

Time-dependent CP violation in B decays at Belle

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for Belle collaboration

- $\sin 2\phi_1^{\text{eff}}$ measurements in



$$B^0 \rightarrow \eta' K^0$$

$$B^0 \rightarrow \omega K_S^0$$

- ϕ_2 related measurements in

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

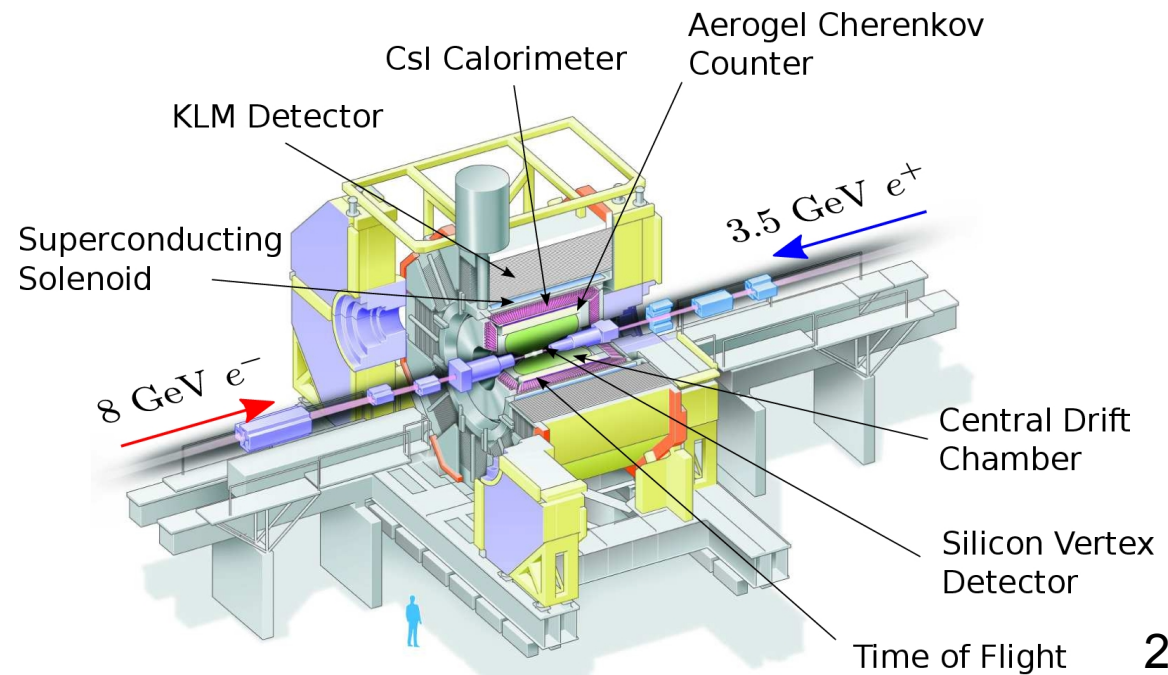
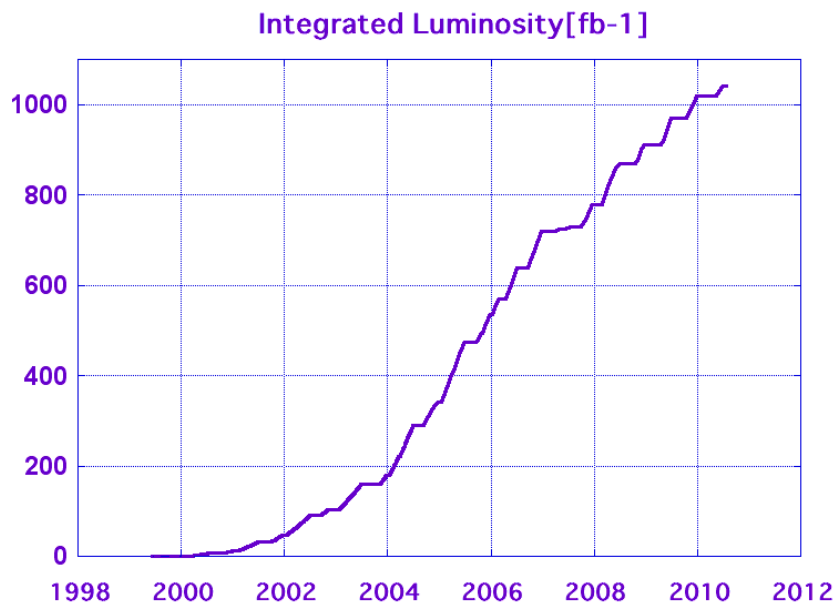
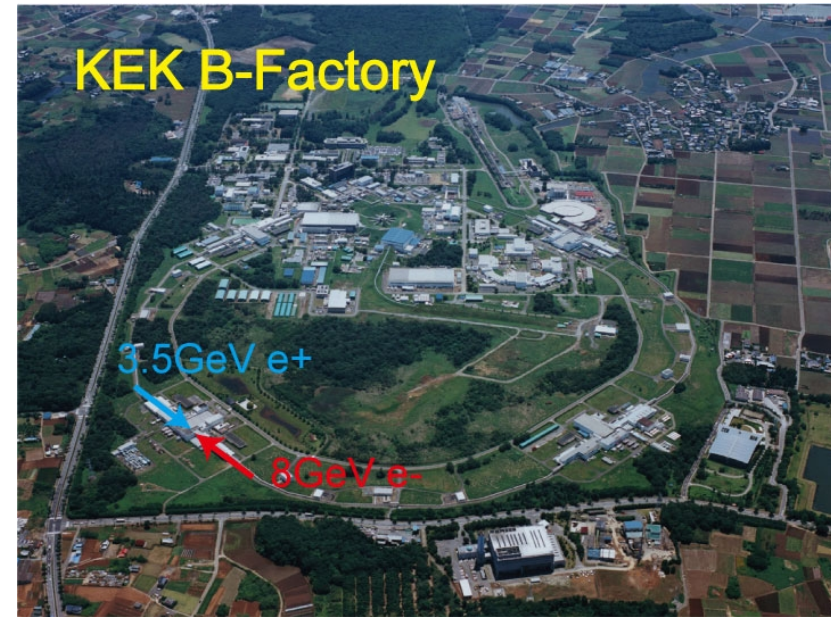
$$B^0 \rightarrow \rho^0 \rho^0$$



Belle experiment



- Operating at KEKB collider (1999-2010).
- Asymmetric beam energy:
 $8.0 \text{ GeV } e^-$ on $3.5 \text{ GeV } e^+$
- Boosted B meson pair produced in
 $e^- \rightarrow \leftarrow e^+ \Rightarrow \Upsilon(4S) \Rightarrow B\bar{B}$
- Collected about 772M BB pairs.



