New and conventional charmonium states

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(Belle Collaboration)

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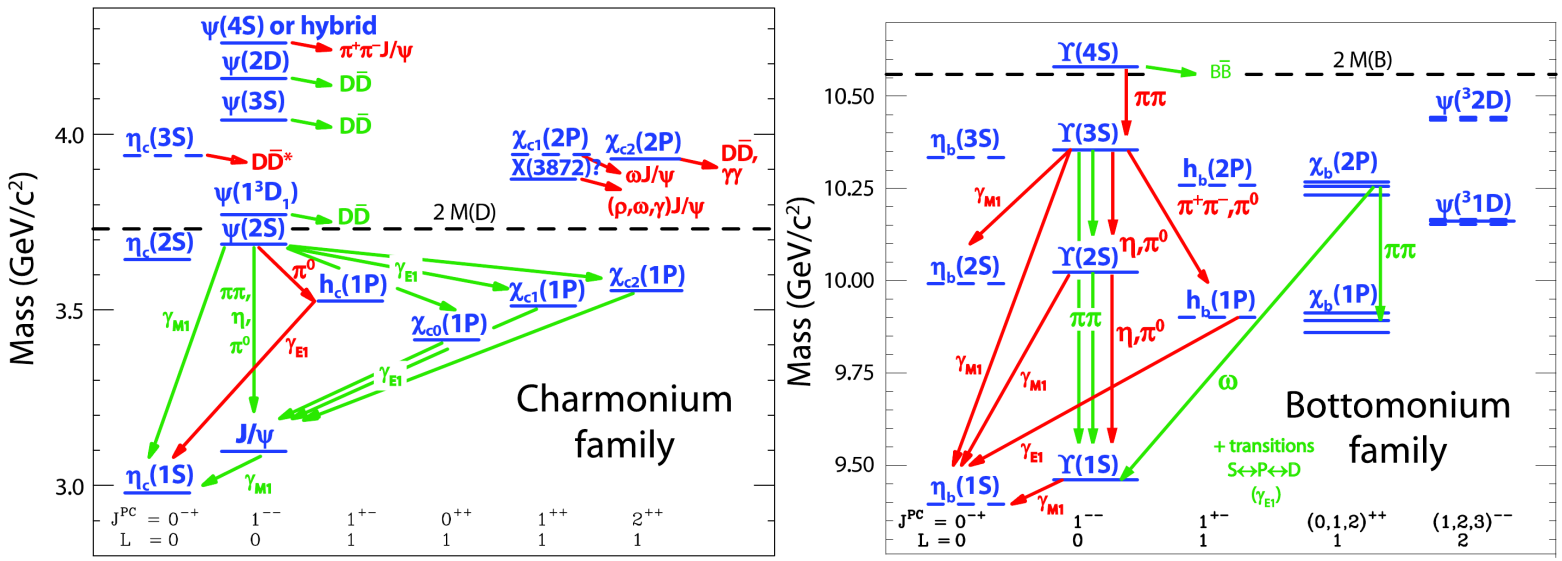
Introduction

- Quarkonia – Both charmonium and bottomonium are successful stories of QCD.
- Charmonia – Well studied at Charm and B factories. Many charmonium(-like) states found these years.
- XYZ particles – Many exotic properties! What is their nature? (QWG, Eur. Phy. J. C71, 1534(2011))



Eichten et al, Rev. Mod. Phys.80,1161(2008)

A table of XYZ

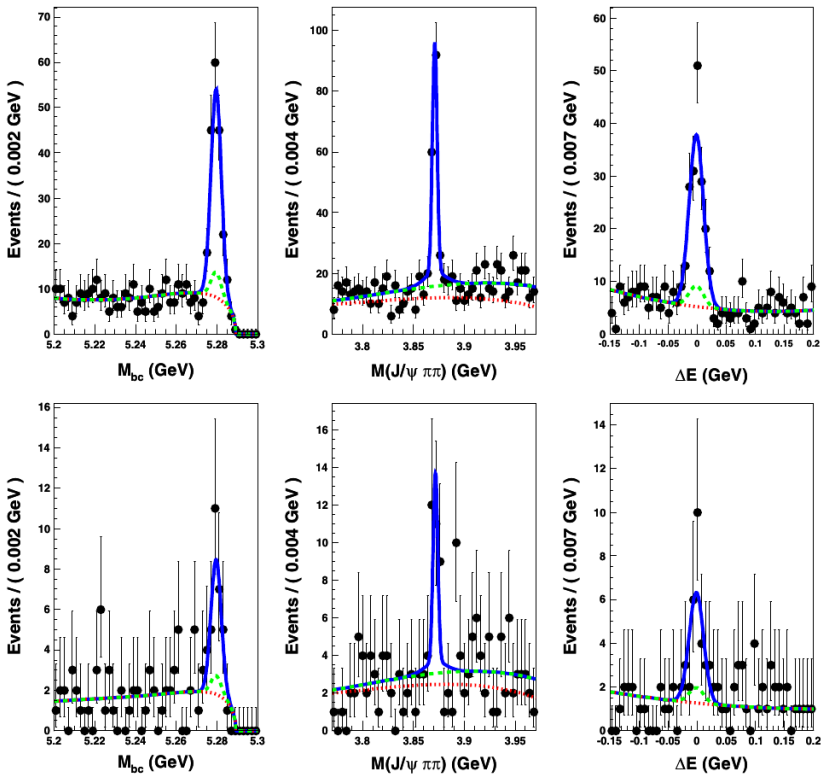
State	m (MeV)	Γ (MeV)	J^{PC}	Modes	Interpretation
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$\pi^+\pi^- J/\psi$	$D^{*0}\bar{D}^0$ molecule (bound)
				$D^{*0}\bar{D}^0$	$D^{*0}\bar{D}^0$ unbound
				$\gamma J/\psi, \gamma\psi(2S)$	if 1^{++}, $\chi_{c2}(2P)$
				$\omega J/\psi$	if 2^{-+}, $\eta_{c2}(1D)$
					charmonium + mesonic-molecule mixture
					QCDSR: $[cq]_{\bar{3}}[\bar{c}\bar{q}]_3$ (S + A)
					QCDSR: $[c\bar{q}]_1[\bar{c}q]_1$ (P + V)
					QCDSR: $[c\bar{c}]_1$(A) + $[c\bar{q}]_1[\bar{c}q]_1$ (P + V)
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0,\ 2^{?+}$	$\omega J/\psi$	$D^{*+}D^{*-} + D^{*0}\bar{D}^{*0}$
$Z(3930)$	3927.2 ± 2.6	24.1 ± 6.1	2^{++}	$D\bar{D}$	$\chi_{c2}(2P)$ (i.e., $2^3P_2\ c\bar{c}$)
					$1^3F_2\ c\bar{c}$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$D\bar{D}^*$	
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$D\bar{D}$	Coupled-channel effect
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$\pi^+\pi^- J/\psi$	
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$\pi^+\chi_{c1}(1P)$	hadrocharmonium
$Y(4140)$	4143.0 ± 3.1	$11.7^{+9.1}_{-6.2}$	$?^{?+}$	$\phi J/\psi$	QCDSR: $[c\bar{q}]_1[\bar{c}q]_1$ (V + V)
					QCDSR: $[c\bar{s}]_1[\bar{c}s]_1$ (V + V)
					$D_s^{*+}D_s^{*-}$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$D\bar{D}^*$	
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$\pi^+\chi_{c1}(1P)$	hadrocharmonium
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$\pi^+\pi^- J/\psi$	charmonium hybrid
				$\pi^0\pi^0 J/\psi$	$J/\psi f_0(980)$ bound state
					$D_0\bar{D}^*$ molecular state
					$[cs][\bar{c}\bar{s}]$ tetraquark state
					hadrocharmonium
					QCDSR: $[c\bar{q}]_1[\bar{c}q]_1$ (S + V)
					QCDSR: $[c\bar{q}]_1[\bar{c}q]_1$ (P + A)
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	(see $Y(4140)$)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,\ 2^{++}$	$\phi J/\psi$	
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$\pi^+\pi^-\psi(2S)$	hadrocharmonium
					crypto-exotic hybrid

.....

(QWG, Eur. Phy. J. C71, 1534(2011))

Update on $X(3872) \to \pi^+\pi^- J/\psi$ at Belle

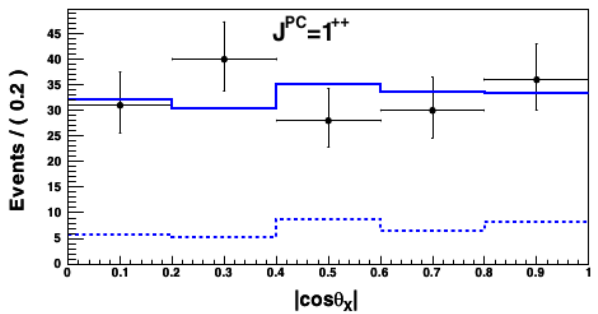
- Discovered by Belle about 10 years ago in $B \to J/\psi\pi^+\pi^- K$. It's the beginning of XYZ field. (Belle: PRL91, 262001(2003))
- The update from Belle (772×10^6 $B\overline{B}$): PRD84, 052004(2011).

