

Spin effects in bottomonium

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Quarkonium spectroscopy
and transitions

Quarkonium Decays

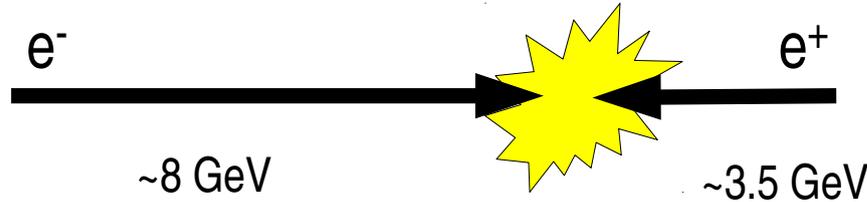
DIS2014
05/01/2014

The Belle experiment

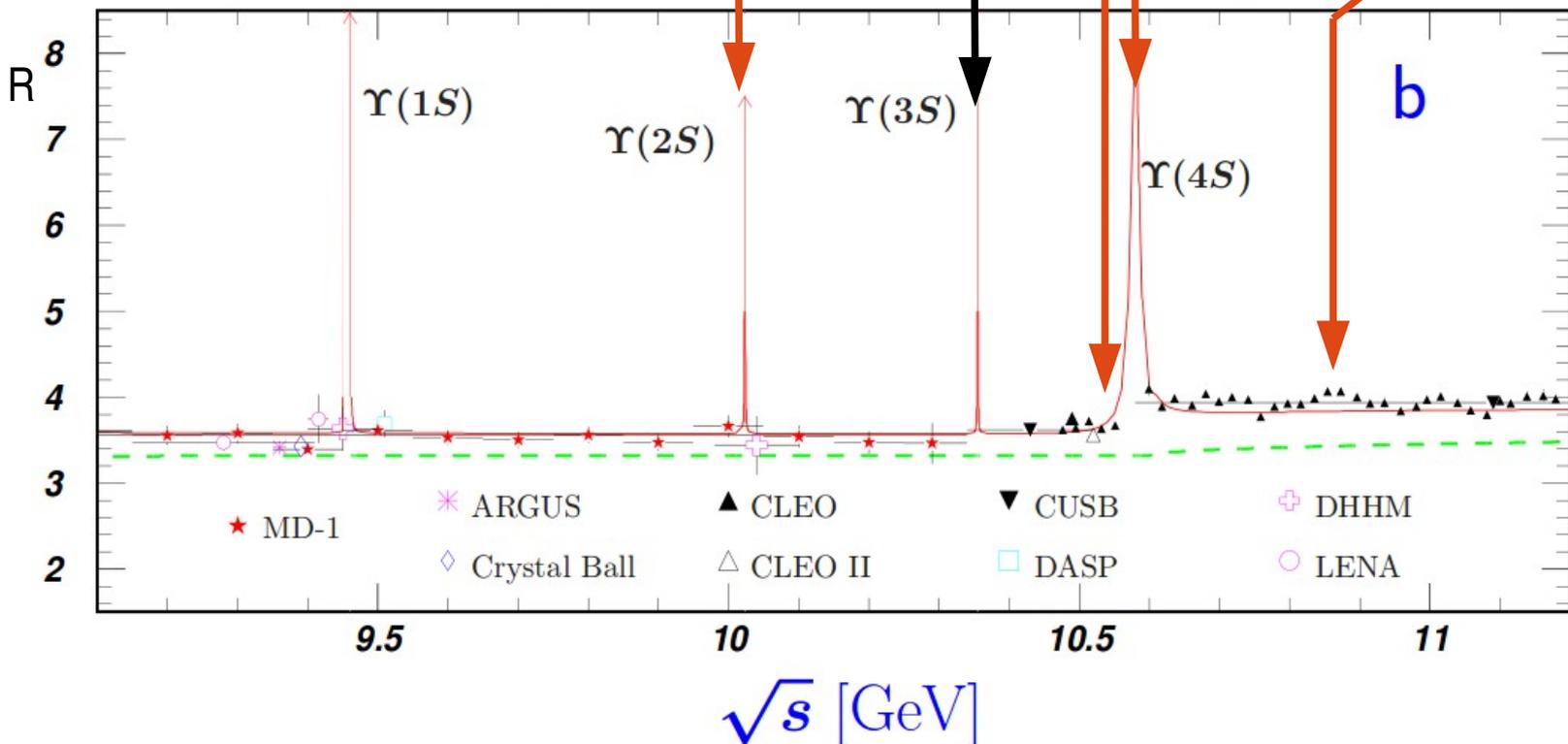
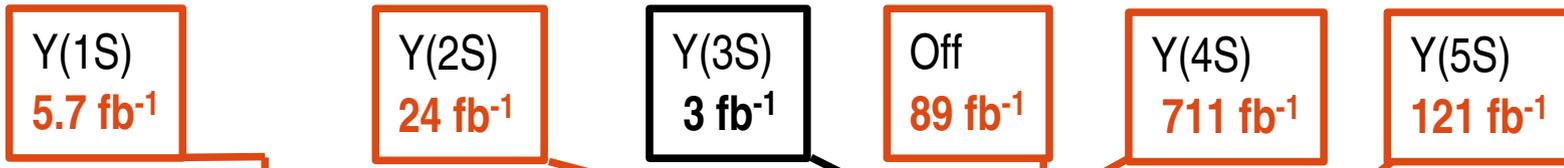


For a summary of Belle's results: arXiv:1212.5342v1

KEKB
asymmetric
collider



1-- quarkonium states
produced at rest



~ 1 ab of e+e-
events

World largest
samples of
Y(1S), Y(2S),
Y(4S), Y(5S)
and off-resonance

~ 770 M of
of Y(4S) → BB
events

Part I

Bottomonium transitions and spectroscopy

Hadronic transitions in quarkonia

QCD multipole expansion [Kuang Front.Phys.China 1, 19 \(2006\)](#)

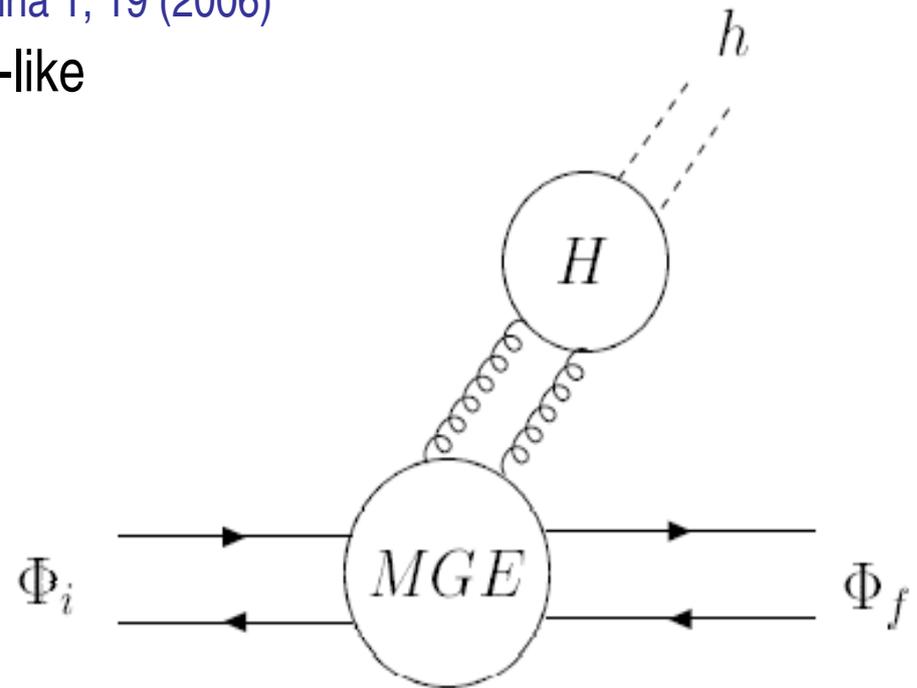
QCD hamiltonian can be expanded in a multipole-like

→ **Chromoelectric terms (E1 , E2 ...)**

Non spin flipping

→ **Chromomagnetic terms (M1 , M2 ...)**

Spin flipping → $(m_b)^{-2}$ suppression



E1E1 transition

$Y(nS) \rightarrow \pi \pi Y(mS)$

No Spin Flip

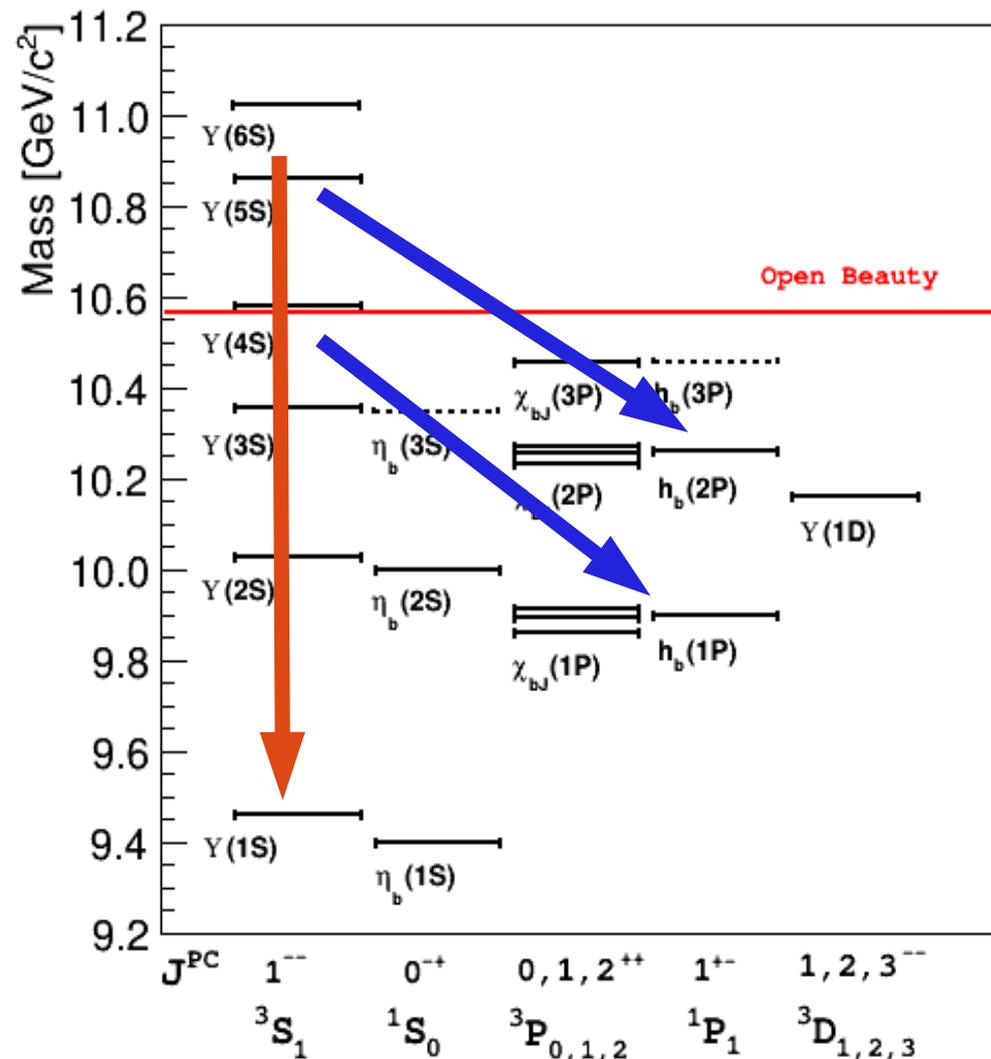
E1M2 transition

$Y(nS) \rightarrow \eta, \pi^0 Y(mS)$

Spin Flip

Hadronic transitions in quarkonia

If heavy quark spin symmetry is the dominant effect...



Suppression of spin flipping in $S \rightarrow S$ transitions

$$R^{SS}(\pi\pi, \eta) = \frac{\text{BF}(Y(nS) \rightarrow \eta Y(mS))}{\text{BF}(Y(nS) \rightarrow \pi\pi Y(mS))} \ll 1$$

Suppression of spin flipping in $S \rightarrow P$ transitions

$$R^{SP}(\pi\pi, \eta) = \frac{\text{BF}(Y(nS) \rightarrow \eta h_b(mP))}{\text{BF}(Y(nS) \rightarrow \pi\pi h_b(mP))} \geq 1$$

... $\eta/\pi\pi$ amplitudes are primary determined by the spin properties of the initial/final state 4

$RSS(\pi\pi, \eta)$ Experimental status

	Y(2S) →	Y(3S) →	Y(4S) →	Y(5S) →
Y(1S)	$\sim 2 \times 10^{-3}$	$< 2 \times 10^{-3}$		
Y(2S)				
Y(3S)				
Y(4S)				

Almost OK



RSS($\pi\pi, \eta$) Experimental status

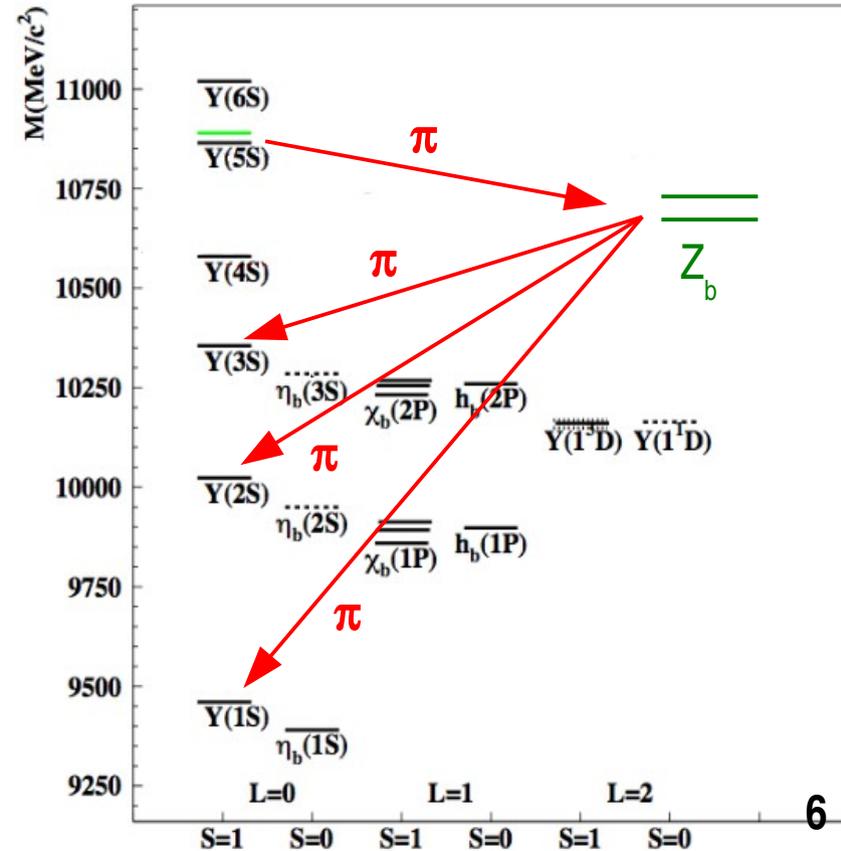
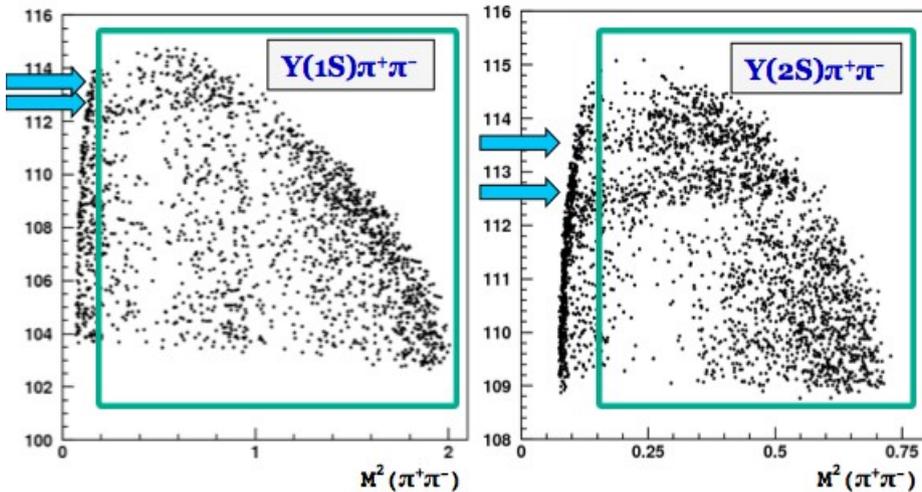
	Y(2S) \rightarrow	Y(3S) \rightarrow	Y(4S) \rightarrow	Y(5S) \rightarrow
Y(1S)	$\sim 2 \times 10^{-3}$	$< 2 \times 10^{-3}$	2.4	0.1
Y(2S)				0.4
Y(3S)				
Y(4S)				

Almost OK

Not a Zb effect.
Other coupled channel effects?

