The Physics of the B Factories

BaBar and Belle Collab., Eur. Phys. J. C (2014) 74: 3026

published in Nov. 19th, 2014

Yusuke Namekawa for journal club

Contents

1 Introduction

A summary review "book" of B factories(BaBar and Belle) is published.

- 928 pages
- 2000 authors from 200 institutes
  - ◇ It has submitted to arXiv, only in PDF (no source is available, probably due to too large size, 32 MByte in PDF).

[Contents of the review book]

- The facilities
- Tools and methods
- The results and their interpretation
  - ◇ The CKM matrix and the Kobayashi-Maskawa mechanism
  - ◇ B physics
  - ◇ Quarkonium physics
  - ◇ Charm physics
  - ◇ Tau physics
  - ◇ Initial state radiation studies
  - ◇ Two-photon physics
  - ◇ B_s^0 physics at $\Upsilon(5S)$
  - ◇ QCD-related physics
  - ◇ Global interpretation

[Cabbibo-Kobayashi-Maskawa matrix]
The principal target of B factories is to establish CP violation in B meson system, which is characterized by non-trivial phase $\delta_{\rm KM}$ in CKM matrix.

“ CP Violation in the Renormalizable Theory of Weak Interaction ” .

M.Kobayashi and T.Maskawa, Prog. Theor. Phys. 49, 652657 (1973)

- #citations = 7923

$$V_{\rm CKM} := \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{\rm CKM}^{\rm Original} := \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta_{\rm KM}} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta_{\rm KM}} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta_{\rm KM}} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta_{\rm KM}} \end{pmatrix} \quad \text{not } s_3$$

where $s_i := \sin\theta_i, c_i := \cos\theta_i$

[CKM matrix(continued)]

- Parameterization of CKM matrix depends on the phase convention.
- PDG standard is chosen so that $s_{ij}, c_{ij} > 0$.

$$V_{\mathrm{CKM}} := \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{\mathrm{CKM}}^{\mathrm{PDG}} := \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

$$V_{\mathrm{CKM}}^{\mathrm{Original}} := \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\delta_{\mathrm{KM}}} & c_1c_2s_3 + s_2c_3e^{i\delta_{\mathrm{KM}}} \\ s_1s_2 & c_1s_2c_3 + c_2s_3e^{i\delta_{\mathrm{KM}}} & c_1s_2s_3 - c_2c_3e^{i\delta_{\mathrm{KM}}} \end{pmatrix} \quad \text{not } s_3$$

where $s_{ij} := \sin\theta_{ij}, c_{ij} := \cos\theta_{ij}$

[CKM matrix(continued)]

- (Parameterization of CKM matrix depends on the phase convention.)
- Angles of the unitarity triangle are often used, phase convention free.

$$
\begin{aligned}
V_{\mathrm{CKM}} &:= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\
\beta &= \phi_1 := \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \\
\alpha &= \phi_2 := \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \\
\gamma &= \phi_3 := \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)
\end{aligned}
$$

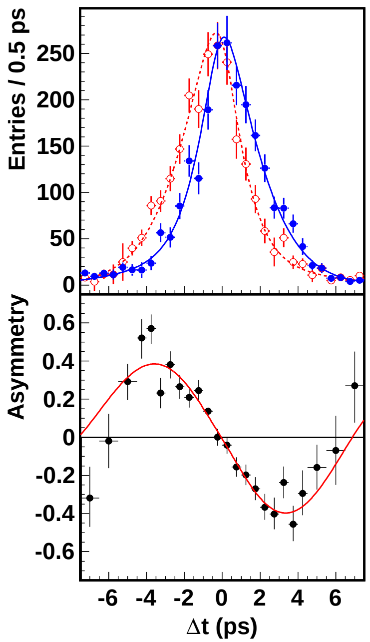
- BaBar naming: α, β, γ
- Belle naming: ϕ_2, ϕ_1, ϕ_3

