Quark Flavor Physics from Belle II

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Lattice QCD Meets Experiment 2014 @ Fermilab
SuperKEKB/Belle II

- New intensity frontier facility
- Target luminosity:
  \[ L_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \]
  \[ L_{\text{int}} > 50 \text{ab}^{-1} \text{ by early 2020's.} \]
  \[ \Rightarrow \sim 10^{10} \, B\bar{B}, \tau^+ \tau^- \text{ and charms per year!} \]
Motivation of Belle II

- Search for New Physics through processes sensitive to presence of virtual heavy particles.
- Complementary to direct search at LHC high $P_T$ programs.

Flavour constraints in CMSSM in $(m_{1/2}, m_0)$

ATLAS SUSY direct search limit w/ 20.3fb$^{-1}$

Higgs mass can reach 122 GeV
Key Measurements

- CPV in $b \rightarrow s$ penguin decays
- FCNC
- Tauonic decays
- LFV $\tau$ decays

Ultimate measurements down to theory error!

<table>
<thead>
<tr>
<th>Observable</th>
<th>Belle 2006 ($\sim 0.5 \text{ ab}^{-1}$)</th>
<th>SuperKEKB (5 $\text{ ab}^{-1}$)</th>
<th>SuperKEKB (50 $\text{ ab}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic $b \rightarrow s$ transitions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta S_{\phi K^0}$</td>
<td>0.22</td>
<td>0.073</td>
<td>0.029</td>
</tr>
<tr>
<td>$\Delta S_{\eta' K^0}$</td>
<td>0.11</td>
<td>0.038</td>
<td>0.020</td>
</tr>
<tr>
<td>$\Delta S_{K^0, K^0, K^0}$</td>
<td>0.33</td>
<td>0.105</td>
<td>0.037</td>
</tr>
<tr>
<td>$\Delta A_{\pi^0 K^0}$</td>
<td>0.15</td>
<td>0.072</td>
<td>0.042</td>
</tr>
<tr>
<td>$\Delta A_{\phi K^0}$</td>
<td>0.17</td>
<td>0.05</td>
<td>0.014</td>
</tr>
<tr>
<td>$\phi^H_{(\phi K_S)}$ Dalitz</td>
<td></td>
<td>3.3°</td>
<td>1.5°</td>
</tr>
<tr>
<td>Radiative/electroweak $b \rightarrow s$ transitions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{S}_{K^*}$</td>
<td>0.32</td>
<td>0.10</td>
<td>0.03</td>
</tr>
<tr>
<td>$\mathcal{B}(B \rightarrow X_s \gamma)$</td>
<td>13%</td>
<td>7%</td>
<td>6%</td>
</tr>
<tr>
<td>$A_{CP}(B \rightarrow X_s \gamma)$</td>
<td>0.058</td>
<td>0.01</td>
<td>0.005</td>
</tr>
<tr>
<td>$C_9$ from $A_{FB}(B \rightarrow K^* \ell^+ \ell^-)$</td>
<td>-</td>
<td>11%</td>
<td>4%</td>
</tr>
<tr>
<td>$C_{10}$ from $A_{FB}(B \rightarrow K^* \ell^+ \ell^-)$</td>
<td>-</td>
<td>13%</td>
<td>4%</td>
</tr>
<tr>
<td>$C_7/C_9$ from $A_{FB}(B \rightarrow K^* \ell^+ \ell^-)$</td>
<td>-</td>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>$R_K$</td>
<td></td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow K^+ \nu \nu)$</td>
<td></td>
<td>$\lesssim 3 \mathcal{B}_{SM}$</td>
<td>30%</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow K^0 \nu \nu)$</td>
<td></td>
<td>$\lesssim 40 \mathcal{B}_{SM}$</td>
<td>35%</td>
</tr>
<tr>
<td>Radiative/electroweak $b \rightarrow d$ transitions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{S}_{\tau}$</td>
<td>-</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>$\mathcal{B}(B \rightarrow X_d \gamma)$</td>
<td>-</td>
<td>24% (syst.)</td>
<td></td>
</tr>
<tr>
<td>Leptonic/semitleptonic $B$ decays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow \tau^+ \nu)$</td>
<td>3.5$\sigma$</td>
<td>10%</td>
<td>3%</td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow \mu^+ \nu)$</td>
<td></td>
<td>$\lesssim 2.4\mathcal{B}_{SM}$</td>
<td>4.3 $\text{ ab}^{-1}$ for 5$\sigma$ discovery</td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow D\tau\nu)$</td>
<td>-</td>
<td>8%</td>
<td>3%</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow D\tau\nu)$</td>
<td>-</td>
<td>30%</td>
<td>10%</td>
</tr>
<tr>
<td>LFV in $\tau$ decays (U.L. at 90% C.L.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \rightarrow \mu \gamma)$</td>
<td>45</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \rightarrow \mu \eta)$</td>
<td>65</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \rightarrow \mu \mu \mu)$</td>
<td>21</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
Precision CKM Measurements

