Results on new particles from BELLE

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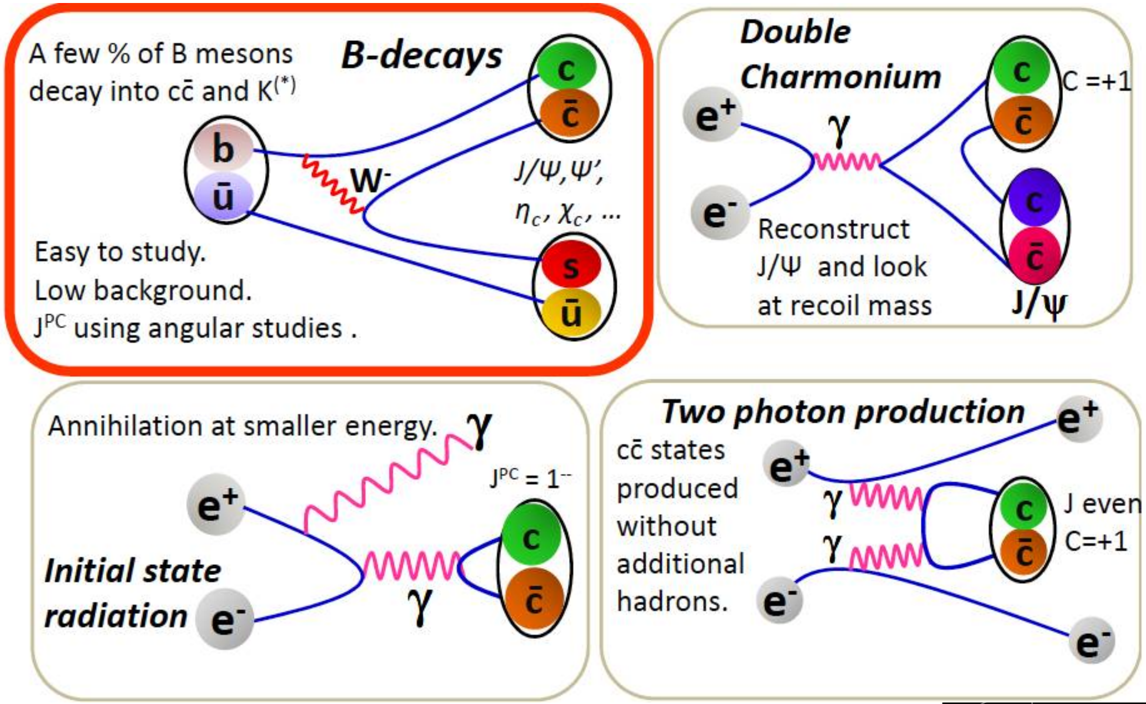
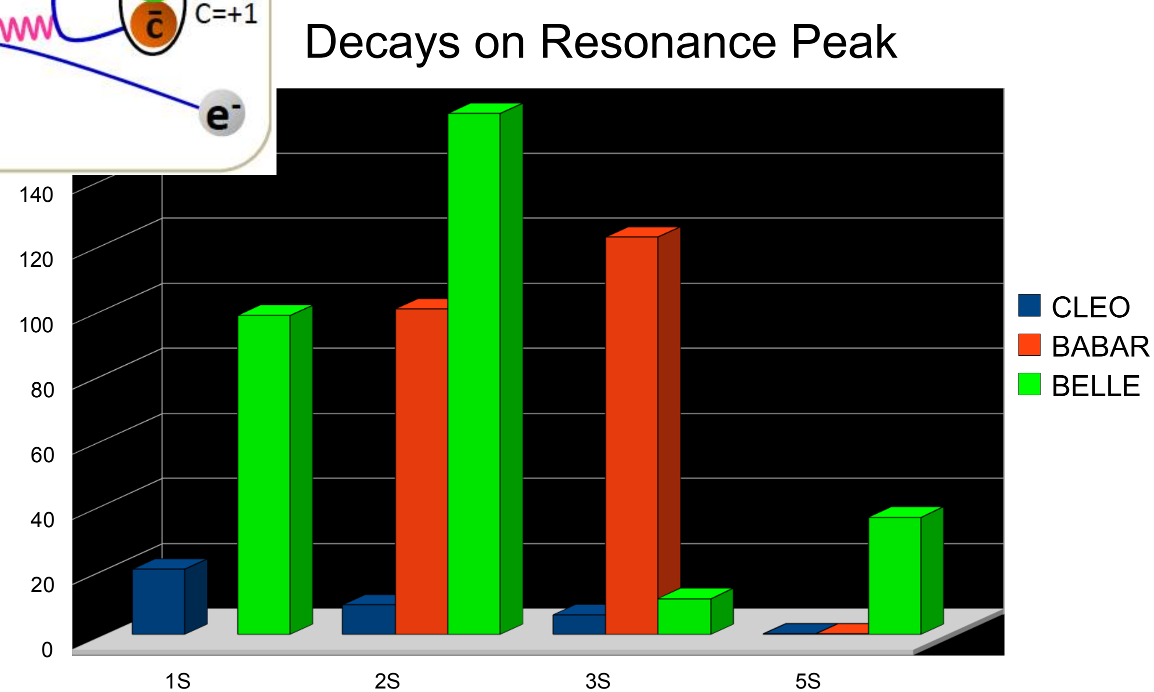
DPF , Santa Cruz, August 2013

Outline

- Charged onia ($qQ\overline{qQ}$)
- Parabottomonia
- D waves
- 6q states





Discovery of charged bottomonia

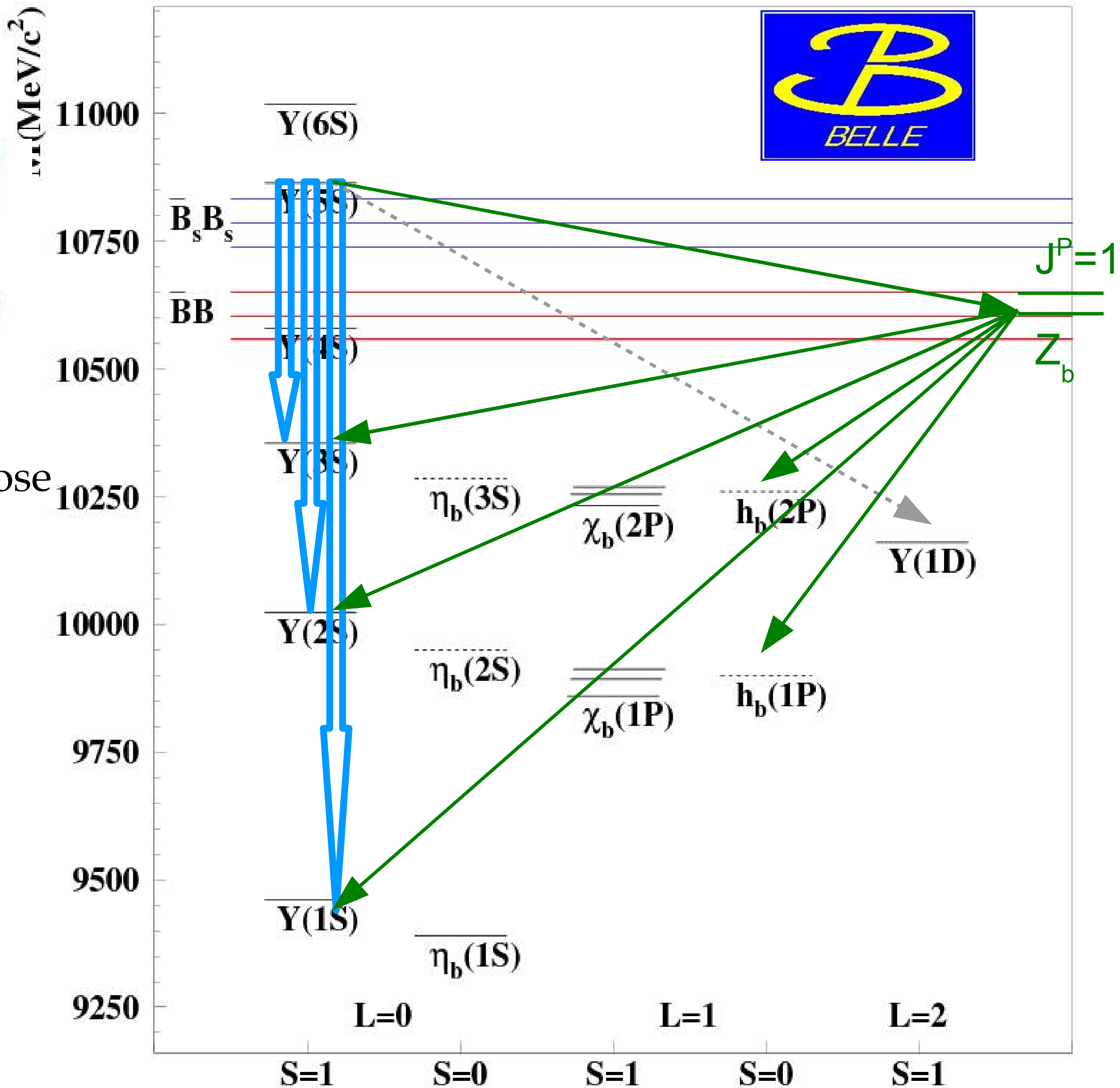
Belle has discovered two charged bottomonium-like resonances:

$Z_b(10610)$	M = 10608.1 ± 1.7 MeV Γ = 15.5± 2.4 MeV
$Z_b(10650)$	M = 10653.3 ± 1.5 MeV Γ = 14.0 ± 2.8 MeV

The states are observed in 5 final states, all with consistent masses, close to the BB* and B*B* threshold.

Analysis of angular distributions suggests $J^P=1^+$ for these states.

PRL108,122001(2011)



For:

Search for the neutral partners Z_b^0

Search for decays to BB* and B*B*

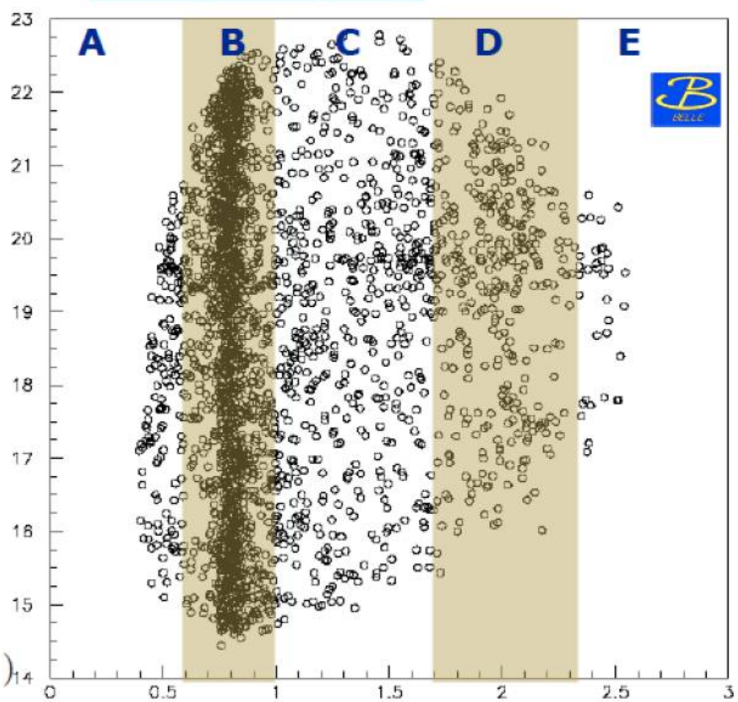
Transitions to Y(1D)

See Santel's talk

Discovery of charged charmonium : $Z_c(4430)$

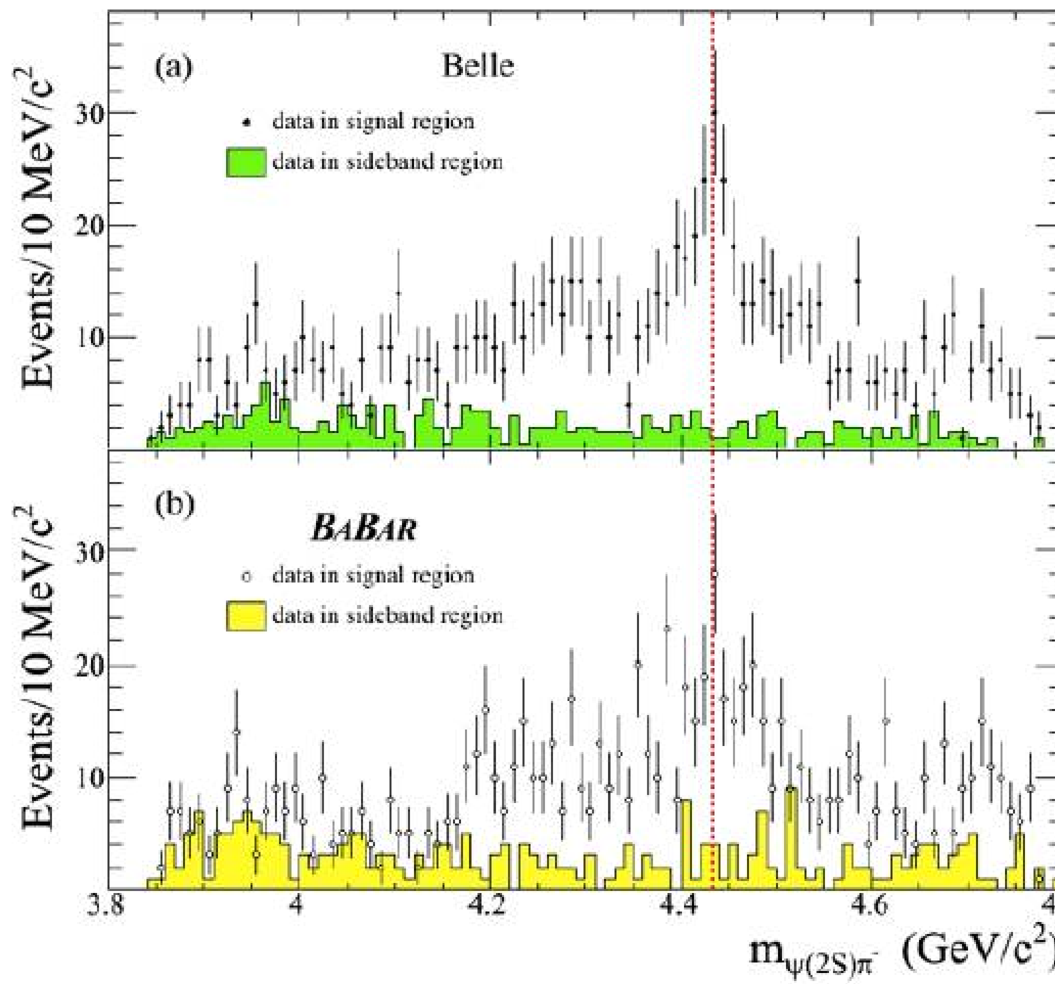
First charged charmonium observed by Belle in $B \rightarrow K(\pi\psi')$,
Babar controversy: data FULLY COMPATIBLE with Belle, but different interpretation: interference with K* resonances?

