

# Measurements of $\eta_c$ and $\eta_c(2S)$ at Belle

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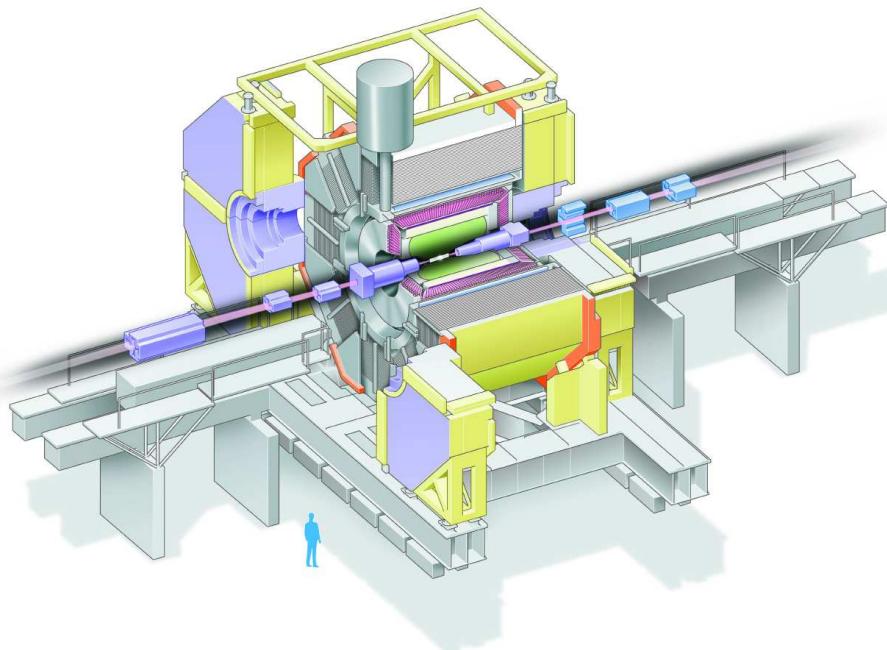
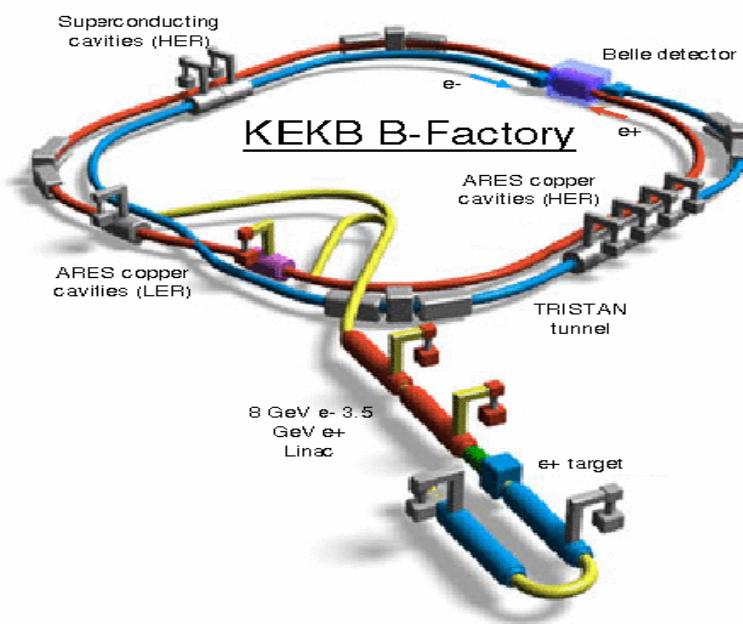
## Outline

1. Studies of the  $\eta_c(\eta_c(2S))$  in  $B$  decays
2.  $\gamma\gamma \rightarrow \eta_c(\eta_c(2S)) \rightarrow 6$  prongs   Preliminary!
3.  $\gamma\gamma \rightarrow \eta_c(\eta_c(2S)) \rightarrow VV (V = \omega, \phi)$    Preliminary!
4. Conclusions

## Motivation

- Since their first observations many measurements of  $\eta_c$  and  $\eta_c(2S)$  mass and width have been performed showing a big scatter of the values
- ( $c\bar{c}$ ) produced in  $B$  decays are accompanied with significant non-resonant background
- Measurement of the parameters should take into account interference
- Until very recently  $\eta_c(2S)$  was observed in a single mode  $K_SK^\pm\pi^\mp$  only with a negative result in searche for a dozen of final states, although 28 different decay modes are known for  $\eta_c$
- $\eta_c(2S)$  was not observed in 4-body decays with  $395 \text{ fb}^{-1}$ , so a search moved to 6-body final states with x2.5 luminosity

## KEKB, Belle Detector



$$3.5 \text{ GeV } e^+ \times 8.0 \text{ GeV } e^- \quad \mathcal{L}_{\max} = 2.1 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$$

$$\text{Continuous injection} \Rightarrow 1.2 \text{ fb}^{-1}/\text{day} \quad \int \mathcal{L} dt \approx 1040 \text{ fb}^{-1}$$

## Previously measured $\eta_c$ parameters

Experiment	Process	Mass, MeV/ $c^2$	Width, MeV/ $c^2$
E835 2001	$p\bar{p} \rightarrow \gamma\gamma$	$2984.1 \pm 2.1 \pm 1.0$	$20.4_{-6.7}^{+7.7} \pm 2.0$
BES 2003	$J/\psi \rightarrow \gamma\eta_c$	$2977.5 \pm 1.0 \pm 1.2$	$17.0 \pm 3.7 \pm 7.4$
CLEO 2004	$\gamma\gamma \rightarrow K_S^0 K^\pm \pi^\mp$	$2981.8 \pm 1.3 \pm 1.5$	$24.8 \pm 3.4 \pm 3.5$
Belle 2008	$\gamma\gamma \rightarrow \text{hadrons}$	$2986.1 \pm 1.0 \pm 2.5$	$28.1 \pm 3.2 \pm 2.2$
BaBar 2008	$B \rightarrow K\bar{K}\pi K^{(*)}$	$2985.8 \pm 1.5 \pm 3.1$	$36.3_{-3.6}^{+3.7} \pm 4.4$
Belle 2008	$\gamma\gamma \rightarrow K_S^0 K^\pm \pi^\mp$	$2981.4 \pm 0.5 \pm 0.4$	$36.6 \pm 1.5 \pm 2.0$
BaBar 2011	$\gamma\gamma \rightarrow K_S^0 K^\pm \pi^\mp$	$2982.5 \pm 0.4 \pm 1.4$	$32.2 \pm 1.1 \pm 1.3$
BaBar 2011	$\gamma\gamma \rightarrow K^+ K^- \pi^+ \pi^- \pi^0$	$2984.5 \pm 0.8 \pm 3.1$	$36.2 \pm 2.8 \pm 3.0$