- Comparison between
  - tree-based; $|V_{ub}| + \phi_3$
  - loop-based; $\phi_1$, $\phi_2$, $|V_{td}|$
    $\rightarrow$ NP in loop

- Belle II is unique for $|V_{cb}|$ and $|V_{ub}|$
Uniqueness of Belle II

- Fully reconstructed tags to produce “offline B meson beam”.
- Strong tool for modes with neutrinos
  \[ B \rightarrow X l \nu, X \tau \nu, \tau \nu, K^{(*)} \nu \nu . . . \]
- Excellent \( \gamma \) & \( \pi^0 \) detection capability
- \( S (K_S^0 \pi^0 \gamma) \), \( Br(X_S \gamma) \), \( A_{CP}(X_S \gamma) \)

Belle hadronic tags w/ NeuroBayes

\[ M_{bc} = \sqrt{E_{mc}^2 - \rho^2_{bc}} \]

Signal: \( \sim 135,000 \), Purity: \( \sim 26\% \)

Signal: \( \sim 68,000 \), Purity: \( \sim 26\% \)

Michael Feindt (2011)

NIM A654, 432 (2011)
**Lattice QCD and Belle II**

- Lattice QCD is important for CKM physics.

**USQCD “Lattice QCD at the Intensity Frontier”**
http://www.usqcd.org/documents/13flavor.pdf

<table>
<thead>
<tr>
<th>Quantity</th>
<th>CKM element</th>
<th>Present expt. error</th>
<th>2007 forecast lattice error</th>
<th>Present lattice error</th>
<th>2018 lattice error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_K/f_\pi$</td>
<td>$[V_{us}]$</td>
<td>0.2%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.15%</td>
</tr>
<tr>
<td>$f_{K\pi}^{-}(0)$</td>
<td>$[V_{us}]$</td>
<td>0.2%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.2%</td>
</tr>
<tr>
<td>$f_D$</td>
<td>$[V_{cd}]$</td>
<td>4.3%</td>
<td>5%</td>
<td>2%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>$f_{D_s}$</td>
<td>$[V_{cs}]$</td>
<td>2.1%</td>
<td>5%</td>
<td>2%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>$D \to \pi \ell \nu$</td>
<td>$[V_{cd}]$</td>
<td>2.6%</td>
<td>4.4%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>$D \to K \ell \nu$</td>
<td>$[V_{cs}]$</td>
<td>1.1%</td>
<td>2.5%</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>$B \to D^* \ell \nu$</td>
<td>$[V_{cb}]$</td>
<td>1.3%</td>
<td>1.8%</td>
<td>&lt; 1%</td>
<td></td>
</tr>
<tr>
<td>$B \to \pi \ell \nu$</td>
<td>$[V_{ub}]$</td>
<td>4.1%</td>
<td>8.7%</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>$f_B$</td>
<td>$[V_{ub}]$</td>
<td>9%</td>
<td>2.5%</td>
<td>&lt; 1%</td>
<td></td>
</tr>
<tr>
<td>$\xi$</td>
<td>$[V_{ts}/V_{td}]$</td>
<td>0.4%</td>
<td>2-4%</td>
<td>4%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>$\Delta M_s$</td>
<td>$[V_{ts}V_{tb}]^2$</td>
<td>0.24%</td>
<td>7-12%</td>
<td>11%</td>
<td>5%</td>
</tr>
<tr>
<td>$B_K$</td>
<td>$\text{Im}(V_{td}^2)$</td>
<td>0.5%</td>
<td>3.5-6%</td>
<td>1.3%</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

