Meson spectroscopy at electron-positron colliders

Marko Bračko

University of Maribor

Univerza v Mariboru

&

J. Stefan Institute, Ljubljana, Slovenia

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From Quarks and Gluons to Hadrons and Nuclei
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Outline

- Introduction & motivation
- Experiments
- Charmonium and
  charmonium-like states
- Bottomonium and
  bottomonium-like states
- Summary

Introduction & motivation

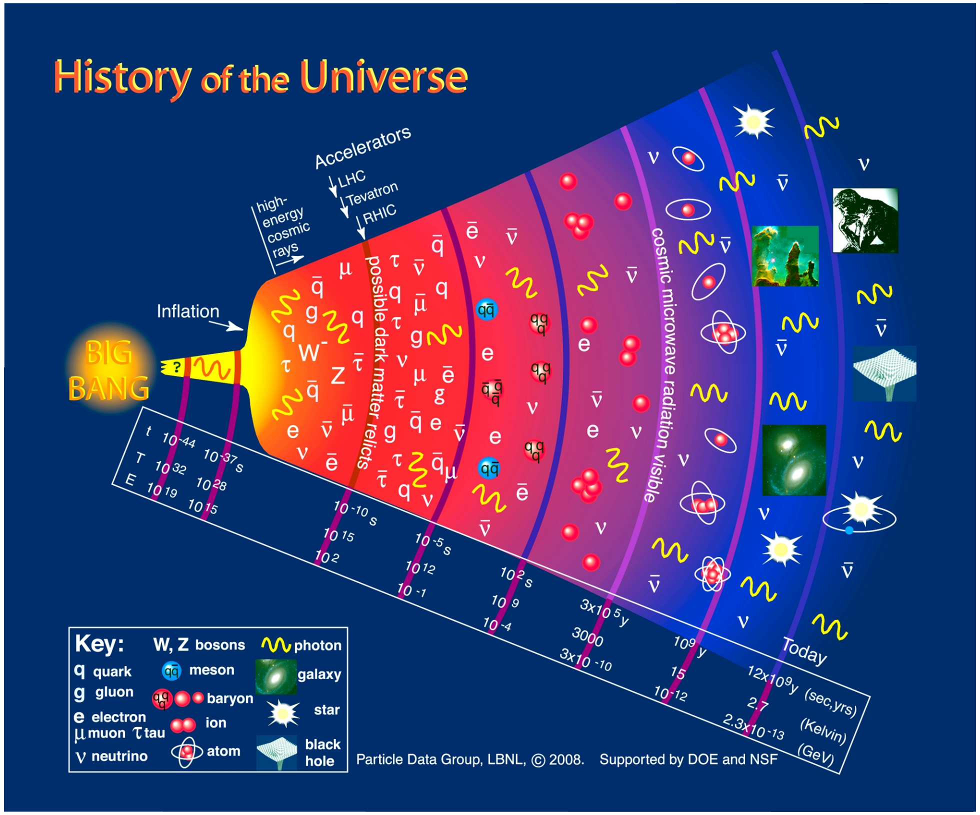
Studies of hadrons
(mesons) → Studies of strong interaction

- Quark models based on QCD:
  - **Predict** states (also beyond the qqq, $q\bar{q}$ sytems)
  - **Predict** properties (masses, widths, decays, …)

- **Measurements**:
  - Tests of QCD predictions
  - Provide the feedback for improvement of models

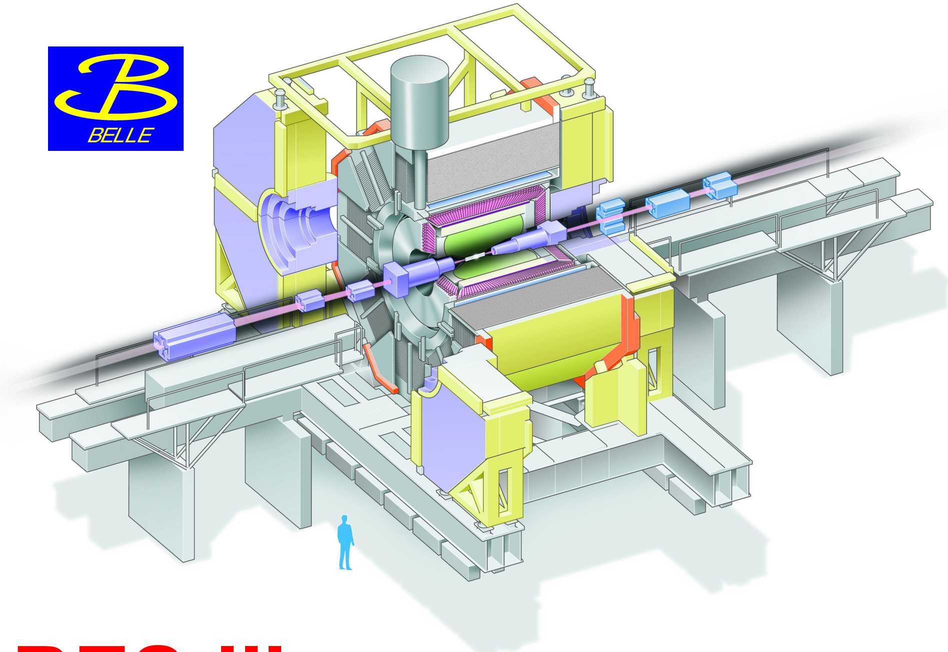
- **Disagreements** with models

→ New phenomena, new particles, ...

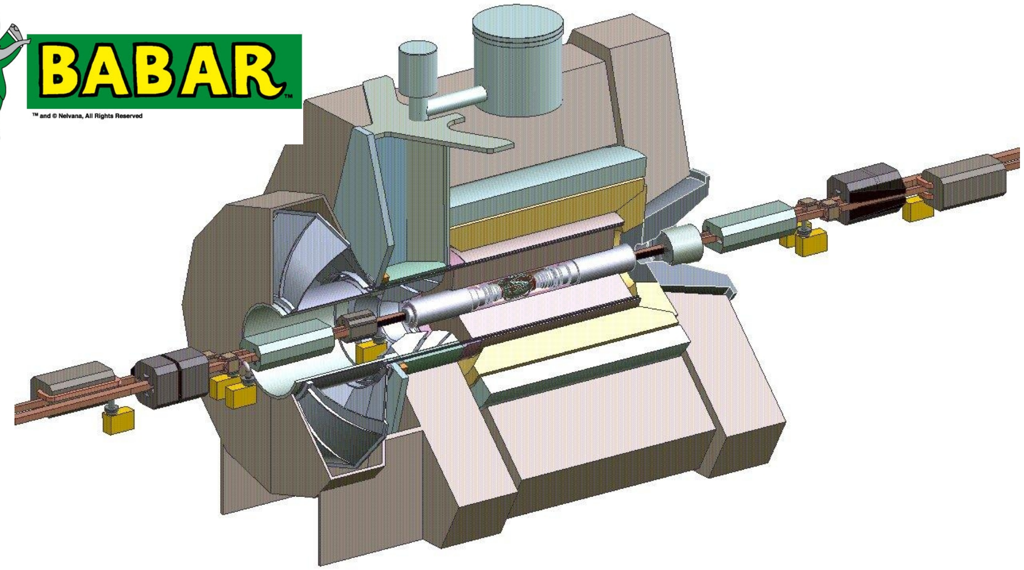


Experiments

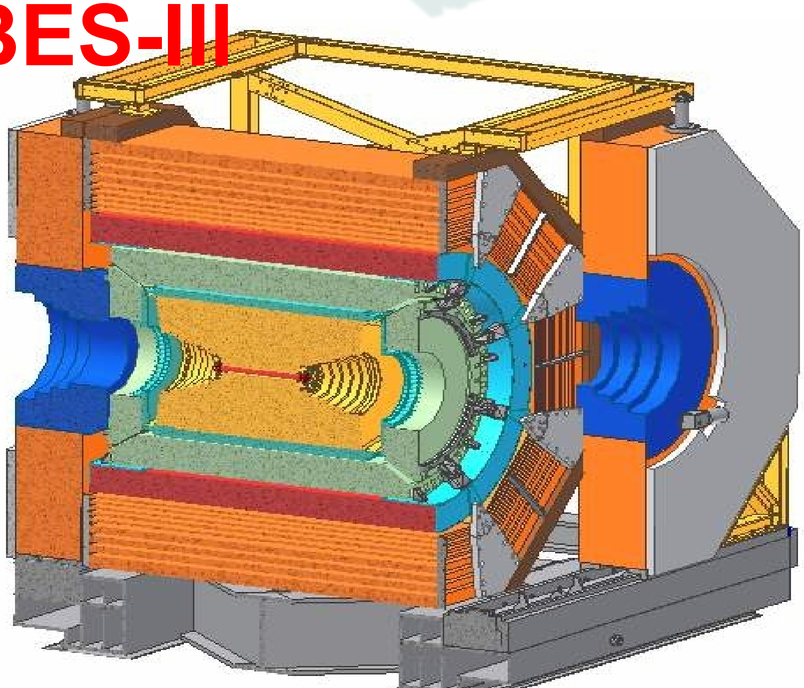
BELLE



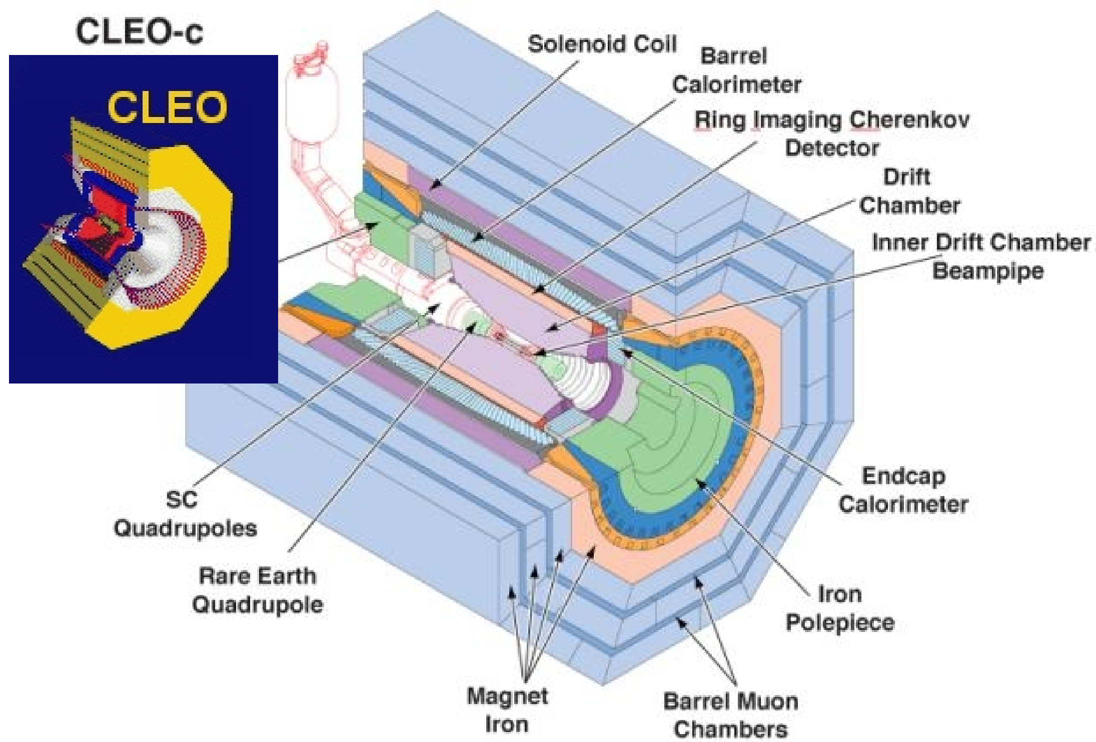
BABAR



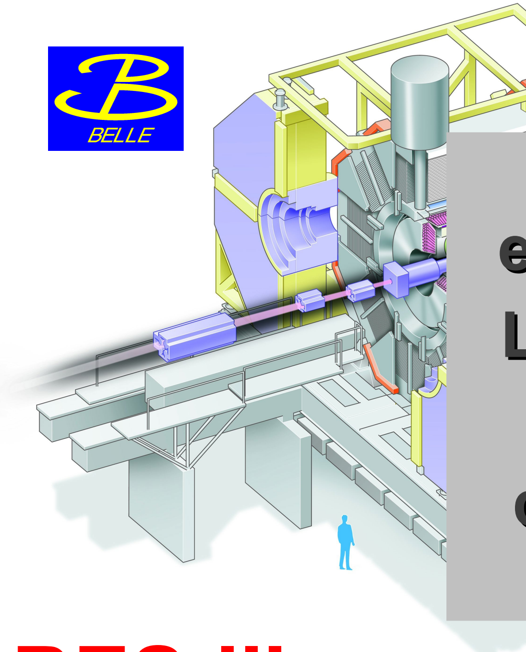
BES-III

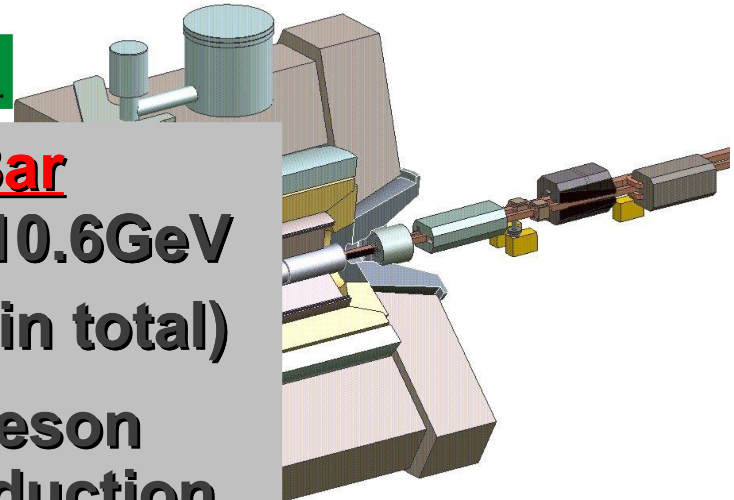


CLEO-c



Experiments





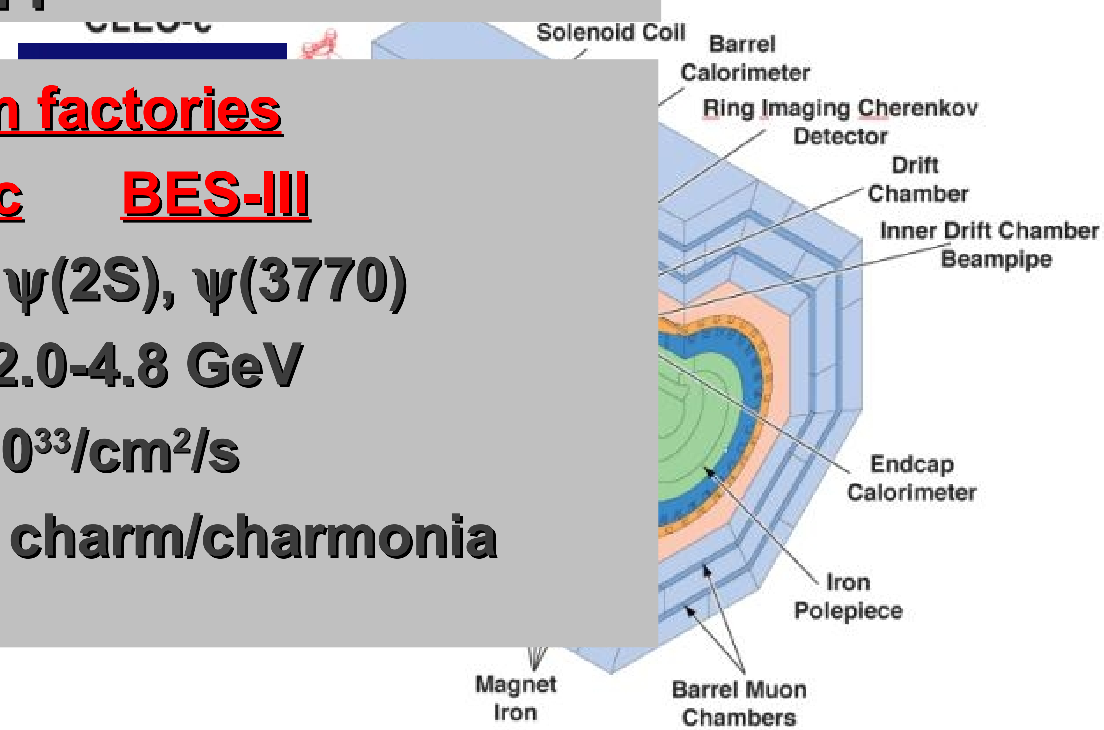
B-factories: Belle BaBar

$e^+e^- \to \Upsilon(4S)$ and nearby $\sqrt{s} \sim 10.6$GeV

$L \sim 10^{34}/cm^2/s$ (~1000+530 fb^{-1} in total)

Charm hadrons from B-meson decays, ISR, continuum production and $\gamma\gamma$ fusion

BES-III



Charm factories

CLEO-c BES-III

$e^+e^- \to J/\psi$, $\psi(2S)$, $\psi(3770)$

scan 2.0-4.8 GeV

$L \sim 10^{33}/cm^2/s$

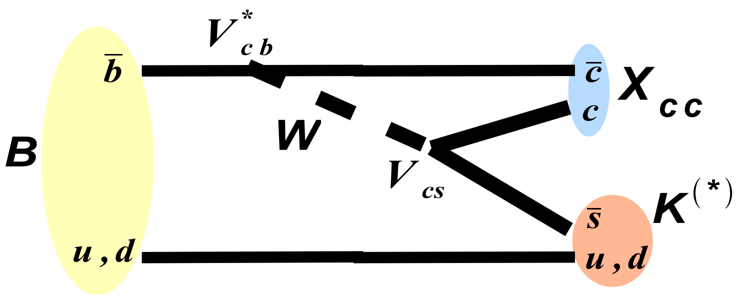
Dedicated to charm/charmonia

Charmonium(-like) states

cc[-like] production at B-factories

Colour-suppressed B decays:

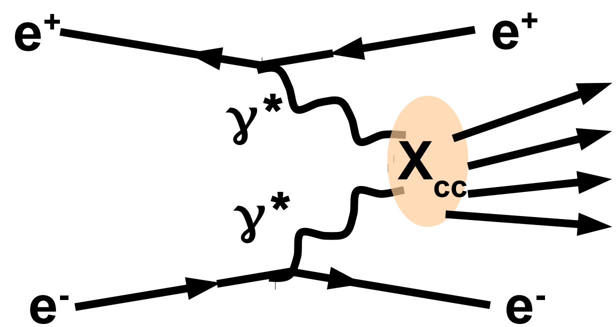
e.g. $B \to X_{cc}\ K^{(*)}$



$0^{-+}, 1^{--}, 1^{++}$

Two-photon production:

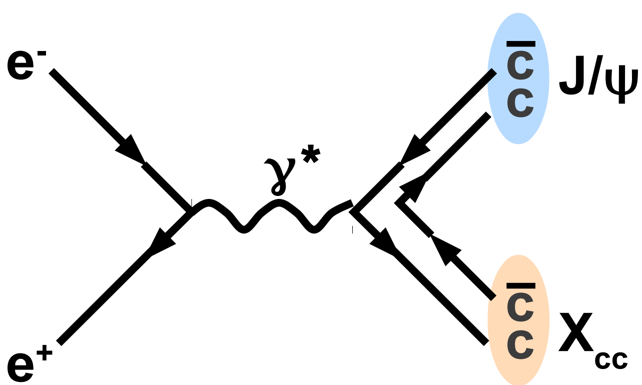
$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X_{cc}$



$0^{-+}, 0^{++}, 2^{++}, 2^{-+}$

Double $c\bar{c}$ production:

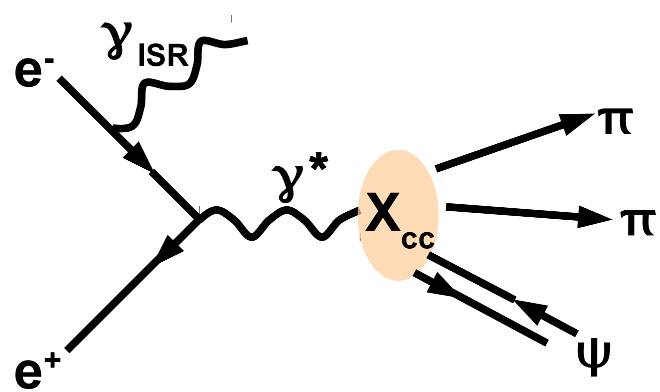
e.g. $e^+e^- \to J/\psi\ \ X_{cc}$



states with C=+

e+e- radiative return (ISR):

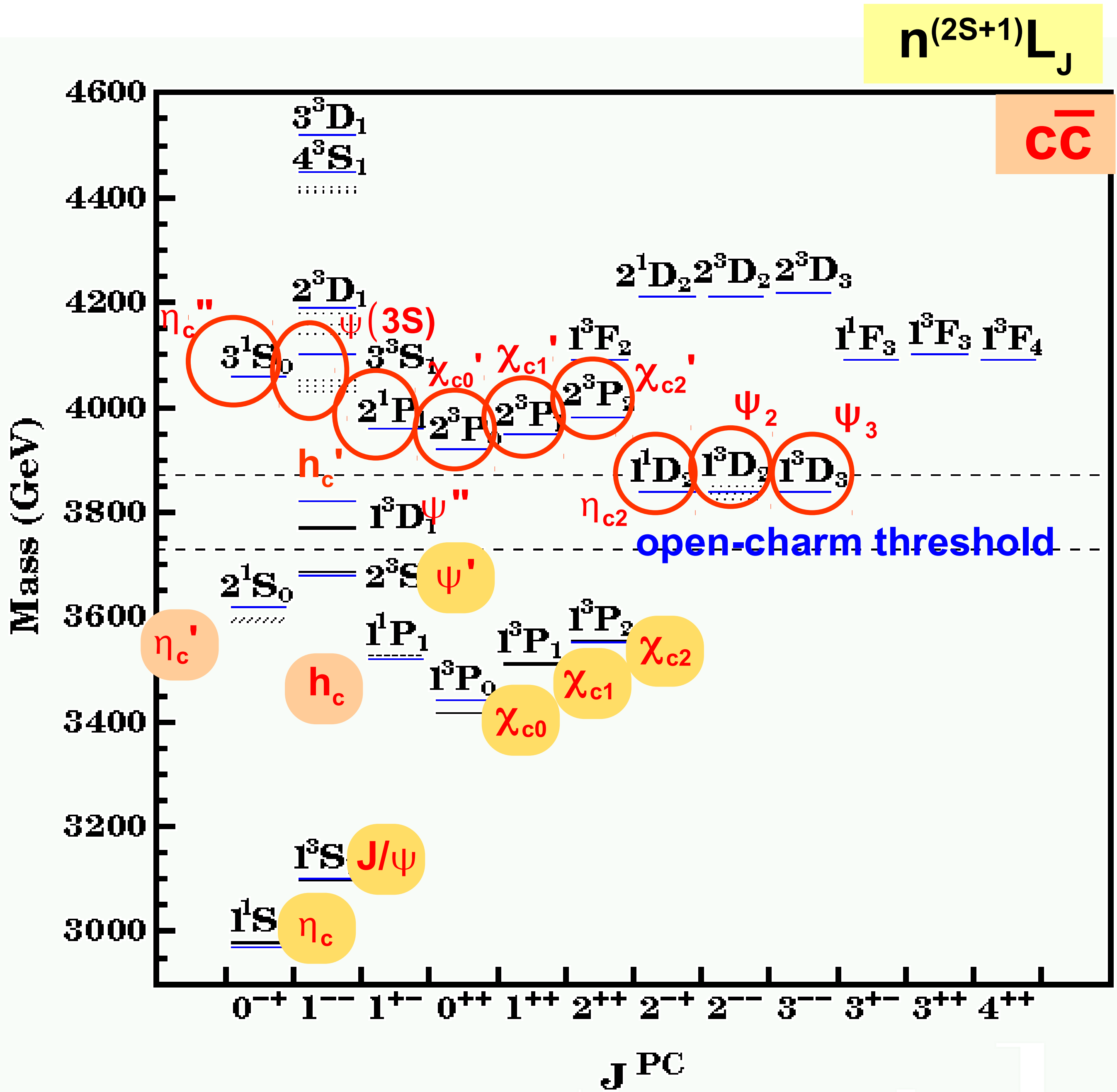
e.g. $e^+e^- \to \gamma_{ISR}\ X_{cc} \to \gamma_{ISR}\psi\pi\pi$



1^{--} only

Standard Charmonium States

c c



n radial quantum number

S total quark-antiquark spin

L relative orbital ang. mom.

(L = 0, 1, 2 ... S,P,D states)

$J = S + L$

$P = (-1)^{L+1}$ parity

$C = (-1)^{L+S}$ charge conjugation

$M_D + M_{D^*}$

$2M_D$

Below the DD threshold:

States are narrow

All states observed

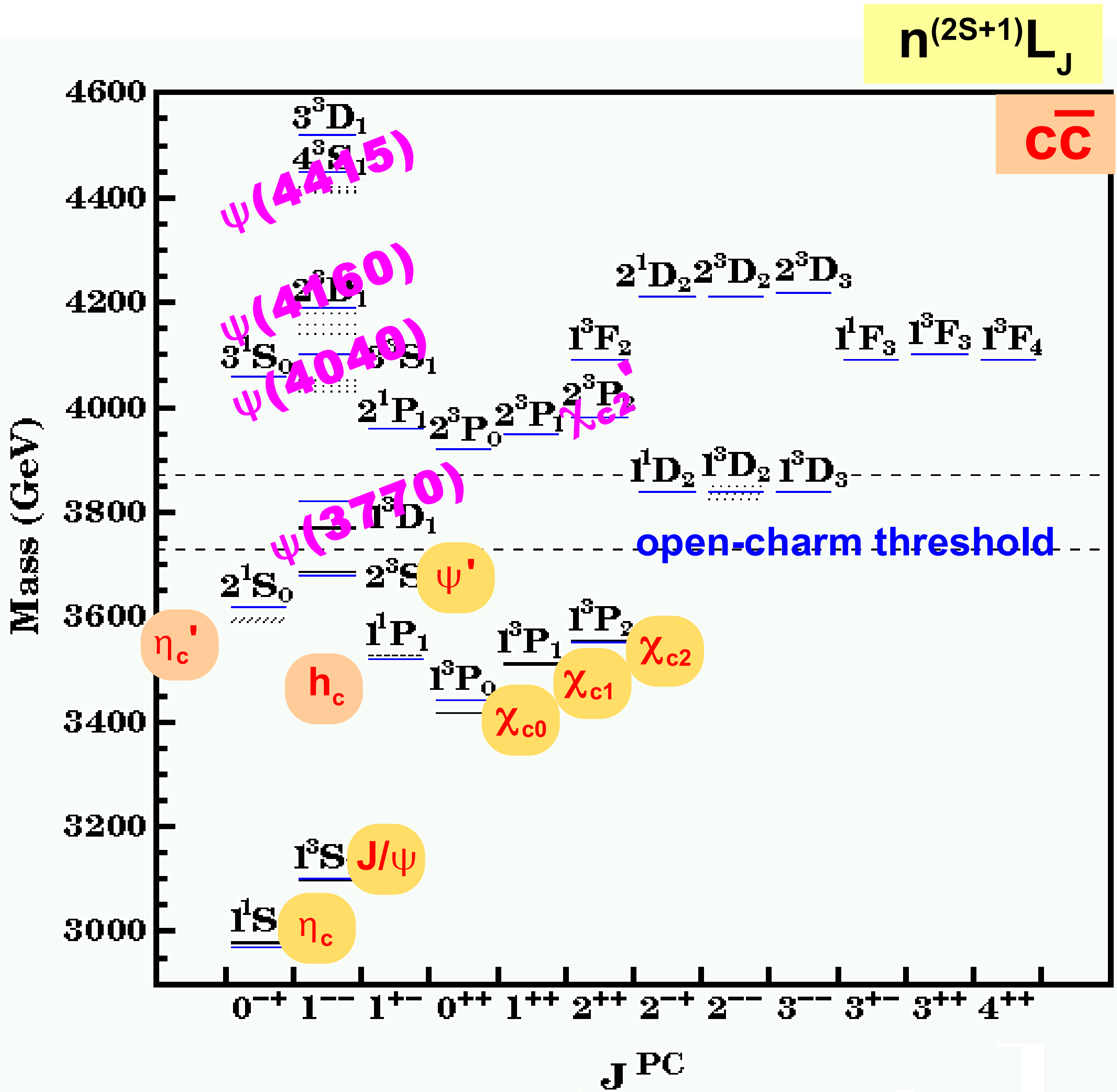
well measured(1974-80)

recently observed :

$\eta_c(2S)$@Belle: PRL 89,102001 (2002)

$h_c(1P)$@CLEO:PRL 95,102003 (2005)

Standard Charmonium States



n radial quantum number

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(L = 0, 1, 2 ... S,P,D states)

$J = S + L$

$P = (-1)^{L+1}$ parity

$C = (-1)^{L+S}$ charge conjugation

$M_D + M_{D^*}$

$2M_D$

Above the DD threshold:

States expected to be wide

Only five states measured and identified; last was $\chi_{c2}(2P)$@Belle:PRL 96,082003(2006)

Many candidates available

Standard Charmonium States c c

Observed recently (= since 2002)

from **Eur. Phys. J. C71, 1534 (2011)**

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$h_c(1P)$	3525.45 ± 0.15	0.73 ± 0.53	1^{+-}	$\psi(2S) \to \pi^0(\gamma\eta_c(1S))$
		(<1.44)		$\psi(2S) \to \pi^0(\gamma...)$
				$p\bar{p} \to (\gamma\eta_c) \to (\gamma\gamma\gamma)$
				$\psi(2S) \to \pi^0(...)$
$\eta_c(2S)$	3637 ± 4	14 ± 7	0^{-+}	$B \to K(K^0_S K^- \pi^+)$
				$e^+e^- \to e^+e^-(K^0_S K^- \pi^+)$
				$e^+e^- \to J/\psi\ (...)$
$\chi_{c2}(2P)$	3927.2 ± 2.6	24.1 ± 6.1	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$

[Z(3930) – at discovery]

… and many exotic candidates (X, Y, Z)

New states — *from Eur. Phys. J. C71, 1534 (2011)*

State	M, MeV	Γ, MeV	J^{PC}	Process
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$
		(< 2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$
				$B \to K(\omega J/\psi)$
				$B \to K(D^{*0} D^0)$
				$B \to K(\gamma J/\psi)$
				$B \to K(\gamma\psi(2S))$
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$
				$\gamma\gamma \to (\omega J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
				$e^+e^- \to J/\psi\ (\ldots)$
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi')$
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$

... and many candidates (X, Y, Z)

New states — *from Eur. Phys. J. C71, 1534 (2011)*

State	M, MeV	Γ, MeV	J^{PC}	Process
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6 (< 2.2)	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$ $p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$ $B \to K(\omega J/\psi)$ $B \to K(D^{*0} D^0)$ $B \to K(\gamma J/\psi)$ [redacted]
[redacted]				
$Z_2(4250)^+$	$4248^{[redacted]}_{-45}$	$177^{[redacted]}_{-72}$	[redacted]	[redacted] $\chi_{c1}(1P))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ $e^+e^- \to (\pi^+\pi^- J/\psi)$ $e^+e^- \to (\pi^0\pi^0 J/\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi')$
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+ \psi(2S))$
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+ \Lambda_c^-)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$

Only some of these states will be mentioned.

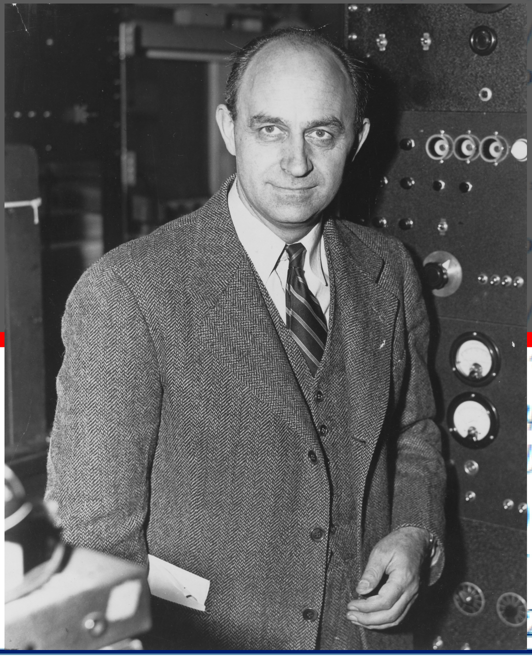
… and many candidates (X, Y, Z)

New states — *from Eur. Phys. J. C71, 1534 (2011)*

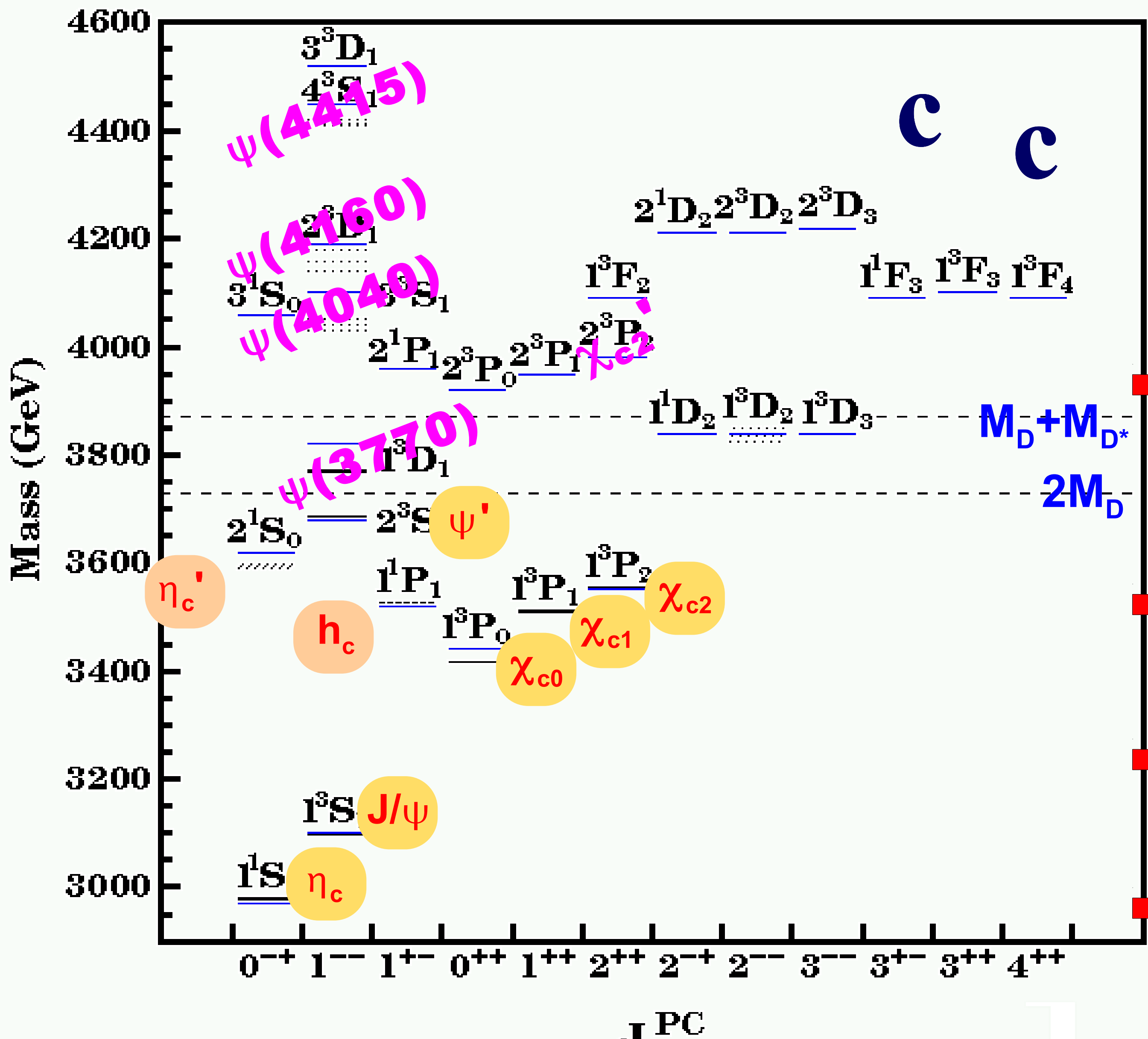
State	M, MeV	Γ, MeV	J^{PC}	Process
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6 (< 2.2)	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$ $p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$ $B \to K(\omega J/\psi)$ $B \to K(D^{*0} D^0)$ $B \to K(\gamma J/\psi)$ $B \to K(\gamma\psi(2S))$
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$ $\gamma\gamma \to$ [illegible] $J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$ [illegible] $\to J/\psi\ (\ldots)$
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	[illegible] $\psi)$
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	[illegible] $))$
$Y(4140)$	4143.4 ± 3.0	15^{+11} [illegible]	$?^{?+}$	[illegible]
$X(4160)$	4156^{+29}_{-25}	[illegible] $_{-65}$	[illegible] $^{?+}$	[illegible] $^*)$
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	[illegible] $))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	[illegible] $\psi)$ [illegible] $\psi)$ [illegible] $\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	[illegible] $\psi')$
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	[illegible] $)$
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	[illegible] $)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	[illegible] $2S))$

If I could remember the names of all these particles, I'd be a botanist.