PRD 80, 031104 (2009)



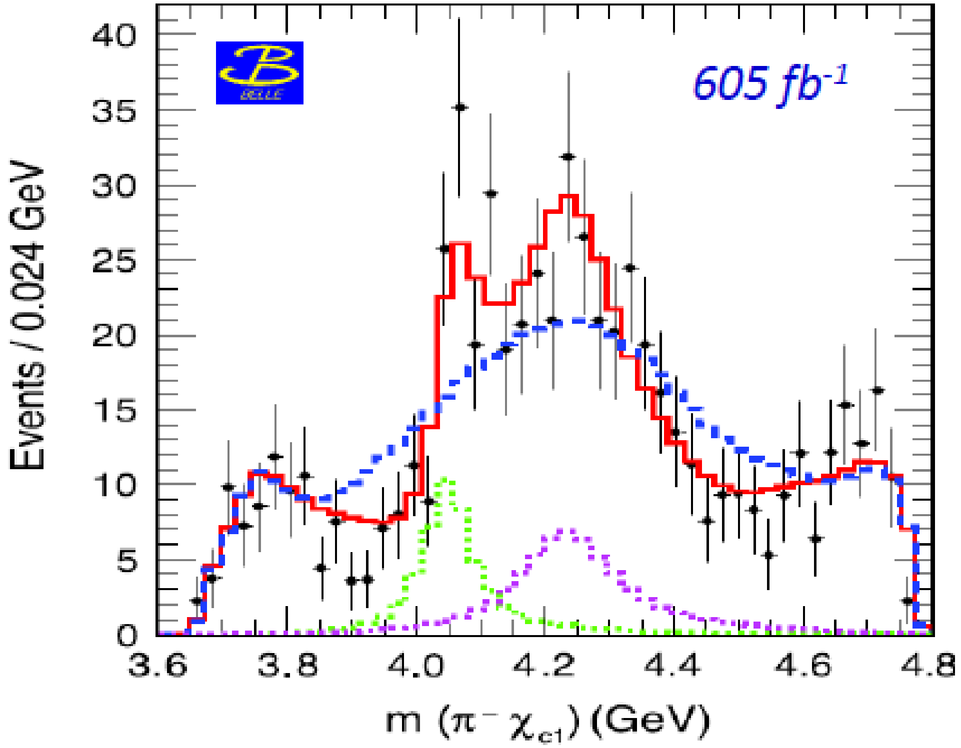
N_{sig}	N_{cont}	BW Mass (GeV)	Γ (GeV)
121 ± 30	766 ± 39	4.433 ± 0.004	$0.045^{+0.018}_{-0.013}$

$$\mathcal{B}(\bar{B}^0 \rightarrow K^- Z^+(4430)) \times \mathcal{B}(Z^+(4430) \rightarrow \pi^+ \psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5},$$

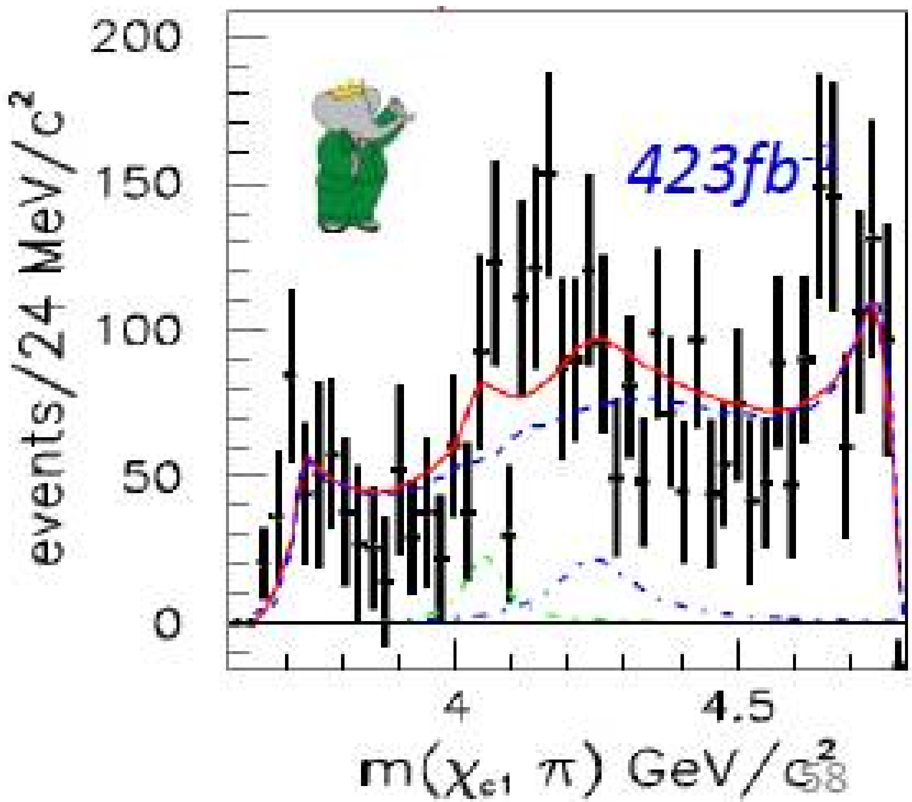


$Z_c(4050)$ and $Z_c(4250)$: Babar vs Belle again

Two more charged charmonia observed by Belle in $B \to K\,(\pi\chi_{c1})$, disconfirmed by Babar: interference from K* resonances?



PRD80, 031104 (2009)



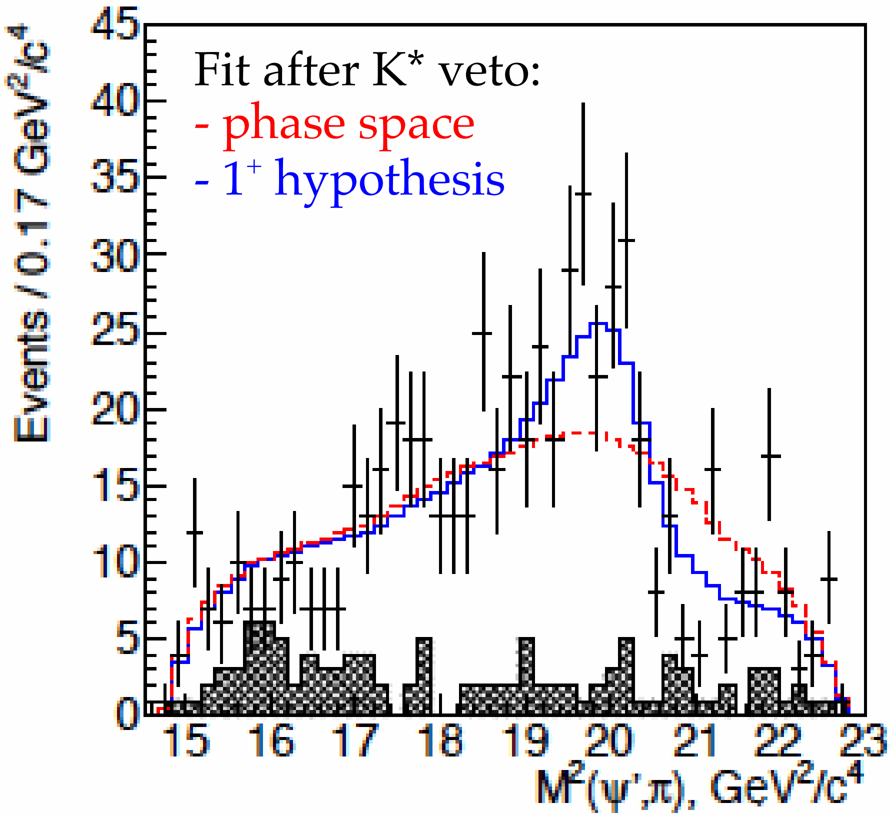
arXiv:1111.5919v2

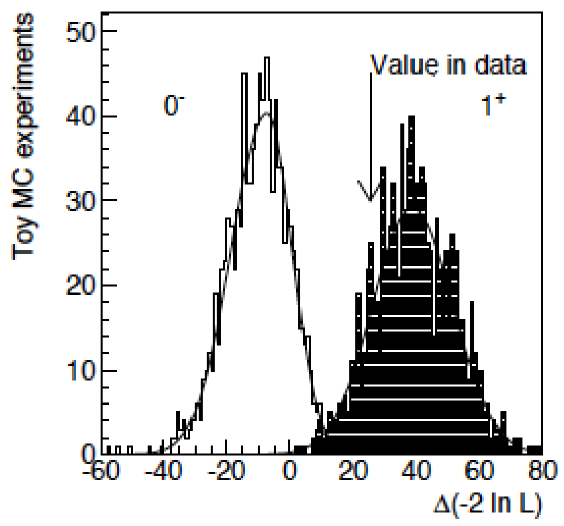
New: $Z_c(4430)$ quantum numbers

ArXiV:1306.4894 , $\int Ldt = 711\ fb^{-1}$ at Y(4S)

Full amplitude analysis in 4D:
Dalitz Plot + angular distribution

$$\mathcal{B}(\bar{B}^0 \to \psi' K^- \pi^+) = (5.80 \pm 0.36) \times 10^{-4},$$
$$\mathcal{B}(\bar{B}^0 \to \psi' K^*(892)) = (5.20^{+0.28+1.45}_{-0.20-0.39}) \times 10^{-4},$$
$$\mathcal{B}(\bar{B}^0 \to Z(4430)^+ K^-) \times \mathcal{B}(Z(4430)^+ \to \psi' \pi^+) =$$
$$(3.5^{+1.2+0.4}_{-0.8-1.3}) \times 10^{-5} \quad \text{for } J^P = 1^+ \text{ or}$$
$$(1.5^{+0.7+0.7}_{-0.5-0.2}) \times 10^{-5} \quad \text{for } J^P = 0^-,$$





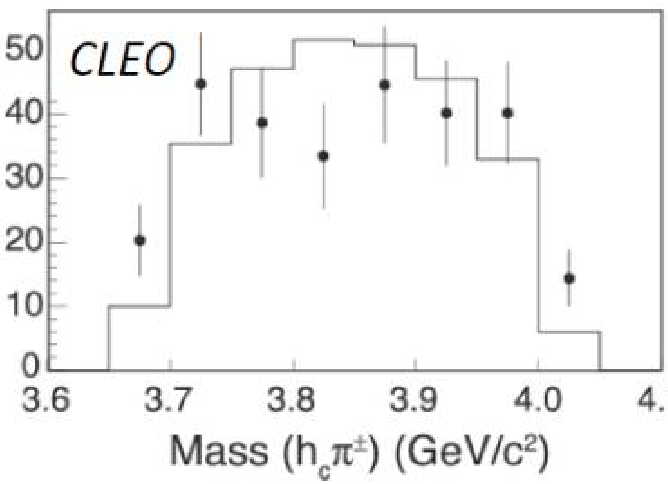
J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4470 ± 20	4482 ± 4	4500 ± 12	4545 ± 2	4367 ± 2
Width, MeV	139 ± 36	10.9 ± 0.3	126 ± 20	11.2 ± 0.6	9.1 ± 0.6
Significance	4.4σ	1.2σ	6.1σ	2.3σ	2.6σ

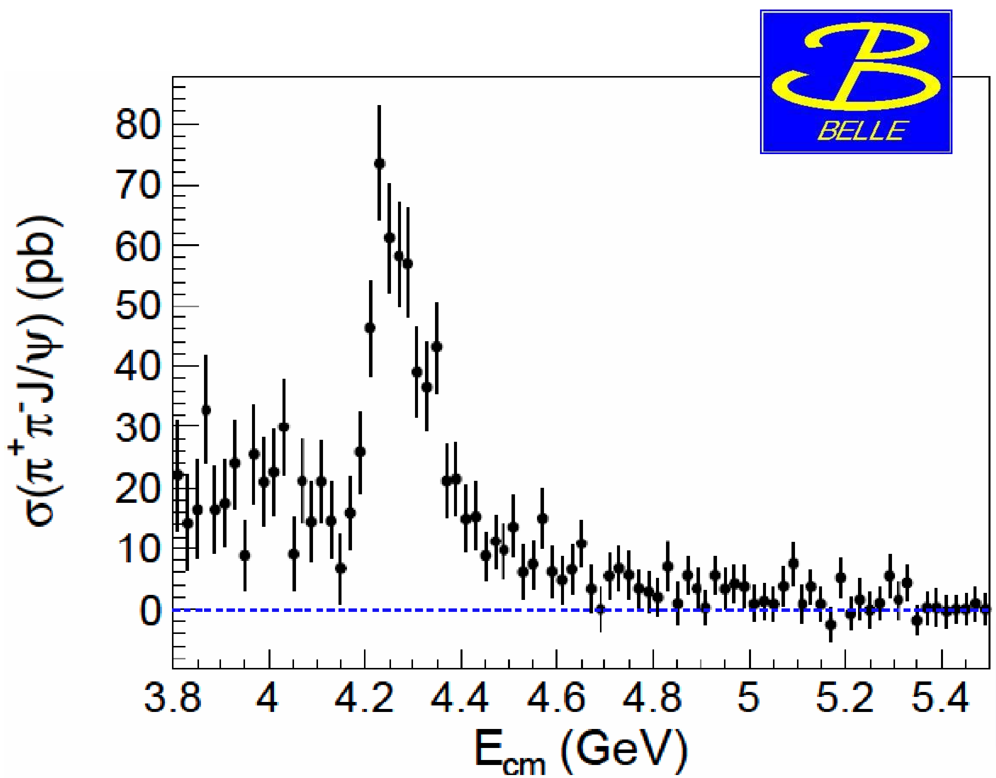
Discovery of charged charmonia: Zc(3900)

Hints of deviations from phase space were observed by CLEO in data at 4170 MeV
PRL107,041803 (2011)

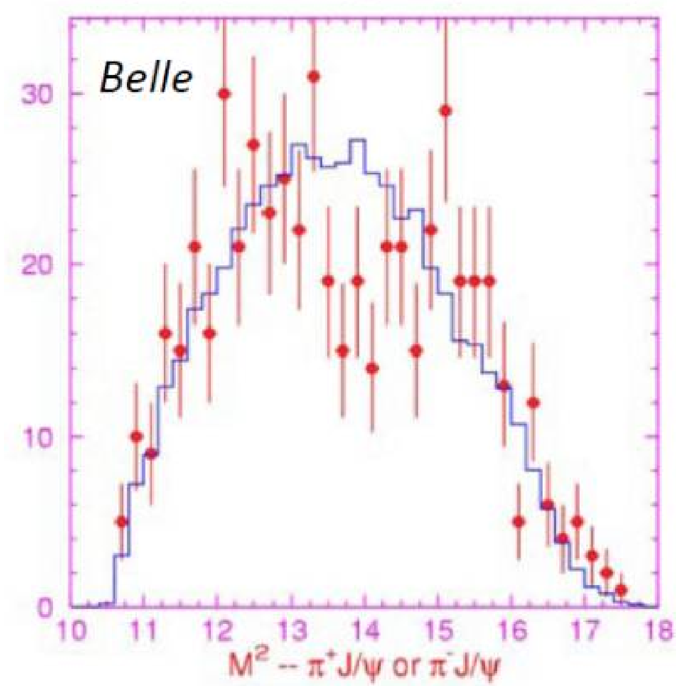
Belle ISR data at Y(4260) confirmed this in the $e+e- \rightarrow J/\psi\ \pi\pi$ channel : this suggested a dedicated run on Y(4260) peak at BES-III (December 2013)

