e^- \rightarrow \Upsilon(4S)] = 1.11 \text{ nb} \]

\[ \sigma [e^+e^- \rightarrow \tau^+ \tau^- (\gamma)] = 0.92 \text{ nb} \]
\[ \sigma [e^+e^- \rightarrow \mu^+\mu^- (\gamma)] = 1.15 \text{ nb} \]
\[ \sigma [e^+e^- \rightarrow \bar{d}d (\gamma), s\bar{s} (\gamma)] = 0.78 \text{ nb} \]
\[ \sigma [e^+e^- \rightarrow e^+e^- (\gamma)] = 74.4 \text{ nb} \]

\[ \sqrt{s} = 10.58 \text{ GeV} \]
\[ \sigma_{\text{TOT}} = 143 \text{ nb} \]

\[ \sigma [e^+e^- \rightarrow c\overline{c} (g)] = 1.3 \text{ nb} \]
\[ \sigma [e^+e^- \rightarrow u\overline{u} (\gamma)] = 1.6 \text{ nb} \]
\[ \sigma [e^+e^- \rightarrow \gamma\gamma (\gamma)] = 3.3 \text{ nb} \]
\[ \sigma [e^+e^- \rightarrow e^+e^-\mu^+\mu^-] = 18.9 \text{ nb} \]
\[ \sigma [e^+e^- \rightarrow e^+e^-e^+e^-] = 39.7 \text{ nb} \]

The Belle II Physics book
[arXiv:1808.10567]
Belle II physics program

- Precise measurement of the CKM parameters

\[
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d_{\text{mass}} \\
  s_{\text{mass}} \\
  b_{\text{mass}}
\end{pmatrix}
\]

\[V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0\]

\[\frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}} + 1 + \frac{V_{tb}^*V_{td}}{V_{cb}^*V_{cd}} = 0\]

- Search of new physics with precise measurements of B, charm and \(\tau\) decays

\[
\mathcal{R}_{D^*} \equiv \frac{\mathcal{B}(B \rightarrow D^{*}\tau\nu)}{\mathcal{B}(B \rightarrow D^{*}\ell\nu)} \quad \mathcal{R}_D \equiv \frac{\mathcal{B}(B \rightarrow D\tau\nu)}{\mathcal{B}(B \rightarrow D\ell\nu)}
\]

- Hadron spectroscopy and dark sector
Belle II physics program

CKM fitter Summer19
1.0 ab$^{-1}$ Belle + 0.5 ab$^{-1}$ Babar

BELLE2-PUB-PH-2018-001 50 ab$^{-1}$ Belle II

2$\sigma$ errors
(mean values when asymmetric)

$B^0 - \bar{B}^0$ oscillation frequency

$B \rightarrow \pi\pi/\rho\pi/\rho\rho$

$\Delta\rho$ ±13% → ±2.5%
$\Delta\eta$ ±5.1% → ±1.1%

$\Delta\phi_2$ ±3.2° → ±0.6°

$B \rightarrow \pi l\nu$

$B^0 \rightarrow J/\psi K_S$
$\Phi K_S/\eta' K_S$

$\Delta\phi_1$ ±1.0° → ±0.3°

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Belle II physics results

2 published PRL dark-sector searches:

- Search for an invisibly decaying Z’ boson [PRL 124(2020)141801] (published 6 April 2020)

12 conference papers posted to arXiv:

- B0 → D** ℓν ( (1) first result, (2) untagged, (3) using FEI ). (12 June, 18 Aug., 16 Sep. 2020)
  used to make “rediscovery” of CPV in B → J/ψ Ks. [BELLE2-NOTE-PL-2020-11-1]
- B → charmless ( (1) first result, (2) CP asymmetries ). (27 May, 20 Sep. 2020)

Charmless B decays → Riccardo Manfredi talk
Dark sector: $Z' \rightarrow$ invisible

Simple extensions of the SM: $Z'$ boson originated for extra U(1)' symmetry that couples both to SM and NP invisible particles.

$L_{\mu} - L_{\tau}$ model

$e^+ e^- \rightarrow \mu^+ \mu^- Z'$. ($Z' \rightarrow$ invis.)

LFV scenario (e - $\mu$ coupling)

$e^+ e^- \rightarrow e^\pm \mu^\mp Z'$, ($Z' \rightarrow$ invis.)

