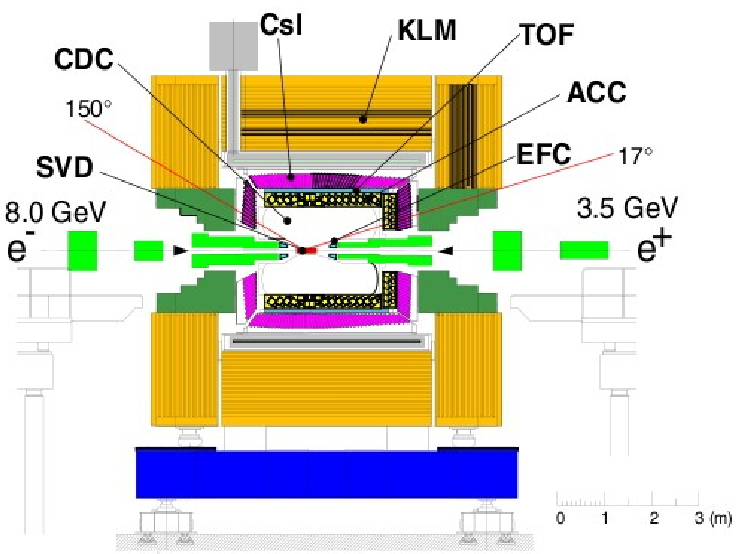
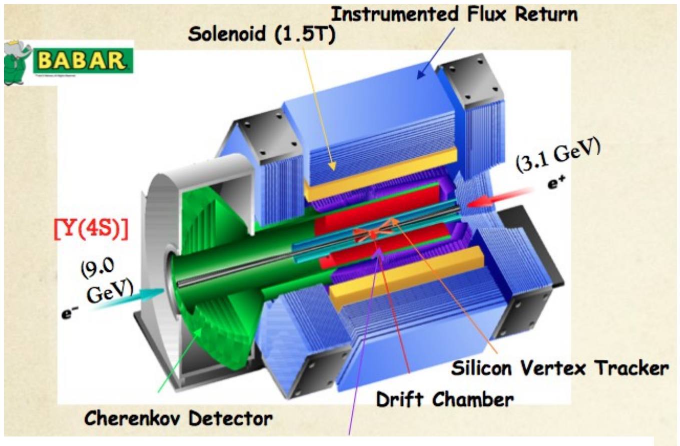
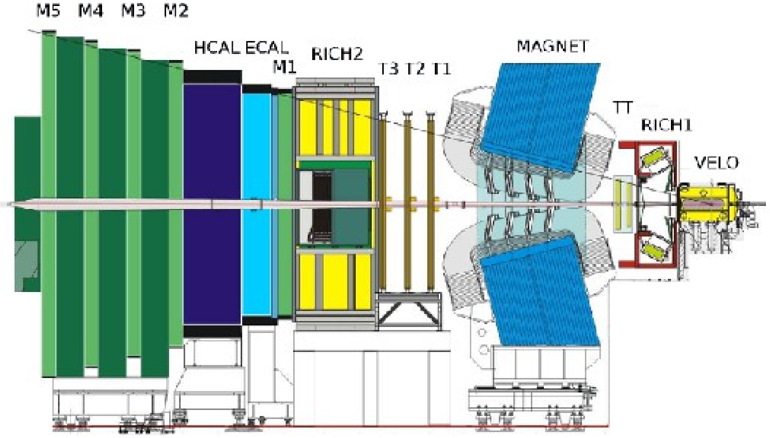
Hadron Spectroscopy

e+e- colliders /B-factories

Roberto Mussa
INFN Torino

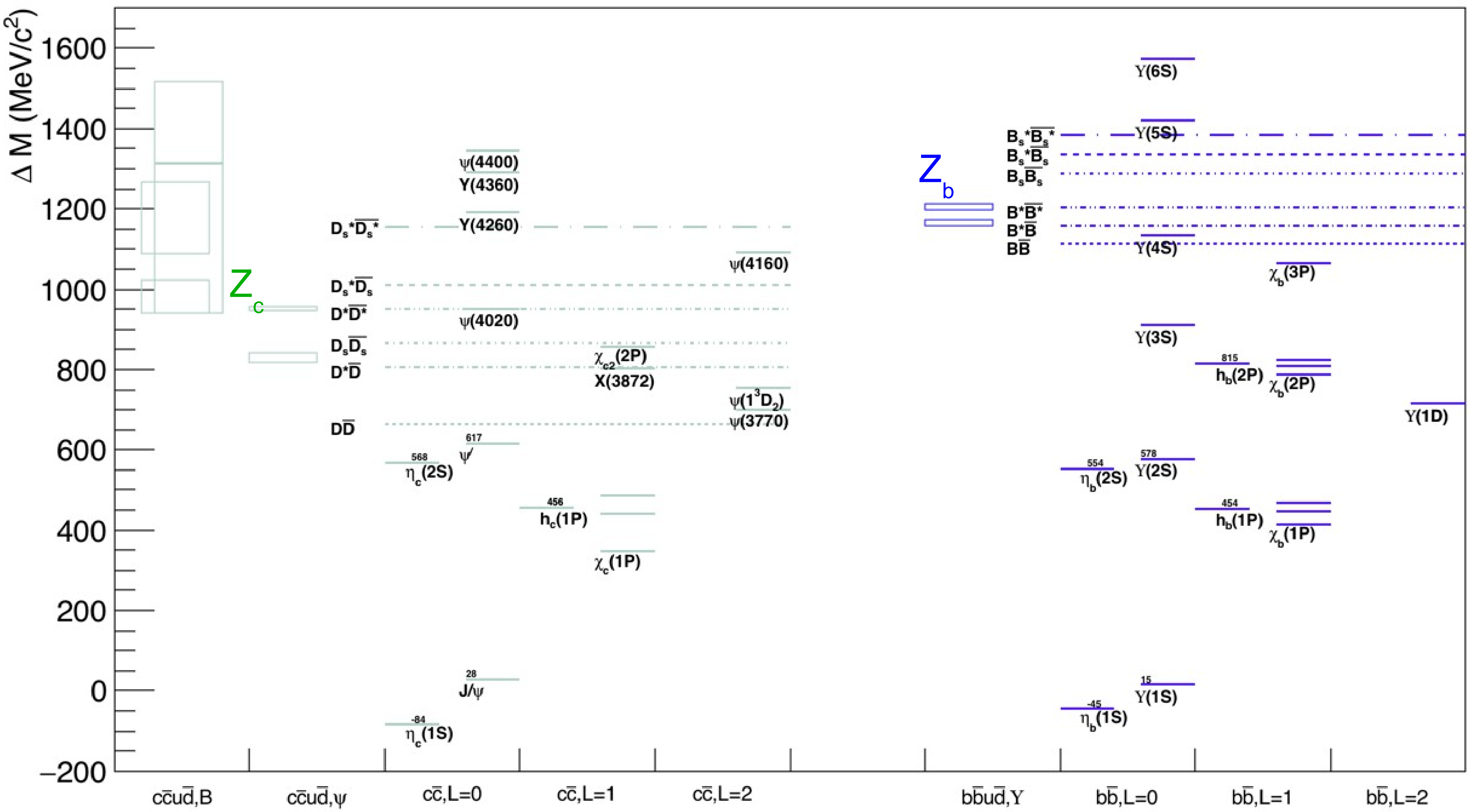






Spectra

Charmonium Bottomonium



Hadron transitions to lower $c\bar{c}$
$Z_c(4200)$
Z_c in ψ vs B decays

New $\chi_b(3P)$ masses
D-waves
Hadron transitions to lower $b\bar{b}$
X_b searches

χ_b(3P) @ LHCb

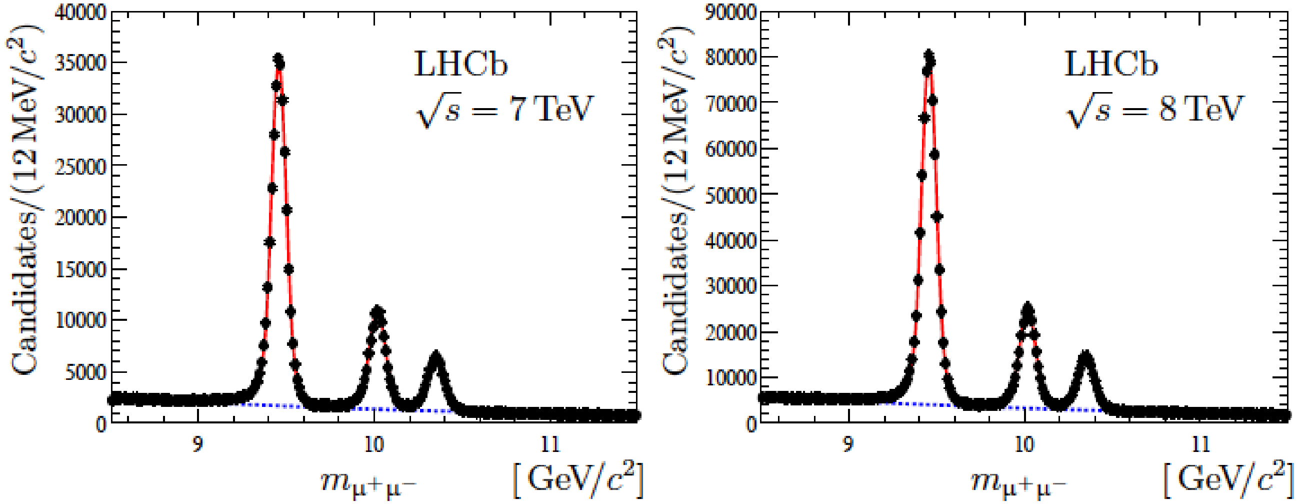
JHEP 1410 (2014) 88

Excellent resolution , perfect separation between the three Υ(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 Υ(nS) produced from decays of χ_b states.



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

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

$\chi_b(3P)$

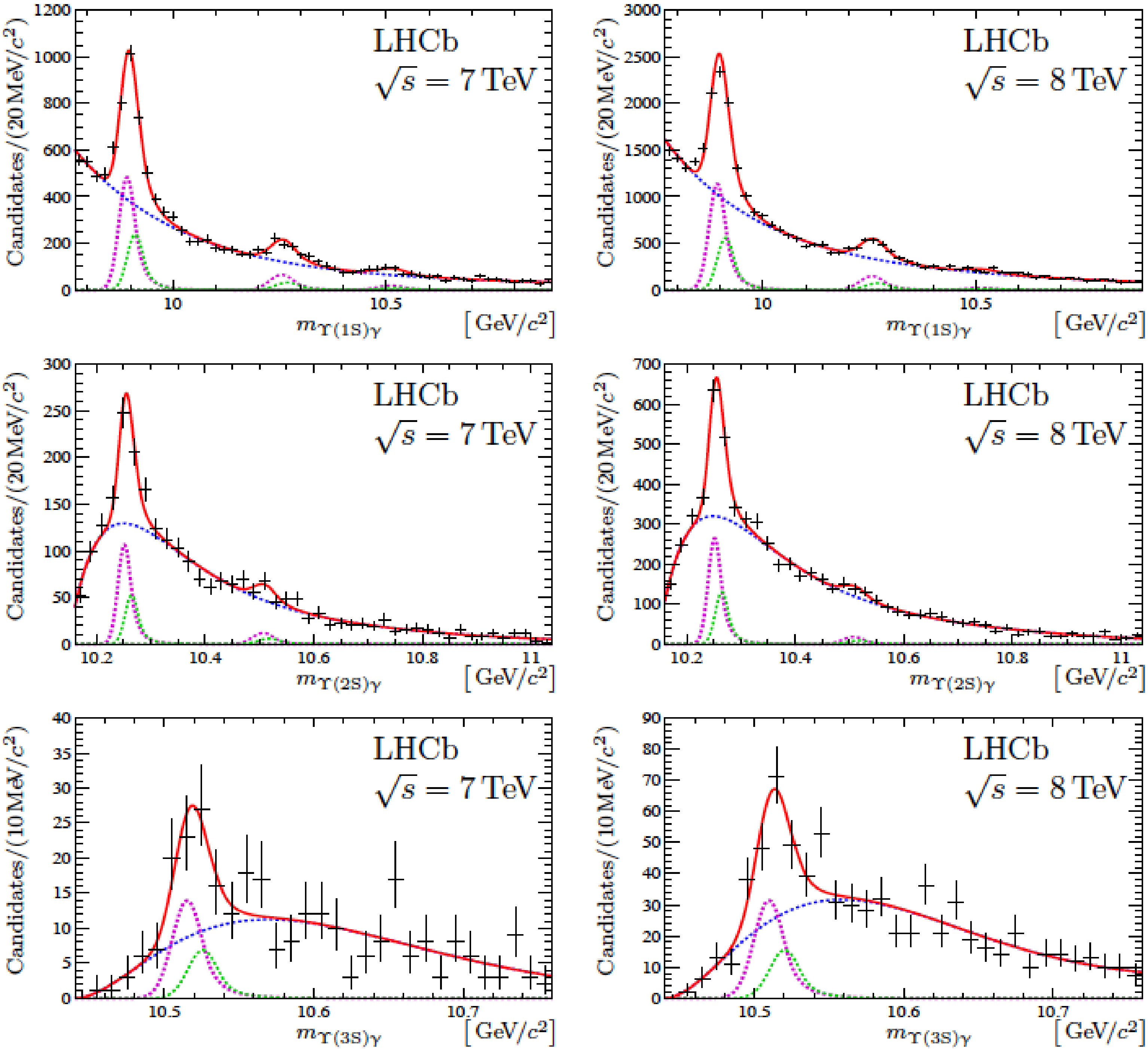
EPJC74 (2014) 10, 3092

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

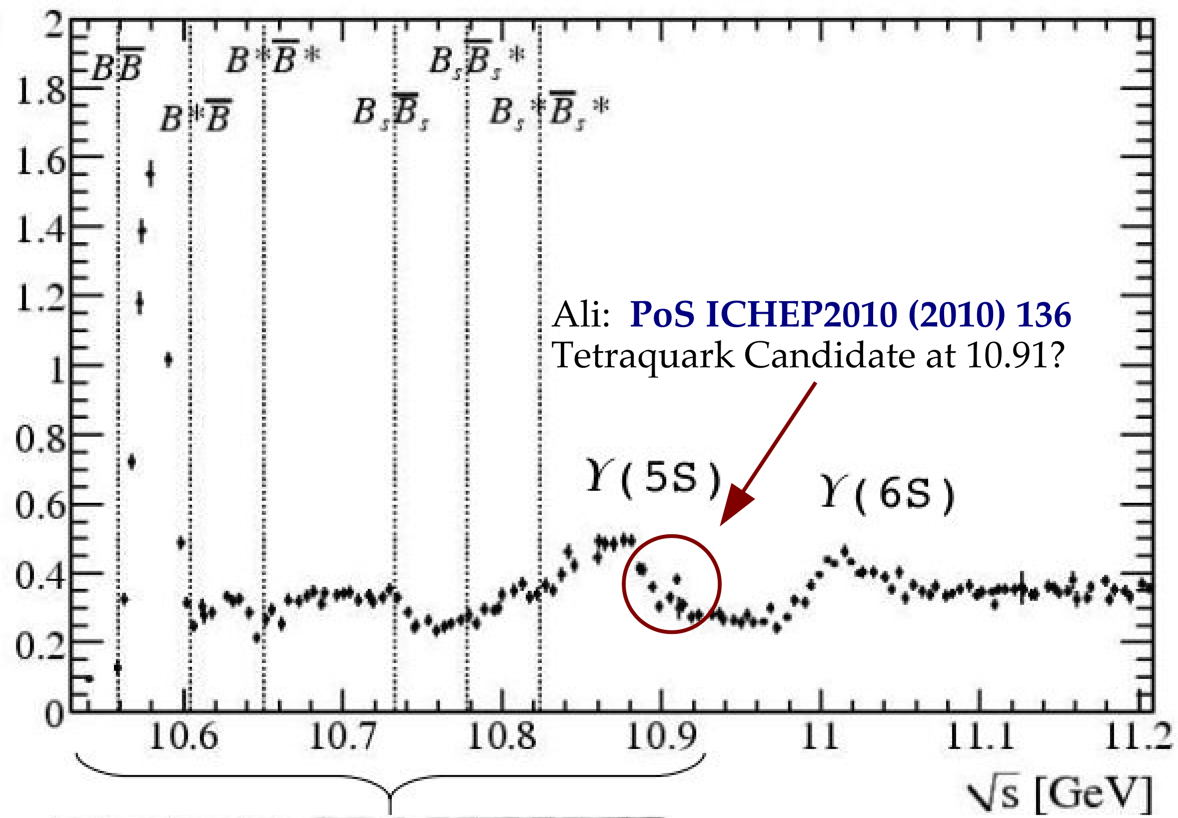
Best measurement of mass:
LHCB 10511.3±1.7
(mass of χ_{b1}(3P))

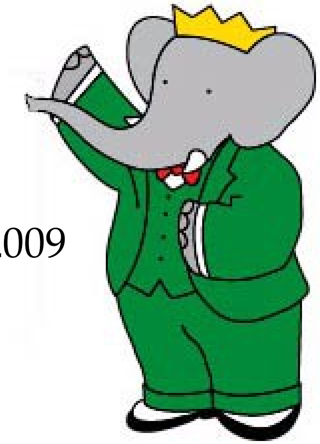
Previous:
ATLAS 10530±5±9
PRL108 (2012) 152001
DØ 10551±14±17
(mixed χ_{b1}(3P)+χ_{b2}(3P))
PRD86 (2012) 031103

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



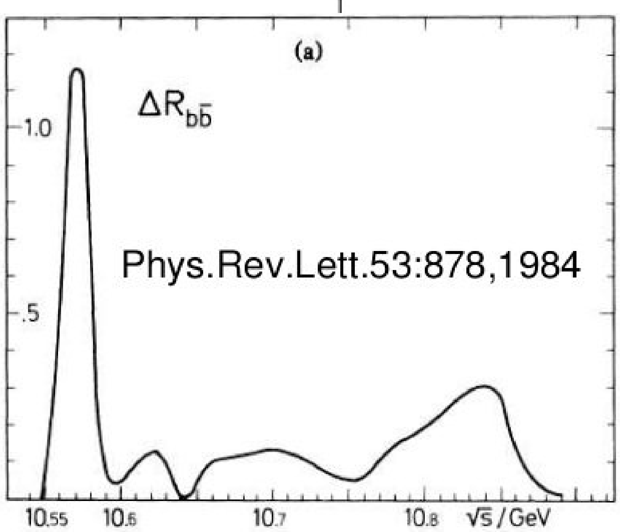
Scan of the Y(5S)-Y(6S) region: Babar





Phys.Rev.Lett.102:012001,2009

- 130 points, 25 pb^{-1} , ΔE=5 MeV
- $\sqrt{s}$ = 10.54-11.2 GeV
- $R_{b\bar{b}}=\sigma(b\bar{b})/\sigma(\mu\mu)$



Predicted by Tornqvist , using the Coupled Channel Model (Eichten et al.)

Υ(5-6S) scans: Υππ vs R_b

ArXiV:1501.01137

Measurements of $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$ and $\sigma(e^+e^- \to b\bar{b})$ in the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonance regions

Data samples:
- 121.4 fb^{-1} on Υ(5S) nominal peak, at √s = 10865 GeV
- 61 points, 50 pb^{-1} , √s = 10.75-11.05 GeV
- 16 points, 1 fb^{-1} , √s = 10.63-11.02 GeV
- continuum data at √s = 10520 GeV

Selection criteria for Rb:

N_{tracks}>4 (P_T>100 MeV) ;

N_{cl}>1 (E>100 MeV)

$E_{tot,ECL}$ = (0.1-0.8)*√s

E_{vis}>0.5* √s

Fox Wolfram R_2<0.2

ΔR<1.5 cm; Δz<3.5 cm

Rb is calculated subtracting the $q\bar{q}$ (q=u,d,s,c) continuum

$$\tilde{R}_{b,i} = \frac{1}{\epsilon_{b\bar{b}}}\left(\frac{N_i}{\mathcal{L}_i\sigma^0_{\mu\mu,i}} - \frac{N_{\rm ct}}{\mathcal{L}_{\rm ct}\sigma^0_{\mu\mu,{\rm ct}}}\frac{\epsilon_{q\bar{q},i}}{\epsilon_{q\bar{q},{\rm ct}}}\right)$$

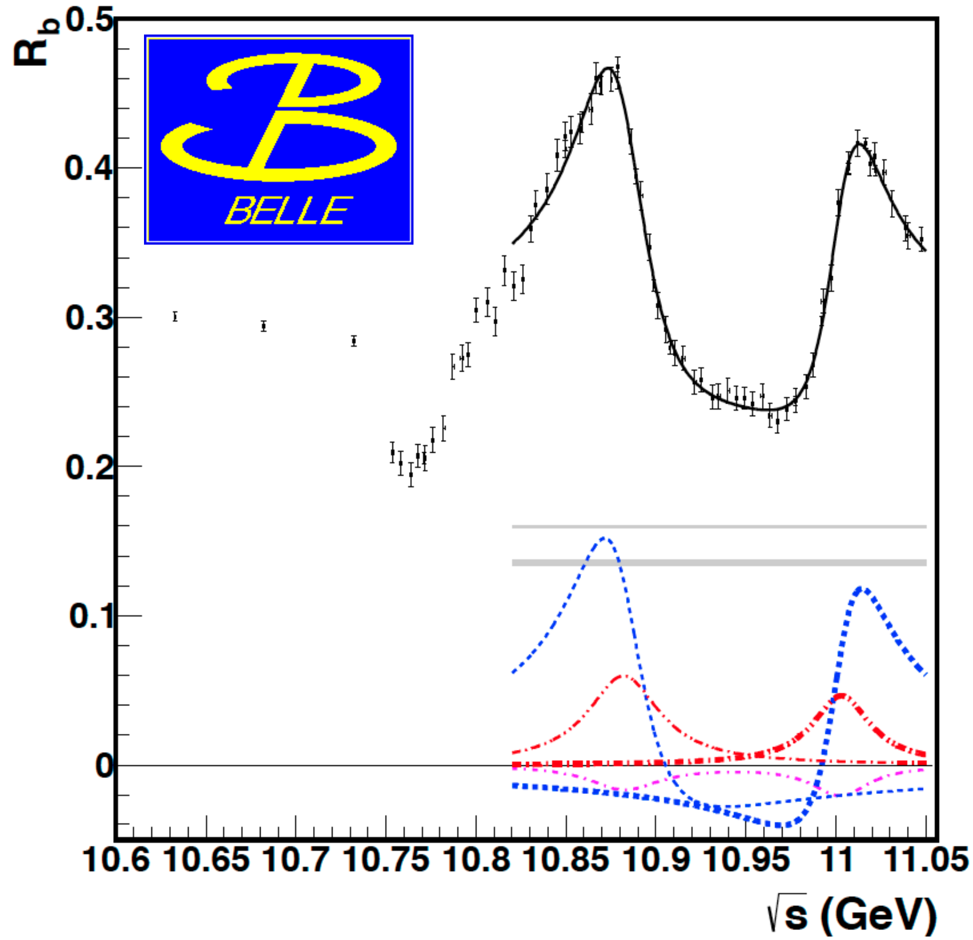
Rb' after correcting for ISR

$$R'_{b,i} \equiv R_{b,i} - \sum \sigma_{{\rm ISR},i}/\sigma^0_{\mu^+\mu^-,i}$$

R.Mussa, Ha

Rb and Rb' are fitted in the range √s=10.82-11.05 with :

$$\mathcal{F} = |A_{\rm nr}|^2 + |A_{\rm r} + A_{5S}e^{i\phi_{5S}}f_{5S} + A_{6S}e^{i\phi_{6S}}f_{6S}|^2$$



Y(5-6S) scans: Yππ vs R_b

ArXiV:1501.01137

Measurements of $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$ and $\sigma(e^+e^- \to b\bar{b})$ in the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonance regions

Data samples:

- 121.4 fb^{-1} on Y(5S) nominal peak, at √s = 10865 GeV
- 61 points, 50 pb^{-1} , √s = 10.75-11.05 GeV
- 16 points, 1 fb^{-1} , √s = 10.63-11.02 GeV
- continuum data at √s = 10520 GeV

Selection criteria for Rb:

N_{tracks}=4 (P_T>100 MeV) ;

ΔR<1 cm; Δz<5 cm

| $\Delta z_{\pi\pi}$ 2 $\Delta z_{\mu\mu}$ | < 3mm

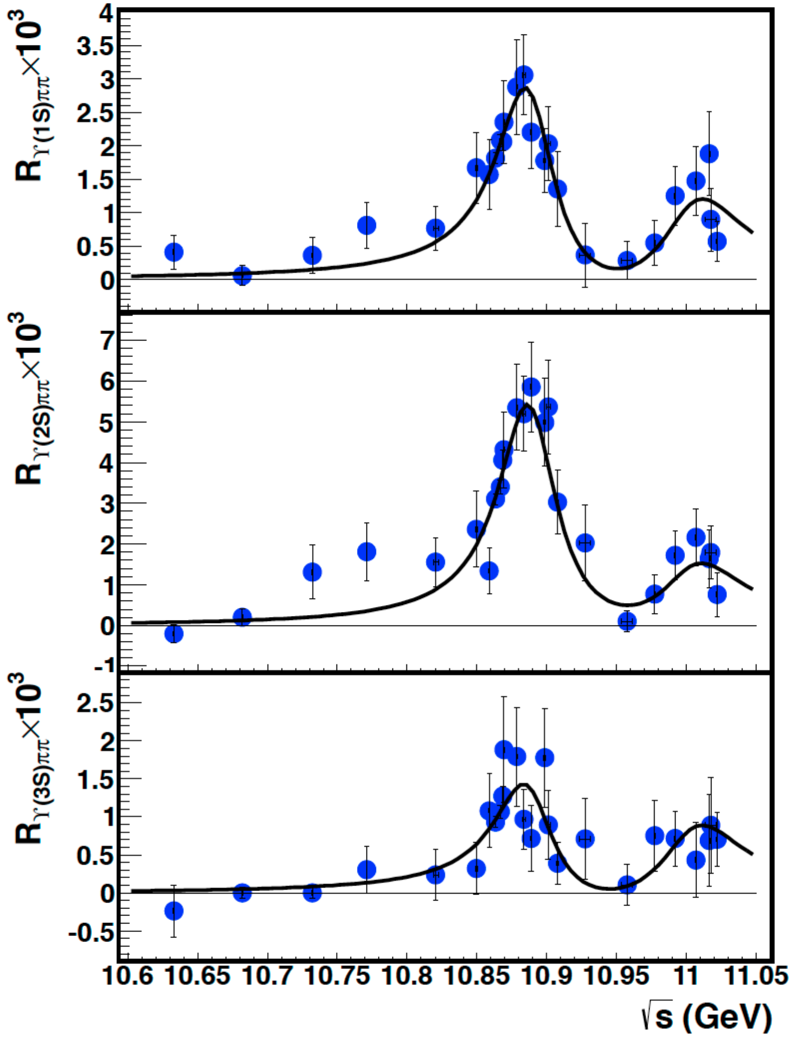
| M(ππμμ)2√s|<0.2 GeV

Rb is calculated subtracting the $q\bar{q}$ (q=u,d,s,c) continuum

$$\tilde{R}_{b,i} = \frac{1}{\epsilon_{b\bar{b}}}\left(\frac{N_i}{\mathcal{L}_i\sigma^0_{\mu\mu,i}} - \frac{N_{\rm ct}}{\mathcal{L}_{\rm ct}\sigma^0_{\mu\mu,{\rm ct}}}\frac{\epsilon_{q\bar{q},i}}{\epsilon_{q\bar{q},{\rm ct}}}\right)$$

