

Indirect CP -violation at Belle





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INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK (IEKP)



Measurements

-  **Search for time-dependent CPT -violation**
Combination of multiple decay channels
-  **Precise measurement of time-dependent CP -violation in $B^0 \rightarrow (c\bar{c})K^0$ decays**
“Golden channel“ of time-dependent CP -violation
-  **Studies of $B^0 \rightarrow D^{(*)+}D^{(*)-}$ decays**
Measurement of the branching fractions and CP -violation of three different decay channels
-  **Measurement of CP -violation at the $\Upsilon(5S)$ resonance**
Measurement of $\sin 2\phi_1$ with new tagging method

CP - and CPT -violation in the B_d system

General PDF to describe the decay of a neutral B meson:

$$\mathcal{P}(\Delta t) = \frac{1}{2\tau_{B_d}} e^{-|\Delta t|/\tau_{B_d}} \left[\frac{|\eta_+|^2 + |\eta_-|^2}{2} \cosh\left(\frac{\Delta\Gamma_d}{2}\Delta t\right) - \text{Re}(\eta_+^* \eta_-) \sinh\left(\frac{\Delta\Gamma_d}{2}\Delta t\right) + \frac{|\eta_+|^2 - |\eta_-|^2}{2} \cos(\Delta m \Delta t) + \text{Im}(\eta_+^* \eta_-) \sin(\Delta m \Delta t) \right],$$

where

z describes CPT violation

$$\eta_+ = A_1 \bar{A}_2 - \bar{A}_1 A_2$$

$$\eta_- = \sqrt{1 - z^2} \left(\frac{p}{q} A_1 A_2 - \frac{q}{p} \bar{A}_1 \bar{A}_2 \right) + z (A_1 \bar{A}_2 + \bar{A}_1 A_2)$$

$$\downarrow \begin{cases} - \text{No } CPT\text{-violation} \rightarrow z = 0 \\ - \Delta\Gamma_d \approx 0 \\ - \left| \frac{q}{p} \right| \approx 1 \end{cases}$$

$$\mathcal{P}(\Delta t) = \frac{1}{4\tau_{B_d}} e^{-|\Delta t|/\tau_{B_d}} \{1 \pm [S \sin(\Delta m \Delta t) + \mathcal{A} \cos(\Delta m \Delta t)]\},$$

where

S is related to mixing-induced CP -violation

\mathcal{A} is related to direct CP -violation

Measurement of CPT violation

Data sample of 535×10^6 $B\bar{B}$ pairs

Decay modes:

B decay mode	N_{ev}	Purity (%)	Sensitivity
$J/\psi K_S$	7713	97.0	Mainly $\mathcal{R}e(z)$ and $\Delta\Gamma_d$
$J/\psi K_L$	10966	59.2	
$D^- \pi^+$	39366	83.2	Mainly $\mathcal{I}m(z)$ and flavor tagging quality
$D^{*-} \pi^+$	46292	81.5	
$D^{*-} \rho^+$	45913	66.3	
$D^{*-} \ell^+ \nu_\ell$	383818	75.2	
$J/\psi K^+$	32150	97.3	Resolution parameters
$\bar{D}^0 \pi^+$	216605	63.9	

Fit parameters

include eight physics parameters,
with three of them being

$\mathcal{R}e(z)$

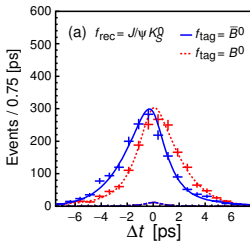
$\mathcal{I}m(z)$

$\Delta\Gamma_d$

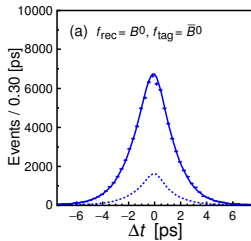
⇒ Calibration of flavor tagging and
resolution parameters is performed
simultaneously on real data

Measurement of CPT violation

$$B^0 \rightarrow J/\psi K_S$$

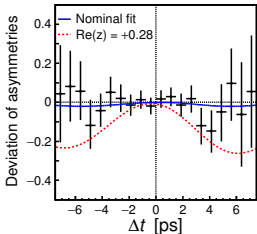


$$B^0 \rightarrow \text{flavor specific}$$

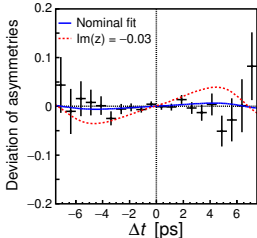


Illustration

(a) $B^0 \rightarrow J/\psi K_S^0$ decay



(c) Flavor-specific B decays



$$\begin{aligned} \text{Re}(z) &= (1.9 \pm 3.7 \pm 3.3) \cdot 10^{-2} \\ \text{Im}(z) &= (-5.7 \pm 3.3 \pm 3.3) \cdot 10^{-3} \\ \Delta\Gamma_d/\Gamma_d &= (-1.7 \pm 1.8 \pm 1.1) \cdot 10^{-2} \end{aligned}$$

