The Belle II Experiment at SuperKEKB

Leo Piilonen, Virginia Tech

... with an acknowledgement to my colleagues for their contributions
SuperKEKB is the intensity frontier

40x higher luminosity than KEKB

Peak luminosity trends at $e^+e^-$ colliders
B factories: a success story

- Measurements of **CKM** matrix elements and **angles** of the unitarity triangle
- Observation of **direct** CP violation in B decays
- Measurements of rare decay modes (e.g., $B \to \tau \nu$, $D \nu$)
- $b \to s$ transitions: probe for new sources of CPV and constraints from the $b \to s \gamma$ branching fraction
- Forward-backward asymmetry ($A_{FB}$) in $b \to s l^+ l^-$ has become a powerful tool to search for physics beyond SM.
- Observation of **D mixing**
- Searches for **rare** $\tau$ decays
- Observation of **new** hadrons

Possible also because of unique capabilities of B factories: **detection of neutrals, neutrinos, clean event environment**.
Belle physics output (compiled by Simon Eidelman)

<table>
<thead>
<tr>
<th># citations ➤</th>
<th>50-99</th>
<th>100-199</th>
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<td>1</td>
<td>$X(3872)$</td>
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<td>2002</td>
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<td>D0 mixing</td>
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<td>2006</td>
<td>277</td>
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<td>8</td>
<td>$2c\bar{c}$</td>
<td>2002</td>
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<td>$D_s^*(2317), D_{s1}(2460)$</td>
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<td>$D^{**}$</td>
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<td>12</td>
<td>$Z(4430)$</td>
<td>2008</td>
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<td>13</td>
<td>$D_s J$</td>
<td>2006</td>
<td>221</td>
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<td>14</td>
<td>$X(3940)$ in $2c\bar{c}$</td>
<td>2007</td>
<td>204</td>
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</table>

Growing at ≈100/year

375 papers published plus ≈30/year
Searching for New Physics with Belle II

Indirect searches for New Physics complement direct searches at LHC

Flavor changing neutral currents
(virtual contributions of new, heavy particles in loops)

Precision test of **CKM unitarity**
(search for new CP-violating phases)

Search for **New Physics**
in **B** decays with **τ** leptons
(charged Higgs, ...)

See Tom Browder’s talk

For sensitive New Physics searches, need **O(10^2)** times more data

**Belle / KEKB ⇒ Belle II / SuperKEKB**
Belle II physics prospects: B decays

CP violation in s-Penguins

\[ \Delta S = S(b \rightarrow q\bar{q}s) - S(b \rightarrow c\bar{c}s) = -0.04 \pm 0.04 \]

(HFAG, Summer 2012)

B decays with \( \tau \) leptons

- \( B \rightarrow \tau \nu \) and \( B \rightarrow D(\ast)\tau \nu \)
- Sensitive to charged Higgs

... see Tom Browder’s talk

B factory upper limits

\[ \Delta S \text{ uncertainty} \]

\[ \Delta S \text{ uncertainty} \]

Belle II (10 ab\(^{-1}\))

5\( \sigma \) discovery

ATLAS 7 TeV (4.6 fb\(^{-1}\))
Precision Tests of CKM

> Much more improved measurements
> Overconstrain Unitarity Triangle
> Discrepancy between measurements $\rightarrow$ new physics?

2012 ($\sim$1000 fb$^{-1}$ at Belle and BaBar)

Expected constraint at 50 ab$^{-1}$
Belle II physics prospects: Tau and charm

Lepton flavor violation in $\tau$ decays

- strongly suppressed in SM: $\text{BF} \sim 10^{-53}-10^{-49}$
- Possible enhancements in NP models up to $\text{BF} \sim 10^{-9}-10^{-7}$