Rb' after correcting for ISR

$$R'_{b,i} \equiv R_{b,i} - \sum \sigma_{{\rm ISR},i}/\sigma^0_{\mu^+\mu^-,i}$$

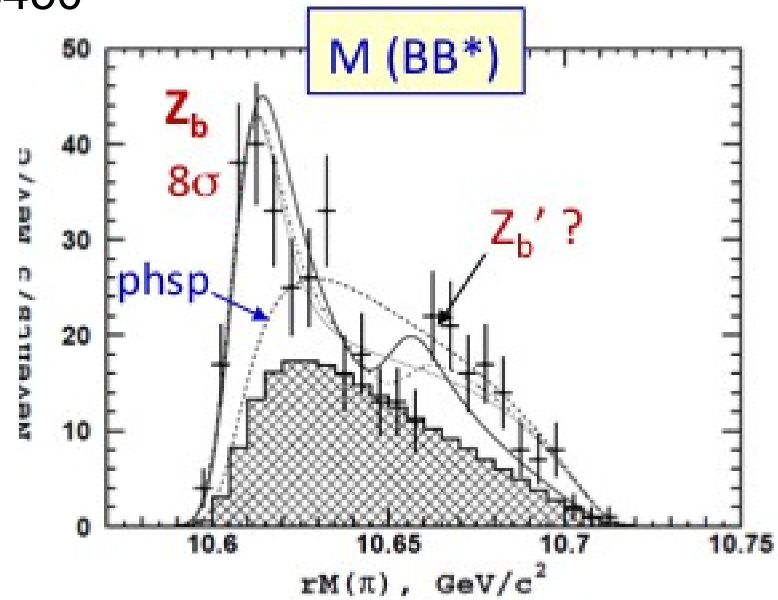


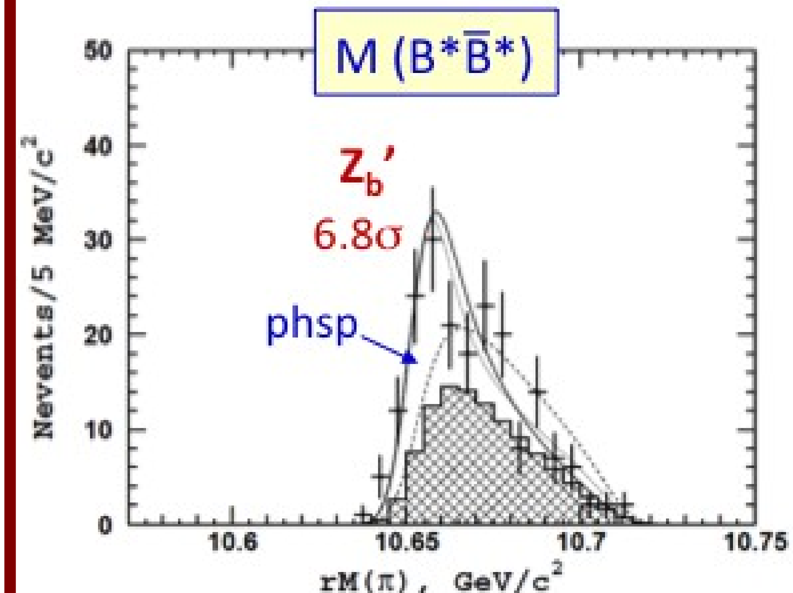
$Z_b \to \bar{B}B^* + B\bar{B}^*,\ B^*\bar{B}^*$

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.	
$B\bar{B}^* + \bar{B}B^*$	(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

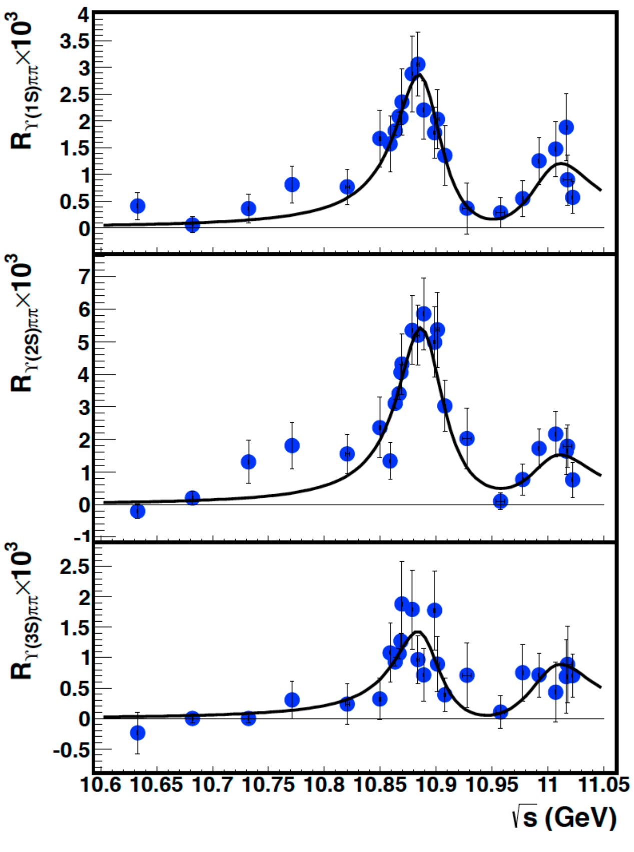


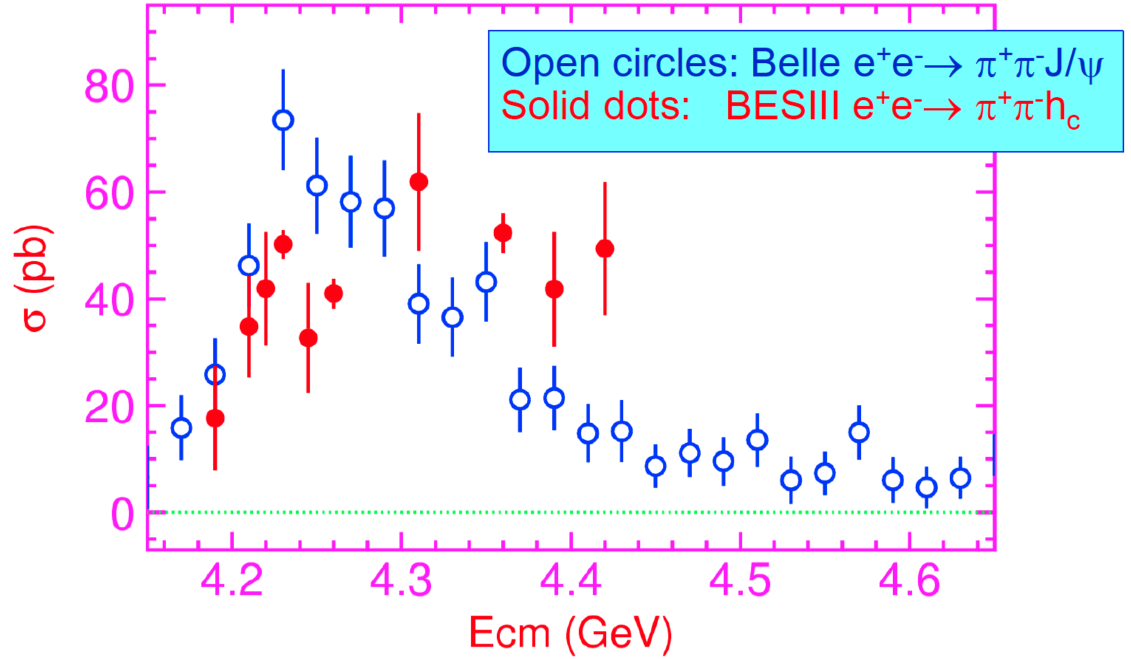


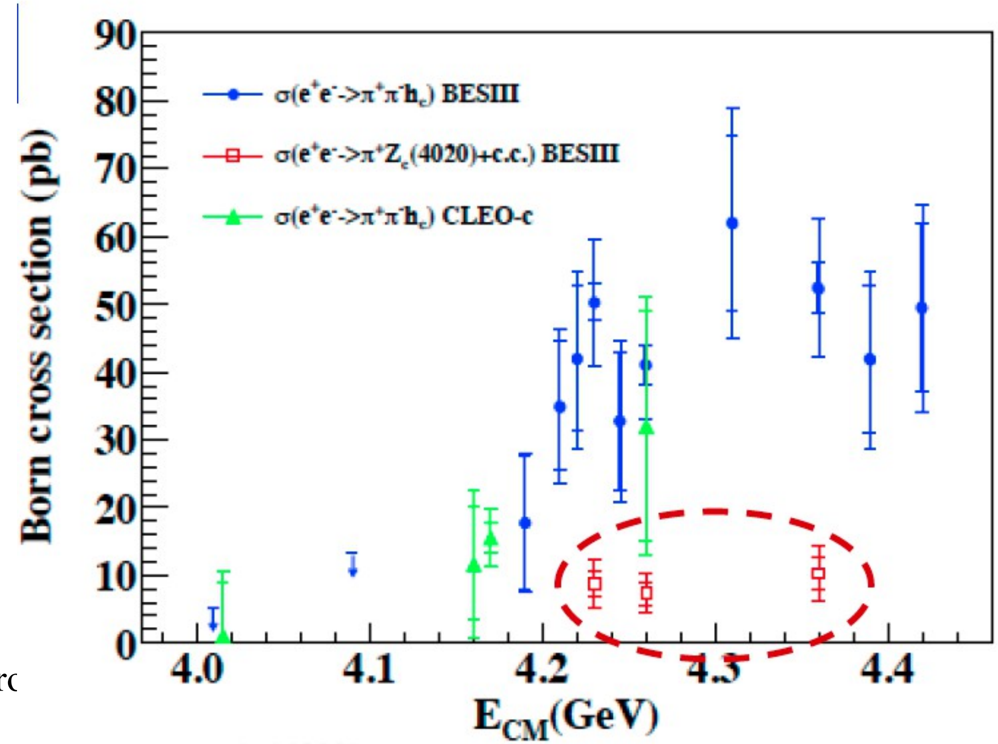
High energy scans: $b\bar{b}$ vs $c\bar{c}$

Differences:
- Υ(5,6S) peaks are well resolved, Y(4.26,4.36) are NOT

- Transitions to h_b dominated by Z_b, While only 20% of h_c is reached via Z_c

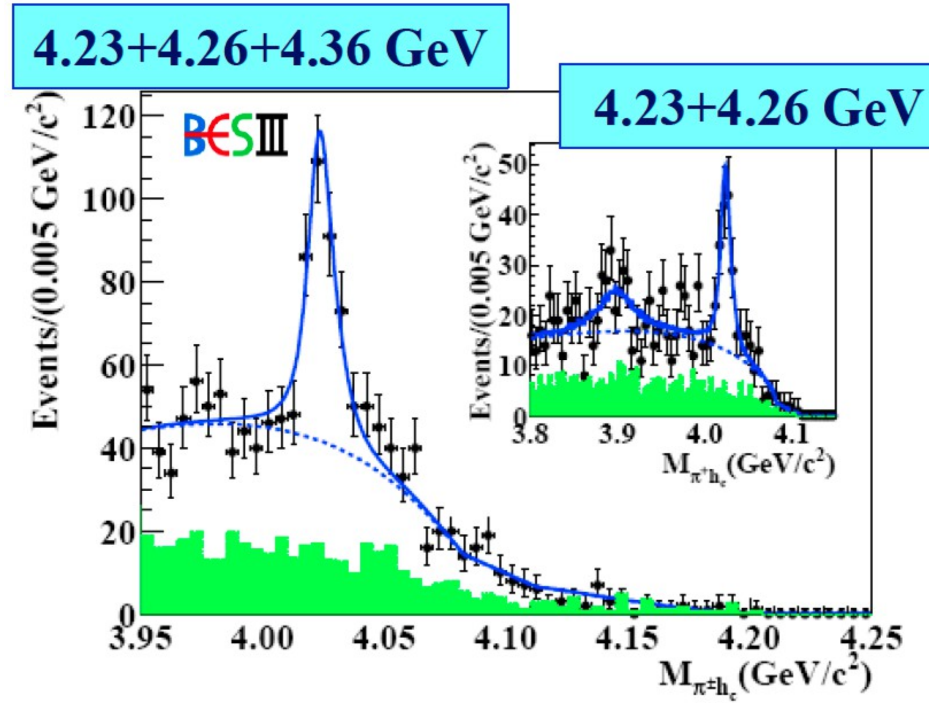






Z_b vs Z_c

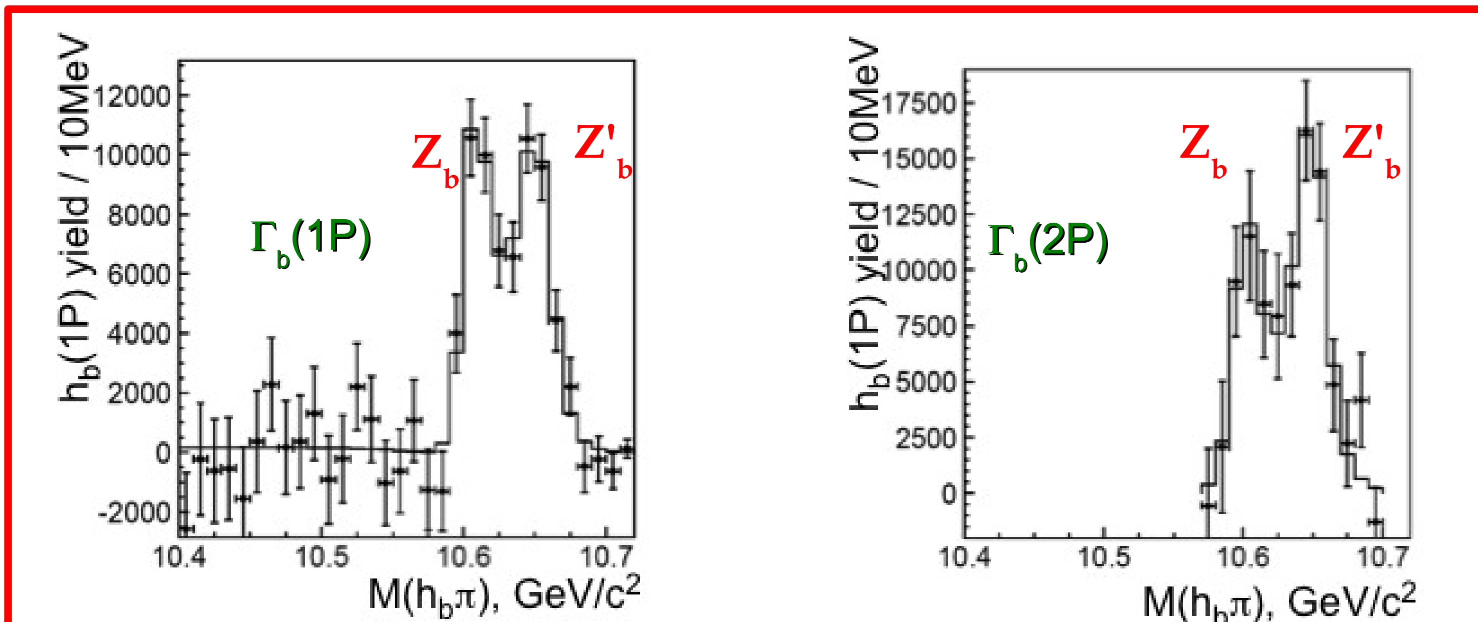
BES-III high statistics results are from exclusive analysis of data taken at
Ecm = 4.23,4.26,4.36 GeV



Cannot yet exclude $Z_c(3.9) \to \pi h_c$!!!

All Belle results on Zb are from the Y(5S) peak from inclusive analysis

Belle analysis on hb from Y(6S) much harder: stay tuned



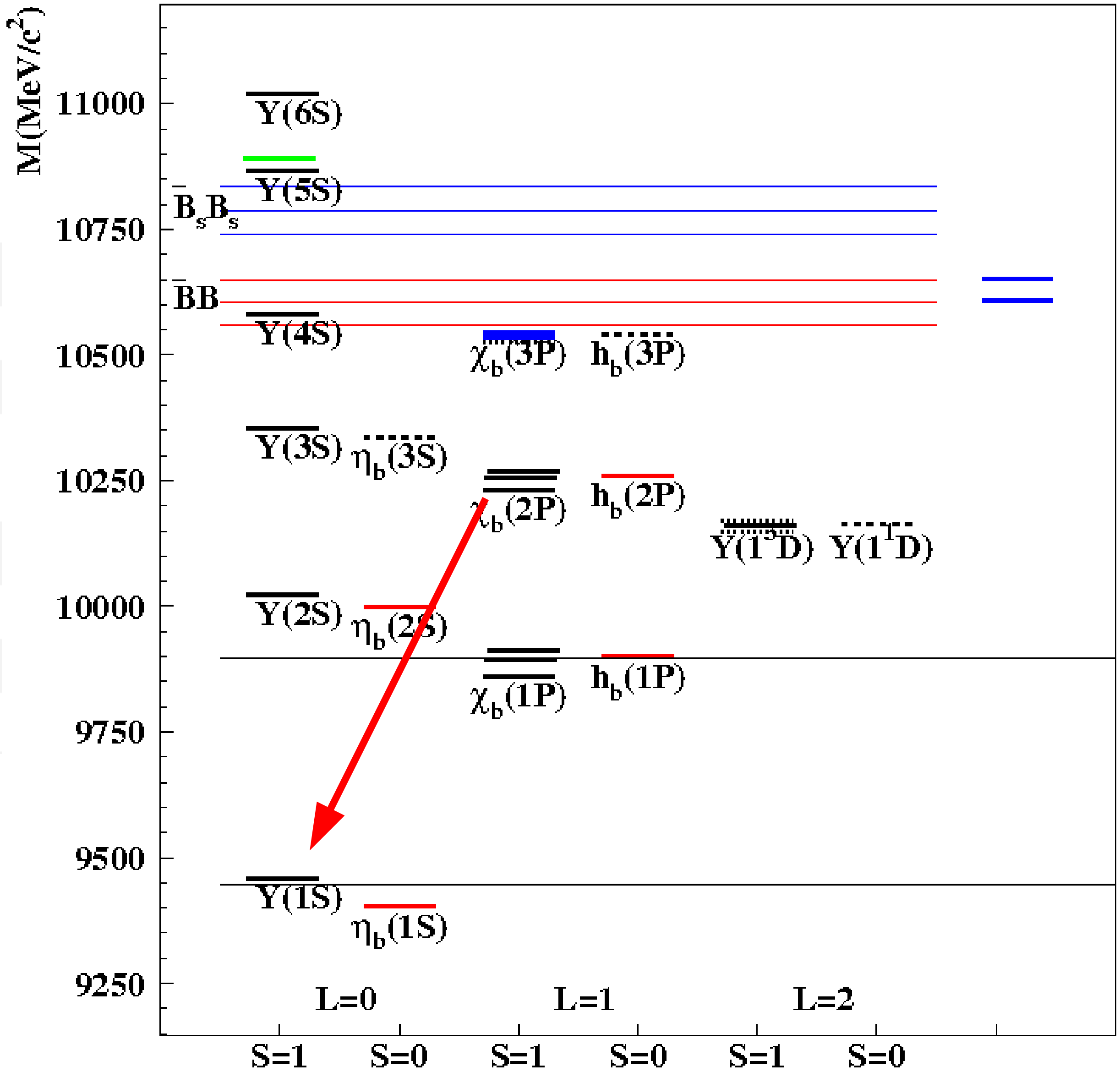
The ω transitions

Observed by CLEO in 2004
PRL 92,222002 (2004)

$\chi_{b1}(2P) \to \omega\Upsilon(1S)$	$1.63\ ^{+0.40}_{-0.34}\ \%$
$\chi_{b1}(2P) \to \gamma\Upsilon(2S)$	$.199 \pm .019$
$\chi_{b1}(2P) \to \gamma\Upsilon(1S)$	$9.2 \pm 0.8\ \%$
$\chi_{b1}(2P) \to \pi\pi\chi_{b1}(1P)$	$(9.1 \pm 1.3) \times 10^{-3}$

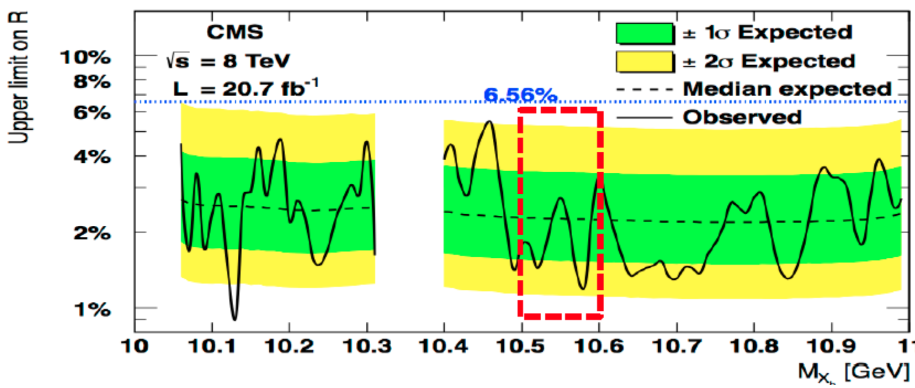
$\chi_{b2}(2P) \to \omega\Upsilon(1S)$	$1.10\ ^{+0.34}_{-0.30}\ \%$
$\chi_{b2}(2P) \to \gamma\Upsilon(2S)$	$.106 \pm .026$
$\chi_{b2}(2P) \to \gamma\Upsilon(1S)$	$7.0 \pm 0.7\ \%$
$\chi_{b2}(2P) \to \pi\pi\chi_{b2}(1P)$	$(5.1 \pm 0.9) \times 10^{-3}$

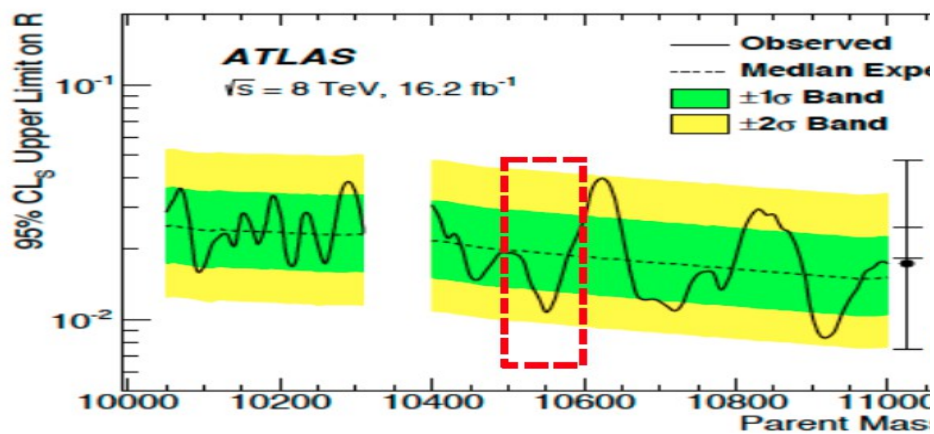
In charmonium, ω transitions are observed from X(3872) and Y(3915)



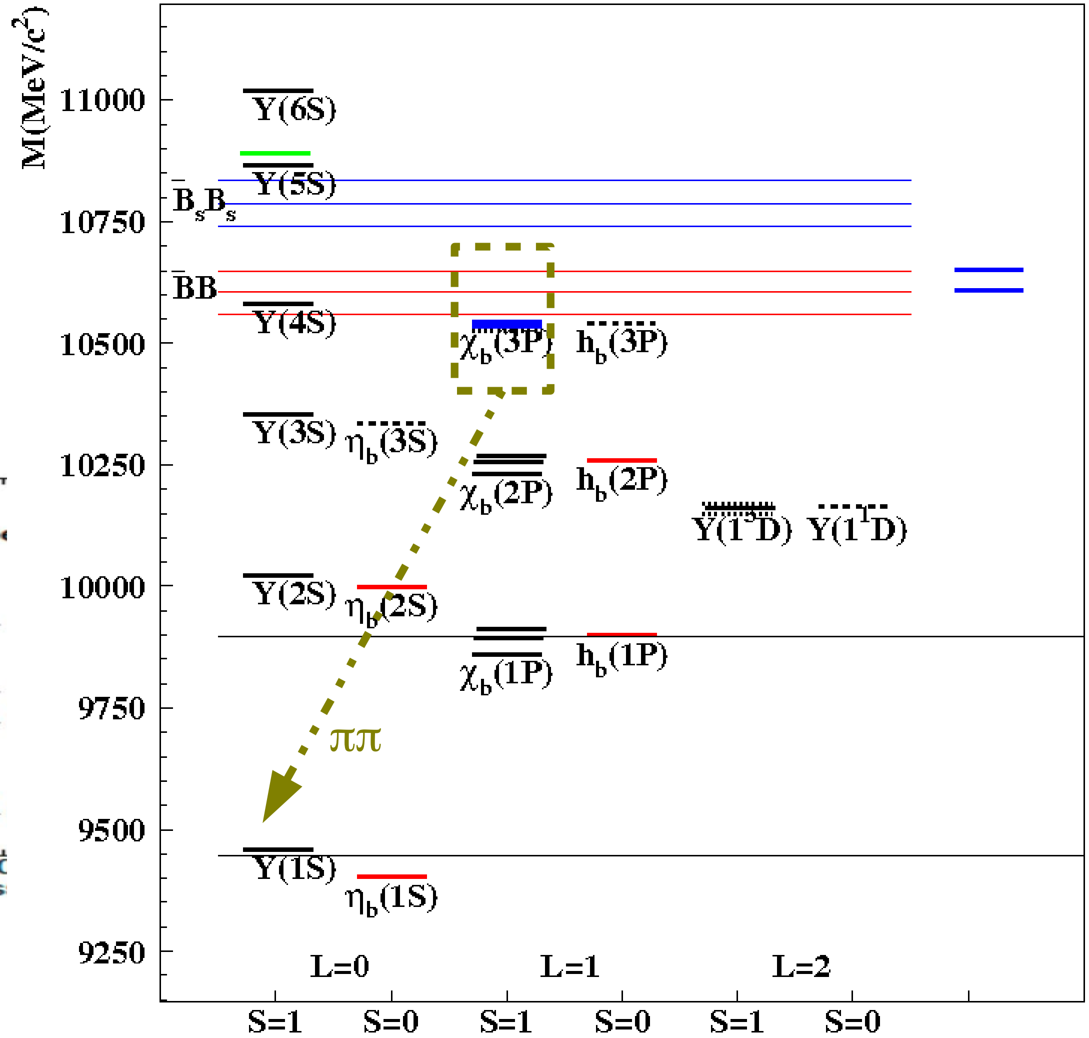
What about a bottomonium analogue?