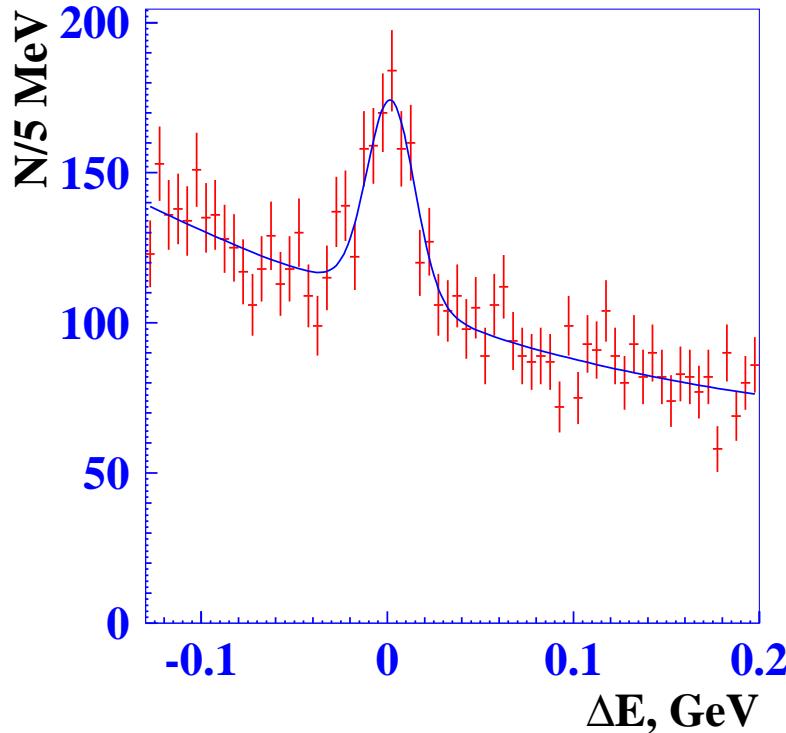
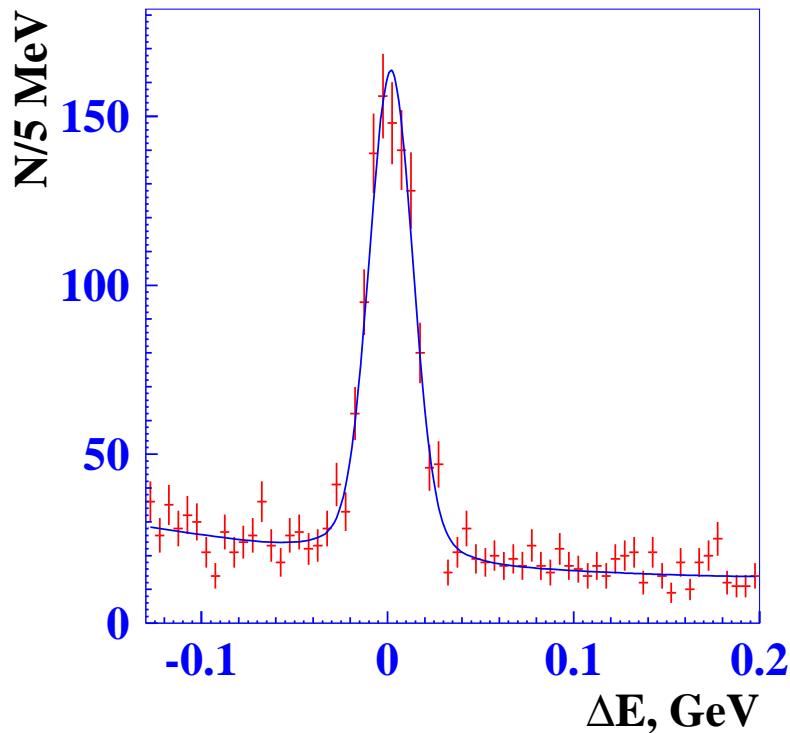
$\Delta M \sim 7 \text{ MeV}, \quad \Delta \Gamma \sim 20 \text{ MeV},$   
 rather large for claimed uncertainties

## Previously measured $\eta_c(2S)$ parameters

Experiment	Process	Mass, MeV/ $c^2$	Width, MeV/ $c^2$
Belle 2002	$B \rightarrow K K_S^0 K^\pm \pi^\mp$	$3654 \pm 6 \pm 8$	$< 55$
BaBar 2004	$\gamma\gamma \rightarrow K \bar{K} \pi$	$3630.8 \pm 3.4 \pm 1.0$	$17.0 \pm 8.3 \pm 2.5$
CLEO 2004	$\gamma\gamma \rightarrow K_S^0 K^\pm \pi^\mp$	$3642.9 \pm 3.1 \pm 1.5$	$6.3 \pm 12.4 \pm 4.0$
BaBar 2005	$e^+ e^- \rightarrow J/\psi c\bar{c}$	$3645.0 \pm 5.5^{+4.9}_{-7.8}$	$22 \pm 14$
Belle 2007	$e^+ e^- \rightarrow J/\psi c\bar{c}$	$3626 \pm 5 \pm 6$	—
Belle 2008	$\gamma\gamma \rightarrow K_S^0 K^\pm \pi^\mp$	$3633.7 \pm 2.3 \pm 1.9$	$19.1 \pm 6.9 \pm 6.0$
BaBar 2011	$\gamma\gamma \rightarrow K_S^0 K^\pm \pi^\mp$	$3638.5 \pm 1.5 \pm 0.8$	$13.4 \pm 4.6 \pm 3.2$
BaBar 2011	$\gamma\gamma \rightarrow K^+ K^- \pi^+ \pi^- \pi^0$	$3640.5 \pm 3.2 \pm 2.5$	13.4 (fixed)

$$\Delta M \sim 28 \text{ MeV}, \quad \Delta \Gamma \sim 16 \text{ MeV}$$

$$B^\pm \rightarrow K^\pm(c\bar{c}) \rightarrow K^\pm K_S^0 K^\pm \pi^\mp - I$$

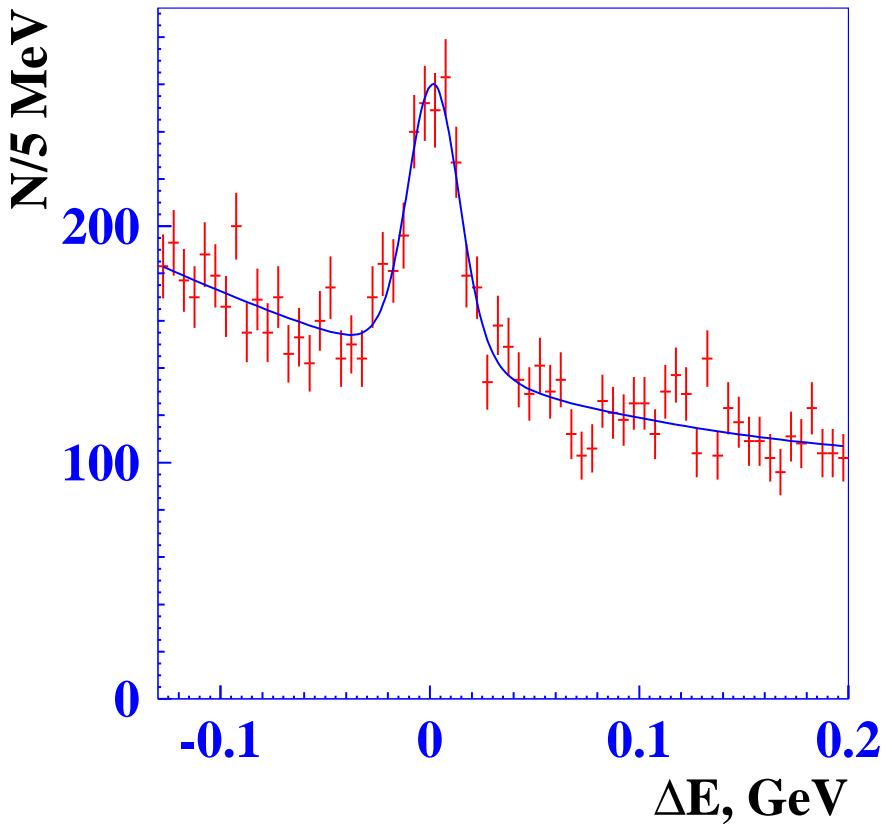
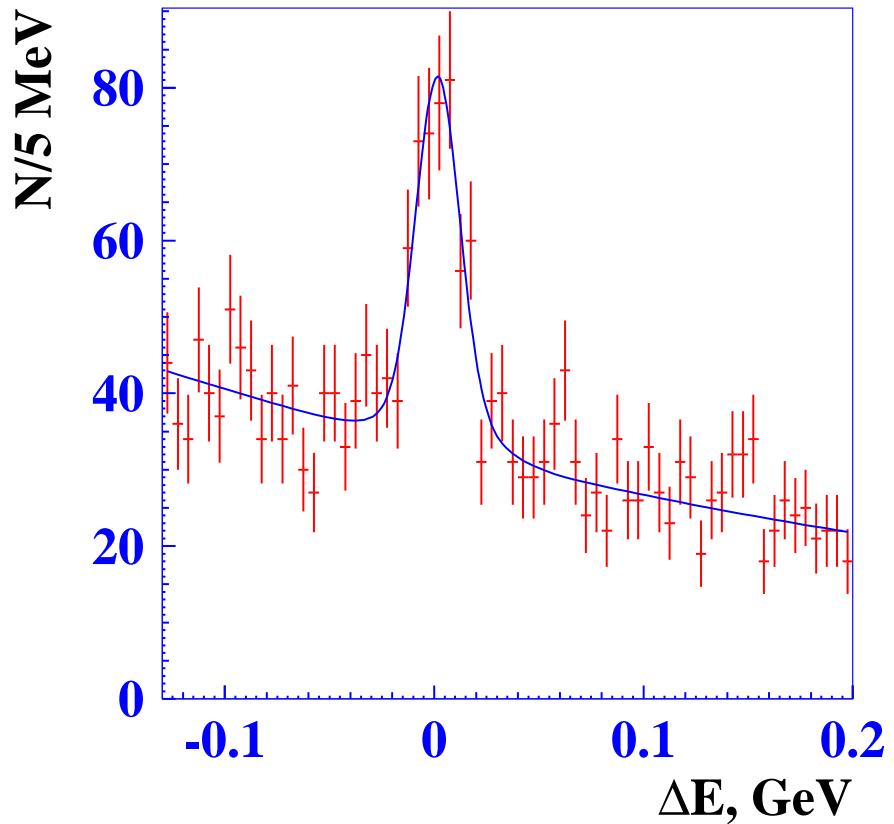


