26th Rencontres de Blois 2014, May 19-23

Recent results on quarkonium(-like) states at B-factories

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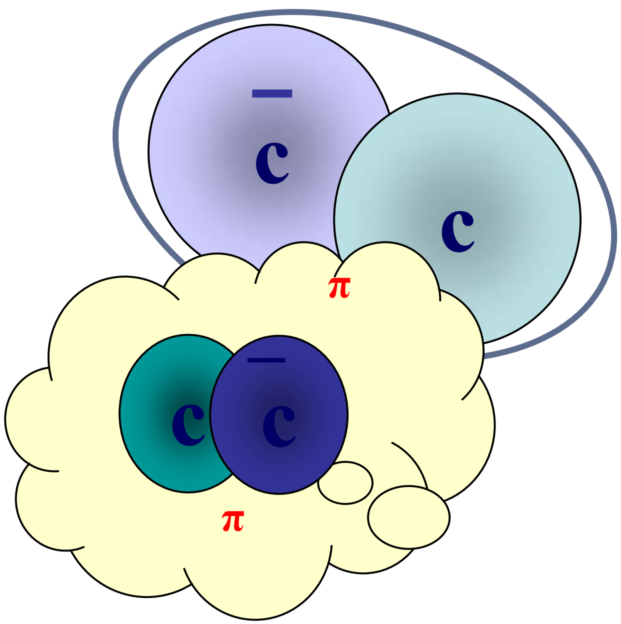
Representing

the Belle Collaboration

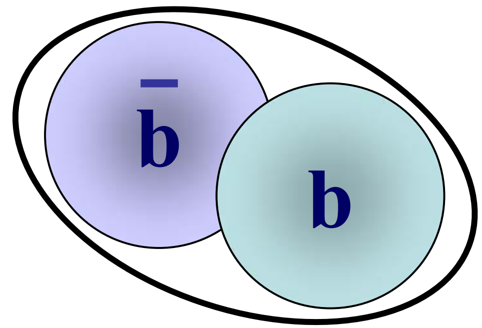


OUTLINE:

