Physics Prospects and Status of Belle II

Matter and the Universe

Sergey Yashchenko
FZ Jülich, 29.09.2015
Introduction: Intensity Frontier

> Higgs discovery at LHC
  - Triumph of the Standard Model and particle physics in general

> No New Physics observed yet
  - Direct: no BSM particles or decays
  - Indirect: no significant deviations from the SM

> Important
  - Joint efforts in energy and intensity frontier
  - High experimental precision
  - Theoretical cleanliness
Achievements of $e^+e^-$ B Factories

- $e^+e^-$ B Factories: Belle at KEKB and BaBar at PEP-II
- Successful confirmation of Kobayashi-Maskawa mechanism of CP violation in the Standard Model
  - Nobel Prize for Kobayashi and Maskawa in 2008
- Precise measurements of CKM elements and angles of UT
- Much more
  - Measurements of rare B-decay modes
  - $b \to s$ transitions: new sources of CPV
  - Observation of D mixing (charm factory)
  - Searches for LFV tau decays (tau factory)
  - Observation of exotic hadrons
Belle II: Why Upgrade?

> B factories collected a lot of data

> Results compatible with the Standard Model

> Observed hints on deviations from the SM not significant

> Many measurements still limited in statistics

> Systematic uncertainties can be reduced with more data

> Some parameters of theoretical calculations can be better constrained using high-statistics data
Precision Tests of CKM

> Much more improved measurements
> Overconstrain the Unitarity Triangle
> Discrepancy between measurements → New Physics?

2015 (~1000 fb⁻¹ at Belle and BaBar, LHCb)

Expected constraint at 50 ab⁻¹
## Summary of CKM Metrology

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>BaBar</th>
<th>Global Fit CKMfitter</th>
<th>LHCb Run-2</th>
<th>Belle II 50 ab(^{-1})</th>
<th>LHCb Upgrade 50 fb(^{-1})</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varphi_1: ccs)</td>
<td>0.9°</td>
<td></td>
<td>0.9°</td>
<td>0.6°</td>
<td>0.3°</td>
<td>0.3°</td>
<td>v. small.</td>
</tr>
<tr>
<td>(\varphi_2: uud)</td>
<td></td>
<td>4°(^{WA})</td>
<td>2.1°</td>
<td>1°</td>
<td></td>
<td></td>
<td>(~1-2°)</td>
</tr>
<tr>
<td>(\varphi_3: DK)</td>
<td>14°</td>
<td></td>
<td>3.8°</td>
<td>4°</td>
<td>1.5°</td>
<td>1°</td>
<td>negl.</td>
</tr>
<tr>
<td>(</td>
<td>V_{cb}</td>
<td>^{intrinsic})</td>
<td>1.7%</td>
<td></td>
<td>2.4%</td>
<td></td>
<td>1.2%</td>
</tr>
<tr>
<td>(</td>
<td>V_{cb}</td>
<td>^{exclusive})</td>
<td>2.2%</td>
<td></td>
<td></td>
<td></td>
<td>1.4%</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>^{intrinsic})</td>
<td>7%</td>
<td></td>
<td>4.5%</td>
<td></td>
<td>3.0%</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>^{exclusive})</td>
<td>8%</td>
<td></td>
<td></td>
<td></td>
<td>2.4%</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>^{leptonic})</td>
<td>14%</td>
<td></td>
<td></td>
<td></td>
<td>3.0%</td>
</tr>
</tbody>
</table>

**Experiment**

- No result
- Moderate precision
- Precise
- Very Precise

**Theory**

- Moderate precision
- Clean / LQCD
- Clean

Courtesy to Phillip Urquijo
Unique Capabilities of $e^+e^-$ B Factories

- Clean event environment
- Detection of neutral particles
- Example: full reconstruction method

$e^- (8 \text{ GeV}) \rightarrow \Upsilon(4S) \rightarrow B \rightarrow \tau\nu, D\tau\nu$

$B \rightarrow X_u l\nu$

$B \rightarrow K\nu\nu$

$B \rightarrow D\pi \text{ etc}$

Effective offline B meson beam

Full reconstruction

Semileptonic tagging
\[ B \rightarrow D^* \tau \nu \]

- New Physics could change
  - Branching fraction
  - Tau polarization
- Effect could be different for D and D*
- 3.4 \sigma deviation from SM observed by BaBar
- Experimental challenge: 2 or 3 undetected neutrino
- Measurement of branching ratio relative to corresponding decay to light leptons

