



# Hadronic physics @ the B factories

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On behalf of BaBar collaboration

WIN '05, Delphi – Greece

June 6-11, 2005



# Outline



- The X(3872) state
- Charmonium on the recoil
- Double charmonium
- Search for pentaquarks



# Babar and Belle

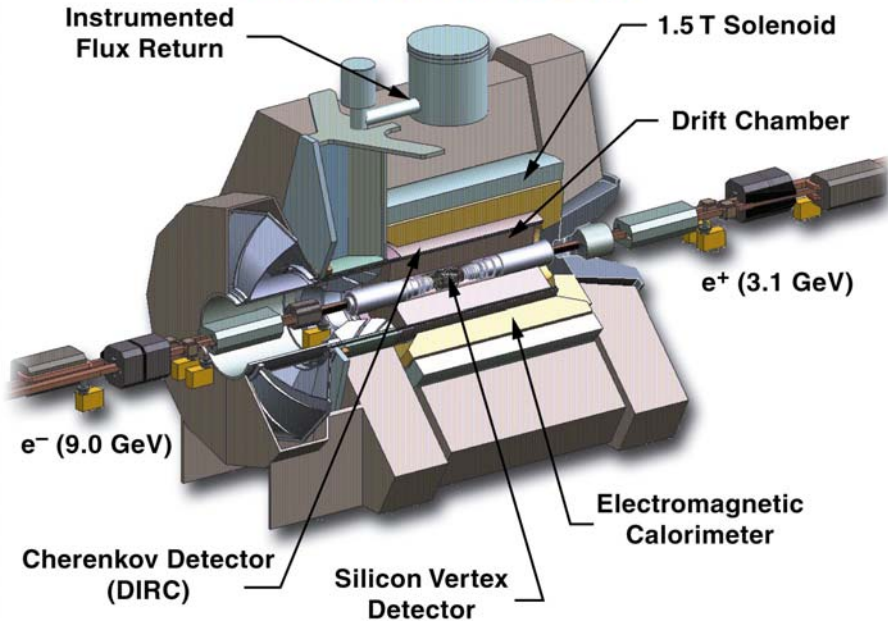
## At PEP II

Peak luminosity:  $9.2 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$

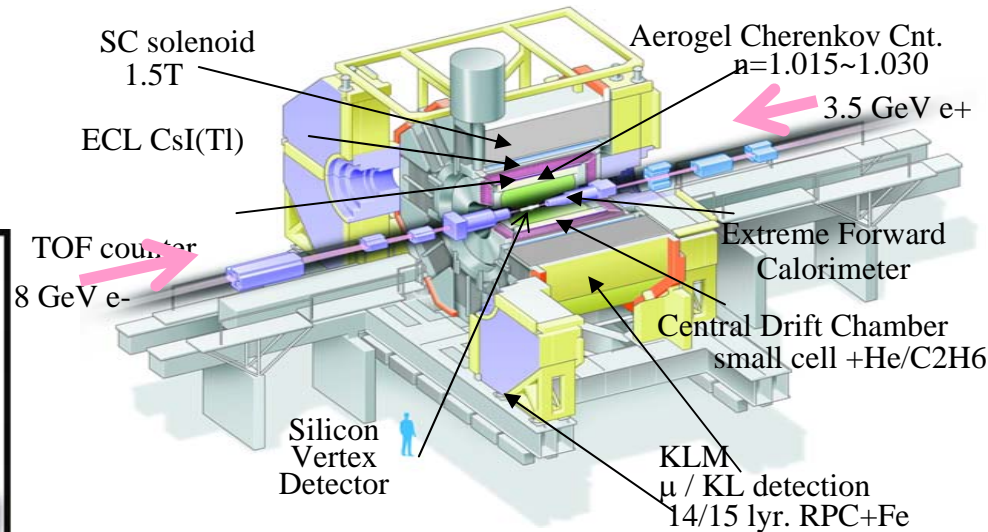
Beam energy:  $e^- 9.0 \text{ GeV}$   
 $e^+ 3.1 \text{ GeV}$



## BABAR Detector



## Belle Detector



## At KEK-b

Peak luminosity:  $16.8 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$

Beam energy:  $e^- 8 \text{ GeV}$   
 $e^+ 3.5 \text{ GeV}$

# The X(3872) state

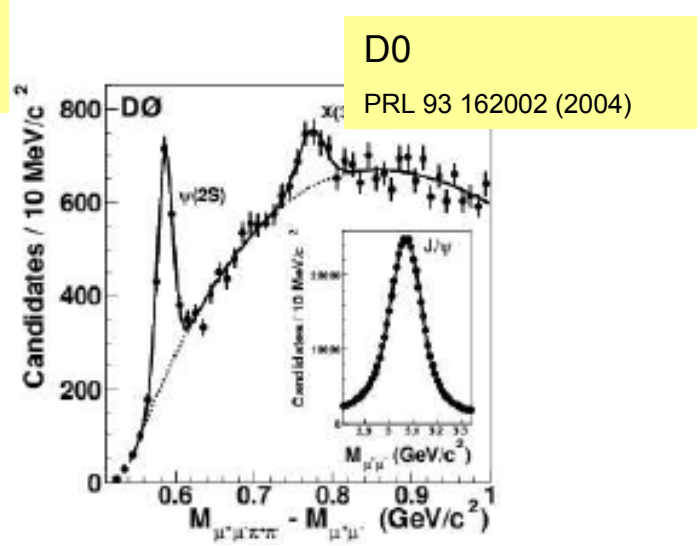
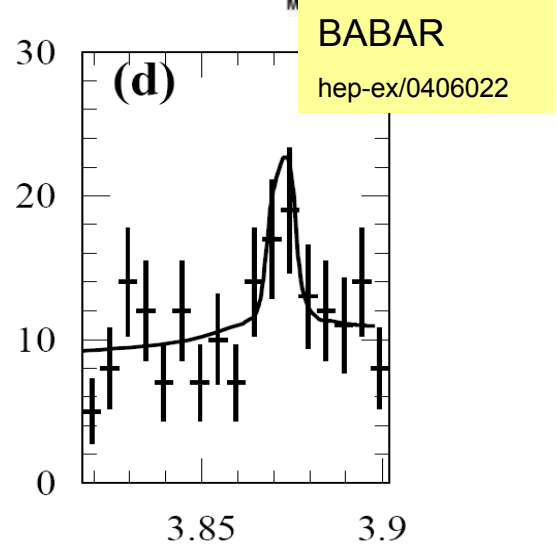
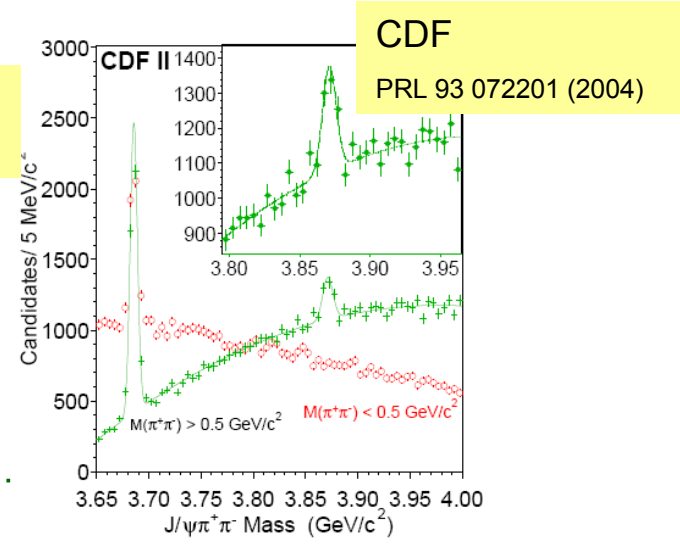
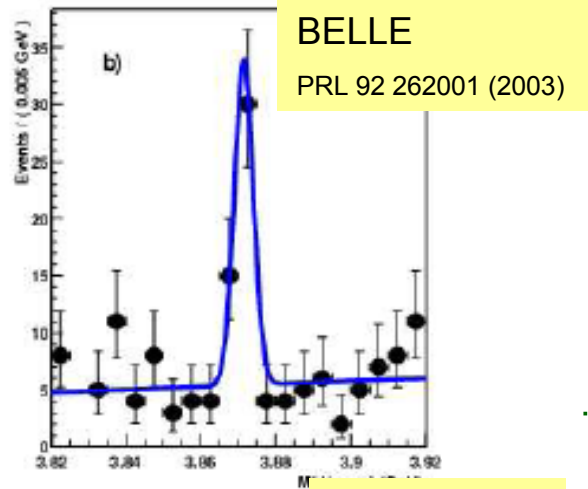
Discovered by Belle  
( $140\text{fb}^{-1}$ )

$B \rightarrow X(3872)K$   
 $X(3872) \rightarrow J/\psi \pi^+ \pi^-$

then confirmed by  
BaBar, CDF and D0.

Average mass

$3871.9 \pm 0.5 \text{ MeV}$



# The X(3872) state

- Charmonium state
  - absence of an isospin partner
- Molecule state
  - highly suppressed  $B^0 \rightarrow X(3872)K_S^0$  predicted
- Diquark-antidiquark state
  - different masses of X(3872) in  $B^0$  and  $B^+$  decays  
predicted:  $|\Delta M| > 5 \text{ MeV}/c^2$

E. Braaten, M. Kusunoki  
hep-ph/0412268

L. Maiani, F. Piccini,  
A.D. Polosa, V. Riquer  
PRD 71 (2005) 014028

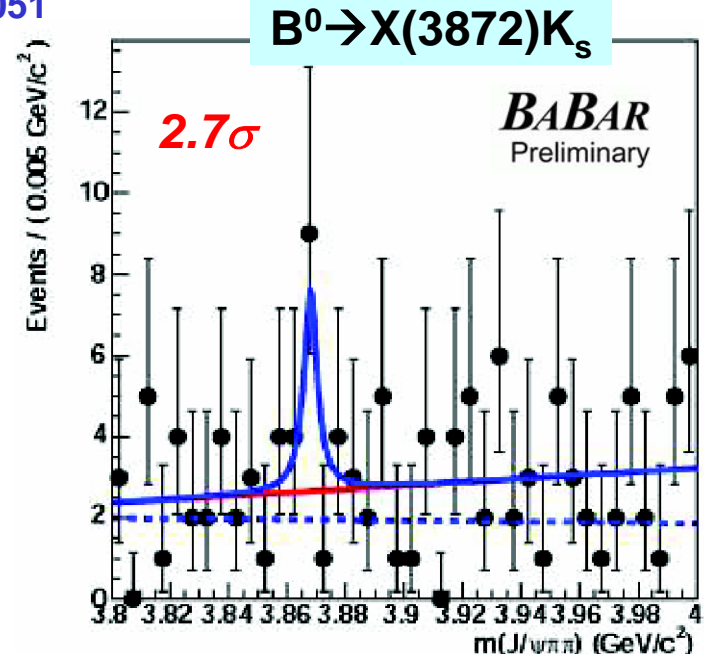
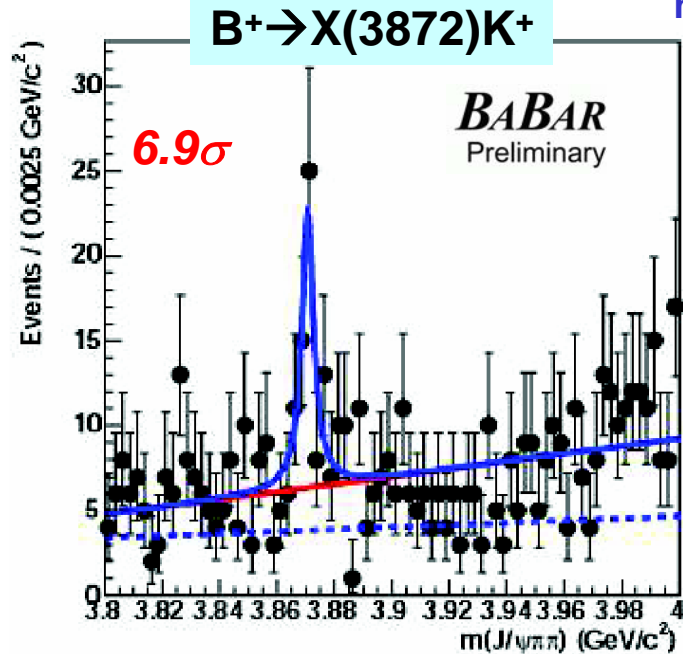
Are we at a stage where we can start to discriminate among them?