- Also for rare decay processes: ex) $B \to K^{(*)}l^+l^-$, $B \to K^* \gamma$
|V_{cb}| at present

- Exclusive |V_{cb}| (relevant to lattice QCD) comes mainly from $B^0 \rightarrow D^{*-} l^+ \nu$.
- Precision at the level of $\sim 2\%$, but slight difference from inclusive ($\sim 2\sigma$).

$$|V_{cb}|_{\text{excl}} = (39.48 \pm 0.50_{\text{exp}} \pm 0.74_{\text{th}}) \times 10^{-3}$$
$$F(1) = (0.908 \pm 0.017) [\text{arXiv:1011.2166}]$$

$$|V_{cb}|_{\text{incl}} = (41.88 \pm 0.73) \times 10^{-3}$$

W. Dungel et al. PRD 82, 112007 (2010)
New calculation of $F(1)$ by FNAL/MILC [arXiv:1403.0635]

$F(1) = 0.906 (4) (12)$

$\Rightarrow |V_{cb}| = (39.04 \pm 0.49_{\text{exp}} \pm 0.53_{\text{QCD}} \pm 0.19_{\text{QED}}) \times 10^{-3}$

Update of $|V_{cb}|$ from the $\bar{B} \to D^* \ell \bar{\nu}$ form factor at zero recoil with three-flavor lattice QCD

Jon A. Bailey,1 A. Bazavov,2 C. Bernard,3 C. M. Bouchard,4 C. DeTar,5 Daping Du,6,7 A. X. El-Khadra,6,8 J. Foley,5 E. D. Freeland,9,10 E. Gámiz,11 Steven Gottlieb,12 U. M. Heller,13 A. S. Kronfeld,8,‡ J. Laiho,14,7,‡ L. Levkova,5 P. B. Mackenzie,8 E. T. Neil,8,15 Si-Wei Qiu,5 J. Simone,8 R. Sugar,16 D. Toussaint,17 R. S. Van de Water,8 and Ran Zhou12,8

Abstract

We compute the zero-recoil form factor for the semileptonic decay $B^0 \to D^{*+} \ell^- \bar{\nu}$ (and modes related by isospin and charge conjugation) using lattice QCD with three flavors of sea quarks. We use an improved staggered action for the light valence and sea quarks (the MILC asqtad configurations), and the Fermilab action for the heavy quarks. Our calculations incorporate higher statistics, finer lattice spacings, and lighter quark masses than our 2008 work. As a byproduct of tuning the new data set, we obtain the $D_s$ and $B_s$ hyperfine splittings with few-MeV accuracy. For the zero-recoil form factor, we obtain $F(1) = 0.906(4)(12)$, where the first error is statistical and the second is the sum in quadrature of all systematic errors. With the latest HFAG average of experimental results and a cautious treatment of QED effects, we find $|V_{cb}| = (39.04 \pm 0.49_{\text{exp}} \pm 0.53_{\text{QCD}} \pm 0.19_{\text{QED}}) \times 10^{-3}$. The QCD error is now commensurate with the experimental error.

PACS numbers: 12.38.Gc, 13.20.He, 12.15.Hh
**$|V_{cb}|$ Prospect at Belle II**

- Tagged measurement of $B \rightarrow D^{*}l\nu$ and $B \rightarrow Dl\nu$ will yield $|V_{cb}|$ with a similar level of precision.
  - Require good prediction for $F(w)$ and $G(w)$
  - Fit with lattice data at different kinematic points?
- Improvement in inclusive $|V_{cb}|$ will be far modest.