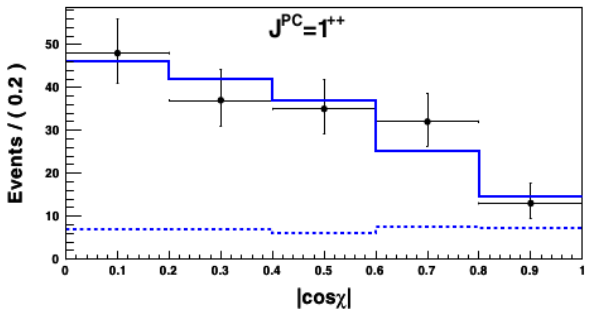


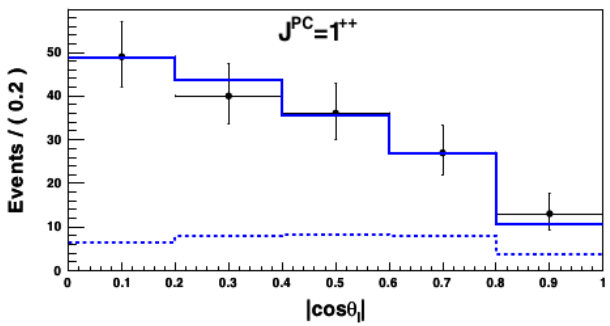
- $M_{X(3872)} = 3871.84 \pm 0.27 \pm 0.19$ MeV/c^2; $\Gamma_{X(3872)} < 1.2$ MeV @ 90% C.L.
- Mass difference of $X(3872)$ from B^+ and B^0: $\Delta M_{X(3872)} = -0.69 \pm 0.97 \pm 0.19$ MeV/c^2.

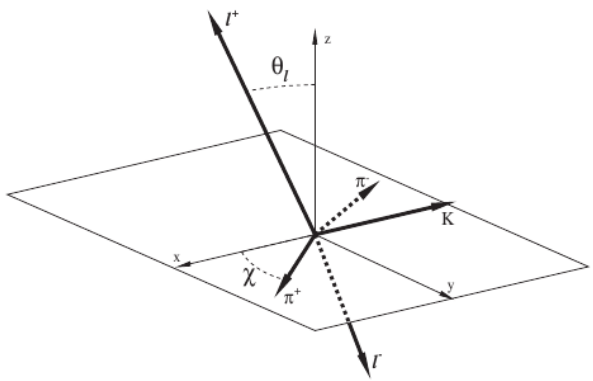
Angular analysis of $X(3872)$ at Belle

- $J^{PC} = 1^{++}$ or 2^{-+} from angular analysis by CDF. (PRL98, 132002(2007)).
- For $X(3872) \to J/\psi\rho \to J/\psi\pi^+\pi^-$ with $J/\psi - \rho$ orbital momentum L and S:
  $J^{PC} = 1^{++}$: L = 0, S = 1 $\to$ 1 amplitude; $J^{PC} = 2^{-+}$: L = 1, S = 1 or 2 $\to$ 2 amplitudes B_{11} and B_{12}.

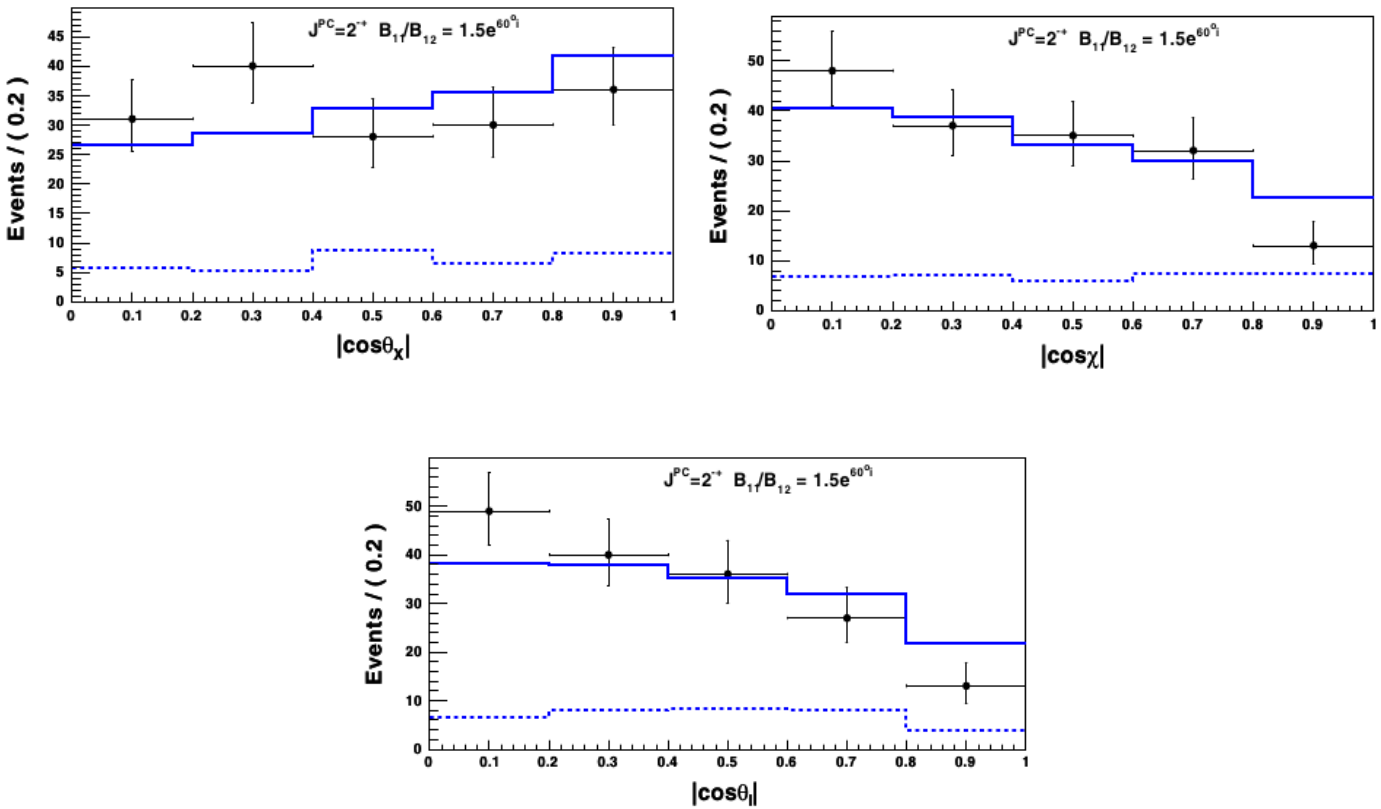








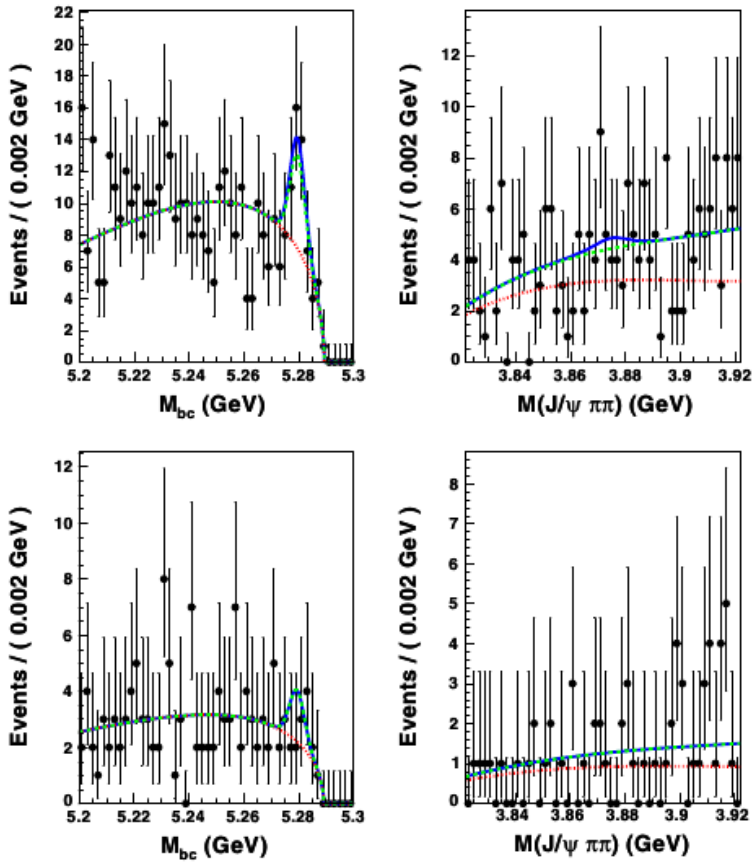
Angular analysis of $X(3872)$ at Belle



Both $J^{PC} = 1^{++}$ and $J^{PC} = 2^{-+}$ (for certain B_{11}/B_{12}) describe data well.

Search for charged X

- A charged partner could be possible if $X(3872)$ is exotic.
- Charged partner could be searched for in $X(3872)^+ \to J/\psi\rho(\to \pi^+\pi^0)$.