# $B \rightarrow X(3872)K, X(3872) \rightarrow J/\psi \pi^+ \pi^-$

244 fb<sup>-1</sup>

hep-ex/0412051



$$m_X = (3871.3 \pm 0.6) \text{ MeV}/c^2$$

$$\text{BF}(B^+ \rightarrow XK^+, X \rightarrow J/\psi \pi^+ \pi^-) = (8.5 \pm 2.3 \pm 0.8) \times 10^{-6}$$

$$m_X = (3868.6 \pm 1.2) \text{ MeV}/c^2$$

$$\text{BF}(B^0 \rightarrow XK^0, X \rightarrow J/\psi \pi^+ \pi^-) = (5.1 \pm 2.7 \pm 0.7) \times 10^{-6}$$

$$\Delta M = m_X(B^+) - m_X(B^0) = (2.7 \pm 1.3) \text{ MeV}/c^2$$

$$0.15 < \text{BF}(B^0 \rightarrow XK_s) / \text{BF}(B^+ \rightarrow XK^+) < 1.34 \text{ @ } 90\% \text{ CL}$$

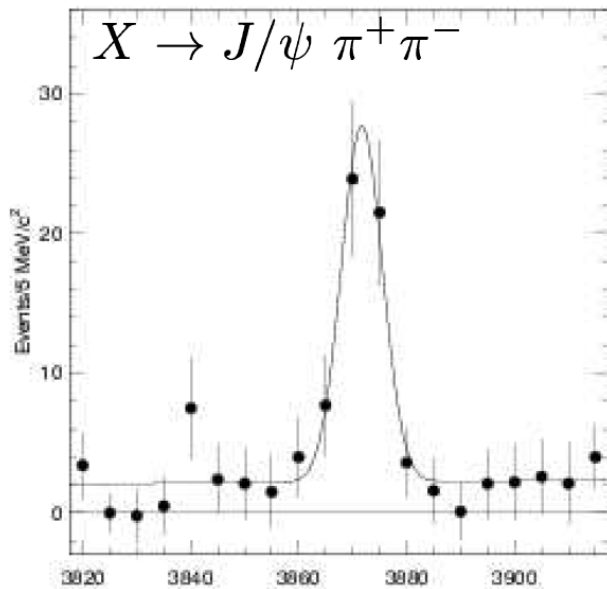
Not yet at the stage to discriminate among models, but method promising...

# X(3872) Belle update

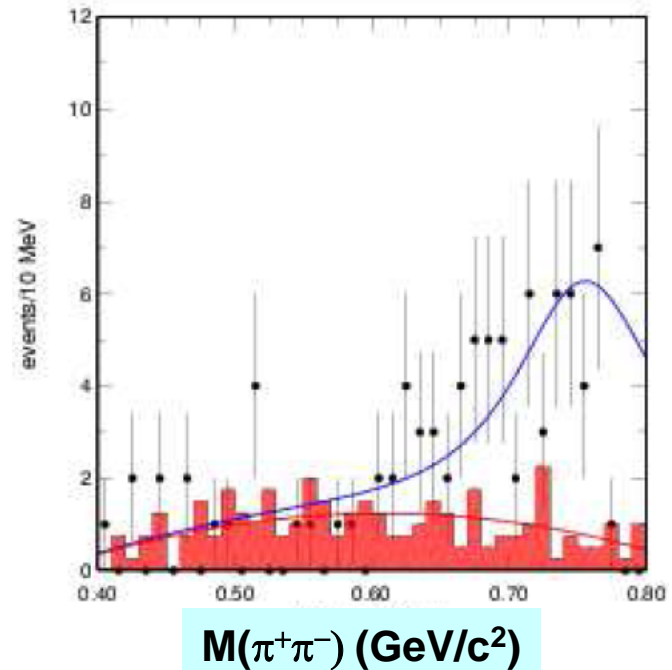


$N = 46.6 \pm 7.8$  events

$MASS(X) = 3872.4 \pm 0.7$  MeV



253 fb<sup>-1</sup>



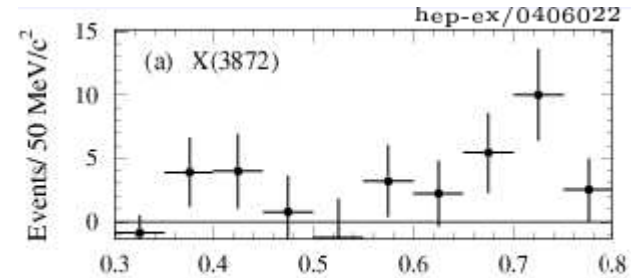
$M(\pi^+ \pi^-)$  is consistent with  $\rho^0$ !

$C(X(3872)) = +1$



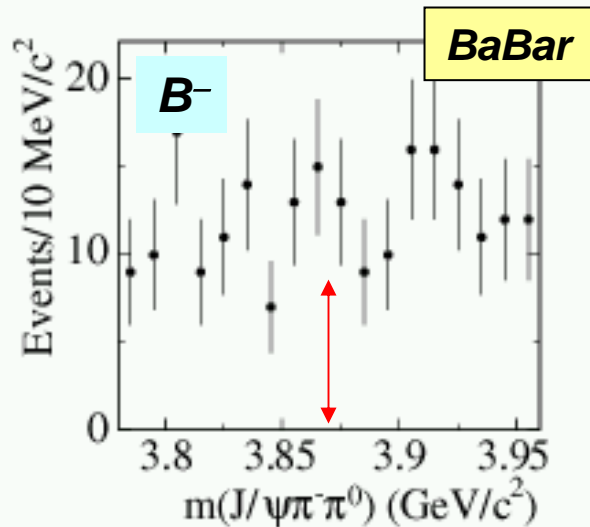
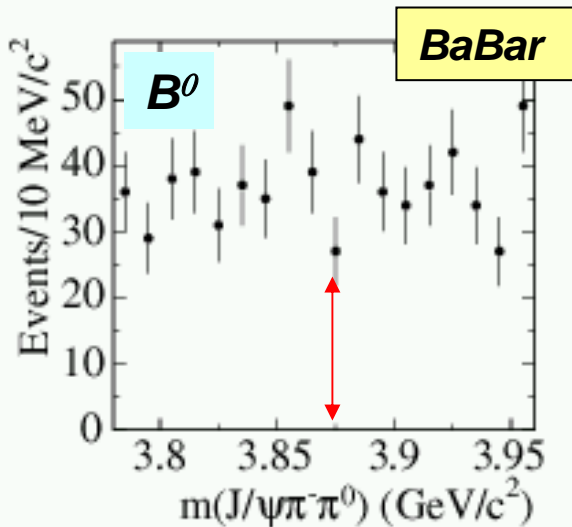
# Search for X(3872) charged partner

- Is really  $X(3872) \rightarrow J/\psi \rho^0 \rightarrow J/\psi (\pi^+ \pi^-)$ ?
  - If so  $I_{X(3872)} = 1 \Rightarrow$  Expect  $X(3872)^- \rightarrow J/\psi \rho^-$
- If X(3872) belongs to isospin triplet we expect
  - $\Rightarrow \text{BF}(B \rightarrow X^- K) \sim 2 \text{BF}(B \rightarrow X^0 K)$
- BaBar searched for  $B^0 \rightarrow X^- K^+$  and  $B^- \rightarrow X^- K_S$  with  $X^- \rightarrow J/\psi \rho^-$



$M(\pi^+\pi^-)$  (GeV/c<sup>2</sup>)

No evidence near 3872 MeV

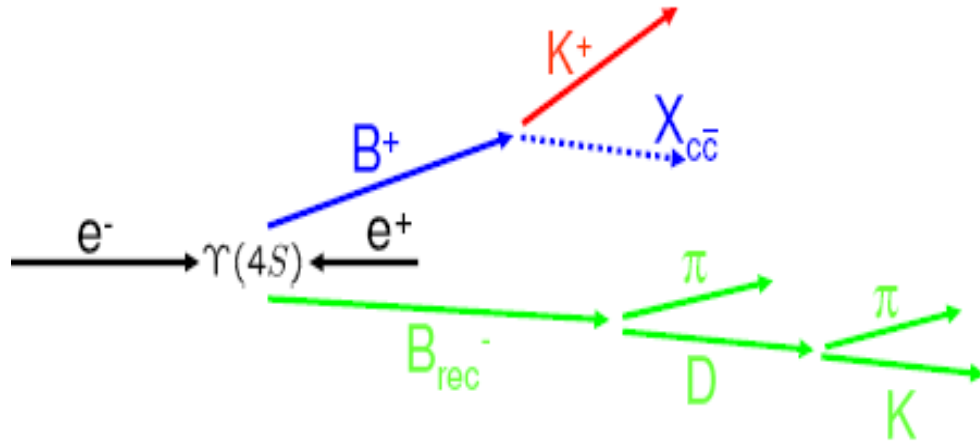


212 fb<sup>-1</sup>

Isovector hypothesis excluded  
[PRD RC 71,031501 (2005)]



# Charmonium on the recoil

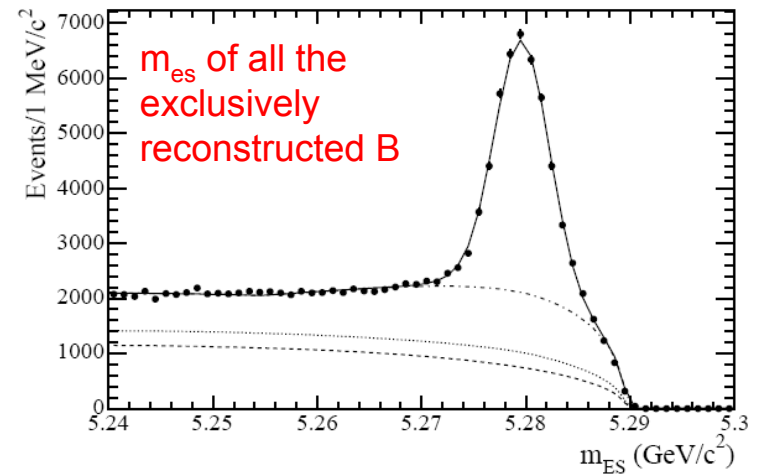


Fully reconstruct one B

Recoil momentum from Breco and beam parameters

Look for a recoil kaon. K momentum in the B rest frame

- Study of the 2-body decay  $B \rightarrow K + X$
- Measure the absolute branching ratios  $BR(B \rightarrow K + X)$
- Observation of X states independently from their decays
- Study of the X(3872) states



