Heavy Quarkonium Spectroscopy
... and beyond

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Outline

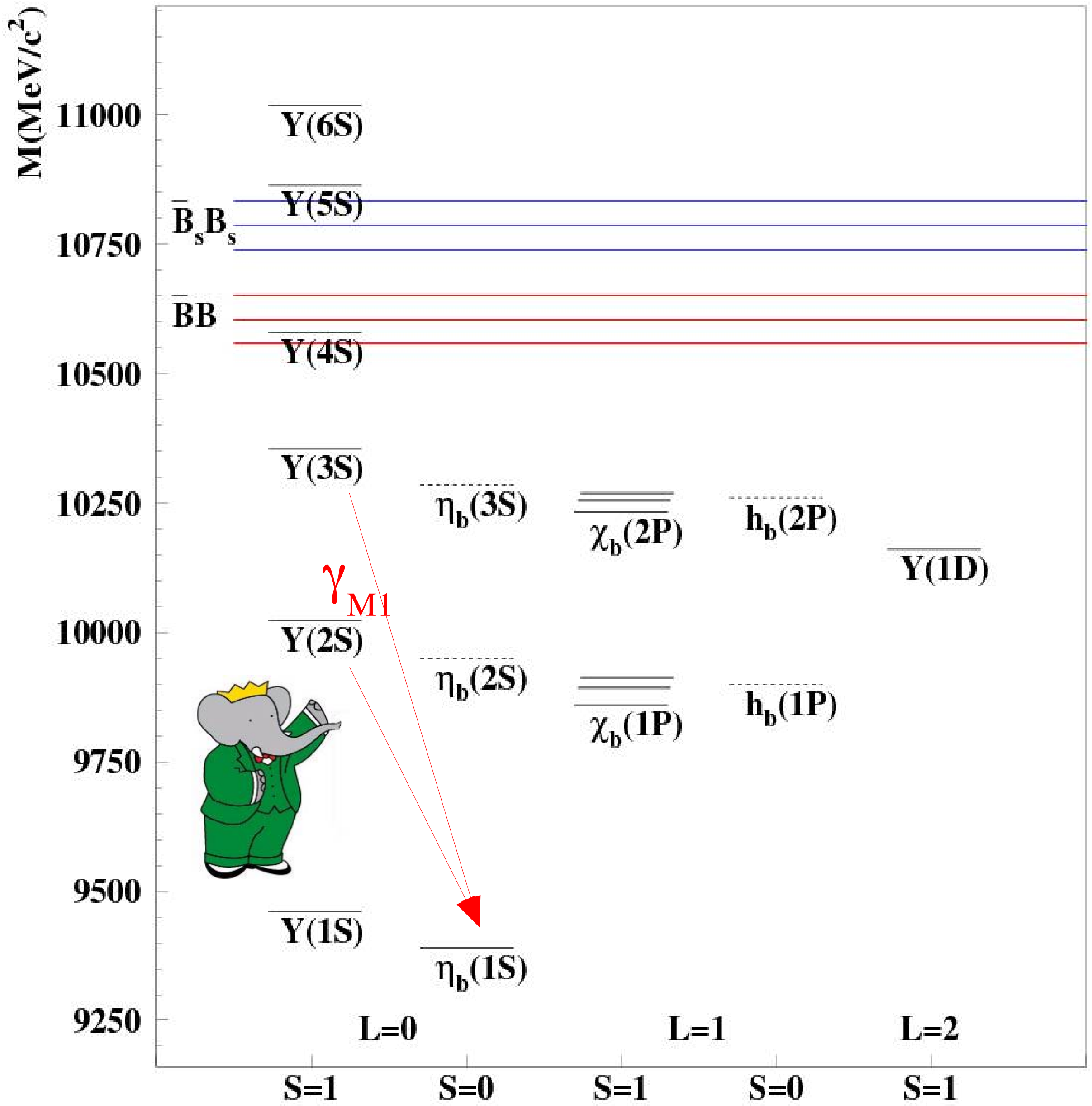
* parabottomonia
* heavy-light hadrons
* $\chi_b(3P)$
* D waves
* XYZ
* B_c

Parabottomonia

The quest for parabottomonia

5 amazing years for bottomonium spectroscopy:

- 2008 Discovery of η_b(Babar) via M1 transitions from Y(2,3S)



The quest for parabottomonia

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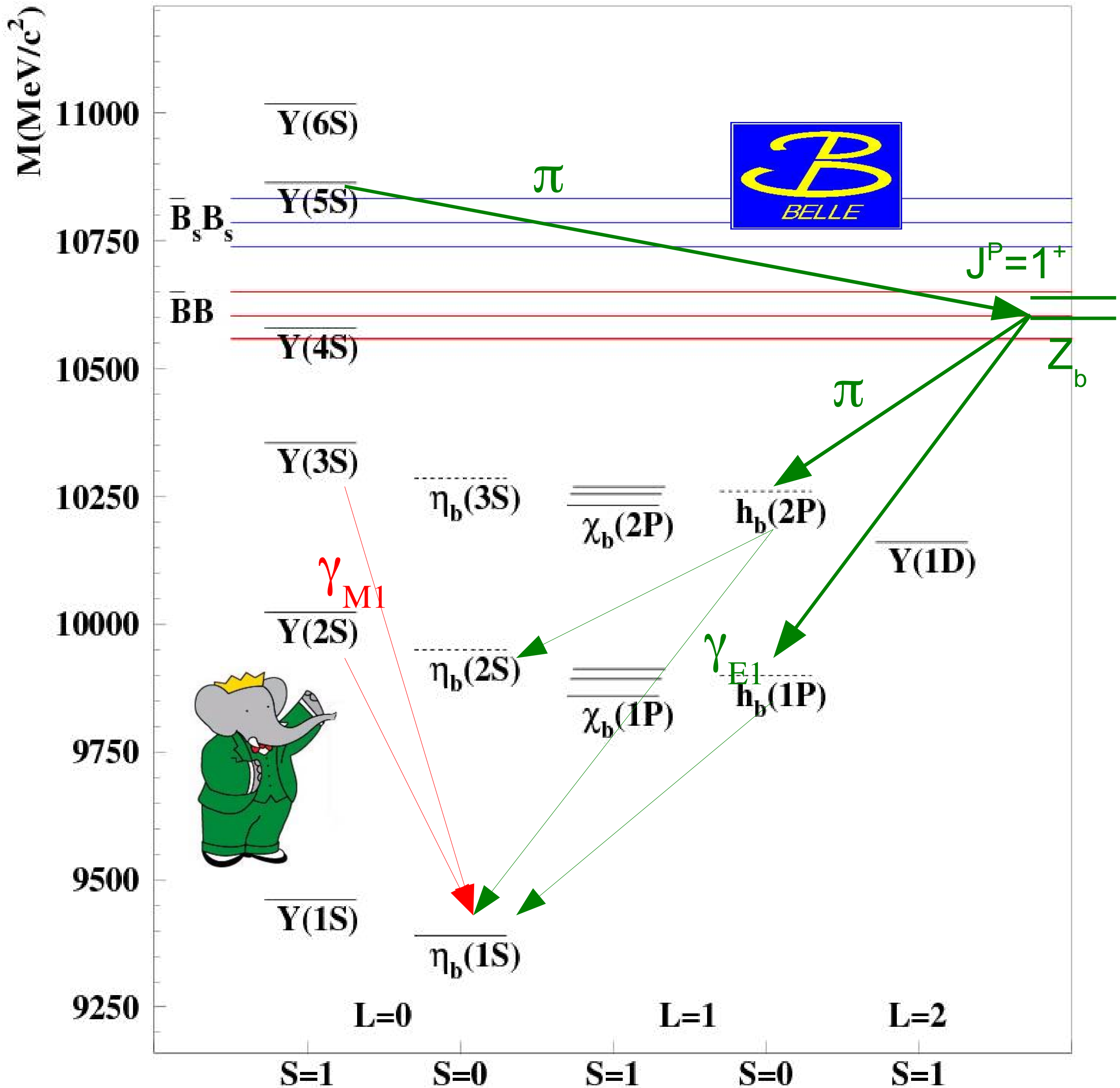
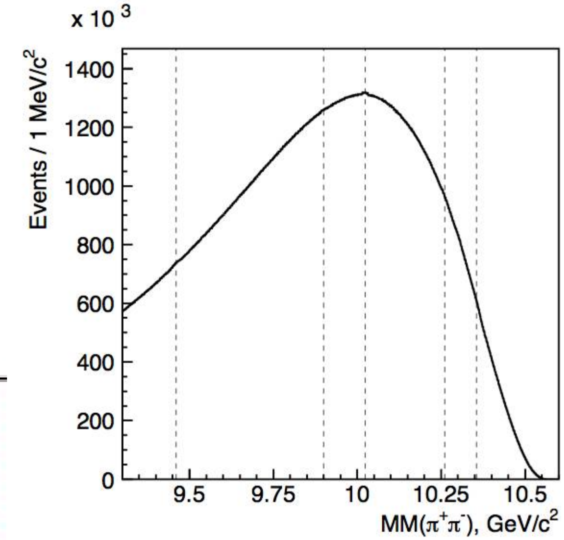
- 2011-2: Discovery of the triple cascade (Belle): Y(5S) $\rightarrow Z_b \rightarrow h_b \rightarrow \eta_b$

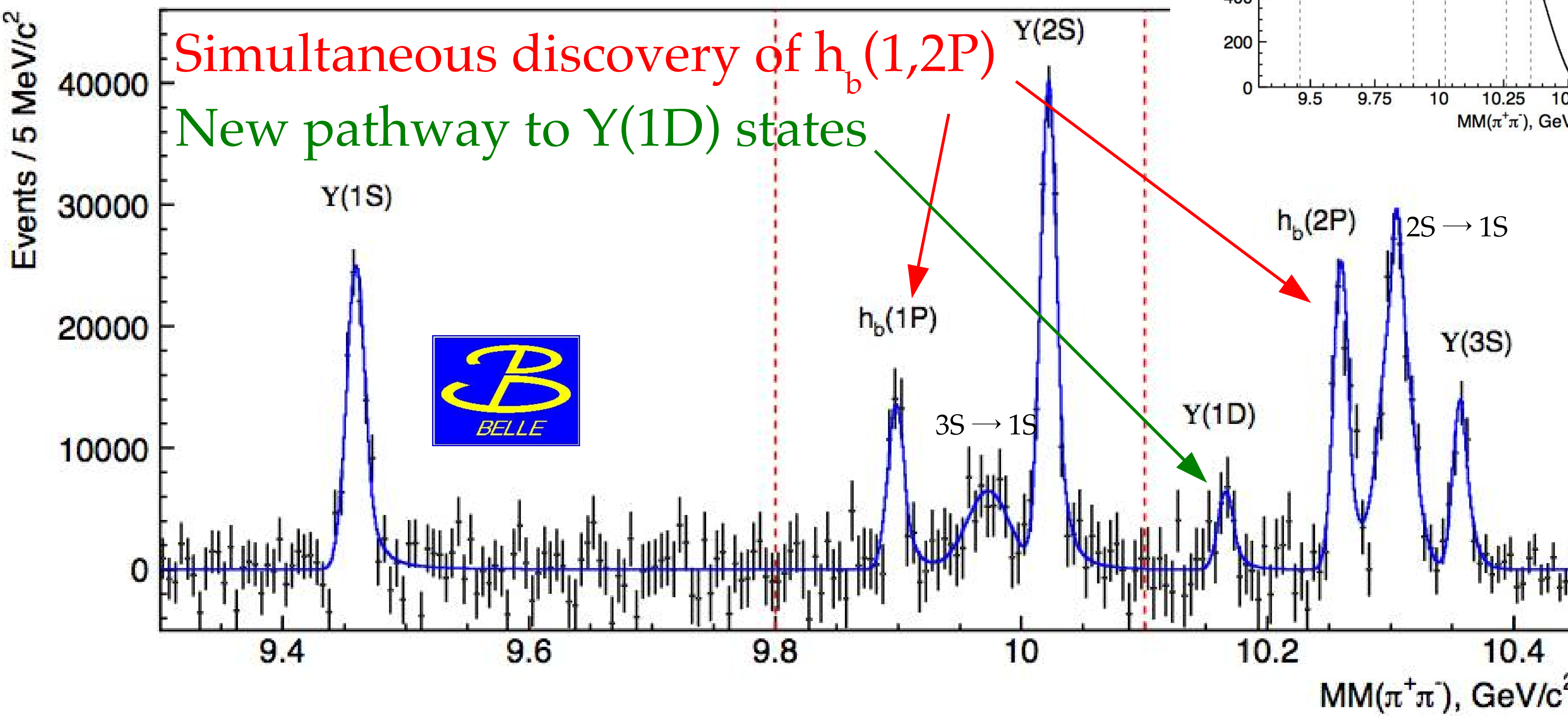


h_b(1,2P) from Υ(5S)

PRL108,032001

Inclusive search : $e^+e^- \to \Upsilon(5S) \to \pi^+\pi^- + \ldots$

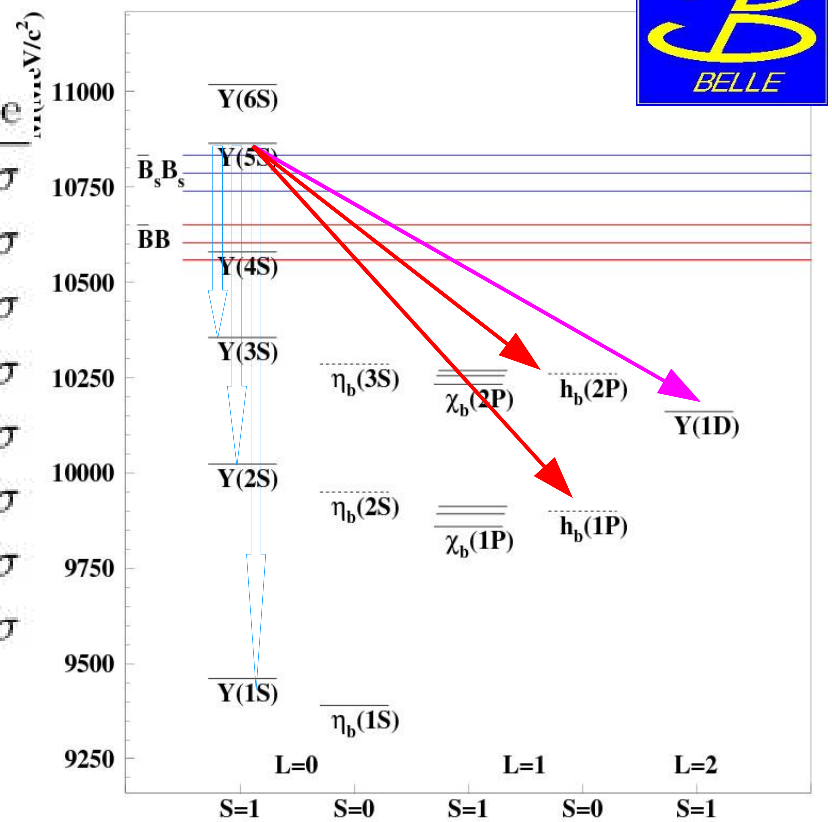




h_b(1,2P) from Υ(5S)

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	↔	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	↔	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$		$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	⇔	$8.5\,\sigma$

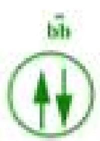


Significance after correcting for systematics effects: $h_b(1P)$ 5.5σ, $h_b(2P)$ 11.2σ

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

Ratio of spin flip vs noflip dipion transitions totally unexpected from theory....



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

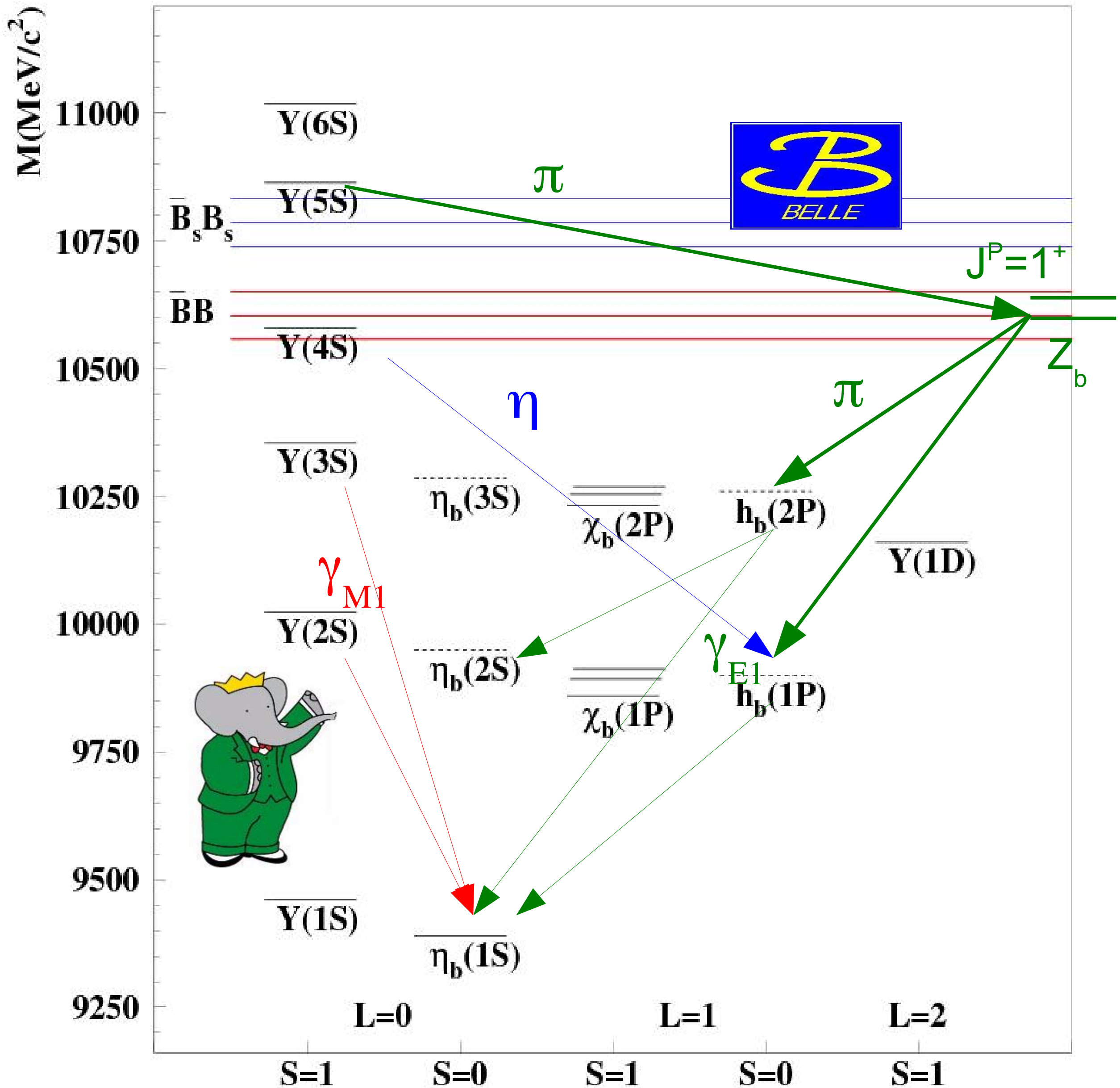
The quest for parabottomonia

5 amazing years for bottomonium spectroscopy:

- 2008 Discovery of η_b(Babar) via M1 transitions from Y(2,3S)

- 2011-2: Discovery of the triple cascade (Belle): $Y(5S) \to Z_b \to h_b \to \eta_b$

- 2014: Discovery of the $Y(4S) \to \eta h_b$ transition (Belle)



The η transitions

In 2008, Babar found out that η transitions from ϒ(4S) to ϒ(1S) are MORE INTENSE than ππ transitions.

Babar *PRD78,112002 (2008)*

$B(\Upsilon(4S) \to \eta\Upsilon(1S))$
$= (1.96\pm0.06\pm0.09) \times 10^{-4}$
$= 2.5 \times B(\Upsilon(4S) \to \pi\pi\Upsilon(1S))$

Belle

$B(\Upsilon(5S) \to \eta\Upsilon(1S)) = (7.3\pm1.6\pm0.8) \times 10^{-4}$
$= 0.25 \times B(\Upsilon(5S) \to \pi\pi\Upsilon(1S))$

$B(\Upsilon(5S) \to \eta\Upsilon(2S)) = (38\pm4\pm5) \times 10^{-4}$
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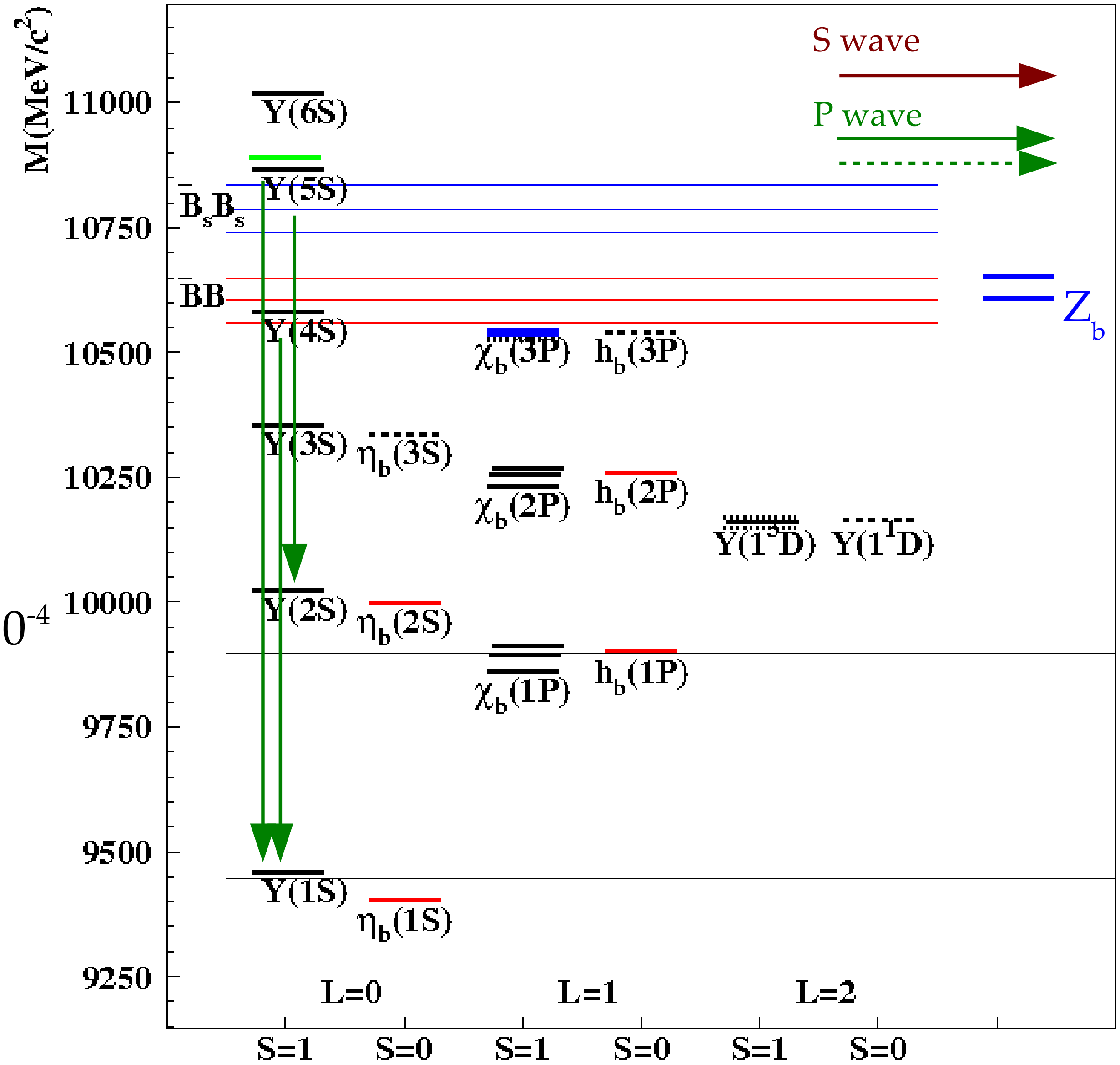
All measured η transitions are P-wave.