Time dependent CPV measurements



What ?

$$B^0(0) = B^0 \quad \bar{B}^0(0) = \bar{B}^0$$

flavor eigenstates

$$A_f(\Delta t) = \frac{\Gamma(B^0(\Delta t) \rightarrow f) - \Gamma(\bar{B}^0(\Delta t) \rightarrow f)}{\Gamma(B^0(\Delta t) \rightarrow f) + \Gamma(\bar{B}^0(\Delta t) \rightarrow f)} = \mathcal{A}_f \cos \Delta M \Delta t + \mathcal{S}_f \sin \Delta M \Delta t$$

How ?

Quantum coherence

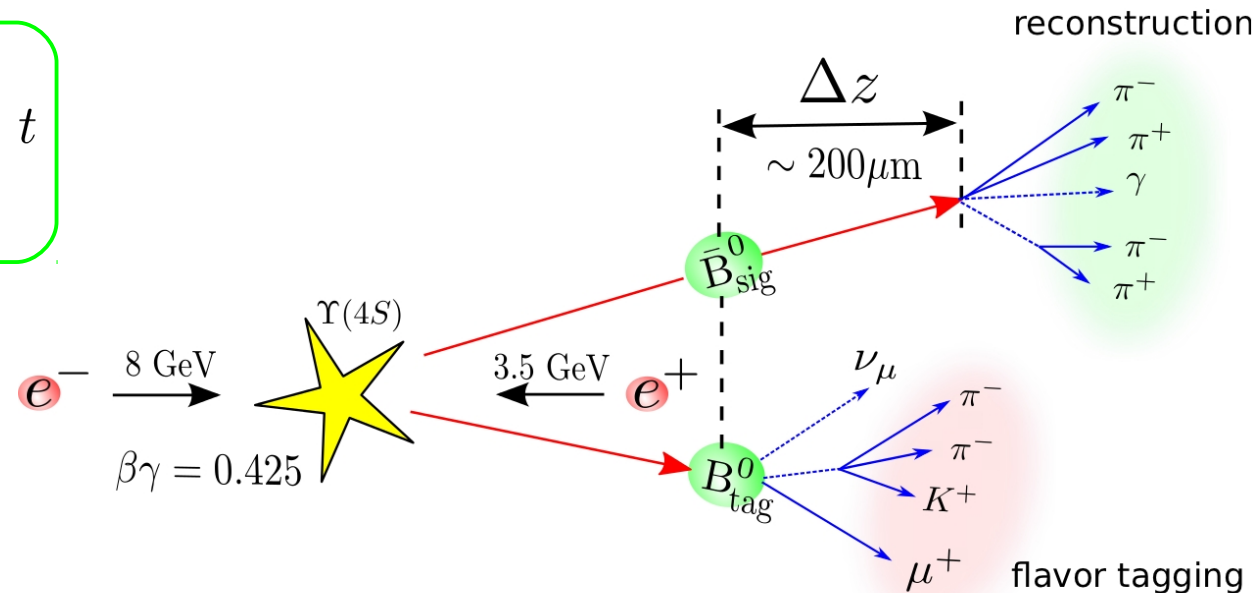
$B_{tag} \rightarrow B^0(\bar{B}^0)$ flavor specific at t

B_{sig} was $\bar{B}^0(B^0)$ at t

Mass of $\Upsilon(4S)$ just above $2M_B$
B pair ~ at rest in CMS

Asymmetric beam energy

$$\Delta t = \Delta z / \beta \gamma c$$



We need to:

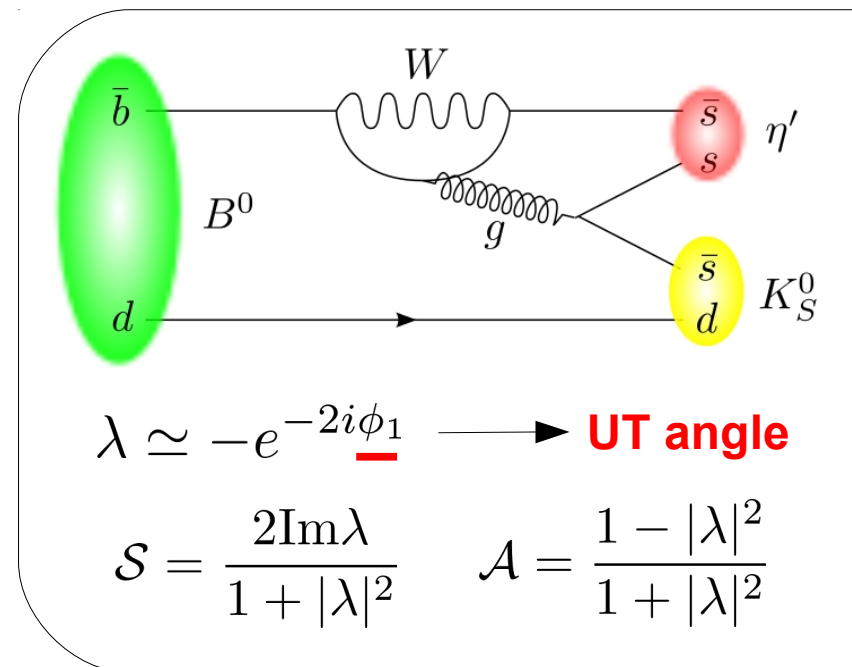
1. Determine the flavor of B_{tag} .
2. Reconstruct B_{sig} into final state f .
3. Measure the distance between the decay vertices.