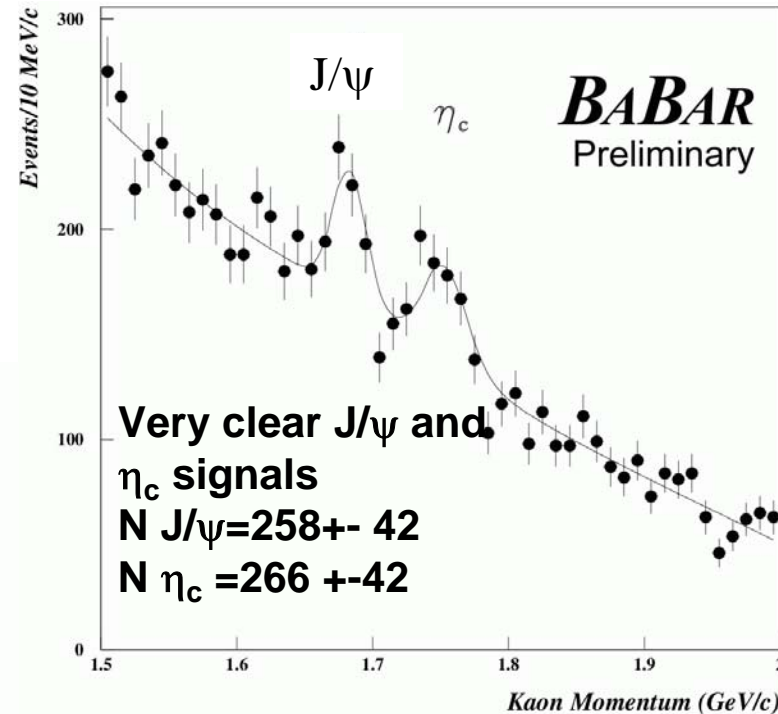
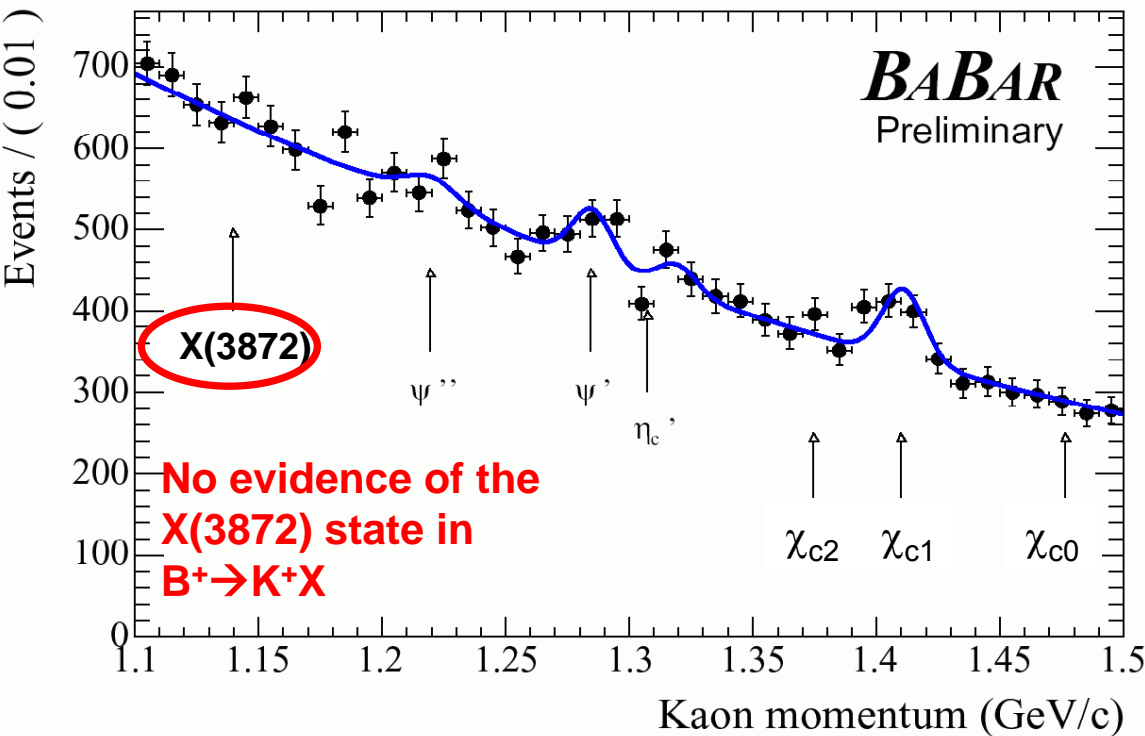
$m_{ES}$  : B mass using beam energy



# $B^+ \rightarrow K^+ X_{cc}$ Babar

244 fb<sup>-1</sup>

- Events with at least one charged kaon in the recoil selected with a NN
- Secondary K rejection with another NN



X(3872) production smaller than other charmonium states



# Branching ratios for $B^+ \rightarrow K^+ X_{cc}$ states

Particle	BR ( $10^{-4}$ )	BR(PDG2004)	BR(BABAR)
$\eta_c$	$8.9 \pm 1.5$	$9.0 \pm 2.7$	$13.4 \pm 4.4$
$J/\psi$	$8.1 \pm 1.6$	$10.0 \pm 0.4$	$10.6 \pm 0.5$
$\chi_{c0}$	$< 1.8^*$	$6 \pm 2.4 \pm 2.1$	$2.7 \pm 0.7$
$\chi_{c1}$	$7.0 \pm 1.6$	$6.8 \pm 1.2$	$5.8 \pm 0.7$
$\chi_{c2}$	$< 2$	No entry	$< 0.3$
$\eta_c(2S)$	$3.1 \pm 1.5$	No entry	
$\psi'$	$4.2 \pm 1.4$	$6.8 \pm 0.4$	$6.2 \pm 0.5$
$\psi''$	$3.2 \pm 2.3$	No entry	
X(3872)	$< 3.2^{**}$	No entry	

\* Recently Belle measured  $2.0 \pm 0.4 \pm 0.4$

[hep-ex/0412066](http://hep-ex/0412066)

\*\* Lower limit on

$BF(X \rightarrow J/\psi \pi^+ \pi^-) > 4.2\% @ 90\% C.L$

from  $BF(B^+ \rightarrow XK^+, X \rightarrow J/\psi \pi^+ \pi^-) = (13.3 \pm 2.5) 10^{-6}$   
average from

*hep-ex/0406022*

*PRL 91,262001(2003)*

BaBar

Belle

# What else we learn

- This analysis gives  $BR(B^+ \rightarrow \eta_c K^+) = (8.9 \pm 1.5) 10^{-4}$
- From BABAR,

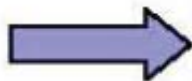
$$BR(B \rightarrow \eta_c K) * BR(\eta_c \rightarrow KK\pi) = (74 \pm 5 \pm 7) 10^{-6}$$



$$BR(\eta_c \rightarrow KK\pi) = (8.3 \pm 1.7)\%$$

- From BES, MARKIII and DM2,

$$BR(\eta_c \rightarrow KK\pi) * BR(J/\psi \rightarrow \gamma \eta_c) = (6.7 \pm 0.9) 10^{-4}$$



$$BR(J/\psi \rightarrow \gamma \eta_c) = (0.81 \mp 0.17)\%$$

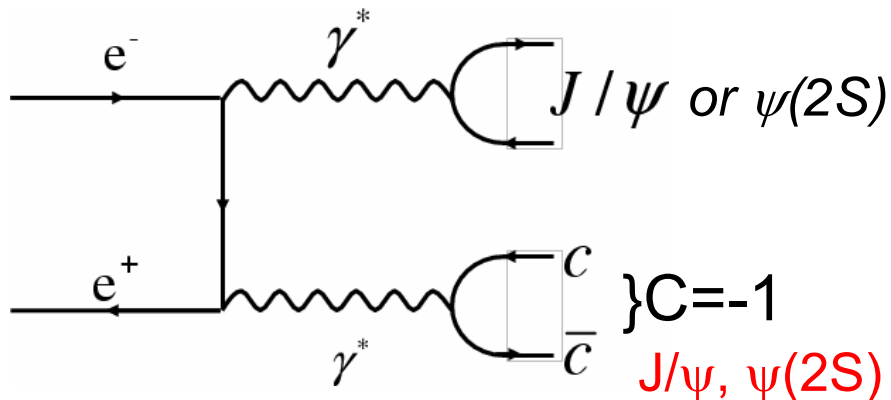
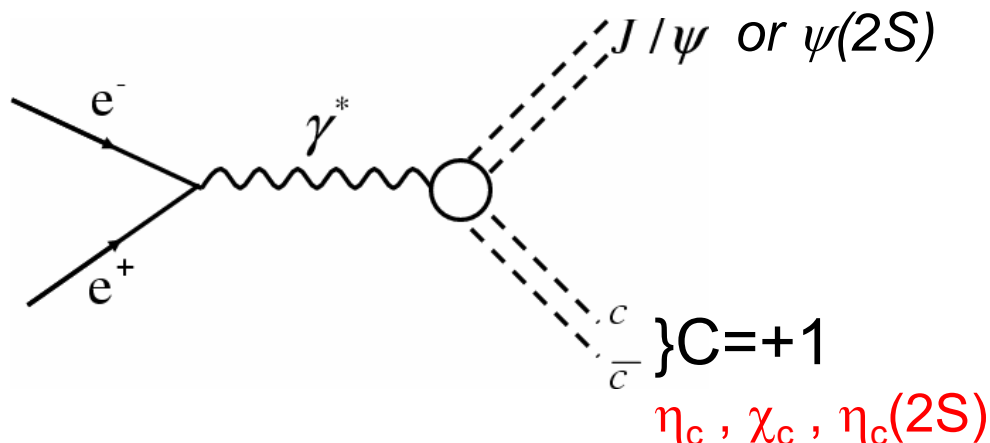
- From PDG2004  $\Gamma(\eta_c \rightarrow \gamma\gamma) * BR(\eta_c \rightarrow KK\pi) = (0.48 \pm 0.06) \text{ keV}$