The η transitions

In 2008, Babar found out that η transitions from Υ(4S) to Υ(1S) are MORE INTENSE than ππ transitions.

Babar *PRD78,112002 (2008)*

$B(\Upsilon(4S) \to \eta\Upsilon(1S))$

$= (1.96 \pm 0.06 \pm 0.09) \times 10^{-4}$

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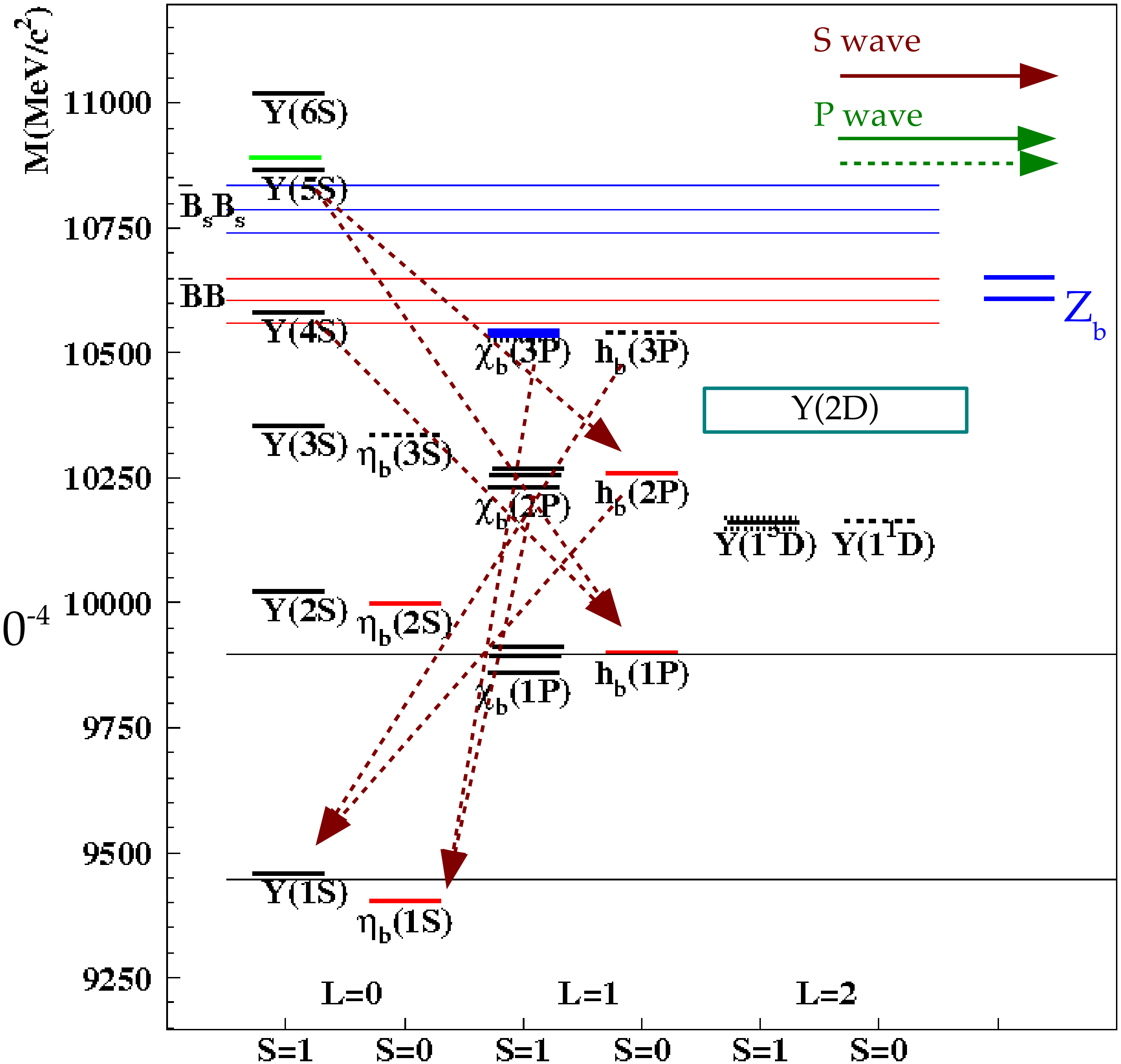
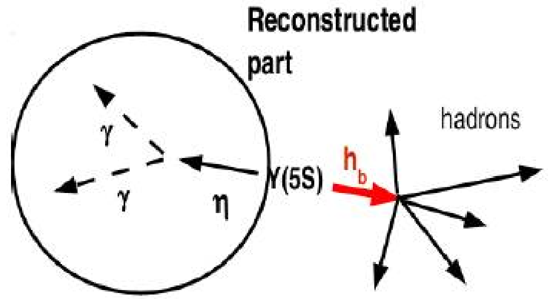
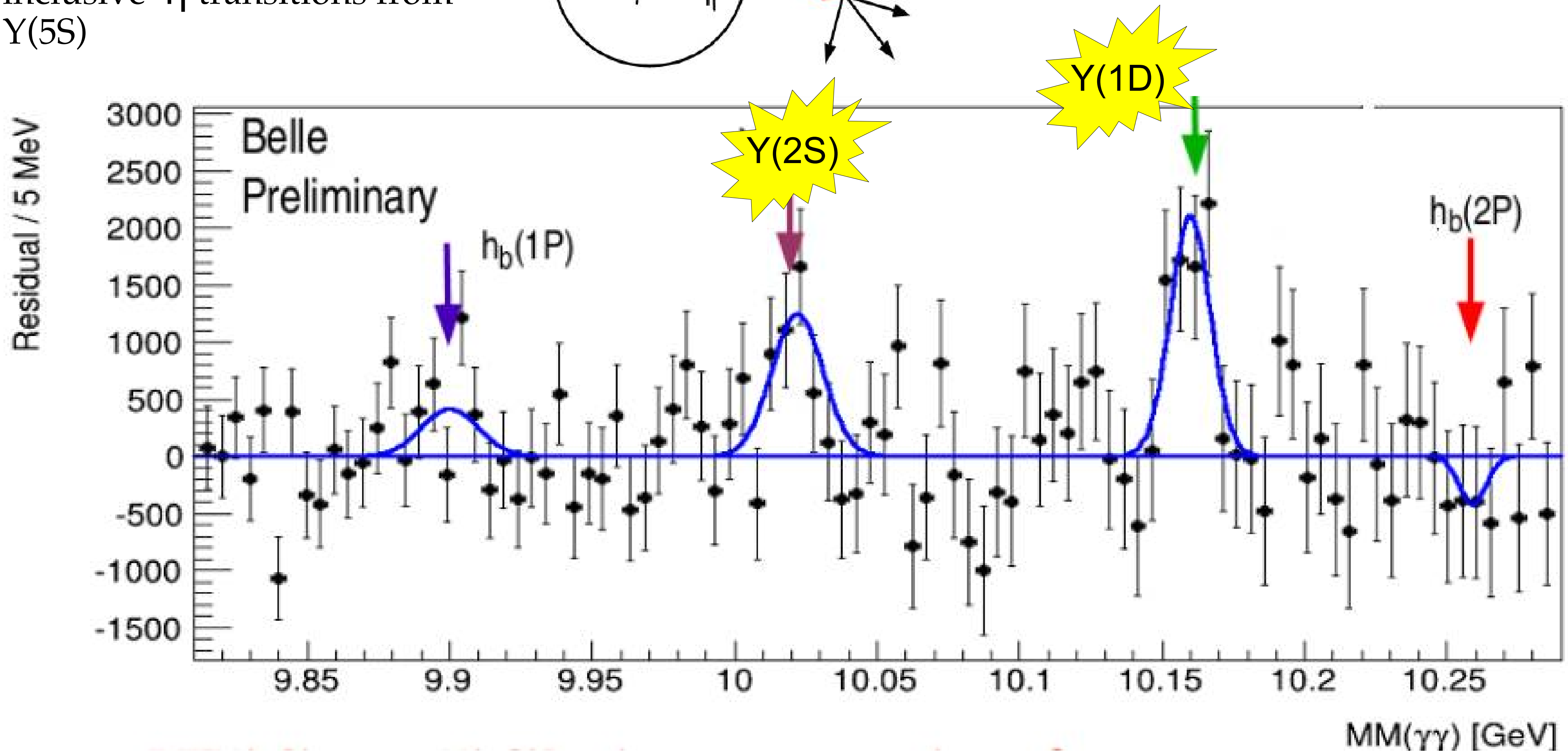
Why S-wave transitions are not observed?



The η transitions

In 2014, Belle studied the inclusive η transitions from Υ(5S)





$B(\Upsilon(5S) \rightarrow \eta\Upsilon(1D)) = (28 \pm 7 \pm 4) \times 10^{-4}$ $B(\Upsilon(5S) \rightarrow \eta h_b(2P)) < 37 \times 10^{-4}$

$B(\Upsilon(5S) \rightarrow \eta\Upsilon(2S)) = (21 \pm 7 \pm 3) \times 10^{-4}$ $B(\Upsilon(5S) \rightarrow \eta h_b(1P)) < 33 \times 10^{-4}$

The η transitions

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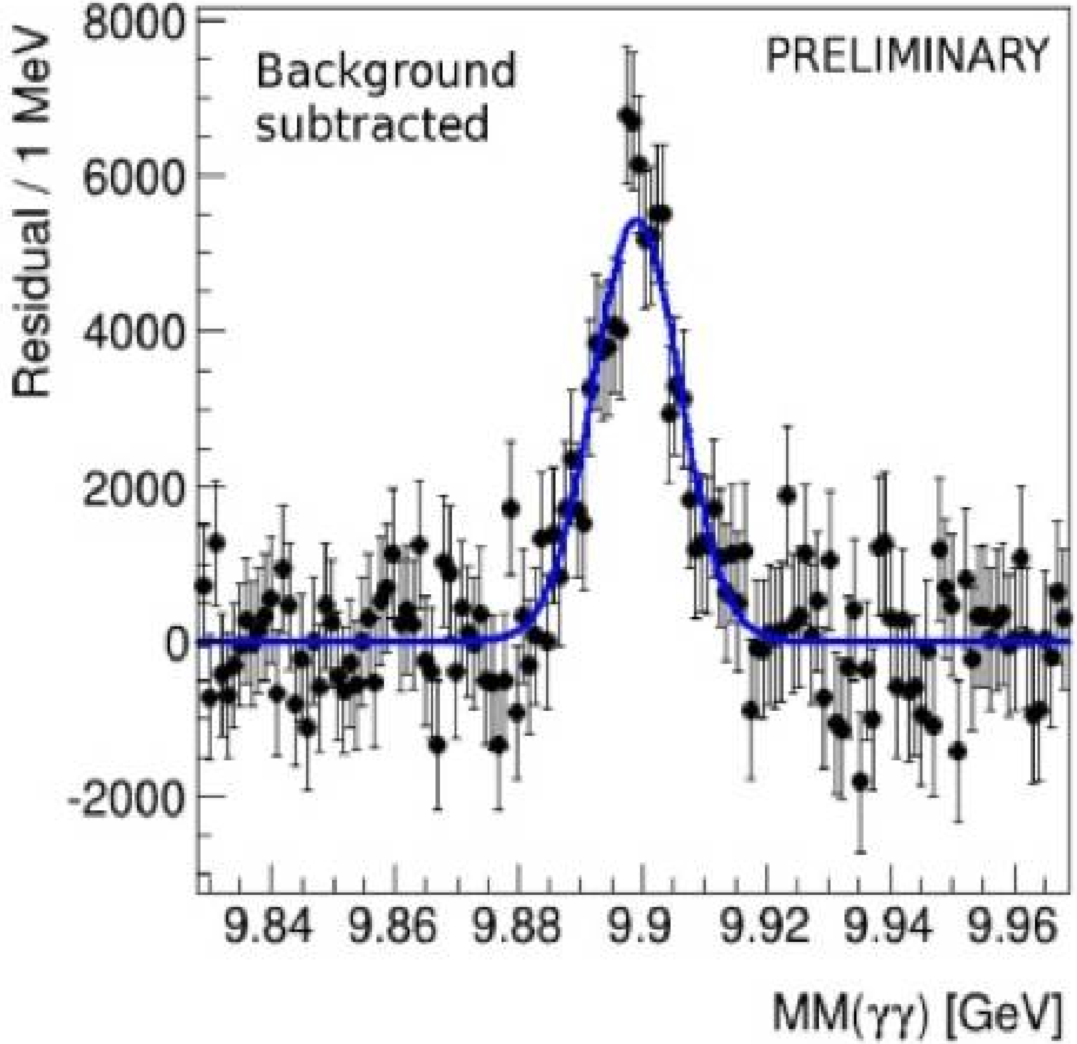

$B(\Upsilon(4S) \to \eta h_b(1P)) = (18.3\pm1.6\pm1.7)\times 10^{-4} > 9\times B(\Upsilon(4S) \to \eta\Upsilon(1S))$

Compatible with theory prediction, Guo et al, PRL105,162001(2010) : $\sim10^{-3}$

The η transitions

In 2014, Belle studied the inclusive η transitions from $\Upsilon(5S)$

Babar *PRD78,112002 (2008)*

$B(\Upsilon(4S) \to \eta\Upsilon(1S))$

$= (1.96\pm0.06\pm0.09)\times 10^{-4}$

$= 2.5 \times B(\Upsilon(4S) \to \pi\pi\Upsilon(1S))$

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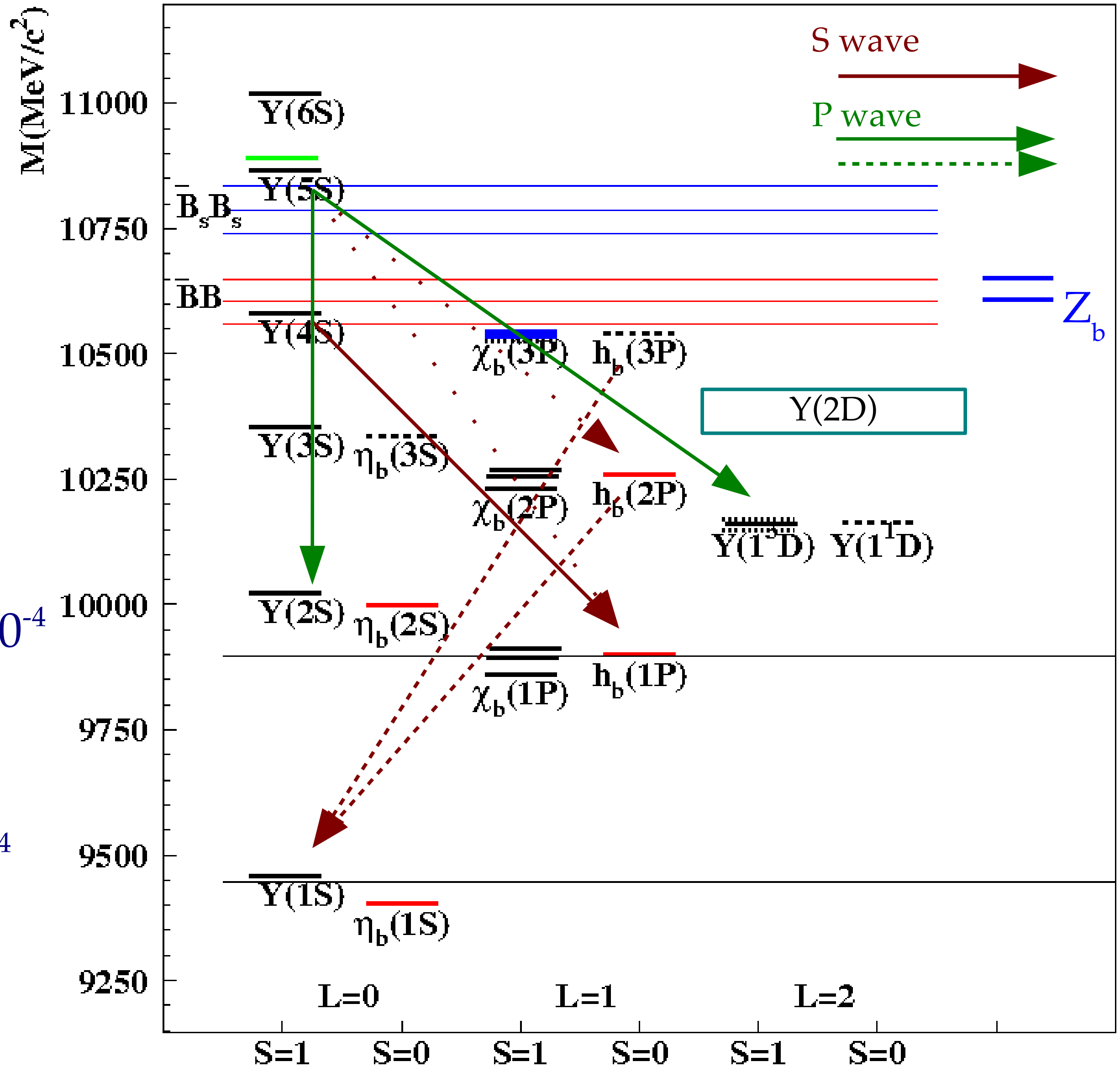

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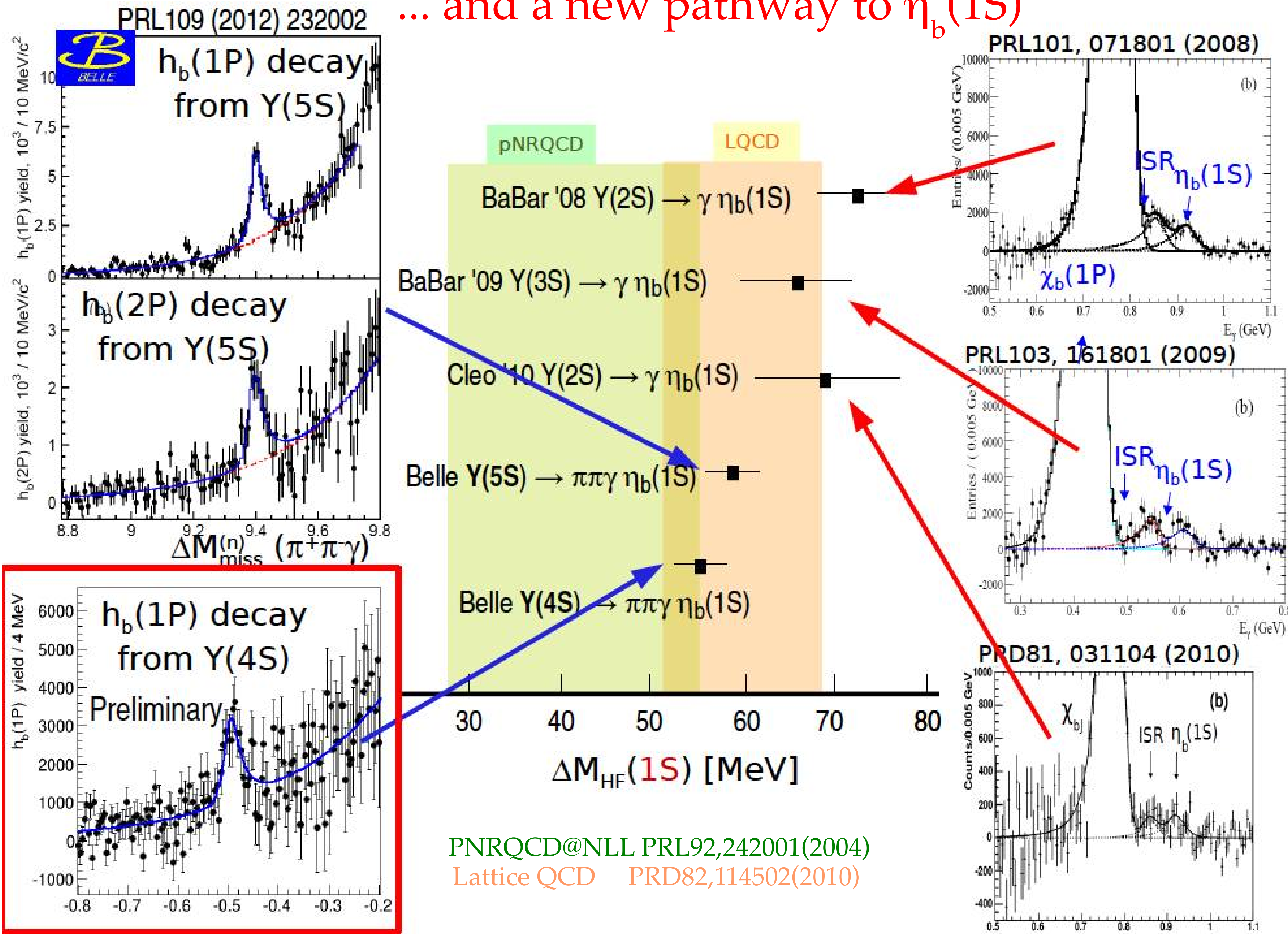
The largest hadronic transition from 4S to lower states !!!