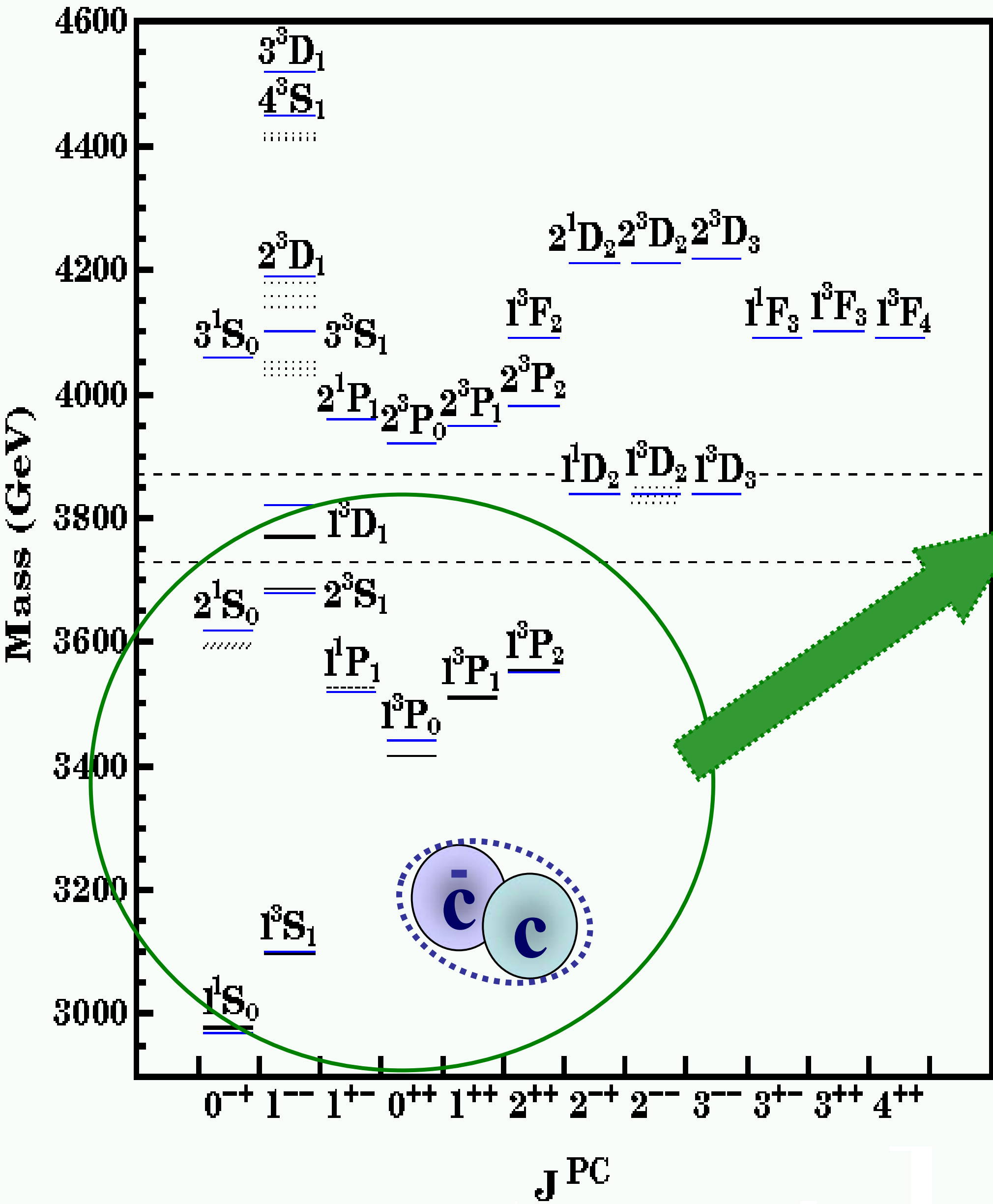
X(3872), Z^+

X(4140/4270) $\rightarrow$ J/$\psi\,\phi$

Υ(4/5S)$\rightarrow h_b\,\eta$



Predictions for conventional charmonia



$\eta_c(1S) \equiv 1^1S_0$

$J/\psi \equiv 1^3S_1$

$\chi_{cJ}(1P) \equiv 1^3P_J$

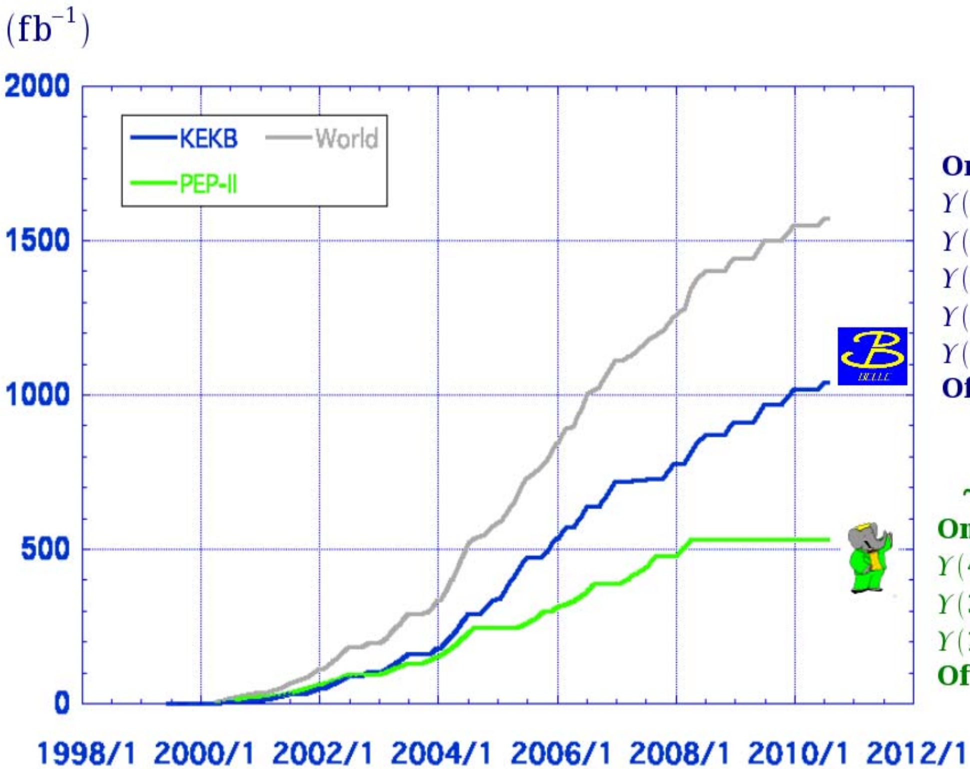
Theory described well the observed spectrum of cc states →

The charmonium system is ideal place to search for *exotic states = deviations from conventional charmonium spectroscopy.*

Until the B-factories –

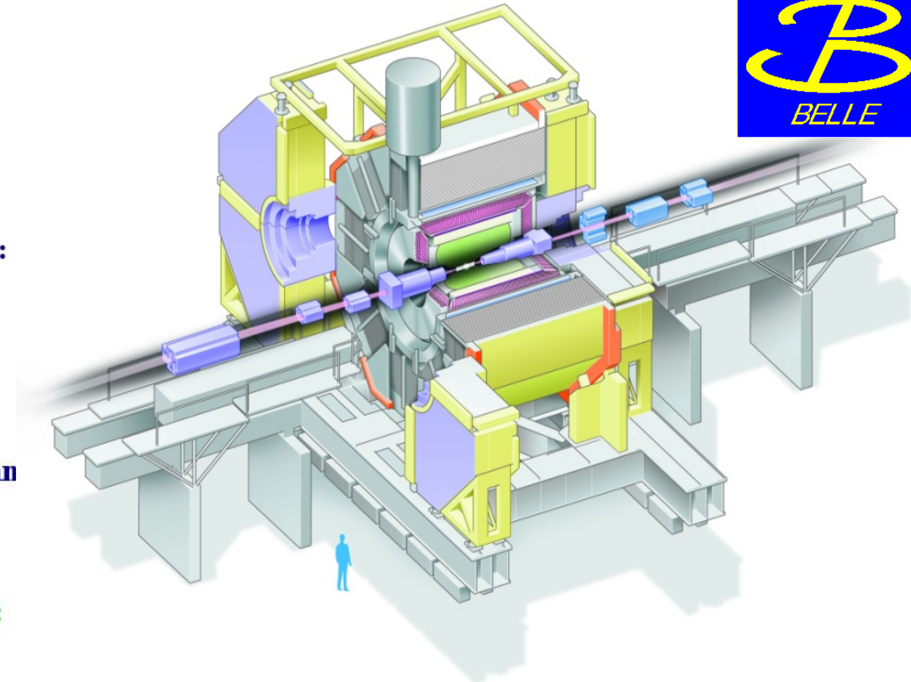
no evidence for such deviations

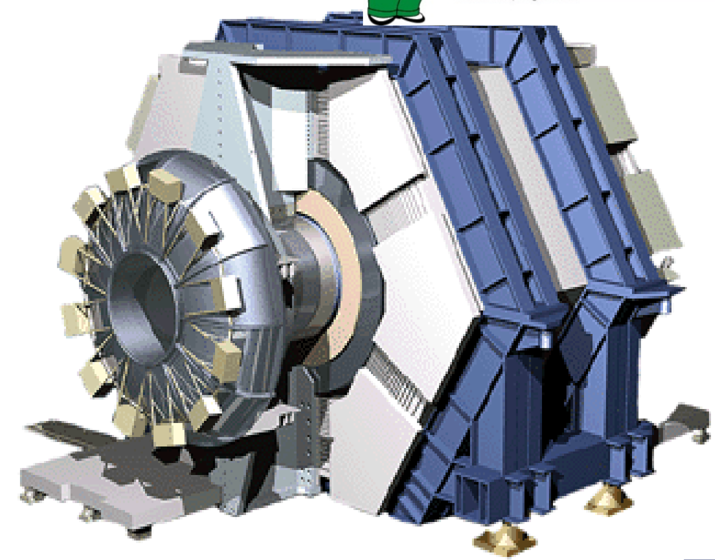
Luminosity at B factories



> 1 ab^{-1}
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 reson./scan
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