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

- Same detectable final state particles of signal and normalization mode \rightarrow reduction of systematic uncertainties
B → D*τν

> Belle results consistent with SM, BaBar and with 2HDM

> Belle II could potentially resolve SM/2HDM with projected uncertainties

2-Higgs doublet model:

\[ \mathcal{B}(B \to D^{(*)}\tau\nu) \propto \mathcal{B}_{SM} \cdot m_W \left( \frac{\tan \beta}{m_H} \right) \]
$\mathbf{B \rightarrow \tau \nu}$ using full reconstruction method with hadronic tag \cite{PRL110, 131801 (2013)}

- Belle, hadronic tag: $0.72^{+0.27}_{-0.25} \pm 0.11$
- Belle, semileptonic tag: $1.54^{+0.38+0.29}_{-0.37-0.31}$
- Belle, combined: $0.96 \pm 0.26$
- BaBar, hadronic tag: $1.83^{+0.53}_{-0.49} \pm 0.24$
- BaBar, semileptonic tag: $1.7 \pm 0.8 \pm 0.2$
- BaBar, combined: $1.79 \pm 0.48$
- World average: $1.14 \pm 0.22$

Aim to measure $B \rightarrow \tau \nu$ at Belle II with precision of 3-5%
B → τν

Using full reconstruction method with hadronic tag *PRL 110, 131801 (2013)*

\[ B \rightarrow \tau\nu \]

- **Belle, hadronic tag**: \(0.72^{+0.27}_{-0.25} \pm 0.11\)
- **Belle, semileptonic tag**: \(1.54^{+0.38}_{-0.37} \pm 0.29\)
- **Belle, combined**: \(0.96 \pm 0.26\)
- **BaBar, hadronic tag**: \(1.83^{+0.53}_{-0.49} \pm 0.24\)
- **BaBar, semileptonic tag**: \(1.7 \pm 0.8 \pm 0.2\)
- **BaBar, combined**: \(1.79 \pm 0.48\)
- **World average**: \(1.14 \pm 0.22\)

**Aim to measure** \(B \rightarrow \tau\nu\) **at Belle II** with precision of 3-5%
$B \rightarrow \tau \nu$: Search for Charged Higgs

$$B = \frac{G_F^2}{8\pi} |V_{ub}|^2 f_B \left(1 - \frac{m_{\tau}^2}{m_B^2}\right)^2 \left(\frac{m_B}{m_{\tau}}\right)^2 \times \left(1 - \frac{m_B^2}{m_{H^+}^2}\right)^2$$

$B \equiv B^{SM}$

$2HDM$ (Type II)

$\equiv r_H$

Now

50 ab$^{-1}$

Y. Sato
\[ B \rightarrow X_s \gamma \]

- \( b \rightarrow s\gamma \) transition: FCNC
- Forbidden at tree level in the SM, proceeds via loop diagrams
- Inclusive branching fraction sensitive to new particles in the loop

- Recent result from Belle
  *T. Saito et al., Phys. Rev. D 91, 052004*

- Semi-inclusive (sum-of-exclusive) approach
- Consistent with the SM
- Key measurement at Belle II among other FCNC processes such as \( B \rightarrow X_{sI}, B \rightarrow K(*)\nu\nu \)
Search for Charged Higgs at Belle II

Constraint from four observables

<table>
<thead>
<tr>
<th></th>
<th>Exp.</th>
<th>Th.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Now</td>
<td>5 ab⁻¹</td>
</tr>
<tr>
<td>( B \to \tau \nu )</td>
<td>25%</td>
<td>10%</td>
</tr>
<tr>
<td>( B \to D \tau \nu )</td>
<td>30%</td>
<td>11%</td>
</tr>
<tr>
<td>( B \to D^* \tau \nu )</td>
<td>19%</td>
<td>7%</td>
</tr>
<tr>
<td>( B \to X_s \gamma )</td>
<td>7%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Y. Sato
Lepton Flavor Violation in $\tau$ Decays

<table>
<thead>
<tr>
<th>$l\gamma$</th>
<th>$lP^0$</th>
<th>$lS^0$</th>
<th>$lV^0$</th>
<th>$III$</th>
<th>$Ihh$</th>
<th>$\Lambda h$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

> Null test of the SM (BF $< 10^{-25}$), NP models predict $10^{-7}$-$10^{-10}$

> Sensitivity at Belle II about 100 times higher for $\tau \rightarrow 3l$ and 10 times higher for $\tau \rightarrow l\gamma$ (irreducible background)
Belle II Theory Interface Platform (B2TIP)

> **Joint theory-experiment effort** to study the potential impacts of the Belle II program and complementarity with LHCb

https://belle2.cc.kek.jp/~twiki/bin/view/Public/B2TIP

> What is new in Belle II compared to Belle/BaBar?