$\Delta E$  distribution for  $\eta_c$ : signal and sideband,

$\Delta E = \sum E_i - E_b$ , with  $E_b$  – the beam energy and  $E_i$  – energies of  $B$  decay products.

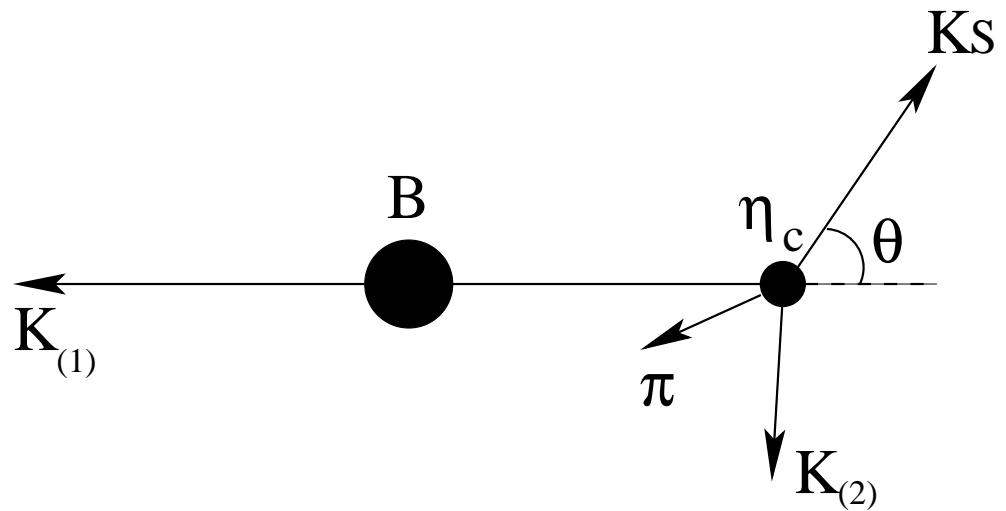
From a fit  $N_{\text{obs}} = 889 \pm 37$ ,  $N_{\text{nr}} = 87 \pm 11 \Rightarrow N_{\text{sig}} = 980 \pm 570$

$$B^\pm \rightarrow K^\pm(c\bar{c}) \rightarrow K^\pm K_S^0 K^\pm \pi^\mp - \text{II}$$



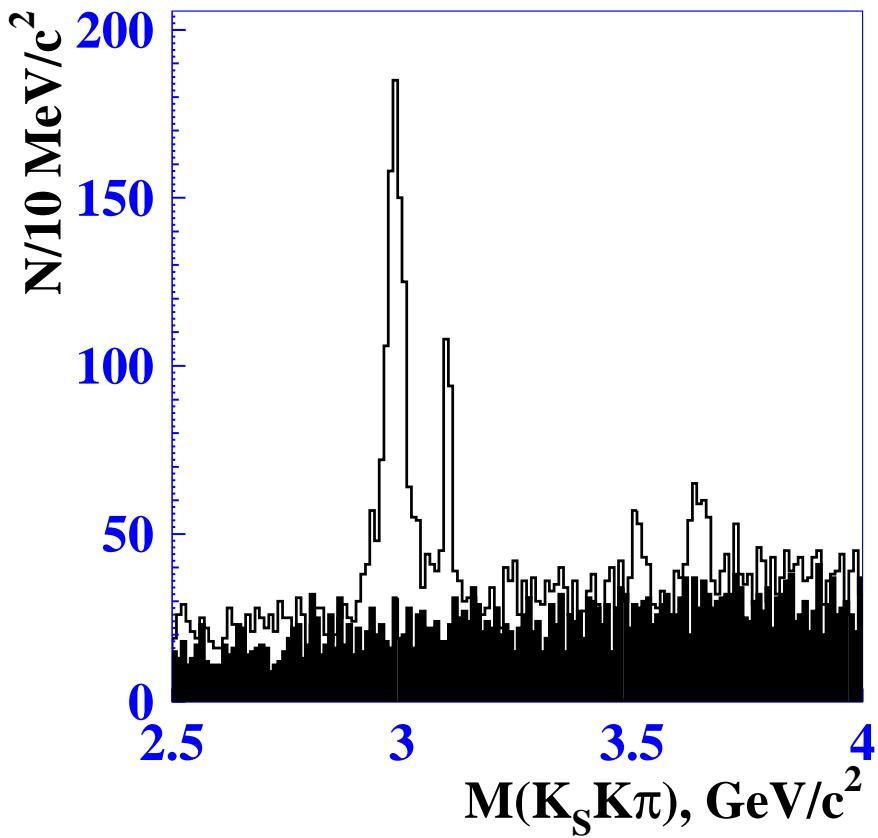
$\Delta E$  distribution for  $\eta_c(2S)$ : signal and sideband;  
for both  $\eta_c$  and  $\eta_c(2S)$  significant peaking BG  $\Rightarrow$  possible interference

$$B^\pm \rightarrow K^\pm(c\bar{c}) \rightarrow K^\pm K_S^0 K^\pm \pi^\mp - \text{III}$$