Search for X_b at LHC





$$R = \frac{\sigma(pp \to X_b \to \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)}$$



In charm, $M(D^+)$-$M(D^0)$ = 4.73 MeV → large isospin violation: $BR(J/\psi\omega) \approx BR(J/\psi\rho)$

In bottom, $M(B^+)$-$M(B^0)$ = 0.32 → no isospin violation→$BR(X_b \to \Upsilon\rho) \approx 0$

Belle has searched for $X_b \to \Upsilon\omega$ in $\Upsilon(5S)$ decays, as suggested in PRD91,014014 (2015)

Observation of $\Upsilon(5S) \to \omega\chi_b(1P)$

PRL 113,142001(2014)

PRL 113, 142001 (2014) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2014

Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ and Search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s} = 10.867$ GeV

Sample=118 fb^{-1} at $\Upsilon(5S)$ peak

χ_{bJ} decays to $\gamma ee, \gamma\mu\mu$

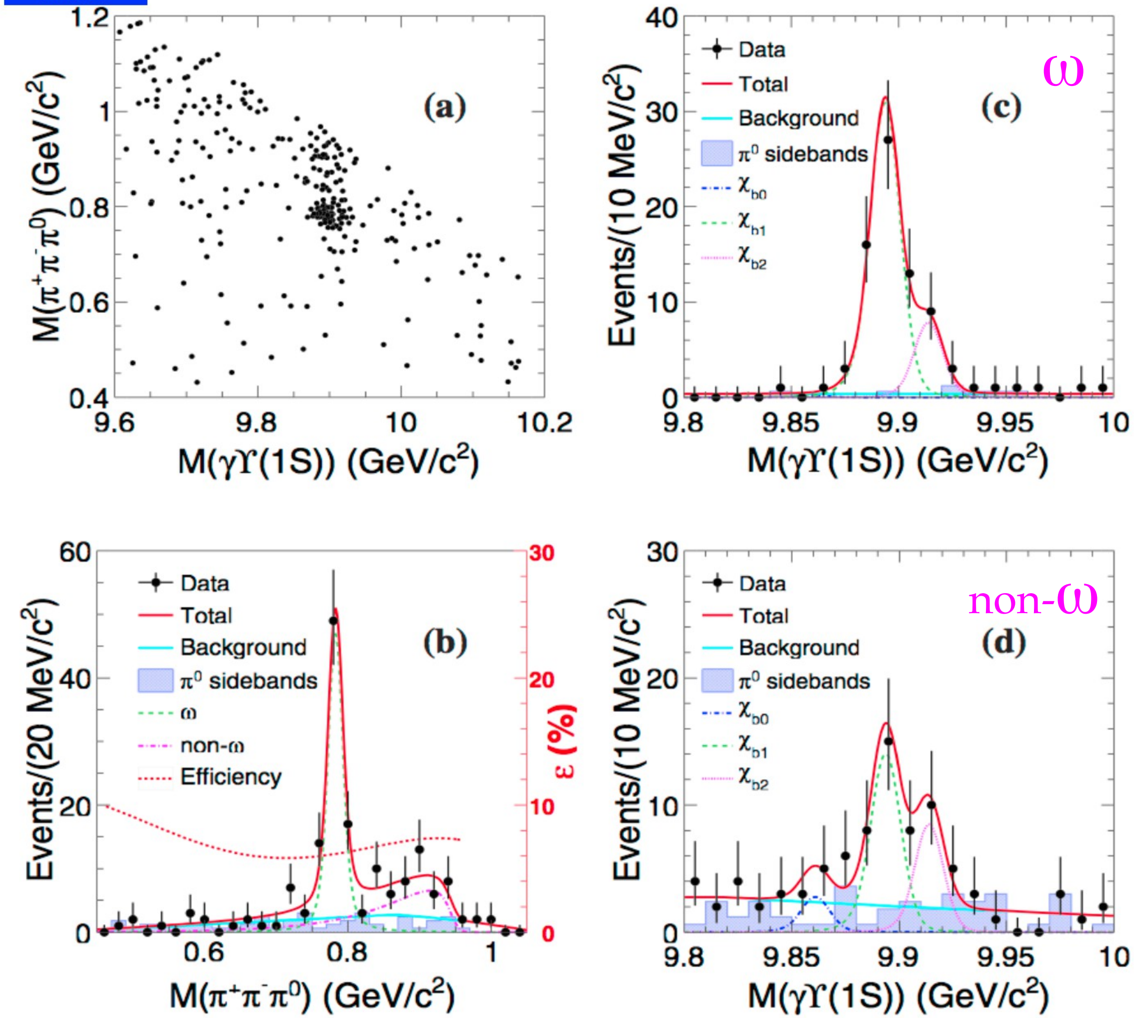
Significant 3π contribution observed also from outside ω peak, stronger at the χ_{b2}

Mode	σ_B (pb)	$\mathcal{B}$ (10^{-3})
$\pi^+\pi^-\pi^0\chi_{b0}$	< 3.1	< 6.3
$\pi^+\pi^-\pi^0\chi_{b1}$	$0.90 \pm 0.11 \pm 0.13$	$1.85 \pm 0.23 \pm 0.23$
$\pi^+\pi^-\pi^0\chi_{b2}$	$0.57 \pm 0.13 \pm 0.08$	$1.17 \pm 0.27 \pm 0.14$
$\omega\chi_{b0}$	< 1.9	< 3.9
$\omega\chi_{b1}$	$0.76 \pm 0.11 \pm 0.11$	$1.57 \pm 0.22 \pm 0.21$
$\omega\chi_{b2}$	$0.29 \pm 0.11 \pm 0.08$	$0.60 \pm 0.23 \pm 0.15$
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b0}$	< 2.3	< 4.8
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b1}$	$0.25 \pm 0.07 \pm 0.06$	$0.52 \pm 0.15 \pm 0.11$
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b2}$	$0.30 \pm 0.11 \pm 0.14$	$0.61 \pm 0.22 \pm 0.28$

The total contribution of $\omega\chi_b(1P)$ to BR is 0.3%, comparable with the larger hadronic transitions to lower bottomonia

$$R = \frac{\sigma(e+e- \to \omega\chi_{b2})}{\sigma(e+e- \to \omega\chi_{b1})} = 0.38 \pm 0.16(stat.) \pm 0.09(syst.)$$

$$R = \frac{\sigma(e+e- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{b2})}{\sigma(e+e- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{b1})} = 1.20 \pm 0.55(stat.) \pm 0.65(syst.)$$



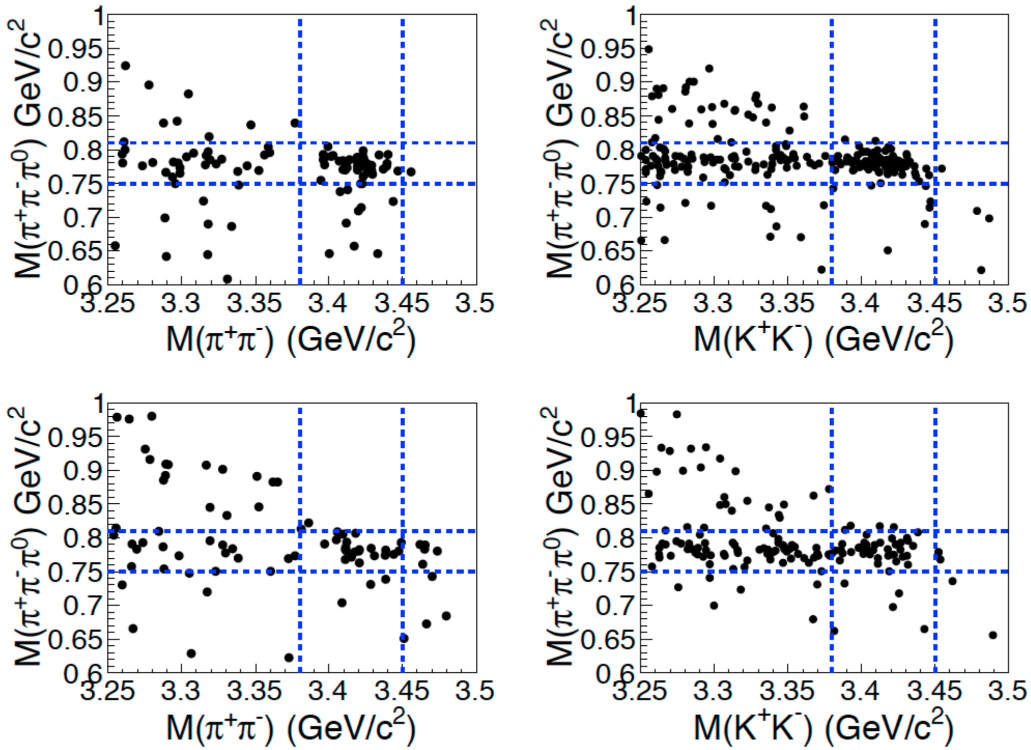
The ω transitions in charmonium

BES-III study

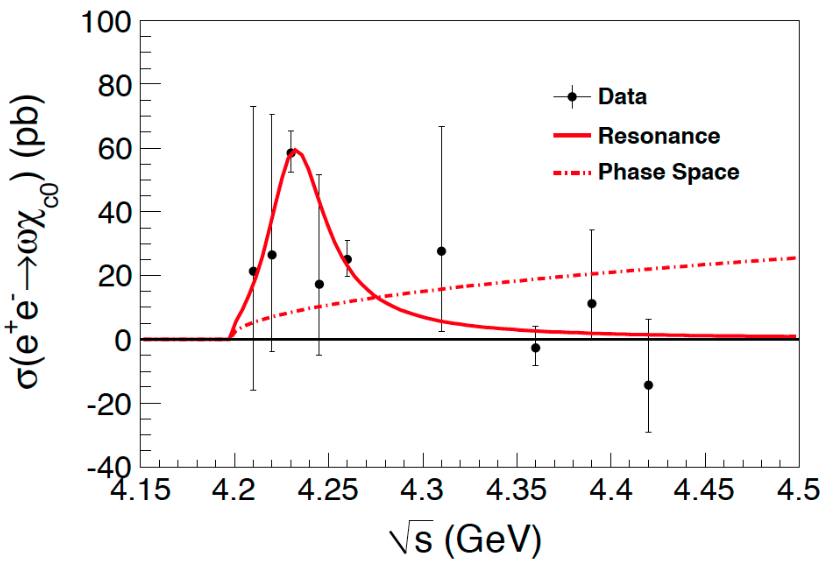
ArXiV:1410.6538

$e^+e^- \rightarrow \omega\chi_{c0}$

With $\chi_{c0} \rightarrow KK, \pi\pi$



ArXiV:1410.6538



Search for X_b at Belle

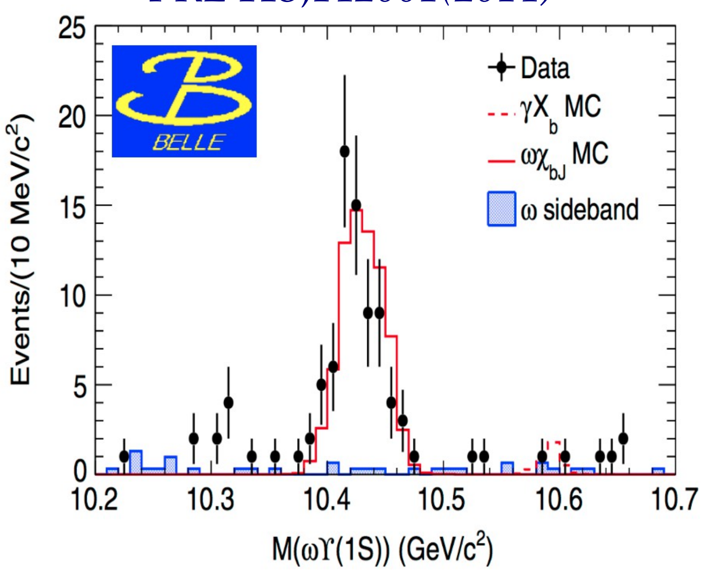
No evidence of a signal of X_b is observed in the region between 10.5 and 10.6: the broad peak at 10.4 is actually a reflection from the $\omega\chi_b(1P)$ transition.

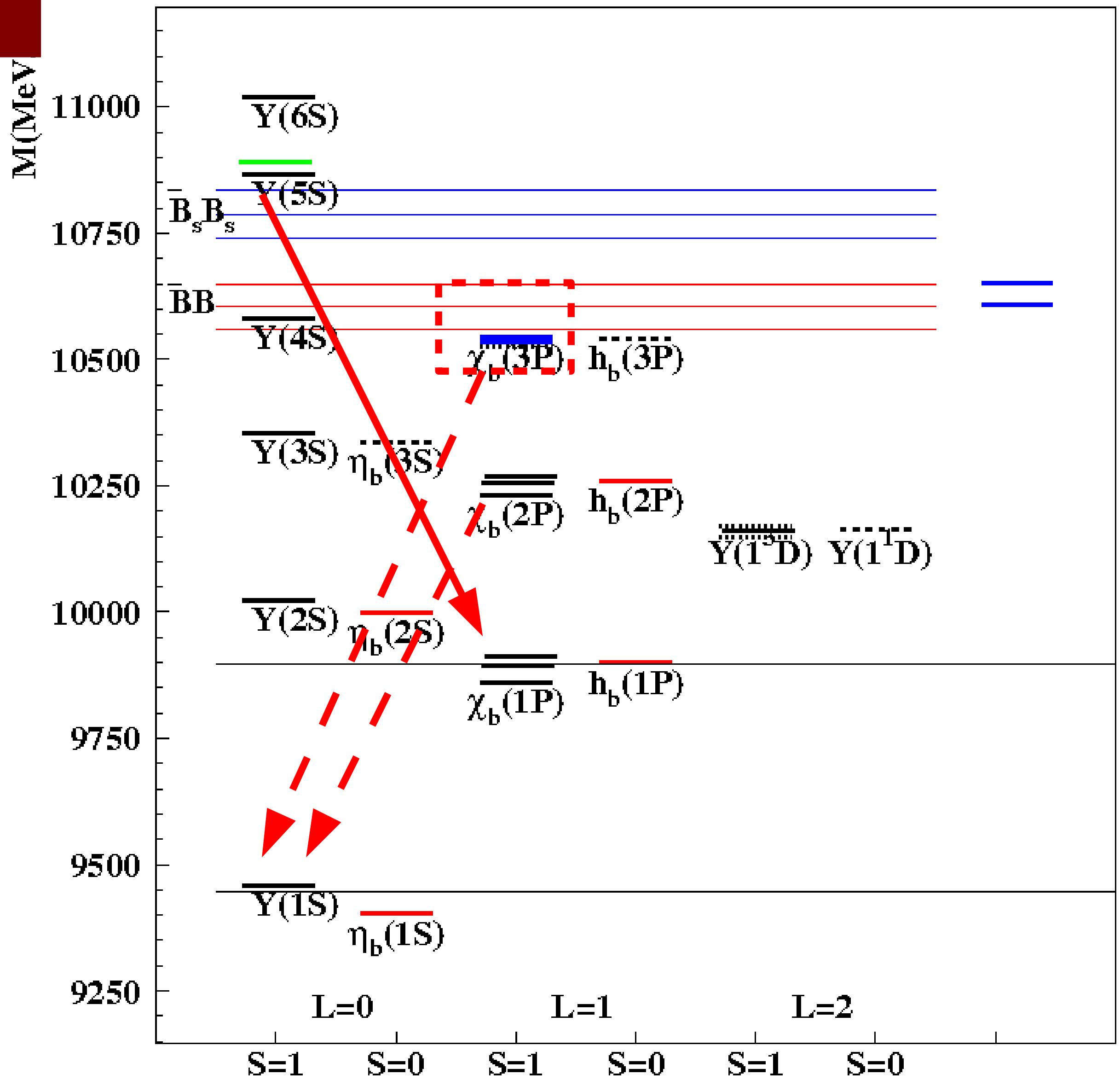
Also, no evidence of radiative transitions to $\chi_b(2P)$.

Upper limits :

$BR(\Upsilon(5S)\to X_b)BR(X_b\to\gamma\Upsilon(1,2S)) < 2.9*10^{-5}$

PRL 113,142001(2014)





Analysis of ωY(1S) transitions on Y(4S) dataset is under way. Results will be available soon

The η transitions

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

Babar *PRD78,112002 (2008)*

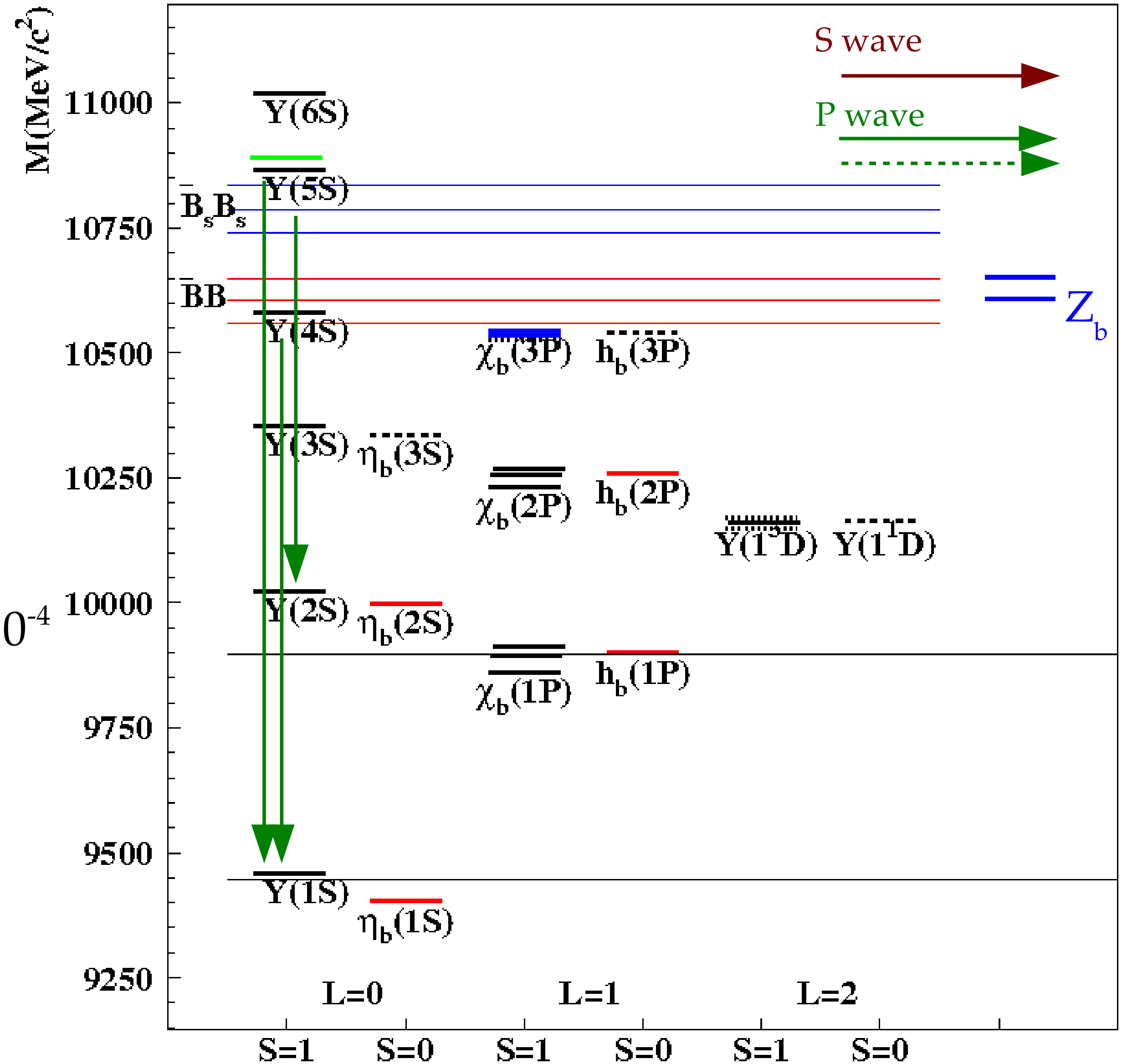
$B(\Upsilon(4S) \to \eta\Upsilon(1S))$
$= (1.96 \pm 0.06 \pm 0.09) \times 10^{-4}$
$= 2.5 \times B(\Upsilon(4S) \to \pi\pi\Upsilon(1S))$

Belle (preliminary)

$B(\Upsilon(5S) \to \eta\Upsilon(1S)) = (7.3 \pm 1.6 \pm 0.8) \times 10^{-4}$
$= 0.25 \times B(\Upsilon(5S) \to \pi\pi\Upsilon(1S))$

$B(\Upsilon(5S) \to \eta\Upsilon(2S)) = (38 \pm 4 \pm 5) \times 10^{-4}$
$= B(\Upsilon(5S) \to \pi\pi\Upsilon(2S))$

All measured η transitions are P-wave.



The η transitions

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

Babar *PRD78,112002 (2008)*

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

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

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

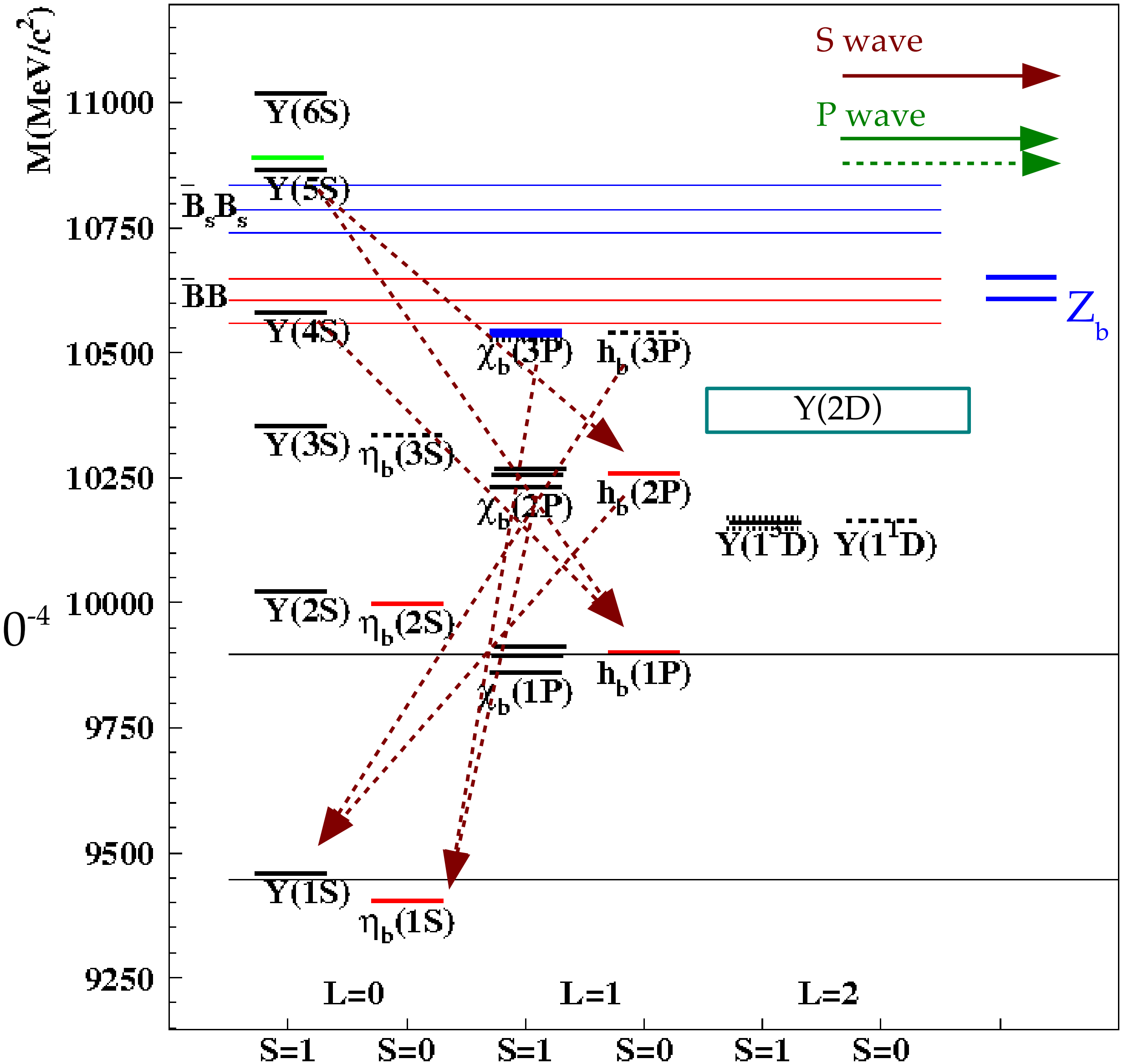
Belle (preliminary)

$B(\Upsilon(5S) \to \eta\Upsilon(1S)) = (7.3 \pm 1.6 \pm 0.8) \times 10^{-4}$

$= 0.25 \times B(\Upsilon(5S) \to \pi\pi\Upsilon(1S))$

$B(\Upsilon(5S) \to \eta\Upsilon(2S)) = (38 \pm 4 \pm 5) \times 10^{-4}$

$= B(\Upsilon(5S) \to \pi\pi\Upsilon(2S))$

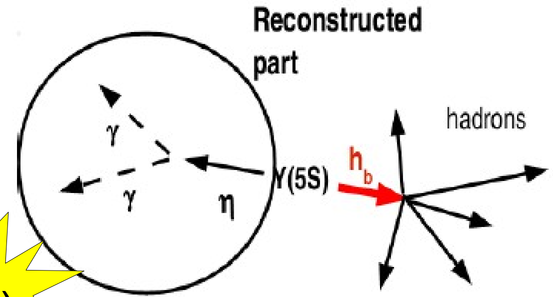


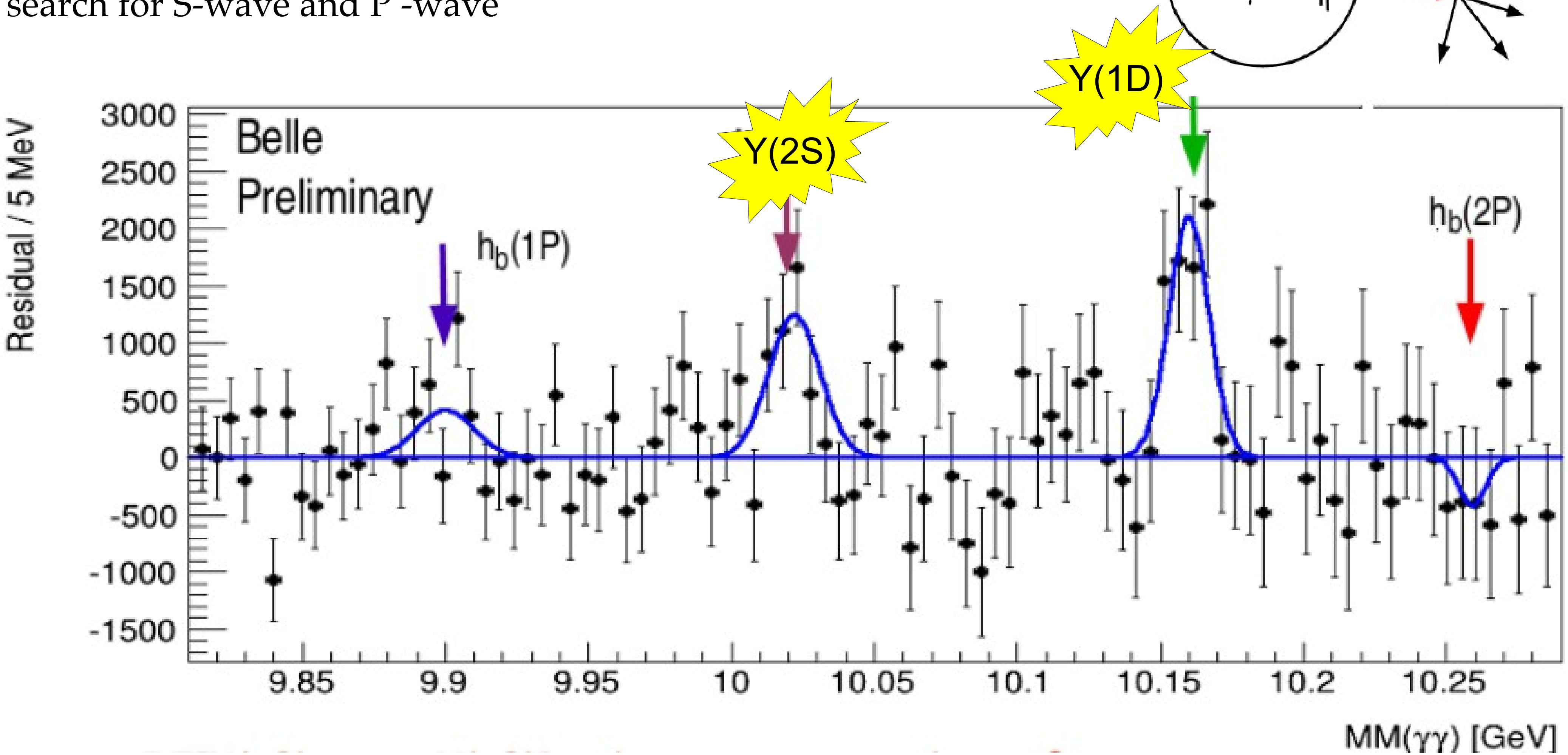
All measured η transitions are P-wave.

Why S-wave transitions are not observed?