  - Efficiencies and precision of new hardware
  - New analysis software and methods

> What is new in theory after Belle/BaBar and LHCb results?

  - New physics models and their constraints, new observables
  - Progress in QCD

> Next B2TIP workshop together with 5th KEK Flavor Factory Workshop in October 26-29 in Tokio/Tsukuba

https://kds.kek.jp/indico/event/19103/

> Desirable: “KEK yellow report” by the end of 2016
SuperKEKB: Accelerator Design

Low emittance lattice

Replace short dipoles with longer ones (LER)

New superconducting/permanent final focusing quadrupole near the IP

Damping ring for low emittance positron injection

Add RF systems for higher beam current

TiN-coated beam pipe with antechambers

New positron capture section
Strategy for SuperKEKB

Lorentz factor

\[ L = \frac{\gamma_{e^\pm}}{2eR_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{I_{e^\pm} + \xi e_y^*}{\beta_y^*} \right) \left( \frac{R_L}{R_{\xi_y}} \right) \]

Beam current

Beam-beam parameter

Geometrical reduction factors (crossing angle, hourglass effect)

Classical electron radius

Beam size ratio at IP 1-2% (flat beam)

Vertical beta function at IP

Nano-beam scheme:

P. Raimondi for SuperB

http://www.ln.infn.it/conference/superb06/talks/raimondi1.ppt

<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)</th>
<th>L (cm(^{-2})s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LER/HER</td>
<td>LER/HER</td>
<td>LER/HER</td>
<td>LER/HER</td>
<td></td>
<td></td>
</tr>
<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>
SuperKEKB: Progress

> Fabrication and installation of all magnets needed for Phase 1 completed

> Final precise measurement and alignment of magnets before Phase 1 ongoing from June through September 2015

> Startup and electrical current test of over two thousands power supply systems connected to magnets underway

Magnets in a mid-arc section

Wiggler magnets for LER and HER

Checking a MW-class power supply for wiggler magnets
SuperKEKB: Damping Ring

DR tunnel construction

Mar. 2013

Tunnel and buildings completed

Mar. 2014

Installation of accelerator components ongoing

Sep. 2014

Commissioning of DR will start after phase 1 and before phase 2

Parameter | Value
---|---
Energy | 1.1 GeV
Bunches | 2 x 2
Circumference | 135.5 m
H. damping | 10.87 ms
Ext. emittance (H/V) | 42.5/3.15 nm
Max. current | 70.8 mA
Belle II Detector

CsI(Tl) EM calorimeter:
  waveform sampling electronics, pure CsI for endcaps

K_\mu and muon counter:
  scintillator + Si-PM for endcaps

Vertex detector:
  2 pixel layers (DEPFET)
  4 double-sided strip layers

Central drift chamber:
  longer lever arm
  smaller cell size

Aerogel RICH
  (forward)

Time-of-propagation
  (barrel)

Details in TDR arXiv:1011.0352
Belle II with Respect to Belle

> Beam energy asymmetry 7 GeV (e-) x 4 GeV (e+), \( \beta \gamma = 0.28 \) (Belle: 8 GeV (e-) x 3.5 GeV (e+), \( \beta \gamma = 0.425 \))
  - Better hermiticity, important for modes with neutrinos (e.g., \( B \to \tau \nu \))

> Smaller beam pipe radius 1 cm (Belle: 1.5 cm) \( \to \) innermost silicon pixel detector closer to the IP: 1.3 cm (Belle: 2.0 cm)
  - Improve resolution in z direction significantly

> Larger outer radius of silicon detector 14 cm (Belle: 20 cm)

> More \( K^0_S \) for the time-dependent analysis using \( K^0_S \) vertexing

> Higher reconstruction efficiency of slow pions from \( D^* \)

> PID improvements (\( K/\pi \) separation, flavor tagging, …)

> Higher \( K_L \) veto efficiency used in mixing energy analyses
Luminosity Projection