- First row is $\overline{B}^0 \to K^-\rho^+J/\psi$, and the second row is $B^+ \to K^0\rho^+J/\psi$.
- $\mathcal{B}(\overline{B}^0 \to X^+K^-) \times \mathcal{B}(X^+ \to J/\psi\rho^+) < 4.2 \times 10^{-6}$
- $BR(B^+ \to X^+K^0) \times \mathcal{B}(X^+ \to J/\psi\rho^+) < 6.1 \times 10^{-6}$

Search for C-odd X

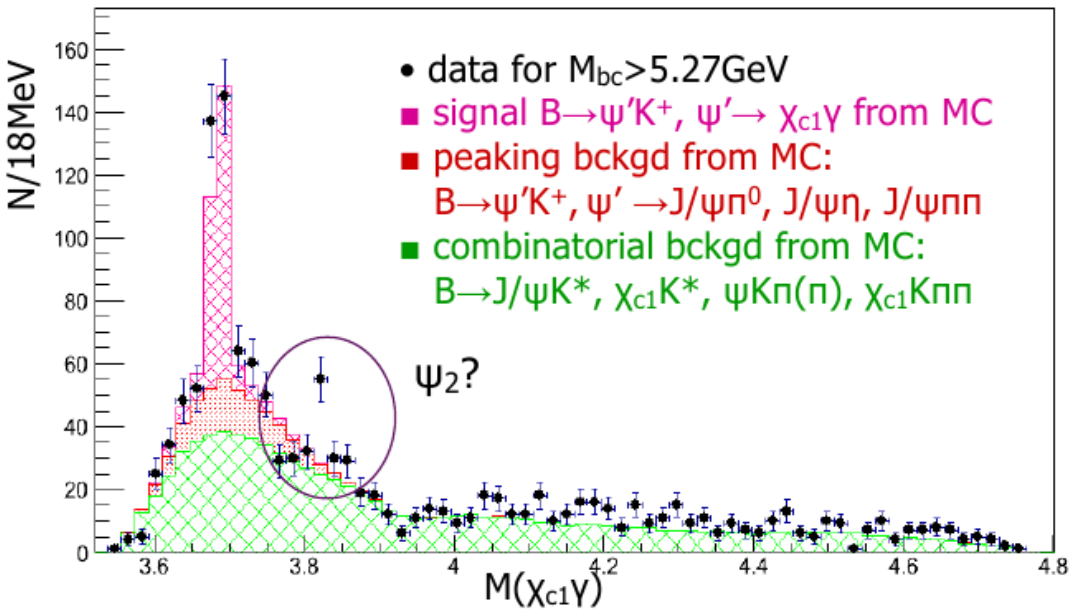
- Is there a C-odd partner of $X(3872)$ if it's an exotic state?
- Channel I: $B \to K + \gamma\chi_{c1}$
  $\psi_2 \to \gamma\chi_{c1}$ was predicted.
  Godfrey-Isgur, PRD21,189(1985); Eichten-Lane-Quigg, PRL89, 162002(2002) and PRD69, 094019(2004)

name	spect.	J^{PC}	M_{exp}	M_{model}[MeV]	dominant decay
η_{c2}	1^1D_2	2^{-+}	--	3780–3840	$\eta_c\pi\pi$
ψ''	1^3D_1	1^{--}	3772.9(4)	3785–3819	$D\bar{D}$
ψ_2	1^3D_2	2^{--}	--	3800–3840	$\chi_{c1,2}\gamma$
ψ_3	1^3D_3	3^{--}	--	3810–3850	$D\bar{D}^{(*)}$

  $\Gamma(\psi_2 \to \gamma\chi_{c1}) = 260$ keV predicted.
- Channel II: $B \to K + \eta J/\psi$.

Study of $\gamma\chi_{c1}$

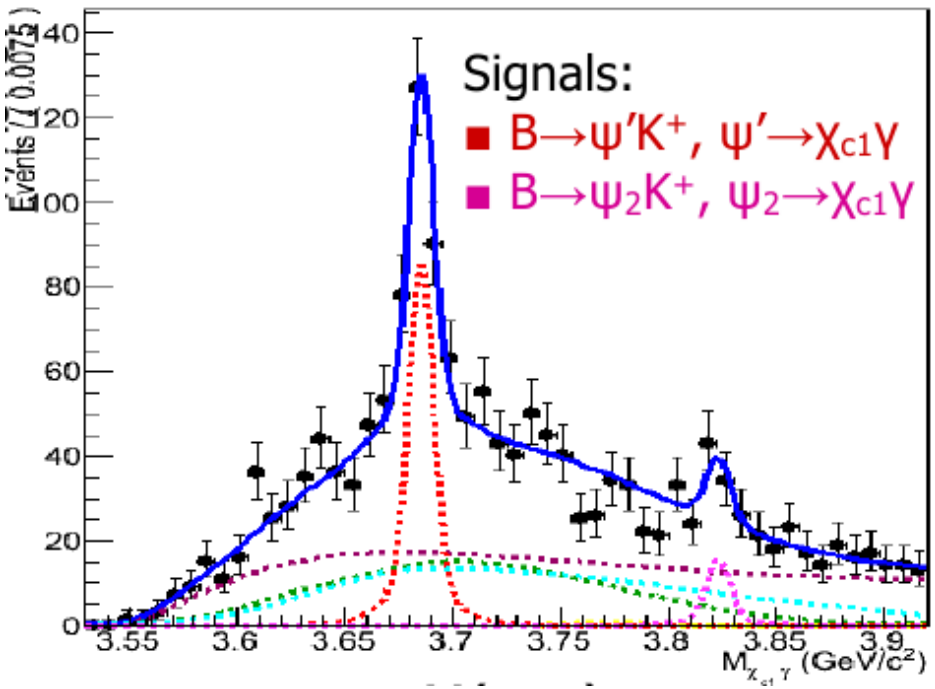
- $B^+ \to \gamma\chi_{c1}K^+$ with $\chi_{c1} \to \gamma J/\psi$ using 772×10^6 $B\overline{B}$.
- Efficiency and resolution improve with increasing $M_{\gamma\chi_{c1}}$



- $M_{\gamma\chi_{c1}}$ in data agree with inclusive MC simulation, except for the peak at 3.82 GeV/c^2.
- Missing $\psi_2(1^3D_2)$ charmonium? Mass agrees with prediction.

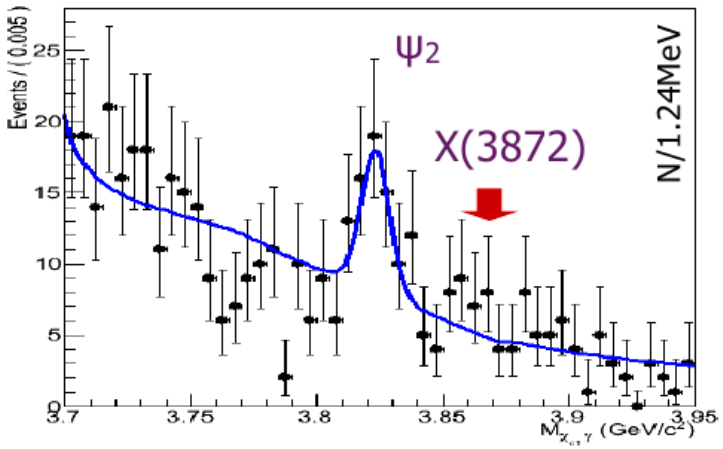
$\psi_2 \to \gamma\chi_{c1}$

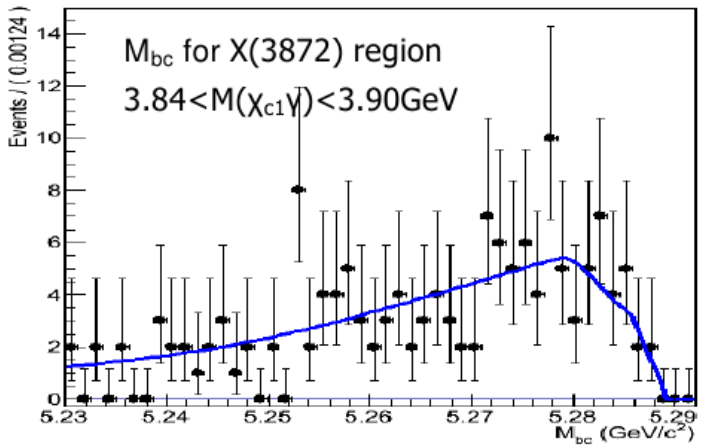
- ψ_2 significance 4.2σ w/syst. First evidence!
- $\Gamma(\psi_2) = 4 \pm 6$ MeV/c^2 if fitted.



yield	Mass[MeV]	$BR\left(B^+ \to \psi\left(\to \chi_{c1}\gamma\right)K^+\right)$
ψ' 193±18	3685.3±0.6	$\left(7.7 \pm 0.8 \pm 0.9\right)\times 10^{-4}$
ψ_2 33±9	3823.5±2.8	$\left(9.7^{+2.8}_{-2.5} \pm 1.1\right)\times 10^{-6}$

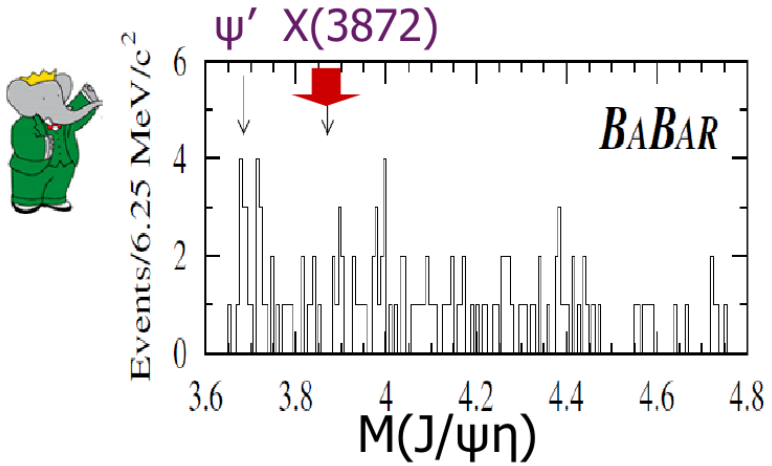
$X(3872) \to \gamma\chi_{c1}$

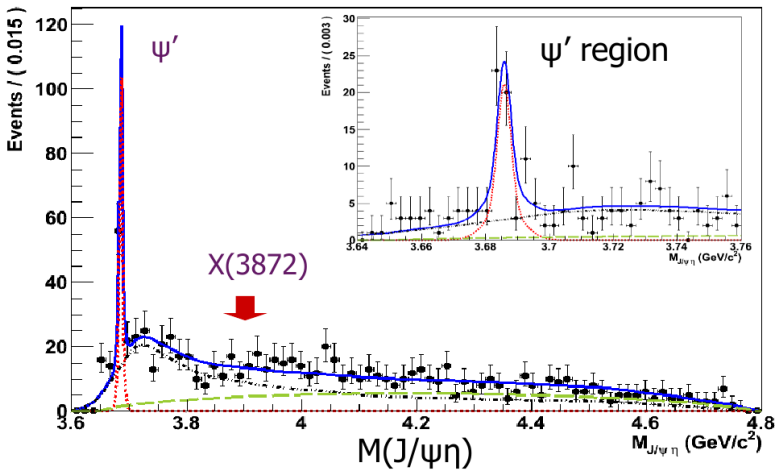




- No $X(3872)$ signal observed: $N_{sig} = -1 \pm 5$.
- $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X \to \gamma\chi_{c1}) < 2.0 \times 10^{-6}$ 90% C.L.
- $\frac{\mathcal{B}(X \to \gamma\chi_{c1})}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} < 0.26$ 90% C.L.,
  according to PRD84, 052004(2011)(Belle):
  $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X \to \pi^+\pi^- J/\psi) = (8.6 \pm 0.8 \pm 0.5) \times 10^{-6}$