CP violation in D mixing

- Direct and indirect CPV in $D^0$-$\bar{D}^0$ mixing

Constraints on indirect CPV parameters

See Tom Browder’s and Dave Hitlin’s talks
Complementary to LHCb

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected th. accuracy</th>
<th>Expected exp. uncertainty</th>
<th>Facility</th>
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<tbody>
<tr>
<td>$</td>
<td>V_{us}</td>
<td>$ [K → πτν]</td>
<td>**</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ [B → X_sτν]</td>
<td>**</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ [B_d → πτν]</td>
<td>*</td>
</tr>
<tr>
<td>sin(2φ) [ππσK_S]</td>
<td>***</td>
<td>8 · 10⁻³</td>
<td>Belle II/LHCb</td>
</tr>
<tr>
<td>$ϕ_2$</td>
<td>***</td>
<td>1.5°</td>
<td>Belle II</td>
</tr>
<tr>
<td>$ϕ_3$</td>
<td>***</td>
<td>3°</td>
<td>LHCb</td>
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<tr>
<td>CPV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S(B_s → ψϕ)$</td>
<td>**</td>
<td>0.01</td>
<td>LHCb</td>
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<tr>
<td>$S(B_s → ϕϕ)$</td>
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<td>0.05</td>
<td>LHCb</td>
</tr>
<tr>
<td>$S(B_d → φK)$</td>
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<tr>
<td>$S(B_s → φγ)$</td>
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<td>LHCb</td>
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<td>$S(B_d → ργ)$</td>
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<td>$A_{CP}(B_d → sγ)$</td>
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<td>rare decays</td>
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<td>$B(B → τν)$</td>
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<td>$B(B → Dτν)$</td>
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<tr>
<td>$B(B_d → μν)$</td>
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<tr>
<td>zero of $A_{FB}(B → K^*μμ)$</td>
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<td>LHCb</td>
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<tr>
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<tr>
<td>$B(B → sγ)$</td>
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<td>4%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B_s → γγ)$</td>
<td></td>
<td>0.25 · 10⁻⁶</td>
<td>Belle II (with 5 ab⁻¹)</td>
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<tr>
<td>$B(B → Dτν)$</td>
<td>**</td>
<td>10%</td>
<td>K-factory</td>
</tr>
<tr>
<td>$B(K → πνν)/B(K → μνν)$</td>
<td>***</td>
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<td>K-factory</td>
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<tr>
<td>charm and τ</td>
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<tr>
<td>$B(τ → μγ)$</td>
<td>***</td>
<td>3 · 10⁻⁹</td>
<td>Belle II</td>
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<tr>
<td>$</td>
<td>q/p</td>
<td>_D$</td>
<td>***</td>
</tr>
<tr>
<td>$arg(q/p)_D$</td>
<td>***</td>
<td>1.5°</td>
<td>Belle II</td>
</tr>
</tbody>
</table>

→ Need both LHCb and super B factories to cover all aspects of precision flavour physics


Power of $e^+e^-$, example: Full Reconstruction Method

- Fully reconstruct one of the B mesons to
  - Tag B flavor/charge
  - Determine B momentum
  - Exclude decay products of one B from further analysis

> Offline B meson beam!

Powerful tool for B decays with neutrinos
Search for New Physics at Belle II

> Precision test of CKM unitarity

> Search for New Physics in B decays with missing energy
  \( B \rightarrow \tau \nu, D^{(*)}\tau \nu, K \nu \nu, \ldots \)

> Search for LFV in B and \( \tau \) decays

> FCNC (via virtual heavy particles in loops)

> Charm physics (including exotica)

"A unified and unbiased attack on new physics" – Tom Browder
Strategies for increasing luminosity

1. Smaller $\beta_y^*$
2. Increase beam currents
3. Increase $\xi_y$

Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB
### Machine design parameters

<table>
<thead>
<tr>
<th>parameters</th>
<th>KEKB</th>
<th>SuperKEKB</th>
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<tr>
<td></td>
<td>LER</td>
<td>HER</td>
</tr>
<tr>
<td>Beam energy</td>
<td>$E_b$</td>
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<td>Half crossing angle</td>
<td>$\phi$</td>
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<tr>
<td>Horizontal emittance</td>
<td>$\varepsilon_x$</td>
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<tr>
<td>Emittance ratio</td>
<td>$\kappa$</td>
<td>0.88</td>
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<td>Beta functions at IP</td>
<td>$\beta_x^<em>/\beta_y^</em>$</td>
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<td>Beam currents</td>
<td>$I_b$</td>
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<tr>
<td>beam-beam parameter</td>
<td>$\xi_y$</td>
<td>0.129</td>
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<tr>
<td>Luminosity</td>
<td>$L$</td>
<td>$2.1 \times 10^{34}$</td>
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</table>

- **Nano-beams and a factor of two more beam current** to increase luminosity
- **Large crossing angle**
- **Change beam energies** to solve the problem of short lifetime for the LER
KEKB to SuperKEKB

To obtain x40 higher luminosity

- Replace short dipoles with longer ones (LER)
- Redesign the lattices of HER & LER to squeeze the emittance
- TiN-coated beam pipe with antechambers
- Add / modify RF systems for higher beam current
- New positron target / capture section
- New superconducting / permanent final focusing quads near the IP
- New IR
- Colliding bunches

Low emittance positrons to inject
Low emittance electrons to inject
Entirely new LER beam pipe with ante-chamber and Ti-N coating.

Beam pipe is made of aluminum.