... and a new pathway to $\eta_b(1S)$



PNRQCD@NLL PRL92,242001(2004)

Lattice QCD PRD82,114502(2010)

The η transitions in charmonium

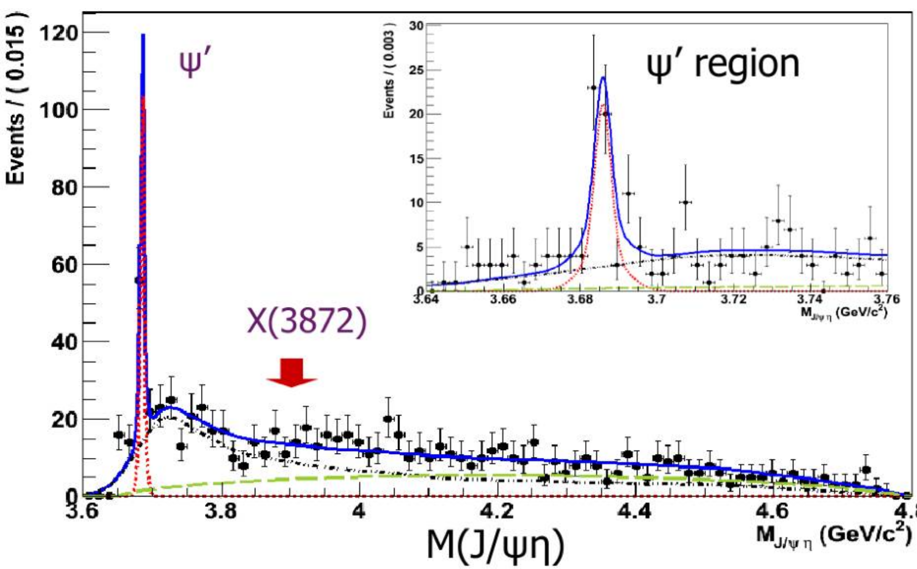
$e^+e^- \rightarrow \gamma_{ISR}\eta\, J/\psi$ at Belle

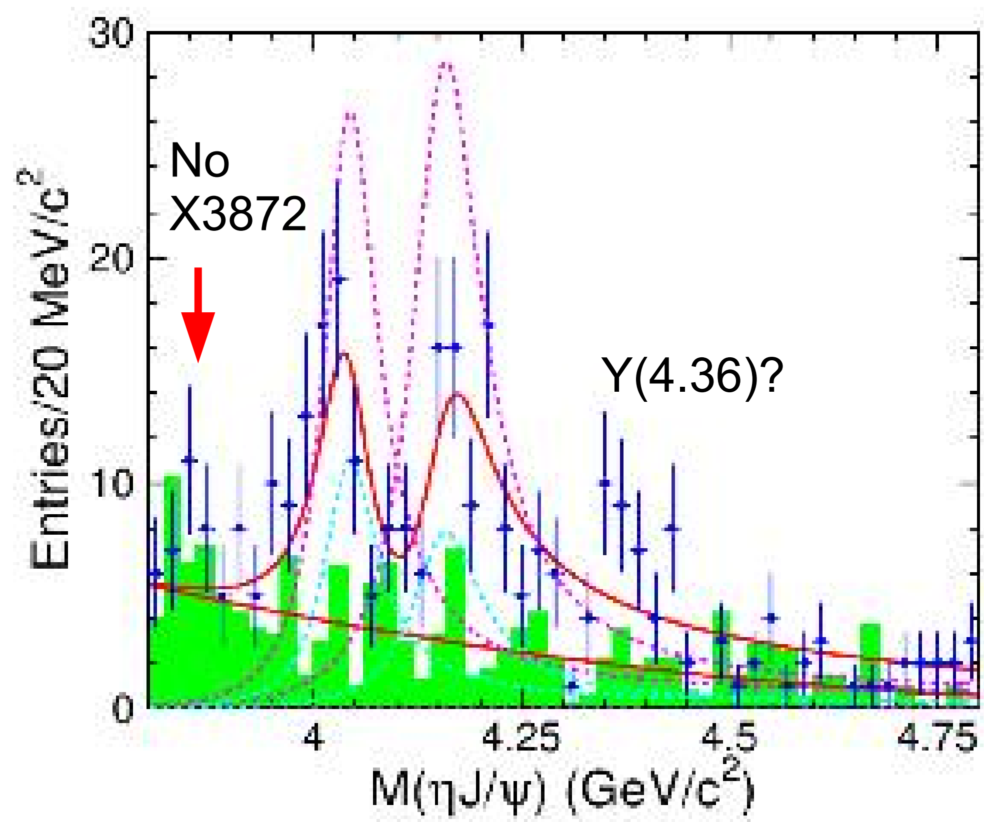
PRD87,051101 (2013)

Taking $\Gamma_{e^+e^-}(\psi(4040)) = (0.86 \pm 0.07)$ keV from PDG →
$\mathcal{B}(\psi(4040) \rightarrow \eta J/\psi) = (0.59 \pm 0.11 \pm 0.14)\%$ or
$\mathcal{B}(\psi(4040) \rightarrow \eta J/\psi) = (1.44 \pm 0.18 \pm 0.18)\%$.
Taking $\Gamma_{e^+e^-}(\psi(4160)) = (0.83 \pm 0.07)$ keV from PDG →
$\mathcal{B}(\psi(4160) \rightarrow \eta J/\psi) = (0.50 \pm 0.07 \pm 0.11)\%$ or
$\mathcal{B}(\psi(4160) \rightarrow \eta J/\psi) = (1.83 \pm 0.21 \pm 0.24)\%$.

Search for X(3872) → $\eta\, J/\psi$ at Belle

PTEP 2014,043C01 (2014)



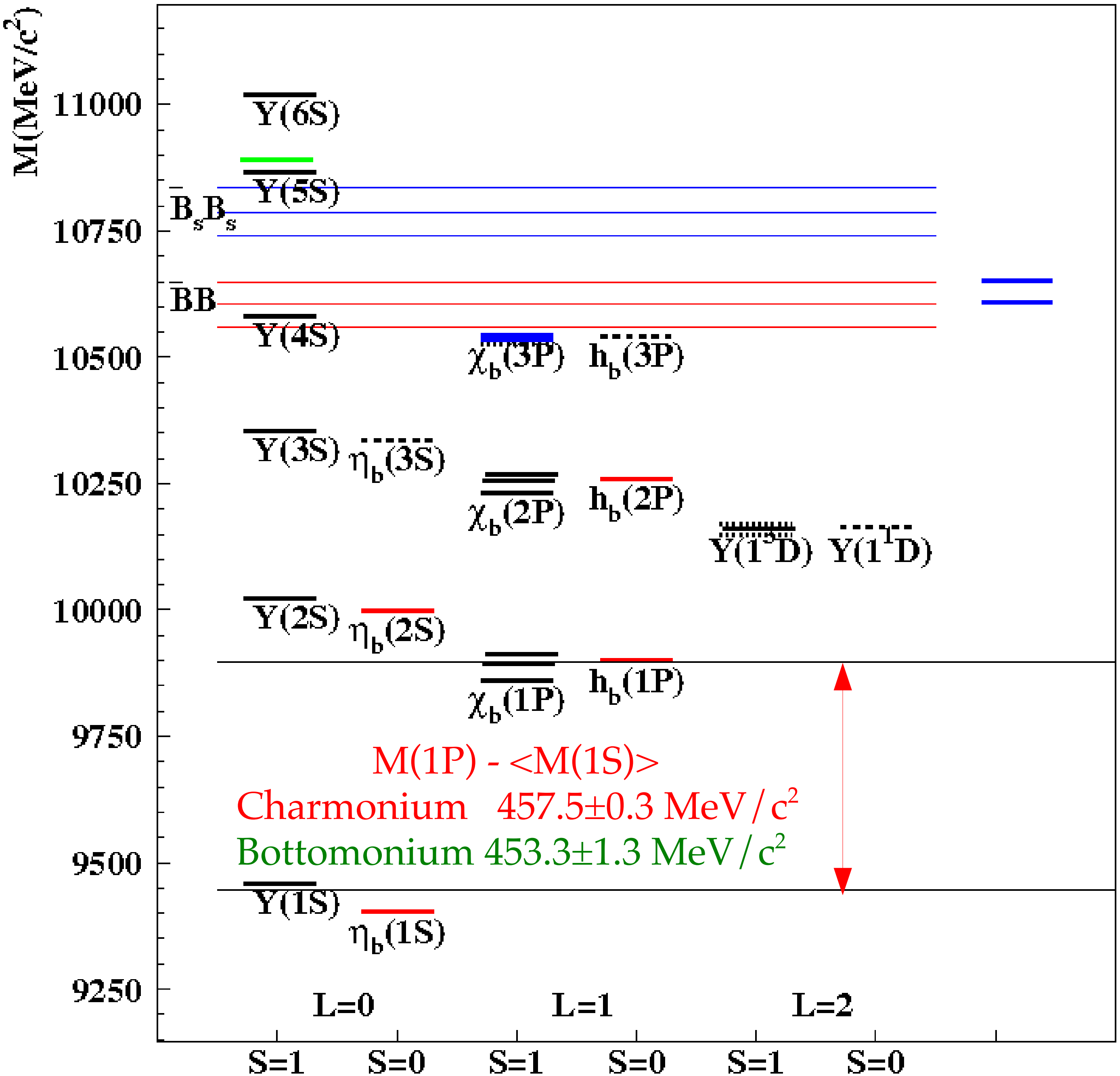


BES-III ?

1P-1S splitting

Bottomonium

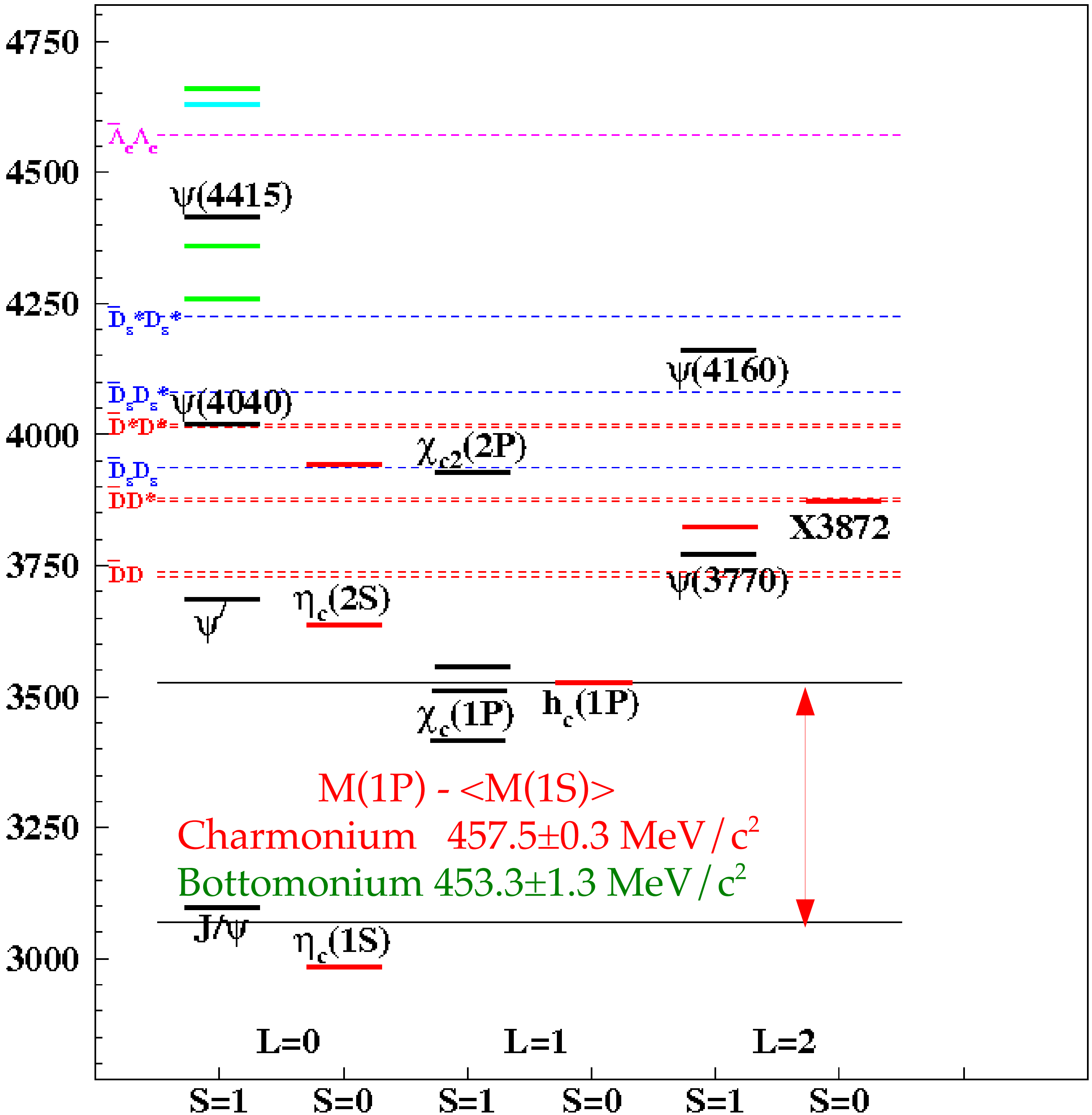
The spin averaged 1P-1S splitting does not depend on the hard scale: only 1% difference between $b\bar{b}$ and $c\bar{c}$.
Why?



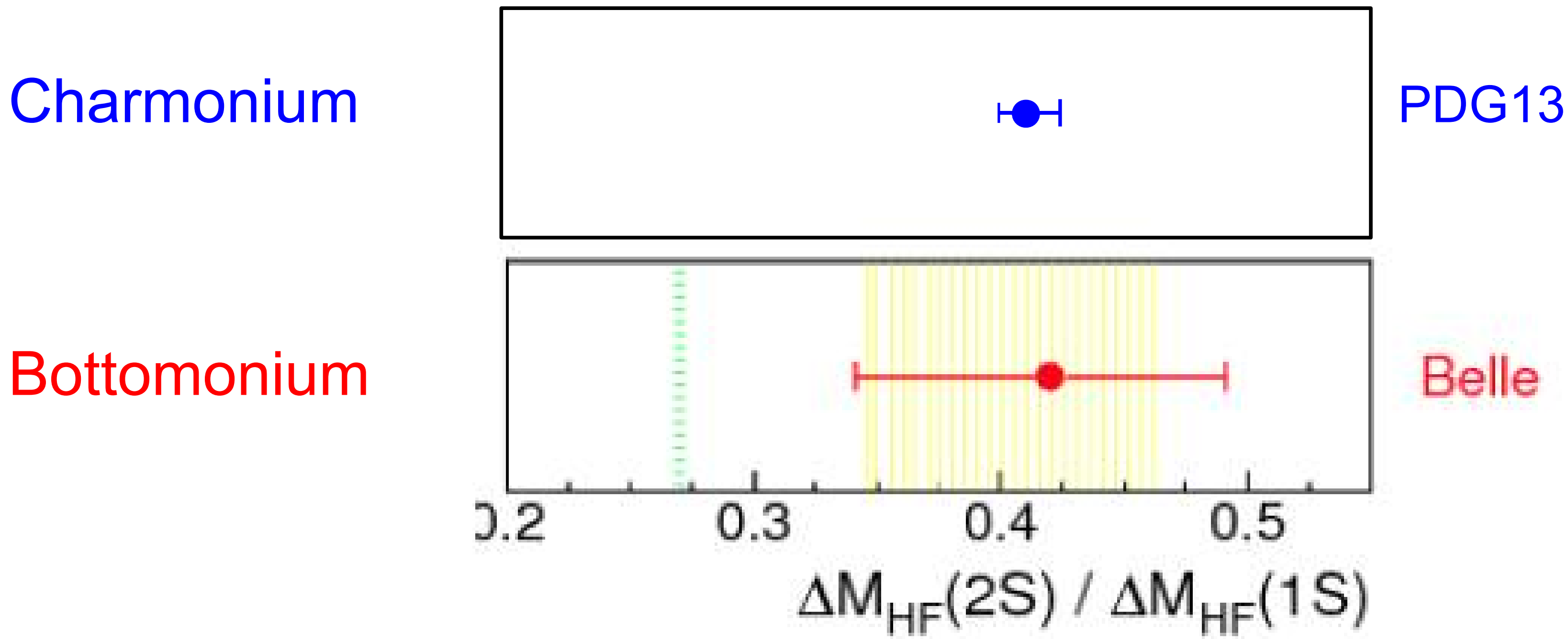
1P-1S splitting

Charmonium

The spin averaged 1P-1S splitting does not depend on the hard scale: only 1% difference between $b\bar{b}$ and $c\bar{c}$.
Why?



HF splitting ratio

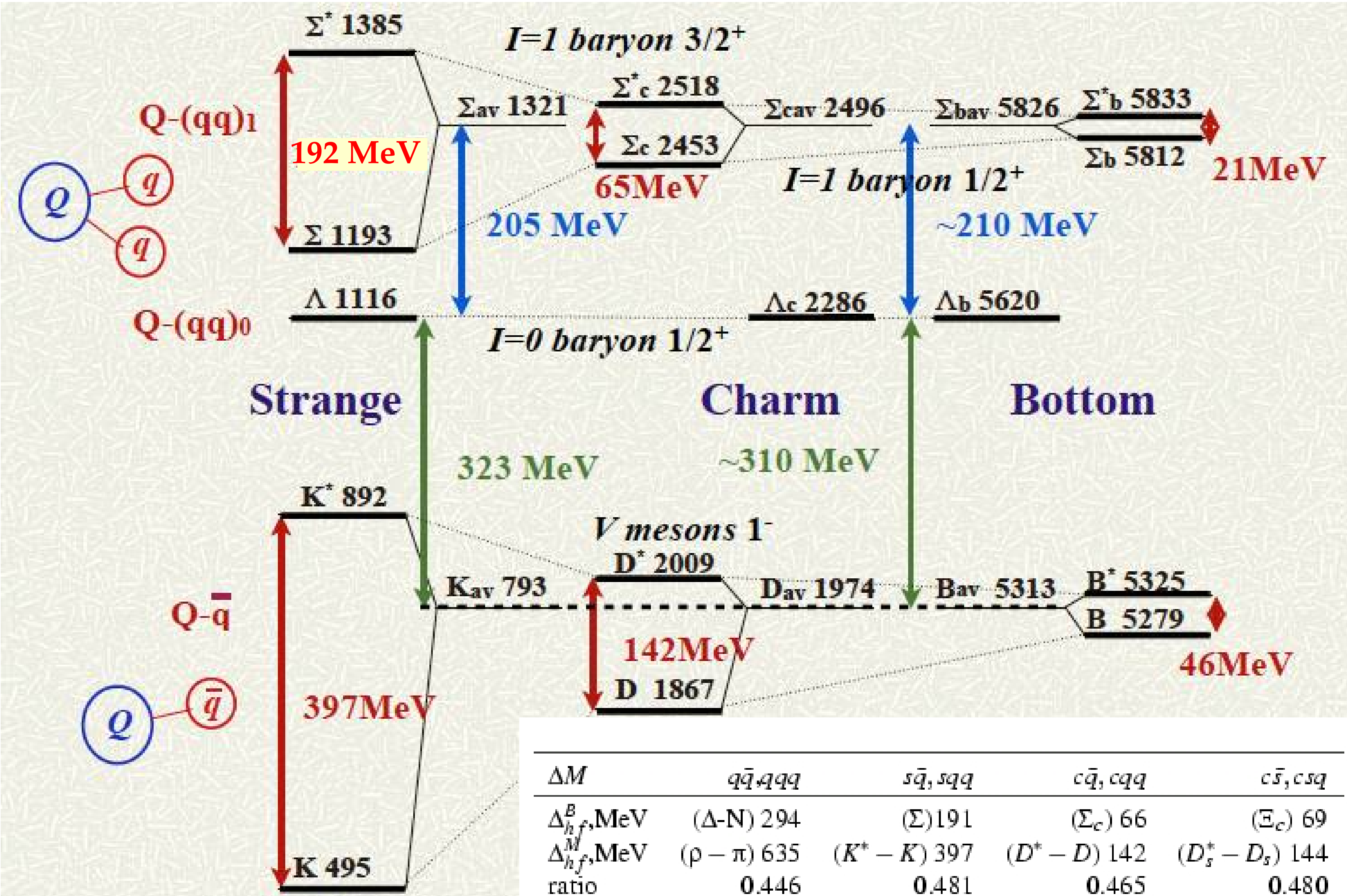


In green: the pNRQCD prediction (quote)
In yellow: the Lattice QCD prediction (quote)

The experimental error, dominated by the 2S splitting, is still large , but ... what if ... also this does not depend on the mass scale?

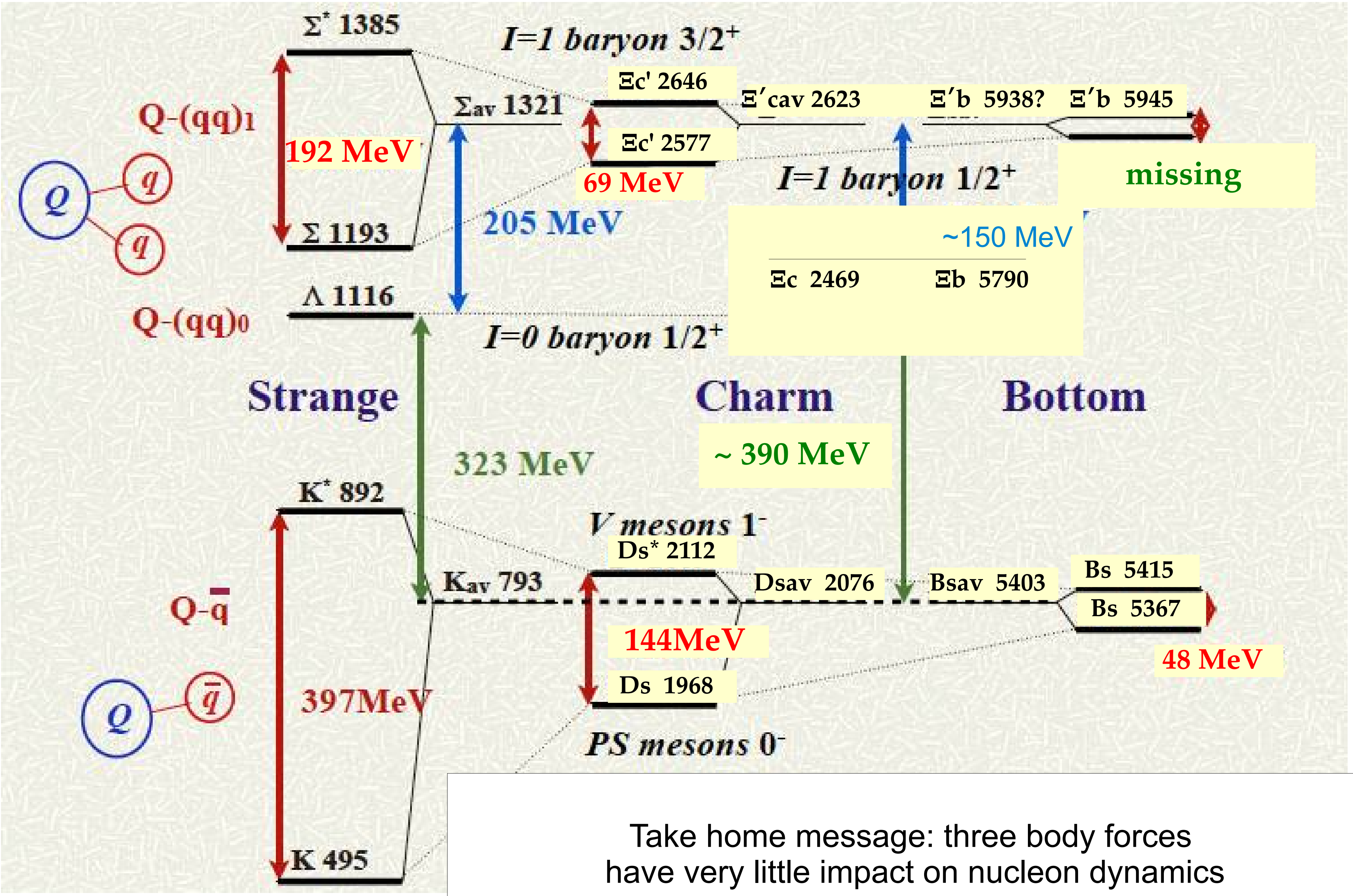
Charmed and Beauty hadron spectra

From Oka's talk
at Hadron 2013



ΔM	$q\bar{q}, qqq$	$s\bar{q}, sqq$	$c\bar{q}, cqq$	$c\bar{s}, csq$
Δ^B_{hf},MeV	(Δ-N) 294	(Σ)191	(Σ_c) 66	(Ξ_c) 69
Δ^M_{hf},MeV	($\rho-\pi$) 635	(K^*-K) 397	(D^*-D) 142	($D^*_s-D_s$) 144
ratio	0.446	0.481	0.465	0.480

Strange Charmed and Beauty hadron spectra



Take home message: three body forces
have very little impact on nucleon dynamics

The unexpected success of constituent quark model

Using a very simple mass formula for the ground states , Karliner and Lipkin (hep-ph/0307243) calculated constituent quark mass differences and ratios in baryons and mesons with 2-3% differences: why such a precision?

$$M = \sum_i m_i + \sum_{i>j} \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i \cdot m_j} \cdot v_{IE}^{hyp}$$

Ya.B. Zeldovich and A.D. Sakharov, Yad. Fiz **4**(1966)395;

$$\langle m_s - m_u \rangle_{Bar} = M_{sud} - M_{uud} = M_\Lambda - M_N = 177\,\text{MeV}$$

$$\langle m_s - m_u \rangle_{Mes} = \frac{3(M_{\mathcal{V}_{s\bar{d}}} - M_{\mathcal{V}_{u\bar{d}}}) + (M_{\mathcal{P}_{s\bar{d}}} - M_{\mathcal{P}_{u\bar{d}}})}{4} = \frac{3(M_{K^*} - M_\rho) + M_K - M_\pi}{4} = 179\,\text{MeV}$$

$$\left(\frac{m_c}{m_s}\right)_{Bar} = \frac{M_{\Sigma^*} - M_\Sigma}{M_{\Sigma_c^*} - M_{\Sigma_c}} = 2.84 = \left(\frac{m_c}{m_s}\right)_{Mes} = \frac{M_{K^*} - M_K}{M_{D^*} - M_D} = 2.81$$

$$\left(\frac{m_c}{m_u}\right)_{Bar} = \frac{M_\Delta - M_p}{M_{\Sigma_c^*} - M_{\Sigma_c}} = 4.36 = \left(\frac{m_c}{m_u}\right)_{Mes} = \frac{M_\rho - M_\pi}{M_{D^*} - M_D} = 4.46$$

$$\left(\frac{\frac{1}{m_u^2} - \frac{1}{m_u m_c}}{\frac{1}{m_u^2} - \frac{1}{m_u m_s}}\right)_{Bar} = \frac{M_{\Sigma_c} - M_{\Lambda_c}}{M_\Sigma - M_\Lambda} = 2.16 \approx \left(\frac{\frac{1}{m_u^2} - \frac{1}{m_u m_c}}{\frac{1}{m_u^2} - \frac{1}{m_u m_s}}\right)_{Mes} = \frac{(M_\rho - M_\pi) - (M_{D^*} - M_D)}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 2.10$$