M($h_c\pi$) from $e^+e^- \rightarrow \pi^+\pi^- h_c$ at 4170



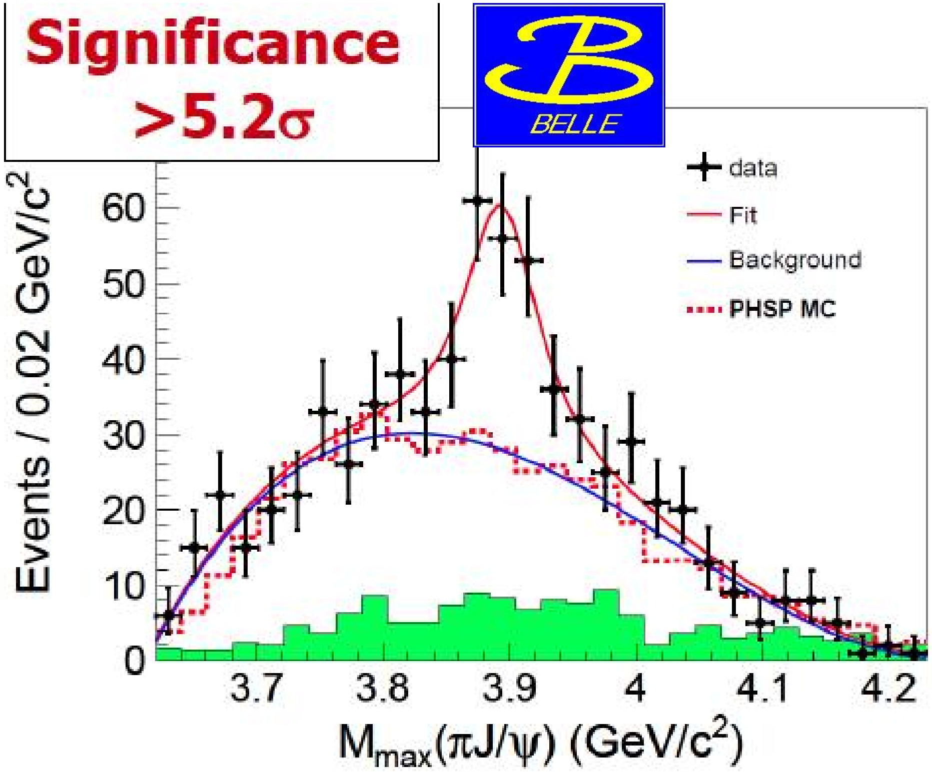


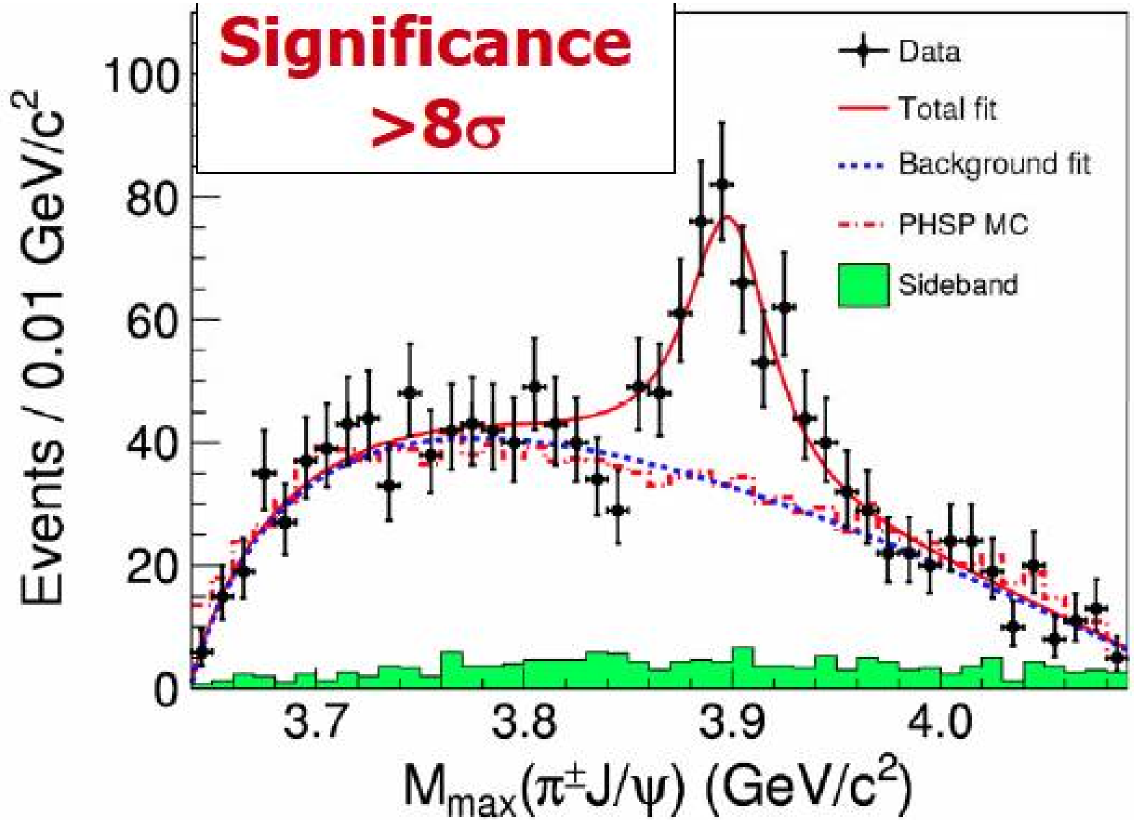
M($J/\psi\pi$) from $\psi(4260) \rightarrow \pi^+\pi^- J/\psi$



Discovery of charged charmonia: Zc(3900)

BES-III





Belle: 927 fb^{-1} of ISR data at Υ(nS) energy

Phys.Rev.Lett. 110 (2013) 252002

- Mass = (3894.5±6.6±4.5) MeV
- Width = (63±24±26) MeV
- Fraction = (29.0±8.9)% (stat. error only)

BES-III: 525 pb^{-1} @ Y(4260) peak energy

Phys.Rev.Lett. 110 (2013) 252001

- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

Parabottomonia: new paths to the η_b

The high yield of $h_b(1,2P)$:

$$N[h_b(1P)] = (50.4 \pm 7.8\ ^{+4.5}_{-1.9}) \times 10^3$$

$$N[h_b(2P)] = (84.4 \pm 6.8\ ^{+23}_{-10}) \times 10^3$$

opens new perspectives to study the $\eta_b(1,2S)$

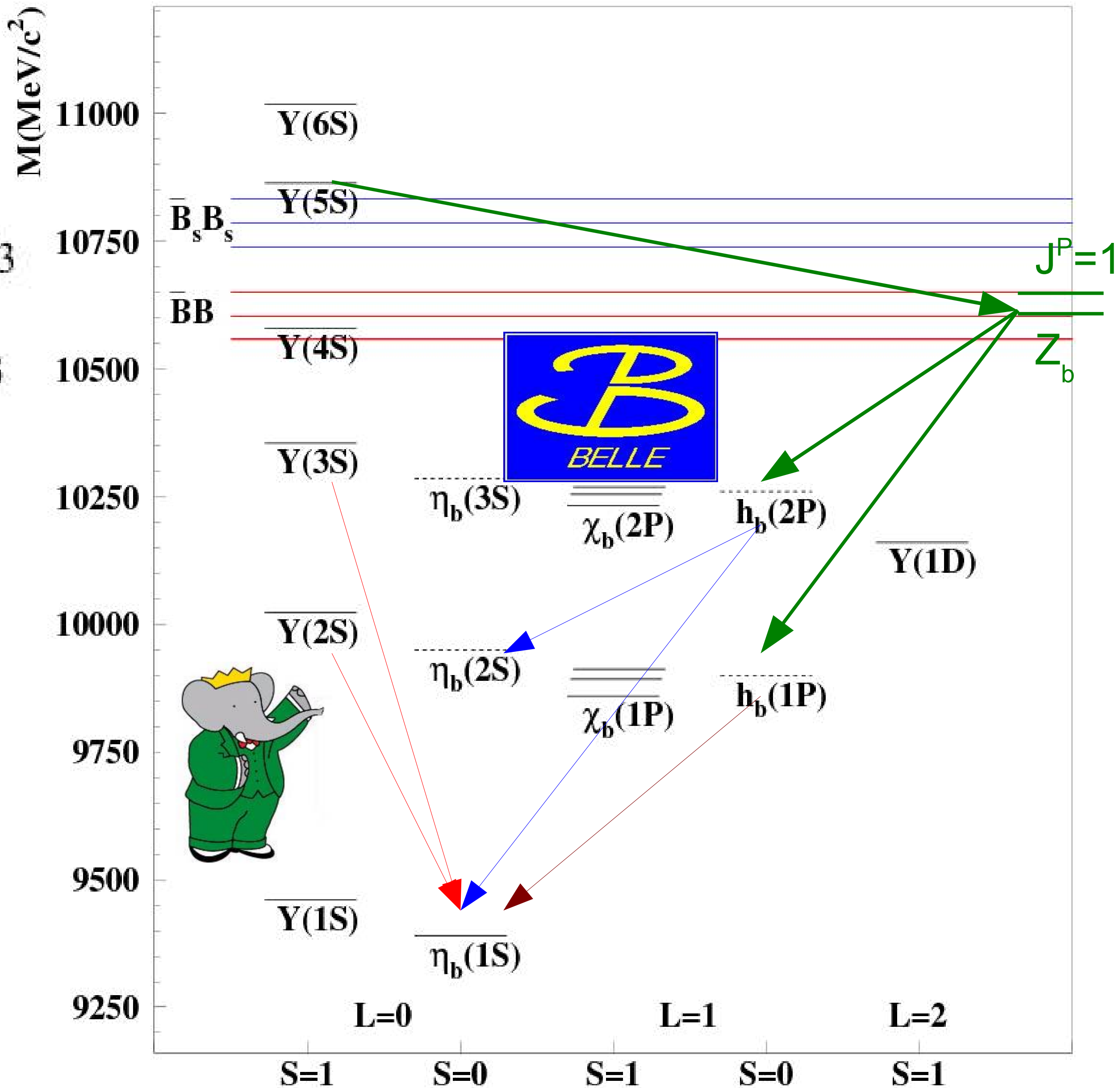
Expected E1 rates:

Godfrey&Rosner, PRD66 014012 (2002)

$$h_b(1P) \longrightarrow \gamma\eta_b(1S) = 41\%$$

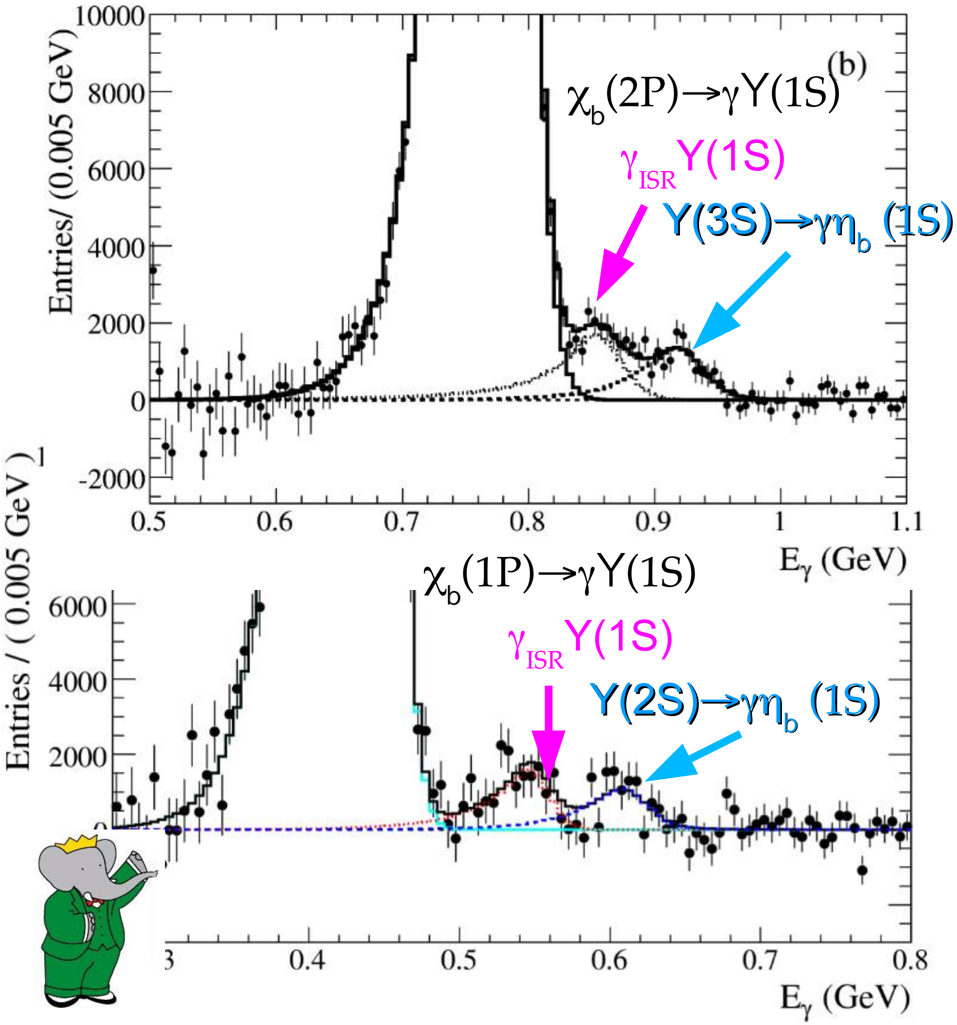
$$h_b(2P) \longrightarrow \gamma\eta_b(1S) = 13\%$$

$$h_b(2P) \longrightarrow \gamma\eta_b(2S) = 19\%$$



Rediscovery of η_b

Babar 2008:



PRL 101,071801(2008)
PRL 103,161801(2009)

