Status and prospects of Belle II at SuperKEKB

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SuperKEKB
Status and improvements since KEKB

e+e− accelerator located in Tsukuba, Japan

Built in tunnels of KEKB, but is almost entirely new machine:

• x20 smaller beam focus at interaction region

• Doubled beam currents

This yields x40 higher peak luminosity
(8x10^{34} \text{ cm}^{-2}\text{s}^{-1})

First beams in 2016
First collisions: next month
The Belle II detector
Design and key performance numbers

**Vertex detector**
- Tracking: $\sigma_{z_0} \sim 15 \mu m$
  - *(2x better than Belle)*

**Drift chamber**
- Tracking: $\sigma_{r\phi} \sim 100 \mu m$
  - $\sigma_{dE/dx} \sim 5\%$

**$K_L$ and Muon detector**
- $\Delta \phi = \Delta \theta \sim 10-20$ mrad (for $K_L$)
  - $\mu/\pi$ separation:
  - $\varepsilon \sim 90\% @ 1.5\%$ fake

**Time of Propagation and RICH detectors**
- $K/\pi$ separation:
  - $\varepsilon \sim 96\% @ 1\%$ fake

**EM Calorimeter**
- $\sigma_{E/E} = 2\%$
  - *(for $E=1$ GeV)*

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7 GeV $e^-$
4 GeV $e^+$
Belle II schedule

Phase 1: first beams
Goal: Main ring commissioning

Phase 2: first collisions
Goal: Establish nano-beam scheme and reach KEKB luminosity
Goal: Understand backgrounds

Phase 3 luminosity milestones:
1ab⁻¹ after one year of data taking
5ab⁻¹ mid 2020
50ab⁻¹ by 2025
Belle II at Phase 2

Special conditions and unique opportunities

• Belle II and SuperKEKB will soon start collecting data of the first collisions during the Phase 2 of commissioning.
• We aim to get 20-40 fb$^{-1}$ of data in e$^+$e$^-$ collisions
• Phase II special conditions:
  ‣ Dedicated detector that includes VXD sector and radiation monitors (BEAST II) is installed to measure radiation and backgrounds levels. Will be replaced by VXD in Phase 3.
  ‣ To demonstrate the nano-beam scheme, we will reach $1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ instantaneous luminosity, 1.25% of the SuperKEKB design.
  ‣ Low initial luminosity allows to open up triggers for low-multiplicity events

Time for physics searches going hand in hand with detector studies!
An example of Physics at Phase II

Dark photon search

Dark matter manifests itself in numerous cosmological and astrophysical observations, but yet is not discovered in laboratory environment.

- Dark sector can be connected to the SM through the Dark Photon $A'$: it has kinetic mixing with $\gamma$ of strength $\epsilon$.
- One of experimental signatures for this signal is a single photon in the detector with the recoil mass peaking at the mass of $A'$.
- Biggest challenge: performance study of the photon detection.
- Improvement of BaBar results already at 20 fb$^{-1}$!
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- Improvement of BaBar results already at 20 fb$^{-1}$!
Belle II has a rich physics programme that is being summarised in a single document (664 pages now):

• Leptonic and semileptonic B decays
• Radiative and EWP B decays
• Precise measurements of CKM parameters
• Charm physics
• Quarkonium physics
• Tau physics
• BSM searches

Impossible to cover everything in short talk, but let's discuss some planned measurements showing key features of Belle II.
At Belle II, B-mesons are produced in pairs during decay of the $\Upsilon(4S)$. This is just above the $b\bar{b}$ threshold, i.e. only the two B-mesons are produced in the collision.

If we fully reconstruct one B-meson decay than we can study final states with missing energy because the initial state is well known.

Useful variable here is missed 4-momentum:

$$p_{\text{miss}} = (p_{\text{beam}} - p_{\text{Btag}} - p_{\text{Signal}})$$
Some of the Phase III key measurements

**R(D) and R(D*) measurement**

Combined R(D)/R(D*) measurement is $4\sigma$ away from the SM prediction

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)} \tau \bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)} l \bar{\nu}_l)}$$

Belle II R(D) measurement strategy:

- Using the **Full Event Interpretation (FEI)** algorithm: reconstruct both B-mesons to missed momentum of signal candidate.