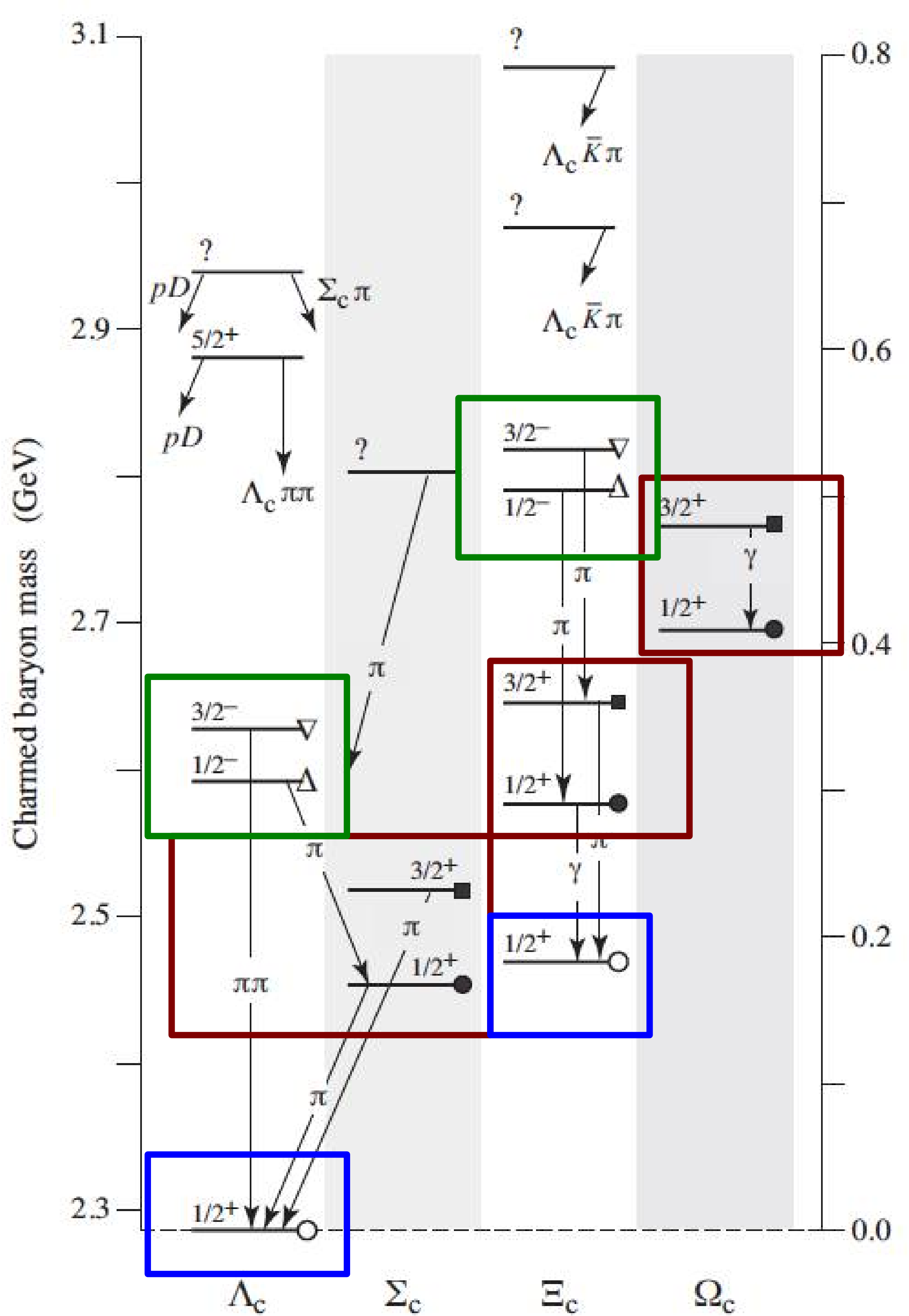
Charmed baryon spectra: P waves

In blue: J=0 diquark ; L=0

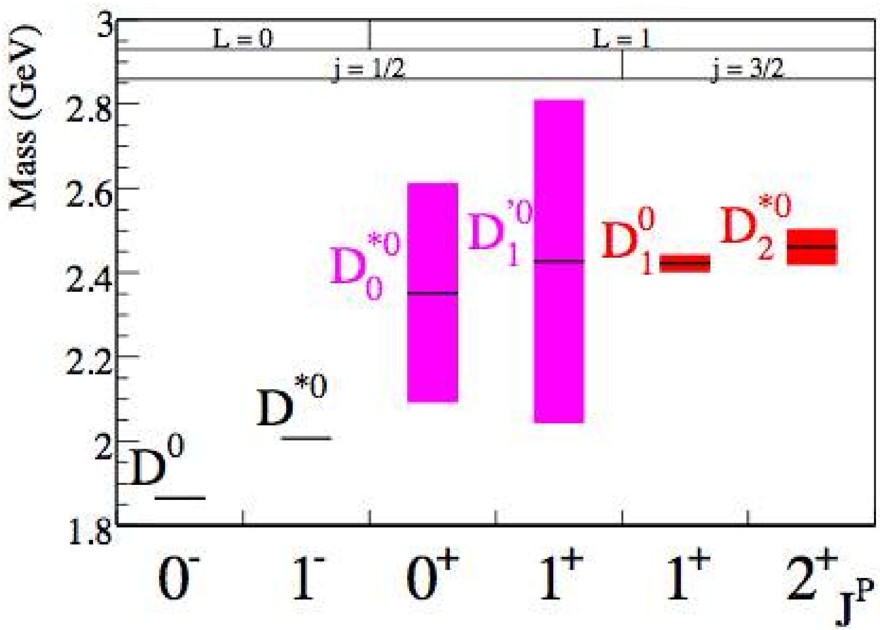
In red: J=1 diquark ; L = 0
HF splitting:
$M(3/2^+)-M(1/2^+)$
[ud]c = 65 MeV
[qs]c = 69 MeV
[ss]c = 71 MeV

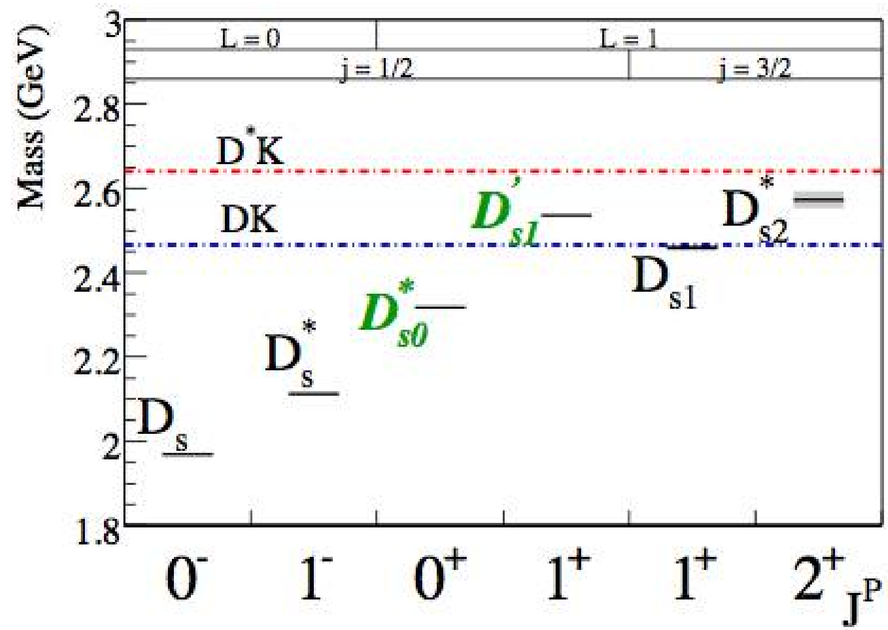
In green: J=0 diquark ; L=1
LS splitting:
$[2*M(3/2^-)+M(1/2^-)]/3-M(1/2^+)$

[ud]s = 366.3 MeV
[ud]c = 329.7MeV
[qs]c = 339.8 MeV
[ud]b = 297.8 MeV



Heavy-light meson spectra: tensor-vector splitting





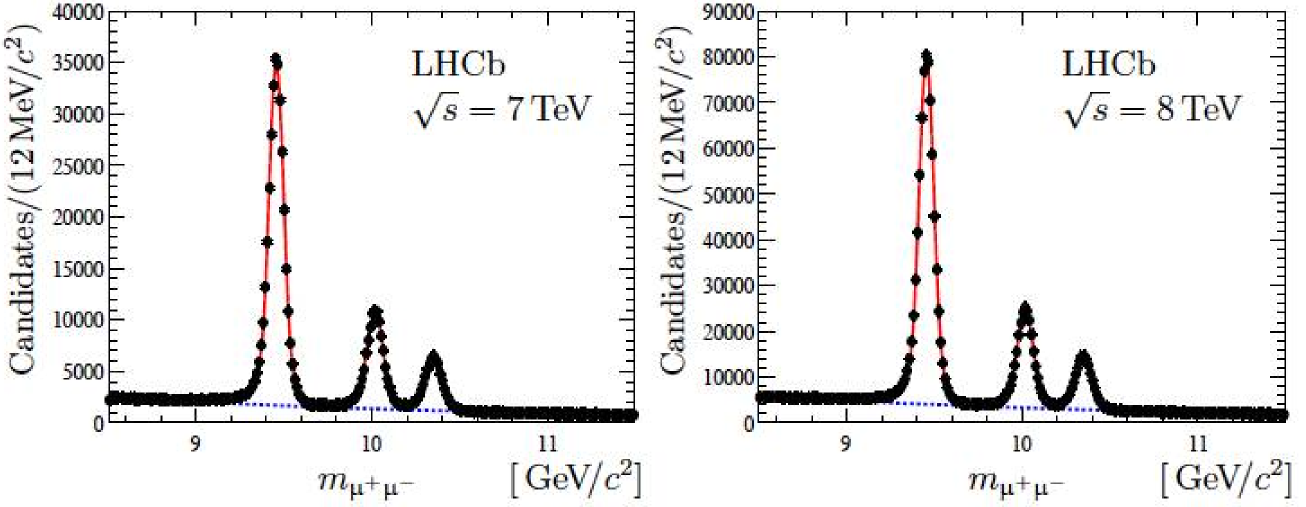
The heavy light mesons are the QCD counterpart of hydrogen atom, with a light quark orbiting around the heavier one. As the motion of the light quark is relativistic, the total angular momentum is properly described as $J=j_q+s_Q$. P wave D mesons with $j_q=1/2$ are very broad, and cannot be used for doing averages. Therefore we study the 2^+-1^- splitting.

If Q=c: $c\bar{q}$: 450 $c\bar{s}$:461 $c\bar{c}$: 458

If Q=b: $b\bar{q}$: 418 $b\bar{s}$: 424 $b\bar{b}$: 452

$\chi_b(3P)$

χ_b(3P) @ LHCb



Excellent resolution , perfect separation between the three Y(nS) states.

Amazing statistics from a total of 3 fb^{-1} (7+8 TeV)

Photons detected and measured in ECAL: high stats but low resolution (analysis with converted photons in progress)

Goal: quantify the fraction of Y(nS) produced from decays of χ_b states.

Signal yield	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
$N_{\Upsilon(1S)}$	326 300 ± 638	747 610 ± 969
$N_{\Upsilon(2S)}$	100 620 ± 395	229 950 ± 576
$N_{\Upsilon(3S)}$	57 613 ± 312	129 450 ± 459

Decay mode	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
$N_{\chi_b(1P)\to\Upsilon(1S)\gamma}$	1908 ± 71	4608 ± 115
$N_{\chi_b(2P)\to\Upsilon(1S)\gamma}$	390 ± 41	904 ± 68
$N_{\chi_b(3P)\to\Upsilon(1S)\gamma}$	133 ± 31	196 ± 50
$N_{\chi_b(2P)\to\Upsilon(2S)\gamma}$	265 ± 30	660 ± 46
$N_{\chi_b(3P)\to\Upsilon(2S)\gamma}$	48 ± 17	73 ± 26
$N_{\chi_b(3P)\to\Upsilon(3S)\gamma}$	56 ± 12	126 ± 20

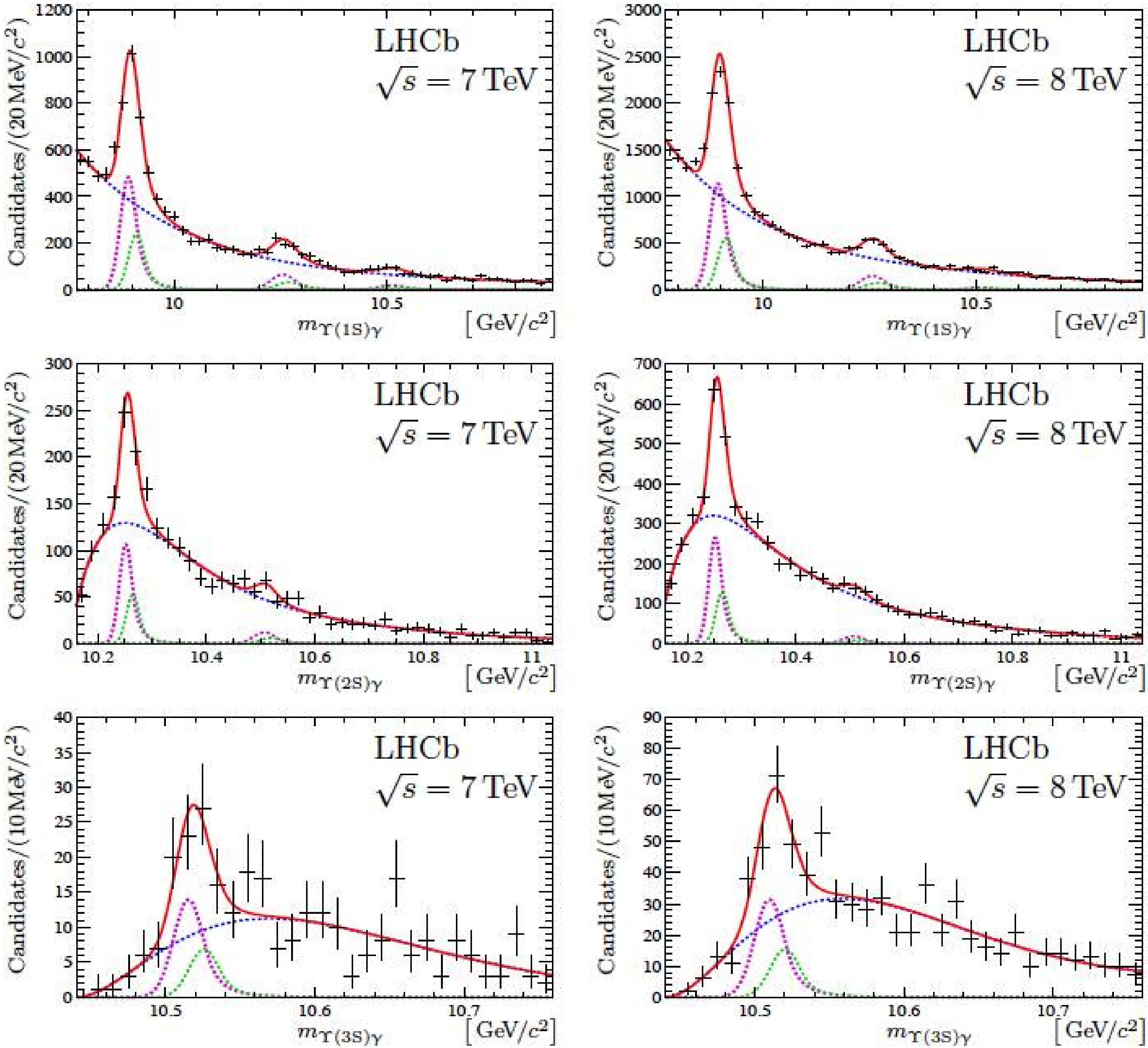
$\chi_b(3P)$

First observation of the radiative transition to Y(3S)

Best measurement of mass:

ATLAS 10530±5±9
DØ 10551±14±17
(mixed $\chi_{b1}(3P)+\chi_{b2}(3P)$)
LHCB 10511.3±1.7±??
(mass of $\chi_{b1}(3P)$)

More than 30% of the Y(nS) produced at LHC are coming from $\chi_b(1,2,3P)$ decays