The signature is a bump in the recoil mass distribution of the $\ell^+\ell^-$ system

[References: PRL 124(2020)141801]
Dark sector: $Z' \rightarrow$ invisible

We used $0.276 \text{ fb}^{-1}$ of good-quality data with full PID information taken in Phase2. No anomalies were observed above $3\sigma$ local significance. We placed nontrivial exclusion limits:

$L_\mu - L_\tau$ model

90\% C.L. upper limits on coupling constant $g'$

The red band shows the region that could explain the anomalous muon magnetic moment

LFV scenario

90\% C.L. upper limits on signal efficiency times cross section
Dark sector: Axion-like particles

Axion/Axion-like: singlet neutral scalar or pseudoscalar

2γ decay and 3γ final state

Signal can be identified by a peak in the 2γ invariant mass or in the recoil invariant mass

σ(M^2_{γγ}) and σ(M^2_{recoil}) with uncertainties as a function of the ALP mass

Diphoton better if m_a < 6.5 GeV

Recoil better if m_a > 6.5 GeV

[PRL 125(2020)161806]
Dark sector: Axion-like particles

We used 0.445 fb$^{-1}$ of good-quality data taken in Phase2.

We model the peaking contribution using a Crystal Ball function. The mass-dependent CB parameters used in the real data are fixed by fitting simulated events.

No significant excess seen, the highest local significance is 2.8$\sigma$
\[ \overline{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell \]

Measurements of semileptonic $\overline{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$ decay ($D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+$, $\ell$=e or $\mu$) [arXiv:2008.10299] Full Event Interpretation (FEI algorithm) [arXiv:2008.07198] Untagged

FEI: one of the B mesons produced in the collision event with hadronic decay channels (B$_{tag}$) is reconstructed and used to extract the signal of the other B meson (B$_{sig}$)

\[ m_{\text{miss}}^2 = (p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_\ell)^2 \quad m_{\text{miss}}^2 \approx m_{\nu}^2 \sim 0 \]

Untagged: B meson direction constrained on a cone around $Y = D^{*+} \ell^-$ direction

**Belle II** Preliminary $\int L \, dt = 34.6$ fb$^{-1}$

**Belle II preliminary** $\int L \, dt = 34.6$ fb$^{-1}$

**B [B$^0$ $\rightarrow$ D$^*$\ell\nu]**

FEI: 4.51 %
\[ \pm 0.41(\text{stat}) \%
\pm (0.27(\text{syst}) \pm 0.45(\text{ps})) \%
\]

Untag: 4.60 %
\[ \pm 0.05(\text{stat}) \%
\pm (0.17(\text{syst}) \pm 0.45(\text{ps})) \%
\]

PDG: 5.05 %
\[ \pm 0.14 \% \]
\[
\text{B}^0 \rightarrow \text{D}^{*+} \ell^- \bar{\nu}_\ell \\
\\
\text{LFV test:} \quad R_{e\mu} = \frac{\mathcal{B}(\text{B}^0 \rightarrow \text{D}^{*+} e^- \bar{\nu}_e)}{\mathcal{B}(\text{B}^0 \rightarrow \text{D}^{*+} \mu^- \bar{\nu}_\mu)} = 0.99 \pm 0.03
\]

Electron and muon semileptonic B decays are a background for the \(\tau\) decay. Their understanding is also important for a precise measurement of \(R_{\tau\ell}\) where we have a discrepancy with respect to SM expectation:

\((R_D, R_{D^*})_{\text{measured}} vs \ (R_D, R_{D^*})_{\text{SM}}\)

- 3.9 \(\sigma\) discrepancy in 2015
- 3.0 \(\sigma\) discrepancy in 2019
**BB mixing and time-dependent CPV**

[BELLE2-NOTE-PL-2020-11-1] We used 34.6 fb$^{-1}$ of events

**BB mixing on a sample of $B^0 \rightarrow D^-\pi^+$**

![Graph showing BB mixing on a sample of $B^0 \rightarrow D^-\pi^+$](image)

### Equations

- **Mixing Amplitude**: $A_{mixing}(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)} = D \cos(\Delta m \cdot t)$
- **CP Violation Amplitude**: $A_{CP}(t) = D \sin2\beta \cdot S \sin(\Delta m \cdot t)$

- **Current Result**: $\Delta m = (0.531 \pm 0.046 \pm 0.013) \text{ ps}^{-1}$
- **World Average**: $\Delta m = (0.5065 \pm 0.0019) \text{ ps}^{-1}$

- **Mixing Parameter**: $D = (1 - 2w)$
- **Wrong Tag Fraction**: $w$

**Time-dependent CP violation on $B^0 \rightarrow J/\psi K_S$**

![Graph showing Time-dependent CP violation on $B^0 \rightarrow J/\psi K_S$](image)