$$\Gamma(\eta_c \rightarrow \gamma\gamma) = 5.8 \pm 1.2 \text{ keV}$$

# Double charmonium

Study the double charmonium in  $e^+e^-$  annihilation



Theorists predict the cross sections of the 2 processes to be comparable

G. T. Bodwin, E. Braaten & J. Lee  
PRD67, 054023 (2003)

**Technique:**

Fully reconstruct one  $J/\psi$  or  $\psi(2S)$

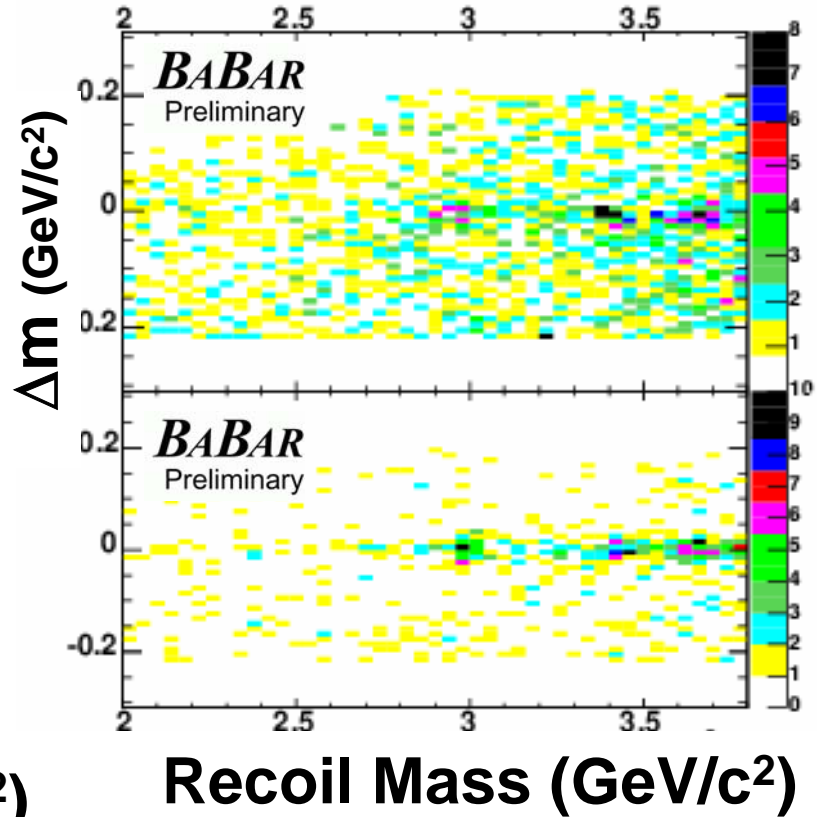
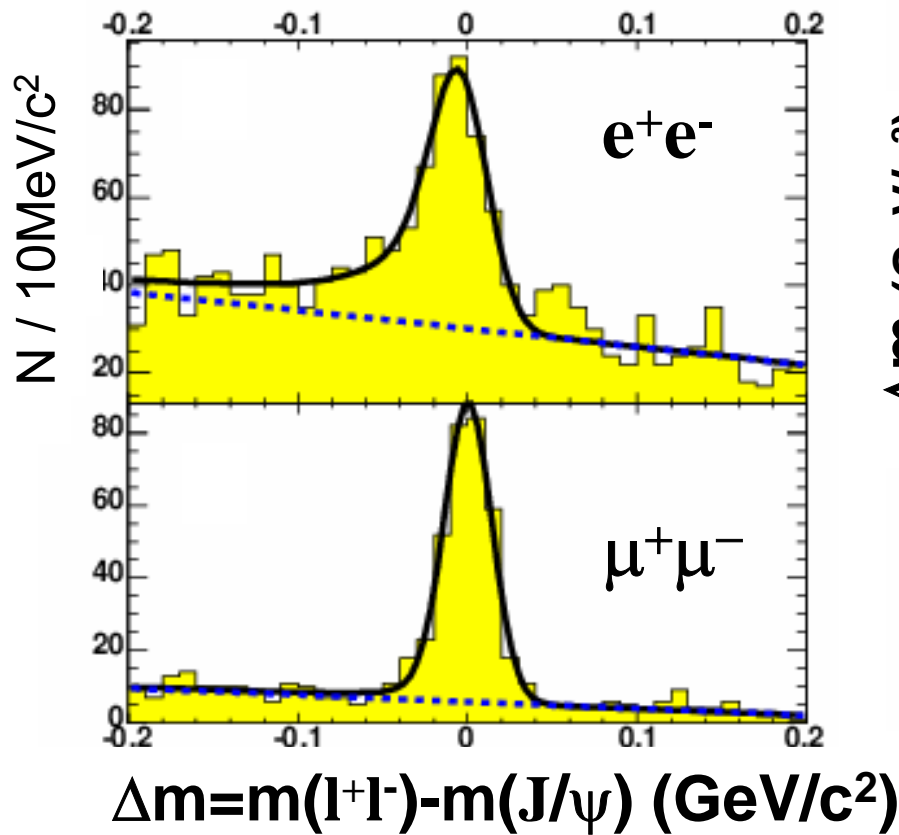
Look at the recoil mass spectrum



# $c\bar{c}+J/\psi$ Babar

124 fb<sup>-1</sup>

Reconstruct  $J/\psi \rightarrow l^+l^-$  and study recoil mass spectrum





# Double charmonium @ Babar

124 fb<sup>-1</sup>

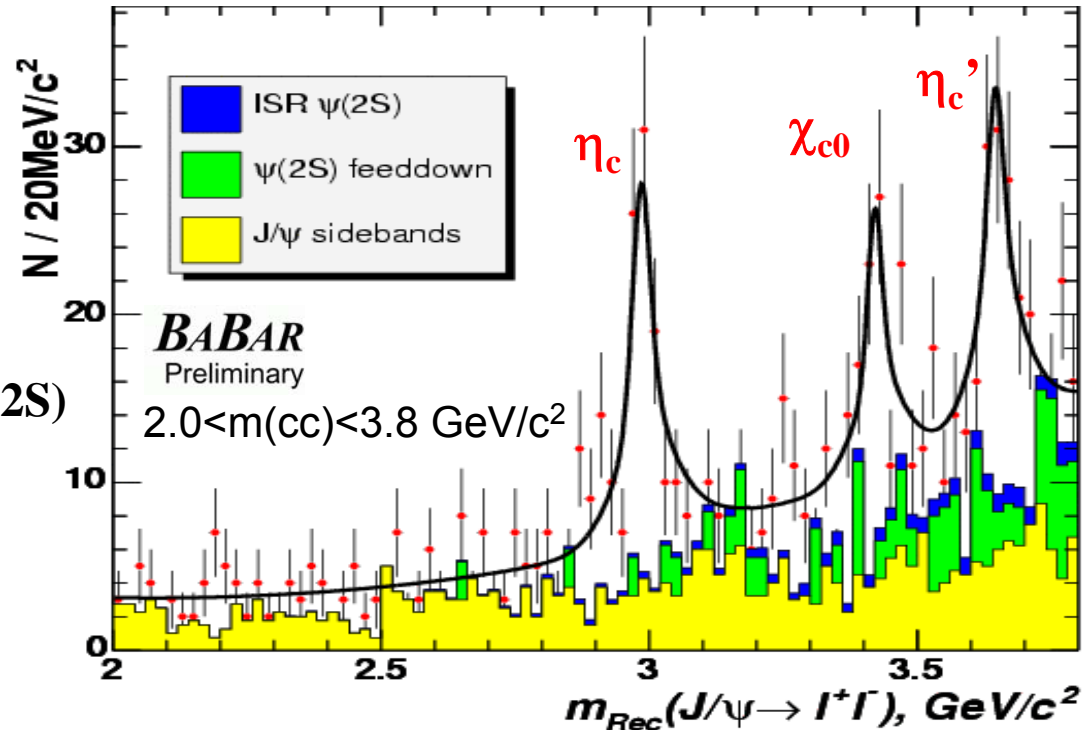
Observe

$\eta_c(1S)$   $\chi_{c0}(1P)$   $\eta_c(2S)$

No evidence for  $J/\psi$ ,  $\chi_{c1}$ ,  $\chi_{c2}$ ,  $\psi(2S)$

❖ Single virtual photon only?

❖ J=0 only?



$J/\psi + c\bar{c}(\rightarrow 2 \text{ charged})$	$\eta_c$	$\chi_{c0}$	$\eta_c(2S)$
N(signals)	$127 \pm 20$	$81 \pm 16$	$121 \pm 20$
Efficiency (%)	$29.5 \pm 0.7$	$32.2 \pm 0.7$	$30.2 \pm 0.8$
Cross-section (fb)	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
Mass ( $MeV/c^2$ )	$2984.8 \pm 4.0^{+4.5}_{-5.0}$	$3420.5 \pm 4.8^{+11.5}_{-9.5}$	$3645.0 \pm 5.5^{+4.9}_{-7.8}$

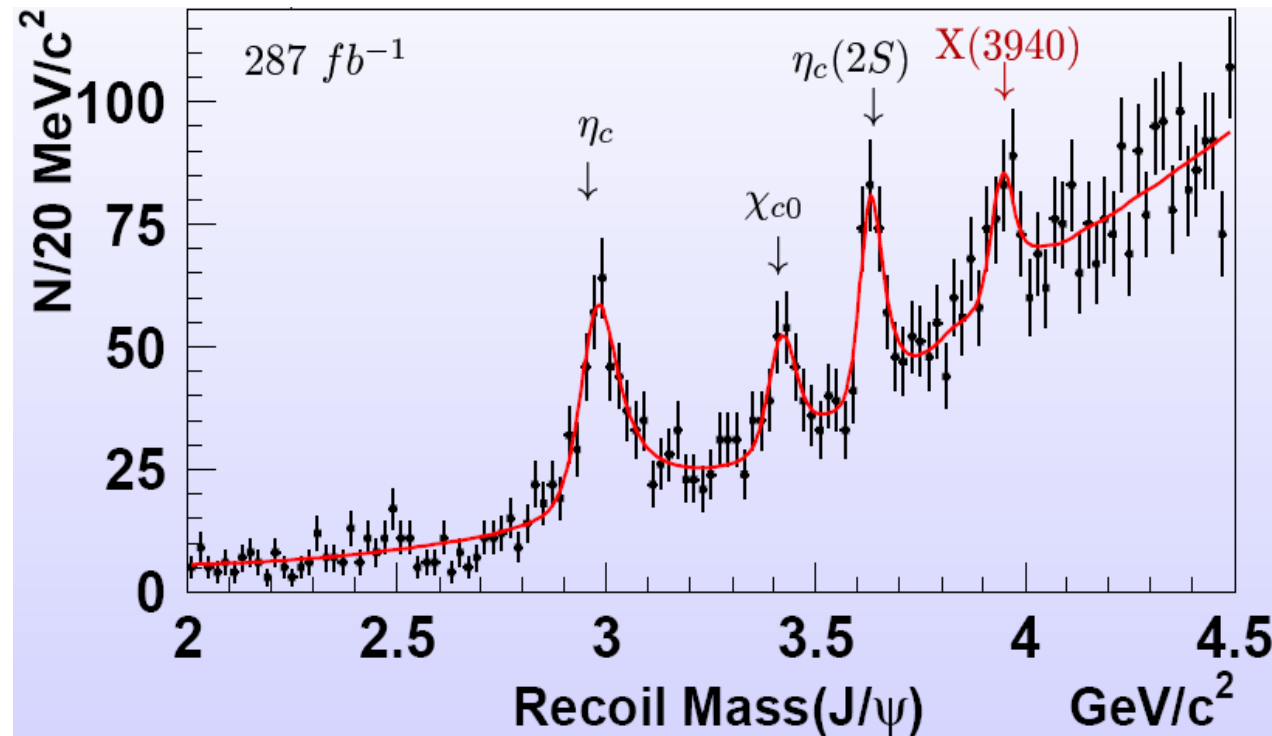
# Double charmonium @ Belle



As for BaBar no evidence of  $J/\psi$ ,  $\chi_{c1}$ ,  $\chi_{c2}$ ,  $\psi(2S)$ .