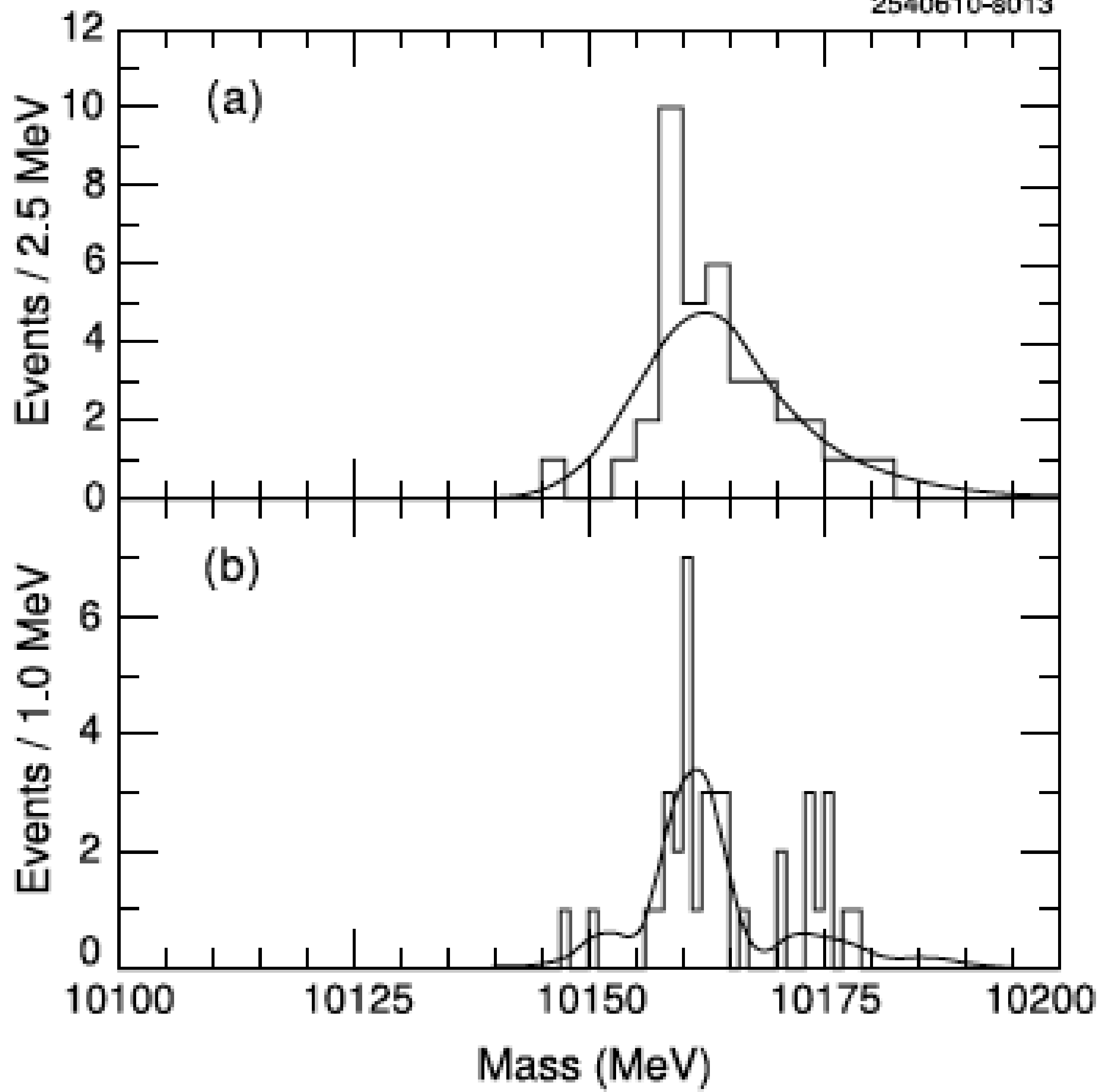


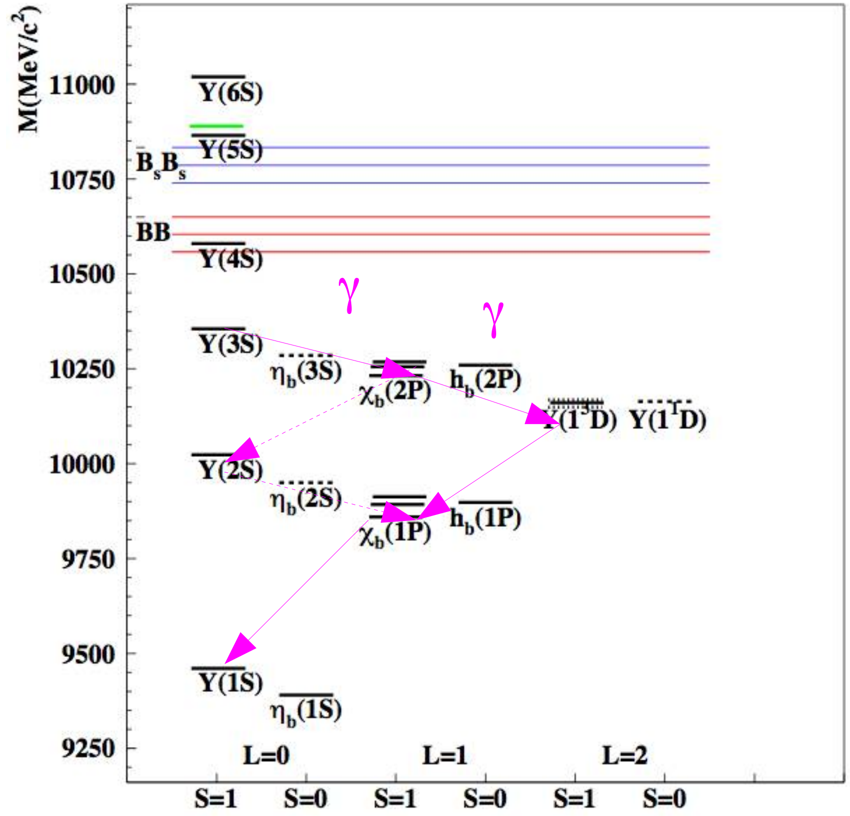
D waves

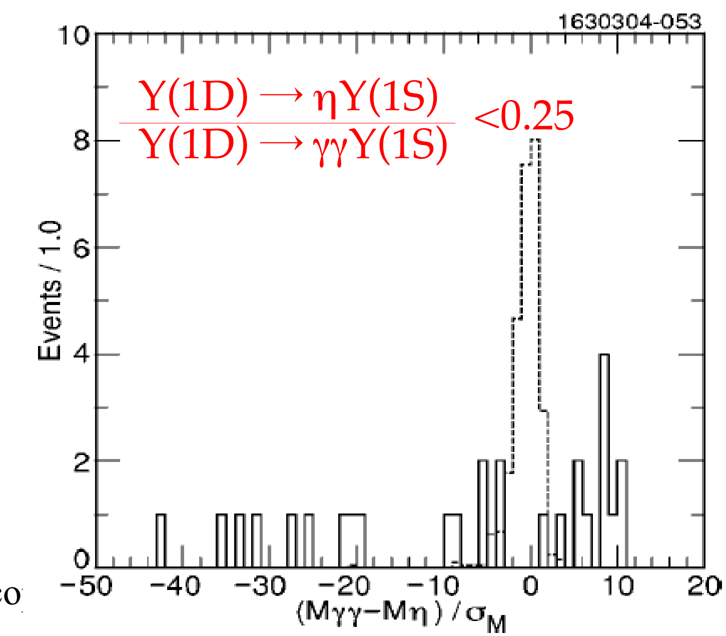
Bottomonium D waves

Υ(1D) discovered by CLEO in 2004

PHYSICAL REVIEW D 70, 032001, 2004

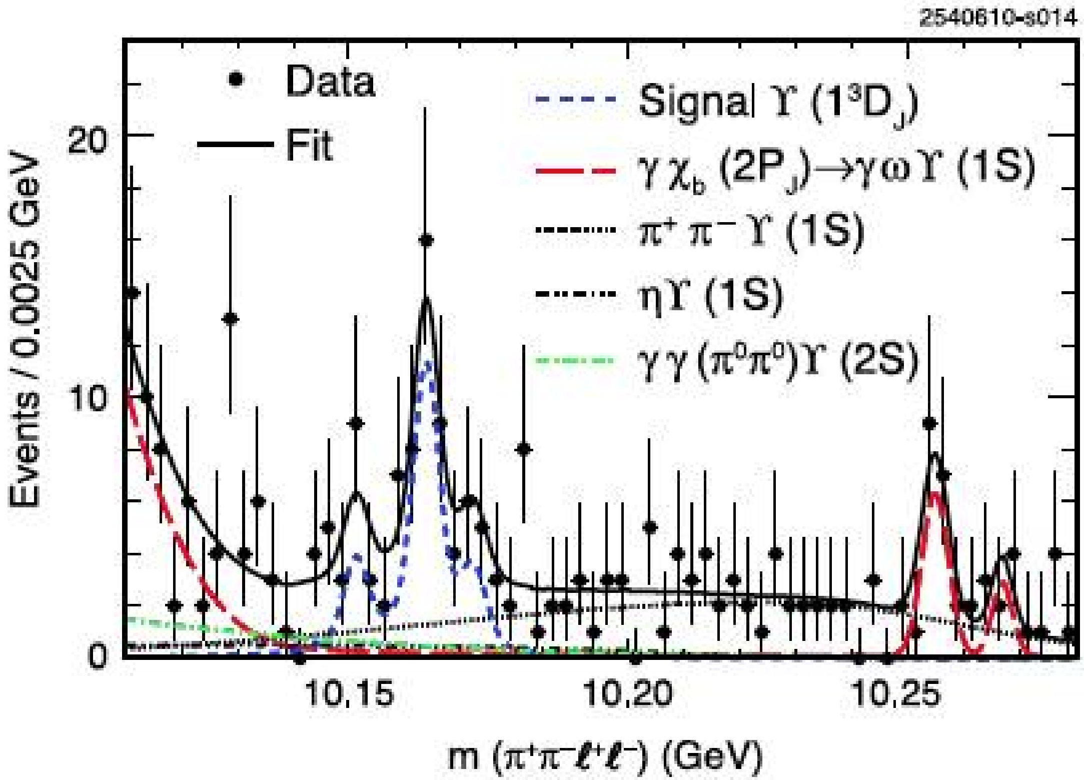


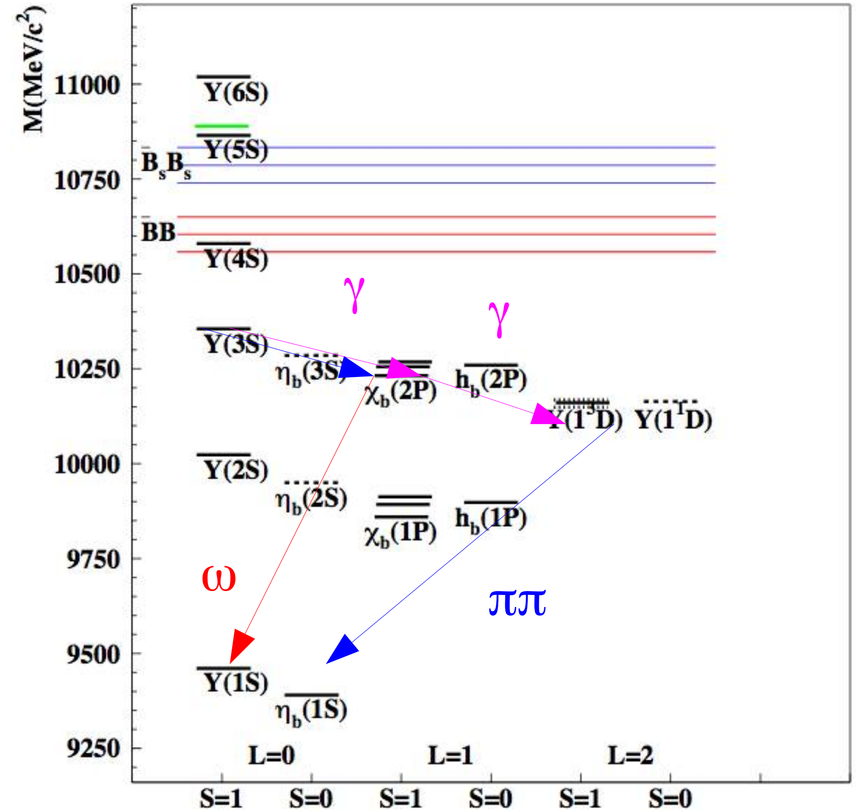




Bottomonium D waves

... and confirmed by Babar in 2010
Phys.Rev. D82,111102 (2010)



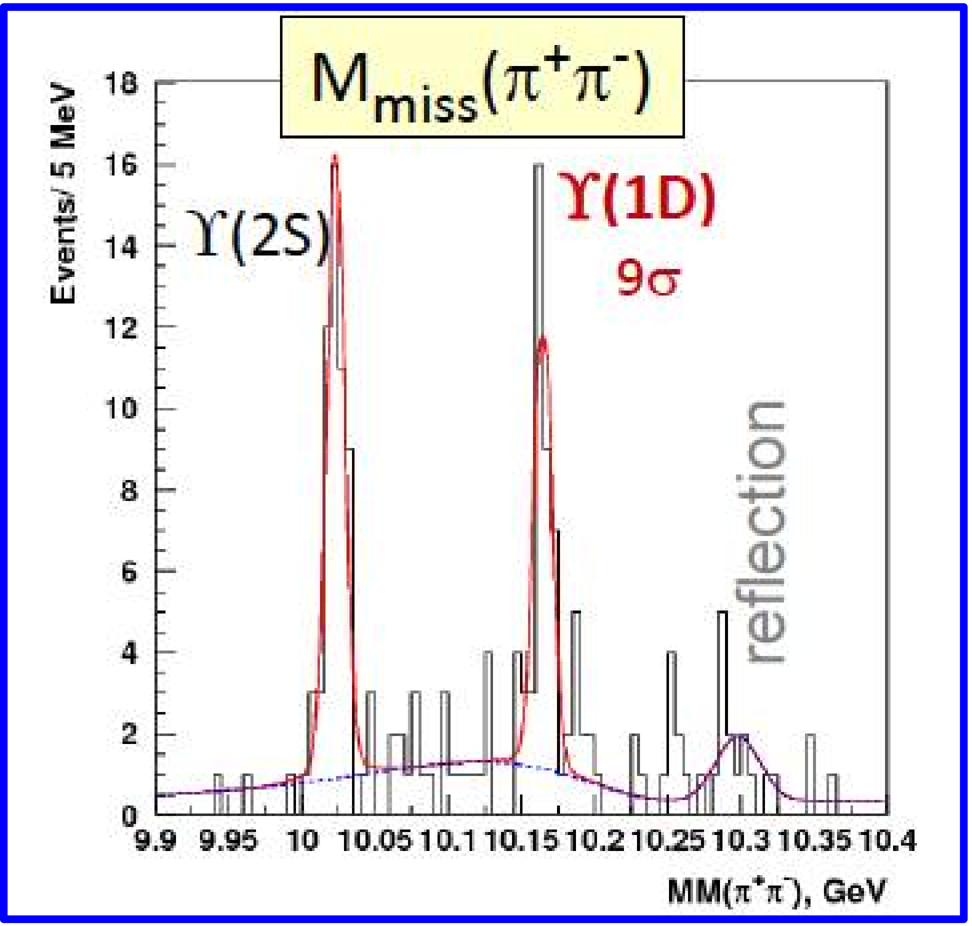


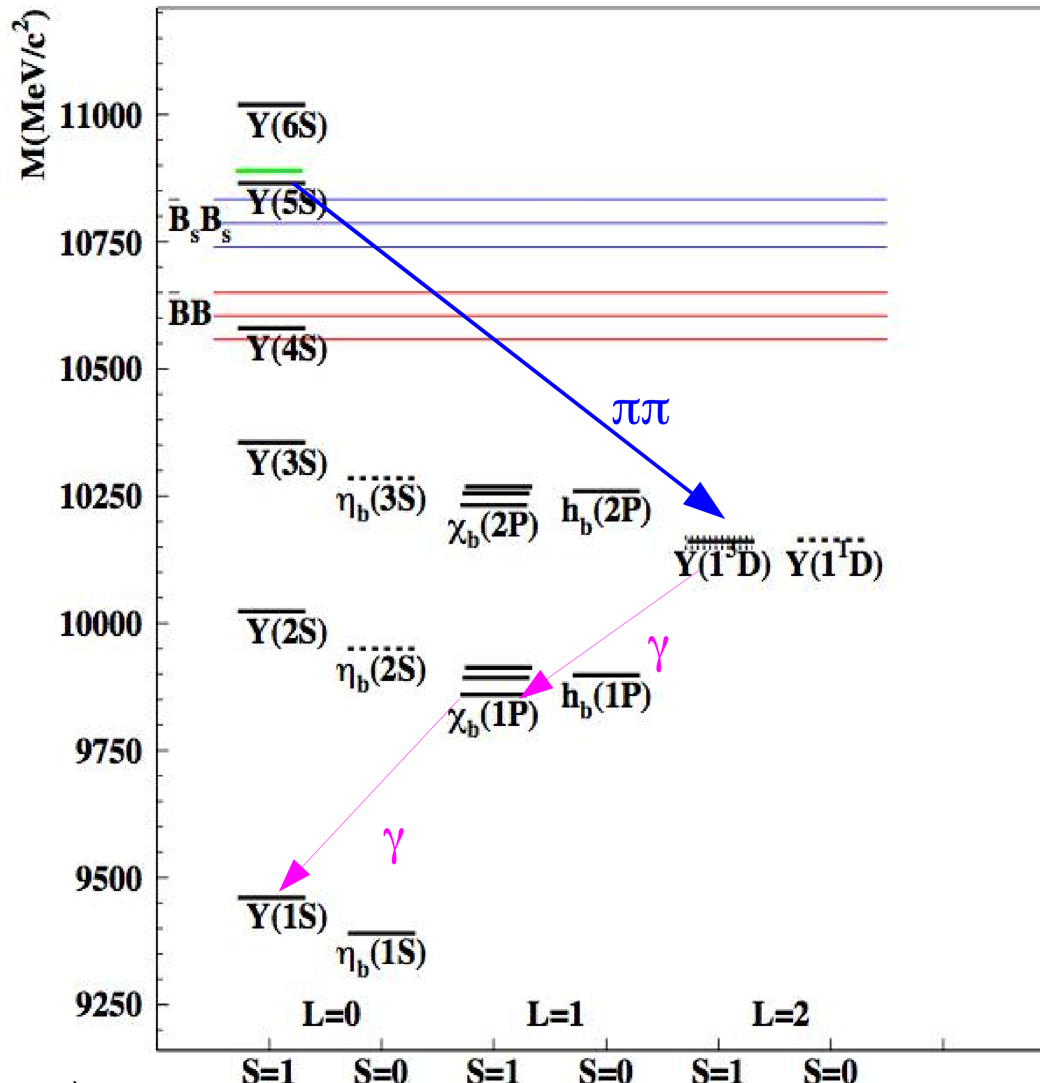
$B(\Upsilon(1D)\to\pi\pi\,\Upsilon(1S)) = (6.6\pm1.6)\times10^{-3}$

J	Event yields	Significance (w.syst.)	Fitted mass value
1	$10.6_{-4.9}^{+5.7}$	2.0 (1.8) σ	
2	$33.9_{-7.5}^{+8.2}$	6.5 (5.8) σ	10164.5 ± 0.8 ± 0.5
3	$9.4_{-5.2}^{+6.2}$	1.7 (1.6) σ	

(*) The two peaks at 10.26 and 10.28 are due to :
$\chi_b(2P)\to\omega\Upsilon(1S)$ with $\omega\to\pi\pi$ (1.5%)

Bottomonium D waves





Belle observes 1D both inclusively (PRL108,032001) and exclusively (Proc.EPS-HEP 2013) from Υ(5S). Assuming that:

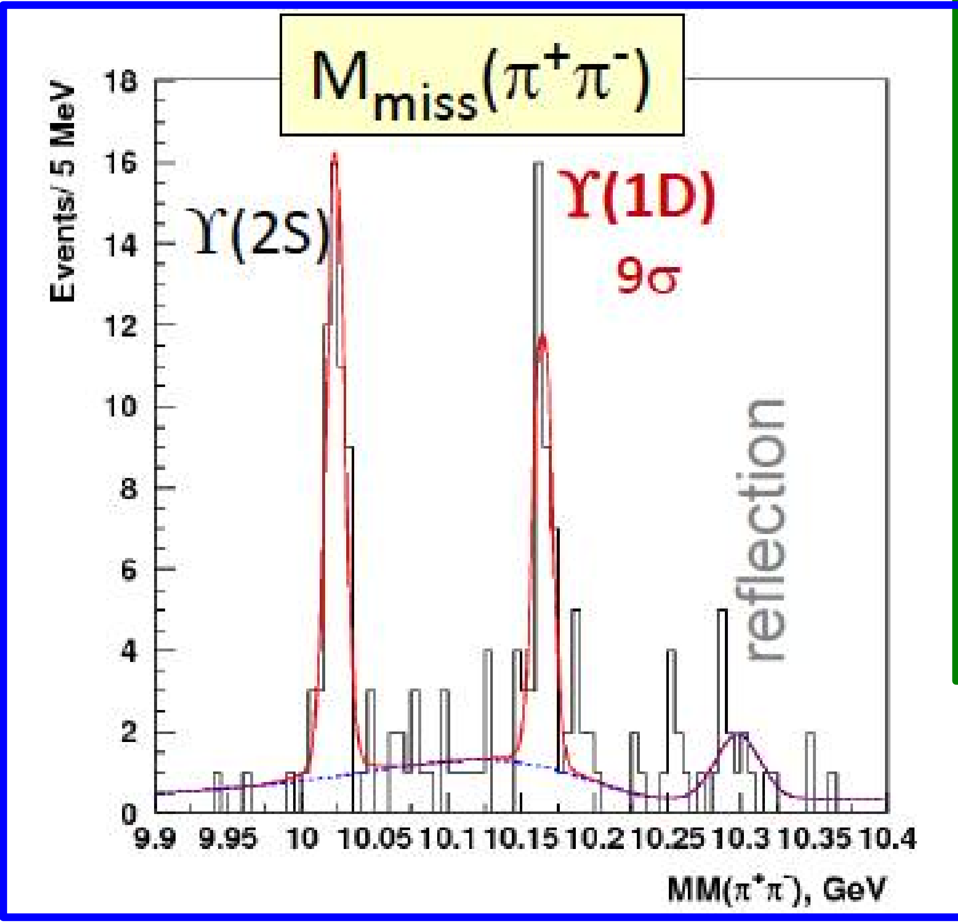
- the J=1,2,3 state is produced with ratios 3:5:7,
- $B(1^3D_J \rightarrow \gamma\ 1^3P_{J'})$ from Kwong,Rosner PRD 38, 279 (1998)
- $B(1^3P_{J'} \rightarrow \gamma\ \Upsilon(1S))$ from measured values (PDG)

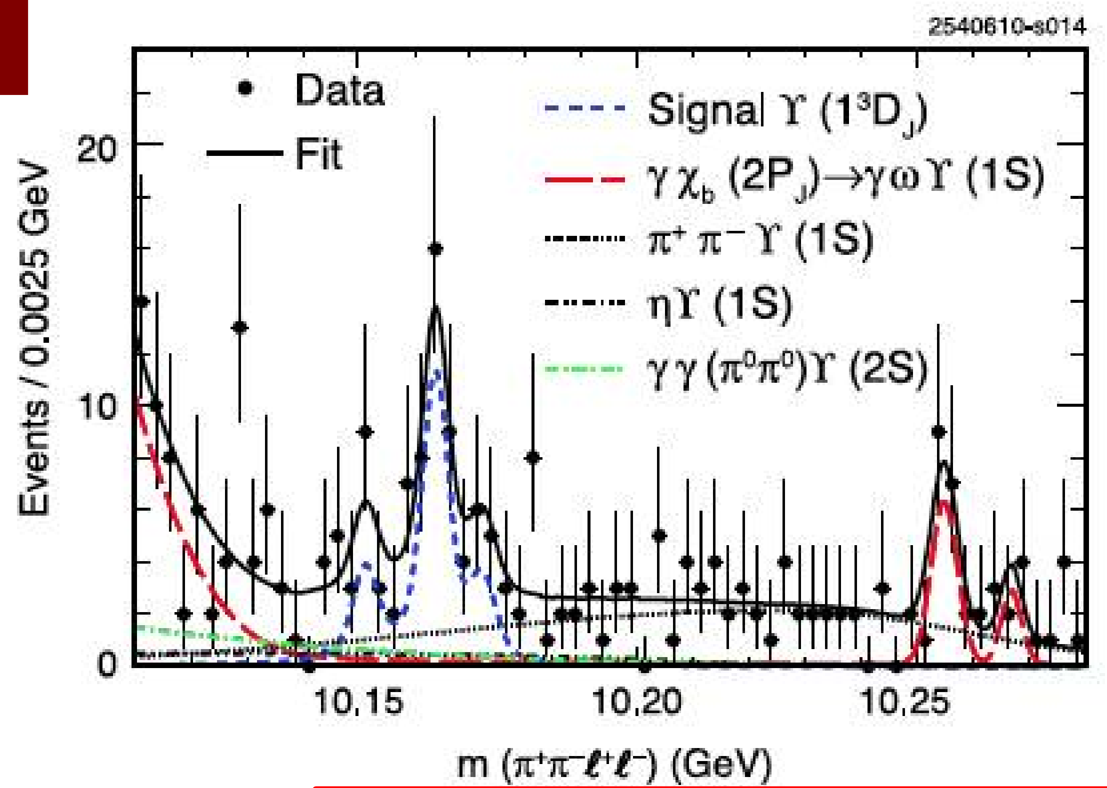
Belle obtains the production rate of Υ(1D) : J= 1 2 3

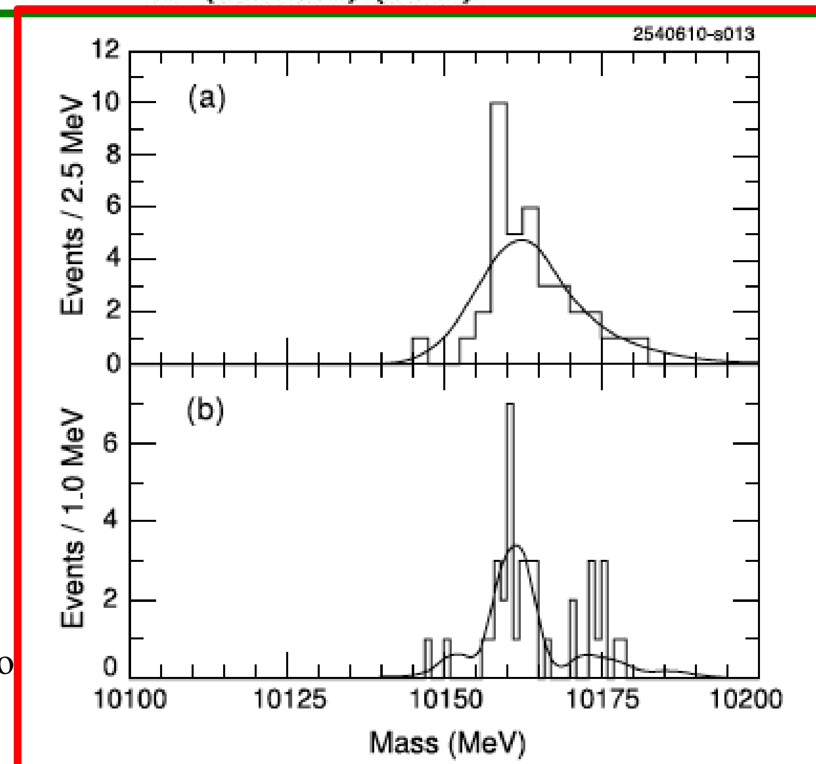
10% : 49% : 41%

Neglecting the J=1, Belle fits with double gaussian to obtain the upper limit $M(^3D_3)-M(^3D_2)<10$ MeV

Bottomonium D waves







Belle $10164.7 \pm 1.4 \pm 1.0$ MeV

BaBar $10164.5 \pm 0.8 \pm 0.5$ MeV

CLEO $10161.1 \pm 0.6 \pm 1.6$ MeV

Charmonium D waves

V.Bhardwaj, CHARM2012

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

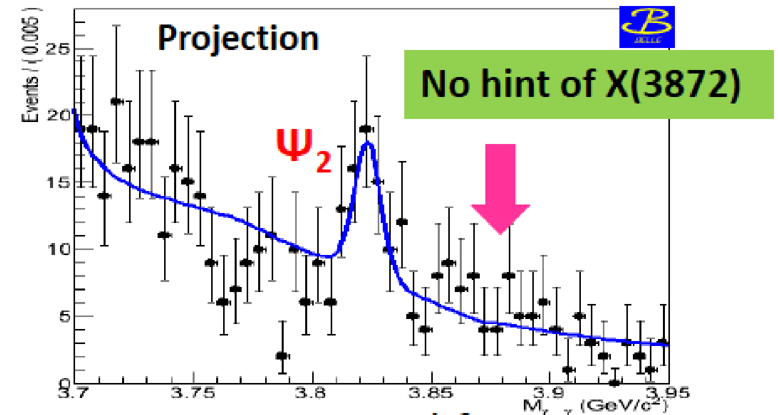
No signal of "X(3872)" $\rightarrow \gamma\chi_{c1,2}$

Evidence (4.2 σ) of the long sought $^3D_2$ state of charmonium!

