May 14, 2009

Study of $B \to K\eta_c$ and $B \to K\eta_c(2S)$ decays

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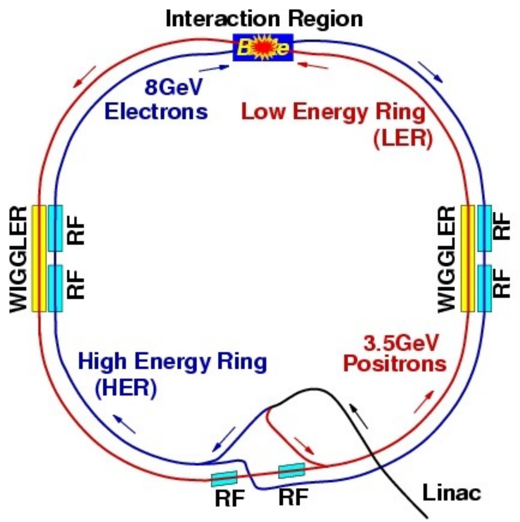
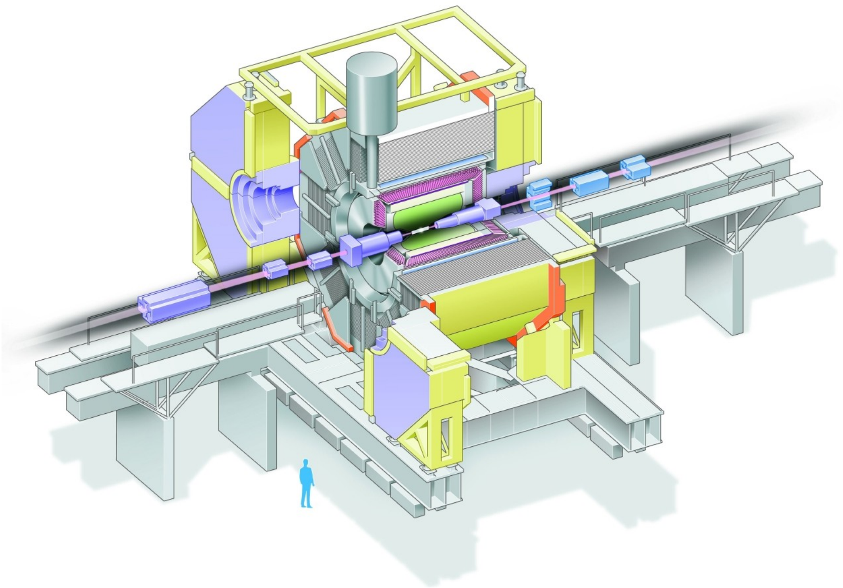




KEKB

- 3.5 GeV $e^+ \times$ 8.0 GeV e^-
- $\sqrt{s}$ = 10.58 GeV
- $\mathscr{L}_{max} = 1.9 \cdot 10^{34}\ cm^{-2}\ s^{-1}$
- $\int \mathscr{L} dt > 840\ fb^{-1}$

BELLE

- Si vertex detector
- drift chamber
- time-of-flight counters
- aerogel Cherenkov counters
- CsI(Tl) calorimeter
- 1.5 T solenoid
- μ and K_L identification system

Motivation

- Decays $\eta_c \to$ hadrons are not very well studied, their branching fractions are known with rather poor accuracy
- $B^{\pm} \to K^{\pm} c\bar{c}$ is a copious source of charmonia
- $\eta_c(2S)$ meson is an excited state of η_c – similar analysis algorithm
- $\eta_c(2S)$ was seen in one hadronic decay ($\eta_c(2S) \to K_s K\pi$) only
- A data sample accumulated at Belle allows to improve the existing values of branching products of η_c and $\eta_c(2S)$ decaying to ($K_s K\pi$)
- $c\bar{c} \to K_s K\pi$ mode can be used to determine masses and widths of η_c and $\eta_c(2S)$ mesons

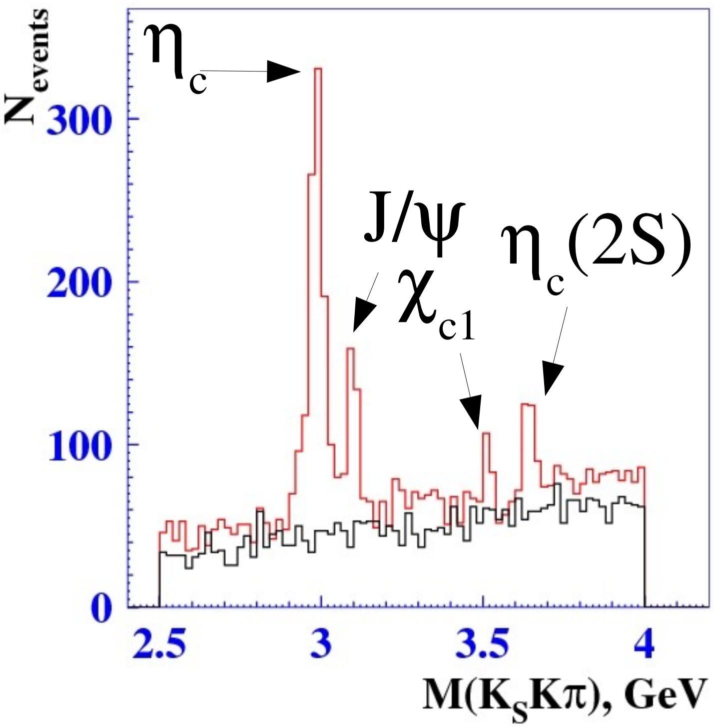
Decay modes

1. $B^{\pm} \rightarrow K^{\pm}\eta_c$, $\eta_c \rightarrow K_s K\pi$, $K_s \rightarrow \pi^+\pi^-$
2. $B^{\pm} \rightarrow K^{\pm}\eta_c(2S)$, $\eta_c(2S) \rightarrow K_s K\pi$, $K_s \rightarrow \pi^+\pi^-$

The data sample of ~535 million $B\bar{B}$ pairs was used.

