SuperKEKB and Belle II status, and prospects on two-photon physics

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The KEKB Collider

from 1999 to 2010

Belle detector

8 x 3.5 GeV
22 mrad crossing angle

World record: \( L = 2 \times 10^{34} / \text{cm}^2 / \text{sec} \)

 harvesting

ARES(LER)

Ares RF cavity

e\(^+\) source

Mt. Tsukuba

~1 km in diameter

1.1 nb \( \sigma(e^+e^- \rightarrow Y(4S)) \)

~3 nb \( \sigma(e^+e^- \rightarrow q\bar{q}) \)

\( (q = u, d, s, c) \)

10.58 GeV

\( Y(4S) \)
The primary goal of the Belle and BaBar experiments was to discover the CP violation in B mesons and to measure the parameters of CPV. This was achieved by both experiments in 2001. However, a lot of other important results were obtained:

- Observation of direct CP violation in B decays
- Measurements of the CPV parameters in different modes (ϕK⁰, η’K⁰, K₅K₅K₅, ...)
- Measurements of rare decay modes (e.g., B→τν, Dτν)
- Observation of new charmonium-like and bottomonium-like hadronic states
- b→s transitions: probe for new sources of CPV and constraints from the b→sγ branching fraction
- Forward-backward asymmetry (A_{FB}) in b→sl⁺l⁻ has become a powerful tool to search for physics beyond SM.
- Observation of D mixing
- Search for lepton flavour violation in τ decays
- Study of the hadronic τ decays
- Precise measurement of the hadronic cross sections in γγ and e⁺e⁻(γ_{ISR}) processes

So wide researches area become possible because of clean event environment and well defined initial state in the e⁺e⁻ experiments as well as high luminosity and general purpose detectors.
### Two-Photon Measurements at Belle

| System          | Mass (GeV) | $|\text{cost}|$ (fb) | Reference          | Year   |
|-----------------|------------|----------------|---------------------|--------|
| $\gamma J/\psi$ | 3.2 - 3.8  | 32.6           | PLB540, 33          | 2002   |
| $\pi^+\pi^-$    | 2.4 - 4.1  | 88             | PLB15, 39           | 2005   |
| $0.8 - 1.5$     | 86         | PRD75, 051101  | 2007               |
| $K^+K^-$        | 1.4 - 2.4  | 67             | EPJC32, 323         | 2003   |
| $2.4 - 4.1$     | 88         | PLB15, 39      | 2005               |
| $\pi^0\pi^0$   | 0.6 - 4.0  | 95             | PRD78, 052004       | 2008   |
| $0.6 - 4.1$     | 223        | PRD79, 052009  | 2009               |
| $\eta\pi^0$    | 0.84 - 4.0 | 223            | PRD80, 032001       | 2009   |
| $\eta\eta$     | 1.096 - 3.8| 393            | PRD82, 114031       | 2010   |
| $\omega J/\psi$| 3.9 - 4.2  | 694            | PRL104, 092001      | 2010   |
| $\phi J/\psi$  | 4.2 - 5.0  | 825            | PRL104, 112004      | 2010   |
| $\omega\phi, \omega J/\psi, \phi J/\psi$ | $\text{thr} - 4.0$ | 870 | PRL108, 232001 | 2012 |
| $\eta'\pi^+\pi^-$ | 1.4 - 3.4 | 673            | PRD86, 052002       | 2012   |
| $\pi^0$         | $Q_2[4,40]\text{GeV}$ | 759 | PRD86, 092007 | 2012   |
| $\pi^0\pi^0$   | $Q_2<30\text{GeV}$ | 759 | PRD93, 032003 | 2016   |
| $pp\bar{p}K^+K^-$ | 3.2 - 5.6 | 980            | PRD93, 112017       | 2016   |

Recent results from two-photon processes at Belle – the talk of Wenbiao Yan at this conference.