E. Fermi

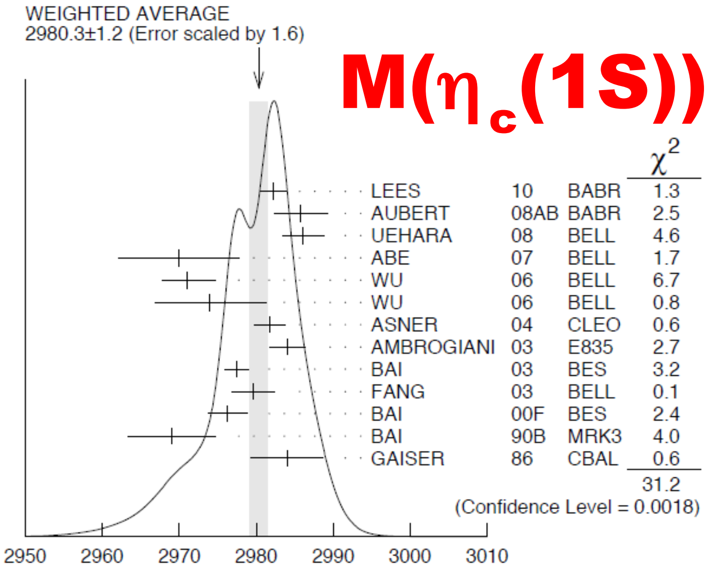


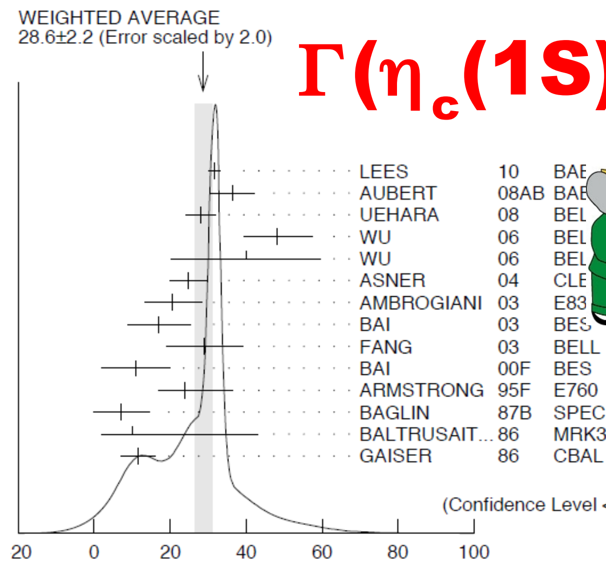
Standard Charmonia - News



- Updated masses and widths of η_c , η_c' , h_c
- 1^{st} obs. : $\psi \rightarrow \gamma \eta_c'$
- New η_c' decay mode
- Resonant parameters of J/ψ , ψ' , $\psi(3770)$

$\eta_c(1S)$ & $\eta_c(2S)$ – Status @ PDG2010





$\gamma\gamma \rightarrow \eta_c(1S) \rightarrow K_S K^+ \pi^-$

LEES et al., BaBar, Phys. Rev. D81(2010)052010

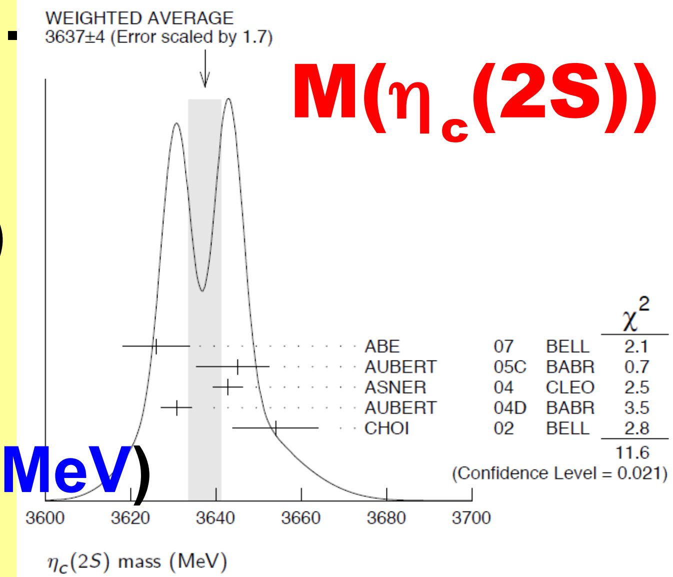
$$m_{\eta_c} = 2982.2 \pm 0.4 \pm 1.6 \text{ MeV}/c^2,$$
$$\Gamma = 31.7 \pm 1.2 \pm 0.8 \text{ MeV}.$$

$\eta_c(1S)$: 1 $^1S_0$, $J^{PC}=0^{-+}$

Large spread in measured masses, widths, e.g.

$\Gamma(\eta_c(1S))$ ~ 15 MeV (J/ψ , ψ' radiative decays)

$\Gamma(\eta_c(1S))$ ~ 30 MeV (B decays; γγ interactions)

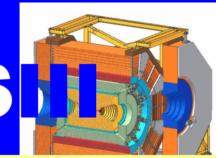


$\eta_c(2S)$: 2 $^1S_0$, $J^{PC}=0^{-+}$

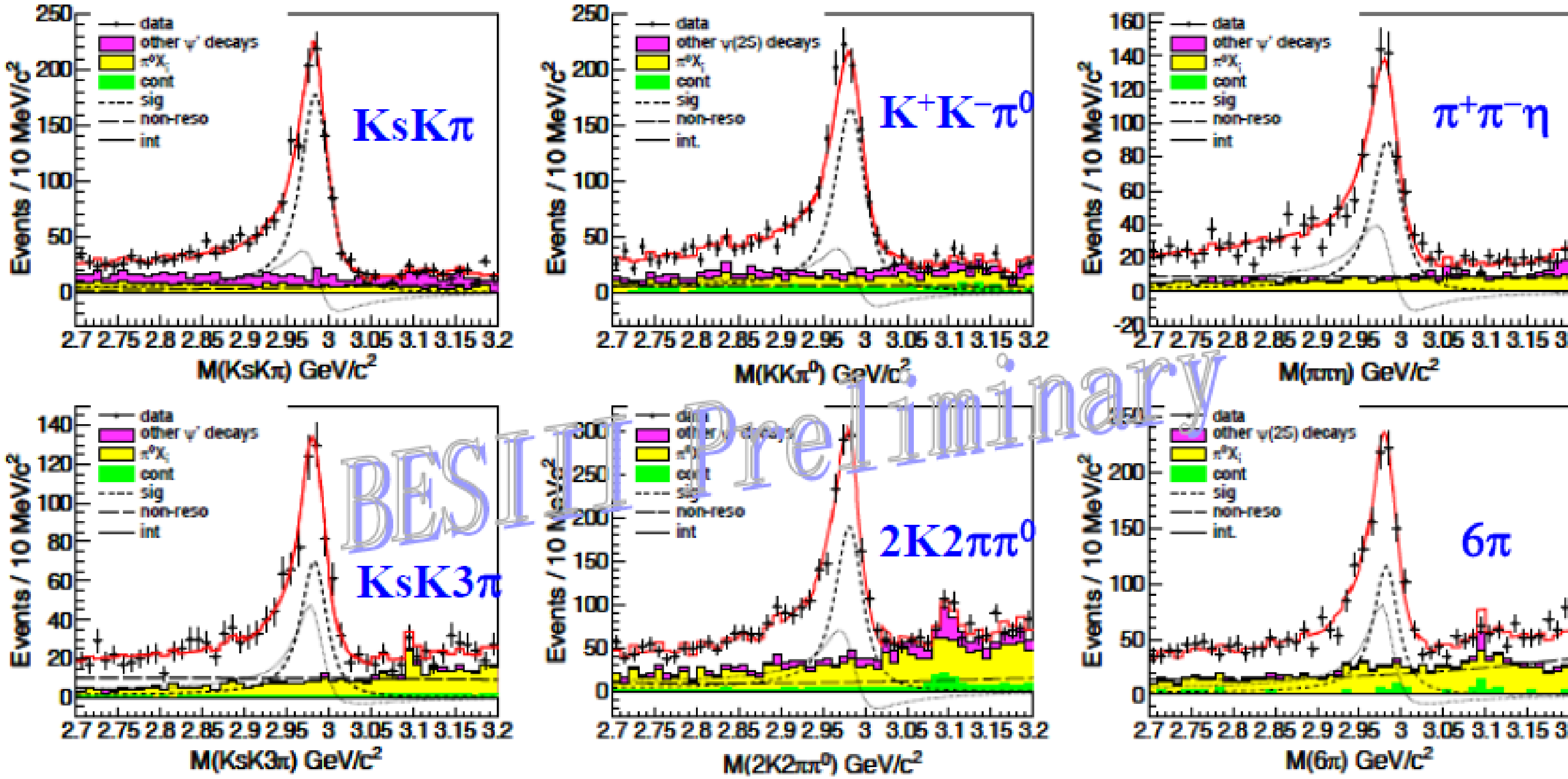
Measured parameters lack precision ($\Gamma = 14 \pm 7$ MeV)

Only seen in exclusive $K\bar{K}\pi$ decays

$\eta_c(1S)$ properties: $\psi' \to \gamma \eta_c(1S)$ decays at BESIII



Hai-Bo Li @ LP11

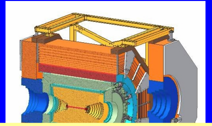


Considering the interference between η_c and non-resonant decays,

mass: $2984.4 \pm 0.5_{stat} \pm 0.6_{sys}$ MeV/c^2
width: $30.5 \pm 1.0_{stat} \pm 0.9_{sys}$ MeV
ϕ: $2.35 \pm 0.05_{stat} \pm 0.04_{sys}$ rad

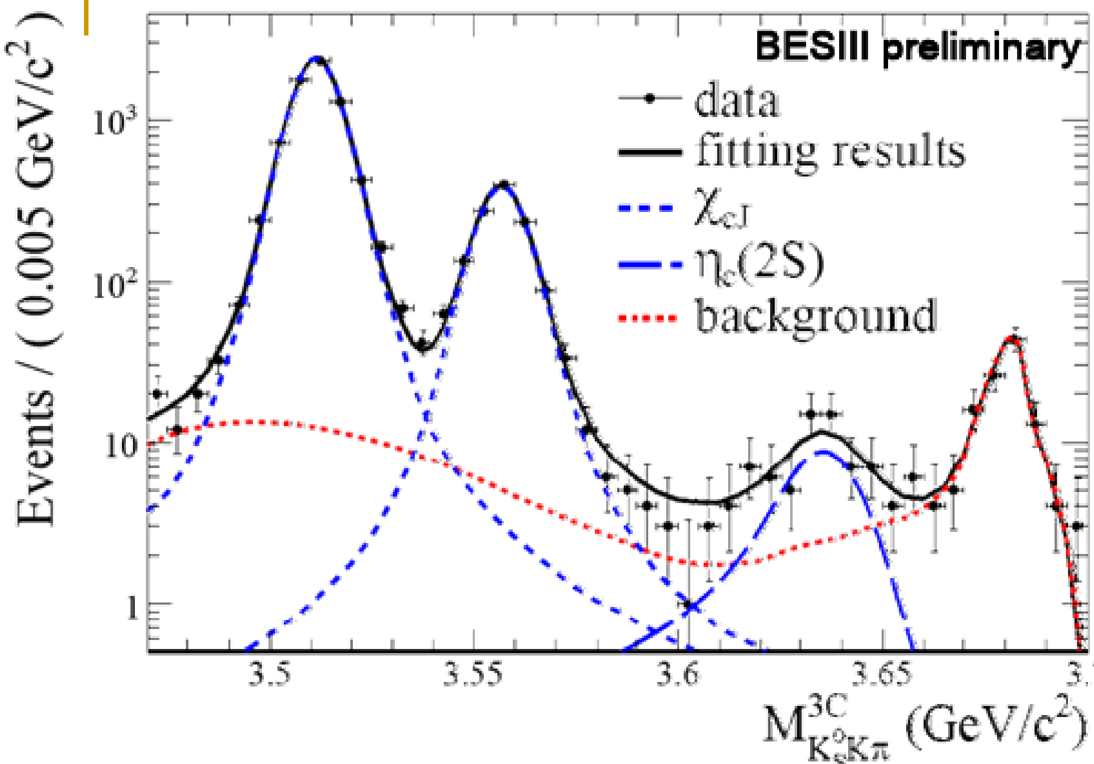
ϕ: relative phase between η_c and non-resonant component. An universal phase for different modes is used.

First $\psi' \to \gamma \eta_c(2S)$ decays at BESIII



Hai-Bo Li @ LP11

First observation of $\eta_c(2S)$ in $\psi' \to \gamma\eta_c(2S), \eta_c(2S) \to K_s K\pi$



With 106M ψ' events at BESIII:

$M(\eta_c(2S)) = (3638.5 \pm 2.3 \pm 1.0)$ MeV/c^2

$N(\eta_c(2S)) = 50.6 \pm 9.7$

Statistical significance larger than 6.0σ!

$$(E_\gamma^3 \times BW(m) \times damping(E_\gamma)) \otimes Gauss(0, \sigma)$$

M1 transition

$$\frac{E_0^2}{E_\gamma E_0 + (E_\gamma - E_0)^2}$$

$\Gamma(\eta_c(2S))$ fixed to 12MeV (world average)

$Br(\psi' \to \gamma\eta_c(2S) \to \gamma K_s K\pi)$
$= (2.98 \pm 0.57_{stat} \pm 0.48_{sys}) \times 10^{-6}$

+

$Br(\eta_c(2S) \to KK\pi) = (1.9 \pm 0.4 \pm 1.1)\%$
From BABAR(PRD78,012006)

⇩

$Br(\psi' \to \gamma\eta_c(2S))$
$= (4.7 \pm 0.9_{stat} \pm 3.0_{sys}) \times 10^{-4}$

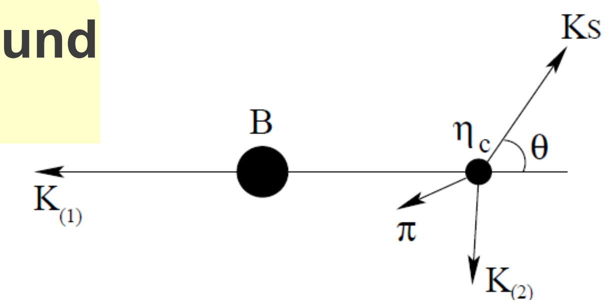
CLEO-c: $<7.6\times10^{-4}$ PRD81,052002(2010)

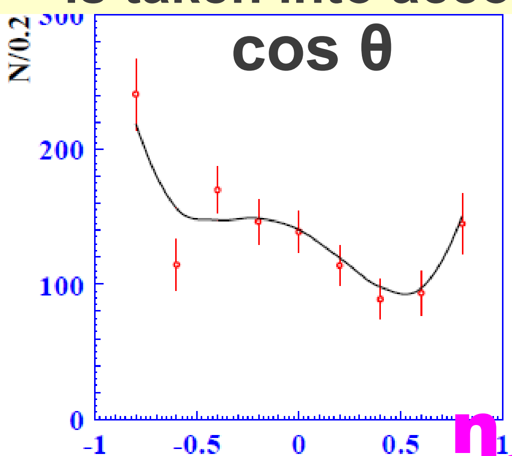
Potential model: $(0.1\text{–}6.2)\times10^{-4}$
PRL89,162002(2002)

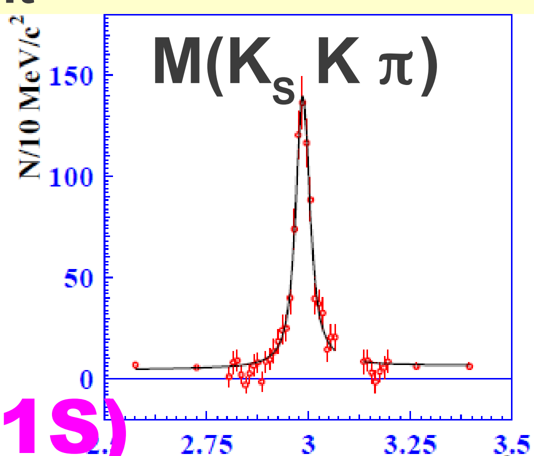
$\eta_c(1S)$, $\eta_c(2S)$ properties: B decays

- 2-D fit of angle θ vs. $M(K_s\, K\, \pi)$ distributions is performed
- Interference between signal and non-resonant background is taken into account

arXiv: 1105.0978 submitted to PLB

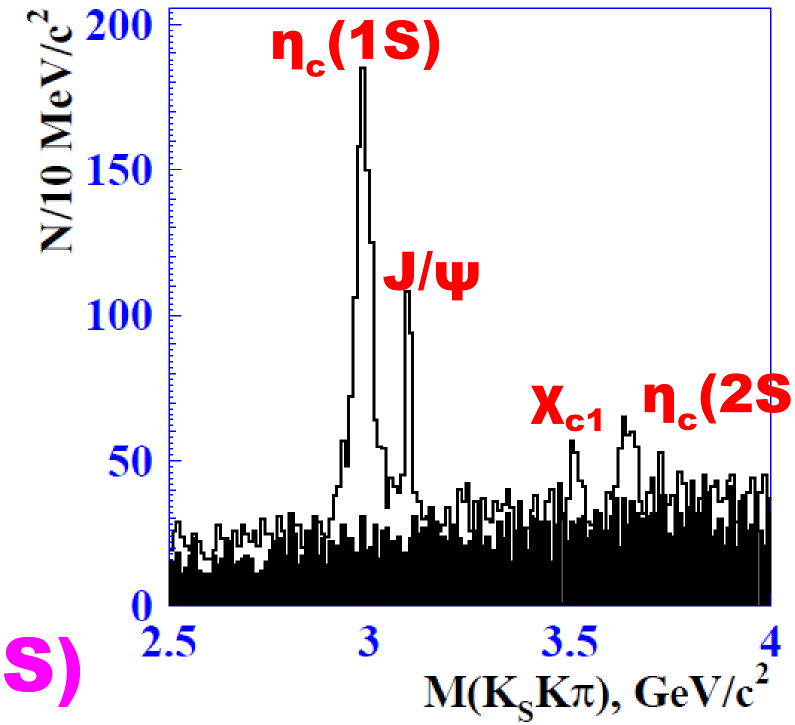


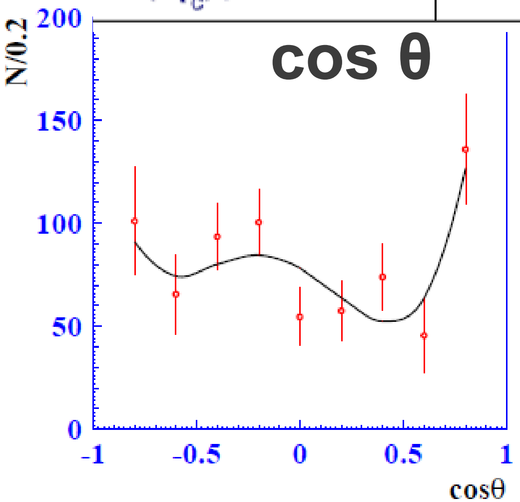


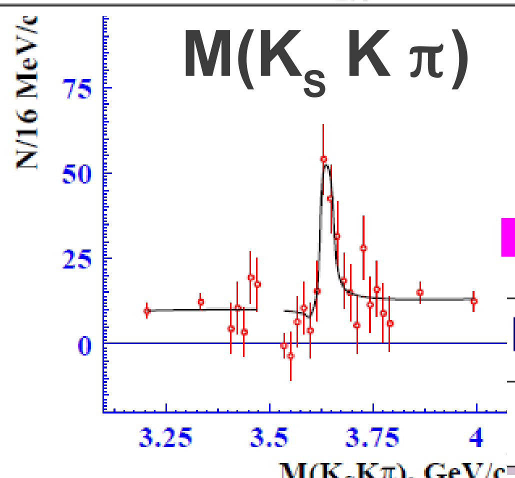


$\eta_c(1S)$

$M(\eta_c)$, MeV	$2985.4\pm1.5(stat)^{+0.2}_{-2.0}(syst)$
$\Gamma(\eta_c)$, MeV	$35.1\pm3.1(stat)^{+1.0}_{-1.6}(syst)$







$\eta_c(2S)$

$M(\eta_c(2S))$, MeV	$3636.1\ ^{+3.9}_{-4.2}(stat+model)\ ^{+0.5}_{-2.0}(syst)$
$\Gamma(\eta_c(2S))$, MeV	$6.6\ ^{+8.4}_{-5.1}(stat+model)\ ^{+2.6}_{-0.9}(syst)$

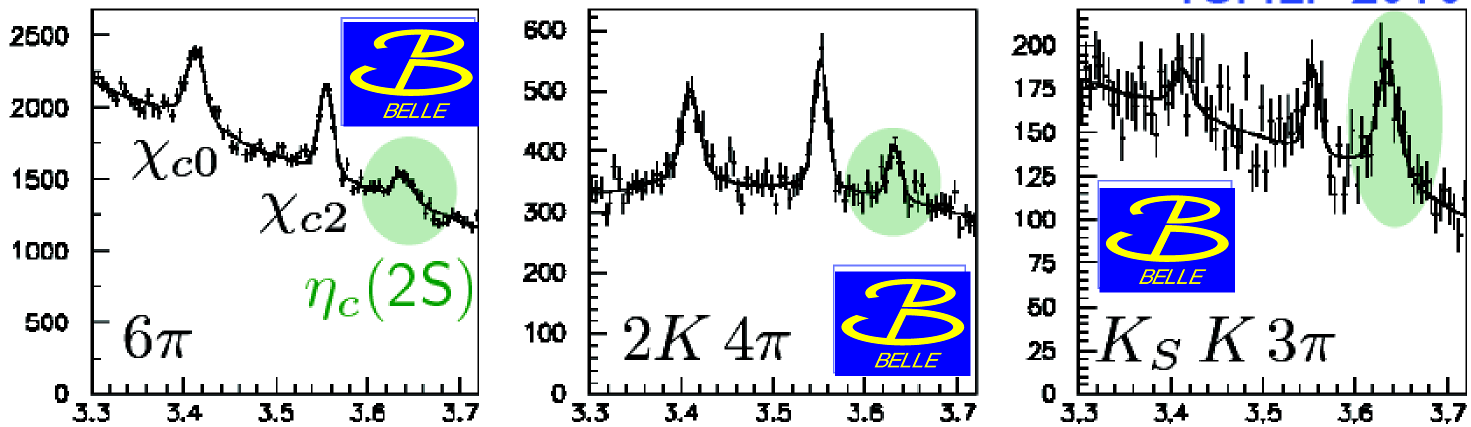
$\eta_c(2S)$: new decay modes in γγ reactions

Belle studied $\gamma\gamma \to \eta_c(2S) \to$ 6-prong with 923 /fb.

6-prong: 6π, $2K4\pi$, $4K2\pi$, $K_SK3\pi$.

- Only one exclusive mode ($K_SK\pi$) seen until recently
- Not seen in 4-prong final state: Belle EPJC 53, 1 (2008)
- Seen in 6-prong final states:

ICHEP 2010



	M, MeV	Γ, MeV	Signif.	$\Gamma_{\gamma\gamma}\mathcal{B}$, eV
6π	$3638.9 \pm 1.6 \pm 2.3$	10.7 ± 4.9	8.5σ	$20.1 \pm 3.7 \pm 3.2$
$2K4\pi$	$3634.7 \pm 1.6 \pm 2.8$	< 13 @ 90%CL	6.2σ	$10.2 \pm 2.3 \pm 3.4$
$K_SK3\pi$	$3636.5 \pm 1.8 \pm 2.4$	15.9 ± 5.7	8.7σ	$30.7 \pm 3.9 \pm 3.7$

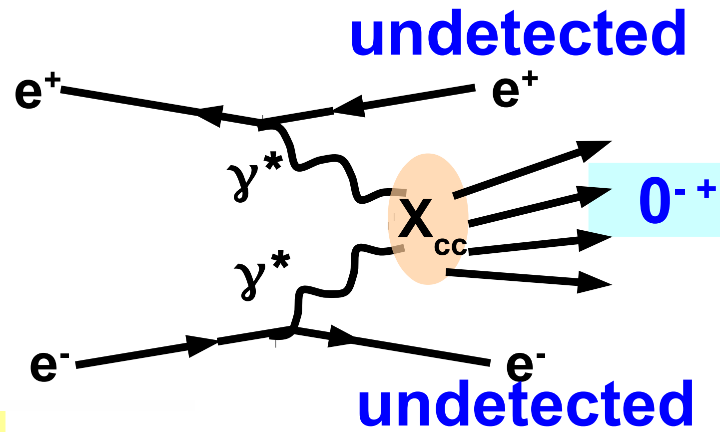
$M(\eta_c(2S)) = 3636.9 \pm 1.1 \pm 2.5 \pm 5.0$ MeV (possible interference

$\Gamma(\eta_c(2S)) = 9.9 \pm 3.2 \pm 2.6 \pm 2.0$ MeV with background)

$\eta_c(2S)$: new decay modes in $\gamma\gamma$ reactions

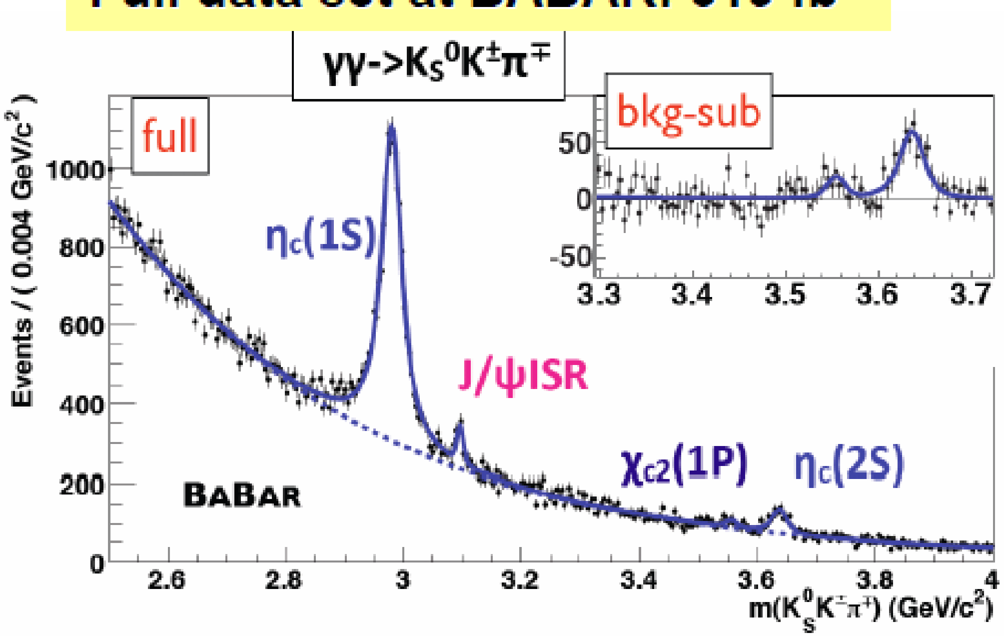
$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\eta_c^{(\prime)}$

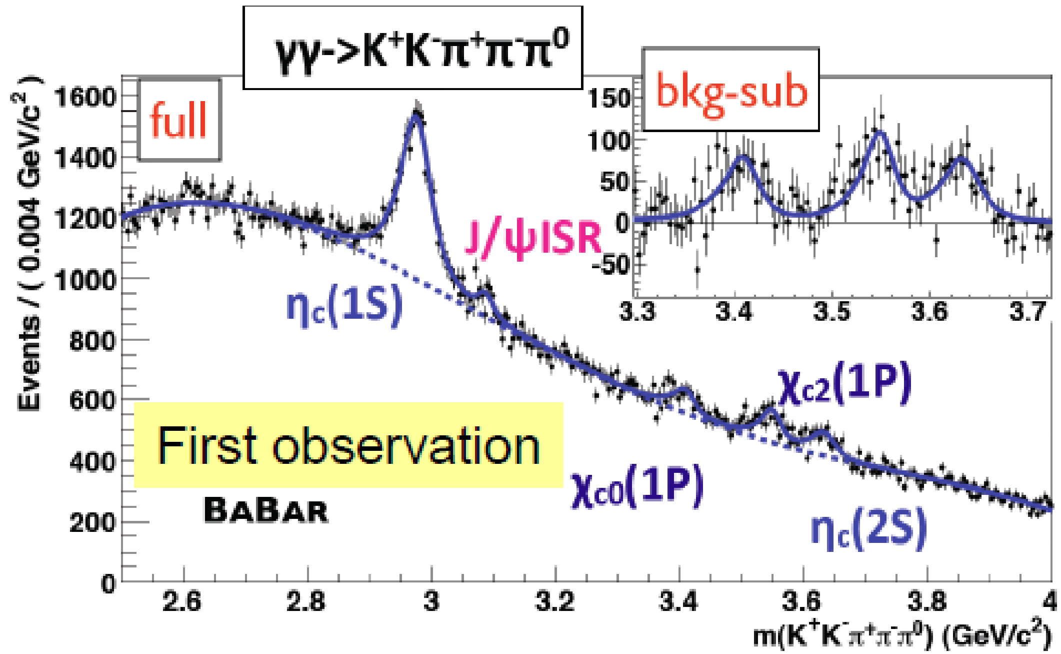
PRD-RC 84, 012004(2011)
519 1/fb



$0^{-+}, 0^{++}, 2^{++}, 2^{-+}$

Full data set at BABAR: 519 fb^{-1}





$M(\eta_c(1S)) = 2982.2 \pm 0.4 \pm 1.4$ MeV/c^2
$\Gamma(\eta_c(1S)) = 32.1 \pm 1.1 \pm 1.3$ MeV

$M(\eta_c(2S)) = 3638.5 \pm 1.5 \pm 0.8$ MeV/c^2
$\Gamma(\eta_c(2S)) = 13.4 \pm 4.6 \pm 3.2$ MeV

Most precise measurement for $\eta_c(2S)$

$\eta_c(1S)$ & $\eta_c(2S)$ – Update @ PDG2011

	BESIII [2011] preliminary $\psi(2S)\to\gamma\eta_c/\eta_c(2S)$	Belle[2011] arXiv:1105.0978 B decays	BABAR[2011] PRD 84 012004 $\gamma\gamma$ fusion	PDG 2011
$M(\eta_c)$, MeV/c^2	$2984.4\pm0.5\pm0.6$	$2985.4\pm1.5^{+0.2}_{-2.0}$	$2982.2\pm0.4\pm1.4$	2980.3 ± 1.2
$\Gamma(\eta_c)$,MeV	$30.5\pm1.0\pm0.9$	$35.1\pm3.1^{+1.0}_{-1.6}$	$32.1\pm1.1\pm1.3$	28.6 ± 2.2
$M(\eta_c(2S))$,MeV	$3638.5\pm2.3\pm1.0$	$3636.1^{+3.9}_{-1.5}{}^{+0.5}_{-2.0}$	$3638.5\pm1.5\pm0.8$	3637 ± 4
$\Gamma(\eta_c(2S))$,MeV	12 (fixed)	$6.6^{+8.4}_{-5.1}{}^{+2.6}_{-0.9}$	$13.4\pm4.6\pm3.2$	14 ± 7

- First observation of $\eta_c(2S)$ in $\psi(2S)$ radiative decay from BESIII
- Most precise measurement for η_c parameters is from BESIII
- Most precise measurement for $\eta_c(2S)$ parameters is from BABAR $\gamma\gamma$ fusion
- Hyperfine splitting: $\Delta M(1S) = 112.5\pm0.8$ MeV; $\Delta M(2S) = 47.6\pm1.7$ MeV

Spreads in measured masses and widths between different processes are getting smaller.

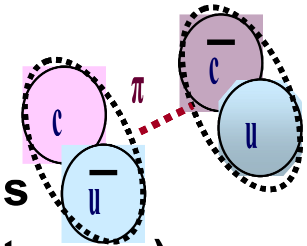
Exotic Charmonium-like States

Multiquark states

- *Molecular states*

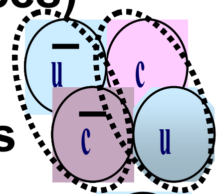
  Loosely bound pair of charm mesons

  (q,g/pion exchange at short/long distances)



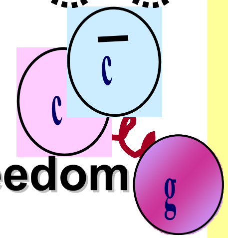
- *Tetraquarks*

  Tightly bound diquark-diantiquark states

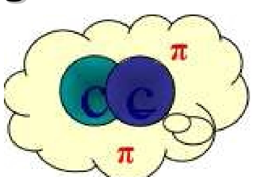


Charmonium hybrid states

States with excited gluonic degrees of freedom



Hadro-Charmonium



Compact charmonium states bound inside light hadronic matter

Threshold-effects

Virtual states at the threshold

Charmonium states with shifted masses due to nearby $D^{(*)}D^{(*)}$ thresholds

Mixture of the above or something even more exotic?