Selection criteria

- $|\Delta R| < 0.2$ cm, $|\Delta Z| < 2.5$ cm
- $P_t > 0.1$ GeV/c
- $18° < \theta_{track} < 152°$
- PID(K/π) > 0.6 for K mesons
- PID(π/K) > 0.2 for π mesons
- $|\cos\theta_{Th}| < 0.8$



$B^{\pm} \to K^{\pm}\eta_c$, $\eta_c \to K_s K\pi$, $K_s \to \pi^+\pi^-$

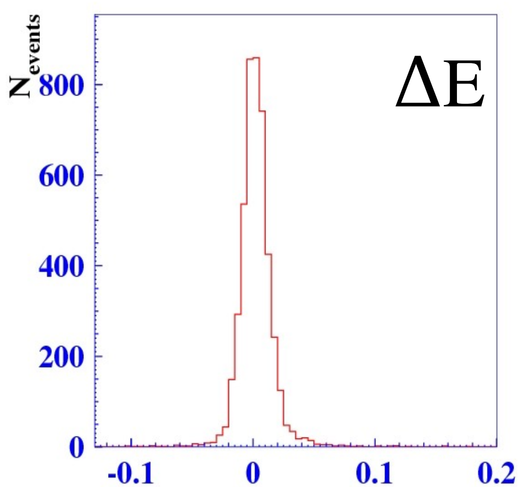
Events with invariant mass combinations M(KKK), M(KK), M(Kπ), $M(K_sK\pi)$, $M(K_sK)$ consistent with φ (1.02 ± 0.01 GeV), D^0 (1.865 ± 0.015 GeV), $D^{\pm}$ (1.869 ± 0.015 GeV), or $D_s^{\pm}$(1.968 ± 0.03 GeV) mesons were excluded from the analysis.

In case of multiple candidates the one with the best K_s mass, vertex coordinate, and η_c mass was chosen.

Number of events was obtained from the fit of the ΔE distribution by $f = N_{events} \cdot ((1-\alpha)\cdot\text{Gauss1} + \alpha\cdot\text{Gauss2}) + c_0(1+c_1x+c_2x^2)$ (c_1 is fixed from sideband)

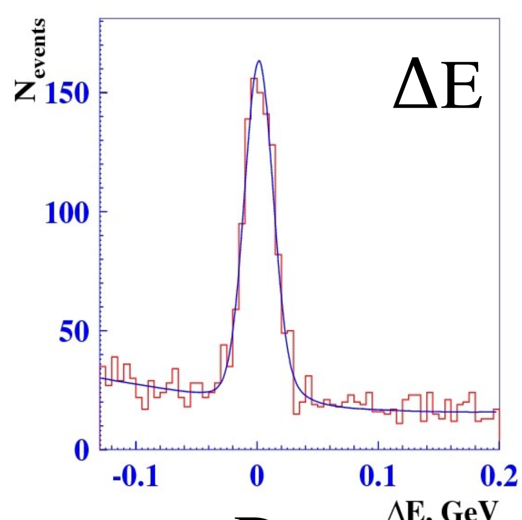
Signal region: $|\Delta E|<0.03$ $|M_{bc}-5.279|<0.006$

$\varepsilon = (11.07 \pm 0.12)\%$



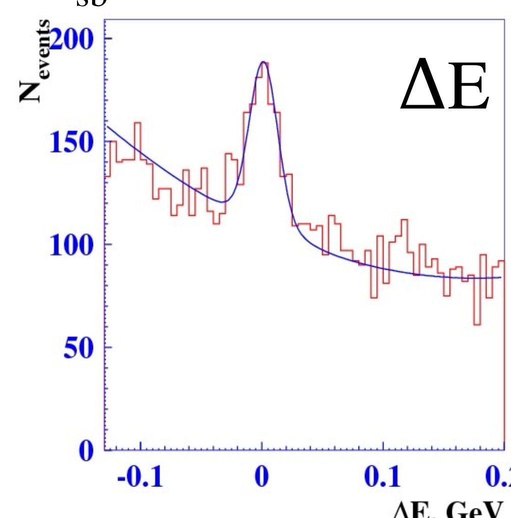
MC

$N = 877 \pm 36$



Data

$N_{sb}/5.33 = 88 \pm 8$



$M(\eta_c)$ sideband

Effect of the interference between η_c signal and non-resonant contribution on the number of signal events

$$N_{observed} = K \cdot |A_{signal} + A_{non\text{-}res}|^2 =$$

$$= K \cdot (|A_{signal}|^2 + |A_{non\text{-}res}|^2 + 2\Re(A_{signal} A^*_{non\text{-}res}))$$

Assumption 1: no interference

$$N_{observed} = K \cdot (|A_{signal}|^2 + |A_{non\text{-}res}|^2) \qquad N_{signal} = K \cdot |A_{signal}|^2 = 789 \pm 37$$

Assumption 2: destructive interference

$$N_{observed} = K \cdot (|A_{signal}|^2 + |A_{non\text{-}res}|^2 + 2|A_{signal}| \cdot |A_{non\text{-}res}|) \qquad N_{signal} = 1345 \pm 44$$