hep-ex/0412041

Charmonium production rate comparable to BaBar results



Evidence for X(3940) in double charmonium production

$M(X(3940))=3940\pm 12$  MeV

$\Gamma(X(3940))<96$  MeV

@ 90%CL

Decays into  $D\bar{D}$  and  $DD^*$

# Pentaquark searches

Pentaquark discovery in 2003 was immediately confirmed by 10 experiments  
(statistical significance of individual experiments is not high  $\sim 5\text{-}6\sigma$ )

## Claims of exotic narrow baryons

LEPS, CLAS, + others:  $\Theta_5(1540)^+$  [uudds]

$$M=(1542\pm 5)\text{MeV}/c^2$$

$$\Gamma < 21\text{MeV}/c^2$$

NA49:  $\Xi_5(1860)^{--}$  [ddssu]

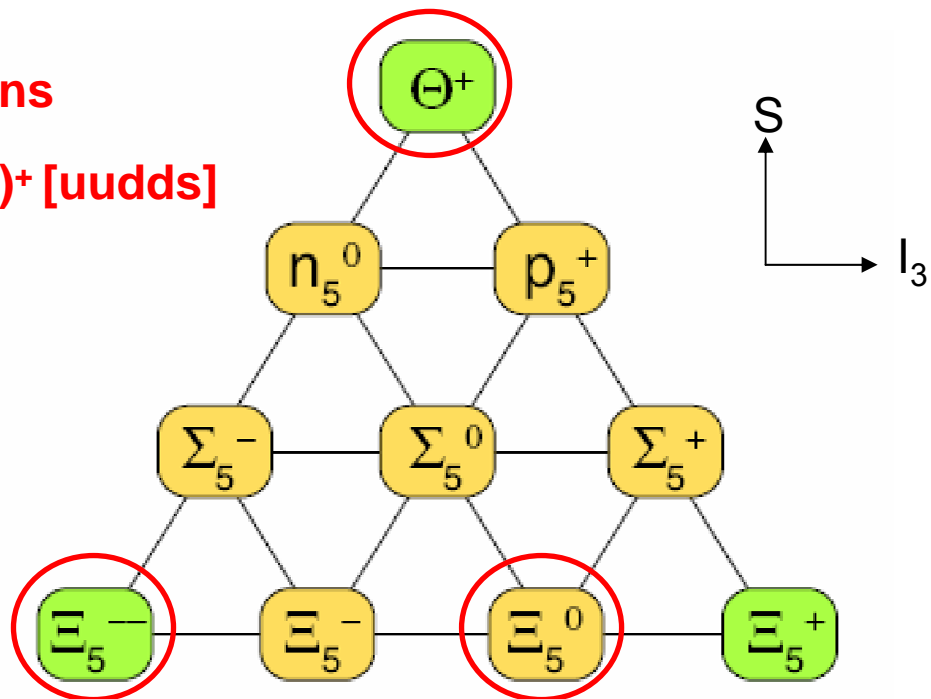
$$M=(1862\pm 2)\text{MeV}/c^2$$

$$\Gamma < 18\text{MeV}/c^2$$

H1:  $\Theta_{5c}(3100)^0$  [uuddc]

$$M=(3099\pm 6)\text{MeV}/c^2$$

$$\Gamma < 28\text{MeV}/c^2$$



Pentaquark theory expect  $\Theta_5^+$  and  $\Xi_5^{--}$  to be member of the anti-decuplet

# Pentaquark searches @ the B factories

## ① Inclusive search in $e^+e^-$ interaction

$$e^+e^- \rightarrow PX$$

$$\Theta_5(1540)^+ \rightarrow p K_s^0$$

$$\Xi_5(1860)^{-} \rightarrow \Xi^- \pi^-$$

$$\Xi_5(1860)^0 \rightarrow \Xi^- \pi^+$$

## 2. PQ search in B decays

$$B^0 \rightarrow \Theta^{++} p$$

$$\Theta^{++} \rightarrow K^+ p$$

## ③ Inclusive search in electro- and hadro-production

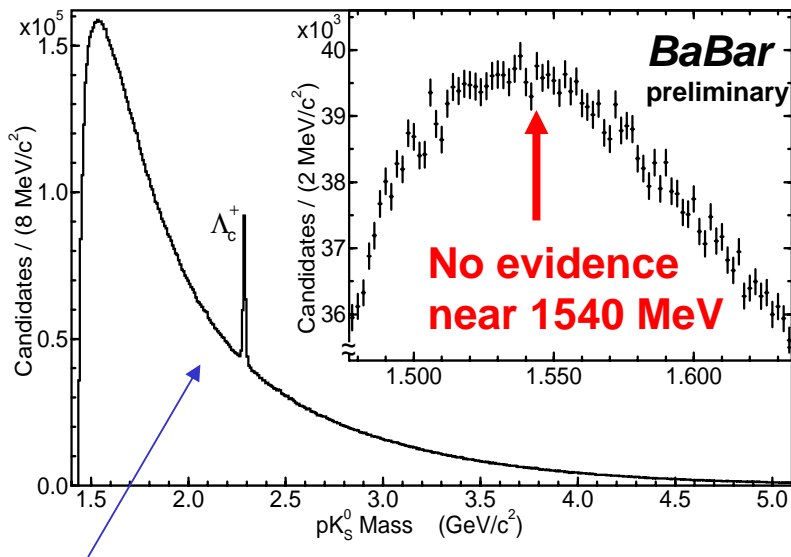
New technique

(inner detector used as target)

$$\Theta_5(1540)^+ \rightarrow p K_s^0$$



$\Theta_5(1540)^+ \rightarrow p K_s^0$



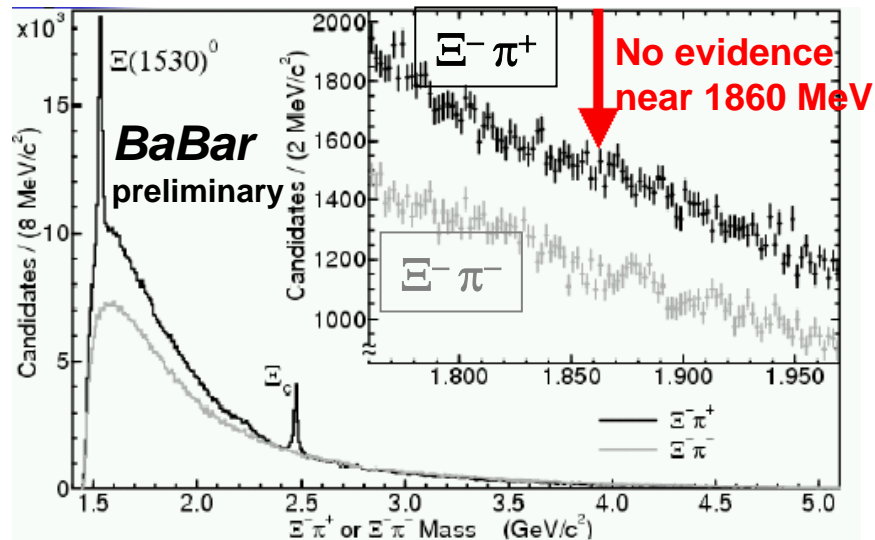
98,000  $\Lambda_c^+$  used to check MC, mass resolution and efficiency

Clear signal for known particles:

24,000  $\Xi(1530)^0 \rightarrow \Xi^- \pi^+$

8,000  $\Xi_c(2470)^0 \rightarrow \Xi^- \pi^+$

$\Xi_5^{--} \rightarrow \Xi^- \pi^-$  and  $\Xi_5^0 \rightarrow \Xi^- \pi^+$



2 displaced vertices:  $\Xi^-, \Lambda$

$\Xi_5^0 \rightarrow \Xi^- \pi^+$

$\Xi^- \rightarrow \Lambda \pi^-$

$\Lambda \rightarrow p \pi^-$

$\Xi_5^{--} \rightarrow \Xi^- \pi^-$

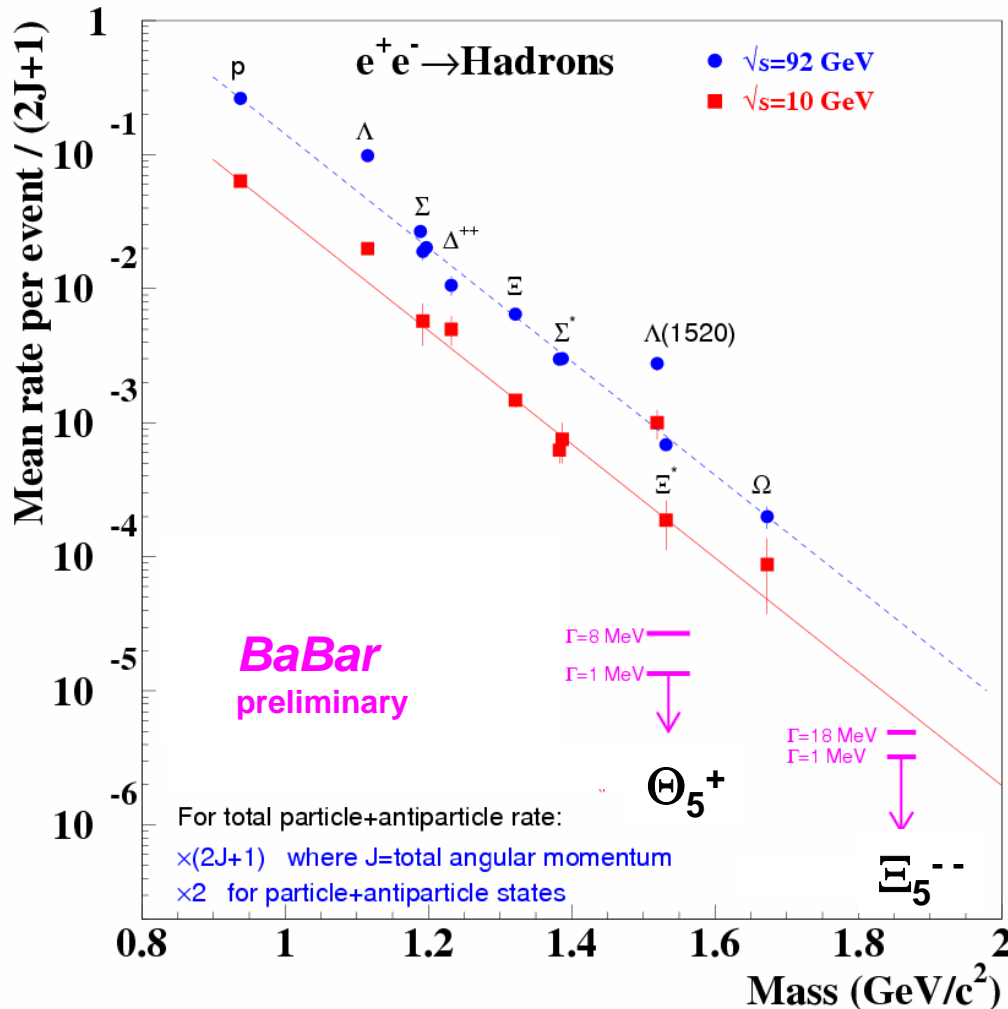
$\Xi^- \rightarrow \Lambda \pi^-$

$\Lambda \rightarrow p \pi^-$



# Pentaquark searches

hep-ex/0502004



Assuming same production rate in  $e^+e^-$  annihilation as for conventional baryons we expect:

