

Meson spectroscopy

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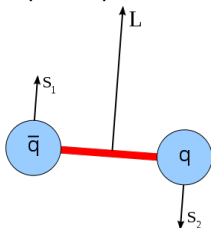
PWA7 – Camogli, 23-27 September, 2013

Mesons

The simplest colorless configuration with zero baryon number is $q\bar{q}$:

$$\text{SU}(3) \quad q \otimes \bar{q}' = 3 \otimes \bar{3} = 8 \oplus 1 \quad q \text{ and } \bar{q} \text{ in color singlet } (q\bar{q})_0$$

Quantum numbers determined from relative angular momentum L and quark spin relative orientation \vec{s}_1 and \vec{s}_2 :



- $P = (-1)^{L+1}$
- $|L - S| \leq J \leq |L + S|$
- C only defined for flavor-less mesons

QCD can allow other color-less states with 0 baryon number:

- glueballs
- $q\bar{q} - g$ hybrids
- a variety of 4-quark states:
 - molecules
 - diquark-anti-diquark
 - hadro-quarkonium

How to identify exotic mesons?

Smoking guns:

quark content and/or quantum numbers not allowed for $(q\bar{q})_0$

- manifestly exotic quantum numbers: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \dots$
- charged charmonium or bottomonium states

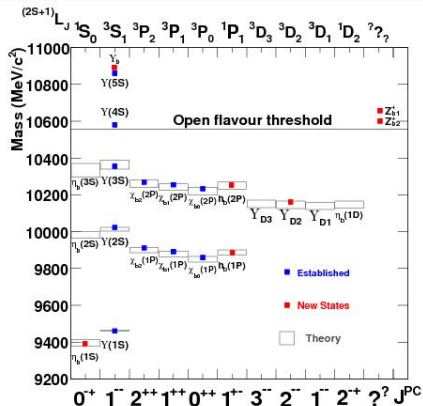
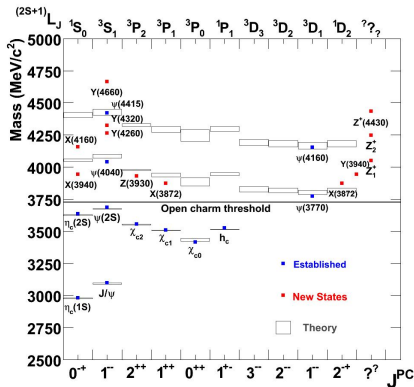
not-so-smoking guns:

- over-population of the spectrum
- anomalous decay or production properties

But

- threshold effects, mixing and coupled channels can significantly affect masses and decay widths eg of conventional quarkonia
- Artifacts (cusps, virtual states, **reflections**) can be mistaken as resonances

Charmonium and bottomonium spectrum



(nearly) all states below threshold observed at masses close to predictions

- overpopulated spectrum
- candidates with manifestly exotic quantum numbers

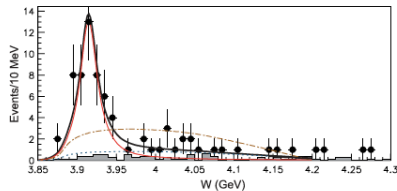
The $X(3915) \rightarrow J/\psi\omega$ observed in $\gamma\gamma$ reactions: $\chi_{c0}(2P)$?

Observed by Belle PRL 104, 092001 (2010)

$$M = 3915 \pm 3 \pm 2 \text{ MeV}/c^2$$

$$\Gamma = 17 \pm 10 \pm 3 \text{ MeV}$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 61 \pm 17 \pm 8 \text{ eV} \quad (J = 0)$$

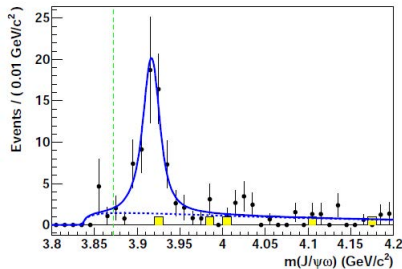


Confirmed by BABAR PRD 86, 072002 (2012)

$$M = 3919.4 \pm 2.2 \pm 1.6 \text{ MeV}/c^2$$

$$\Gamma = 13 \pm 6 \pm 3 \text{ MeV}$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 52 \pm 10 \pm 3 \text{ eV} \quad (J = 0)$$