05.06.2019
**SuperKEKB**

- **e⁺ 4 GeV 3.6 A**
- **e⁻ 7 GeV 2.6 A**

**Key Changes:**
- New beam pipe & bellows
- Low emittance gun
- TiN-coated beam pipe with antechambers
- Redesign the lattices of both rings to reduce the emittance

- **Biased bunches**
- New IR
- New superconducting /permanent final focusing quads near the IP

**Additional Improvements:**
- Add / modify RF systems for higher beam current
- New positron target / capture section
- New positron source
- Redesign the lattices of both rings to reduce the emittance

**Equation:**

\[
L = \frac{\gamma \pm}{2er_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{I_{\pm} \xi_{\pm}}{\beta_y^*} \right) \left( \frac{R_L}{R_y} \right)
\]

**New IR**

**05.06.2019
Photon 2019, Frascati, Italy**
Design Concept of SuperKEKB

- Increase the luminosity by 40 times based on “Nano-Beam” scheme, which was first proposed for SuperB by P. Raimondi.
  - Vertical $\beta$ function at IP: $5.9 \rightarrow 0.27/0.30$ mm ($\times 20$)
  - Beam current: $1.7/1.4 \rightarrow 3.6/2.6$ A ($\times 2$)
  - Beam-beam parameter: $0.09 \rightarrow 0.09$ ($\times 1$)
  - Beam energy: $3.5/8.0 \rightarrow 4.0/7.0$ GeV

$\sigma_x \sim 100 \mu$m, $\sigma_y \sim 2 \mu$m

$\frac{L}{2e\rho_e} = \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{L_y}{L_y^*} \frac{R_y}{R_y^*} \right) = 8 \times 10^{35}$ cm$^{-2}$s$^{-1}$

- Beam energy: $3.5/8.0 \rightarrow 4.0/7.0$ GeV
  - LER: Longer Touschek lifetime and mitigation of emittance growth due to the intra-beam scattering
  - HER: Lower emittance and smaller SR power

<table>
<thead>
<tr>
<th></th>
<th>$E$ (GeV)</th>
<th>$\beta^*_y$ (mm)</th>
<th>$\beta^*_x$ (cm)</th>
<th>$\varphi$ (mrad)</th>
<th>$I$ (A) LER/HER</th>
<th>$L$ (cm$^{-2}$s$^{-1}$) LER/HER</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEKB</td>
<td>3.5/8.0</td>
<td>5.9/5.9</td>
<td>120/120</td>
<td>11</td>
<td>1.6/1.2</td>
<td>$2.1 \times 10^{34}$</td>
</tr>
<tr>
<td>SuperKEKB</td>
<td>4.0/7.0</td>
<td>0.27/0.30</td>
<td>3.2/2.5</td>
<td>41.5</td>
<td>3.6/2.6</td>
<td>$80 \times 10^{34}$</td>
</tr>
</tbody>
</table>

05.06.2019

Photon 2019, Frascati, Italy
Demands on the detector

Total cross section and trigger rates with $L = 8 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ from various physics processes at $\Upsilon(4S)$.

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Cross section (nb)</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(4S) \rightarrow BB$</td>
<td>1.2</td>
<td>960</td>
</tr>
<tr>
<td>Hadron production from continuum</td>
<td>2.8</td>
<td>2200</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>0.8</td>
<td>640</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>0.8</td>
<td>640</td>
</tr>
<tr>
<td>Bhabha ($\theta_{lab} &gt; 17^\circ$)</td>
<td>44</td>
<td>350(a)</td>
</tr>
<tr>
<td>$\gamma\gamma$ ($\theta_{lab} &gt; 17^\circ$)</td>
<td>2.4</td>
<td>19 (a)</td>
</tr>
<tr>
<td>$2\gamma$ processes ($\theta_{lab} &gt; $17°, pt &gt; 0.1GeV/c)</td>
<td>~80</td>
<td>~15000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>~130</strong></td>
<td><strong>~20000</strong></td>
</tr>
</tbody>
</table>

(a) rate is pre-scaled by a factor of 1/100

Beam-related backgrounds are 10-20 x KEKB.
Radiative Bhabha, Touschek scattering, 2-photon

*Fake hits, pile up, radiation damage!!*
Belle II Detector

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

EM Calorimeter: CsI(Tl), waveform sampling electronics (barrel)

Central Drift Chamber
Smaller cell size, long lever arm

Vertex Detector
2 layers Si Pixels (DEPFET) + 4 layers Si double sided strip DSSD

Electrons (7GeV)

Positrons (4GeV)

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

05.06.2019 Photon 2019, Frascati, Italy
SuperKEKB/Belle II Interaction Region

- 2 layers of DEPFET pixel sensors in the innermost part
- 4 layers of double-sided silicon strip sensors
- Low material VXD (0.16% X0 for layer 1)
- Closer to the IP
- Vertex detector only tracking possible

