Belle recent news on Flavor Physics

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on behalf of Belle collaboration

- Belle/KEKB
- UT measurements
  - Angles, |Vub|
- Belle-II/Super KEKB
- Summary
High luminosity B-Factory

• Many fruitful physics topics in High luminosity $e^+e^-$ collider
  • B-physics: CP, CKM, Rare decay (⇒ V.Gaur’s talk on PSession II-2, Today)
  • Tau physics: (⇒ D.Epifanov’s Talk on Session 11, Thursday)
  • Charm physics
  • Two photon
  • Exotic hadron, QCD, hadron fragmentation and more

• B-factory is an another frontier for NP in luminosity (⇌ in energy by LHC) and the pioneer of flavor physics
  • SM evaluation in high precision had been successfully done.
  • Search for new physics (NP) will continues.
    • Flavor and CPV scale is higher than the TeV scale?

Only limited topics covered in this talk. Sorry!
KEKB accelerator
- 3 km circumference electron-positron synchrotron.
- Peak luminosity: $2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Total integrated luminosity: $711 \text{ fb}^{-1}$ ($\Upsilon(4S)$ on resonance) $\Rightarrow 772 \text{ million } B\bar{B}$
- Energy: 3.5 GeV ($e^+$), 8.0 GeV ($e^-$) (full data)

Belle detector
Combination of particle detectors for various measurements:
- $B$ decay vertex reconstruction
- Charged particle tracking
- Particle identification
- $\gamma$/electron energy measurement
- $\mu$ identification
- Neutral meson detection
Analysis Outline

In collision of $e^+e^-$, $B\bar{B}$ meson pair is created.

- Reconstruct signal side $B$ (calculate kinematic variables: beam constraint mass, energy, momentum etc. from decay products)
  → used for signal selection

- Tag side $B$ information is also used for
  - Determine $B$ flavor if signal side has no information (ex. $B^0\rightarrow J/\psi K^0$)
  - Identify the decay modes which include neutrino by calculating “missing” variables using initial state $e^+e^-$ energy information (↔ Hadron collider)
Discovery of CP violation in the B system (2001) and a precision measurement (2012)

Significant improvements in ten years
Angles of Unitarity Triangle
($CP$ violation)
Quark mixing and CP violation

3-generation quark mixing: Cabbibo-Kobayashi-Maskawa matrix

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
= \begin{pmatrix}
1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\
-\lambda & 1-\lambda^2/2 & A\lambda^2 \\
A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

Wolfenstein representation

CP violation is induced by complex phase of CKM matrix

\[\Sigma_i V_{ij}^* V_{ik} = \delta_{jk} \Rightarrow V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \ (k = b)\]

UT angles

\[\phi_1(=\beta) = \arg(V_{cd} V_{cb}^* / V_{td} V_{tb}^*)\]
\[\phi_2(=\alpha) = \arg(V_{ud} V_{ub}^* / V_{td} V_{tb}^*)\]
\[\phi_3(=\gamma) = \arg(V_{cd} V_{cb}^* / V_{ud} V_{ub}^*)\]

Unitary triangle
Time-dependent CP violation: Quantum interference between $B^0 - \bar{B}^0$ mixing and $B^0$ decay to CP eigenstate.

\[
A_{\text{CP}}(\Delta t) = \frac{\mathcal{P}(\bar{B}^0(\Delta t) \rightarrow f_{CP}) - \mathcal{P}(B^0(\Delta t) \rightarrow f_{CP})}{\mathcal{P}(\bar{B}^0(\Delta t) \rightarrow f_{CP}) + \mathcal{P}(B^0(\Delta t) \rightarrow f_{CP})}
\]

\[
= S \sin \Delta m \Delta t + A \cos \Delta m \Delta t
\]

$S$: Mixing induced CPV parameter
$A$ ($= -C$): Direct CPV parameter
$\Delta m$: $B$-$B$ mass difference
$\Delta t$: $B$-$B$ decay time difference

Precise measurement of $\sin^2 \phi_1^{\text{eff}}$ in various modes is also a good check for NP.

$B \rightarrow DD, \phi K, K_S K^+ K^-$ ....
$\phi_1 (\beta)$ measurement

Final measurement at Belle with full data (772 million BB).

