Recent results on charmonium from Belle and BaBar

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Moriond QCD 2008

Outline

New "charmonium-like" in B decays: X(3872), Y(3940), Z(4430)

New "charmonium-like" recoiling on J/ψ: X(3940), X(4160)

Formation of Z(3930) $=\chi_{c2}(2P)$ in $\gamma\gamma$ fusion

Precision measurements on low lying charmonia

Not in this review:

- New charmonium-like in ISR: Y(4260), Y(4360), Y(4660)

- $e^+e^- \rightarrow D^{(*(*))}D^{(*)}$ at Ecm= (3.8-4.5) GeV

- Recent CLEO-c measurements on h_c mass and η_c lineshape

X(3872)

X(3872): established facts

Discovered (Belle, 2003) in B decays $\rightarrow$ K $J/\psi\pi\pi$

Prompt production also seen at Tevatron:

(only 16% are from $B \rightarrow K\, J/\psi\pi\pi$)

$M_{\pi\pi}$ consistent with $J/\psi\rho$ (I=1)

X(3872) $\rightarrow$ $J/\psi\,\gamma$ seen (Belle, BaBar); confirms C=+1

C=+1 implies $I_{\pi\pi}$=1 $\rightarrow$ isospin violation in $J/\psi\pi\pi$ decay

It is NOT observed in $\gamma\gamma$ (CLEO: Γ < 12 eV)

It is NOT observed in e^+e^- (ISR)

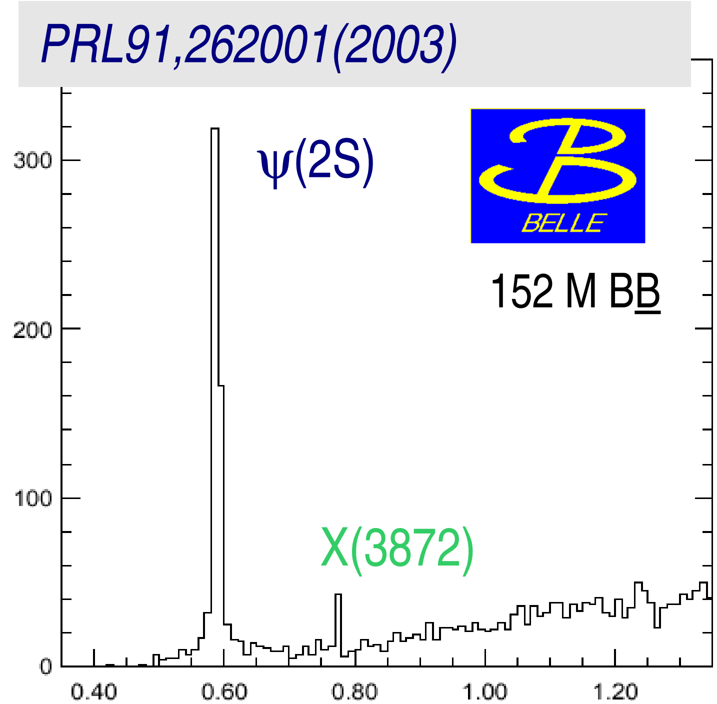
Angular distributions favor $J^{PC} = 1^{++}$ or 2^{-+}

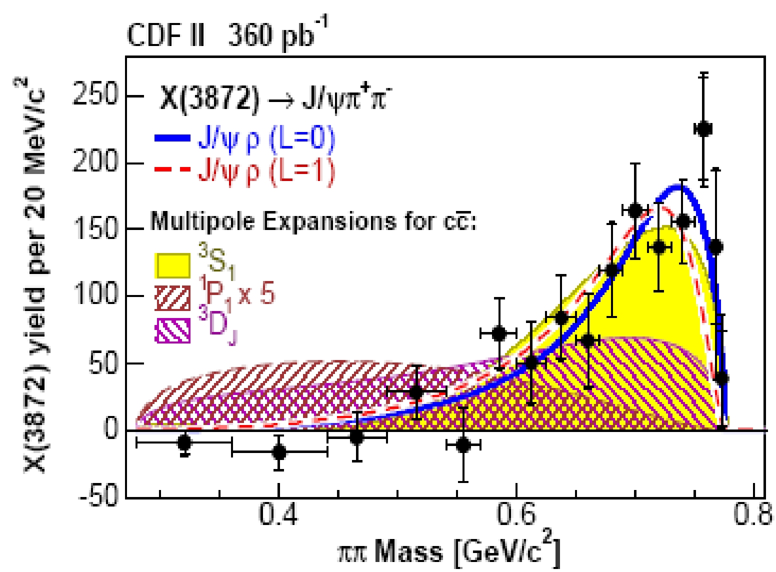
Observation in B decay suggests $J^{PC} = 1^{++}$

Mass (PDG2007) = 3871.4±0.6 MeV/c^2

[$M(D^0+D^{0*})$ = 3871.81±0.36 MeV/c^2]

Width (PDG2007) < 2.3 MeV (90%CL)

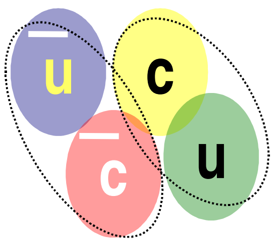


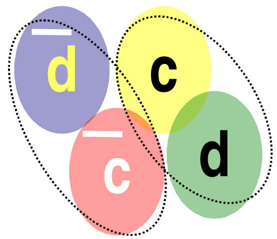


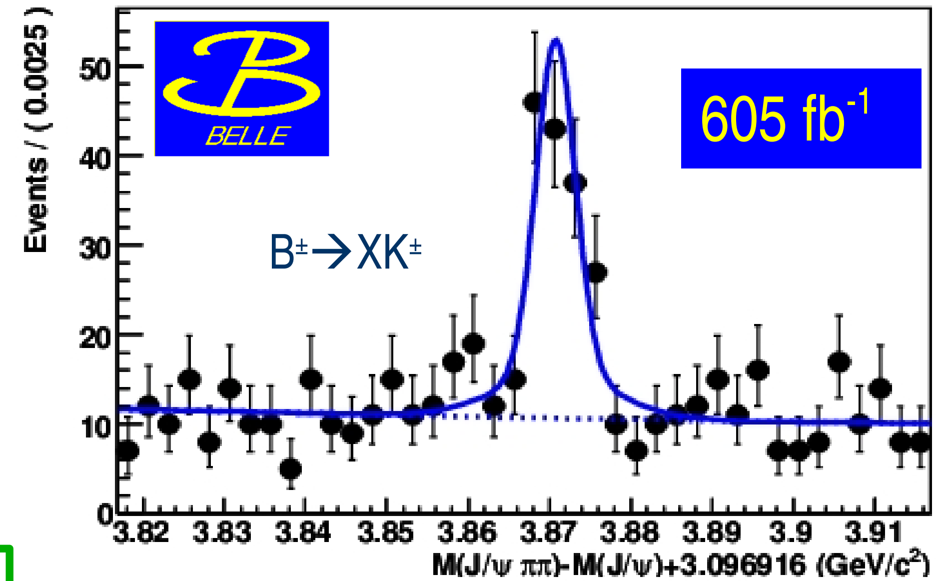
X(3872): a tetraquark doublet?

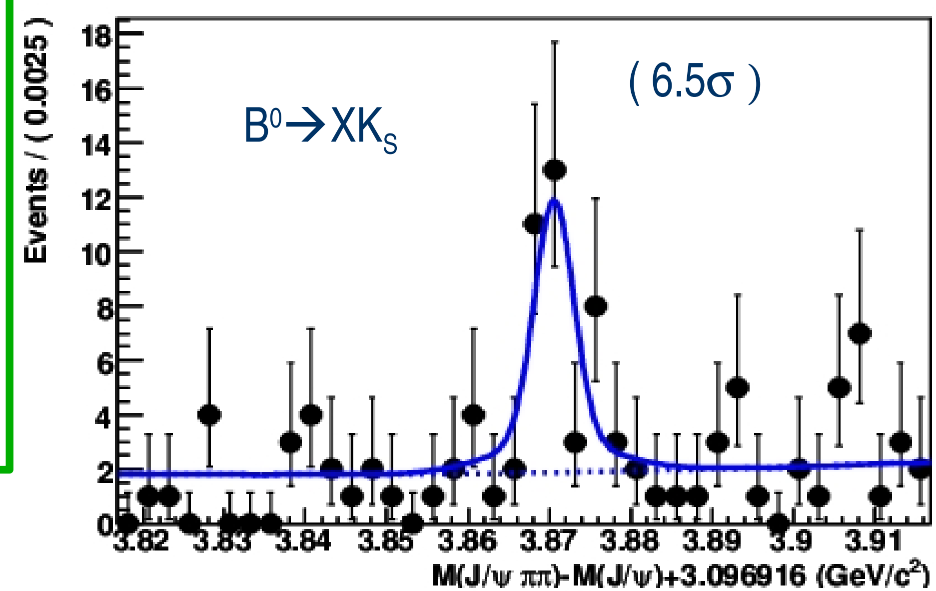
Maiani et al PRD 71,014028 (2005)

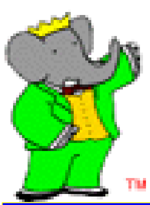
$\Delta M = M(X_u) - M(X_d) = (7 \pm 2)\cos(2\theta)$ MeV

$X_u =$ 

$X_d =$ 







	$\frac{\mathcal{B}(B^0 \to K^0 X(3872))}{\mathcal{B}(B^- \to K^- X(3872))}$	ΔM [MeV/c^2]
BaBar	0.61±0.36±0.06 *PRD73, 011101 (2006)*	2.7±1.3±0.2
BELLE	0.94±0.24±0.10 *BELLE-CONF-0711*	0.22±0.90±0.27

No evidence of mass splitting expected from tetraquark model

X(3872) in B decays to $\pi^0 D^0 \underline{D}^0$

$Br(B \to KX)Br(X \to \pi^0 D^0 \underline{D}^0)$:

$(1.27 \pm 0.31^{+0.22}_{-0.39}) \times 10^{-4}$ [10 x$Br(J/\psi\pi\pi)$]

Mass: $3875.4 \pm 0.7^{+0.7}_{-1.7} \pm 0.8$ MeV/c^2

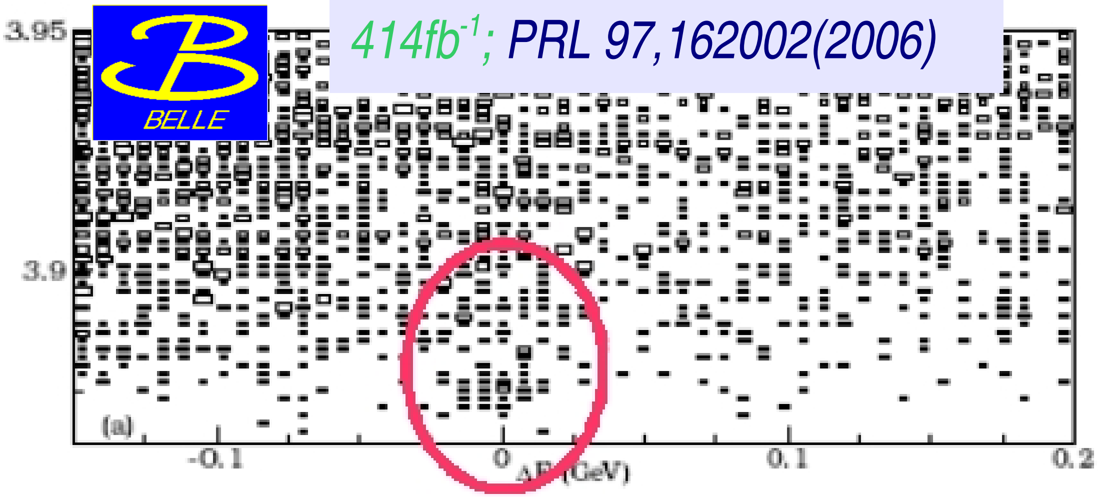
$Br(B \to KX)Br(X \to \pi^0 D^0 \underline{D}^0)$:

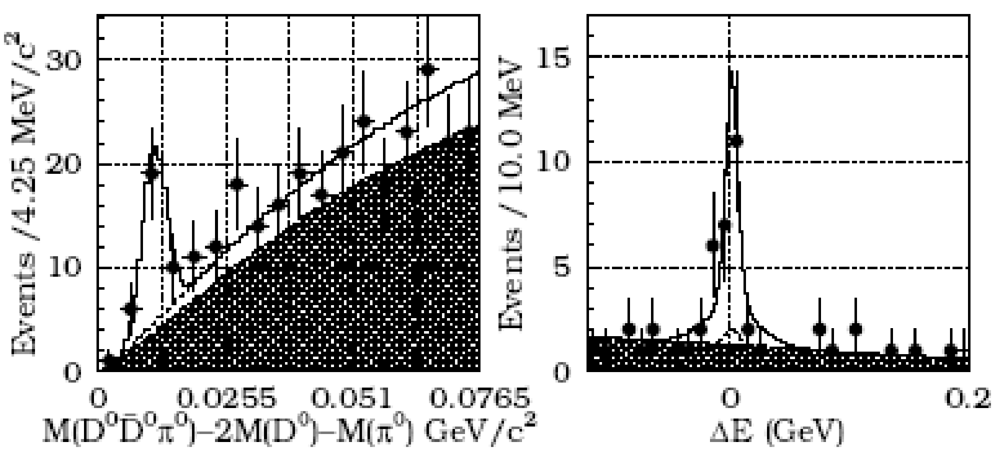
$(1.67 \pm 0.36 \pm 0.58) \times 10^{-4}$