$$\tau_{B^0} = 1.531 \pm 0.004 \text{ ps}$$

$$\tau_{B^+} = 1.640 \pm 0.006 \text{ ps}$$

$$\Delta m_d = 0.506 \pm 0.003 \text{ ps}^{-1}$$

$$\lambda_{CP} - 1 = (1.1 \pm 0.38) \cdot 10^{-3}$$

$$\arg(\eta_{CP} \lambda_{CP}) = -0.700 \pm 0.042$$

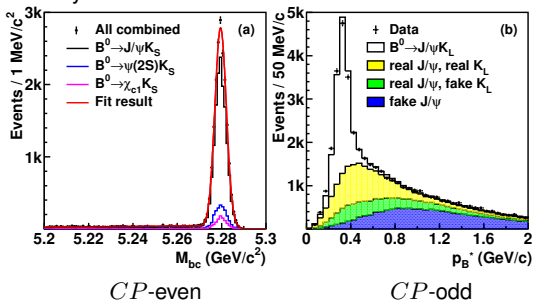
PRD 85, 071105(R) (2012)

$$\lambda_{CP} = \frac{q}{p} \frac{A_{\bar{B}^0 \rightarrow f_{CP}}}{A_{B^0 \rightarrow f_{CP}}}$$

CP violation in $B^0 \rightarrow (c\bar{c})K^0$ decays

Final Belle data sample of $772 \times 10^6 B\bar{B}$ pairs

Reconstruction in 5 decay modes:



Decay mode	N_{sig}	Purity (%)
$J/\psi K_S^0$	12649 ± 114	97
$\psi(2S)(\ell^+\ell^-)K_S^0$	904 ± 31	92
$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0$	1067 ± 33	90
$\chi_{c1}K_S^0$	940 ± 33	86
$J/\psi K_L^0$	10040 ± 154	63

CP violation in $B^0 \rightarrow (c\bar{c})K^0$ decays

Extraction of CP parameters:

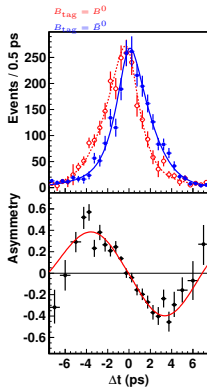
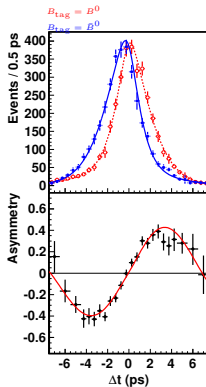
Combination of all decay channels

$$S = 0.667 \pm 0.023 \pm 0.012$$

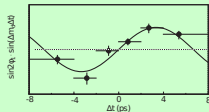
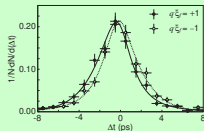
$$\mathcal{A} = 0.005 \pm 0.016 \pm 0.012$$

SM expectation: $S = \sin 2\phi_1$ and $\mathcal{A} = 0$

PRL 108, 171802 (2012)



Comparison: First observation of CP violation in the neutral B system (2001)

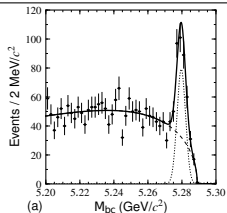


CP -violation in double charm decays

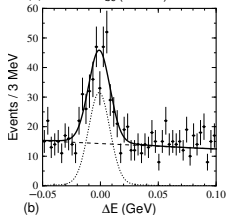
Final Belle data sample of $772 \times 10^6 B\bar{B}$ pairs

$$B^0 \rightarrow D^+ D^-$$

Showed huge direct CP -violation



(a)

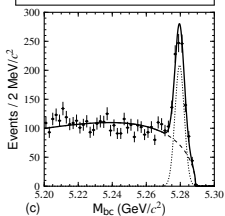


(b)

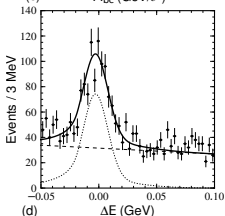
$$N_{\text{sig}} = 269 \pm 21$$

$$B^0 \rightarrow D^{*+} D^{\mp}$$

No CP -eigenstate



(c)