The η transitions

In 2014, Belle studied the inclusive η transitions from Υ(5S) to search for S-wave and P -wave





$B(\Upsilon(5S) \to \eta\Upsilon(1D))=(28\pm7\pm4) \times 10^{-4}$ $B(\Upsilon(5S) \to \eta h_b(2P))< 37 \times 10^{-4}$

$B(\Upsilon(5S) \to \eta\Upsilon(2S))=(21\pm7\pm3) \times 10^{-4}$ $B(\Upsilon(5S) \to \eta h_b(1P))< 33 \times 10^{-4}$

The η transitions

Then, the search for inclusive transitions was extended to Υ(4S)

Babar *PRD78,112002 (2008)*

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

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

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

Belle exclusive analysis:

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

$= 0.25 \times B(\Upsilon(5S) \rightarrow \pi\pi\Upsilon(1S))$

$B(\Upsilon(5S) \rightarrow \eta\Upsilon(2S))=(38\pm4\pm5) \times 10^{-4}$

$= B(\Upsilon(5S) \rightarrow \pi\pi\Upsilon(2S))$

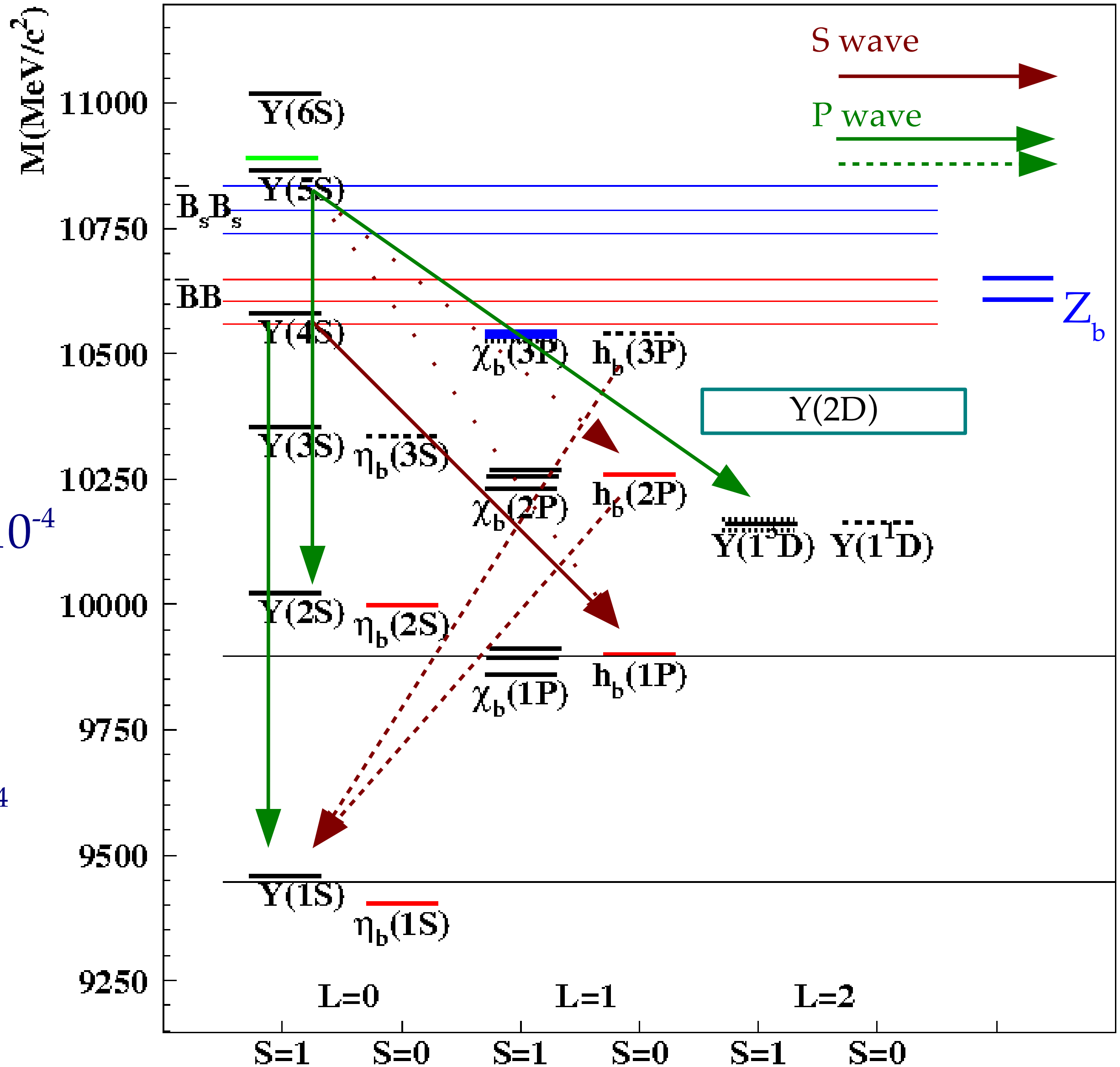
Belle inclusive analysis:

$B(\Upsilon(5S) \rightarrow \eta\Upsilon(1D))=(28\pm7\pm4) \times 10^{-4}$

$B(\Upsilon(5S) \rightarrow \eta\Upsilon(2S))=(21\pm7\pm3) \times 10^{-4}$

$B(\Upsilon(5S) \rightarrow \eta h_b(2P))< 37 \times 10^{-4}$

$B(\Upsilon(5S) \rightarrow \eta h_b(1P))< 33 \times 10^{-4}$



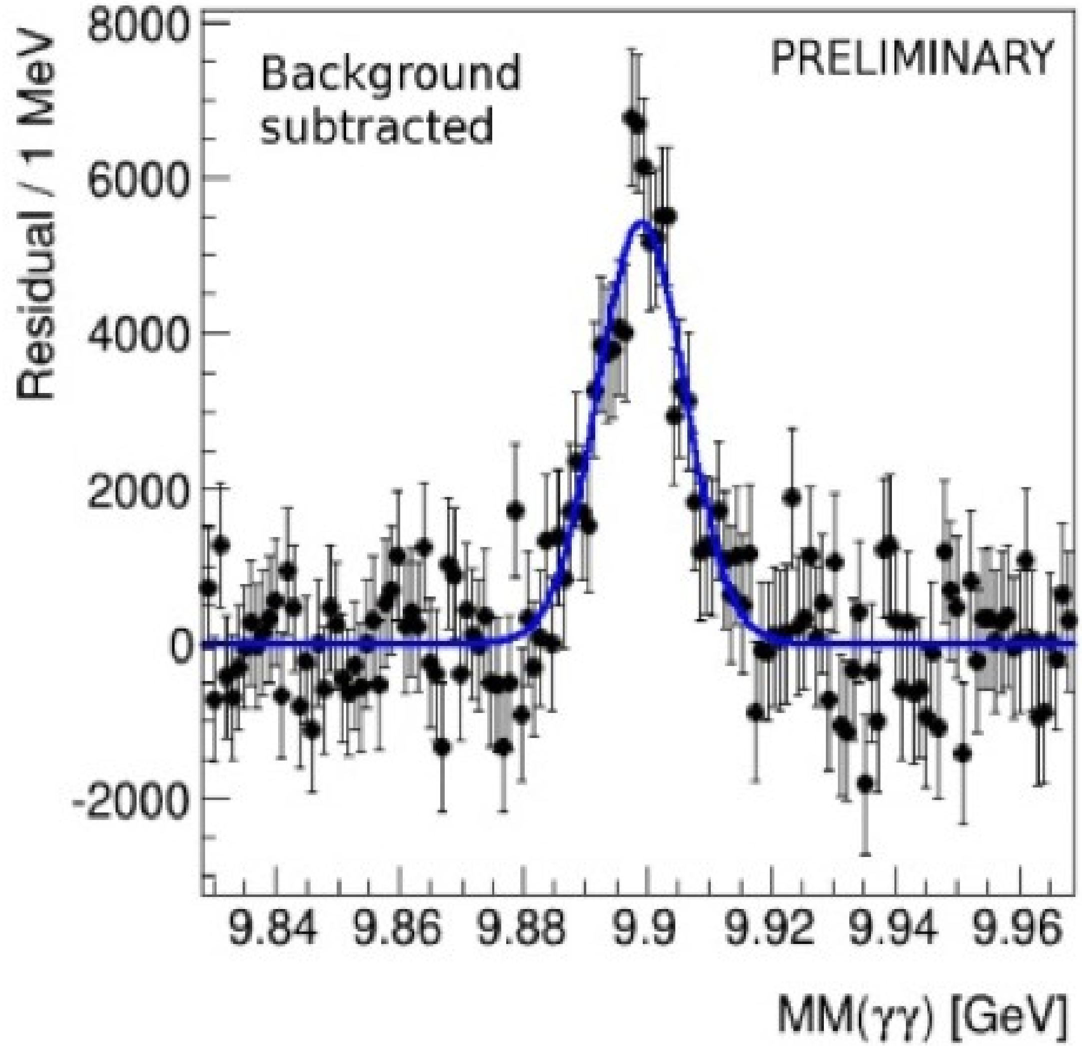
The largest Υ(4S) transition to lower states !!!

Then, the search for inclusive transitions was extended to Υ(4S)

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 exclusive analysis:
$B(\Upsilon(5S) \to \eta\Upsilon(1S))=(7.3\pm1.6\pm0.8)\times 10^{-4}$
$= 0.25 \times B(\Upsilon(5S) \to \pi\pi\Upsilon(1S))$
$B(\Upsilon(5S) \to \eta\Upsilon(2S))=(38\pm4\pm5)\times 10^{-4}$
$= B(\Upsilon(5S) \to \pi\pi\Upsilon(2S))$

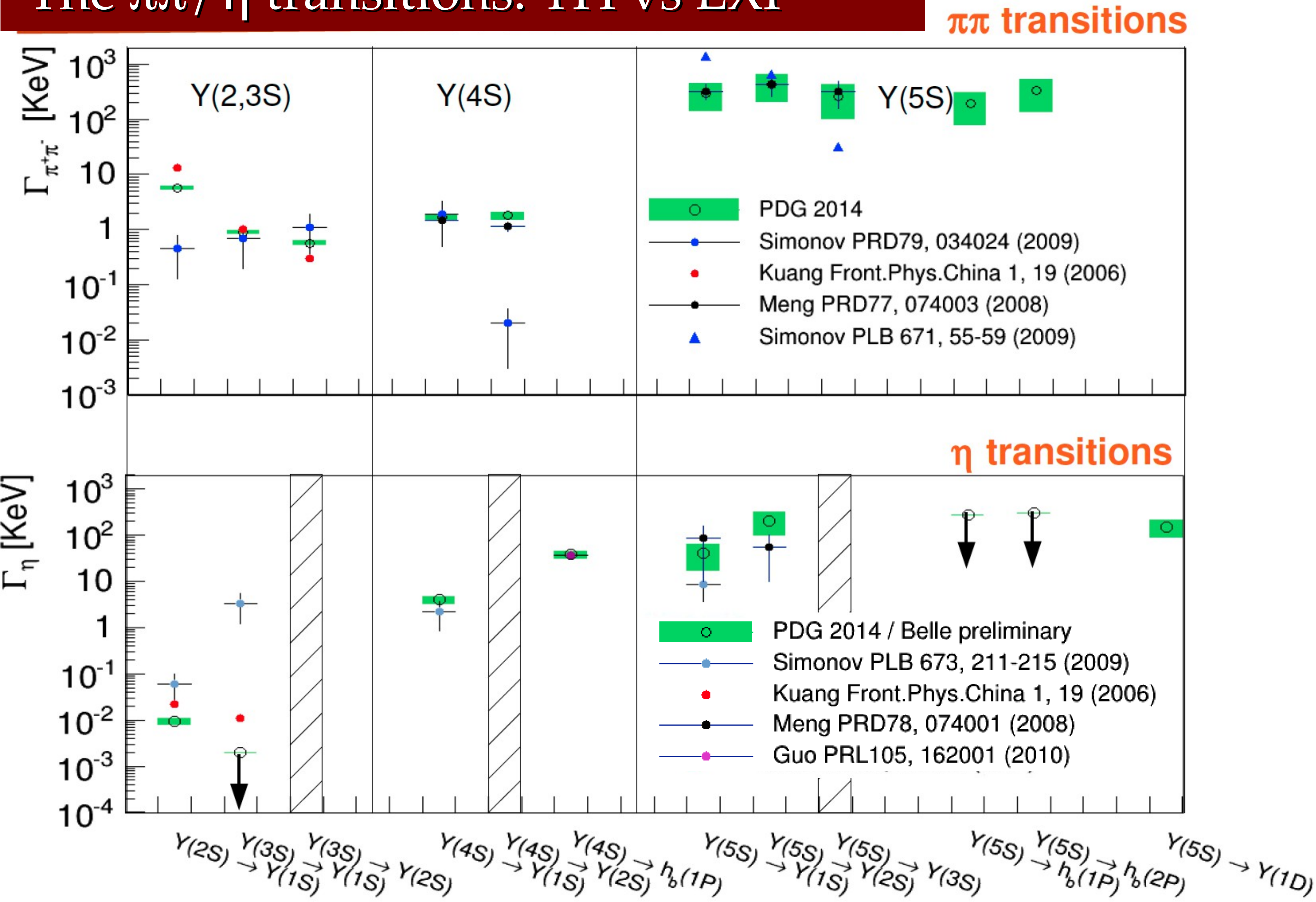
Belle inclusive analysis:
$B(\Upsilon(5S) \to \eta\Upsilon(1D))=(28\pm7\pm4)\times 10^{-4}$
$B(\Upsilon(5S) \to \eta\Upsilon(2S))=(21\pm7\pm3)\times 10^{-4}$
$B(\Upsilon(5S) \to \eta h_b(2P)) < 37\times 10^{-4}$
$B(\Upsilon(5S) \to \eta h_b(1P)) < 33\times 10^{-4}$



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

Only one theory prediction: Guo et al, PRL105,162001(2010) : $\sim 10^{-3}$

The ππ / η transitions: TH vs EXP



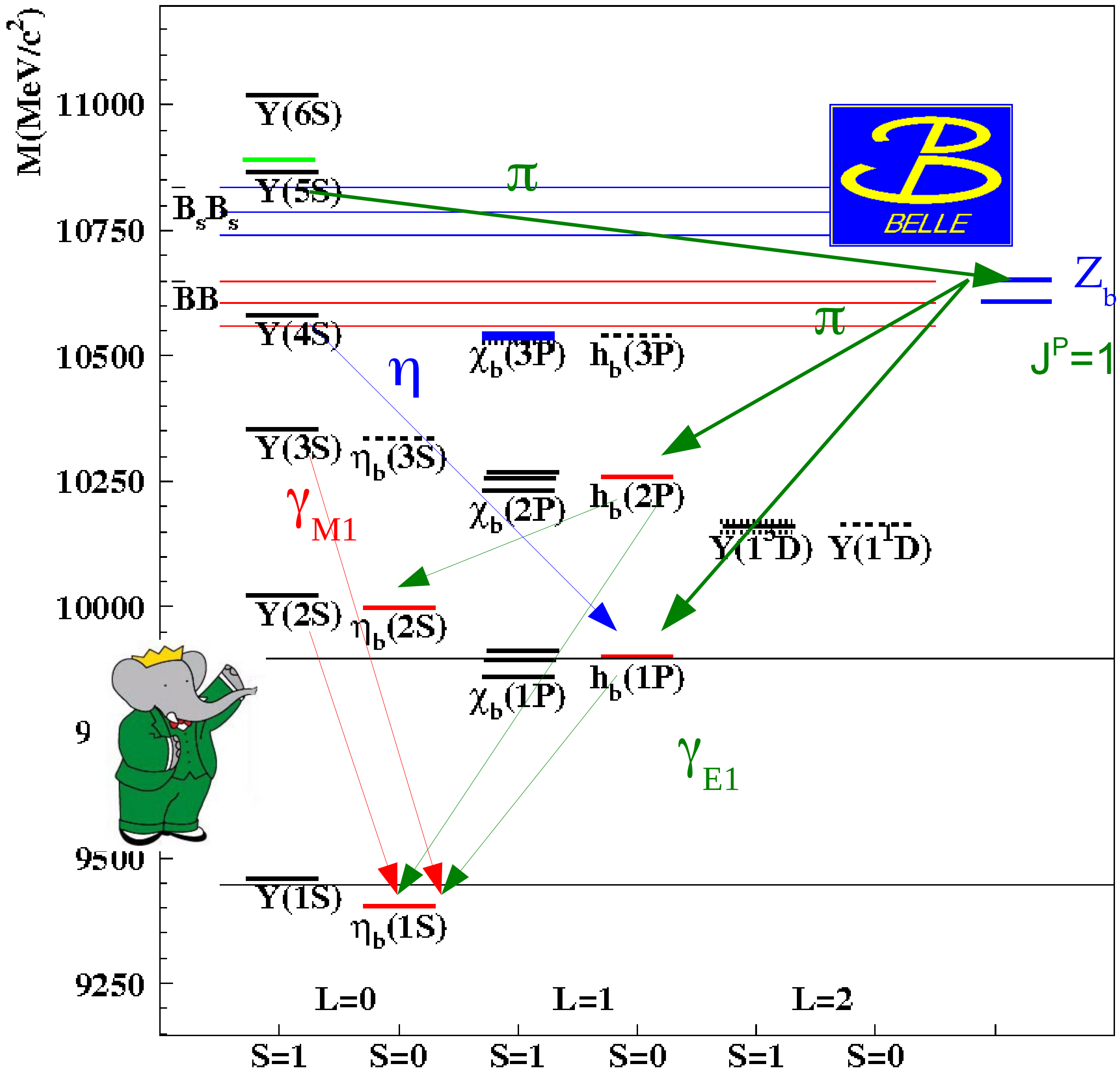
A new pathway to η_b

5 amazing years for bottomonium spectroscopy:

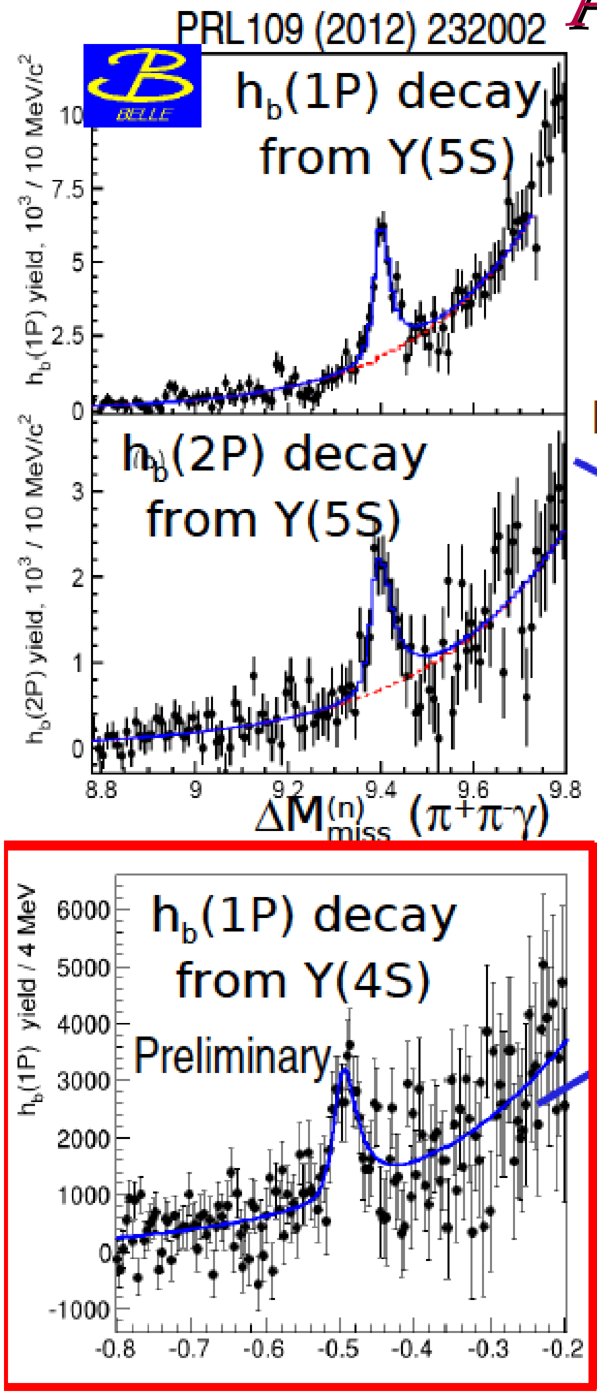
- 2008 Discovery of η_b(Babar) via M1 transitions from Y(2,3S)

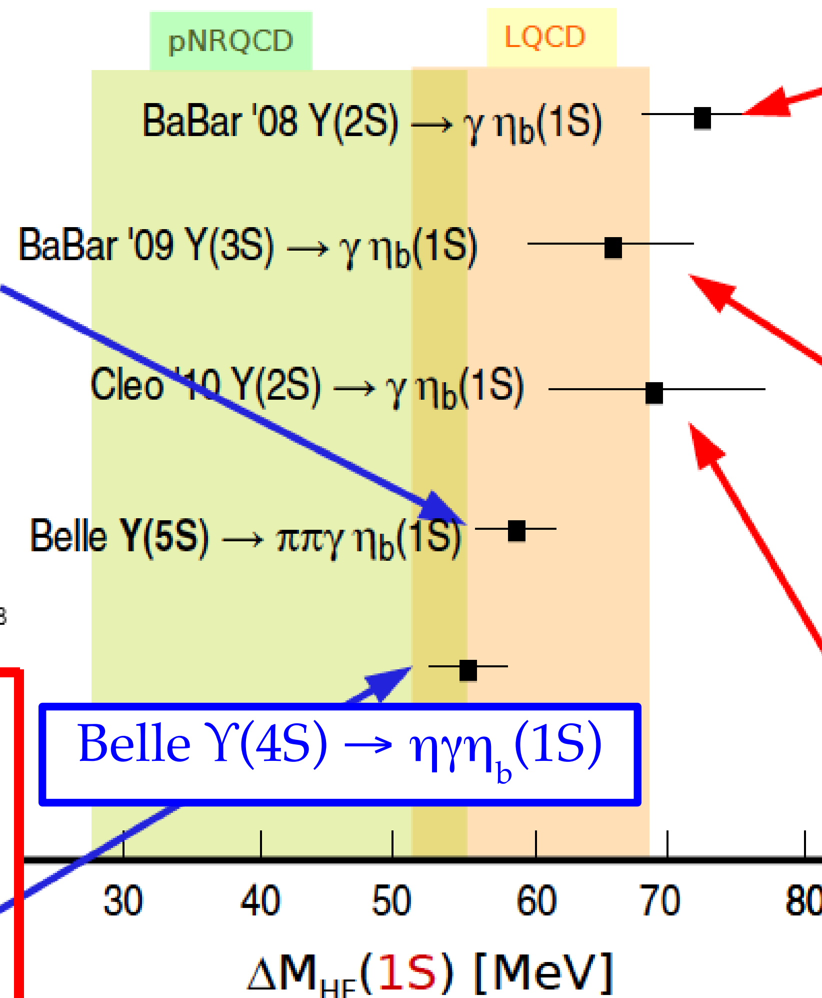
- 2011-2: Discovery of the triple cascade (Belle): $\Upsilon(5S) \to Z_b \to h_b \to \eta_b$

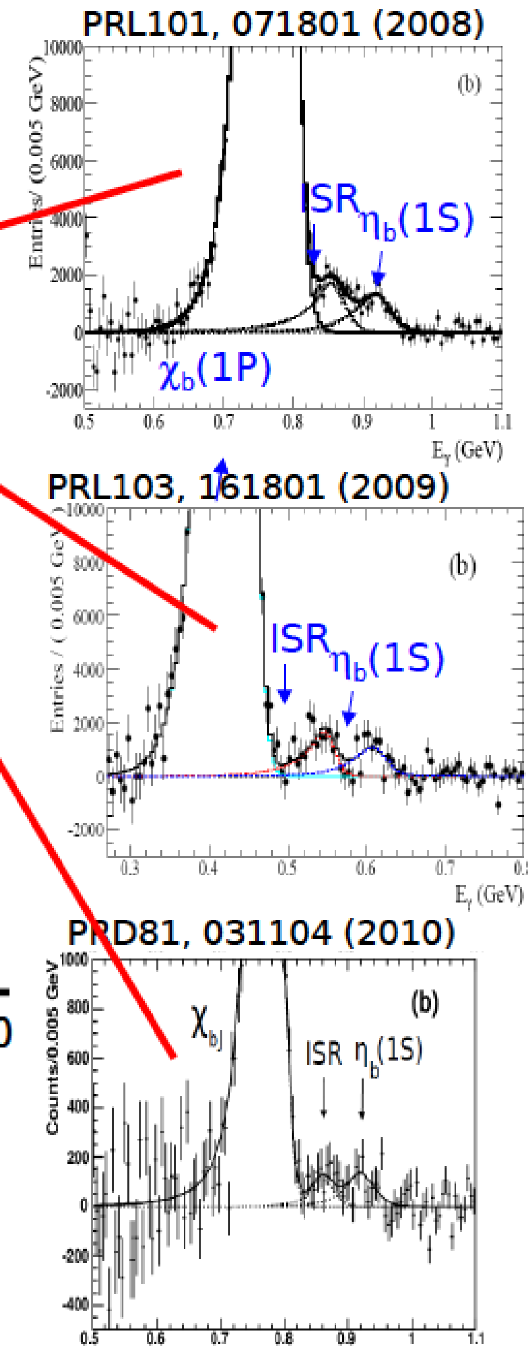
- 2014: Discovery of the $\Upsilon(4S) \to \eta h_b$ transition (Belle)



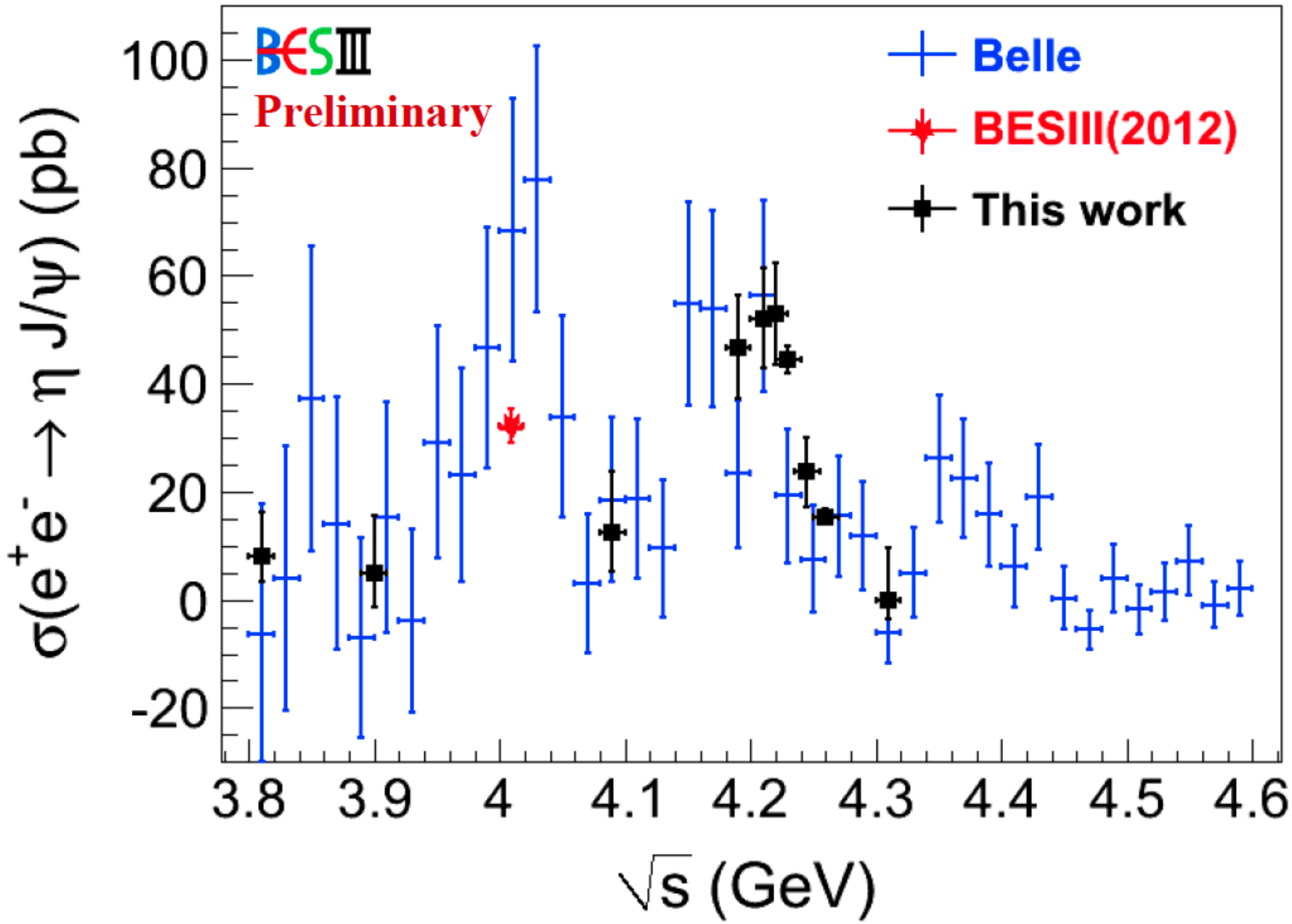
A new pathway to η_b







The η transitions in charmonium



- good agreement with previous results and more precise
- cross sections peaks at ~ 4.2 GeV
- higher energy points' analysis on going