Data taking will start in 2018

Goal: 50 ab$^{-1}$
23 countries/regions, 98 institutions, 638 collaborators
Summary

➢ Belle II at SuperKEKB will collect high-statistics data on heavy flavor during the next decade

➢ Complementary to direct searches for New Physics at LHC

➢ Joint activity of experimentalists and theorists (B2TIP)

➢ SuperKEKB and Belle II construction ongoing on schedule

➢ Belle II first data in 2017, with complete detector in 2018
Heavy Flavor Physics at Belle II

- **Belle II**
  - Well-defined initial state
  - Ability to reconstruct final states with photons, $\pi^0$s and neutrinos

- Complementary to direct searches for New Physics at LHC
- Need precise theoretical predictions

**Key observables** *(arXiv:1311.1076)*

<table>
<thead>
<tr>
<th>Observable</th>
<th>SM theory</th>
<th>Current measurement (early 2013)</th>
<th>Belle II (50 ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S(B \to \phi K^0)$</td>
<td>0.68</td>
<td>$0.56 \pm 0.17$</td>
<td>$\pm 0.03$</td>
</tr>
<tr>
<td>$S(B \to \eta' K^0)$</td>
<td>0.68</td>
<td>$0.59 \pm 0.07$</td>
<td>$\pm 0.02$</td>
</tr>
<tr>
<td>$\alpha$ from $B \to \pi\pi, \rho\rho$</td>
<td></td>
<td>$\pm 5.4^\circ$</td>
<td>$\pm 1.5^\circ$</td>
</tr>
<tr>
<td>$\gamma$ from $B \to DK$</td>
<td></td>
<td>$\pm 11^\circ$</td>
<td>$\pm 1.5^\circ$</td>
</tr>
<tr>
<td>$S(B \to K_S \pi^0\gamma)$</td>
<td>$&lt; 0.05$</td>
<td>$-0.15 \pm 0.20$</td>
<td>$\pm 0.03$</td>
</tr>
<tr>
<td>$S(B \to \rho\gamma)$</td>
<td>$&lt; 0.05$</td>
<td>$-0.83 \pm 0.65$</td>
<td>$\pm 0.15$</td>
</tr>
<tr>
<td>$A_{CP}(B \to X_{s+d}\gamma)$</td>
<td>$&lt; 0.005$</td>
<td>$0.06 \pm 0.06$</td>
<td>$\pm 0.02$</td>
</tr>
<tr>
<td>$A_{SL}^d$</td>
<td>$-5 \times 10^{-4}$</td>
<td>$-0.0049 \pm 0.0038$</td>
<td>$\pm 0.001$</td>
</tr>
<tr>
<td>$B(B \to \tau\nu)$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>$(1.64 \pm 0.34) \times 10^{-4}$</td>
<td>$\pm 0.05 \times 10^{-4}$</td>
</tr>
<tr>
<td>$B(B \to \mu\nu)$</td>
<td>$4.7 \times 10^{-7}$</td>
<td>$&lt; 1.0 \times 10^{-6}$</td>
<td>$\pm 0.2 \times 10^{-7}$</td>
</tr>
<tr>
<td>$B(B \to X_s \gamma)$</td>
<td>$3.15 \times 10^{-4}$</td>
<td>$(3.55 \pm 0.26) \times 10^{-4}$</td>
<td>$\pm 0.13 \times 10^{-4}$</td>
</tr>
<tr>
<td>$B(B \to K\nu\bar{\nu})$</td>
<td>$3.6 \times 10^{-6}$</td>
<td>$&lt; 1.3 \times 10^{-5}$</td>
<td>$\pm 1.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>$B(B \to X_s \ell^+\ell^-)$ ($1 &lt; q^2 &lt; 6 \text{ GeV}^2$)</td>
<td>$1.6 \times 10^{-6}$</td>
<td>$(4.5 \pm 1.0) \times 10^{-6}$</td>
<td>$\pm 0.10 \times 10^{-6}$</td>
</tr>
<tr>
<td>$A_{FB}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing</td>
<td>7%</td>
<td>18%</td>
<td>5%</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ from $B \to \pi\ell^+\nu$ ($q^2 &gt; 16 \text{ GeV}^2$)</td>
<td>9%</td>
</tr>
</tbody>
</table>
Physics at Super B factory: 
*arXiv:1002.5012*  
*arXiv:1008.1541*

Belle II and LHCb will provide complementary information

Adopted from G. Isidori et al.,  
Pixel Vertex Detector (PXD)