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



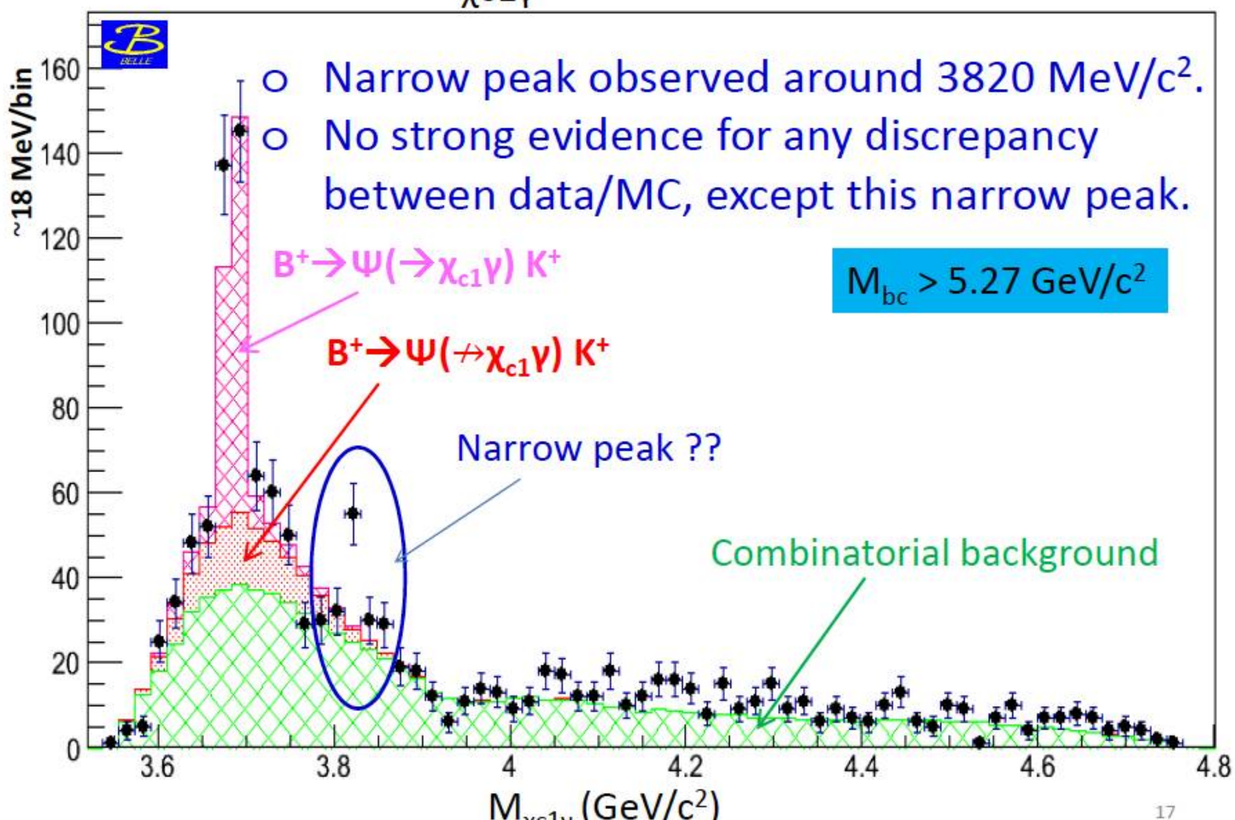
$M_{\chi c1\gamma}$ (GeV/c²)

$M_{bc} > 5.27$ GeV/c²

711 fb⁻¹ NEW

$M_{\chi c1\gamma}$ distribution

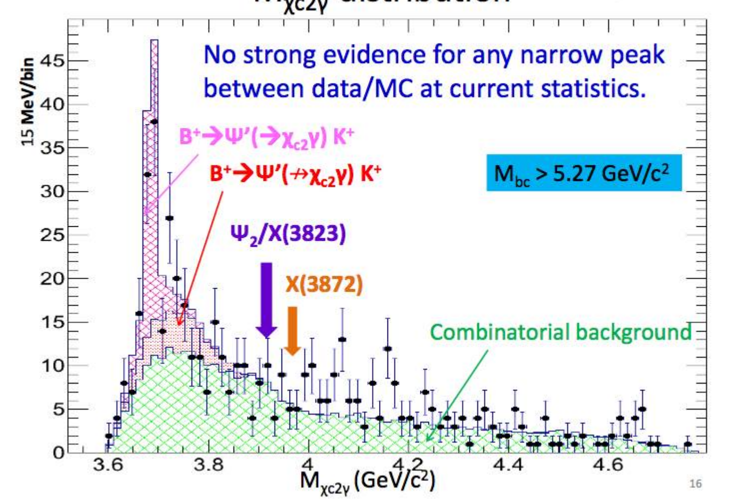
$B^\pm \rightarrow \chi_{c1}\gamma K^\pm$



711 fb⁻¹

$M_{\chi c2\gamma}$ distribution

$B^\pm \rightarrow \chi_{c2}\gamma K^\pm$



Future studies at Belle-II

Spin triplet D waves ($^3D_{1,2,3}$):

$\sigma(\Upsilon(5S) \rightarrow \pi\pi\ \Upsilon(1^3D_J)\ ) = 0.3$ pb

With (3:5:7) ratio for J=1,2,3

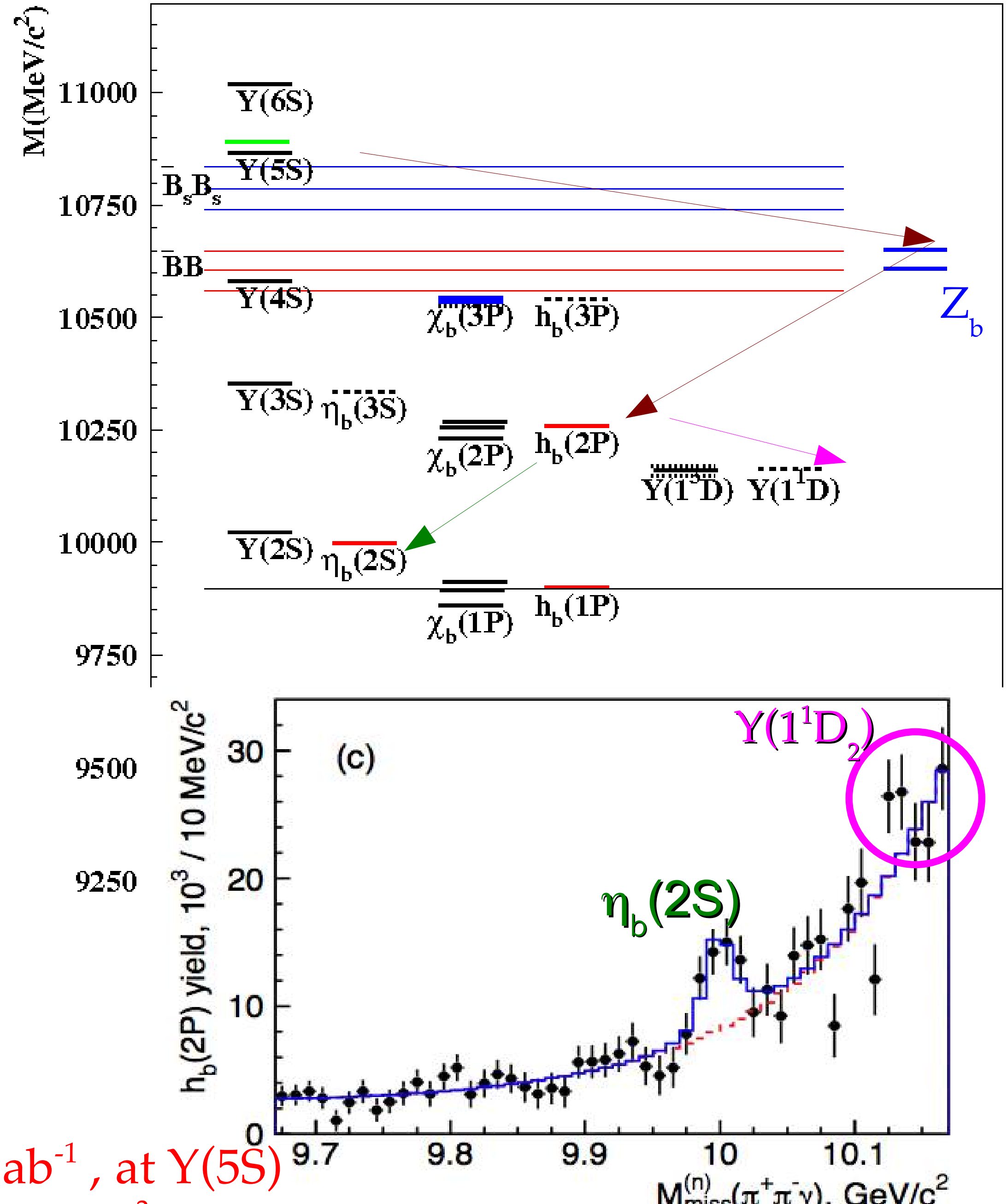
$\sigma(\Upsilon(3S) \rightarrow \gamma\gamma\ \Upsilon(1^3D_J)\ ) = 18$ pb

With (2:5:3) ratio for J=1,2,3

With 200 fb^{-1} Υ(3S) data we can study the multiplet splittings using a total of 3.6 M decays of 1D states

Spin singlet D wave ($^1D_2$):

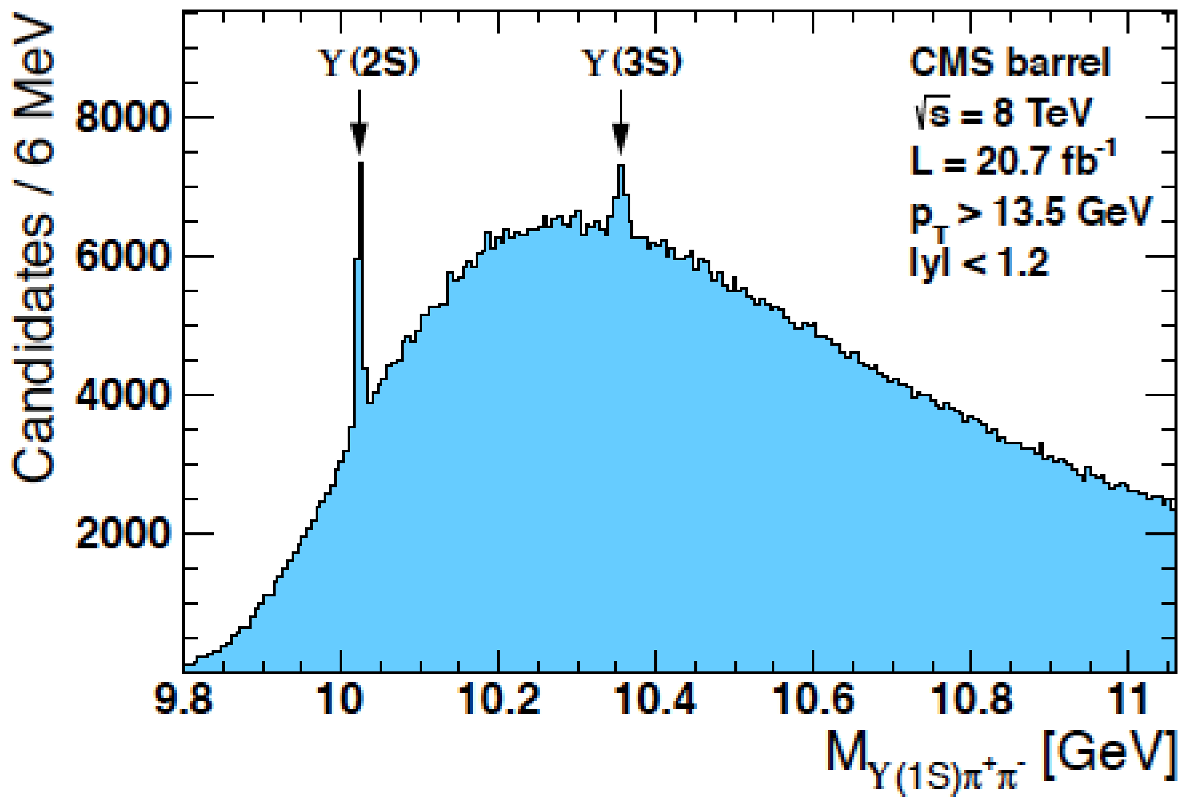
Reachable from Υ(5,6S) via ππ to $h_b(2P)$ and E1 transitions to $^1D_2$ (peak in γππ recoil spectrum).



Belle-II will probably need more than 1 ab^{-1} , at Υ(5S) or above, to observe the elusive states $^1D_2$ and $^3D_3$

XYZ

X(3872) news



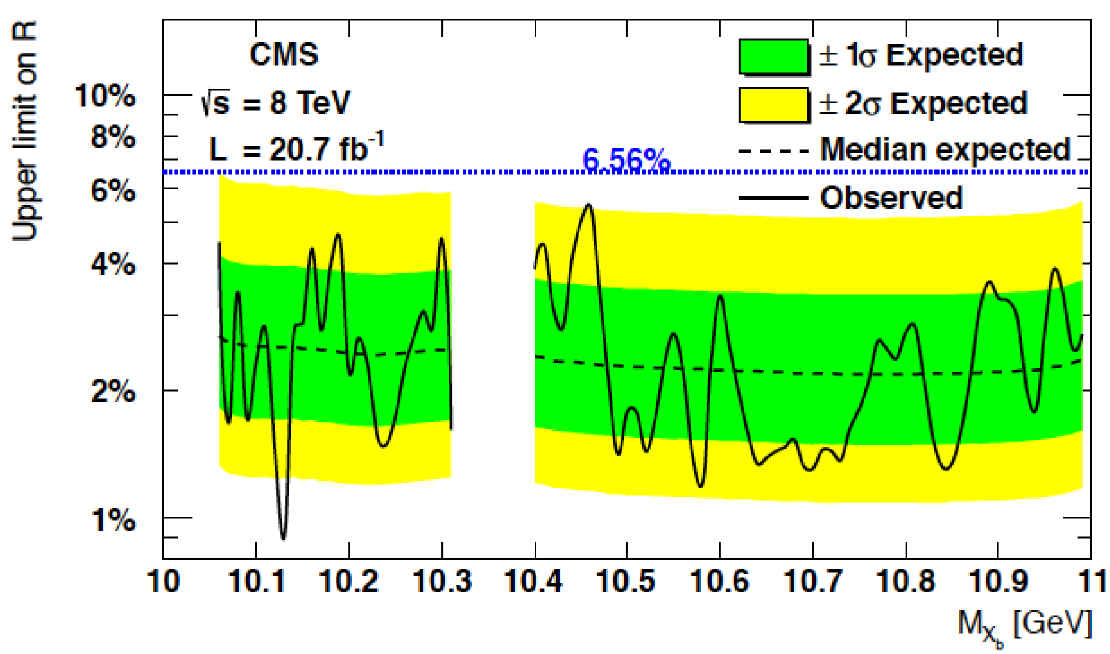
Search for bottom counterpart of X(3872) at LHC: CMS (ArXiV:1309.0250) sets 95% CL limits over all the expected mass range (close to the BB and BB* thresholds): no smoking gun!

LHCb: observation of the radiative decay X(3872) to psi(2S)

Final determination of X(3872) quantum numbers JPC=1++

BES-III observes the radiative transition Y(4260) to X(3872)

See Kupsc talk

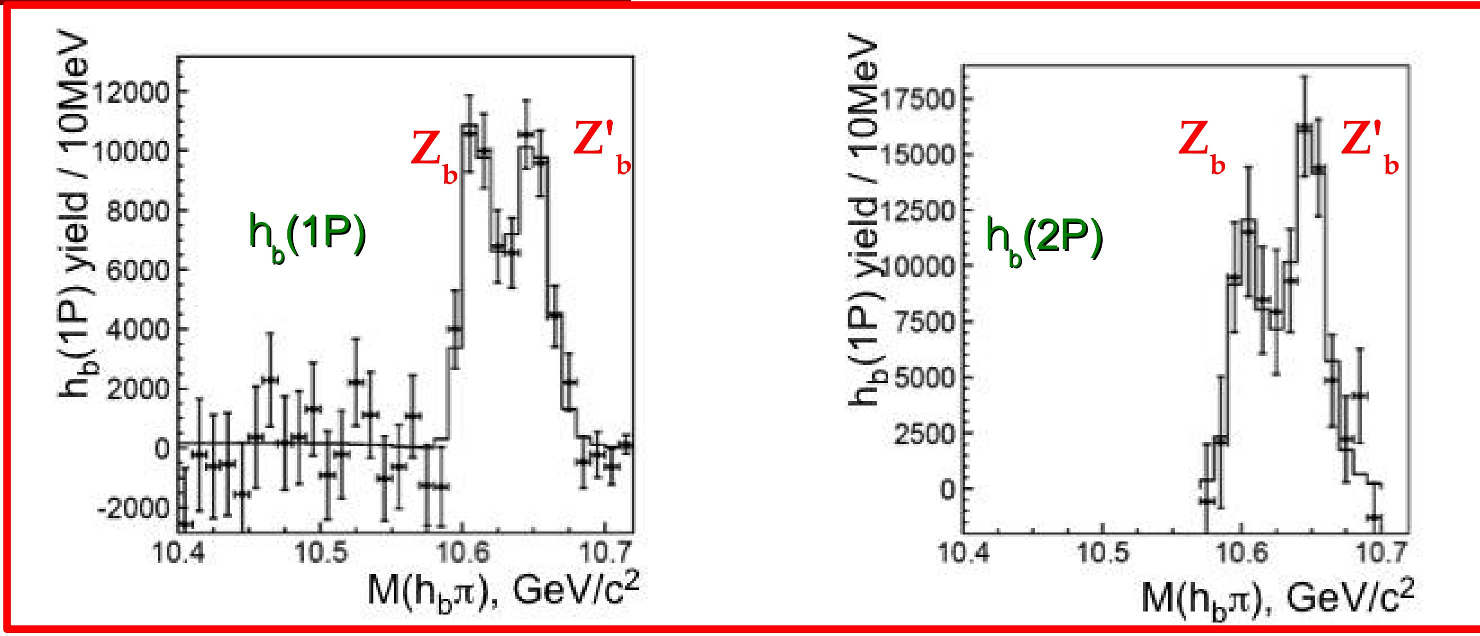


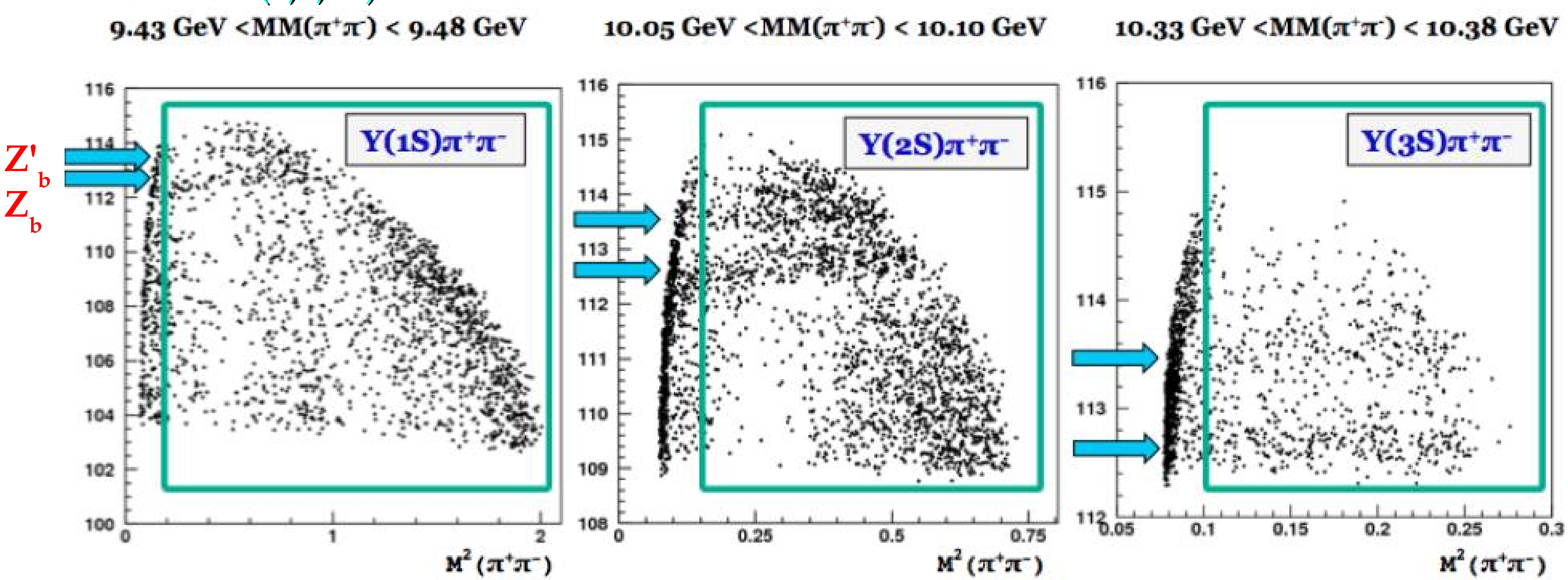
Charged Bottomonia : Z_b's

The two charged bottomonium states are observed in single pion recoil in 5 processes:

- inclusive Υ(5S) decays to h_b(1,2P)

- Dalitz plot of exclusive Υ(5S) dipion transitions to Υ(1,2,3S)





Z_b parameters

PRL108,122001(2011)

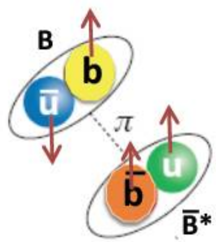
Belle discovered two charged bottomonium-like resonances:

Z(10610)

M=10607.2±2.0 MeV

Γ=18.4±2.4 MeV

$M_B + M_{B*}$ = 10604.5±0.6 MeV

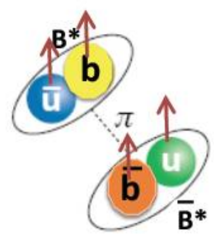


Z(10650)

M=10652.2±1.5 MeV

Γ=11.5±2.2 MeV

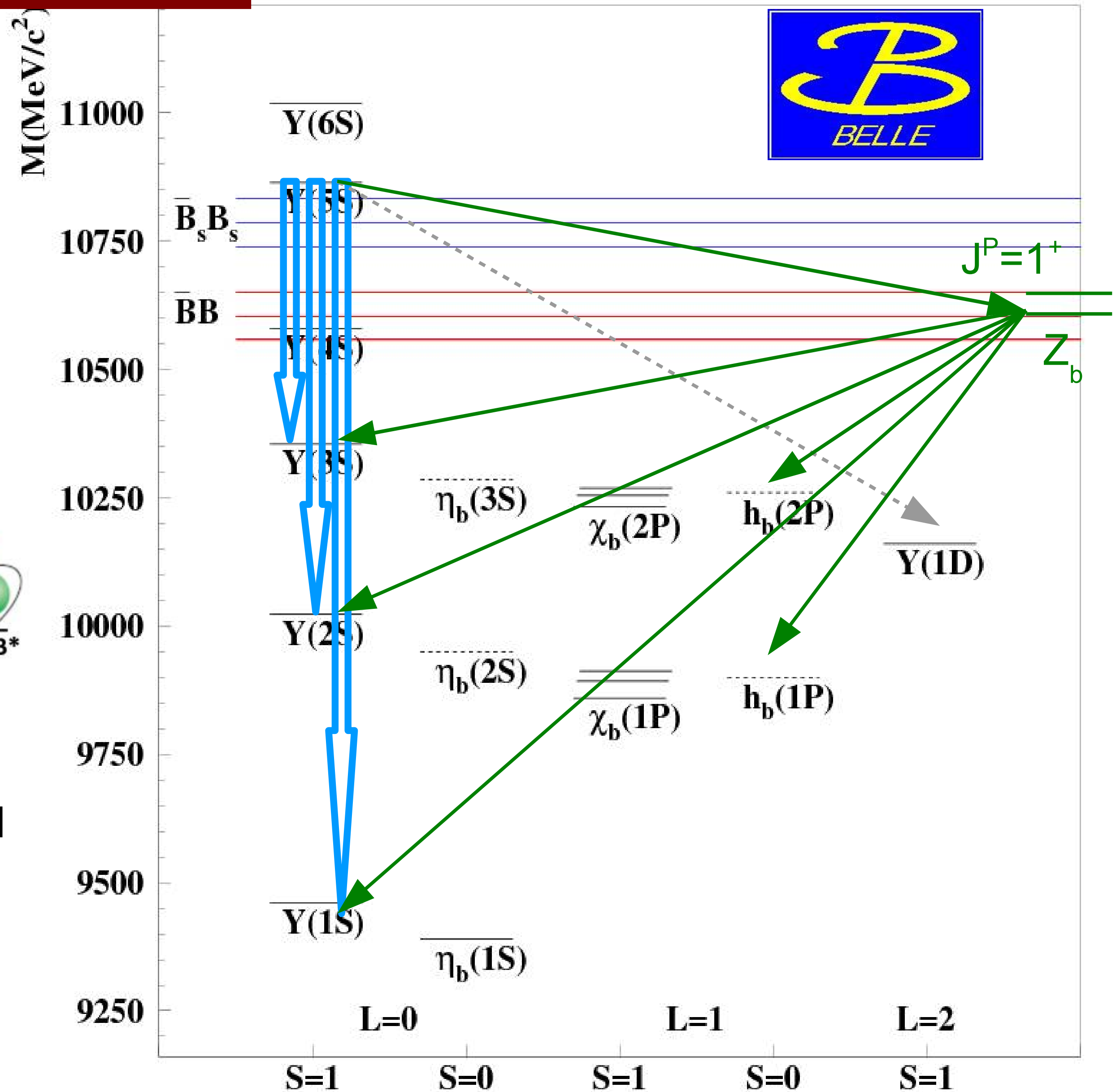
$M_{B*} + M_{B*}$ = 10650.2 ± 1.0 MeV



Analysis of angular distributions suggests $J^P=1^+$ for both these states. Observation of Zb decays to BB* and B*B* is consistent with molecular nature of the charged bottomonia. (Voloshin, Bondar, et al)