- Discriminate signal ($B \to D^{(*)} \tau \bar{\nu}$), normalisation ($B \to D^{(*)} \ell \bar{\nu}$, $\ell = \mu, e$) and backgrounds events in 2D fit to ($m_{\text{miss}}^2$; $|p_l|$) plane

Current World Average precision for R(D*) is $12\% (6\%)$. **With only 5ab$^{-1}$ Belle II will measure both values twice more precise** according to simulations study.
Belle II Key techniques

Time-dependent CP violation

As with the FEI technique, measurement of the TD CPV requires reconstruction of the both mesons.

Unlike FEI, we don’t need to fully reconstruct the tag B: we only need to find its decay vertex and flavour.

\[
a_f(\Delta t) = \frac{\Gamma_{B^0 \rightarrow f}(\Delta t) - \Gamma_{\bar{B}^0 \rightarrow f}(\Delta t)}{\Gamma_{B^0 \rightarrow f}(\Delta t) + \Gamma_{\bar{B}^0 \rightarrow f}(\Delta t)} = S_f \sin(\Delta m \Delta t) + A_f \cos(\Delta m \Delta t)
\]

\[
<\Delta z> \sim 130 \mu m \text{ at Belle II}
\]
Some of the Phase III key measurements

Time-dependent CP violation in penguin-dominated decays

Theory gives clean constraints on $\Delta S_I = S_I - (\sin \phi_1)_{ccs}$ for penguin-dominated $b \to qqs$ ($q = u, d, s$) processes, while the experiment is behind in precision.

$B \to \eta' K^0$ has among the strictest predictions here:

- $\Delta S_{QCDF}^{\eta' K^0} = 0.01 \pm 0.01$
- $\Delta S_{Data}^{\eta' K^0} = -0.05 \pm 0.06$

- Belle II will test several combinations for the final states:
  - $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-; \eta' \to \eta(\pi^+\pi^-\pi^0)\pi^+\pi^-; \eta' \to \rho\gamma$
  - $K_S \to \pi^+\pi^-; K_S \to \pi^0\pi^0; K_L$

- Key components of the measurement:
  - **Tagging**: Effective tagging efficiency is ~37%
  - **Vertexing**: signal $\Delta t$ resolution is 20% better than for Belle
  - **Sensitivity to neutrals**: 23% selection efficiency for $B \to \eta' \to \eta(\gamma\gamma)\pi^+\pi^- K^0_S$ final state

Current World Average precision for $S_{\eta' K^0}$ is 10%.

**With only 5ab$^{-1}$ Belle II will measure it twice as precise** according to simulation
**Belle II Key features**

**Belle II as a tau factory**

Belle II is the best laboratory to study $\tau$ physics:

- **High rate of the tau**: $45 \times 10^9 \tau^+ \tau^-$ pairs are expected in the full dataset.
  \[ \sigma(ee \rightarrow \tau\tau) \approx 0.91 \text{nb}; \ \sigma(ee \rightarrow b\bar{b}) \approx 1.05 \text{nb} \]

- **Clean environment**: exclusive production of $\tau$ pairs in $e^+e^- \rightarrow \tau^+ \tau^-$

Belle II reconstruction procedure for $\tau$:

- For each reconstructed $\tau$ we calculate invariant mass and $\Delta E = E_{\tau}^{CM} - E_{beam}^{CM} / 2$

- Use event shape variables to discriminate from non-tau backgrounds ($e^+e^- \rightarrow q\bar{q}$)

- For neutrinoless $\tau$ decays (CLFV searches), the missing momentum of the tag side can also be used as a discriminating variable
Some of the Phase III key measurements

Charged Lepton Flavour Violation in \( \tau \) decays

\( \tau \rightarrow \mu \gamma \) decays are prohibited in SM (\( \text{Br}(\tau \rightarrow \mu \gamma) \sim 10^{-40} \)) and among the most sensitive to loop-generated CLFV.