~ 2 -3 order of magnitude above th. expectations

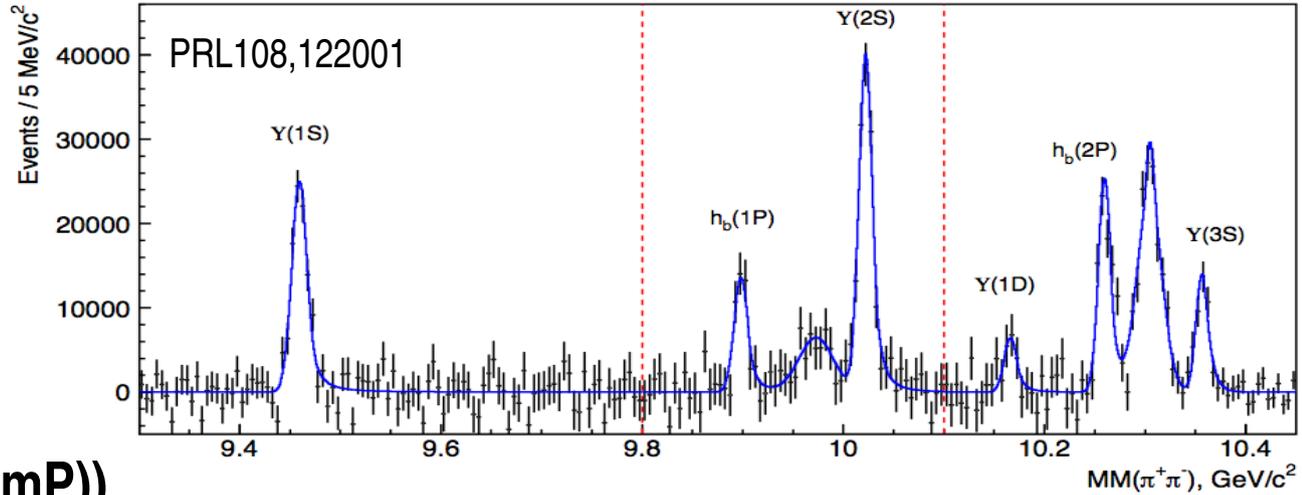
But $\pi\pi$ transition is mediated also by Zb intermediate states



R^{SP}(ππ,η) Experimental status

	Y(4S) →	Y(5S) →
hb(1P)	?	?
hb(2P)		?

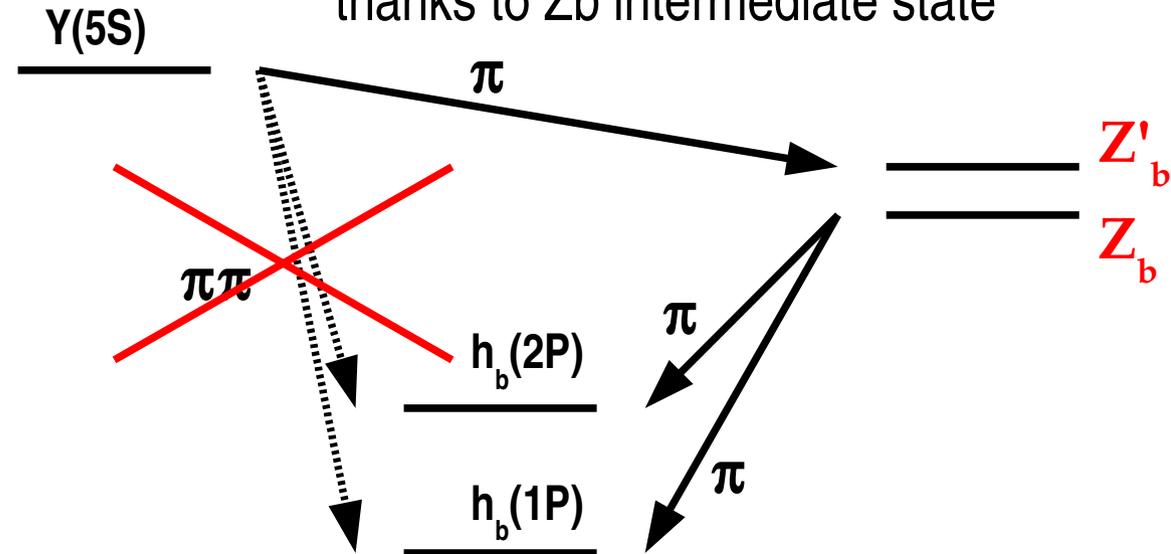
ππ transitions observed from Y(5S) @ Belle



$$R^{SP}(\pi\pi, \eta) = \frac{BF(Y(nS) \rightarrow \eta h_b(mP))}{BF(Y(nS) \rightarrow \pi\pi h_b(mP))}$$

E1M1 transition.

Suppressed but observed in Y(5S) thanks to Z_b intermediate state



Z_b ~ |BB*⟩

arXiv:1209.6450v2

Z'_b ~ |B*B*⟩

with negligible |BB*⟩ component

Spin flip occurs thanks to light quark contribute

RSP($\pi\pi, \eta$) Experimental status

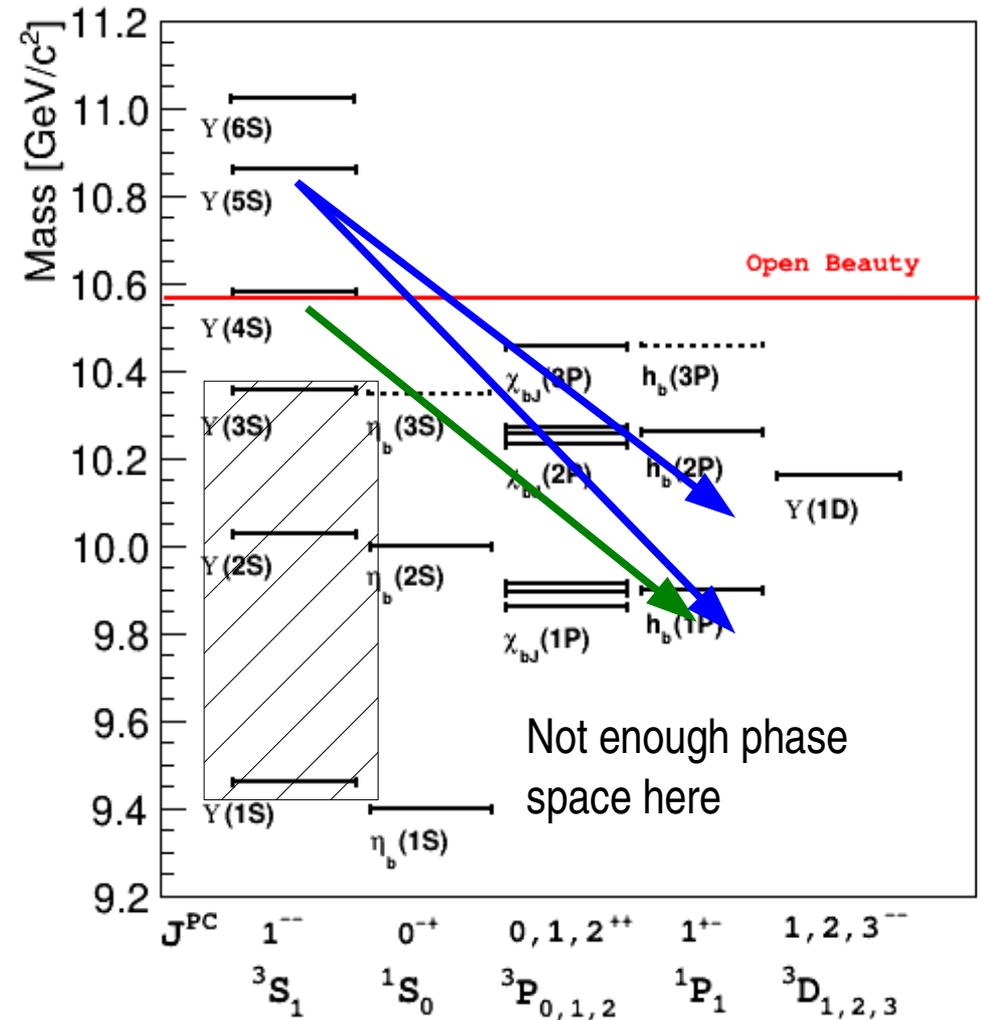
	Y(4S) \rightarrow	Y(5S) \rightarrow
hb(1P)	?	?
hb(2P)		?

$$RSP(\pi\pi, \eta) = \frac{\text{BF}(Y(nS) \rightarrow \eta h_b(mP))}{\text{BF}(Y(nS) \rightarrow \pi\pi h_b(mP))}$$

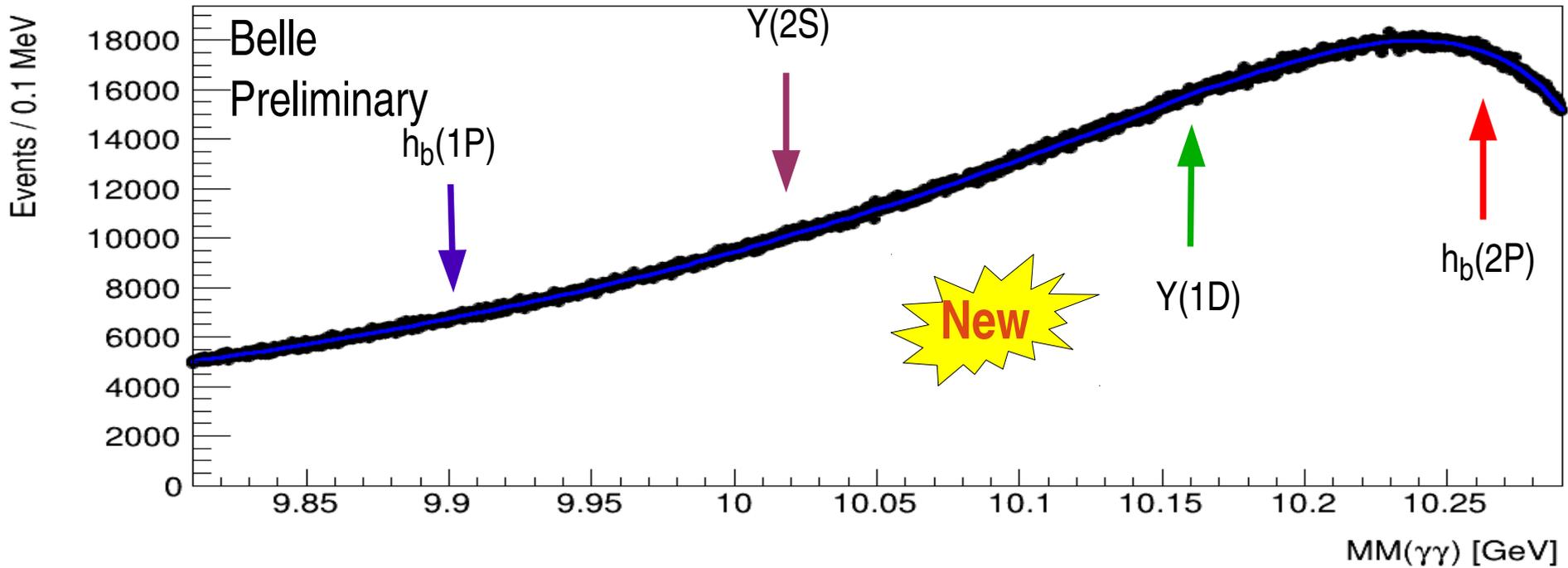
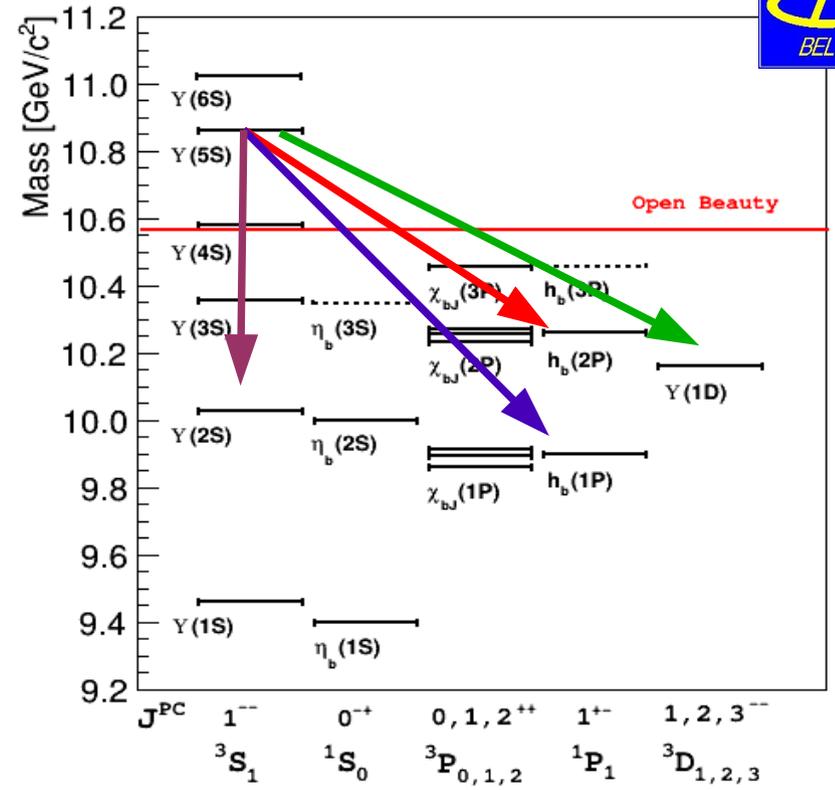
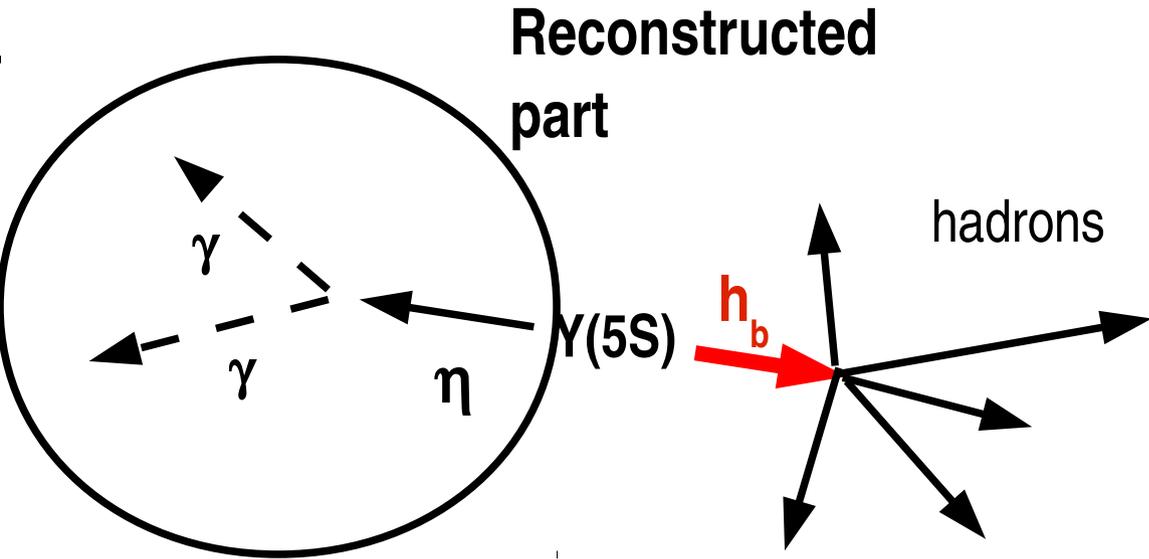
Y(5S) $\rightarrow \eta h_b(mP)$ never observed so far

Y(4S) $\rightarrow \eta h_b(mP)$ expected to be as large as 10^{-3} with small coupled channel effect contributions [PRL 105 (2010) 162001]