**Expected relative uncertainty in $|V_{cb}|$ from $B \rightarrow D^{*}l\nu$**

<table>
<thead>
<tr>
<th></th>
<th>Statistical (reducible, irreducible)</th>
<th>Systematic (reducible, irreducible)</th>
<th>Total Exp</th>
<th>Theory</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ exclusive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>711 fb$^{-1}$</td>
<td>0.6</td>
<td>(2.8, 1.1)</td>
<td>3.1</td>
<td>1.8</td>
<td>3.6</td>
</tr>
<tr>
<td>5 ab$^{-1}$</td>
<td>0.2</td>
<td>(1.1, 1.1)</td>
<td>1.5</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>50 ab$^{-1}$</td>
<td>0.1</td>
<td>(0.3, 1.1)</td>
<td>1.2</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*Tracking eff. (statistics limited)*

*Normalization: $N(Y(4S))$, $f_{+}/f_{0}$, $B^{0}$ lifetime, $Br(D^{*}\rightarrow D^{0}\pi)$, $Br(D^{0}\rightarrow K\pi)$*
$|V_{ub}|$ at present

- $B \rightarrow \pi l\nu$ with hadronic tag

- 703/fb of Belle Y(4S) data
- Hadronic tag
- Yield extracted from $M_{\text{miss}}^2$ in 13 (7) bins of $q^2$ for $B^0 \rightarrow \pi^+ l\nu$ ($B^+ \rightarrow \pi^0 l\nu$)
- Main systematics: tag calibration

[PRD 88, 032005 (2013)]
Prospect at Belle II

- Belle II should resolve the "$|V_{ub}|$ problem".
- Precision of the tagged $B \rightarrow \pi \nu\nu$ will be similar to the untagged one.

Can LQCD extend to lower $q^2$ region?

- Inclusive $|V_{ub}|$ needs better knowledge on shape function, "cocktail" modelling of $B \rightarrow X_u \nu\nu$, and fragmentation.

| $|V_{ub}|$ exclusive (had. tagged) | Statistical | Systematic | Total | Exp | Theory | Total |
|-----------------------------------|-------------|------------|-------|-----|--------|-------|
| 711 fb$^{-1}$                     | 5.8         | (2.3, 1.0) | 6.3   | 8.7 (2.0) | 10.8 (6.6) |
| 5 ab$^{-1}$                       | 2.2         | (0.9, 1.0) | 2.6   | 4.0 (2.0) | 4.7 (3.3)  |
| 50 ab$^{-1}$                      | 0.7         | (0.3, 1.0) | 1.3   | 2.0 | 2.4    |

| $|V_{ub}|$ exclusive (untagged)    |             |            |       |     |        |       |
|-----------------------------------|-------------|------------|-------|-----|--------|-------|
| 605 fb$^{-1}$                     | 2.7         | (2.1, 0.8) | 3.5   | 8.7 (2.0) | 9.4 (4.0) |
| 5 ab$^{-1}$                       | 1.0         | (0.8, 0.8) | 1.5   | 4.0 (2.0) | 4.2 (2.5)  |
| 50 ab$^{-1}$                      | 0.3         | (0.3, 0.8) | 0.9   | 2.0 | 2.2    |

| $|V_{ub}|$ inclusive               |             |            |       |     |        |       |
|-----------------------------------|-------------|------------|-------|-----|--------|-------|
| 605 fb$^{-1}$ (old $B$ tag)       | 4.5         | (3.4, 2.3) | 6.0   | 2.5 | 6.5    |
| 5 ab$^{-1}$                       | 1.1         | (1.2, 2.3) | 2.8   | 2.5 | 3.8    |
| 50 ab$^{-1}$                      | 0.4         | (0.4, 2.3) | 2.4   | 2.5 | 3.4    |

Belle II Internal Note #0021

Theory error for Inclusive $|V_{ub}|$ uncertainty (2.5% in GGOU 4.5% in BLNP approach)
### B → τ ν

- Proceed via W-exchange, helicity suppressed.

\[
B^- \rightarrow \tau^- \nu \bar{\nu}
\]

\[
\mathcal{B}(B^- \rightarrow \ell^- \bar{\nu}) = \frac{G_F^2 m_B m^2_\ell}{8\pi} \left(1 - \frac{m^2_\ell}{m^2_B}\right)^2 \frac{f^2_B |V_{ub}|^2}{\tau_B}
\]

- Parameters
  - B decay constant: \( f_B = 191 \pm 9 \text{ MeV} \) \( \text{HPQCD, PDG2012} \)
  - CKM matrix: \( |V_{ub}| = (4.15 \pm 0.49) \times 10^{-3} \) \( b \rightarrow u \nu \), PDG2012

\[
Br_{SM}(\tau \nu) = (1.20 \pm 0.25) \times 10^{-4}
\]

\[
Br(B \rightarrow e \nu) = 10^{-11}
\]

\[
Br(B \rightarrow \mu \nu) = 10^{-7}
\]

\[
Br(B \rightarrow \tau \nu) = 10^{-4}
\]
Both Belle and BaBar provide results with hadronic and semileptonic tags.

