Charmonium and Bottomonium at Belle

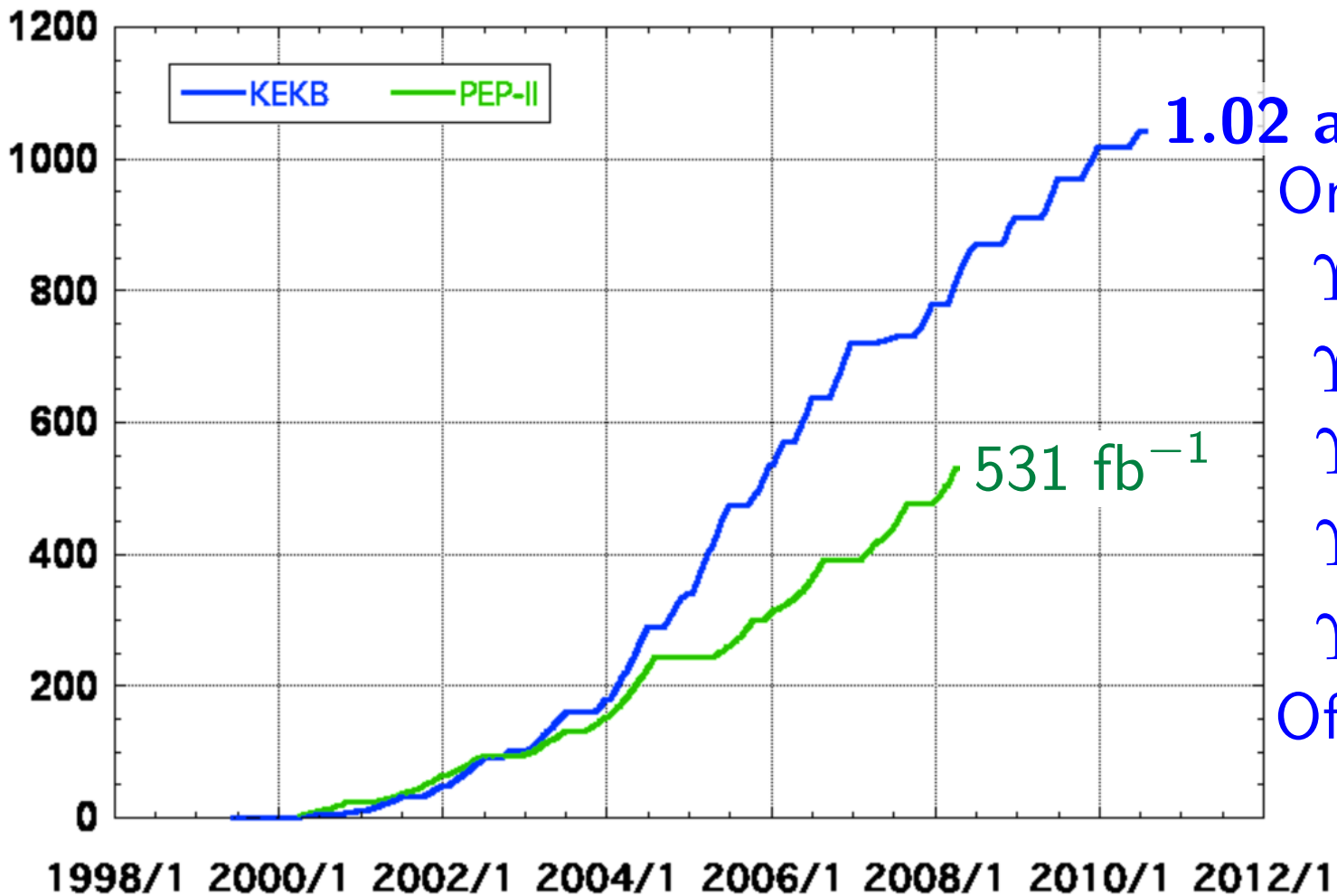
Leo Piilonen, Virginia Tech

on behalf of the Belle Collaboration

As is now well known, Japan suffered a terrible earthquake and tsunami onMarch 11, which has caused tremendous damage, especially in the Tohoku area. Fortunately, all KEK personnel and users are safe and accounted for. The injection linac did suffer significant but manageable damage, and repairs are underway. The damage to the KEKB main rings appears to be less serious, though non-negligible. No serious damage has been reported so far at Belle. Further investigation is necessary. We would like to convey our deep appreciation to everyone for your generous expressions of concern and encouragement.

DIS2011 April 10-15, 2011

Integrated luminosity at the B factories



On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 24 fb^{-1}

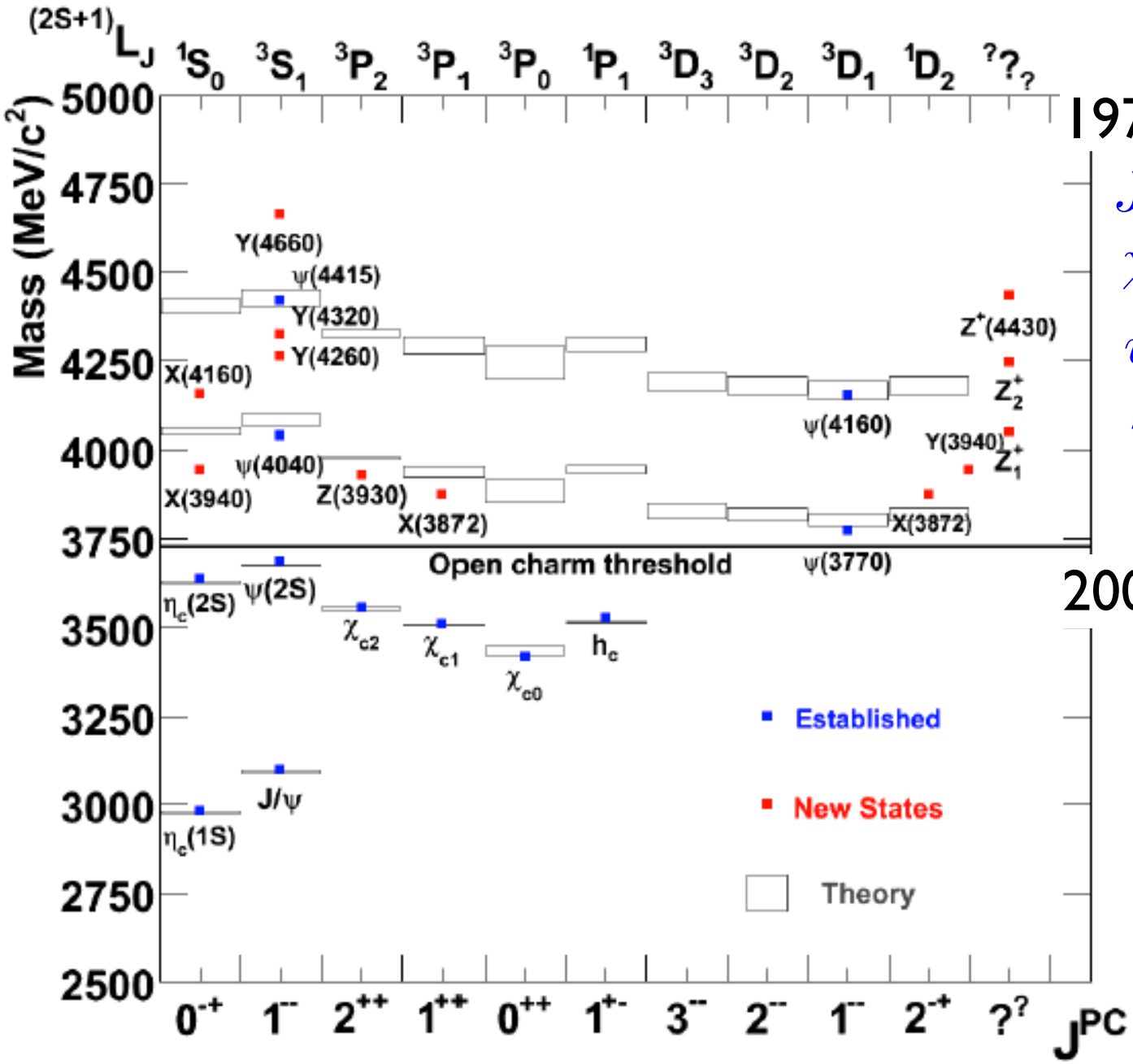
$\Upsilon(1S)$: 6 fb^{-1}

Off resonance/scan:

155 fb^{-1}

Charmonium / Exotic States

Exotic/charmonium spectroscopy



1974–1980:

$J/\psi,\ \psi(2S),\ \eta_c,$
$\chi_{c0},\ \chi_{c1},\ \chi_{c2},$
$\psi(3770),\ \psi(4040),$
$\psi(4160),\ \psi(4415)$

2002–now:

$\eta_c(2S),\ h_c,$
$X(3872),\ \ldots$

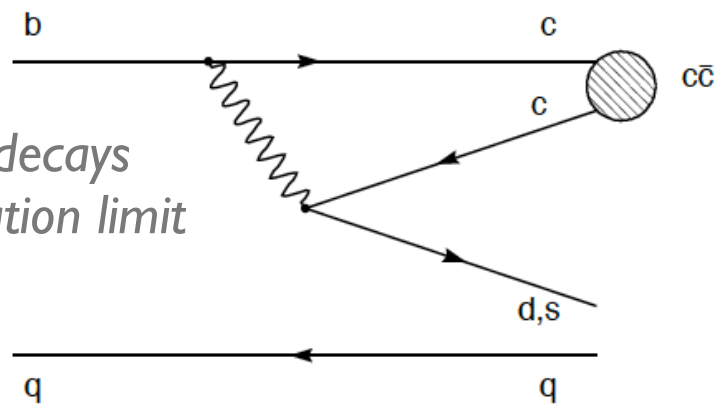
New states

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^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$