Mass: $3875.1 \pm 1.1 \pm 0.5$ MeV/c^2

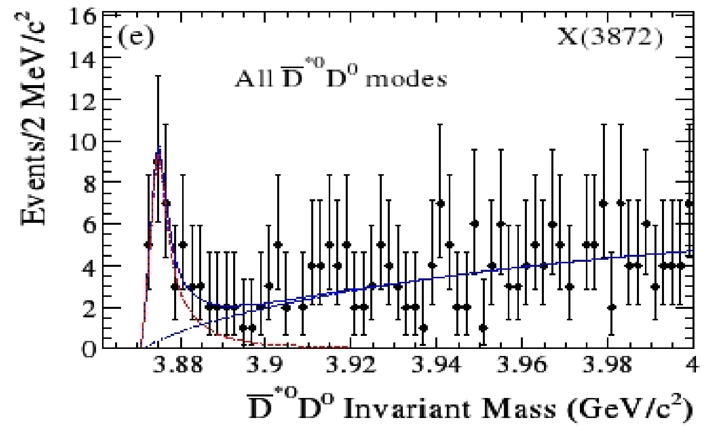
Width: $3.0^{+4.6}_{-2.3} \pm 0.9$ MeV

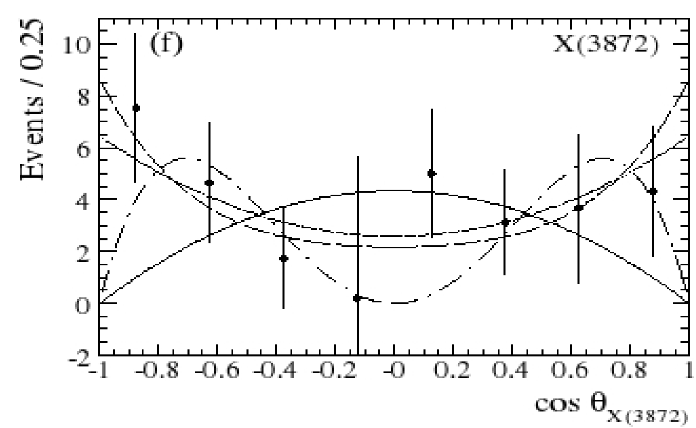
414fb^{-1}; PRL 97,162002(2006)





347 fb^{-1}; Phys.Rev.D77, 011102(R)(2008)





Y(3940)

Y(3940) in B decays to K ω J/ψ

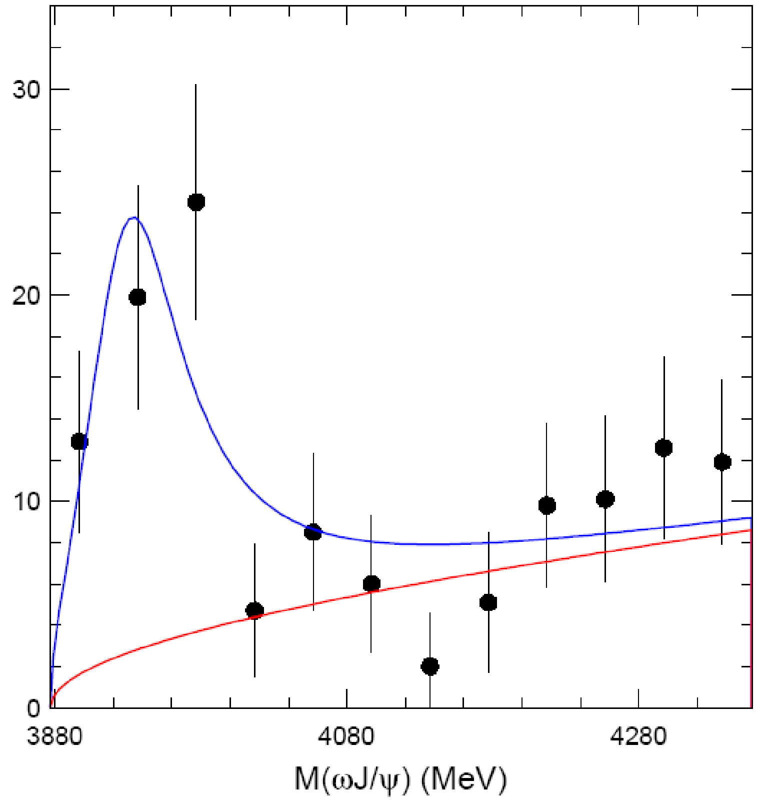
255 fb^{-1}: PRL94, 182002 (2005)

$M = 3943 \pm 11 \pm 13$ MeV

$\Gamma = 87 \pm 22 \pm 26$ MeV

BELLE

$$\mathcal{B}(B \to KY(3940))\mathcal{B}(Y(3940) \to \omega J/\psi) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}$$

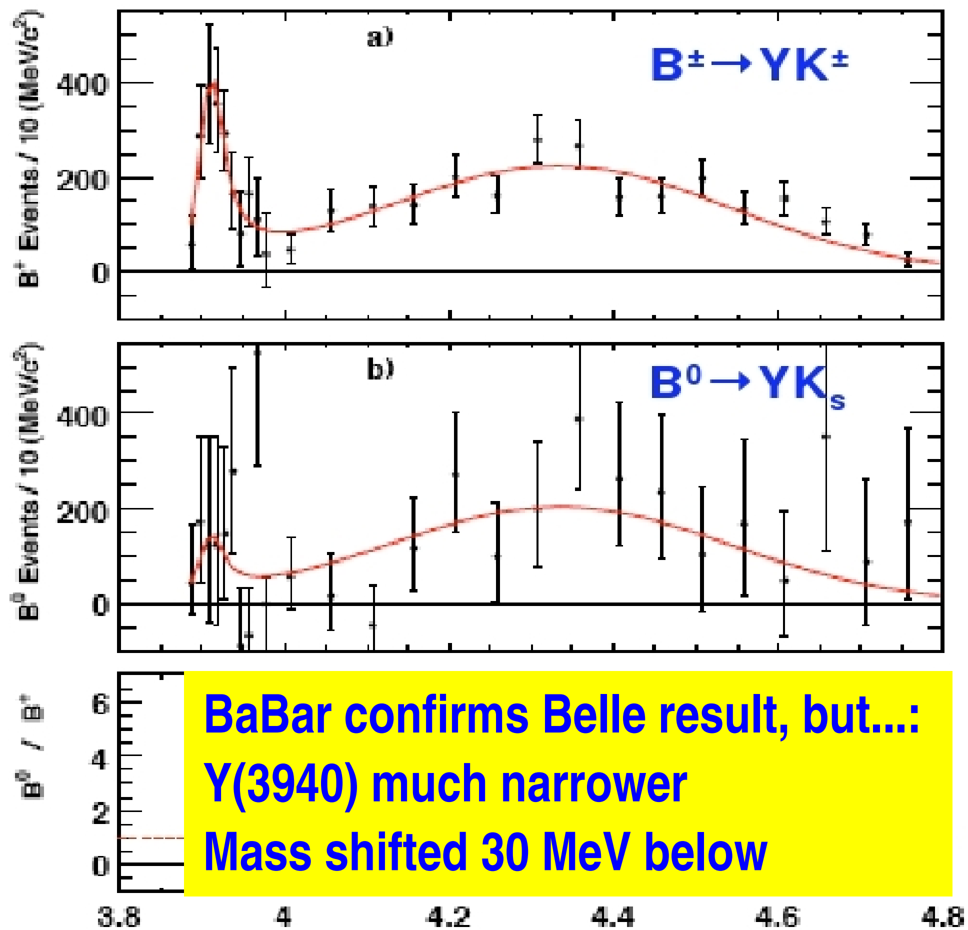


350 fb^{-1} : 0711.2047 , PRL

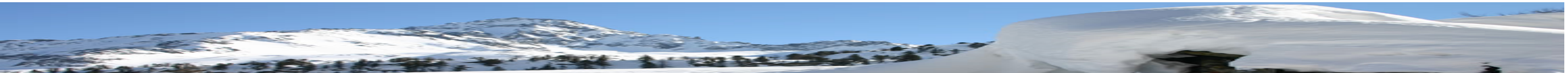
$M = 3914.3 \pm^{3.4}_{3.8} \pm 1.6$ MeV

$\Gamma = 33 \pm^{12}_{8} \pm 6$ MeV

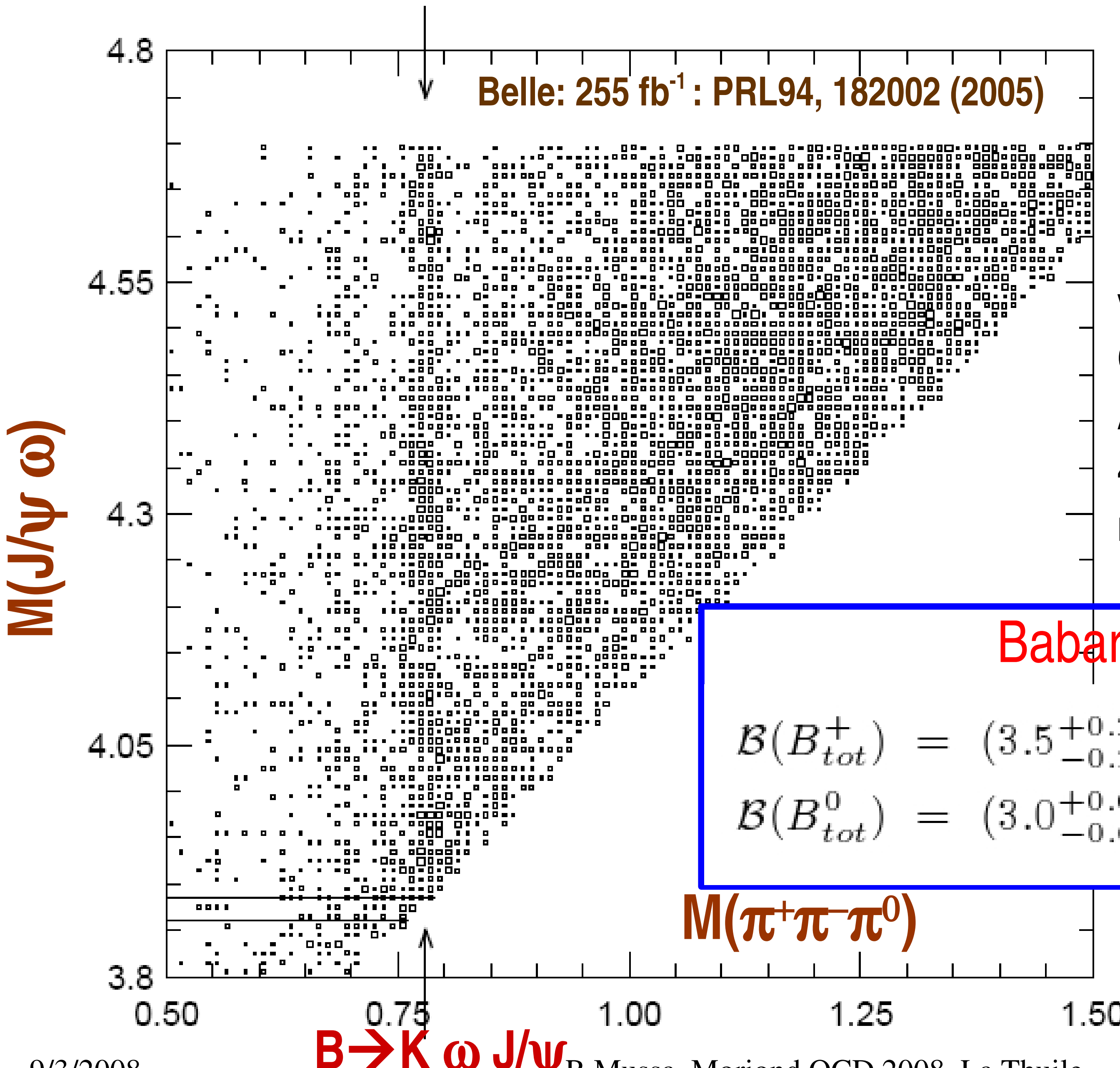
$$\mathcal{B}(B^+) = (4.9^{+1.0}_{-1.0}(stat)^{+0.5}_{-0.5}(syst)) \times 10^{-5},$$
$$\mathcal{B}(B^0) = (1.5^{+1.4}_{-1.2}(stat)^{+0.2}_{-0.2}(syst)) \times 10^{-5},$$



BaBar confirms Belle result, but...:
Y(3940) much narrower
Mass shifted 30 MeV below



Y(3940) in B decays to K ω J/ψ



Extraction of the ω signal is very clean at M(J/ψω) > 4.1 GeV, but is harder below.