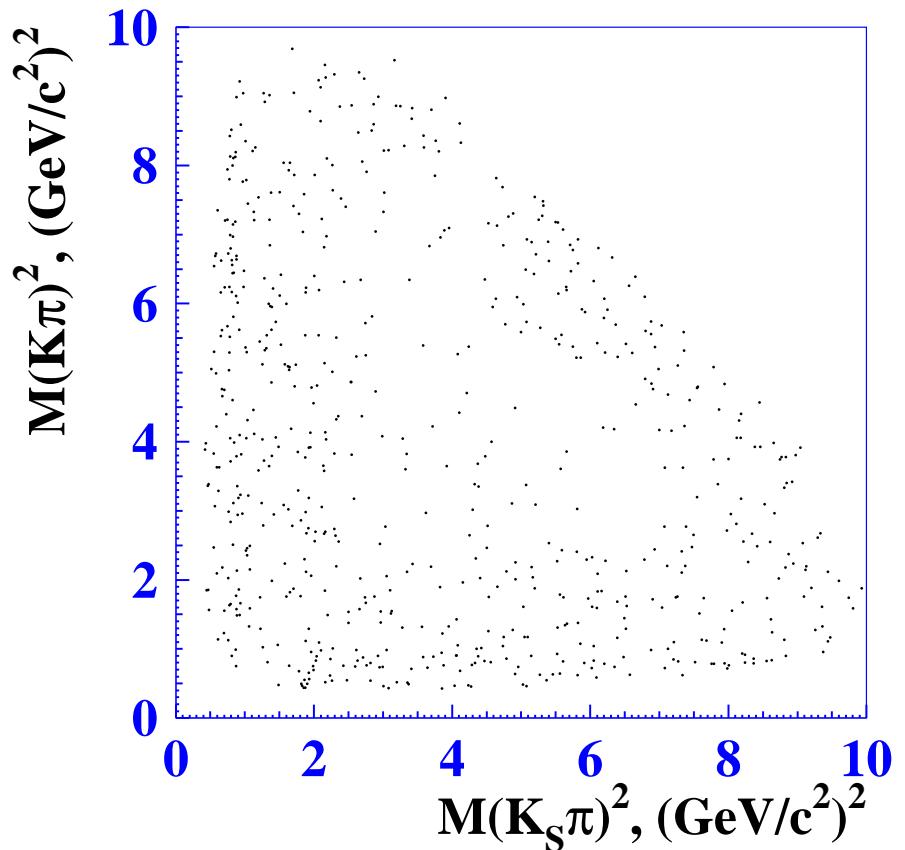
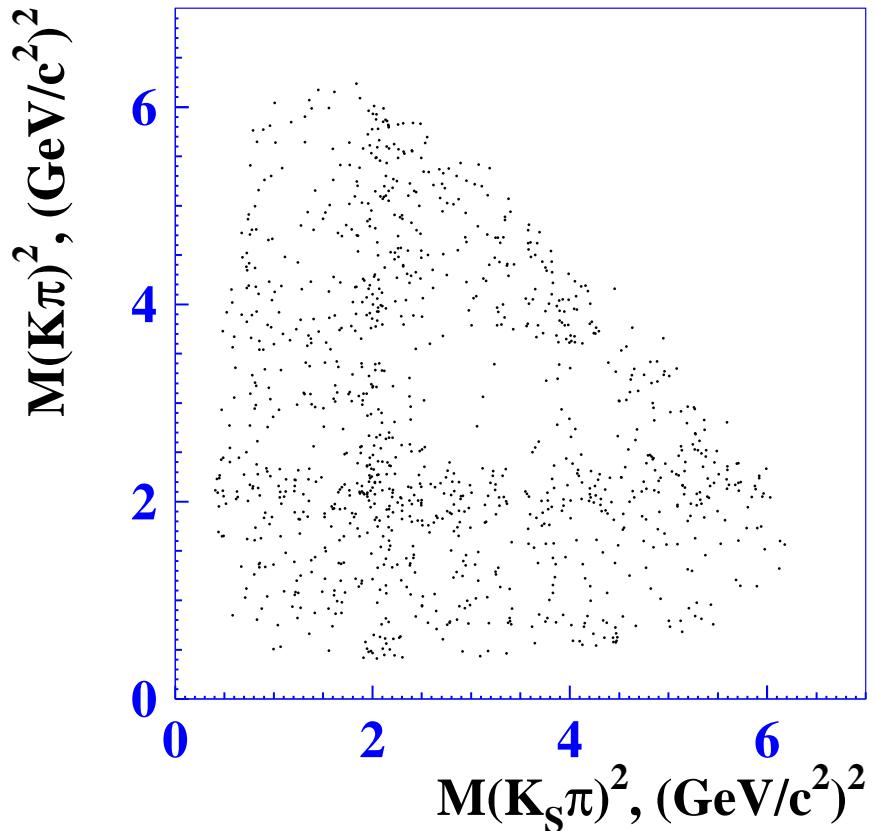
For the  $B \rightarrow K_{(1)} K_S^0 K_{(2)} \pi$  there are  $3 \times 4 - 4(E, \vec{p} \text{ cons.}) - 3(\text{B decay angles}) = 5$ , we select 5 independent variables:  $M(K_S^0 K_{(2)} \pi)$ ,  $M(K_{(2)} \pi)^2$ ,  $M(K_S^0 \pi)^2$ ,  $\theta$ ,  $\phi$ ;  $\theta$  – the angle btw. the  $K_S^0$  and  $K_{(1)}$  in the  $K_S^0 K_{(2)} \pi$  system,  $\phi$  – angle btw. the planes  $K_{(1)} - \pi$  and  $K_{(1)} - K_S^0$

$$B^\pm \rightarrow K^\pm(c\bar{c}) \rightarrow K^\pm K_S^0 K^\pm \pi^\mp - \text{IV}$$



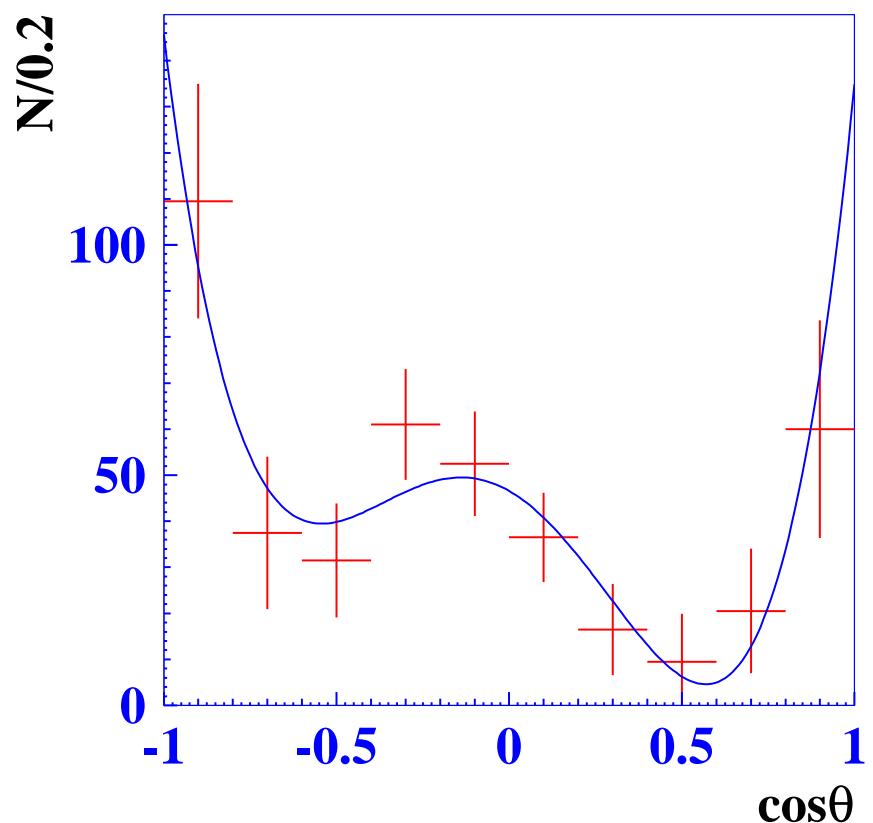
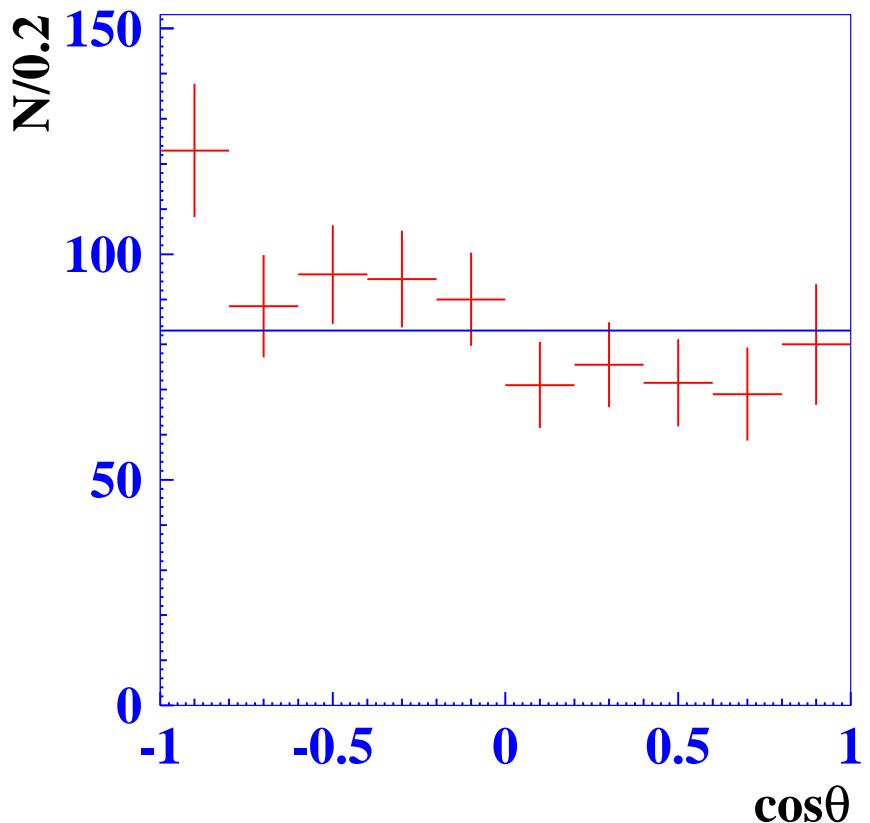
The  $M(K_S^0 K_{(2)}\pi)$  distribution shows  $\eta_c$ ,  $J/\psi$ ,  $\chi_{c1}$  and  $\eta_c(2S)$  and the non-resonant BG interfering with  $\eta_c$  or  $\eta_c(2S)$