ArXiV:1207.4345 (unpublished)

Evidence of neutral partner of lower Zb in $\Upsilon\pi^0$ with 4.9 sigma significance

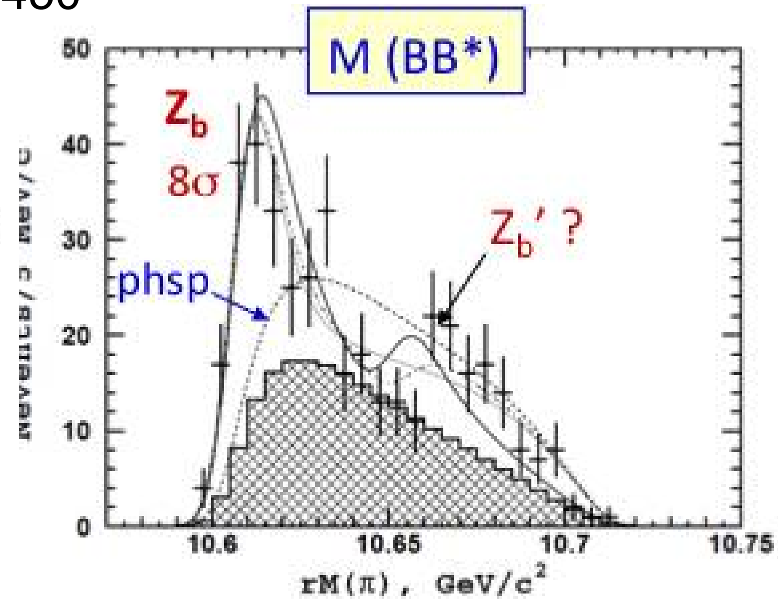


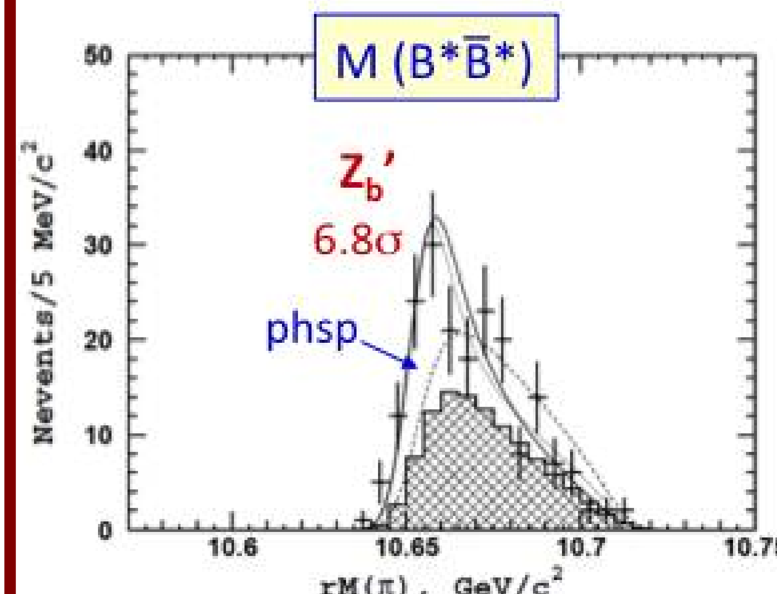
$Z_b \to \bar{B}B^* + B\bar{B}^*, B^*\bar{B}^*$

ArXiV:1209.6450

BF[$\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$]	preliminary Belle 121.4 fb^{-1}	significance
$B\bar{B}$	<0.60 % at 90% C.L.	
$B\bar{B}^* + B\bar{B}^*$	(4.25 ± 0.44 ± 0.69) %	9.3σ
$B^*\bar{B}^*$	(2.12 ± 0.29 ± 0.36) %	5.7σ

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0



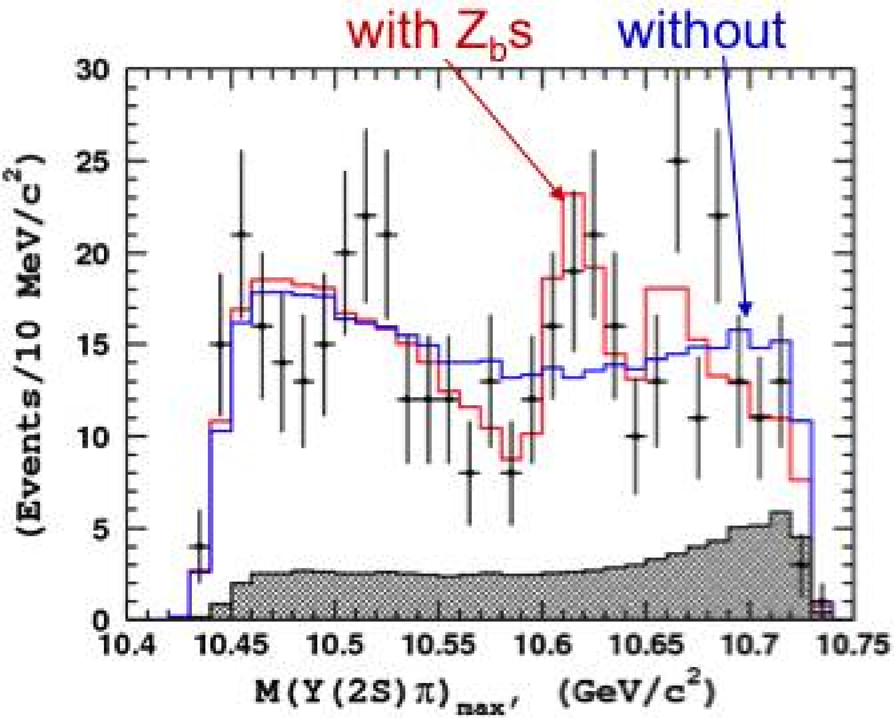


See P.Krokovny's talk this afternoon, in the Heavy Hadrons session.

The neutral partner Z_b^0

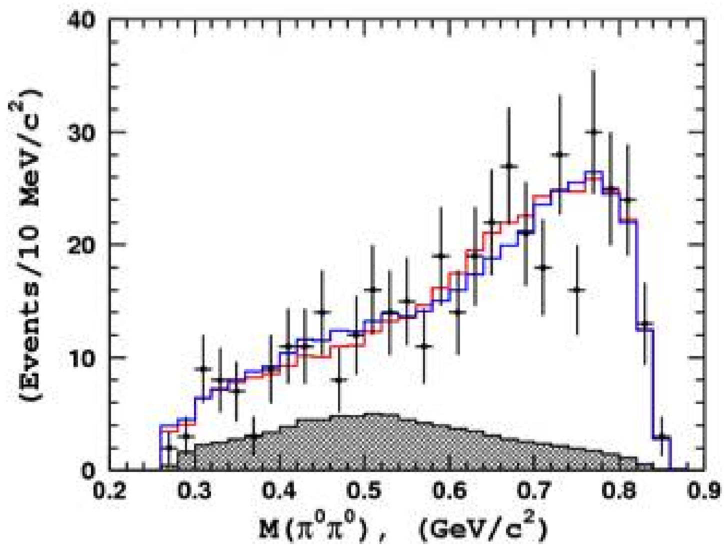
ArXiV:1207.4345

Dalitz plot analysis



4.9 sigma evidence of $Z_b^0(10610)$

Not enough statistics to confirm $Z_b^0(10650)$: only 2 sigma



Final state	Signal region, GeV/c^2	Signal yield	ϵ, %	$\mathcal{B}$, 10^{-3}	Events	Purity
$\Upsilon(1S) \to \mu^+\mu^-$	$9.41 < M_{\rm miss}(\pi^0\pi^0) < 9.53$	261 ± 15	11.2	2.28 ± 0.13	247	0.95
$\Upsilon(1S) \to e^+e^-$	$9.41 < M_{\rm miss}(\pi^0\pi^0) < 9.53$	123 ± 13	5.61	2.15 ± 0.23	140	0.78
$\Upsilon(2S) \to \mu^+\mu^-$	$9.99 < M_{\rm miss}(\pi^0\pi^0) < 10.07$	241 ± 18	8.04	3.77 ± 0.28	253	0.87
$\Upsilon(2S) \to e^+e^-$	$9.99 < M_{\rm miss}(\pi^0\pi^0) < 10.07$	108 ± 13	3.58	3.84 ± 0.46	151	0.66
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	$10.00 < M(\Upsilon\pi^+\pi^-) < 10.05$	24 ± 5	2.27	2.85 ± 0.60	28	0.86

$Z_b \to \bar{B}B^*+B\bar{B}^*, B^*\bar{B}^*$

ArXiV:1209.6450

BF[$\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$]	preliminary Belle 121.4 fb^{-1}	significance
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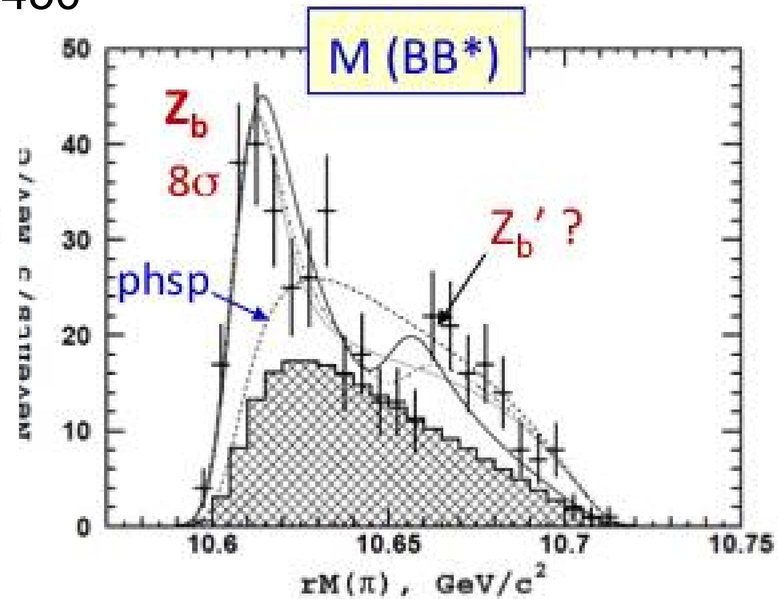
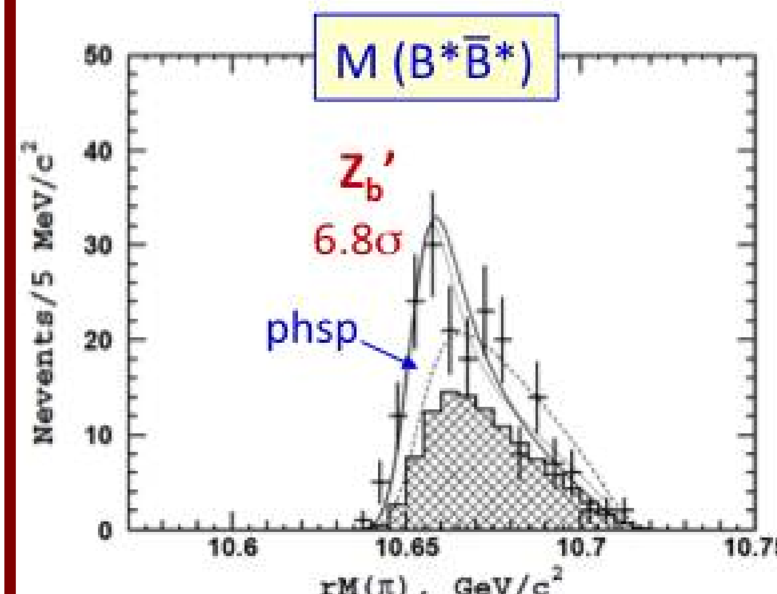




Belle-II: future prospects

Neutral partners of Zb states proposed by Bondar et al.

arXiv:1105.5829

$$\left|Z'_b\right\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} - \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

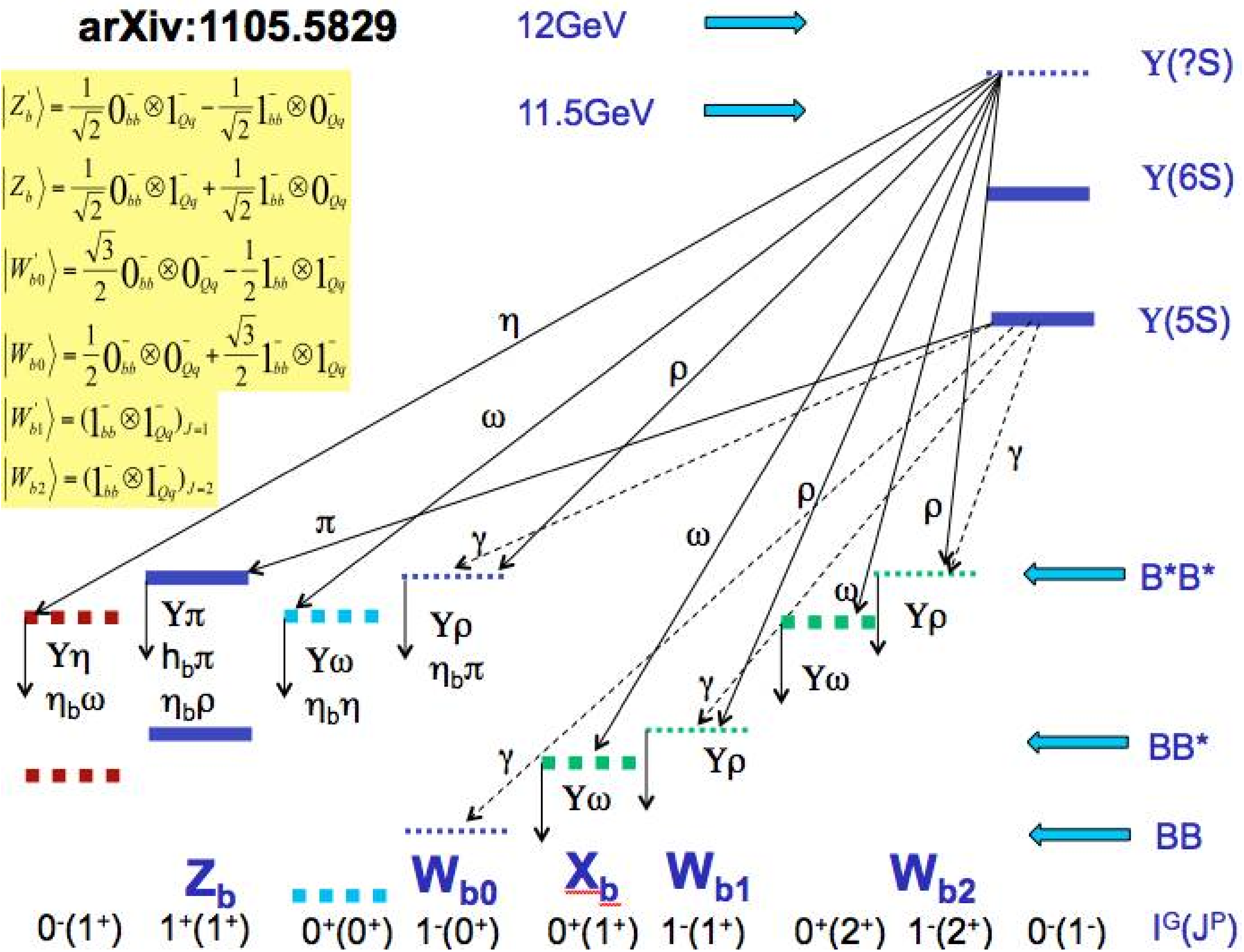
$$\left|Z_b\right\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} + \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

$$\left|W'_{b0}\right\rangle = \frac{\sqrt{3}}{2} 0^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}} - \frac{1}{2} 1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}}$$

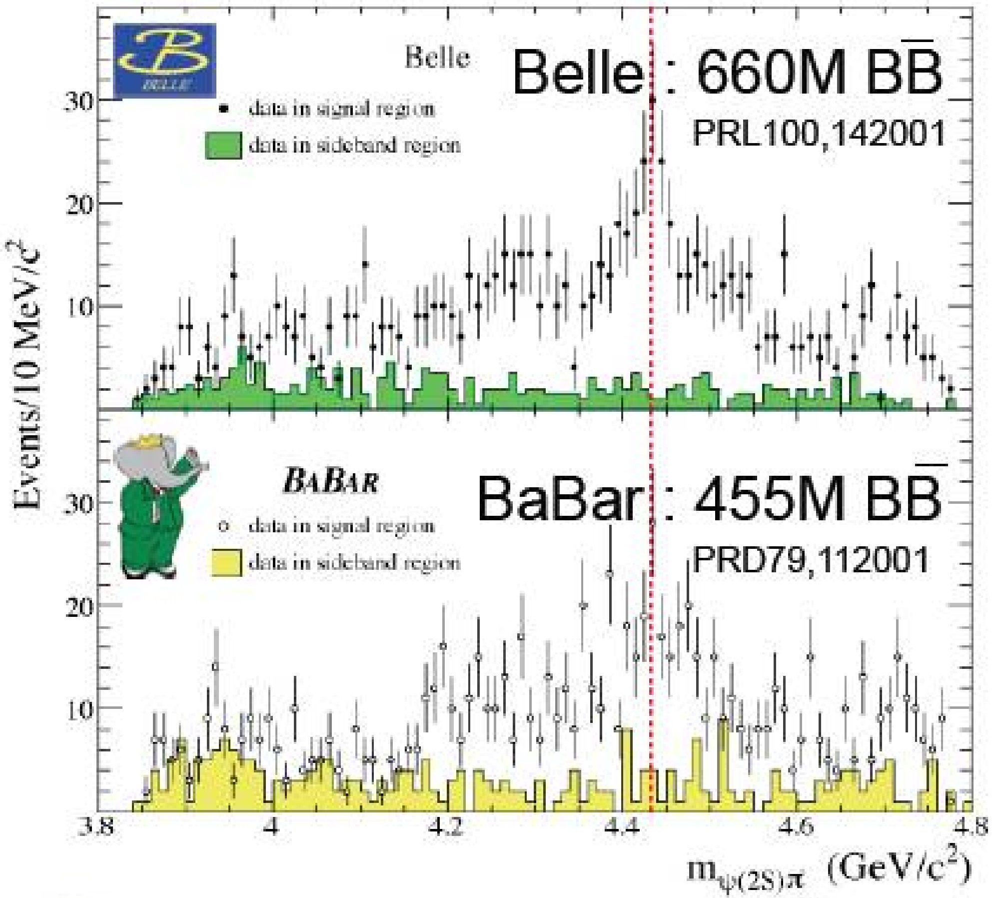
$$\left|W_{b0}\right\rangle = \frac{1}{2} 0^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}} + \frac{\sqrt{3}}{2} 1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}}$$

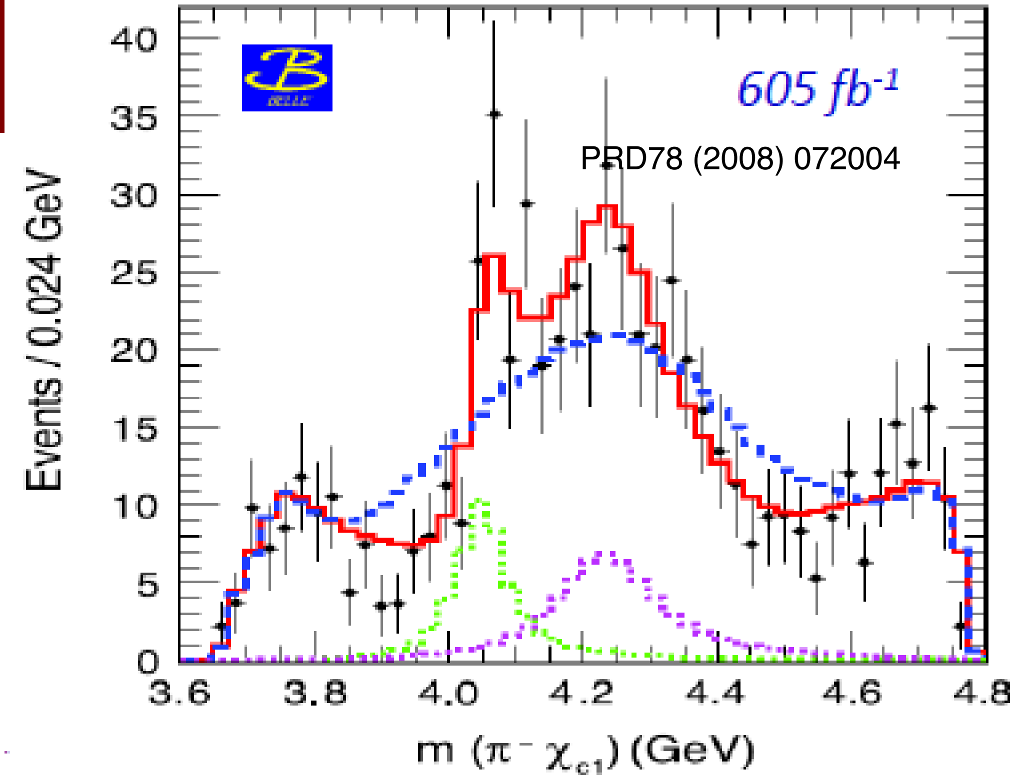
$$\left|W'_{b1}\right\rangle = (1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}})_{J=1}$$

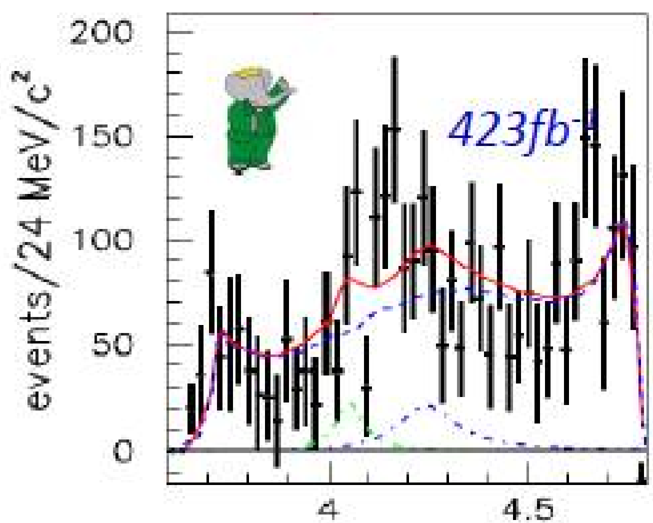
$$\left|W_{b2}\right\rangle = (1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}})_{J=2}$$

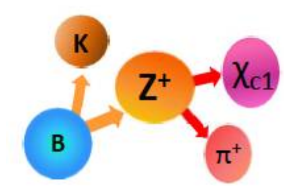


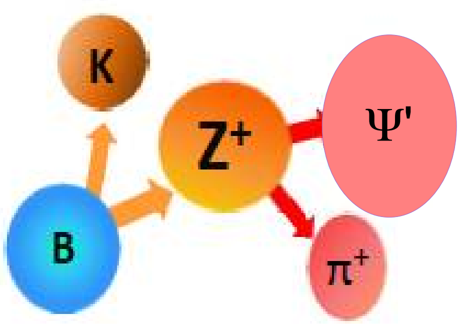
Open questions: B $\to$ K Z_c











Belle observed 3 charged peaks in B decays to charmonium + K

cc=Ψ' > Zc(4430)

cc=χ_{c1} > Zc(4050,4250)

Never confirmed by Babar

LHCb confirms Zc(4430) !