Motivation

- Decays dominated by $b \rightarrow s\bar{q}q$ transition. FCNC \rightarrow penguin diagram
- The asymmetry parameters within the SM:

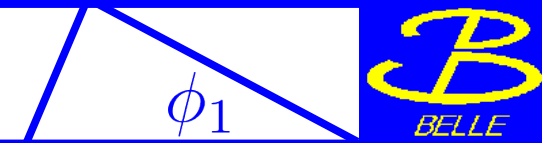
$$\mathcal{A}_{s\bar{q}q} \simeq 0 \quad \mathcal{S}_{s\bar{q}q} \simeq -\xi_f \sin 2\phi_1$$

\downarrow
 CP eigenvalue



- $\sin 2\phi_1$ can be very accurately measured in $B^0 \rightarrow J/\psi K^0$.
- Loop dominated \rightarrow sensitive to new physics. $\mathcal{S}_{s\bar{q}q} \rightarrow -\xi_f \sin 2\phi_1^{eff}$
- Observing the difference $|\mathcal{S}_{s\bar{q}q} - \mathcal{S}_{J/\psi K^0}|$ to be large \rightarrow sign of new physics.

$B^0 \rightarrow \eta' K^0$ analysis



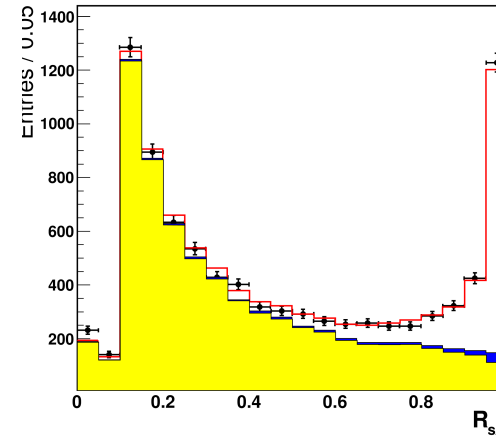
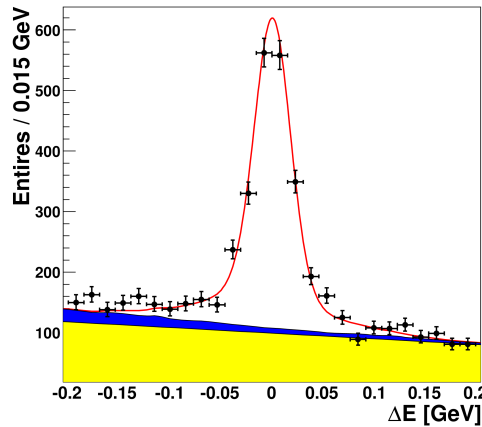
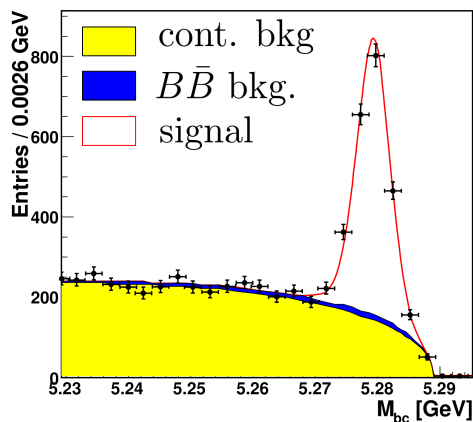
$$\Delta E = E_B^{cms} - E_{beam}^{cms}$$

$$M_{bc} = \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$$

- To obtain signal yield we perform 3D fit to data distribution in

$\mathcal{R}_{s/b}$ - likelihood ratio from event shape variables

$\eta' K_S^0$ $M_{bc}, \Delta E, \mathcal{R}_{s/b}$

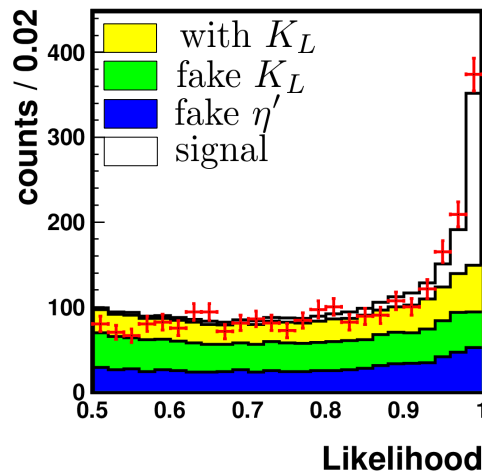
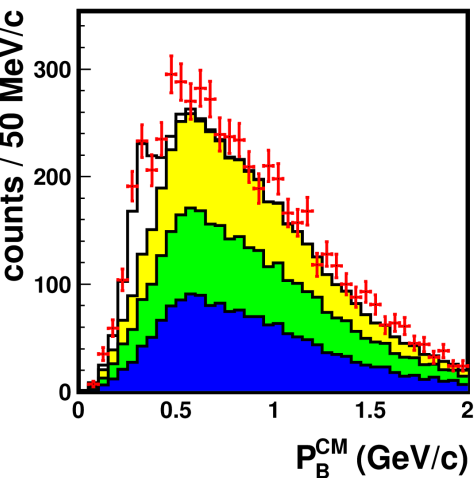


To separate signal and main background, from

$$e^+ e^- \rightarrow q \bar{q}$$

($q = u, d, s, c$)

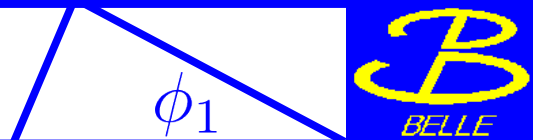
$\eta' K_L^0$ $p_B^{cms}, \mathcal{R}_{s/b}, r$



mode	This analysis N_{sig}	2007 analysis N_{sig}
$\eta' K_S$	$772 \text{ M } B\bar{B}$ 2506.3 ± 63.1	$534 \text{ M } B\bar{B}$ 1256.6 ± 42.1
$\eta' K_L$	1041.7 ± 41.1	478.8 ± 41.1

Beside new data, about 25% improvement in reconstruction efficiency

$B^0 \rightarrow \eta' K^0$ analysis



With 772 M BB we obtain

Preliminary results

$$\mathcal{S}_{\eta' K^0} = 0.68 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$$