If $\Gamma_{\gamma\gamma} = \mathcal{O}(1 \text{ keV})$ (typical $c\bar{c}$), then $\mathcal{B}(J/\psi\omega) > (1 - 6)\%$

$J^P = 0^+$ strongly favoured by BABAR angular analysis

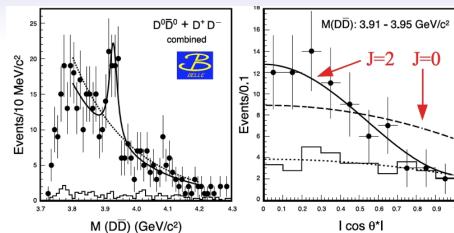
The $Z(3930) \rightarrow D\bar{D}$ observed in $\gamma\gamma$: $\chi_{c2}(2P)$ candidate

Observed by Belle in $\gamma\gamma \rightarrow D\bar{D}$
 NOT in $D\bar{D}^*$

$$M = 3929 \pm 5 \pm 2 \text{ MeV}/c^2$$

$$\Gamma = 29 \pm 10 \pm 2 \text{ MeV}$$

$$\Gamma_{\gamma\gamma} \times \mathcal{B}(D\bar{D}) = 0.18 \pm 0.05 \pm 0.03 \text{ keV}$$

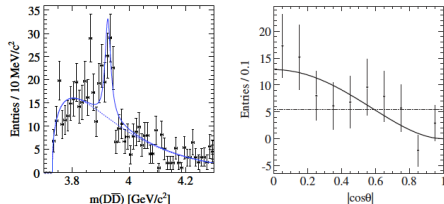


Confirmed by *BABAR*

$$M = 3926.7 \pm 2.7 \pm 1.1 \text{ MeV}/c^2$$

$$\Gamma = 21.3 \pm 6.8 \pm 3.6 \text{ MeV}$$

$$\Gamma_{\gamma\gamma} \times \mathcal{B}(D\bar{D}) = 0.241 \pm 0.054 \pm 0.043 \text{ keV}$$



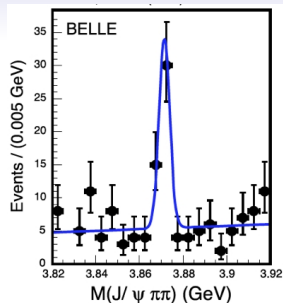
Angular distribution strongly favors $J = 2$: generally identified as $\chi_{c2}(2P)$ candidate

Mass lower by $\approx 50 \text{ MeV}/c^2$ but Γ , $\Gamma_{\gamma\gamma}$ and $\mathcal{B}(D\bar{D})$ consistent with expectations

Could be interesting to search for $J/\psi\gamma$, $\psi(2S)\gamma$, $\chi_{c0}\pi^+\pi^-$ or $J/\psi\omega$

X(3872)

Narrow peak in $J/\psi\pi^+\pi^-$ invariant mass observed by Belle in $B^+ \rightarrow (J/\psi\pi^+\pi^-)K^+$ decays



PRL 91 (2003) 262001

- $J^{PC} = 1^{++}$ recently established by LHCb (see R. Cardinale's talk)
- mass within errors coinciding with $D^0\bar{D}^{*0}$ threshold
- decays into $J/\psi\pi^+\pi^-$ (likely $J/\psi\rho^0$, $l=1$), $J/\psi\gamma$, $J/\psi\omega$, $D^0\bar{D}^{*0}$
- large decays to $\psi(2S)\gamma$ reported by *BABAR* not confirmed by Belle
- Observed in B decays and in prompt $p\bar{p}$ and pp collisions (Tevatron, LHC)

X(3872) interpretation

- charmonium $\chi_{c1}(2P)$
radiative decay should be two orders of magnitude larger mass off by 100 MeV/c²
- Tetraquark:
No I-spin partners, no neutral doublet

Mixture of $D^0\bar{D}^{*0}$ and $\chi_{c1}(2P)$??