$$8 \times 10^{-4} \Theta_5^+/\text{event}$$

$$4 \times 10^{-5} \Xi_5^{--}/\text{event}$$

- Branching fraction assumptions

$$\text{BF}(\Theta_5^+ \rightarrow pK_S) \sim 25\%$$

$$\text{BF}(\Xi_5^{--} \rightarrow \Xi^- \pi^-) \sim 50\%$$

— BaBar preliminary upper limits (95%CL):

$$\Theta_5^+ < 1/8 \text{ baryon rate}$$

$$\Xi_5^{--} < 1/4 \text{ baryon rate}$$

# Pentaquark searches in electro- and hadro-production

- **Electro-production:** off-beam  $e^-$  and  $e^+$  with Be beam-pipe

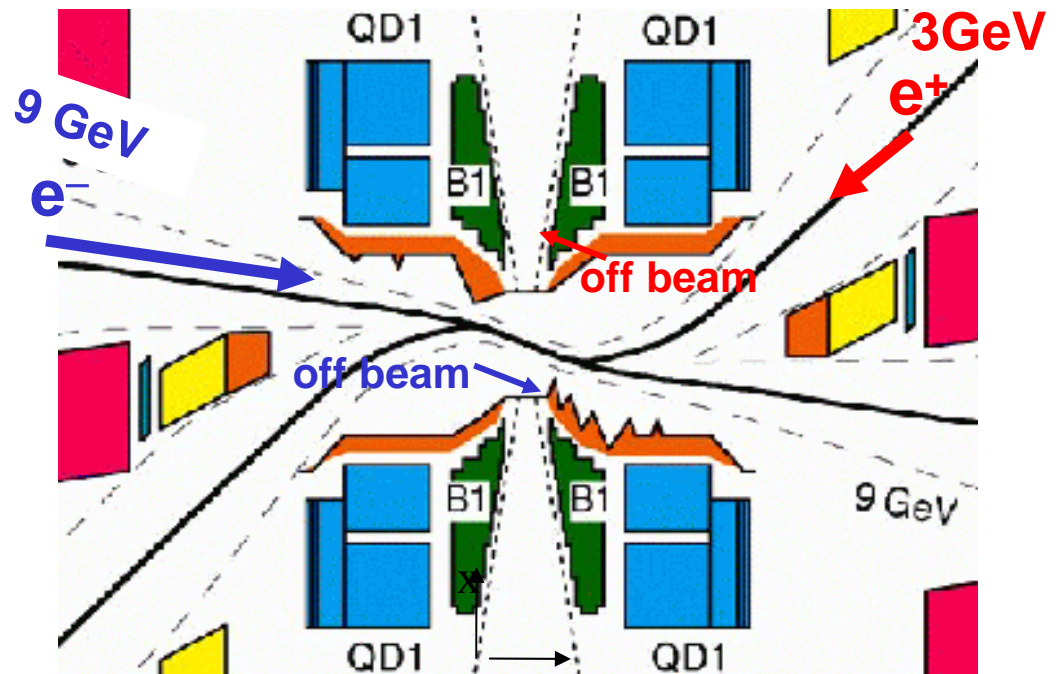
- **Hadro-production:** interactions of hadrons produced in  $e^+e^-$  annihilation with detector material

Beam pipe

+ vertex detector

+ drift chamber inner wall (Be)

Schematic plan view of interaction region

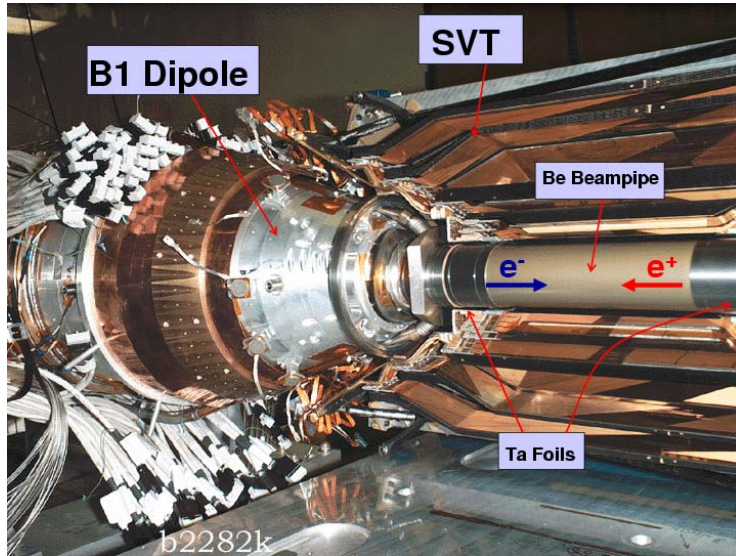


*different  $x$  and  $z$  scales*

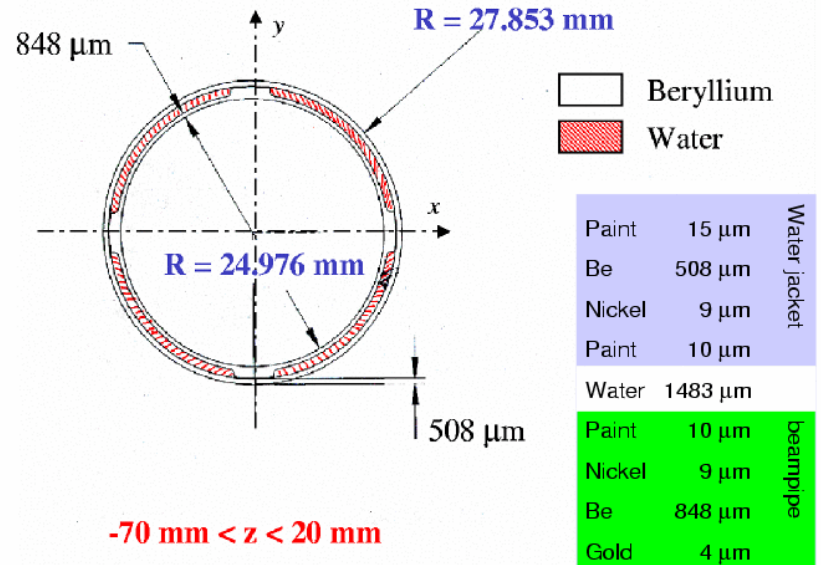
Results can be compared to fixed target experiments



# BaBar Target Material:

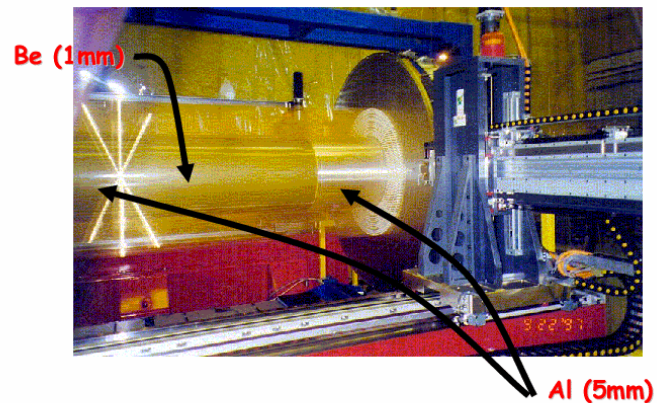
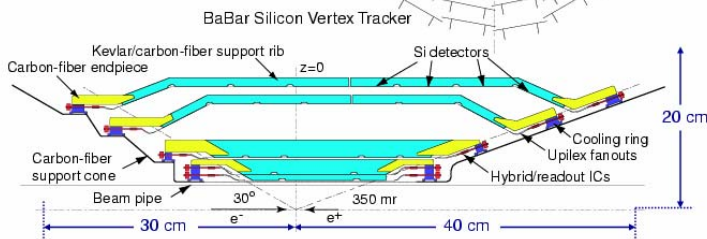
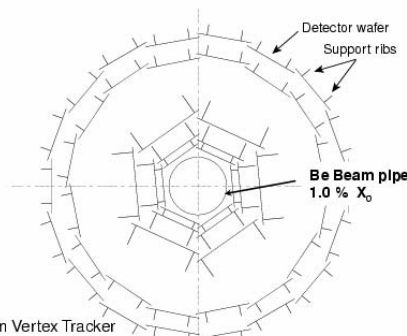


## DCH Be Inner Cylinder



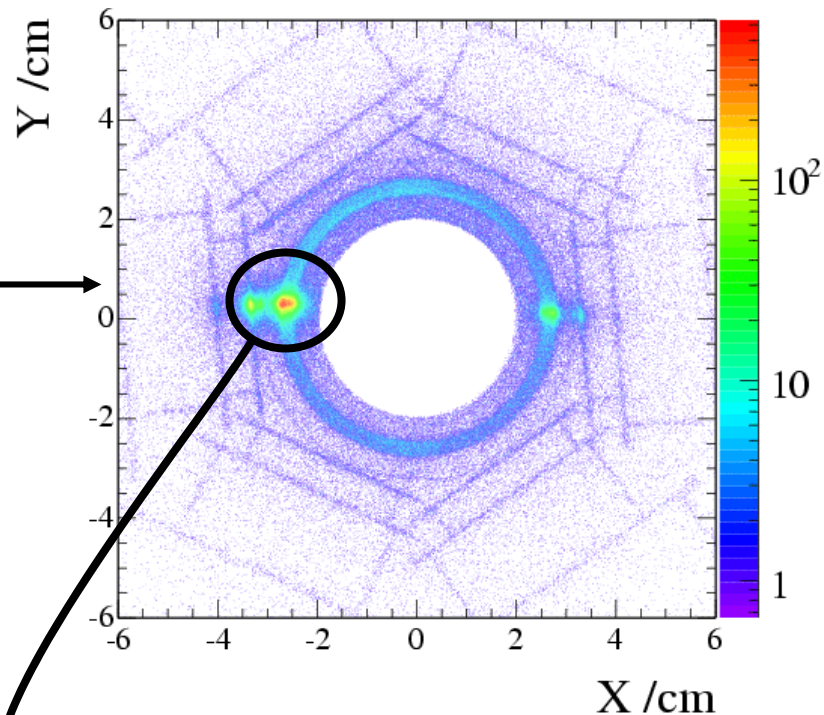
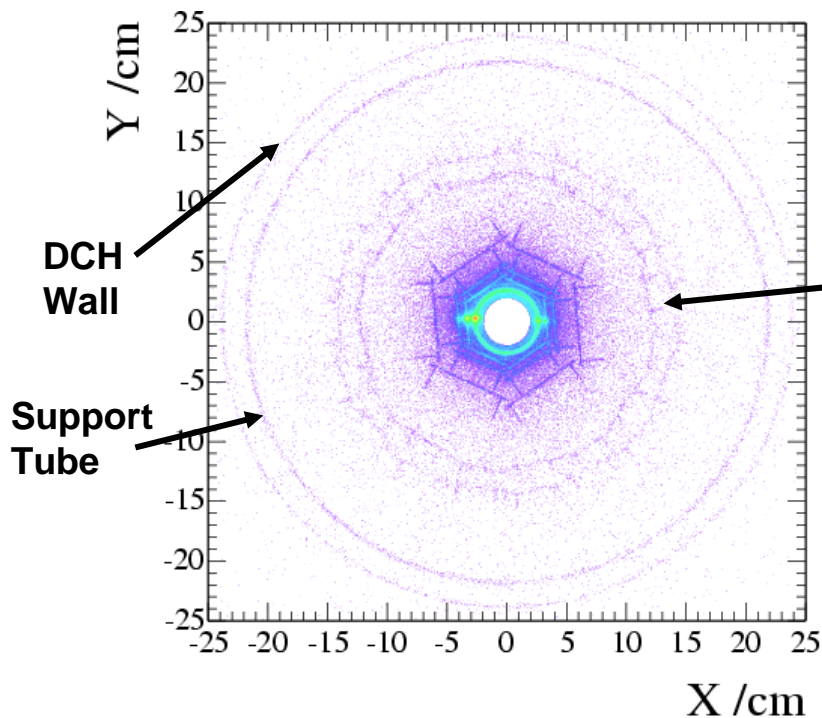
## SVT