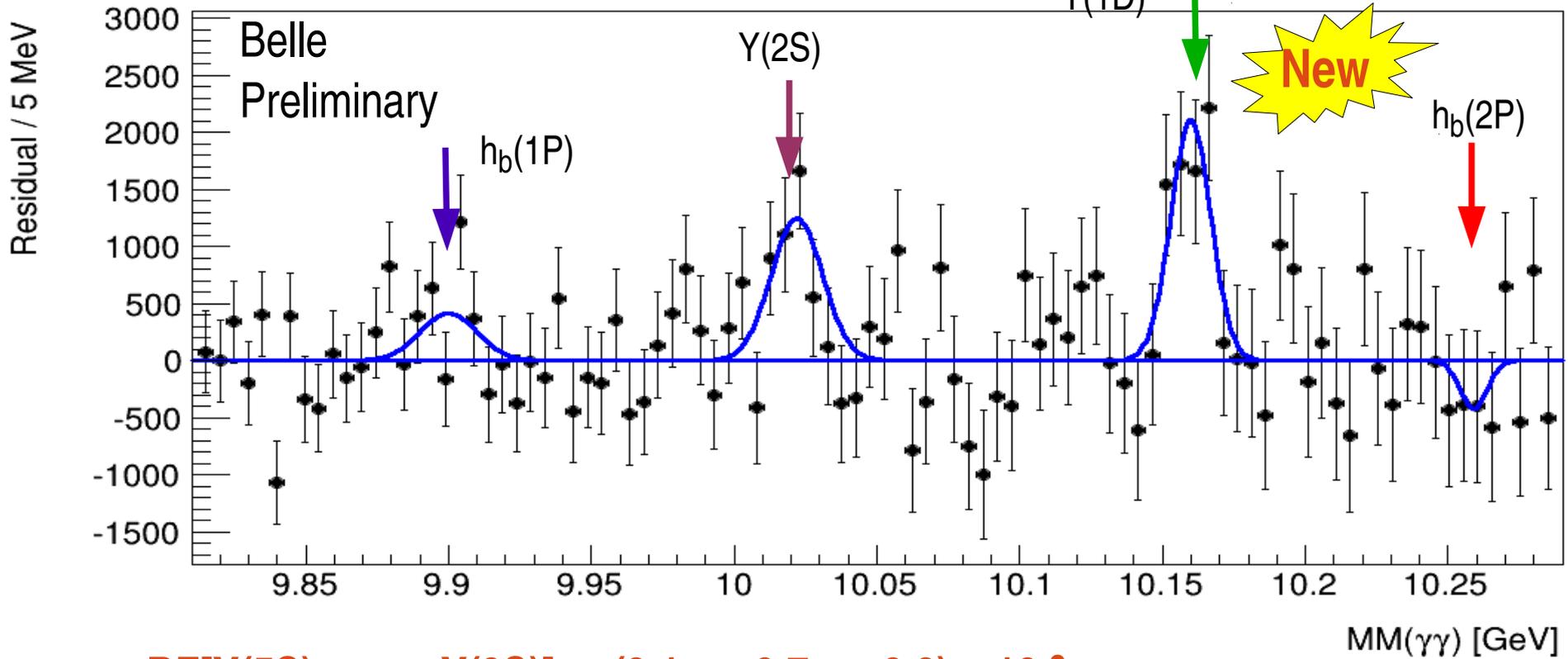
\rightarrow possible test of spin effects with $RSP(\pi\pi, \eta)$



hb(nP) has no known exclusive decays



Combinatorial background subtracted




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


 $BF[Y(5S) \rightarrow \eta Y(1D)] = (2.8 \pm 0.7 \pm 0.4) \times 10^{-3}$
 → First evidence of single meson transition to Y(1D)


 $BF[Y(5S) \rightarrow \eta hb(1P)] = < 3.3 \times 10^{-3} \quad (90\% \text{ CL})$
 → $R^{SP}(\pi\pi, \eta) < 0.94$


 $BF[Y(5S) \rightarrow \eta hb(2P)] = < 3.7 \times 10^{-3} \quad (90\% \text{ CL})$
 → $R^{SP}(\pi\pi, \eta) < 0.62$

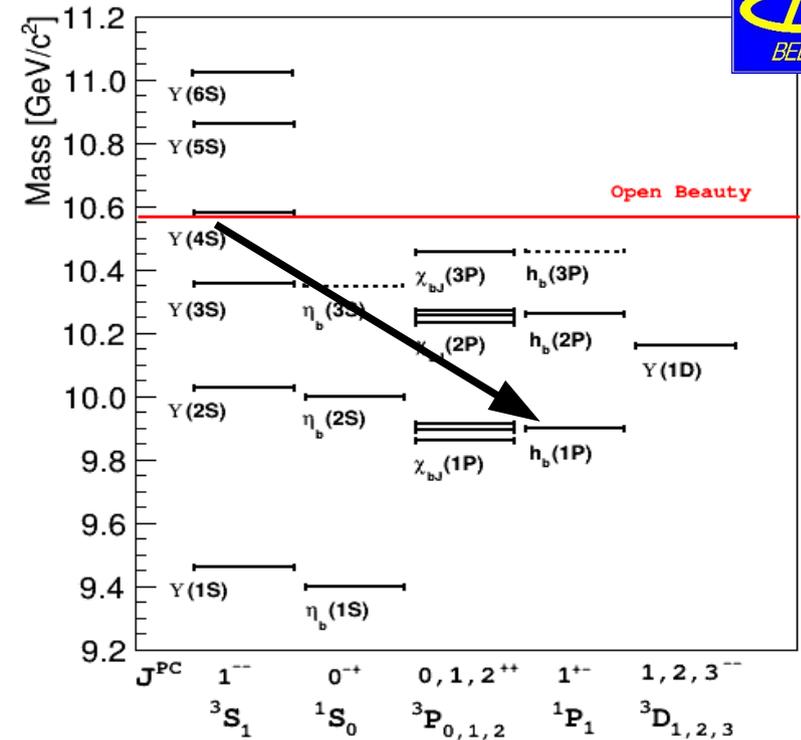
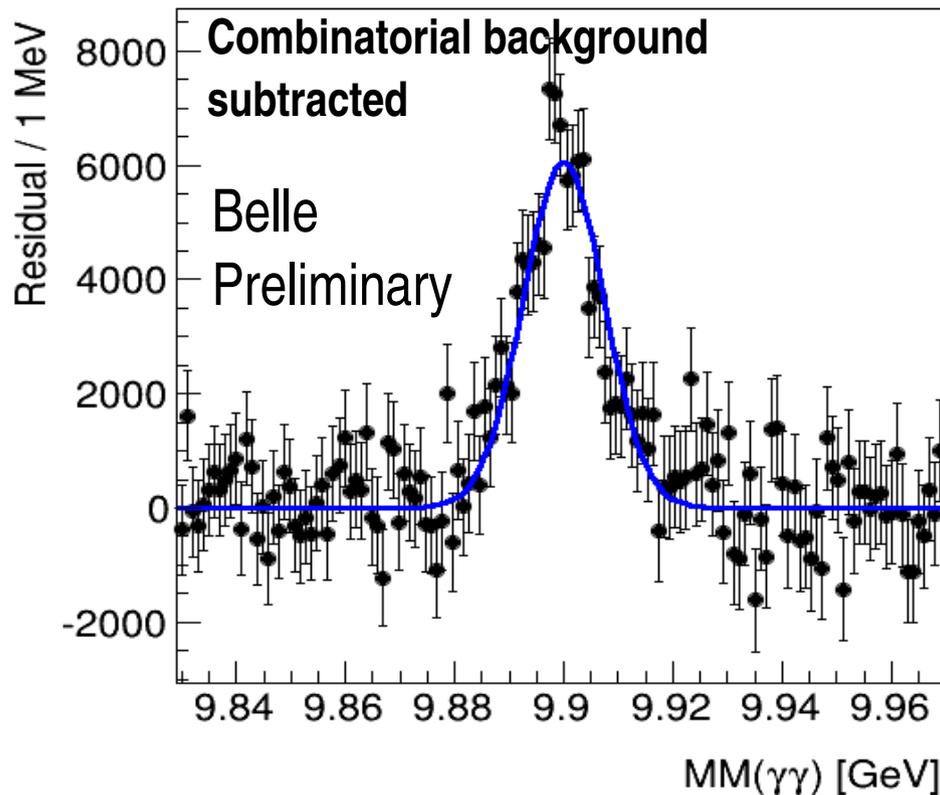
Expected to be ≥ 1
 Assuming heavy
 quark spin symmetry only

η transitions from $Y(4S)$

Theory [PRL 105 (2010) 162001]

→ $BF \sim 10^{-3}$

→ Small Couple-channel related term (~20%)



First single meson, S-wave transition observed with $> 5\sigma$

$$BF[Y(4S) \rightarrow \eta \text{ hb}(1P)] = (1.83 \pm 0.16 \pm 0.17) \times 10^{-3}$$

$$\rightarrow R^{SP}(\pi\pi, \eta) > 2.0$$

Belle
Preliminary

Spin-flip updated

Spin-flipping based prediction matched if light quark contribution is small

$$\frac{\text{BF}(Y(nS) \rightarrow \eta Y(mS))}{\text{BF}(Y(nS) \rightarrow \pi\pi Y(mS))}$$

$$\frac{\text{BF}(Y(nS) \rightarrow \eta h_b(mP))}{\text{BF}(Y(nS) \rightarrow \pi\pi h_b(mP))}$$

	Y(2S) →	Y(3S) →	Y(4S) →	Y(5S) →
Y(1S)	~ 2 x 10 ⁻³	< 2 x 10 ⁻³	2.4	0.1
Y(2S)				0.4
Y(3S)				
Y(4S)				

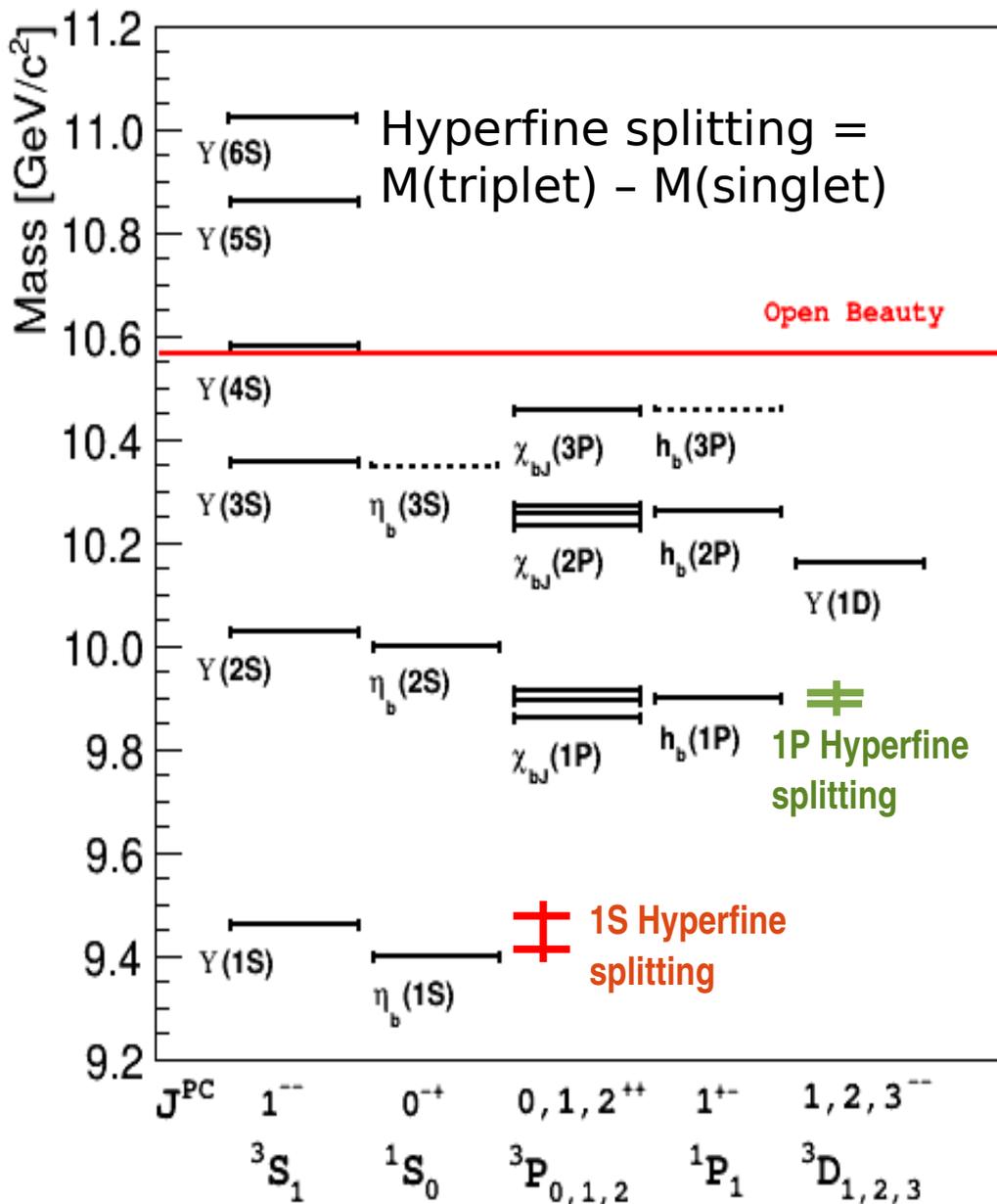
	Y(4S) →	Y(5S) →
hb(1P)	> 2.0	< 0.9
hb(2P)		< 0.6

Not the end of the story

$$\text{BF}[hb(1P) \rightarrow \gamma \eta b(1S)] \sim 50\%$$

Y(5S) anomalous behavior due to Z_b intermediate states

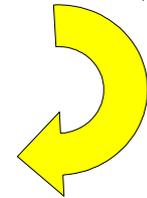
Spin singlet states



Spin interaction term:

$$V_{SS} = \frac{16\pi\alpha_s}{9m^2} \cdot \delta(\vec{r})$$

$$\Delta M_{HF} \propto |\psi(0)|^2$$



P wave \rightarrow Odd $\psi(r) \rightarrow |\psi(0)|^2 = 0$

$$\Delta M_{HF}(1P) = +0.8 \pm 1.1 \text{ MeV}$$

$$\Delta M_{HF}(2P) = +0.5 \pm 1.2 \text{ MeV}$$

S wave \rightarrow Even $\psi(r) \rightarrow |\psi(0)|^2 \neq 0$

pNRQCD: $41 \pm 14 \text{ MeV}$

Kniehl et al., PRL92,242001(2004)

Lattice: $60 \pm 8 \text{ MeV}$

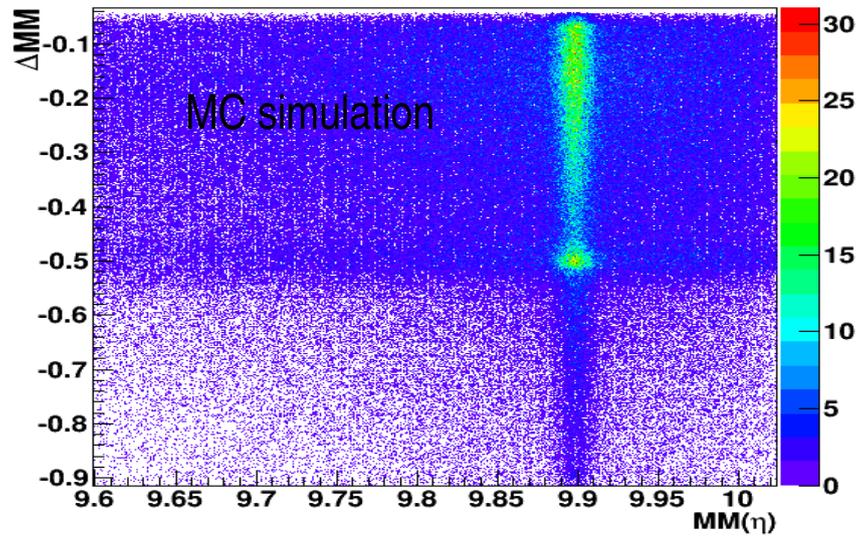
Meinel, PRD82,114502(2010)