Exotic states:

Are not forbidden in SM;

Have exotic J^{PC}

(0^{+-}, 1^{-+}, 2^{+-},... forbidden for $q\bar{q}$);

exotic decay modes

(not possible for $q\bar{q}$);

strange properties (widths,...);

Multiquark states could also have

non-zero charge $[cu\overline{cd}]$,

strangeness $[cd\overline{cs}]$

or both $[cu\overline{cs}]$

The "good old" X(3872): discovery

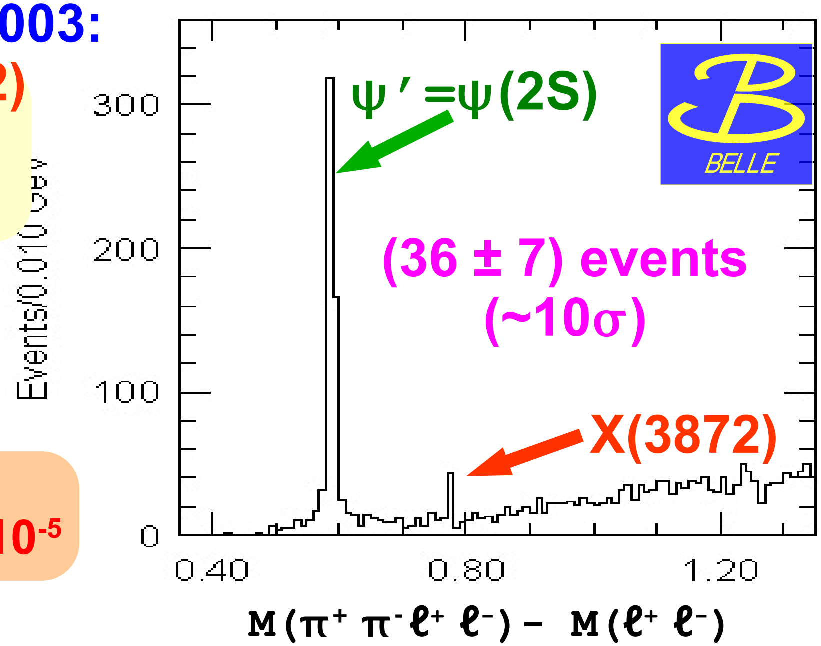
• **Observed first by Belle in 2003:**

$B^{\pm} \rightarrow K^{\pm} \pi^{+}\pi^{-} J/\psi$ — X(3872); $J/\psi \rightarrow \ell^{+}\ell^{-}$

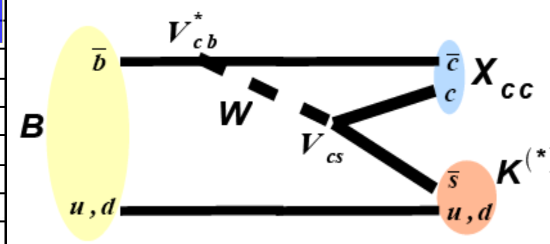
M = (3871.9 ± 0.5) MeV/c^2

Γ < 2.3 MeV @ 90% C.L.

BR($B^{-} \rightarrow XK^{-}$)xBR($X \rightarrow J/\psi\, \pi^{+}\pi^{-}$) = (1.3 ± 0.3)x10^{-5}



Belle : 152M BB
PRL 91, 262001 (2003)



•**Confirmed soon by:**

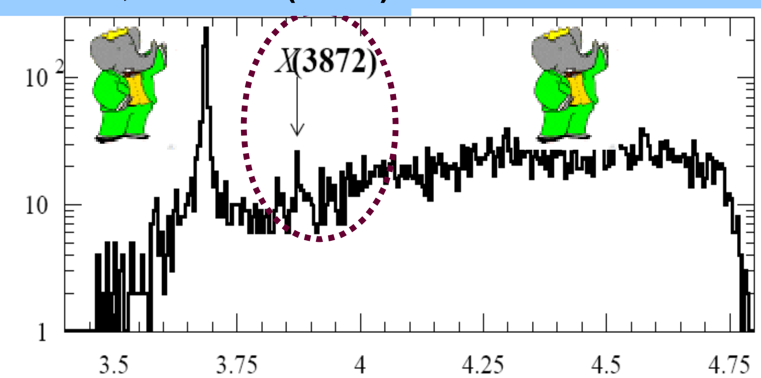
pp→X(3872) + anything

PRL 93,072001 (2004)

PRL 93,162002 (2004)

PRD71,071103R(2005)

PRD73,011101R(2006)



B decays

The X(3872) summary

- A narrow state discovered by Belle in $B^+ \to J/\psi\pi^+\pi^- K^+$, S.-K.Choi et al.,PRL 91, 262001 (2003)
- Confirmed by BaBar, B.Aubert et al., PRL 93, 041801 (2004); at Tevatron: CDF, D.Acosta et al., PRL 93, 072001 (2004) and D0, V.M.Abazov et al., PRL 93, 162002 (2004)

Now also:
CMS & LHCb

- Charged partner not found by BaBar, B.Aubert et al., PRD 71, 031501 (2005)

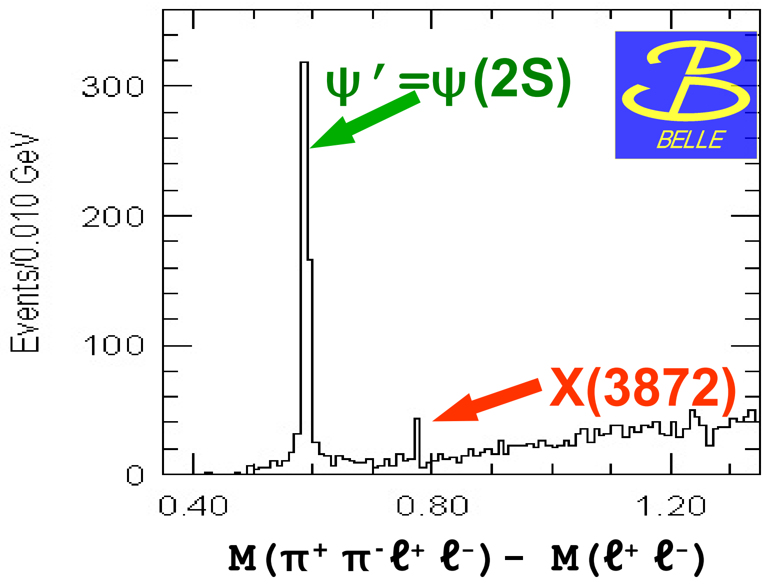
Determination of quantum numbers of X(3872)

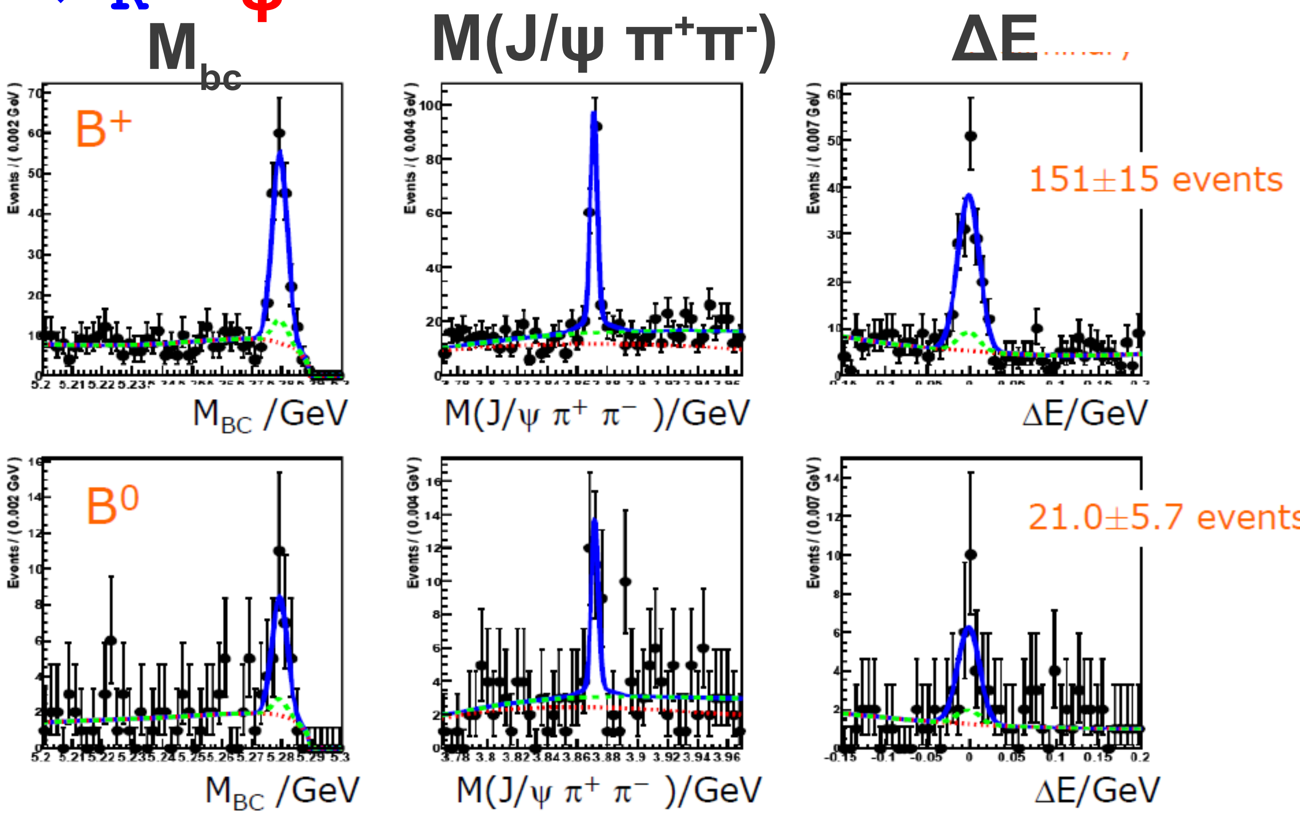
- Evidence for X(3872)$\to J/\psi\gamma$ established C = +1
  [Belle arXiv:1105.0177; BABAR PRL 102 132001]
- X(3872)$\to J/\psi\pi^+\pi^-$ by CDF $\Rightarrow$ 1^{++} or 2^{-+} [PRL 98 132002]
- X(3872) not seen $\chi_{c1}\gamma$, $\chi_{c2}\gamma$ and $J/\psi\eta$ modes
  indicate that X may be not a conventional cc state
- X(3872) $\to J/\psi\ \omega$ by BABAR favors 2^{-+} [PRD 82 011101]

$X(3872) \to J/\psi\ \pi^+\pi^-$ from B (update)

- **Using full Belle Y(4S) data sample: 711 fb^{-1}**
- **Charged & neutral decays: $B^{0,\pm} \to K^{0,\pm} X$**
- **Reference channel: $B^{0,\pm} \to K^{0,\pm} \psi'$**

PRD 84, 052004 (2011)
711 1/fb





X from $B^0, B^\pm$ are the same: $\Delta M_{X(3872)} = (-0.69 \pm 0.97(\mathrm{stat}) \pm 0.19(\mathrm{syst}))$ MeV

$BR(B^- \to XK^-) \times BR(X \to J/\psi\ \pi^+\pi^-) = (8.61 \pm 0.82 \pm 0.52) \times 10^{-6}$
$BR(B^0 \to XK^0) / BR(B^- \to XK^-) = (0.50 \pm 0.14 \pm 0.04)$

$X(3872) \to J/\psi\ \pi^+\pi^-$ from B (update)

BELLE

Using full Belle Y(4S) data sample: 711 fb^{-1}

PRD 84, 052004 (2011)
711 1/fb

X(3872) mass in $\pi^+\pi^- J/\psi$ channel only

Belle result contains MC/data shift 0.92 ± 0.006 MeV, fixed from reference channel ψ'

Experiment	X mass
CDF 2	3871.61 ± 0.16 ± 0.19 MeV
BaBar (B^+)	3871.4 ± 0.6 ± 0.1 MeV
BaBar (B^0)	3868.7 ± 1.5 ± 0.4 MeV
D0	3871.8 ± 3.1 ± 3.0 MeV
Belle (This result) Preliminary	3871.84 ± 0.27 ± 0.19 MeV
World Average	**3871.62 ± 0.19 MeV**
LHCb (new)	3871.96 ± 0.46 ± 0.10 MeV
World Average again	**3871.67 ± 0.17 MeV**
$M(D^0)+M(D^{*0})$ PDG2010	3871.79 ± 0.30 MeV

$<M_X>_{prev\_WA} = 3871.46 \pm 0.19$ MeV

Here former Belle measurement
3872.0 ± 0.6 ± 0.5 MeV
not considered anymore
(superseded by new measurement)

"Binding Energy"
$m(X)-m(D^{*0})-m(D^0)$
becomes smaller:

Old: $\Delta m = -0.32 \pm 0.35$ MeV

New: $\Delta m = -0.17 \pm 0.36$ MeV

New w/ LHCb:
$\Delta m = -0.12 \pm 0.35$ MeV

Reminder: $\Delta m(\text{deuteron}) = -2.2$ MeV

X(3872) →J/ψ π⁺π⁻ from B (update)

BELLE

Using full Belle Y(4S) data sample: 711 fb^{-1}

PRD 84, 052004 (2011)
711 1/fb

X(3872) mass in $\pi^+\pi^- J/\psi$ channel only

Belle result contains MC/data shift 0.92 ± 0.006 MeV, fixed from reference channel ψ´

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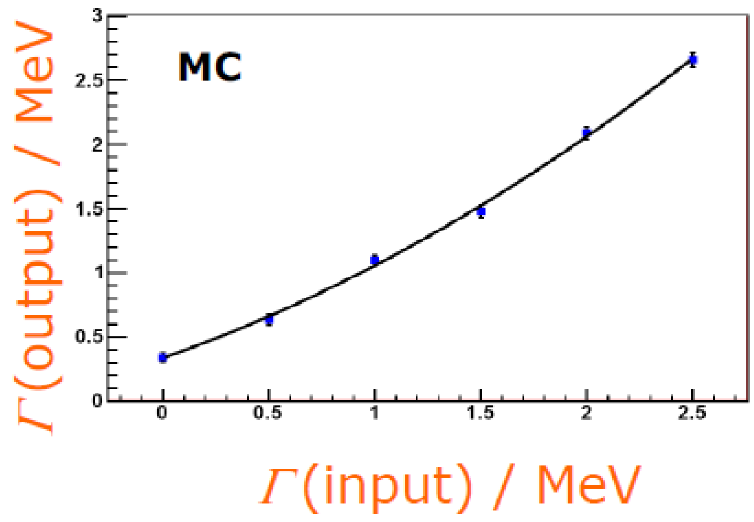
Reminder: $\Delta m(\text{deuteron}) = -2.2$ MeV

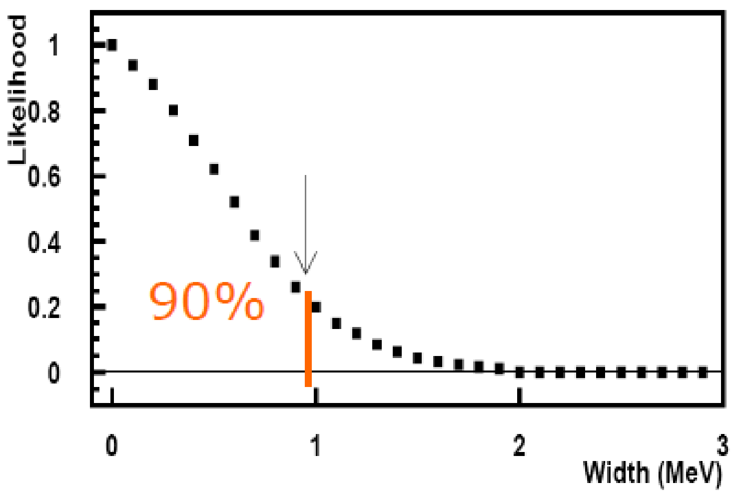
X(3872) →J/ψ π⁺π⁻ from B (update)

PRD 84, 052004 (2011)
711 1/fb

New measurement of width

- Previous best limit
  $\Gamma_{X(3872)} < 2.3$ MeV (90% CL)
- 3-dim fits are sensitive to natural widths narrower than resolution $<\sigma> \simeq 4$ MeV because of constraints (m_{BC}, ΔE)
- Method validated with ψ′ width
  $\Gamma_{\psi'} = 0.52 \pm 0.11$ MeV
  (PDG 0.304 ± 0.009 MeV)
  → bias 0.23 ± 0.11 MeV
- procedure for upper limit:
  width in 3-dim fit fixed
  n_{signal} and $n_{peaking\ BG}$ floating
  → calculate likelihood
- $\Gamma_{X(3872)} < 0.95$ MeV + bias = 1.2 MeV



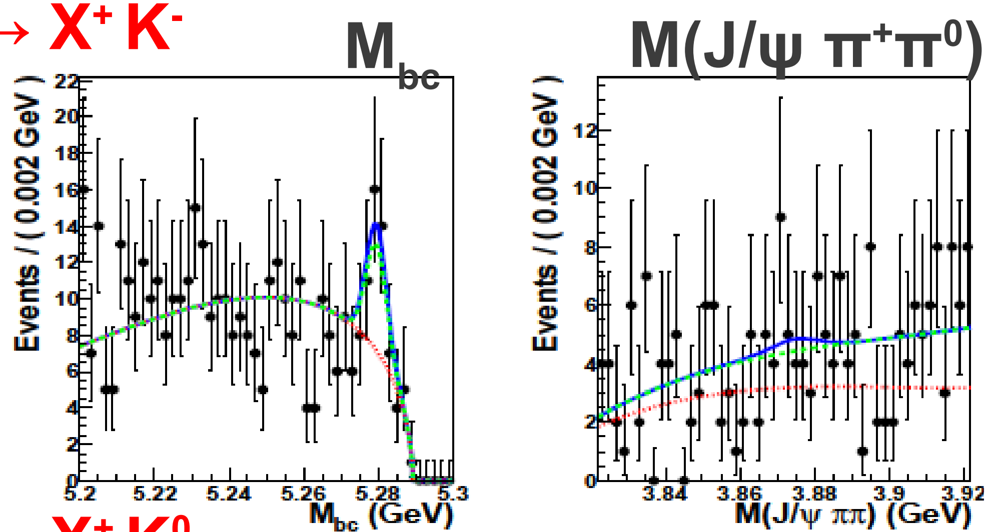


$X^+(3872) \to J/\psi\ \pi^+\pi^0$ search

Search for a charged X(3872) partner:
X(3872) is a singlet or triplet?

PRD 84, 052004 (2011)
711 1/fb

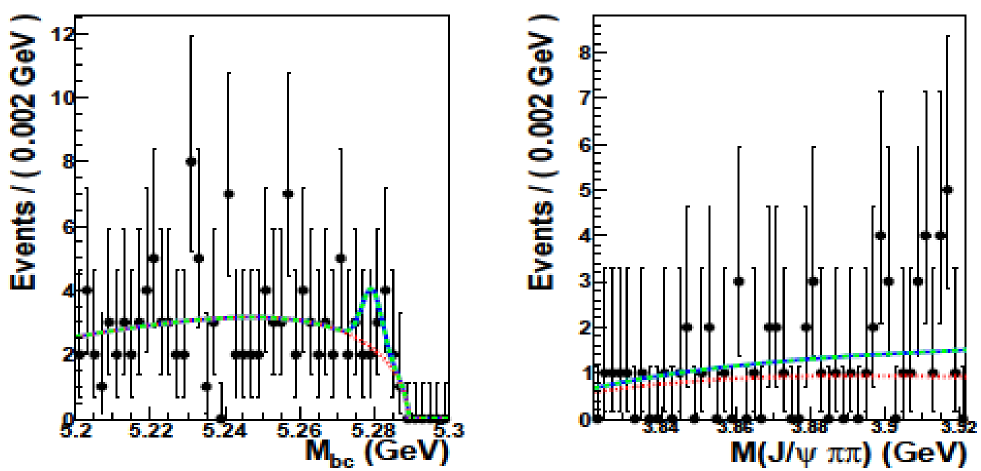
$B^0 \to X^+ K^-$



$$\mathcal{B}(\bar{B}^0 \to K^- X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 4.2 \times 10^{-6}$$

and

$B^+ \to X^+ K^0$



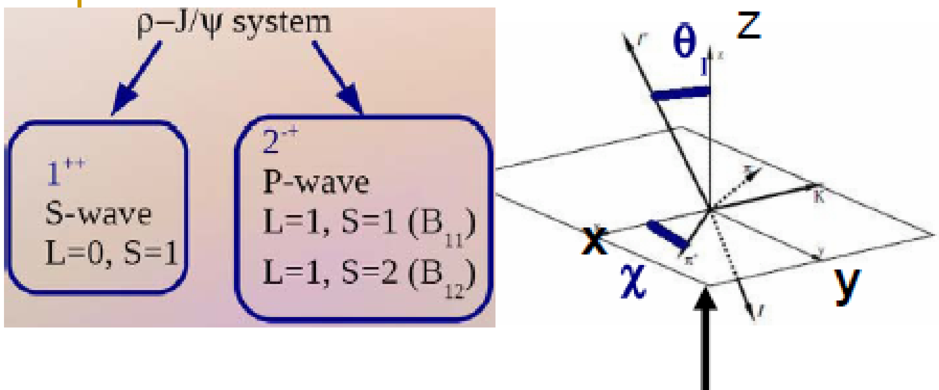
$$\mathcal{B}(B^+ \to K^0 X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 6.1 \times 10^{-6}.$$

No evidence for a charged partner: I = 0

X(3872) →J/ψ π⁺π⁻ from B (update)

Angular analysis

PRD 84, 052004 (2011)
711 1/fb

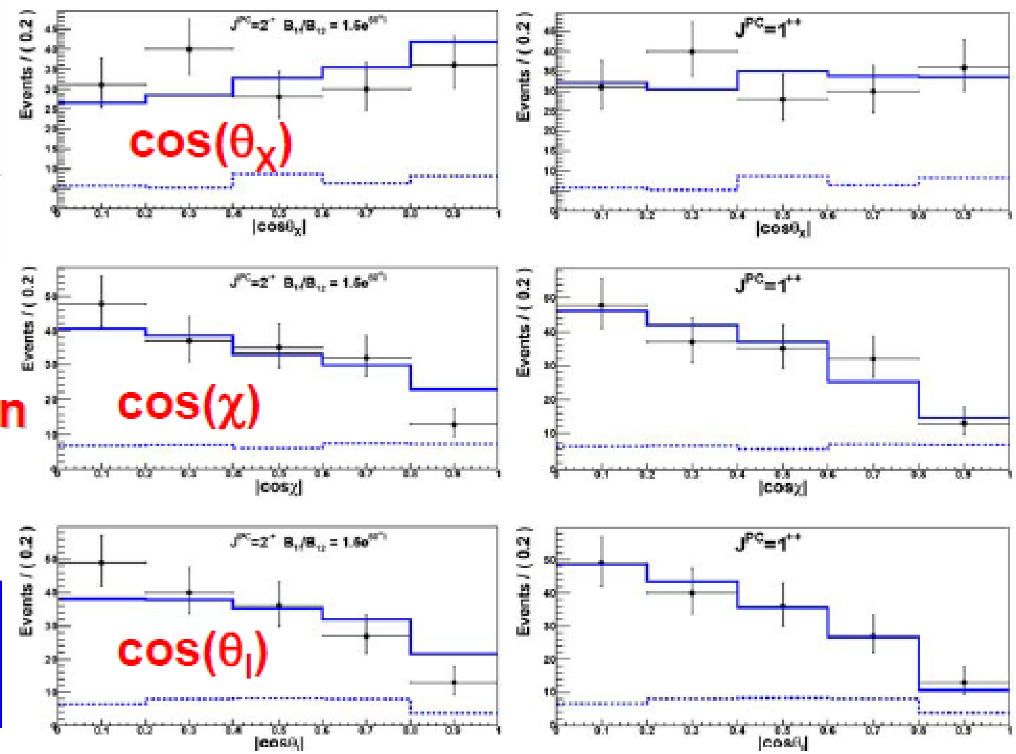


Angular correlation (θ_X, χ, θ_l)

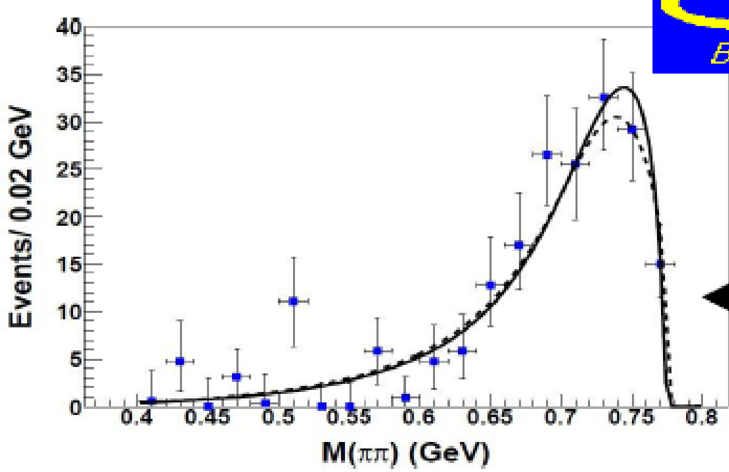
θ_X: J/ψ and direction of opposite to K in X rest frame

⇒ 1^{++} and 2^{-+} are both possible,

⇒ more statistics needed.



2^{-+} 1^{++}



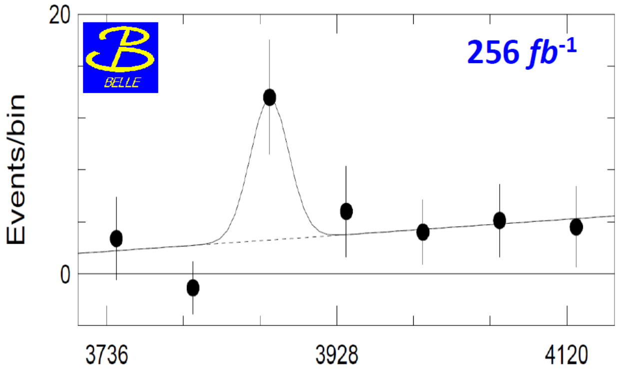
Fit to the $M(\pi^+\pi^-)$ distribution taking ρ–ω mixing into account ⇒ 1^{++} and 2^{-+} are both possible

Needs more statistics ...

X(3872): radiative decays

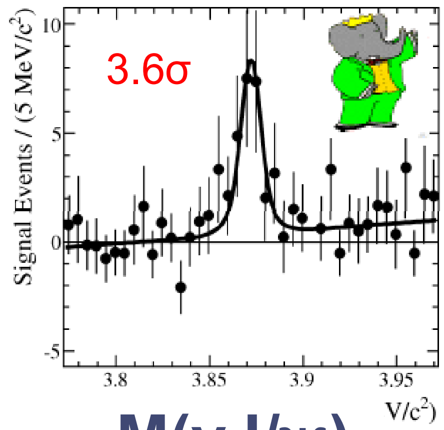
arXiv:0505037

X(3872)→γJ/ψ



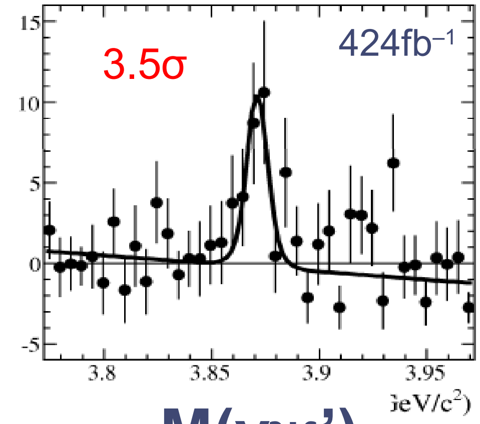
M(γJ/ψ)

X(3872)→γJ/ψ



M(γJ/ψ)

X(3872)→γψ'



M(γψ')

PRL102, 132001 (2009)

$$\frac{BR(X \to \gamma J/\psi)}{BR(X \to J/\psi\, \pi\pi)} = 0.14 \pm 0.05$$

$$\frac{BR(X \to \gamma \psi')}{BR(X \to \gamma J/\psi)} = 3.5 \pm 1.4$$

$$\frac{BR(X \to \gamma \psi')}{BR(X \to J/\psi\, \pi\pi)} = 1.1 \pm 0.4$$

$$BR(B^+ \to X(3872)K^+) \times BR(X \to \gamma J/\psi) = (1.8 \pm 0.6 \pm 0.1) \times 10^{-6}$$

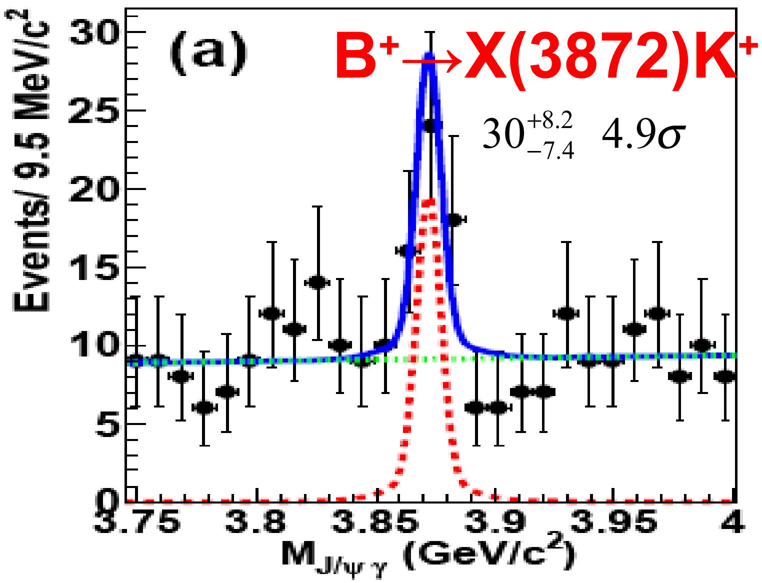
$$BR(B^+ \to X(3872)K^+) \times BR(X \to \gamma J/\psi) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$$

Important implications:

- Imply even C-parity of X(3872)
- Give more information on X(3872) nature

Rad. quarkonia decays in B mesons

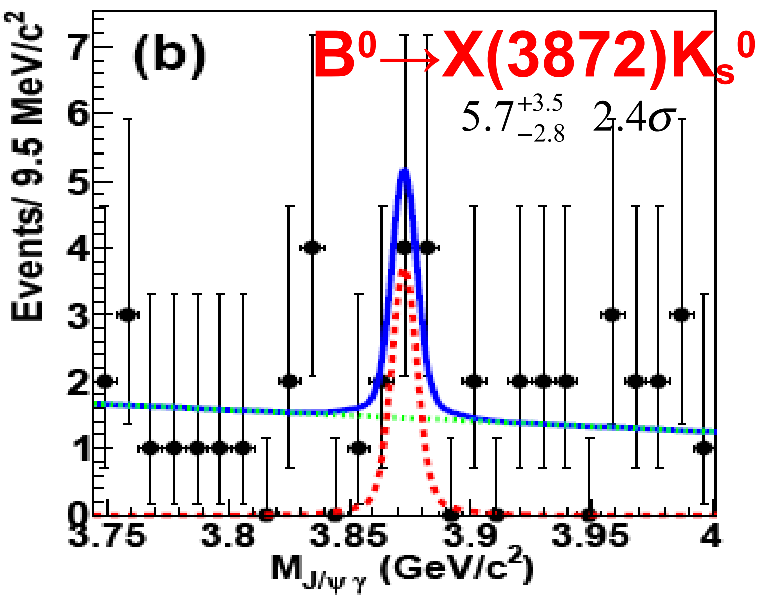
BELLE



Mode	Events	Significance
$B^+ \to X(3872)\,K^+$	$30.0^{+8.2}_{-7.4}$	$4.9\ \sigma$
$B^0 \to X(3872)\,K_S^0$	$5.7^{+3.5}_{-2.8}$	$2.4\ \sigma$

$$BR\left(B^+ \to X(3872)K^+\right) \times BR\left(X \to \gamma J/\psi\right) = \left(1.78 \pm 0.46 \pm 0.12\right) \times 10^{-6}$$

$$\frac{BR\left(X \to J/\psi\gamma\right)}{BR\left(X \to J/\psi\,\pi\pi\right)} = 0.22 \pm 0.05$$



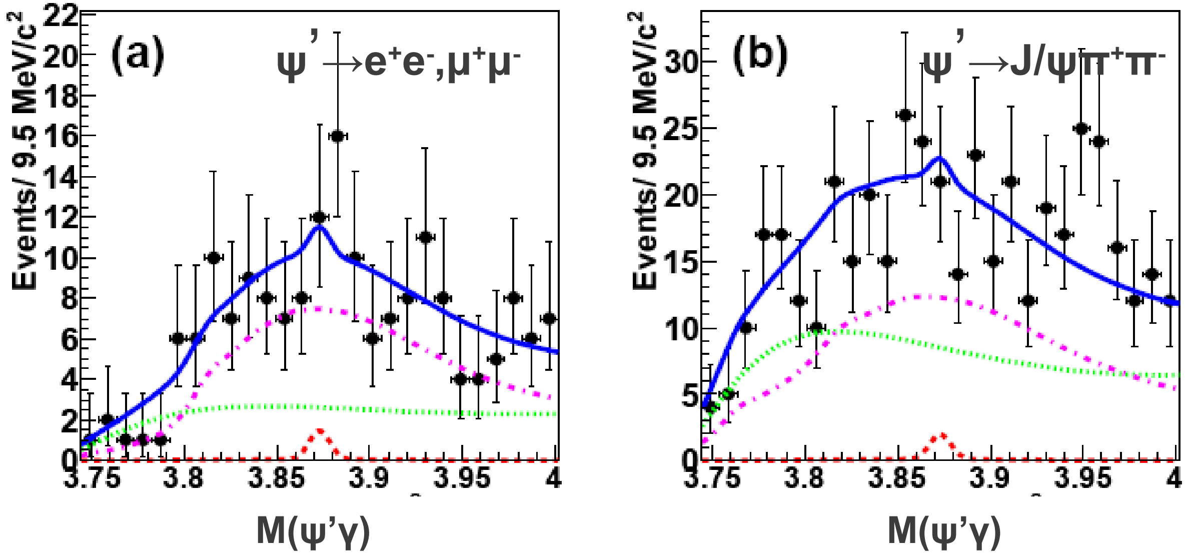
$$BR\left(B^0 \to X(3872)K^0\right) \times BR\left(X \to \gamma J/\psi\right) < 2.4 \times 10^{-6}\ @\,90\%\mathrm{CL}$$

PRL 107, 091803 (2011)
711 1/fb

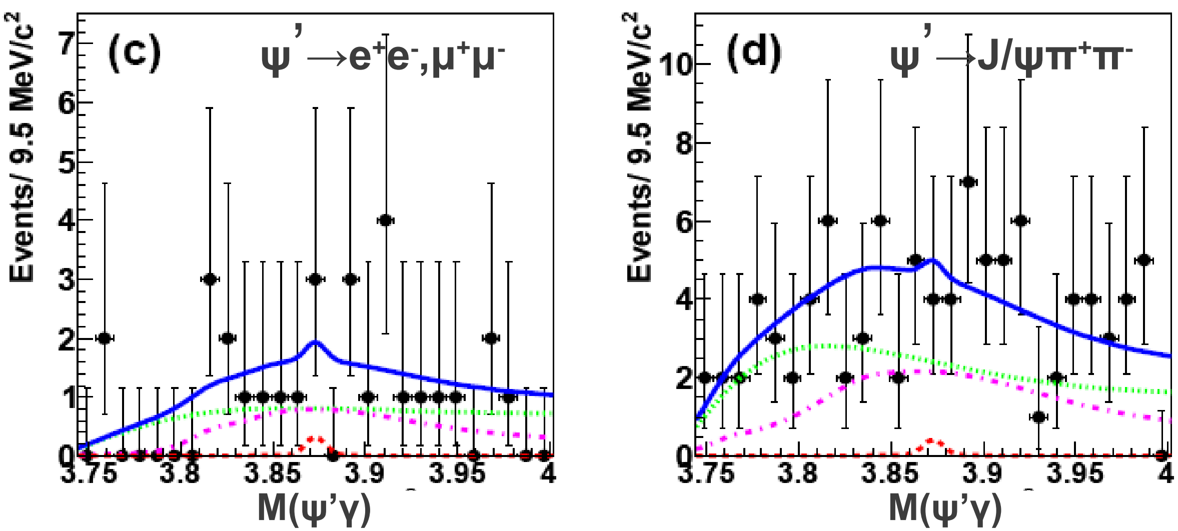
Rad. quarkonia decays in B mesons

BELLE

- $B^+ \to \psi' \gamma K^+$ $5.0^{+11.9}_{-11.0}$ 0.4σ



- $B^0 \to \psi' \gamma K_s^0$ $1.5^{+4.8}_{-3.9}$ 0.2σ



Fit components:

Signal

ψ’K*+ψ’K background

combinatorial (with non-ψ)

- **No signal observed**

$$BR\left(B^+ \to X(3872)K^+\right) \times BR\left(X \to \psi'\gamma\right) < 3.4\times10^{-6}\ @90\%\mathrm{CL}$$

$$\frac{\mathcal{B}(X \to \psi'\gamma)}{\mathcal{B}(X \to J/\psi\gamma)} < 2.0\ @\ 90\%\ \mathrm{CL}$$

BaBar 3.4 ± 1.4

$$BR\left(B^0 \to X(3872)K^0\right) \times BR\left(X \to \psi'\gamma\right) < 6.6\times10^{-6}\ @90\%\mathrm{CL}$$

PRL 107, 091803 (2011)
711 1/fb

Rad. quarkonia decays - summary

Belle: X(3872)→J/ψγ clearly observed

Most precise measurement, agrees with previous evidence

Belle: No X(3872)→ψ'γ signal observed

Disagrees with Babar's evidence

Results on $\mathcal{B}(B^+ \to K^+ X(3872)) \cdot \mathcal{B}(X(3872) \to R\gamma), 10^{-6}$

Group	Belle	BaBar
$\int \mathcal{L}dt$, fb^{-1}	711	424
$R = J/\psi$	$1.78^{+0.48}_{-0.44} \pm 0.12$	$2.8 \pm 0.8 \pm 0.1$
$R = \psi$	< 3.45	$9.5 \pm 2.7 \pm 0.6$

From the absence of $X(3872) \to \psi'\gamma$ it may not have a large $c\bar{c}$ admixture with a $D^{*0}\bar{D}^0$ molecular component

Pure molecular interpretation of X(3872) is back?