Rediscovery of η_b

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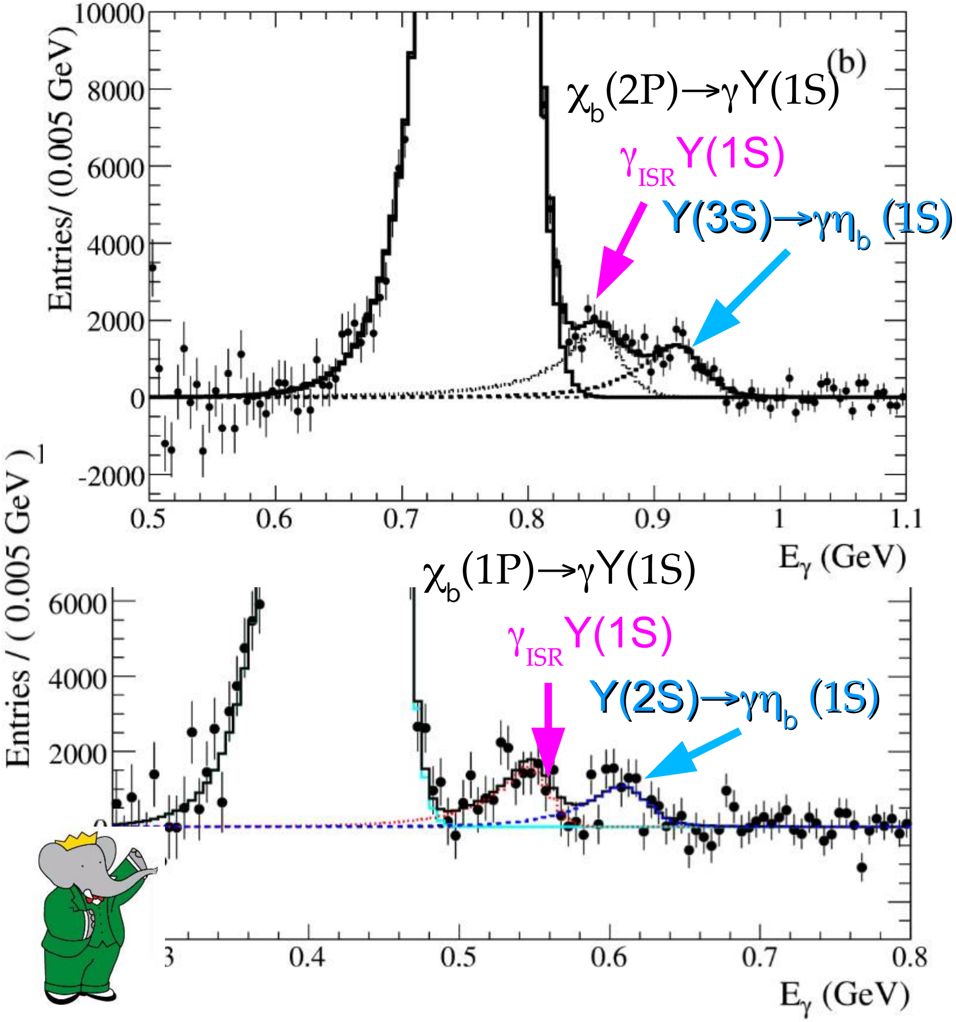
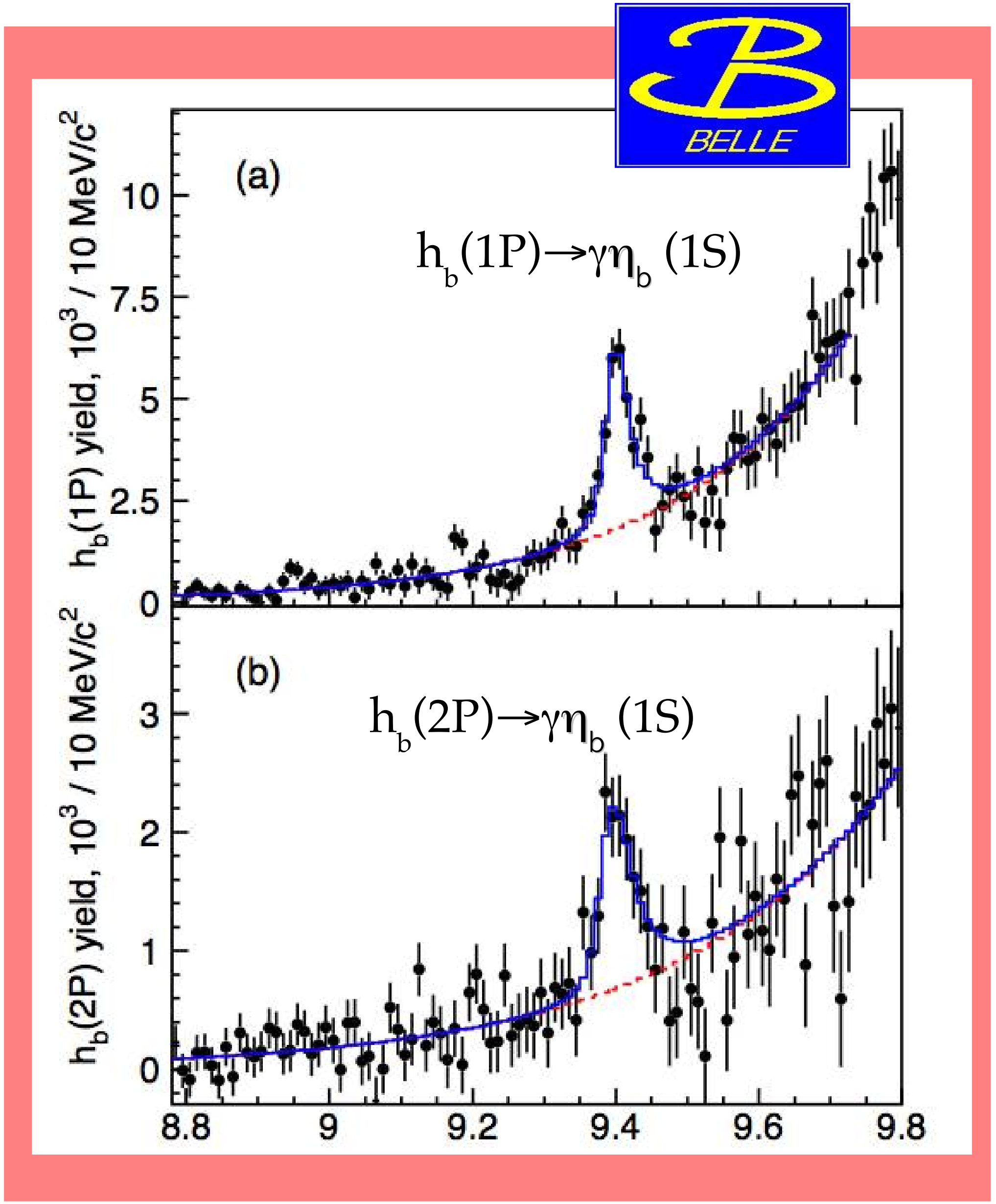


PRL 101,071801(2008)
PRL 103,161801(2009)

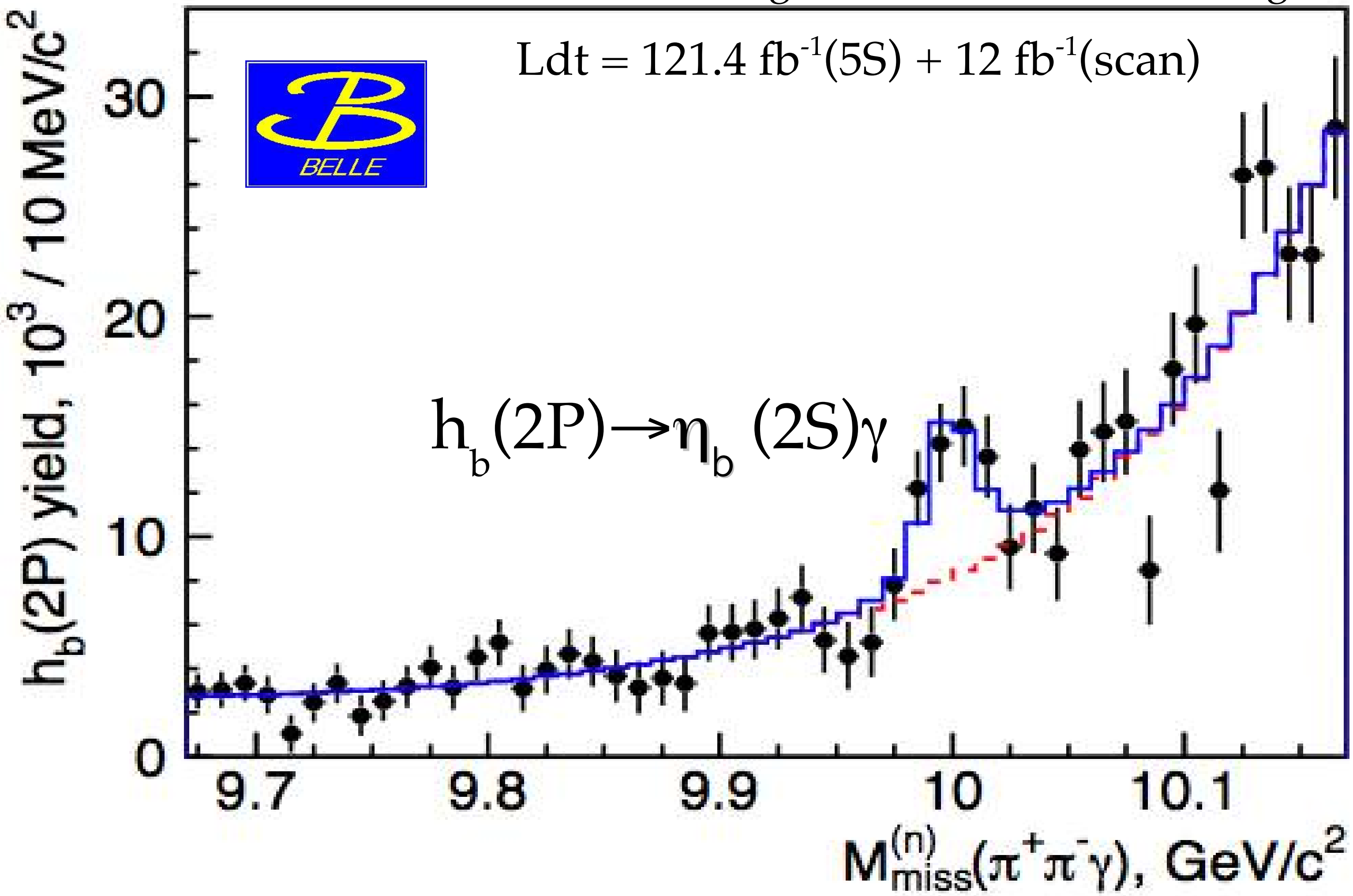


PRL 109, 232002 (2012)

Evidence of $\eta_b(2S)$

PRL 109, 232002 (2012)

Significance : 4.2 σ, including all systematics



$$m_{\eta_b(2S)} = 9999.0 \pm 3.5^{+2.8}_{-1.9}\ \mathrm{MeV/c^2}$$

$$\mathrm{B.F.}\ [h_b(2P) \to \eta_b(2S)\gamma] = (47.5 \pm 10.5^{+6.8}_{-7.7})\%$$

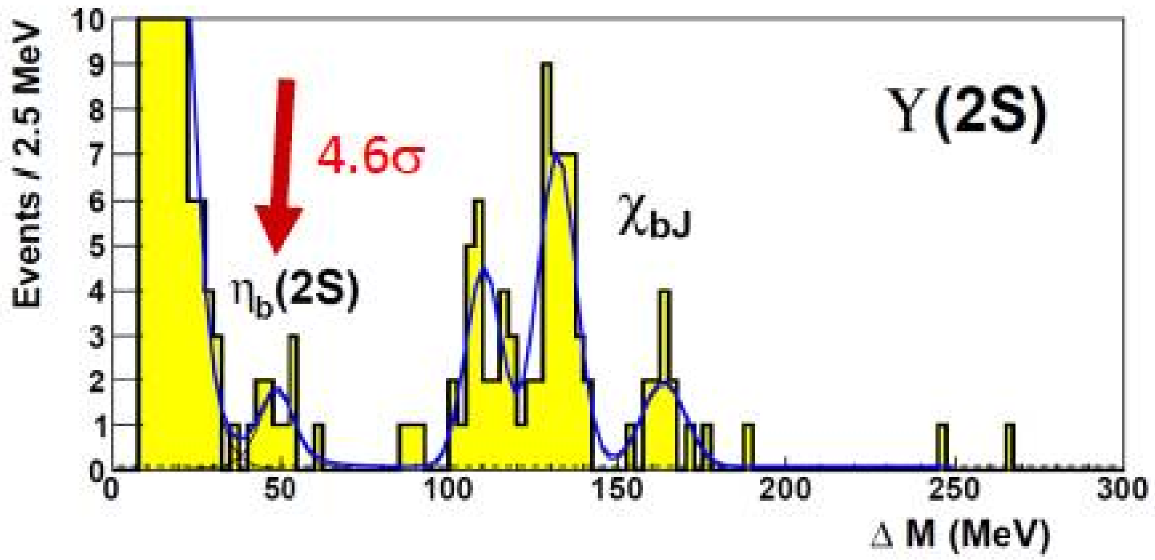
Search for $\eta_b(2S)$ in exclusive modes

Exclusive reconstruction of 26 decay modes: $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$, $4(\pi^+\pi^-)$, $5(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^-2(\pi^+\pi^-)$, $K^+K^-3(\pi^+\pi^-)$, $K^+K^-4(\pi^+\pi^-)$, $2(K^+K^-)$, $2(K^+K^-)\pi^+\pi^-$, $2(K^+K^-\pi^+\pi^-)$, $2(K^+K^-)3(\pi^+\pi^-)$, $\pi^+\pi^-p\bar{p}$, $2(\pi^+\pi^-)p\bar{p}$, $3(\pi^+\pi^-)p\bar{p}$, $4(\pi^+\pi^-)p\bar{p}$, $\pi^+\pi^-K^+K^-p\bar{p}$, $2(\pi^+\pi^-)K^+K^-p\bar{p}$, $3(\pi^+\pi^-)K^+K^-p\bar{p}$, $K_S^0K^\pm\pi^\mp$, $K_S^0K^\pm\pi^\mp\pi^+\pi^-$, $K_S^0K^\pm\pi^\mp 2(\pi^+\pi^-)$, $K_S^0K^\pm\pi^\mp 3(\pi^+\pi^-)$, $2K_S^0(\pi^+\pi^-)$, $2K_S^02(\pi^+\pi^-)$, $2K_S^03(\pi^+\pi^-)$.

The claim of :
Dobbs et al **PRL109 (2012) 082001**
(analysis of CLEO data by Seth's group)

$B(\Upsilon(2S)\to\eta_b(2S)\gamma)*\Sigma_i B_i(\eta_b(2S)\to f_i) = 46.2^{+29.2}_{-14.2} \pm 10.6)\times 10^{-6}$

@ M = 9974.6 ±2.3 ±2.1 MeV



is inconsistent with Belle result from $h_b(2P)\to\eta_b(2S)\gamma$
$M = 9999.0 \pm 3.5\,^{+2.8}_{-1.9}$ MeV

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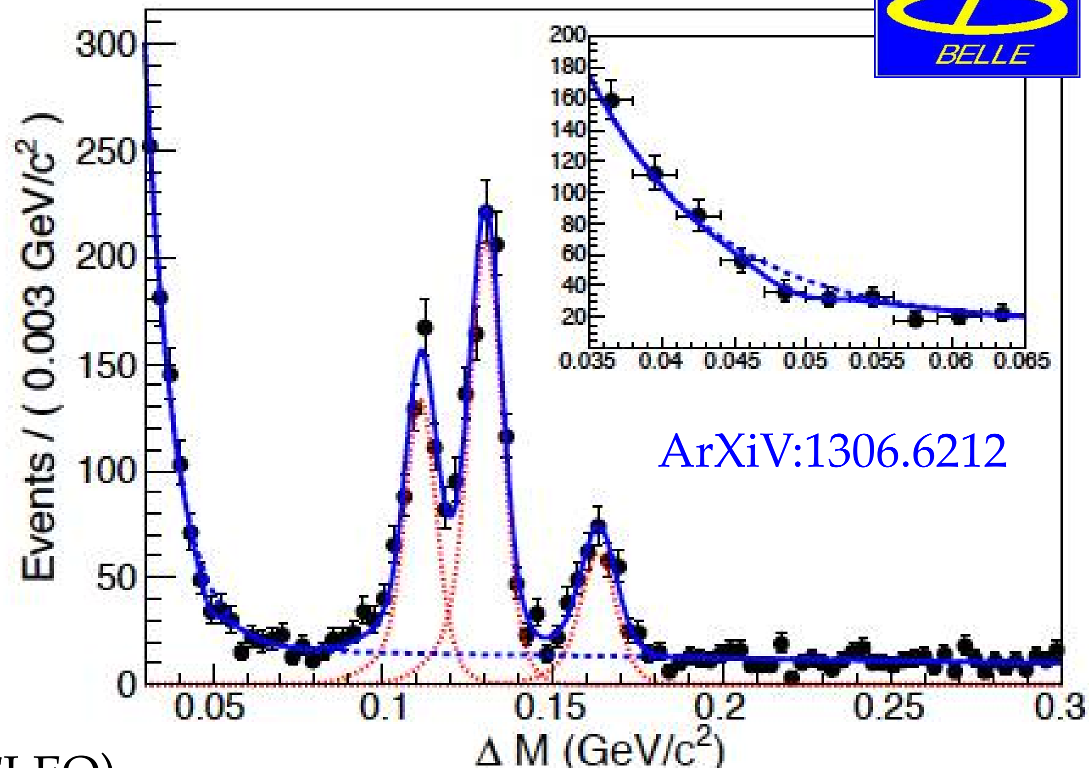
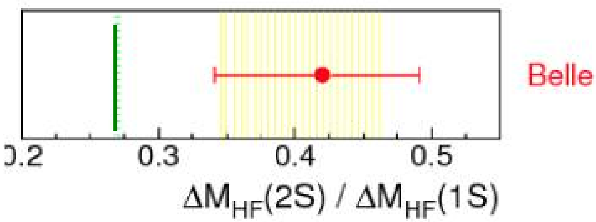


IS DISCONFIRMED BY BELLE:
Using our record data sample:
- on peak 25 fb^{-1} (157.8M $\Upsilon(2S)$ decays, 16x CLEO)
- bkg: 87 fb^{-1} @ 10.52 GeV

We set the UL @ 90% CL: < 4.9×10^{-6} (including syst.)