Belle 5S : $57.9 \pm 2.3^{+1.6}_{-1.2} \text{ MeV}$

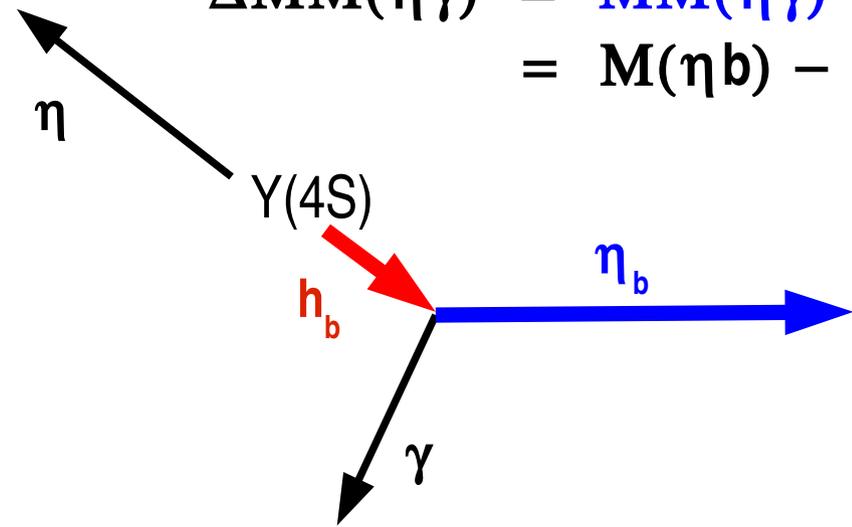
PRL109 (2012) 232002

PDG '12 : $69.3 \pm 2.8 \text{ MeV}$

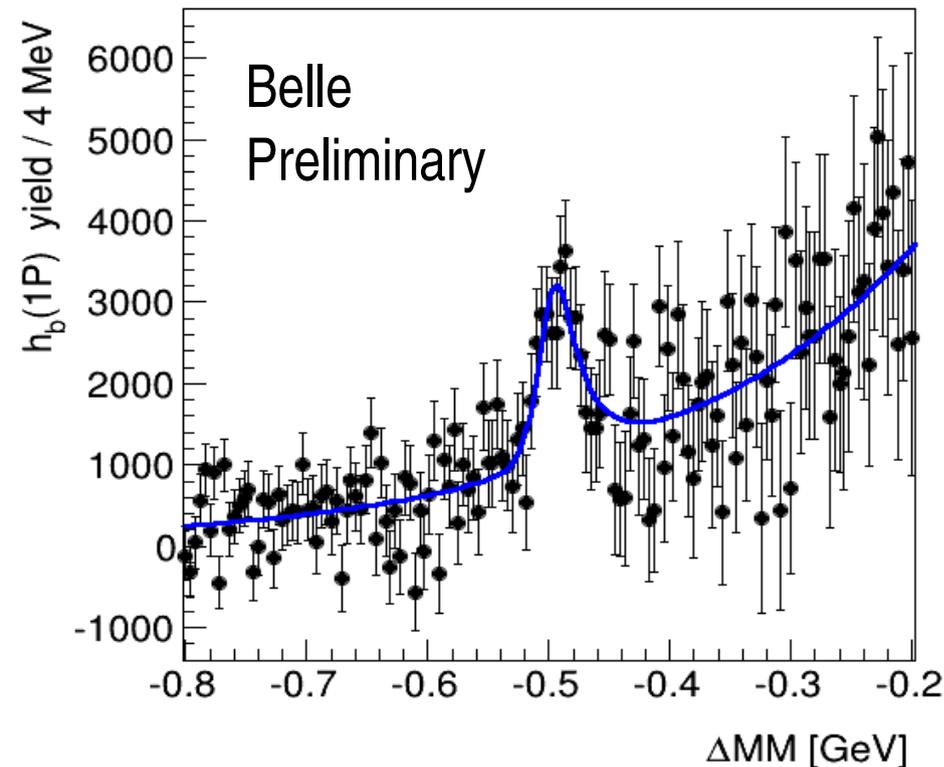
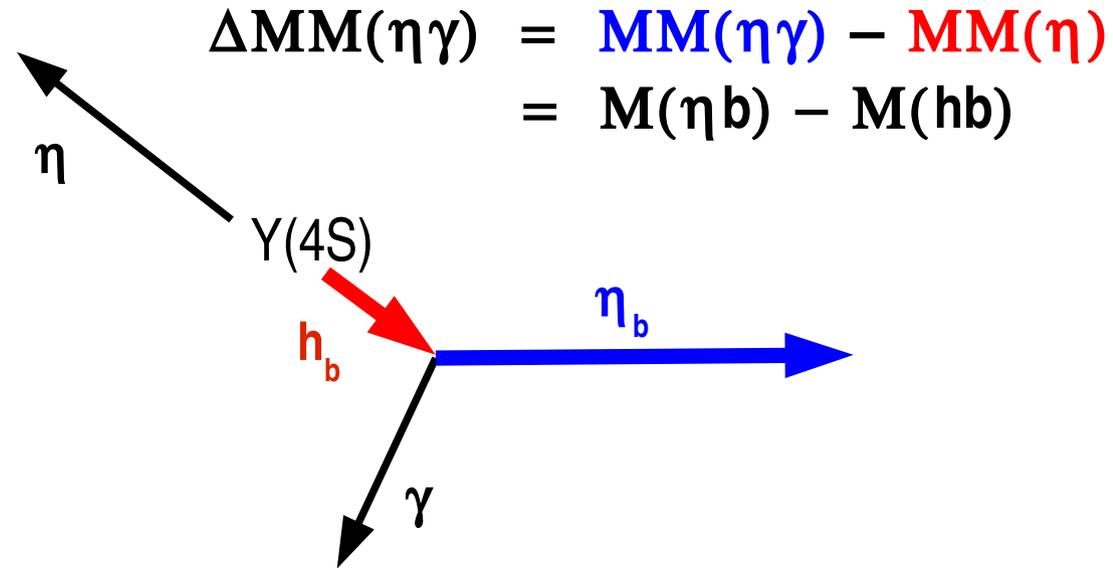
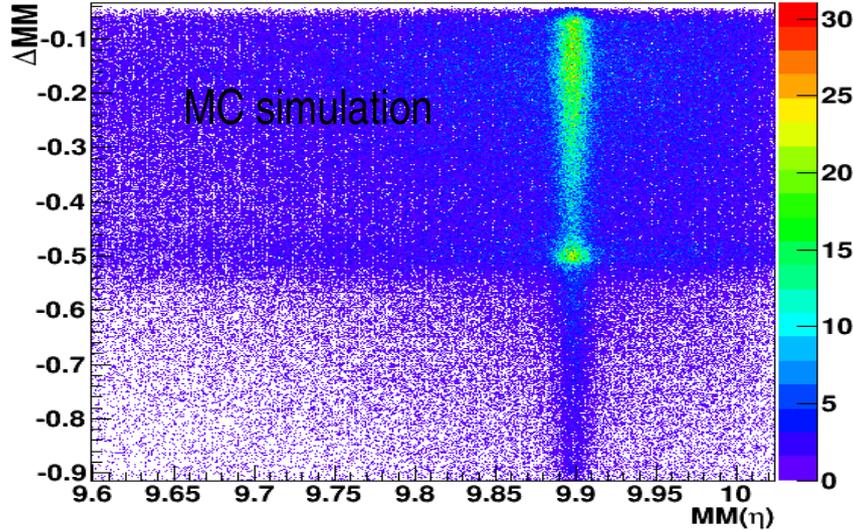
Detecting spin singlets



$$\begin{aligned}\Delta MM(\eta\gamma) &= MM(\eta\gamma) - MM(\eta) \\ &= M(\eta b) - M(hb)\end{aligned}$$



Detecting spin singlets



$$M[\eta b(1S)] = (9405.3 \pm 1.3 \pm 3.0) \text{ MeV}$$

$$\Gamma[\eta b(1S)] = (11^{+8}_{-6} \pm 3) \text{ MeV}$$

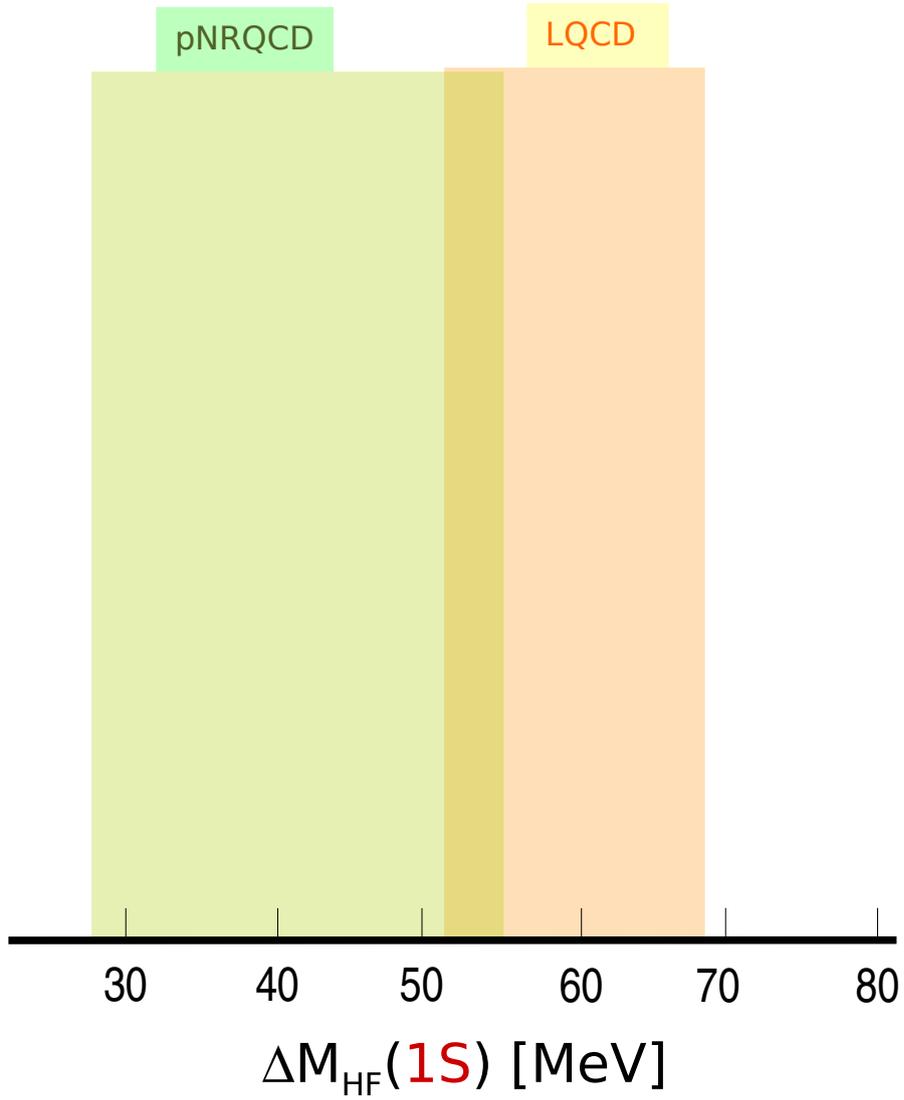
$$\text{BF}[hb(1P) \rightarrow \gamma \eta b(1S)] = (52^{+11}_{-10} \pm 4) \%$$

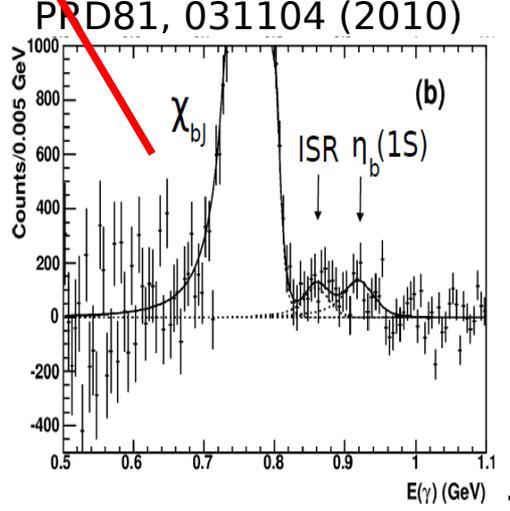
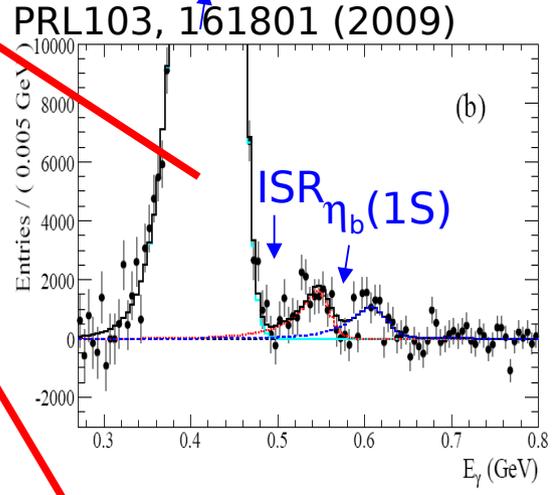
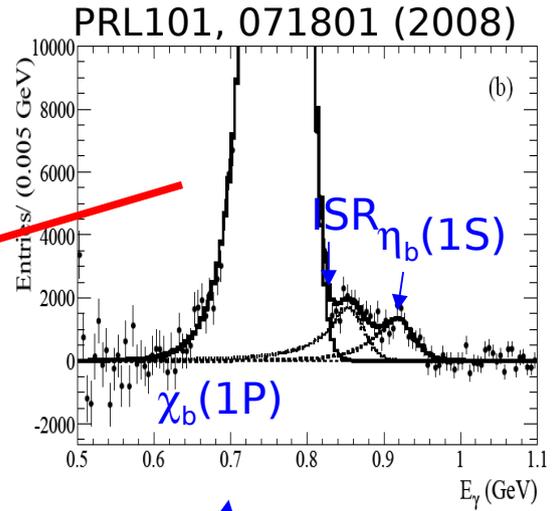
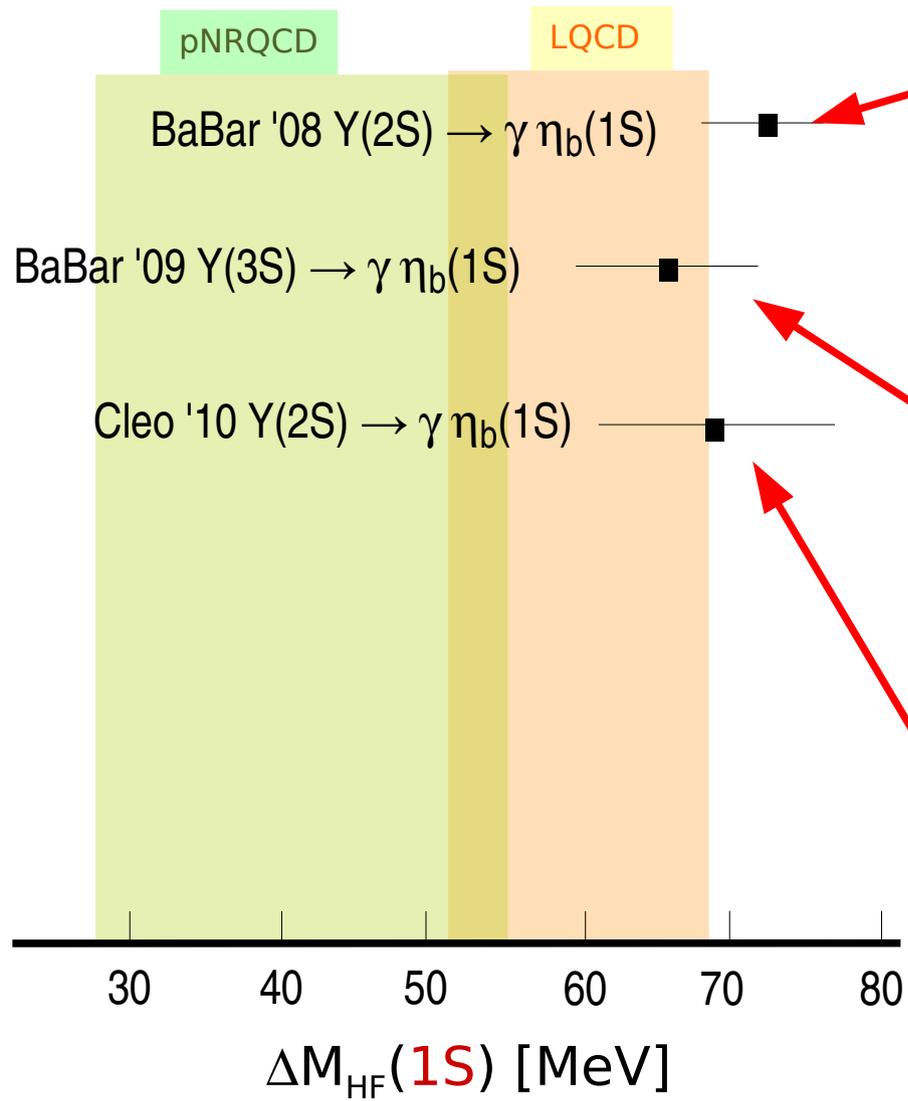
$$\Delta M_{\text{HF}}(\eta_b) = M(\eta_b) - M(Y(1S)) = (55.0 \pm 1.3 \pm 3.2) \text{ MeV}$$

Assuming $Y(1S)$ mass = 9460.3 MeV

Kniehl et al,
PRL92,242001(2004)

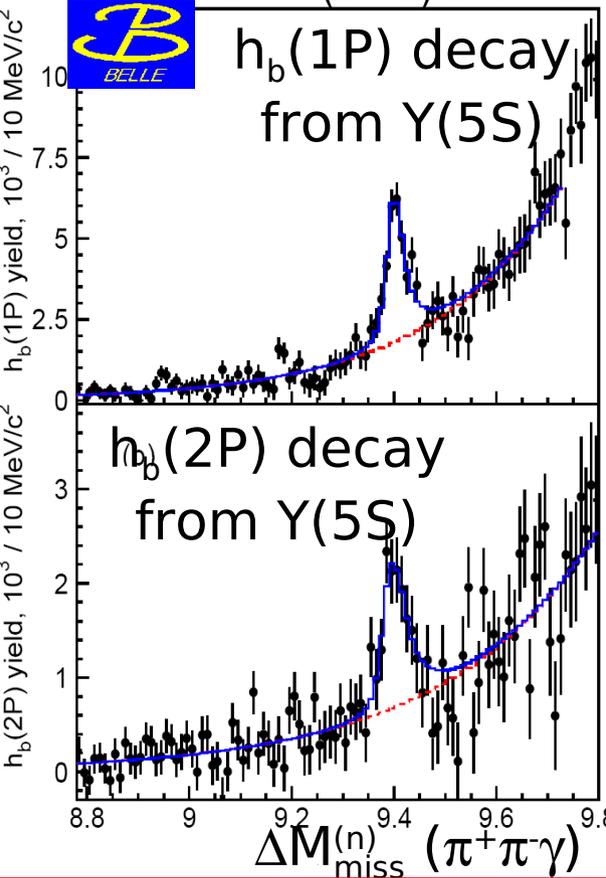
Meinel,
PRD82,114502(2010)



