Large CP Violation in $B \to \phi \phi X_s$ Decays

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Masashi Hazumi (KEK)

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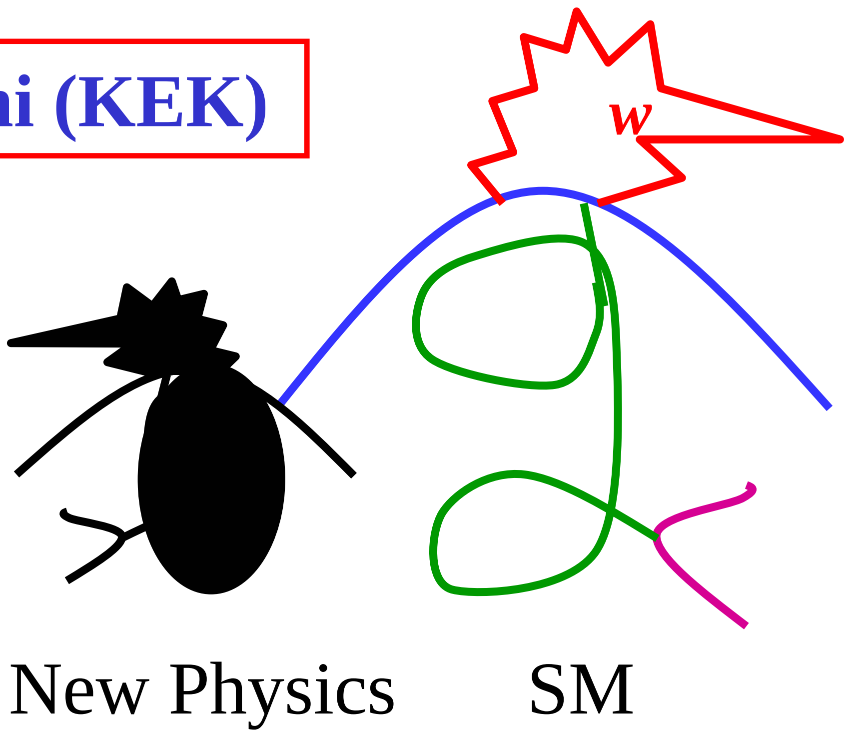
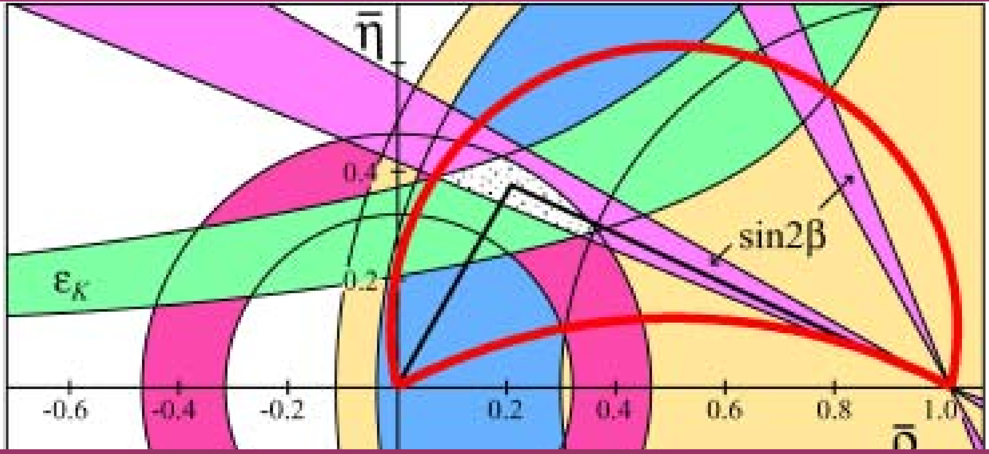
- Basic ideas
- Experimental sensitivity
- Observation at Belle
- Summary