Signal events peak in \((\Delta E; M_{\mu \gamma})\) plane.

![Signal region (\( \tau \rightarrow \mu \gamma \))](image)

\[ \Delta E = E_{\mu \gamma}^{\text{CM}} - E_{\text{beam}}^{\text{CM}} / 2 \]

Belle II expected sensitivity at 50 ab\(^{-1}\) is \( \text{Br}(\tau \rightarrow \mu \gamma) < 10^{-9} \)

<table>
<thead>
<tr>
<th>Model</th>
<th>( \text{Br}(\tau \rightarrow \mu \gamma) )</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUSY+GUT</td>
<td>(10^{-7} )</td>
<td>PRD 66(2002)11501</td>
</tr>
<tr>
<td>SUSY SO(10)</td>
<td>(10^{-8} )</td>
<td>PRD 68(2003)033012</td>
</tr>
<tr>
<td>SM+ heavy ( V_R )</td>
<td>(10^{-9} )</td>
<td>PRD 66(2002)034008</td>
</tr>
<tr>
<td>Non-universal ( Z' )</td>
<td>(10^{-9} )</td>
<td>PLB 547(2002)252</td>
</tr>
<tr>
<td>Little Higgs</td>
<td>(10^{-10} )</td>
<td>JHEP 0705, 013 (2007)</td>
</tr>
<tr>
<td>SUSY Higgs</td>
<td>(10^{-10} )</td>
<td>PLB 566(2003)217</td>
</tr>
<tr>
<td>SM</td>
<td>(10^{-40} )</td>
<td>EPJ C8 (1999) 513</td>
</tr>
</tbody>
</table>
Some of the Phase III key measurements

Energy scan of heavy bottomonium

Inner structure of heavy hadrons above the open flavour limit is still unclear: are there XYZ states, analogous to charmonium case?

• Cross-sections around 10.75 have different behaviour for BB, $h_b(nP)\pi\pi$ and $\Upsilon(nS)\pi\pi$ states

• Belle II will make precise scan of the region and decompose cross-sections to different BB states, that are predicted to have rich structure

• Scans beyond $\Upsilon(6S)$ will investigate new resonances around new thresholds

No other experiment, running or planned, can address the open topics in bottomonium physics

Current samples in fb⁻¹ (millions of events), and the proposal for Belle II

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Upsilon(1S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(3S)$</th>
<th>$\Upsilon(4S)$</th>
<th>$\Upsilon(5S)$</th>
<th>$\Upsilon(6S)$</th>
<th>$\Upsilon(nS)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>1.2 (21)</td>
<td>1.2 (10)</td>
<td>1.2 (5)</td>
<td>16 (17.1)</td>
<td>0.1 (0.4)</td>
<td>-</td>
<td>23%</td>
</tr>
<tr>
<td>BaBar</td>
<td>-</td>
<td>14 (99)</td>
<td>30 (122)</td>
<td>433 (471)</td>
<td>$R_b$ scan</td>
<td>$R_b$ scan</td>
<td>11%</td>
</tr>
<tr>
<td>Belle</td>
<td>6 (102)</td>
<td>25 (158)</td>
<td>3 (12)</td>
<td>711 (772)</td>
<td>121 (36)</td>
<td>5.5</td>
<td>23%</td>
</tr>
<tr>
<td>BelleII</td>
<td>-</td>
<td>-</td>
<td>300 (1200)</td>
<td>$5 \times 10^4$ ($5.4 \times 10^4$)</td>
<td>1000 (300)</td>
<td>100+400(scan)</td>
<td>3.6%</td>
</tr>
</tbody>
</table>


No other experiment, running or planned, can address the open topics in bottomonium physics
Summary

• Next month Belle II will start collect data from the first collisions (without the vertex detector)
• The goal for this year’s data taking is to understand the machine and backgrounds, but early physics program aimed at low multiplicity physics is also planned
• By the end of the year, vertex detector will be installed and Belle II will start data taking fully operational in early 2019
• Rich physics programme with plenty of unique measurements
• Looking forward to the first results