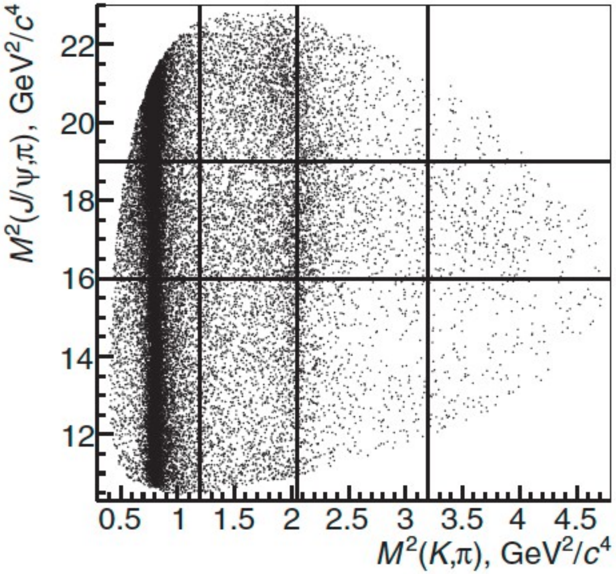
A new Z_c from Belle

PRD 90, 112009 (2014)

$Z^{\pm}(4200) \rightarrow \psi\pi^{\pm}$

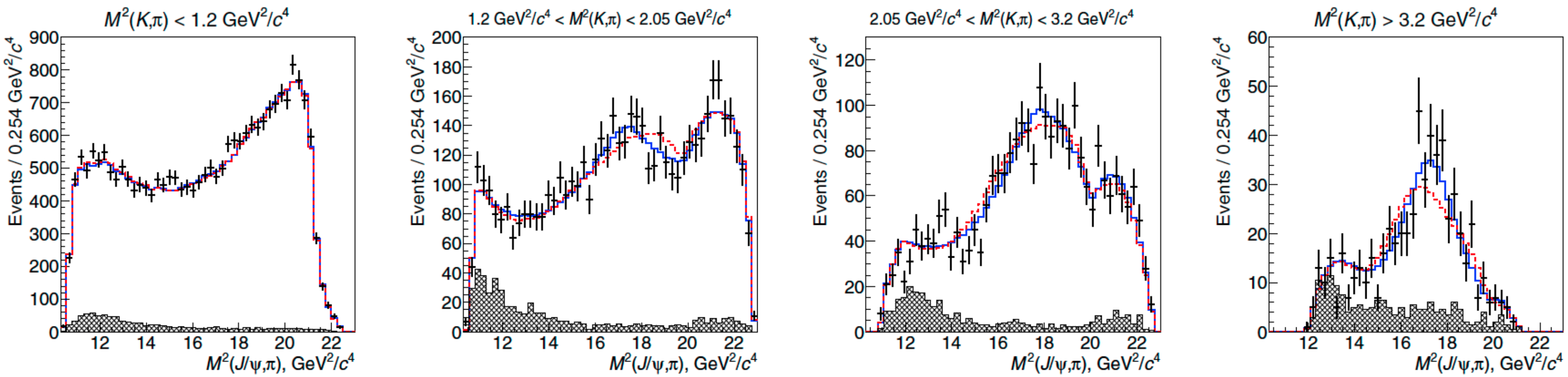
- Search in $B^0 \rightarrow J/\psi K^+\pi^-$
- 4D amplitude analysis for $(M^2_{K\pi},\ M^2_{J/\psi\pi},\ \theta_{J/\psi},\ \phi)$
- decay model includes 10 states of K^*
  $(K_0^*(800),\ K^*(892),\ K^*(1410),\ K_0^*(1430),\ K_2^*(1430),$
  $K^*(1680),\ K_3^*(1780),\ K_0^*(1950),\ K_2^*(1980),\ K_4^*(2045))$
  and $Z_c(4430)^+$

  $\Rightarrow$ new decay channel $Z_c(4430)^+ \rightarrow J/\psi\pi^+$
- and a search with additional Z_c^+



$J^P=1^+$, sig=6.2 σ

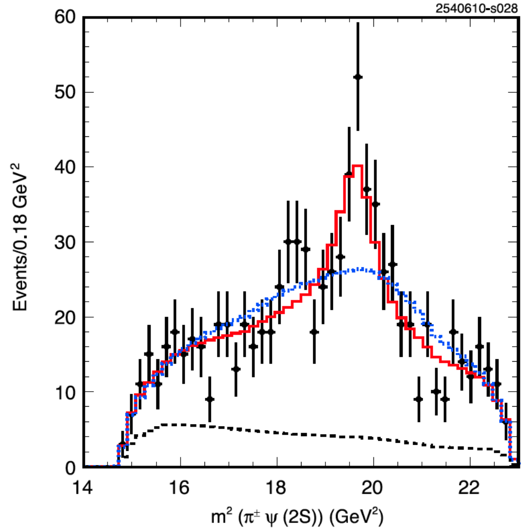
$$M = 4196^{+31+17}_{-29-13}\ \mathrm{MeV}/c^2,\ \Gamma = 370^{+70+70}_{-70-132}\ \mathrm{MeV}$$

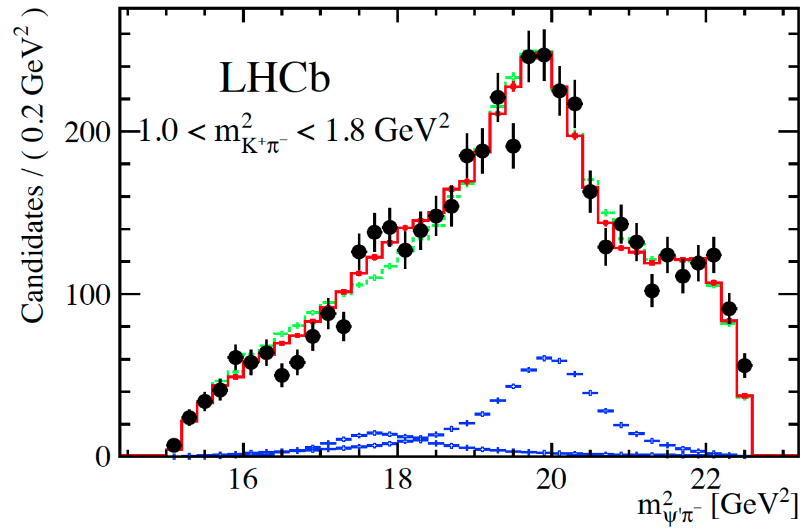


Z_c's in B decays

- $Z_c(4430) \rightarrow \psi' \pi$

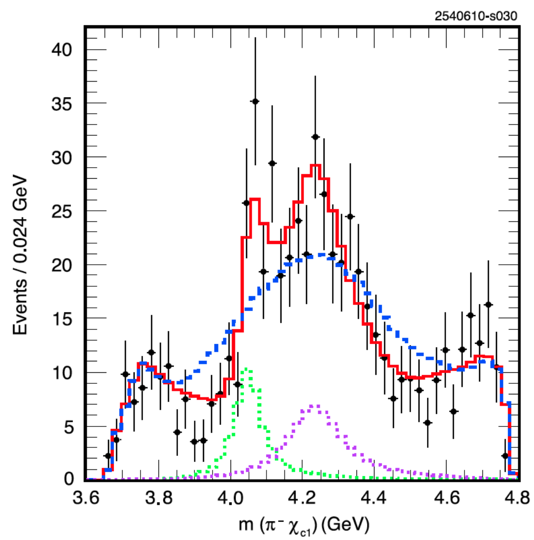
Belle:PRL 100(2008)142001
LHB:PRL 112(2014)222002





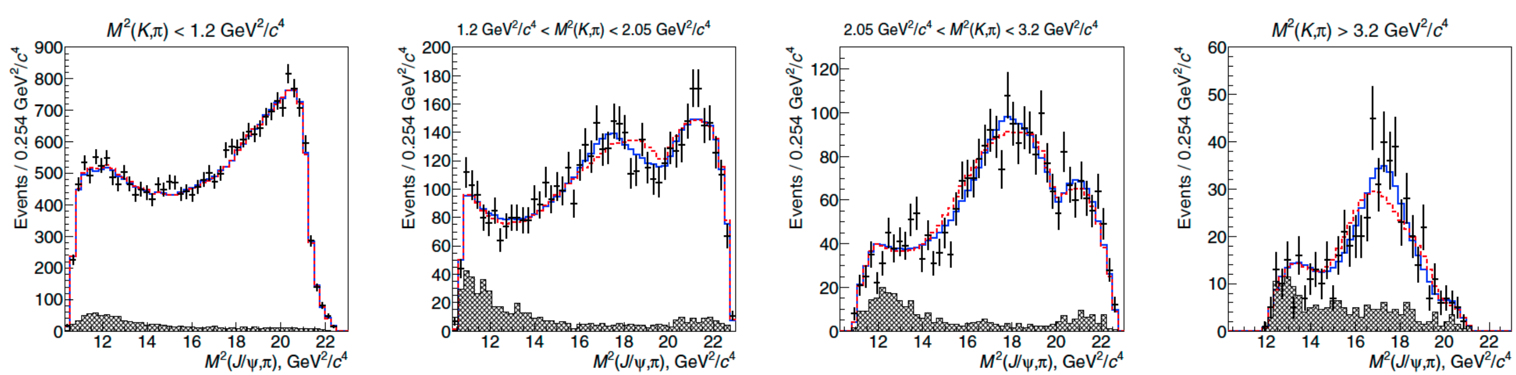
- $Z_c(4050) \rightarrow \chi_{c1}\pi$
- $Z_c(4250) \rightarrow \chi_{c1}\pi$

Belle:PRD 78, 072004(2008)



- $Z_c(4200) \rightarrow \psi\pi$

PRD 90, 112009 (2014)



Z_c : ψ(nS) vs B decays

BES-III results

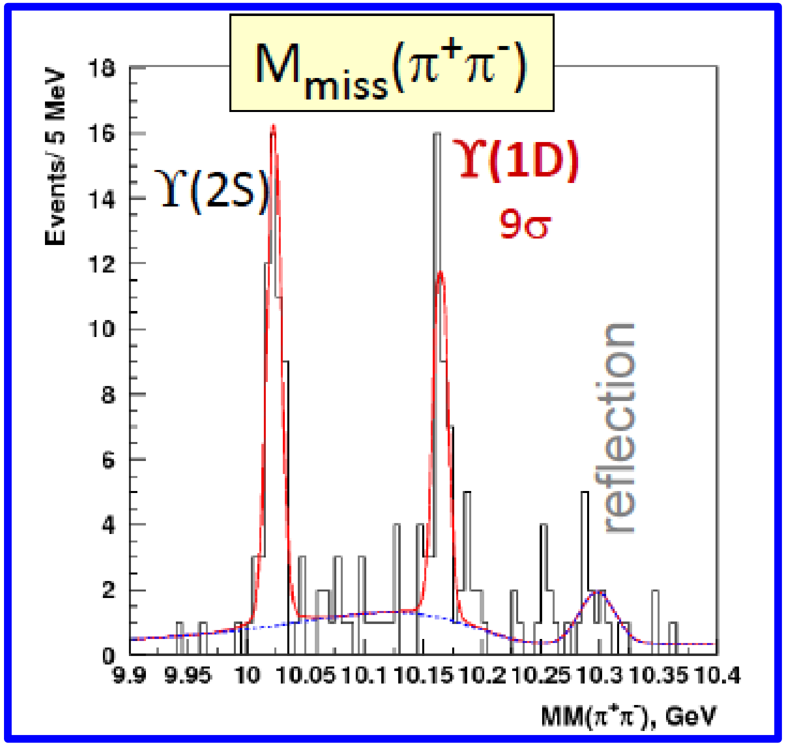
$Z_c(3900)^{\pm}$	3899.0±3.6 ±4.9	46±10 ±20	$\pi^{\pm}J/\psi$	$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^0$	3894.8±2.3±2.7	29.6±8.2±8.2	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3885)^{\pm}$	3883.9±1.5±4.2 [single D tag] 3884.3±1.2±1.5 [double D tag]	24.8±3.3±11.0 [single D tag] 23.8±2.1±2.6 [double D tag]	D^0D^{*-} D^-D^{*0}	$e^+e^- \to \pi^+ D^0 D^{*-}$ $e^+e^- \to \pi^+ D^- D^{*0}$
$Z_c(4020)^{\pm}$	4022.9±0.8 ±2.7	7.9±2.7 ±2.6	$\pi^{\pm}h_c$	$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^0$	4023.9±2.2 ±3.8	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^{\pm}$	4026.3±2.6±3.7	24.8±5.6±7.7	$D^{*0}D^{*-}$	$e^+e^- \to \pi^+(D^* \bar{D}^*)^-$

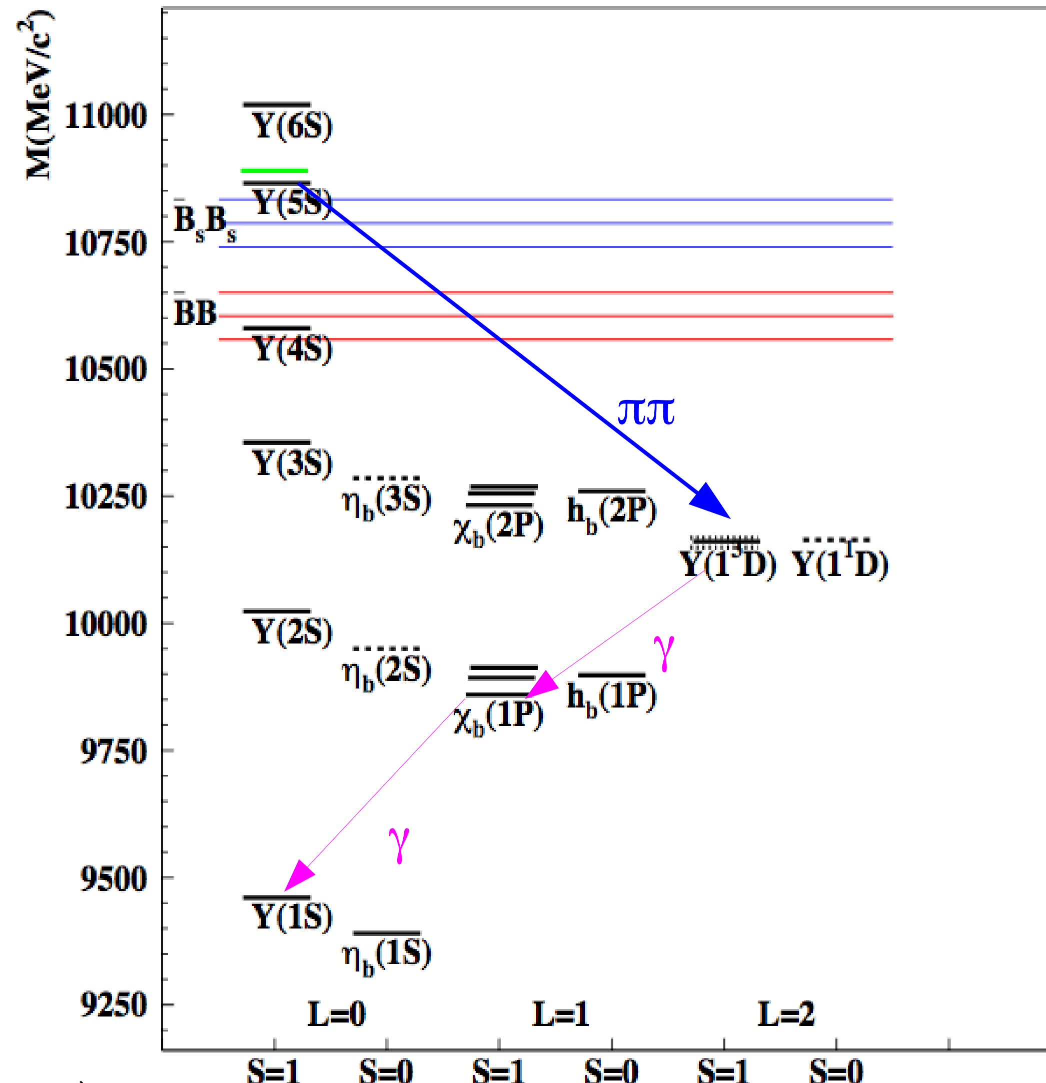
Belle results

$Z_c(4050)^{\pm}$	4051^{+24}_{-40}	82^{+50}_{-28}	$\pi^{\pm}\chi_{c1}$	B decays
$Z_c(4200)^{\pm}$	4196^{+31+17}_{-29-13}	$370^{+70+70}_{-70-132}$	$\pi^{\pm}J/\psi$	B decays
$Z_c(4250)^{\pm}$	4248^{+190}_{-50}	177^{+320}_{-70}	$\pi^{\pm}\chi_{c1}$	B decays
$Z_c(4430)^{\pm}$	4485^{+40}_{-25}	200^{+50}_{-60}	$\pi^{\pm}\psi'$	B decays

Bottomonium D waves

First observations from Υ(3S):
CLEO *PRD70,03200 (2010)*
BABAR *PRD82,111102 (2010)*





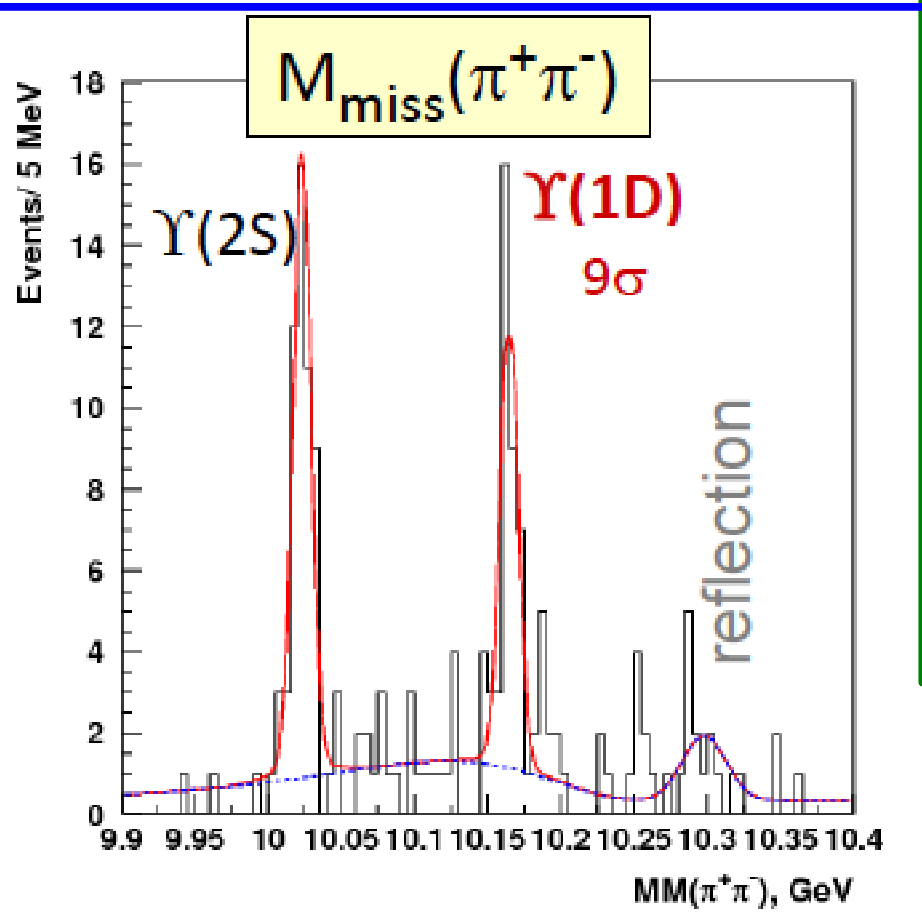
Belle observes 1D both inclusively (PRL108,032001) and exclusively (Proc.EPS-HEP 2013) from Υ(5S). Assuming that:

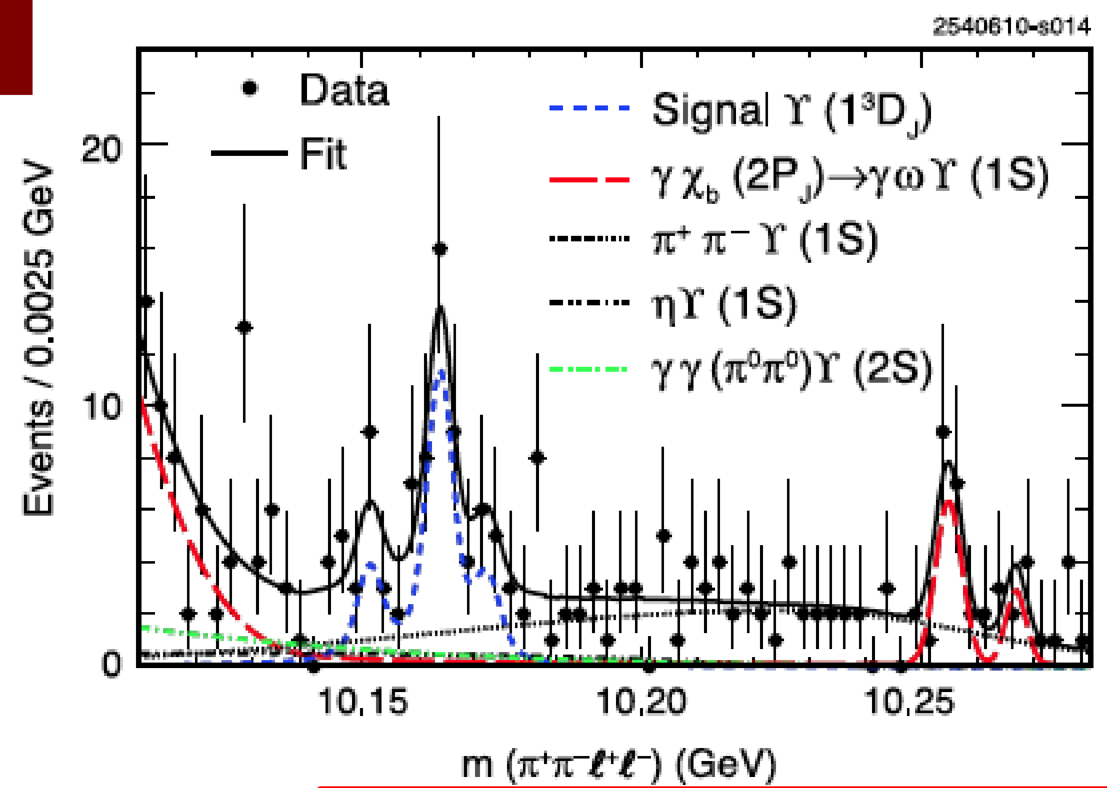
- the J=1,2,3 state is produced with ratios 3:5:7,
- $B(1^3D_J \to \gamma\, 1^3P_{J'})$ from Kwong,Rosner PRD 38, 279 (1998)
- $B(1^3P_{J'} \to \gamma\, \Upsilon(1S))$ from measured values (PDG)

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

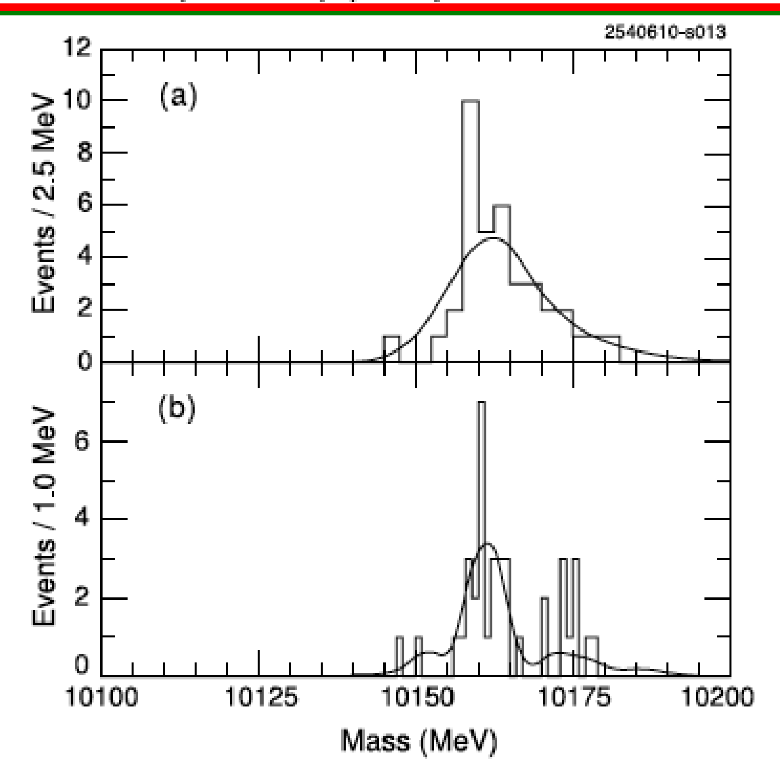




Belle $10164.7 \pm 1.4 \pm 1.0$ MeV

BaBar $10164.5 \pm 0.8 \pm 0.5$ MeV

CLEO $10161.1 \pm 0.6 \pm 1.6$ MeV



Stay tuned on more Belle results on Y(1D)

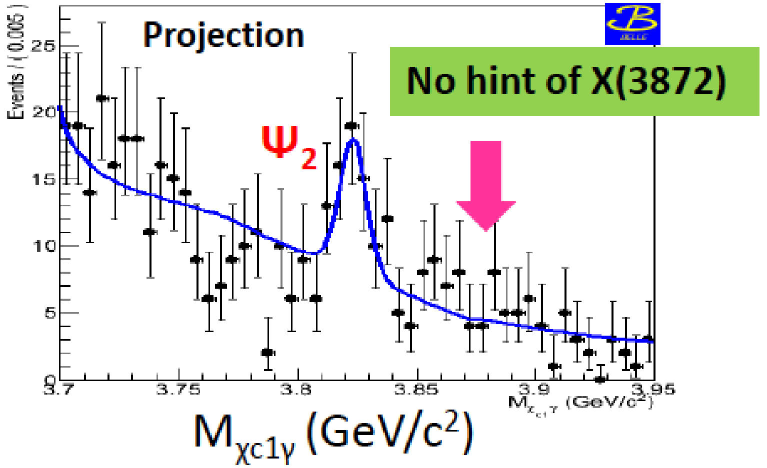
Charmonium D waves

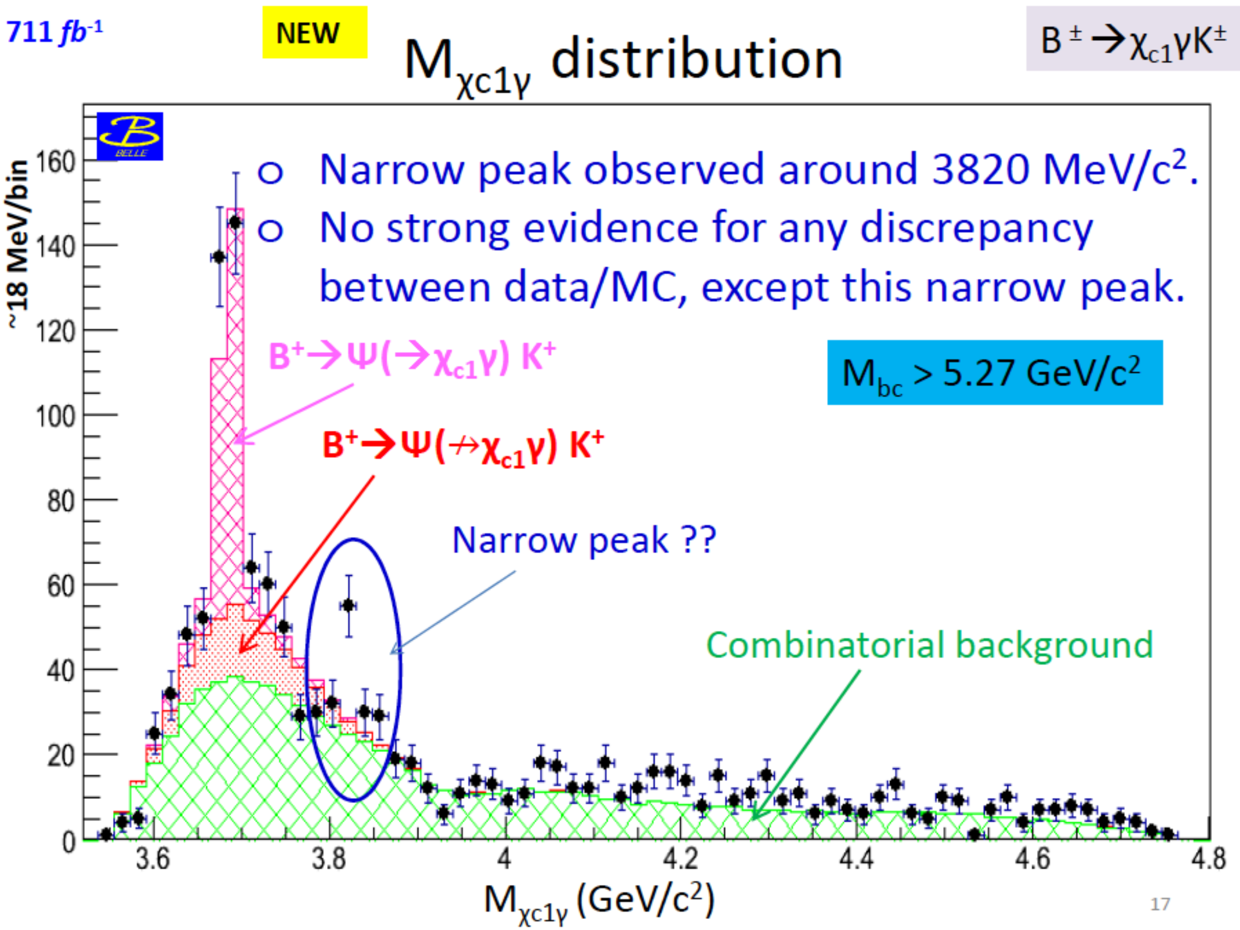
PRL 111,032001(2013)

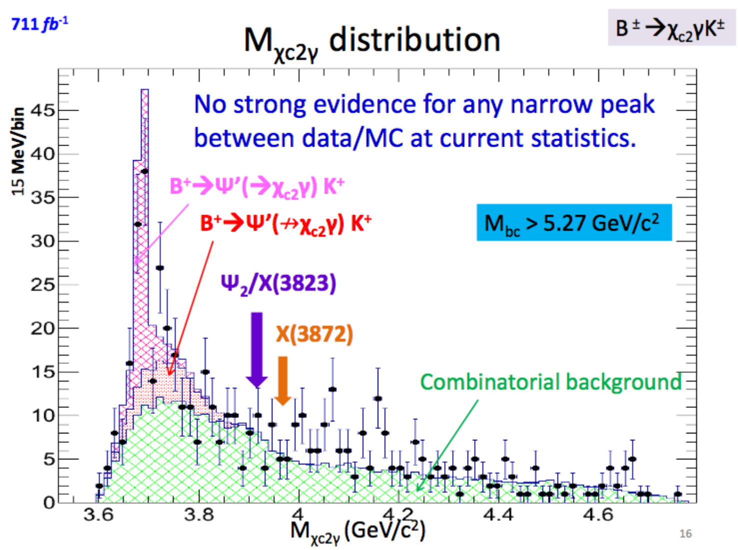
Evidence (3.8 σ) of the $^3D_2$ state of charmonium, in B decays!