Motivation

1. Very likely KM phase is the dominant source of CPV in the quark sector. However,

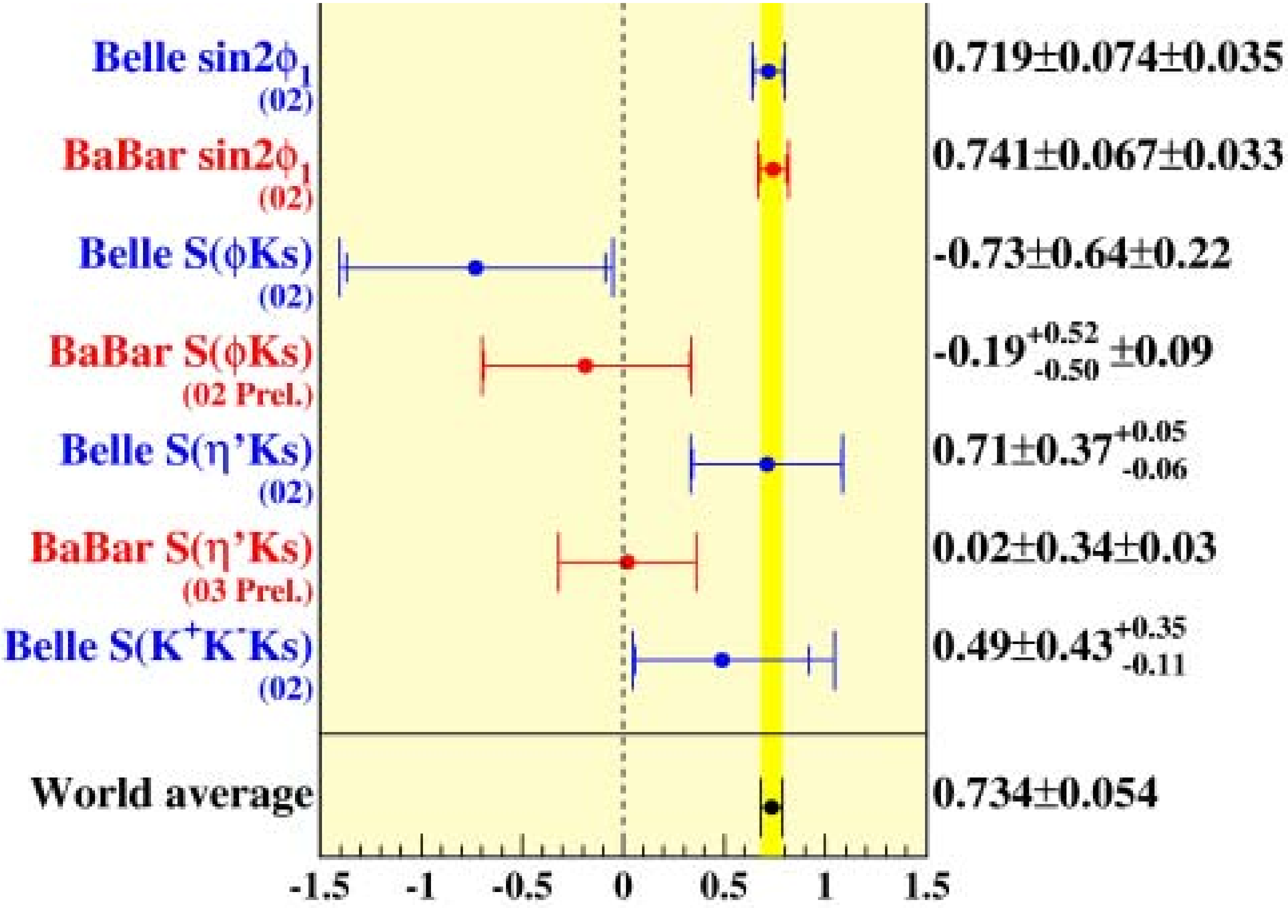


2. *Matter-dominant universe requires something more than KM phase.*
3. *Many new physics scenarios allow more than one CPV phase, which can be seen in FCNC processes. Even more, such information is useful to narrow down possible new physics models.*

Search for new CPV in $b \rightarrow s$ transition is very important !

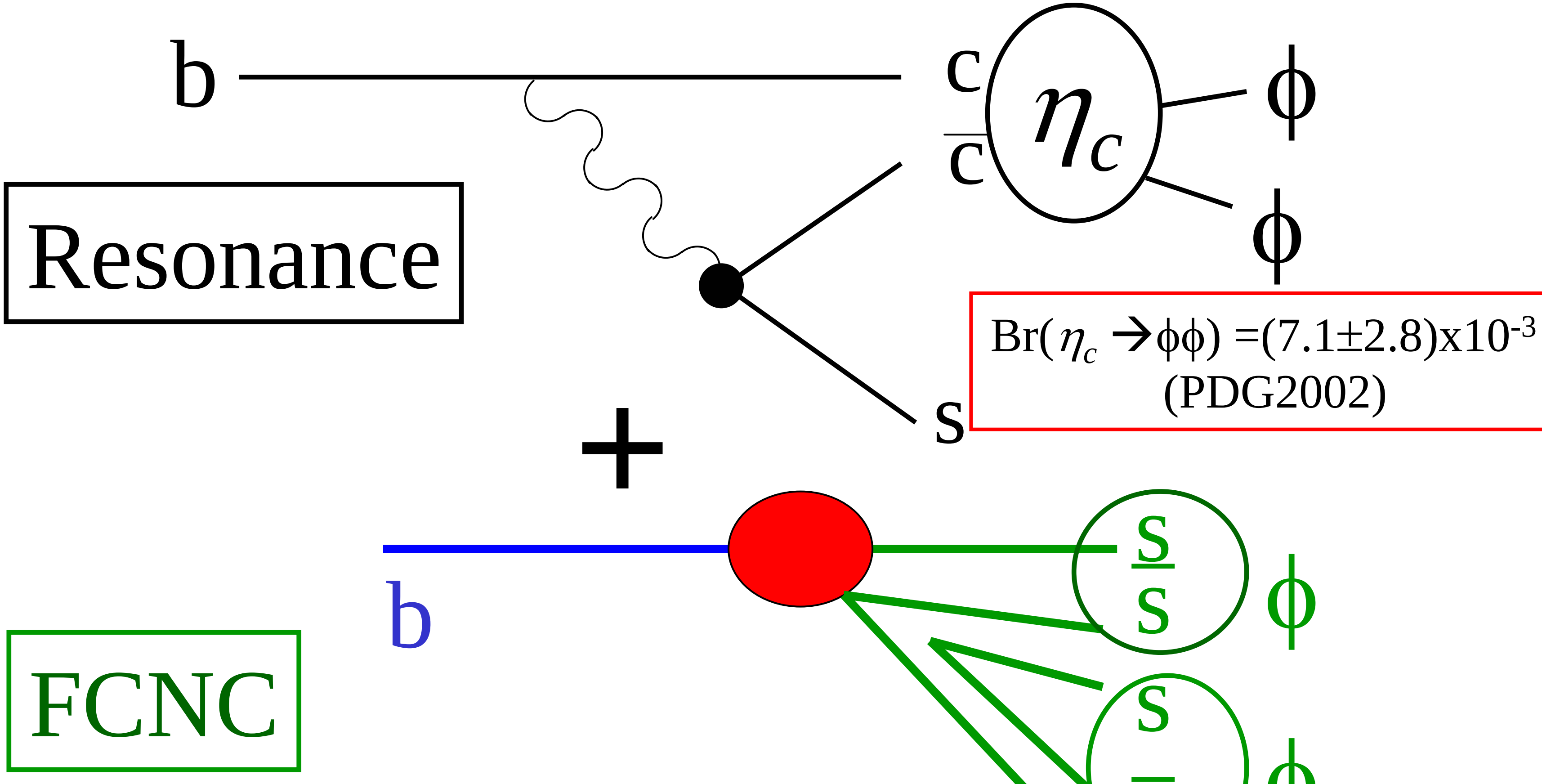
Motivation (cont.)