### Beam Pipe = DEPFET

<table>
<thead>
<tr>
<th>Layer</th>
<th>Belle II</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10mm</td>
<td>15mm</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### DSSD

<table>
<thead>
<tr>
<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14mm</td>
<td>22mm</td>
<td>38mm</td>
<td>80mm</td>
<td>104mm</td>
<td>135mm</td>
</tr>
<tr>
<td></td>
<td>20mm</td>
<td>43.5mm</td>
<td>70mm</td>
<td>43.5mm</td>
<td>88mm</td>
<td>135mm</td>
</tr>
</tbody>
</table>

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**PXD:** excellent spatial granularity (resolution ~15 μm)
low material (0.16%X₀ for layer 1) **but** significant amount of background hits, huge data rate.

**SVD:** precise timing (2–3 ns RMS) **but** has ambiguities in space due to 1D strip.

Combining both yields a very powerful device!

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**Belle II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Belle</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner most sense wire</td>
<td>r=88mm</td>
<td>r=168mm</td>
</tr>
<tr>
<td>Outer most sense wire</td>
<td>r=863mm</td>
<td>r=1111.4mm</td>
</tr>
<tr>
<td>Number of layers</td>
<td>50</td>
<td>56</td>
</tr>
<tr>
<td>Total sense wires</td>
<td>8400</td>
<td>14336</td>
</tr>
<tr>
<td>Gas</td>
<td>He:C₂H₆</td>
<td>He:C₂H₆</td>
</tr>
<tr>
<td>Sense wire</td>
<td>W(Φ30μm)</td>
<td>W(Φ30μm)</td>
</tr>
<tr>
<td>Field wire</td>
<td>Al(Φ120μm)</td>
<td>Al(Φ120μm)</td>
</tr>
</tbody>
</table>

**Equations:**

\[ \sigma_{P_t}/P_t = 0.19P_t \oplus 0.30/\beta \]

\[ \sigma_{P_t}/P_t = 0.11P_t \oplus 0.30/\beta \]
Particle Identification in Belle II

Cherenkov ring imaging with precise time measurement.

Device uses internal reflection of Cerenkov ring images from quartz like the BaBar DIRC.

Cherenkov angle reconstruction from two hit coordinates and the time of propagation of the photon.

Aerogel RICH (endcap PID)

RICH with a novel “focusing” radiator – a two layer radiator

Employ multiple layers with different refractive indices → Cerenkov images from individual layers overlap on the photon detector.

6.6 $\sigma_{\pi/K}$ at 4 GeV/c!

16 Quartz radiators
2.6m$^3$ x 45cm$^W$ x 2cm$^T$
Excellent surface accuracy

MCP-PMT
Hamamatsu 16ch MCP-PMT
Good TTS (<35ps) & enough lifetime

Multalkali photo-cathode

Hamamatsu HAPD

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BELLE Electromagnetic Calorimeter

Number of crystal: 8736
Total weight is ~43ton

- Calorimeter successfully worked for more than 10 years since 1999 to 2010
- All 8736 channels are operable
- It demonstrated high resolution and good performance.

CsI(Tl) crystals
$L_{cr} = 30 \text{ cm} = 16.2X_0$

Modification of the electronics.

- Pipe-line readout with waveform analysis:
  - 16 points within the signal are fitted by the signal function $F(t)$:
    $$F(t) = H \cdot f(t-t_0)$$
  - Both amplitude ($H$) and time ($t_0$) are obtained by the on-line shape fit.

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The Geography of the International Belle II collaboration

Belle II now has grown to ~900 researchers from 26 countries
SuperKEKB and Belle II status and plans

<table>
<thead>
<tr>
<th>Japan FY</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JFY2016</td>
<td>JFY2017</td>
<td>JFY2018</td>
<td>JFY2019</td>
</tr>
<tr>
<td></td>
<td>Summer shutdown (power saving)</td>
<td>Summer shutdown (power saving)</td>
<td>Power saving after mid July 2018</td>
<td>Summer shutdown (power saving)</td>
</tr>
<tr>
<td>MR startup</td>
<td>phase 1</td>
<td>w/o QCS</td>
<td>w/o Belle II</td>
<td>phase 2 (MR)</td>
</tr>
<tr>
<td>MR renovation for phase 2, including installation of QCS and Belle II</td>
<td>(end Feb. – mid Jul. 2018)</td>
<td>w/ QCS</td>
<td>w/ Belle II</td>
<td>phase 3</td>
</tr>
<tr>
<td>DR installation &amp; startup</td>
<td>DR commissioning</td>
<td>HER start</td>
<td>LER start</td>
<td>VXD installation</td>
</tr>
<tr>
<td>Assumed phase 3 operation 9 months/year</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Phase 1**: Beam operation without final focus magnets and Belle II