Exotic/charmonium production at B factories

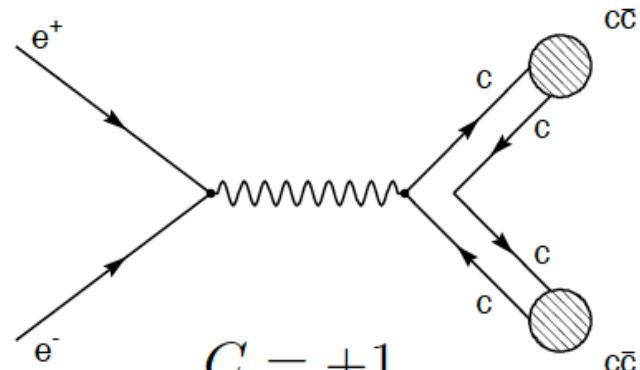
B decay



in 2–body decays
in factorization limit

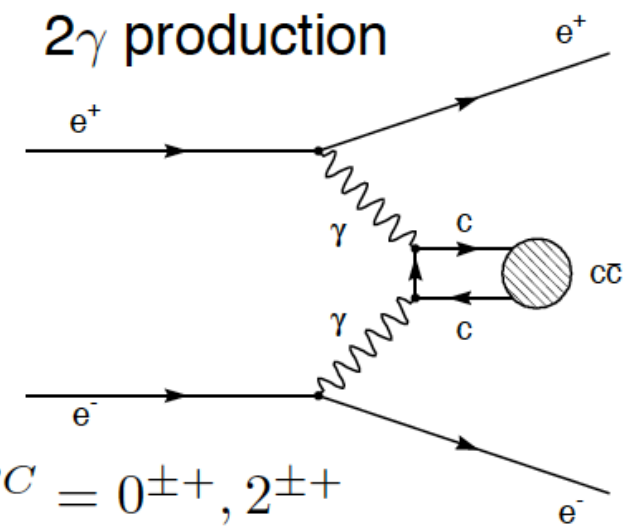
$$J^{PC} = 0^{-+},\ 1^{--},\ 1^{++}$$

Double charmonium production



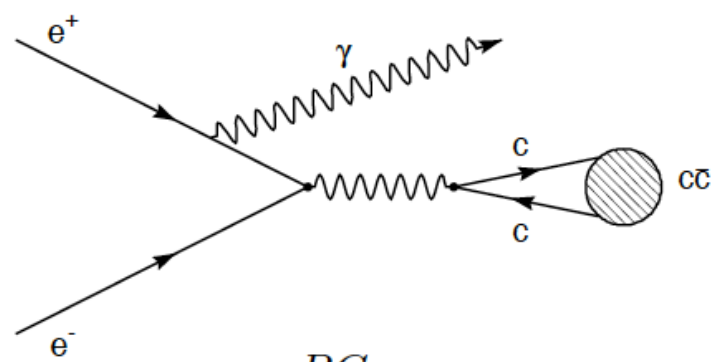
$$C = +1$$

2γ production



$$J^{PC} = 0^{\pm+}, 2^{\pm+}$$

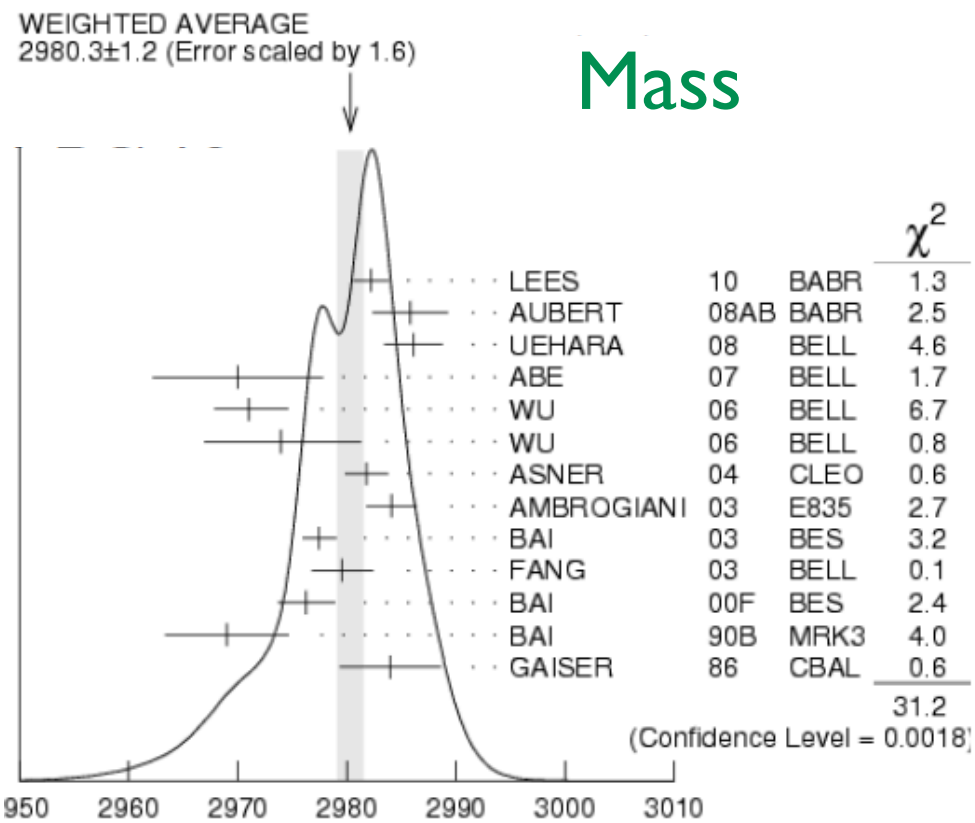
Initial State Radiation (ISR)

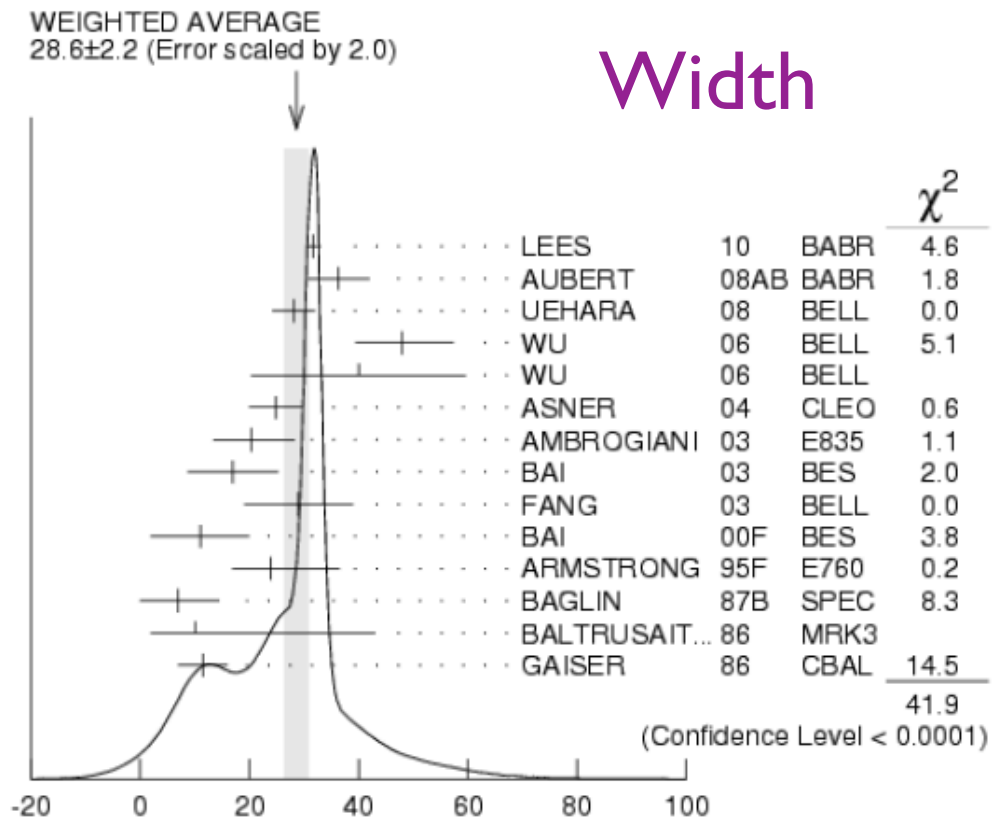


$$J^{PC} = 1^{--}$$

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

η_c properties from PDG 2010:





Large spread

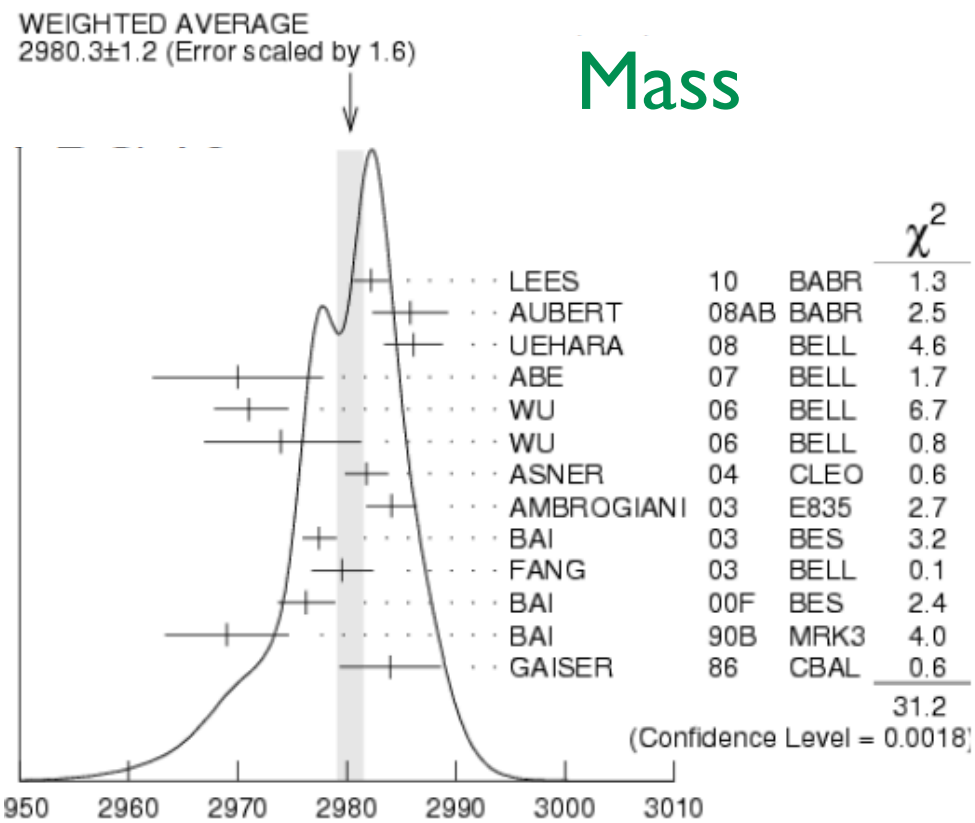
Large spread ➡ C.L. < 0.0001

$\Gamma \simeq 15$ MeV in J/ψ and ψ' radiative decays

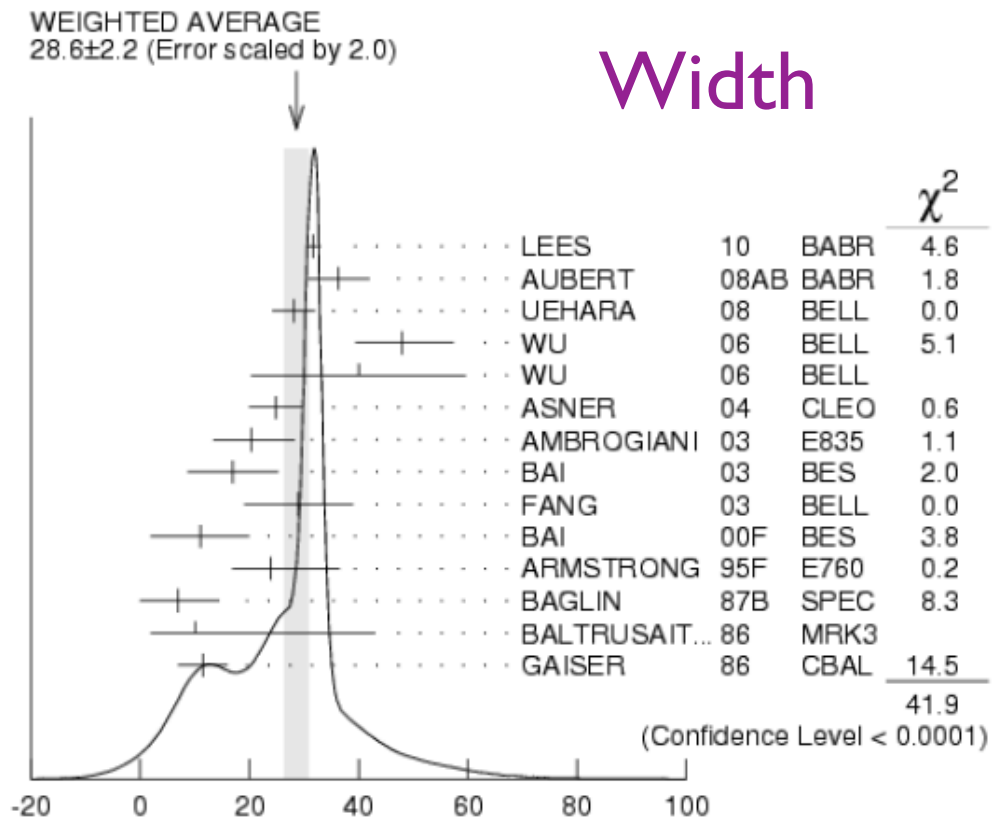
$\Gamma \simeq 30$ MeV in B decays

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

η_c *properties from PDG 2010:*



Large spread



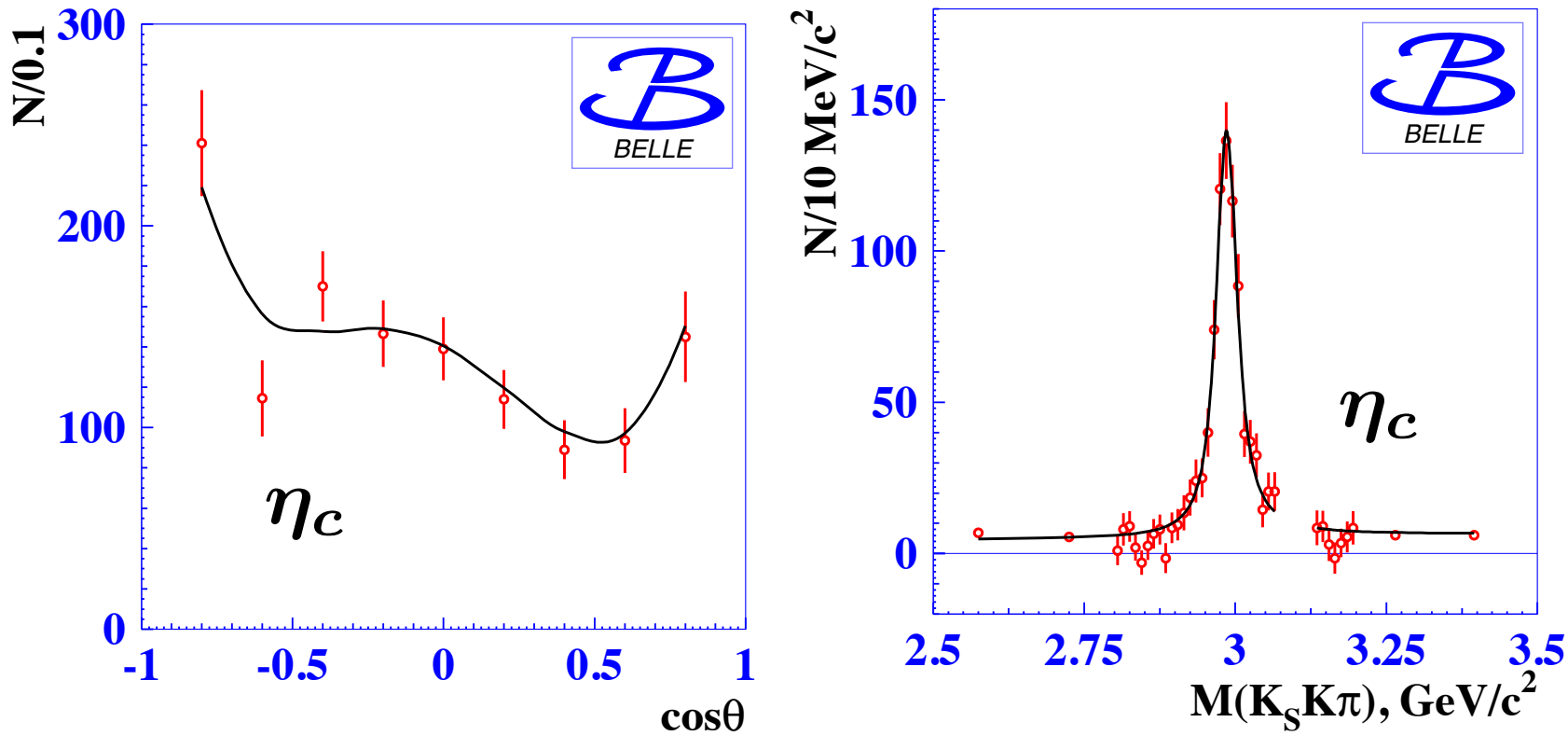
Large spread ➡ C.L. < 0.0001

$\Gamma \simeq 15$ MeV in J/ψ and ψ' radiative decays

$\Gamma \simeq 30$ MeV in B decays

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

η_c in $B^+ \to K^+(K_S K\pi)^0$ *to be submitted to PLB*



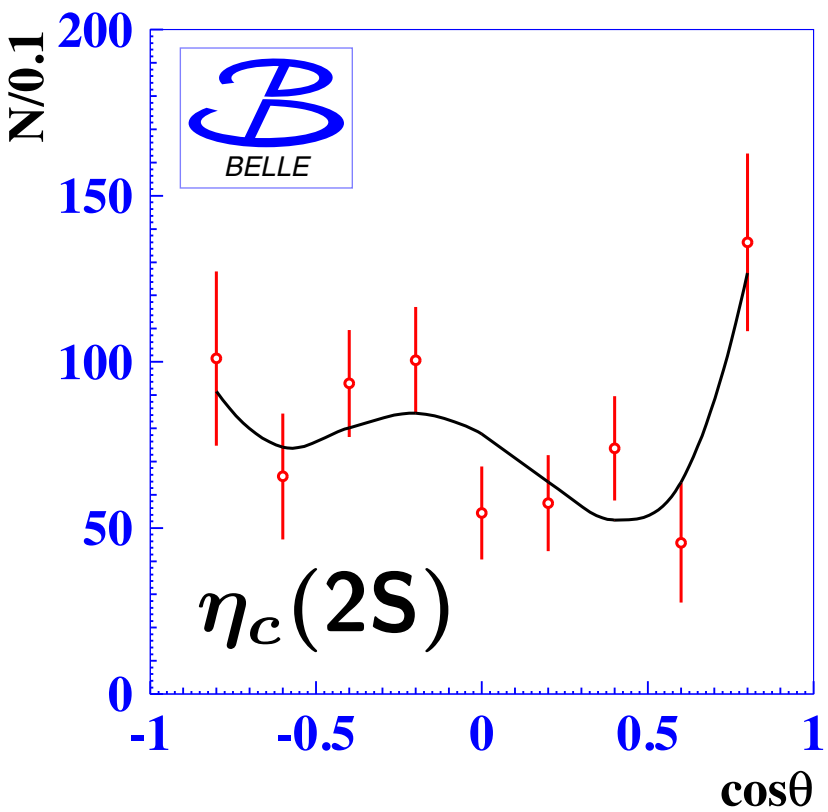
- 2D fit of $\angle(K^+ K_S)$ *vs* $M(K_S K\pi)$