A full Dalitz analysis on the 4body phase space is needed.

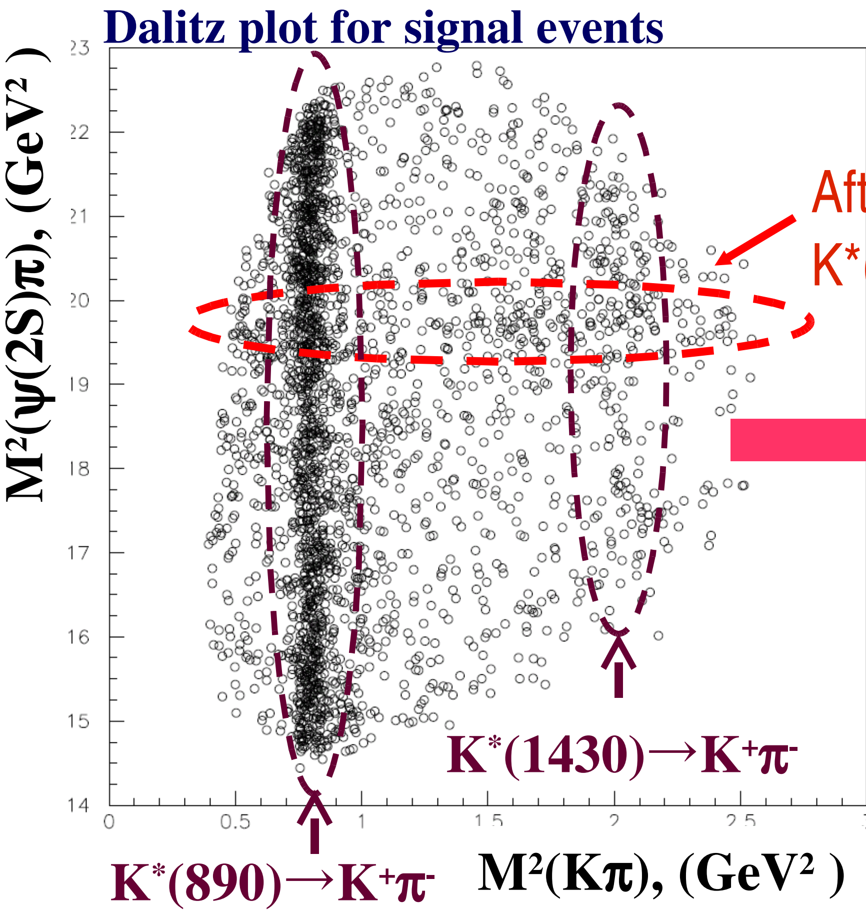
Babar: $\mathcal{B}$(B→K ω J/ψ)

$$\mathcal{B}(B^+_{tot}) = (3.5^{+0.2}_{-0.2}(stat)^{+0.4}_{-0.4}(syst)) \times 10^{-4},$$

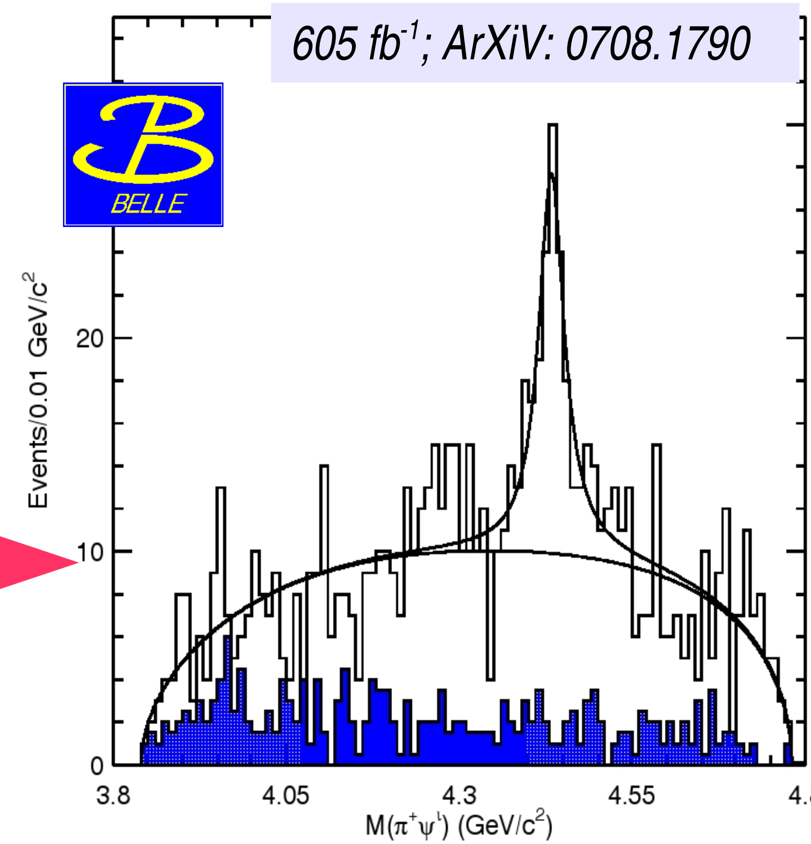
$$\mathcal{B}(B^0_{tot}) = (3.0^{+0.6}_{-0.6}(stat)^{+0.3}_{-0.3}(syst)) \times 10^{-4}.$$

Z(4430)

$Z^{\pm}(4430)$ in $B \to K \pi^{\pm} \psi'$



After applying $K^*(890)$*$K^*(1430)$ VETO ....



ψ' reconstructed in:

- $\psi' \to (ee, \mu\mu)$
- $\psi' \to J/\psi\, \pi\pi$

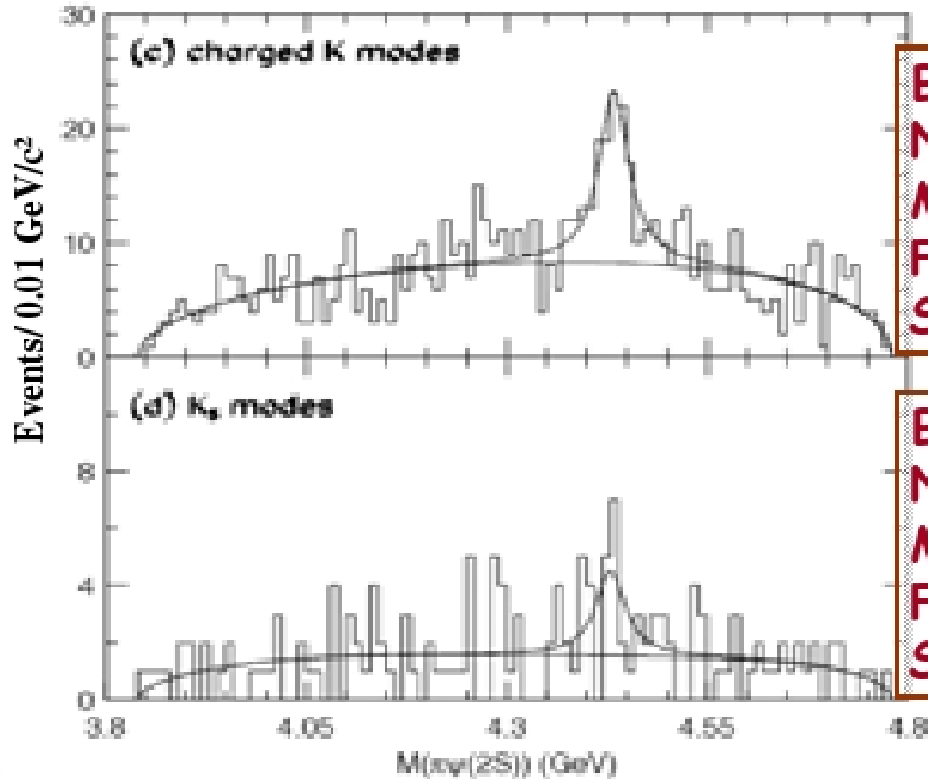
First charged charmonium-like tetraquark?

BW Fit Results

N_{signal} = 124.4 ± 30.8 evts
Mass = 4433 ± 4 MeV
FWHM Γ = 44^{+17}_{-13} MeV
χ^2/dof = 72.3/94.0 (95.3% CL)
Significance = 7.3 σ

$Z^{\pm}(4430)$ in $B \to K \pi^{\pm} \psi'$

Compare data subsamples
$B^0 \to K^- \pi^+ \psi'$ *vs* $B^+ \to K_S \pi + \psi'$



$B^0 \to K^- \pi^+ \psi'$
N_{signal} = 107± 27 evts
Mass = 4434 ± 5 MeV
FWHM Γ = 46^{+17}_{-13} MeV
Signif = 6.6 σ

$B^+ \to K_S \pi^+ \psi'$
N_{signal} = 21 ± 8 evts
Mass = 4430 ± 9 MeV
FWHM Γ = 46 MeV(fixed)
Signif = 3.0 σ

For equal B^+/B^0 Bf's, expect: $N(K_S)/N(K^-)=0.19$ in agreement with measurement: 0.20 +- 0.09

B decays to K + charmonium

PDG2007

$\mathcal{B} \times 10^4$	$K^\pm$	K^0	$K^{*\pm}$	K^{*0}	+anything
η_c	9.1 ± 1.3	9.1 ± 1.9		16 ± 7	< 90
J/ψ	10.08 ± 0.35	8.72 ± 0.33	14.1 ± 0.8	13.3 ± 0.6	78 ± 3
χ_{c0}	1.6 ± 0.5	< 5	< 28.6	< 7.7	
χ_{c1}	5.3 ± 0.7	3.9 ± 0.4	3.6 ± 0.9	3.2 ± 0.6	31.6 ± 2.5
χ_{c2}	< 0.29	< 0.26	< 0.12	< 0.36	16.5 ± 3.1
$\eta_c(2S)$	3.4 ± 1.8				
ψ'	6.48 ± 0.45	6.2 ± 0.6	6.7 ± 1.4	7.2 ± 0.8	30.7 ± 2.1

Babar $\psi(3770)$ 2.6 ± 0.6

Belle+Babar $X(3872)$ 1.41 ± 0.40 $/ BR(D^0 D^0 \pi^0)$

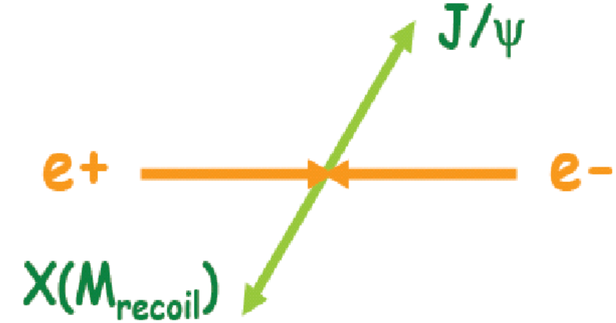
Belle+Babar $X(3872)$ $0.114 \pm 0.020 / BR(\psi \pi^+ \pi^-)$

Belle+Babar $Y(3940)$ $(0.15 \div 0.71) / BR(\psi\omega)$

Belle $Z^\pm(4430)$ $0.41 \pm 0.18 / BR(\psi\pi^\pm)$

X(3940) & X(4160)

Scanning C=+1 charmonia with J/ψ recoil



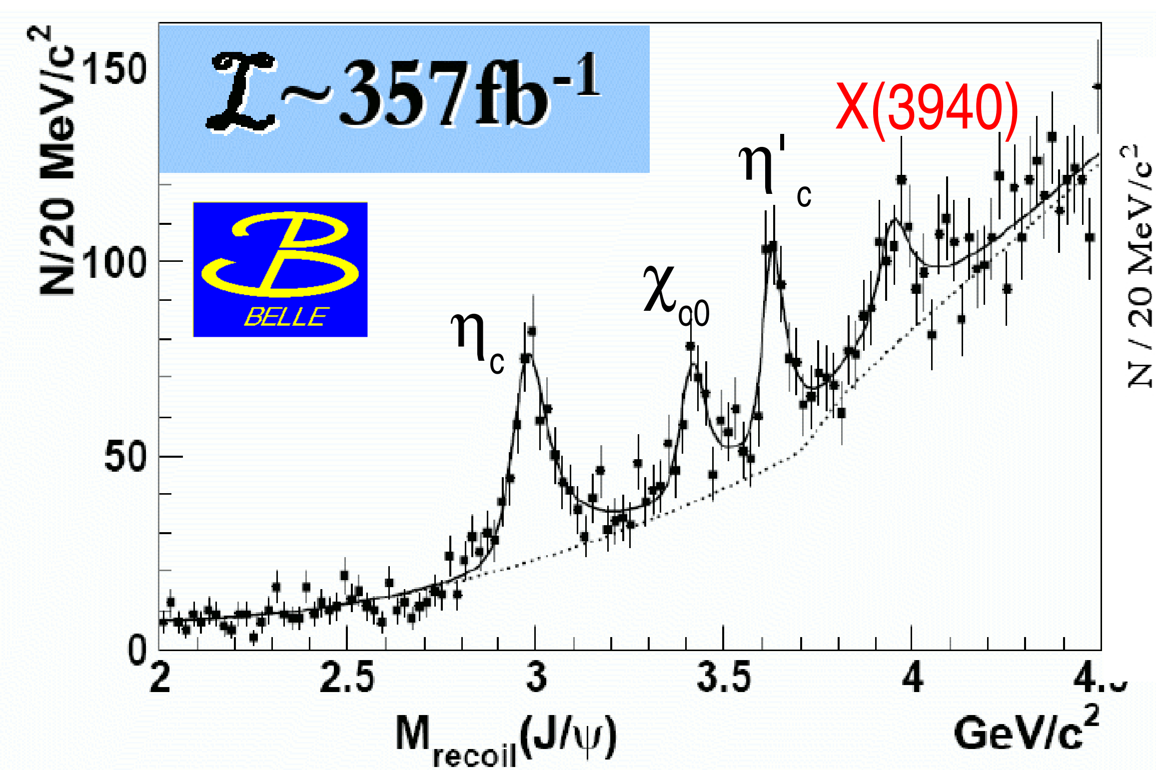
Belle: PR D 70, 071102(R) (2004)