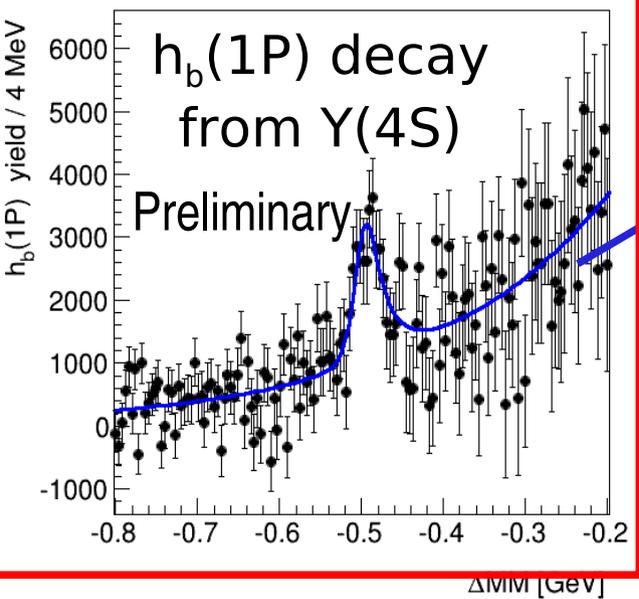




$h_b(1P)$ decay from $Y(5S)$

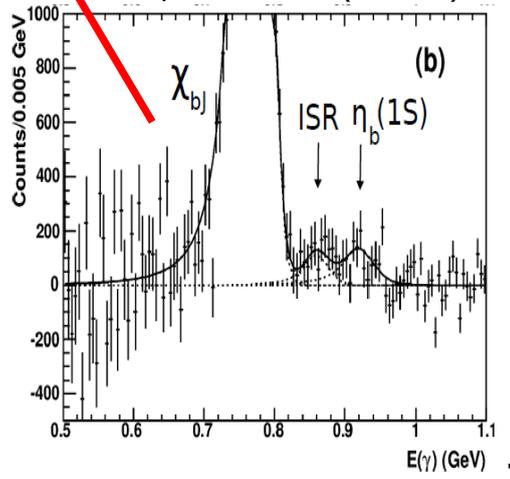
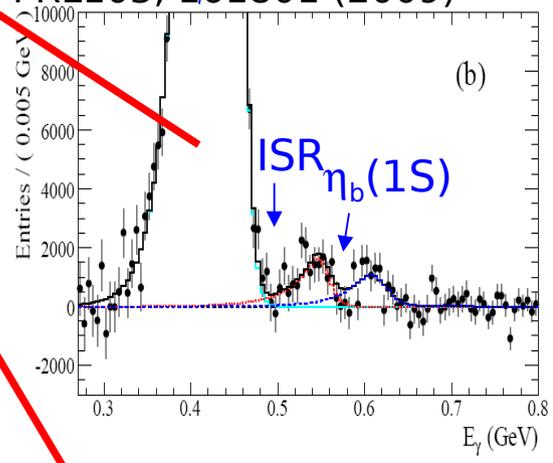
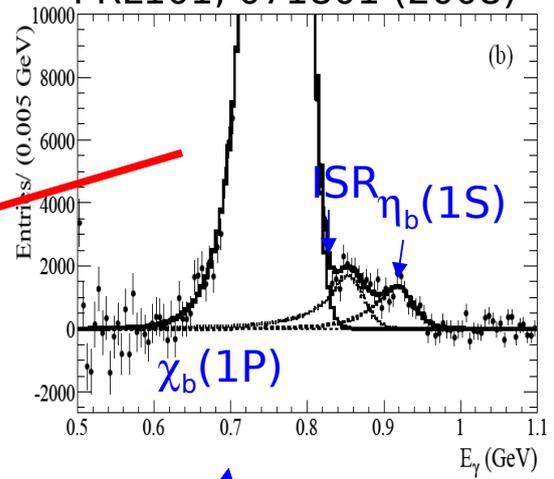
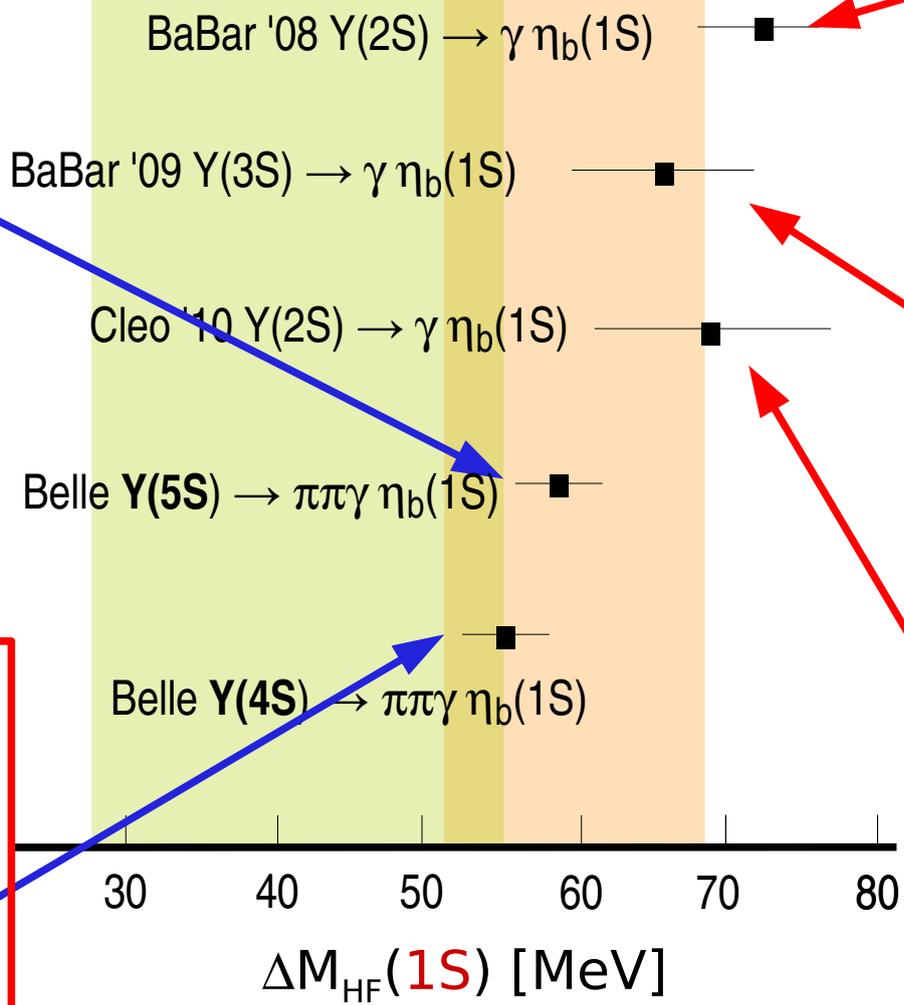


$h_b(1P)$ decay from $Y(4S)$



pNRQCD

LQCD



Part II

Hyperons in bottomonium decays

$Y(1,2S) \rightarrow \Lambda + X$

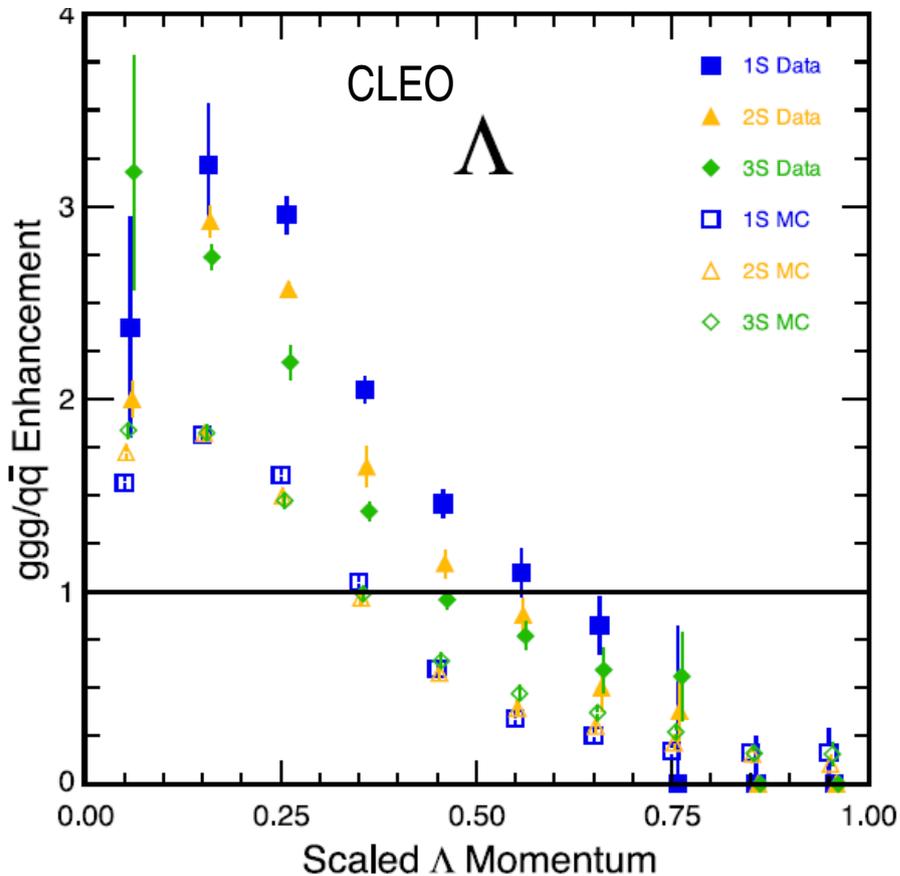
Hyperon production is **enhanced** in Y decays with respect to the nearby continuum and is **large**.

$$BF(Y(1S) \rightarrow \Lambda + X) \sim 10\%$$

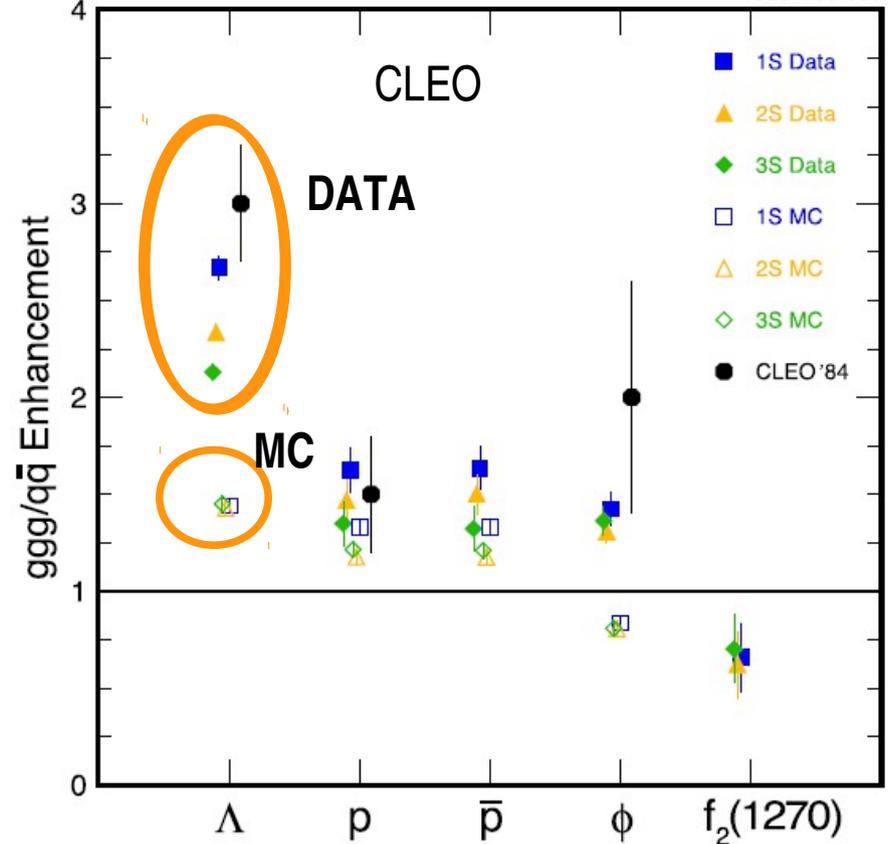
Enhancement for baryon \mathcal{B} :

$$\frac{\sigma[e^+e^- \rightarrow Y(nS) \rightarrow \mathcal{B} + X]}{\sigma[e^+e^- \rightarrow q\bar{q} \rightarrow \mathcal{B} + X]}$$