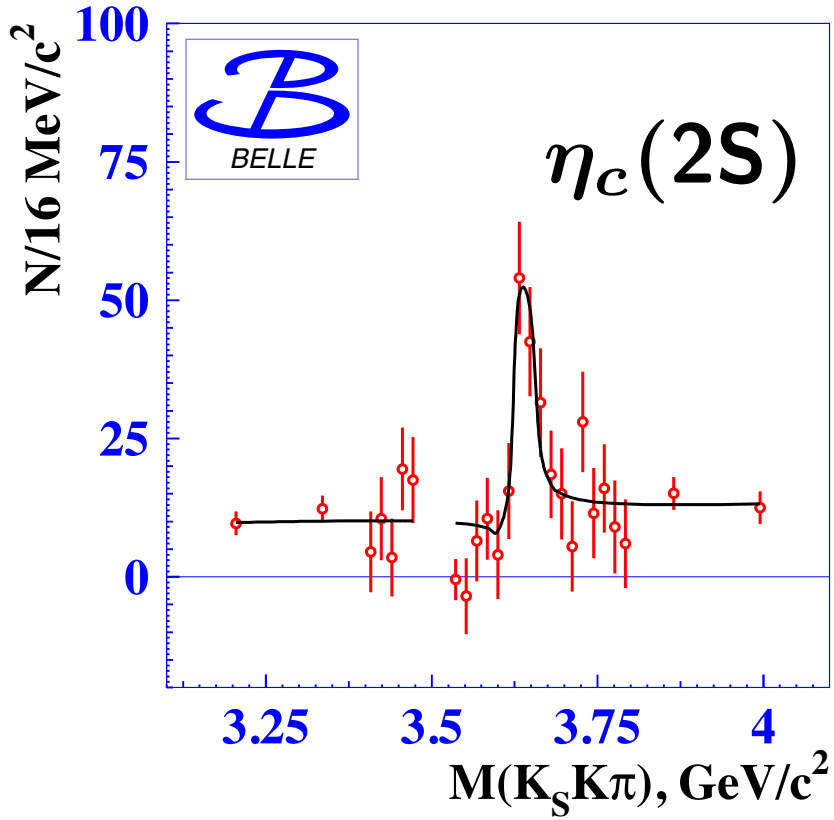
➡ $M = 2985.4 \pm 1.5 \pm {}^{0.2}_{2.0}$ MeV
$\Gamma = 35.1 \pm 3.1 \pm {}^{1.0}_{1.6}$ MeV

agree with BaBar's 2010 measurement in $\gamma\gamma \to \eta_c$

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

$\eta_c(2S)$ in $B^+ \to K^+(K_S K\pi)^0$ *to be submitted to PLB*





$$M = 3636.1 \pm {}^{3.9}_{4.1} \pm {}^{0.5}_{2.0}\ \text{MeV}$$
$$\Gamma = 6.6 \pm {}^{8.4}_{5.1} \pm {}^{2.6}_{0.9}\ \text{MeV}$$

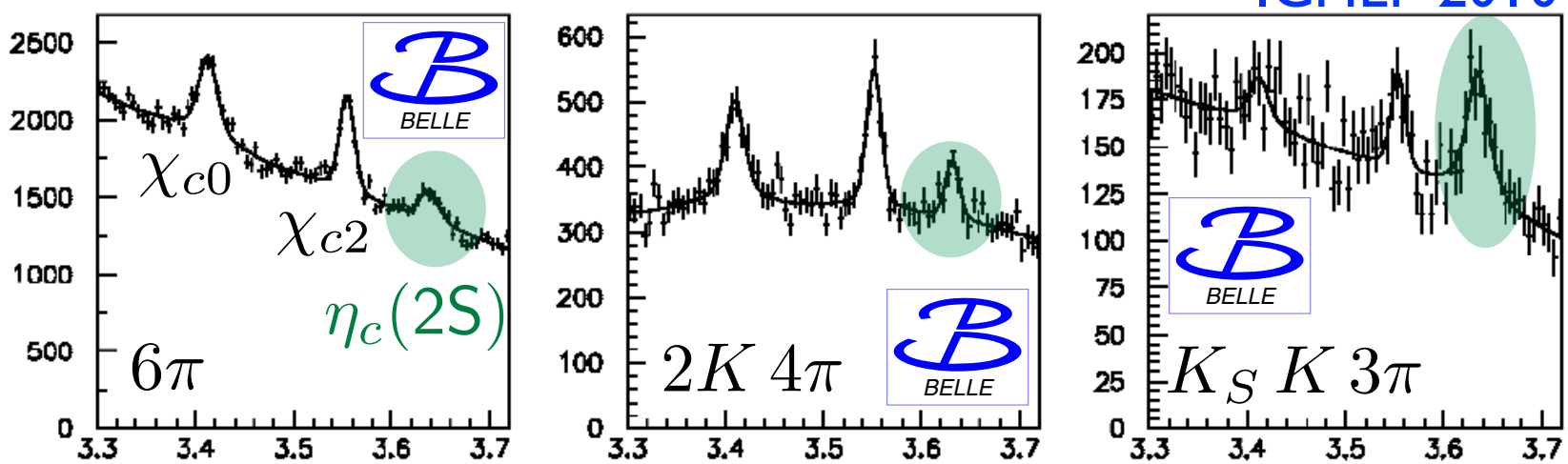
Interference is important!

Refit with no interference: $\Gamma = 41.1 \pm 12.0 \pm {}^{6.4}_{10.9}$ MeV

New final states seen for $\eta_c(2S)$

- Only one exclusive mode ($K_S K \pi$) 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	$10.2 \pm 2.3 \pm 3.4$
$K_S K 3\pi$	$3636.5 \pm 1.8 \pm 2.4$	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)

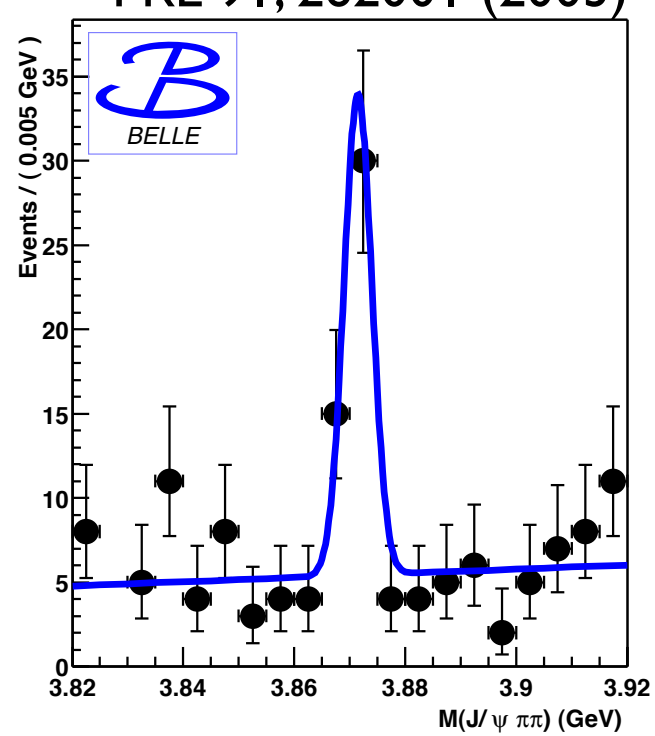
$X(3872)$ properties

- $M_X - (m_{D^0} + M_{D^{*0}}) = -0.32 \pm 0.35$ MeV
- In $X \to \pi^+\pi^- J/\psi$, $M_{\pi\pi}$ is consistent with ρ

  $\Rightarrow$ large isospin violation; suggests $C = +1$
- In $X \to \pi^+\pi^-\pi^0 J/\psi$, $M_{\pi\pi\pi^0}$ is consistent with ω, different isospin than $\rho J/\psi$. $J^{PC} = 1^{++}$ or 2^{-+} from an angular analysis.
- An S–wave $D^0\bar{D}^{*0}$ molecular state?