- DEPFET technology: thin (75μm) sensors
- Work in high occupancy close to the interaction region
- Fast readout
Silicon Vertex Detector (SVD)

> Double-sided silicon strip detectors
> Pipelined readout to reduce dead time, pile-up rejection
> Larger acceptance (by 30%) for detection of pions from $K_S$ decay $\rightarrow$ significant improvement in $\delta S(K_S \pi^0 \gamma)$

SVD design

SVD mockup
**Vertex Detector: PXD+SVD**

> Significant improvement in IP resolution

**Closest approach resolution**

- Less multiple scattering

**Z resolution**

- PXD close to the beam pipe

\[ \sigma \text{[\text{	extmu}m]} \]

- Belle
- Belle II

\[ p/\beta \sin(\theta)^{3/2} \text{[GeV/c]} \]

\[ p/\beta \sin(\theta)^{5/2} \text{[GeV/c]} \]
Read out "Region Of Interest" scheme in PXD works
(In order to reduce the Gbit/s data volume from pixels)
Central Drift Chamber (CDC)

- Smaller cells near beam pipe
- Extended outer radius for better momentum resolution
- Faster readout electronics to reduce dead time

\[ \sigma_p/p \sim 0.3\% + 0.1\% \times p(\text{GeV}) \text{ in } B = 1.5\text{T} \]
\[ \sigma(dE/dx) \sim 6\% \]

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innermost sense wire</td>
<td>R=88mm</td>
<td>R=168mm</td>
</tr>
<tr>
<td>Outermost sense wire</td>
<td>R=863mm</td>
<td>R=1111.4m</td>
</tr>
<tr>
<td>Number of layers</td>
<td>50</td>
<td>56</td>
</tr>
<tr>
<td>Total number of sense wires</td>
<td>8400</td>
<td>14336</td>
</tr>
<tr>
<td>Gas</td>
<td>He : C_2H_6</td>
<td>He : C_2H_6</td>
</tr>
<tr>
<td>Sense wires</td>
<td>W(Ø30μm)</td>
<td>W(Ø30μm)</td>
</tr>
<tr>
<td>Field wires</td>
<td>Al(Ø120μm)</td>
<td>Al(Ø120μm)</td>
</tr>
</tbody>
</table>
CDC Cosmic Test

CDC detector and FEEs

COPPER readout
Boards in E-hut

Display of a cosmic ray event

- CDC detector placed outside of the Belle-II detector in Tsukuba hall and the detector and backend-DAQ system in Electronics-hut are connected by optical fibers.
- Cosmic ray data have been taken with 18 FEE boards.
- Scintillator is currently used for generating a trigger signal. Tracking with the CDC Trigger system will be soon tested.
- ’Partitioned DAQ’ has been developed so that ECL and CDC DAQ systems can run independently in the same PC-farm and trigger/timing distribution system of the Belle-II DAQ.
Barrel PID: Time of Propagation Detector (TOP)

- Compact design
- Improved $K/\pi$ separation

Linear-array type photon detector

Quartz radiator

400mm

20mm

Parameters are not fixed yet

Sergey Yashchenko | Physics prospects and status of Belle II | 29.05.15 | Page 37
Endcap PID: Aerogel RICH

- Novel proximity-focusing two-layer radiator
- Employ multiple layers with different refractive indices
- Cherenkov images from individual layers overlap on the photon detector

Test Beam setup

Aerogel

Hamamatsu HAPD Q.E.~33%

NIM A548 (2005) 383
Electromagnetic Calorimeter

- Barrel: reuse existing CsI(Tl)
- Readout electronics:
  - Upgrade to 2 MHz waveform sampling
  - Online signal processing
- Endcaps: considering upgrade to pure CsI
- Better performance & radiation hardness
- Improved energy resolution

Better signal-to-background separation

![Image of calorimeter components and diagram]

Sergey Yashchenko | Physics prospects and status of Belle II | 29.05.15 | Page 39
$K_L$ and $\mu$ Detection (KLM)

- End-caps upgrade: Resistive Plate Chambers → scintillator-based KLM
- Scintillators + SiPM → better beam-background tolerance
- Barrel KLM: some RPC layers may be replaced as background increases with luminosity
Software Upgrade

- New framework with dynamic module loading, parallel processing, python steering, root I/O, and use of GRID
- Full detector simulation with Geant4
- Tracking with Genfit
- Alignment with Millepede II