Parabottomonia vs theory

$\eta_b(2S)$ vs $\eta_b(1S)$

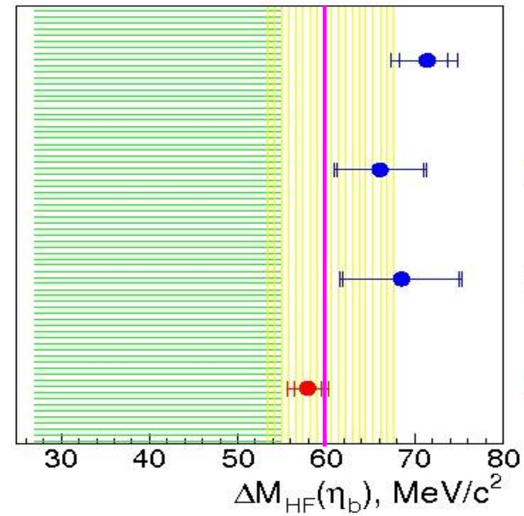


PNRQCD@NLL PRL92,242001(2004)

Lattice QCD PRD82,114502(2010)

Godfrey-Isgur, PRD32,189 (1985)

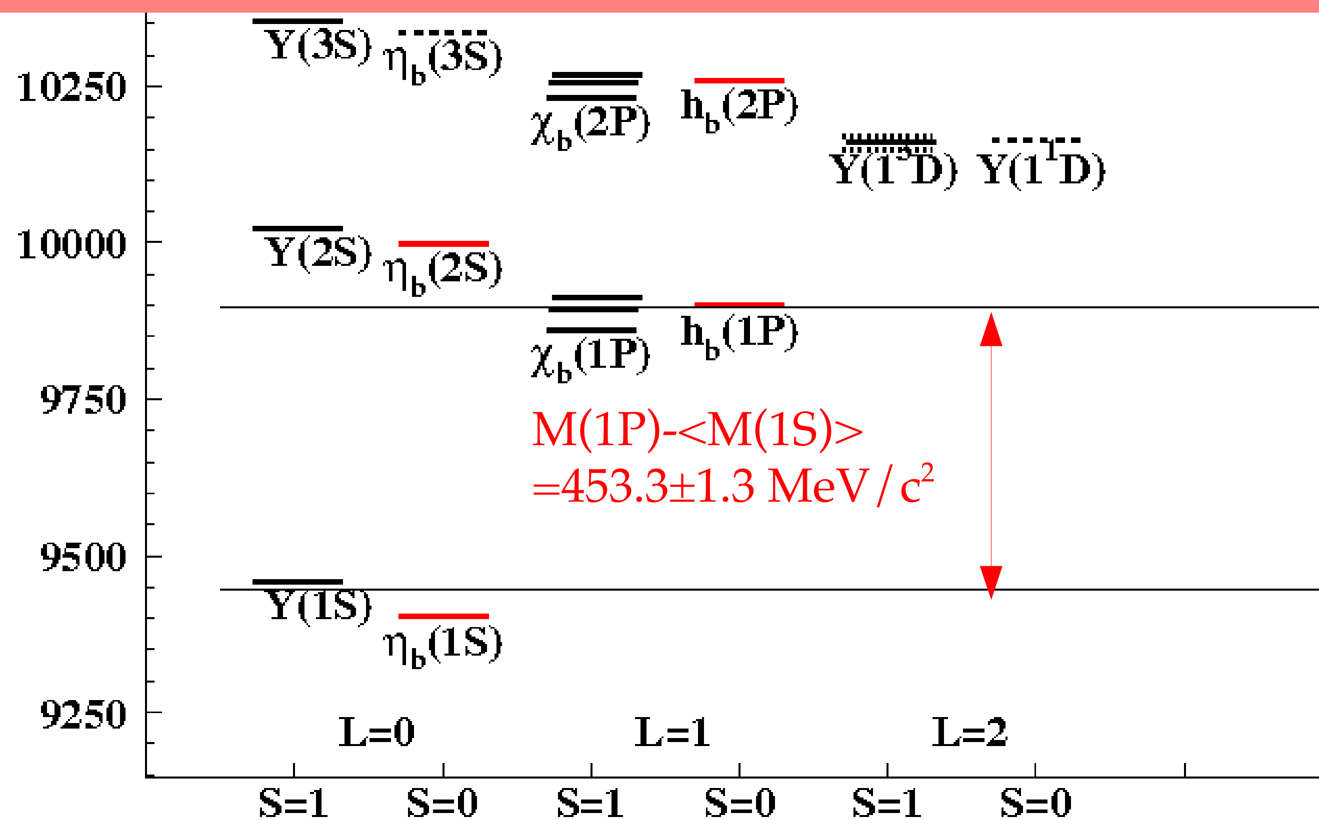
10 MeV discrepancy w/ earlier Babar and CLEO results



$\eta_b(1S)$

Some tension with the most accurate NRQCD prediction , but very close to lattice QCD (Meinel) predictions.

Spin averaged 1P-1S splitting seems not to depend on scale !!



Parabottomonia vs theory

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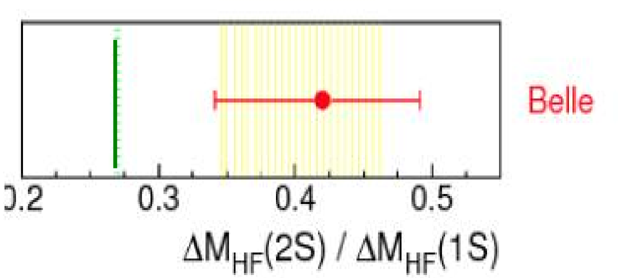

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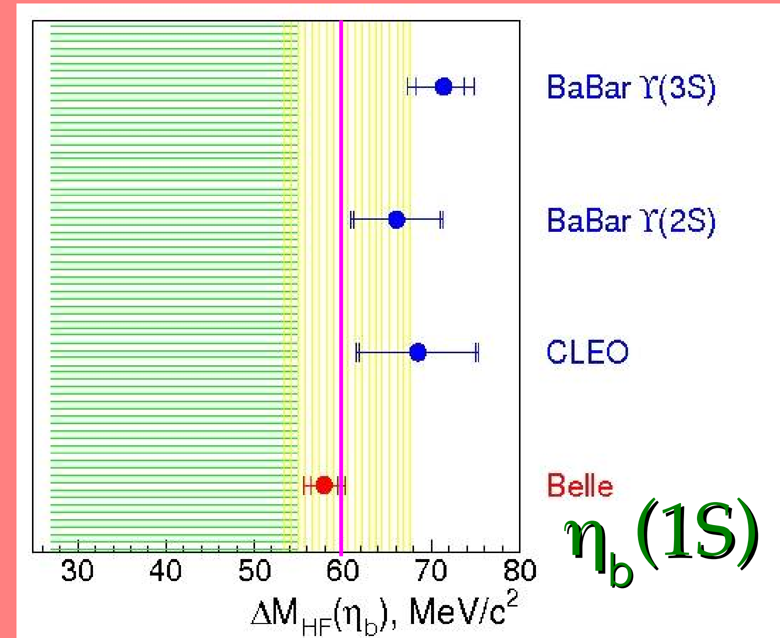
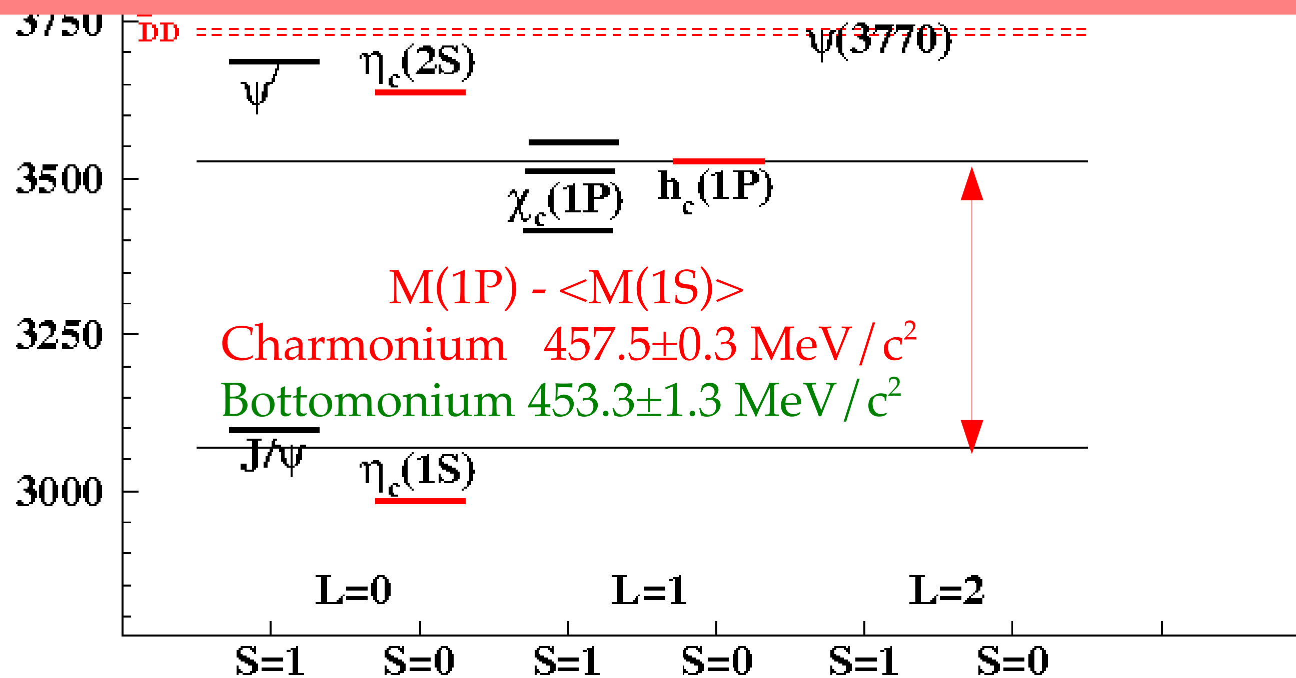


Spin averaged 1P-1S splitting seems not to depend on scale: only 1% relative difference with charmonium



Charmonium D wave

PRL111,032001(2013)

Tetraquark model : C-odd partner of X3872 decays in $\gamma\chi_{c1,2}$

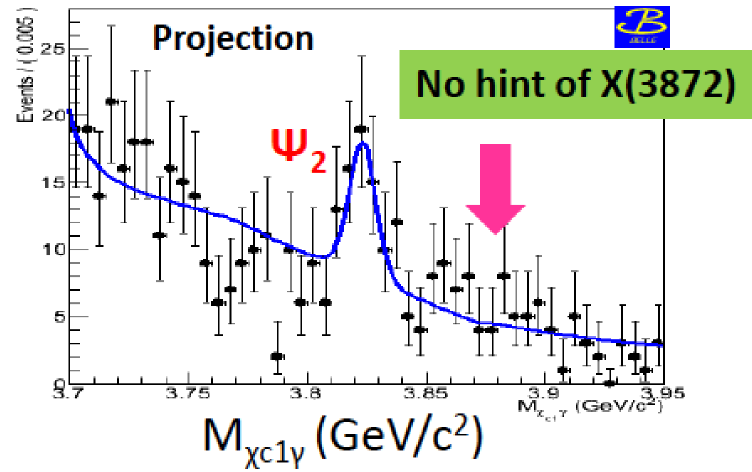
No signal of "X(3872)" $\rightarrow \gamma\chi_{c1,2}$

… but another peak .... with a significance : 4.2 σ

Preliminary: $M(^3D_2) = 3823.5 \pm 2.8$ MeV/c^2

90% CL UL on $\Gamma(^3D_2 \rightarrow \gamma\chi_{c2}) / \Gamma(^3D_2 \rightarrow \gamma\chi_{c1}) < 0.42$ (Th: ~ 0.2)