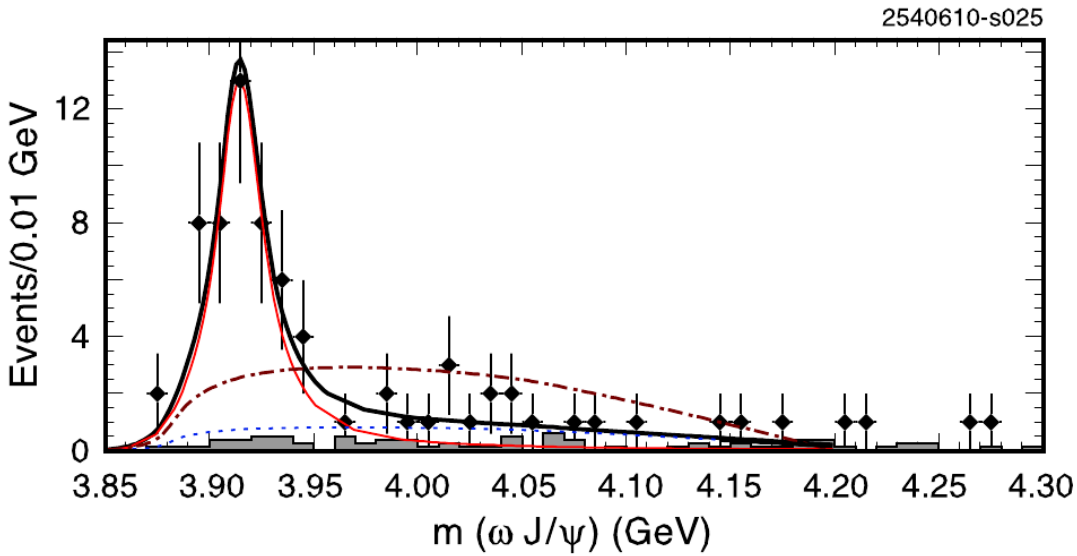
Search in $B \to K + \eta J/\psi$





- BaBar: with 90×10^6 $B\overline{B}$, no X signal. PRL99,041801(2004)
  $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X \to \eta J/\psi) < 7.7 \times 10^{-6}$ @90% C.L.
  $\mathcal{B}(B^+ \to \eta J/\psi K^+) = (10.8 \pm 2.3 \pm 2.4) \times 10^{-5}$.
- Belle: only ψ' signal and non-resonant component, no $X(3872)$.
  $\mathcal{B}(B^+ \to \psi' K^+) \times \mathcal{B}(\psi' \to \eta J/\psi) = (5.8 \pm 0.9 \pm 0.4) \times 10^{-4}$.
  $\mathcal{B}(B^+ \to \eta J/\psi K^+)_{NR} = (1.17 \pm 0.07 \pm 0.11) \times 10^{-4}$.
  $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X \to \eta J/\psi) < 3.8 \times 10^{-6}$ @90% C.L.

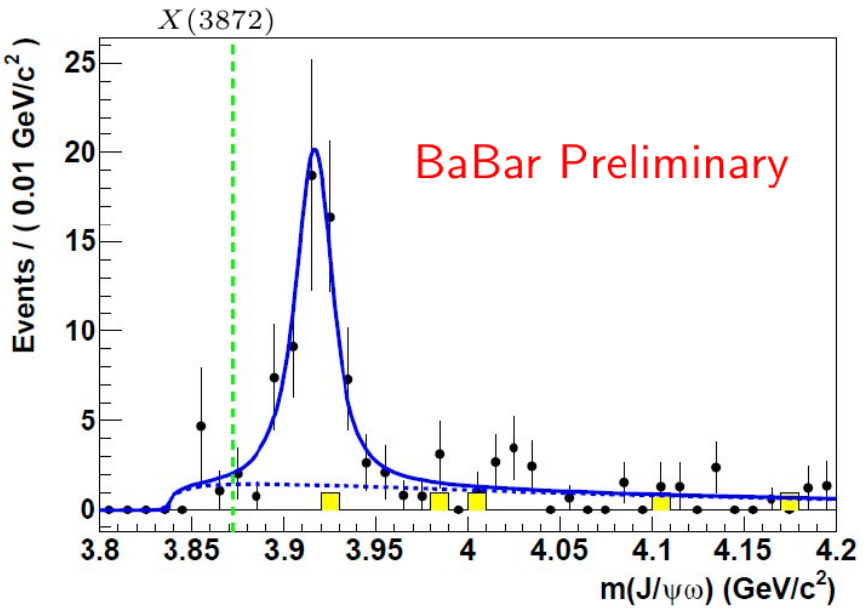
Study of $\gamma\gamma \to \omega J/\psi$



- $M(X(3915)) = 3914 \pm 3 \pm 2$ MeV/c^2.
- $\Gamma(X(3915)) = 23 \pm 10^{+2}_{-8}$ MeV/c^2.
- Significance is 7.8σ. $N^{sig} = 55 \pm 14^{+2}_{-14}$.

Belle: Uehara *et al.*, PRL104,092001(2010).

Study of $\gamma\gamma \to \omega J/\psi$



		$m(\,\mathrm{MeV}/c^2)$	$\Gamma(\,\mathrm{MeV})$	$\Gamma_{\gamma\gamma} \times \mathcal{B}(J/\psi\,\omega)$ (eV)
X(3915)	7.6σ	$3919.4 \pm 2.21.6$	$13 \pm 6 \pm 3$	$52 \pm 10 \pm 3$ $(J = 0)$
				$10.5 \pm 1.9 \pm 0.6$ $(J = 2)$
X(3872)	not seen			< 1.7

BaBar: Confirm Belle's measurement, using 519 fb^{-1} data.

Study of $\gamma\gamma \to \eta_c\pi^+\pi^-$ at BaBar

Predictions :

– $\Gamma(\eta_c(2S) \to \eta_c\pi^+\pi^-)/\Gamma(\psi(2S) \to J/\psi\,\pi^+\pi^-) = 2.9$
That is $\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) = (2.2^{+1.6}_{-0.6})\%$

Mod. Phys. Lett. A 17 (2002) 1533

– Then

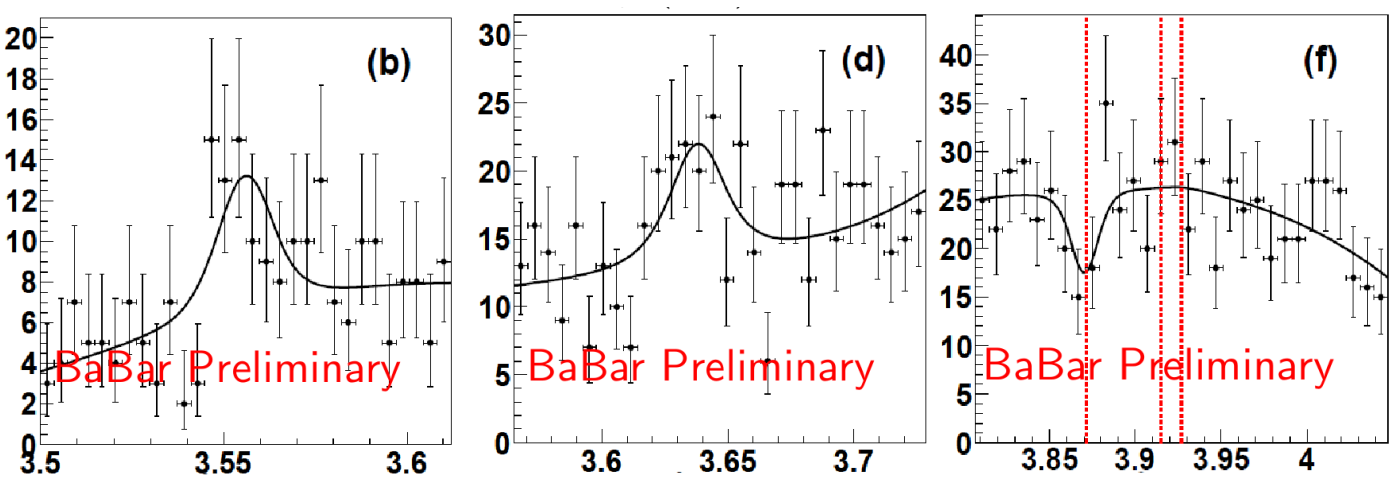
- If $X(3872) \equiv \eta_{c2}$ $(1^1D_2,\ J^{PC} = 2^{-+})$,
- then $\mathcal{B}(X(3872) \to \eta_c\pi^+\pi^-) > \mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-)$

(Int J. Mod. Phys A 20 240 (2005))

– $\Rightarrow$ what about $X \to \eta_c\pi^+\pi^-$?