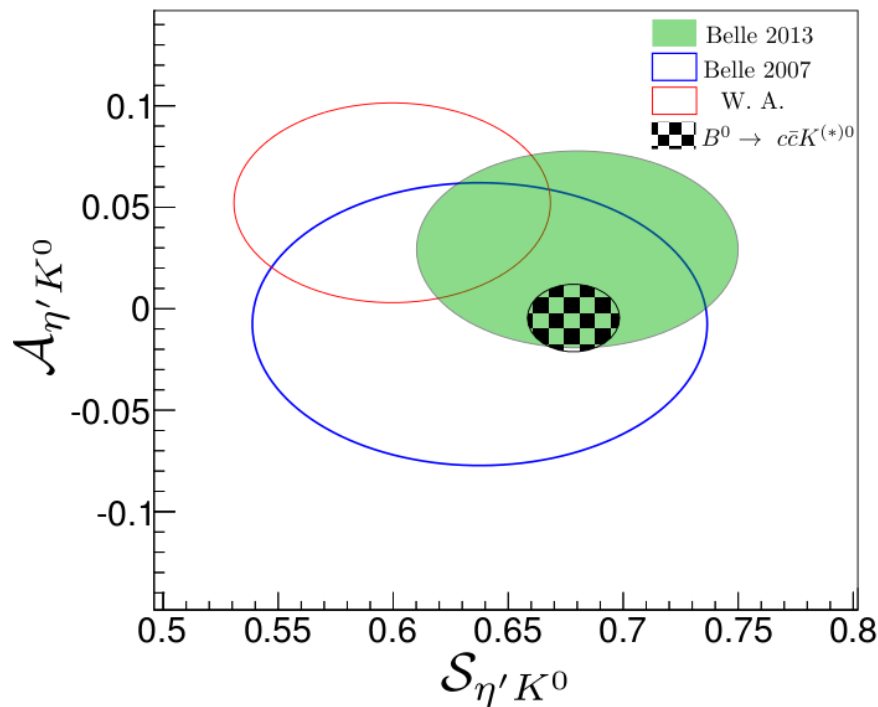
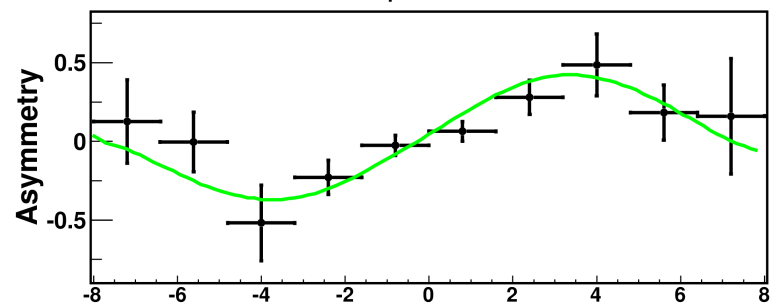
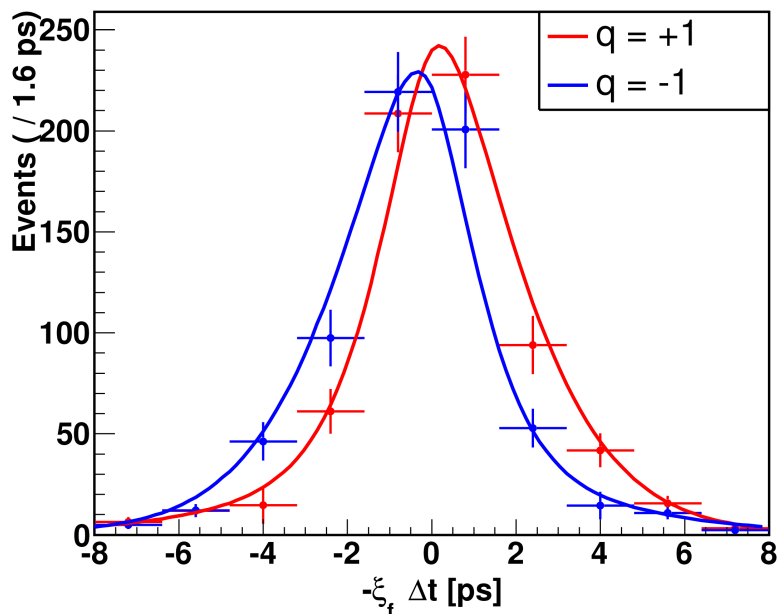
$$\mathcal{A}_{\eta' K^0} = +0.03 \pm 0.05(\text{stat}) \pm 0.03(\text{syst})$$

mode	772 M BB	
	$-\xi_f \mathcal{S}$	\mathcal{A}
$\eta' K_S^0$	0.71 ± 0.07	0.02 ± 0.05
$\eta' K_L^0$	0.46 ± 0.21	0.09 ± 0.14

Errors are statistical only

World's most precise measurement of CPV in: $B^0 \rightarrow \eta' K^0$
 $b \rightarrow s\bar{q}q$

Well consistent with $\sin 2\phi_1$



$B^0 \rightarrow \omega K_S^0$ analysis



ϕ_1

- 7D fit to

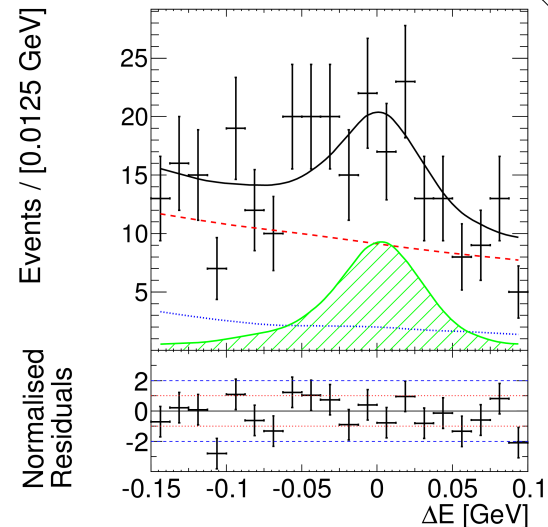
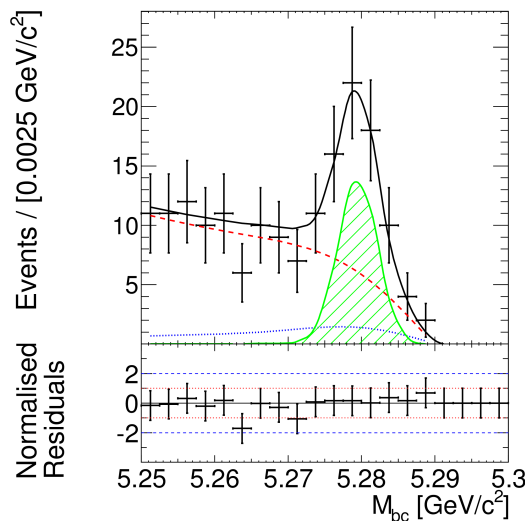
$$\Delta E, M_{bc}, \mathcal{R}_{s/b}, m_{3\pi}, \mathcal{H}_{3\pi}, \Delta t, q$$