$M(^3D_2) = 3823.1 \pm 1.8 \pm 0.7\ MeV/c^2$

X(3872) yield : -0.9±5.1 events



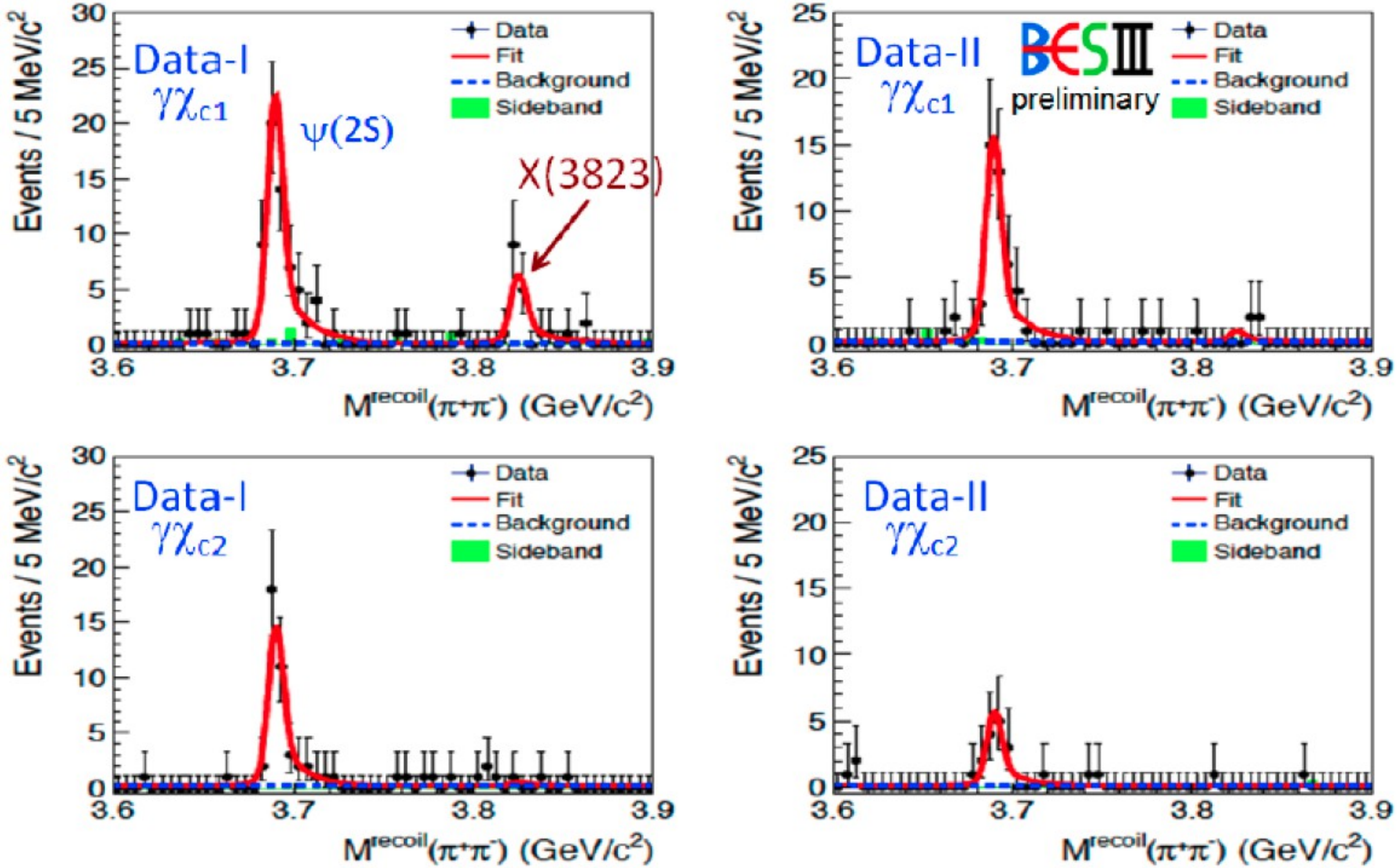




Charmonium D waves

Exclusive evidence of $e^+e^- \rightarrow \pi^+\pi^2\psi'$, $\pi^+\pi^2\psi(1^3D_2)$ at BES-III

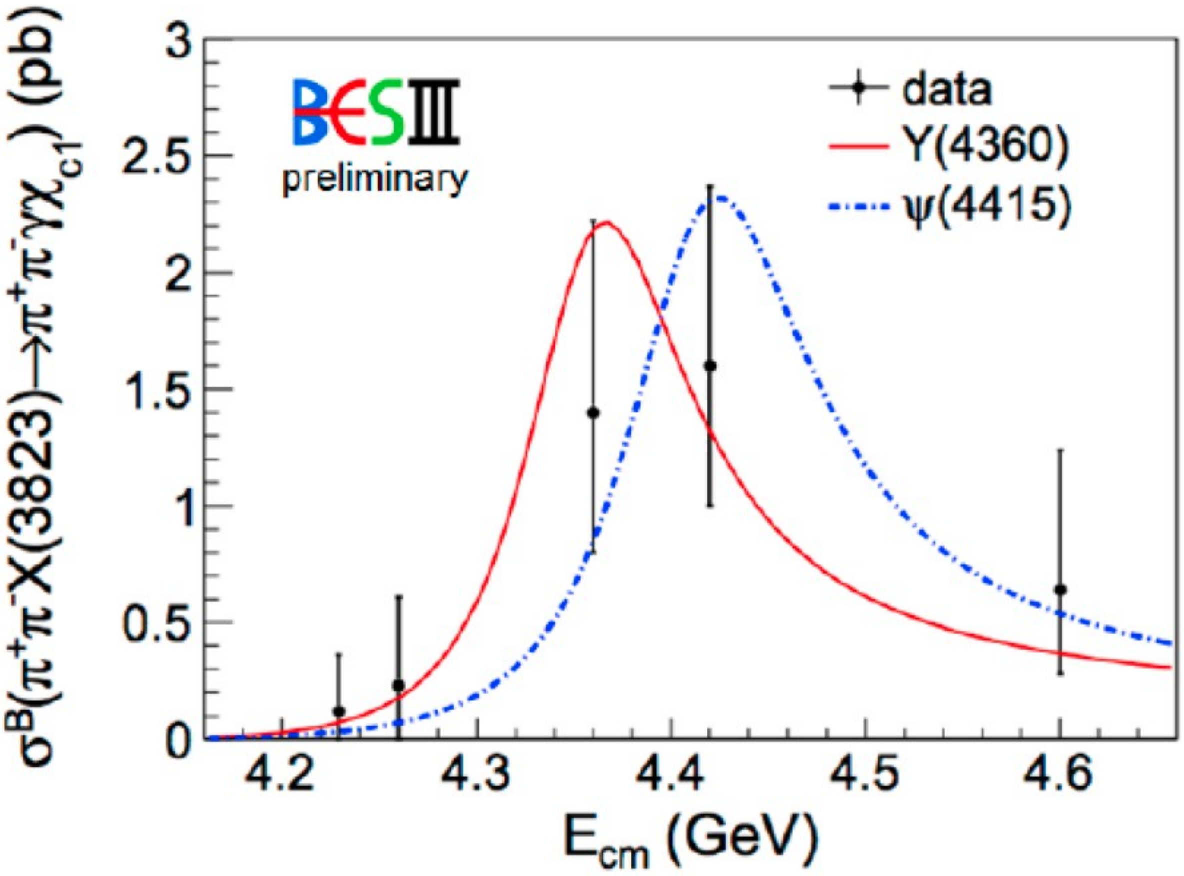
Ecm > 4.35 Ecm = (4.23-4.26)



Analogy with Y(5S) transitions to Y(1D) and Y(2S)?

Charmonium D waves

Exclusive evidence of $e^+e^- \to \pi^+\pi^2\psi'$, $\pi^+\pi^2\psi(1^3D_2)$ at BES-III



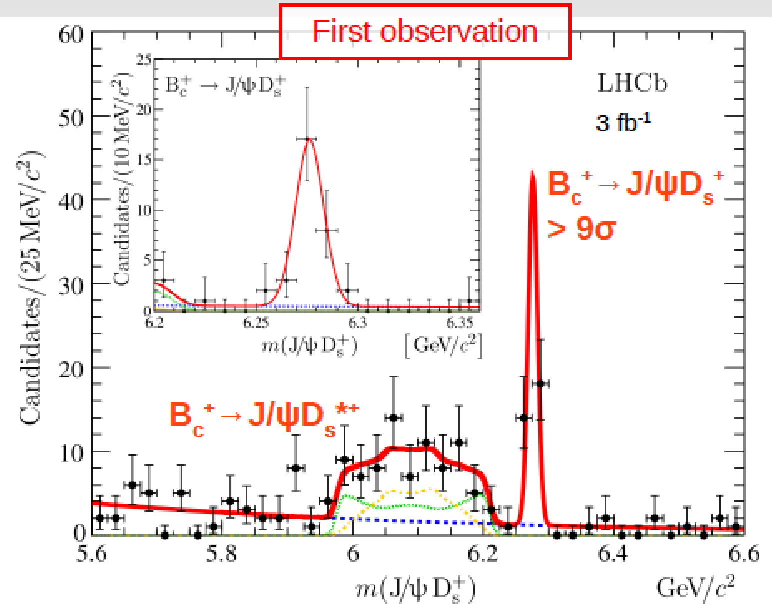
Ψ(4415) or Y(4360) ? Need more statistics

Bc spectroscopy

Most precise mass measurement

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

First observation



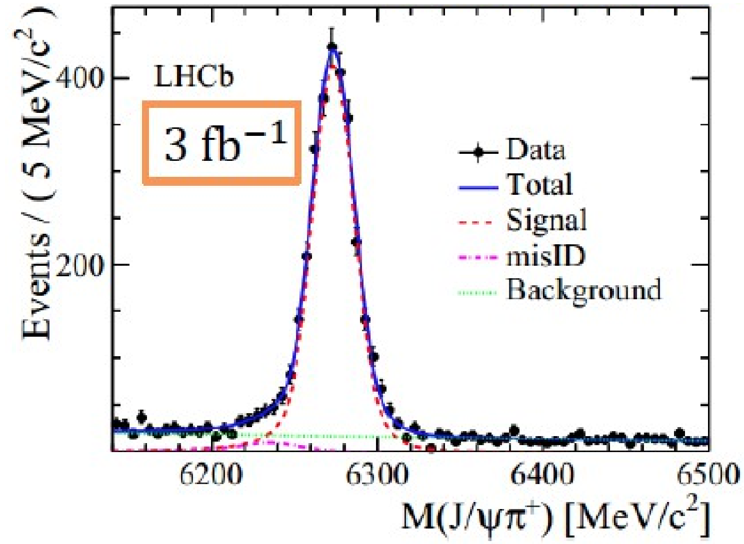
$$m_{B_c^+} = 6276.28 \pm 1.44\,(stat) \pm 0.36\,(syst)\; MeV/c^2$$

LHCb, 3 fb⁻¹, PRD 87 (2013) 112012

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

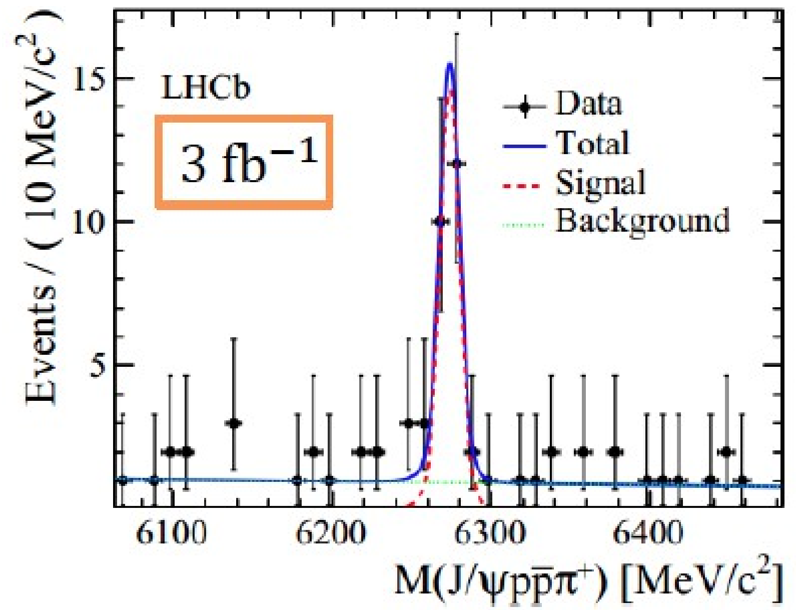
Polyakov Ivan, Moriond QCD, 24 March 2014

Reference transition



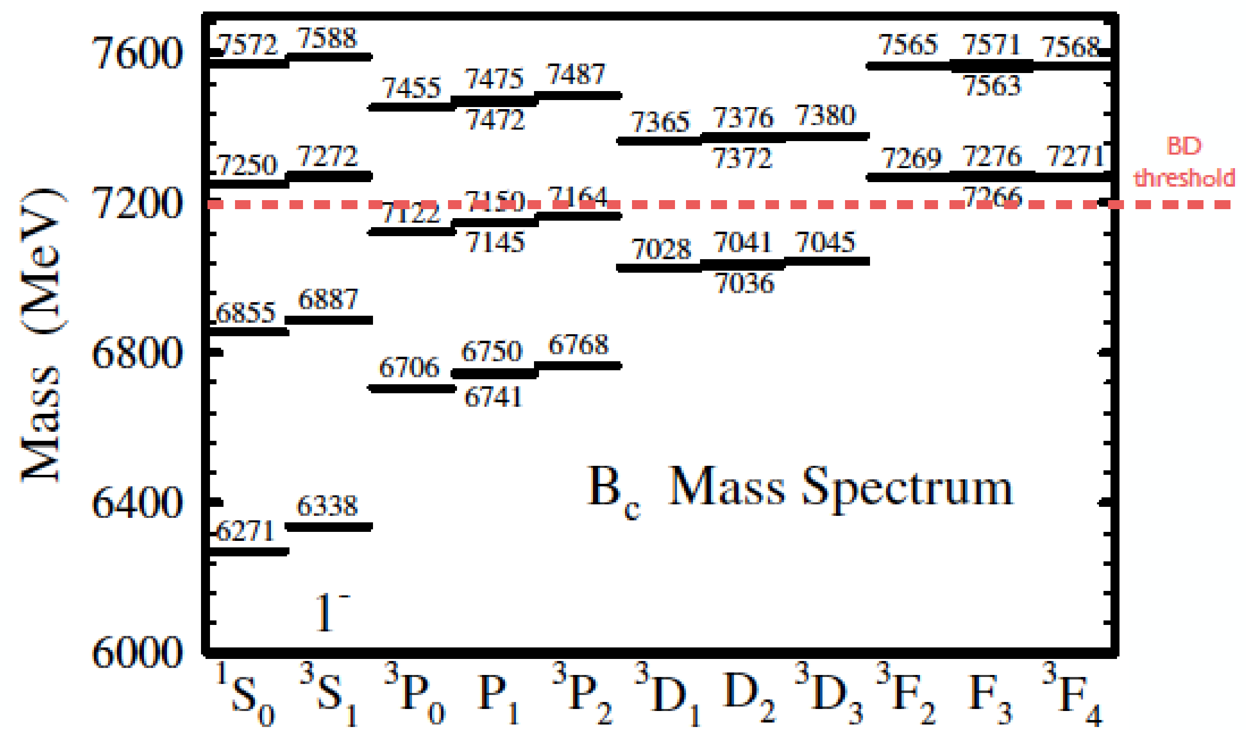
$N_{sig} = 2835 \pm 58$

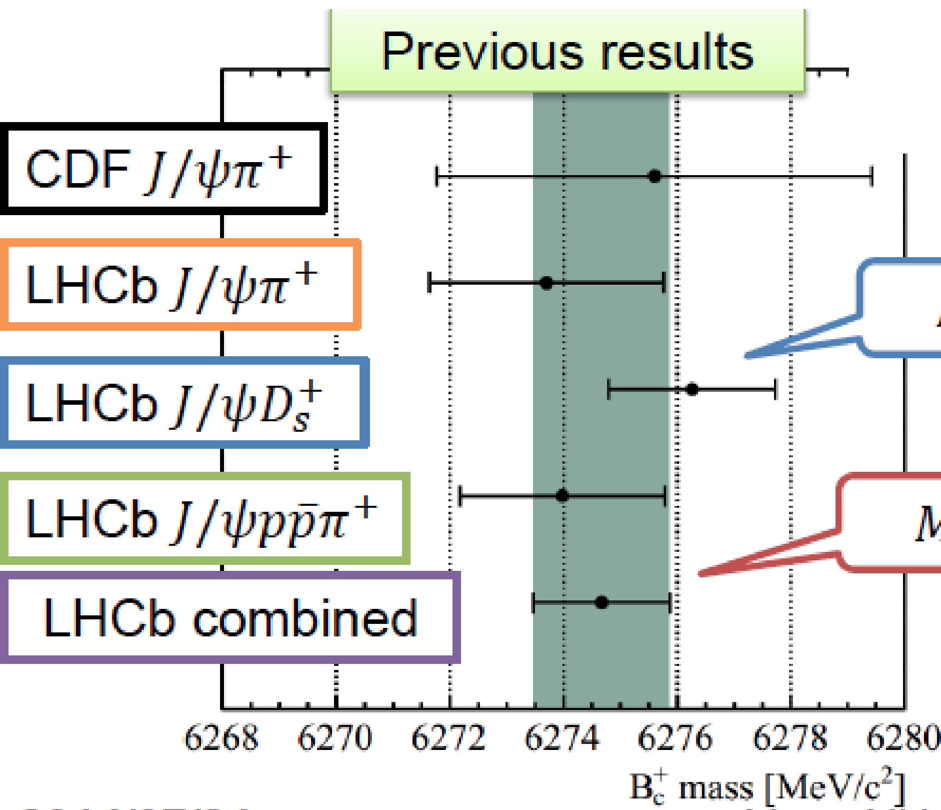
First decay to baryons



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

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

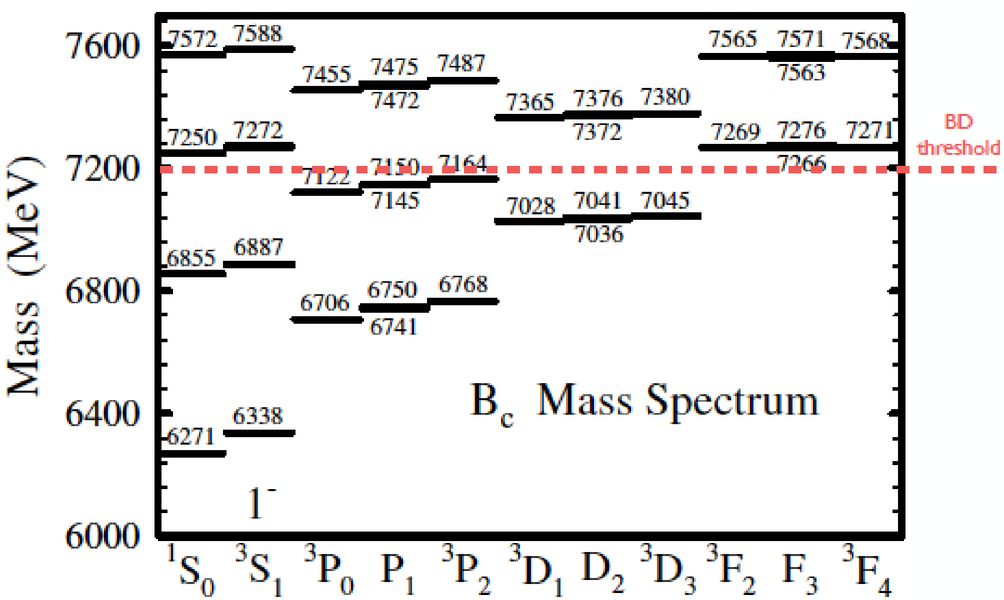
First observation of $B_c(2S)$

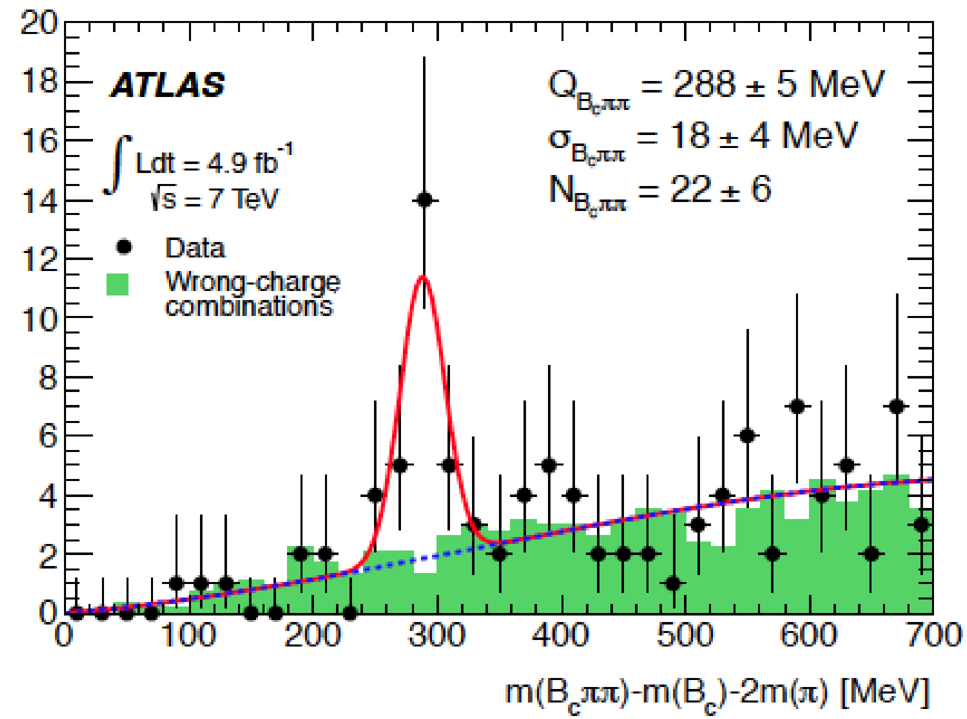
ATLAS detects the Bc decaying to $J/\psi\pi$ mode
Significance (7+8 TeV data) :5.2 sigma

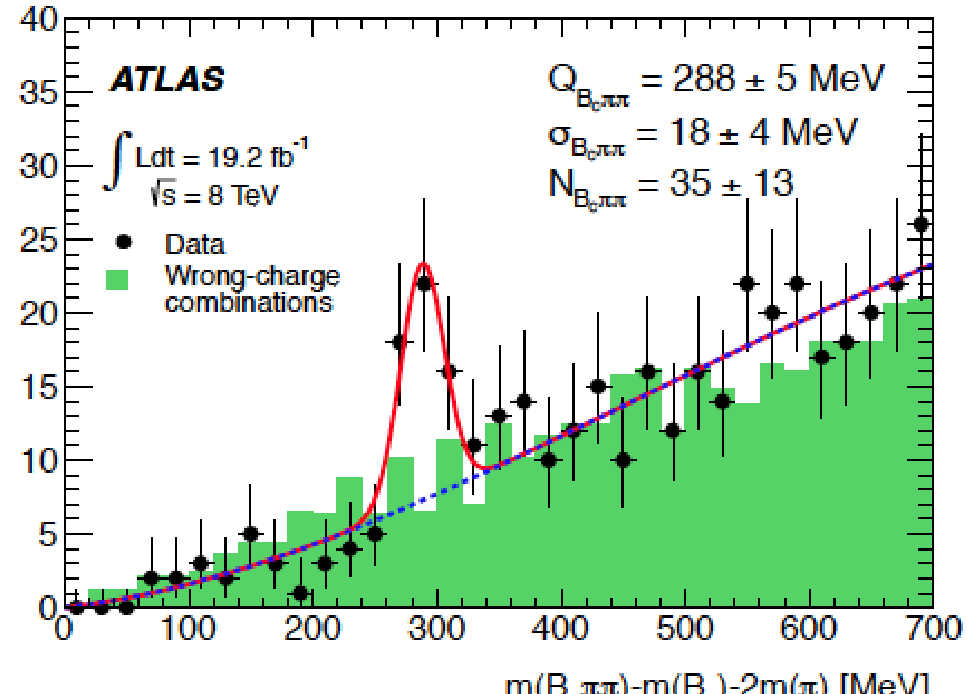
Can be a combination of two transitions:
$B_c(2^1S_0) \to B_c(1^1S_0)\pi\pi$;
$B_c(2^3S_1) \to B_c(1^1S_0)\pi\pi+(\gamma)_{\text{not seen}}$;