3 peaks, from J=0 charmonia,

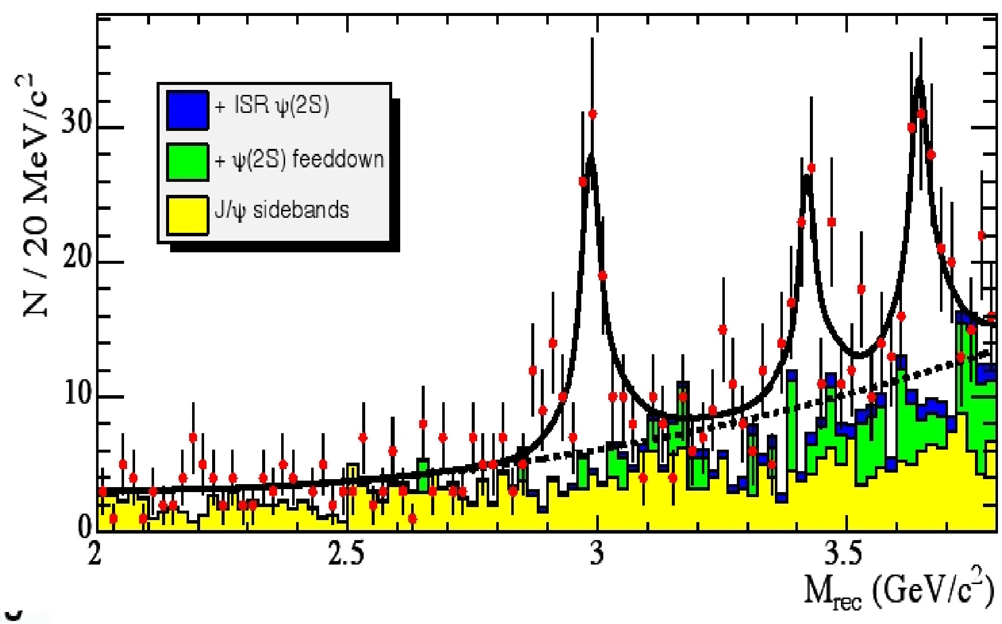
with 2nd evidence of $\eta_c(2S)$:

Belle: PRL 98, 082001 (2007)

Discovery of X(3940)



BaBar: PR D 72, 031101(R) (2005)



Charmed mesons recoiling on $J/\psi+D^{(*)}$

Belle: hep-ex/0708.3812

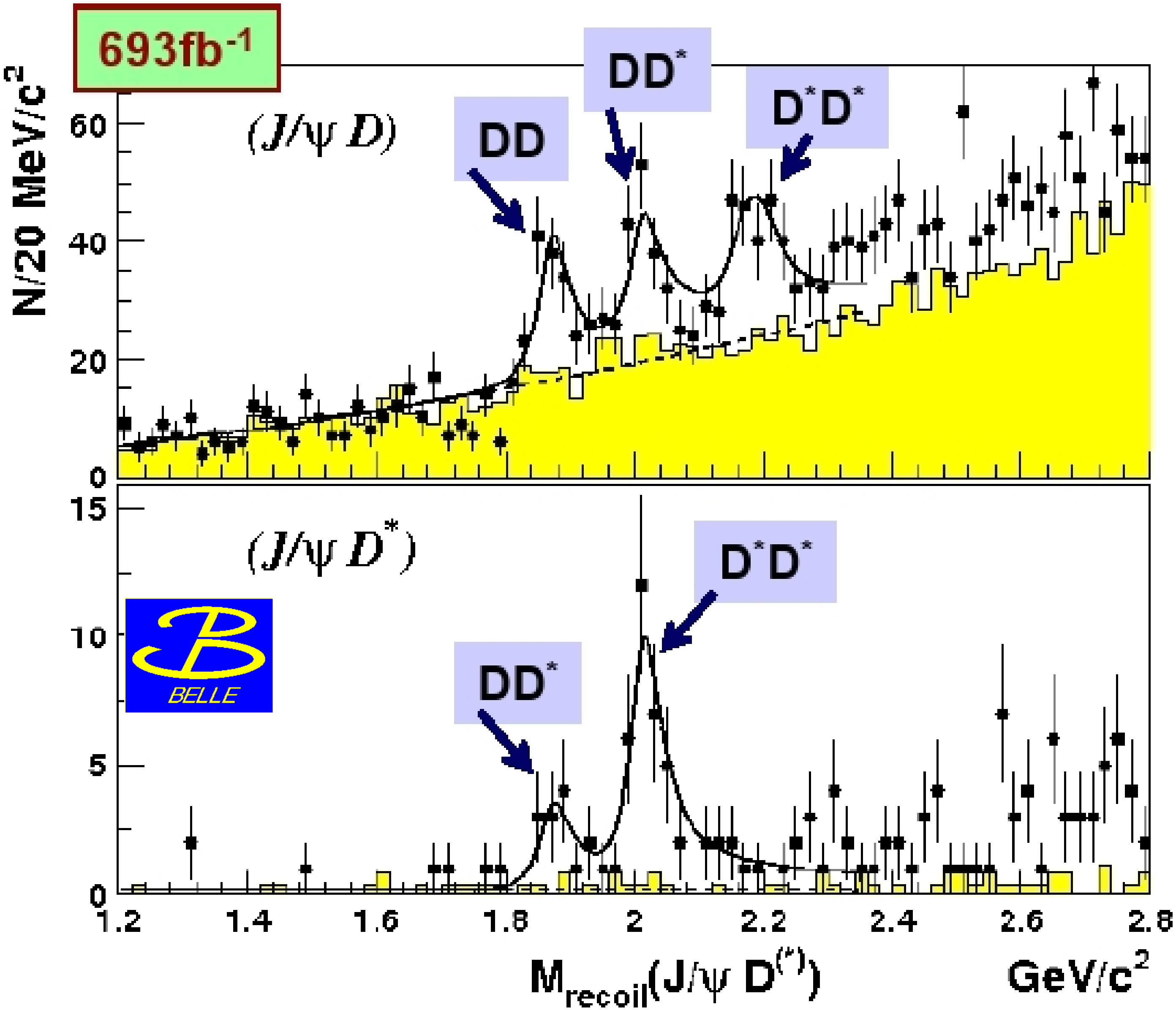
Further development:

D^+ reconstructed in 3 decay modes (12%):

$K^-\pi^+\pi^-$, $K^+K^-\pi^+$, $K_S^0\pi^+$

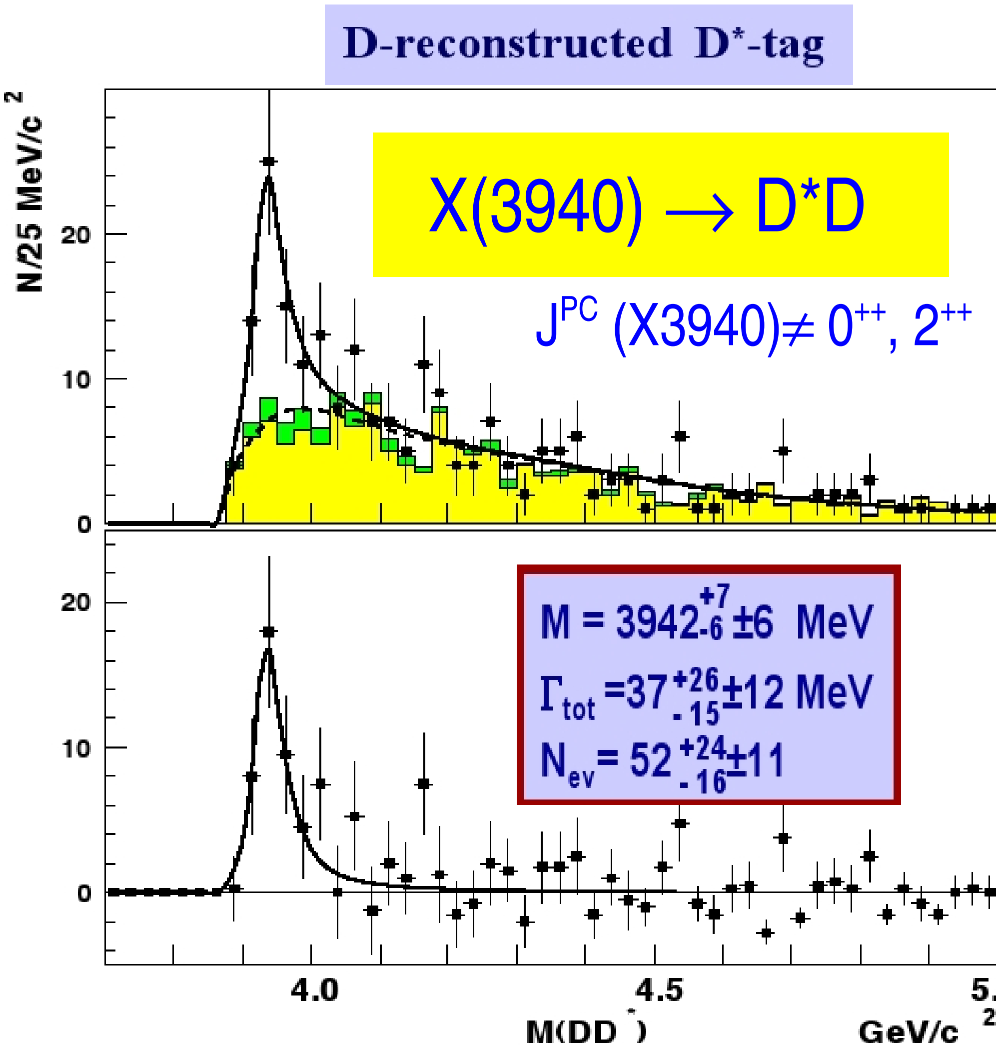
D^0 reconstructed in 5 decay modes (29%):

$K^-\pi^+$, K^+K^-, $K^-\pi^+\pi^-\pi^+$, $K_S^0\pi^+\pi^-$, $K^+\pi^-\pi^0$

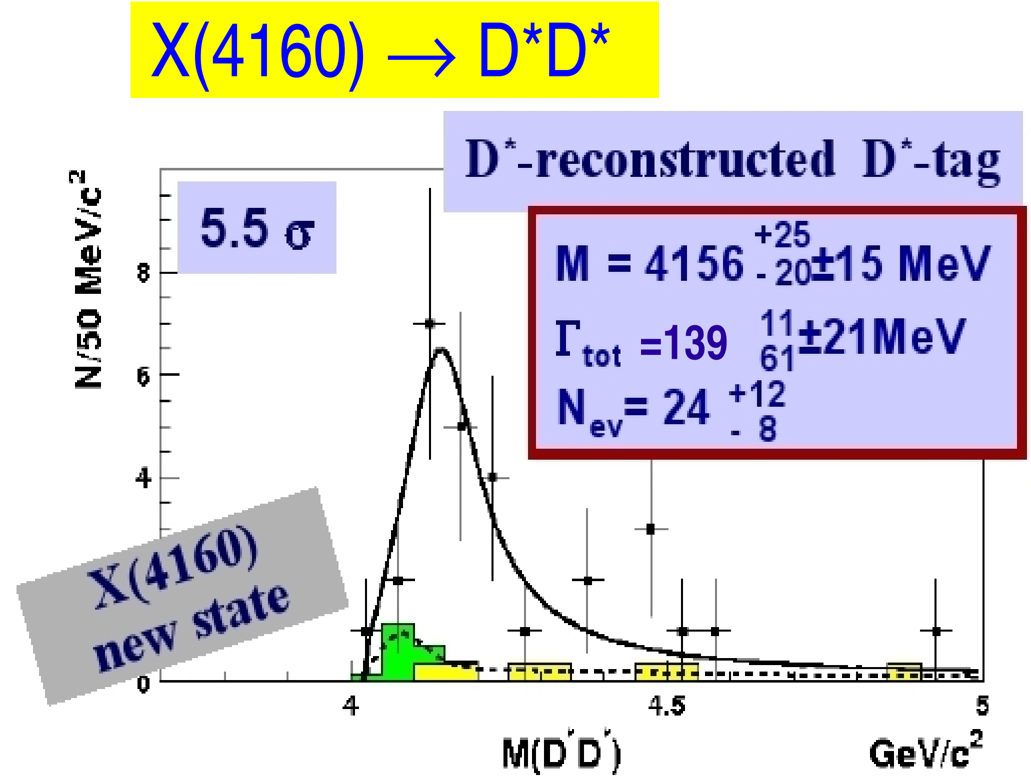


New charmonium-like states recoiling off J/ψ

[hep-ex/0708.3812]



$\eta_c(3S)$?