$\cos \theta_{Hel}$



to obtain branching fraction and CPV parameters

- Branching fraction $\mathcal{B}(B^+ \rightarrow \omega K^+)$ also measured



Fit result

Branching fractions:

$$\mathcal{B}(B^0 \rightarrow \omega K^0) = (4.5 \pm 0.4(stat) \pm 0.3(syst)) \times 10^{-6}$$

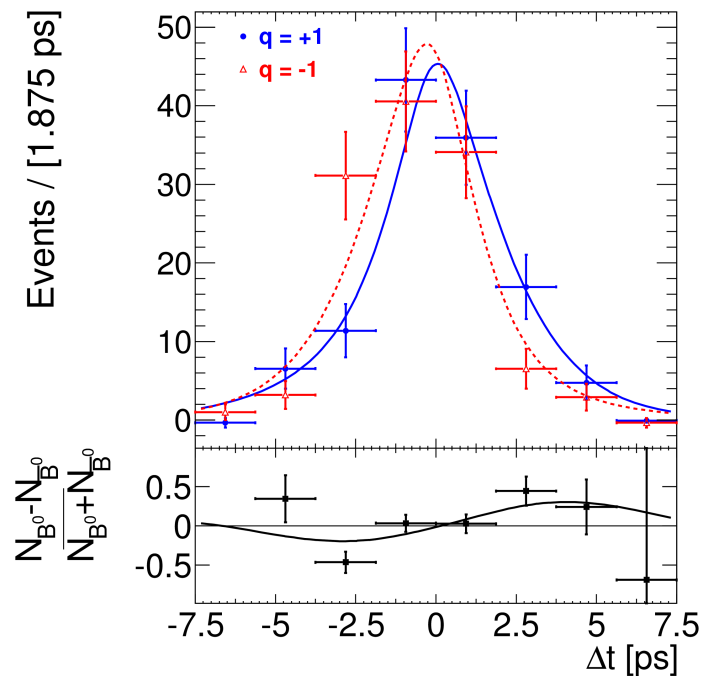
$$\mathcal{B}(B^+ \rightarrow \omega K^+) = (6.8 \pm 0.4(stat) \pm 0.4(syst)) \times 10^{-6}$$

CPV parameters:

$$\mathcal{S}_{\omega K_S^0} = +0.91 \pm 0.32(stat) \pm 0.05(syst)$$

$$\mathcal{A}_{\omega K_S^0} = -0.36 \pm 0.19(stat) \pm 0.05(syst)$$

Preliminary results



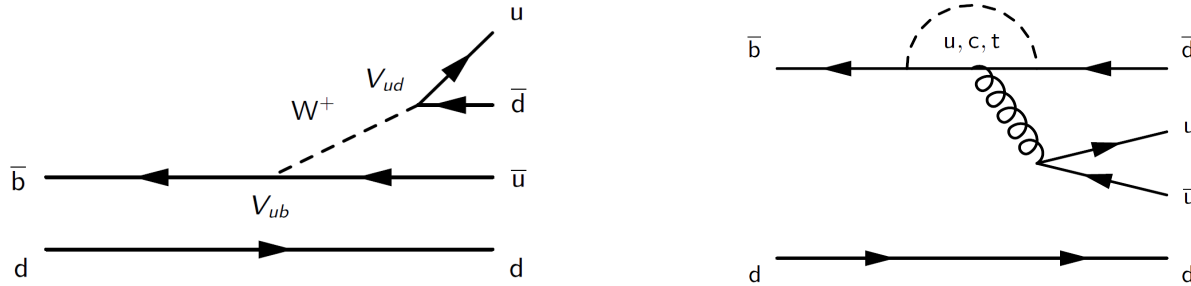
First evidence of CPV in $B^0 \rightarrow \omega K^0$

$B^0 \rightarrow \pi^+ \pi^-$ analysis

ϕ_2



- Decay dominated by $b \rightarrow u\bar{u}d$ transition.



$\lambda \simeq e^{-2i\phi_2} \rightarrow$ **UT angle**

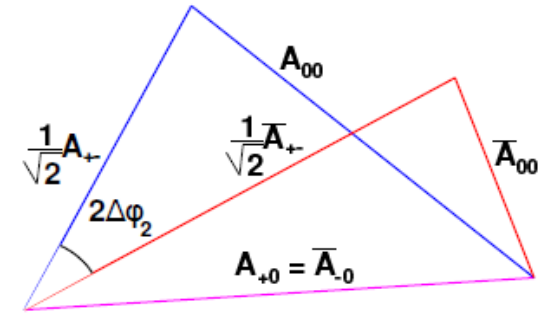
$$S = \frac{2\text{Im}\lambda}{1 + |\lambda|^2} \quad A = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}$$

But penguin is not small!