Phys.Rev.D76, 012005

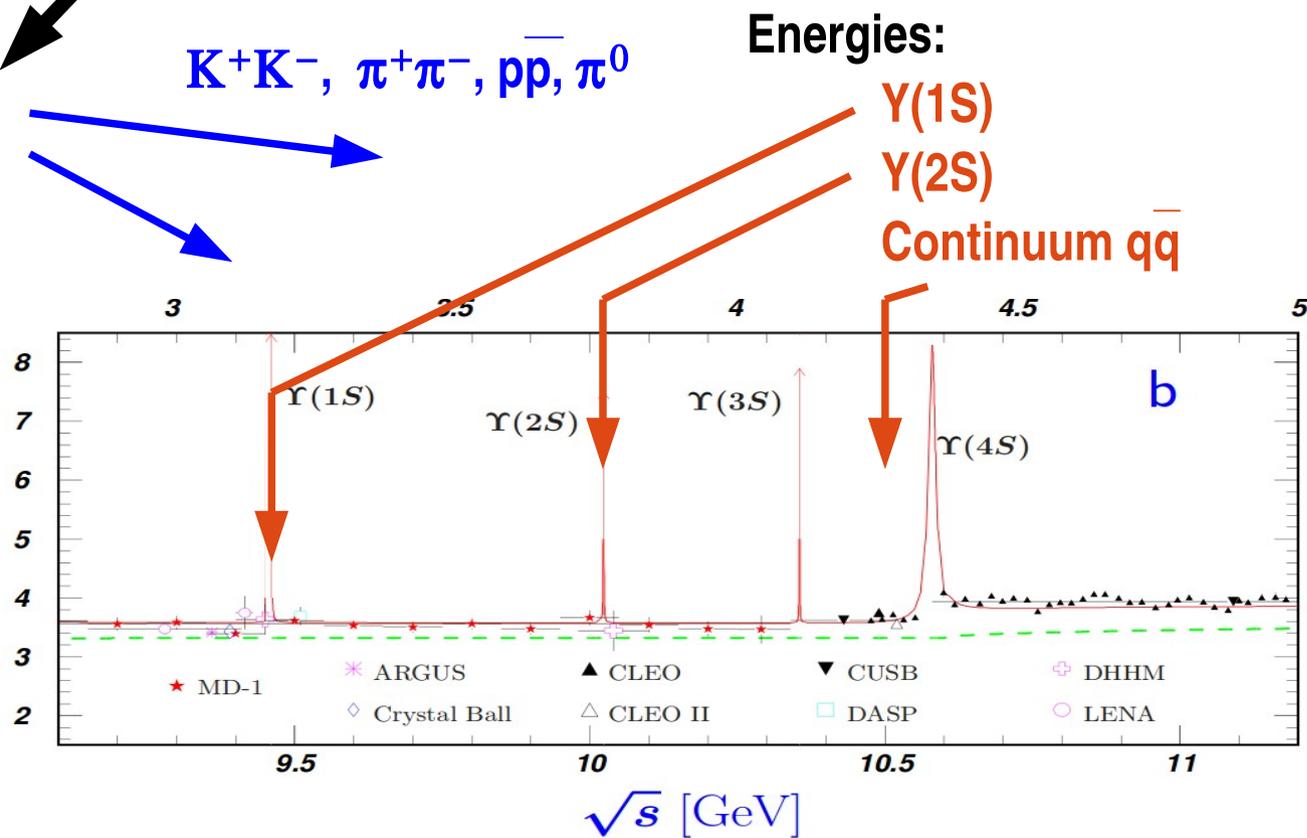
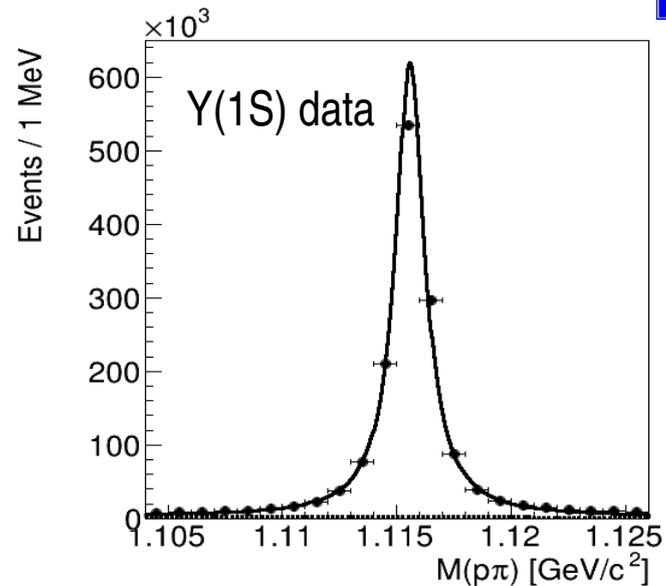
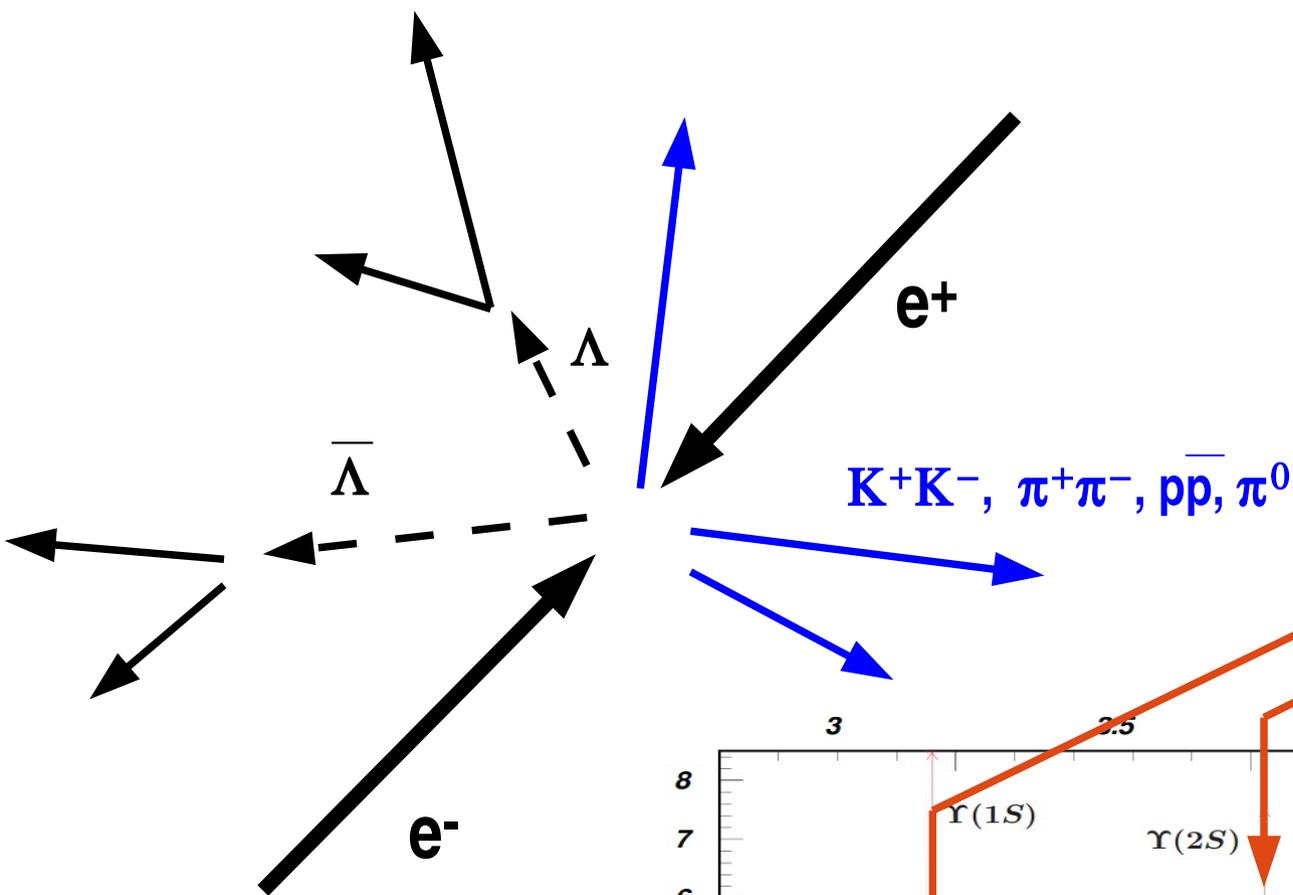


Phys.Rev.D76, 012005



$Y(1,2S) \rightarrow \text{exclusive } \Lambda \bar{\Lambda} + X$

What is the environment in which these hyperons are produced?



$Y(1,2S) \rightarrow \text{exclusive } \Lambda\bar{\Lambda} + X$

Preliminary



X = combination of K^+K^- , $\pi^+\pi^-$, $p\bar{p}$ and π^0

Max 9 bodies, Max one π^0 \rightarrow 48 channels

$$\sum_X BF[Y(1S) \rightarrow X] \simeq 2 \times 10^{-4}$$

$$\sum_X BF[Y(2S) \rightarrow X] \simeq 0.7 \times 10^{-4}$$

$$\frac{BF[Y(2S) \rightarrow X]}{BF[Y(1S) \rightarrow X]} \sim \frac{|\psi_{2S}(0)|^2}{|\psi_{1S}(0)|^2} = \mathbf{0.77}$$

Channel	$\mathcal{B}[\Upsilon(1S) \rightarrow X] [\times 10^{-6}]$	$\mathcal{B}[\Upsilon(2S) \rightarrow X] [\times 10^{-6}]$	Q
$\Lambda\bar{\Lambda} + \pi^+\pi^-$	$1.43 \pm 0.48 \pm 0.23$		
$\Lambda\bar{\Lambda} + K^+K^-$	$1.29 \pm 0.51 \pm 0.20$	$1.27 \pm 0.47 \pm 0.20$	$0.98 \pm 0.53 \pm 0.11$
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)$	$6.99 \pm 1.28 \pm 1.11$	$3.81 \pm 0.97 \pm 0.61$	$0.55 \pm 0.17 \pm 0.06$
$\Lambda\bar{\Lambda} + \pi^+\pi^-K^+K^-$	$11.83 \pm 2.01 \pm 1.87$		
$\Lambda\bar{\Lambda} + \pi^+\pi^-p\bar{p}$	$2.99 \pm 0.86 \pm 0.47$		
$\Lambda\bar{\Lambda} + 3(\pi^+\pi^-)$	$13.14 \pm 2.36 \pm 2.10$	$4.72 \pm 1.64 \pm 0.75$	$0.36 \pm 0.14 \pm 0.04$
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)K^+K^-$	$18.99 \pm 3.60 \pm 3.04$		
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)p\bar{p}$	$6.03 \pm 1.67 \pm 0.96$		
$\Lambda\bar{\Lambda} + \pi^+\pi^-2(K^+K^-)$		$2.93 \pm 1.49 \pm 0.47$	
$\Lambda\bar{\Lambda} + \pi^+\pi^- \pi^0$	$2.00 \pm 0.97 \pm 0.34$		
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-) \pi^0$	$13.86 \pm 3.96 \pm 2.35$	$9.76 \pm 3.06 \pm 1.66$	$0.70 \pm 0.30 \pm 0.08$
$\Lambda\bar{\Lambda} + \pi^+\pi^-K^+K^- \pi^0$	$18.26 \pm 4.68 \pm 3.11$		
$\Lambda\bar{\Lambda} + \pi^+\pi^-p\bar{p} \pi^0$	$5.85 \pm 2.35 \pm 0.99$		
$\Lambda\bar{\Lambda} + 3(\pi^+\pi^-) \pi^0$	$52.83 \pm 8.93 \pm 9.07$	$23.35 \pm 5.97 \pm 4.02$	$0.44 \pm 0.14 \pm 0.05$
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)K^+K^- \pi^0$	$31.78 \pm 9.35 \pm 5.54$	$30.70 \pm 8.60 \pm 5.36$	$0.97 \pm 0.39 \pm 0.12$
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)p\bar{p} \pi^0$	$15.95 \pm 5.81 \pm 2.76$		

$Y(1,2S) \rightarrow \text{exclusive } \Lambda\bar{\Lambda} + X$



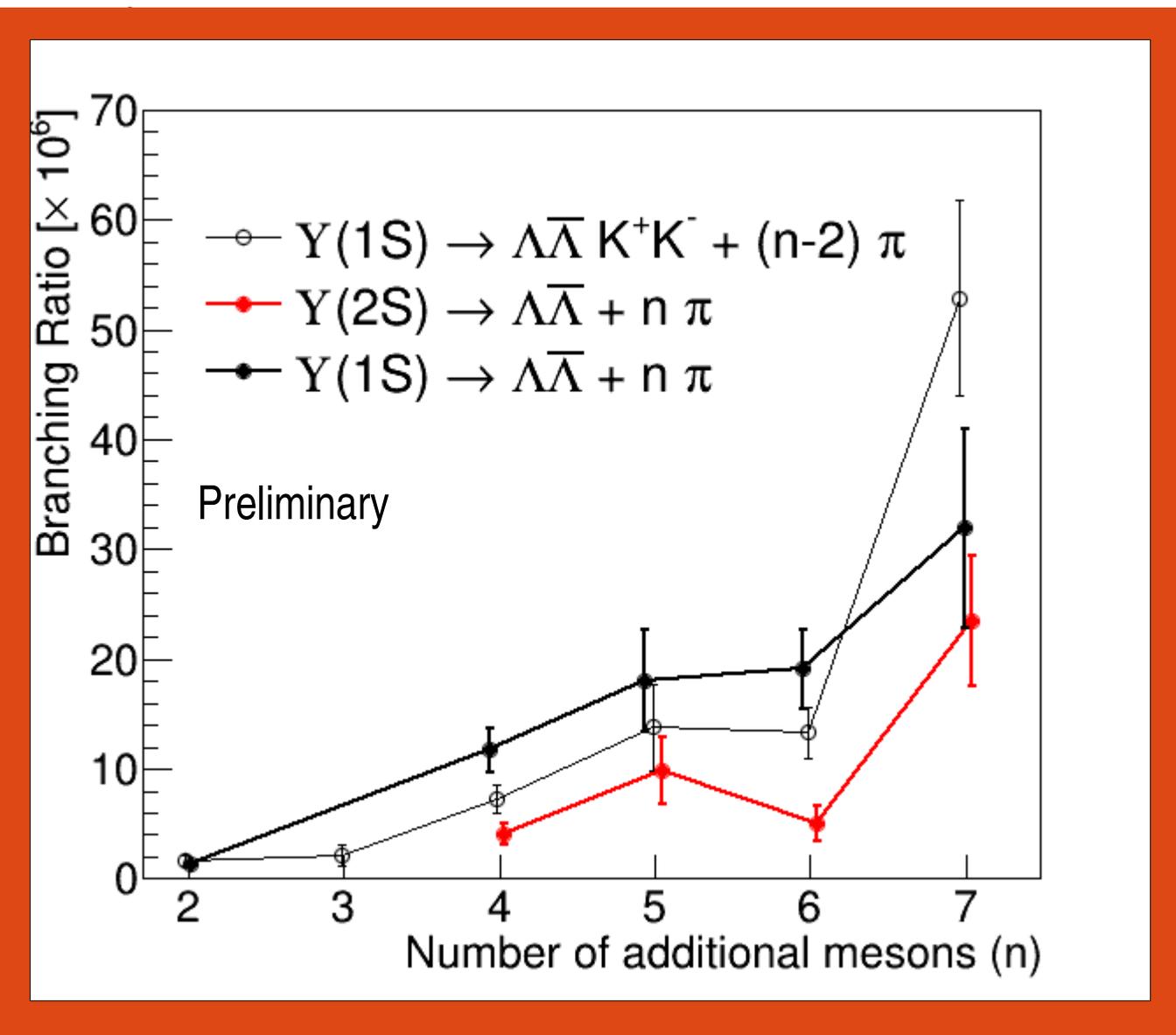
X = combination of K^+K^- , $\pi^+\pi^-$, $p\bar{p}$ and π^0

Max 9 bodies, Max

$$\sum_X BF[Y(1S) \rightarrow \Lambda\bar{\Lambda} + X]$$

$$\sum_X BF[Y(2S) \rightarrow \Lambda\bar{\Lambda} + X]$$

Channel
$\Lambda\bar{\Lambda} + \pi^+\pi^-$
$\Lambda\bar{\Lambda} + K^+K^-$
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)$
$\Lambda\bar{\Lambda} + \pi^+\pi^-K^+K^-$
$\Lambda\bar{\Lambda} + \pi^+\pi^-p\bar{p}$
$\Lambda\bar{\Lambda} + 3(\pi^+\pi^-)$
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)$
$\Lambda\bar{\Lambda} + \pi^+\pi^-2(\pi^+\pi^-)$
$\Lambda\bar{\Lambda} + \pi^+\pi^- \pi^0$
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)$
$\Lambda\bar{\Lambda} + \pi^+\pi^-K^+K^-$
$\Lambda\bar{\Lambda} + \pi^+\pi^-p\bar{p}$
$\Lambda\bar{\Lambda} + 3(\pi^+\pi^-)$
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)K^+K^- \pi^0$
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)p\bar{p} \pi^0$



$$\frac{|\dots\rangle|^2}{|\dots\rangle|^2} = 0.77$$

Q
$\pm 0.53 \pm 0.11$
$\pm 0.17 \pm 0.06$
$\pm 0.14 \pm 0.04$
$\pm 0.30 \pm 0.08$
$\pm 0.14 \pm 0.05$
$0.97 \pm 0.39 \pm 0.12$

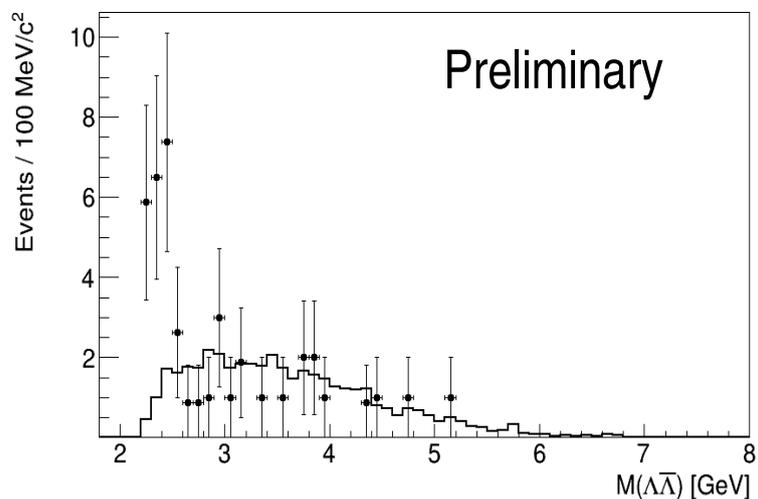
$31.78 \pm 9.35 \pm 5.54$	$30.70 \pm 8.60 \pm 5.36$
$15.95 \pm 5.81 \pm 2.76$	

$Y(1,2S) \rightarrow \text{exclusive } \Lambda \bar{\Lambda} + X$

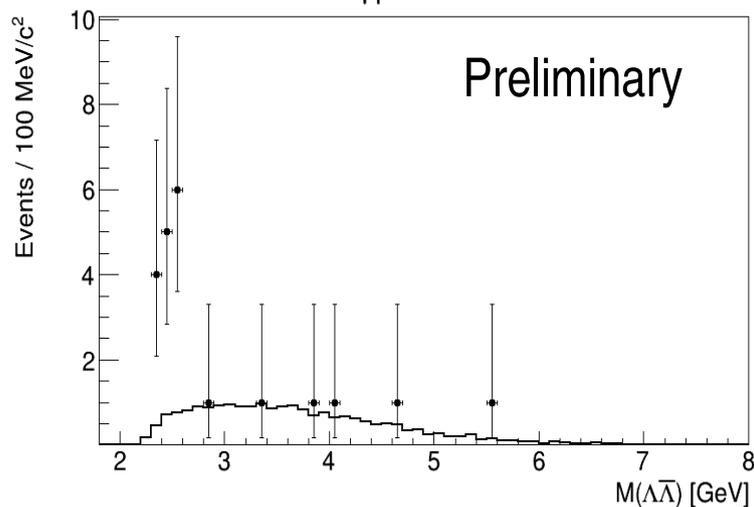
Dynamical interaction within the $\Lambda \bar{\Lambda}$ pair