Assumption 3: constructive interference

$$N_{observed} = K \cdot (|A_{signal}|^2 + |A_{non\text{-}res}|^2 - 2|A_{signal}| \cdot |A_{non\text{-}res}|) \qquad N_{signal} = 662 \pm 31$$

Model uncertainty is very large: $N_{signal} = K \cdot |A_{signal}|^2 = 1000 \pm 340$

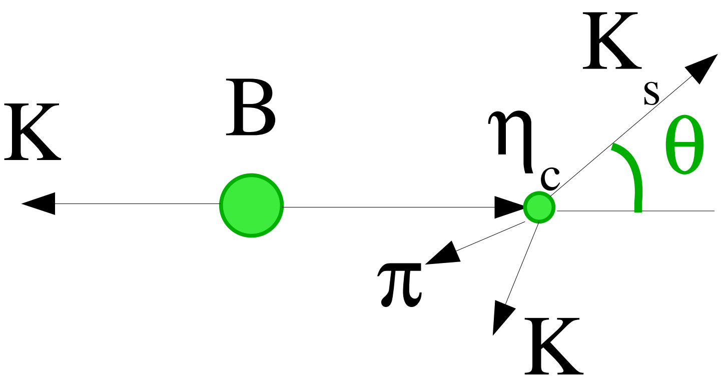
To decrease this uncertainty the interference needs to be taken into account.

Interference

4-particle decay $B^{\pm}\to K^{\pm}K_sK\pi$ has 5 (4×3 – 4 conserv. laws – 3 B decay angles)

independent variables in phase space: Dalitz variables (q_1=M$(K\pi)^2$, q_2=M$(K_S\pi)^2$),

angles (θ, ϕ), and $K_sK\pi$ invariant mass.

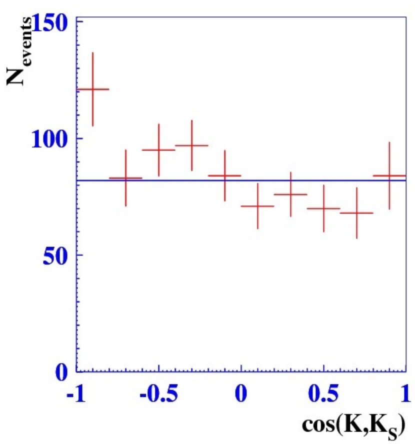


Due to low statistics we don't use angle ϕ (between planes ($K\pi$) and (K_sK)) or Dalitz plot to extract non-resonant contribution.

For our study we use cosθ and M($K_sK\pi$) distributions.

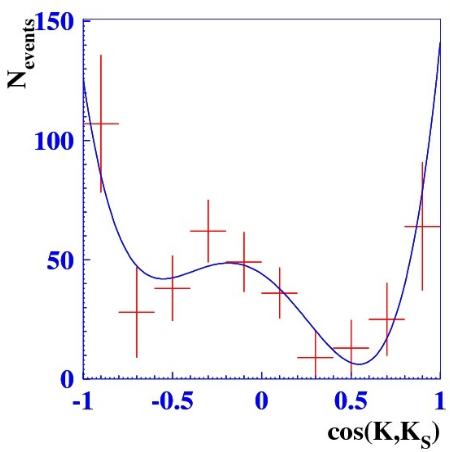
Signal:

M(η_c) siganl region



Non-resonant term:

M(η_c) sideband



Decay $\eta_c(0^-)\to K_sK\pi$ has uniform dependence on cosθ.

From the angular distribution of non-resonant term we assume that there are at least S, P, and D-wave contributions.

Fitting function

efficiency correction: $(1+\varepsilon_1 x+\varepsilon_2 x^2)$

S-wave non-res: $\alpha A_S(q_1,q_2)$

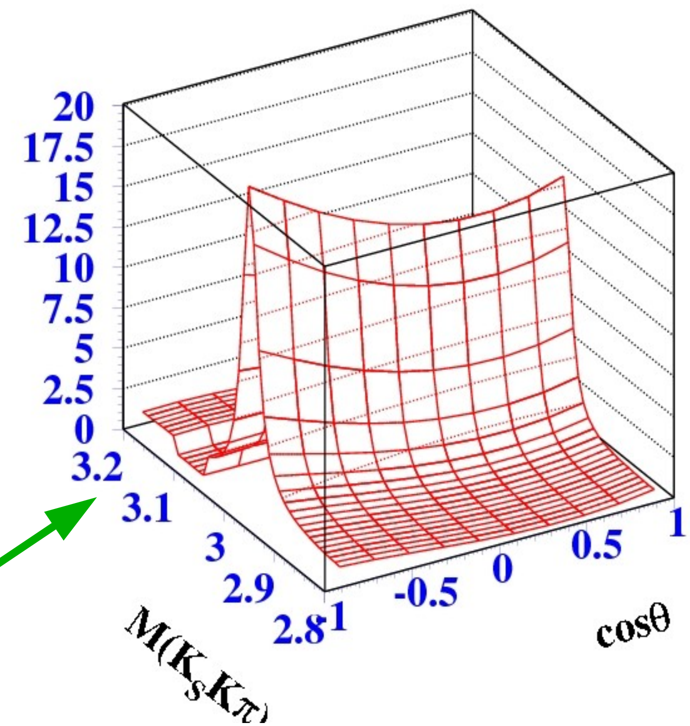
P-wave non-res: $\beta A_P(q_1,q_2)P$

D-wave non-res: $\gamma A_D(q_1,q_2)D$

η_c S-wave signal: $\frac{\sqrt{N}}{s-M^2+iM\Gamma}A_\eta(q_1,q_2)$

$$F = (1+\varepsilon_1 x+\varepsilon_2 x^2)\cdot \int \left|\left(\frac{\sqrt{N}}{s-M^2+iM\Gamma}A_\eta(q_1,q_2)+\alpha A_S(q_1,q_2)\right)S+\beta A_P(q_1,q_2)P+\gamma A_D(q_1,q_2)D\right|^2 dq_1^2\, dq_2^2\, d\phi$$