## Dalitz plots for $\eta_c$ and $\eta_c(2S)$



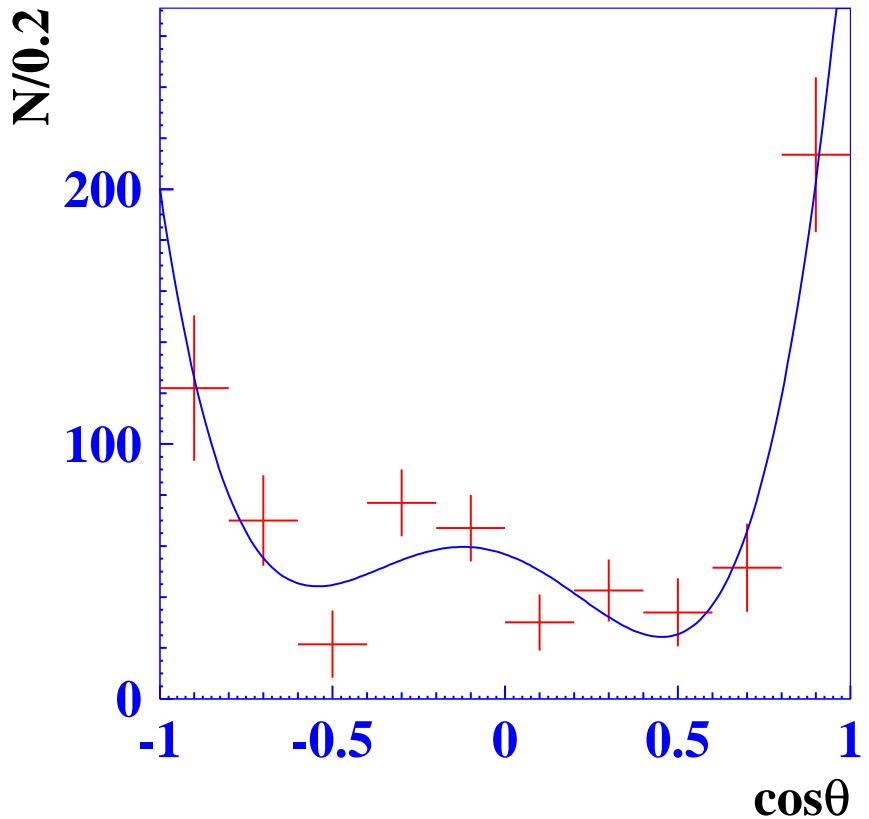
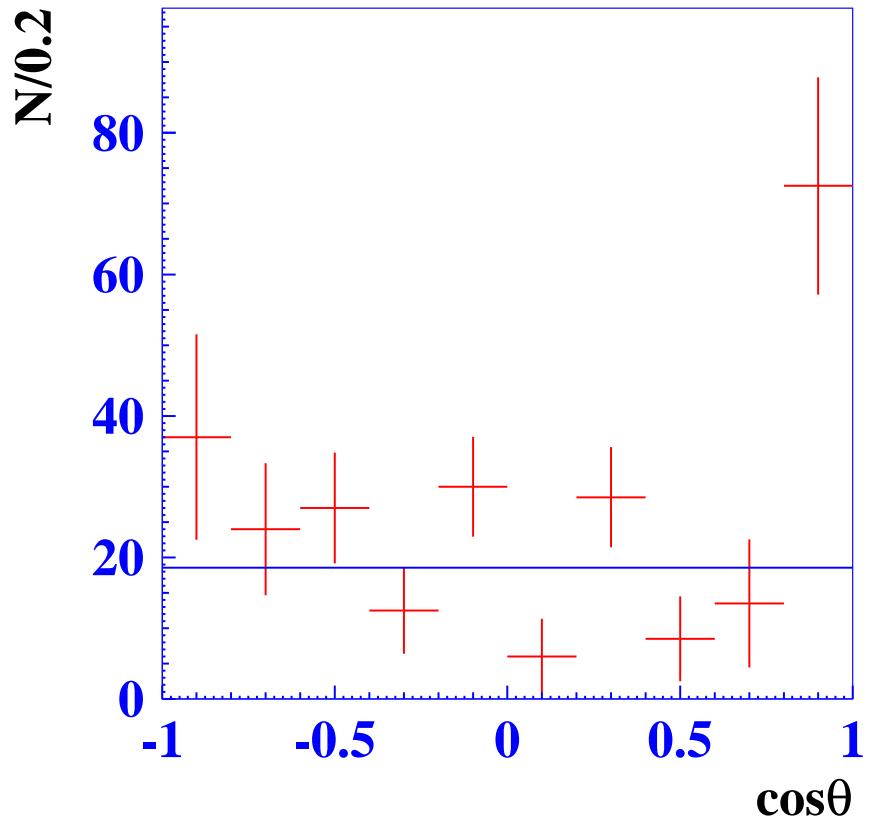
Dalitz plots show some structure at 1.4 GeV,  
but low statistics preclude Dalitz analysis

## $\cos \theta$ approximation for $\eta_c$



S-wave dominates in the signal, while the sideband is a sum of S-, P-, D-waves

## $\cos \theta$ approximation for $\eta_c(2S)$



Separation of the S- from P- and D-waves in the sideband  $\Rightarrow$  smaller uncertainty