Layer	Radius
1	3.3 cm
2	4.0 cm
3	5.9 cm
4	9.1 to 12.7 cm
5	11.4 to 14.6 cm



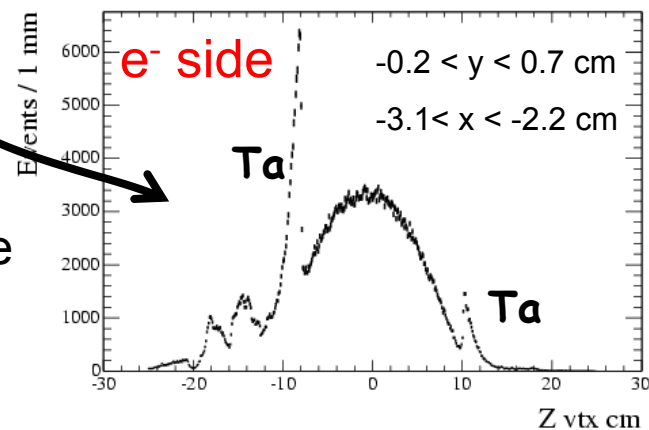


# Detector Tomography with $pK_S$ Vertices



**+ many other features well reproduced**

Z profile



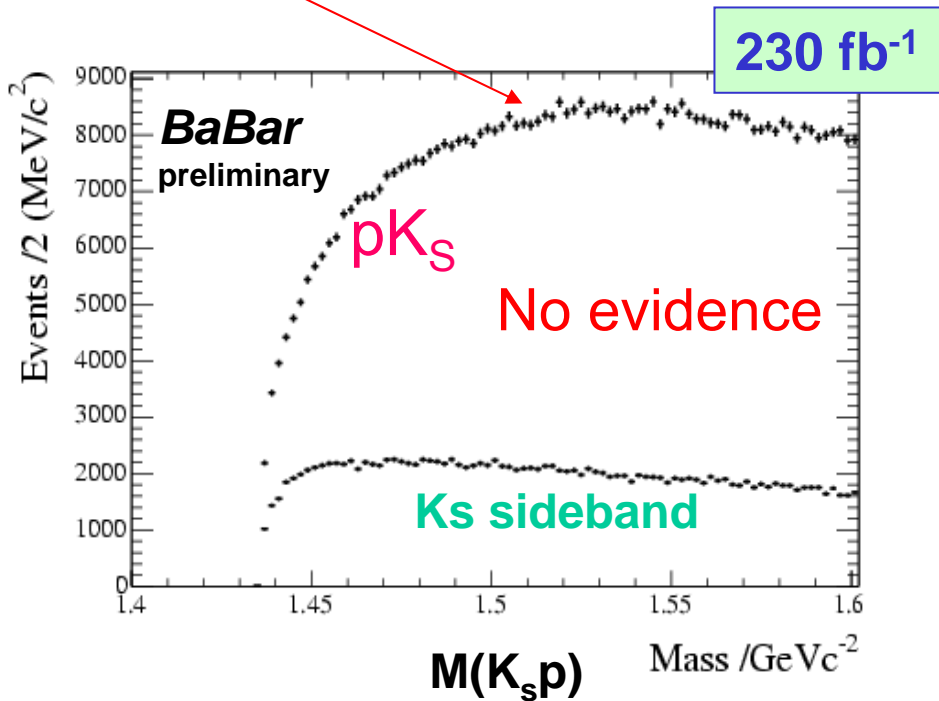


# Pentaquark searches in electro- and hadro-production

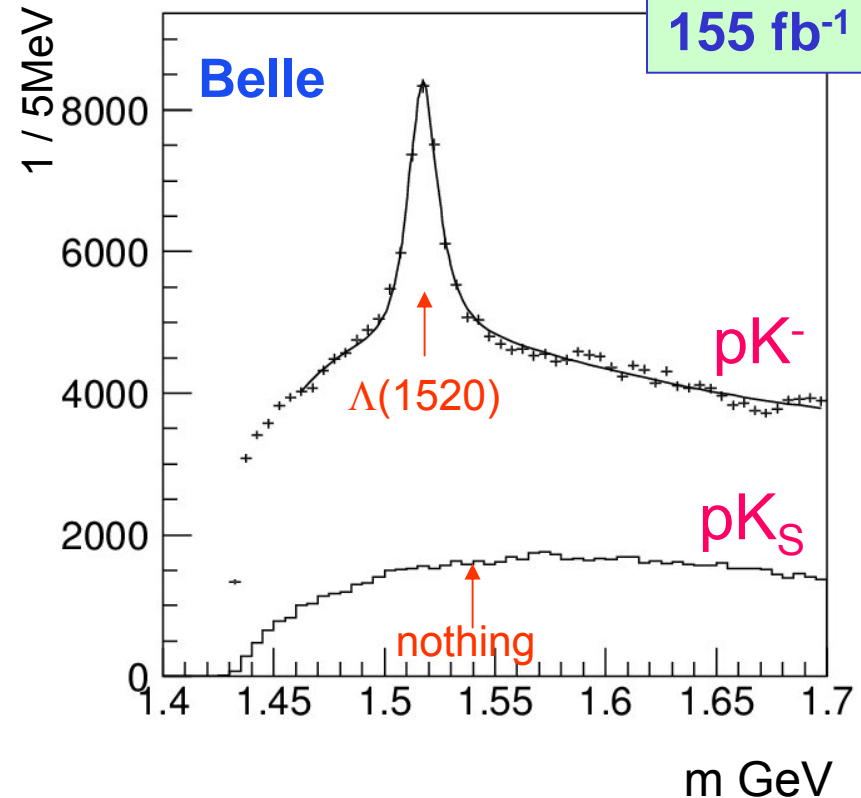


$$\Theta_5(1540)^+ \rightarrow p K_s^0$$

Ks signal region



electro-+hadro- production



Select secondary pK pairs to search for the pentaquarks.

# Summary (I)

---

- The X(3872) state
  - Discovered in  $J/\psi\pi^+\pi^-$
  - Steps ahead have been done in understanding its nature
  - No charged partner found: isovector hypothesis excluded (BaBar)
  - Need more data to discriminate among the models
- Charmonium on the recoil
  - Measure the absolute branching ratios  $BR(B^+ \rightarrow K^+ X)$
  - **Lower limit on  $BF(X \rightarrow J/\psi\pi\pi) > 4.3\%$  @ 90% C.L**

# Summary (II)

---

- Double charmonium
  - No evidence for  $J/\psi$ ,  $\chi_{c1}$ ,  $\chi_{c2}$ ,  $\psi(2S)$
  - Evidence of X(3940) @ Belle
- Search for pentaquarks
  - Searched in  $e^+e^-$  annihilation, B decays and electro/hadro production
  - **No evidence @ the B factories**
  - Put upper limits on production rate in  $e^+e^-$  annihilation

**Backup slides**

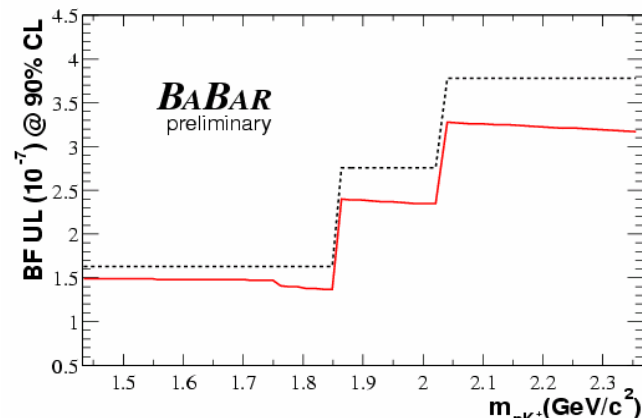
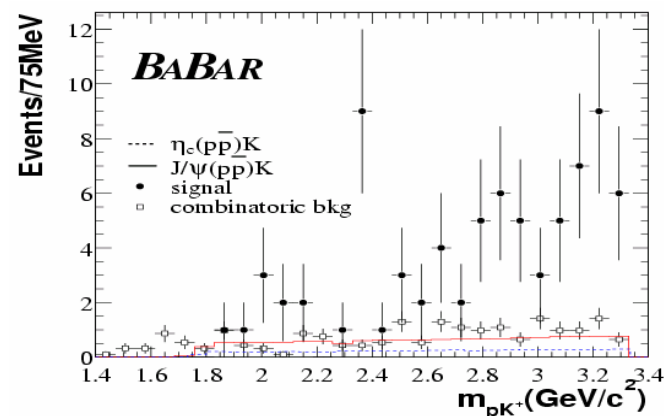
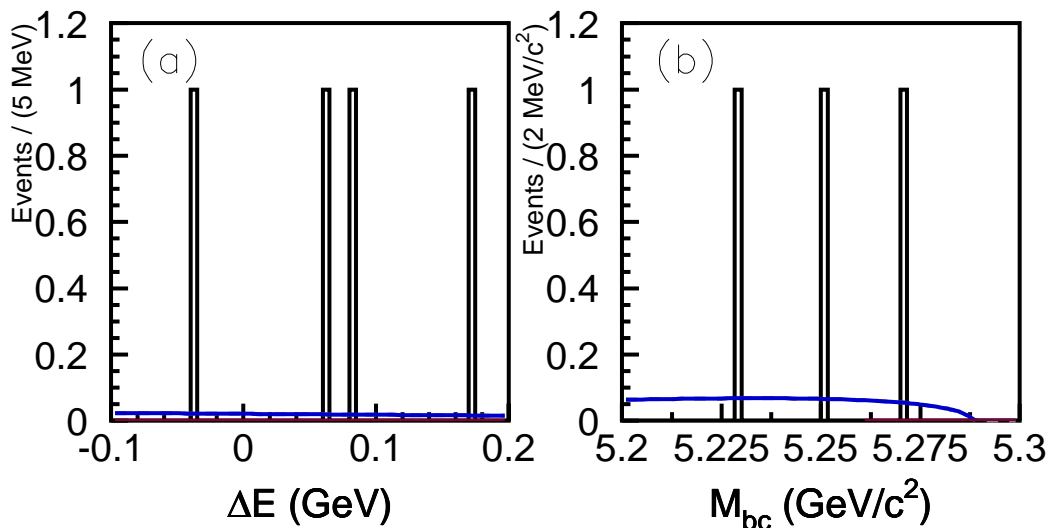
# Pentaquark searches in B decays