- $x \equiv \cos\theta$
- $s \equiv M(K_s K\pi)$
- $S = \frac{1}{\sqrt{2}}$, $P = \sqrt{\frac{3}{2}}x$, $D = \frac{3}{2}\sqrt{\frac{5}{2}}(x^2-1/3)$
- $\int |A_{\eta,S,P,D}(q_1,q_2)|^2 dq_1^2\, dq_2^2\, d\phi = 1$

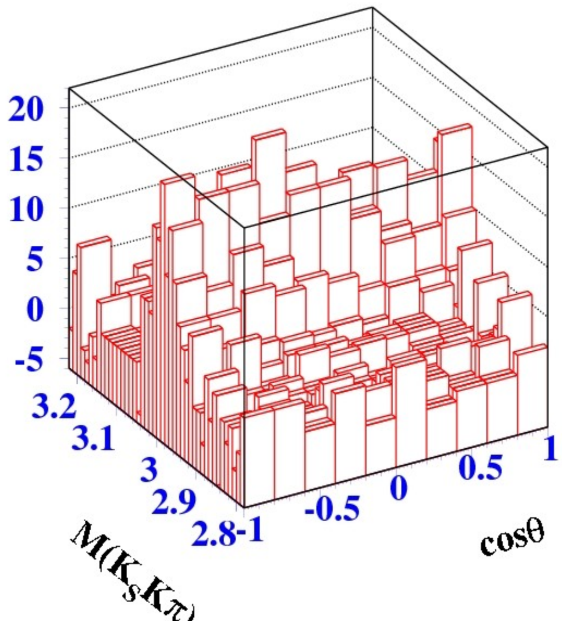


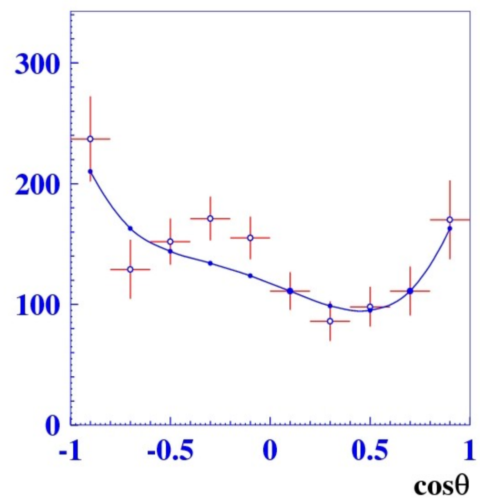
η_c region: J/ψ veto

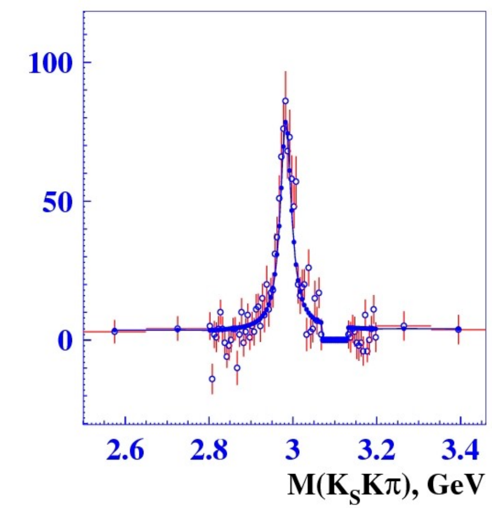
$\eta_c(2S)$ region: χ_{c1} veto

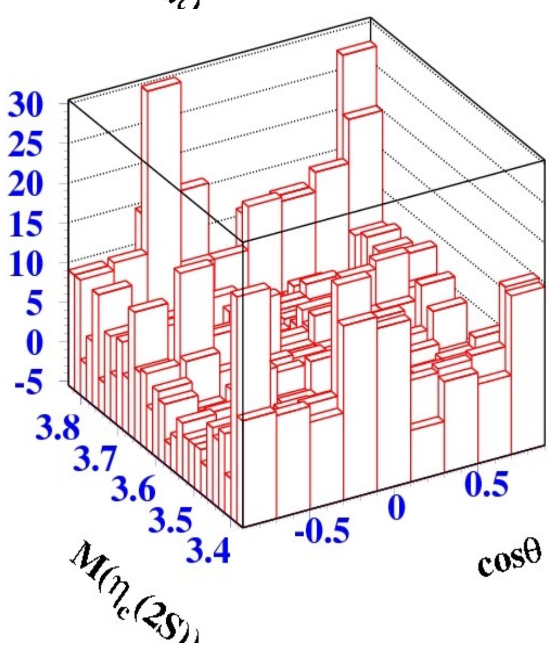
Distribution of signal and non-resonant term events