We may already be beginning to see a hint.



Important to pursue measurements by all means

Basic idea: phase difference from η_c resonance



- Standard Model (SM) → CPV ~ 0
- New Physics (NP) → CPV can be large

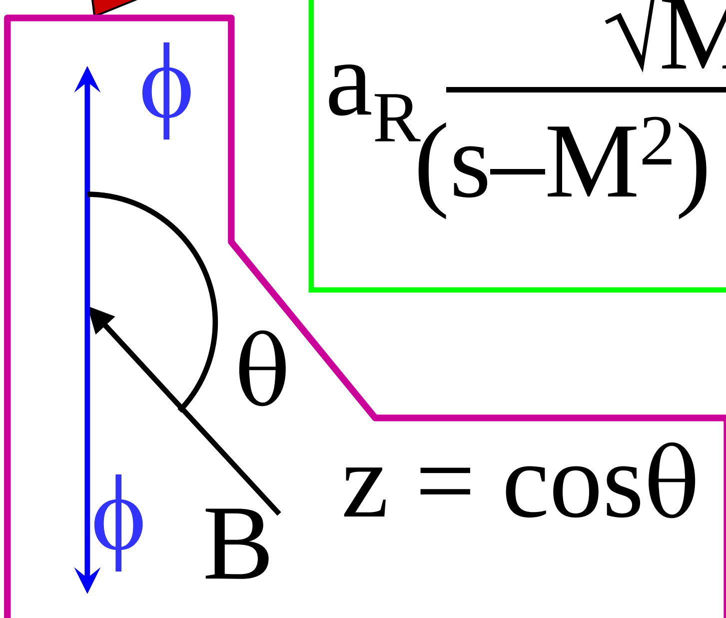
Comments on $B^{\pm} \to \eta_c(\chi_{c0})\pi^{\pm}$

- $\sin\phi 3$ with $B^{\pm} \to \eta_c(\chi_{c0})\pi^{\pm}$
  (Eilam, Gronau, Mendel, PRL 74 (1995) 4984)
  - $\eta c \to \pi\pi$ etc., interference with $B^{\pm} \to (\pi\pi \text{ etc.})\pi^{\pm}$
  - Vub in $B^{\pm} \to (\pi\pi \text{ etc.})\pi^{\pm}$ is the source of direct CPV
  - Very interesting idea !, but two problems
    - Smaller branching fraction, S/B is not good
    - Precise measurement of $\sin\phi 3$ will be difficult

Both problems are solved in $B \to \phi\phi Xs$

Decay Rates of B^+ and B^-

$$\frac{1}{\Gamma_B}\frac{d\Gamma^{\pm}}{dz} = \int_{(M-3\Gamma)^2}^{(M+3\Gamma)^2} ds\,|R(s) + D^{\pm}(s,z)|^2$$



$$a_R \frac{\sqrt{M\Gamma}}{(s-M^2) + iM\Gamma}$$

$$D_{SM}(s,z) + D^{\pm}_{NP}(s,z)$$

$$\propto \exp(\pm i\Theta_{NP})$$

Definitions

$$D^{\pm}(s \approx M^2, z) \equiv D_{\mathrm{SM}}(s \approx M^2, z) + D^{\pm}_{\mathrm{NP}}(s \approx M^2, z),$$

$$D_{\mathrm{SM}}(s \approx M^2, z) \equiv \frac{a_{\mathrm{D}}(z)}{\sqrt{M\Gamma}}\, e^{i\delta},$$

$$D^{\pm}_{\mathrm{NP}}(s \approx M^2, z) \equiv \frac{a_{\mathrm{NP}}(z)}{\sqrt{M\Gamma}}\, e^{i\delta'} e^{\pm i\Theta_{\mathrm{NP}}},$$

$\delta = \delta'$ assumed in the following;
we ignore the case where we had additional direct CPV
just from interference between SM and NP direct transitions.