Charged charmonium-like states ($Z^{\pm}$)

$Z^{\pm}(4430)$

$Z^{\pm}(4050)$

&

$Z^{\pm}(4250)$

Observation of $Z^+(4430)$ state

PRL 100, 142001(2008)
657 $B\bar{B}$

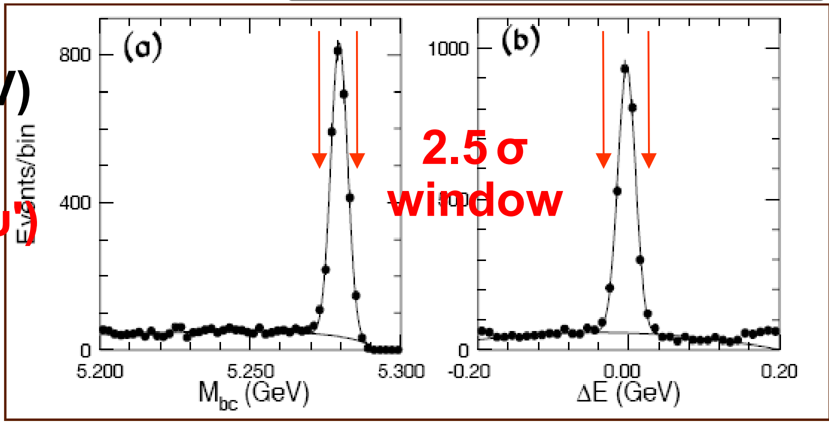
New state observed in $B \to K\pi^\pm\psi(2S)$ decays

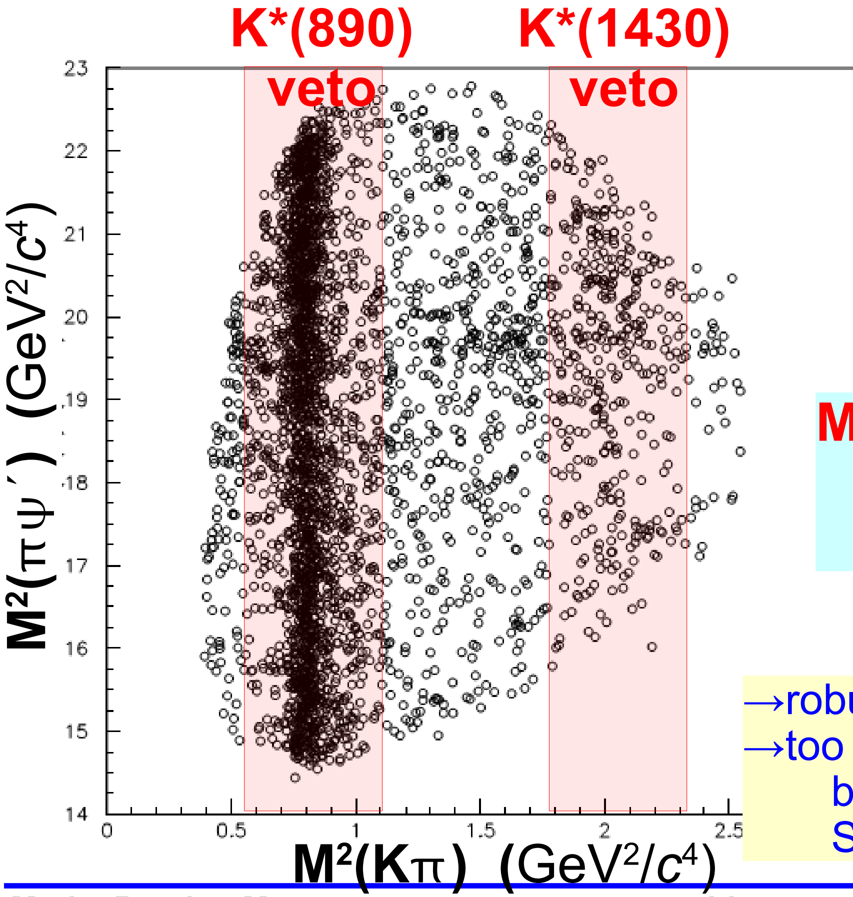
$B \to K\pi^\pm\psi'$ ($K=K^\pm$, K_S^0;
$\psi' \to \ell^+\ell^-$ or $J/\psi(\to \ell^+\ell^-)\pi^+\pi^-$ with $m_{\pi^+\pi^-} > 0.44$GeV)

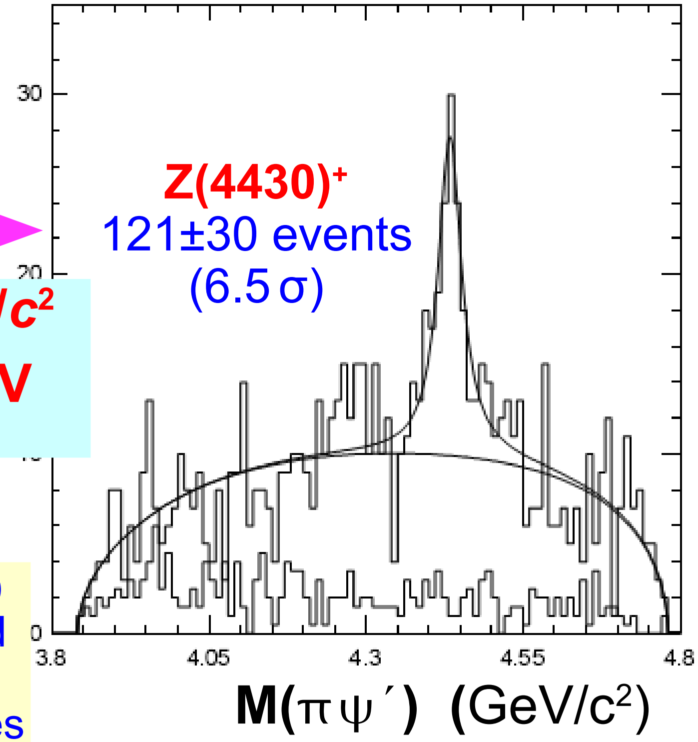
Clear signals in both ΔE and M_{bc} seen

$m_{K\pi\psi'}$ kinemat. constrained to m_B → σ~2.5MeV for $M(\pi\psi')$

M($\pi^\pm\psi'$) fit: S-wave Breit-Wigner and PS-like function







$M = (4433 \pm 4 \pm 2)$ MeV/c^2

$\Gamma = (45\ ^{+18}_{-13}\ ^{+30}_{-13})$ MeV

→robust signal (subsamples;veto)
→too narrow state to be explained by interference of known S-, P-, D-wave $K\pi$ resonances

Observation of $Z^+(4430)$ state

PRL 100, 142001(2008)
657 $B\overline{B}$

$Z(4430)^+ \to \psi(2S)\pi^+$:

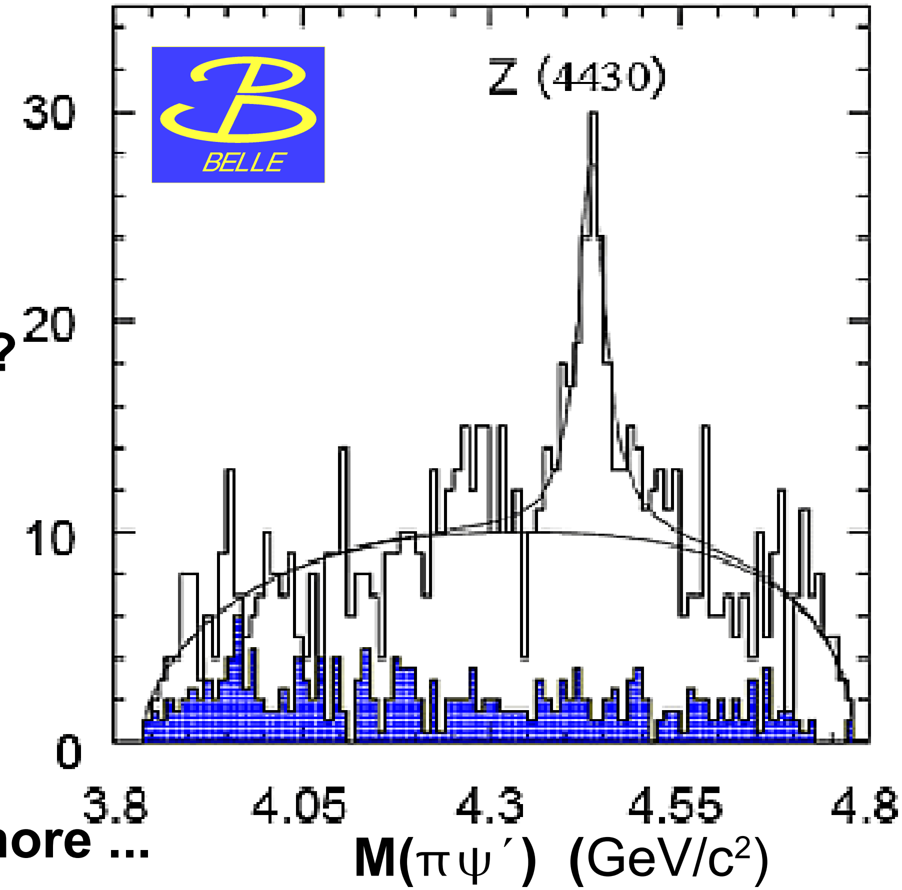
Charged state that decays like charmonium (= **charged charmonium-like state**)

$$Br(\overline{B}^0 \to K^- Z^+(4430)) \times Br(Z^+(4430) \to \pi^+ \psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$$

Not enough statistics to determine J^P

(Some) possible interpretations:

- $[cu][\bar{c}\bar{d}]$ tetraquark with $J^P=1^+$
  (Radial excitation of X(3872) family?)
  - Neutral partner in decays: $\psi'\pi^0/\eta$, $\eta_c'\rho^0/\omega$?
  - Charged 1S state in decays: $\psi\pi^\pm$, $\eta_c\rho^\pm$?
  { Maiani et al., arXiv:hep-ph/0708.3997 }
- $D^*\overline{D}_1(2420)$ threshold effect
  { Rosner, PRD 76, 114002 (2007) }
- $D^*\overline{D}_1(2420)$ molecule with $J^P=0^-, 1^-$
  Decay to $D^*D^*\pi$ expected.
  { Meng et al., hep-ph/0708.4222 } ... and more ...



➡ **First serious tetraquark candidate** ➡ **Confirmation needed**

Z⁺(4430) update: Dalitz analysis

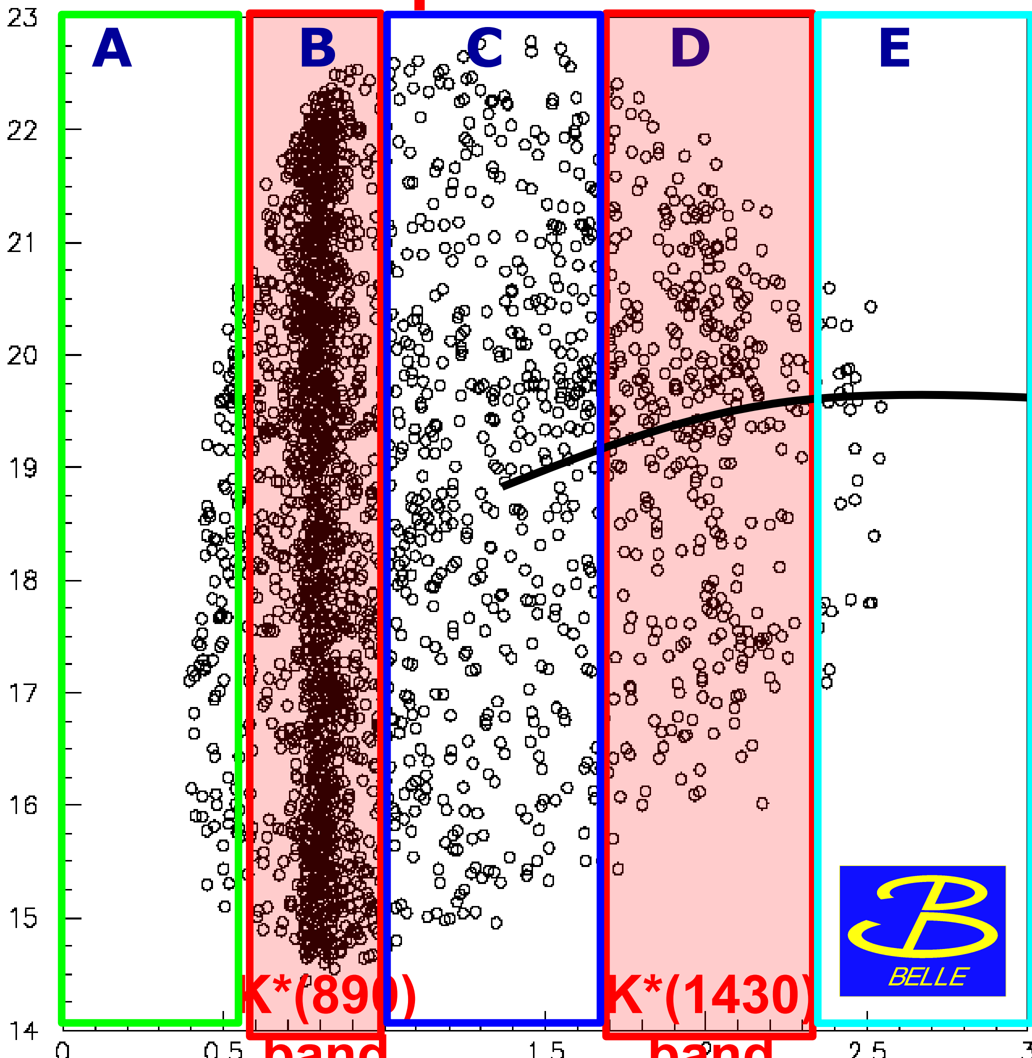
The default Dalitz fit model used:

All known K* resonances with J=0,1,2 below 1780 MeV/c²

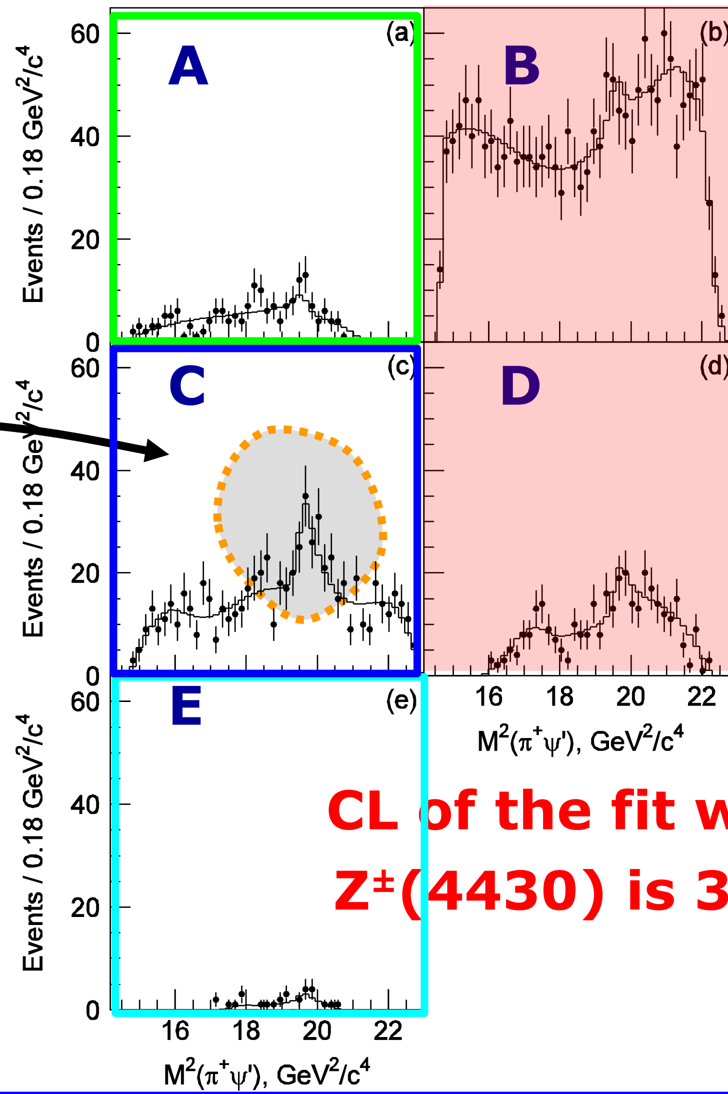
$B \rightarrow K\pi^{\pm}\psi(2S)$

PRD(RC) 80, 031104(2009)
657 $B\overline{B}$

Dalitz plot slices:



Fit with a Z resonance:

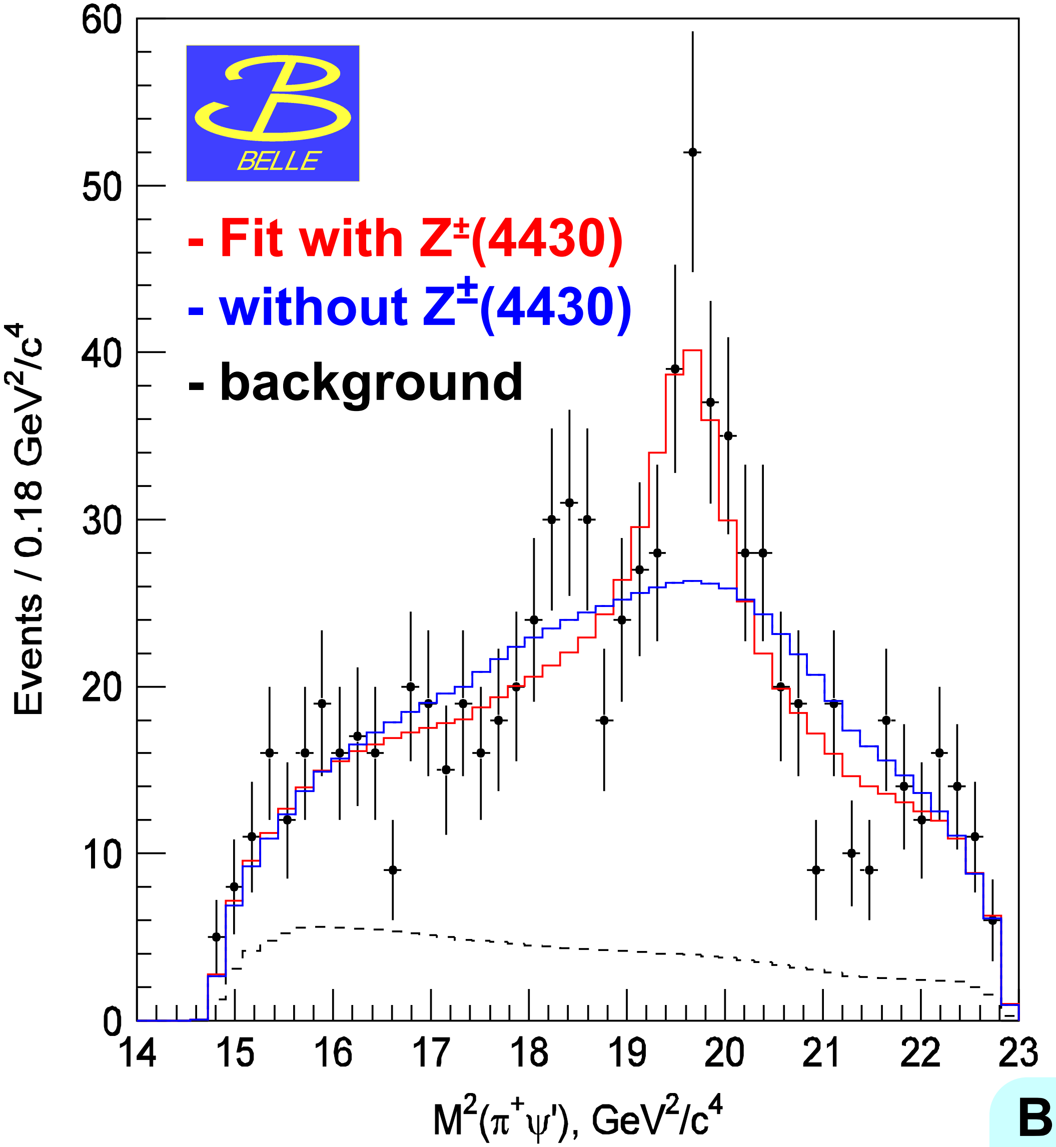


CL of the fit with $Z^{\pm}(4430)$ is 36%

$Z^+(4430)$ update: Dalitz analysis

PRD(RC) 80, 031104(2009)
657 $B\bar{B}$

Sum of A, C, E slices (= K*'s veto) :



Original result confirmed (w K* veto) & $Z^{\pm}(4430)$ parameters updated (w/o veto):

$$M = (\ 4443\ ^{+15}_{-12}\ ^{+19}_{-13}\ )\ \mathrm{MeV}/c^2$$

$$\Gamma = (\ 107\ ^{+86}_{-43}\ ^{+74}_{-56}\ )\ \mathrm{MeV}$$

Width larger than original (45MeV), but uncertainties are also large

Systematics studies/crosscheks:

- $Z^{\pm}(4430)$ signif. in different fit models **always > 5.4σ**
- Not a $B\to\psi' K_3^*(1780)$ reflection

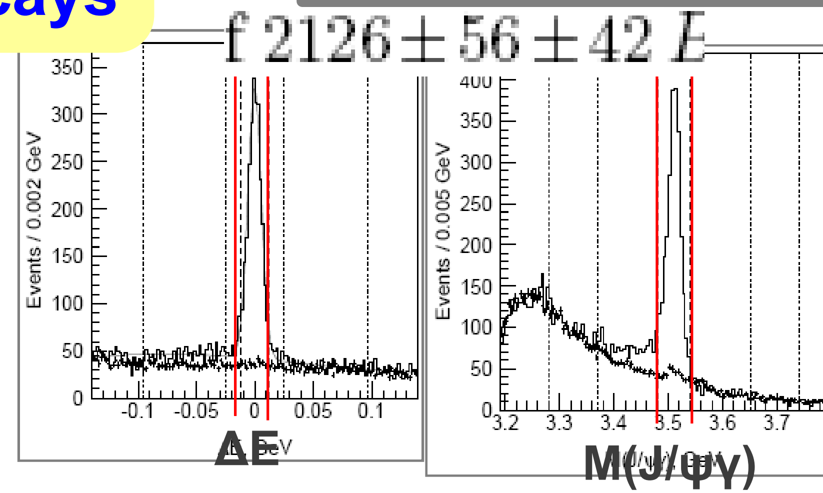
$$Br(\bar{B}^0\to K^- Z^+(4430))\times Br(Z^+(4430)\to\pi^+\psi') = (\ 3.2^{+1.8}_{-0.9}\ ^{+5.3}_{-1.6}\ )\times 10^{-5}$$

More Z^+ states: $Z^+(4050)$ & $Z^+(4250)$

PRD 78, 072004 (2008)
657 $B\bar{B}$

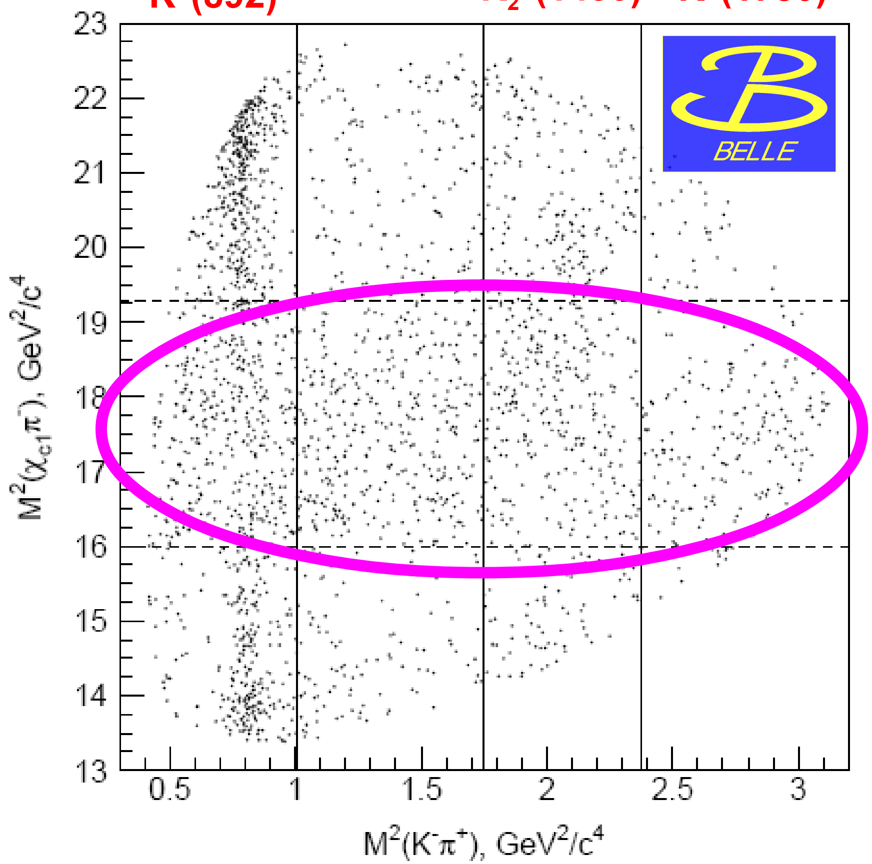
Another $B \to K^-\pi^+(c\bar{c})$ mode :

New states observed in $\bar{B}^0 \to K^-\pi^+\chi_{c1}$ decays



$B^0 \to K^-\pi^+\chi_{c1}$ ($\chi_{c1} \to J/\psi\gamma$; $J/\psi \to l^+l^-$)
Clear signals in ΔE, M_{bc} , $M(J/\psi\gamma)$

Dalitz plot analysis:



???

- **Fit model: Include all K* resonances below 1900 MeV/c^2**
- **Integrated χ_{c1}, J/ψ angular distributions (no sensitivity)**
- **Correction for Lorentz non-invariance of helicity**
- **Binned (400x400) maximum likelihood fit**
- **Fit results depicted in M_1^2 for M_2^2 bands**

More Z^+ states: $Z^+(4050)$ & $Z^+(4250)$

PRD 78, 072004 (2008)
657 BB

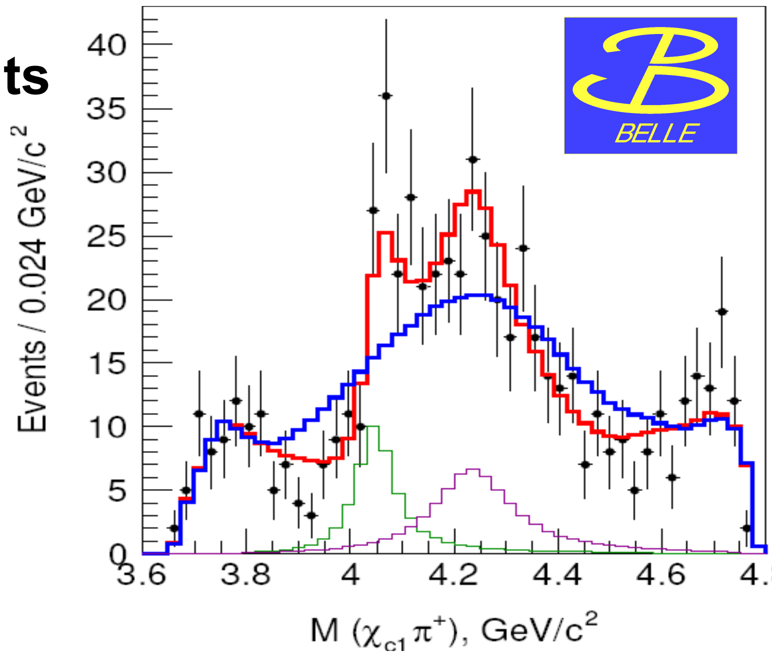
Data favour fit with 2 resonant structures:
one Z (10.7σ) ; Z_1 and Z_2 (13.2σ ; 5.7σ wrt. one Z)

Spin of $Z_{1,2}$ is not determined:
J=0 and J=1 hypotheses give comparable results

$Z_{1,2}$ parameters:
large syst. errors due to model uncertainties

	Z_1^+	Z_2^+
M/MeV	$4051 \pm 14^{+20}_{-41}$	$4248^{+44}_{-29}{}^{+180}_{-35}$
Γ/MeV	$82^{+21}_{-17}{}^{+47}_{-22}$	$177^{+54}_{-39}{}^{+316}_{-61}$
$\mathcal{B}_{\overline{B}^0} \times \mathcal{B}_{Z^+}$	$(3.1^{+1.5}_{-0.9}{}^{+3.7}_{-1.7}) \times 10^{-5}$	$(4.0^{+2.3}_{-0.9}{}^{+19.7}_{-0.5}) \times 10^{-5}$

$M(\chi_{c1}\pi^+)$ for $1<M^2(K^-\pi^+)<1.75$GeV



null hypothesis (CL=3×10^{-10})
Z_1+Z_2 model (CL = 42%)
Z_1 contribution
Z_2 contribution

BF product comparable to $Z^+(4430)$, X(3872)…

$Z^+(4050)$, $Z^+(4250)$ join $Z^+(4430)$ as charged charmonium-like exotics:

Tetraquark candidates

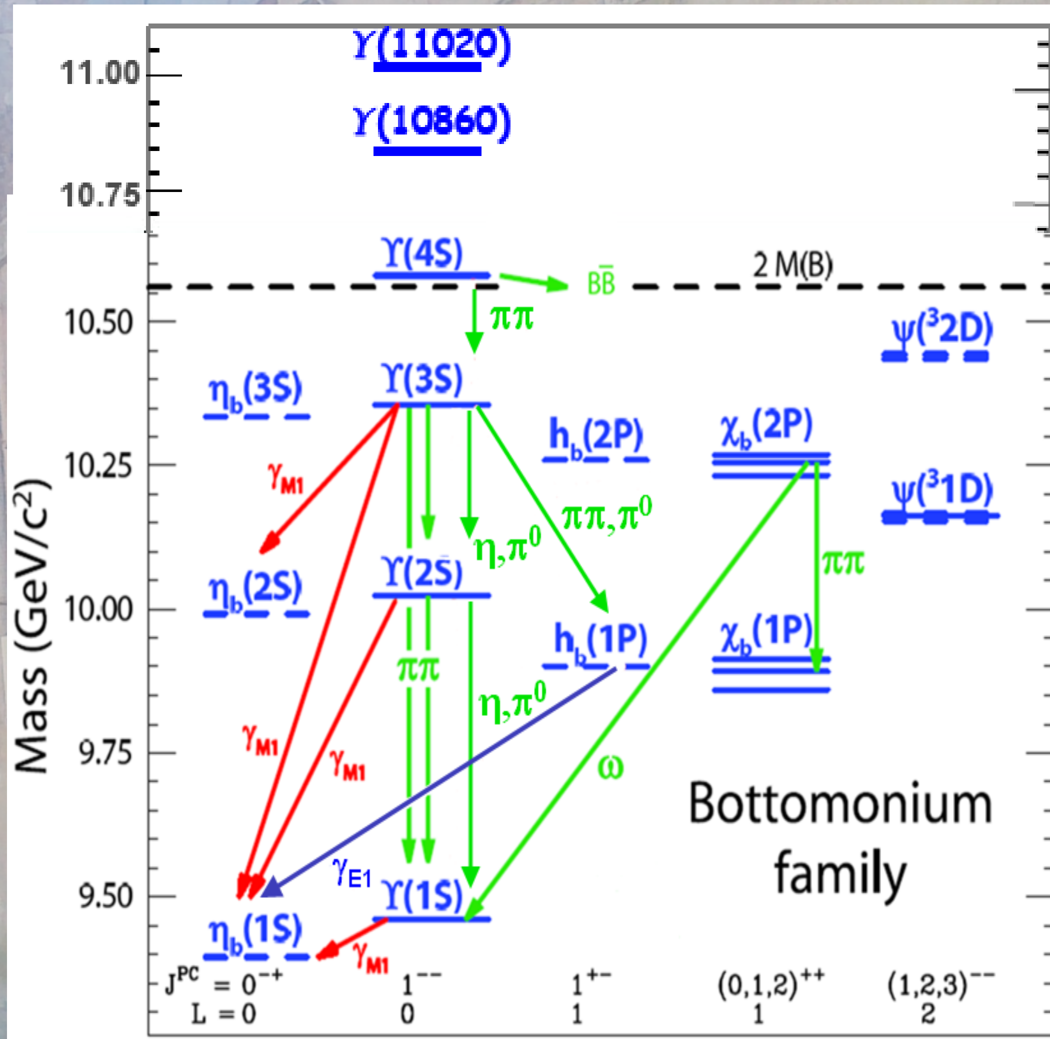
→ Experimental confirmation is still needed for all of them