- $D^0\bar{D}^{*0}$ molecule
natural explanation for mass almost coincident with threshold
 $D^0\bar{D}^{*0}$ decay
 $J^{PC} = 1^{++}$ ($D^0\bar{D}^{*0}$ in S-wave)
small $J/\psi\gamma$ can be accommodated but
 - too large $\psi(2S)\gamma$ (if confirmed)
 - small binding energy \rightarrow large radius, difficult to explain production in high energy pp or $p\bar{p}$ collisions

The $Y(3940) \rightarrow J/\psi\omega$ observed in B decays

Observed by Belle

PRL 94,180002 (2005)

$$M = 3943 \pm 11 \pm 13 \text{ MeV}/c^2$$

$$\Gamma = 87 \pm 22 \pm 26$$

$$\mathcal{B}(B \rightarrow YK) \cdot \mathcal{B}(Y \rightarrow \omega J\psi) = (7.3 \pm 1.3 \pm 3.1) \cdot 10^{-5}$$

confirmed by BABAR

PRD-RC 82,011101(2010)

$$M = 3919.1_{-3.5}^{+3.8} \pm 2.0 \text{ MeV}/c^2$$

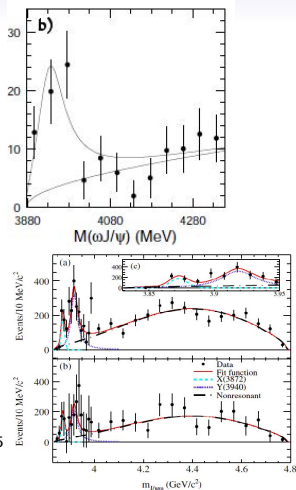
$$\Gamma = 31_{-8}^{+10} \pm 5, \text{ MeV}$$

$$\mathcal{B}(B^+ \rightarrow YK^+) \cdot \mathcal{B}(Y \rightarrow \omega J\psi) = (3.0_{-0.6}^{+0.7+0.5}) \cdot 10^{-5}$$

$$\mathcal{B}(B^0 \rightarrow YK^0) \cdot \mathcal{B}(Y \rightarrow \omega J\psi) = (2.1 \pm 0.9 \pm 0.3) \cdot 10^{-5}$$

Not seen in $B \rightarrow D\bar{D}^*K$ (expected dominant for 1^{++})

$\mathcal{B}(B \rightarrow YK)$ large for 2^{++} in B decays. $0^{++}, 0^{-+}???$

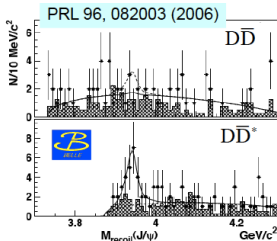
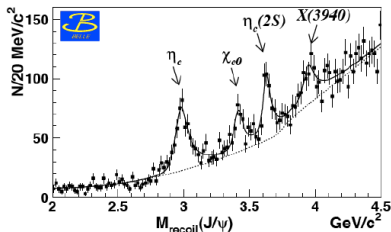
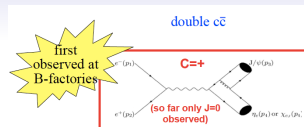


The $X(3940) \rightarrow D\bar{D}^*$ observed in double $c\bar{c}$ production

Unexpectedly large cross section for $\sigma(e^+e^- \rightarrow J/\psi(c\bar{c}))$ measured by Belle

Observe known $0^{\pm+}$ states recoiling against a J/ψ

+ another one



PRL 100:202001,2008

$$M = 3942_{-6}^{+7} \pm 6 \text{ MeV}/c^2$$

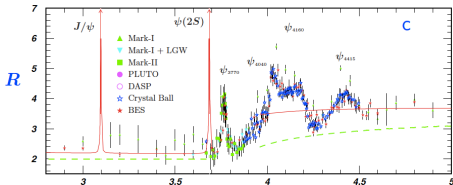
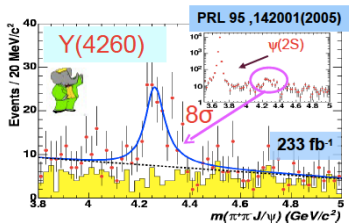
$$\Gamma = 37_{-15}^{+26} \pm 8 \text{ MeV}$$

- observed in the recoil of the J/ψ (double $c\bar{c}$) ...
- The only other states clearly visible have $J=0$ $C=+$
→ that suggest either $\chi_{c0}(2P)$ or $\eta_c(3S)$
- decay to $D\bar{D}^*$ but not to $D\bar{D}$ suggest $P=-1$ thus hypothesis of $\eta_c(3S)$
- the 3^1S_0 mass is predicted at ~ 4050 or above

not seen in $B \rightarrow D\bar{D}^*K$

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

Observed by *BABAR* in ISR process, confirmed by Belle and CLEO, which observes also $J/\psi \pi^0 \pi^0$ compatible with I-spin expectations