$A \neq 0$

$S \propto \sin 2(\phi_2 + \Delta\phi_2)$

isospin analysis $\rightarrow \phi_2$

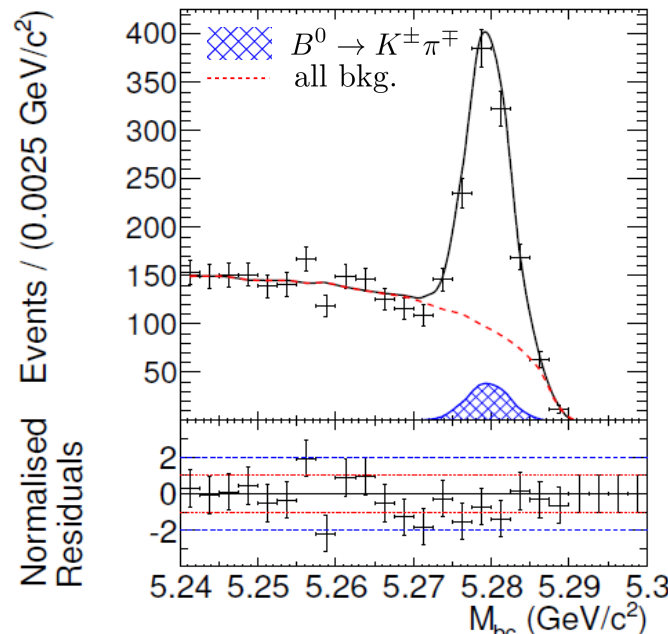
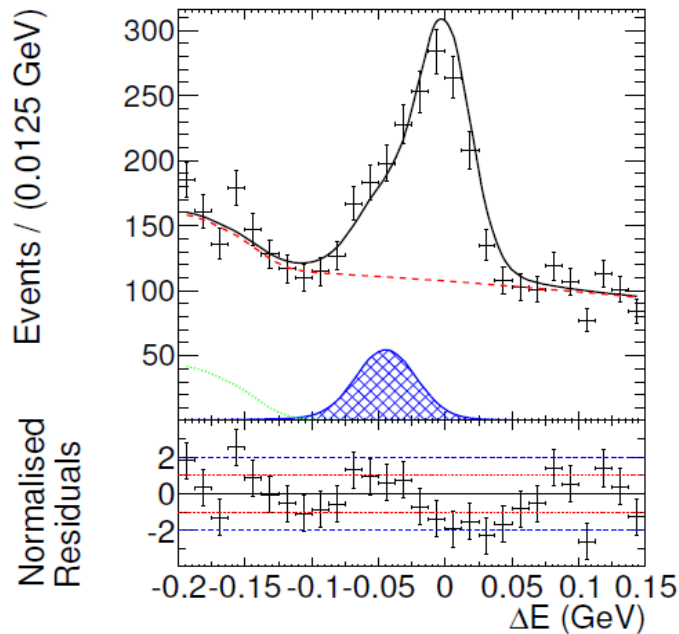


Needed: S, A, B

$B^0 \rightarrow \pi^+ \pi^-, \pi^0 \pi^0$

$B^+ \rightarrow \pi^+ \pi^0$

- 7D fit to: $\Delta E, M_{bc}, \mathcal{L}_{K\pi}^+, \mathcal{L}_{K\pi}^-, \mathcal{R}_{s/b}, \Delta t, q$



This analysis	
772 M $B\bar{B}$	
N_{sig}	
$\pi^+ \pi^-$	$\simeq 2360$
Previous	
534 M $B\bar{B}$	
N_{sig}	
$\pi^+ \pi^-$	1464

$B^0 \rightarrow \pi^+ \pi^-$ analysis

ϕ_2

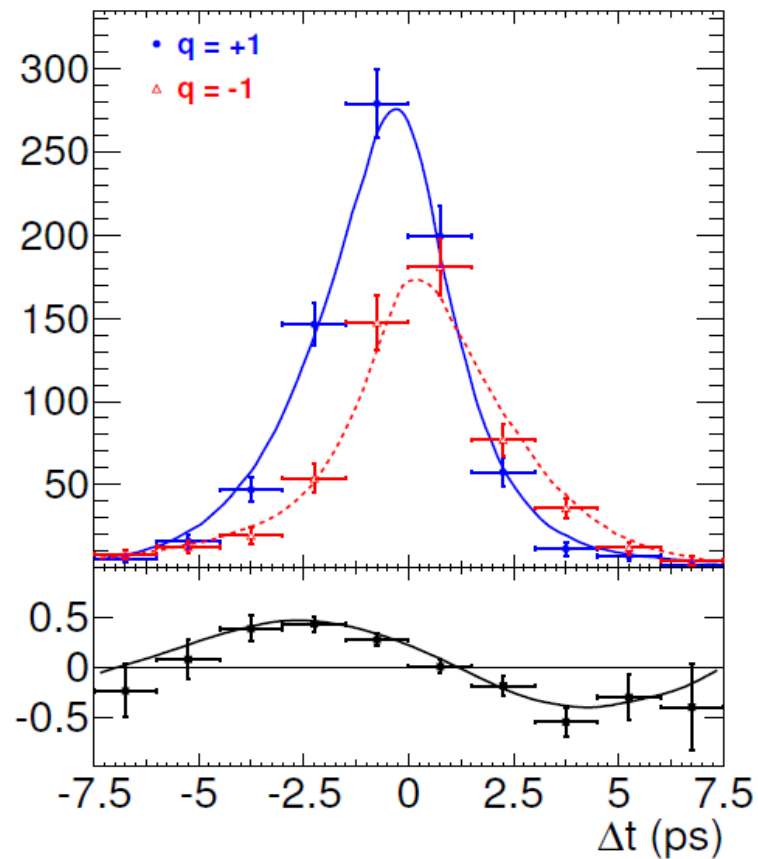
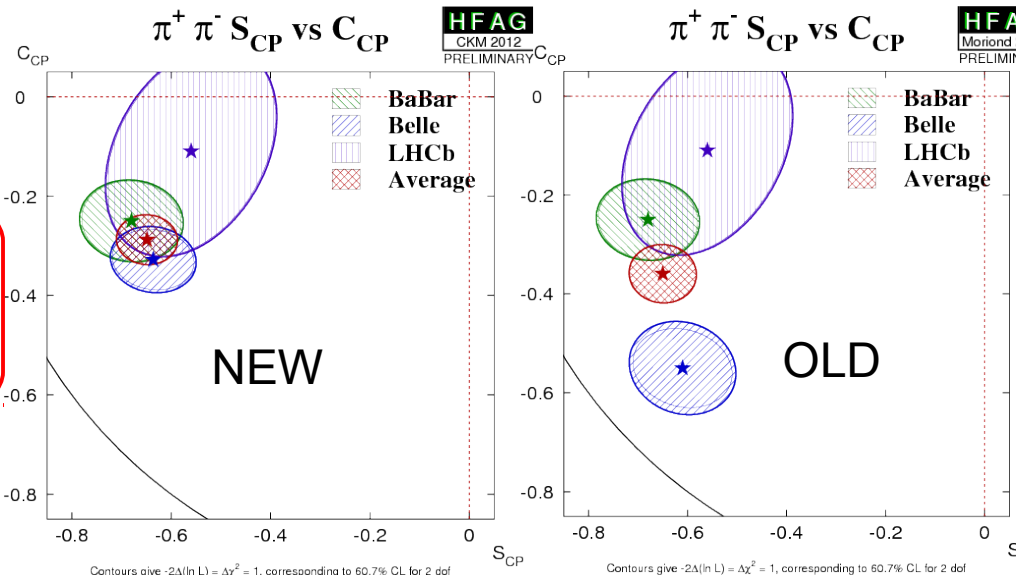