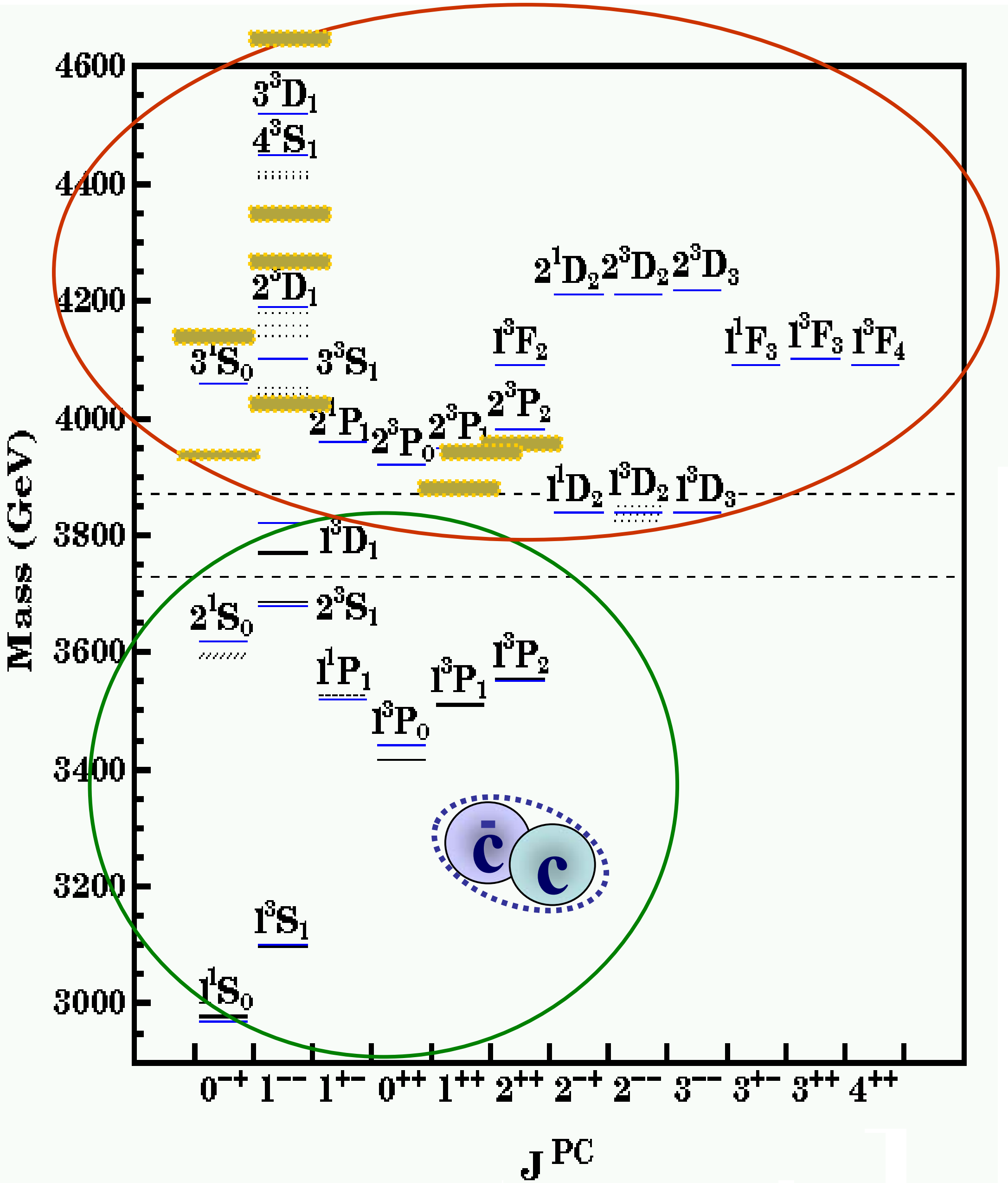




In sum $\mathcal{L}$ >1552 fb^{-1}

For 9 years the B-factories have observed a number of states that do not admit a conventional quarkonium interpretation.
These states could be made of more than 2 quarks.
So, unworried heavy quarkonium picture is broken!

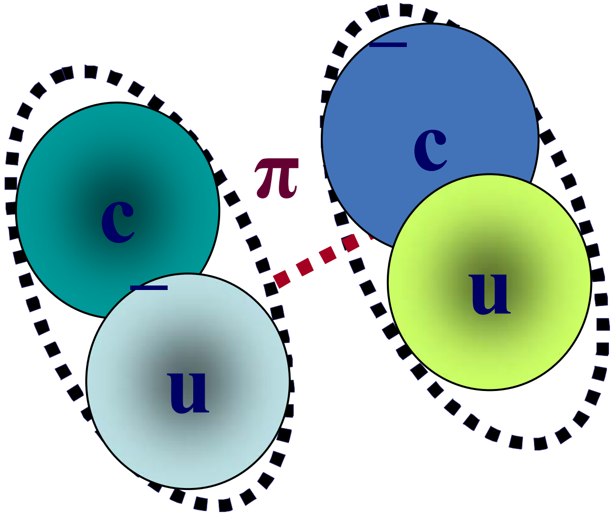
New $c\bar{c}$-like states



A number of unexpected exotic states above $D\bar{D}^{(*)}$ thresholds that do not fit into available $c\bar{c}$ slots were found

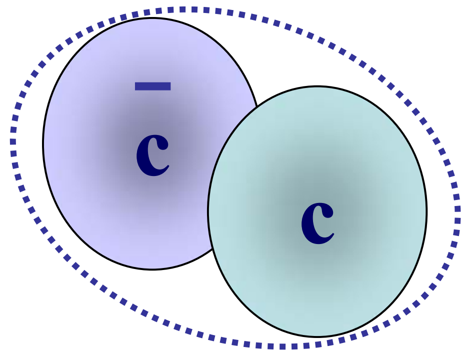
State	M, MeV	Γ, MeV	J^{PC}	Process
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6 (< 2.2)	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$ $p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$ $B \to K(\omega J/\psi)$ $B \to K(D^{*0}D^0)$ $B \to K(\gamma J/\psi)$ $B \to K(\gamma\psi(2S))$
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$ $\gamma\gamma \to (\omega J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$ $e^+e^- \to J/\psi\ (...)$
$Y(4008)$	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^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$

X(3872): a mixture of



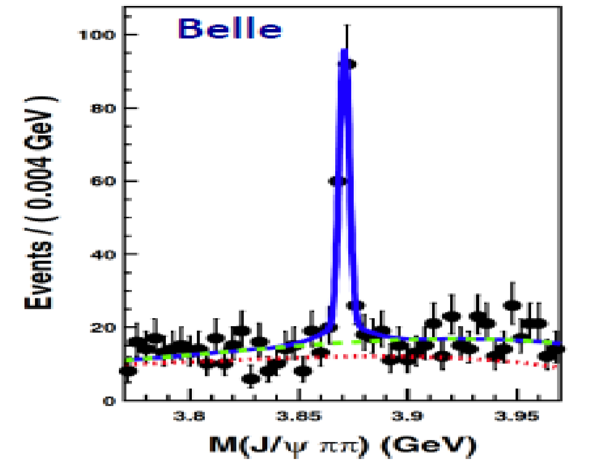
'peripheral' part
dominant at large distance

molecule



'core' part
localized at short distance,
e.g. 2^3P_1+'others'..

charmonium



$M_X = 3871.85 \pm 0.27 \pm 0.19$ MeV

Belle: PRD 84 052004

X(3872) was confirmed by all players in heavy flavours

Decays into DD*
And $J/\psi\ \rho^0$,
$J/\psi\ \omega$

Isospin mixed
pionic transitions

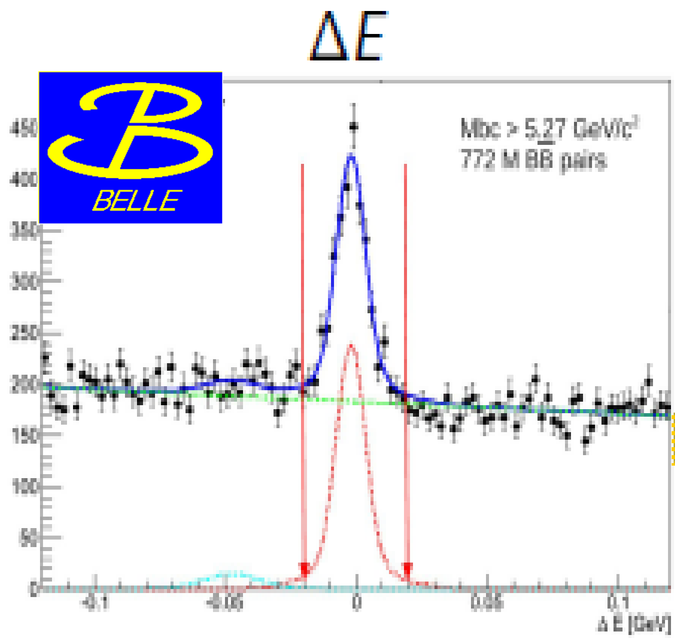
Production
And decays into
$J/\psi\ \gamma$ and $\psi(2S)\ \gamma$