It has been searched (and not found) in

- many exclusive $D_{(s)}^{(*)} \bar{D}_{(s)}^{(*)}$ modes
- many exclusive light hadron modes
- $\rho \bar{\rho}$

The hadronic cross section has a dip at this mass

Comparing total and peak cross sections estimate

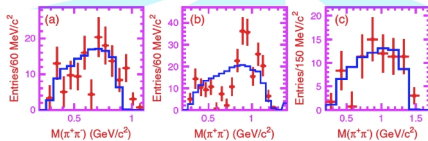
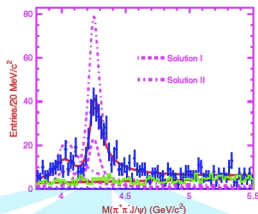
$$\mathcal{B}(Y \rightarrow J/\psi \pi^+ \pi^-) > 8\%$$

$$\Gamma(Y \rightarrow J/\psi \pi^+ \pi^-) > 8 \text{ MeV}$$

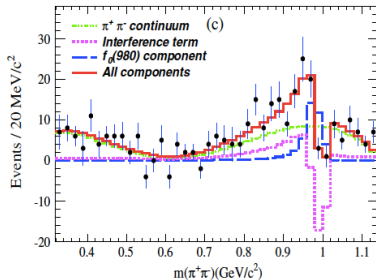
Y(4260) and study of $\pi^+\pi^-$ spectrum

Belle finds that the $\pi^+\pi^-$ invariant mass spectrum in the Y(4260) region peaks at $f_0(980)$

PRL 99, 142002 (2007)



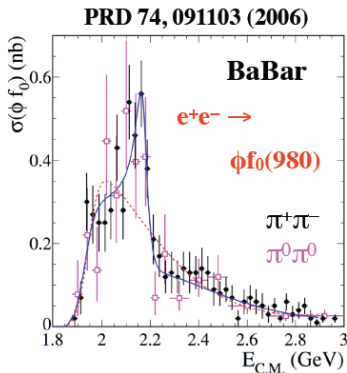
BABAR finds **non dominant $f_0(980)$ contribution** PRD 86, 051102 (2012)



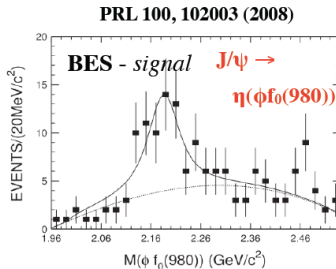
$$\frac{B(Y_{4260} \rightarrow J/\psi f_0(980), f_0(980) \rightarrow \pi^+\pi^-)}{B(Y_{4260} \rightarrow J/\psi \pi^+\pi^-)} = (17 \pm 13)\%$$

Y(2175) strange partner of the Y(4260)?

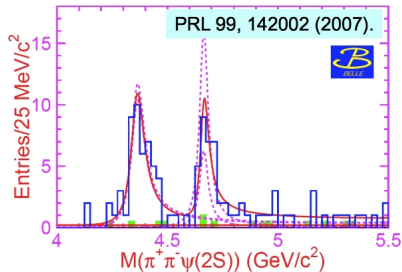
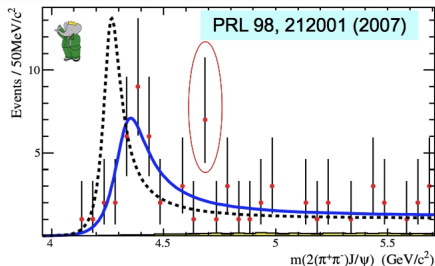
observed by *BaBar* in ISR



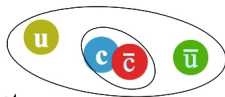
also seen by BES in J/ψ decays



$Y(4350)$ and $Y(4660) \rightarrow \psi(2S)\pi\pi$



- observed by BaBar in $\text{ISR } \psi(2S)\pi^+\pi^-$
- confirmed by Belle, which finds a significant excess also at 4660 MeV
- no evidence for $Y(4260)$...
- why are there states decaying to 2^3S_1 and not to 1^3S_1



hadro-charmonium?