$p\bar{p}K_s/K^+$  final states

$\theta^+$ : Belle : 140 fb<sup>-1</sup>

$\theta^{++}$ : BABAR : 81 fb<sup>-1</sup>



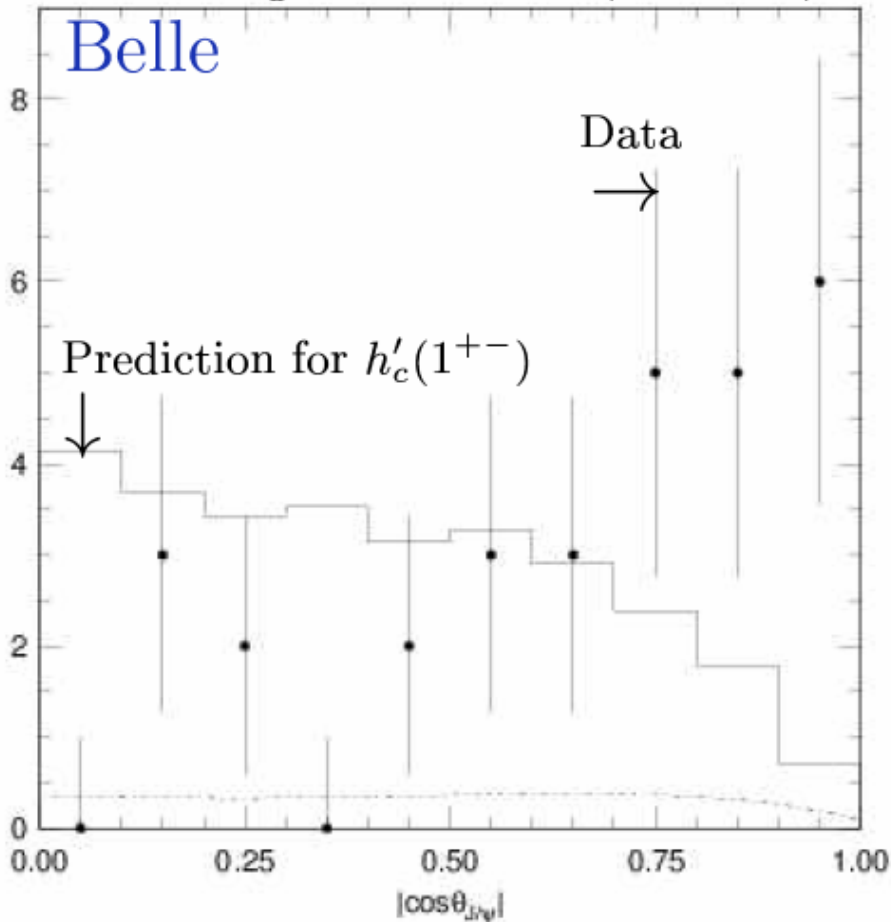
Fixed background shape from sideband data

Count the events in signal region and compare with background estimation

Upper limit  $\mathcal{B}(B^0 \rightarrow \theta^+ p) \times \mathcal{B}(\theta^+ \rightarrow p K_s^0) < 2.3 \times 10^{-7}$  at 90% C.L.

$\theta^{++}$ : Belle:  $\mathcal{B} < 9.1 \times 10^{-8}$

Helicity angle distribution ( $140 \text{ fb}^{-1}$ ):



- $\Rightarrow \mathcal{B}(B^+ \rightarrow XK^+, X \rightarrow J/\psi \pi^+ \pi^-) \sim 10^{-5}$   
too high for  $\eta_{c2}$  ( $1^1D_2, J^{PC} = 2^{-+}$ )  
with dominant  $\eta_{c2} \rightarrow \eta_c \pi^+ \pi^-$ ,  $h_c \gamma$
- $\Rightarrow$  Inconsistent ( $\chi^2/n\text{dof} = 75/9$ )  
with  $h'_c(2^1P_1, J^{PC} = 1^{+-})$
- $\Rightarrow \frac{\mathcal{B}(X \rightarrow J/\psi \gamma)}{\mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-)} < 0.40$  @ 90% CL  
too small for  $\chi'_{c1}$  ( $2^3P_1, J^{PC} = 1^{++}$ )
- $\Rightarrow \frac{\mathcal{B}(X \rightarrow \chi_{c2} \gamma)}{\mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-)} < 1.1$  @ 90% CL  
too small for  $\psi_3$  ( $1^3D_3, J^{PC} = 3^{--}$ )
- $\Rightarrow \frac{\mathcal{B}(X \rightarrow \chi_{c1} \gamma)}{\mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-)} < 0.89$  @ 90% CL  
too small for  $\psi_2$  ( $1^3D_2, J^{PC} = 2^{--}$ )
- $\Rightarrow \frac{\mathcal{B}(X \rightarrow D\bar{D})}{\mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-)} < 7$  @ 90% CL  
and narrow width  $\Gamma < 2.3 \text{ MeV}$   
suggests  $J^{PC} = 0^+, 1^-, 2^+$  are ruled out
- $\Rightarrow M(\pi^+ \pi^-)$  tends to peak near  $\rho^0$

# Indirect measurement on $\eta_c(2S)$

BELLE ha misurato

$$\frac{\text{BR}(B^\pm \rightarrow \eta_c(2S)K^\pm) \text{BR}(\eta_c(2S) \rightarrow \text{KK}\pi)}{\text{BR}(B^\pm \rightarrow \eta_c(1S)K^\pm) \text{BR}(\eta_c(1S) \rightarrow \text{KK}\pi)} = 0.38 \pm 0.12 \pm 0.05$$

BaBar ha misurato

$$\text{BR}(B^\pm \rightarrow \eta_c(1S)K^\pm) \text{BR}(\eta_c(1S) \rightarrow \text{KK}\pi) = (74 \pm 5 \pm 7) 10^{-6}$$

$$\text{BR}(B^\pm \rightarrow \eta_c(2S)K^\pm) = (3.1 \pm 1.5) 10^{-4} \rightarrow \text{BR}(\eta_c(2S) \rightarrow \text{KK}\pi) = (9 \pm 5)\%$$

CLEO measured

$$\frac{\Gamma(\eta_c(2S) \rightarrow \gamma\gamma) \text{BR}(\eta_c(2S) \rightarrow \text{KK}\pi)}{\Gamma(\eta_c(1S) \rightarrow \gamma\gamma) \text{BR}(\eta_c(1S) \rightarrow \text{KK}\pi)} = 0.18 \pm 0.05 \pm 0.02$$

$$\Gamma(\eta_c(1S) \rightarrow \gamma\gamma) \text{BR}(\eta_c(1S) \rightarrow \text{KK}\pi) = (0.407 \pm 0.022 \pm 0.028) \text{ keV}$$

$$\Gamma(\eta_c(2S) \rightarrow \gamma\gamma) \text{BR}(\eta_c(2S) \rightarrow \text{KK}\pi) = (0.073 \pm 0.022) \text{ keV}$$

$$\Gamma(\eta_c(2S) \rightarrow \gamma\gamma) = (0.8 \pm 0.5) \text{ keV}$$

# cc+J/psi

## Comparison BaBar, Belle & Theory

$J/\psi c\bar{c}$	$\eta_c$	$\chi_{c0}$	$\eta_c(2S)$
Nevt, BaBar ( $124.4 fb^{-1}$ ) Nevt, Belle ( $155 fb^{-1}$ ) <sup>(*)</sup>	$127 \pm 20$ $235 \pm 26$	$81 \pm 16$ $89 \pm 24$	$121 \pm 20$ $164 \pm 30$
(+) $\sigma_{Born} \times \mathcal{B}_{>2}$ , BaBar $\sigma_{Born} \times \mathcal{B}_{>2}$ , Belle <sup>(*)</sup>	$17.6 \pm 2.8 \pm 2.1$ $25.6 \pm 2.8 \pm 3.4$	$10.3 \pm 2.5 \pm 1.8$ $6.4 \pm 1.7 \pm 1.0$	$16.4 \pm 3.7 \pm 3.0$ $16.5 \pm 3.0 \pm 2.4$
(+) NRQCD by Braaten and Lee [1]	$2.31 \pm 1.09$	$2.28 \pm 1.03$	$0.96 \pm 0.45$
(+) NRQCD by Liu, He and Chao [2]	5.5	6.9	3.7

(+) cross sections in fb, (\*) [hep-ex/0412041](#), [hep-ex/0407009](#)

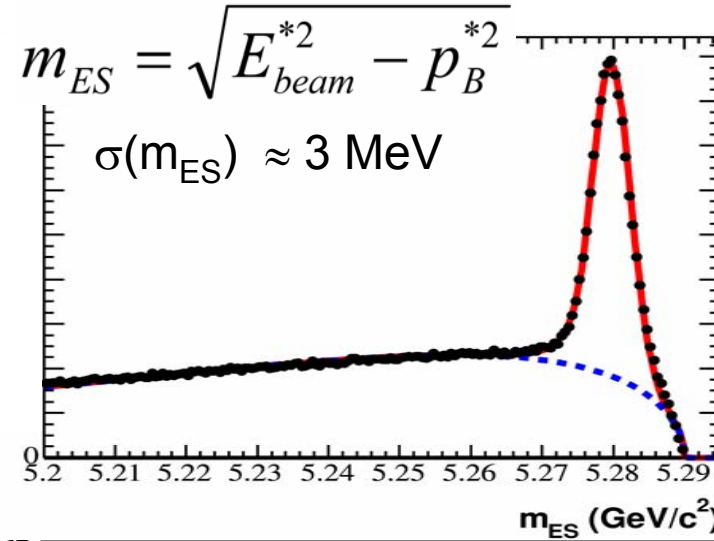
[1] PRD 67, 054007 (2003), [2] [hep-ph/0408141](#)



$$E_B^* = \frac{\sqrt{s}}{2} = \frac{\sqrt{q_{e^+} + q_{e^-}}}{2} \equiv E_{beam}^*$$

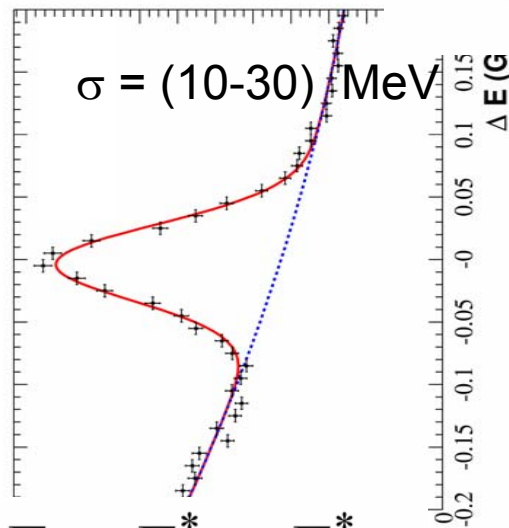
$B$  energy in the  $\Upsilon(4S)$  frame:

- Reco'd Energy :  $E_B^* = E_{B\text{reco}}^*$
- Beam energy :  $E_B^* = E_{beam}^*$



$m_{ES}$  :  $B$  mass using beam energy

$\Delta E$  : difference between beam and reco'd energy



$$\Delta E = E_{B\text{reco}}^* - E_{beam}^*$$