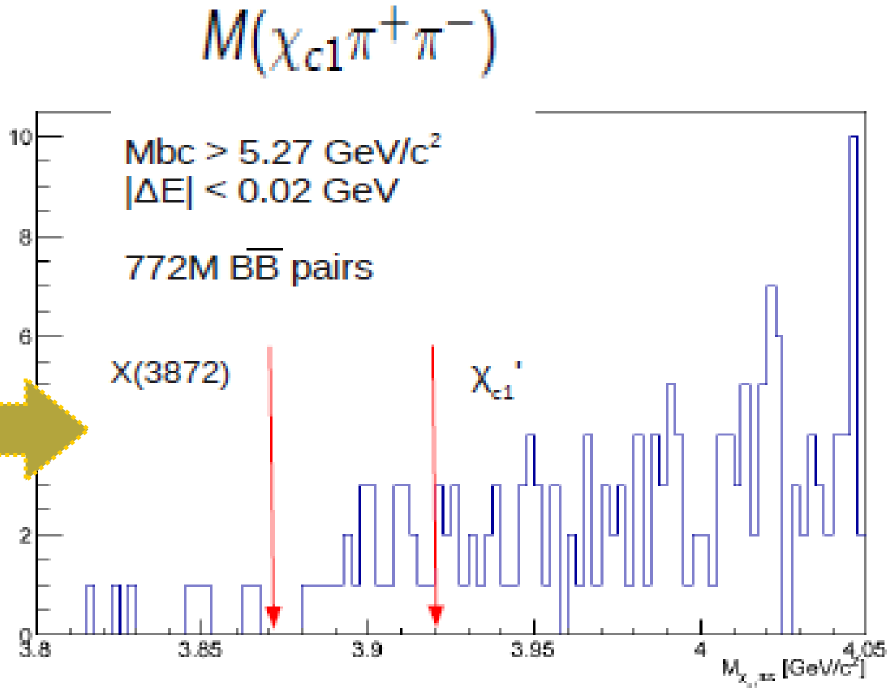
One or other part may be important in specific processes

Searches for new X decay modes are needed to explore in detail its properties and internal structure

Recent results on X(3872) decays:

Search for $X(3872) \to \chi_{c1}\pi^+\pi^-$ in $B^+ \to \chi_{c1}\pi^+\pi^- K^+$





- no evidence for either X(3872) nor χ_{c1}'

Observation of $B^\pm \to \chi_{c1}\pi^+\pi^-K^\pm$ (1597 ± 76 events).

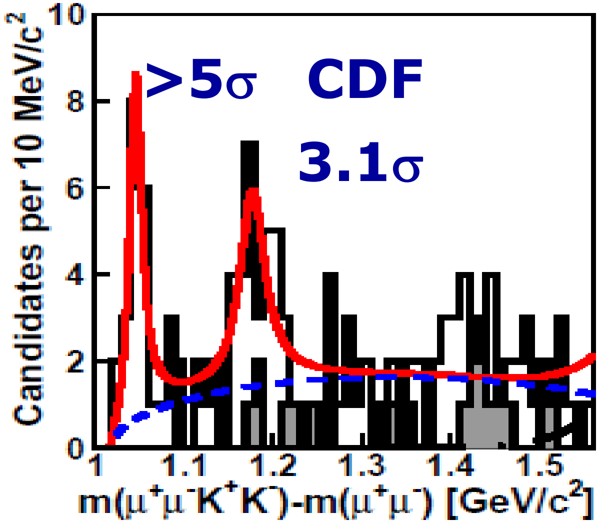
Search for $X(3872)$ / $\chi_{c1}(2P)$: no resonances found.

$\mathcal{B}(B \to \chi_{c1}\pi^+\pi^-K) = (3.94 \pm 0.19 \pm 0.30) \times 10^{-4}$.

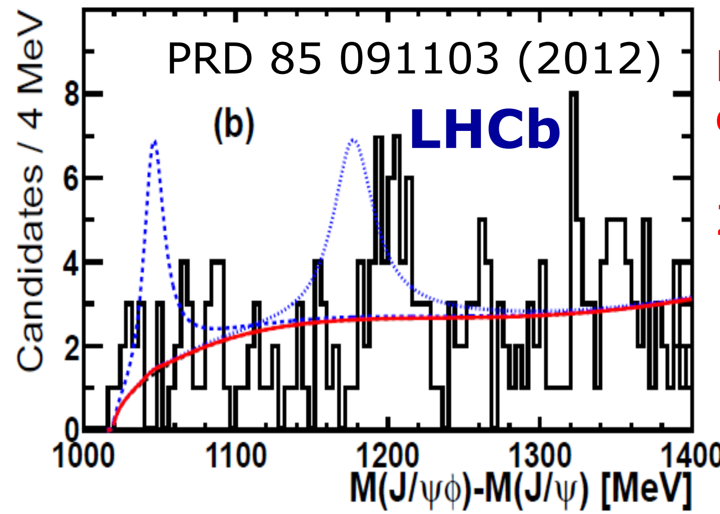
Preliminary

The X(4140), X(4270) →J/ψϕ story

arXiv:1101.6058 (2011)

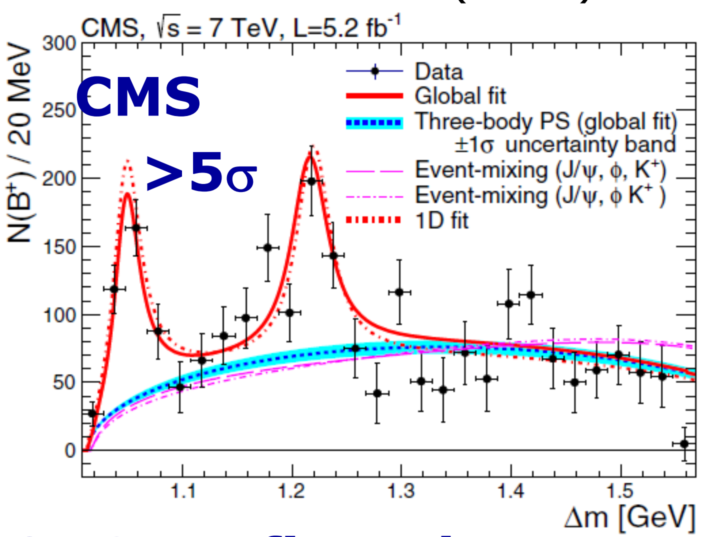


CDF reported the study of the decay mode $B^+ \to J/\psi\,\phi\,K^+$

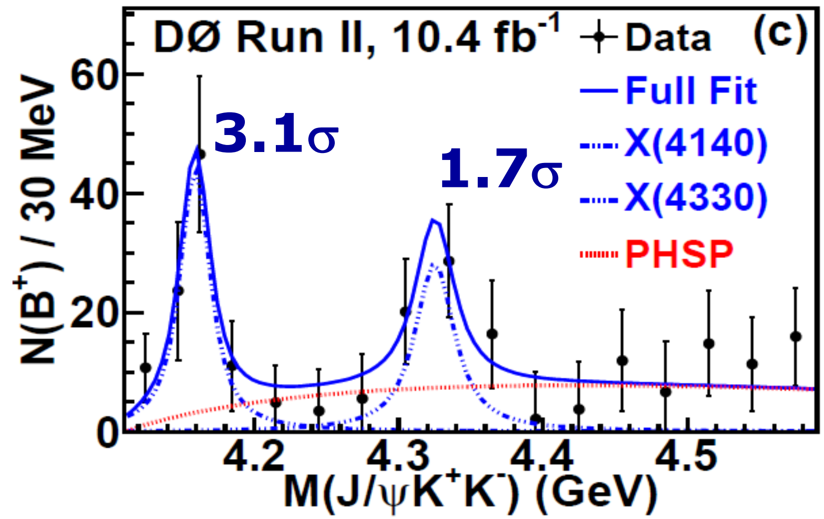


LHCb didn't confirm these peaks, 2.4σ disagr. with CDF

arXiv:1309.6920 (2011)