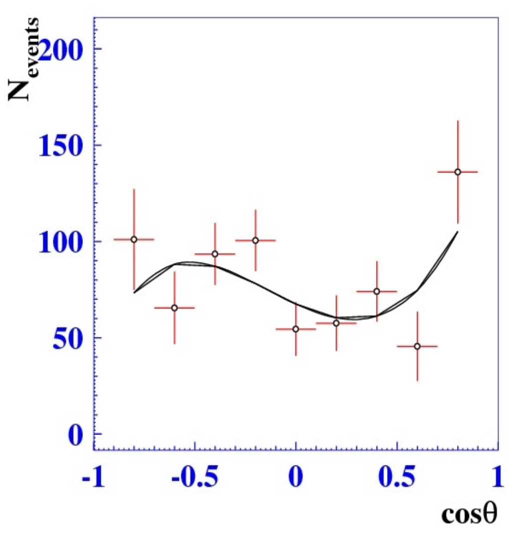
Projections

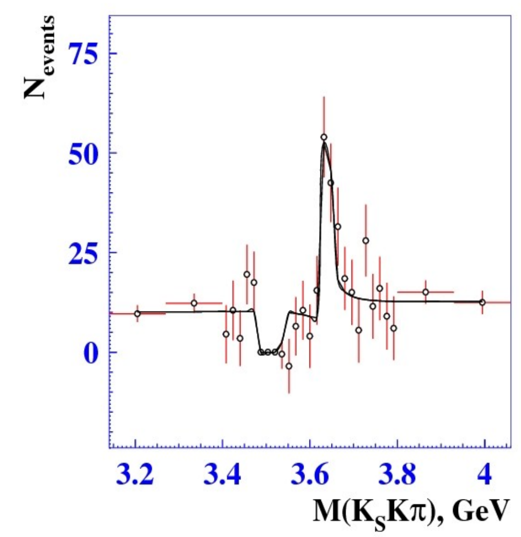












Preliminary results

	This work	BaBar	CLEO	Belle
$\mathcal{B}(B^\pm \to K^\pm \eta_c) \times \mathcal{B}(\eta_c \to K_s K\pi)$, $\times 10^{-6}$	$20.5 \pm 1.2(\text{stat})\,^{+1.4}_{-2.2}(\text{syst}) \pm 4.4(\text{model})$		21.2±4.7	(PDG)
$M(\eta_c)$, MeV	$2984.2 \pm 1.2(\text{stat})\,^{+0}_{-1.8}(\text{syst}) \pm 0.2(\text{model})$	2982.5±1.1±0.9	2981.8±1.3±1.5	2979.6±2.3±1.6
$\Gamma(\eta_c)$, MeV	$30.7 \pm 2.3(\text{stat})\,^{+0.4}_{-1.2}(\text{syst}) \pm 0.4(\text{model})$	34.3±2.3±0.9	24.8±3.4±3.5	29±8±6
$\mathcal{B}(B^\pm \to K^\pm \eta_c(2S)) \times \mathcal{B}(\eta_c(2S) \to K_s K\pi)$, $\times 10^{-6}$	$2.2 \pm 0.6(\text{stat})\,^{+0.6}_{-0.1}(\text{syst}) \pm 0.8(\text{model})$		2.2±1.8	(PDG)
$M(\eta_c(2S))$, MeV	$3638.2 \pm 2.3(\text{stat})\,^{+1.3}_{-2.4}(\text{syst}) \pm 0.8(\text{model})$	3645.0±5.5±6.4	3642.9±3.1±1.5	3654±6±8
$\Gamma(\eta_c(2S))$, MeV	$6.0\,^{+13.3}_{-1.4}(\text{stat})\,^{+8.1}_{-0.8}(\text{syst}) \pm 2.5(\text{model})$	17.0±8.3±2.5	6.3±12.4±4.0	< 55

Model error comes from the uncertainty of the interference between signal and non-resonant contribution.

Conclusion

- Large amount of data allows to determine mass and width of the charmonium states η_c and $\eta_c(2S)$ with rather small statistical errors
- The effect of intereference between signal and non-resonant contribution is estimated and included as model uncertainty for the values of branching product $B(B^{\pm}\rightarrow K^{\pm}\eta_c)\times B(\eta_c\rightarrow K_s K\pi)$, $B(B^{\pm}\rightarrow K^{\pm}\eta_c(2S))\times B(\eta_c(2S)\rightarrow K_s K\pi)$, and also η_c and $\eta_c(2S)$ mass and width
- Obtained branching products have the best accuracy and their values are consistent with the world average

Plans

- The interference effect will be studied in other hadronic decay modes of η_c, such as (ηK^+K^-), $(\eta\pi^+\pi^-)$, and $(\pi^0K^+K^-)$
- To study similar decay modes of the excited state $\eta_c(2S)$

Backup

$B^{\pm} \to K^{\pm}\eta_c(2S)$, $\eta_c(2S) \to K_s K\pi$, $K_s \to \pi^+\pi^-$

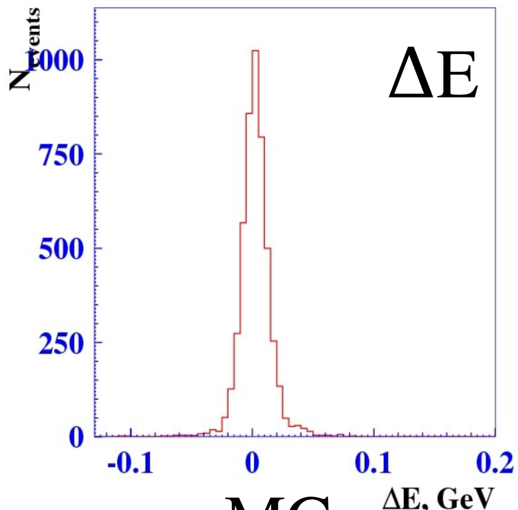
Events with invariant mass combinations M(KKK), M(KK), M(Kπ), $M(K_sK\pi)$, $M(K_sK)$ consistent with φ (1.02 ± 0.01 GeV), D^0 (1.865 ± 0.015 GeV), $D^{\pm}$ (1.869 ± 0.015 GeV), or $D_s^{\pm}$(1.968 ± 0.03 GeV) mesons were excluded from the analysis.