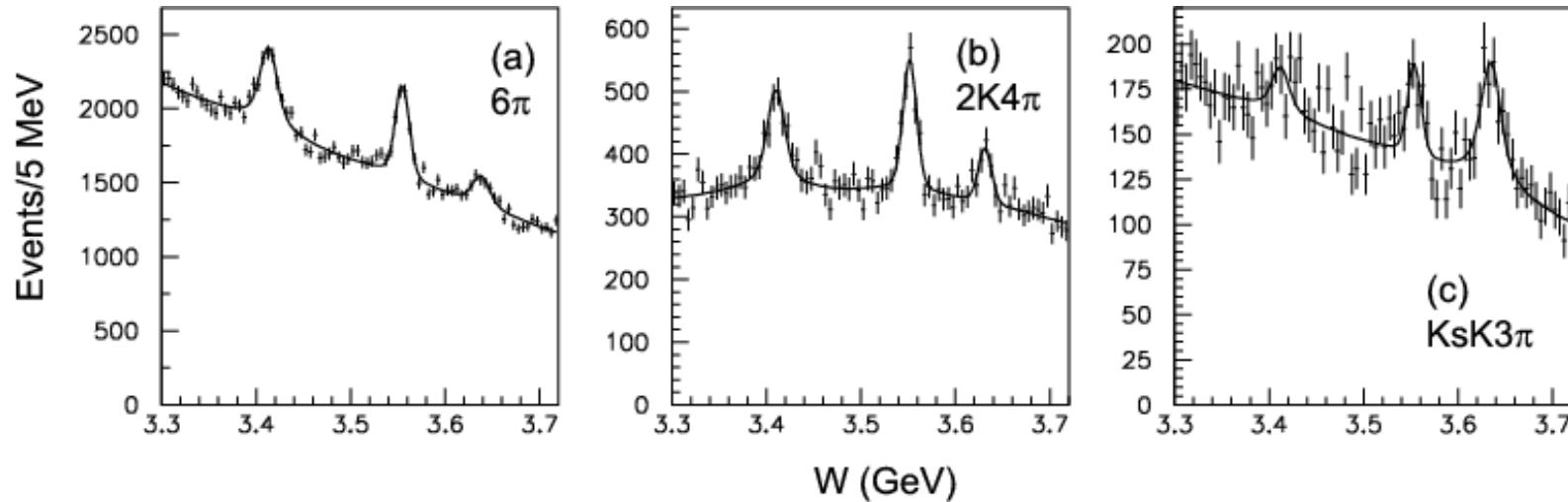
## Results with and without interference

A fit is performed in the 2D  $M(K_S^0 K_{(2)} \pi) - \theta$

	Without interference	With interference
$B^\pm \rightarrow K^\pm \eta_c, \eta_c \rightarrow (K_S K \pi)^0$		
$\mathcal{B} \times \mathcal{B}, 10^{-6}$	$24.0 \pm 1.2(stat)^{+2.1}_{-2.0}(syst)$	$26.7 \pm 1.4(stat)^{+2.9}_{-2.6}(syst) \pm 4.9(model)$
Mass, MeV	$2984.8 \pm 1.0(stat)^{+0.1}_{-2.0}(syst)$	$2985.4 \pm 1.5(stat)^{+0.5}_{-2.0}(syst)$
Width, MeV	$35.4 \pm 3.6(stat)^{+3.0}_{-2.1}(syst)$	$35.1 \pm 3.1(stat)^{+1.0}_{-1.6}(syst)$
$B^\pm \rightarrow K^\pm \eta_c(2S), \eta_c(2S) \rightarrow (K_S K \pi)^0$		
$\mathcal{B} \times \mathcal{B}, 10^{-6}$	$3.1 \pm 0.8(stat) \pm 0.2(syst)$	$3.4^{+2.2}_{-1.5}(stat + model)^{+0.5}_{-0.4}(syst)$
Mass, MeV	$3646.5 \pm 3.7(stat)^{+1.2}_{-2.9}(syst)$	$3636.1^{+3.9}_{-4.1}(stat + model)^{+0.7}_{-2.0}(syst)$
Width, MeV	$41.1 \pm 12.0(stat)^{+6.4}_{-10.9}(syst)$	$6.6^{+8.4}_{-5.1}(stat + model)^{+2.6}_{-0.9}(syst)$

PDG:  $\Gamma(\eta_c) = (28.6 \pm 2.2)$  MeV,  $\Gamma(\eta_c(2S)) = (14 \pm 7)$  MeV

## Six-prong final states in $\eta_c(2S)$ decay - I



$923 \text{ fb}^{-1}$  used to look for 6-prong final states:

$$\begin{aligned} &3(\pi^+\pi^-) - 6\pi, K^+K^- 2(\pi^+\pi^-) - 2K4\pi, \\ &2(K^+K^-)\pi^+\pi^- - 4K2\pi, K_S^0 K^\pm \pi^\mp \pi^+\pi^- - K_S^0 K3\pi \end{aligned}$$

No consistent account for interference further

## Six-prong final states in $\eta_c(2S)$ decay - II

Mode	$M$ , MeV/ $c^2$	$\Gamma$ , MeV/ $c^2$	$N_{\text{ev}}$	$S, \sigma$	$\Gamma_{\gamma\gamma}\mathcal{B}$ , eV
$6\pi$	$3638.9 \pm 1.6 \pm 2.3$	$10.7 \pm 4.9$	$1485 \pm 274$	8.5	$20.1 \pm 3.7 \pm 3.2$
$2K4\pi$	$3634.7 \pm 1.6 \pm 2.8$	$1.4^{+6.3}_{-1.4}(< 13)$	$407 \pm 91$	6.2	$10.2 \pm 2.3 \pm 3.4$
$K_s K 3\pi$	$3636.5 \pm 1.8 \pm 2.4$	$15.9 \pm 5.7$	$563 \pm 71$	8.7	$30.7 \pm 3.9 \pm 3.7$
$K^+ K^- 3\pi$	$3640.5 \pm 3.2 \pm 2.5$	13.4 (fixed)	$1201 \pm 228$	5.3	$30.0 \pm 6.0 \pm 5.0$

Averaging the Belle  $\gamma\gamma$  results over three modes gives for the  $\eta_c(2S)$ :

Mass =  $3636.9 \pm 1.1 \pm 2.5 \pm 5.0$  MeV, Width =  $9.9 \pm 3.2 \pm 2.6 \pm 2.0$  MeV

consistent with the Belle results from  $B^\pm \rightarrow K^\pm(K_S K\pi)^0$ :

Mass =  $3636.1^{+3.0+0.5}_{-3.4-2.0}$  MeV, Width =  $6.6^{+4.9+3.0}_{-3.4-0.9}$  MeV

Belle (preliminary): reported at ICHEP-2010,

BaBar: P. del Amo Sanchez et al., Phys. Rev. D84, 012004 (2011).

### Six-prong final states in $\eta_c(2S)$ decay - III

State	$N_{\text{ev}}$	$\Gamma_{\gamma\gamma}\mathcal{B}$ , eV	PDG, eV
$\chi_{c0}$	$3734 \pm 194$	$41 \pm 2 \pm 5$	$29 \pm 5$
$\chi_{c2}$	$2994 \pm 144$	$7.6 \pm 0.4 \pm 0.9$	$4.4 \pm 1.0$

Measured:  $\chi_{c0}, \chi_{c2} \rightarrow 2K4\pi, K_SK3\pi; \chi_{c2} \rightarrow 4K2\pi; \eta_c \rightarrow K_SK3\pi$  –  
observation or evidence of the new decay modes.