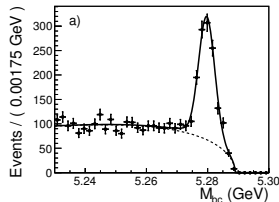


(d)

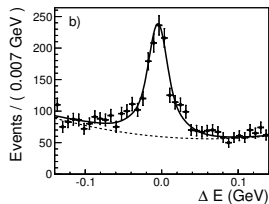
$$N_{\text{sig}} = 887 \pm 39$$

$$B^0 \rightarrow D^{*+} D^{*-}$$

Admixture of CP -eigenstates



a)



b)

$$N_{\text{sig}} = 1225 \pm 59$$

CP -violation in double charm decays

PDF for $B^0 \rightarrow D^{*\pm} D^\mp$ decays

Final state is no CP -eigenstate, but

$$\left. \begin{array}{l} B^0 \rightarrow D^{*+} D^- \\ \bar{B}^0 \rightarrow D^{*+} D^- \\ B^0 \rightarrow D^{*-} D^+ \\ \bar{B}^0 \rightarrow D^{*-} D^+ \end{array} \right\} \mathcal{P}_{D^{*\pm} D^\mp}(\Delta t) = (1 \pm A) \frac{1}{4\tau_{B_d}} e^{-|\Delta t|/\tau_{B_d}} \times \{1 \pm [(\mathcal{S} \pm \Delta\mathcal{S}) \sin(\Delta m \Delta t) + (\mathcal{A} \pm \Delta\mathcal{A}) \cos(\Delta m \Delta t)]\}$$

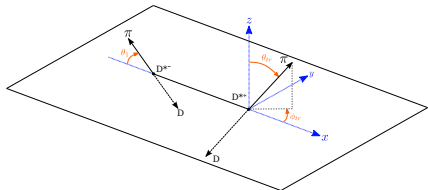
A is related to the asymmetry between $D^{*+} D^-$ and $D^{*-} D^+$

$\Delta\mathcal{S}$ is related to the asymmetry in \mathcal{S} between the two

$\Delta\mathcal{A}$ is related to the asymmetry in \mathcal{A} between the two

CP -violation in double charm decays

Angular Analysis of $B^0 \rightarrow D^{*+} D^{*-}$ decays

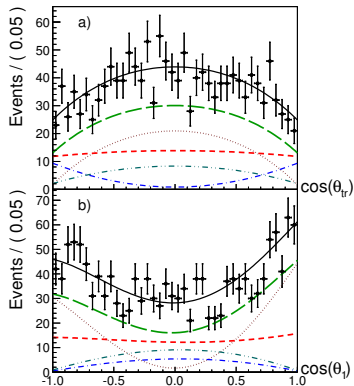


Decay rate:

$$\frac{1}{\Gamma} \frac{d^2\Gamma(B^0 \rightarrow D^{*+} D^{*-})}{d \cos \theta_{tr} d \cos \theta_1} = \frac{9}{16} \sum_{i=0,\pm,||} R_i H_i(\cos \theta_{tr}, \cos \theta_1)$$

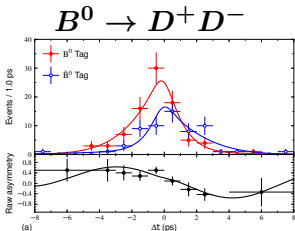
$$R_0 = 0.62 \pm 0.03 \pm 0.01$$

$$R_{\perp} = 0.14 \pm 0.02 \pm 0.01$$



Blue/ R_{\perp} : CP -odd component

CP -violation in double charm decays



$$S = -1.06^{+0.21}_{-0.14} \pm 0.08$$

$$\mathcal{A} = 0.43 \pm 0.16 \pm 0.05$$

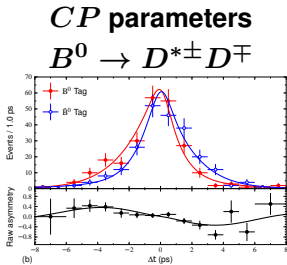
Significance: 4.2σ

PRD 85, 091106(R) (2012)