Definitions (cont.)

$$\gamma^{\pm}(z) \equiv \frac{1}{\Gamma_B}\left(\frac{d\Gamma^+}{dz} \pm \frac{d\Gamma^-}{dz}\right)$$

The difference between the decay rates of B^+ and B^- is given by

$$\frac{1}{\Gamma_B}\left(\frac{d\Gamma^+}{dz} - \frac{d\Gamma^-}{dz}\right) \equiv \gamma^-(z) \cong -4\pi a_{\rm R} a_{\rm NP}(z) \cos\delta \cdot \sin\Theta_{\rm NP} \ . \qquad (6)$$

Similarly the sum of two decay rates is given by

$$\frac{1}{\Gamma_B}\left(\frac{d\Gamma^+}{dz} + \frac{d\Gamma^-}{dz}\right) \equiv \gamma^+(z) \cong 2\pi a_{\rm R}^2 + 24 a_{\rm D}^2(z)(r^2 + 2r\cos\Theta_{\rm NP} + 1) - 4\pi a_{\rm R} a_{\rm D}(z)(r\cos\Theta_{\rm NP} + 1)\sin\delta, \qquad (7)$$

where $r \equiv a_{NP}/a_D$

- z dependence of r reflects the spin components of the $\phi\phi$ system
- measurable from the differential decay rates in the η_c mass sideband
- Thus we assume pseudo-scaler component dominates the direct transition for simplicity.

CP Violation

Experimental study adopts fits to differential distributions.
Just for convenience, we use the following integrated CP asymmetry as the measure of CP violation.

$$\mathcal{A}_{CP} \equiv \sqrt{\frac{\int_{-1}^{1} dz\, \gamma^{-}(z)^2}{\int_{-1}^{1} dz\, \gamma^{+}(z)^2}}$$

$$\mathcal{B}_{NP} \equiv \frac{1}{M\Gamma} \int_{(M-3\Gamma)^2}^{(M+3\Gamma)^2} ds \int_{-1}^{1} dz\, a_{NP}^2(z).$$

$$\cong \sin\Theta_{NP} \sqrt{\frac{\pi}{3} \frac{\mathcal{B}_{NP}}{\mathcal{B}(B^+ \to \eta c(\to \phi\phi) Xs^+) + 2(1+r^{-2})\mathcal{B}_{NP}}}$$

Branching fractions

- $B(B^+ \to \eta_c(\to \phi\phi) Xs^+) \sim 2 \times 10^{-5}$
  - $B_{th}(B+ \to \eta_c Xs^+) = 2\sim5 \times 10^{-3}$ (theoretical estimations)
    - $B(B+ \to \eta_c K^+) = (1.25 \pm 0.14 {}^{+0.24}_{-0.34} \pm 0.38) \times 10^{-3}$ Belle PRL 90 (2003) 071801
    - $B(B^0 \to \eta_c K^{*0}) = (1.62 \pm 0.32 {}^{+0.10}_{-0.12} \pm 0.50) \times 10^{-3}$ Belle PRL 90 (2003) 071801
  - $B(\eta_c \to \phi\phi) = (7.1 \pm 2.8) \times 10^{-3}$ (PDG2002)

- $B_{NP} \leq 5 \times 10^{-6}$
    - estimation based on LUND fragmentation with JETSET-standard $s\bar{s}$ popping
    - $B(b \to s\bar{s}s) \leq 1\%$ is allowed with present exp. data (e.g. $B_{exp}(B \to \phi K)$)

- $B(B \to \phi\phi Xs)_{SM} = 3\sim9 \times 10^{-7}$ in the η_c mass region
    - method 1: from $B_{th}(B \to \phi Xs) \sim 10^{-4}$ + fragmentation → 3×10^{-7}
    - method 2: from $B_{th}(b \to s\bar{s}s) \sim 0.2\%$ + fragmentation → 9×10^{-7}

$r^2 \leq 5$ is allowed

CP Violation (cont.)

$B_{NP} \sim 1\times10^{-6}$ (for $r \sim 1$, or $D_{SM} \sim D_{NP}$)

$$A_{CP} \cong \sin\Theta_{NP}\sqrt{\frac{\pi}{3}\,\frac{B_{NP}}{B(B^+\to\eta_c(\to\phi\phi)Xs^+) + 2(1+r^{-2})B_{NP}}}$$

$\sim 2\times10^{-5}$

A large CP asymmetry of 20% is allowed. ($A_{CP} \sim 0\%$ in SM)

($A_{CP} \sim 40\%$ allowed within the present exp. bound; $r^2 \leq 5$)