**B$^0 \to (c\bar{c})K^0_S**

<table>
<thead>
<tr>
<th>Events / 1 MeV/c$^2$</th>
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<tbody>
<tr>
<td>3000</td>
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<td>2000</td>
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Signal region of reconstructed energy

Beam constraint mass:

$$M_{bc} = \sqrt{E_{\text{beam}}^2 - P_B^2}$$

**B$^0 \to J/\psi K^0_L**

<table>
<thead>
<tr>
<th>Events / 50 MeV/c$^2$</th>
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<tbody>
<tr>
<td>5000</td>
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$\sin^2 \phi_1 = 0.676 \pm 0.026$

$A = 0.000 \pm 0.019$

Precision ~ 4%! Good reference point for other UT measurements.

$\sin^2 \phi_1 = 0.668 \pm 0.023 \pm 0.013$, $A = 0.007 \pm 0.016 \pm 0.013$

$\sin^2 \phi_1 = 0.641 \pm 0.047$, $A = 0.019 \pm 0.026$

$(c\bar{c})K^0_S, J/\psi K^0_L$ combined
The most promising mode: $B^0 \rightarrow \eta' K^0$

- Large branching fraction ($6.6 \times 10^{-5}$)
- Small contribution from other SM diagrams ($\Delta S = 0.01 \pm 0.01$)

$\sin 2\phi_1^{\text{eff}} = 0.64 \pm 0.10 \pm 0.04$

$A = 0.01 \pm 0.07 \pm 0.05$

Belle 535M BB (PRL98 031802)

Update using full data is ongoing
\[ \phi_2(\alpha) = \arg[ -V_{td} V_{tb}^* / V_{ud} V_{ub}^* ] \rightarrow b \rightarrow u \bar{u} d \]

\[ A_{CP} = \frac{\mathcal{P}(\bar{B}^0(\Delta t) \rightarrow f_{CP}) - \mathcal{P}(\bar{B}^0(\Delta t) \rightarrow f_{CP})}{\mathcal{P}(\bar{B}^0(\Delta t) \rightarrow f_{CP}) + \mathcal{P}(\bar{B}^0(\Delta t) \rightarrow f_{CP})} \]

\[ = S \sin \Delta m \Delta t \quad + \quad A \cos \Delta m \Delta t \]

mixing induced CPV  

direct CPV

where \( S = -\xi_f (1-A^2) \sin 2 \phi_2^{\text{eff}} \)

\( \xi_f: CP \) eigenvalue

\( \Delta m: B-\bar{B} \) mass difference

\( \Delta t: B-\bar{B} \) decay time difference

\[ \phi_2^{\text{eff}} = \phi_2 - \Delta \phi_2 \] ("effective" \( \phi_2 \))

To distinguish penguin contamination, isospin relations between \( B \rightarrow \pi^i \pi^j / \rho^i \rho^j \) \((i, j = 0, +, -)\) decay amplitudes is used. (Gronau and London, PRL65 3381)

\[ A^{+0} = \frac{1}{\sqrt{2}} A^{+-} + A^{00} \]

\[ \bar{A}^{-0} = \frac{1}{\sqrt{2}} \bar{A}^{+-} + \bar{A}^{00} \]

\( A^{ij} : \) Decay amplitude of \( B \rightarrow \pi^i \pi^j / \rho^i \rho^j \)

\[ \Rightarrow \Delta \phi_2 \] is determined with four-fold ambiguity.
$B^0 \rightarrow \pi^+ \pi^-$

Measurement with Belle full data (772 million $B\bar{B}$).

Signal yield = $2886 \pm 82$

Clear mixing induced CP violation and presence of penguin

$S = -0.64 \pm 0.08 \pm 0.03$
$A = 0.33 \pm 0.06 \pm 0.03$

PRD 87, 031103(R) (2013).

Added as information for $\phi_2$ constraint

$\phi_2 = [85.0^{\circ}, 148.0^{\circ}]$
(Belle $B \rightarrow \pi\pi$ isospin analysis)
**$\phi_2(\alpha)$ results:** $\pi\pi, \rho\pi, \rho\rho :$ results just before

\[ B \rightarrow \pi\pi \]

\[ B \rightarrow \rho\pi \]

\[ B \rightarrow \rho\rho \]

\[ 88.7^\circ \pm 4.4^\circ \]
**φ₃ (γ) measurement**

Most difficult to measure experimentally….
Measurements from direct CPV using interference between $V_{ub}$ contribution and another weak vertex.