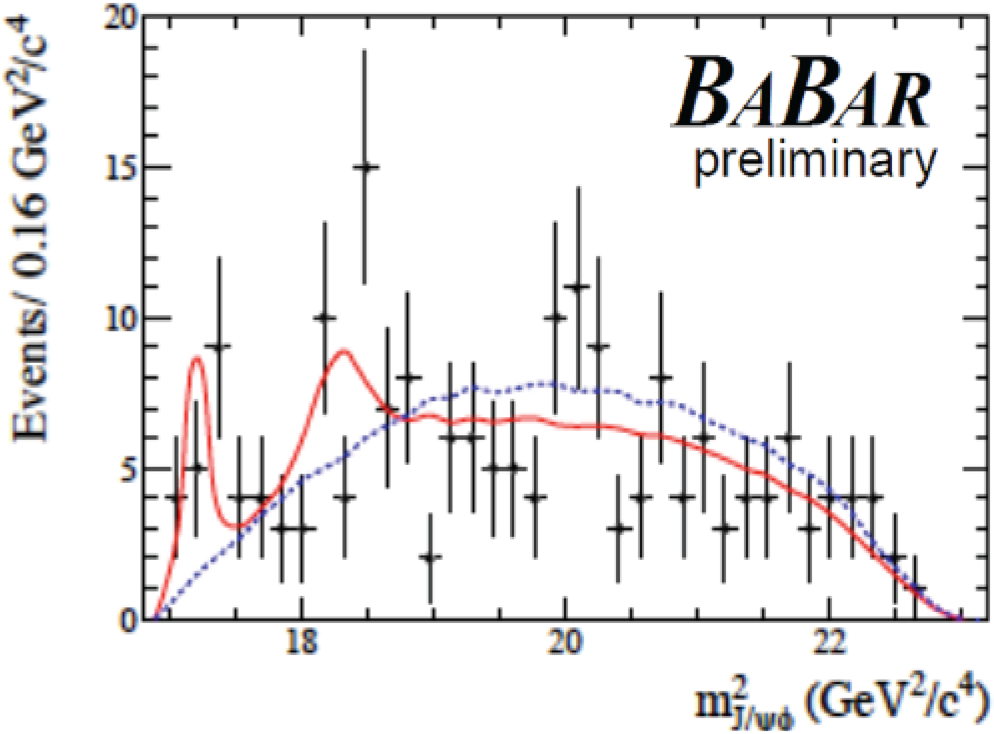


CMS confirmed two resonances



D0 published evidence for these resonances

Search for X(4140) in $B^+ \to J/\psi\, \phi K^+$ decays at BaBar



Experiments	$f\,(4140)$ [%]	$f\,(4270)$ [%]
CDF	$14.9 \pm 2.9 \pm 2.4$	-
LHCb	<7	< 8
D0	$19 \pm 7 \pm 4$	-
CMS	13.4 ± 3.0 (*)	18.0 ± 7.3 (*)

Fit fractions with the assumption of two resonances

- f(4140) = (7.3 ± 2.5 ± 3.8)%; Upper Limit (90% CL) = 12.1%
- f(4270) = (7.7 ± 3.7 ± 5.2)%; Upper Limit (90% CL) = 16.4%

No clear conclusion from BaBar on these resonances

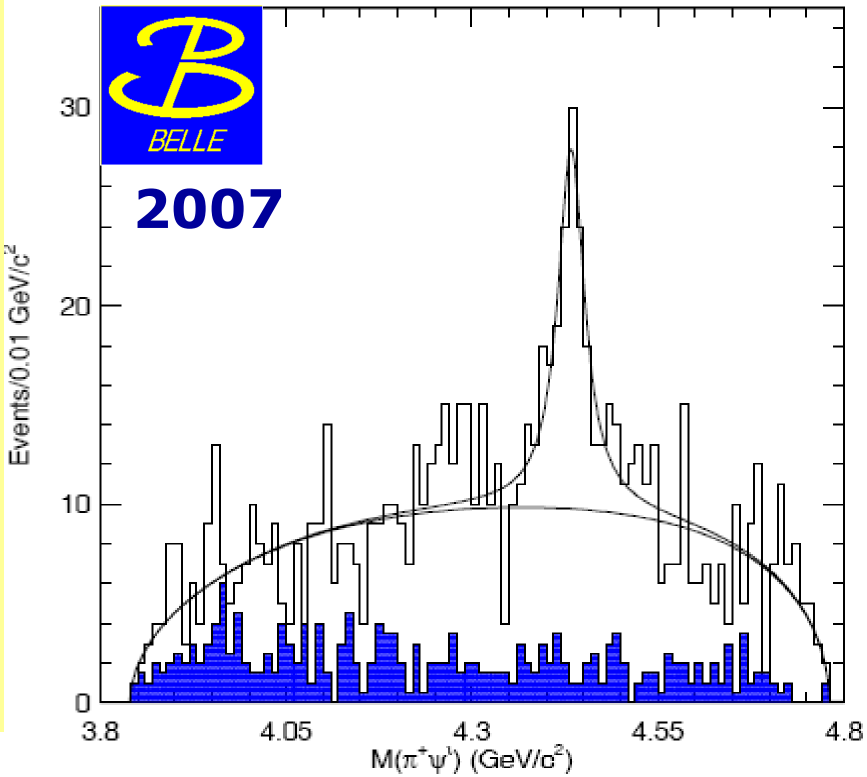
- Lack of **statistics**
- Need a **full Dalitz plot analysis**