Experimental sensitivity

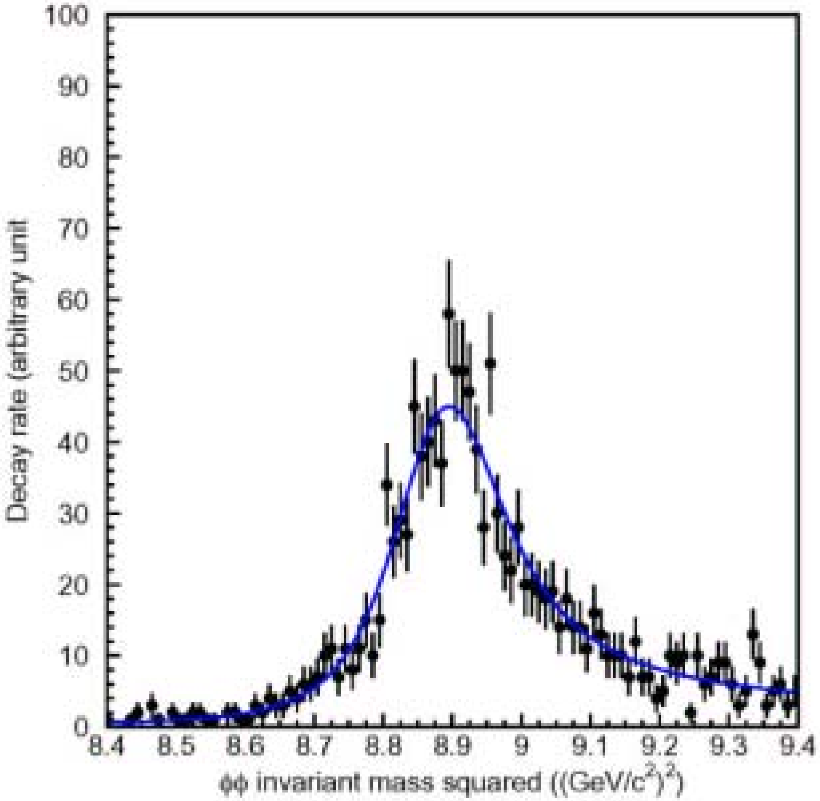
- Study for $B^{\pm} \rightarrow \phi\phi K^{\pm}$ only
- Background level expected to be negligible
- Reconstruction efficiency and $\phi\phi$ mass resolution estimated using GEANT-based detector simulator for the Belle detector.
- ~300 events expected for $N_B = 10^9$ (~ $1ab^{-1}$)
  - N_B = the number of charged B mesons recorded by a detector.
- Unbinned maximum-likelihood fit to the differential decay rate distribution with two free parameters
  - $A^0_{CP} \equiv -2r(a_D/a_R)$ → asymmetry parameter
  - $B \equiv a_D^2(r^2 + 2r\cos\Theta_{NP} + 1)$ → ~ branching fraction for mass sideband

$$\delta A^0_{CP} \sim 0.06 \quad \text{for} \quad N_B = 10^9$$

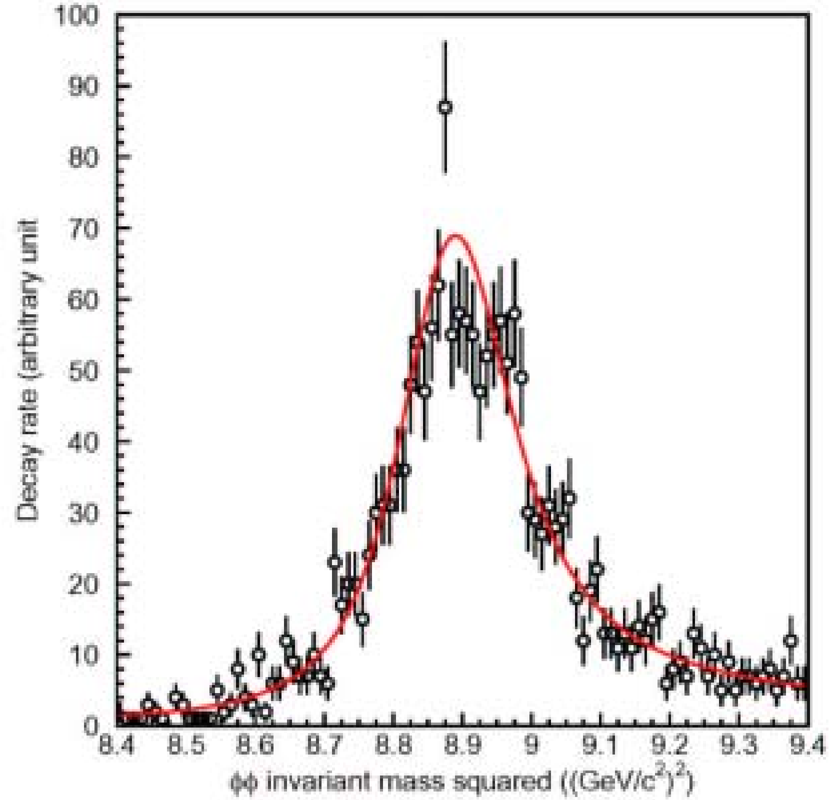
Toy MC results

($10ab^{-1}$, $r^2 = 1$, $\sin\Theta_{NP} = 1$)