•MB Voloshin
arXiv:0711.4556
•Dubynsky, & Voloshin
PLB 671 (2009) 82

$Y(4350)$ and $Y(4660)$ confirmed by *BABAR* on final dataset

arXiv:1211.6271

$Y(4140), Y(4274) \rightarrow \phi J/\psi$ decay?

Observed by CDF in $B^+ \rightarrow J/\psi \phi K^+$

PRL 102, 242002 (2009)

updated in

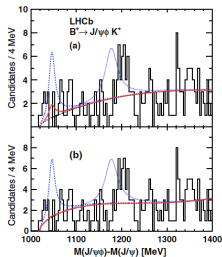
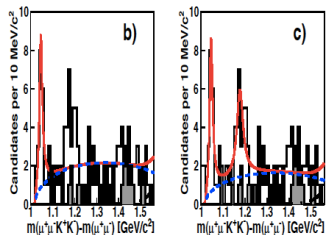
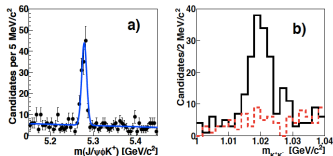
arXiv:1101.6058

Not seen by LHCb

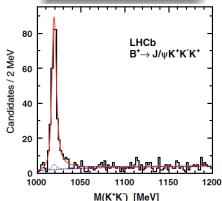
$382 \pm 22 B^+$

Allowed $J^{PC} = 0^{++}, 1^{+-}, 2^{++}$

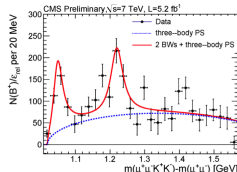
$115 \pm 12 B^+$ events



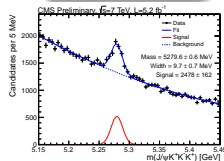
PRD 85, 091103 (2012)



seen at CMS?



CMS-BPH-11-026



Search for $\gamma\gamma \rightarrow Y(4140) \rightarrow \phi J/\psi$

Belle searched for $\gamma\gamma \rightarrow Y(4140) \rightarrow \phi J/\psi$ PRL 104, 112004 (2010)

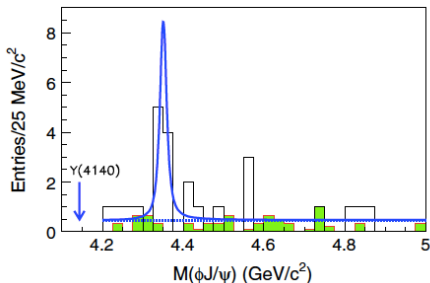
No evidence for $Y(4140)$

set upper limits

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J/\psi\phi) < 41 \text{ eV} \quad (J = 0)$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J/\psi\phi) < 6 \text{ eV} \quad (J = 2)$$

Find 3.1σ evidence for a new structure...



$$M = 4350.6_{-5.1}^{+4.6} \pm 0.7 \text{ MeV}/c^2$$

$$\Gamma = 13_{-9}^{+18} \pm 4 \text{ MeV}$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J/\psi\phi) = 6.7_{-2.4}^{+3.2} \pm 1.1 \text{ eV} \quad (J = 0)$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J/\psi\phi) = 1.5_{-0.6}^{+0.7} \pm 0.3 \text{ eV} \quad (J = 2)$$

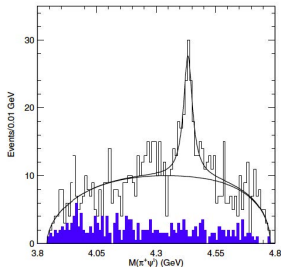
Charged charmonium? $Z(4430)^\pm \rightarrow \psi(2S)\pi^\pm$

Observed by Belle in

$$\bar{B}^0 \rightarrow K^+ \psi(2S) \pi^-$$

PRL 100, 142001 (2008)

quark content at least $c\bar{c}u\bar{d}$

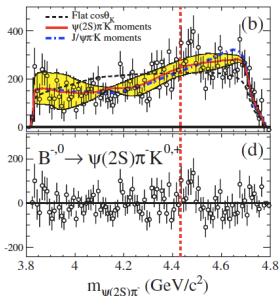


confirmed by a Dalitz re-analysis by Belle

PRD 80, 031104 (2009)

NOT confirmed by BABAR

PRD 79, 112001 (2009)

