The Belle II Experiment

C. Marinas
University of Bonn
• Flavor Physics Program
• The SuperKEKB Accelerator
• The Belle II Detector
The Three Frontiers

- The **Intensity Frontier**: Search for rare new phenomena using *medium-energy ultra-high-luminosity machines*.
Why Super B-Factories?
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50:1
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\[
\frac{\text{Belle II data set}}{\text{Belle data set}} \sim 50
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• Paradigm shift: From ‘Is the SM with CKM right?’ to ‘How is the SM wrong?’
Why Super B-Factories?

50:1

Belle II data set \( \sim 50 \) \( \frac{\text{Belle data set}}{\text{2009 BaBar data set}} \) \( \sim 50 \) \( \frac{\text{1999 CLEO data set}}{\text{1999 CLEO data set}} \)

- Larger data set will lead to an increase in sensitivity to higher mass scales just by simply redoing existing measurements.
- Larger and more precise data sets always spurred new theoretical ideas.
- In terms of NP reach this step is as big as going from LHC 8 TeV to LHC 14 TeV.
• The B factories Belle and BaBar ran from 1999 to 2010.
• They recorded over 1.5 ab$^{-1}$ of data (1.25·10$^9$ BB).
• Both experiments provided the experimental confirmation that led to the 2008 Nobel prize.
• Search for physics phenomena beyond SM in B, D and τ decays through precision measurements of the CKM sector and studies of rare or forbidden processes
• Many potential NP sources:
  – Flavor changing neutral currents
  – Lepton flavor violating decays
  – B → τ tree level new physics
  – New sources of CPV

1. High luminosity (SuperKEKB)
2. High-resolution and large-coverage detector (Belle II)
New physics could significantly modify the SM branching ratio via the exchange of a new charged particle (charged Higgs)
An Example: Leptonic Decays With Missing Energy

$B \rightarrow \tau \nu$

$\delta(\text{Br}) \sim 6\% @ 50 \text{ ab}^{-1}$

- New physics could significantly modify the SM branching ratio via the exchange of a new charged particle (charged Higgs)
- Experimentally very clean but non-trivial measurement
  → Signal signature: Just a **single charged track + nothing else**
Example: $B \rightarrow \tau \nu$ Candidate Event in Belle Data

\[ B^+ \rightarrow D^0 \pi^+ \]
\[ (\rightarrow K \pi^- \pi^+ \pi^-) \]
\[ B^- \rightarrow \tau (\rightarrow e \nu \bar{\nu}) \nu \]

Strengths of $e^+e^-$ B factories:
- Final states with neutral particles, in particular neutrinos
- Inclusive measurements

The clean $e^+e^-$ environment makes this possible
The SuperKEKB Accelerator

SuperKEKB:
- Asymmetric energy $e^+e^-$ collider
- $E_{cm} = m(\Upsilon(4S)) = 10.58$ GeV
- Peak luminosity: $\mathcal{L} = 8 \cdot 10^{35}$ cm$^{-2}$s$^{-1}$ (x40 than KEKB)
- Beam size reduction. Higher current (x2 higher).
The SuperKEKB Accelerator

SuperKEKB: Asymmetric energy $e^+e^-$ collider
$E_{cm} = m(\Upsilon(4S)) = 10.58$ GeV

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Belle II

Goal of Belle II

Phase 1: Accelerator commissioning
Phase 2: BEAST and partial Belle II
Phase 3: Full Belle II detector

$L \sim \frac{N_1 N_2}{\sigma_x \sigma_y}$
The SuperKEKB Accelerator

\[ \mathcal{L} \sim \frac{N_1 N_2}{\sigma_x \sigma_y} \]

Belle II

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KEKB SuperKEKB

Nano beams!

50 nm
The SuperKEKB Accelerator

SuperKEKB ring (HER+LER)

Belle II detector

Mt. Tsukuba

Linac

KEK - Tsukuba
Going For a Super B-Factory: SuperKEKB

Complete refurbishment to achieve x40 higher luminosity compared to KEKB

- Replace short dipoles with longer ones (LER)
- Redesign the lattices of HER & LER to squeeze the emittance
- TiN-coated beam pipe with antechambers
- New bellows
- New IR
- New e⁻ damping ring
- New positron target
- New final focusing quads near the IP
- New RF systems
- New e⁺ damping ring
- New positron target

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Phase 1 Results:
- First turns at SuperKEKB
- Vacuum scrubbing
- Initial background studies