Also measured  $\eta_c \rightarrow 6\pi, 2K4\pi$

## Branching fractions of $\eta_c(2S)$

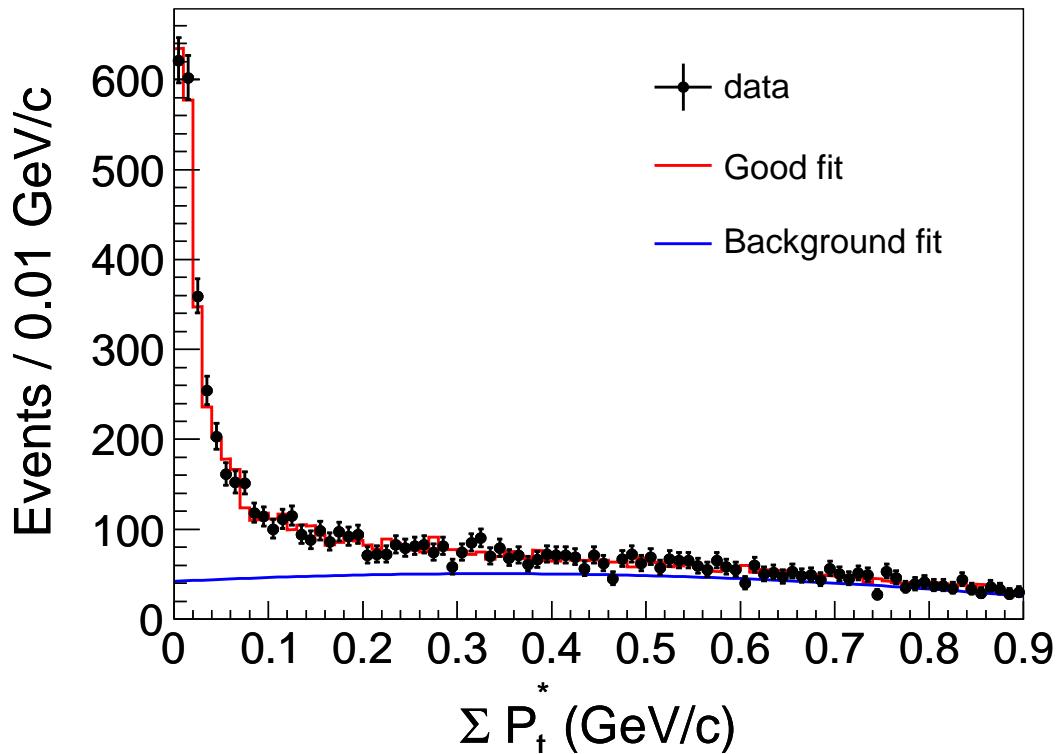
Mode	$\Gamma_{\gamma\gamma}\mathcal{B}$ , eV	Mode	$\Gamma_{\gamma\gamma}\mathcal{B}$ , eV
$4\pi$	$< 6.5$	$6\pi$	$20.1 \pm 3.7 \pm 3.2$
$2K2\pi$	$< 6.5$	$2K4\pi$	$10.2 \pm 2.3 \pm 3.4$
$4K$	$< 6.5$	$K_S^0 K3\pi$	$30.7 \pm 3.9 \pm 3.7$
$K_S^0 K\pi$	$41 \pm 4 \pm 6$	$K^+ K^- 3\pi$	$30 \pm 6 \pm 5$

- $\mathcal{B}$ 's of the new decay modes are comparable to  $\mathcal{B}(K_S^0 K\pi)$
- PDG:  $\mathcal{B}(K\bar{K}\pi) = (1.9 \pm 1.2)\%$
- All new modes have  $\mathcal{B} \sim 1.5\%$
- About 95% not yet observed!

$$\gamma\gamma \rightarrow VV (V = \omega, \phi)$$

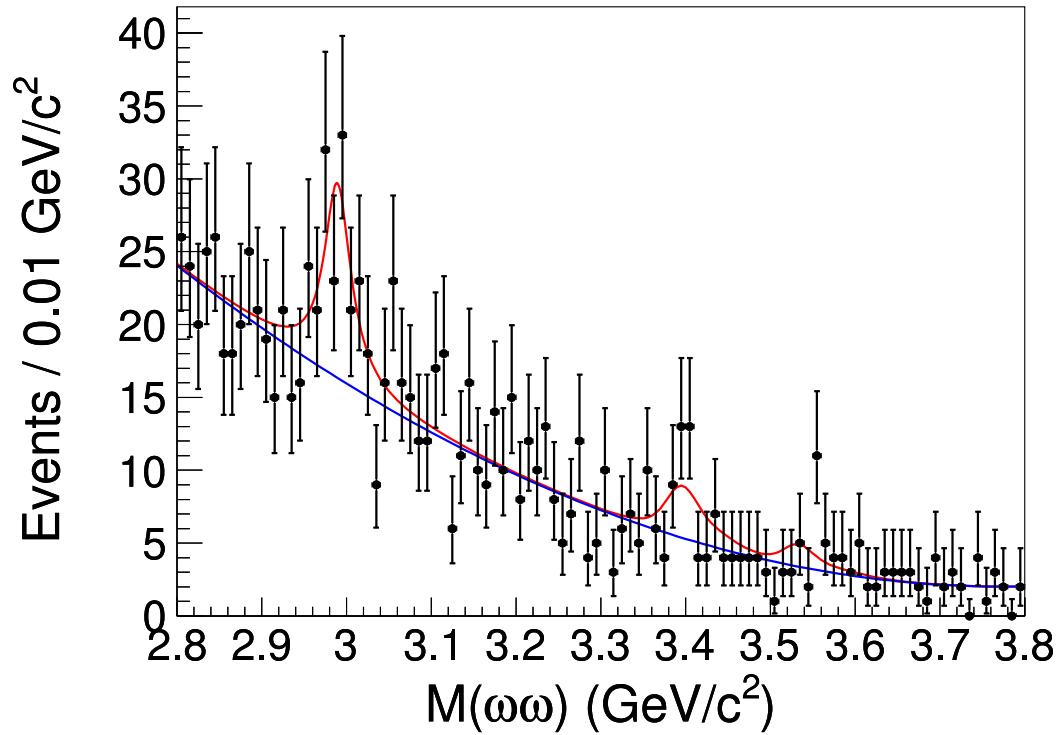
- A search for  $\gamma\gamma \rightarrow VV (V = \omega, \phi)$  with integrated luminosity of 870 fb<sup>-1</sup>
- First reported at  $\phi$ to $\psi$ -2011 – results preliminary
- Inspired by the observation of  
 $\gamma\gamma \rightarrow Z(3930) \rightarrow \omega J/\psi$  at Belle and BaBar ( $\chi_{c2}(2P)$  candidate?)  
and evidence for  $\gamma\gamma \rightarrow Y(4350) \rightarrow \phi J/\psi$
- Observation of 6-prong decays in  $\gamma\gamma$  stimulates searches for dynamics
- Reconstruction via  $\omega \rightarrow \pi^+ \pi^- \pi^0$ ,  $\phi \rightarrow K^+ K^-$