Study of $\gamma\gamma \to \eta_c \pi^+ \pi^-$ (BaBar)

- 473.9 fb^{-1} data used, and $\eta_c \to K^0_S K^+ \pi^-$.
- No evidence for $\gamma\gamma$ production of $X(3872)$, $X(3915)$ nor $\chi_{c2}(2P)$.



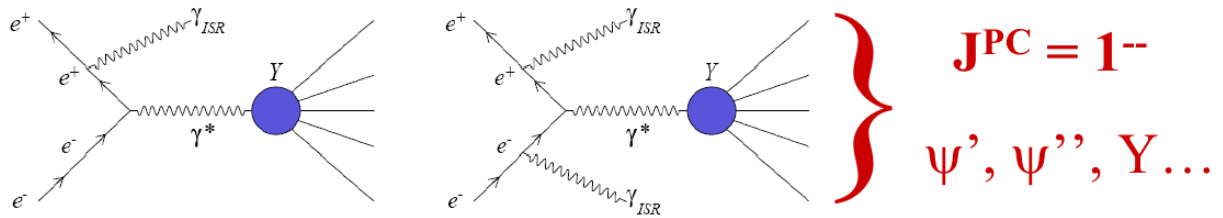
Left-$chi_{c2}(1P)$. Middle-$\eta_c(2S)$. Left-$X(3872)/X(3915)/\chi_{c2}(2P)$

- $\frac{\mathcal{B}(\chi_{c2}(1P)\to\eta_c\pi^+\pi^-)}{\mathcal{B}(\chi_{c2}(1P)\to K^0_S K^+\pi^- + c.c.)} = 14.5^{+10.9}_{-8.9} \pm 7.3 \pm 2.5$, $\mathcal{B}(\chi_{c2} \to \eta_c\pi^+\pi^-) < 2.2\%$
- $\frac{\eta_c(2S)\to\eta_c\pi^+\pi^-}{\eta_c(2S)\to K^0_S K^+\pi^- + c.c.} = 4.9^{+3.5}_{-3.3} \pm 1.3 \pm 0.8$, $\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) < 7.4\%$
- $\Gamma_{\gamma\gamma}(X) \cdot \mathcal{B}(X \to \eta_c\pi^+\pi^-) < 11.1/16/19$ eV for $X(3872)/X(3915)/\chi_{c2}(2P)$

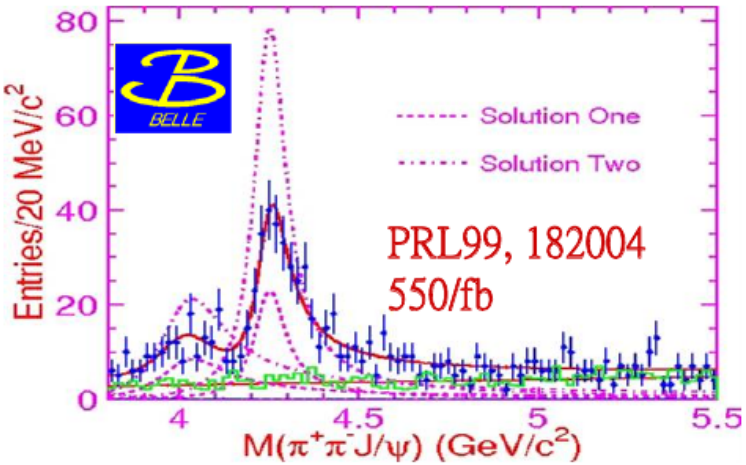
From Bernard's talk at GNP2012.

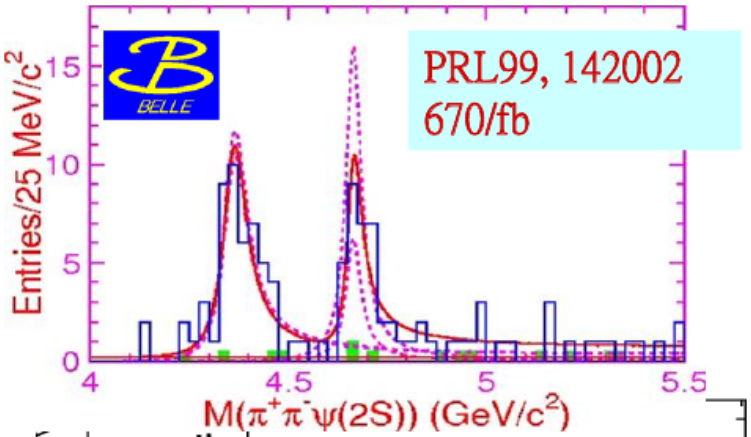
1^{--} family from ISR

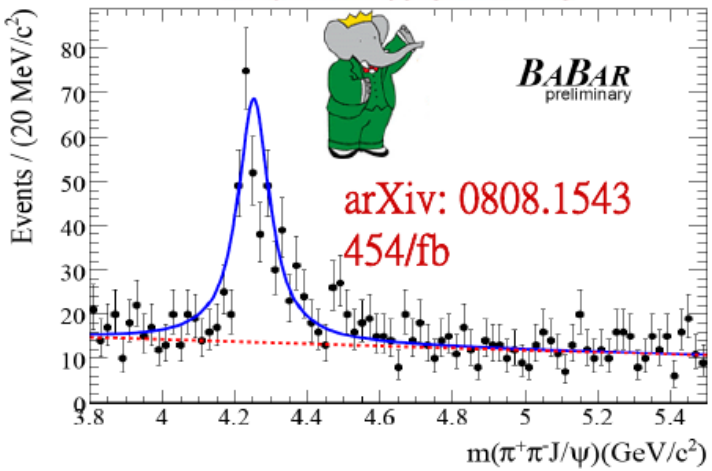
ISR: initial state radiation

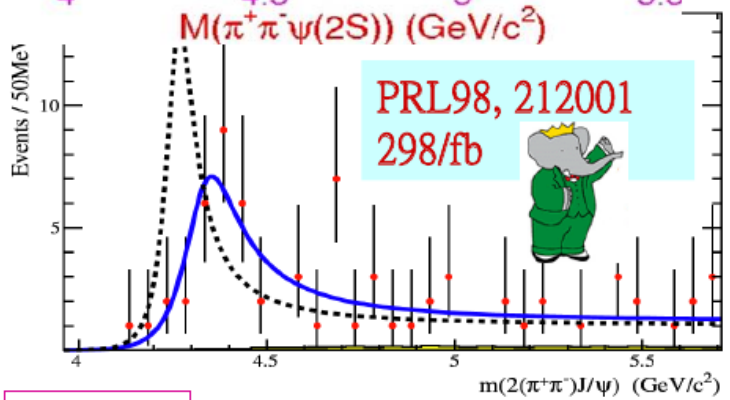


The Y states

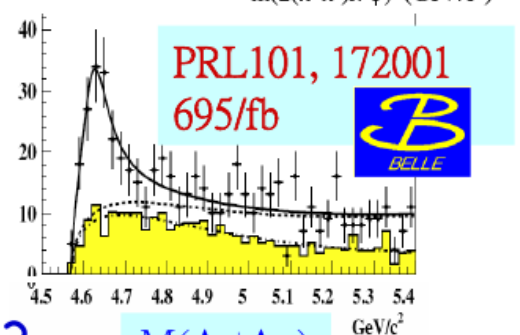








Y(4008)
Y(4260)
Y(4360)
Y(4660)
Y(4630)



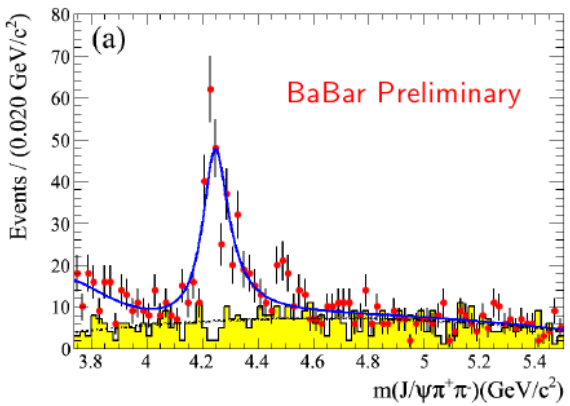
Above DD̄ threshold, decay to open charm?

$M(\Lambda_c^+\Lambda_c^-)$

BaBar update on ISR

- no photon tagging

$Y \to J/\psi\,\pi^+\pi^-$ 454 fb^{-1}
$J/\psi \to \ell^+\ell^-$ (e, μ)
$-0.50 < m^2_{miss} < +075(\,\mathrm{GeV}/c^2)^2$



$m(Y(4260)) = 4244 \pm 5 \pm 4\,\mathrm{MeV}/c^2$
$\Gamma = 114^{+16}_{-15} \pm 7\,\mathrm{MeV}/c^2$

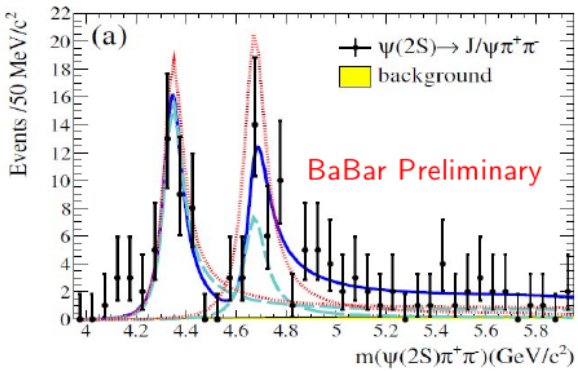
Don't confirm Belle's Y(4.01)

$\Gamma_{e^+e^-} \times \mathcal{B}(J/\psi\,\pi^+\pi^-) = 9.2 \pm 0.8 \pm 0.7$ eV

arXiv :1204.2158

Both Preliminary

$Y \to \psi(2S)\pi^+\pi^-$ 520 fb^{-1}
$\psi(2S) \to J/\psi\,\pi^+\pi^-$ or $\ell^+\ell^-$
missing p and missing p_T