Fabrication of the LER arc beam pipe section is completed.
Al ante-chamber before coating

After TiN coating before baking

After baking
All 100 4 m long dipole magnets have been successfully installed in the low energy ring (LER)!

*Three magnets per day!*  

Installing the 4 m long LER dipole *over* the 6 m long HER dipole (remains in place).
Magnet installation

field measurement
move into tunnel
carry on an air-pallet
carry over existing HER dipole

Installation of 100 new LER bending magnets done

install done

SuperKEKB Status, 7th BPAC, Mar. 11, 2013, K. Akai
Upgrade of RF system to cope with twice beam currents and 2.5 times beam power

RF high power system

1.2 MW CW klystron

Superconducting cavities

Six ARES cavities in D5 moved from HER to LER. HER wiggler magnets were installed close to the ARES.
DR under construction on 18/Dec/2012

Positron Damping Ring (new)

- Tunnel construction under way in 2012-13; half year delay due to budget suspend caused by the earthquake.
- Construction of buildings for DR will start in April this year.
- Fabrication of accelerator components ongoing. Installation starts in 2014.
- DR commissioning will start in 2015.

Inside DR tunnel

Now DR has been buried.
in production

design being finalized

→ in production from summer
Experimental Challenges at High Luminosity

> High background (10-20 times higher than at Belle)
  ▪ Fake hits, pile up, radiation damage

> Higher trigger rate
  ▪ Typical Level1 trigger rate: 20kHz
  ▪ High performance DAQ

> Important improvements
  ▪ Hermeticity for full reconstruction analyses
  ▪ IP and secondary vertex resolution
  ▪ $K_s$ and $\pi^0$ identification efficiency
  ▪ Improve Kaon/pion separation

> Details in TDR arXiv:1011.0352
Belle II detector

Higher backgrounds ($\times 20$) $\Rightarrow$ higher occupancy, radiation damage

Higher event rate $\Rightarrow$ faster trigger, DAQ, computing

Special requirements, e.g. low-momentum $\mu$ ID ($b\to s\mu\mu$), hermeticity ($\nu$ reco.)
Belle II Detector – vertex region

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD
### Vertex Detector

<table>
<thead>
<tr>
<th>Component</th>
<th>Layer</th>
<th>$r$ (mm)</th>
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<tr>
<td>Beam Pipe</td>
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<tr>
<td>DEPFET</td>
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<td></td>
<td>Layer 2</td>
<td>22</td>
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<tr>
<td>DSSD</td>
<td>Layer 3</td>
<td>38</td>
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<tr>
<td></td>
<td>Layer 4</td>
<td>80</td>
</tr>
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<td>Layer 5</td>
<td>115</td>
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<tr>
<td></td>
<td>Layer 6</td>
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</table>

Mechanical mockup of pixel detector

DEPFET pixel sensor

DEPFET sensor: very good S/N

DEPFET:
[http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome](http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome)
Gearing up for ladder production!
Expected performance

\[ \sigma = a + \frac{b}{p \beta \sin^\nu \theta} \]

**Significant improvement in vertex resolution!**

- Less Coulomb scattering
- Pixel detector close to the beam pipe

**Significant improvement in \( \delta S(K_S \pi^0 \gamma) \)**

- B decay point reconstruction with \( K_S \) trajectory
- Larger radial coverage of SVD
Main tracking device: small cell drift chamber

Central Drift Chamber
He(50%):C₂H₆(50%), small cells, long lever arm, fast electronics

Missing E (ν)

B → τν candidate event
Central drift chamber

- **Extended** outer radius
- **Smaller cells** near beampipe
- **Faster** readout electronics

⇒ Improved \( p \) and \( \Delta E/dx \) resolution

\[
\sigma_p/p \sim 0.3\% + 0.1\% \times p(\text{GeV}) \text{ in } B=1.5\text{T}
\]

\[
\sigma(\Delta E/dx) \sim 6\%
\]

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innermost sense wire</td>
<td>( r=88\text{mm} )</td>
<td>( r=168\text{mm} )</td>
</tr>
<tr>
<td>Outermost sense wire</td>
<td>( r=863\text{mm} )</td>
<td>( r=1111.4\text{mm} )</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>( \text{He}:\text{C}_2\text{H}_6 )</td>
<td>( \text{He}:\text{C}_2\text{H}_6 )</td>
</tr>
<tr>
<td>Sense wire</td>
<td>( W(\Phi 30\mu\text{m}) )</td>
<td>( W(\Phi 30\mu\text{m}) )</td>
</tr>
<tr>
<td>Field wire</td>
<td>( \text{Al}(\Phi 120\mu\text{m}) )</td>
<td>( \text{Al}(\Phi 120\mu\text{m}) )</td>
</tr>
</tbody>
</table>

Wire configuration:

- **Belle**
- **Belle II**

**Belle**

- 10~20 mm
- 18 mm
- 6~8 mm

**Belle II**

- Normal cell
- Small cell

\( \sigma_p/p \sim 0.3\% + 0.1\% \times p(\text{GeV}) \text{ in } B=1.5\text{T} \)

\( \sigma(\Delta E/dx) \sim 6\% \)
Belle II CDC

Wire stringing in a clean room
- thousands of wires,
- 1 year of work...