→ Low threshold enhancement in $M(\mathcal{B}\bar{\mathcal{B}})$ is a common feature in B meson baryonic decays

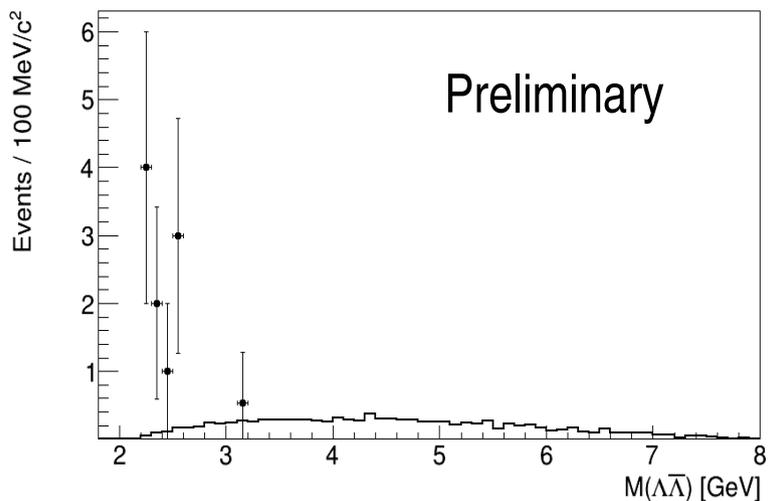
$Y(1S) \rightarrow \Lambda \bar{\Lambda} \pi^+ \pi^- K^+ K^-$



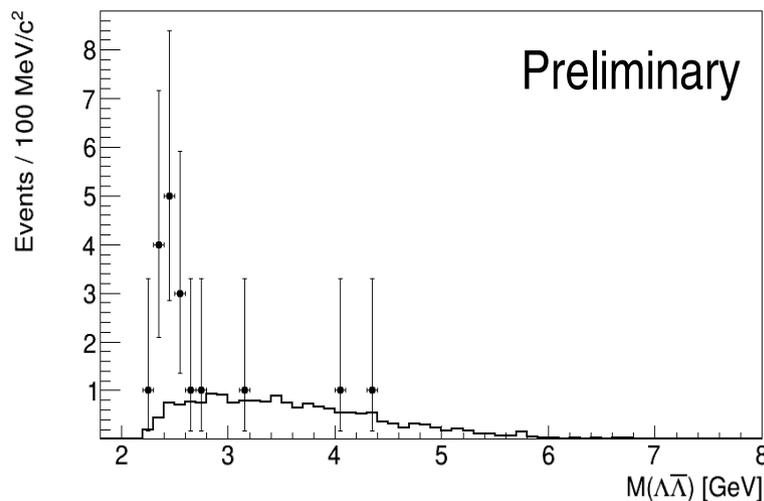
$e^+e^- \rightarrow q\bar{q} \rightarrow \Lambda \bar{\Lambda} \pi^+ \pi^- \pi^+ \pi^-$



$Y(2S) \rightarrow \Lambda \bar{\Lambda} K^+ K^-$



$e^+e^- \rightarrow q\bar{q} \rightarrow \Lambda \bar{\Lambda} \pi^+ \pi^- K^+ K^-$

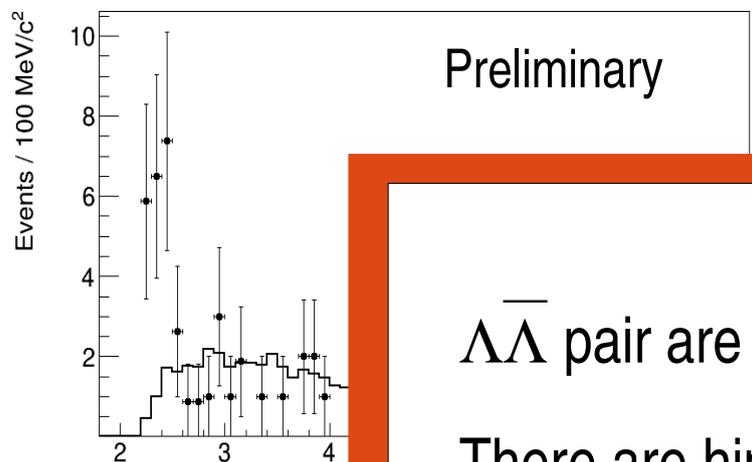


$Y(1,2S) \rightarrow \text{exclusive } \Lambda\bar{\Lambda} + X$

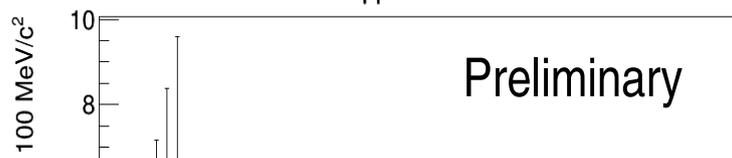
Dynamical interaction within the $\Lambda\bar{\Lambda}$ pair

→ Low threshold enhancement in $M(\mathcal{B}\bar{\mathcal{B}})$ is a common feature in B meson baryonic decays

$Y(1S) \rightarrow \Lambda\bar{\Lambda}\pi^+\pi^-K^+K^-$



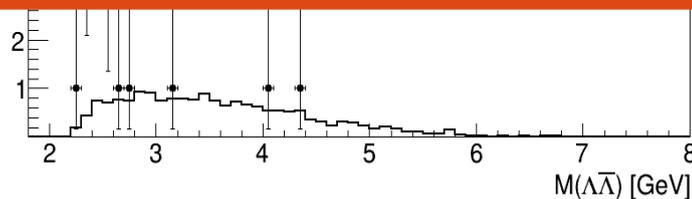
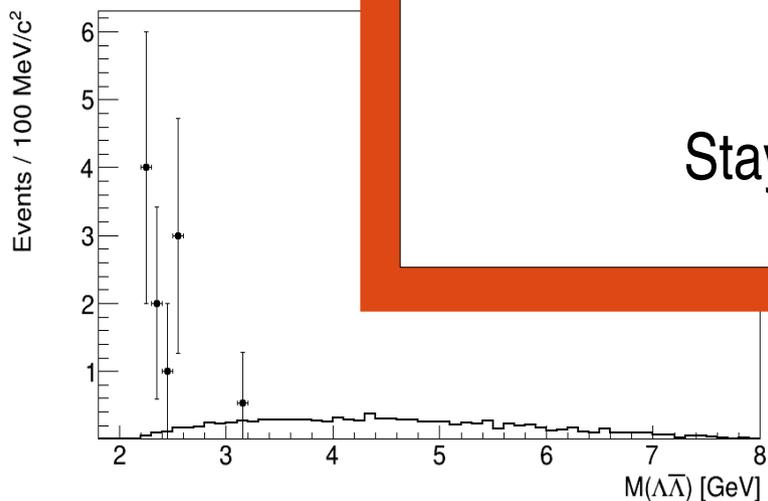
$e^+e^- \rightarrow q\bar{q} \rightarrow \Lambda\bar{\Lambda}\pi^+\pi^-\pi^+\pi^-$



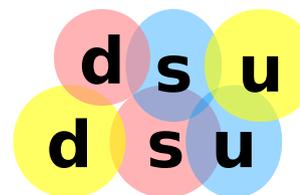
$\Lambda\bar{\Lambda}$ pair are produced in high multiplicity events
There are hints of interaction between Λ and $\bar{\Lambda}$

Stay tuned for inclusive analysis

$Y(2S)$

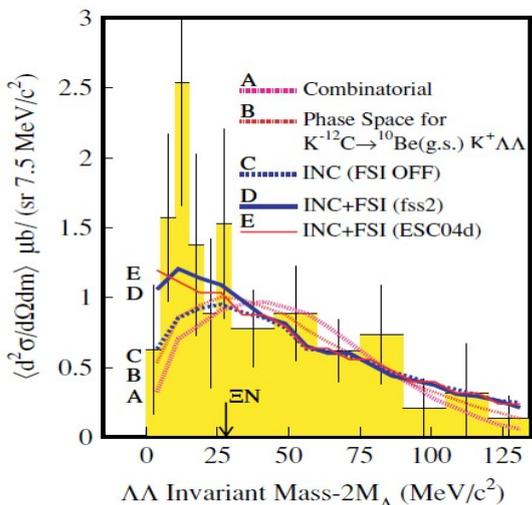


Search for H dibaryon

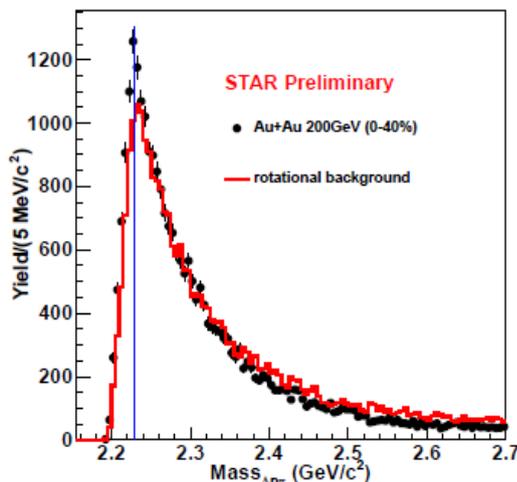


Exotic state (Jaffe, 1977)

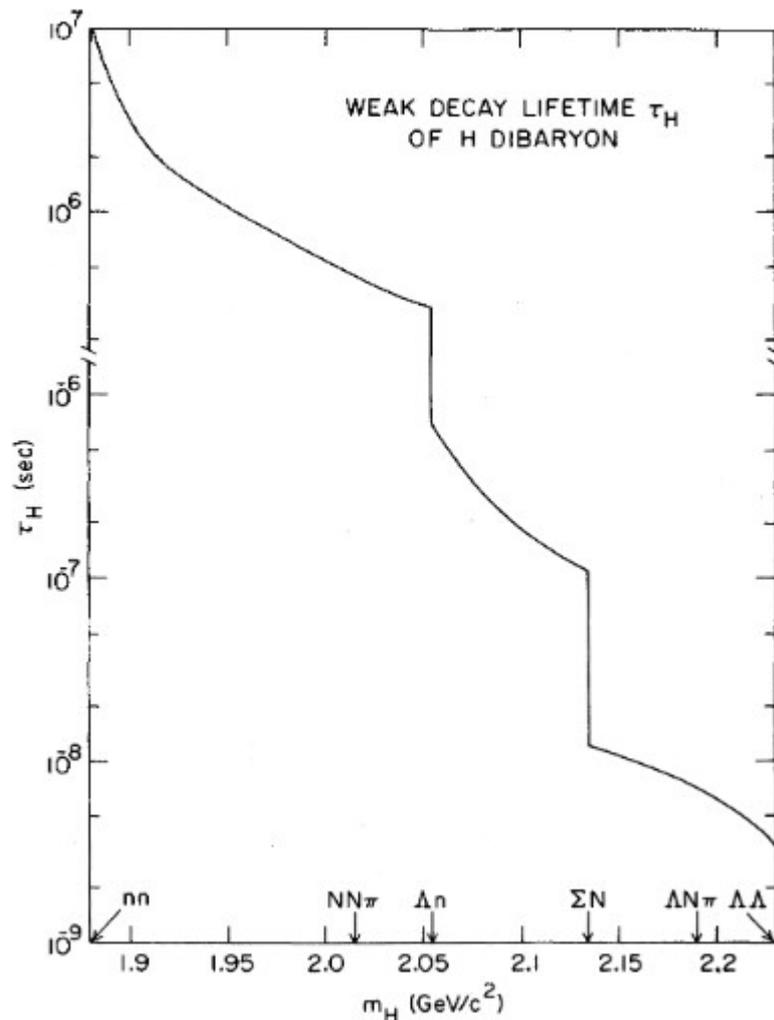
→ completely antisymmetric arrangement of uuddss



KEK-PS
E522(2007)



RHIC-STAR
(2011)



Y(nS) can produce **bound baryon-baryon states**
high yield of low momentum Λ .

→ can the H^0 be produced also?

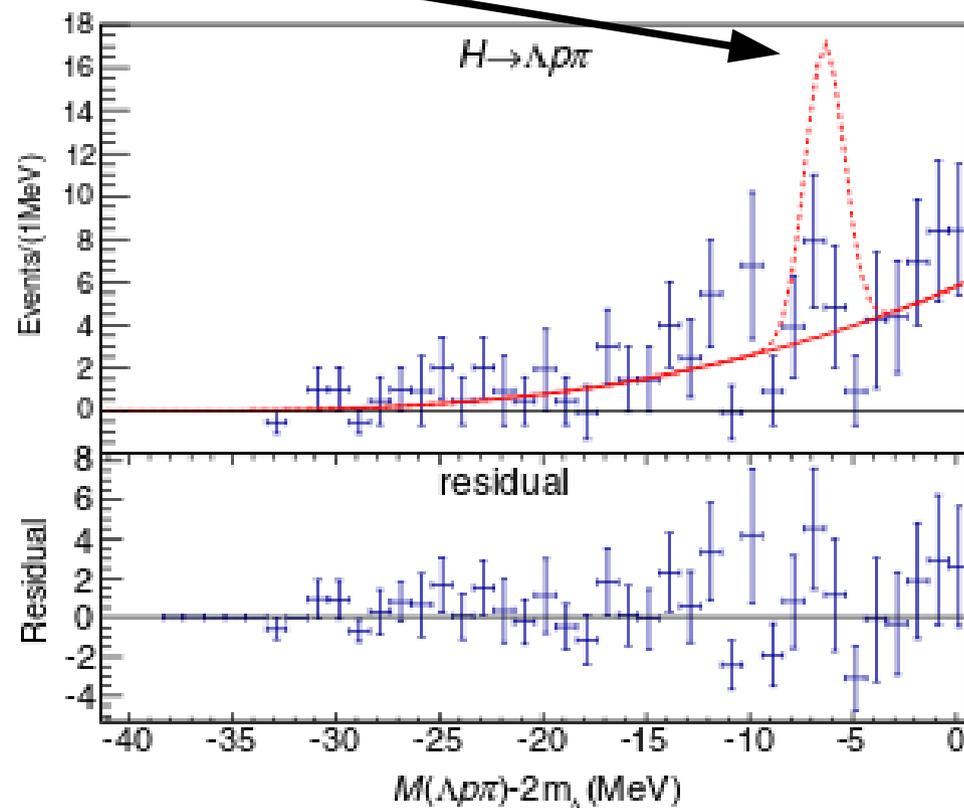
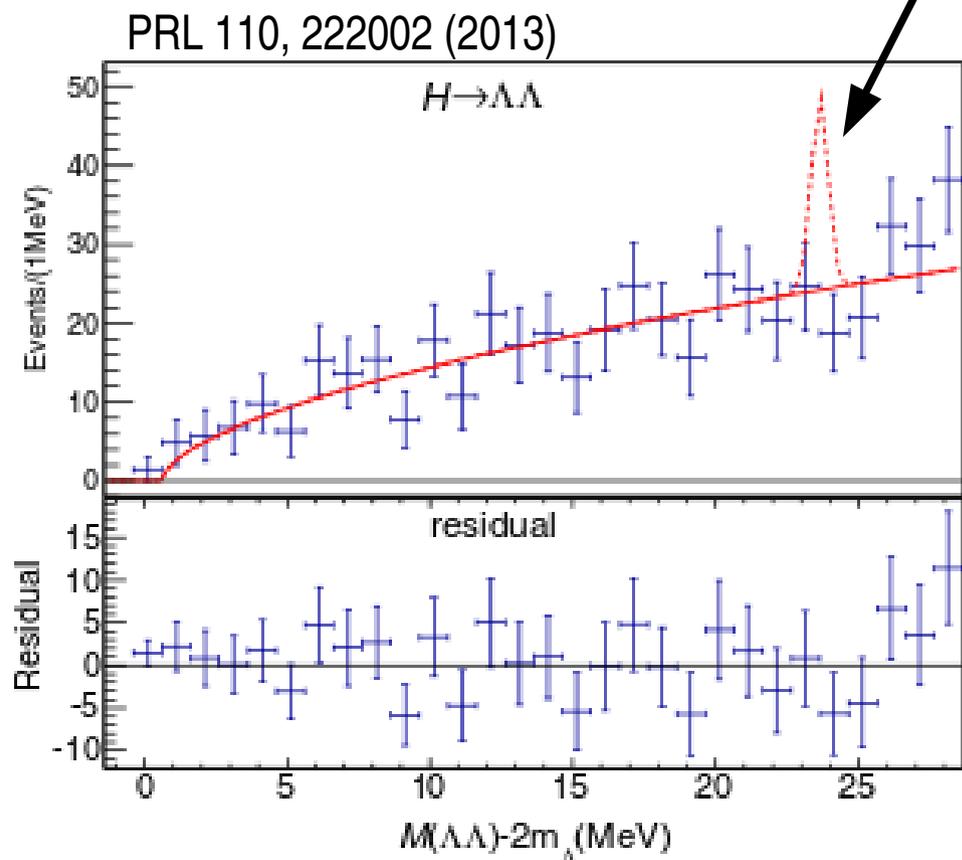
Search for H dibaryon