<http://arxiv.org/abs/1302.0551>

Fit result

$$A_{\pi^+ \pi^-} = +0.33 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})$$

$$S_{\pi^+ \pi^-} = -0.64 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})$$



ϕ_2 isospin analysis

Belle data only

772 M $B\bar{B}$

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

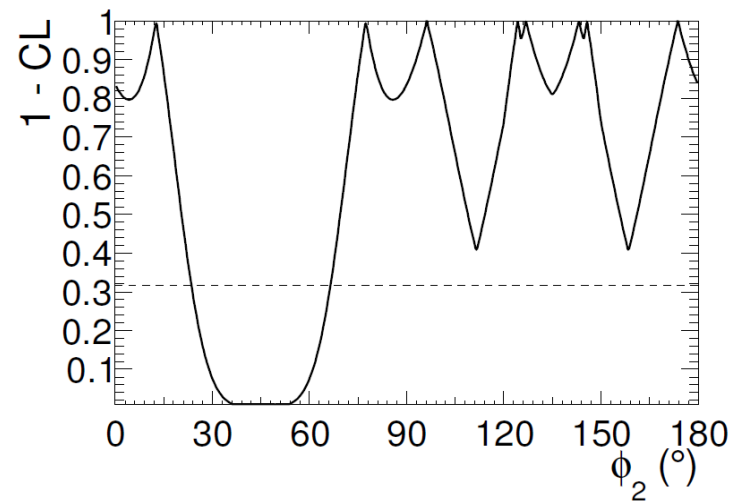
$B^+ \rightarrow \pi^+ \pi^0$

253 M $B\bar{B}$

$B^0 \rightarrow \pi^0 \pi^0$

Excluded at 1σ C.L.

$$23.8^\circ < \phi_2 < 66.8^\circ$$

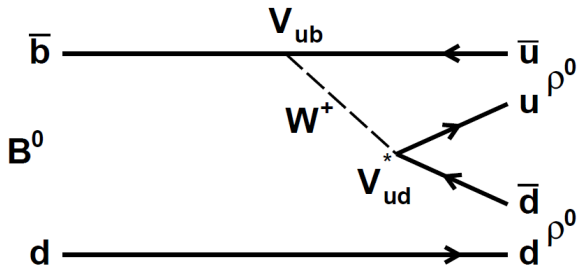


$B^0 \rightarrow \rho^0 \rho^0$ analysis

ϕ_2



- Decay dominated by $b \rightarrow u\bar{u}d$ transition.



- tree dominated
- color suppressed
- isospin analysis $\rightarrow \phi_2$

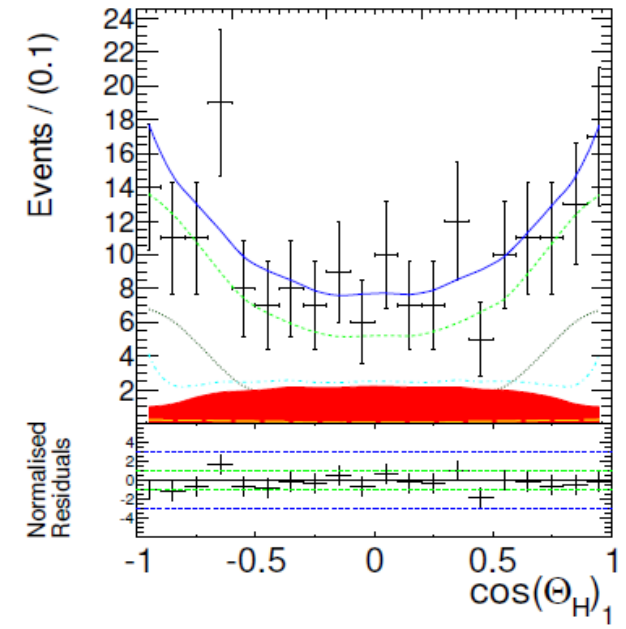
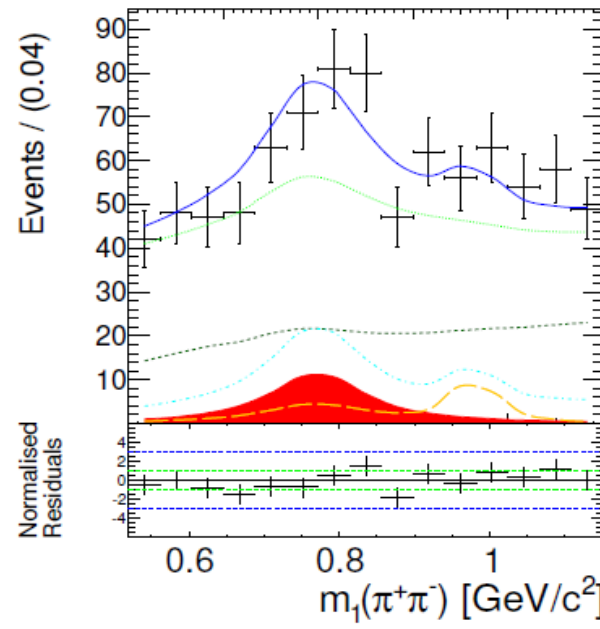
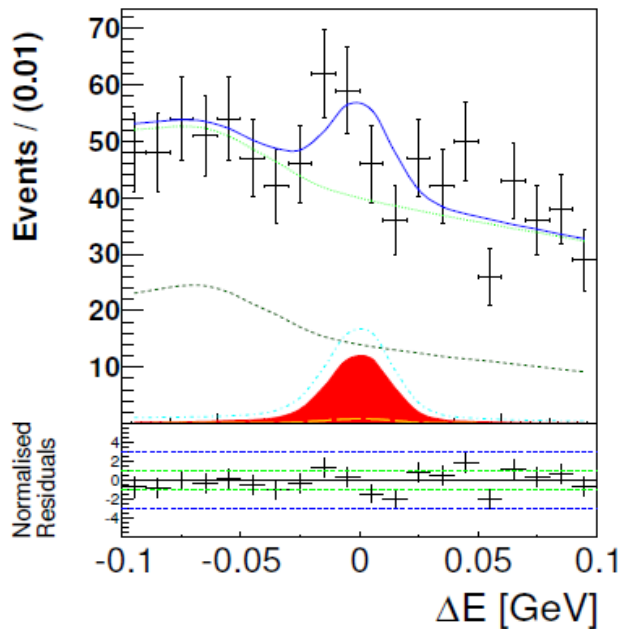
$\rho^0 \rho^0$ not pure CP eigenstate
(longitudinal component CP even,
transverse CP even + odd)