$\psi(4160)$? NO: wrong C parity;

$\chi_{c0}(3P)$? $\eta_c(4S)$?

Cross sections for double ccbar: exp vs theory

X_{cc} = lower charmonia		$\eta_c\,(1S)$	$\chi_{c0}\,(1P)$	$\eta_c\,(2S)$
Belle	$\sigma(J/\psi+X_{cc}) \times \mathcal{B}(N_{ch}>2)$[fb]	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
Babar	$\sigma\,(J/\psi+X_{cc}) \times \mathcal{B}(N_{ch}>2)$[fb]	$17.6 \pm 2.8\,^{+1.5}_{-2.1}$	$10.3 \pm 2.5\,^{+1.4}_{-1.8}$	$16.4 \pm 3.7\,^{+2.4}_{-3.0}$
NRQCD-LO	$\sigma(J/\psi+X_{cc})$ [fb]	3.78 ± 1.26	2.40 ± 1.02	1.57 ± 0.52
NRQCD-NLO	$\sigma(J/\psi+X_{cc})$ [fb]	16.7 ± 4.2		

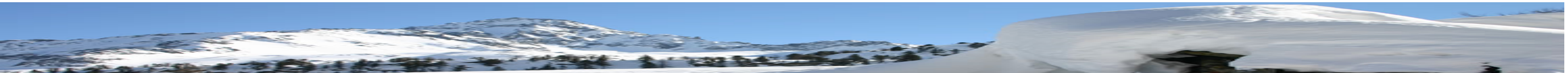
Belle	$\sigma(\psi(2S)+X_{cc}) \times \mathcal{B}(N_{ch}>2)$[fb]	$16.3 \pm 4.6 \pm 3.9$	$12.5 \pm 3.8 \pm 3.1$	$16.0 \pm 3.1 \pm 3.8$

X_{cc} = new states		X(3940)	X(4160)
Belle	$\sigma(J/\psi+X_{cc}) \times \mathcal{B}(DD^*)$[fb]	$13.9\,^{+6.4}_{-4.1} \pm 2.2$	
Belle	$\sigma(J/\psi+X_{cc}) \times \mathcal{B}(D^*D^*)$[fb]		$24.7\,^{+12.8}_{-8.3} \pm 5.0$

Large NLO corrections needed to fit the data

Do not decrease in $\psi(2s)$ recoil

Do not decrease if higher masses recoil on J/ψ



Cross sections for double ccbar: exp vs theory

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Do not decrease in ψ(2s) recoil

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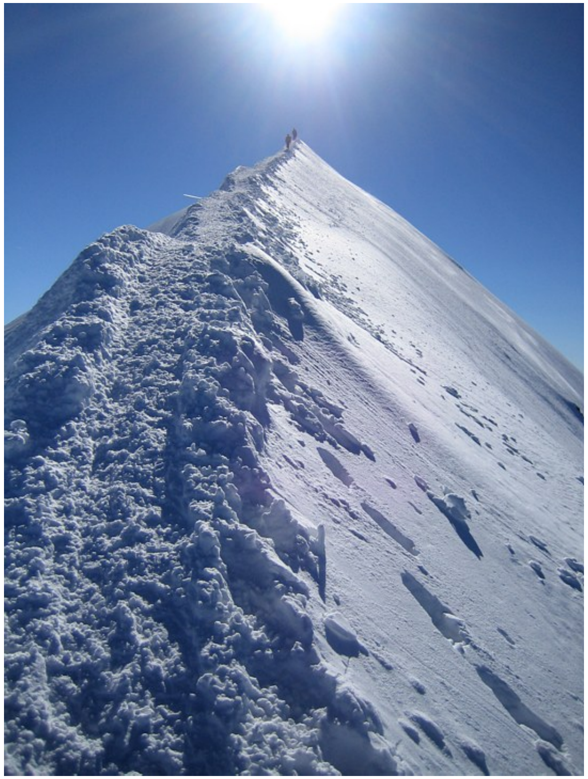
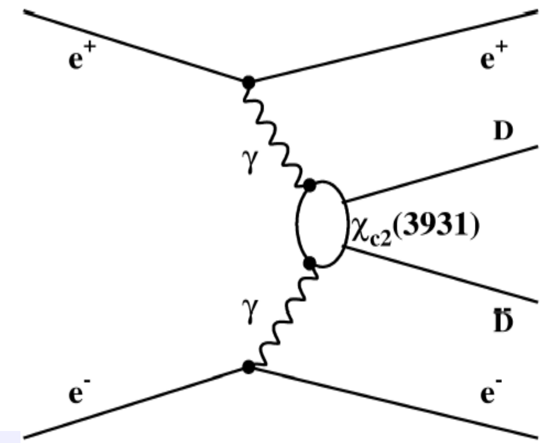
Z(3930)



Z(3930) in $\gamma\gamma$ fusion



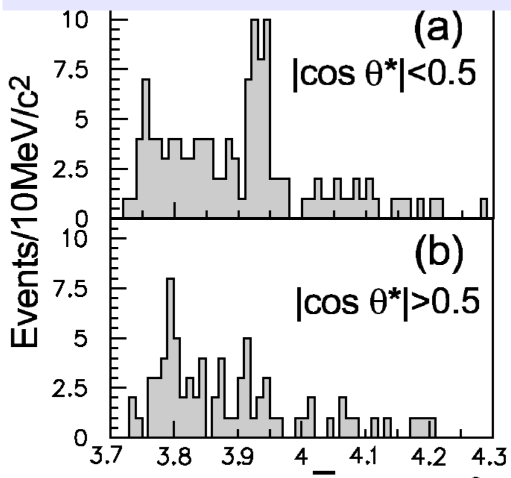
Belle, 395 fb^{-1}: PRL 96 (2006), 82003 (hep-ex/0507033)

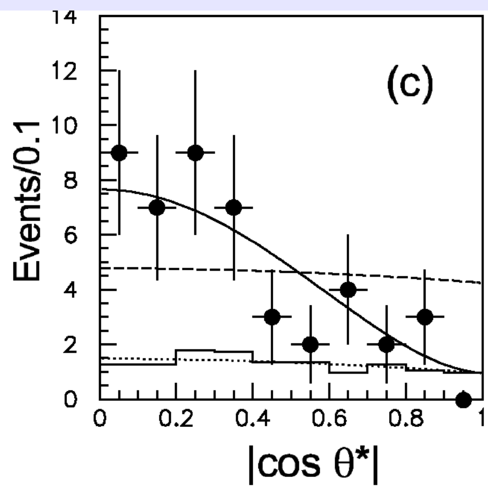
M=3929 ± 5 ± 2 MeV ; Γ=29±10 ±2 MeV

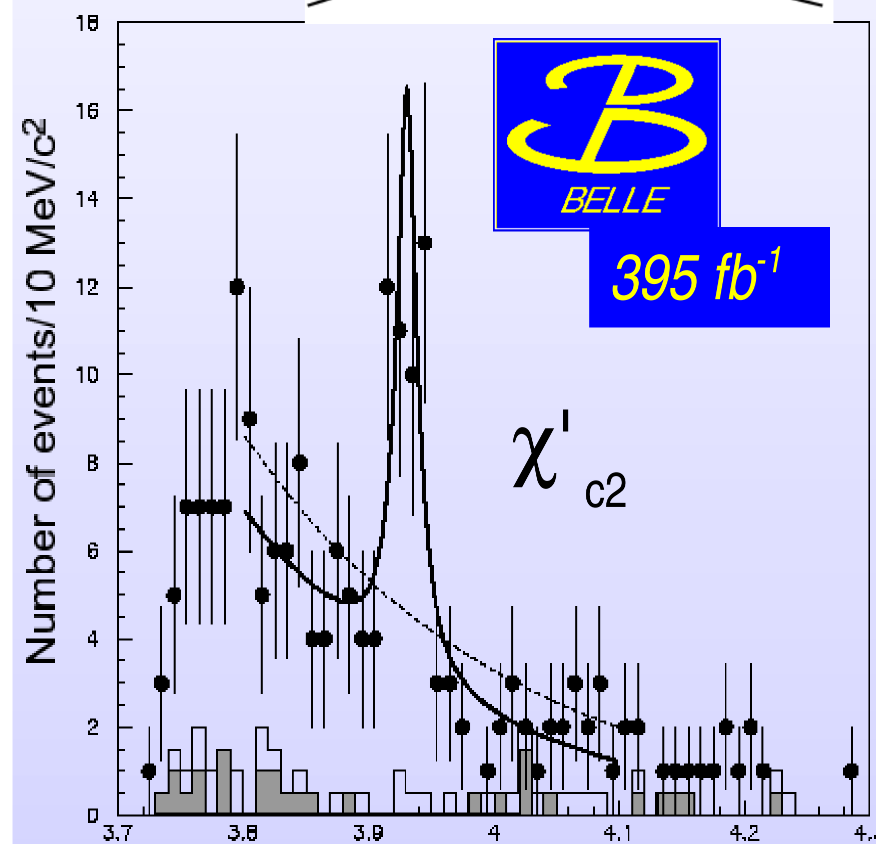
$\Gamma_{\gamma\gamma}\cdot BR(Z\to D\underline{D})$ **= 180±50±30 eV**

64± 18 evts (5.3σ significance)

Angular distributions favor $J^{PC} = 2^{++}$







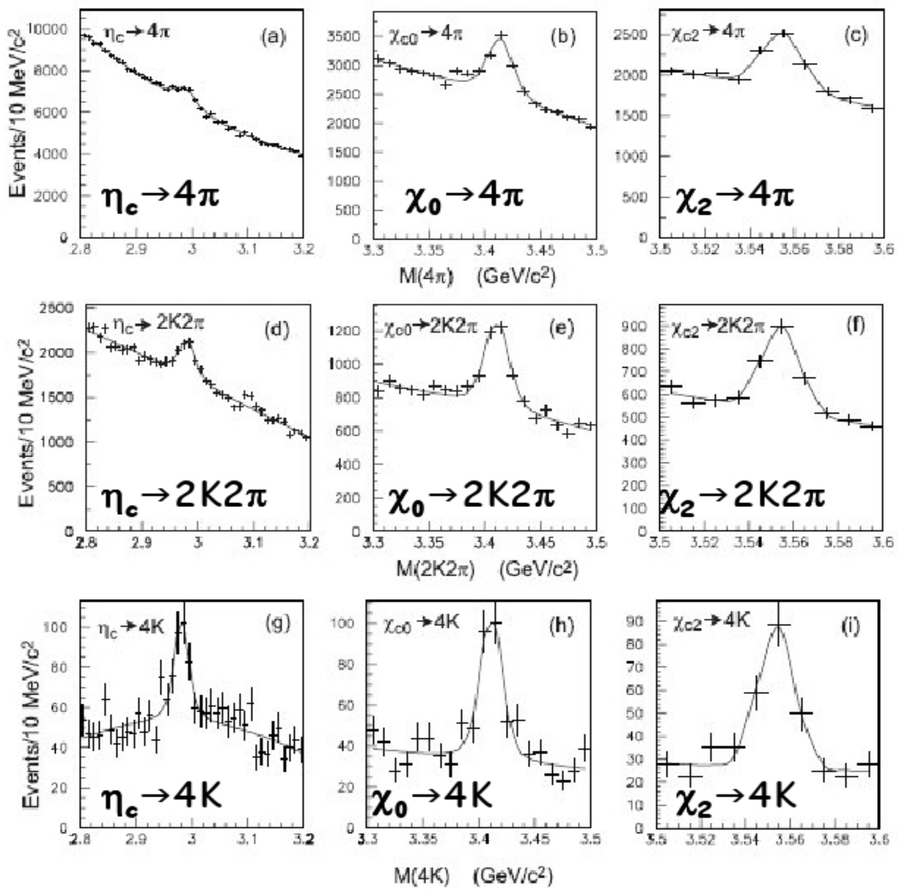
Fits charmonium hypothesis as χ'_{c2}(2P)

NEED: CONFIRMATION BY BaBar , DD : D*D ratio

Precision studies on partial widths

BELLE: thorough study of

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



EPJ C53(2008),14
(arXiv:0706.3955)

Results on πKK decay mode

M, MeV	Group	η_c	$\eta_c(2S)$
	Belle	$2981.4 \pm 0.5 \pm 0.4$	$3633.7 \pm 2.3 \pm 1.9$
	PDG-07	2979.8 ± 1.2	3637.0 ± 4.0
	CLEO	$2981.8 \pm 1.3 \pm 1.5$	$3642.9 \pm 3.1 \pm 1.5$
	BaBar	$2982.5 \pm 1.1 \pm 0.9$	$3630.8 \pm 3.4 \pm 1.0$
Γ, MeV	Group	η_c	$\eta_c(2S)$
	Belle	$36.6 \pm 1.5 \pm 2.0$	$19.1 \pm 6.9 \pm 6.0$
	PDG-07	25.5 ± 3.4	14.0 ± 7.0
	CLEO	$24.8 \pm 3.4 \pm 3.5$	$6.3 \pm 12.4 \pm 4.0\ (< 31)$
	BaBar	$34.3 \pm 2.3 \pm 0.9$	$17.0 \pm 8.3 \pm 2.5$
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV	Group	η_c	$\eta_c(2S)$
	Belle	$142 \pm 4 \pm 14$	$11.2 \pm 2.4 \pm 2.7$

Only upper limits for $\eta_c(2S)$ decays to $4\pi, 2K\,2\pi$, 4K even if hints of signals are visible.