Much bigger than in Belle!
Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)
- MCP-PMT
- Focus mirror (sphere r=7000)
- Quartz radiator
- Small expansion block
- Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)
- 200mm
- Cherenkov photon
- Aerogel radiator
- n~1.05
- Hamamatsu HAPD + new ASIC

Quartz radiator
Focusing mirror
Barrel PID: Time of propagation (TOP) counter

- Cherenkov ring imaging with precise time measurement.
- Device uses internal reflection of Cerenkov 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)
  - Photon detector (MCP-PMT)
    - Good time resolution \( \sim 40 \) ps
    - Single photon sensitivity in 1.5 T field
    - Hamamatsu SL10
Pattern in the coordinate-time space (‘ring’) of a pion hitting a quartz bar with ~80 MAPMT channels.

Time distribution of signals recorded by one of the PMT channels: different for $\pi$ and K (~shifted in time).
Aerogel RICH (endcap PID)

Test Beam setup

Aerogel

Hamamatsu HAPD

Clear Cherenkov image observed

Cherenkov angle distribution

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

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

Employ multiple layers with different refractive indices → Cherenkov images from individual layers overlap on the photon detector.
RICH with a focusing radiator

Increases the number of photons without degrading the resolution

4cm aerogel single index

$\chi^2/\text{ndf} = 2467. / 116$
$P1 = 5495.$
$P2 = 0.2965$
$P3 = 0.2072E-01$
$P4 = 85.32$
$P5 = 796.0$

$n_f = 7.69$
$n_b = 1.09$

2+2cm aerogel

$\chi^2/\text{ndf} = 1095. / 116$
$P1 = 7289.$
$P2 = 0.3074$
$P3 = 0.1428E-01$
$P4 = 74.49$
$P5 = 884.4$

$n_f = 7.46$
$n_b = 0.83$

→NIM A548 (2005) 383
EM calorimeter: upgrade needed because of higher rates (barrel: \textit{electronics}, endcap: electronics and CsI(Tl) $\rightarrow$ pure CsI) and radiation load (endcap: CsI(Tl) $\rightarrow$ pure CsI)
Detection of **muons and KLs**: Parts of the present RPC system have to be replaced to handle higher backgrounds (mainly from neutrons).

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

Expected to improve KL and muon detection efficiency beyond Belle performance.
SuperKEKB/Belle II schedule

<table>
<thead>
<tr>
<th>Calendar</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
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<tbody>
<tr>
<td>Japan FY</td>
<td>2010</td>
<td>2011</td>
<td>2012</td>
<td>2013</td>
<td>2014</td>
<td>2015</td>
<td>2016</td>
<td>2017</td>
<td>· · ·</td>
</tr>
</tbody>
</table>

- **SuperKEKB construction**
  - Detector upgrade to Belle II
    - Belle roll out
  - Dismantling KEKB
  - Fabrication and tests of ring components
    - Install and set up
      - Electricity and cooling facility
      - MR & DR buildings
      - DR tunnel
  - Linac upgrade / operation for PF&PF-AR
    - Upgraded Linac operation for SuperKEKB, PF, PF-AR

- **SuperKEKB operation**
  - Belle II roll in QCS install
  - VXD install
  - Accelerator tuning BEAST
  - Physics run

- **KEKB operation**
  - Linac
  - KEKB operation

- **Timeline**
  - Mar. 2013
  - Jan. 2015
Timeline & goal

Goal of Belle II/SuperKEKB

Plan to reach 50 \( \text{ab}^{-1} \) by end of 2022

Commissioning starts in early 2015.

Shutdown for upgrade


Calendar Year
> 21 countries/regions, 76 institutions, ~480 collaborators

We welcome new collaborators!

Open collaboration meeting on July 4–7 at Virginia Tech
Summary

> Very successful e^+e^- B Factories: Belle and BaBar

> Major upgrade: SuperKEKB and Belle II

> 50 times larger integrated luminosity compared to Belle
  ▪ Challenges to both accelerator and detector

> Fully approved and construction is ongoing

> First physics run in 2016

> New era of discoveries, complementary to LHC

We welcome new collaborators!

Open collaboration meeting on July 4–7 at Virginia Tech