Belle combined: $B = (0.96 \pm 0.26) \times 10^{-4}$

BaBar combined: $B = (1.79 \pm 0.48) \times 10^{-4}$

A naive world average: $B = (1.15 \pm 0.23) \times 10^{-4}$

cf) $B = (1.14 \pm 0.22) \times 10^{-4}$ [HFAG2013]
Constraint on Charged Higgs from $B \rightarrow \tau \nu$

- Assume Type-II 2HDM.

$$B(B \rightarrow \tau\nu) = B(B \rightarrow \tau\nu)_{\text{SM}} \times r_H$$

$$r_H = \left(1 - \frac{m_B^2}{m_H^2} \tan^2 \beta \right)^2$$

- Use
  - $B(B \rightarrow \tau\nu) = (1.15 \pm 0.23) \times 10^{-4}$
  - $B(B \rightarrow \tau\nu)_{\text{SM}} = (1.11 \pm 0.28) \times 10^{-4}$

where $B(B \rightarrow \tau\nu)_{\text{SM}}$ is obtained from

- $f_B = (191 \pm 9)$ MeV (HPQCD, PDG2012)
- $|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$ (PDG, PDG2012)

Stringent constraint on $\tan \beta$ and $m_H$ obtained.

Note: constraint strongly depends on $f_B$ and $|V_{ub}|$. 

Figure from Y. Horii.
Prospect at Belle II

- $7 \text{GeV } e^- \times 4 \text{GeV } e^+$,
- $L_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$,
- $L_{\text{int}} = 50 \text{ab}^{-1}$

- $B \to \tau \nu$
  - Precision $\sim$ a few %
  - Need better precision for $f_B |V_{ub}|$.

- $B \to \mu \nu, e \nu$
  - $5 \sigma$ observation expected for $B(B \to \mu \nu)_\text{SM}$ at $\sim 10 \text{ ab}^{-1}$.
  - $O(10^{-8})$ sensitivity at $50 \text{ ab}^{-1}$.
  - Interesting to compare with $B \to \tau \nu$
Prospect for D Leptonic Decays

- Important for both testing the SM and search for NP.
- Belle developed the method to tag D

<table>
<thead>
<tr>
<th>Statistical</th>
<th>Systematic</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>reducible</td>
<td>irreducible</td>
</tr>
<tr>
<td>$\mathcal{B}(D_s \to \mu\nu)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>913 fb$^{-1}$</td>
<td>5.3%</td>
<td>0%</td>
</tr>
<tr>
<td>5 ab$^{-1}$</td>
<td>2.3%</td>
<td>1.6%</td>
</tr>
<tr>
<td>50 ab$^{-1}$</td>
<td>0.7%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\mathcal{B}(D_s \to \tau\nu)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>913 fb$^{-1}$</td>
<td>3.7%</td>
<td>4.4%</td>
</tr>
<tr>
<td>5 ab$^{-1}$</td>
<td>1.6%</td>
<td>1.9%-2.3%</td>
</tr>
<tr>
<td>50 ab$^{-1}$</td>
<td>0.5%</td>
<td>0.6%-0.7%</td>
</tr>
</tbody>
</table>

Irreducible error sources
- $\text{Br}(\tau \to X)$, $\text{Br}(D_s)$, $D^0/D^+$ fraction in $c\bar{c}$ fragmentation
- Data-MC difference in $E_{ECL}$ (residual energy recorded in EM calorimeter)
Hadron Spectroscopy

- Many charmonium-like and also bottomonium-like hadrons are observed.
- Many of them do not fit to the mass spectra predicted by the quark model.

Can lattice QCD explain these states?