In case of multiple candidates the one with the best K_s mass, vertex coordinate, and η_c mass was chosen.

Number of events was obtained from the fit of the ΔE distribution by the sum of the Crystal Ball function and the background function $f = N_{events} \cdot ((1-\alpha)\cdot Gauss1 + \alpha\cdot Gauss2) + c_0(1+c_1x+c_2x^2)$ (c_1 is fixed from sideband)

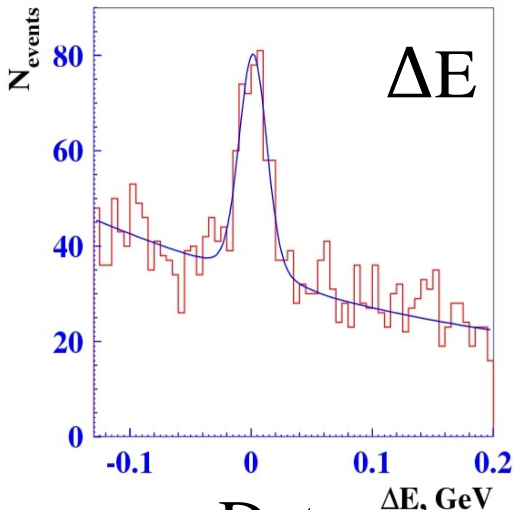
Signal region: $|\Delta E|<0.03$ $|M_{bc}-5.279|<0.006$

ε = (12.69 ± 0.19)%



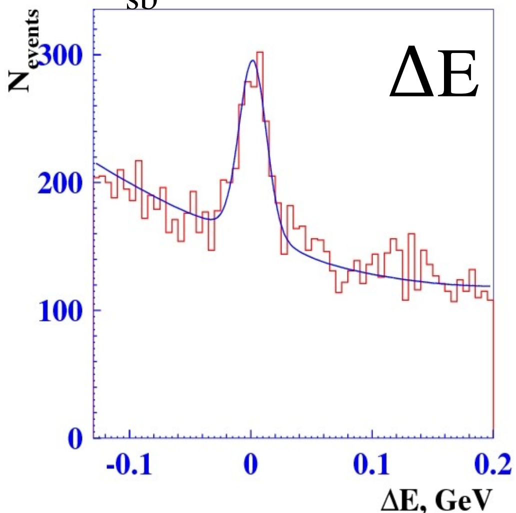
MC

N = 282 ± 30



Data

$N_{sb}/5 = 154 \pm 10$



$M(\eta_c(2S))$ sideband

Fitting function (2)

13 parameters:

- N, α, β, γ
- interf. between A_η and $A_{S,P,D}$ (6): $\int\Re(A_\eta A^*_{S,P,D})dq_1^2dq_2^2d\phi$, $\int\Im(A_\eta A^*_{S,P,D})dq_1^2dq_2^2d\phi$
- interf. between A_S, A_P, and A_D (3): $\int\Re(A_S A^*_{P,D})dq_1^2dq_2^2d\phi$, $\int\Re(A_P A^*_D)dq_1^2dq_2^2d\phi$

$$F = \frac{1+\varepsilon_1 x+\varepsilon_2 x^2}{(s-M^2)^2+(M\Gamma)^2}\sum_{i=0}^{2}\sum_{j=0}^{4} C_{ij}\, s^i x^j \qquad \Rightarrow 15\ C_{ij}$$

$C_{03} = \delta_1 C_{13}$, $C_{13} = \delta_2 C_{23}$
$C_{04} = \delta_1 C_{14}$, $C_{14} = \delta_2 C_{24}$
} linearly dependent

From the fit we can obtain only

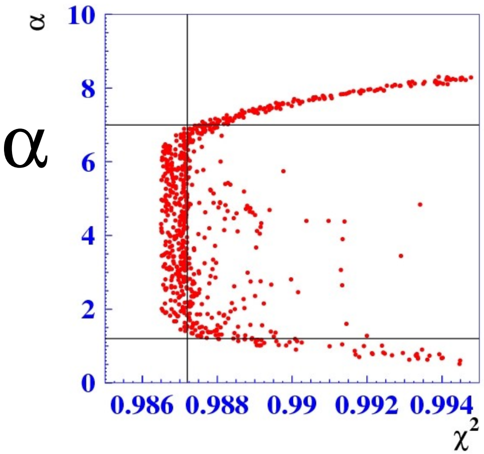
15–4=11 independent parameters

2 parameters (α & $\int\Im(A_\eta A^*_S)dq_1^2dq_2^2d\phi$)

cannot be determined, so we scan over them.

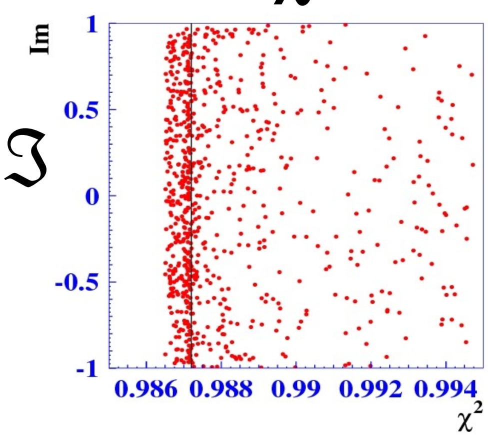
For α the correct interval is determined by good χ^2.