$\gamma\gamma \rightarrow VV (V = \omega, \phi)$



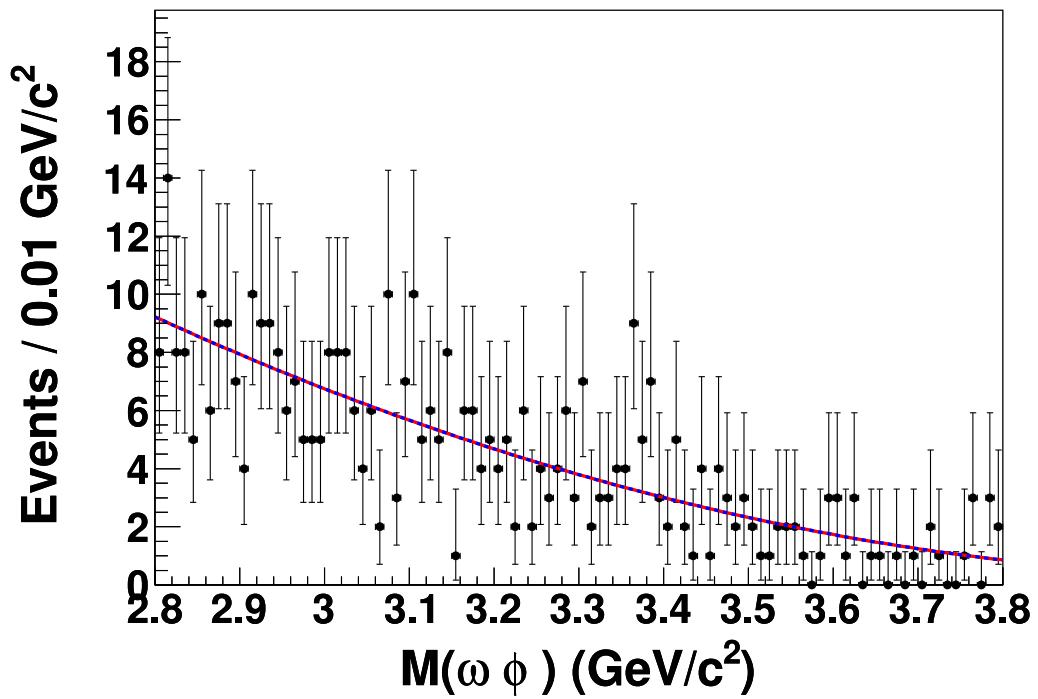
$\Sigma P_t^*$  distribution peaking at zero – distinctive feature of  $\gamma\gamma$  events

$\gamma\gamma \rightarrow \omega\omega$



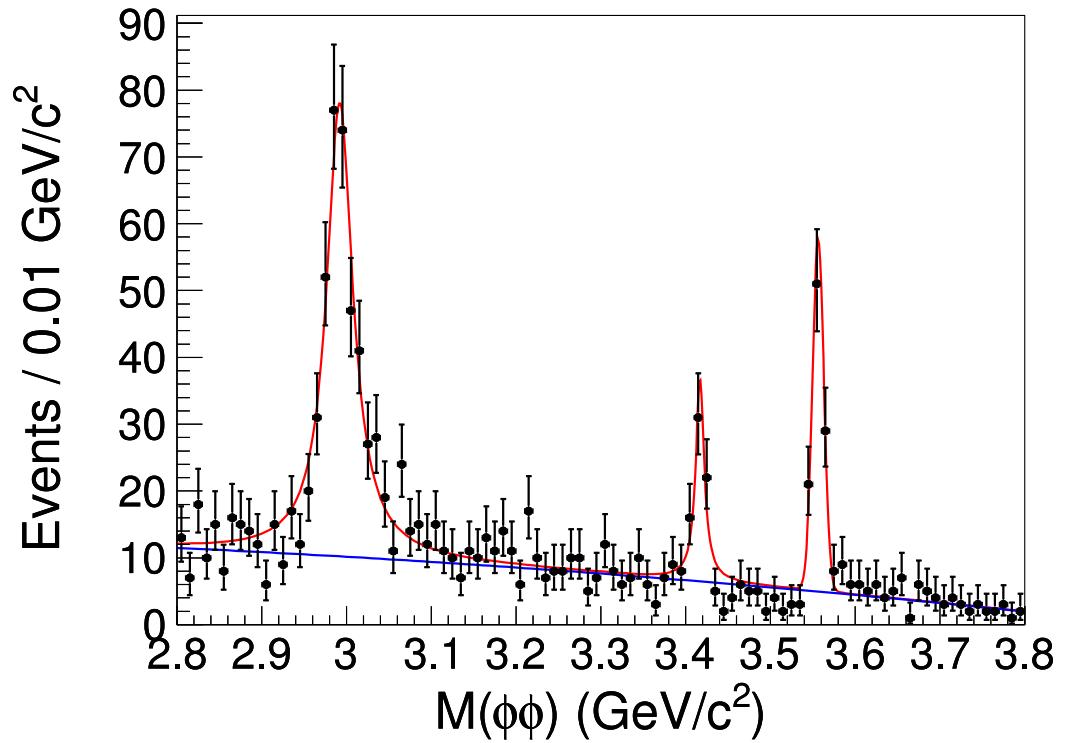
Evidence for  $\eta_c$ ,  $\chi_{c0}$ ,  $\chi_{c2}$  seen, for  $\eta_c$  – first time

$\gamma\gamma \rightarrow \omega\phi$



No signals seen

$\gamma\gamma \rightarrow \phi\phi$



Prominent signals of  $\eta_c$ ,  $\chi_{c0}$ ,  $\chi_{c2}$  observed

$$\gamma\gamma \rightarrow VV (V = \omega, \phi)$$

Mode	$\eta_c$	$\chi_{c0}$	$\chi_{c2}$
$\omega\omega$	$8.64 \pm 2.92 \pm 0.96$	$< 5.5$	$< 0.59$
$\omega\phi$	$< 0.46$	$< 0.43$	$< 0.04$
$\phi\phi$	$7.72 \pm 0.66 \pm 0.61$	$1.72 \pm 0.33 \pm 0.14$	$0.62 \pm 0.07 \pm 0.05$
$\phi\phi$	$6.8 \pm 1.2 \pm 1.3$	$2.3 \pm 0.9 \pm 0.4$	$0.58 \pm 0.18 \pm 0.16$

Belle:  $\phi$ to $\psi$ -2011

Belle (4-prongs): S. Uehara et al., Eur. Phys. J. C53, 1 (2008)

## Conclusions

- First consistent account for interference in  $B \rightarrow K(c\bar{c})$  decays shows their significance for extraction of parameters
- Three new (topological) decay modes of the  $\eta_c(2S)$  observed at Belle:  
 $3(\pi^+\pi^-)$ ,  $K^+K^-2(\pi^+\pi^-)$ ,  $K_S^0K^\pm\pi^\mp\pi^+\pi^-$   
and one more by BaBar –  $K^+K^-\pi^+\pi^-\pi^0$
- New decay modes of the  $\eta_c(2S)$  have  $\mathcal{B}$ 's comparable to that for  $K_S^0K^\pm\pi^\mp$ , but in total make less than 5%
- First evidence for the new decay mode  $\eta_c \rightarrow \omega\omega$
- Evidence or observation of the new decay modes:  
 $\chi_{c0}, \chi_{c2} \rightarrow 2K4\pi, K_S^0K3\pi; \chi_{c2} \rightarrow 4K2\pi; \eta_c \rightarrow K_S^0K3\pi$
- Remember about interference while extracting the parameter values!

Backup slides

Systematic uncertainties of the product branching fractions (in %)

Source	$\eta_c$	$\eta_c(2S)$
Number of $B\bar{B}$ pairs	1.3	1.3
Model efficiency dependence	$+8.6$ $-6.7$	$+2.0$ $-1.5$
Background approximation	—	+2.3
Bin size	-3.3	$+13.3$ $-3.9$
$\Delta E$ cut	-2.2	+2.3
Detector resolution	+1.1	$+4.7$ $-8.6$
$M_{inv}$ efficiency dependence	+2.2	+0.8
Track reconstruction	3	3
$K^\pm$ identification	1.6	1.6
$\pi^\pm$ identification	1.5	1.5
$K_S$ reconstruction	4.4	4.4
Total, %	$+10.7$ $-9.8$	$+15.8$ $-11.9$

## Systematic uncertainties of masses and widths (in $\text{MeV}/c^2$ )

Source	$\eta_c$		$\eta_c(2S)$	
	Mass	Width	Mass	Width
Background approximation	—	—	+0.2	-0.1
Bin size	+0.2	-1.0	-1.1	+2.4
Detector resolution	-0.1	+1.0 -1.2	+0.5 -0.1	+1.8 -0.9
Scale uncertainty	-2.0	—	-1.7	—
Total, $\text{MeV}/c^2$	+0.2 -2.0	+1.0 -1.6	+0.5 -2.0	+2.6 -0.9