2 ϕ_1 from B factories

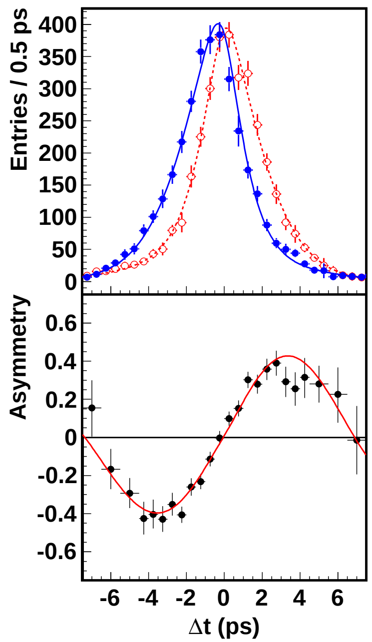
Non-zero value of $\phi_1 := \arg(-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*))$ is obtained by B factories.
$\rightarrow$ It leads to Nobel prize of Kobayashi-san and Maskawa-san.

- Asymmetry $A(\Delta t)$ (defined in the next slide) relates to ϕ_1 s.t.
  $A(\Delta t) = \mp C^1_{\text{known}} \sin 2\phi_1 \sin(C^2_{\text{known}} \times \Delta t)$ for CP$= \pm$ Bigi and Sanda,1981

CP = +



CP = -



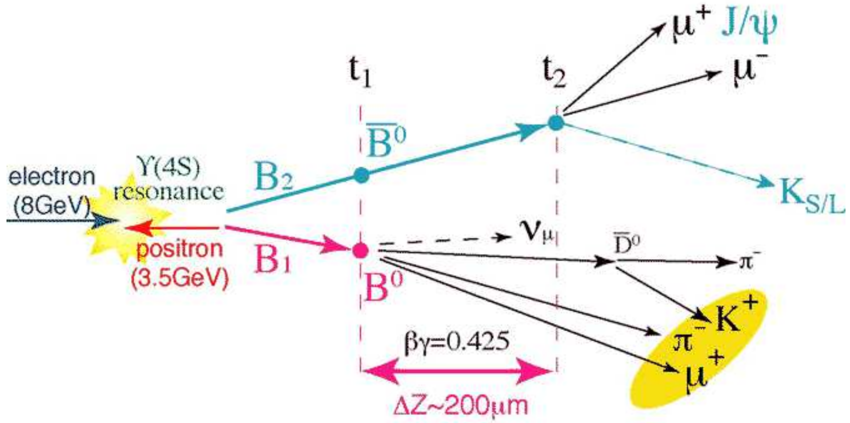
[ϕ_1 from B factories(continued)]

$$A(\Delta t) := \frac{\Gamma_+(\Delta t) - \Gamma_-(\Delta t)}{\Gamma_+(\Delta t) + \Gamma_-(\Delta t)}$$

$$\Gamma_+ := \Gamma(B^0 \to f_{CP}) \quad : \text{decay rate to final CP eigenstate } f_{CP}$$

$$\Gamma_- := \Gamma(\bar{B}^0 \to f_{CP})$$

$$\Delta t := \text{decay time difference between } B^0 \text{ and } \bar{B}^0$$



[ϕ_1 from B factories(continued)]

- $\sin 2\phi_1$ deviates from 0, confirming CP-violation in CKM matrix.
- Results of BaBar and Belle agree with each other.

	$\sin 2\phi_1$ (final)
BaBar	0.687(28)(12)
Belle	0.667(23)(12)

cf.	$\sin 2\phi_1$ (in 2000)
BaBar	0.12(37)(9)
Belle	0.45(44)(9)

3 $|V_{ub}|, |V_{cb}|$ from B factories

$|V_{ub}|, |V_{cb}|$ are determined by semileptonic decay rates from experiments, combined with form factors from lattice QCD.

$$(\text{Decay rate})_{\text{exp}} = \text{const } (\text{Form factor})_{\text{LQCD}} |V_{\text{CKM}}|^2$$

- There are deviations of $|V_{\text{CKM}}|$ in decay channels
  - ◇ $|V_{ub}|_{\text{exclusive}}$ differs from $|V_{ub}|_{\text{inclusive}}$ by 3 σ in experimental error, not including lattice QCD error
  - ◇ $|V_{cb}|_{\text{exclusive}}$ differs from $|V_{cb}|_{\text{inclusive}}$ by 2.5 σ in exp error

$|V_{ub}|_{\text{exclusive}}(B \to \pi l \nu_l)$	$3.23(55)_{\text{exp}}(73)_{\text{LQCD}} \times 10^{-3}$
$|V_{ub}|_{\text{inclusive}}(B \to X_u l \nu_l)$	$4.42(20)_{\text{exp}}(15)_{\text{LQCD}} \times 10^{-3}$

4 Exotic charmonium-like states

Another important discovery in B factories is exotic states, such as $Z(4430)^+$.