α



χ^2

ℑ



Systematic errors

Sources of systematic uncertainties	η_c %	$\eta_c(2S)$ %
Number of BB pairs	1.3	1.3
$B(K_s \to \pi^+\pi^-)$	0.1	0.1
Efficiency	1.1	1.5
Bin size	(+4.8) (-9.6)	+27.5
Background approximation	–	+0.07
Track reconstruction	3	3
$K^{\pm}$ identification	1.6	1.6
$\pi^{\pm}$ identification	1.5	1.5
K_s reconstruction	2.8	2.8
Total	**(+6.9) (-10.8)**	**(+28.0) (-5.1)**

Sources of systematic uncertainties	η_c Mass, MeV	$\eta_c(2S)$ Mass, MeV
Background approximation	–	–
Bin size	-0.8	-2.0
Scale uncertainty	-1.6	1.3
Detector resolution	–	–
Total	**(+0) (-1.8)**	**(+1.3) (-2.4)**

Sources of systematic uncertainties	η_c Width, MeV	$\eta_c(2S)$ Width, MeV
Background approximation	-0.1	+0.1
Bin size	(+0.1) (-1.1)	+8.1
Scale uncertainty	–	–
Detector resolution	0.4	0.8
Total	**(+0.4) (-1.2)**	**(+8.1) (-0.8)**

Interference between signal and peaking background

- Assumption 1: No interference

Breit-Wigner

$$f = \left| \frac{1}{x^2 - M^2 + i\,M\,\Gamma} \right|^2 \otimes Gauss + bg$$

- Assumption 2: 100% interference

Breit-Wigner and additional non-resonant background with phase ϕ

$$f = \left| \frac{1}{x^2 - M^2 + i\,M\,\Gamma} + \alpha\, e^{-i\phi} \right|^2 \otimes Gauss + bg1$$

We fit $M(\eta_c)$ sideband region by $f = \alpha^2 + bg1$ (bg1 is fixed from ΔE sideband, ϕ is a floating parameter) $\Rightarrow$ obtain α

Results

Decay mode	ε, %	Number of events	Sign	Branching product $\times 10^{-6}$	PDG $\times 10^{-6}$
$B^{\pm}\to K^{\pm}\eta_c$, $\eta_c \to \eta\pi^+\pi^-$	13.34 ± 0.12	476 ± 95	5.0	$16.9 \pm 3.4 ^{+0.7}_{-1.2}$	29.7 ± 11.5
$B^{\pm}\to K^{\pm}\eta_c(2S)$, $\eta_c(2S) \to \eta\pi^+\pi^-$	13.72 ± 0.13	108 ± 73	1.5	< 7.4	—
$B^{\pm}\to K^{\pm}\eta_c$, $\eta_c \to \eta K^+K^-$	10.31 ± 0.11	133 ± 42	3.2	6.1 ± 1.9 ± 0.3	< 14.1
$B^{\pm}\to K^{\pm}\eta_c(2S)$, $\eta_c(2S) \to \eta K^+K^-$	10.84 ± 0.12	19 ± 26	0.7	< 2.6	—
$B^{\pm}\to K^{\pm}\eta_c$, $\eta_c \to \pi^0 K^+K^-$	11.51 ± 0.11	510 ± 72	7.1	8.4 ± 1.2 ± 0.4	10.6 ± 2.4
$B^{\pm}\to K^{\pm}\eta_c(2S)$, $\eta_c(2S) \to \pi^0 K^+K^-$	11.68 ± 0.11	80 ± 51	1.6	< 2.5	—
$B^{\pm}\to K^{\pm}\eta_c$, $\eta_c \to K_s K\pi$	13.63 ± 0.20	856 ± 39	21.9	$17.0 \pm 0.8 ^{+0.9}_{-1.0}$	21.2 ± 4.7
$B^{\pm}\to K^{\pm}\eta_c(2S)$, $\eta_c(2S) \to K_s K\pi$	14.30 ± 0.21	119 ± 33	3.6	2.2 ± 0.6 ± 0.1	—

Assumption: no interference between signal and peaking background

Results (cont.)

1\. a) $B(\eta_c \to \eta\pi^+\pi^-) / B(\eta_c \to K_s K\pi) = 0.99 \pm 0.20\,^{+0.04}_{-0.07}$

From PDG: 1.40 ± 0.57

b) $B(\eta_c(2S) \to \eta\pi^+\pi^-) / B(\eta_c(2S) \to K_s K\pi) < 4.8$

2\. a) $B(\eta_c \to \eta K^+K^-) / B(\eta_c \to K_s K\pi) = 0.36 \pm 0.11 \pm 0.02$