B^+



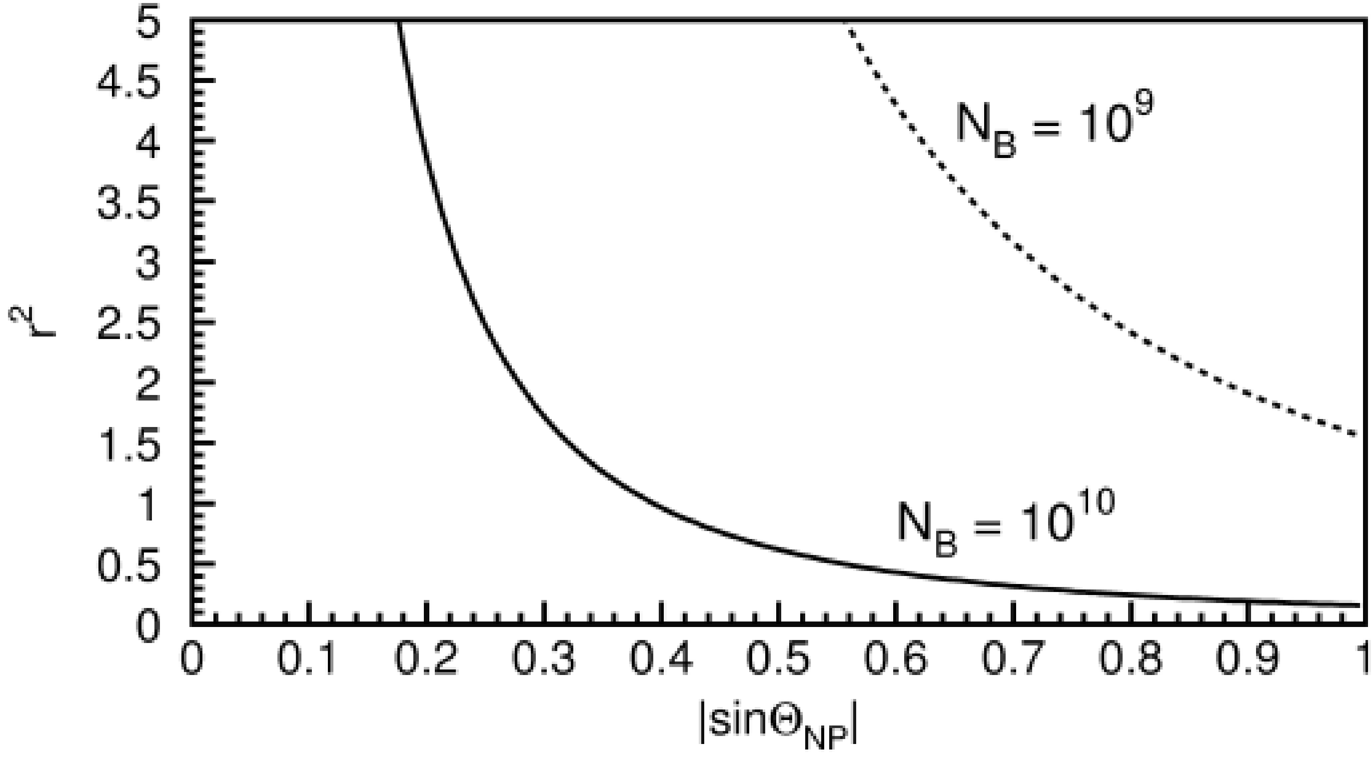
B^-



Clear direct CPV is seen

5σ discovery region

Discovery possible in a large parameter space above the curves

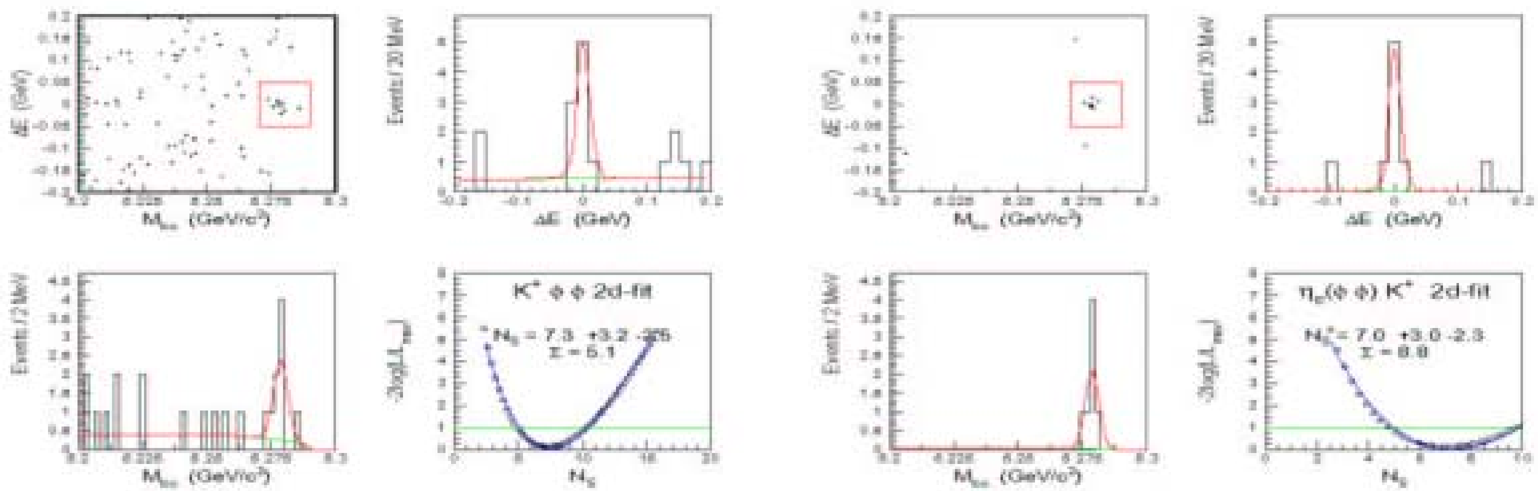


Observation at Belle

(La Thuile Mar. 2003)

will be submitted soon

First observation of $B^+ \to \phi\phi K^+$ decay



Belle preliminary $L = 78$ fb^{-1}

$(B^+ \to \phi\phi K^+) = (2.6^{+1.1}_{-0.9} \pm 0.3) \cdot 10^{-6}$ $(M_{\phi\phi} < 2.85\,\mathrm{GeV/c^2})$.