Relative phase of $B^± → DK^±$

\[ |\tilde{D}> = |D^0> + re^{iθ}|\bar{D}^0> \]

\[ θ = ± φ₃ + δ \]

(weak phase) + (strong phase)

$D$ final states

- $K_s π^+ π^− + K^−$ GGSZ
- $(K^+ K^-)$ or $K_s π^0$ + $K^−$ GLW
- $(K^+ π^-)$ + $K^−$ ADS

Several decays modes of $D$ meson are used to determine $φ₃$
Measurement of $\phi_3$ with GGSZ

Dalitz plot analysis using $D \to K_{S}^{0} \pi^{+} \pi^{-}$ 3-body decay gives strong constraint on $\phi_3$.


\[ d\sigma_{\pm}(m_{+}^{2}, m_{-}^{2}) \sim |M_{\pm}|^{2} dm_{+}^{2} dm_{-}^{2} \]

\[ |M_{\pm}(m_{+}^{2}, m_{-}^{2})|^{2} = |f_{D}(m_{+}^{2}, m_{-}^{2}) + re^{i\delta_{B} \pm i\phi_{3}} f_{D}(m_{-}^{2}, m_{+}^{2})|^{2} \]

\[ m_{+}^{2} = m_{K_{S}^{0} \pi^{+}}^{2}, \quad m_{-}^{2} = m_{K_{S}^{0} \pi^{-}}^{2} \]

$D^{0} \to K_{S}^{0} \pi^{+} \pi^{-}$ amplitude $f_{D}$: fit to flavor-tagged $D^{*} \to D^{0} \pi$ sample. (Phase term is based on model assumption)

Binned Dalitz plot analysis: Model independent

→ estimated from quantum correlations between $D^{0}$ and $D^{0}$ in $\psi(3770) \to D^{0}D^{0}$ decays
CLEOc collaboration, PRD 82, 112006 (2010)
⇒ No model uncertainty

Fit simultaneously $x_{\pm} = r_{B} \cos(\delta_{B} \pm \gamma)$, $y_{\pm} = r_{B} \sin(\delta_{B} \pm \gamma)$
Measurement of $\phi_3$ with GGSZ

Parameterized by model

$$\phi_3 = (78^{+11}_{-12} \pm 4 \pm 9)^\circ$$

657 MBB, PRD 81, 112002(2010)

- Statistical error is dominated
- 3rd errors are came from Dalitz model and uncertainty from binned data
  → improved by charm-factory results (BES-III)

Binned. Model independent

$$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$$

772MBB, PRD 85, 112014(2012)

$\phi_3 = (67 \pm 11)^\circ$  BaBar/Belle combined
$V_{ub}$

$B \rightarrow ul \nu, \tau \nu, D^{(*)} \tau \nu,$
$|V_{ub}|$ from Semi-leptonic B decays

$|V_{ub}|$ is extracted from differential decay rate of exclusive analysis.

$$
\frac{d\Gamma(B \rightarrow \pi\ell^+\nu_\ell)}{dq^2} = \frac{G_F^2|V_{ub}|^2}{24\pi^3}|p_\pi|^3|f_+(q^2)|^2
$$

Here, form factor $f_+(q^2)$ is input from theory.

Signal event is extracted by calculating missing mass (= neutrino mass) from all observable in event.

$$
B(B^0 \rightarrow \pi^-\ell^+\nu) = (1.49\pm0.09\pm0.07) \times 10^{-4}
$$

$$
B(B^+ \rightarrow \pi^0\ell^+\nu) = (0.80\pm0.08\pm0.04) \times 10^{-4}
$$
Errors are dominated by theoretical uncertainty.
\[ B \rightarrow \tau \nu \]

- **Standard Model (SM)**

\[
\mathcal{B}(B \rightarrow \ell\nu) = \frac{G_F^2m_B}{8\pi}m_\ell^2(1 - \frac{m_\ell^2}{m_B^2})^2f_B^2|V_{ub}|^2\tau_B
\]