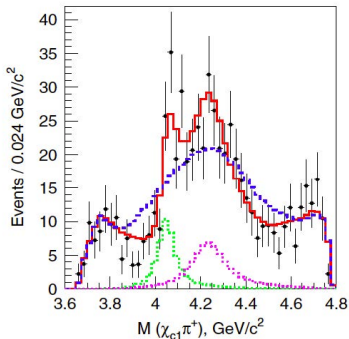


finds that its data can be described by $K\pi$ reflections without need for new resonance

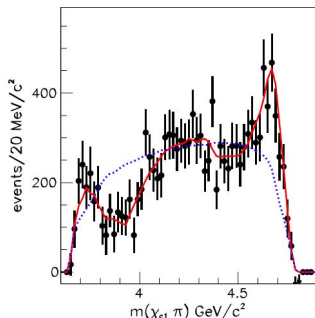
$Z(4430)^+ \rightarrow J/\psi \pi^+$ not seen by either experiment

More charged states in $B^0 \rightarrow \chi_{c1}\pi^+K^-$

Two new peaks in $\chi_{c1}\gamma$ invariant mass reported by Belle $Z_1(4050)^+$ and $Z_2(4250)^+$



PRD 79, 112001 (2009)



PRD 79, 112001 (2009)

again *BABAR* finds that data can be described by $K\pi$ substructures without introducing new resonances

$\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(ns)$

Belle searched for non- $B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}$ decays of the $\Upsilon(5S)$

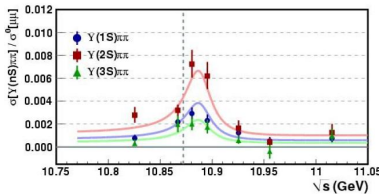
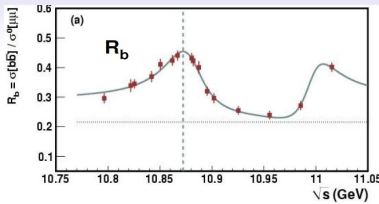
The resonance parameters measured in $\Upsilon(nS)\pi^+\pi^-$ final state differ from the parameters measured in the ratio

$$R_b = \frac{\sigma(e^+e^- \rightarrow b - \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

interference with continuum? non trivial description of R_b

Bottomonium partner of the $\Upsilon(4260)$?

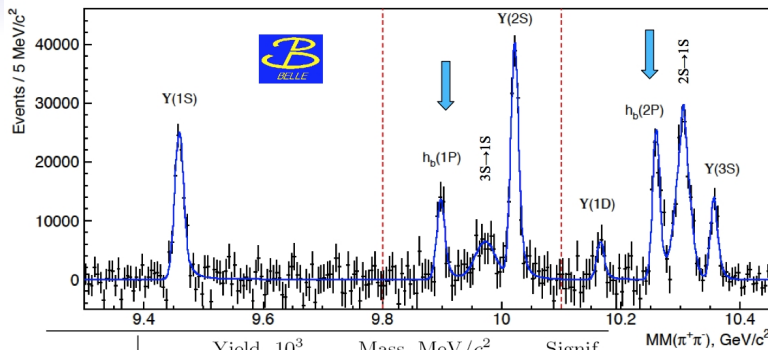
- anomalously large partial widths $\Gamma(\Upsilon(nS)\pi^+\pi^-)$ *dipion transitions are large also at the $\Upsilon(4S)$*
- $\Gamma(\Upsilon(1S)\pi^+\pi^-) \approx 2 \times \Gamma(\Upsilon(2,3S)\pi^+\pi^-)$



PRL 100, 112001 (2008)

PRD-RC 82, 091106 (2010)

$\Upsilon(5S) \rightarrow \pi^+\pi^- X$: observation of $h_b(1P)$ and $h_b(2P)$



121.4 fb⁻¹

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

MM($\pi^+\pi^-$), GeV/c²

Significance w/
systematics

$h_b(1P)$ 5.5 σ

$h_b(2P)$ 11.2 σ

PRL 108, 032001, (2012)

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

Deviations from CoG of χ_{bj} masses



$$\left. \begin{array}{l} h_b(1P) \quad 1.62 \pm 1.52 \text{ MeV}/c^2 \\ h_b(2P) \quad 0.48^{+1.57}_{-1.22} \text{ MeV}/c^2 \end{array} \right\} \text{consistent with zero, as expected}$$

PRL 108, 032001, (2012)