$(B^+ \to \eta_c K^+) \times Bf(\eta_c \to \phi\phi) = (2.2^{+1.0}_{-0.7} \pm 0.3) \cdot 10^{-6}$ $(2.94 < M_{\phi\phi} < 3.02\,\mathrm{GeV/c^2})$.

- Almost background-free in the η_c mass region !
- 3-body decays also observed with a reasonable branching fractions

$\eta_c \to \phi\phi$ branching fractions

TABLE II: Measured branching fractions of secondary charmonium decays and the world averages [5]. The branching fractions for modes with K^+K^- pairs include contributions from $\phi \to K^+K^-$.

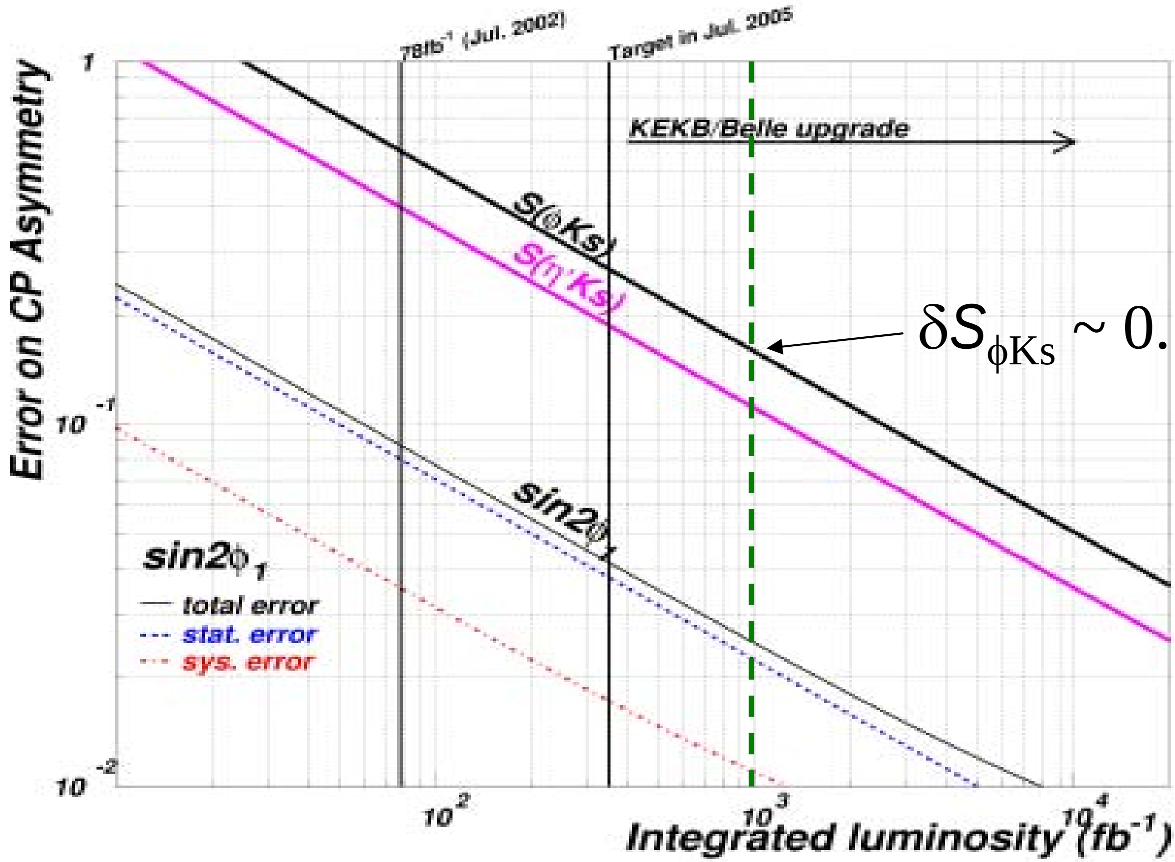
Preliminary

Decay mode	$\mathcal{B}$ (this work)	$\mathcal{B}$ (PDG)
$\eta_c \to \phi\phi$	$(1.8\ ^{+0.8}_{-0.6} \pm 0.7) \times 10^{-3}$	$(7.1 \pm 2.8) \times 10^{-3}$
$\eta_c \to \phi K^+K^-$	$(2.9\ ^{+0.9}_{-0.8} \pm 1.2) \times 10^{-3}$	–
$\eta_c \to 2(K^+K^-)$	$(1.4\ ^{+0.5}_{-0.4} \pm 0.6) \times 10^{-3}$	(2.1 ± 1.2) %
$J/\psi \to \phi K^+K^-$	$(2.4\ ^{+1.0}_{-0.8} \pm 0.3) \times 10^{-3}$	$(7.4 \pm 1.1) \times 10^{-4}$
$J/\psi \to 2(K^+K^-)$	$(1.4\ ^{+0.5}_{-0.4} \pm 0.2) \times 10^{-3}$	$(7.0 \pm 3.0) \times 10^{-4}$

PDG ✕¼ for $B(\eta_c \to \phi\phi) \to$ $\delta A^0_{CP} \sim 0.12$ for $N_B = 10^9$

However, the expected CPV will become larger !
5σ discovery region will remain similar.