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

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







Not confirmed (yet?) by CMS and LHCB

More results on B at LHCB (ArXiV: 1502.02638): Williams in Tuesday Parallel Session**

Heavy Baryons

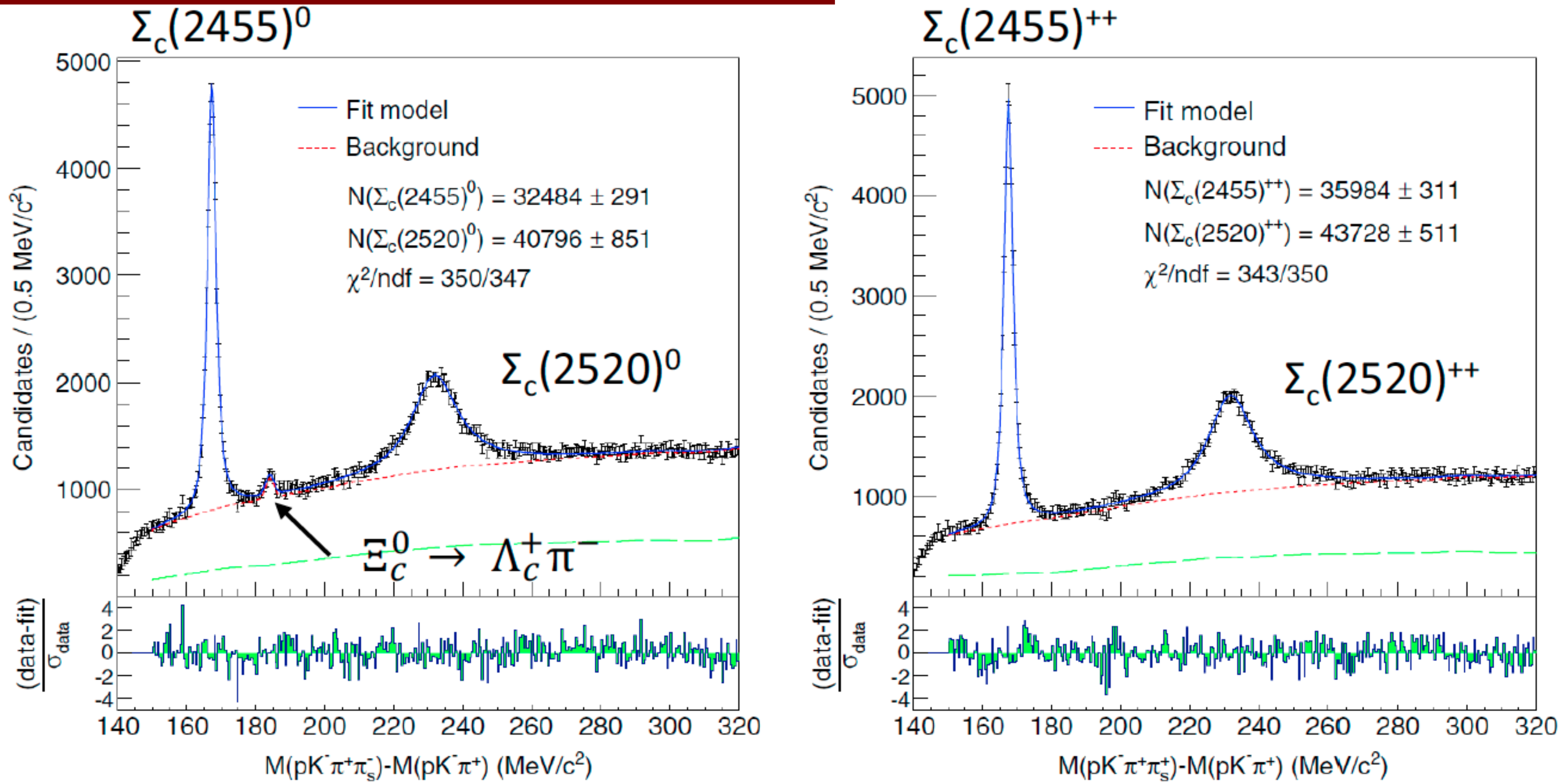
Discovery of Ξ_b

Λ_c excited states

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
Λ_b	$b[ud]$	$1/2^+$	3^*	(0, 0)	0	1
Ξ_b^0	$b[su]$	$1/2^+$	3^*	(1/2, 1/2)	-1	1
Ξ_b^-	$b[sd]$	$1/2^+$	3^*	(1/2, -1/2)	-1	1
Σ_b^+	buu	$1/2^+$	6	(1, 1)	0	1
Σ_b^0	$b\{ud\}$	$1/2^+$	6	(1, 0)	0	1
Σ_b^-	bdd	$1/2^+$	6	(1, -1)	0	1
$\Xi_b^{0\prime}$	$b\{su\}$	$1/2^+$	6	(1/2, 1/2)	-1	1
$\Xi_b^{-\prime}$	$b\{sd\}$	$1/2^+$	6	(1/2, -1/2)	-1	1
Ω_b^-	bss	$1/2^+$	6	(0, 0)	-2	1
Σ_b^{*+}	buu	$3/2^+$	6	(1, 1)	0	1
Σ_b^{*0}	bud	$3/2^+$	6	(1, 0)	0	1
Σ_b^{*-}	bdd	$3/2^+$	6	(1, -1)	0	1
Ξ_b^{*0}	bus	$3/2^+$	6	(1/2, 1/2)	-1	1
Ξ_b^{*-}	bds	$3/2^+$	6	(1/2, -1/2)	-1	1
Ω_b^{*-}	bss	$3/2^+$	6	(0, 0)	-2	1

Precise $\Sigma_c^{(*)}$ masses at Belle

PRD 89, 091102(R) (2014)



	ΔM_0 (MeV/c^2)	Γ (MeV/c^2)	M_0 (MeV/c^2)
$\Sigma_c(2455)^0$	$167.29 \pm 0.01 \pm 0.02$	$1.76 \pm 0.04^{+0.09}_{-0.21}$	$2453.75 \pm 0.01 \pm 0.02 \pm 0.14$
$\Sigma_c(2455)^{++}$	$167.51 \pm 0.01 \pm 0.02$	$1.84 \pm 0.04^{+0.07}_{-0.20}$	$2453.97 \pm 0.01 \pm 0.02 \pm 0.14$
$\Sigma_c(2520)^0$	$231.98 \pm 0.11 \pm 0.04$	$15.41 \pm 0.41^{+0.20}_{-0.32}$	$2518.44 \pm 0.11 \pm 0.04 \pm 0.14$
$\Sigma_c(2520)^{++}$	$231.99 \pm 0.10 \pm 0.02$	$14.77 \pm 0.25^{+0.18}_{-0.30}$	$2518.45 \pm 0.10 \pm 0.02 \pm 0.14$

(*) the mass of $\Sigma_c^{(*)+}$, which decay to $\Lambda_c \pi^0$, was last measured by CLEO in 2001.

Search for $\Sigma^{(*)}_{b0}$ at LHCb

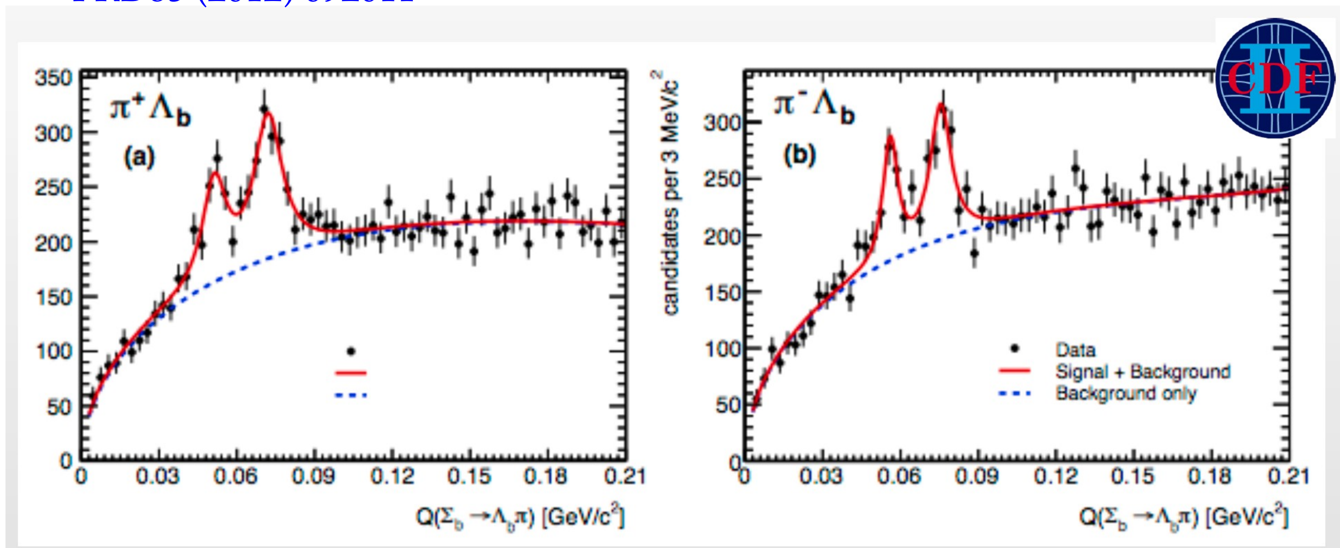
$\Sigma^{(*)}_{b0}$=b{ud}$_{J=1}$

LHCb is challenged to make the first observation of the neutral state, which decays to $\Lambda_b\pi^0$, and is much harder to detect.

Stay tuned!

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
Λ_b	$b[ud]$	1/2+	3*	(0, 0)	0	1
Ξ_b^0	$b[su]$	1/2+	3*	(1/2, 1/2)	-1	1
Ξ_b^-	$b[sd]$	1/2+	3*	(1/2, -1/2)	-1	1
Σ_b^+	buu	1/2+	6	(1, 1)	0	1
Σ_b^0	$b\{ud\}$	1/2+	6	(1, 0)	0	1
Σ_b^-	bdd	1/2+	6	(1, -1)	0	1
$\Xi_b^{0\prime}$	$b\{su\}$	1/2+	6	(1/2, 1/2)	-1	1
$\Xi_b^{-\prime}$	$b\{sd\}$	1/2+	6	(1/2, -1/2)	-1	1
Ω_b^-	bss	1/2+	6	(0, 0)	-2	1
Σ_b^{*+}	buu	3/2+	6	(1, 1)	0	1
Σ_b^{*0}	bud	3/2+	6	(1, 0)	0	1
Σ_b^{*-}	bdd	3/2+	6	(1, -1)	0	1
Ξ_b^{*0}	bus	3/2+	6	(1/2, 1/2)	-1	1
Ξ_b^{*-}	bds	3/2+	6	(1/2, -1/2)	-1	1
Ω_b^{*-}	bss	3/2+	6	(0, 0)	-2	1

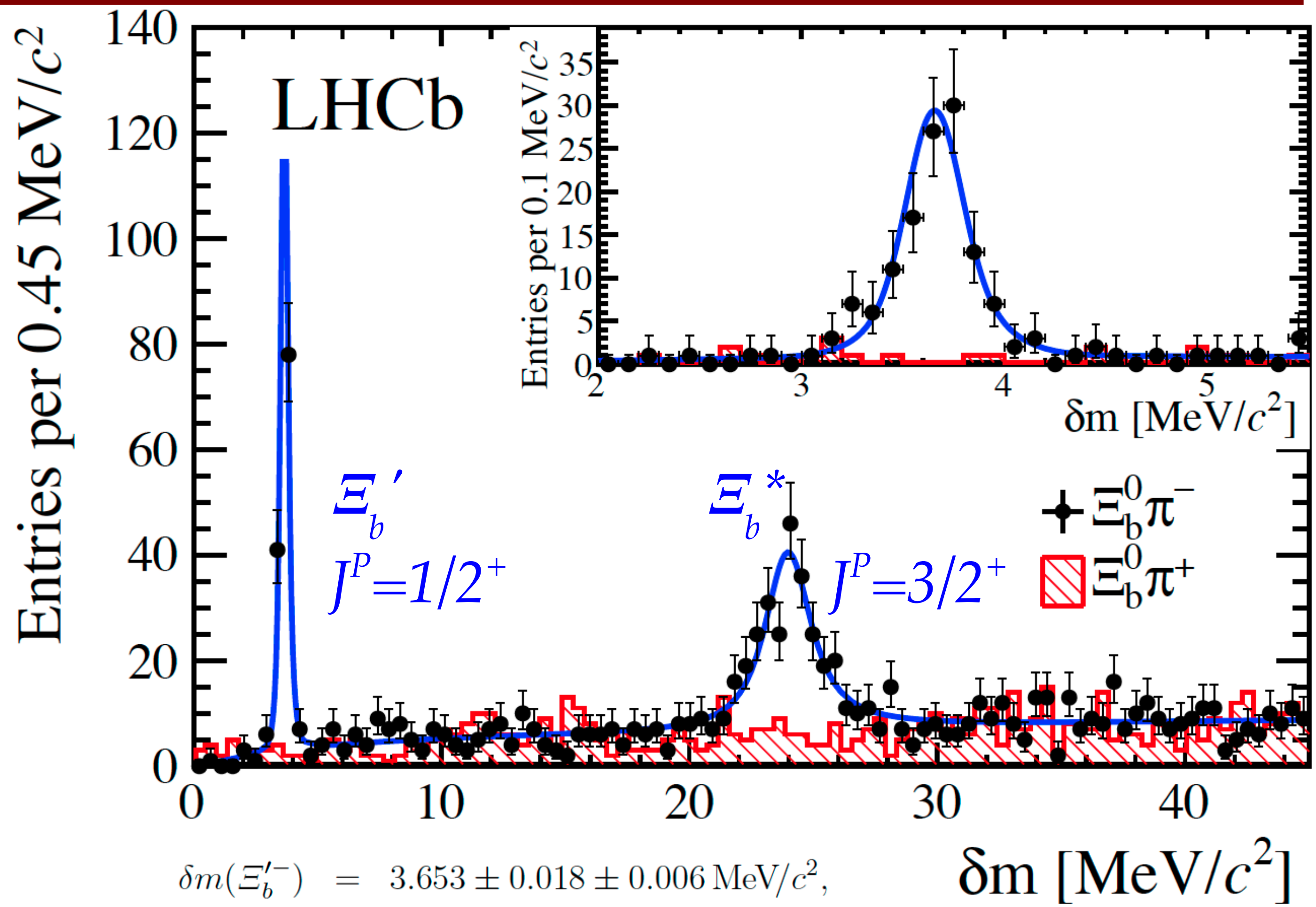
Charged partners observed by CDF with $6fb^{-1}$ at 2TeV
PRD85 (2012) 092011



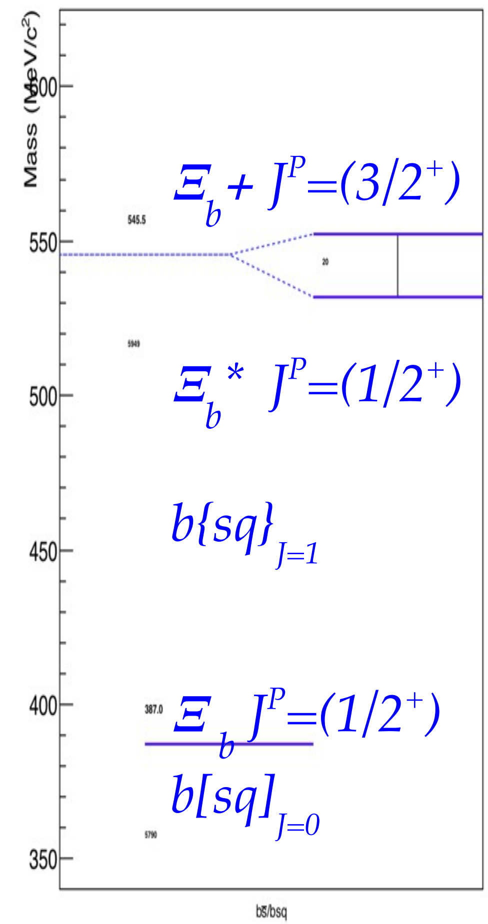
State	Q value, MeV/c^2	Absolute mass m, MeV/c^2	Natural width Γ, MeV/c^2
Σ_b^-	$56.2^{+0.6}_{-0.5}{}^{+0.1}_{-0.4}$	$5815.5^{+0.6}_{-0.5}\pm1.7$	$4.9^{+3.1}_{-2.1}\pm1.1$
Σ_b^{*-}	$75.8\pm0.6^{+0.1}_{-0.6}$	$5835.1\pm0.6^{+1.7}_{-1.8}$	$7.5^{+2.2}_{-1.8}{}^{+0.9}_{-1.4}$
Σ_b^+	$52.1^{+0.9}_{-0.8}{}^{+0.1}_{-0.4}$	$5811.3^{+0.9}_{-0.8}\pm1.7$	$9.7^{+3.8}_{-2.8}{}^{+1.2}_{-1.1}$
Σ_b^{*+}	$72.8\pm0.7^{+0.1}_{-0.6}$	$5832.1\pm0.7^{+1.7}_{-1.8}$	$11.5^{+2.7}_{-2.2}{}^{+1.0}_{-1.5}$
	Isospin mass splitting, MeV/c^2		
$m(\Sigma_b^+)-m(\Sigma_b^-)$		$-4.2^{+1.1}_{-1.0}\pm0.1$	
$m(\Sigma_b^{*+})-m(\Sigma_b^{*-})$		$-3.0^{+1.0}_{-0.9}\pm0.1$	

Observation of Ξ_b+ and Ξ_b*

PRL114 (2015) 062004

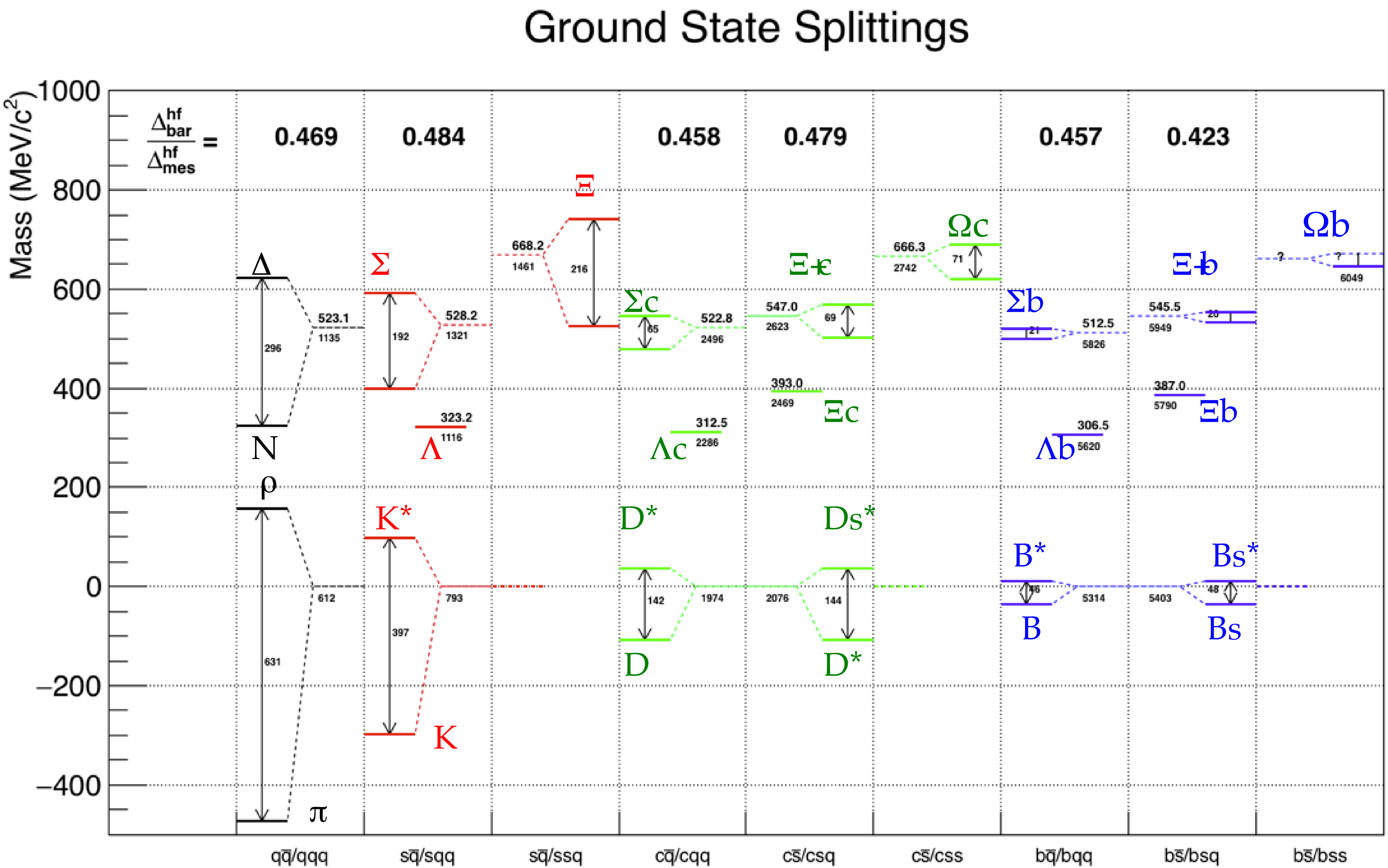


$$\delta m(\Xi_b'^-) = 3.653 \pm 0.018 \pm 0.006\,\mathrm{MeV}/c^2,$$
$$\delta m(\Xi_b^{*-}) = 23.96 \pm 0.12 \pm 0.06\,\mathrm{MeV}/c^2,$$



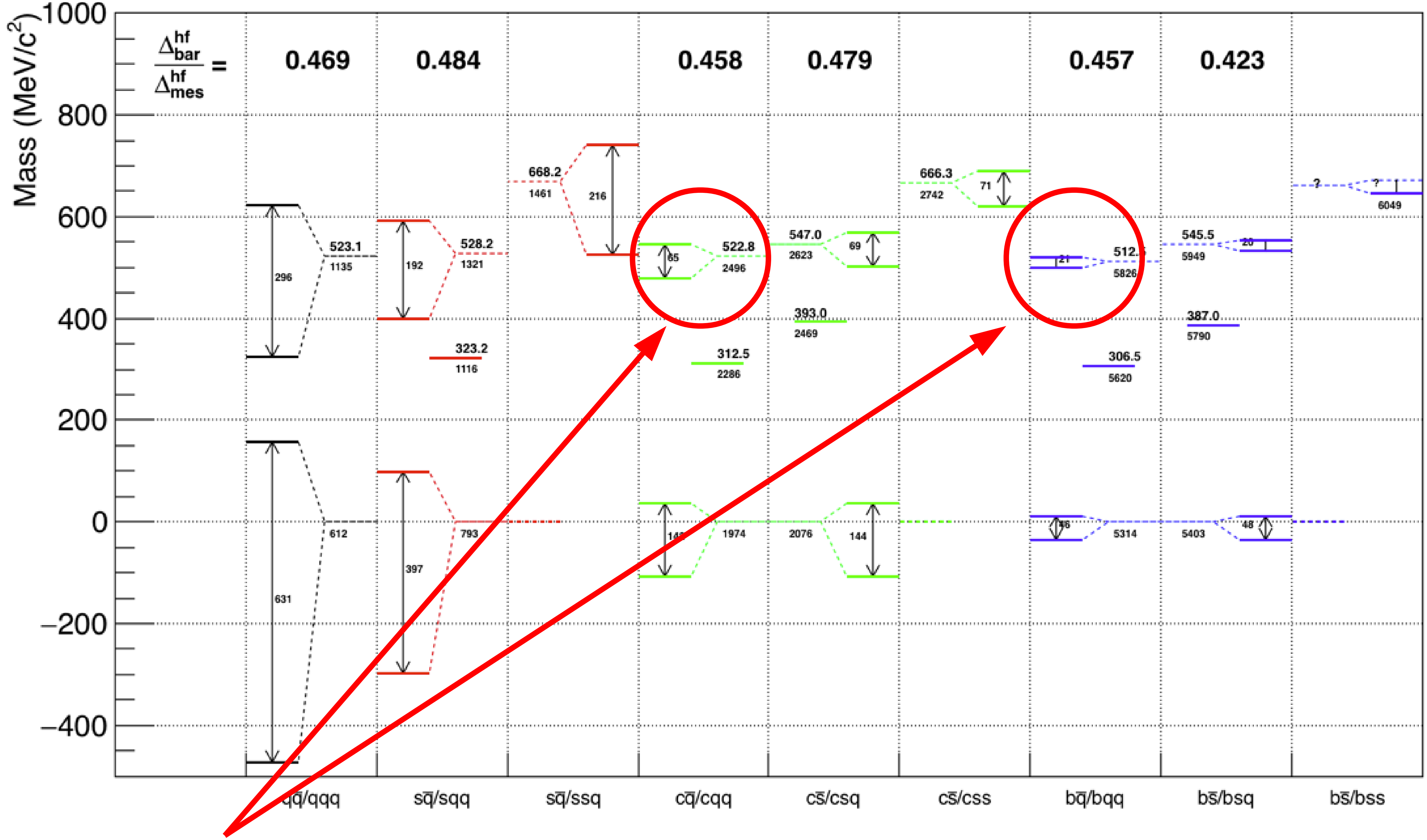
$$m(\Xi_b'^-) = 5935.02 \pm 0.02 \pm 0.01 \pm 0.50\,\mathrm{MeV}/c^2, \quad \Gamma(\Xi_b'^-) < 0.08\ \mathrm{MeV\ at\ 95\%\ CL}$$
$$m(\Xi_b^{*-}) = 5955.33 \pm 0.12 \pm 0.06 \pm 0.50\,\mathrm{MeV}/c^2, \quad \Gamma(\Xi_b^{*-}) = 1.65 \pm 0.31 \pm 0.10\,\mathrm{MeV},$$

More details : talk by Williams in Tuesday Parallel Session



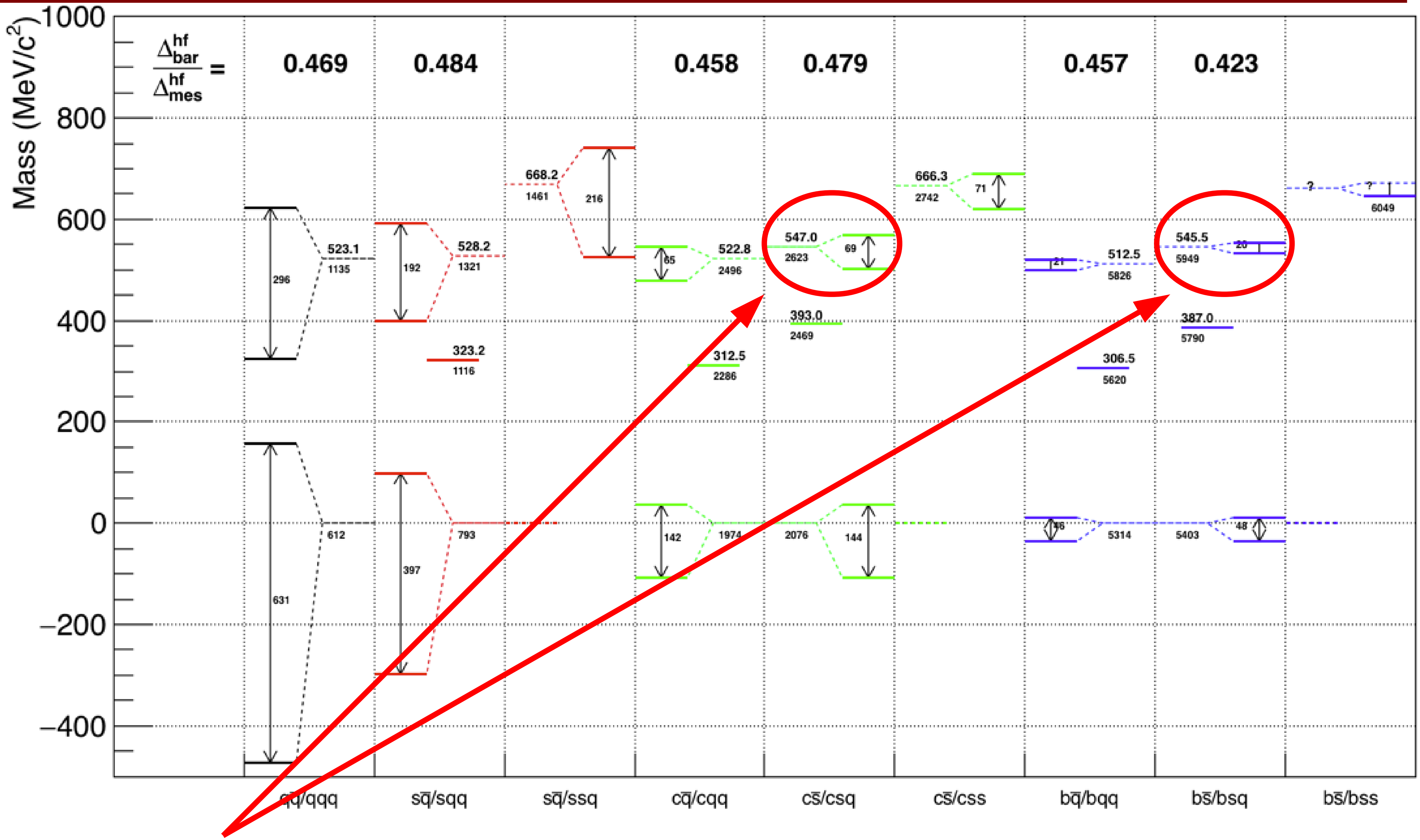
Ground State Splittings
Mass (MeV/c²)
1000
800
600
400
200
0
−200
−400
Δhf bar / Δhf mes =
0.469
0.484
0.458
0.479
0.457
0.423
Δ
N
296
523.1
1135
Σ
Λ
192
528.2
1321
323.2
1116
Ξ
668.2
1461
216
Σc
Λc
65
522.8
2496
312.5
2286
Ξc
547.0
2623
69
393.0
2469
Ωc
666.3
2742
71
Σb
Λb
21
512.5
5826
306.5
5620
Ξb
545.5
5949
20
387.0
5790
Ωb
?
6049
ρ
π
631
612
K*
K
397
793
D*
D
142
1974
Ds*
2076
144
B*
B
46
5314
Bs*
Bs
5403
48
qq̄/qqq
sq̄/sqq
sq̄/ssq
cq̄/cqq
cs̄/csq
cs̄/css
bq̄/bqq
bs̄/bsq
bs̄/bss

The intriguing success of CQM continues ...