Z^+ states: Summary

- No news on $Z(4430)$ seen by Belle in $B \to K\pi^+\psi'$ with 605 fb^{-1}, S.-K.Choi et al., PRL 100, 142001 (2008)
- Not seen by BaBar with 413 fb^{-1}, also in $J/\psi\pi^+$ decay, B.Aubert et al., PRD 80, 031104 (2009)
- Confirmed by Belle in Dalitz plot reanalysis of the same data sample, R.Mizuk et al., PRD 80, 031104 (2010), $M = 4443^{+15+19}_{-12-13}$ MeV, $\Gamma = 107^{+86+74}_{-43-56}$ MeV
- No statistical inconsistency between Belle and BaBar
- With the same 605 fb^{-1} Belle observes in B^0 decays two $\chi_{c1}\pi^-$ states – $Z(4050)$ and $Z(4350)$, R.Mizuk et al., PRD 80, 031104 (2010)
- Non-zero charge $\Rightarrow$ exotic, non-$q\bar{q}$ nature

Other experiments will have to resolve the issue

Bottomonium(-like) states



Puzzles of $\Upsilon(5S)$ decays

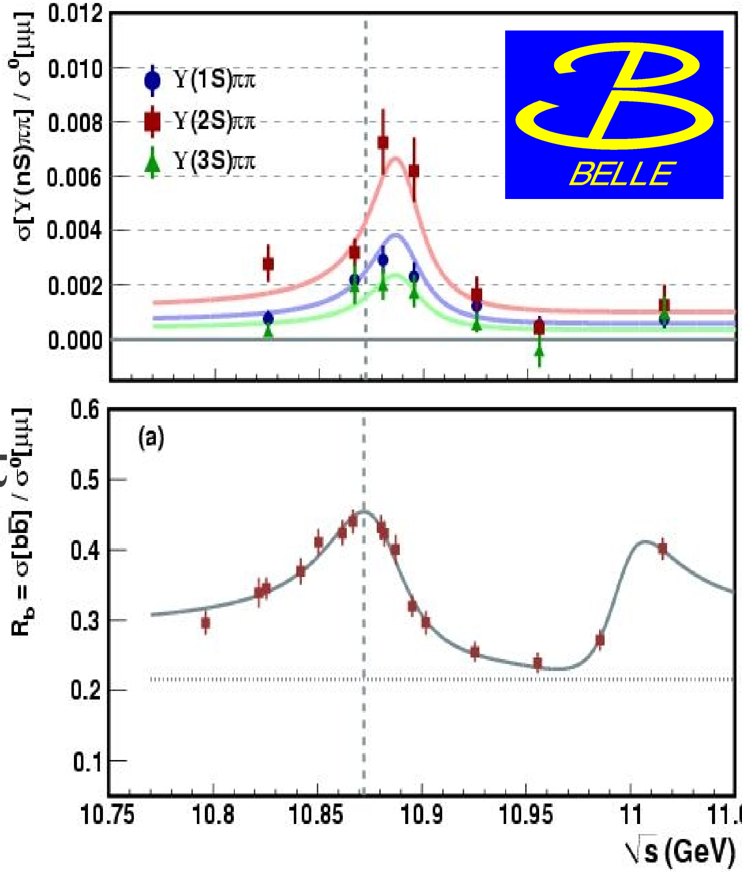
Anomalous production of $\Upsilon(nS)\pi^+\pi^-$ with 21.7 fb^{-1}

PRL100,112001(2008)

	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

10^2

PRD82,091106R(2010)



(1) Rescattering $\Upsilon(5S) \to BB\pi\pi \to \Upsilon(nS)\pi\pi$

Simonov JETP Lett 87,147(2008)

(2) Exotic resonance Y_b near $\Upsilon(5S)$

analogue of Y(4260) resonance

with anomalous $\Gamma(J/\psi\, \pi^+\pi^-)$

Dedicated energy scan $\Rightarrow$

shapes of R_b and $\sigma(\Upsilon\pi\pi)$ different (2σ)

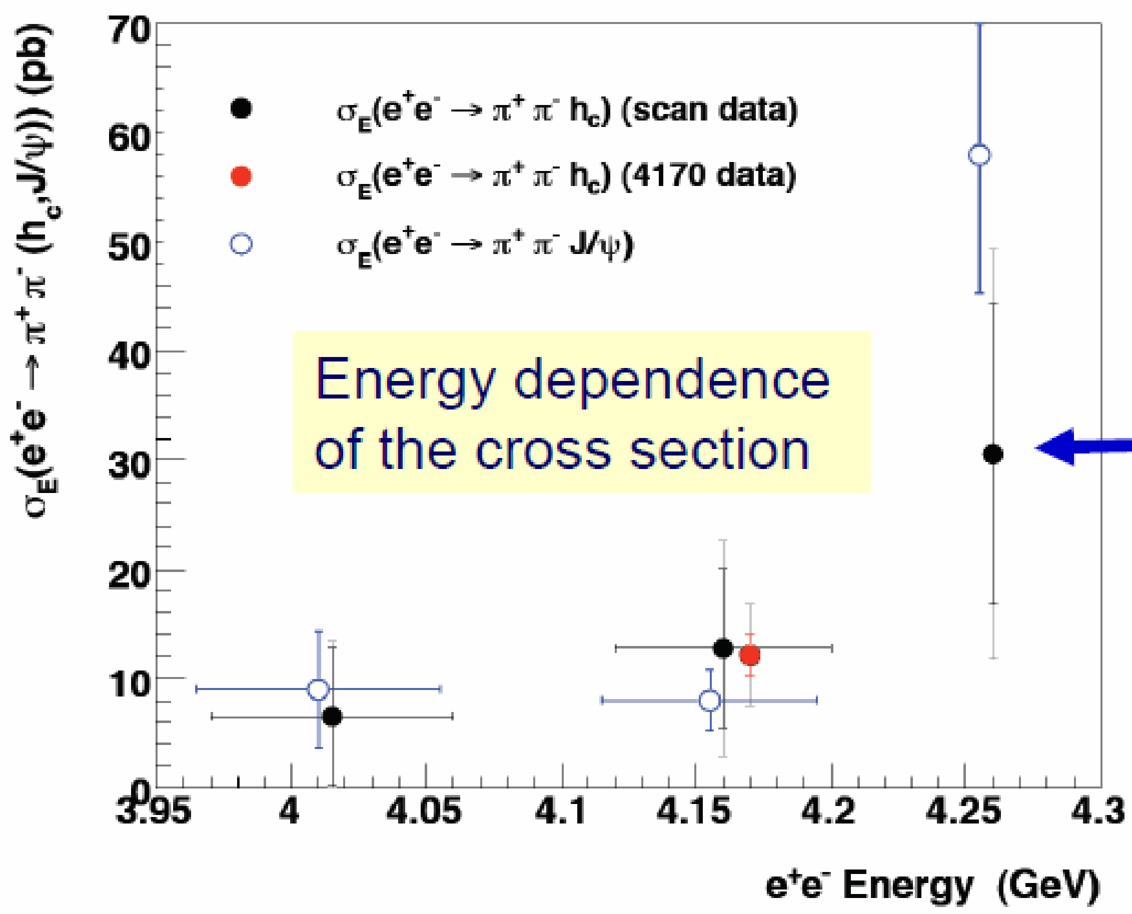
$\Upsilon(5S)$ is very interesting and not yet understood

A. Bondar FPCP2011

Finally Belle recorded 121.4fb^{-1} data set at $\Upsilon(5S)$

$b\bar{b}$ system: Motivation for h_b search

Observation of $e^+e^- \to \pi^+\pi^- h_c$ by CLEO-c arXiv:1104.2025



FPCP 2011, J.Rosner

Enhancement of $\sigma(h_c\, \pi^+\pi^-)$ @ Y(4260)

⇓

$\sigma(h_b\, \pi^+\pi^-)$ is enhanced @ Y_b?

⇒ Belle search for h_b in $\Upsilon(5S)$ data

h_b (nP) states

$(b\bar{b})$: S=0 L=1 $J^{PC}=1^{+-}$

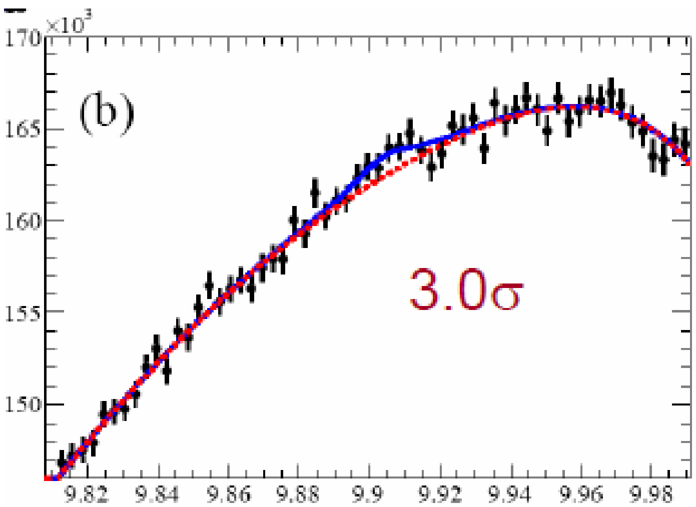
Expected mass (CoG of χ_{bJ})

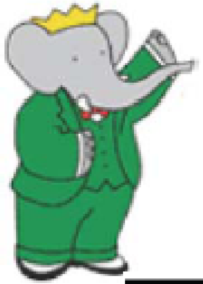
$\approx (M\chi_{b0} + 3\, M\chi_{b1} + 5\, M\chi_{b2}) / 9$

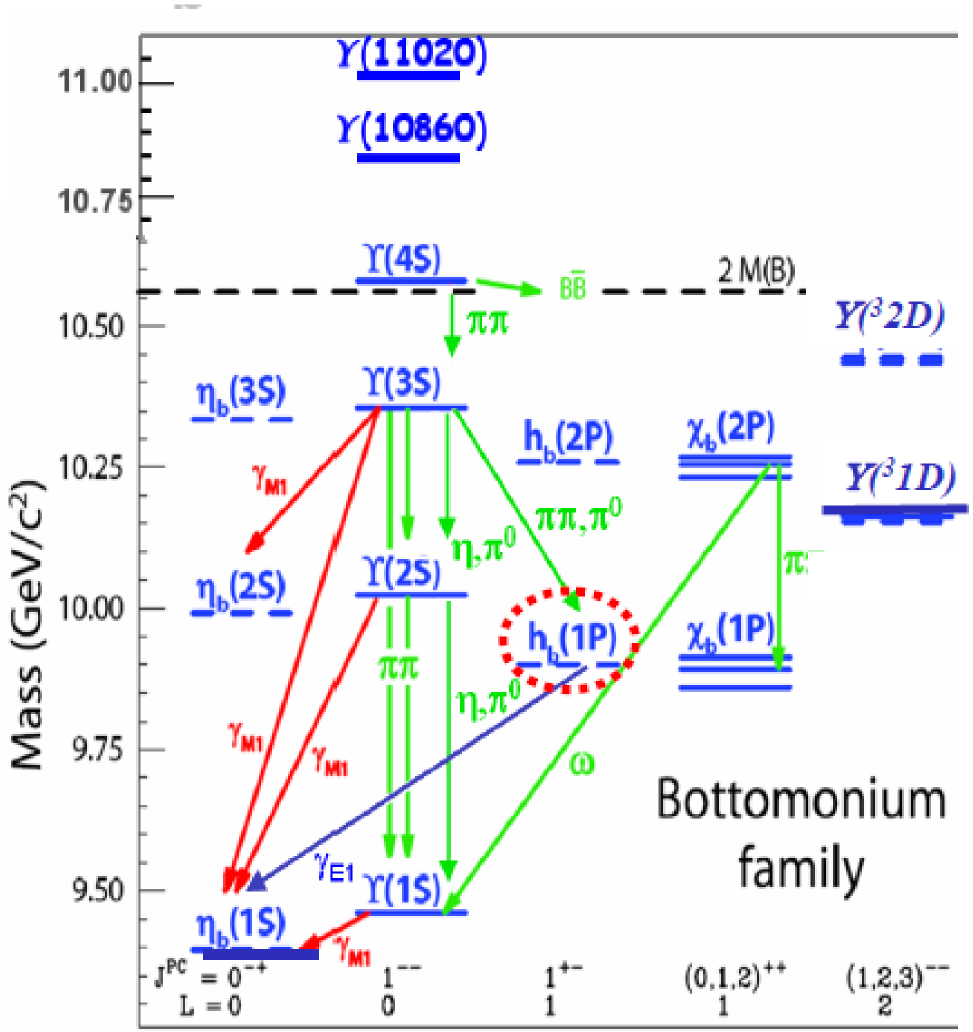
$\Delta M_{HF} \Rightarrow$ test of hyperfine interaction

Evidence from BaBar arXiv:1102.4565

$\Upsilon(3S) \to \pi^0 h_b(1P) \to \pi^0 \gamma\, \eta_b(1S)$







$m(h_b)=9902 \pm 4_{(stat)} \pm 1_{(syst)}$ MeV/c^2

$B(\Upsilon(3S)\to\pi^0 h_b) \times B(h_b\to\gamma\eta_b)=(3.7\pm1.1\pm0.7) \times 10^{-4}$

Observation of $\Upsilon(5S) \to h_b(nP)\,\pi\pi$

Method : missing mass technique

Search for signal $\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$

$P_{\Upsilon(5S)}$ is given by c.m. energy and boost

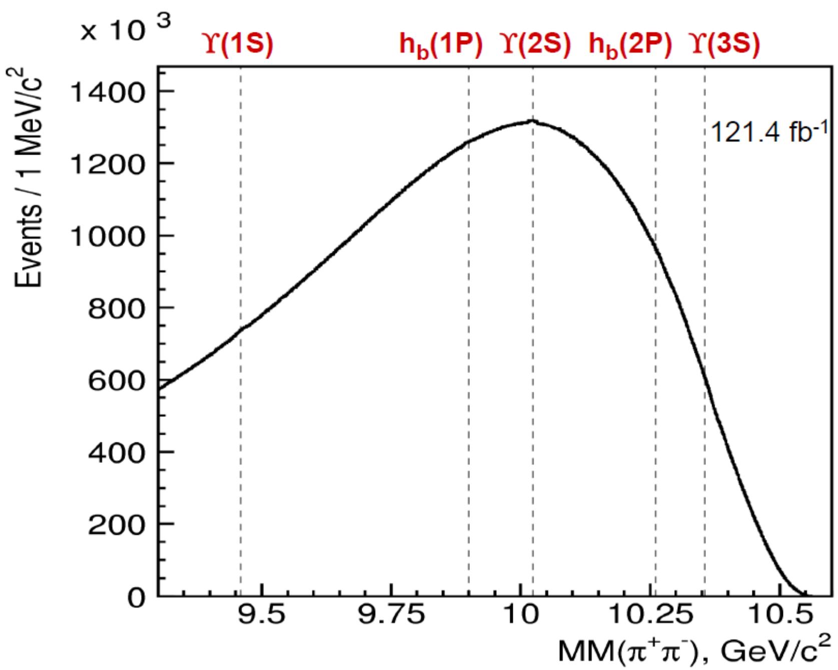
$P_{\pi^+\pi^-}$ is measured

$$M_{hb(nP)} = \sqrt{(P_{\Upsilon(5S)} - P_{\pi^+\pi^-})^2} \equiv MM(\pi^+\pi^-)$$

$\Rightarrow$ **Search for $h_b(nP)$ peaks in $MM(\pi^+\pi^-)$ spectrum**

$\Rightarrow$ **reconstruct $\mu^+\mu^-$ in addition to** $\pi^+\pi^-$ to suppress background

Raw $MM(\pi^+\pi^-)$ spectrum from $\Upsilon(5S)$

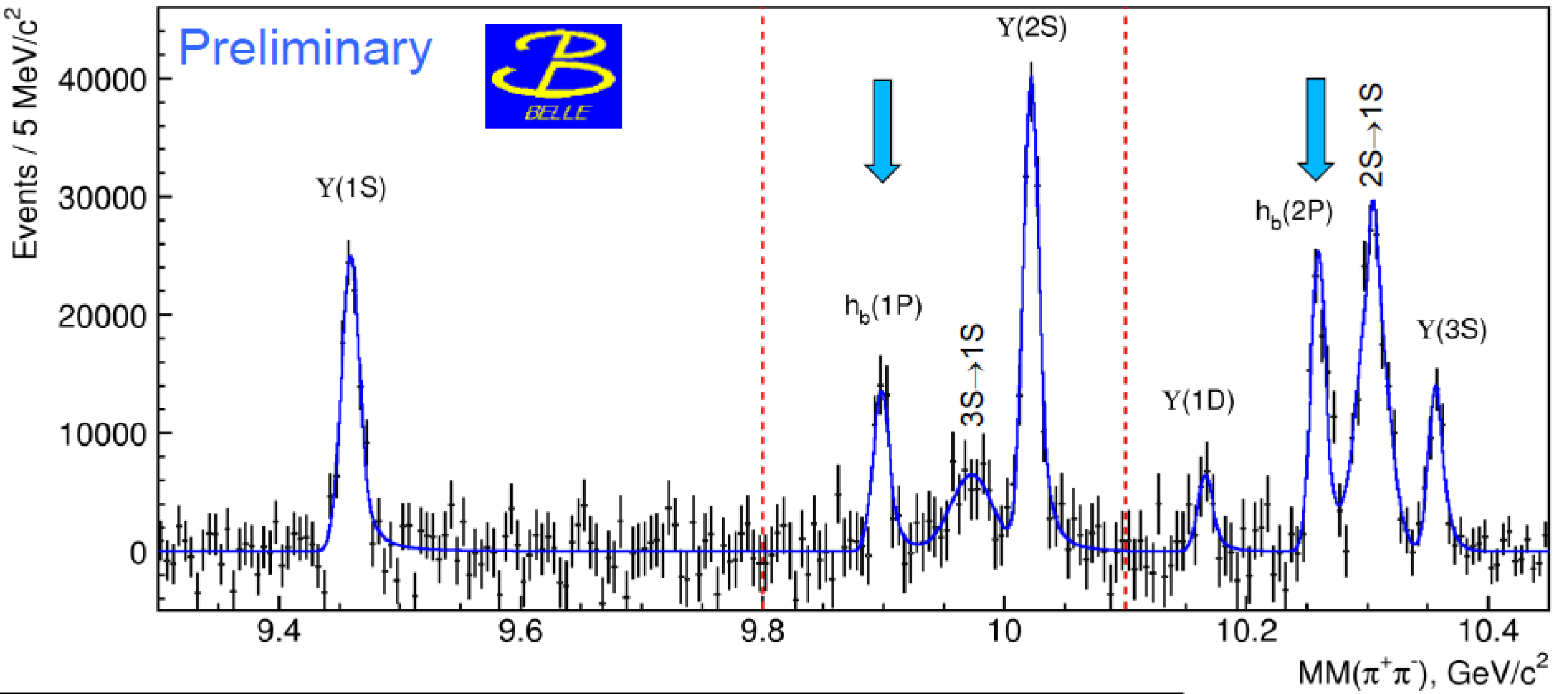


Observation of $\Upsilon(5S) \to h_b(nP)\,\pi\pi$

BELLE

Background Subtracted Results

121.4 fb^{-1}



	Yield, 10^3	Mass, MeV/c^2	Signif.
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.42 \pm 0.53 \pm 1.02$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.25 \pm 1.06^{+1.03}_{-1.07}$	$6.2\,\sigma$
$3S \to 1S$	55 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.4 \pm 8.7 \pm 6.8$	$10022.25 \pm 0.41 \pm 1.01$	$16.6\,\sigma$
$\Upsilon(1D)$	22.1 ± 7.8	10166.2 ± 2.4	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.76 \pm 0.64^{+1.43}_{-1.03}$	$12.4\,\sigma$
$2S \to 1S$	$151.6 \pm 9.7^{+9.0}_{-20.}$	$10304.57 \pm 0.61 \pm 1.03$	$15.7\,\sigma$
$\Upsilon(3S)$	$44.9 \pm 5.1 \pm 5.1$	$10356.56 \pm 0.87 \pm 1.06$	$8.5\,\sigma$

arXiv:1103.3419

Significance w/ systematics

$h_b(1P)$ 5.5σ
$h_b(2P)$ 11.2σ

Observation of $\Upsilon(5S) \to h_b(nP)\,\pi\pi$

BELLE

Mass measurements

Deviations from CoG of χ_{bJ} masses

$h_b(1P)$	1.62 ± 1.52 MeV/c²	consistent with zero, as expected
$h_b(2P)$	$0.48\,^{+1.57}_{-1.22}$ MeV/c²	

Ratio of production rates

$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-]} = \begin{cases} 0.407 \pm 0.079^{+0.043}_{-0.076} & \text{for } h_b(1P) \\ 0.78 \pm 0.09^{+0.22}_{-0.10} & \text{for } h_b(2P) \end{cases}$$

$S(h_b) = 0 \Rightarrow$ spin-flip

no spin-flip

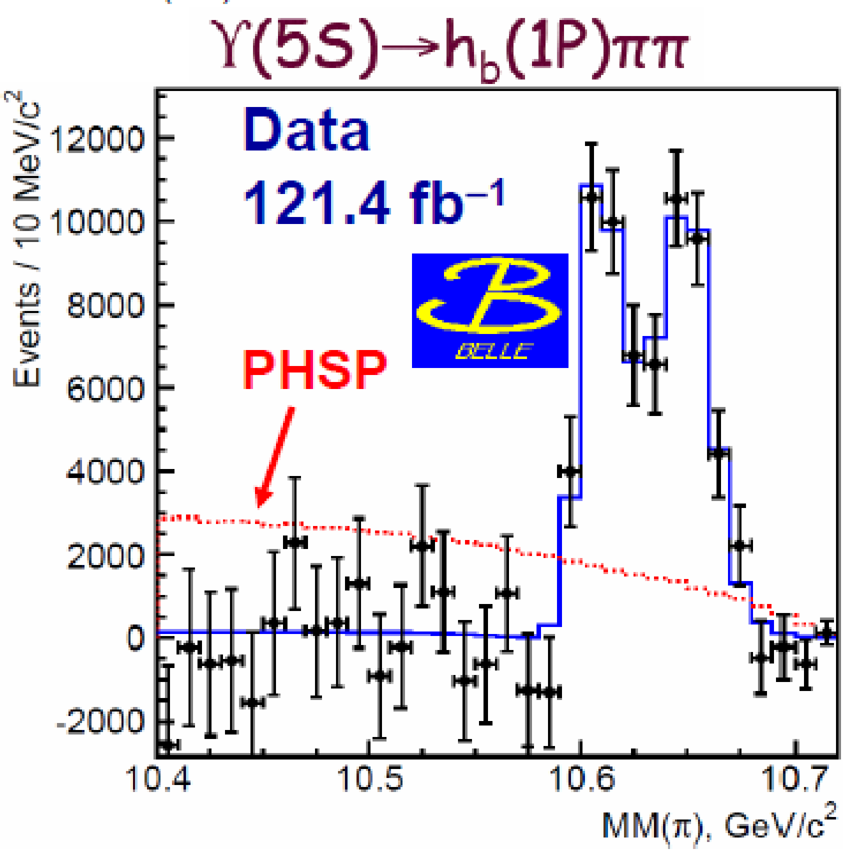
Process with spin-flip of heavy quark is not suppressed

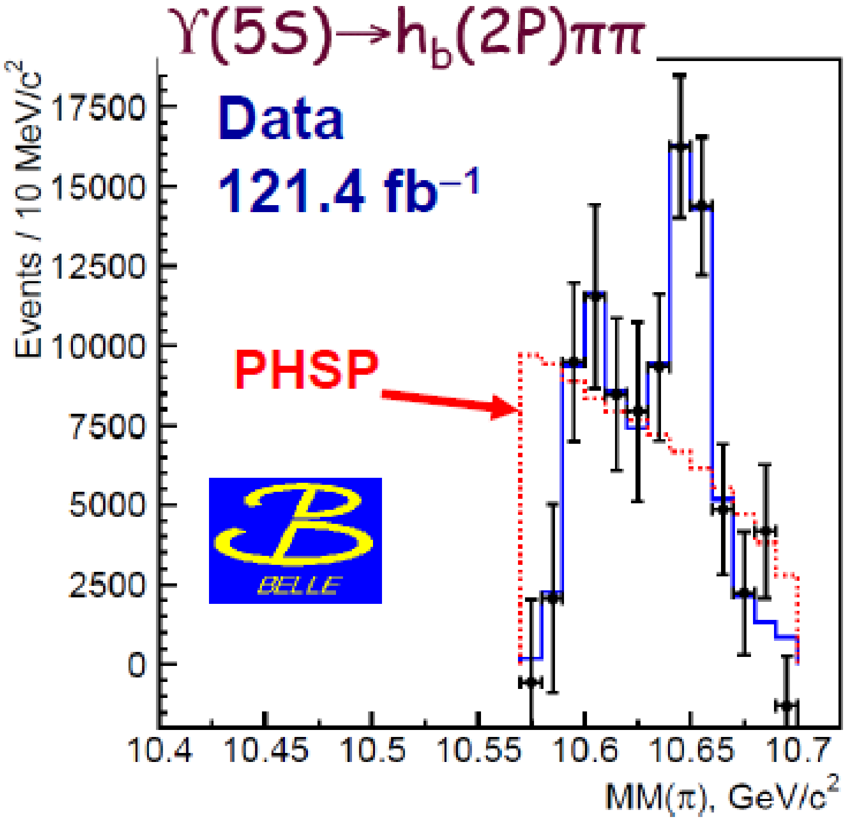
No h_b signal at $\Upsilon(4S)$

$\Rightarrow$ Mechanism of $\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$ decay is exotic!
This motivates us to study resonant substructure of this process

Resonant substructure of Υ(5S) → h_b (nP)ππ

$P(h_b) = P_{\Upsilon(5S)} - P(\pi^+\pi^-) \Rightarrow$ **$M(h_b\pi^+) = MM(\pi^-) \Rightarrow$** ***measure $\Upsilon(5S) \to h_b\pi\pi$ yield in bins of $MM(\pi)$***





Fit function: $|BW(s, M_1, \Gamma_1) + ae^{i\phi}BW(s, M_2, \Gamma_2) + be^{i\psi}|^2 \frac{qp}{\sqrt{s}}$

arXiv: 1105.4583

$Z_b(10610)$ and $Z_b(10650)$

Fit results

[preliminary]

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M(Z_b(10610))$, MeV/c^2	$10609 \pm 3 \pm 2$	$10616 \pm 2^{+3}_{-4}$	$10608 \pm 2^{+5}_{-2}$	$10605.1 \pm 2.2^{+3.0}_{-1.0}$	$10596 \pm 7^{+5}_{-2}$
$\Gamma(Z_b(10610))$, MeV	$22.9 \pm 7.3 \pm 2$	$21.1 \pm 4^{+2}_{-3}$	$12.2 \pm 1.7 \pm 4$	$11.4^{+4.5}_{-3.9}{}^{+2.1}_{-1.2}$	$16^{+16}_{-10}{}^{+13}_{-4}$
$M(Z_b(10650))$, MeV/c^2	$10660 \pm 6 \pm 2$	$10653 \pm 2 \pm 2$	$10652 \pm 2 \pm 2$	$10654.5 \pm 2.5^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$
$\Gamma(Z_b(10650))$, MeV	$12 \pm 10 \pm 3$	$16.4 \pm 3.6^{+4}_{-6}$	$10.9 \pm 2.6^{+4}_{-2}$	$20.9^{+5.4}_{-4.7}{}^{+2.1}_{-5.7}$	$12^{+11}_{-9}{}^{+8}_{-2}$
Rel. amplitude	$0.59 \pm 0.19^{+0.09}_{-0.03}$	$0.91 \pm 0.11^{+0.04}_{-0.03}$	$0.73 \pm 0.10^{+0.15}_{-0.05}$	$1.8^{+1.0}_{-0.7}{}^{+0.1}_{-0.5}$	$1.3^{+3.1}_{-1.1}{}^{+0.4}_{-0.7}$
Rel. phase, degrees	$53 \pm 61^{+5}_{-50}$	$-20 \pm 18^{+14}_{-9}$	$6 \pm 24^{+23}_{-59}$	$188^{+44}_{-58}{}^{+4}_{-9}$	$255^{+56}_{-72}{}^{+12}_{-183}$

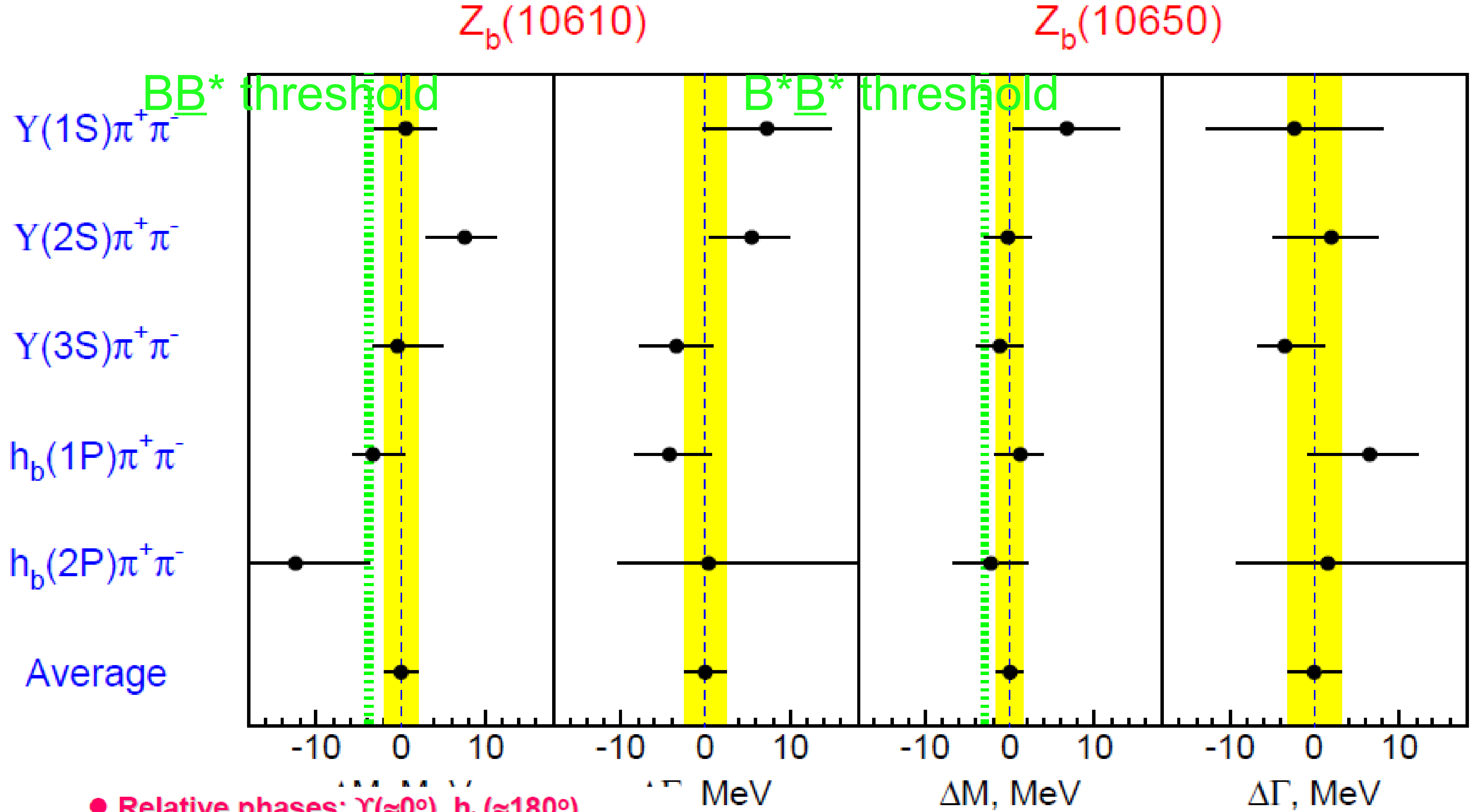
Masses, widths, relative amplitudes are consistent

Relative phases are swapped for Υ and h_b final states ⇐ expectation from a 'molecular' model

$Z_b(10610)$
M=10608.4±2.0 MeV
Γ=15.6±2.5 MeV

$Z_b(10650)$
M=10653.2±1.5 MeV
Γ=14.4 ± 3.2 MeV

$Z_b(10610)$ and $Z_b(10650)$: Summary



- Relative phases: $\Upsilon(\approx 0^o)$, $h_b(\approx 180^o)$
- Mass just above B*B and B*B* thresholds
- Angular analysis favors $J^P=1^+$
  Indicates Z_b's could be molecules

Summary and conclusions

Charmonium(-like) states :

- Following the exciting X(3872) discovery …

  … more information on its properties from radiative decays

  … New exotic state observed by Belle in $B \to \psi(2S)\pi^{\pm}K$ decays:

  $Z(4430)^{+}$ (charged charmonium-like state)

  ... also Z_1^+ and Z_2^+ in $B^0 \to K^- \pi^+ \chi_{c1}$ decays

- New charmonium[-like] spectroscopy established at 4-5GeV?

  Good candidates for molecular states; multiquarks; hybrids; ...

  X(3872); $Z(4430)^{+}$, Z_1^+ and Z_2^+; Y's; ...

- Same type of XYZ spectroscopy seems to be going on in the b-quark sector?