Ratio of production rates

$$\begin{array}{l} \text{spin-flip} \\ \rightarrow \\ \text{no spin flip} \end{array} \rightarrow \frac{\Gamma[\Upsilon(5S) \rightarrow h_b(nP) \pi^+ \pi^-]}{\Gamma[\Upsilon(5S) \rightarrow \Upsilon(2S) \pi^+ \pi^-]} = \begin{cases} 0.407 \pm 0.079^{+0.043}_{-0.076} & \text{for } h_b(1P) \\ 0.78 \pm 0.09^{+0.22}_{-0.10} & \text{for } h_b(2P) \end{cases}$$

$S(\Upsilon) = 1 \quad S(h_b) = 0$

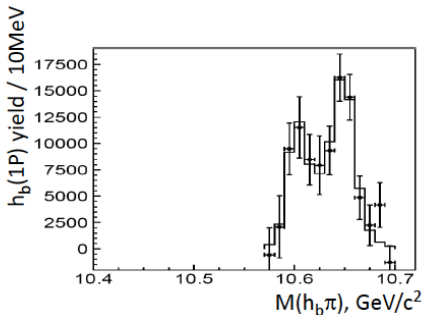
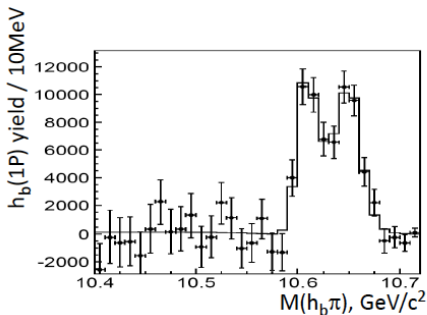
Process with spin-flip of heavy quark is not suppressed

- exotic ?
- rescattering? [Simonov JETP Lett 87,147\(2008\), D. Bugg, arXiv:1101.1659](#)

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

Substructures in $\Upsilon(5S) \rightarrow \pi^+\pi^-h_b(nP)$

Plot of invariant mass recoiling against π^\pm



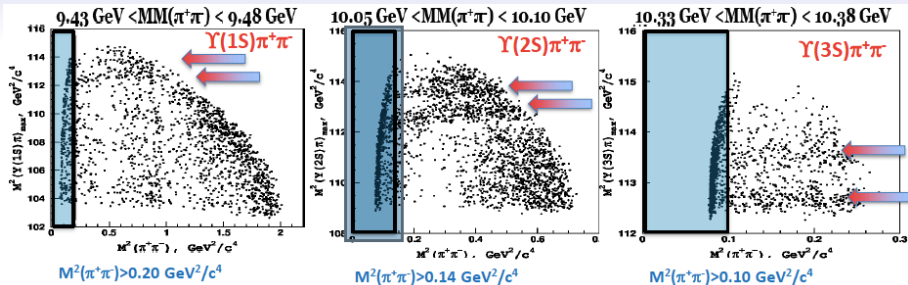
	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M_{Z_{b1}}$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma_{Z_{b1}}$	$11.4^{+4.5+2.1}_{-3.9-1.2}$	13^{+10+9}_{-8-7}
$M_{Z_{b2}}$	$10654 \pm 3^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma_{Z_{b2}}$	$20.9^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7^{+11}_{-7}$
a	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
ϕ	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

Almost all of $h_b(nP)$ seem to be produced through intermediate states

$$\Upsilon(5S) \rightarrow Z^-\pi^+ \rightarrow h_b(nP)\pi^+\pi^-$$

PRL 108, 122001 (2012)

$Z_b(10610)$ and $Z_b(10660)$ in $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(nS)?$



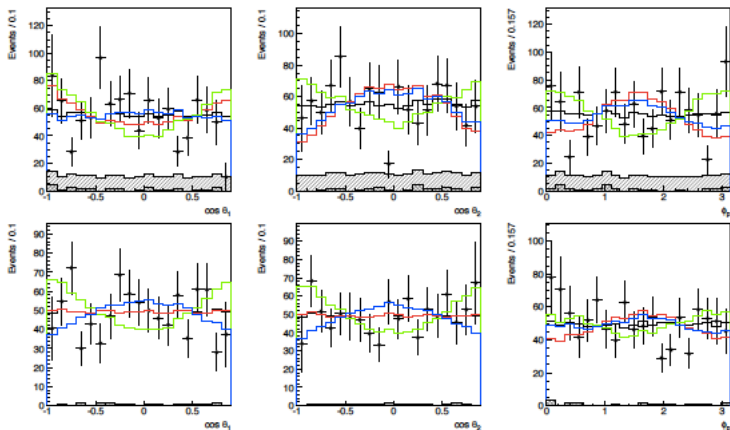
In all modes the two peaks have the same mass and width