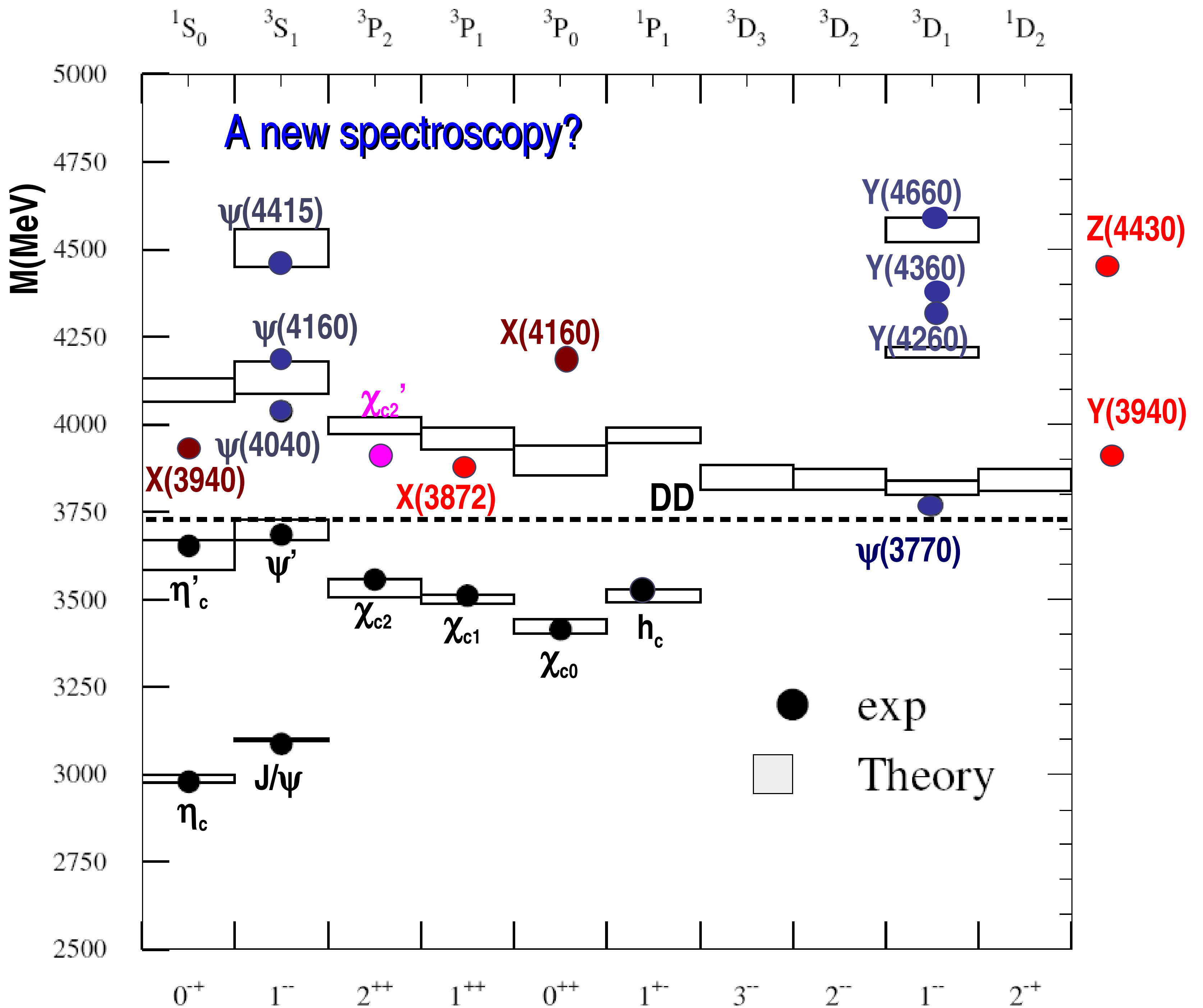
Most new states do not fit predicted decay patterns.

Even Z(3930) is not where the χ_{c2}' was expected

Large rates of dipion transitions even above DD threshold.

Many new vector states above open charm thresholds: hybrids, tetraquarks?

Two narrow D states still missing



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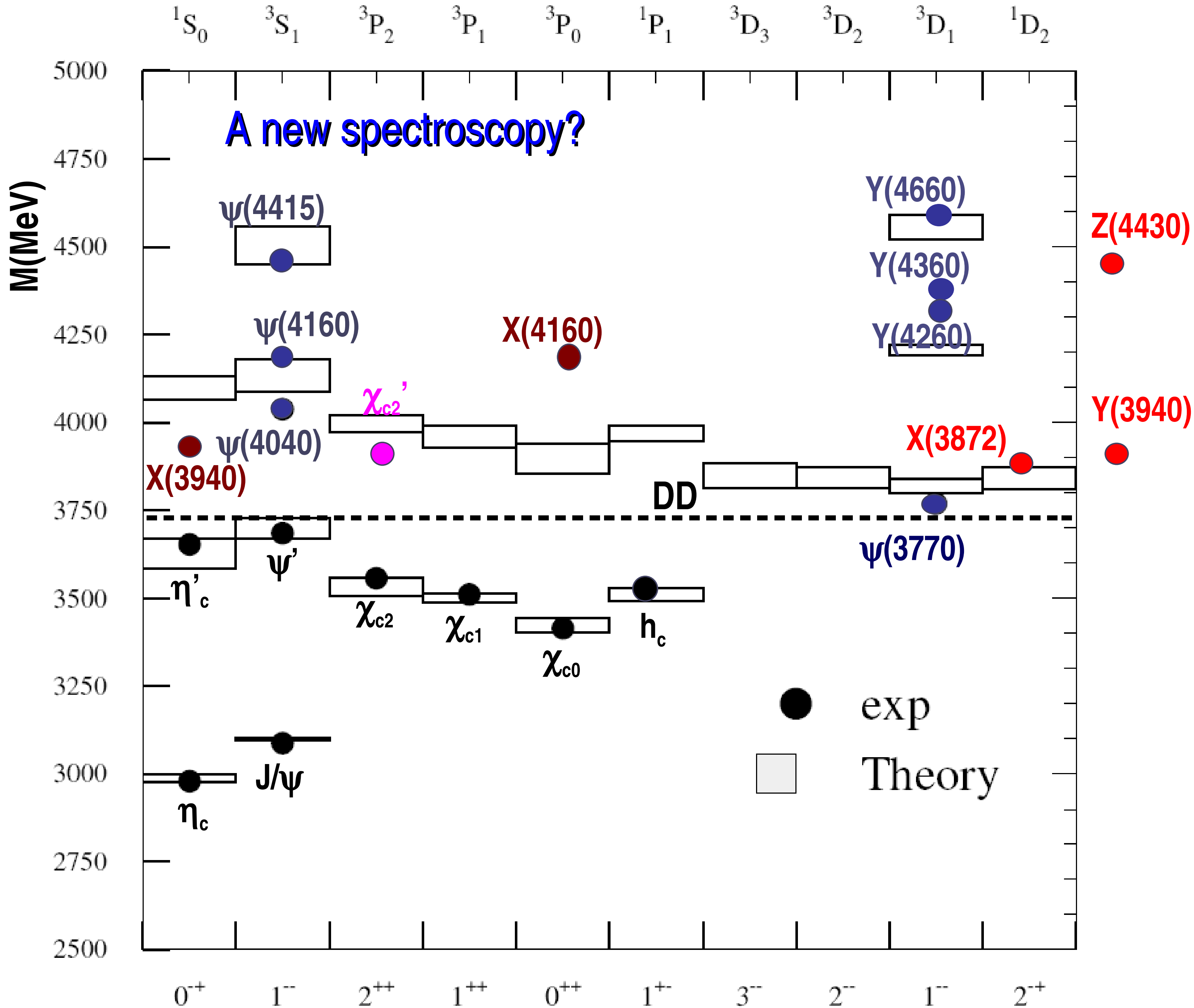


Summary

Lots of new "charmonia" in the last 5 years : a new spectroscopy?

Only the narrow X(3872) has diversified production and decay mechanisms

All the other new states are seen in only one channel

Strong dynamics of B to charmonium K should help to define their nature

Spin dependence of double ccbar still unclear

A clear pattern has not yet emerged, and further studies are under way
B-factories have not yet finished to rewrite charmonium spectroscopy

STAY TUNED : see you at 6th QWG, *Nara(Japan), Dec.2-5,2008*

Large NLO corrections in the NRQCD calculation are needed

$J/\psi\ (c\bar{c})_{res}$		$\eta_c(1S)$	χ_{c0}	$\eta_c(2S)$
Belle	$\sigma \times \mathcal{B}_{>2}$ [fb]	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
BaBar	$\sigma \times \mathcal{B}_{>2}$ [fb]	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
NRQCD:	σ [fb]			
Braaten&Lee[1]		3.78 ± 1.26	2.40 ± 1.02	1.57 ± 0.52
...with relativistic corr^{ns}:		$7.4^{+10.9}_{-4.1}$	–	$7.6^{+11.8}_{-4.1}$
Liu,He,&Chao[2]		5.5	6.9	3.7
Zhang,Gao,&Chao[3]		14.1	–	–
				–

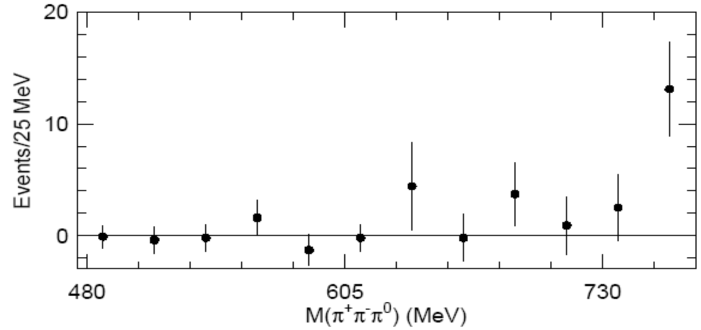
- **The K-factor from the resummed relativistic corrections is greater than that from the QCD NLO corrections found by Zhang, Gao, and Chao.**

$$\text{K-Factor} = (1 + \underbrace{0.8}_{\text{QCD NLO}}) \times (1 + \underbrace{1.45 \pm 0.61}_{v^2\ \text{Resummation}})$$

- Without (QCD NLO)$\times$(v^2 Resum.) term:
  $(3.78\ \text{fb})_{\text{LO}} \times (3.25 \pm 0.61) = \mathbf{12.3 \pm 2.3}$ fb
- With estimated (QCD NLO)$\times$(v^2 Resum.) term:
  $(3.78\ \text{fb})_{\text{LO}} \times (4.41 \pm 1.10) = \mathbf{16.7 \pm 4.2}$ fb