Exotic states := States that are hard to be explained by constituent quarks

- (Constituent quark has been successful in light hadron spectroscopy.)
- New charmed and bottomed hadrons are found in B factories.
  $\leftarrow$ These states are hard to be explained in constituent quark model!

$[X(3872)]$ Fermilab,1994; Belle,2003; CDF,2004; BaBar,2005; LHCb,2012; BES III,2014

- $M_{X(3872)} = 3871.7(2)$ MeV (close to $D\bar{D}$ threshold 3871.8(3) MeV)
- $J^{PC} = 1^{++}$, established by LHCb in 2013
- Very narrow width $\Gamma_{X(3872)} < 2.3$ MeV
- (Fermilab E705 had discovered $X(3872)$ in 1994, before Belle in 2003.)

◇ Constituent quark model failed to predict $X(3872)$
$\leftarrow$ This is the reason why it is named as X.

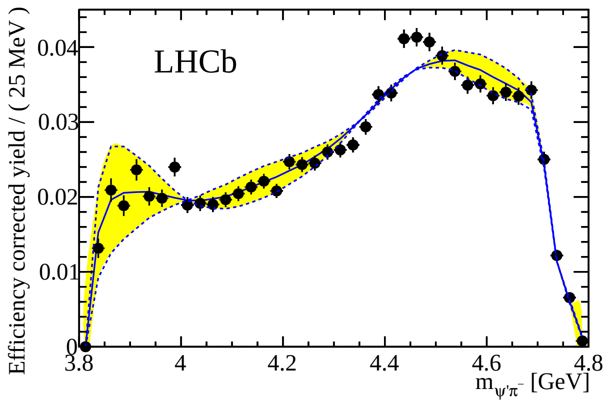
◇ Lattice QCD provided a signal corresponding to $X(3872)$.
Prelovsek and Leskovec, 2013

$E_n(J^{PC} = 1^{++})$	Experiment [GeV]	Constituent quark [GeV]
$E_0(\chi_{c1})$	3.51	3.51
$E_1(X(3872))$	3.87	3.95

[$Z(4430)^+$] Belle,2008; LHCb,2014

- $M_{Z(4430)^+} = 4475(7)(25)$ MeV, $J^{PC} = 1^{+-}$, $\Gamma_{Z(4430)^+} = 172(13)(37)$ MeV
- $Z(4430)^+$ is exotic. $Z(4430)^+$ needs four quarks($c\bar{c}u\bar{d}$), instead of $c\bar{c}$.
  - ◇ $Z(4430)^+$ is discovered by Belle in 2008, but is not confirmed (nor excluded) by BaBar.
    $\leftarrow$ LHCb found $Z(4430)^+$ with 13.9 σ in 2014.
  - ◇ Lattice QCD found no signal for $Z(4430)^+$

    cf. Ishizuka-san's journal club in 2014



5 Conclusion

Main results by B factories are presented.

- BaBar and Belle established CP violation in B meson system, which is originated by CKM matrix.
  $\rightarrow$ Nobel prize of Kobayashi-san and Maskawa-san
- $|V_{ub}|, |V_{cb}|$ are determined, although $|V_{ub,cb}|_{\text{exclusive}}$ differs from $|V_{ub,cb}|_{\text{inclusive}}$ by $2.5 - 3\sigma$ in experimental errors.
  $\rightarrow$ More precise form factor by lattice QCD is required.
- B factories found exotic states, such as $X(3872), Z(4430)^+$.
  - ◇ $X(3872)$ is rediscovered by Belle in 2003.
    $\rightarrow$ Other experiments as well as lattice QCD support $X(3872)$.
  - ◇ $Z(4430)^+$ is found by Belle in 2008.
    $\rightarrow$ $Z(4430)^+$ is confirmed by LHCb with 13.9σ in 2014, but has not been reproduced by lattice QCD.