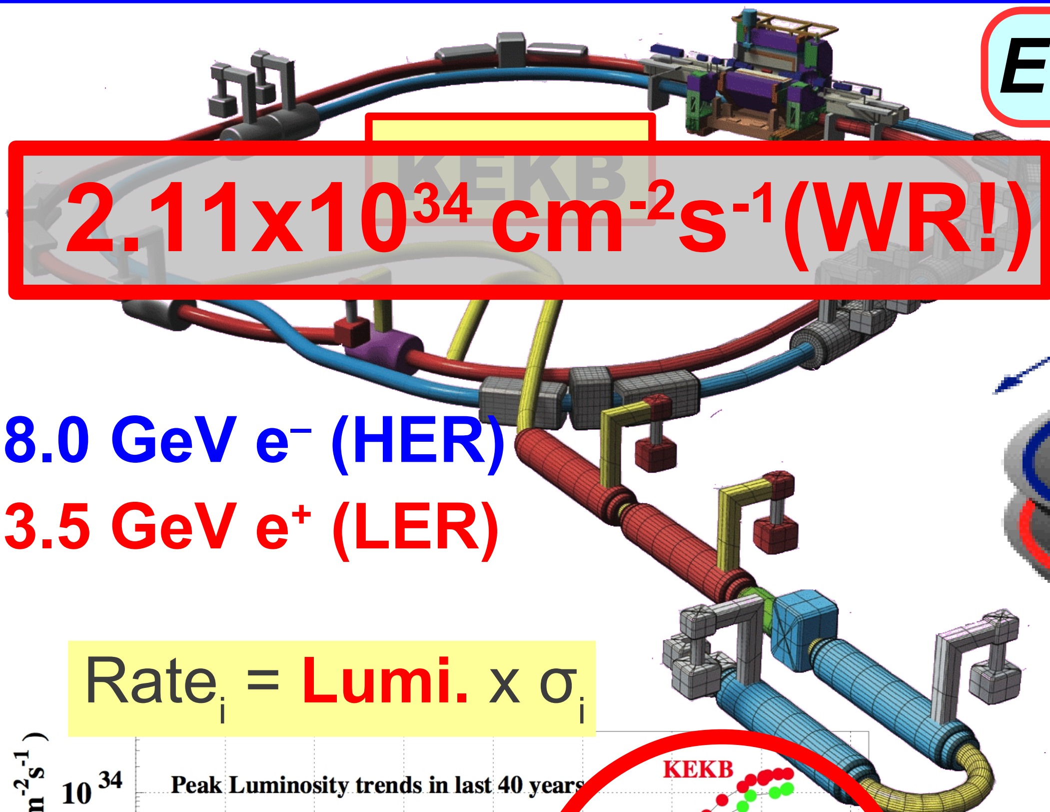
- As the data taking/processing finished last year, final results are now soming from Belle …

- B-factories finished - for some final answers charm-fact., LHC, or we will have to wait for new experiments

Supplementary material

Asymmetric-energy e^+e^- colliders

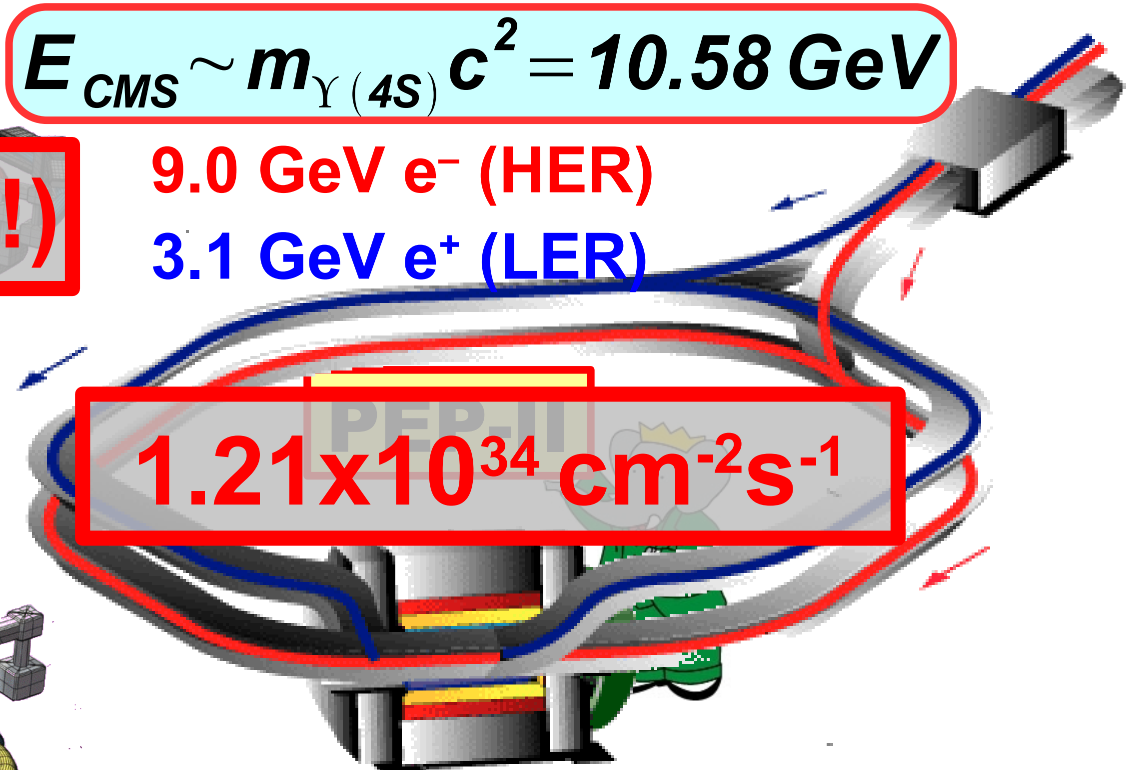
$E_{CMS} \sim m_{\Upsilon(4S)} c^2 = 10.58\ GeV$



$2.11 \times 10^{34}\ cm^{-2}s^{-1}$ (WR!)

8.0 GeV e^- (HER)

3.5 GeV e^+ (LER)

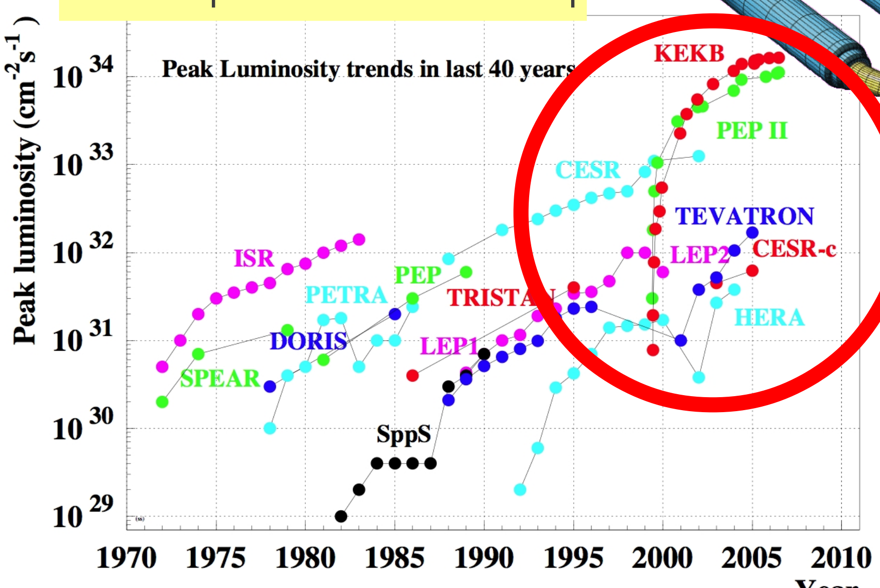


$1.21 \times 10^{34}\ cm^{-2}s^{-1}$

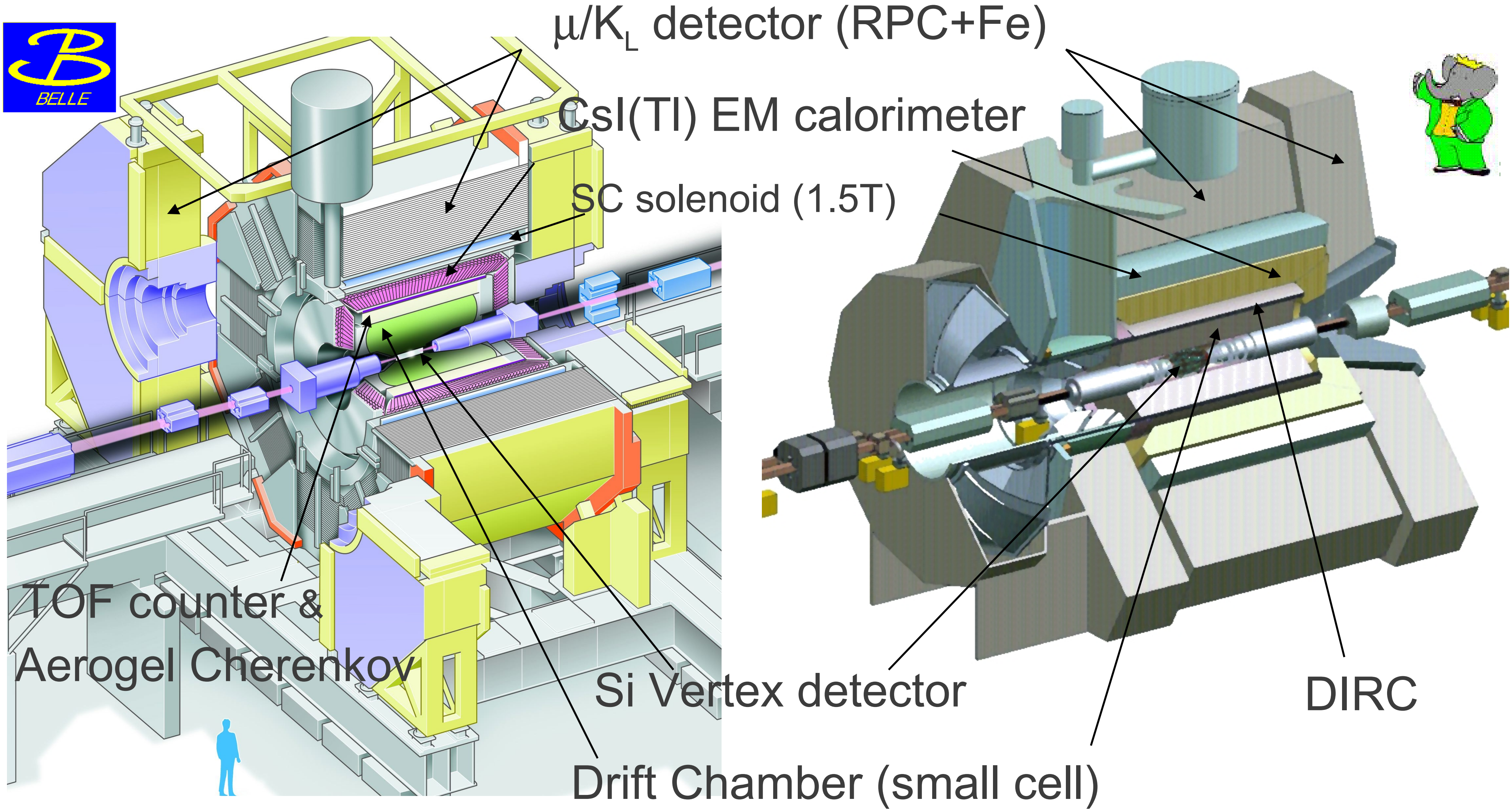
9.0 GeV e^- (HER)

3.1 GeV e^+ (LER)

$Rate_i$ = **Lumi.** x σ_i

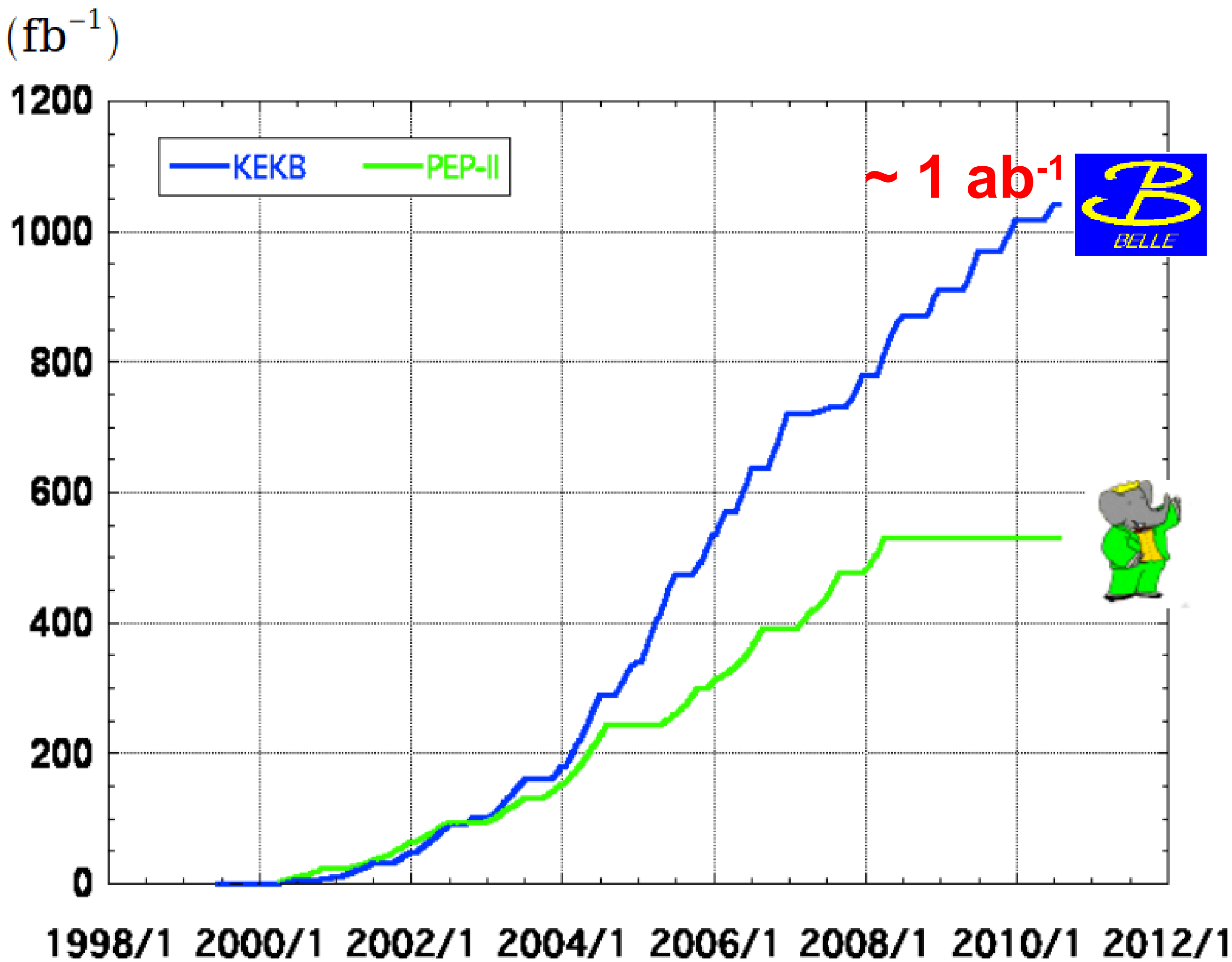


Belle & BaBar Detectors



KEKB/Belle and PEP-II/BaBar integr. luminosity

Integrated luminosity of B factories



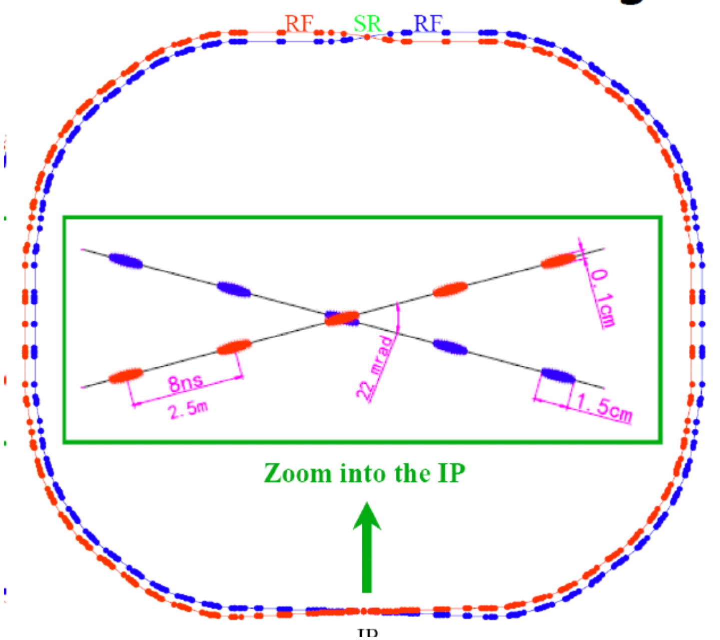
Res / E_{CM}(GeV) / Lumi.

Υ(1S): 9.46, 5.75 fb^{-1}
Υ(2S): 10.02, 25 fb^{-1}
Υ(3S): 10.36, 2.95 fb^{-1}
Υ(4S): 10.58, 710.5 fb^{-1}
Υ(5S): 10.87, 121.4 fb^{-1}
Off resonance/scan:
~ 100 fb^{-1}

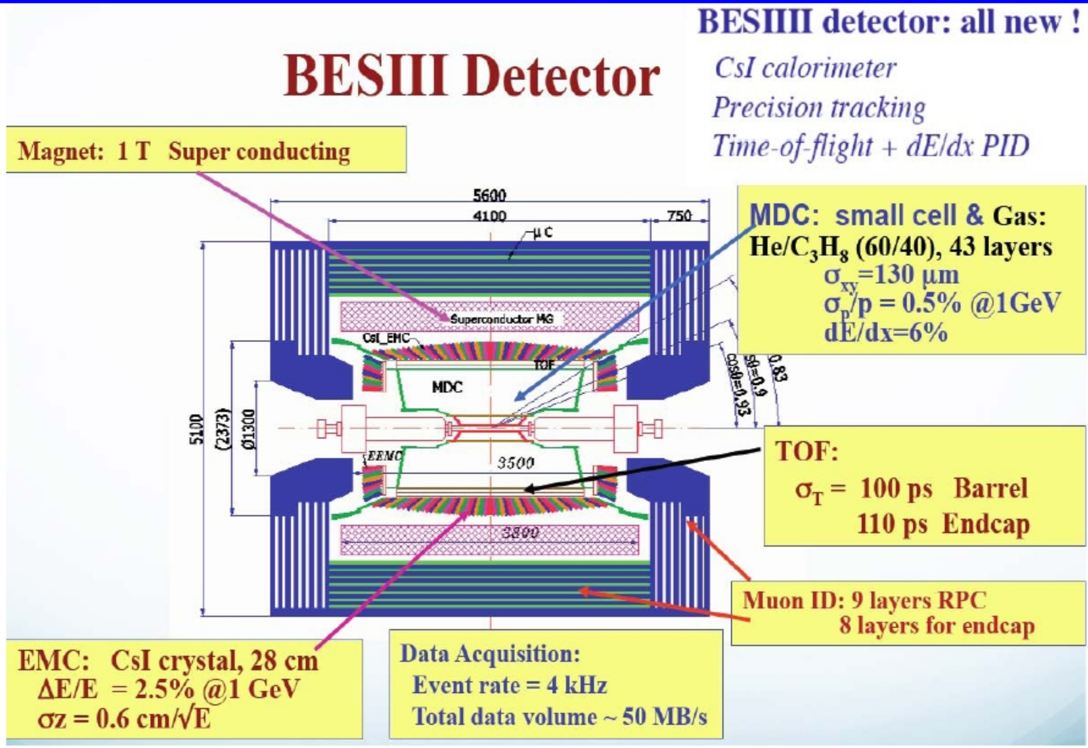
Υ(2S): 10.02, 14 fb^{-1}
Υ(3S): 10.36, 30 fb^{-1}
Υ(4S): 10.58, 433 fb^{-1}
Off resonance:
~ 54 fb^{-1}

BEPCII/BESIII

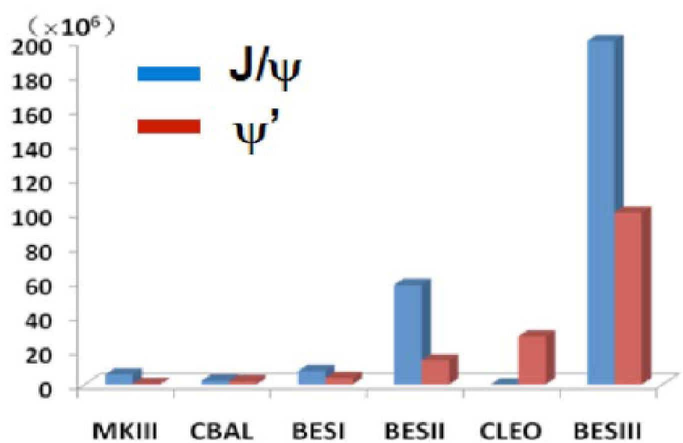
BEPCII storage rings



Beam energy:
1.0-2.3 GeV
Design Luminosity:
$1 \times 10^{33}\ cm^{-2}s^{-1}$
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
Circumference:
237m



- So far BESIII has collected :
  - 2009: 225 Million J/ψ
  - 2009: 106 Million ψ'
  - 2010-11: 2.9 fb^{-1} $\psi(3770)$ ($3.5 \times$ CLEO-c 0.818fb^{-1})
  - May 2011: 0.5fb^{-1} @4010 MeV (one month) for Ds and XYZ spectroscopy
- BESIII will also collect:
  - more J/ψ, ψ', $\psi(3770)$
  - data at higher energies （for XYZ searches, R scan and Ds physics）

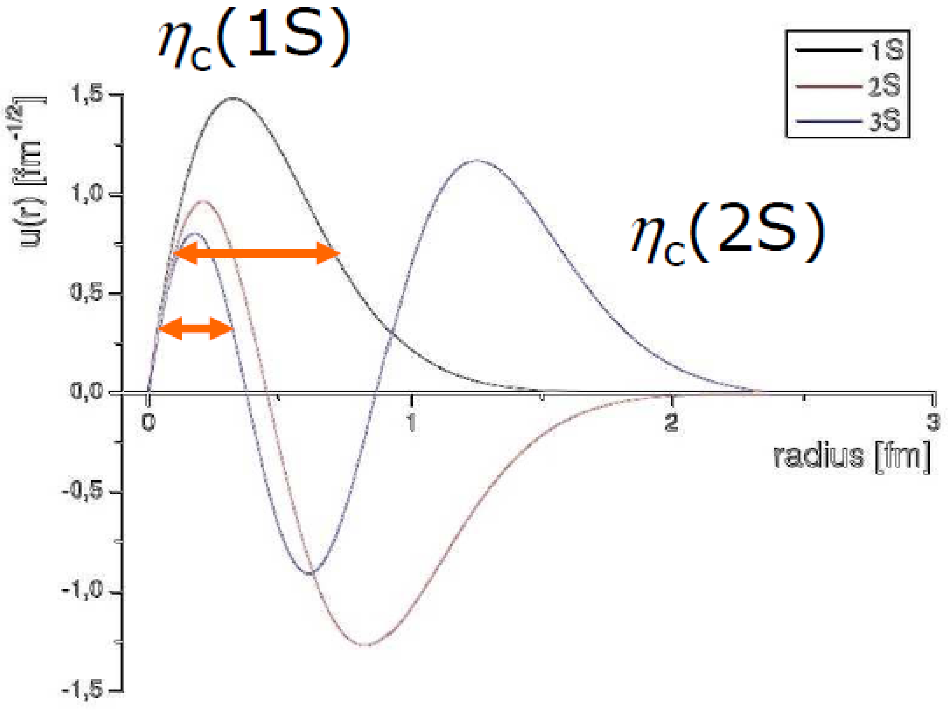


Charmonium-like States (unconventional)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B\to K(\pi^+\pi^-J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p}\to(\pi^+\pi^-J/\psi)+\ldots$	CDF [88–90] (np), DØ [91] (5.2)		
				$B\to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B\to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B\to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B\to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B\to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^-\to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^-\to J/\psi\ (\ldots)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^-\to\gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B\to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B\to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B\to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^-\to(\pi^+\pi^-J/\psi)$	CLEO [111] (11)		
				$e^+e^-\to(\pi^0\pi^0J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B\to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^-\to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B\to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^-\to\gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!

New mass measurement for η_c & $\eta_c(2S)$

Hadronic width of $\eta_c(2S)$ must be smaller than $\eta_c(1S)$



Potential model for $\eta_c(2S)$ width prediction not reliable, because close to $\bar{D}D$ threshold
$\rightarrow$ would be nice test for Lattice QCD

$$\Gamma(^1S_0 \rightarrow gg) = \frac{32\pi}{3} \frac{\alpha_S^2}{m_c^2} |\psi(r=0)|^2$$

3 gluon decay not possible (parity)

X(3872) →J/ψ π⁺π⁻ update

PRD 84, 052004 (2011)
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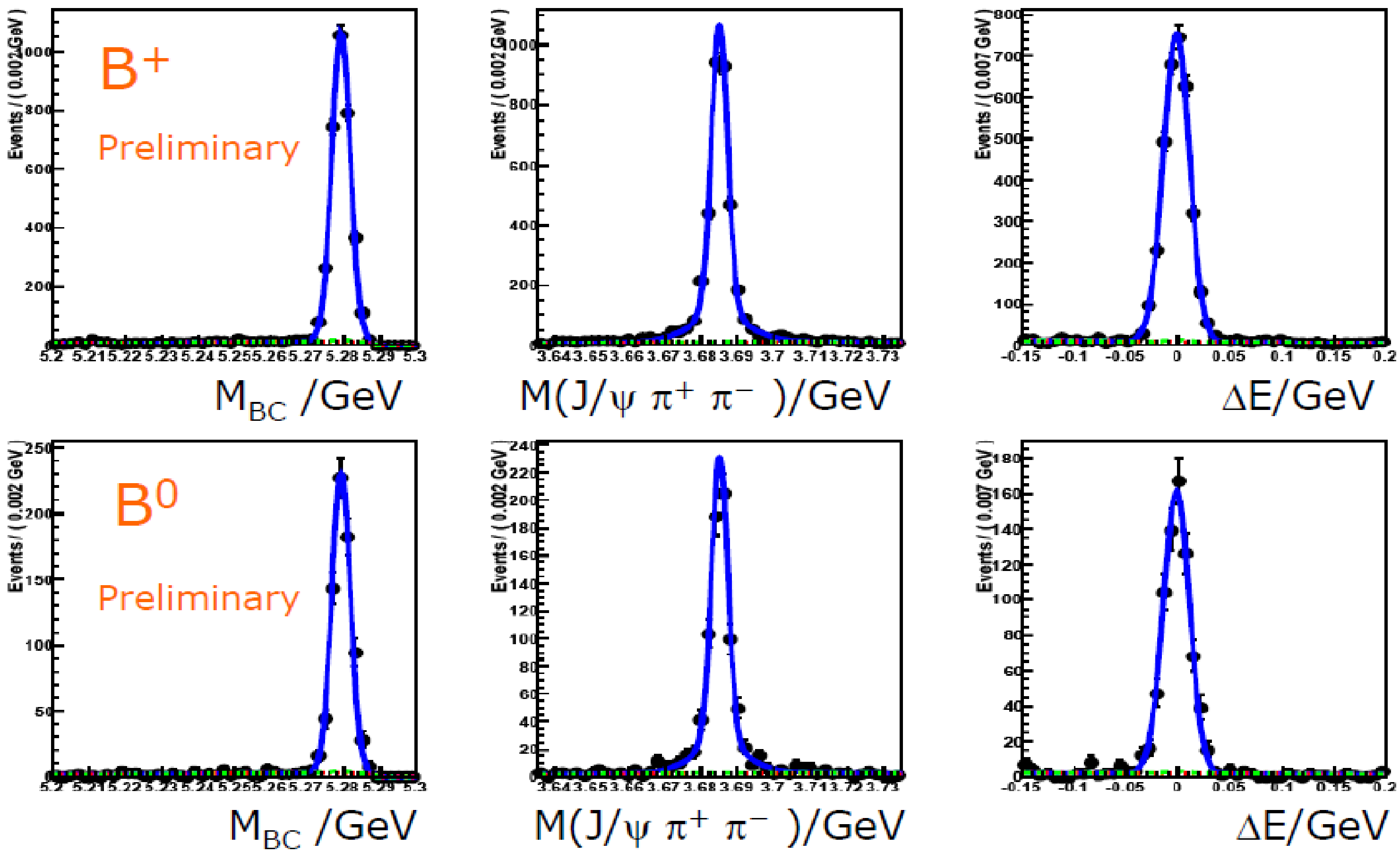
Reference Analysis: $B \to K\psi'$, $\psi' \to J/\psi\, \pi^+\pi^-$

$$M_{bc} \equiv \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$$

$$\Delta E \equiv E_B^{cms} - E_{beam}^{cms}$$



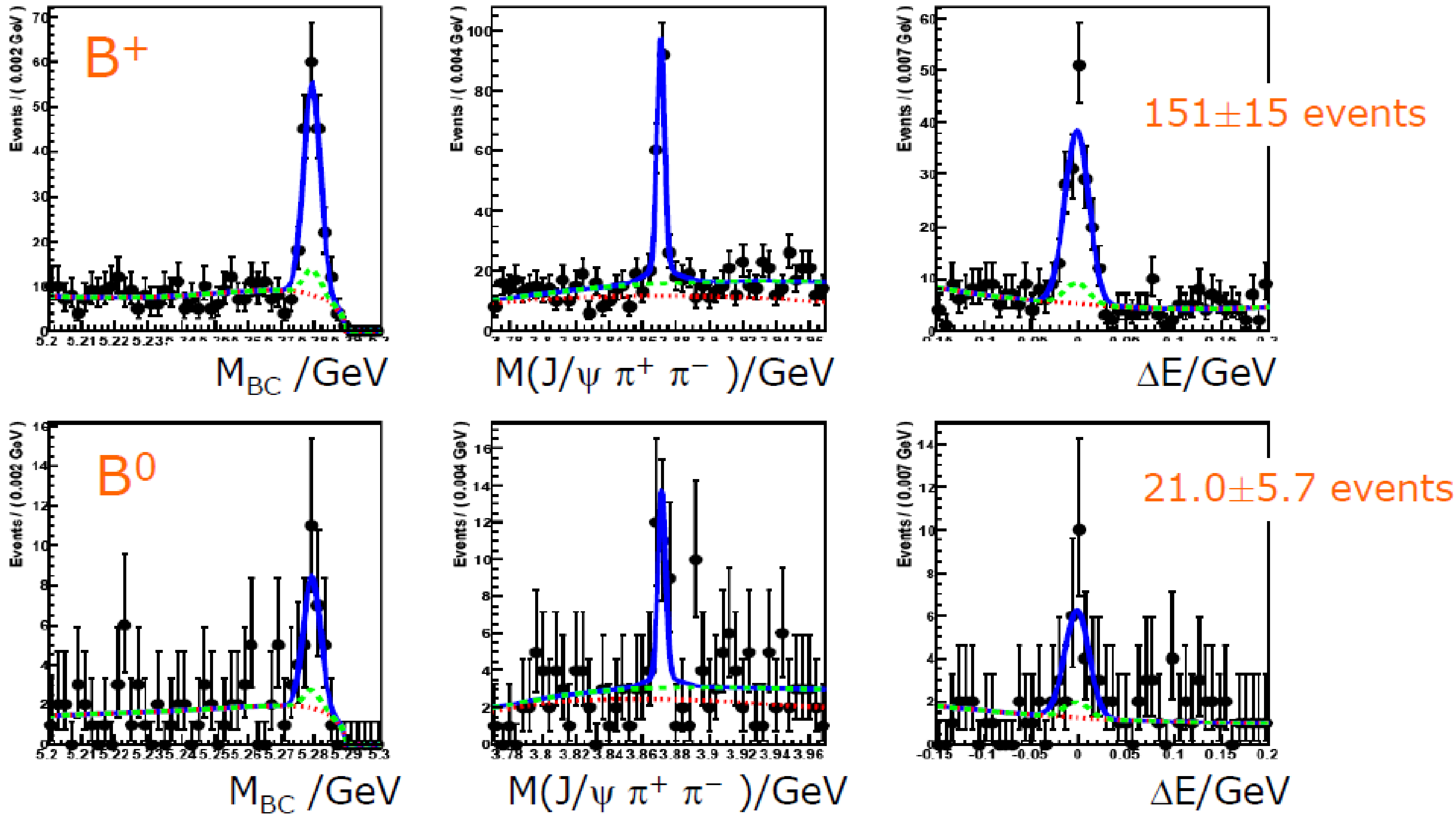
3-dim fit in beam constrained mass, $J/\psi\, \pi^+ \pi^-$ mass and ΔE
at first, fit reference signal ψ'
→ fix core Gaussian and tail Gaussian for resolution parameters

X(3872) →J/ψ π⁺π⁻ update

PRD 84, 052004 (2011)
711 1/fb

Analysis of X(3872) → J/ψ π⁺π⁻

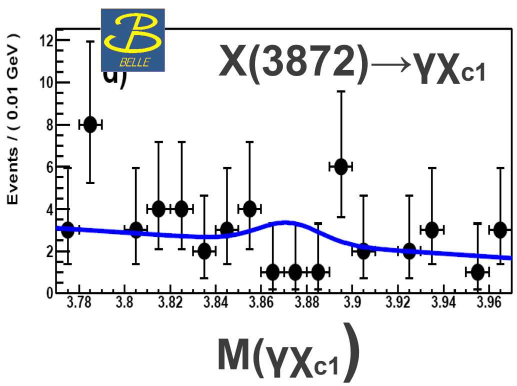
Preliminary

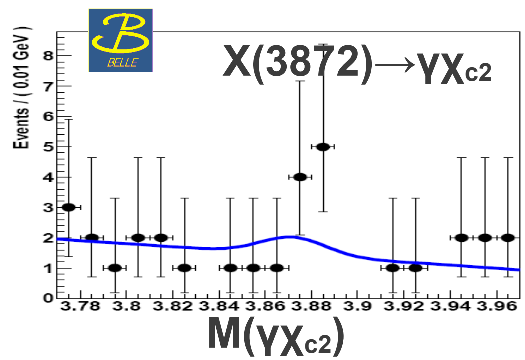


3-dim fit
with fixed resolution parameters from ψ′
Mass MC/data shift +0.92±0.06 MeV, measured and fixed from ψ′ mass