Open questions: X(3872) $\rightarrow \gamma$ (J/ψ , ψ ')

Babar [*PRL 102 (2009), 132001*]:

evidence of radiative decay to both J/ψ and ψ' :

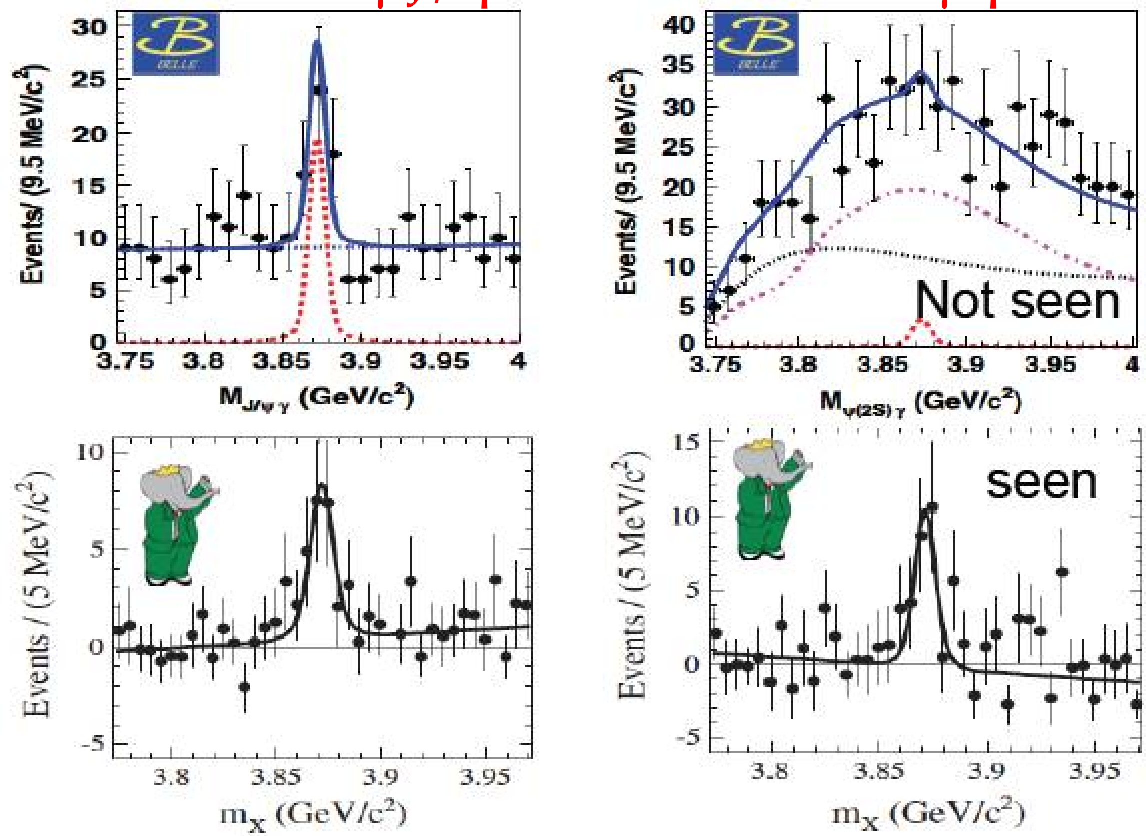
$$\frac{BR(X3872 \rightarrow \gamma\, \psi')}{BR(X3872 \rightarrow \gamma\, J/\psi)} = 3.4 \pm 1.4$$

- disfavors the molecular model,
- favors $J^{PC}=1^{++}$
- disfavors $J^{PC}= 2^{-+}$

Belle [*PRL 102 (2009), 132001*]:

confirms radiative decay to J/ψ but not to ψ'

X3872 $\rightarrow \gamma$ J/ψ X3872 $\rightarrow \gamma\, \psi'$



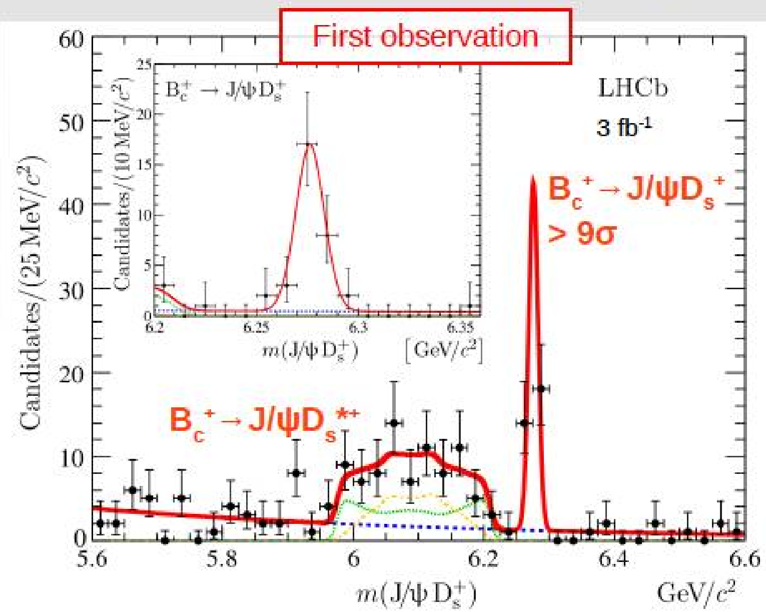
LHCb confirms Babar evidence , finally !

Bc

Bc spectroscopy

Most precise mass measurement

- by studying $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decays



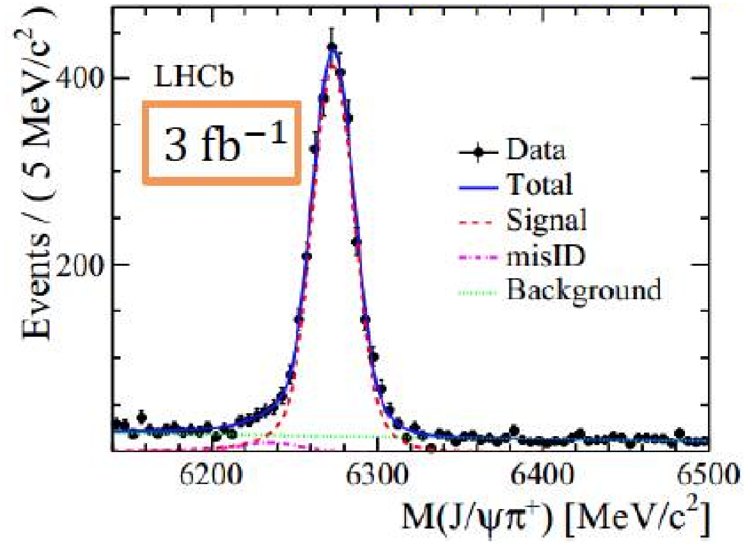
$$m_{B_c^+} = 6276.28 \pm 1.44\,(stat) \pm 0.36\,(syst)\,MeV/c^2$$

LHCb, 3 fb⁻¹, PRD 87 (2013) 112012

- In agreement with world average: $m(B_c^+) = 6274.5 \pm 1.8$ MeV/c²

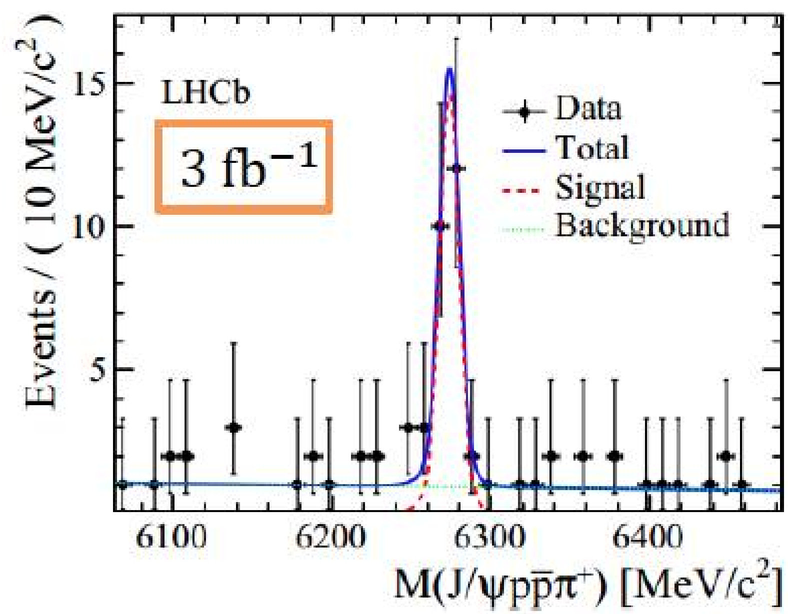
Polyakov Ivan, Moriond QCD, 24 March 2014

Reference transition



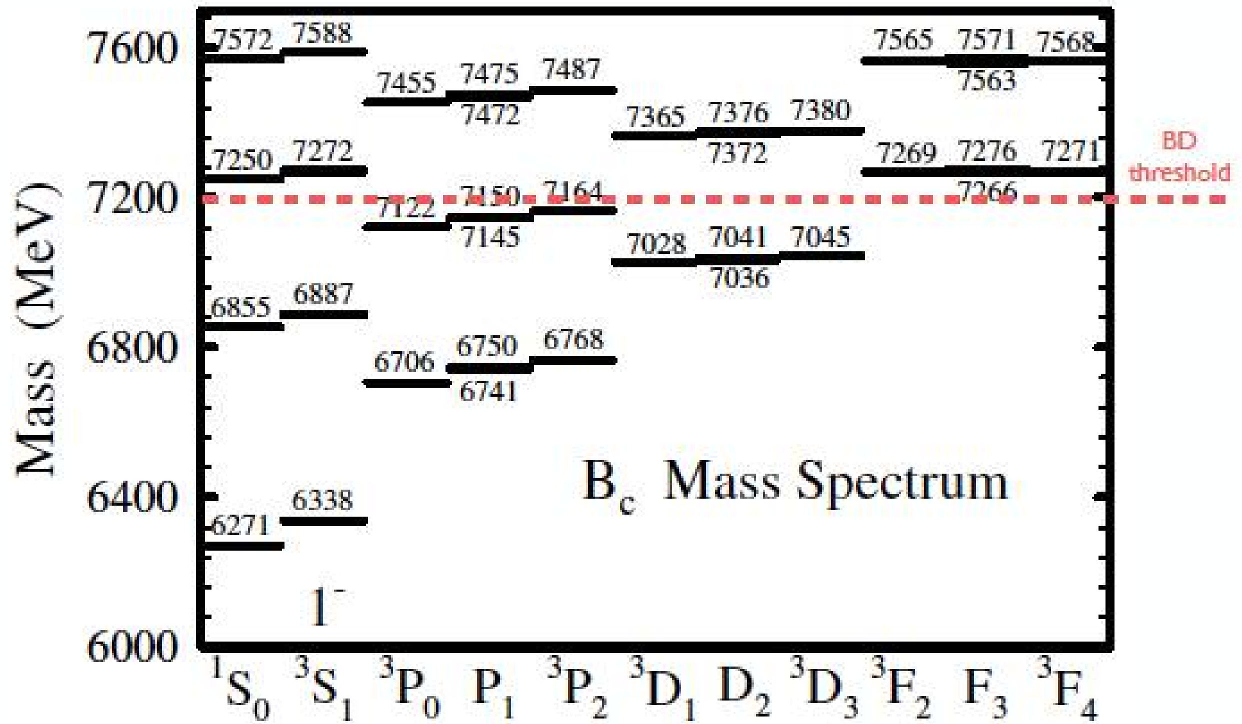
$N_{sig} = 2835 \pm 58$

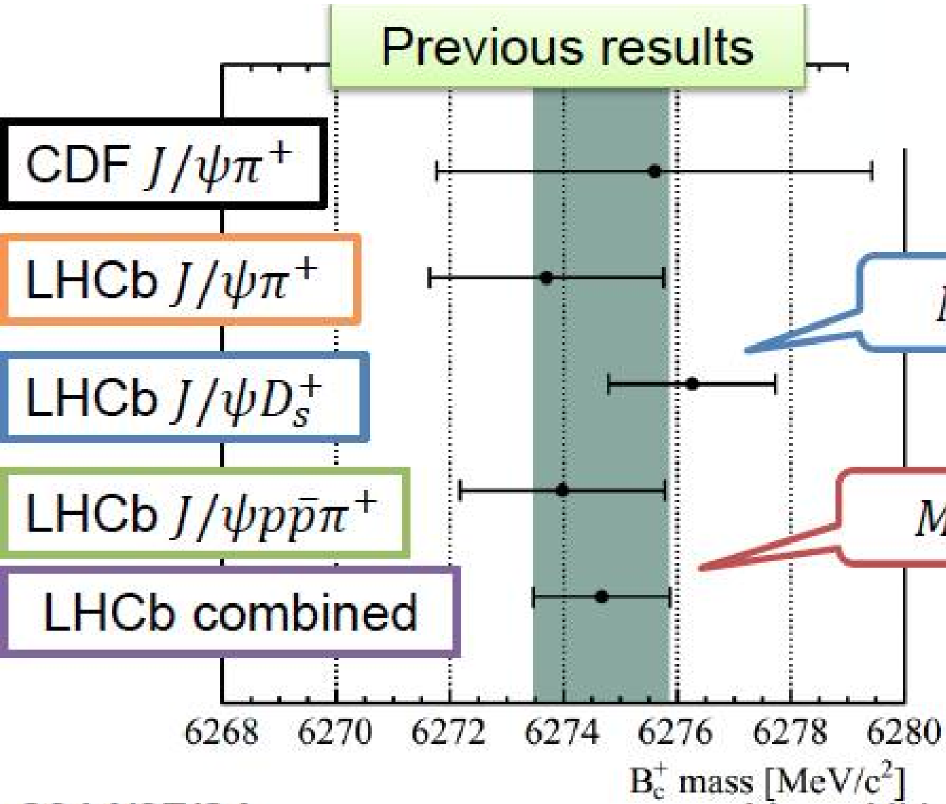
First decay to baryons



$N_{sig} = 23.9 \pm 5.3\ (7.3\ \sigma)$

Bc spectroscopy





$M(B_c^+) = 6276.3 \pm 1.4(\text{stat}) \pm 0.4(\text{syst})\ \text{MeV}/c^2$

$M(B_c^+) = 6274.7 \pm 0.9(\text{stat}) \pm 0.8(\text{syst})\text{MeV}/c^2$

The most precise measurement

LHCb-PAPER-2014-039

First observation of $B_c(2S)$

ATLAS detects the Bc decaying to J/ψπ mode
Significance (7+8 TeV data) :5.2 sigma

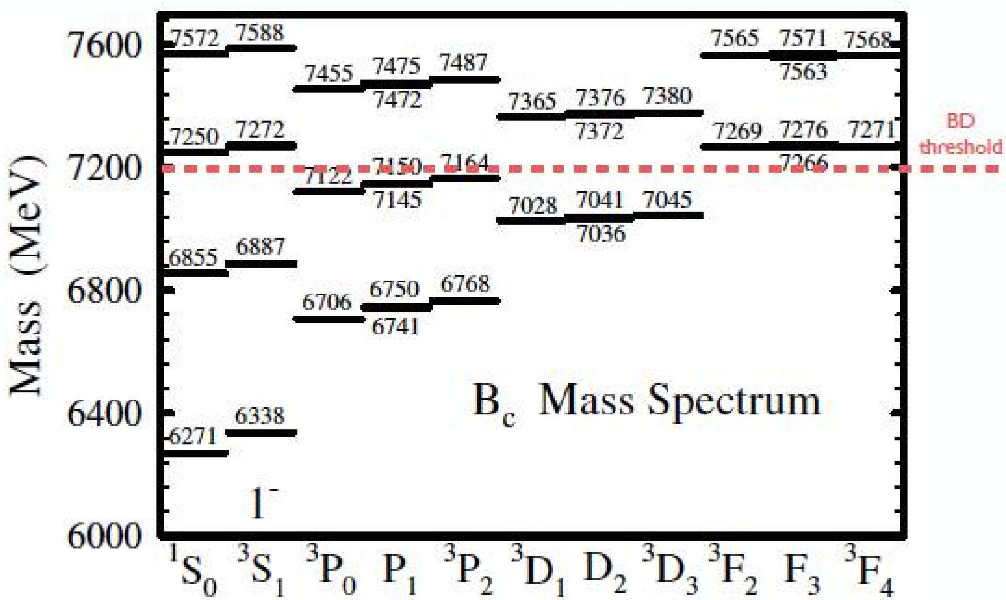
Can be a combination of two transitions:

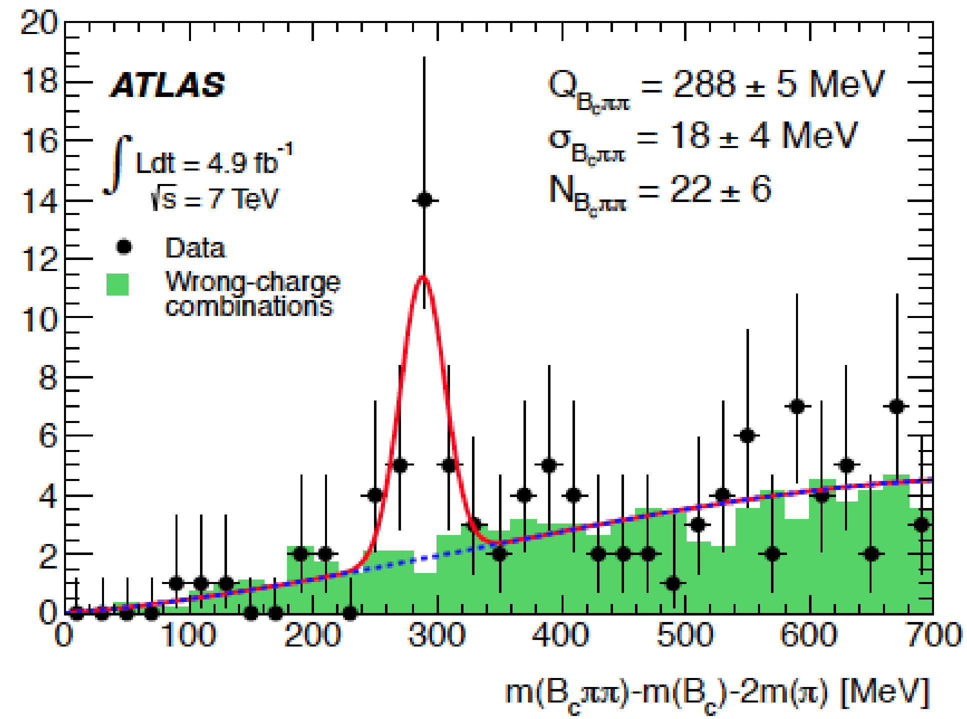
$B_c(2^1S_0) \rightarrow B_c(1^1S_0)\pi\pi$;

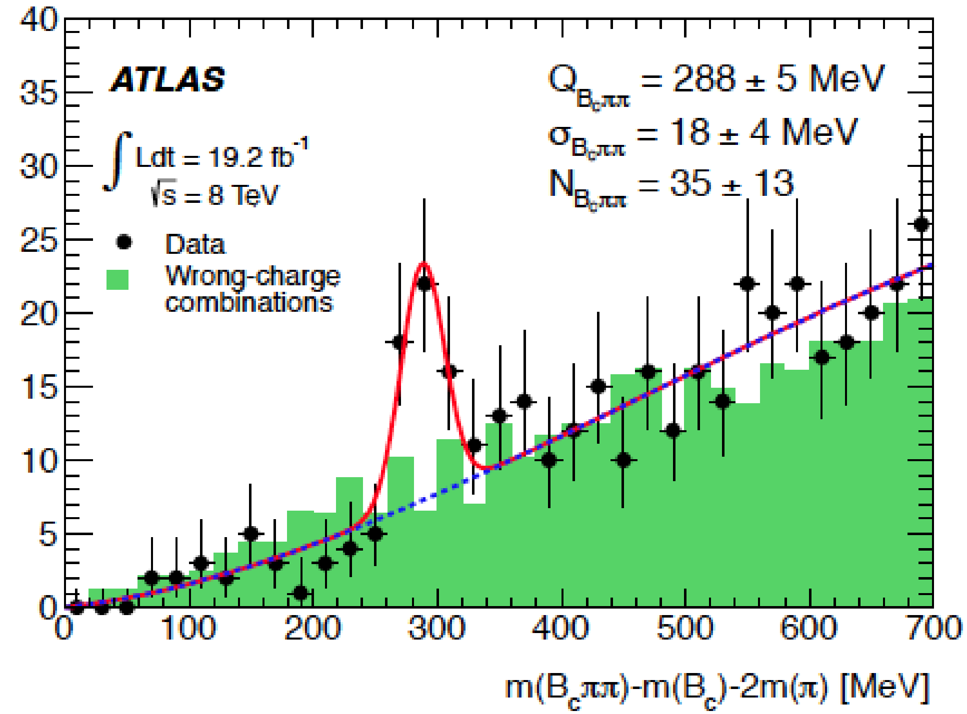
$B_c(2^3S_1) \rightarrow B_c(1^1S_0)\pi\pi + (\gamma)_{\text{not seen}}$;

$$Q = 288.3 \pm 3.5(stat) \pm 4.1(syst)$$

$$6841 \pm 4(stat) \pm 5(syst)\ MeV$$







See talk by P.ŘEZNÍčEK this morning

Summary

Heavy quarkonium reinassance , started by Babar and Belle in 2002, seems not to be over yet: new results are coming every year. LHC experiments are taking over, and largely contributing to fill the missing pieces of the hadron spectroscopy puzzle.

A pretty consistent pattern is emerging in the spectra of heavy baryons, heavy-light mesons, heavy onia, which shows little dependence on the mass scale, and on the running properties of QCD coupling constant. Besides the large developments of QCD based EFTs (NRQCD,HQET, chiral EFT,SCET, and lattice QCD) the success of constituent quark model is hard to be explained from first principles. Are we overlooking some hidden symmetry?

Spin anomalies in hadron transition amplitudes has led to nice surprises in the recent years of heavy quarkonium spectroscopy, and may need to further interesting developments.

Most progress is now expected from states above threshold, where light quark degrees of freedom are originating a new spectroscopy.

Quarkonium working group

www.qwg.to.infn.it

QWG Workshops on Heavy Quarkonium:

- QWG1: CERN, November 8 to 10, 2002
- QWG2: Fermilab, September 20 to 22, 2003
- QWG3: Beijing, October 12 to 15, 2004
- QWG4: Brookhaven, June 27 to 30, 2006
- QWG5: DESY Hamburg, October 12 to 15, 2007
- QWG6: Nara Women's University, December 2 to 5, 2008
- QWG7: Ferrmilab, May 18 to 21, 2010
- QWG8: GSI Darmstadt, October 3 to 7, 2011
- QWG9: IHEP Beijing, April 22 to 26, 2013
- QWG10: CERN, November 10 to 14, 2014

YELLOW REPORT :
CERN-2005-005,
ArXiv: hep-ph/0412158

2nd QWG Report :
Eur.Phys.J. C71 (2011) 1534 ,
ArXiv:1010.5827,