Reference: $B^0 \to \phi K_s$ sensitivity



$\delta S_{\phi Ks} \sim 0.15$ for $N_B = 10^9$

- Similar new phase sensitivity for $\phi\phi K^+$ and ϕK_s
- Advantage to include other modes $\phi\phi K^*$, $\phi\phi K n\pi$ etc.
- All-combined analysis will be the most powerful way

New “CPectroscopy”

- Other resonances also usable (χ_{c0} etc.)
- Neutral B as well (need to take care of time-dep.)
- Dalitz-type analyses for both on- and off-resonance data required to estimate the possible dilution from other spin components
- Spectroscopy for resonances in $B^+(\overline{B}^0)$ and $B^-(B^0)$ decays separately = **CPectroscopy**

Summary :Virtues of $B \to (\phi\phi)_{m \sim m\eta c} Xs$

- "Pure" $b \to s\bar{s}s\bar{s}s$, no CPV from the SM
  - Non-zero CPV is a clear manifestation of new physics
- Reasonable signal yield
  - comparable to (or even better than) $B0 \to \phi Ks$ ICPV study
  - Better sensitivity by including other kaonic resonances (K* etc.)
  - If the BR($\eta c \to \phi\phi$) is smaller than the PDG value, the A_{CP} can be even larger !
- Clean signal
  - thanks to good K/π separation
  - ϕ meson is also special and helps improve S/B
- Hadronic uncertainty less important
  - Enough to find deviation from SM; observation itself is a big discovery

Backup Slides

The direct amplitude $D^{\pm}$ is separated into contributions from the SM, $D_{\rm SM}$, and from NP, $D^{\pm}_{\rm NP}$,

$$D^{\pm}(s \approx M^2, z) \equiv D_{\rm SM}(s \approx M^2, z) + D^{\pm}_{\rm NP}(s \approx M^2, z), \quad (3)$$

$$D_{\rm SM}(s \approx M^2, z) \equiv \frac{a_{\rm D}(z)}{\sqrt{M\Gamma}}\, e^{i\delta}, \quad (4)$$

$$D^{\pm}_{\rm NP}(s \approx M^2, z) \equiv \frac{a_{\rm NP}(z)}{\sqrt{M\Gamma}}\, e^{i\delta'} e^{\pm i\Theta_{\rm NP}}, \quad (5)$$

where $a_{\rm D}(z)$ is a real part of the SM direct amplitude, δ (δ') is a strong phase difference between the resonance amplitude and the SM (NP) direct amplitude, $a_{\rm NP}(z)$ is a real part of the NP amplitude and $\Theta_{\rm NP}$ is a new CP-violating phase. If $\delta \neq \delta'$ holds, direct CP violation can also occur from an interference between the SM and NP direct amplitudes. We do not take this case in our study and assume $\delta = \delta'$ in the following discussion.

As a measure of CP violation, we define the following CP-asymmetry parameter:

$$\mathcal{A}_{CP} \equiv \sqrt{\frac{\int_{-1}^{1} dz \gamma^-(z)^2}{\int_{-1}^{1} dz \gamma^+(z)^2}}. \tag{9}$$

The numerator of $\mathcal{A}_{CP}$ can be expressed with the branching fraction of the resonance $(2\pi a_{\mathrm{R}}^2)$ and that of NP in the resonance region $(\mathcal{B}_{\mathrm{NP}})$:

$$\int_{-1}^{1} dz \gamma^-(z)^2 = (2\pi a_{\mathrm{R}}^2) \cdot \mathcal{B}_{\mathrm{NP}} \cdot \frac{2\pi}{3} \sin^2 \Theta_{\mathrm{NP}} \ , \tag{10}$$

where

$$2\pi a_{\mathrm{R}}^2 \cong \mathcal{B}(B^\pm \to \eta_c X_s^\pm) \cdot \mathcal{B}(\eta_c \to \phi\phi) \ , \tag{11}$$

and

$$\mathcal{B}_{\mathrm{NP}} \equiv \frac{1}{M\Gamma} \int_{(M-3\Gamma)^2}^{(M+3\Gamma)^2} ds \int_{-1}^{1} dz a_{\mathrm{NP}}^2(z). \tag{12}$$

The evaluation of the denominator of $\mathcal{A}_{CP}$ is straightforward with the estimations mentioned above. We obtain the following result for $\mathcal{B}(b \to sg^* \to s\bar{s}s) \sim 1\%$, $2\pi a_{\rm R}^2 = 2 \times 10^{-5}$ and $|\sin\Theta_{\rm NP}| \sim 1$:

$$\mathcal{A}_{CP} \cong \sqrt{\frac{\pi}{3}} \cdot \sqrt{\frac{\mathcal{B}_{\rm NP}}{\mathcal{B}(B^\pm \to \eta_c X_s^\pm) \cdot \mathcal{B}(\eta_c \to \phi\phi) + 2(1 + r^{-2})\mathcal{B}_{\rm NP}}} \cdot \sin\Theta_{\rm NP} \sim 0.40 \cdot \sin\Theta_{\rm NP} \ . \tag{13}$$

A large CP asymmetry of 40% is allowed. The asymmetry is roughly proportional to $|r|$. Therefore the asymmetry can be sizable even with $r^2 < 1$; for example, ~10% is allowed for $r^2 = 0.3$.