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)], \text{MeV}/c^2$	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)], \text{MeV}$	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4^{+4.5+2.1}_{-3.9-1.2}$	13^{+10+9}_{-8-7}
$M[Z_b(10650)], \text{MeV}/c^2$	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)], \text{MeV}$	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

Large decay to both h_b (P singlet) and Υ (S-vector)

PRL 108, 122001 (2012)

$Z_b(10610)$ and $Z_b(10660)$ quantum numbers?



arXiv:1105.4583

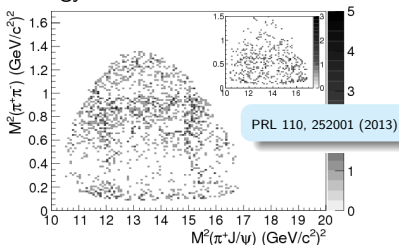
$\pi^+\pi^-$ angular distribution favours $J^P = 1+$

Since $\Upsilon(5S)$ has negative G-parity, the Z_b 's would have positive G-parity

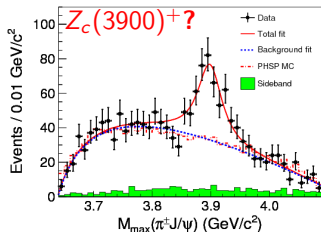
Substructures in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at $Y(4260)$ energy?

BES-III took a large amount of data at energies around the $Y(4260)$

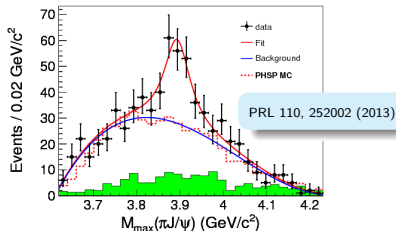
The Dalitz plot of $\pi^+\pi^- J/\psi$ events at this energy shows a substructure



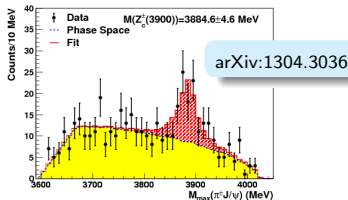
$M(J/\psi\pi^+)$ peaks at 3900 MeV/c²



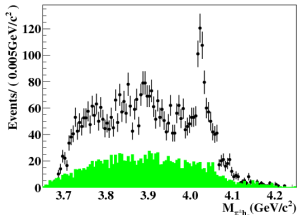
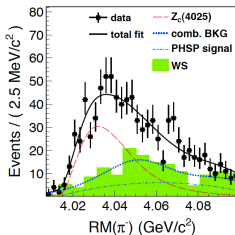
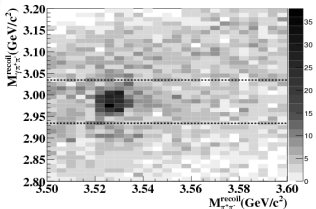
Soon confirmed by Belle in ISR



and by an analysis of CLEO-c data by the Northwestern group



More: $e^+e^- \rightarrow \pi^+\pi^-h_c, D^*\bar{D}^*\pi^+$ at $Y(4260)$ energy
 BES III has clean $h_c \rightarrow \gamma\eta_c$



The π^+h_c invariant mass shows a clear peak: $Z_c(4020)^+$?

arXiv:1309.1896

BES III also studied $e^+e^- \rightarrow D^*\bar{D}^*\pi^+$ and finds a broad structure at threshold in the invariant mass recoiling against the π^+ at a mass 4025 MeV/c²

arXiv:1308.2760

can be the same $Z_c(4020)^+$?

Conclusions

It's been fun to do spectroscopy in the past 10 years!

Every time people looked to an exclusive final state with quarkonia+light hadrons in a different process found a new state (often close to thresholds)

... and sometime two!

Some of these states might "disappear", some will be recognized to be the same state, but most of them are there to stay

If charged states will be recognized as resonances, they are manifestly exotic

Interplay between experiment and theory to sort out what's going on

In the process we could learn how to handle QCD corrections a bit further away from the easy limits