  E.S. Swanson, PLB 588, 189 (2004)

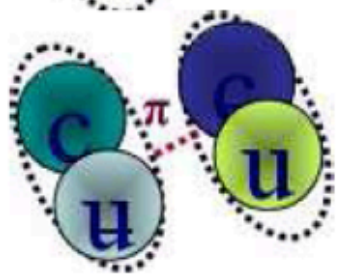
PRL 91, 262001 (2003)



Exotic charmonium-like states

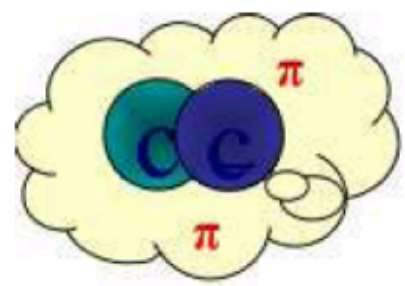
Tetraquark:
four tightly bound quarks

Molecular state:
two loosely bound mesons



Hybrid: states with
excited gluonic degrees of freedom

Hadrocharmonium: charmonium state,
"coated" by excited light-hadron matter

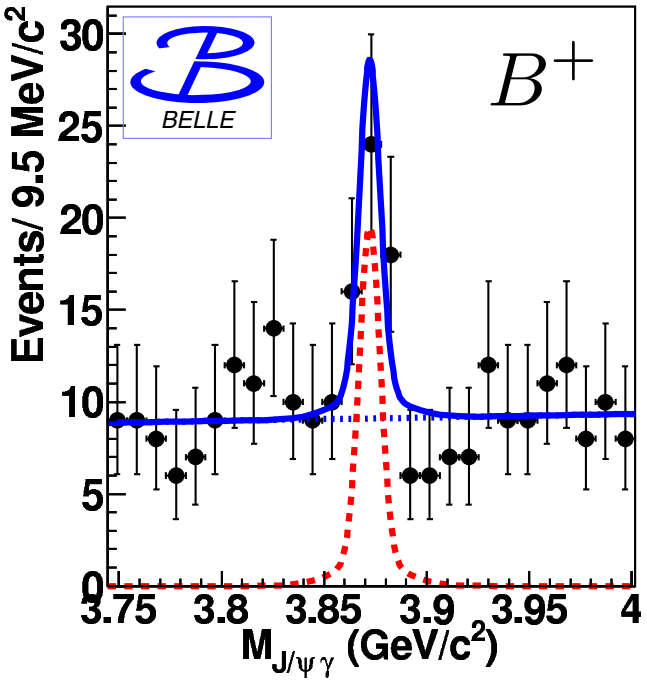


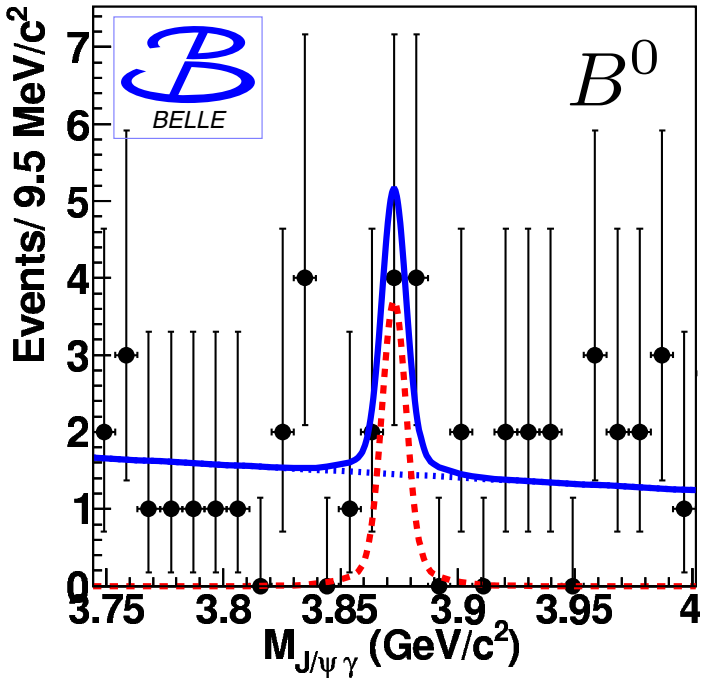
Exotics signature:
- J^{PC}, forbidden for charmonium
- Extremely narrow width for a state above $D\bar{D}$
- Non-zero charge, strangeness

$X(3872) \to J/\psi\,\gamma$ determines $C = +1$ assignment

- First seen by Belle in 2005 hep-ex/0505037
- New Belle measurement:

to be submitted to PRL





$N = 30.0 \pm {}^{8.2}_{7.4}$ $\qquad$ $N = 5.7 \pm {}^{3.5}_{2.8}$

$\mathcal{S} = 4.9\sigma$ $\qquad$ $\mathcal{S} = 2.4\sigma$

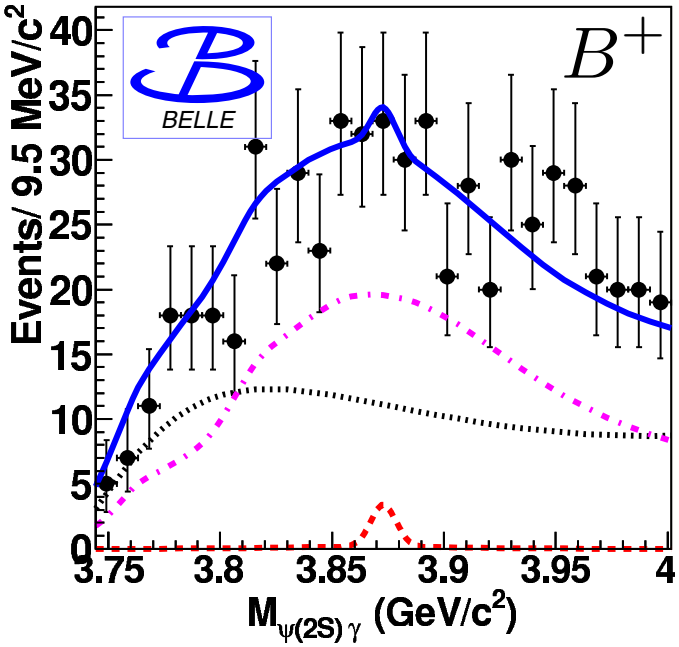
$$\mathcal{B}(B^+ \to K^+ X) \times \mathcal{B}(X \to J/\psi\,\gamma) = (1.8 \pm 0.5) \times 10^{-6}$$

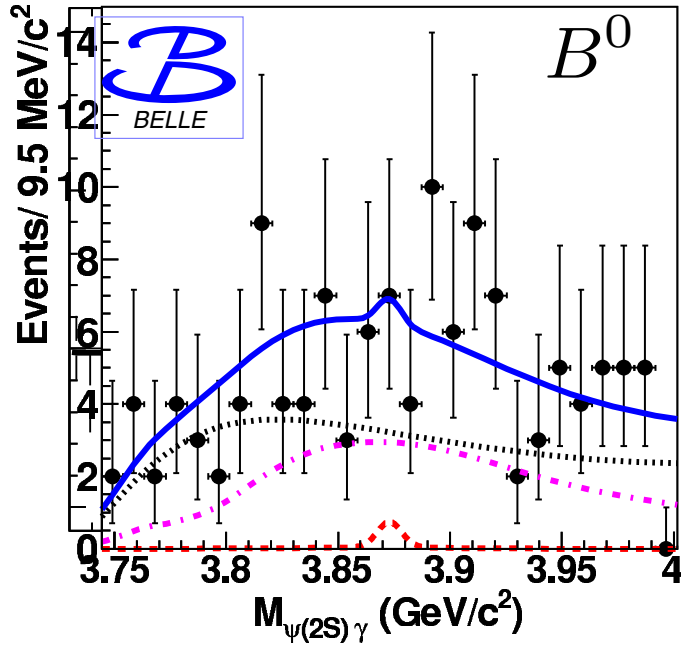
cf BaBar $(2.8 \pm 0.8) \times 10^{-6}$ PRL 102, 132001 (2009)

$X(3872) \to \psi' \gamma$ is not seen by Belle

- *but seen by BaBar PRL 102, 132001 (2009)*
- New Belle measurement:

to be submitted to PRL





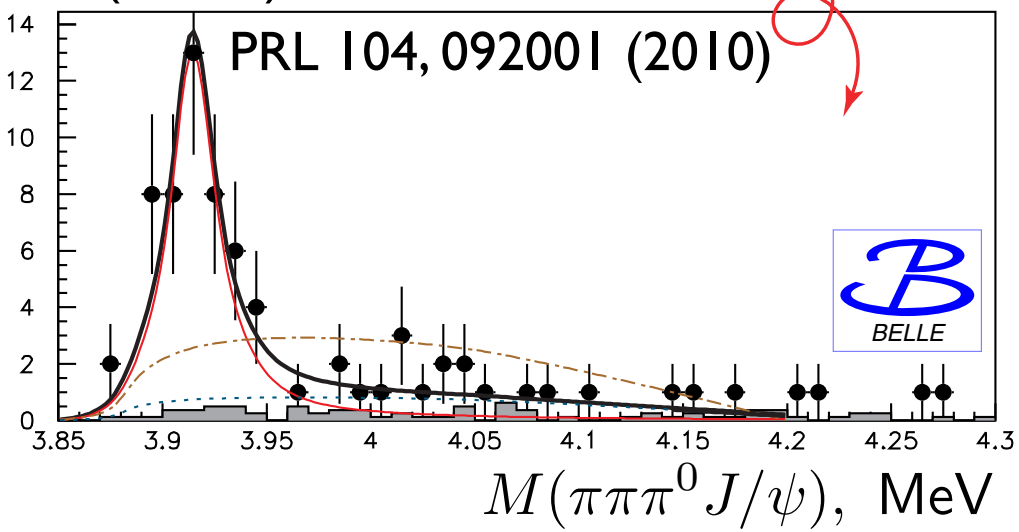
$$N = 5.0 \pm {}^{11.9}_{11.0} \qquad N = 1.5 \pm {}^{4.8}_{3.9}$$