Charged Charmonium-like States

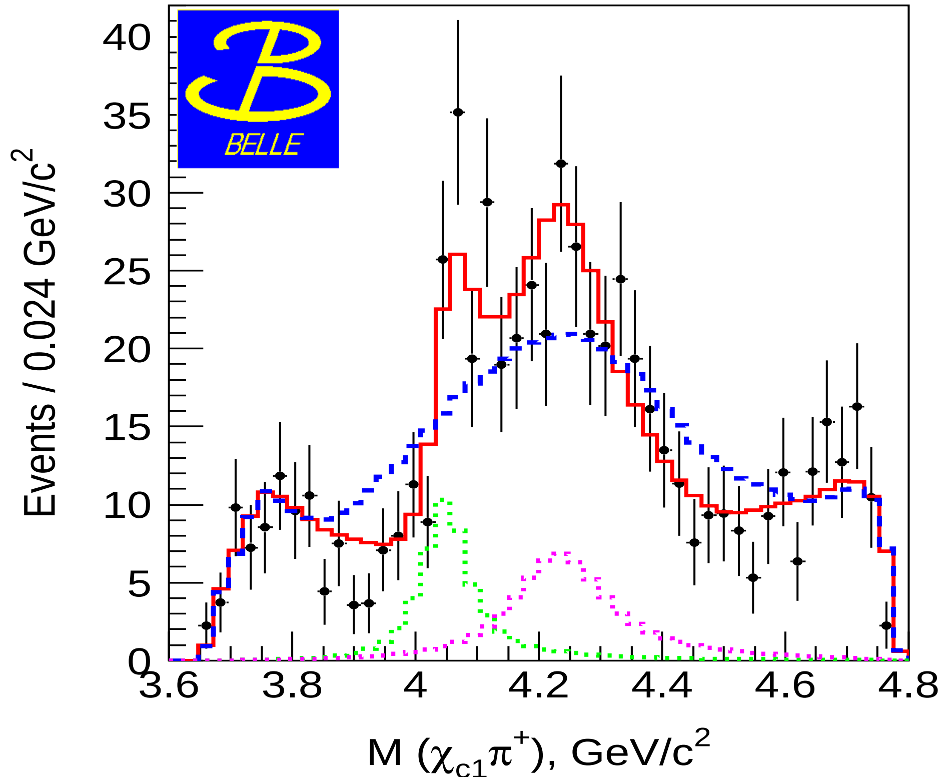
$Z(4430)^+$, $Z(4050)^+$, $Z(4250)^+$ at Belle

PRL 100, 142001 (2008)

$B^0 \to \pi^+\psi(2S)\,K^-$



$B^0 \to \pi^+\chi_{c1}\,K^-$



PRD 78, 072004 (2008)

Total significance: 6.5 σ and >5σ for each Z^+

These states have no chance to be a pure cc (unlike neutral XYZ)

Belle updated $Z(4430)^+ \to \psi(2S)\pi^+$ analysis

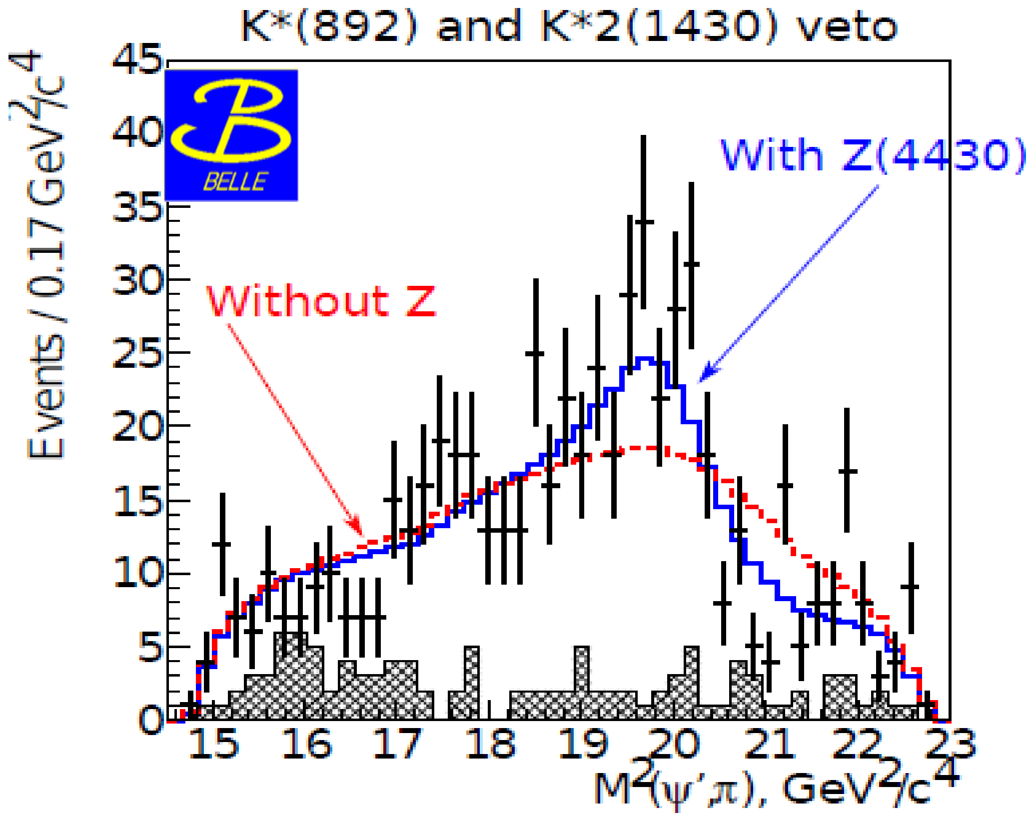
Phys.Rev. D88 074026 (2013)

$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV}/c^2,$$

$$\Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}.$$

Preferred J^P hypothesis: 1^+.
Exclusion levels (0^-, 1^-, 2^- and 2^+ hypotheses): 3.4σ, 3.7σ, 4.7σ and 5.1σ.

4-dimensional amplitude analysis of $B^0 \to \psi(2S)K^+\pi^-$



J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4479 ± 16	4477 ± 4	4485 ± 20	4478 ± 22	4384 ± 19
Width, MeV	110 ± 50	22 ± 14	200 ± 40	83 ± 25	52 ± 28
Significance	4.5σ	3.6σ	6.4σ	2.2σ	1.8σ

Amplitude analysis of $B \to J/\psi\, \pi\, K$

NEW

4D amplitude analysis (similar to $Z(4430)^+$)

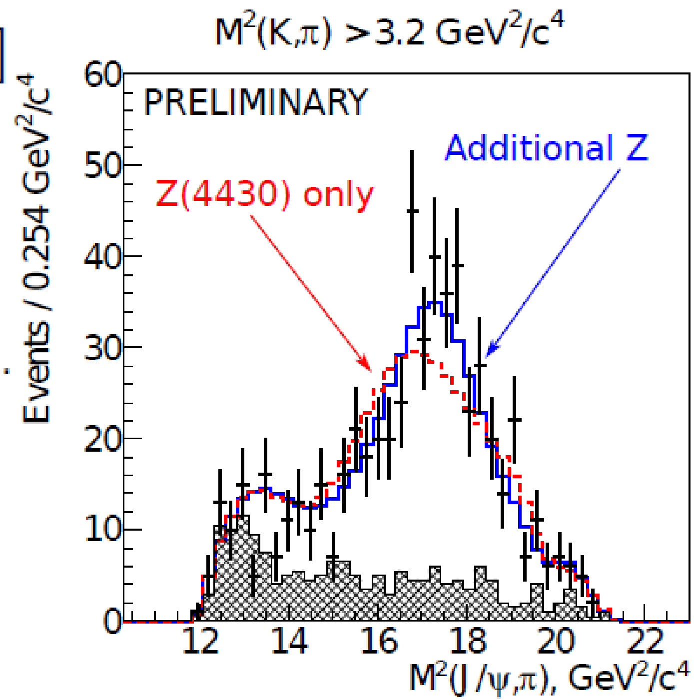
Search for $Z(4430)^+$ and another additional Z^+ decaying into $J/\psi\pi^+$

New Z_c^+ is found ($J^P = 1^+$) [$Z_c(4200)^+$, 7.2σ with syst. error]

$$M = 4196^{+31+17}_{-29-6}\ \mathrm{MeV}/c^2,\ \Gamma = 370^{+70+70}_{-70-85}\ \mathrm{MeV}.$$

$J^P = 1^+$

Exclusion levels ($J^P = 0^-, 1^-, 2^-, 2^+$): 6.7σ, 7.7σ, 5.2σ, 7.6σ.