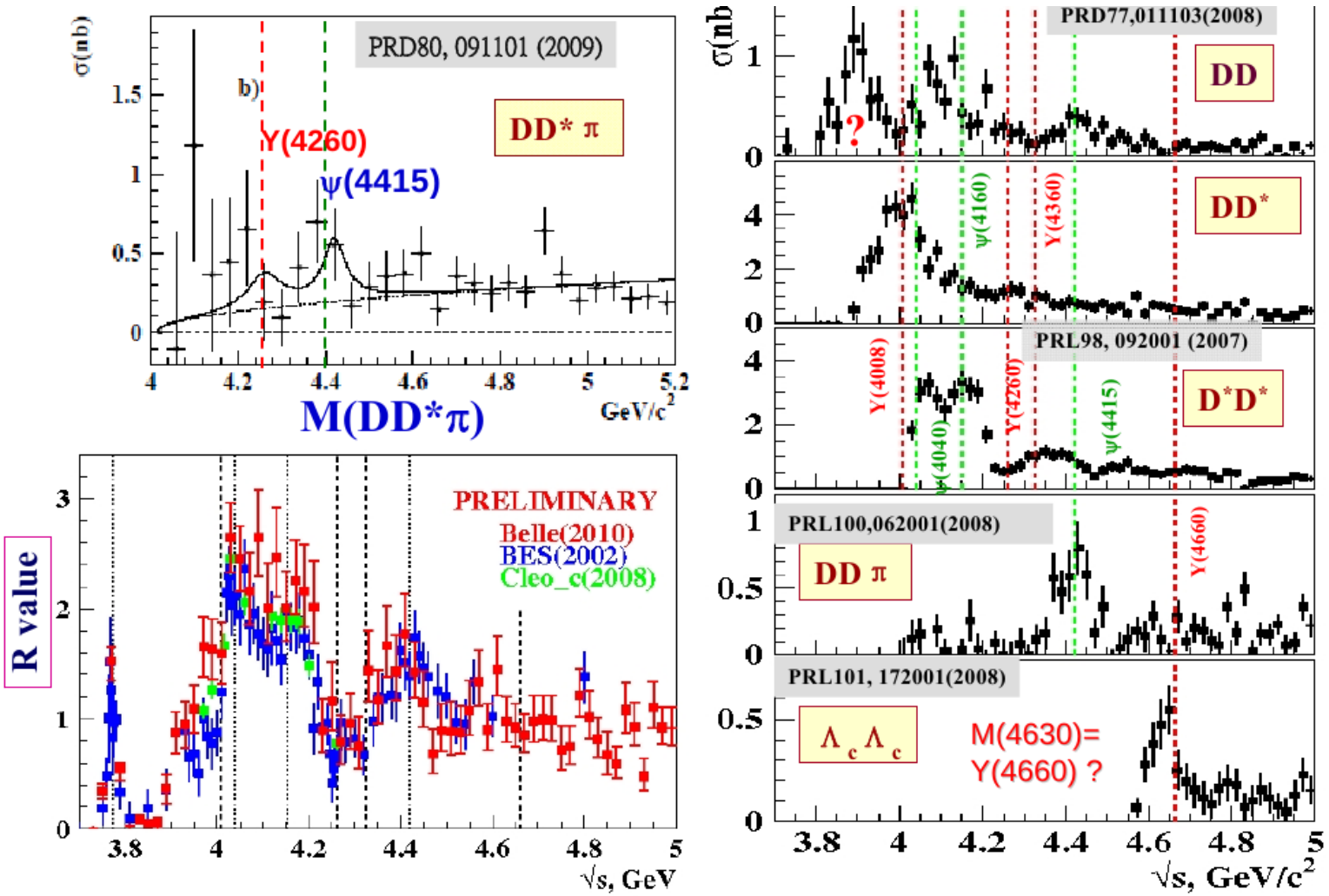


$m(Y(4360)) = 4340 \pm 16 \pm 9\,\mathrm{MeV}/c^2$
$\Gamma = 94 \pm 32 \pm 13\,\mathrm{MeV}$
$m(Y(4660)) = 4669 \pm 21 \pm 10\,\mathrm{MeV}/c^2$
$\Gamma = 104 \pm 48 \pm 10\,\mathrm{MeV}$

not yet on arXiv

From Bernard's talk at GNP2012.

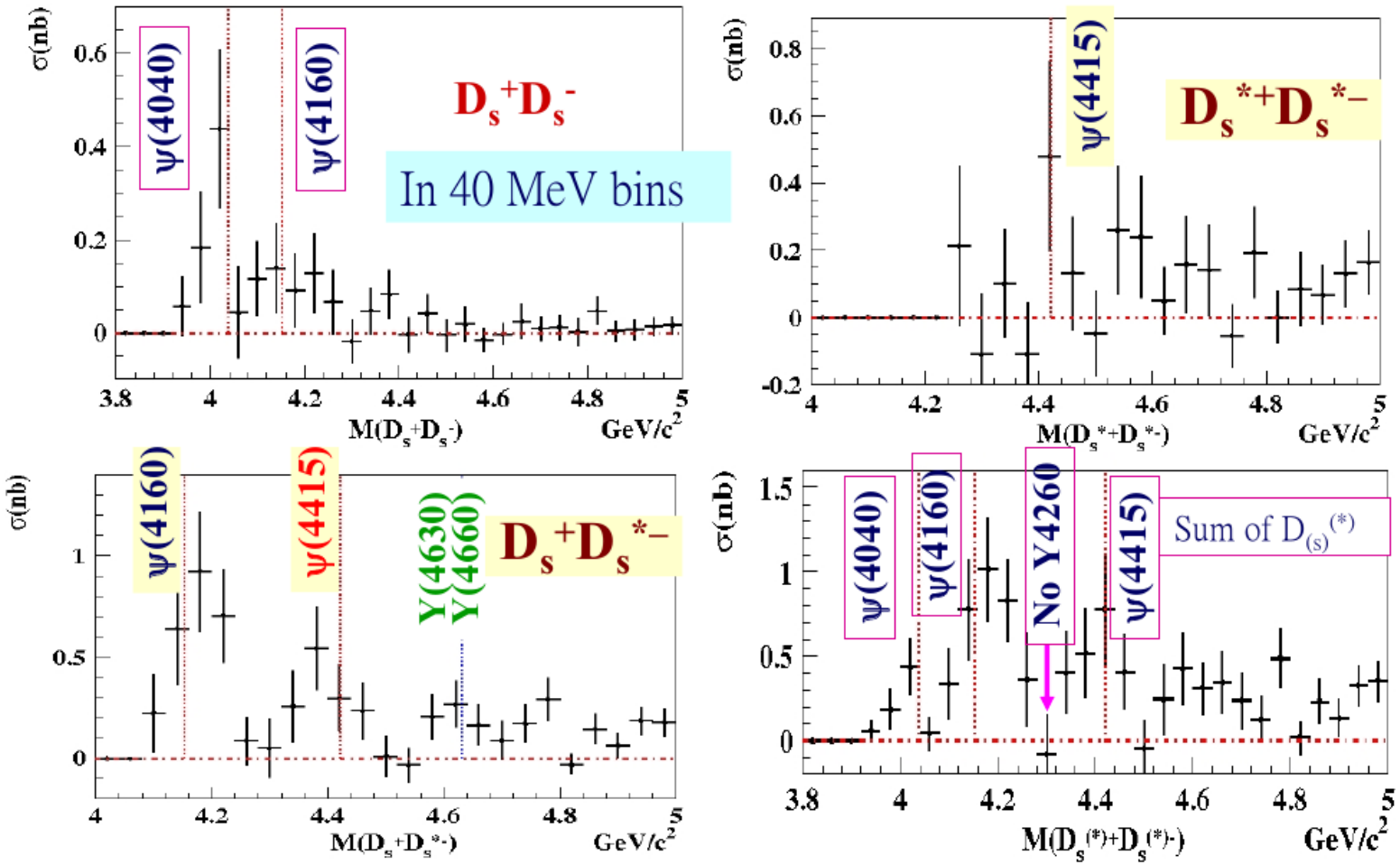
Y states don't match $D_{(s)}^{(*)} D_{(s)}^{(*)}$ peaks



Only clear $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ signals!!!

$D_s^{(*)} D_s^{(*)}$

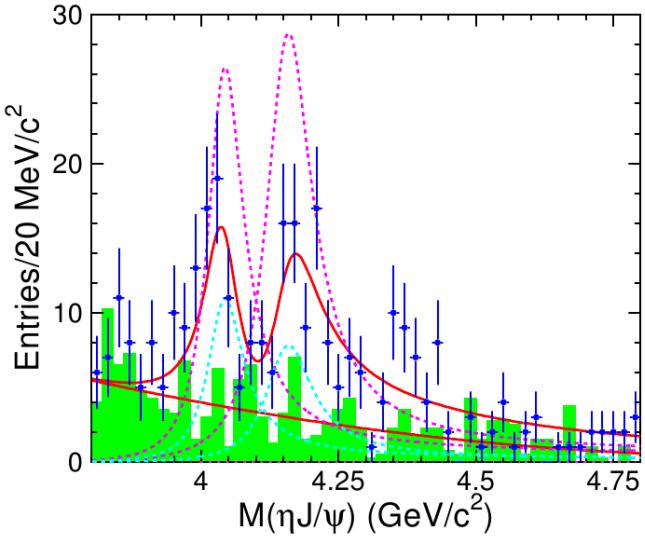
Belle, PRD83, 011101(R)(2011)



No obvious Y states but ψ signals again!