- **CP Violation Parameter**: $S = 0.55 \pm 0.21 \pm 0.04$
- **Wrong Tag Fraction**: $w$

**World Average**: $S = 0.691 \pm 0.017$

Current results will not have a large impact on the WA but the channel is essential to prove the readiness of the experiment to perform complex and precise measurements.
We used 8.8 fb\(^{-1}\) of data accumulated during 2019 at \(\Upsilon(4S)\)

Three-prong \(\tau\) decay: \(\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau\)

Identification of charged particles is based on the selection \(E_{ECL}/P_{lab} < 0.8\)

Mass of \(\tau\) lepton measured from the threshold in “pseudomass” variable:

\[
M_{\min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}
\]

\(M_{\min} \leq m_\tau\) without ISR and FSR

This measurement is in good agreement with the current world average.

Stat. error will dominate up to 50 fb\(^{-1}\)

![Graph showing the distribution of mass measurements]

- Data
  - \(\chi^2/dof = 1.256\)
  - \(N_{evts} = 8742\)

- Belle II (Preliminary): \(m_\tau = 1777.28 \pm 0.75\) MeV/c\(^2\)

- PDG average: \(1776.86 \pm 0.12\) MeV/c\(^2\)
- BES III (2014): \(1776.91 \pm 0.12 \pm 0.13\) MeV/c\(^2\)
- ARGUS (1992): \(1776.3 \pm 2.4 \pm 1.4\) MeV/c\(^2\)
- Belle (2007): \(1776.61 \pm 0.13 \pm 0.35\) MeV/c\(^2\)
- BaBar (2009): \(1776.68 \pm 0.12 \pm 0.41\) MeV/c\(^2\)
- Belle II (2020): \(1777.28 \pm 0.75 \pm 0.33\) MeV/c\(^2\)
Summary

- The SuperKEKB collider and the Belle II detector allowed to have stable data collection in 2019 and 2020. The max. luminosity now at 2.4\times10^{34} \text{ cm}^{-2} \text{s}^{-1} will be increased and will reach 6\times10^{35} \text{ cm}^{-2} \text{s}^{-1} in 2029.

- The data collected in the 2018 commissioning run allowed us to publish two PRL papers adding new exclusion limits in the Dark Sector.

- Belle II started Phase 3 operations in March 2019, up to now a total of 94.5 fb^{-1} integrated luminosity have been recorded.

- Several analysis are ongoing, we are already competitive with BaBar and Belle in the Dark Sector, we plan to get a similar statistics within 2022 and to become competitive with them for all the analysis.
SuperKEKB parameters

\[ \mathcal{L} = \frac{\gamma^{\pm}}{2e r_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{I_{\pm} \zeta_y \pm}{\beta_y^* \pm} \left( \frac{R_L}{R_{\zeta_y}} \right) \]

- \( I_{\pm} \) beam current
- \( \beta_y^* \) vertical beta function
- \( \zeta_y \pm \) beam-beam parameter
- \( R_L, R_{\zeta} \) reduction factors

Machine parameters

<table>
<thead>
<tr>
<th></th>
<th>E (GeV)</th>
<th>I (A)</th>
<th>( \beta_y^* ) (mm)</th>
<th>( \zeta_y \pm )</th>
<th>Crossing angle (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEKB</td>
<td>LER 3.5</td>
<td>HER 8.0</td>
<td>LER 1.64, HER 1.19</td>
<td>LER 5.9, HER 5.9</td>
<td>LER 0.129, HER 0.090</td>
</tr>
<tr>
<td>SuperKEKB</td>
<td>LER 4.0</td>
<td>HER 7.0</td>
<td>LER 2.80, HER 2.00</td>
<td>LER 0.30, HER 0.30</td>
<td>LER 0.088, HER 0.081</td>
</tr>
</tbody>
</table>

The factor 30 of instantaneous luminosity increase can be obtained with a factor 1.5 of beam currents increase and a factor 20 of \( \beta_y^* \) decrease.

\( \beta_y^* \) = distance where \( \sigma_y = 2 \sigma_y \) (IP)
From KEKB to SuperKEKB

- New Titanium-Nitride coated beam-pipe with antechambers to suppress electron cloud effect
- Belle detector upgraded to Belle II
- New QCS final focus magnets for nano-beam scheme
- New RF cavities and modified RF system for high beam current operation
- Optimize beam optics for low emittance beam
- New low emittance $e^-$ gun
- New $e^+$ source
- Positron damping ring to inject positrons in the small acceptance LER
Belle II Collaboration

- 1050 active collaborators (15% are women)
- 120 institutions
- 26 countries/regions