Previous measurement:

$$S = -1.13 \pm 0.37 \pm 0.09$$

$$\mathcal{A} = 0.91 \pm 0.23 \pm 0.06$$



$$S = -0.78 \pm 0.15 \pm 0.05$$

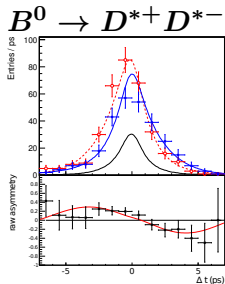
$$\mathcal{A} = 0.01 \pm 0.11 \pm 0.04$$

$$A = 0.06 \pm 0.05 \pm 0.02$$

$$\Delta S = -0.13 \pm 0.15 \pm 0.04$$

$$\Delta \mathcal{A} = 0.12 \pm 0.11 \pm 0.03$$

Significance: 4.0σ



$$S = -0.79 \pm 0.13 \pm 0.03$$

$$\mathcal{A} = 0.15 \pm 0.08 \pm 0.02$$

Significance: 5.4σ

\Rightarrow First observation of CP -violation

CP -violation in double charm decays

Additional: CP -mode separated values of S and \mathcal{A} for $B^0 \rightarrow D^{*+} D^{*-}$

Nominal measurement:

Assumption of the same relative penguin contribution to all components.

Releasing that assumption:

$$\mathcal{P}_{B^0}(\Delta t) = \frac{1}{4\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} \left(1 + ((P_{\text{even}}\mathcal{S}_+ - P_{\text{odd}}\mathcal{S}_\perp) \sin(\Delta m\Delta t) + (P_{\text{even}}\mathcal{A}_+ + P_{\text{odd}}\mathcal{A}_\perp) \cos(\Delta m\Delta t)) \right)$$

$$\mathcal{S}_+ = -0.81 \pm 0.13 \pm 0.03$$

$$\mathcal{A}_+ = 0.18 \pm 0.10 \pm 0.02$$

$$\mathcal{S}_\perp = -1.52 \pm 0.62 \pm 0.03$$

$$\mathcal{A}_\perp = -0.05 \pm 0.39 \pm 0.02$$

SM expectation:

$$\mathcal{S}_+ = \mathcal{S}_\perp = -\sin 2\phi_1$$

$$\mathcal{A}_+ = \mathcal{A}_\perp = 0$$

Belle preliminary

Measurement of $\sin 2\phi_1$ in $\Upsilon(5S)$ decays

Final $\Upsilon(5S)$ Belle data sample of $121 fb^{-1}$

Measurement of $\sin 2\phi_1$ with new tagging method: " $B\pi$ " tagging.

$$\left. \begin{array}{l} \Upsilon(5S) \rightarrow \bar{B}^{(*)0} B^{(*)+} \pi^- \\ \Upsilon(5S) \rightarrow B^{(*)0} B^{(*)-} \pi^+ \end{array} \right\} \text{Charge of } \pi \text{ is known} \Rightarrow \text{Flavor of } B^0 \text{ is known}$$

$$\begin{aligned} \text{Measured: } A_{BB\pi} &= \frac{N_{BB\pi^-} - N_{BB\pi^+}}{N_{BB\pi^-} + N_{BB\pi^+}} \\ &= \frac{\mathcal{S}x + \mathcal{A}}{1 + x^2}, \end{aligned}$$

where $x = \Delta m_d / \Gamma_d$

Time integrated observable, no measurement of Δt necessary

Measurement of $\sin 2\phi_1$ in $\Upsilon(5S)$ decays

$\Upsilon(5S)$

$\bar{B}^{(*)0}$

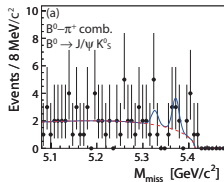
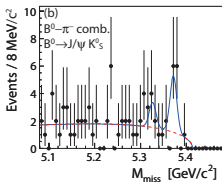
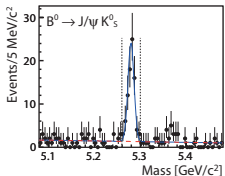
Reconstructed in
 $B^0 \rightarrow J/\psi K_S$

$B^{(*)+}$

Inclusively reconstructed
via M_{miss}

π^-

PRL 108, 171801 (2012)



$$N_{BB\pi^+} = 7.8 \pm 3.9$$

$$N_{BB\pi^-} = 13.7 \pm 5.3$$

$$\mathcal{A} = 0$$

$$\sin 2\phi_1 = 0.57 \pm 0.58 \pm 0.06$$

Conclusion

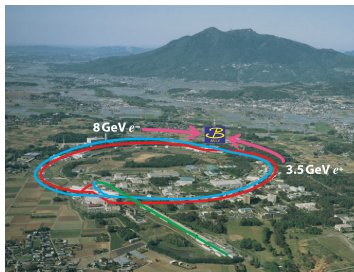
Six measurements have been presented, (nearly) all of them using the final Belle data sample:

- Simultaneous measurement of CPT -violation in eight decay channels
- Most precise measurement of $\sin 2\phi_1$
- CP -violation in three double charm decays, all of them clearly showing CP -violation
- Measurement of $\sin 2\phi_1$ with a new tagging-method

Backup: The KEKB accelerator and the Belle detector

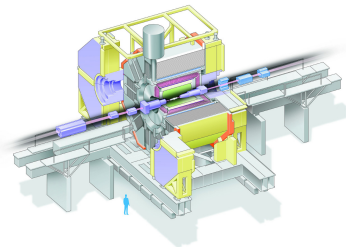
The KEKB accelerator

- Asymmetric e^+e^- collider
- Mainly operates at the $\Upsilon(4S)$ resonance



The Belle detector

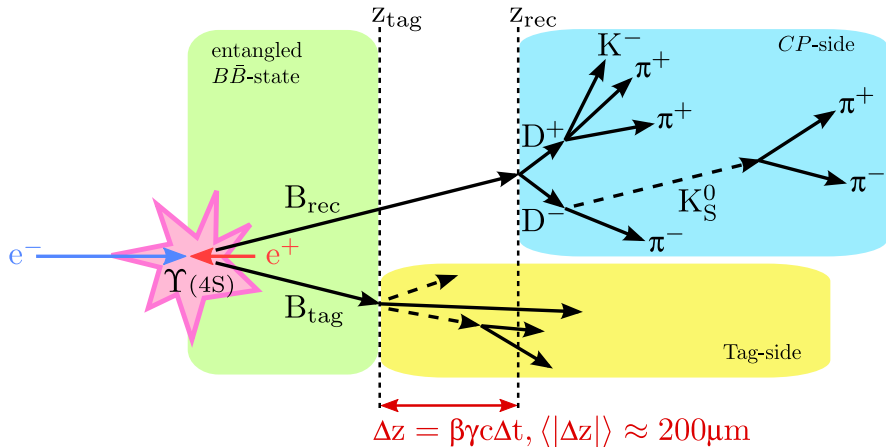
- Typical multi-purpose particle detector



Final data sample

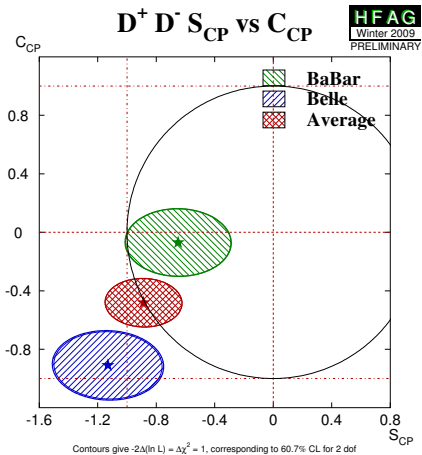
- $711 fb^{-1}$ recorded at the $\Upsilon(4S)$ resonance
- $121 fb^{-1}$ recorded at the $\Upsilon(5S)$ resonance

Δt measurement

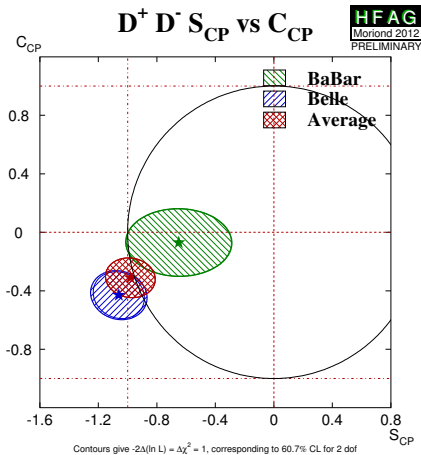


Backup: HFAG $B^0 \rightarrow D^+ D^-$

Old

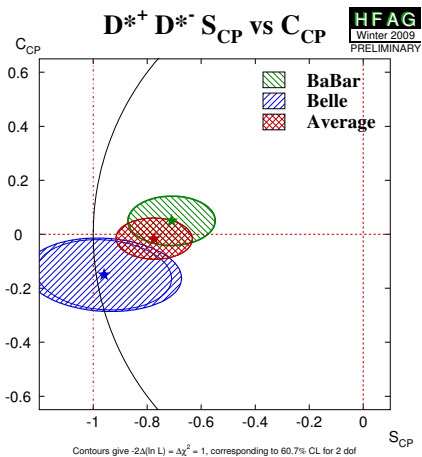


New



Backup: HFAG $B^0 \rightarrow D^{*+} D^{*-}$

Old



New