$\eta J/\psi$ via ISR

Belle: Search for hadronic transition via emitting η. (Preliminary)



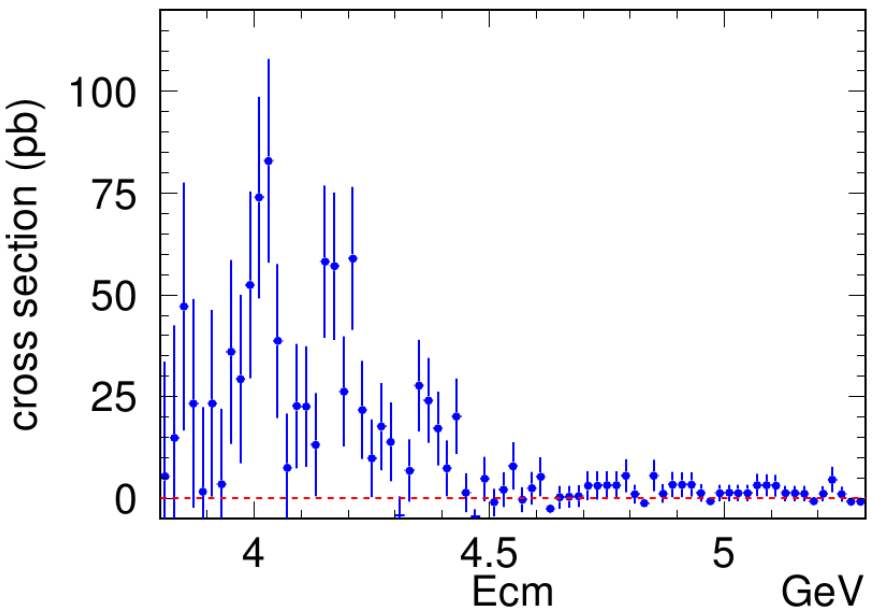
Parameters	Solution I	Solution II
$M(\psi(4040))$	4039 (fixed)	
$\Gamma(\psi(4040))$	80 (fixed)	
$\mathcal{B}(\psi(4040) \to \eta J/\psi) \cdot \Gamma_{e^+e^-}$	$5.1 \pm 0.8 \pm 1.1$	$12.4 \pm 1.2 \pm 1.2$
$M(\psi(4160))$	4153 (fixed)	
$\Gamma(\psi(4160))$	103 (fixed)	
$\mathcal{B}(\psi(4160) \to \eta J/\psi) \cdot \Gamma_{e^+e^-}$	$4.1 \pm 0.5 \pm 0.8$	$15.2 \pm 1.2 \pm 1.5$
$\phi(^\circ)$	$-20 \pm 11 \pm 8$	$-110 \pm 4 \pm 3$

Taking $\Gamma_{e^+e^-}(\psi(4040)) = (0.86 \pm 0.07)$ keV from PDG $\to$
$\mathcal{B}(\psi(4040) \to \eta J/\psi) = (0.59 \pm 0.11 \pm 0.14)\%$ or
$\mathcal{B}(\psi(4040) \to \eta J/\psi) = (1.44 \pm 0.18 \pm 0.18)\%$.
Taking $\Gamma_{e^+e^-}(\psi(4160)) = (0.83 \pm 0.07)$ keV from PDG $\to$
$\mathcal{B}(\psi(4160) \to \eta J/\psi) = (0.50 \pm 0.07 \pm 0.11)\%$ or
$\mathcal{B}(\psi(4160) \to \eta J/\psi) = (1.83 \pm 0.21 \pm 0.24)\%$.

Cross section of $e^+e^- \to \eta J/\psi$

Belle preliminary

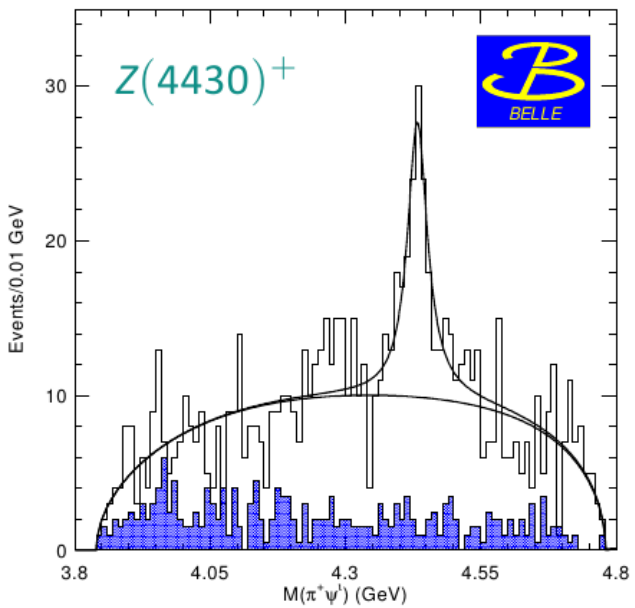
$$\sigma_i = \frac{n_i^{\rm obs} - n_i^{\rm bkg}}{\varepsilon_i \mathcal{L}_i \mathcal{B}(\eta \to \pi^+\pi^-\pi^0 + \gamma\gamma)\mathcal{B}(J/\psi \to \ell^+\ell^-)}$$

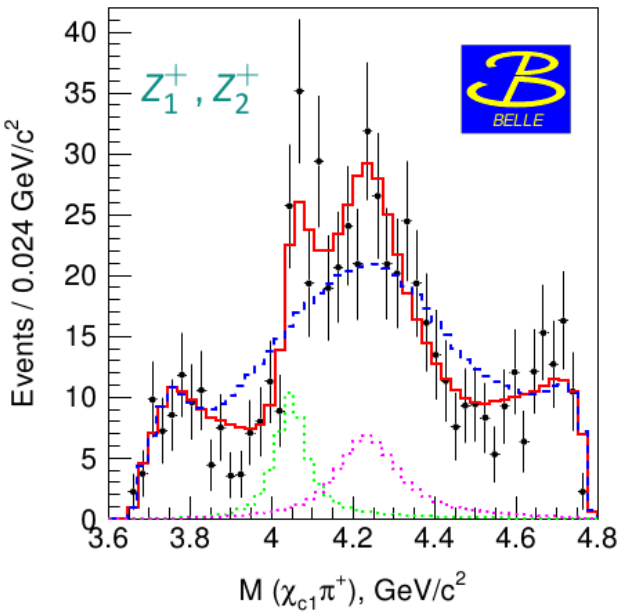


A systematic error of 8.8% to all data points is not shown.

About charged Z

- Belle observed charged charmonium-like states in $c\bar{c}K\pi$ system.

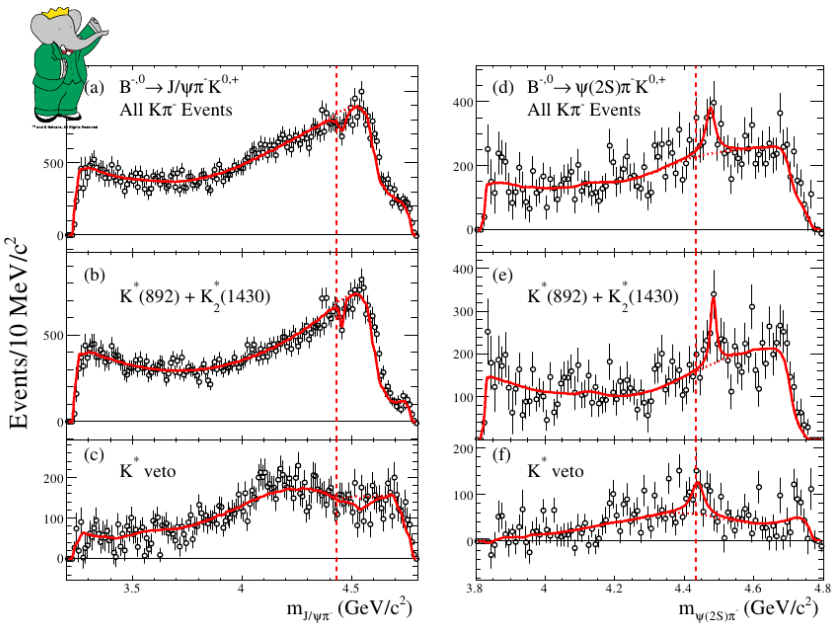




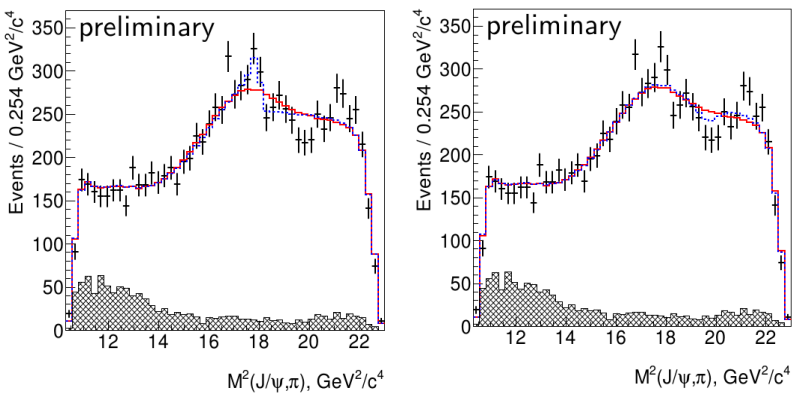
  - $Z(4430)$ in $B \to K + \psi'\pi$, PRL100, 142001(2008).
  - $Z_1(4050)^+$ and $Z_2(4250)^+$ in $B \to K\chi_{c1}\pi$, PRD78,072004(2008).
- Quark content at least $|c\bar{c}u\bar{d}>$ expected.