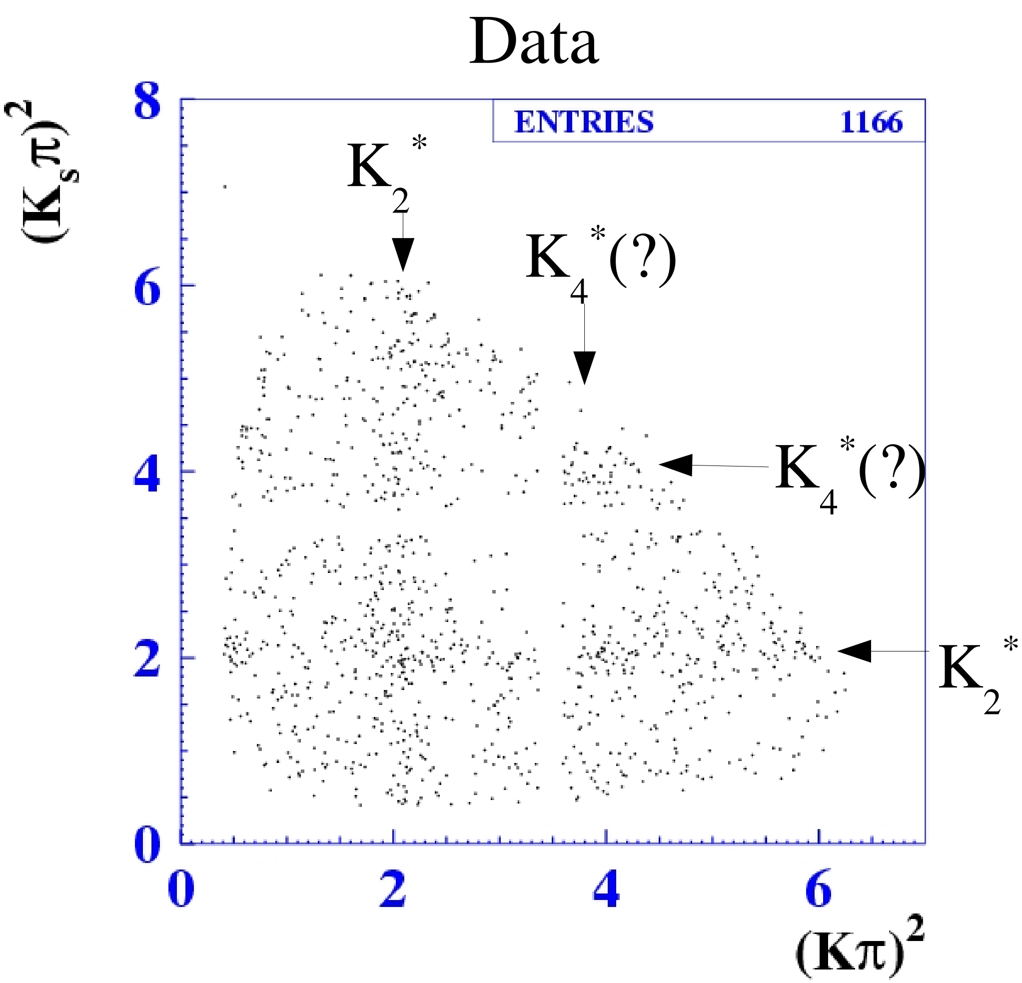
b) $B(\eta_c(2S) \to \eta K^+K^-) / B(\eta_c(2S) \to K_s K\pi) < 1.7$

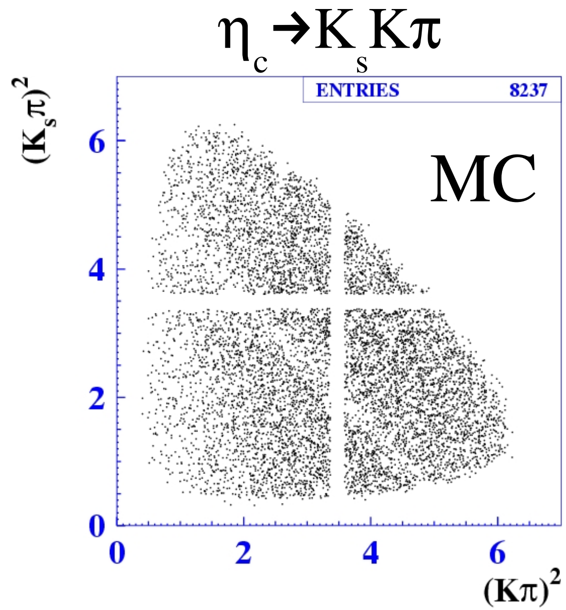
3\. a) $B(\eta_c \to \pi^0 K^+K^-) / B(\eta_c \to K_s K\pi) = 0.49 \pm 0.07 \pm 0.02$

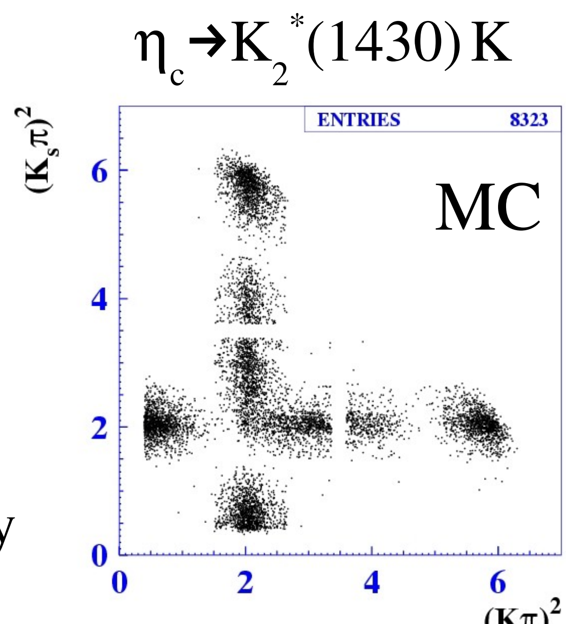
From isotopic symmetry: 0.5 (consistency check!)

b) $B(\eta_c(2S) \to \pi^0 K^+K^-) / B(\eta_c(2S) \to K_s K\pi) < 1.6$

$B^{\pm}\to K^{\pm}\eta_c$, $\eta_c\to K_sK\pi$, $K_s\to\pi^+\pi^-$







The state with the mass near 1.4 GeV can be $K^*(1410)$ or $K_0^*(1430)$ or $K_2^*(1430)$ or most probably the interference of all three. We assume that the biggest contribution is given by $K_2^*(1430)$ (width 98.5 MeV).