Ex)
Sasa Prelovsek, Luka Leskovec
arXiv:1307.5172
Replace short dipoles with longer ones (LER)

Redesign the lattices of both rings to reduce the emittance

TiN-coated beam pipe with antechambers in LER

Low emittance positrons to inject

Damping ring

Positron source

New superconducting final focusing quads near the IP

Add / modify RF systems for higher beam current

New beam pipe & bellows

Low emittance positrons to inject

Low emittance electrons to inject

\[ L = \frac{\gamma_{\pm}}{2e\varepsilon_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{I_{\pm,\mp,\gamma}}{\beta_y^*} \left( \frac{R_L}{R_y} \right) \]

x 40 Gain in Luminosity
Magnets have been installed

March 2013

D1 (Nikko-side)

D2 (Oho-side)
Belle II Detector

- Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (L1 trigger 0.5 → 30 kHz)
- Improved performance and hermeticity

CsI(Tl)
- Waveform sampling electronics,
- Pure CsI for endcaps

RPC $\mu$ & $K_L$ counter:
- Scintillator + Si-PM
  - for end-caps + inner barrel

4 layers DS Si vertex detector
- → 2 layers PXD (DEPFET),
  - + 4 layers DSSD

Central Drift Chamber:
- Smaller cell size, long lever arm

Time-of-Flight, Aerogel Cherenkov Counter →
- Time-of-Propagation (barrel), prox. focusing
- Aerogel RICH (forward)

International collaboration from: Saudi Arabia, Australia, Austria, Canada, China, Czech, Germany, India, Italy, Japan, Korea, Malaysia, Mexico, Viet Nam, Poland, Russia, Slovenia, Spain, Taiwan, Thailand, Turkey, USA, Ukraine

(Recently joined)
Belle II Progress

PXD + SVD: Beam test at DESY
- SVD real data
- Track reconstruction
- PXD and telescope extrapolation

TOP: preproduction of quartz optics

CDC: Wire stringing completed

KLM: Barrel KLM installation
# Construction & Commissioning Schedule

<table>
<thead>
<tr>
<th>Calendar</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SuperKEKBMai</strong>n Ring</td>
<td>fabrication &amp; test of components</td>
<td>installation, assembly and set-up</td>
<td>final assembly, RF-conditioning</td>
<td>QCS-L</td>
<td>QCS-R</td>
</tr>
<tr>
<td><strong>SuperKEKBDamping Ring</strong></td>
<td>fabrication &amp; test of components</td>
<td>installation, assembly and set-up</td>
<td>Phase-1</td>
<td>w/o Belle II detector</td>
<td>w/o QCS</td>
</tr>
<tr>
<td><strong>Belle II Integration</strong></td>
<td>B-KLM</td>
<td>E-KLM</td>
<td>ARICH</td>
<td>ECL</td>
<td>TOP</td>
</tr>
<tr>
<td></td>
<td>w/ Belle II detector</td>
<td>w/o QCS</td>
<td>except for VXD</td>
<td>CDC</td>
<td>VXD</td>
</tr>
</tbody>
</table>

**Legend:**
- **Phase-1**
- **Phase-2**
- **Physics Run**
Luminosity Projection

Goal of Belle II/SuperKEKB

- 50/ab around 2024
- Commissioning starts in early 2015
- Shutdown for upgrade
- Integrated luminosity (ab⁻¹)
- Peak luminosity (cm² s⁻¹)

Calendar Year
Summary

• The Belle II experiment at SuperKEKB aims to find NP with ultimate precision measurement (a few %, typically) of heavy flavor decays ($O(10^{10})$ samples / year).

• Lattice QCD provides crucial inputs to extract physics.
  • Need precise enough calculations timely!

• We will start
  • SuperKEKB commissioning in 2015
  • Belle II physics run in 2016