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

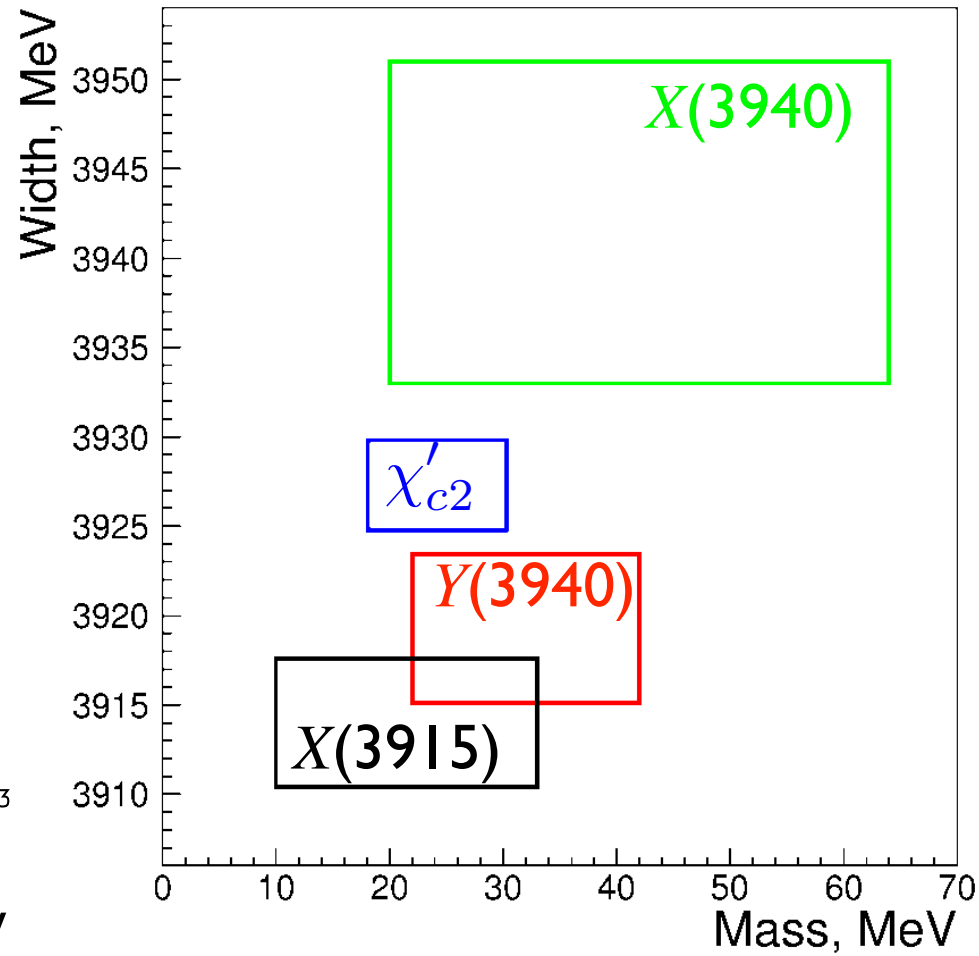
cf BaBar 3.4 ± 1.4

Other exotics near 3940 MeV: X, Y, and Z

- $X(3940)$ in $e^+e^- \to J/\psi\, D\bar{D}$
- $Y(3940)$ in $B \to K\omega J/\psi$
- $Z(3930)$ in $\gamma\gamma \to D\bar{D}$
- $X(3915)$ in $\gamma\gamma \to \omega J/\psi$



$$M(X(3915)) = 3915 \pm 3 \pm 2\,\text{MeV}$$
$$\Gamma(X(3915)) = 17 \pm 10 \pm 3\,\text{MeV}$$

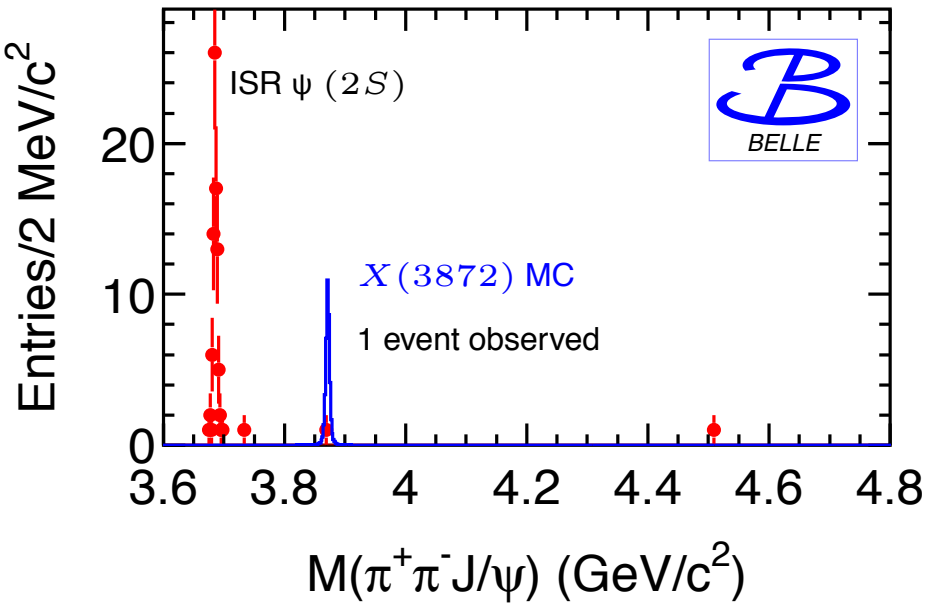


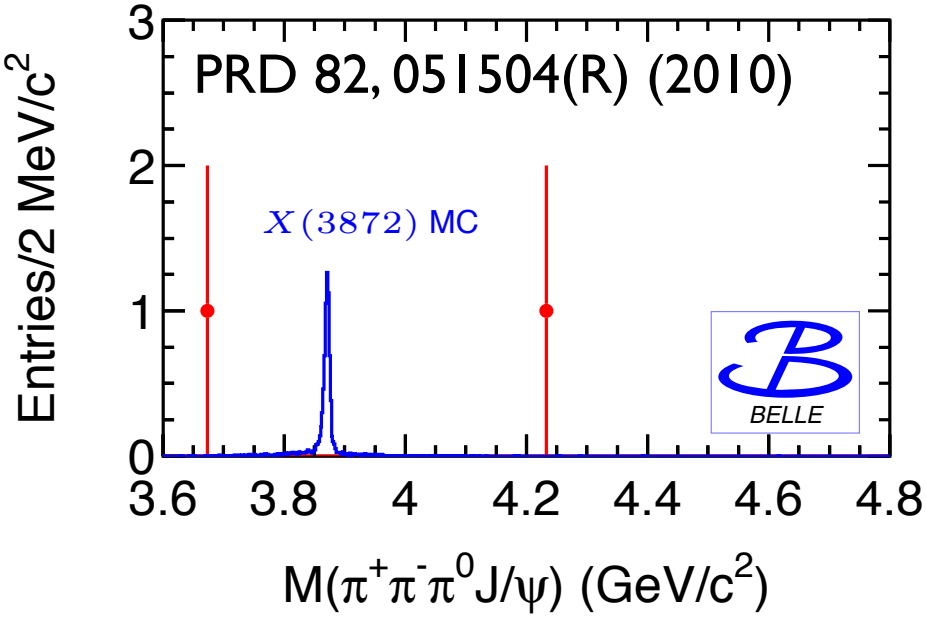
- $X(3915)$ = $Y(3940)$? hypothesis is compatible with data
- $X(3915)$ = $Z(3930)$ = χ'_{c2} ? Then

$$\mathcal{B}(\chi'_{c2} \to \omega J/\psi) > 0.08\,\mathcal{B}(\chi'_{c2} \to D\bar{D})$$ ... huge!?!