X(3872) yield : -0.9±5.1 events

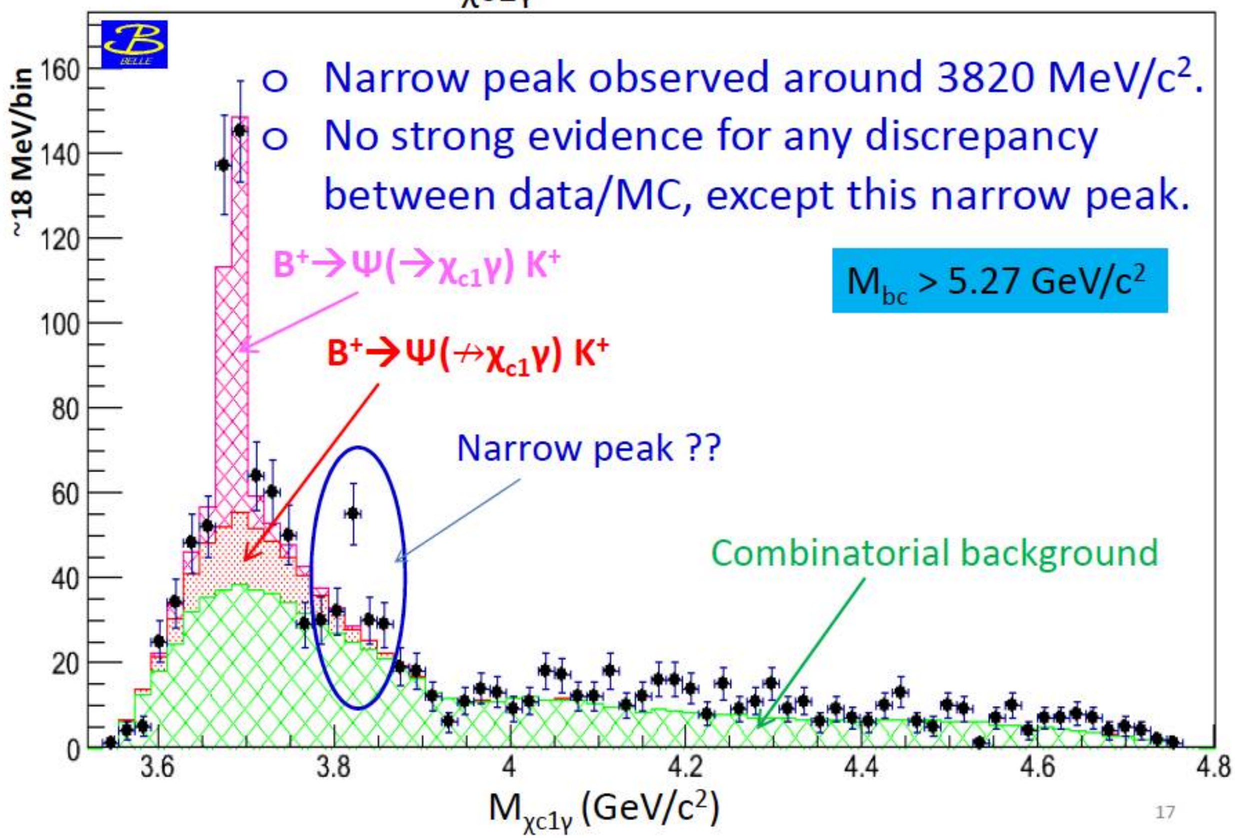


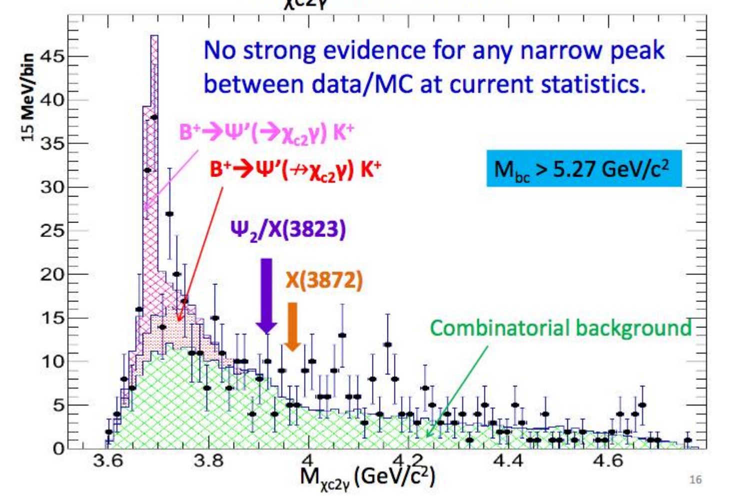
$M_{bc} > 5.27$ GeV/c^2

711 fb^{-1} NEW

$M_{\chi c1\gamma}$ distribution

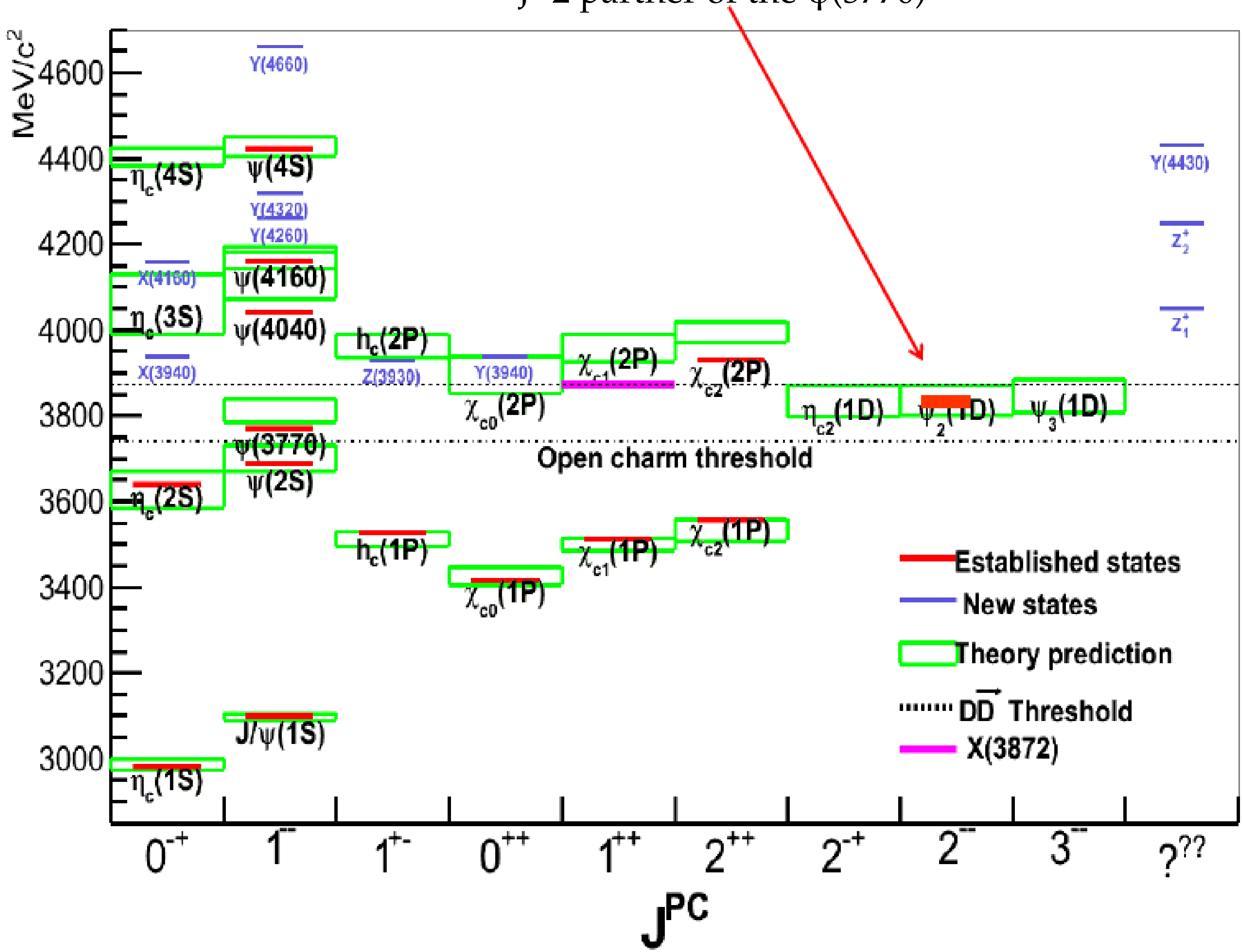
$B^\pm \rightarrow \chi_{c1}\gamma K^\pm$





Charmonium D wave

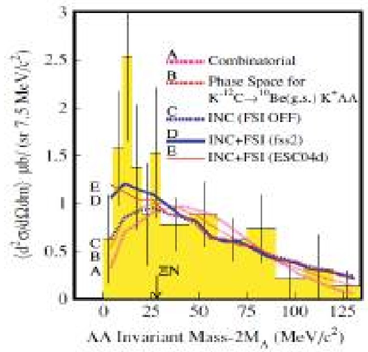
Evidence of the long sought $^3D_2$ state of charmonium
J=2 partner of the ψ(3770)



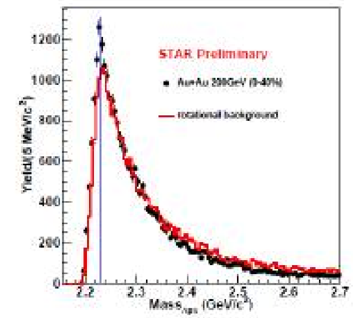
Search for H dibaryon

Observation (ARGUS,CLEO) of :
- enhanced production of hyperons in bottomonium decays
- sizable BR (~3x10-5) of production of antideuteron in Υ(1,2S) decays

Suggested the idea to search for exotic 6 quark states, such as the H dibaryon , suggested by Jaffe in 1977. Controversial claims from expts. E522 and STAR.



KEK-PS E522(2007)



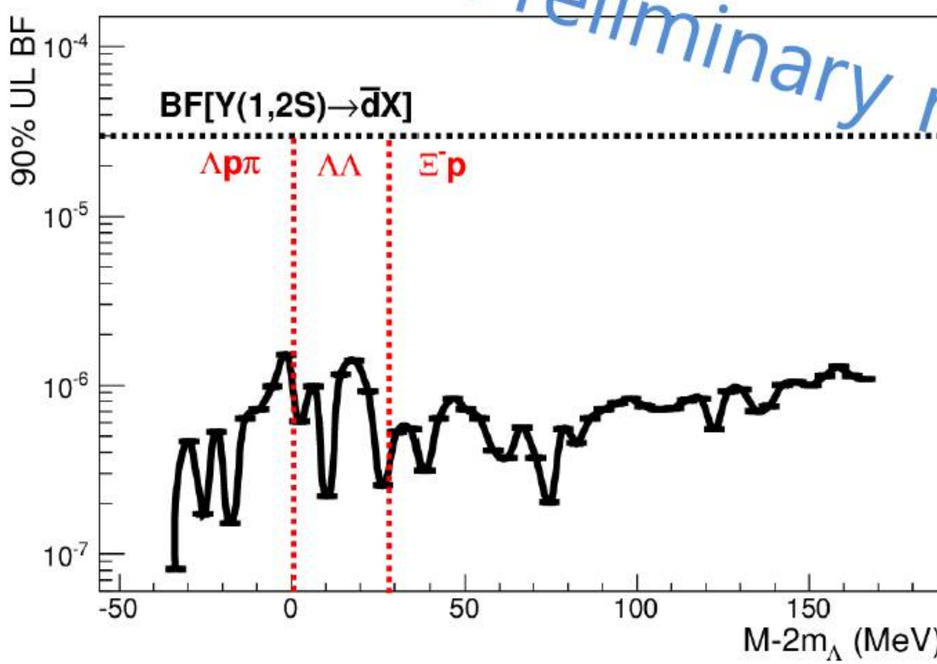
RHIC-STAR detector (2011)

Belle has searched for H dibaryon in the folllowing channels:
- Λπp (+cc)
- ΛΛ (+cc)

[published:PRL 110, 222002 (2013)]
- Ξ p (+cc)

[aiming for a longer paper including also pentaquark searches, inclusive production of Ξ_c and Ξ* from Υ decays]

Preliminary result



Summary

In the last years, Belle has discovered a large number of conventional and exotic states, accumulating increasing evidences that hadrons are not simply made of 2 (mesons) or 3 (baryons) quarks.

In heavy meson systems, the first hints for the existence of 4 quark states (tetraquarks or hadro molecules) came from B decays, the controversy between Belle and Babar on the interpretation of the $Z_c(4430)$ is still unsettled.

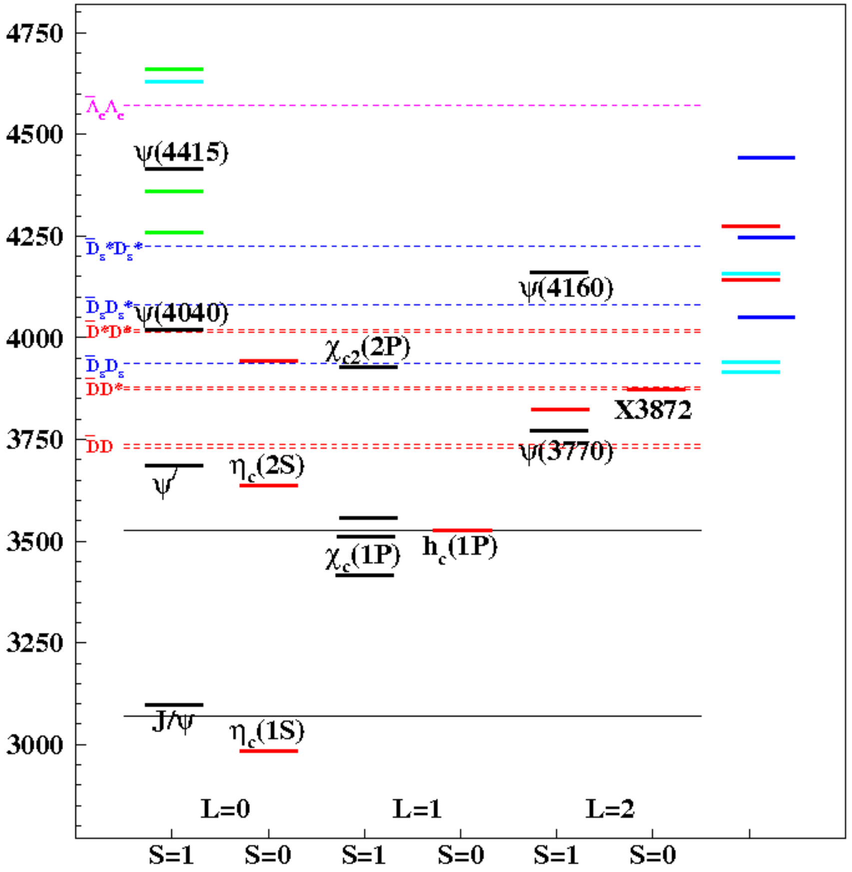
Belle's new analysis of $Z_c(4430)$ quantum numbers favors $J^P=1^+$

More solid evidence of 4-quark states comes from $\Upsilon(4260)$ and $\Upsilon(10860)$ where Zc and Zb states provide new pathways to bound quarkonia:
- $Z_b(10510,10560)$ led to Belle's discovery of 3 missing parabottomonia, $h_b(1,2P)$ and $\eta_b(2S)$, and to the best mass determination of $\eta_b(1S)$
- a similar mechanism seems at work in charmonium, where Zc states at 3900 (Belle and BES-III) and 4020 (BES-III) mediate transitions towards J/ψ and $h_c(1P)$.

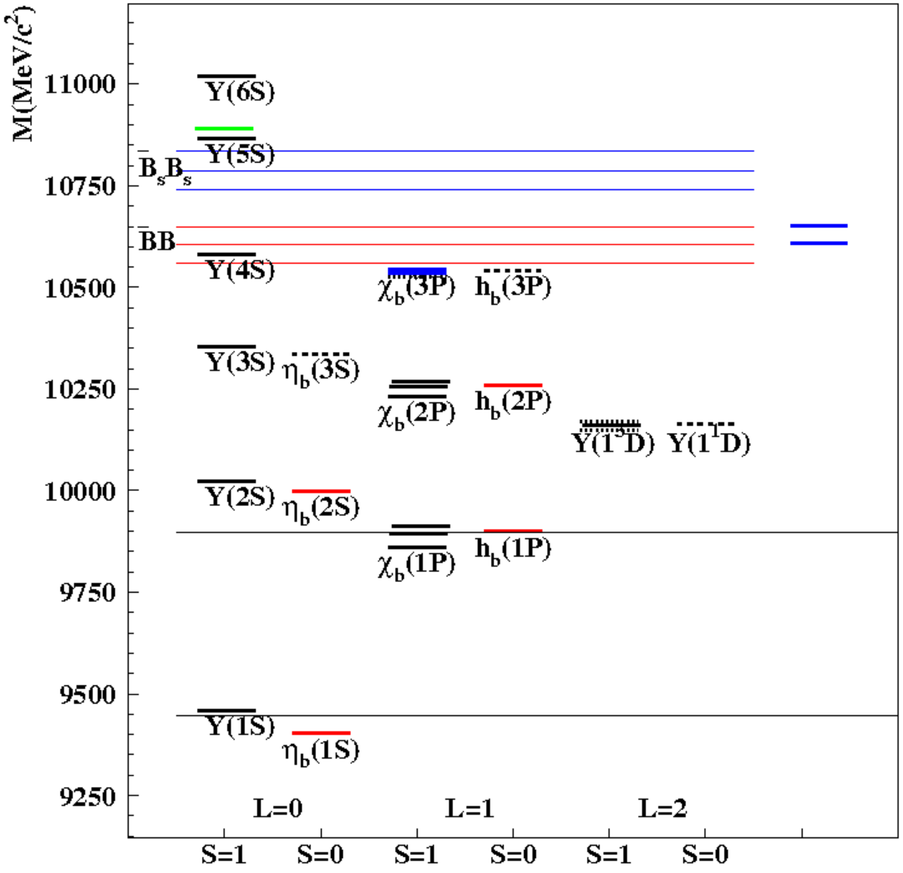
After completing the low lying S and P wave spectra, Belle is making progress on D-wave states: while searching for partners of X(3872), Belle ran into the long sought $^3D_2$ state of charmonium, decaying to , at a mass of $3823.5 \pm 2.8\ \mathrm{MeV}/c^2$.