**Phase 2**: (ended on July 2018)
No final vertex detector but one ladder/layer with background sensors
Achieved Luminosity of $5 \times 10^{33}$ cm$^{-2}$s$^{-1}$
recorded integrated luminosity of 500 pb$^{-1}$

**Phase 3**: 2019 - detector with silicon vertex detector

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At Phase 2 peak luminosity of $5 \times 10^{33}/\text{cm}^2/\text{sec}^{-1}$, the vertical spot is $\sim 700\text{nm}$ high. There is still beam-beam blowup at high currents. At low currents, the vertical spot size is $330\text{ nm}$ high (the final goal is $O(50\text{nm})$ with full capability of the QCS system).
Current Luminosity status

L_{\text{max}} \approx 4.5 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}

By now ~ 1.6 fb\(^{-1}\)

Plan – 5 fb\(^{-1}\) by end of June

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Phase 2 results - photons

$e^+e^- \rightarrow \mu^+\mu^-\gamma$

$\pi^0 \rightarrow \gamma\gamma$

$\eta \rightarrow \gamma\gamma$
Phase 2 results - tracking

\[ \text{KS} \rightarrow \pi^+ \pi^- \]

**Belle II 2018 (preliminary)**

\[ \mu = (497.159 \pm 0.013) \text{ MeV/c}^2 \]
\[ \sigma = (3.462 \pm 0.075) \text{ MeV/c}^2 \]

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Study of Two-Photon Physics at Belle II

Belle II Advantages For Two-photon processes:
• Much higher (integrated) luminosity (up to 50 x)
• Better momentum resolution and identification
• Improved trigger efficiency due to more sophisticated neutral trigger

Most interesting two-photon studies:
Transition form factors of $\pi 0$, $\eta$ and $\eta'$ mesons via single and double tagged events. These are particularly important for light-by-light contribution to muon $(g-2)$;
Study and search for charmonium and charmonium-like states in the two-photon collisions.
$\gamma^* \rightarrow \pi^0$ Single-tag $\pi^0$ production in two-photon process with a large-$Q^2$ and a small-$Q^2$ photon

$|F(Q^2)|^2 = |F(Q^2,0)|^2 = (ds/dQ^2)/(2A(Q^2))$

$A(Q^2)$ is calculated by QED

$|F(0,0)|^2 = 64\pi\Gamma_{\gamma\gamma}/\{(4\pi\alpha)^2m^3\}$

The pion transition form factor for the “asymptotic” (solid line) and different models. The experimental data are from BaBar (circles), Belle (squares) and CLEO (open triangles).
Transition form factors $\gamma^* \gamma \rightarrow \eta$ (left panels) and $\gamma^* \gamma \rightarrow \eta'$ (right panels) compared to the LCSR calculation (Phys. Rev., D90(7), 074019 (2014)).
New-Charmonium (or XYZ) production

Important task is a search for and study above 3.6 GeV:
\( \eta_c(2S), \chi_c(2P) , X(3915) \) and \( X(4350) \) (Discovered by Belle in \( B \) decays and two-photon processes) Now statistics is limited \(<\sim 100 \) evt.

\[ M = (3915 \pm 3 \pm 2) \text{ MeV}, \]
\[ \Gamma = (17 \pm 10 \pm 3) \text{ MeV}, \]
\[ N_{\text{res}} = (49 \pm 14 \pm 4) \text{ events} \]
Signif. = 7.7\( \sigma \),

And search for exotic baryons in \( \gamma\gamma \rightarrow pp \) \( K+K^- \)

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Conclusion

• Last decade demonstrated the fruitfulness and efficiency of the flavor “factory” approach in the particle physics.

• Huge amount of results was obtained at the B-factories, but many new questions appeared and the large field of researches will be opened by the super B factory.

• High luminosity to be brought by SuperKEKB/Belle II will make various analyses possible for two-photon physics:
  • QCD test with exclusive processes at High-W, at High-Q2, with Single and Double tag …
  • Charmonia/XYZ above 3.6 GeV