Null search for charmonium in $\Upsilon(1S)$ radiative decays

- No evidence for excited charmonium states below 4.8 GeV



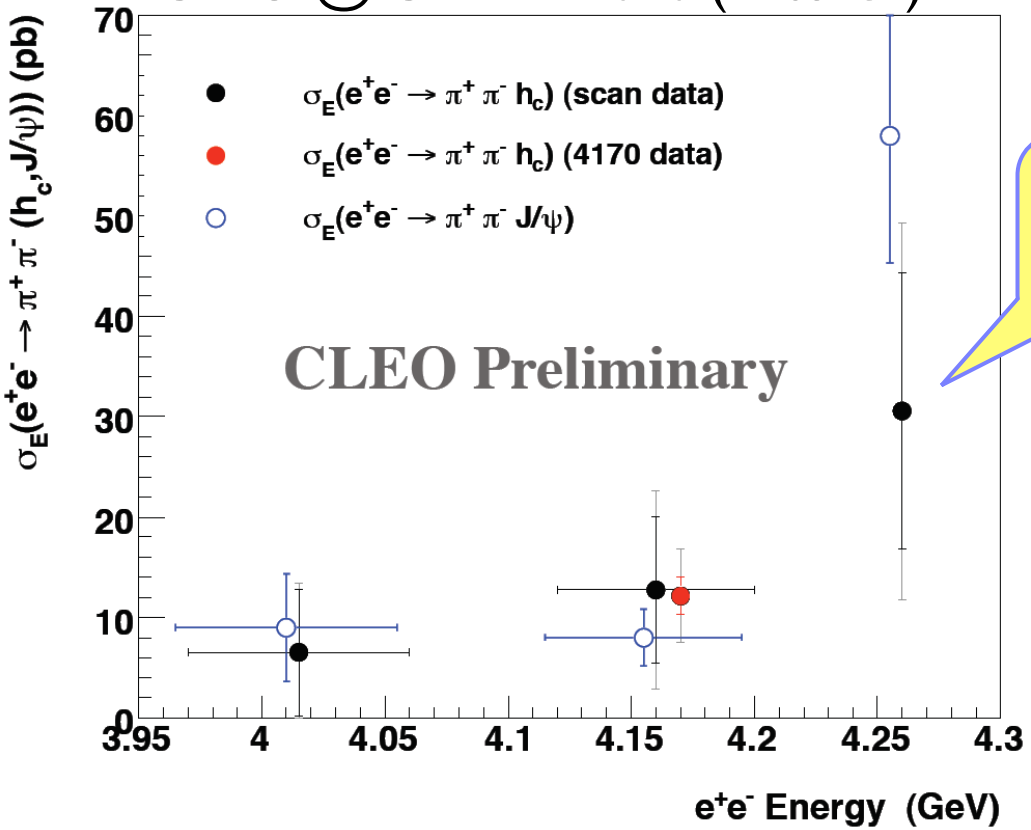


State (R)	$\mathcal{B}(10^{-5})$ Theor.	UL (90% CL)
χ_{c0}	3	< 65
χ_{c1}	1	< 2.3
χ_{c2}	0.6	< 0.76
η_c	5	< 5.7
$X(3872) \to \pi\pi J/\psi$		< 0.16
$X(3872) \to \pi\pi\pi^0 J/\psi$		< 0.28
$X(3915) \to \omega J/\psi$		< 0.30
$Y(4140) \to \phi J/\psi$		< 0.22

Observation of $h_b(1P)$ and $h_b(2P)$

Motivation for the h_b search

CLEO @ CHARM2010 (Mitchell)

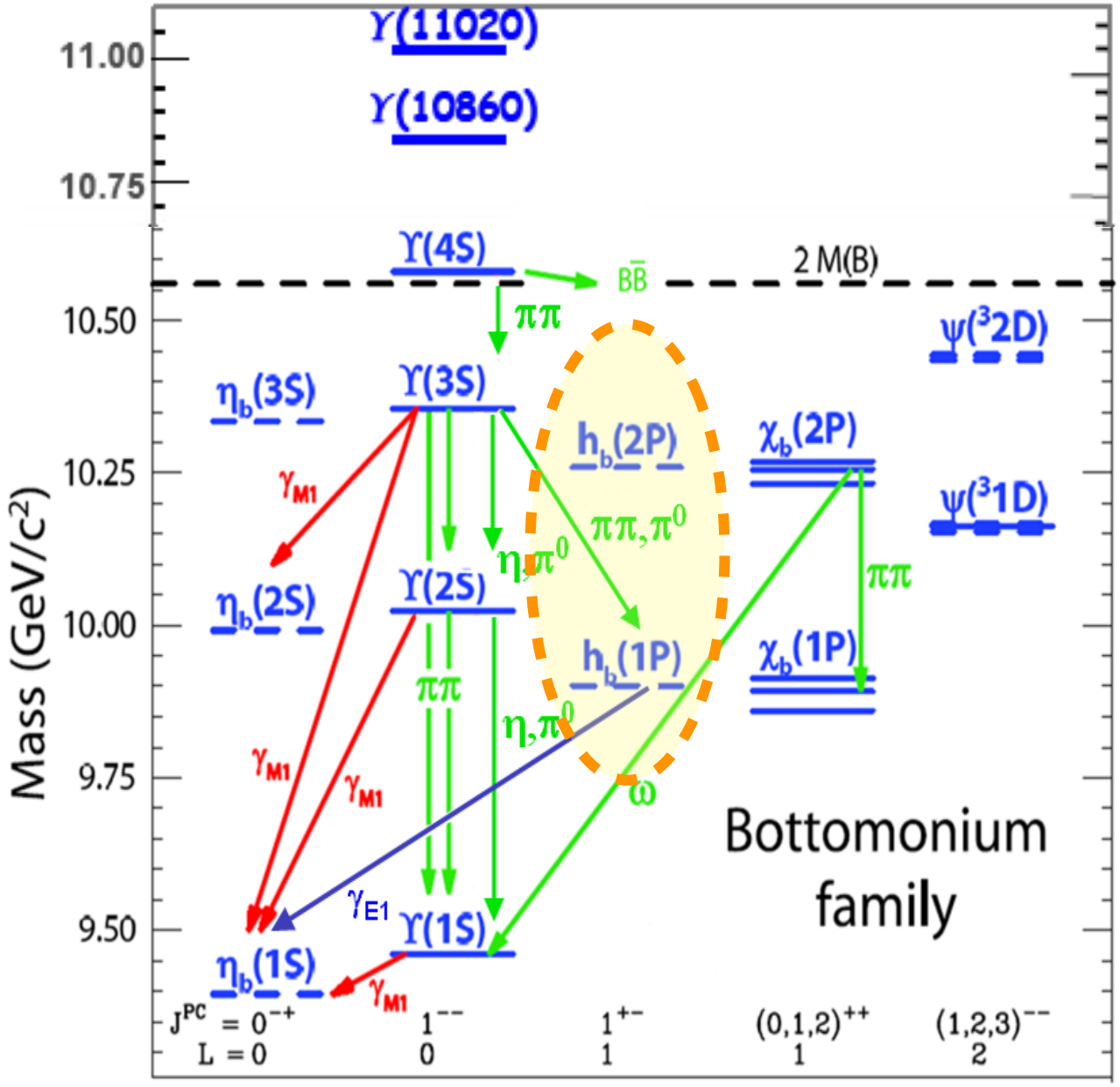


Enhancement of $\sigma(h_c\pi\pi)$ @ $Y(4260)$

... suggests $\sigma(h_b\pi\pi)$ might be enhanced at Y_b, the B analog of $Y(4260)$

- Search for the h_b in our $\Upsilon(5S)$ data

Expectations for the h_b and $h_b(2P)$ masses



Use the missing-mass technique to find h_b and $h_b(2\mathrm{P})$

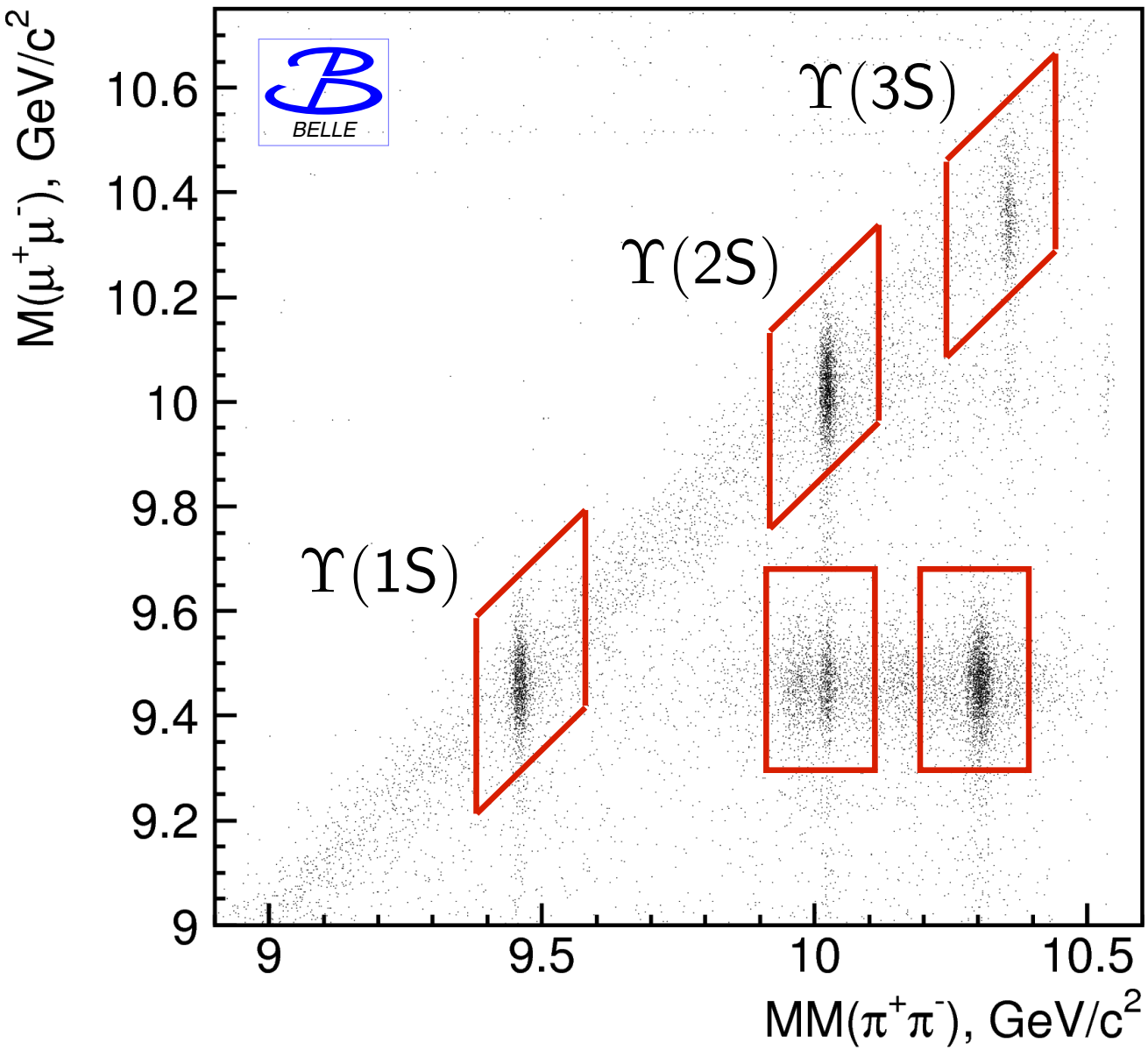
$$\Upsilon(5\mathrm{S}) \to h_b(\mathrm{nP})\,\pi^+\pi^-$$