More studies on $Z(4430)$

- No significant evidence for $Z(4430)$ at BaBar. PRD79,112001(2009)



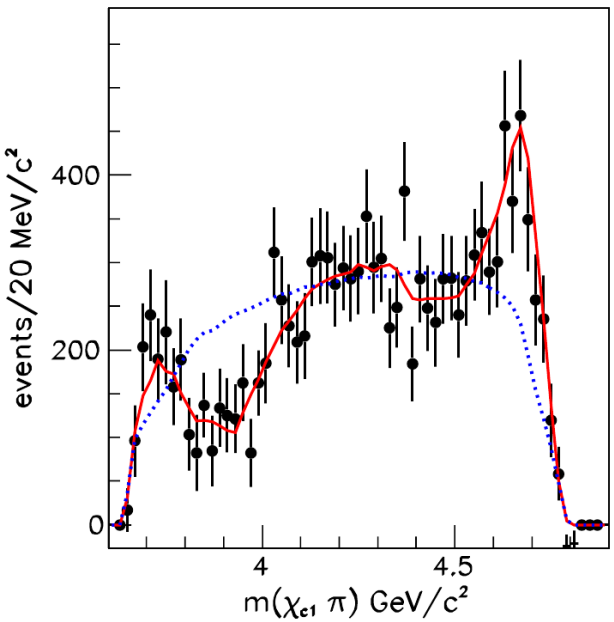
- No significant $Z_c^+ \to J/\psi\pi^+$ at Belle.



The most significant Z is only 3σ.

BaBar's search for Z_1 and Z_2

- $B \to K + \chi_{c1}\pi$, 429 fb^{-1}.
- Resonant structure in $K\pi$ system can describe the $\chi_{c1}\pi$ mass spectrum well. No evidence is found for $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances, but do not statistically rule out existence of Z_1^+ and Z_2^+.



- $\mathcal{B}(\overline{B}^0 \to Z_1^+ K^-) \times \mathcal{B}(Z_1^+ \to \chi_{c1}\pi^+) < 1.8 \times 10^{-5}$ @90% C.L.
- $\mathcal{B}(\overline{B}^0 \to Z_2^+ K^-) \times \mathcal{B}(Z_2^+ \to \chi_{c1}\pi^+) < 4.0 \times 10^{-5}$ @90% C.L.
- For a signle $Z(4150)^+$, $\mathcal{B}(\overline{B}^0 \to Z^+ K^-) \times \mathcal{B}(Z^+ \to \chi_{c1}\pi^+) < 4.7 \times 10^{-5}$ @90% C.L.

Summary

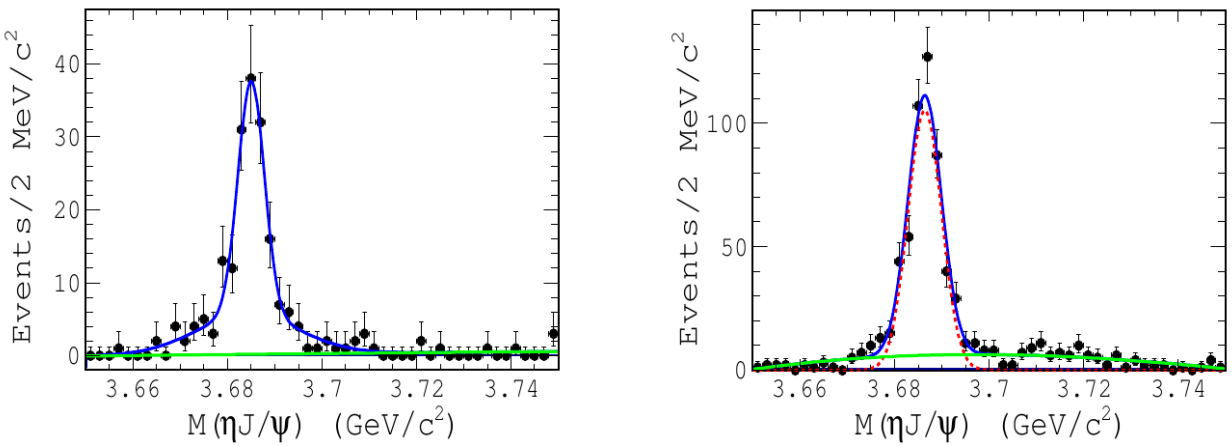
1. About $X(3872)$:
   - Update on $X(3872) \to \pi^+\pi^- J/\psi$ performed by Belle. More precise results got.
   - Both 1^{++} and 2^{-+} describe Belle data well.
   - No charged partner of $X(3872)$ found in $J/\psi\rho^+$ search. No C-odd partner found in $\gamma\chi_{c1}$ or $\eta J/\psi$.
2. The first evidence of ψ_2 is got at $B \to K + \gamma\chi_{c1}$ search. The significance is 4.2σ.
3. From $\gamma\gamma$ collision:
   - $X(3915)$ has been established in $\gamma\gamma \to \omega\psi$.
   - No evidence of $X(3872)$, $X(3915)$ nor $\eta_{c2}(2P)$ found in $\gamma\gamma \to \eta_c\pi^+\pi^-$.
4. From ISR:
   - Measurements updated on $e^+e^- \to \pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi'$ by BaBar confirm the $Y(4660)$ resonance, but not confirm $Y(4008)$.
   - $e^+e^- \to \eta J/\psi$ via ISR is measured for the first time. $\psi(4040) \to \eta J/\psi$ and $\psi(4160)$ are observed in the final states. But no Y state observed.
5. About charged Z_c
   - No $Z(4430)^+$ evidence in $B \to K + J/\psi\pi$.
   - Z_1^+ and Z_2^+ are not confirmed by BaBar.

Thank you!

Back-up

Search on $\eta J/\psi$ via ISR at Belle (Preliminary)

- Reconstructions: $J/\psi \to e^+e^-$ or $\mu^+\mu^-$, $\eta \to \gamma\gamma$ or $\pi^+\pi^-\pi^0$.
- Clear ψ' signals.



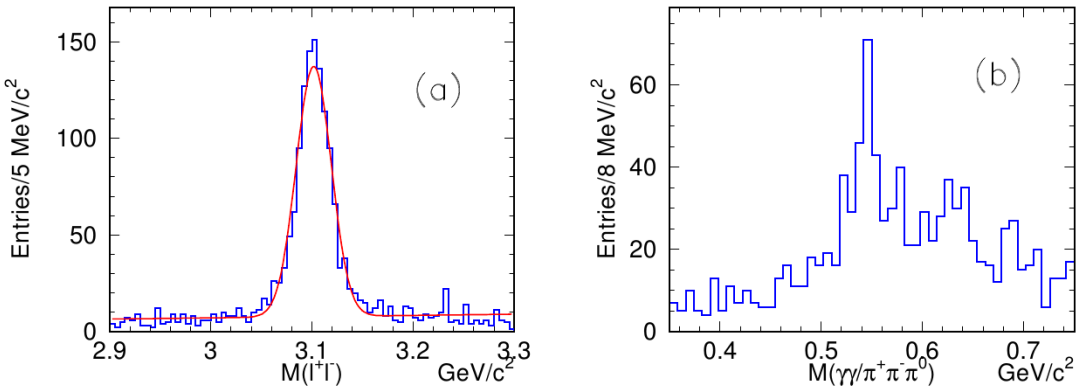
Left is $\eta \to \pi^+\pi^-\pi^0$ mode and right is $\eta \to \gamma\gamma$ mode.
Measurement on cross section of $\sigma(e^+e^- \to \gamma_{\rm ISR}\psi')$ at Belle:

- $\pi^+\pi^-\pi^0$ mode: $n^{sig} = 186 \pm 17$, $\sigma = 13.9 \pm 1.4$ pb.
- $\gamma\gamma$ mode: $n^{sig} = 470 \pm 25$, $\sigma = 14.0 \pm 0.8$ pb.
- Theory calculation: $\sigma = 14.2$ pb.

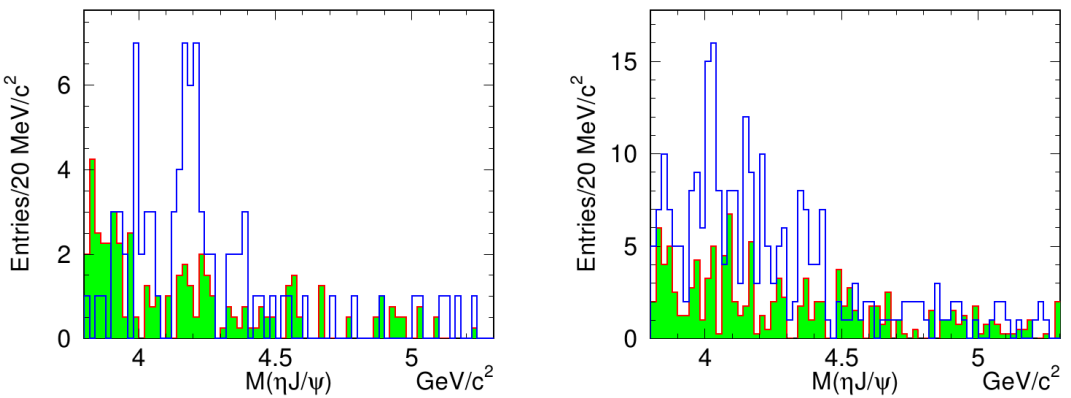
Measurement on ψ' signal is reliable.

$\eta J/\psi$ via ISR at Belle (Preliminary)

The J/ψ signal and η signal at high energy region ($M_{\eta J/\psi} > 3.8$ GeV/c^2):



The $\eta J/\psi$ signals:



The left is $\eta \to \pi^+\pi^-\pi^0$ mode and the right is $\eta \to \gamma\gamma$ mode. Events accumulate around the positions of $\psi(4040)$ and $\psi(4160)$, and no obvious Y states found at $\pi^+\pi^- J/\psi(\psi')$ transitions!

New $\eta J/\psi$ results