- **New Physics**

\[
\mathcal{B}(B^- \rightarrow \tau^-\nu) = \mathcal{B}_{SM}(B^- \rightarrow \tau^-\nu)\left[1 - \frac{m_B^2}{m_{H\pm}^2}\tan^2\beta\right]^2
\]

\[(1.01 \pm 0.29) \times 10^{-4}\]

Mainly from theoretical ambiguities of \(|V_{ub}|\) and \(f_B\)

→ Indirect search for charged Higgs by measuring branching fraction.

\[ B \rightarrow \tau \nu_\tau \]

\[ \rightarrow l \nu_\tau \nu_l \]

\[ \pi \nu_\tau \]

At least 2 missing particle in final state of signal side.

→ Companion \( B \) is fully reconstructed using hadronic decay modes to "tag" decay products of signal \( B \).

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Beam constrained mass \( M_{bc} \)
is calculated from measured \( B \) momentum and beam energy.
- No particle other than that from signal and tag-side $B$ decay is required.
- Most powerful discriminant variable is total energy observed in calorimeter which does not associate with any charged tracks and photons: $E_{ECL}$.

$\rightarrow$ signal events concentrate in 0.
- Missing mass $M_{\text{miss}} \neq 0$ ($\geq 2$ neutrinos)

\[
B(B \rightarrow \tau \nu) = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}
\]

(3.0\sigma significance)

Combined result with Belle result using partially reconstructed semi-leptonic $B$ decay for tag side (PRD 82, 071101 (R) (2010)):

\[
B(B \rightarrow \tau \nu) = (0.96 \pm 0.22 \pm 0.13) \times 10^{-4}
\]
$f_B$ and $|V_{ub}|$ from leptonic decays
Limits for Type-II 2HDM

Hadronic tag

Semileptonic tag

\[ B = [0.72^{+0.27}_{-0.25} \text{(stat)} \pm 0.11 \text{(syst)}] \times 10^{-4} \]
\[ B = [1.83^{+0.53}_{-0.49} \text{(stat)} \pm 0.24 \text{(syst)}] \times 10^{-4} \]

Belle combined: \( B = (0.96 \pm 0.26) \times 10^{-4} \)
BaBar combined: \( B = (1.79 \pm 0.48) \times 10^{-4} \)

Almost full data Analysis result of B-factories

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

\[ \tan \beta / m_H < 0.3 \text{ region is preferred.} \]
What next?

- Need more data!
  - Not only to reduce statistic error. To challenge various ideas.
- In Belle II/Super KEKB
  - 40 times more luminosity, \(8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}\)
  - 50 ab\(^{-1}\) within the next decades

BaBar+Belle = 1.1ab\(^{-1}\)@Y(4S)
1.5ab\(^{-1}\)@Y(1\text{~4S})
KEKB to SuperKEKB

- Replace short dipoles with longer ones (LER)
- Redesign the lattices of HER & LER to squeeze the emittance
- TiN-coated beam pipe with antechambers
- Damping ring
- New positron target / capture section
- New superconducting /permanent final focusing quads near the IP

To obtain x40 higher luminosity
KEKB to SuperKEKB

Installation of 100 new LER bending magnets done

carry on an air-pallet

carry over existing HER dipole

DR under construction on 18/Dec/2012

SuperKEKB Status, 7th BPAC, Mar. 11, 2013, K. Akai

Add / modify RF systems for higher beam current

Low emittance positrons to inject ring

New positron target / capture section

Low emittance gun

Low emittance electrons to inject

To obtain x40 higher luminosity
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 ($b \rightarrow s\mu\mu$), hermeticity ($\nu$ reco.)
Stringing of 70 k wires in clean room in progress. 1 year of tough work…
Summary

- Belle has achieved the exhaustive tests of the Standard Model and shaped Flavor Physics.
  - Measured Unitary Triangle components in high precision.
  - As of now, results show excellent agreement. But still 10~20% NP is allowed.

- Belle-II/SuperKEKB: Construction in Progress
  - L x40 is planning to start physics run in 2016. Study of Flavor physics is crucial for NP search.

- Complementary to LHC(b).
  - B factory has advantage at mode which includes $\pi^0$ and $\nu$. 