$Z(4430)^+$ is also found (4σ) $\Rightarrow$ new decay mode of $Z(4430)^+$

$$\mathcal{B}(\bar{B}^0 \to Z_c(4430)^+ K^-) \times \mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6}$$

$$\mathcal{B}(\bar{B}^0 \to Z_c(4200)^+ K^-) \times \mathcal{B}(Z_c(4200)^+ \to J/\psi\pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5}$$

- $$\frac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} \sim 10$$

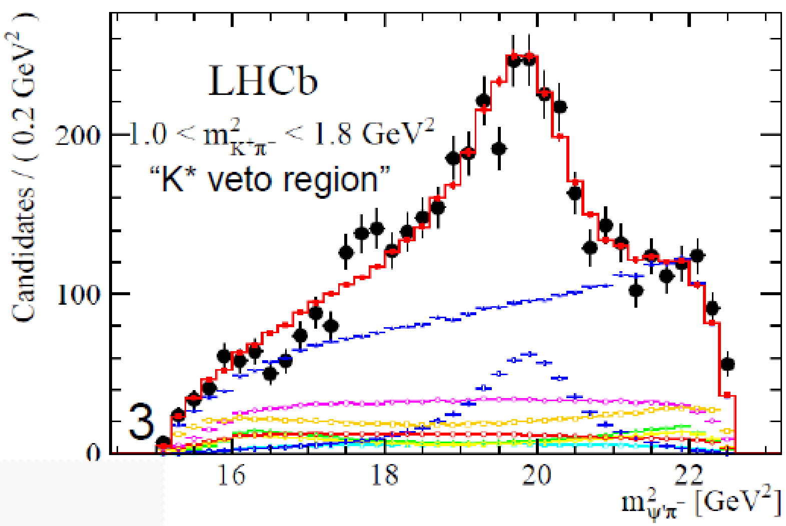
It could be a sign of a complex structure of $Z(4430)^+$ wavefunction

Preliminary

Since 2007 Belle remained confident that their analysis is sound and the peaks in $\pi^+\psi'$ and $\pi^+\chi_{c1}$ masses are not due to the reflections from the dynamics in $K\pi$ system.

Last year new charged charmonium-like state, $Z(3900)^+ \to J/\psi\ \pi^+$, was observed by BES III and Belle.

Very recently the first charmonium-like charged state, $Z(4430)^+ \to \psi(2S)\ \pi^+$, discovered by Belle in 2007 was finally confirmed by LHCb



	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_Z^I [%] (with interferences)	$16.7 \pm 1.6^{+2.6}_{-5.2}$	
Significance	$> 13.9\sigma$	$> 5.2\sigma$

Interpretation of Z^+

Charged, I=1

Cannot be a conventional charmonium or hybrid state

Should contain light quarks in addition to cc

A variety of interpretations (not a complete list…):

- D^*D_1 molecular state
(X. Liu *and* Y.R. Liu, 0711.0494);

- radially excited tetraquark
(L.Maiani, A.D.Polosa, V.Riquer, 0708.3997);

- hadro-charmonium
(S.Dubinskiy,M.B.Voloshin,0803.2224)

η transitions in *bottomonia*

The transitions between Upsilons with η emission are suppressed in comparison with $\pi\pi$ in QCD multipole expansion models. S→Sη requires spin flip (E1 M1 transition)

Ok with theory

	CLEO	BaBar	Belle
$\Upsilon(2S)\to\Upsilon(1S)\,\eta$	$2.1^{+0.7}_{-0.6}\pm0.3$	$2.39\pm0.31\pm0.14$	$3.57\pm0.25\pm0.21$
$\Upsilon(3S)\to\Upsilon(1S)\,\eta$		<0.1	
$\Upsilon(4S)\to\Upsilon(1S)\,\eta$		$1.96\pm0.06\pm0.09$	
$\Upsilon(5S)\to\Upsilon(1S)\,\eta$	2-3 orders of magnitude higher than theoretical. expectations		$7.3\pm1.6\pm0.8$
$\Upsilon(5S)\to\Upsilon(2S)\,\eta$			$38\pm4\pm5$

$\times10^{-4}$

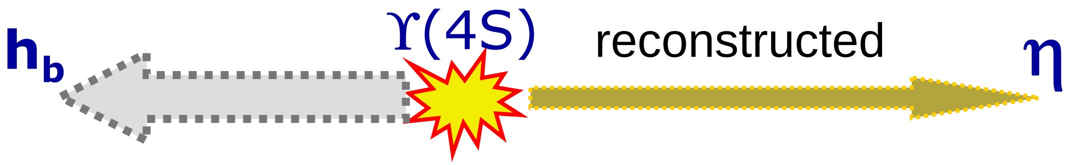
Coupled channels effects (hadronic loops) account for

But what with $\Upsilon(4/5S)\to h_b\eta$? (never observed so far)

$\Upsilon(4S)\to h_b\eta$ is expected to be as large as 10^{-3} [PRL 105 (2010) 162001]

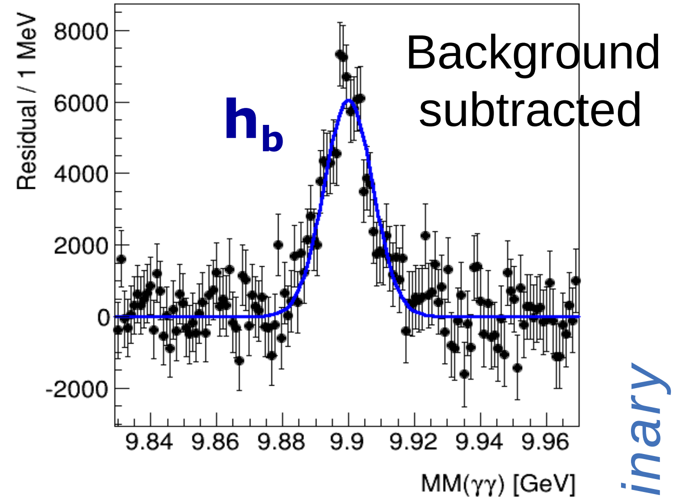
First observation of $\Upsilon(4S) \to h_b \eta$ at Belle

NEW



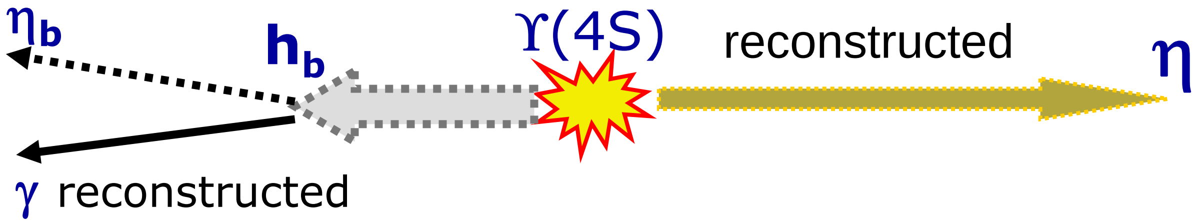
$M(h_b)$ = "Missing mass" = $\sqrt{(P_{e+e-} - P_\eta)^2}$