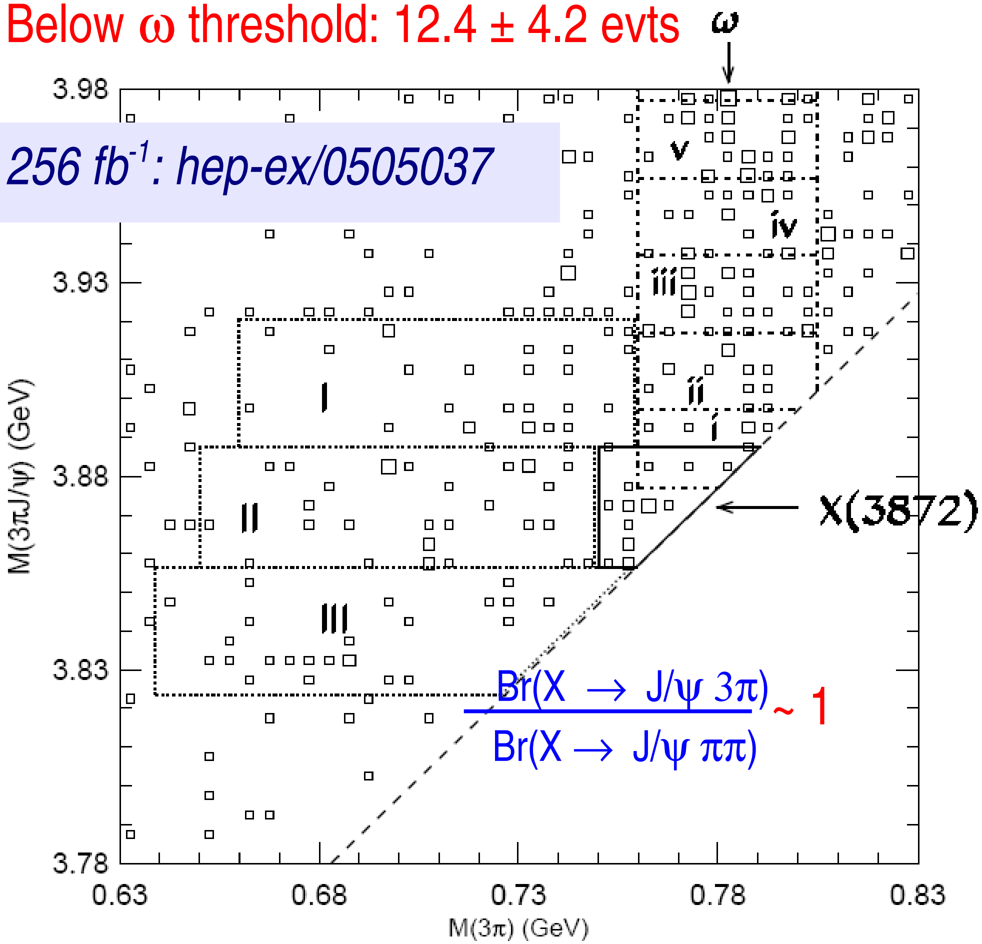
Braaten & Lee (QWG2006)

X(3872) in $B \to K (\pi^0 \pi^+ \pi^- J/\psi)$



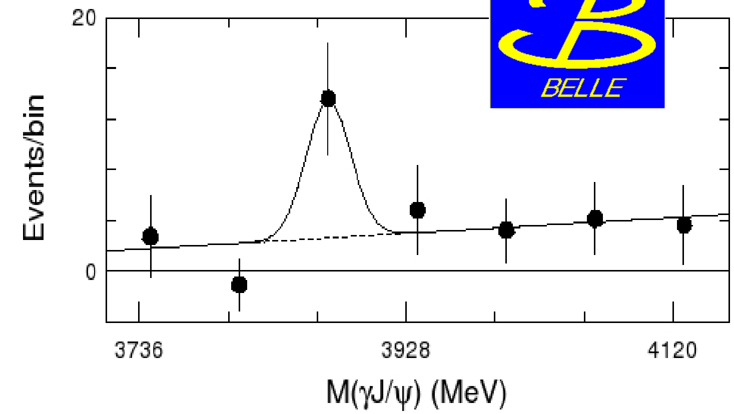
Below ω threshold: 12.4 ± 4.2 evts

256 fb^{-1}: hep-ex/0505037



$$\frac{Br(X \to J/\psi\, 3\pi)}{Br(X \to J/\psi\, \pi\pi)} \sim 1$$

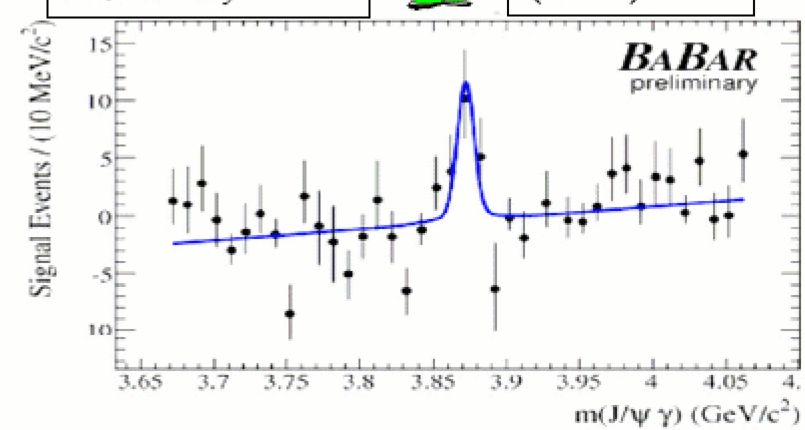
X(3872) in $B \to K (\gamma J/\psi)$



$$\Gamma(X \to \gamma J/\psi)/\Gamma(X \to \pi^+\pi^- J/\psi) = 0.14 \pm 0.05.$$

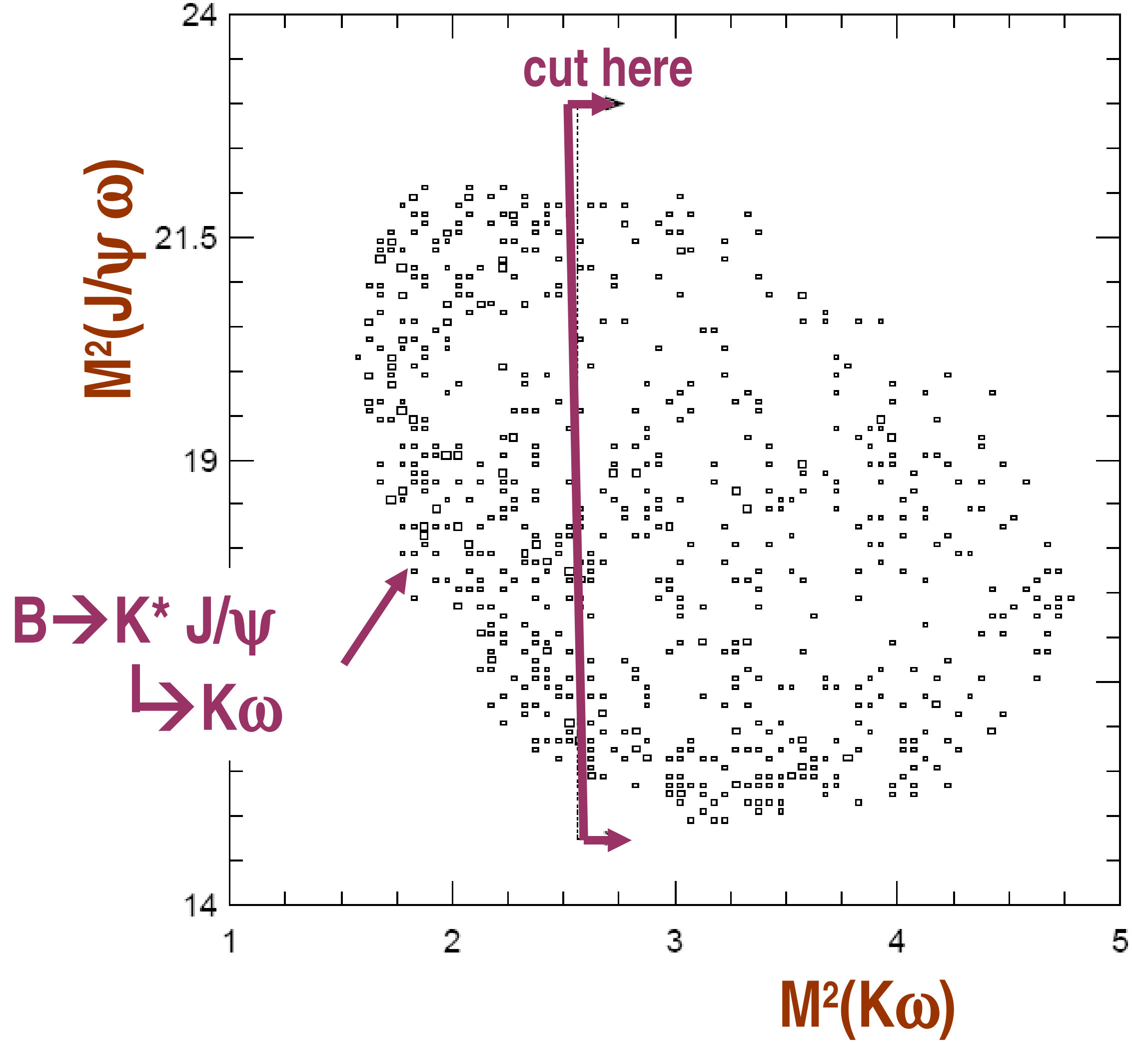
BABAR: 287M $B\bar{B}$
Preliminary

N=19.4±5.7
(3.4 σ)



Y(3940) : Dalitz plot $B \to K\,\omega\,J/\psi$

255 fb^{-1}: PRL94, 182002 (2005)



Cuts:

- ω Mass:

  $760 < M(\pi^+\pi^-\pi^0) < 805$ MeV

- no $B \to K\pi^0\psi'$:

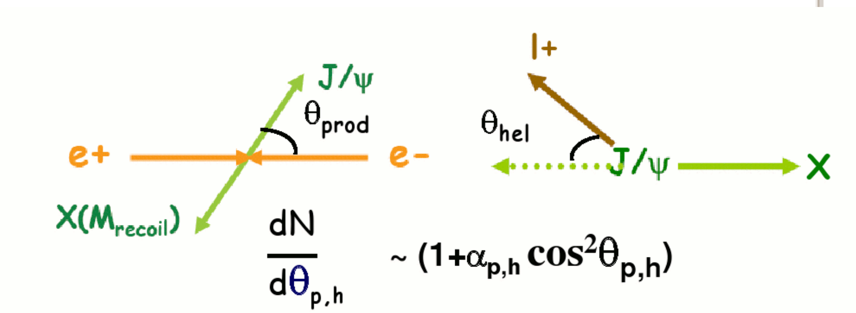
  $|\,M(J/\psi\pi^+\pi^-) - M(\psi')\,| > 3\sigma$

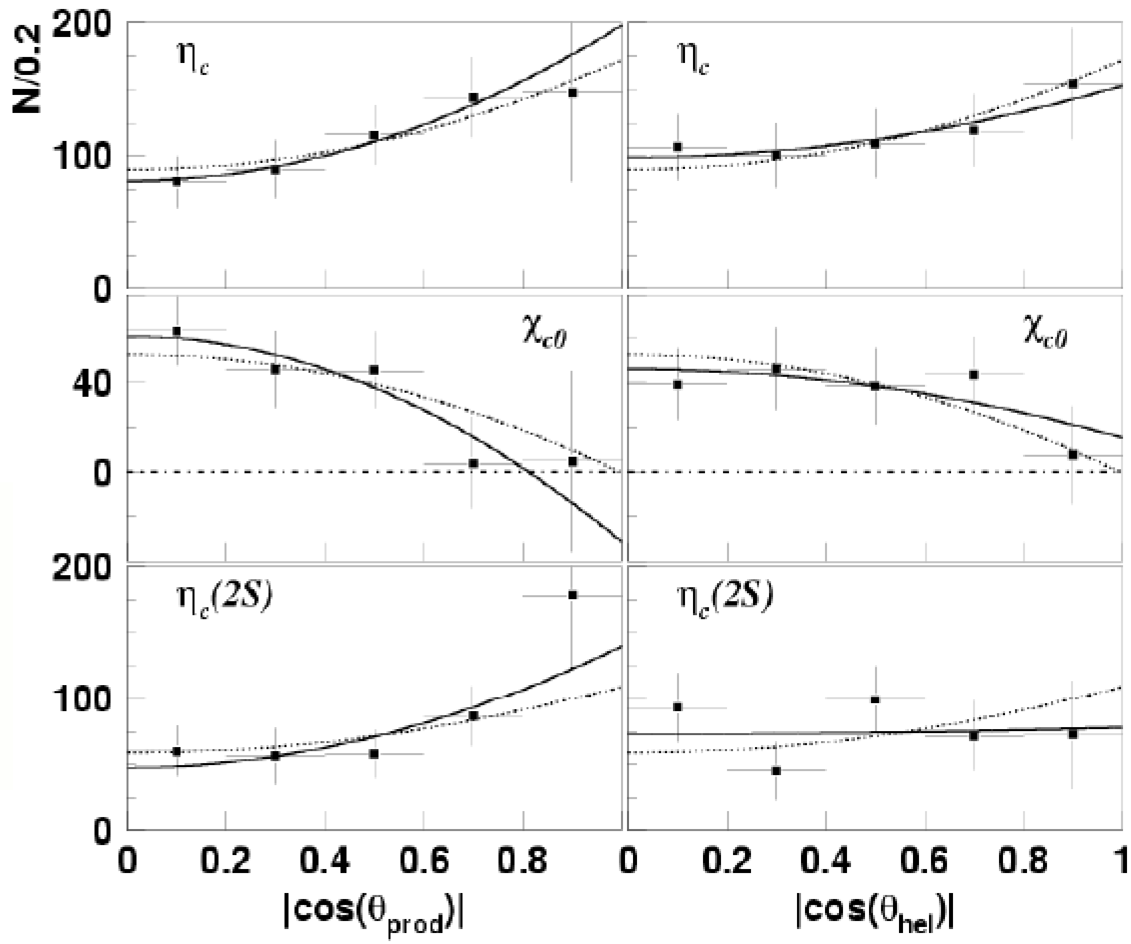
- no K* :