- HER: 870 mA
- LER: 1010 mA

→ Program completed!
The Belle II Detector

40 times higher luminosity implies

- **Higher event rate**
  - Higher trigger rate
  - Increased DAQ and computing requirements
- **Higher background**
  - Radiation damage
  - Occupancy
  - Fake hits and pile-up
- Changes in detector
  - $\beta\gamma$ reduced by factor 1.5
  - Improved vertexing needed

- Results in significant upgrade

  → Belle II
The Belle II Collaboration

101 Institutes
751 Researchers
23 Countries
→ Germany is second largest only after Japan
The Belle II Detector

- Areas of improvement:
  - Light inner detector
  - Precise vertexing/tracking
  - Particle identification
  - E.M. calorimetry
  - $K^0_L$ and muon ID
  - Data handling capabilities

Ready for physics run in **2018**
Vertex Detector (VXD)
Typical Event

\[ e^+ e^- \quad E_{\text{cm}} = 10.58 \text{ GeV} \]
$e^+ e^- \rightarrow \Upsilon(4s)$  \hspace{1cm} $E_{\text{cm}} = 10.58$ GeV
$e^+ e^- \rightarrow \Upsilon(4s) \rightarrow B \bar{B}$  \hspace{1cm} E_{cm} = 10.58 \text{ GeV}
Typical Event

\[ e^+ e^- \rightarrow \Upsilon(4s) \rightarrow B \bar{B} \quad E_{cm} = 10.58 \text{ GeV} \]
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Asymmetric beams:
Lorentz-boost translates lifetime to decay length

Precise vertexing essential to measure time dependent CP violation and mixing
Typical Event

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Asymmetric beams: Lorentz-boost translates lifetime to decay length

Precise vertexing essential to measure time dependent CP violation and mixing

\[ \Delta z = \beta \gamma c \Delta t \approx 150 \mu m \]
Vertex Detector: PXD and SVD

- Silicon Vertex Detector (SVD)
  - 4 layers of DSSD
  - $r = 3.8 \text{ cm}, 8.0 \text{ cm}, 11.5 \text{ cm}, 14 \text{ cm}$
  - $L = 60 \text{ cm}$
  - $\sim 1 \text{ m}^2$
**Vertex Detector: PXD and SVD**

- **Pixel Detector (PXD)**
  - 2 layers of DEPFET pixels
  - $r = 1.4$ cm, $2.2$ cm
  - $L = 12$ cm
  - $\sim 0.027$ m$^2$

- **Silicon Vertex Detector (SVD)**
  - 4 layers of DSSD
  - $r = 3.8, 8.0, 11.5, 14$ cm
  - $L = 60$ cm
  - $\sim 1$ m$^2$
### Belle II VXD Requirements and Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Occupancy</strong></td>
<td>0.4 hits/µm²/s (3% max)</td>
</tr>
<tr>
<td><strong>Radiation</strong></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><strong>Integration time</strong></td>
<td>20 µs</td>
</tr>
<tr>
<td><strong>Momentum range</strong></td>
<td>Low p (50 MeV - 3 GeV)</td>
</tr>
<tr>
<td><strong>Acceptance</strong></td>
<td>$17^\circ - 155^\circ$</td>
</tr>
<tr>
<td><strong>Material budget</strong></td>
<td>0.21% $X_0$ per layer</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>15 µm (50x75 µm²)</td>
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- 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
The DEPFET Ladder

SwitcherB
Row control
AMS/IBM HVCMOS 180 nm
Size 3.6 × 1.5 mm²
Gate and Clear signal
Fast HV ramp for Clear

PXD

DHP (Data Handling Processor)
First data compression
TSMC 65 nm
Size 4.0 × 3.2 mm²
Stores raw data and pedestals
Common mode and pedestal correction
Data reduction (zero suppression)
Timing signal generation

DCDB (Drain Current Digitizer)
Analog frontend
UMC 180 nm
Size 5.0 × 3.2 mm²
TIA and ADC
Pedestal compensation

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Belle II PXD Module

- 768x250 DEPFET Pixels
- 50x75 μm² pixel pitch
- 75 μm thickness
Belle II SVD Module
Belle II Vertex Detector Beam Tests
PXD and SVD Combined Operation

Small sector of final PXD and SVD under electron beam and 1 T magnetic field
• Homogeneous sensor response
• SNR ~ 30
• 14 μm resolution (50 μm)
• $\varepsilon > 99\%$
• Amount of data created by PXD is larger than the data generated by all other subdetectors
• Only reduced PXD data is written to tape
• Use tracks in SVD (and CDC) to find PXD regions of interest
Central Drift Chamber (CDC)
Central Drift Chamber (CDC)