Let’s Keep in Touch!
Backup
SuperKEKB Accelerator

- Low emittance ("nano-beam") scheme employed proposed by P.Raimondi

Machine parameters

<table>
<thead>
<tr>
<th></th>
<th>SuperKEKB LER/HER</th>
<th>KEKB LER/HER</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(GeV)</td>
<td>4.0/7.0</td>
<td>3.5/8.0</td>
</tr>
<tr>
<td>$\varepsilon_x$ (nm)</td>
<td>3.2/4.6</td>
<td>18/24</td>
</tr>
<tr>
<td>$\beta_y$ at IP(mm)</td>
<td>0.27/0.30</td>
<td>5.9/5.9</td>
</tr>
<tr>
<td>$\beta_x$ at IP(mm)</td>
<td>32/25</td>
<td>120/120</td>
</tr>
<tr>
<td>Half crossing angle(mrad)</td>
<td>41.5</td>
<td>11</td>
</tr>
<tr>
<td>I(A)</td>
<td>3.6/2.6</td>
<td>1.6/1.2</td>
</tr>
<tr>
<td>Lifetime</td>
<td>~10min</td>
<td>130min/200min</td>
</tr>
<tr>
<td>$L$(cm$^{-2}$s$^{-1}$)</td>
<td>$80 \times 10^{34}$</td>
<td>$2.1 \times 10^{34}$</td>
</tr>
</tbody>
</table>

Beam at IP will be squeezed by 1/20.

Beam currents will be doubled.
 Charged Higgs exchange interferes with the helicity suppressed W-exchange.

\[
Br = Br_{SM} \times r_H \quad r_H = \left|1 - g_S\right|^2
\]

\[
r_H = \left(1 - \frac{m_B^2}{m_H^2} \tan^2 \beta\right)^2
\]

Type II 2HDM, W. S. Hou, PRD 48, 2342 (1993),
Belle II Collaboration

- 23 countries, 95 institutes, 599 collaborators.
- 13 Institutes / 69 members from US
- Recent new countries: Canada (4/17), Italy (9/48), Mexico (4/6)
# Systematic error for $B \rightarrow D^* \ell \nu$

**TABLE VIII:** Systematic errors on $|V_{cb}|$, with the full Belle 711 fb$^{-1}$ data sample, in percent.

| Source of Systematic Error | Error on $|V_{cb}|$ |
|----------------------------|---------------------|
| Fast track efficiency      | 2.3                 |
| Slow track efficiency      | 0.8                 |
| $\rho_{\pi_s}$ stability   | 0.1                 |
| Lepton identification      | 1.1                 |
| Norm - $D^{**}$            | 0.1                 |
| Norm - Signal Corr.        | 0.1                 |
| Norm - Uncorr              | 0.1                 |
| Norm - Fake $\ell$         | 0.0                 |
| Norm - Fake $D^*$          | 0.0                 |
| Norm - Continuum           | 0.0                 |
| $D^{**}$ composition       | 0.3                 |
| $D^{**}$ shape             | 0.1                 |
| $N(\Upsilon(4S))$          | 0.7 (0.7)           |
| $f_{+}/f_{00}$             | 0.7 (0.4)           |
| $B^0$ lifetime             | 0.3 (0.2)           |
| $B(D^* \rightarrow D^0\pi_s)$ | 0.4 (0.4)     |
| $B(D^0 \rightarrow K\pi)$  | 0.6 (0.6)           |

| Systematic Error (red., irred.) | 3.0 (2.8, 1.1) |

Belle II internal note #0021
Systematic error for $B \rightarrow \pi \ell \nu$

TABLE XI: Systematic errors on the branching fractions of $B \rightarrow \pi \ell \nu$ in hadronic tagged and untagged Belle analyses with 711 fb$^{-1}$ and 605 fb$^{-1}$ data samples, respectively. The precision limit for some systematics is given in brackets.