  $M(K\,\omega) > 1.6$ GeV

X(3940) in double charmonium : 0^{-+} vs 0^{++}

Angular distributions can cast some light on X(3940) quantum numbers :

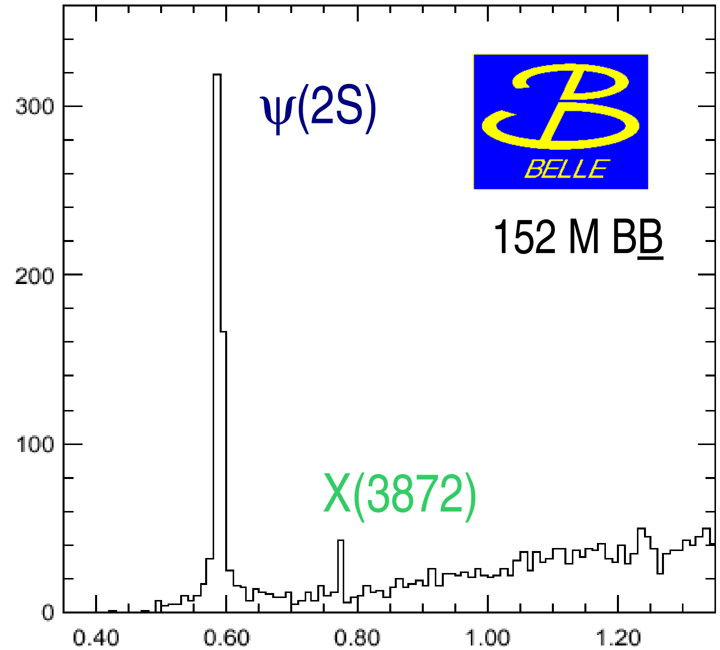




X(3872): discovery in $B \to K (\pi^+ \pi^- J/\psi)$

LP2003, August '03

Discovery in B decays $\to K J/\psi\pi\pi$



Belle : PRL91,262001(2003) [hep-ex/0309032]

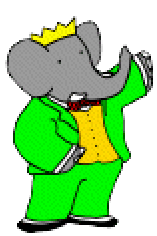
$M = 3872.0 \pm 0.6 \pm 0.5$ MeV/c^2

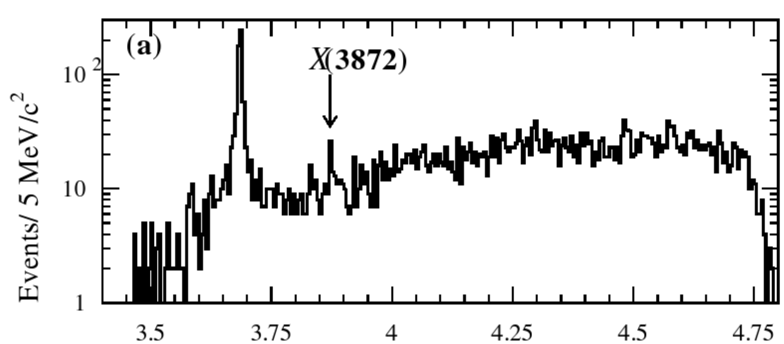
$\Gamma < 2.3$ MeV (90%CL)

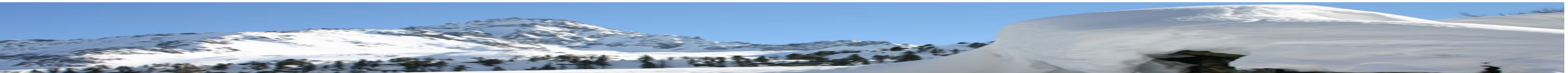
$$\frac{Br(B^+ \to K^+ X) * Br(X \to J/\psi\,\pi\pi)}{Br(B^+ \to K^+ \psi') * Br(\psi' \to J/\psi\,\pi\pi)} = 6.3 \pm 1.2 \pm 0.7\ \%$$

PHYSICAL REVIEW D **71,** 071103 (2005)

BaBar: PRD71,071103(2005) [hep-ex/0406022]





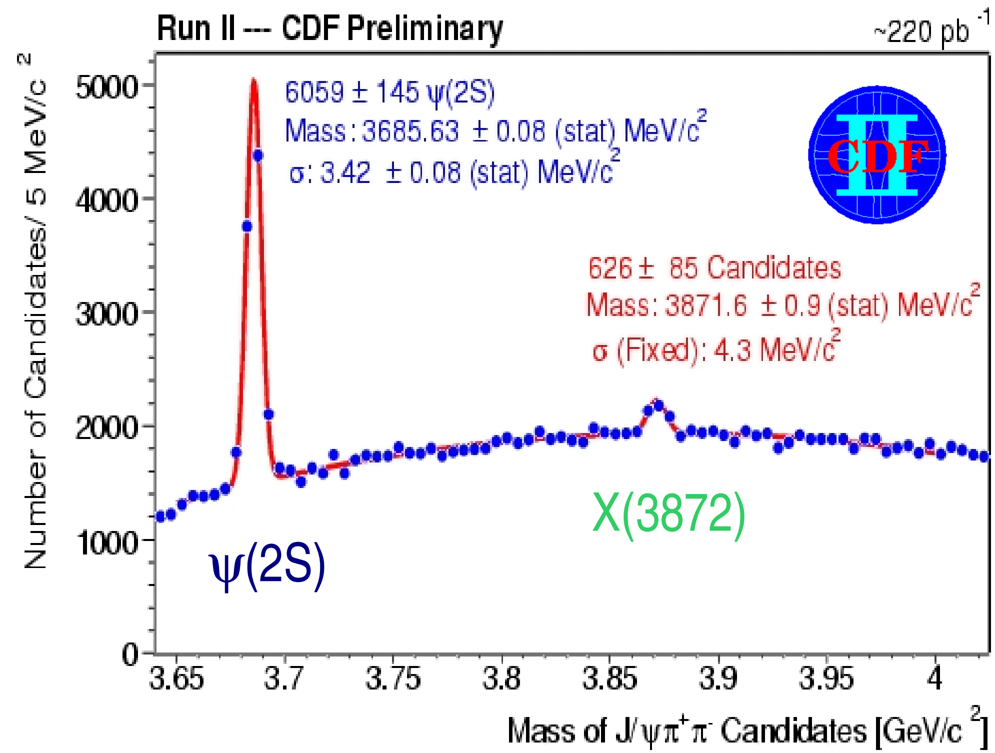


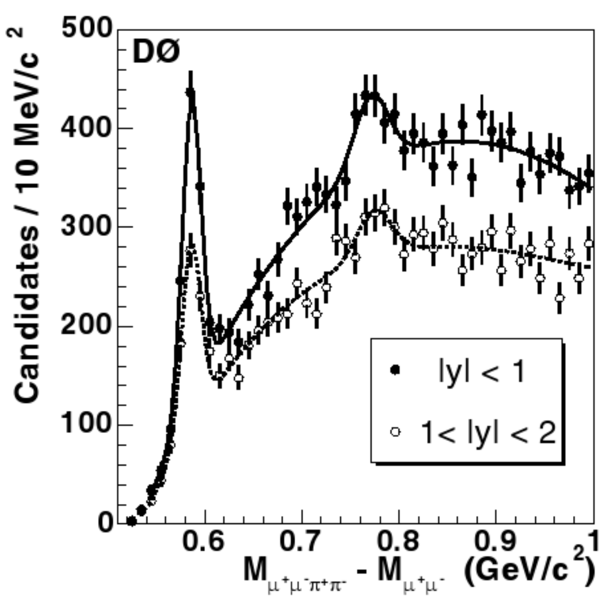
X(3872): production in $p\bar{p}$ annihilations

- Use ~ $220\ pb^{-1}$ Run II Data

CDF: PRL93,072001(2004) [hep-ex/0312021]

Prompt X(3872) is dominant: only 16% from B→ K J/ψππ





DØ PRL93,162002(2004) [hep-ex/0405004]

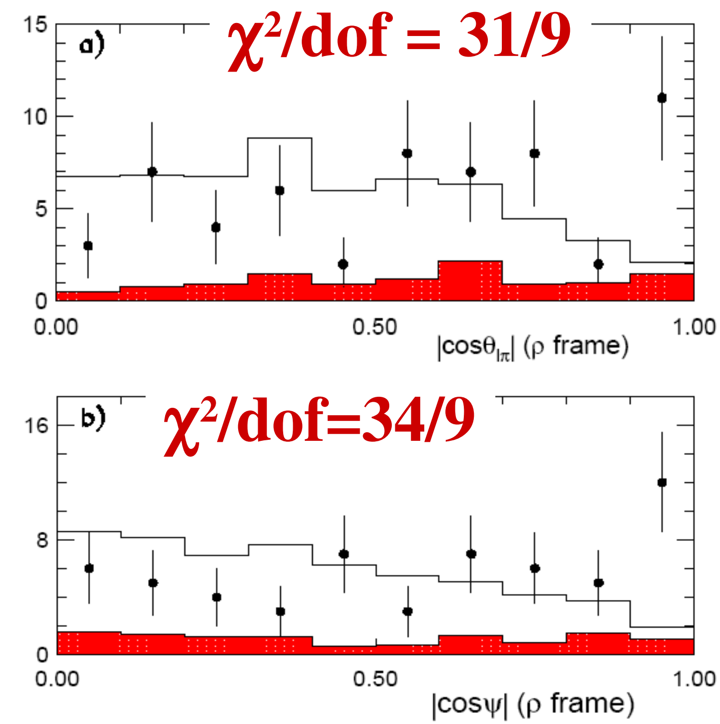
X(3872) production vs pseudo-rapidity

$X(3872) - \pi^+ \pi^- J/\psi$ angular distribution

not 0^{++} $\varepsilon_\rho \cdot \varepsilon_{J/\psi}$

neither 0^{-+} $k \cdot (\varepsilon_\rho \times \varepsilon_{J/\psi})$

BELLE



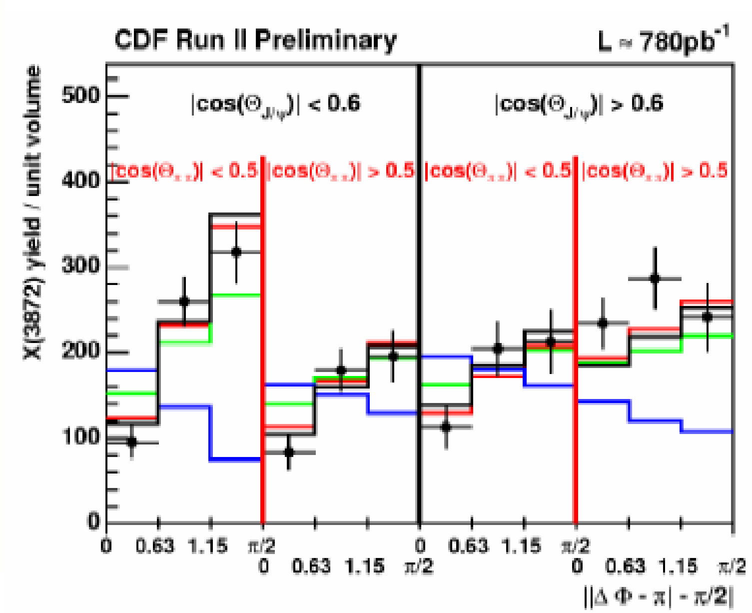
CDF

(CDF reference)

X(3872)
• data points

acc. corrected
prediction for
0^{++}_P
1^{--}_S
1^{++}_P
2^{-+}_P

J^{PC}	χ^2 prob.
1^{++}	27.8%
2^{-+}	25.8%
1^{--}	0.02%
2^{+-}	$5.5 \cdot 10^{-5}$
1^{+-}	$3.8 \cdot 10^{-5}$
2^{--}	$3.8 \cdot 10^{-5}$
3^{+-}	$3.8 \cdot 10^{-5}$
3^{--}	$2.4 \cdot 10^{-5}$
2^{++}	$1.1 \cdot 10^{-5}$
1^{-+}	$4.1 \cdot 10^{-6}$
0^{-+}	$3.5 \cdot 10^{-17}$
0^{+-}	$<1 \cdot 10^{-20}$
0^{++}	$<1 \cdot 10^{-20}$



Favors

$J = 1^{++}$ or 2^{-+}

(But J=2 unseen, in B to K charmonium)

X(3872) vs DD* threshold

BELLE latest update (Beijing 10/04):
[258 fb^{-1} , 48.6 ±7.8 events]
M = 3872.4 ± 0.7 MeV