$\Delta M(\bar{q} \rightarrow \{qq\}_{J=1}) =$ 523(c) vs 512(b) MeV : -2% variation going from c to b

The intriguing success of CQM continues …



$\Delta M(\bar{s} \to \{sq\}_{J=1}) = 547.0(c)$ vs $545.5(b)$: independent of heavy quark mass

P-wave baryons: Λ^*_c , Λ^*_b

Λ^*_c:the result of CDF, *PRD84,012003,* published in 2011, is still the best.
Neither Babar nor Belle updated it.

Λ^*_b:Bottom counterpart, observed by LHCb with 1fb^{-1} *PRL104,172003(2012)*

$$\Delta M_{\Lambda_b^{*0}(5912)} = 292.60 \pm 0.12(\text{stat}) \pm 0.04(\text{syst})\ \text{MeV}/c^2$$

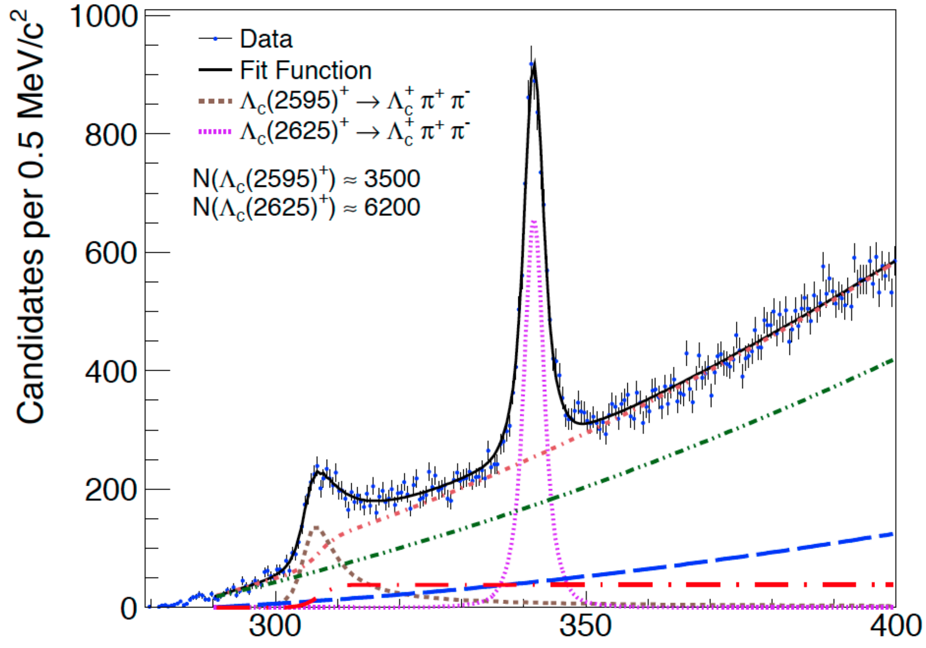
$$\Delta M_{\Lambda_b^{*0}(5920)} = 300.40 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})\ \text{MeV}/c^2$$

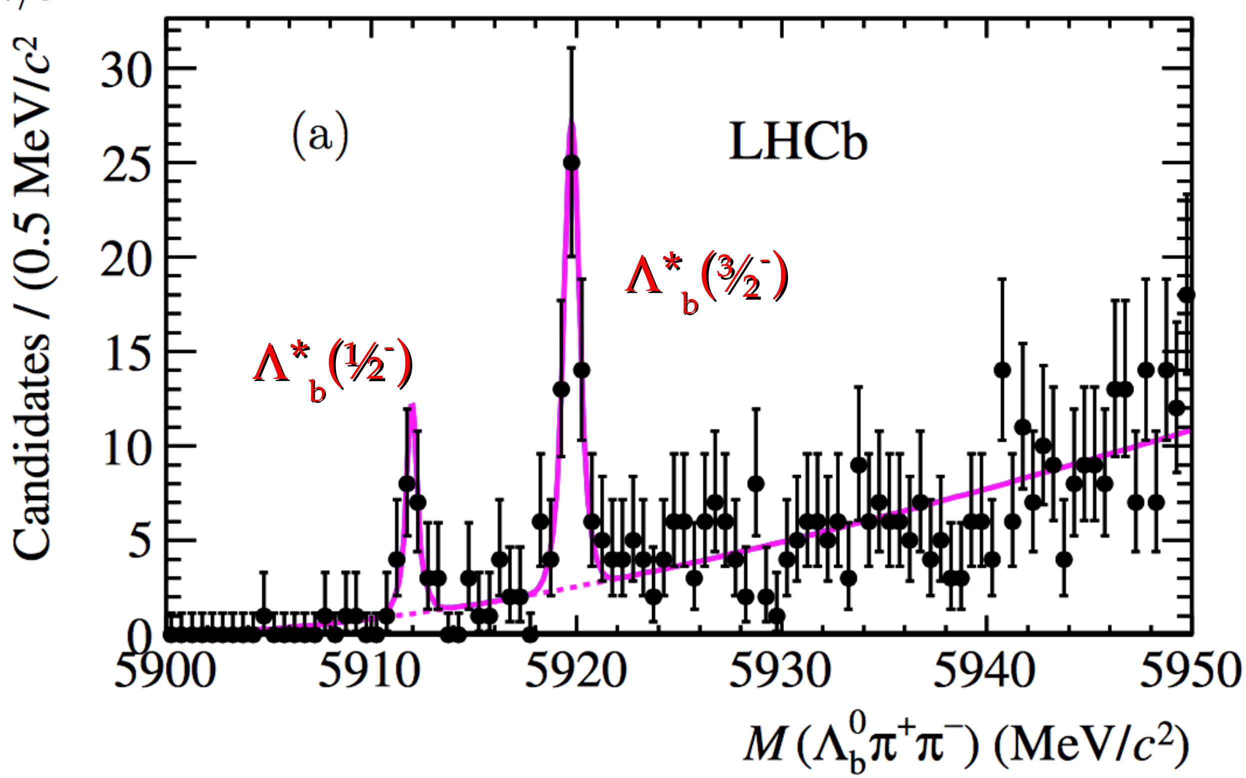
$$M_{\Lambda_b^{*0}(5912)} = 5911.97 \pm 0.12 \pm 0.02 \pm 0.66\ \text{MeV}/c^2$$

$$M_{\Lambda_b^{*0}(5920)} = 5919.77 \pm 0.08 \pm 0.02 \pm 0.66\ \text{MeV}/c^2$$

soon after, evidence of 5920 at CDF

Further studies underway with the larger samples at LHCb, to search for higher excitations.





Summary

Bottomonium and Charmonium bound state spectroscopy is approaching completion: progress mainly on 1D and 3P states

Now it's time to study Bc excited states: go LHCb!

Close to thresholds , analogies and differences are puzzling:
- no X(3872) analogue in bottomonium
- Zb and Zc exhibit different BR patterns
- Upsilon(5S,6S) phenomenology is different from Y(4.26,4.36)

Since 2008, study of hadronic transitions between broad and narrow states have produced an amazing variety of results, but a unified pattern is still missing

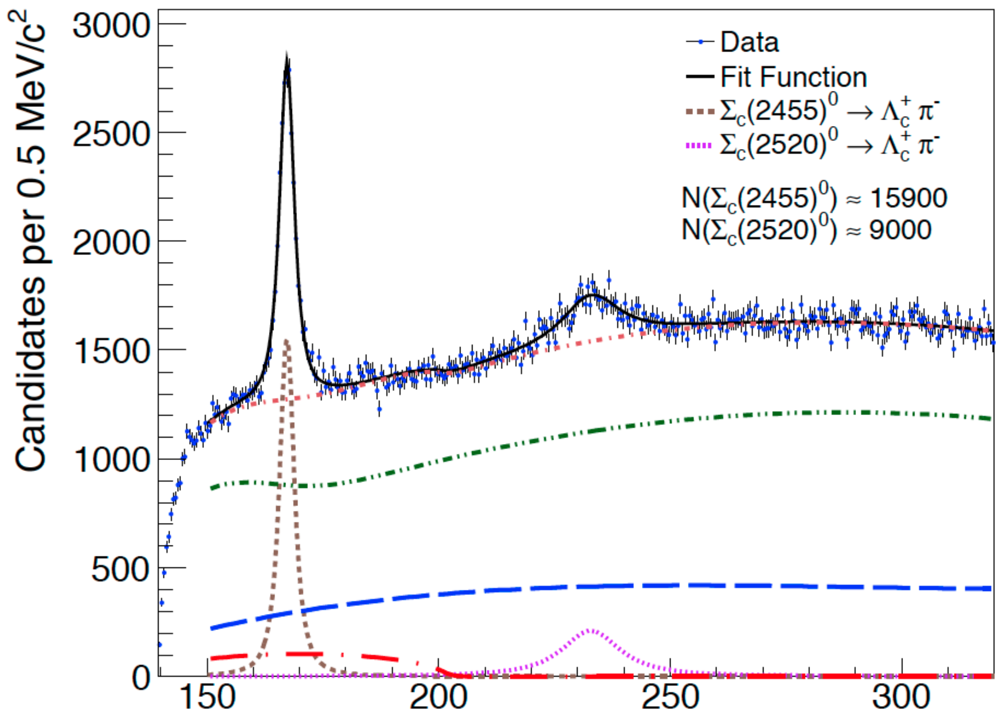
Many interesting results from eta transitions in bottomonium, hopefully
More results will come from charmonium

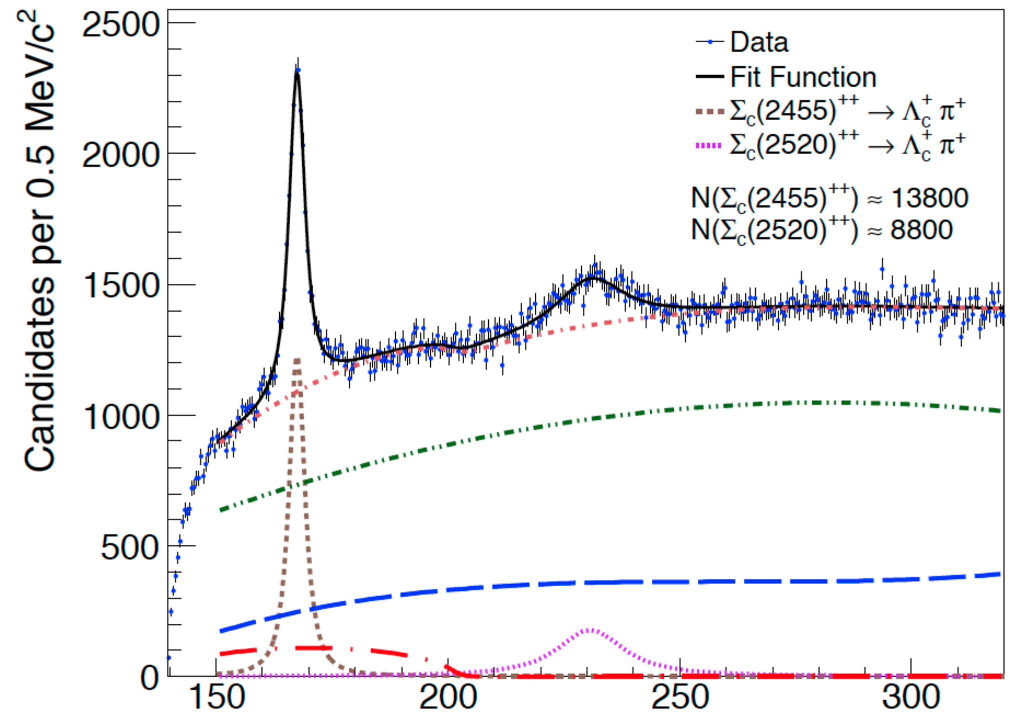
Heavy meson and baryon spectroscopy:
LHC-b has just started to show its huge potential
a plethora of results are still buried in Belle+Babar data , though

LHCB and Belle-II future data taking promise new and even more exciting results

Charged Σ_c splittings from CDF

CDF: PRD 84, 012003 (2011)





Hadron	M [MeV/c^2]	Γ [MeV/c^2]
$\Sigma_c(2455)^{++}$	$2453.90 \pm 0.13 \pm 0.14$	2.34 ± 0.47
$\Sigma_c(2455)^{0}$	$2453.74 \pm 0.12 \pm 0.14$	1.65 ± 0.50
$\Sigma_c(2520)^{++}$	$2517.19 \pm 0.46 \pm 0.14$	15.03 ± 2.52
$\Sigma_c(2520)^{0}$	$2519.34 \pm 0.58 \pm 0.14$	12.51 ± 2.28
$\Lambda_c(2595)^{+}$	$2592.25 \pm 0.24 \pm 0.14$	$h_2^2 = 0.36 \pm 0.08$
$\Lambda_c(2625)^{+}$	$2628.11 \pm 0.13 \pm 0.14$	< 0.97 at 90% C.L.

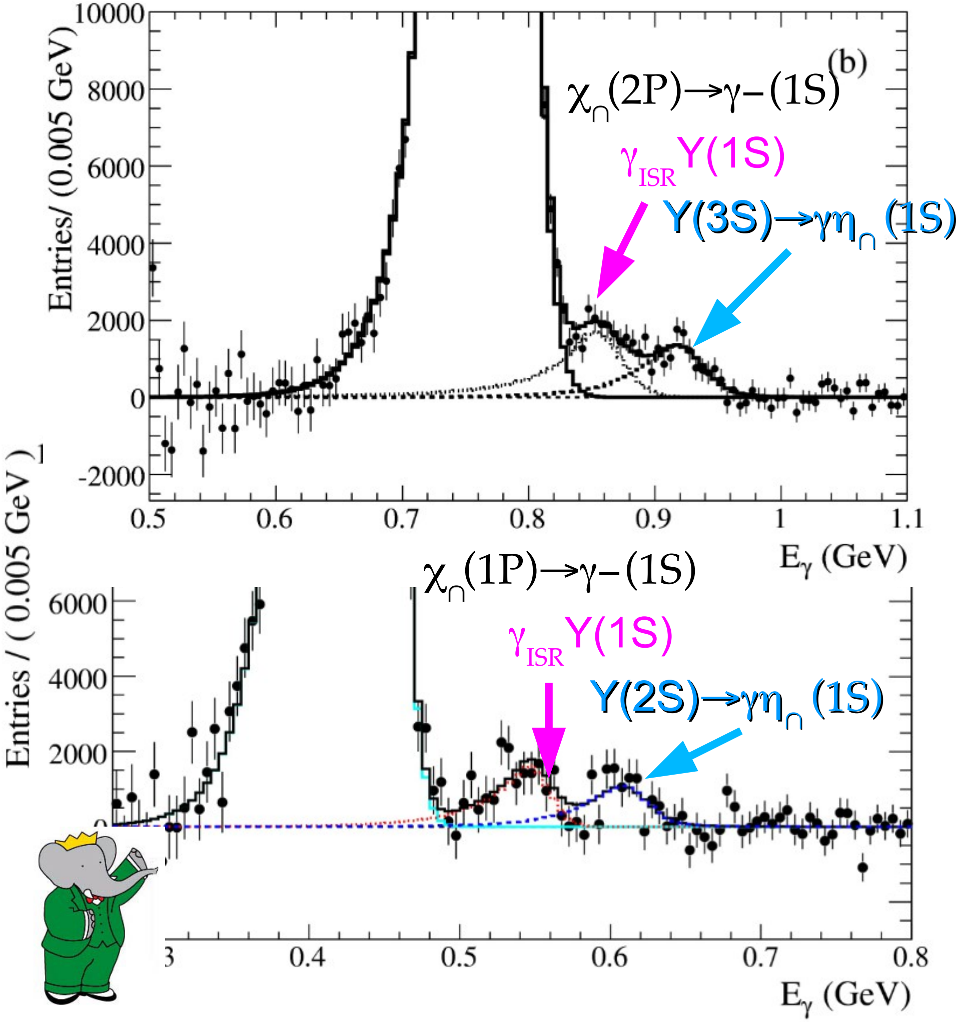
Superseded by :
Belle: PRD 89, 091102(R) (2014)

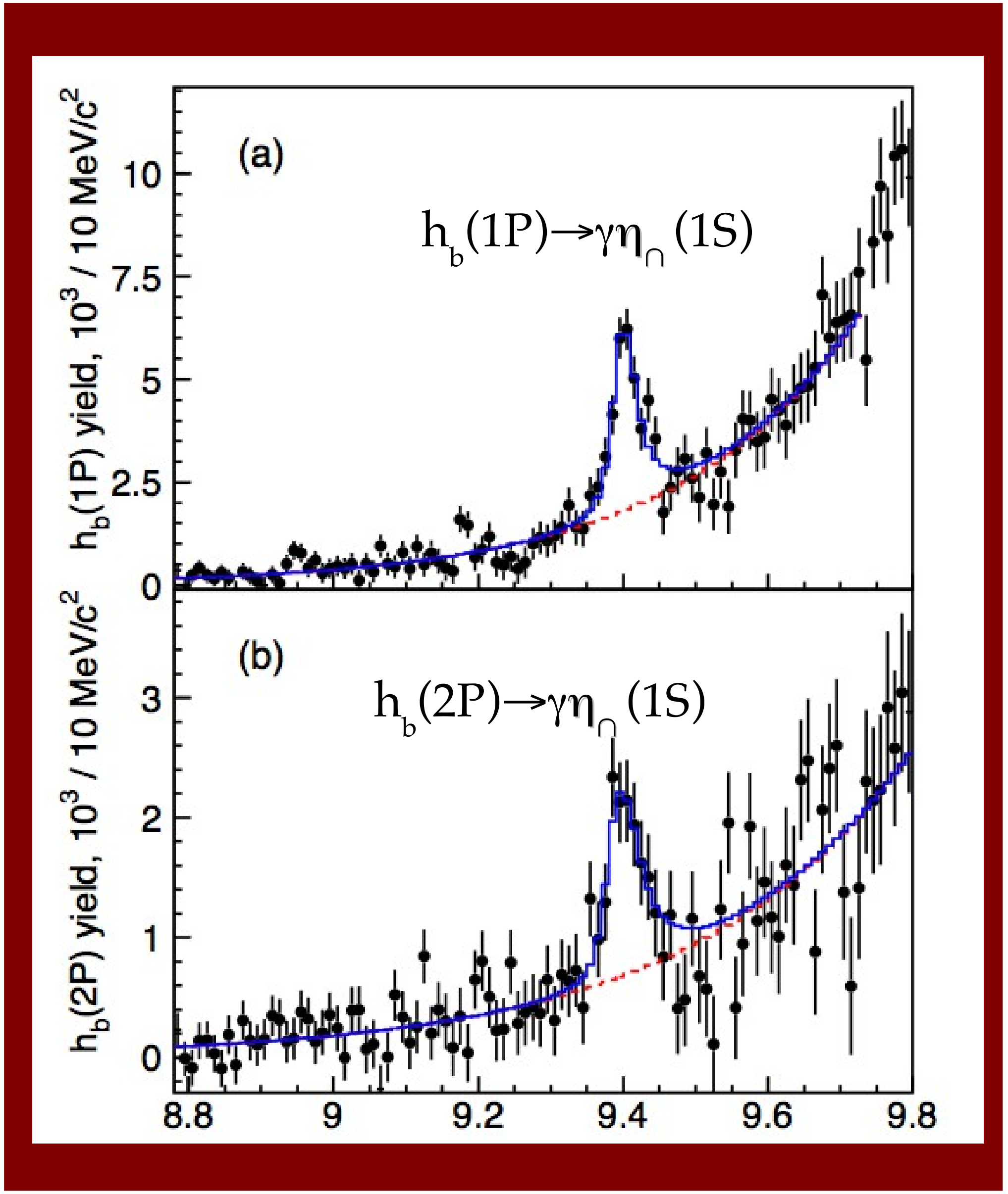
Backup

Rediscovery of η_b

Phys.Rev.Lett. 109 (2012) 232002

Babar 2008:





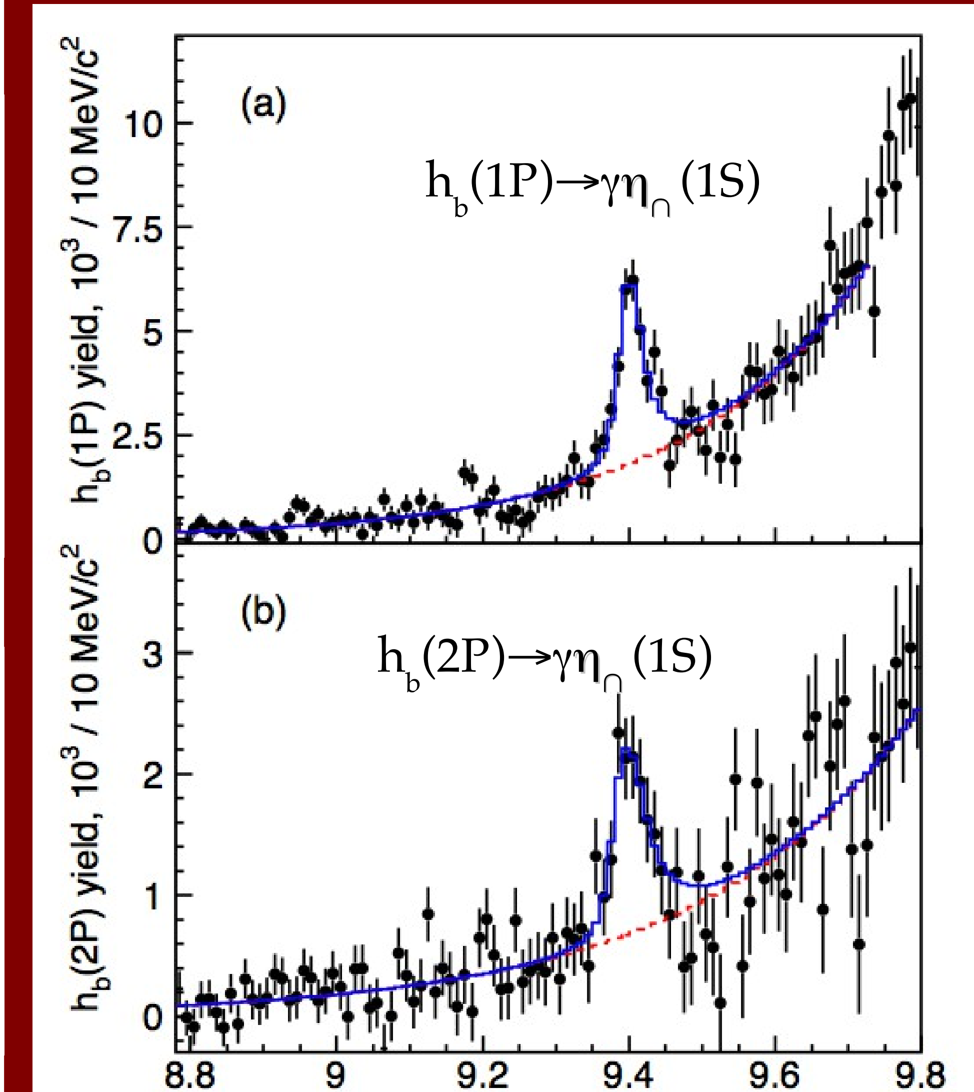
PRL 101,071801(2008)
PRL 103,161801(2009)

Belle results on η∩ (1Δ)

Phys.Rev.Lett. 109 (2012) 232002

Yields from Υ(5S) VIA Z_b states:

	$N,\ 10^3$	Mass, MeV/c^2
$\Upsilon(5S)\to h_b(1P)$	$70.3\pm3.3^{+1.9}_{-0.7}$	$9899.1\pm0.4\pm1.0$
$\Upsilon(3S)\to\Upsilon(1S)$	13 ± 7	9973.0
$\Upsilon(5S)\to\Upsilon(2S)$	61.3 ± 4.1	10021.3 ± 0.5
$\Upsilon(5S)\to\Upsilon(1D)$	14 ± 7	10169 ± 3
$\Upsilon(5S)\to h_b(2P)$	$89.5\pm6.1^{+0.0}_{-5.8}$	$10259.8\pm0.5\pm1.1$
$\Upsilon(2S)\to\Upsilon(1S)$	97 ± 12	10305.6 ± 1.2
$\Upsilon(5S)\to\Upsilon(3S)$	58 ± 8	10357.7 ± 1.0



Measured η∩(1S) parameters:

Transition	$h_b(1P)\to\eta_b$	$h_b(2P)\to\eta_b$
Yield$\times10^{-3}$	23.5 ± 2.0	10.3 ± 1.3
BR$\times10^2$	$49.2\pm5.7\,^{+5.6}_{-3.3}$	$22.3\pm3.8\,^{+3.1}_{-3.3}$
Significance	15σ	9σ
m_{η_b} (MeV/c^2)	$9402.4\pm1.5\pm1.8$	(joint fit)
Δm_{hf} (MeV/c^2)	57.9 ± 2.3	(joint fit)

First measurement $\Gamma = 10.8\,^{+4.0}_{-3.7}\,^{+4.5}_{-2.0}$ MeV

Tension with earlier Babar and CLEO results: asymmetric lineshape, like in charmonium?

Doubly charmed baryons

Babar: PRD74,011103 (2006)
LHCB: ArXiV:1310.2538 (2013)
Belle: PRD89,052003(2014)