Belle does not see any evidence of inclusive production of H-dibaryon

Spectra



4750
4500
4250
4000
3750
3500
3250
3000
ψ(4415)
ψ(4040)
ψ(4160)
χc2(2P)
X3872
ψ(3770)
ηc(2S)
ψ'
χc(1P)
hc(1P)
J/ψ
ηc(1S)
L=0
L=1
L=2
S=1
S=0
S=1
S=0
S=1
S=0



M(MeV/c²)
11000
10750
10500
10250
10000
9750
9500
9250
Υ(6S)
Υ(5S)
BB
Υ(4S)
χb(3P)
hb(3P)
Υ(3S)
ηb(3S)
χb(2P)
hb(2P)
Υ(2S)
ηb(2S)
χb(1P)
hb(1P)
Υ(1S)
ηb(1S)
L=0
L=1
L=2
S=1
S=0
S=1
S=0
S=1
S=0

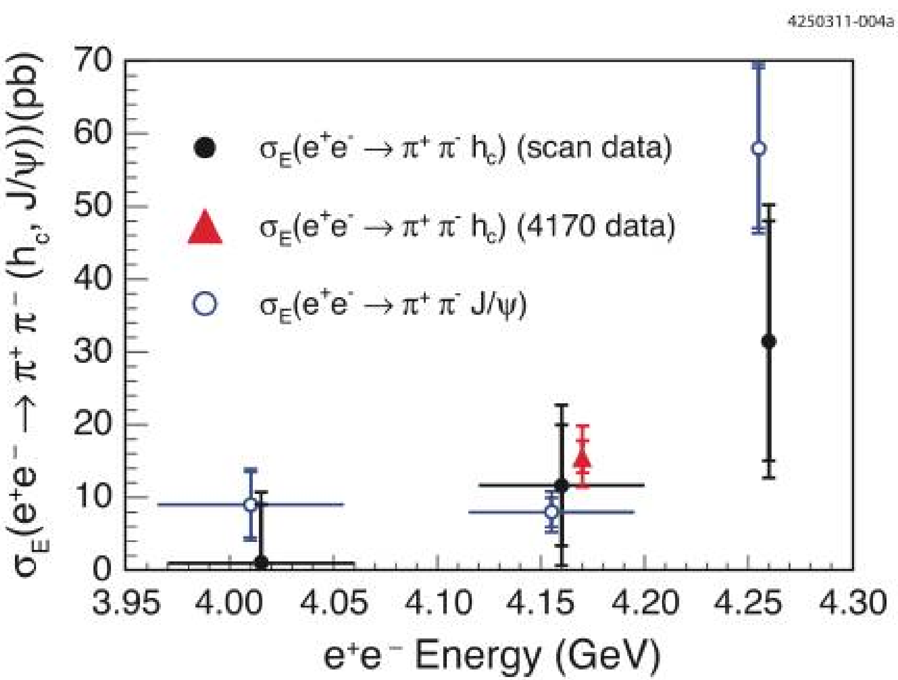
$h_c(1P)$ from $\Psi(4170)$

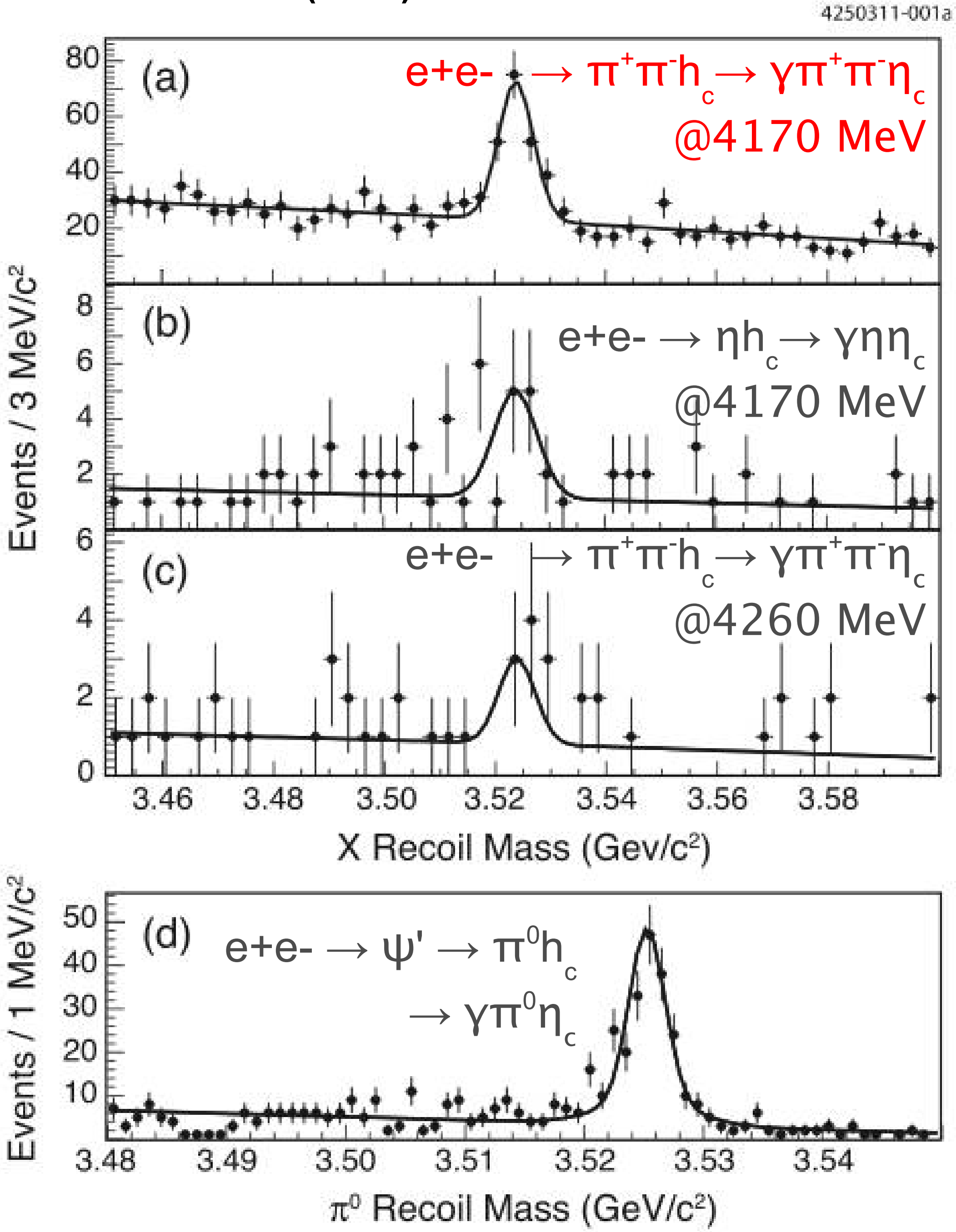
CLEO : PRL 107 (2011) 041803

Exclusive Recostruction of η_c in 12 decay modes:

$\pi^+\pi^+\pi^-\pi^-$, $\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$, $\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$, $K^\pm K_S\pi^\mp$, $K^\pm K_S\pi^\mp\pi^+\pi^-$, $K^+K^-\pi^0$, $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-\pi^0$, $K^+K^-\pi^+\pi^+\pi^-\pi^-$, $K^+K^+K^-K^-$, $\eta\pi^+\pi^-$, $\eta\pi^+\pi^+\pi^-\pi^-$

Cross section DOES NOT peak at 4170

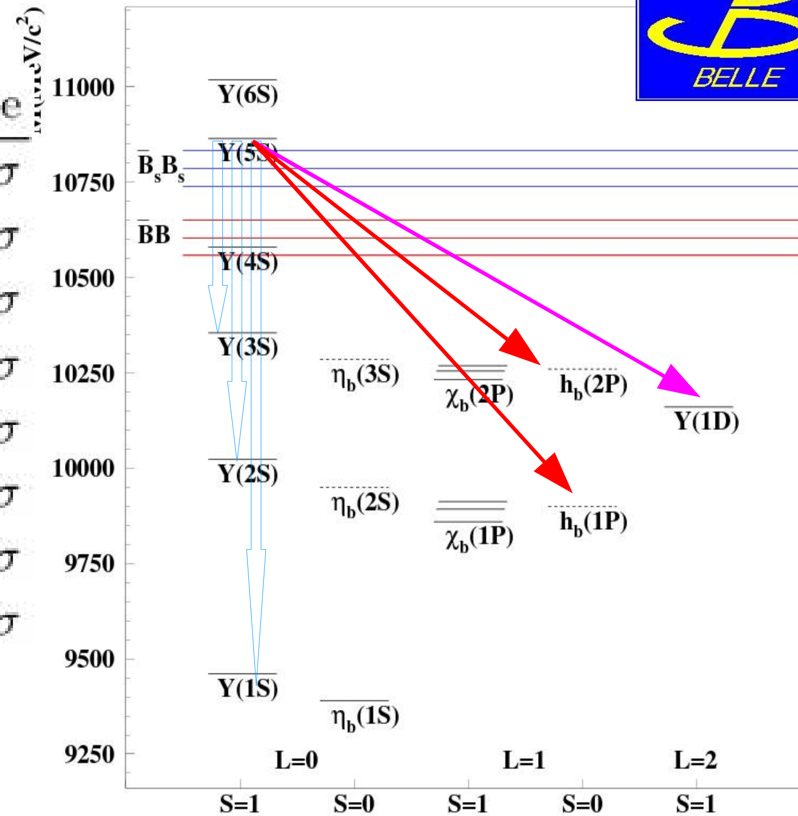




h_b(1,2P) from Υ(5S)

PRL108,032001

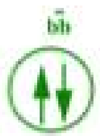
	Yield, 10^3	Mass, MeV/c^2		Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	⇔	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	↔	$6.2\,\sigma$
$3S \to 1S$	56 ± 19	9973.01		$2.9\,\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	⇔	$16.6\,\sigma$
$\Upsilon(1D)$	22.0 ± 7.8	10166.2 ± 2.6	↔	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	↔	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$		$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	⇔	$8.5\,\sigma$



Significance after correcting for systematics effects: $h_b(1P)$ 5.5σ $h_b(2P)$ 11.2σ

Masses very close to the state COG of χ states, as expected from theory

$\Delta M_{HF}(1P) = 1.6 \pm 1.5$ MeV/c^2 $\Delta M_{HF}(2P) = 0.5^{+1.6}_{-1.2}$ MeV/c^2

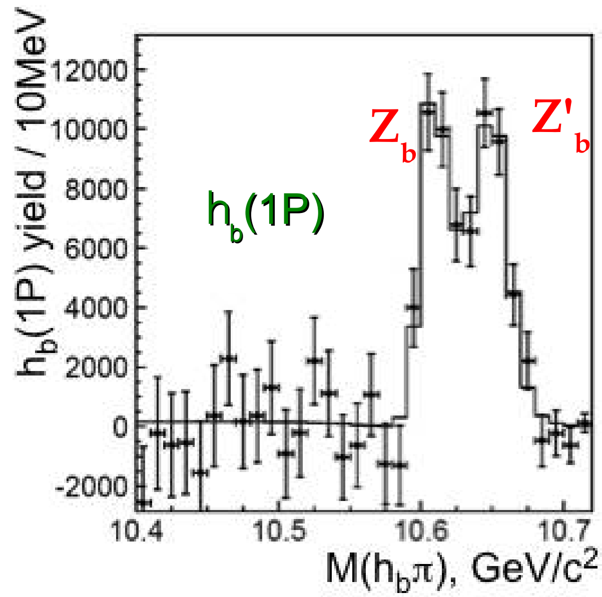


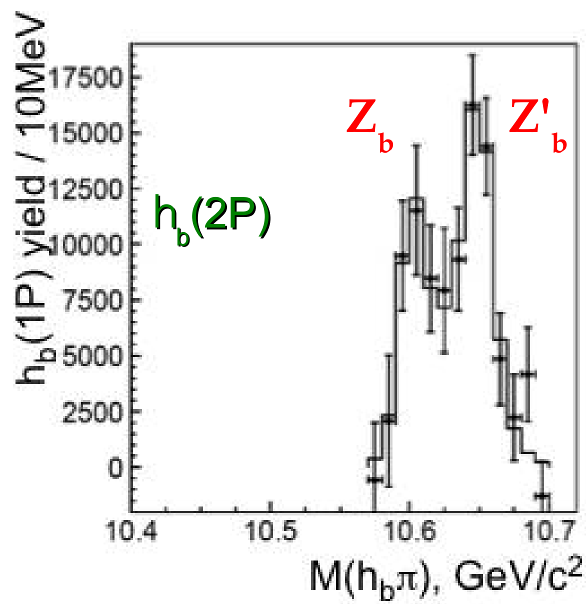
spin-flip

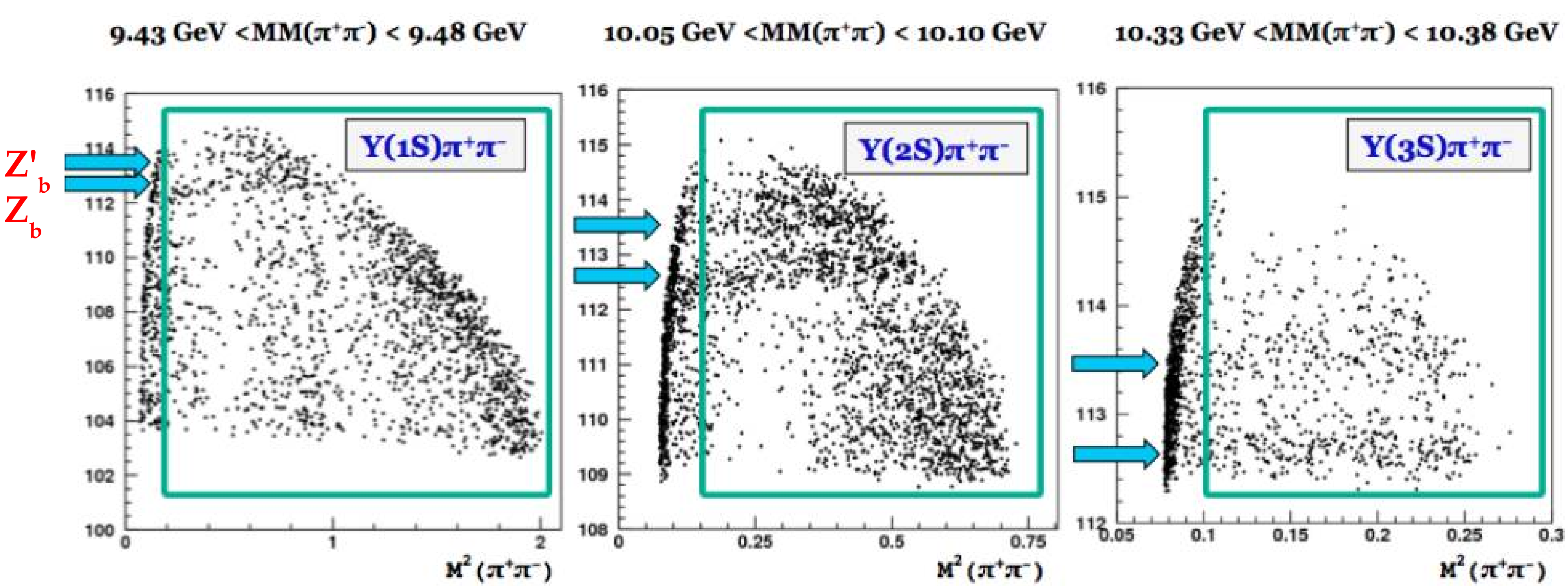
$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-]} = \begin{cases} 0.46 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