X(3872): radiative decays

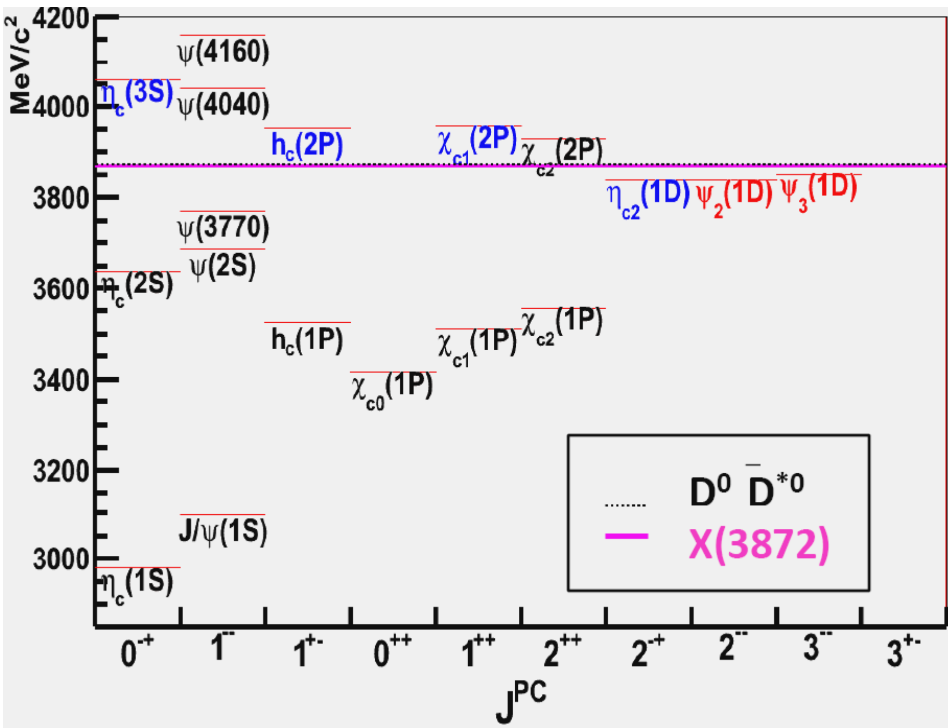
- Radiative transistions of charmonia: well predicted by quark models
- Good way to probe charmonium interpretation of X(3872)





$$\frac{BR(X \to \gamma\chi_{c1})}{BR(X \to J/\psi\,\pi\pi)} < 0.89\,@\,90\%CL$$

$$\frac{BR(X \to \gamma\chi_{c2})}{BR(X \to J/\psi\,\pi\pi)} < 1.1\,@\,90\%CL$$



ψ_2	BR(X→$\gamma\chi_{c1}$) too small
ψ_3	BR(X→$\gamma\chi_{c2}$) too small
h_c'	ruled out by angular analysis
η_{c2}	BR(X→J/ψππ) too large
η_c''	X(3872) too light and narrow
χ_{c1}'	BR(X→γJ/ψ) too small

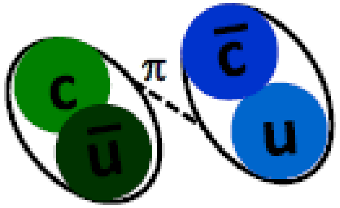
No good charmonium candidate

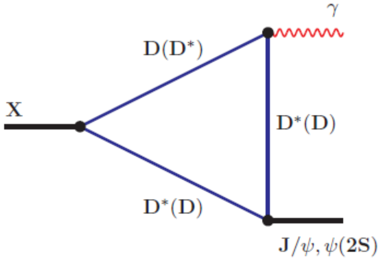
arXiv:0407033

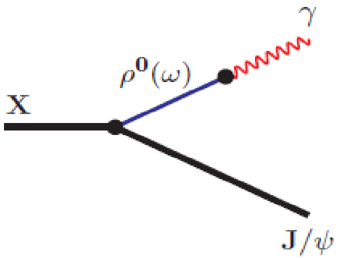
X(3872): rad. decays - interpr. problems

- $\frac{BR(X \to \gamma\psi')}{BR(X \to \gamma J/\psi)} = 3.5 \pm 1.4$ is problematic for molecular interpretation of X(3872)

- Components of molecule: DD* (+ J/ψρ + J/ψω)
  Decay: vector-meson dominance and light-quark annihilation



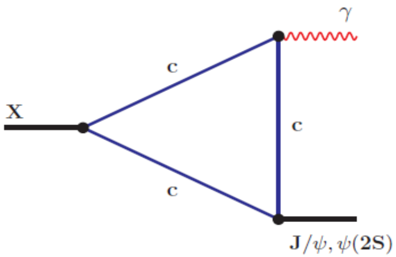




PRD80, 074004 (2009)

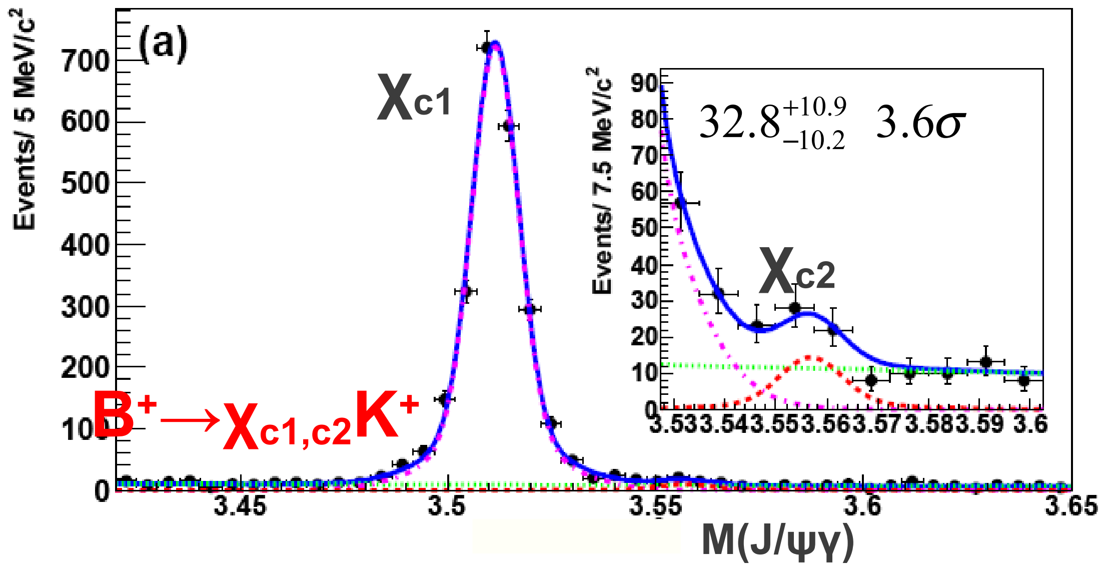
arXiv:0909.0380

- Such decay pattern implies: $BR(X \to \gamma\psi') < BR(X \to \gamma J/\psi)$
- Solution: admixture of charmonium component (for example $\chi_{c1}(2P)$)
  ⇨ Decrease X(3872) →γJ/ψ rate through destructive interference



- Radiative decays are worth studying further

Rad. quarkonia decays in B mesons

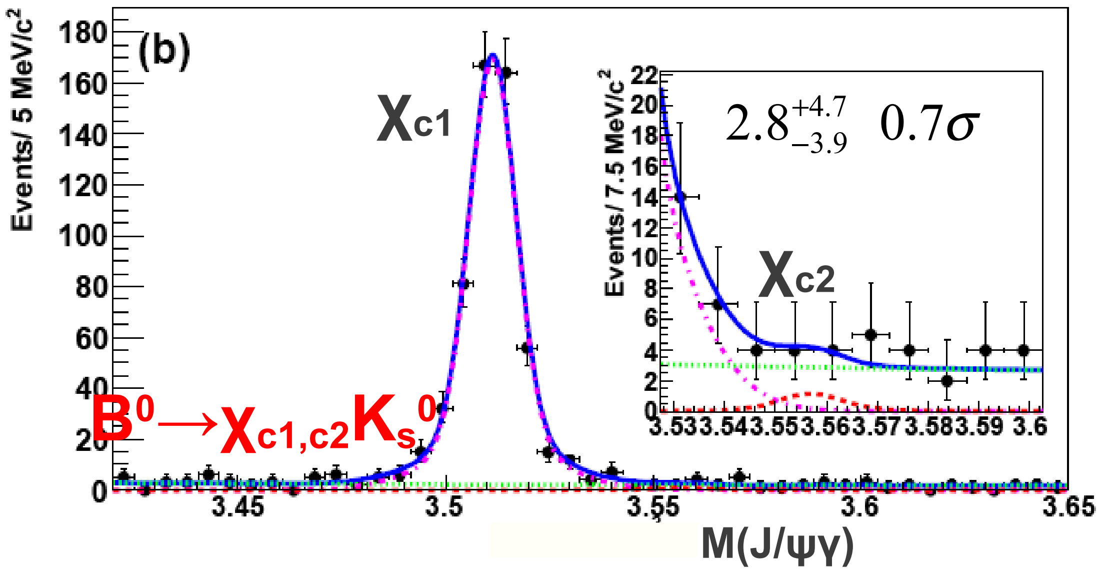


Mode	Events	Significance Σ (σ)
$B^+ \to \chi_{c1} K^+$	2308^{+53}_{-52}	
$B^+ \to \chi_{c2} K^+$	$32.8^{+10.9}_{-10.2}$	3.6

$\mathcal{BR}(B^+ \to \chi_{c2} K^+) = (1.11 \pm 0.35 \pm 0.09) \times 10^{-5}$

First evidence

Significance includes systematics



Mode	Events	Σ (σ)
$B^0 \to \chi_{c1} K_S^0$	542±24	
$B^0 \to \chi_{c2} K_S^0$	$2.8^{+4.7}_{-3.9}$	0.7

$\mathcal{BR}(B^0 \to \chi_{c2} K^0) < 1.5 \times 10^{-5}$ (@ 90% CL)

PRL 107, 091803 (2011)
711 1/fb

V. Bhardwaj et al., arXiv:1105.0177

Different fit models
and the significance of $Z(4430)^+$:

TABLE I: Different fit models that are used to study systematic uncertainties and the significances of the $Z(4430)^+$.

	Model	Significance
1	default*	6.4σ
2	no $K_0^*(1430)$	6.6σ
3	no $K^*(1680)$	6.6σ
4	release constraints on κ mass & width	6.3σ
5	new K^* ($J = 1$)	6.0σ
6	new K^* ($J = 2$)	5.5σ
7	add non-resonant $\psi'(2S)K^-$ term	6.3σ
8	add non-resonant $\psi'(2S)K^-$ term, release constraints on κ mass & width	5.8σ
9	add non-resonant $\psi'(2S)K^-$ term, new K^* ($J = 1$)	5.5σ
10	add non-resonant $\psi'(2S)K^-$ term, new K^* ($J = 2$)	5.4σ
11	add non-resonant $\psi'(2S)K^-$ term, no $K^*(1410)$	6.3σ
12	add non-resonant $\psi'(2S)K^-$ term, no $K^*(1680)$	6.6σ
13	LASS parameterization of S-wave component	6.5σ

Significance of $Z(4430)^+$ in different fit models is always larger than 5.4σ

Z_1^+ & Z_2^+ in $\bar{B}^0 \rightarrow K^- \pi^+ \chi_{c1}$ decays: fit

Fit results: $M^2(\chi_{c1}\pi^+)$ projections in 4 $M^2(K^-\pi^+)$ bands

- • data
- - - - background
- —— fit function
- ..... fit function without Z

Null hypothesis:

all known K*'s;

poor fit :

C.L. ≤ 3×10^{-10}

Add $Z \rightarrow \chi_{c1}\pi^\pm$:

signif. 10.7σ

($\sqrt{-2\ln L/L_0}$),

C.L. = 0.5%

$M_Z = (4150^{+31}_{-16})$ MeV/c²

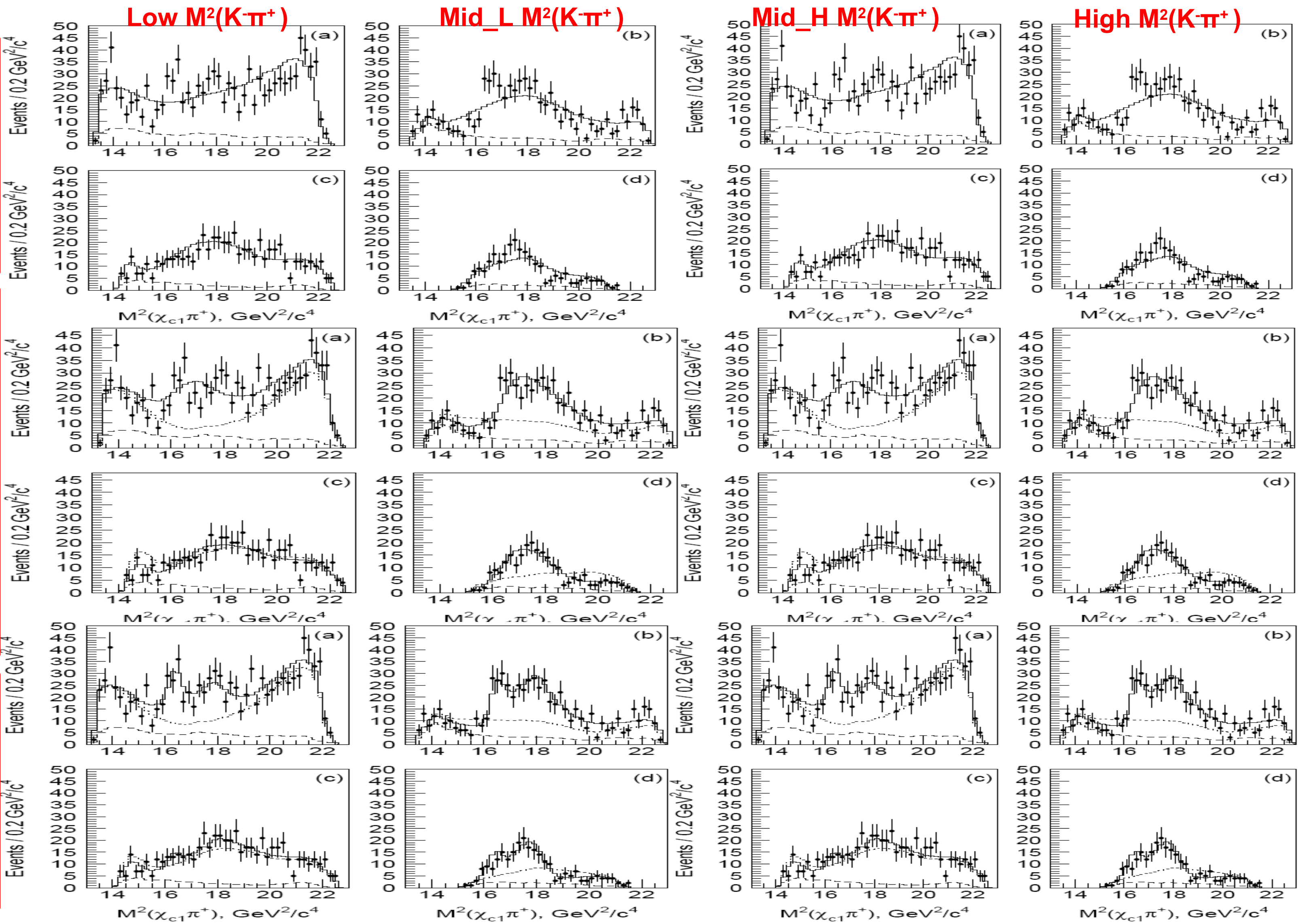
$\Gamma_Z = (352^{+99}_{-43})$ MeV

Two $Z \rightarrow \chi_{c1}\pi^\pm$:

signif. wrt 1 Z:

5.7σ,

C.L. = 42%



Z_1^+ & Z_2^+ : fit fractions

Contribution	One Z^+ Fit fraction	One Z^+ Signif.	Two Z^+ Fit fraction	Two Z^+ Signif.
$Z^+_{(1)}$	$(33.1^{+8.7}_{-5.8})\%$	$10.7\,\sigma$	$(8.0^{+3.8}_{-2.2})\%$	$5.7\,\sigma$
Z^+_2	–	–	$(10.4^{+6.1}_{-2.3})\%$	$5.7\,\sigma$
κ	$(1.9 \pm 1.8)\%$	$2.1\,\sigma$	$(3.6 \pm 2.6)\%$	$3.5\,\sigma$
$K^*(892)$	$(28.5 \pm 2.1)\%$	$10.6\,\sigma$	$(30.1 \pm 2.3)\%$	$9.8\,\sigma$
$K^*(1410)$	$(3.6 \pm 4.4)\%$	$1.3\,\sigma$	$(4.4 \pm 4.3)\%$	$2.0\,\sigma$
$K_0^*(1430)$	$(22.4 \pm 5.8)\%$	$3.4\,\sigma$	$(18.6 \pm 5.0)\%$	$4.5\,\sigma$
$K_2^*(1430)$	$(8.4 \pm 2.7)\%$	$5.2\,\sigma$	$(6.1 \pm 2.9)\%$	$5.4\,\sigma$
$K^*(1680)$	$(5.2 \pm 3.7)\%$	$2.2\,\sigma$	$(4.4 \pm 3.1)\%$	$2.4\,\sigma$
$K_3^*(1780)$	$(7.4 \pm 3.0)\%$	$3.6\,\sigma$	$(7.2 \pm 2.9)\%$	$3.8\,\sigma$
	110.5%		92.8%	

There is small net interference effect

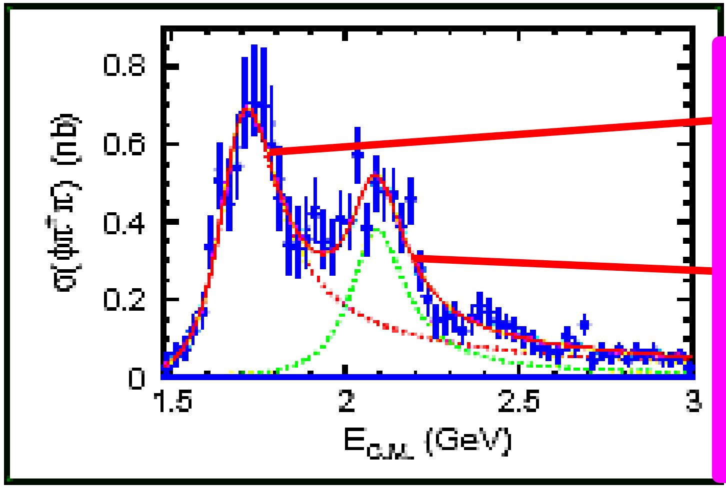
$s\bar{s}$ system: Y(2175) confirmed by Belle

PRD 80, 031101(R) (2009)
673 fb-1

Observed in $\Phi\ \pi^+\pi^-$ system in a dominant
Y(2175) → $\Phi\ f_0(980)$ decay mode by BaBar (PRD 74, 091103 (2006)),
confirmed by BES (PRL 100, 102003 (2008))

Belle: $e^+e^- \rightarrow \Phi\ \pi^+\pi^-$ and $e^+e^- \rightarrow \Phi\ f_0(980)$ cross section measurements with ISR

$\sigma(\phi\pi^+\pi^-)$



Two incoherent BW terms

$\phi(1680)$

$M = 1689 \pm 7 \pm 10$ MeV

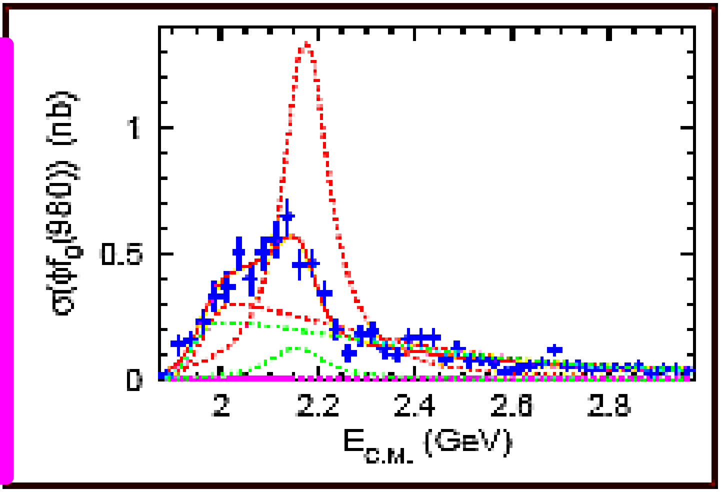
$\Gamma = 211 \pm 14 \pm 19$ MeV

Y(2175)

$M = 2079 \pm 13^{+79}_{-28}$ MeV

$\Gamma = 192 \pm 23^{+25}_{-61}$ MeV

$\sigma(\phi f_0(980))$



One BW term interfering with a non-resonant term (included in systematics)

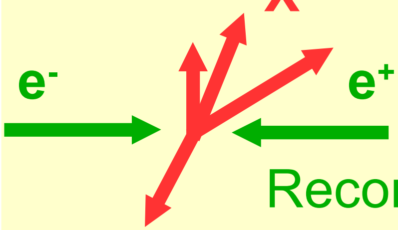
- Results are consistent with BaBar/BES; Y(2175) width is larger, but with larger errors
- Φ(1680) and Y(2175) widths are both ~200 MeV

→ An excited 1^{--} $s\bar{s}$ state or an Y_s ?

Double $c\bar{c}$ production: J/ψ & C=+1 state

Belle : 357 fb^{-1}
PRL 98, 082001 (2007)

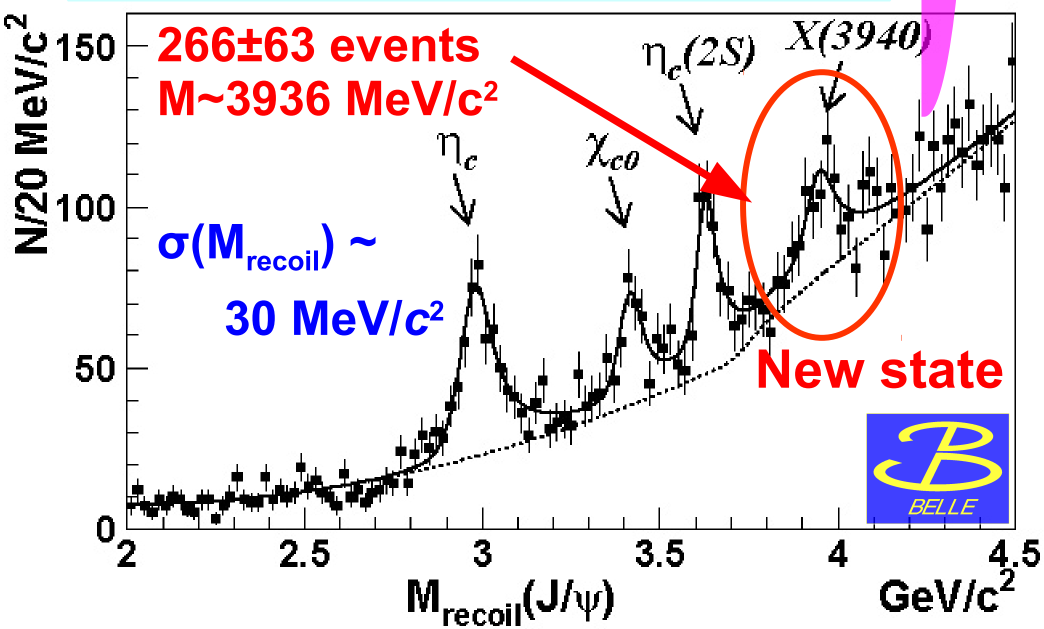
Inclusive production: charmonia factory



Reconstruct J/Ψ → $\ell^+\ell^-$
(mass & vertex constrained fit)

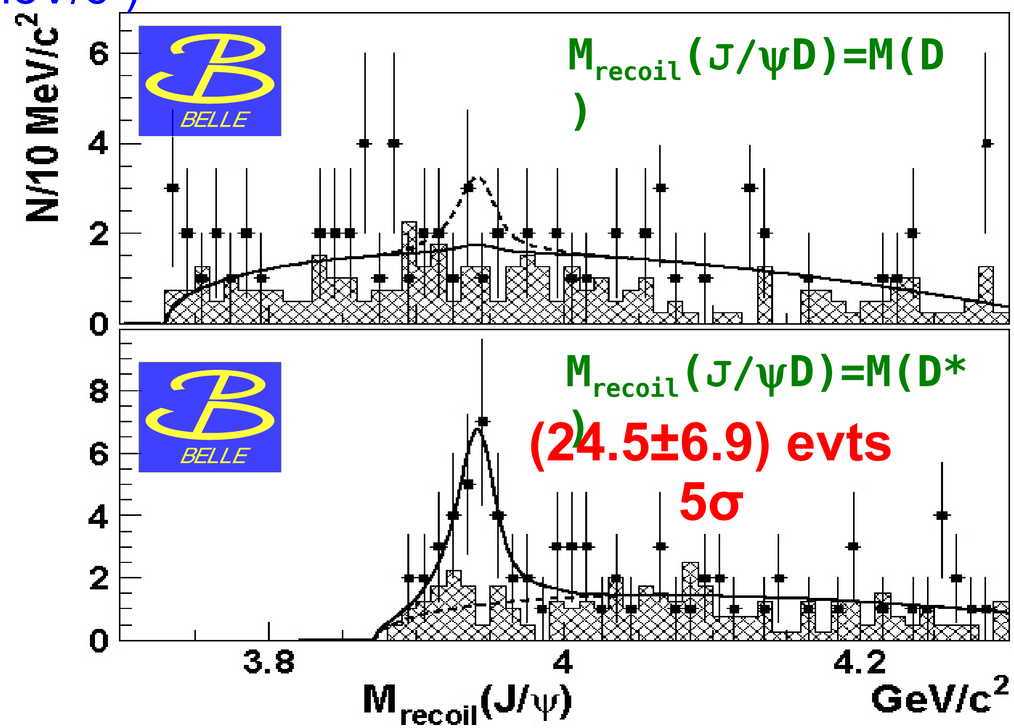
- **Recoil mass (mass of X):**

$$M_{recoil} = \sqrt{(E_{cms} - E^*_{J/\psi})^2 - p^{*2}_{J/\psi}}$$



X(3940)→$D^{(*)}\bar{D}$?

- **reconstruct J/Ψ + only one D**
  (to increase reconstruction efficiency)
- **constrain M_{recoil} (J/Ψ D)=M($D^{(*)}$)**
  (to improve resolution: σ(M_{recoil}(J/ψ))~10 MeV/c²)



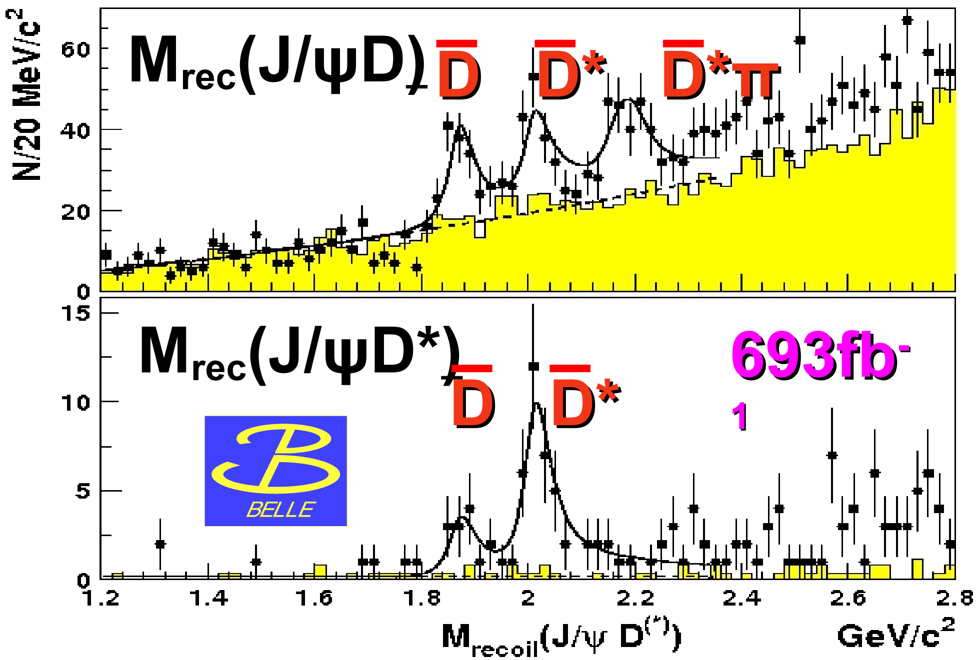
M=(3943±6±6) MeV/c^2
Γ < 52 MeV @90% C.L.

Double $c\bar{c}$ production: update

PRL 100, 202001(2008)
693 fb^{-1}

- Used the established method to look for the $D^{(*)}\bar{D}^{(*)}$ resonances in $e^+e^- \to J/\psi\, D^{(*)}\bar{D}^{(*)}$ with larger statistics ...
- Reconstruct $J/\Psi + D^{(*)}$: Accompanying $\bar{D}^{(*)}$ peaks seen in $M_{recoil}(J/\Psi\, D^{(*)})$ distr.
- Processes tagged in this way: $J/\Psi D\bar{D}$, $J/\Psi D\bar{D}^*$, $J/\Psi D^*\bar{D}^*$, $J/\Psi D^*\bar{D}$, $J/\Psi D^*\bar{D}^*$

(all > 5σ)



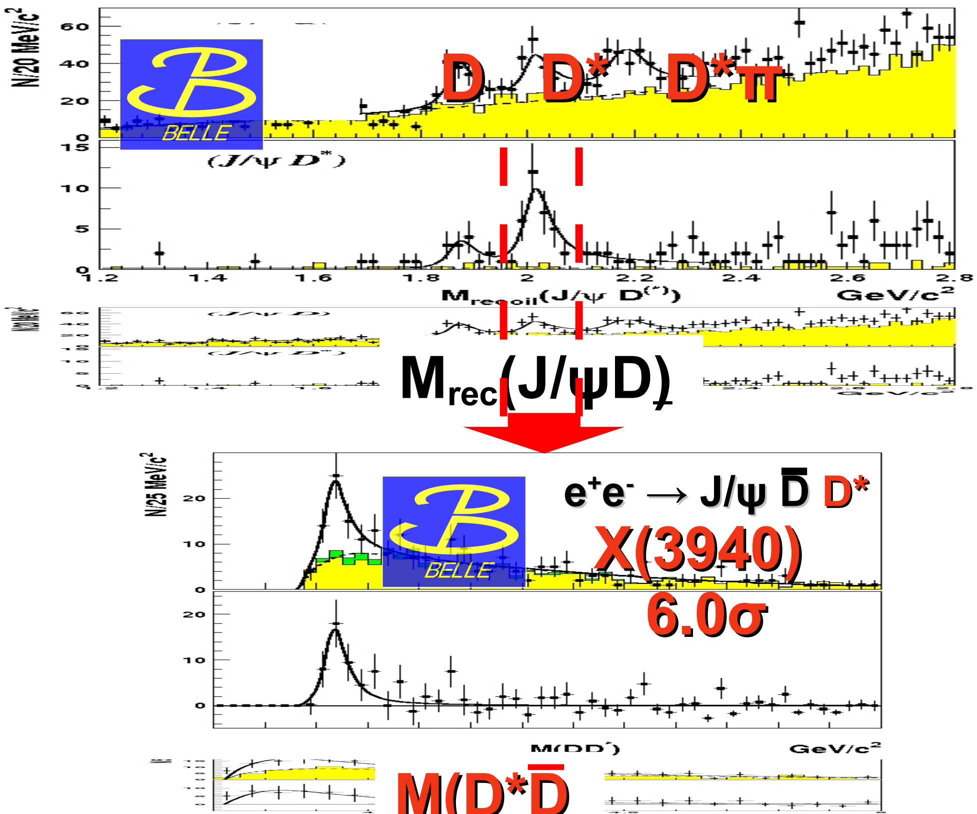
	$J/\psi D_{rec}$		$J/\psi D^*_{rec}$	
	N	N_σ	N	N_σ
$e^+e^- \to J/\psi D\bar{D}$	162 ± 25	7.6	—	—
$e^+e^- \to J/\psi D^*\bar{D}$	159 ± 28	6.5	$19.0\,^{+6.3}_{-5.3}$	5.8
$e^+e^- \to J/\psi D^*\bar{D}^*$	173 ± 32	5.6	$47.2\,^{+8.5}_{-7.8}$	8.4

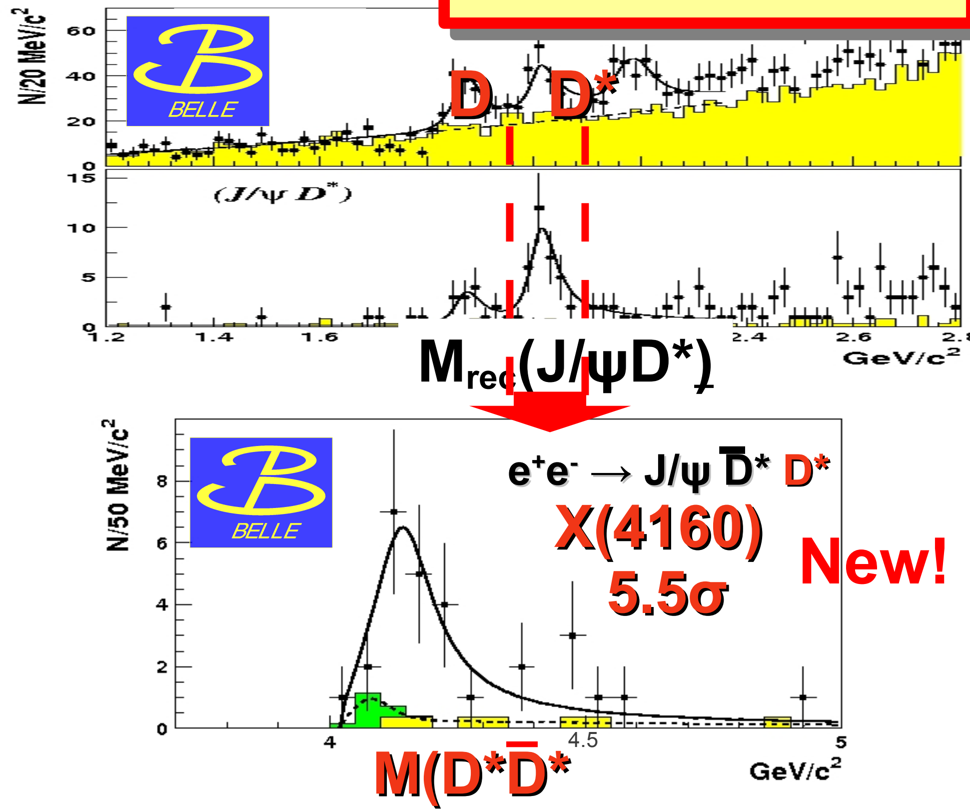
- Constrain $M_{recoil}(J/\Psi\, D^{(*)}) = M_{nominal}(\bar{D}^{(*)})$ and look at

$M_{recoil}(J/\Psi) = M_{recoil}(D^{(*)}\bar{D}^{(*)})$ distributions ...