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

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<tr>
<td>Number of layers</td>
<td>56</td>
</tr>
<tr>
<td>Total sense wires</td>
<td>14336</td>
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<tr>
<td>Gas</td>
<td>He:C$_2$H$_6$ (1:1)</td>
</tr>
<tr>
<td>Sense wire</td>
<td>Au-W (Ø30 µm)</td>
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<tr>
<td>Field wire</td>
<td>Al (Ø126 µm)</td>
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Small cell chamber

Large tracking volume

Stereo and axial layers

Belle II CDC
Central Drift Chamber (CDC)

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Stereo and axial layers

Small cell chamber   Large tracking volume
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\[ \frac{\sigma_{p_t}}{p_t} \sim 0.3\% / \beta \oplus 0.1\% \cdot p_t [GeV/c] \]

\[ \sigma \left( \frac{dE}{dx} \right)_{MIP} \sim 5\% \]
Central Drift Chamber (CDC)
Central Drift Chamber (CDC)

CDC is operational
Time Of Propagation (TOP)
TOP will be used for PID in the barrel region

• When a charged particle passes through the quartz, it emits Cherenkov photons

• The Cherenkov angle, and hence detection time/position depends on the mass of particle (for given track parameters).

\[
\cos \theta_C = \frac{1}{\beta n}
\]
Each TOP module contains two quartz bars (2.5 m x 0.45 m x 2 cm), mirror, and array of photodetectors.

- Photon Detectors
- $K^+ / \pi^+$
- Photon from $\pi^+$
- Photon from $K^+$
- Forward mirror

32 (segmented 4x4) Micro-channel plate PMT
Hamamatsu SL-10 MCP PMT
They can operate in a magnetic field
Gain = $2 \cdot 10^6$
Time resolution $\sigma = 35$ ps
QE > 24% at 380 nm

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<th>Quartz property</th>
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<td>Flatness</td>
<td>&lt; 6.3 µm</td>
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<tr>
<td>Roughness</td>
<td>&lt; 0.5 nm (RMS)</td>
</tr>
<tr>
<td>Bulk transmittance</td>
<td>&gt; 98% /m</td>
</tr>
<tr>
<td>Surface reflectance</td>
<td>&gt; 99.9% /reflection</td>
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Time Of Propagation (TOP)
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TOP is operational
Aerogel Ring Imaging Cherenkov (ARICH)

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Particle identification in the forward endcap

- Radiator: Silica Aerogel
  \( n = 1.045\text{--}1.055 \)
  Transmission length > 40 mm

- Photon detection: Hybrid Avalanche Photo Detectors
  420 units, 144 channels each, 5 mm pixelated
  Gain = \(7 \times 10^5\)
  QE > 28%
Particle identification in the forward endcap

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Aerogel Ring Imaging Cherenkov (ARICH)

ARICH:
• Aerogel sectors completed
• HAPDs being installed
Electromagnetic Calorimeter (ECL)
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E.M. Calorimeter to measure:
Energy and angle of electrons/photons
Luminosity

Need upgrade due to high backgrounds:

• Barrel:
CsI(Tl) crystals reused
16.1 $X_0$ (30 cm)
New electronics 2 MHz waveform sampling

• Endcaps:
CsI(Tl), crystals reused
16.1 $X_0$ (30 cm)
Replacement with pure CsI in future (under study)
Time constant (shaping) 30 ns
Electromagnetic Calorimeter (ECL)

ECL is operational
$K_L$ and Muon Systems (KLM)
Large area thin planar detectors interleaved with the iron plates of the flux return yoke.

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

• **Endcap:**
  RPCs replaced with polystyrene scintillators
  99% geometrical acceptance. $\sigma \sim 1$ns
KLM is operational
Getting Ready for Phase 2

- The SuperKEKB accelerator will be operating, for the first time, with QCS magnets
  - First operation with focused beams
  - First beam collisions

- The Belle II detector, minus the vertex detectors (VXD), will have rolled into the beam line (11.4.17)
Getting Ready for Phase 2

Final focus magnets installed

‘Interaction point’
Motivation for **BEAST II**:

- Machine commissioning
- Radiation safe environment for the VXD:
  - Two ladders PXD
  - Four ladders SVD
  - Dedicated radiation monitors
    FANGS, CLAWS, PLUME
Getting Ready for Phase 2

• Combined operation demonstrated
• Getting ready for installation in November 2017

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German Contribution

- Physics analysis
- Vertex detector
- BEAST
- Tracking
- Computing
Outlook

• The B-Factory experiments have played an pivotal role in understanding the SM and are a unique tool to search for New Physics

• Belle II will further explore these opportunities with a target integrated luminosity of 50 ab$^{-1}$

• Detector to start operation in early 2018 (Phase 2) and start taking physics data beginning 2019 (Phase 3)

• Stay tuned!
Thank you