Helicity analysis to disentangle,
i.e. to measure f_L

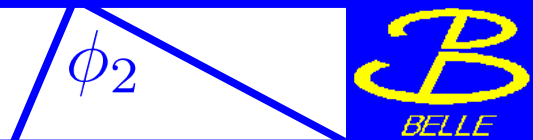
- 6D fit to: ΔE , $M_{\pi^+\pi^-}^1$, $M_{\pi^+\pi^-}^2$, $\cos \theta_H^1$, $\cos \theta_H^2$, $\mathcal{R}_{s/b}$

Dominant background $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$), large $B^0 \rightarrow 4\pi^\pm$

$B^0 \rightarrow \rho^0 \rho^0$, $B^0 \rightarrow f^0 \rho^0$, all $B^0 \rightarrow 4\pi$, non-peaking $B\bar{B}$, all non-peaking



$B^0 \rightarrow \rho^0 \rho^0$ analysis



<http://arxiv.org/abs/1212.4015>

Fit result

$$\mathcal{B}(B^0 \rightarrow \rho^0 \rho^0) = (1.02 \pm 0.3(\text{stat}) \pm 0.22(\text{syst})) \times 10^{-6}$$

2.9 σ significance

$$f_L = 0.21_{-0.22}^{+0.18} \pm 0.11$$

Upper limit (90% C.L.)

$$< 1.5 \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow f_0 \rho^0) \times \mathcal{B}(f_0 \rightarrow \pi^+ \pi^-) = (0.86 \pm 0.27(\text{stat}) \pm 0.15(\text{syst})) \times 10^{-6}$$

first evidence

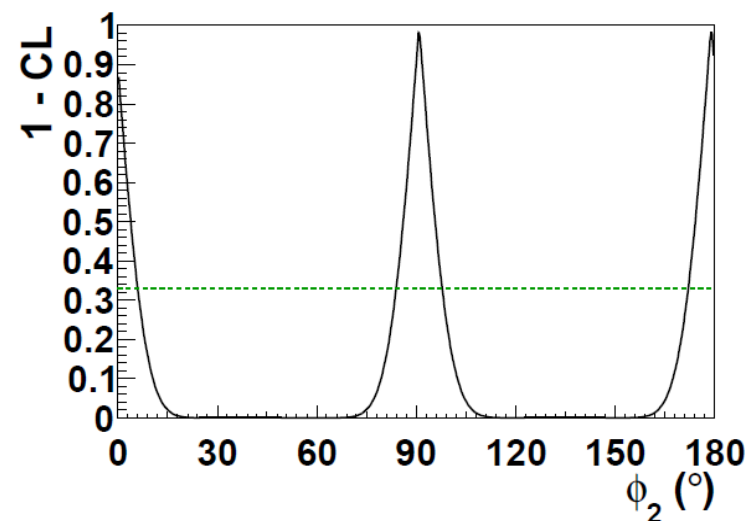
ϕ_2 isospin analysis

input
this $\mathcal{B}(B^0 \rightarrow \rho^0 \rho^0)_L$
W.A. $\left\{ \begin{array}{l} \mathcal{B}(B^0 \rightarrow \rho^+ \rho^-)_L \\ \mathcal{B}(B^+ \rightarrow \rho^+ \rho^0) \\ \mathcal{A}^{+-}, \mathcal{S}^{+-} \end{array} \right.$
BaBar $\mathcal{A}^{00}, \mathcal{S}^{00}$

$$\phi_2 = (91.0 \pm 7.2)^\circ$$

$$\Delta\phi_2 = (0.0 \pm 5.4)^\circ$$

└─► penguin negligible



- Two new measurements of time dependent CPV in $b \rightarrow s\bar{q}q$ transition dominated decays. They provide:

- most precise parameters of CPV in $B^0 \rightarrow \eta' K^0$ to date,

$$\mathcal{S}_{\eta' K^0} = +0.68 \pm 0.07(stat) \pm 0.03(syst)$$

- first evidence of CPV in $B^0 \rightarrow \omega K^0$

$$\mathcal{S}_{\omega K_S^0} = +0.91 \pm 0.32(stat) \pm 0.05(syst)$$

- most precise measurement of $\mathcal{B}(B^0 \rightarrow \omega K^0)$ and $\mathcal{B}(B^+ \rightarrow \omega K^+)$

- Two recent measurements that provide new constraints on ϕ_2 .

- world's most precise parameters of CPV in $B^0 \rightarrow \pi^+ \pi^-$,

$$\mathcal{A}_{\pi^+ \pi^-} = +0.33 \pm 0.06(stat) \pm 0.03(syst)$$

$$\mathcal{S}_{\pi^+ \pi^-} = -0.64 \pm 0.08(stat) \pm 0.03(syst)$$

excluded $23.8^\circ < \phi_2 < 66.8^\circ$ (isospin analysis, Belle only).

- $\mathcal{B}(B^0 \rightarrow \rho^0 \rho^0)$ measured with 2.9σ significance,

$$\mathcal{B}(B^0 \rightarrow \rho^0 \rho^0) = (1.02 \pm 0.3(stat) \pm 0.22(syst)) \times 10^{-6}$$

first evidence of $B^0 \rightarrow f_0 \rho^0$, $\phi_2 = (91.0 \pm 7.2)^\circ$ (isospin analysis, Belle + W.A.)