From CM energy and boost (accelerator information)

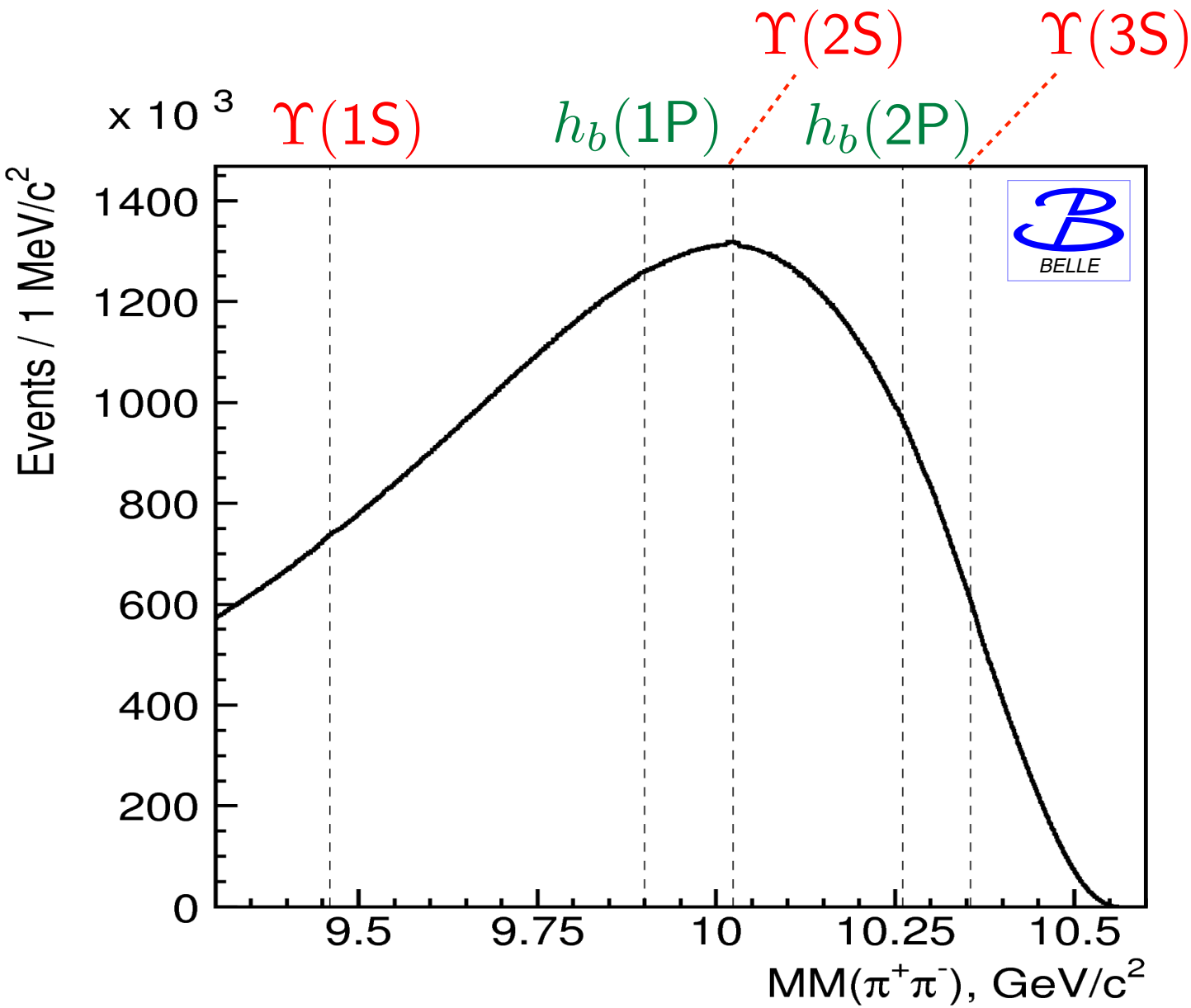
$M(h_b) = \mathrm{MM}(\pi^+\pi^-)$

reconstructed pion pair

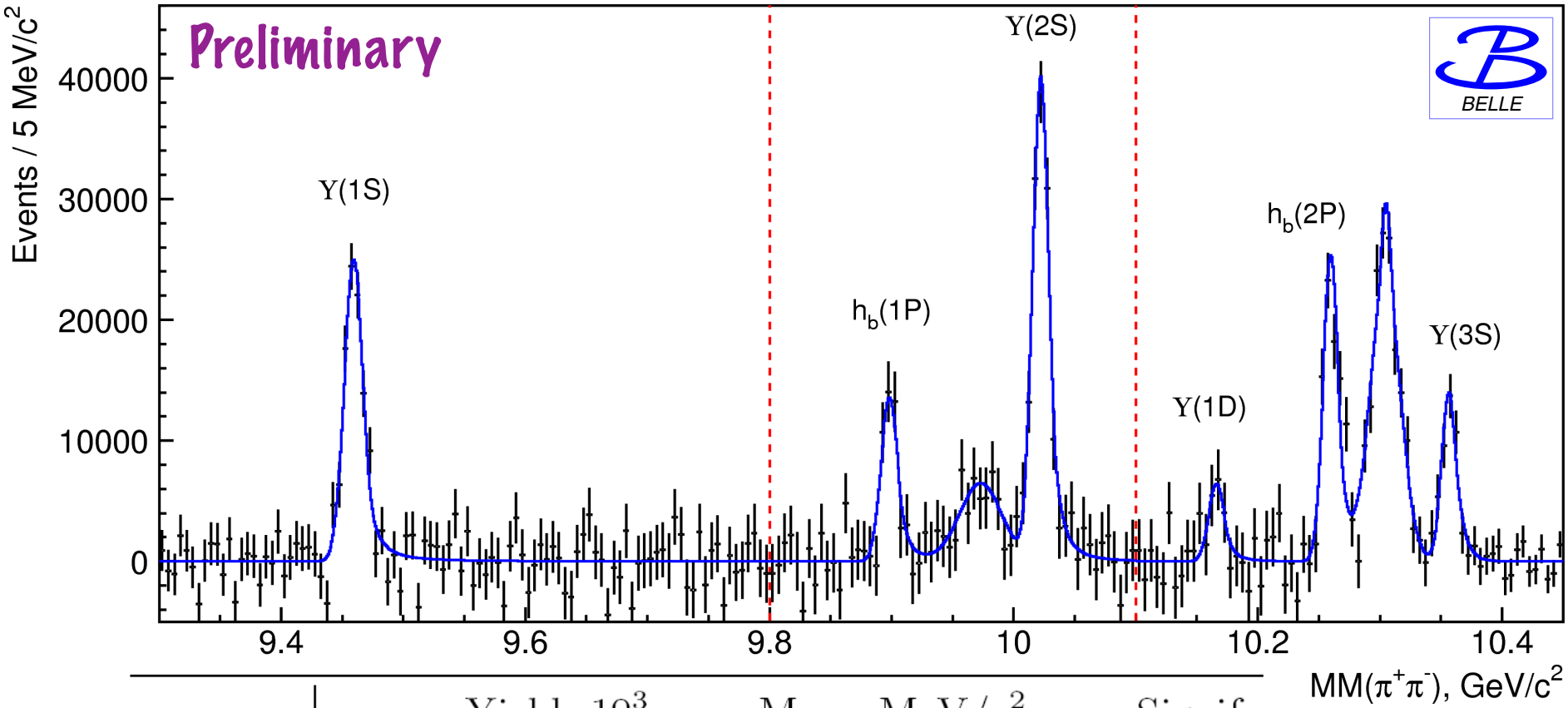
Calibration: $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-, \quad \Upsilon((nS) \to \mu^+\mu^-$



Use the missing-mass technique to find h_b and $h_b(2P)$



Use the missing-mass technique to find h_b and $h_b(2P)$



	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	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.76 \pm 0.64^{+1.43}_{-1.03}$	$12.4\,\sigma$

Results for h_b and $h_b(2\mathrm{P})$

- $M(h_b(1\mathrm{P})) = 9898.25 \pm 1.06 \pm {}^{1.03}_{1.07}$ MeV
- $M(h_b(2\mathrm{P})) = 10259.76 \pm 0.64 \pm {}^{1.43}_{1.03}$ MeV
- Deviations from centre-of-gravity of χ_{bJ} masses is consistent with zero, as expected
- Why are these not $\chi_{b1}(\mathrm{nP})$?
  - The strong decay $\Upsilon(5\mathrm{S}) \to \chi_{b1}(\mathrm{nP})\pi^+\pi^-$ would violate isospin conservation
  - The masses are significantly different:

$$\Delta M(1\mathrm{P}) = -5.47 \pm 1.56 \quad (3.5\sigma)$$
$$\Delta M(2\mathrm{P}) = -4.30 \pm 1.35 \quad (3.2\sigma)$$

$\Rightarrow$ observed states are $h_b(\mathrm{nP})$

Summary

- New precise measurements of masses and widths of η_c and $\eta_c(2S)$ with interference effects included in fits.
- Nature of the X(3872), the first observed exotic state, remains unclear; $X(3872) \to \omega J/\psi$ confirmed
- No $c\bar{c}$ states observed in $\Upsilon(1S)$ radiative decays
- The $h_b(1P)$ and $h_b(2P)$ have been seen with no suppression of production rate for the spin-flip modes

B factories have made surprising studies of new states in charmonia / bottomonia, but more studies and more data are needed to reveal their true nature.