no spin-flip

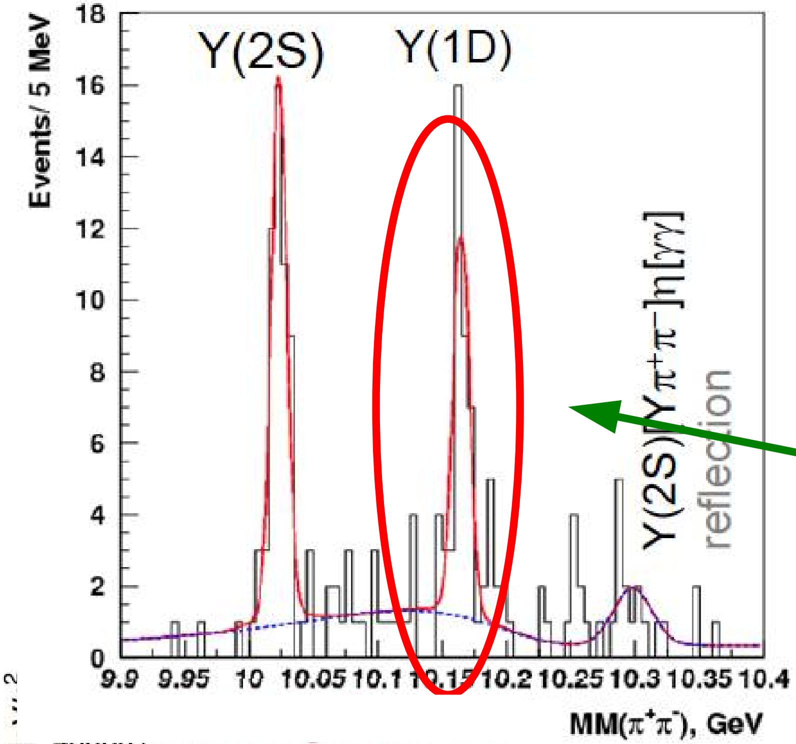
Single π recoil in $\Upsilon(5S) \rightarrow h_b(1,2P)$&$\Upsilon(1,2,3S)$: Z_b's !





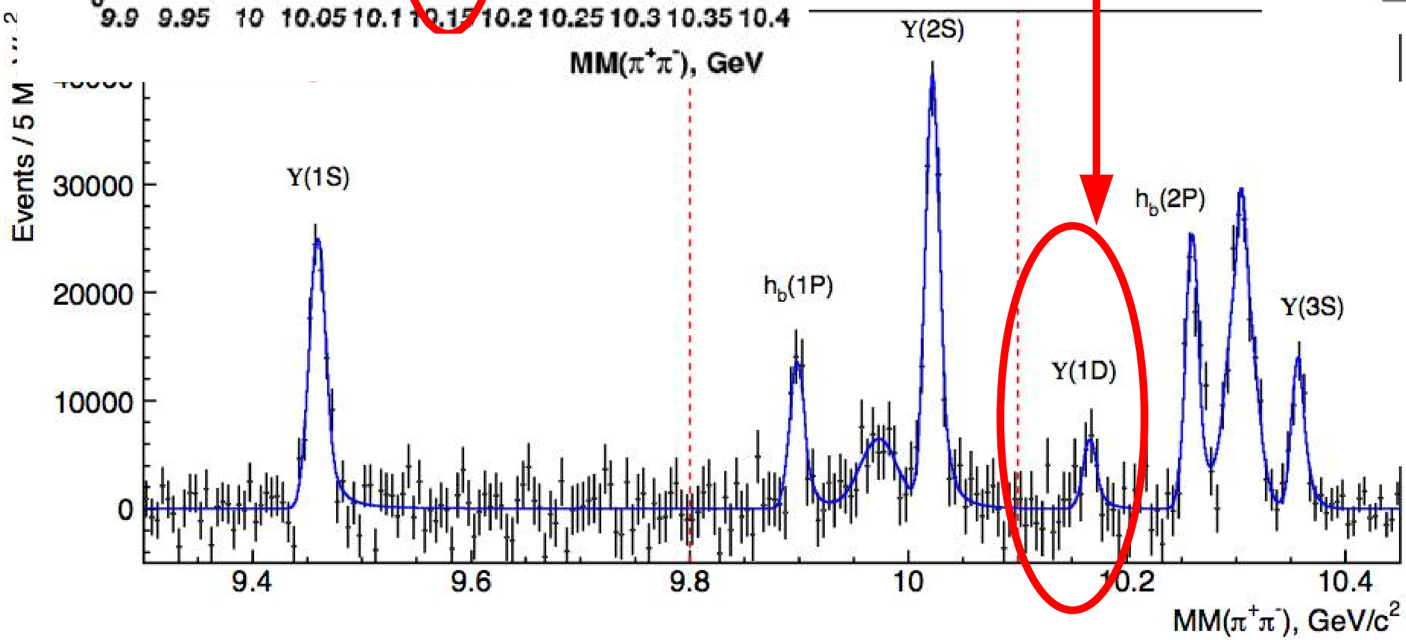


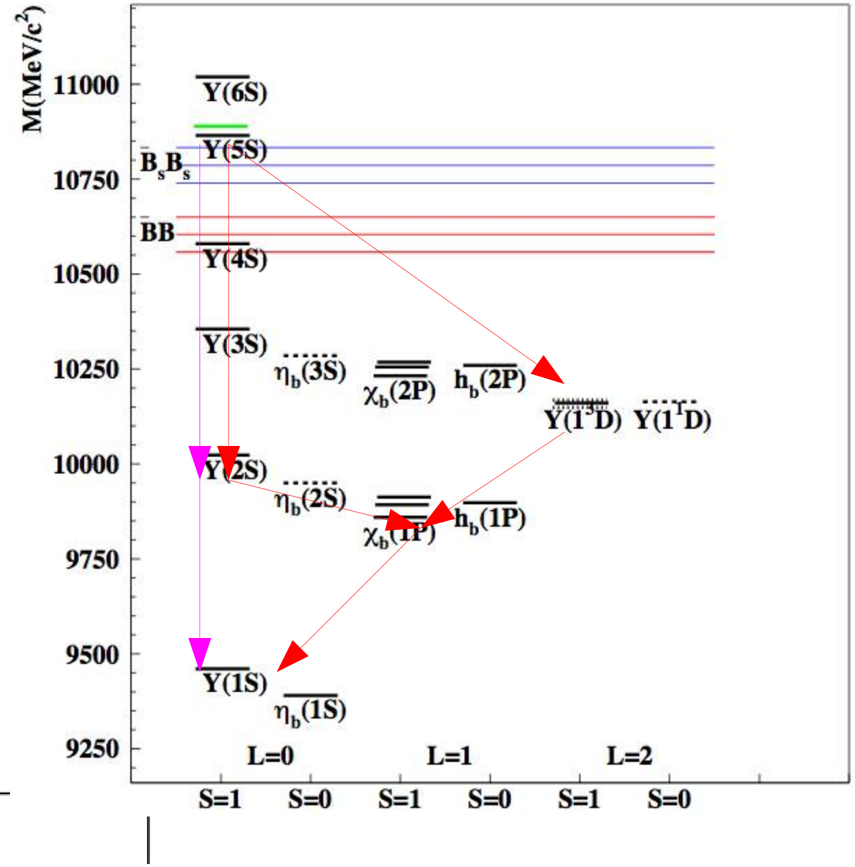
Bottomonium D wave



Already seen by Cleo and Babar from Y(3S)

Significance:
- Exclusive: 9σ
- Inclusive: 2.4σ





CLEO
M = 10161.1±0.6±1.6 MeV
$B[\Upsilon(3S)\to\Upsilon(1D)\gamma\gamma\to\Upsilon(1S)\gamma\gamma\gamma\gamma]$ = $(2.5\pm0.5\pm0.5)\times10^{-5}$

Belle preliminary
$B[\Upsilon(5S)\to\Upsilon(1D)\pi^+\pi\to\Upsilon(1S)\gamma\gamma\pi^+\pi^-]$ = $(2.0\pm0.4\pm0.3)\times10^{-4}$

X_b(3P) @ LHC

First particle(s) found at LHC!
Mass of χ_b(3P) centroid:

ATLAS, 4.4 fb^{-1} @7 TeV

$$M = 10539 \pm 4 \pm 8 \text{ MeV}/c^2$$

Confirmed by Tevatron:
D0, 1.3 fb^{-1} @2 TeV

$$M = 10551 \pm 14 \pm 17 \text{ MeV}/c^2$$

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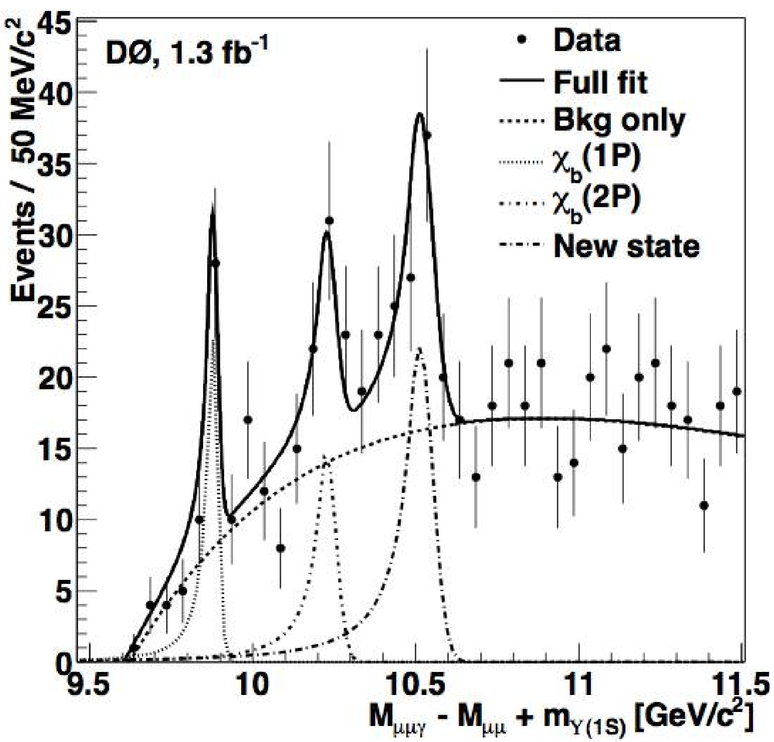

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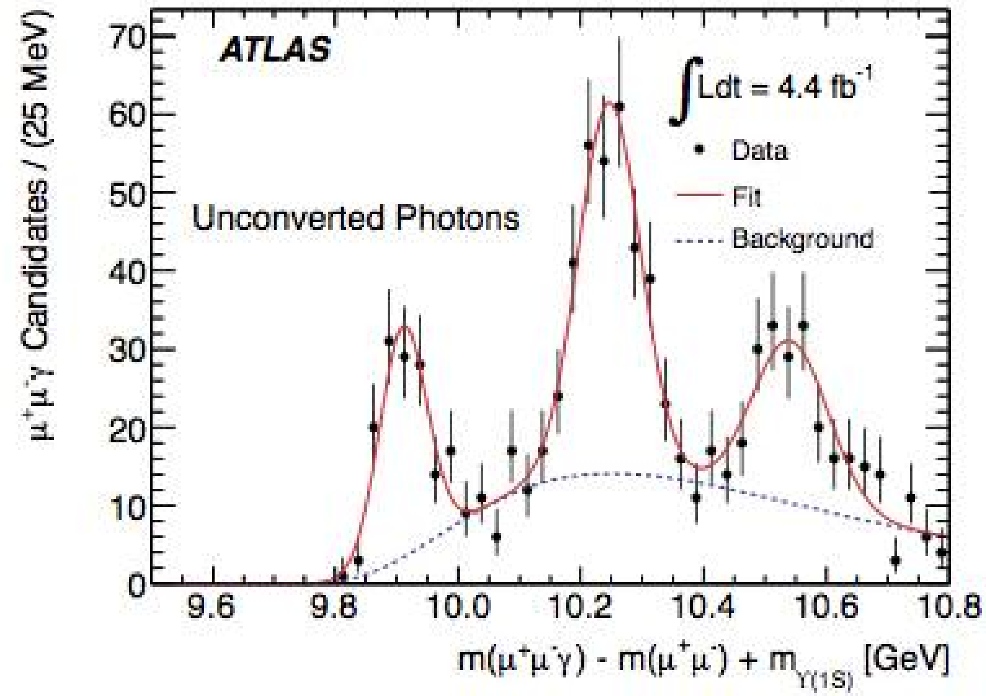
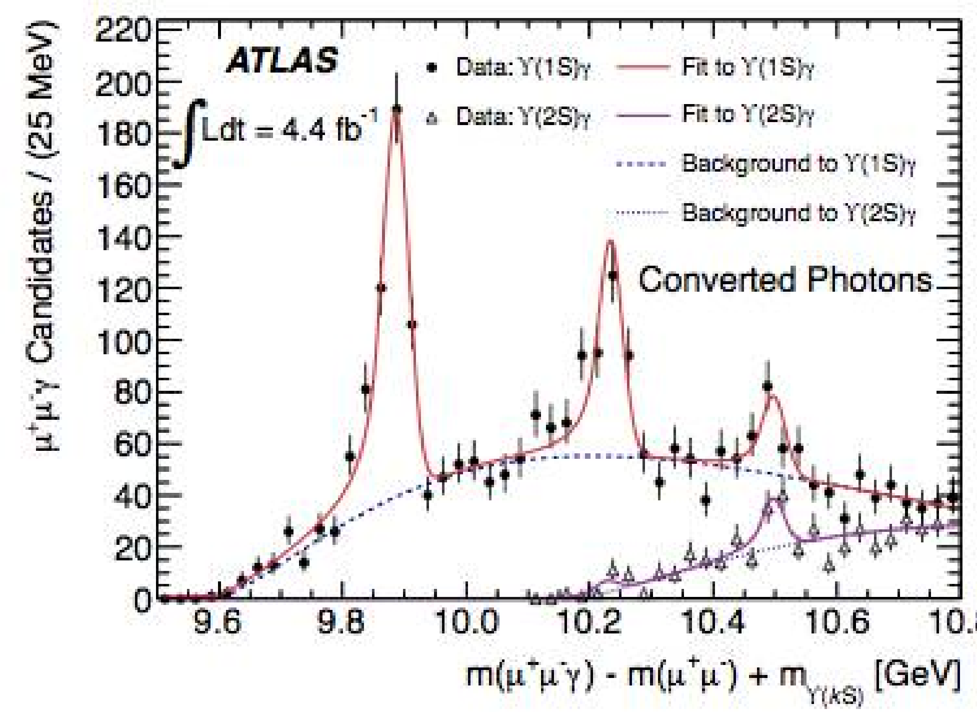


Phys.Rev.Lett. 108 (2012) 152001



(b)