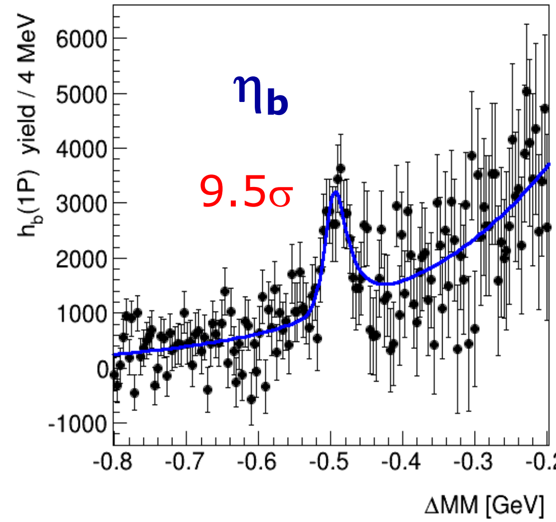
$Br(\Upsilon(4S) \to h_b \eta) = (1.83 \pm 0.16 \pm 0.17) \times 10^{-3}$



Preliminary

Then additional photon is reconstructed
$\Delta MM = MM(\gamma\eta) - MM(\eta) = M(\eta_b) - M(h_b)$





$M(\eta_b) = (9405.3 \pm 1.3 \pm 3.0)$ MeV

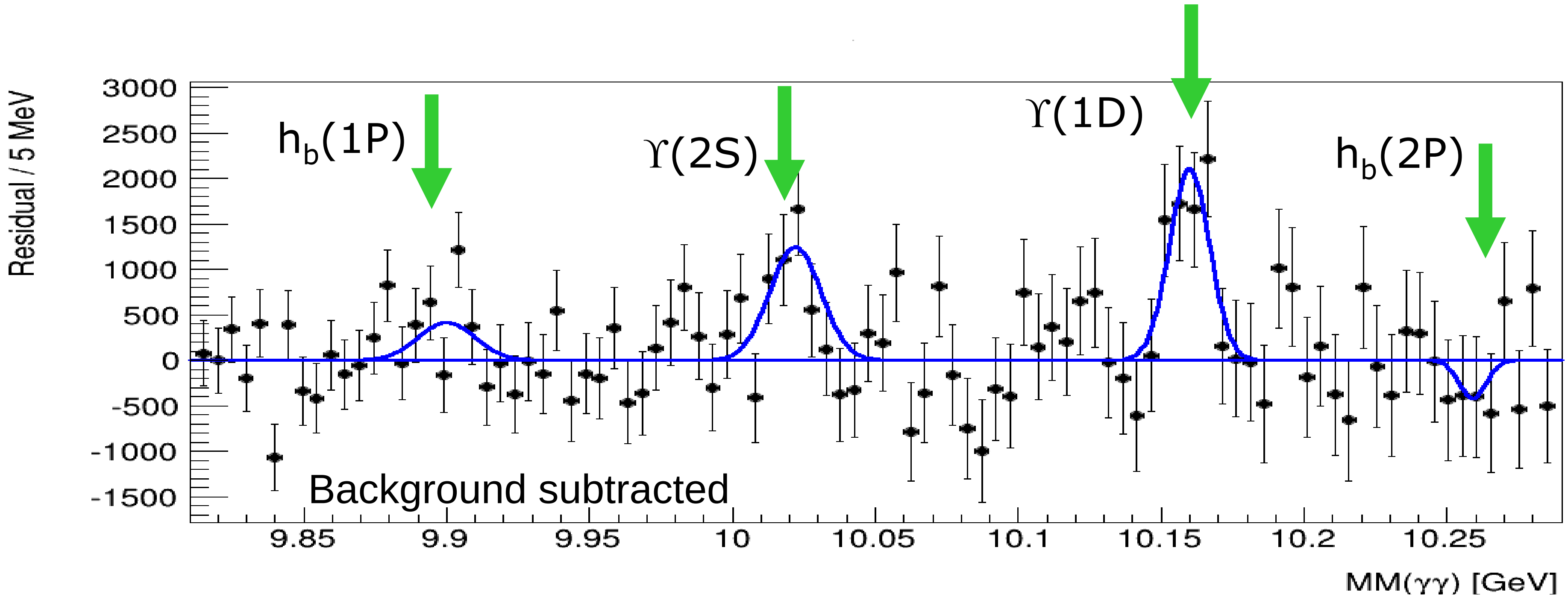
$\Delta M_{HF}(1S) = M(\Upsilon(1S)) - M(\eta_b(1S)) = (55.0 \pm 1.3 \pm 3.2)$ MeV

In a good agreement with the Belle measurement from $\Upsilon(5S) \to \pi^+\pi^- h_b(\to \gamma\eta_b)$ and LQCD but somewhat lower than BaBar and CLEO results from $\Upsilon(2/3S) \to \gamma\eta_b$

$Br(h_b \to \gamma\eta_b) = (52^{+11}_{-10} \pm 4)\%$
$(48 \pm 8)\%$ -previous Belle result

The same analysis in $\Upsilon(5S)$ data: NEW

$\Upsilon(5S) \to (b\bar{b})\,\eta$



Preliminary

BF[Y(5S) $\to \eta$ Y(1D)] = $(2.8 \pm 0.7 \pm 0.4) \times 10^{-3}$

$\to$ **First evidence of single meson transition to Y(1D)**

BF[Y(5S) $\to \eta$ Y(2S)] = $(2.1 \pm 0.7 \pm 0.3) \times 10^{-3}$

BF[Y(5S) $\to \eta$ hb(1P)] = $< 3.3 \times 10^{-3}$ (90% CL)

BF[Y(5S) $\to \eta$ hb(2P)] = $< 3.7 \times 10^{-3}$ (90% CL)

Unexpected behavior in comparison with $\Upsilon(4S)$

Effects that violate heavy spin symmetry may be important !

Summary

- Study of X(3872) continues, Belle searched for $\chi_{c1}\pi^+\pi^-$ mode;
- BaBar searched for X(4140)$\rightarrow J/\psi\ \phi$;
- NEW RESULTS on the first charged Z, $Z(4430)^+ \rightarrow \psi(2S)\pi^+$ and $J/\psi\pi^+$ from Belle;
- New $Z(4200)^+ \rightarrow J/\psi\pi^+$ was found at Belle;
- New observations in bottomonia decays: η transitions in $\Upsilon(4S)$ and $\Upsilon(5S)$ at Belle.

Current picture of quarkonium-like (≡exotic) states is rather scattered.

Today there is no unique theoretical model which coherently describes all experimental data.

X,Y,Z states remain a mystery, especially charged Z;
new efforts are needed to understand new states

Contribution from high-statistics measurements is important:
LHC , BES III and Belle II.