Double $c\bar{c}$ prod.: X(3940) and X(4160)

PRL 100, 202001(2008)
693 fb^{-1}





$M=(3942\ ^{+7}_{-6} \pm 6)$ MeV

$\Gamma=(37\ ^{+26}_{-15} \pm 12)$ MeV

$M=(4156\ ^{+25}_{-20} \pm 15)$ MeV/c^2

$\Gamma=(139\ ^{+111}_{-61} \pm 21)$ MeV/c^2

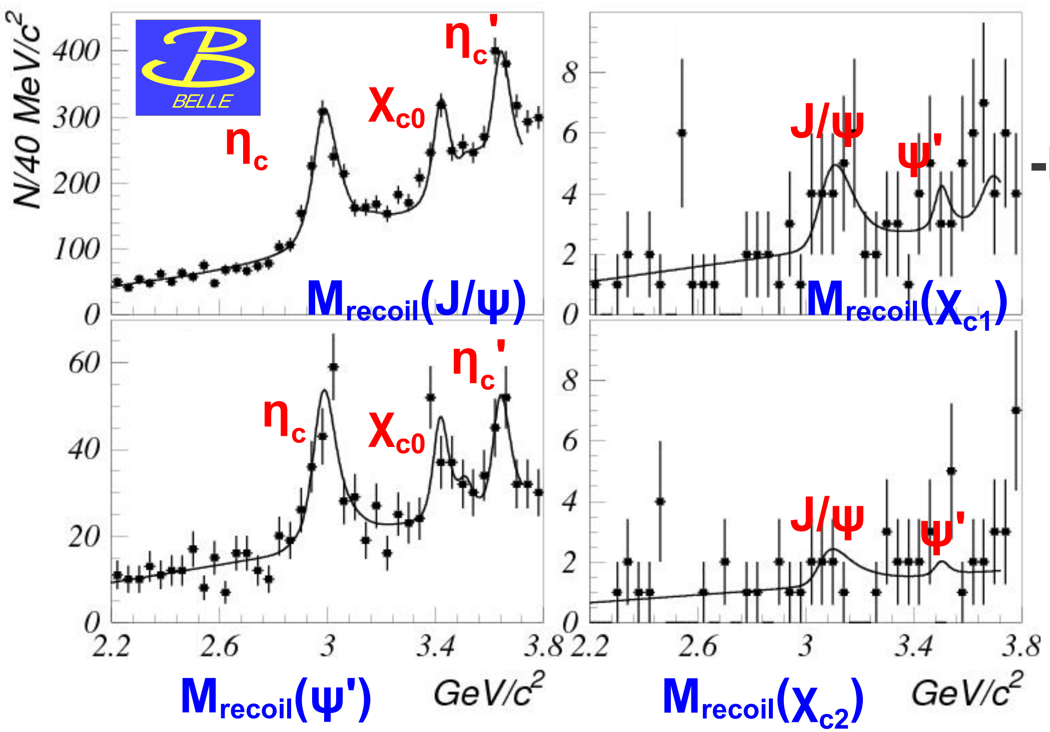
$C_X=+1$:
X(4160)≠ψ(4160)

- **Possible assignments:** $\eta_c(3S)$, $\eta_c(4S)$, $\chi_{c0}(3P)$ (but masses 100-150 MeV too high)
- **Needed to be done:** **angular analysis**; **search in $\gamma\gamma \to D\bar{D}^*$, $D^*\bar{D}^*$**

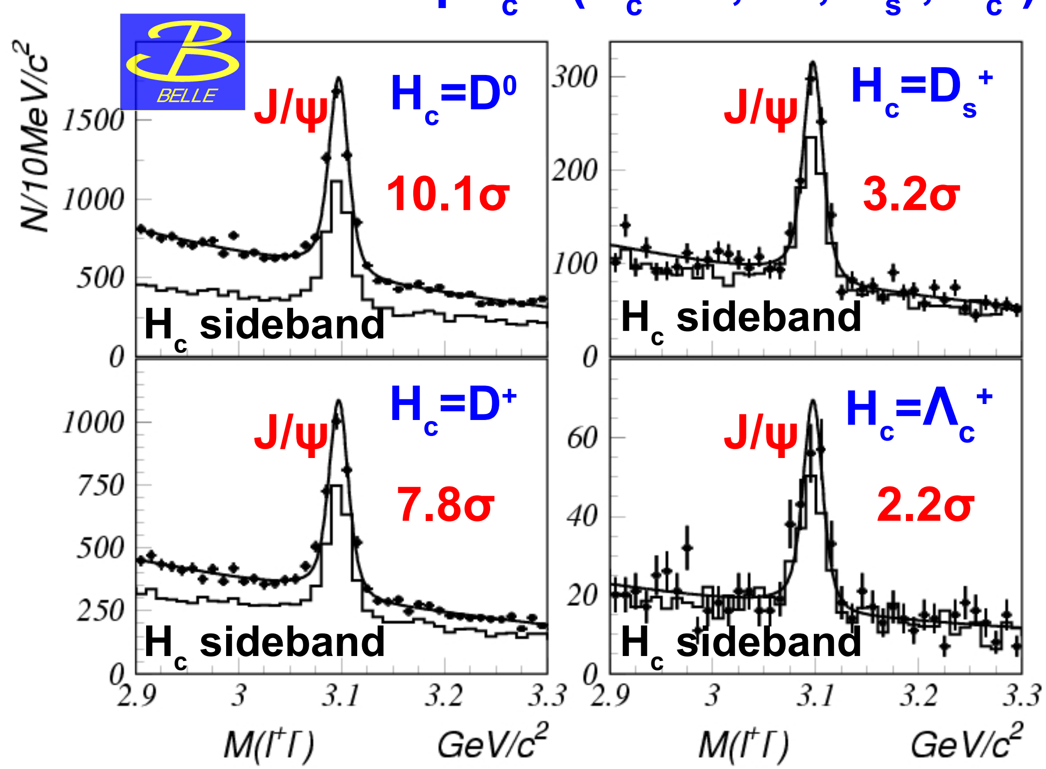
$e^+e^- \to J/\psi c\bar{c}$ cross section @ ~10.6 GeV

- Model-independent measurements of $e^+e^- \to J/\psi c\bar{c}$ cross section
  - Simultaneous fit for all double charmonium final states (below open-charm threshold)

PRD 79, 071101 (2009)
673 fb^{-1}

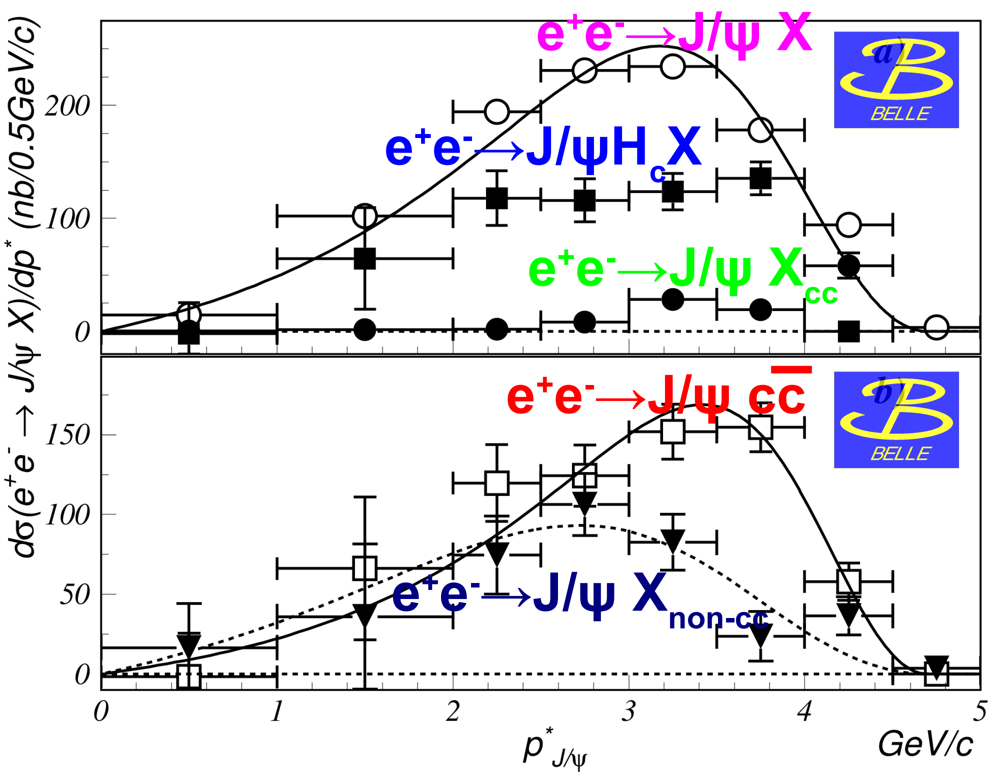


- Pairs of J/ψ and ground state charm hadrons: $e^+e^- \to J/\psi H_c X$ ($H_c = D^0, D^+, D_s^+, \Lambda_c^+$)



$e^+e^-\to J/\psi c\bar{c}$ cross section @ ~10.6 GeV

• Model-independent measurements of $e^+e^-\to J/\psi c\bar{c}$ cross section



PRD 79, 071101 (2009)
673 fb^{-1}

TABLE II. Cross sections for the processes $e^+e^-\to J/\psi X$, $J/\psi c\bar{c}$, and $J/\psi X_{\text{non-}c\bar{c}}$ ([pb]), and characteristics of the J/ψ spectra (ϵ_{Pet}, α_{hel}, and α_{prod}); χ^2/n_{dof} values for the corresponding fits are listed in parentheses.

	$J/\psi X$	$J/\psi c\bar{c}$	$J/\psi X_{\text{non-}c\bar{c}}$
σ	1.17 ± 0.02	0.74 ± 0.08	0.43 ± 0.09
σ_{Pet}	1.19 ± 0.01	0.73 ± 0.05	0.48 ± 0.07
ϵ_{Pet}	$0.16\pm0.01(8.9)$	$0.10\pm0.02(0.6)$	$0.32^{+0.16}_{-0.12}(1.6)$
α_{hel}	$0.03\pm0.03(0.6)$	$-0.19^{+0.25}_{-0.22}(1.0)$	$0.41^{+0.60}_{-0.45}(1.2)$
α_{prod}	$0.69\pm0.05(3.3)$	$-0.26^{+0.24}_{-0.22}(0.5)$	$5.2^{+6.1}_{-2.4}(0.3)$

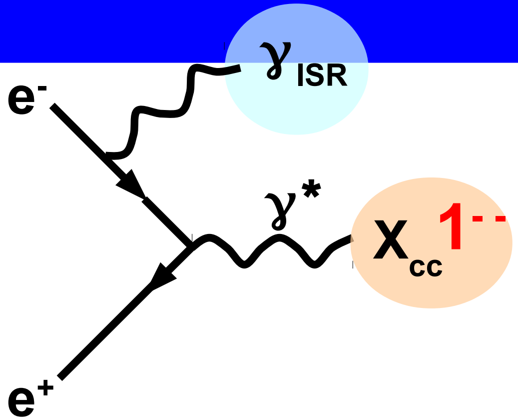
Conclusions (new constraints for theoretical models):

- $e^+e^-\to J/\psi c\bar{c}$ is the dominant mechanism for J/ψ production in e^+e^- annihilations
- $e^+e^-\to J/\psi c\bar{c}$ is dominated by $c\bar{c}$ fragmentation into open charm

  (only (16±3)% from double charmonium)
- $\sigma(e^+e^-\to J/\psi c\bar{c})$ / $\sigma(e^+e^-\to J/\psi X_{non\text{-}cc})$ ~ O(1)

Study of 1^{--} states with ISR

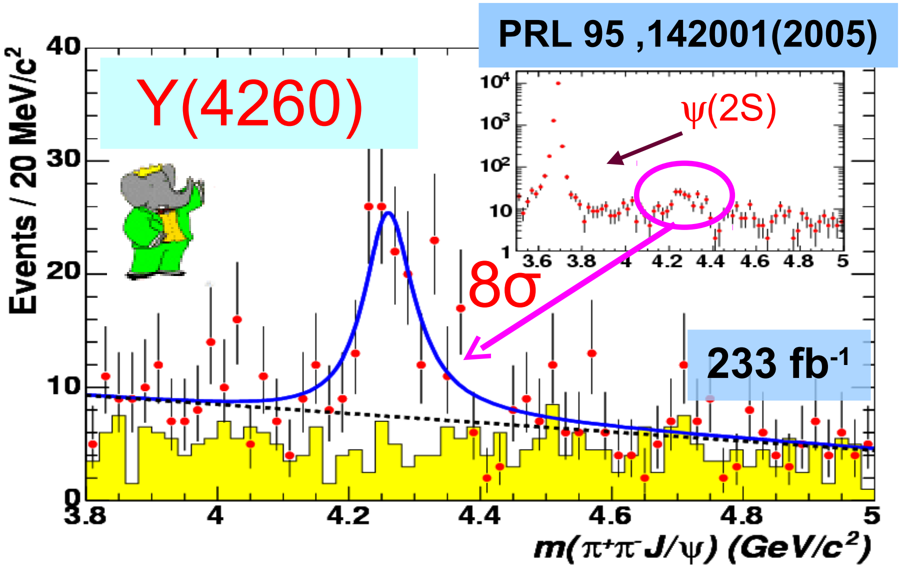
- **Initial state radiation(ISR) gives access to $J^{PC} = 1^{--}$ states**



- **Two main characteristics of ISR physics at B-factories:**
  - **Continuous ISR spectrum gives access to the wide √s range**
  - **High luminosity "compensates" for the emission of hard photons**

⇒ Sensitivity comparable to direct energy scan (e.g. CLEO-c, BES III)

- **$Y(4260) \rightarrow J/\psi\pi^+\pi^-$ observed via ISR by BaBar (confirmed first by CLEO)**

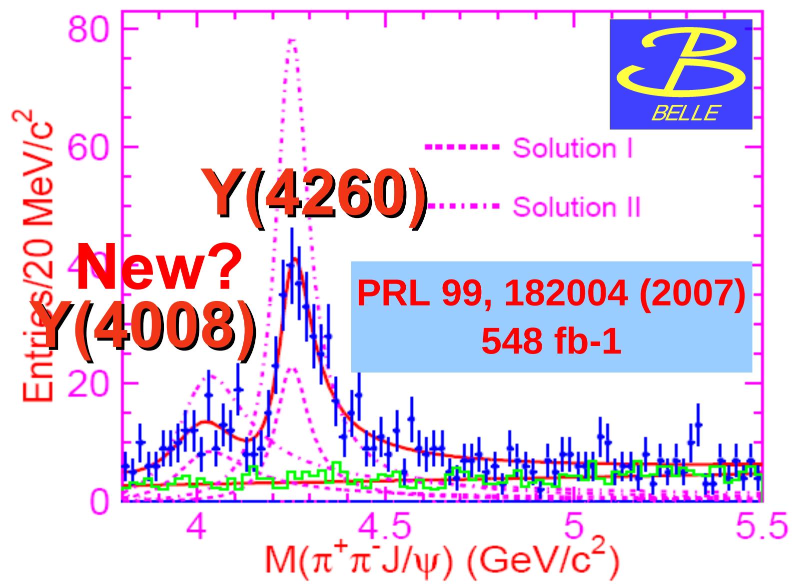


Study of 1^{--} states in $e^+e^-\to\gamma_{ISR} J/\psi\pi^+\pi^-$

Using BaBar's approach

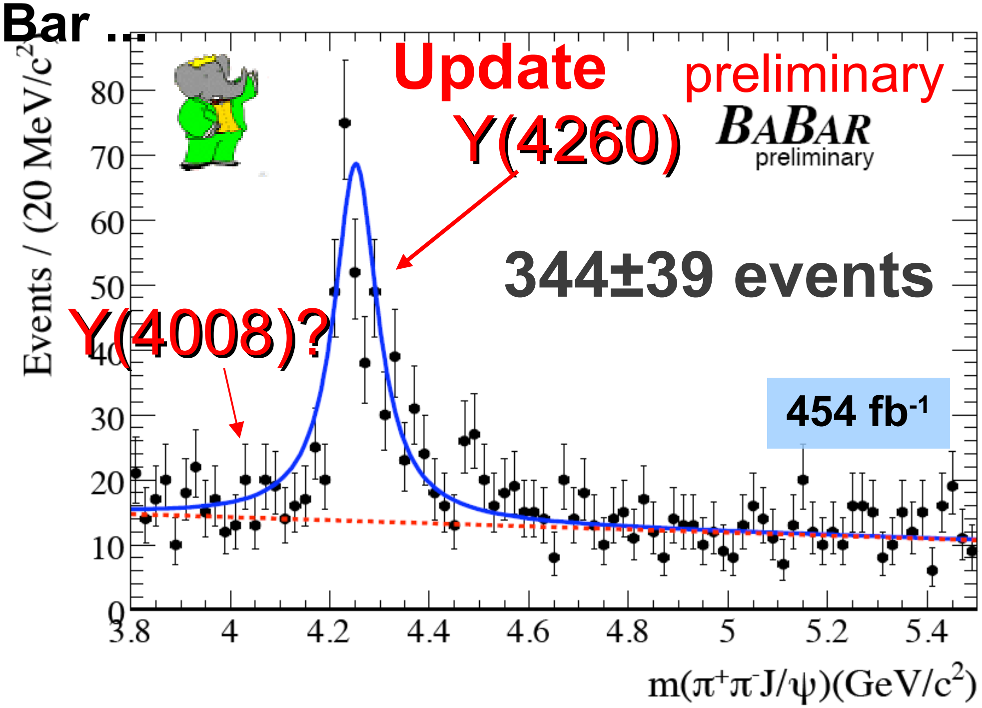
- Study of $e^+e^-\to\gamma_{ISR}\, J/\psi\pi^+\pi^-$ also by Belle
- Reconstruction: $\pi^+\pi^-$ & $J/\psi(\to e^+e^-,\mu^+\mu^-)$
  (no extra tracks allowed; γ_{ISR} not detected)
- Missing(recoil) mass identifies ISR:

$$M_{rec}=\sqrt{(E_{cms}-E^*_{J/\psi\pi^+\pi^-})^2-p^{*\,2}_{J/\psi\pi^+\pi^-}}$$



- Fit to $M(J/\psi\pi^+\pi^-)$ with two coherent BW curves
- Y(4260) is confirmed also by Belle
- New Y(4008) resonance? Not seen by BaBar ...

	State	M, MeV/c²	Γ_{tot}, MeV
BELLE	Y(4008)	$4008\pm40^{+114}_{-28}$	$226\pm44\pm87$
	Y(4260)	$4259\pm8^{+2}_{-6}$	$88\pm23^{+6}_{-4}$
	Y(4260)	$4252\pm6^{+2}_{-3}$	$105\pm18^{+4}_{-6}$
CESR CLEO	Y(4260)	$4284^{+17}_{-16}\pm4$	$73^{+39}_{-25}\pm5$
BELLE	Y(4260)	$4247\pm12^{+17}_{-32}$	$108\pm19\pm10$

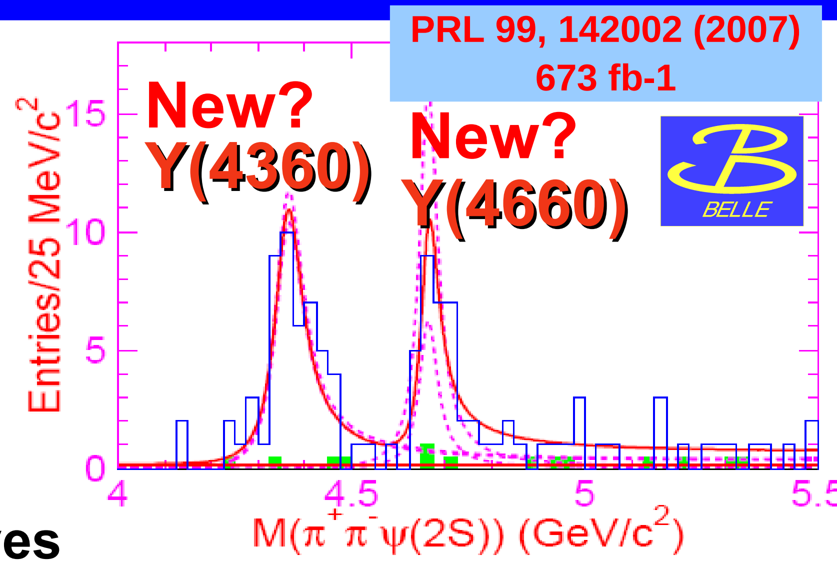


Study of 1^{--} states in $e^+e^- \to \gamma_{ISR}\psi'\pi^+\pi^-$

Similar approach also for:

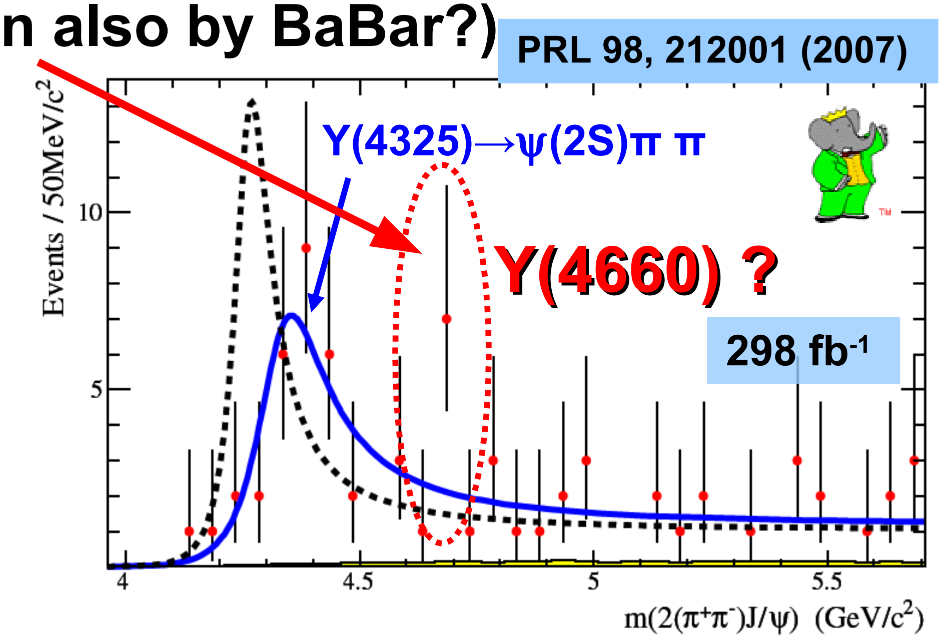
- Study of $e^+e^- \to \gamma_{ISR}\,\psi(2S)\pi^+\pi^-$
- Reconstruction: $\pi^+\pi^-$ & $\psi(2S)(\to\pi^+\pi^- J/\psi(\to e^+e^-,\mu^+\mu^-))$
  (no extra tracks allowed; γ_{ISR} not detected)
- Missing(recoil) mass identifies ISR:

$$M_{rec}=\sqrt{(E_{cms}-E^*_{\psi(2S)\pi^+\pi^-})^2-p^{*\,2}_{\psi(2S)\pi^+\pi^-}}$$



- Fit to $M(\psi(2S)\pi^+\pi^-)$ with two coherent BW curves
- Belle's Y(4360) resonance:
  close to BaBar's Y(4325), but narrower
- New Y(4660) resonance by Belle? (Seen also by BaBar?)

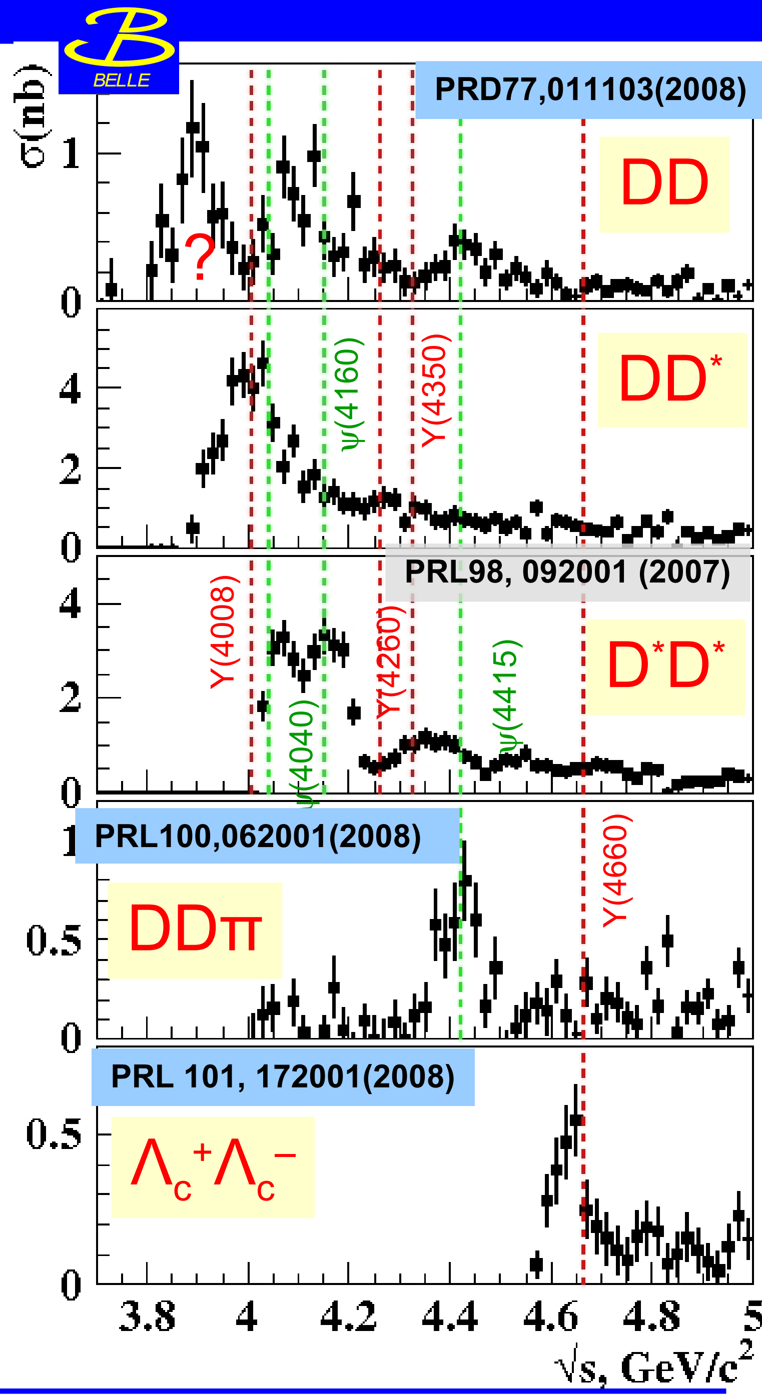
State	M, MeV/c^2	Γ_{tot}, MeV
Y(4325)	4324 ± 24	172 ± 33
Y(4325)	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$
Y(4660)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$



Exclusive $D^{(*)}D^{(*)}$ cross sections w. ISR

- $e^+e^- \rightarrow D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$ cross sections measured with ISR
- $D\bar{D}^*$, $D^*\bar{D}^*$: using partial reconstruction; γ_{ISR} detected

  $D\bar{D}$: fully reconstructed; γ_{ISR} used if detected
- Recoil mass is again used to identify ISR events
- Method is well established
- Difficult interpretation in terms of resonances (there are many maxima/minima, model dependent coupled-channels and threshold effects…)

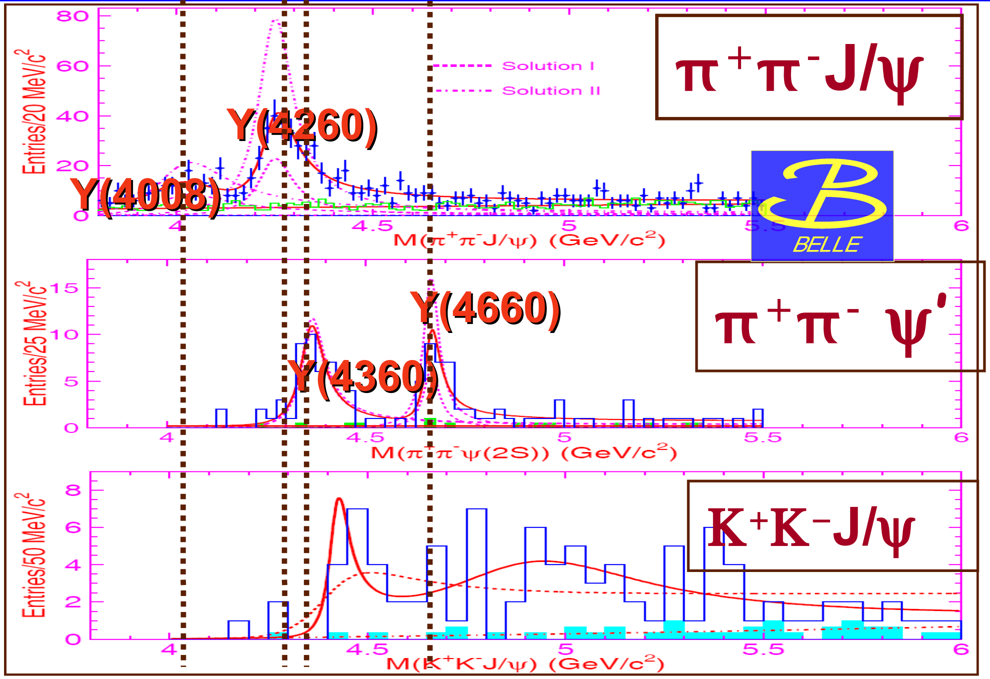


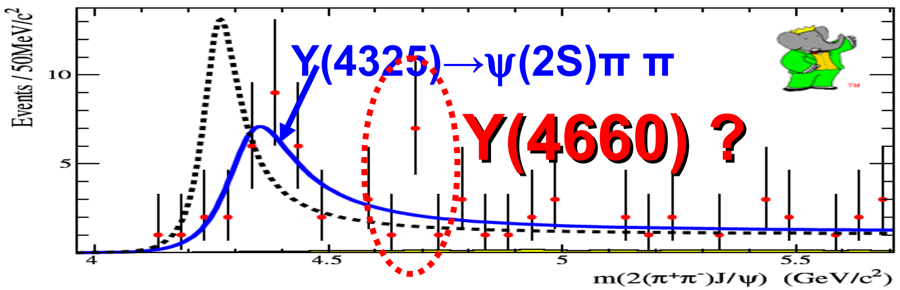
1^{--} Y states: What are they?

➡ Difficult interpretation

Charmonium options:

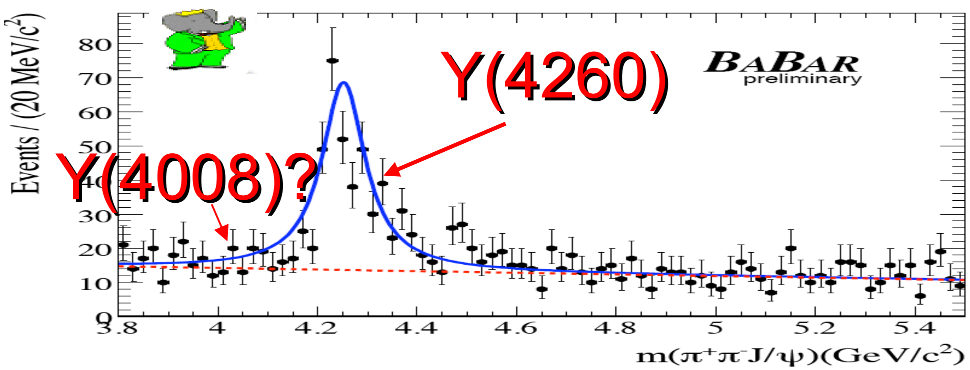
- Y states above $D\bar{D}$ threshold but don't match well the peaks in $D^{(*)}D^{(*)}$ cross-sections
- Large widths for ψππ transition: not likely for conventional $c\bar{c}$
- No $c\bar{c}$ assignments available in this mass region (there are too many 1^{--} states)





Other options:

- Charm-meson threshold effects
- $D\bar{D}_1$ or $D^*\bar{D}_0$ molecules
- $cq\bar{c}\bar{q}$ tetraquarks
- $c\bar{c}g$ hybrids predicted@4.2-5GeV $D\bar{D}_1$ mode should dominate
- Coupled-channel effects



$e^+e^- \rightarrow \gamma_{ISR} \psi' \pi^+\pi^-$: BaBar & Belle combined fit

Combined fit to BaBar and Belle data on $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$

Z. Q. Liu,[1,3] X. S. Qin,[1,2] and C. Z. Yuan[1,*]

arXiv:0805.3560v1 [hep-ex] 23 May 2008

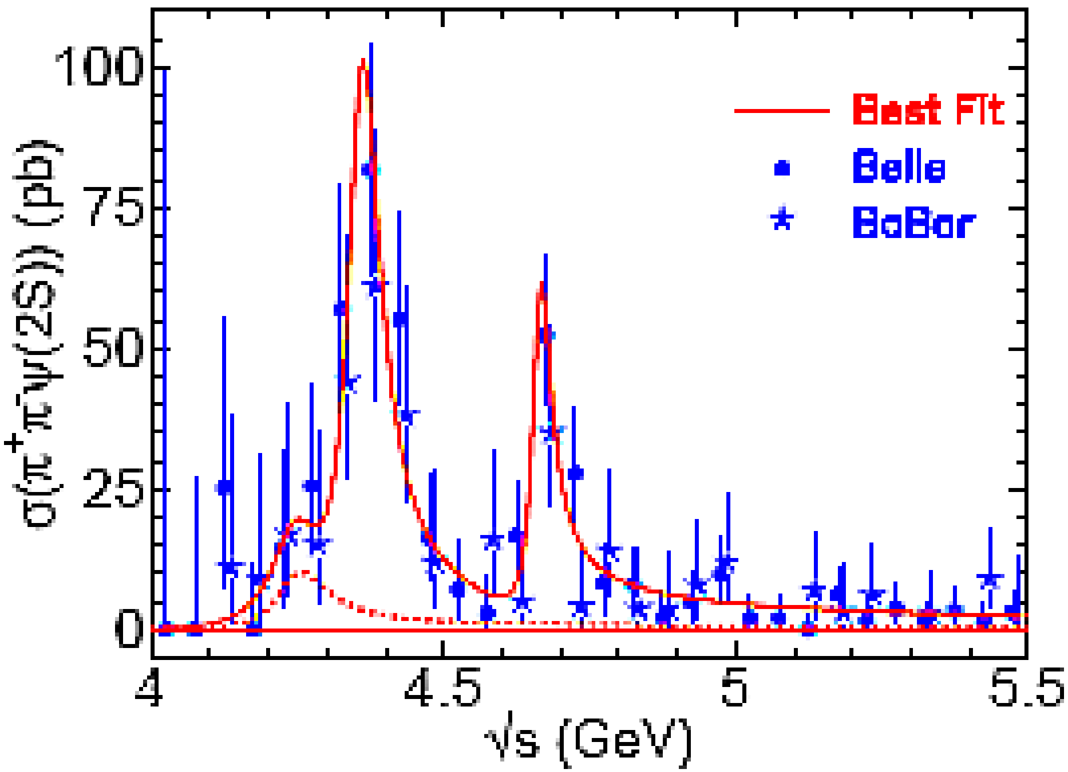


FIG. 4: The results of the fit to $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ data from Belle and BaBar. The solid curve show the best fit with three coherent Breit-Wigners: the $Y(4260)$, $Y(4360)$, and $Y(4660)$, and the dashed curve is the signal shape of the $Y(4260)$.