<table>
<thead>
<tr>
<th>Source</th>
<th>Hadronic tag Error (Limit)</th>
<th>Untagged Error (Limit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track reconstruction</td>
<td>0.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Hadron identification</td>
<td>-</td>
<td>1.3</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>1.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Kaon Veto</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Continuum description</td>
<td>1.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Tag Calibration &amp; $N(\bar{B}B)$</td>
<td>4.5 (2.0)</td>
<td>2.3 (1.0)</td>
</tr>
<tr>
<td>$X_u \ell \nu$ Cross Feed</td>
<td>0.9</td>
<td>0.5 (0.5)</td>
</tr>
<tr>
<td>$X_c \ell \nu$ Background</td>
<td>-</td>
<td>0.2 (0.2)</td>
</tr>
<tr>
<td>Form Factor Shapes(PDF)</td>
<td>1.1</td>
<td>1.0 (1.0)</td>
</tr>
<tr>
<td>Form Factor Background(PDF)</td>
<td>-</td>
<td>0.4 (0.4)</td>
</tr>
<tr>
<td>Systematic error (red., irred.)</td>
<td>5.0 (4.6, 2.0)</td>
<td>4.5 (4.2, 1.6)</td>
</tr>
</tbody>
</table>
Systematic error for $D \rightarrow l \nu, \tau \nu$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mu \nu$ [%]</th>
<th>$\tau \nu$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalization</td>
<td>±2.1</td>
<td>±2.1</td>
</tr>
<tr>
<td>Tag bias</td>
<td>±1.4</td>
<td>±1.4</td>
</tr>
<tr>
<td>Tracking</td>
<td>±0.4</td>
<td>±0.4</td>
</tr>
<tr>
<td>Particle ID</td>
<td>±2.0</td>
<td>±1.7</td>
</tr>
<tr>
<td>Efficiency</td>
<td>±1.8</td>
<td>±0.8</td>
</tr>
<tr>
<td>Fit model</td>
<td>±0.2</td>
<td>$^{+3.3}_{-2.9}$</td>
</tr>
<tr>
<td>$D_s$ background</td>
<td>±0.8</td>
<td>±2.8</td>
</tr>
<tr>
<td>$\tau$ cross-feed</td>
<td>-</td>
<td>±0.9</td>
</tr>
<tr>
<td>$B(\tau \rightarrow X)$</td>
<td>-</td>
<td>±0.2</td>
</tr>
<tr>
<td>Total syst.</td>
<td>±3.8</td>
<td>$^{+5.4}_{-5.2}$</td>
</tr>
</tbody>
</table>

TABLE XV: Summary of relative systematic uncertainties for the branching fraction measurements of leptonic $D_s$ decays from [45].
Charm Projections

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle (2014)</th>
<th>Belle II</th>
<th>$\mathcal{L}_{s}$ [ab$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(D_s \to \mu\nu)$</td>
<td>$5.31 \times 10^{-3} (1 \pm 0.053 \pm 0.038)$</td>
<td>$\pm 2.9%$</td>
<td>$\pm (0.9%-1.3%)$</td>
</tr>
<tr>
<td>$B(D_s \to \tau\nu)$</td>
<td>$5.70 \times 10^{-3} (1 \pm 0.037 \pm 0.054)$</td>
<td>$\pm (3.5%-4.3%)$</td>
<td>$\pm (2.3%-3.6%)$</td>
</tr>
<tr>
<td>$y_{CP}$ [10$^{-2}$]</td>
<td>$1.11 \pm 0.22 \pm 0.11$</td>
<td>$\pm (0.11-0.13)$</td>
<td>$\pm (0.05-0.08)$</td>
</tr>
<tr>
<td>$A_{\Gamma}$ [10$^{-2}$]</td>
<td>$-0.03 \pm 0.20 \pm 0.08$</td>
<td>$\pm 0.10$</td>
<td>$\pm (0.03-0.05)$</td>
</tr>
<tr>
<td>$A_{CP}^{K^+ K^-}$ [10$^{-2}$]</td>
<td>$-0.32 \pm 0.21 \pm 0.09$</td>
<td>$\pm 0.11$</td>
<td>$\pm 0.06$</td>
</tr>
<tr>
<td>$A_{CP}^{\pi^+ \pi^-}$ [10$^{-2}$]</td>
<td>$0.55 \pm 0.36 \pm 0.09$</td>
<td>$\pm 0.17$</td>
<td>$\pm 0.06$</td>
</tr>
<tr>
<td>$A_{CP}^{\phi \gamma}$ [10$^{-2}$]</td>
<td>$\pm 5.6$</td>
<td>$\pm 2.5$</td>
<td>$\pm 0.8$</td>
</tr>
</tbody>
</table>

- Using Belle results and a rough extrapolation to 50 ab$^{-1}$:
  - LHCb dominates $A_{\Gamma}$ and $\Delta A_{CP}$. Belle is competitive in $x'2$, $y'$ and $y_{CP}$.
- Belle II favourable in $A_{CP}$ due to symmetric D-meson production; sensitivity would reach 0.03% level.
- Rare modes: $\rho\gamma$, $\Phi\gamma$ @ 1% expectation (NP up to 10%)