PRL 110, 222002 (2013)

Analysis strategy:

- Inclusive reconstruction in Y(1S) and Y(2S) sample
- Decays with $H \rightarrow \Lambda\Lambda$, $H \rightarrow \Xi^- p$, $H \rightarrow \Lambda p \pi^-$

Assuming $\text{BF}[Y(1,2S) \rightarrow H + X] = 5\% \text{BF}[Y(1,2S) \rightarrow d + X]$

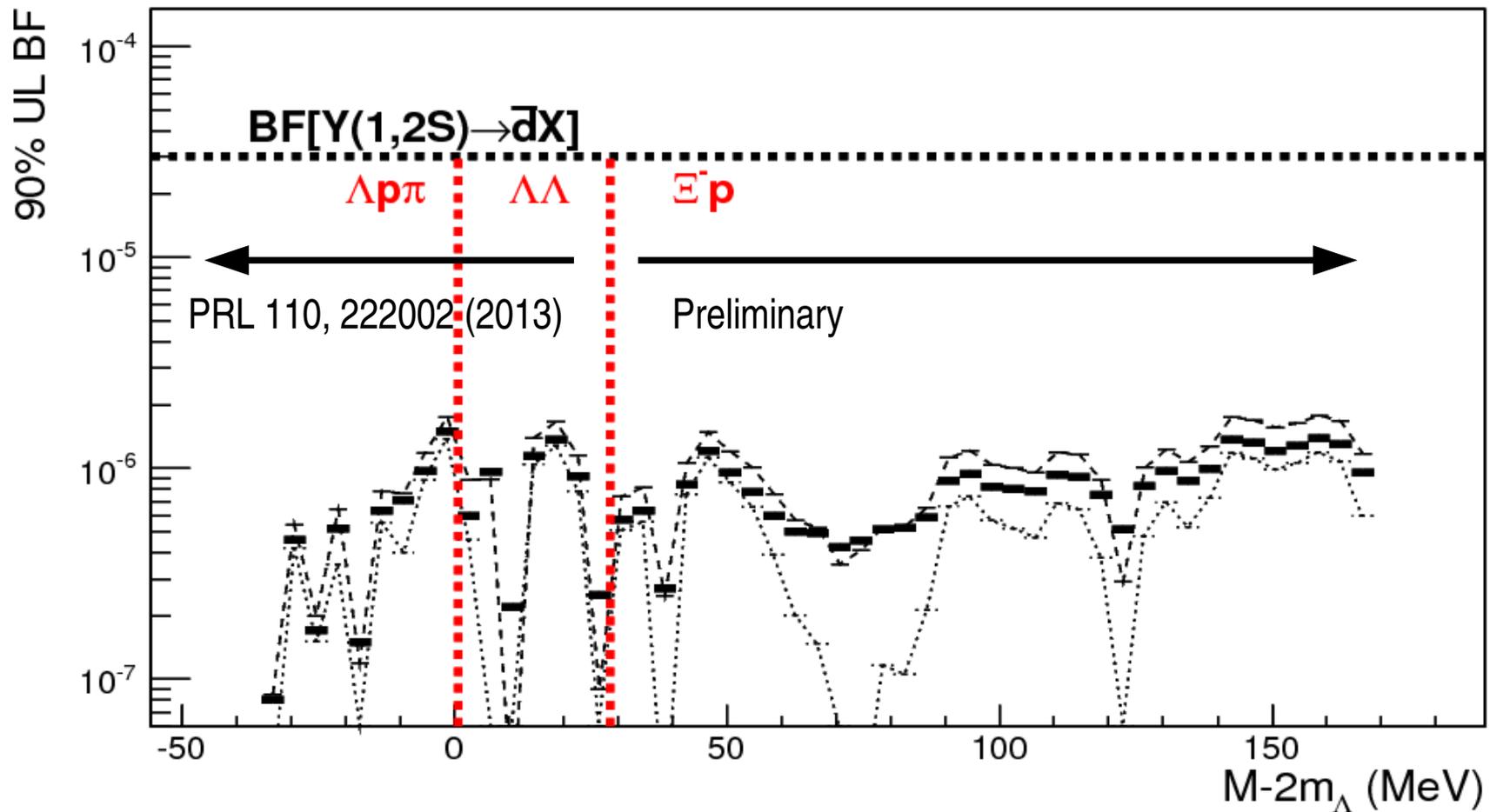


Search for H dibaryon

Analysis strategy:

- Inclusive reconstruction in $Y(1S)$ and $Y(2S)$ sample
- Decays with $H \rightarrow \Lambda\Lambda$, $H \rightarrow \Xi^- p$, $H \rightarrow \Lambda p \pi^-$

Stay tuned for
Pentaquark searches



First observation of $Y(4S) \rightarrow \eta h_b(1P)$ Preliminary

→ First test of QCDME with $\eta h_b(1P)$ transitions

First study of $Y(5S) \rightarrow \eta h_b(1P)$ Preliminary

→ No evidences, but upper limits allows to increase our knowledge of the spin flipping transitions pattern

First study of $Y(5S) \rightarrow \eta h_b(1P)$ Preliminary

→ No evidences, but upper limits allows to increase our knowledge of the spin flipping transitions pattern

Updated parameters of $\eta_b(1S)$ Preliminary

First evidence of near threshold enhancement in bottomonium decays

Stringent upper limits on H dibaryon production

Backup

Z_b in $Y(nS)$ final states

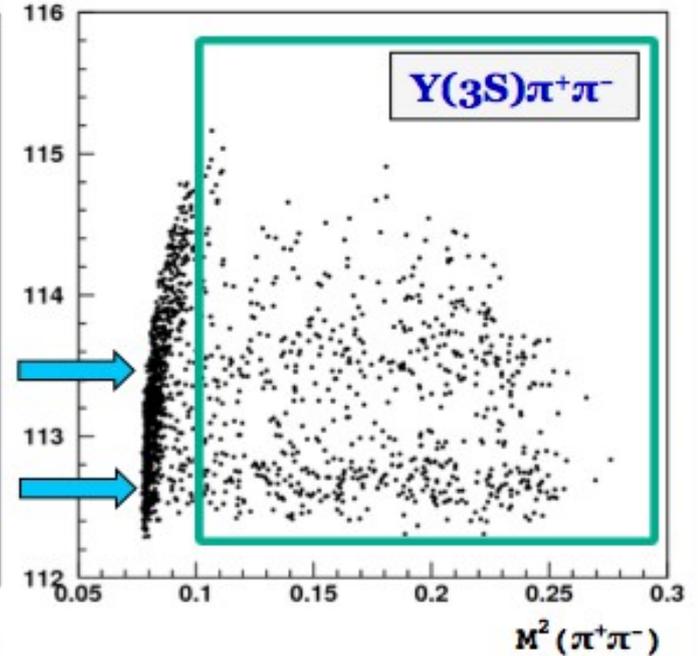
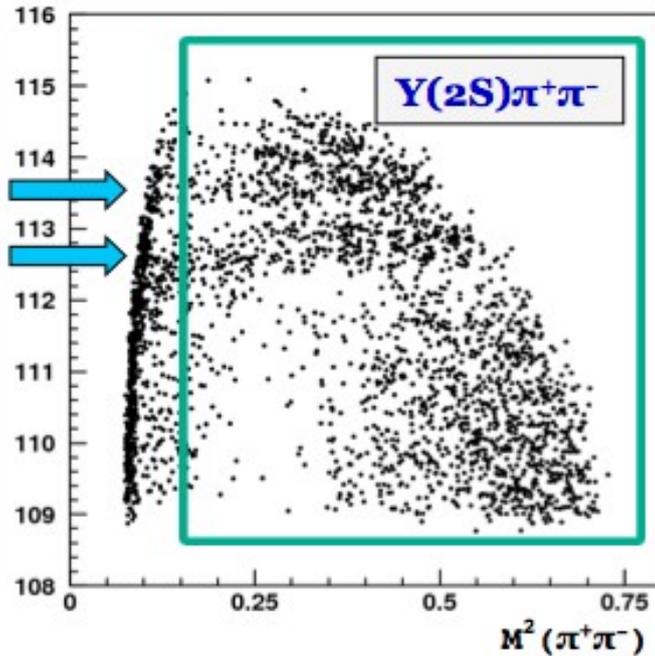
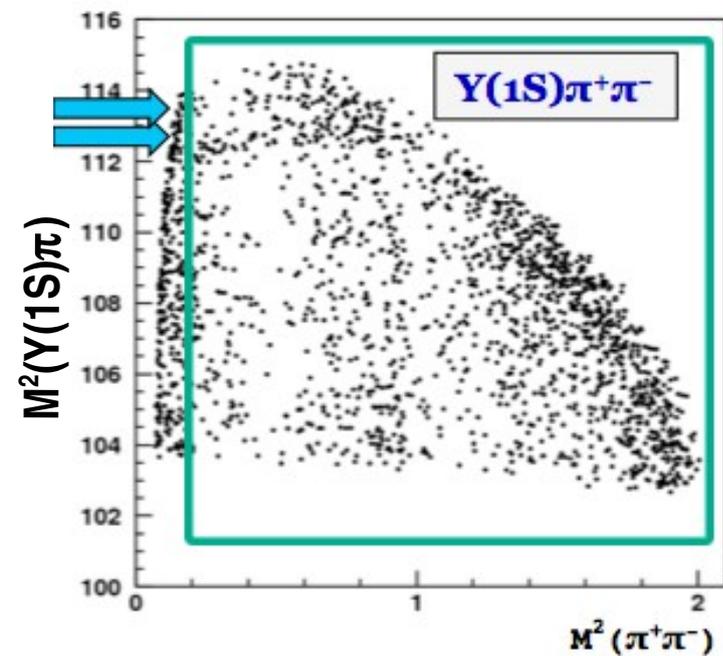
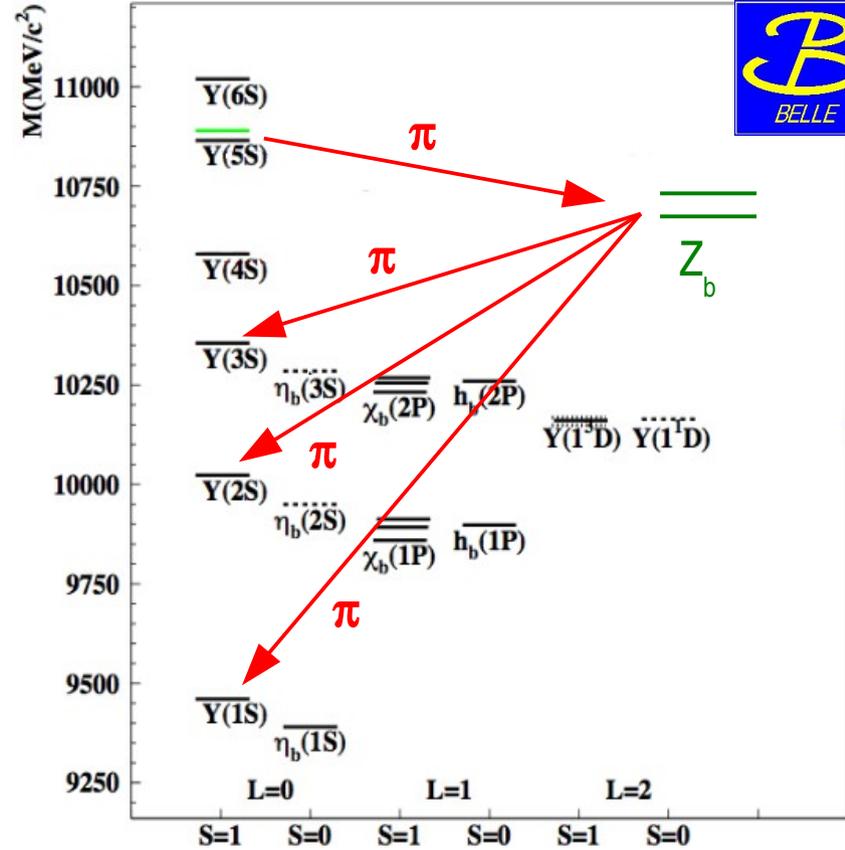
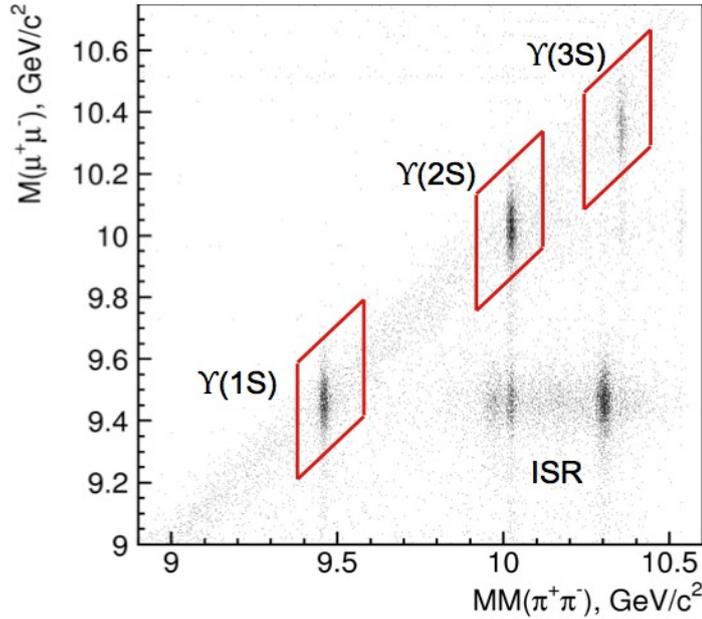
PRL108,122001



$Y(nS) \rightarrow \mu^+\mu^-$

- Clean final state
- Pure $Y(nS)$ sample
- $\pi^+\pi^-$ recoil tag

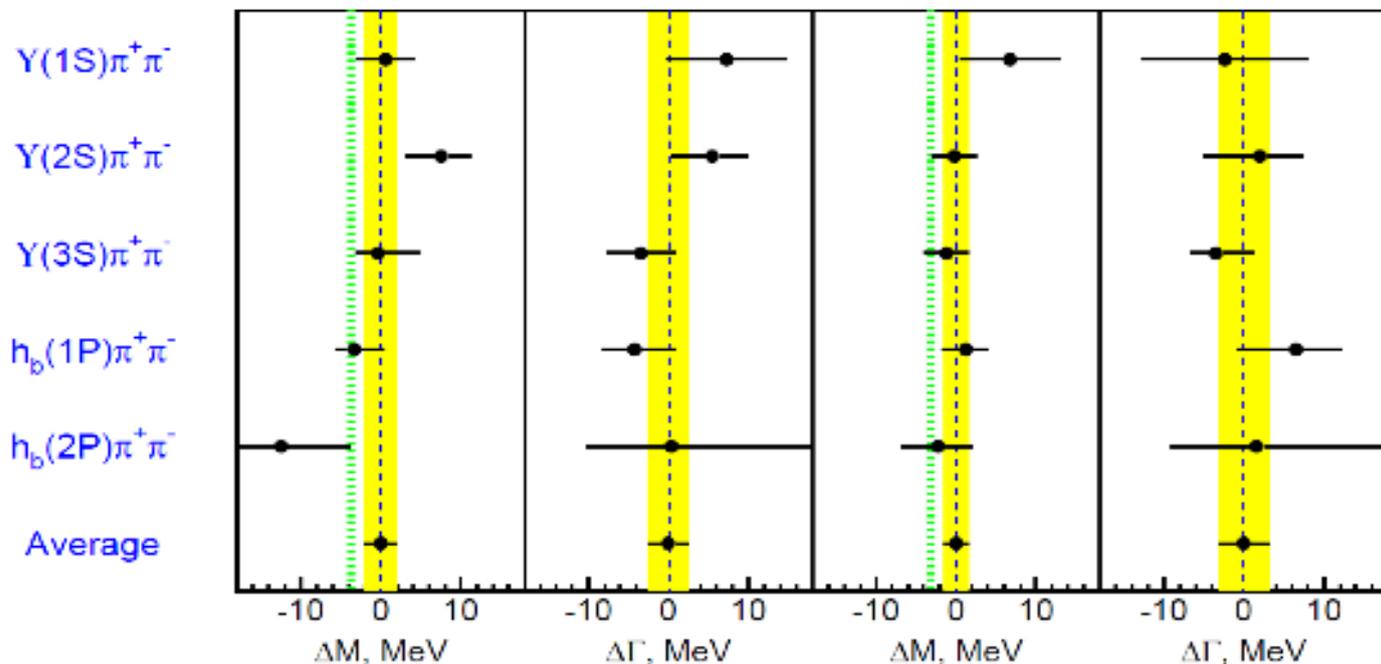
3 other observation of Z_b 's!



Z_b Summary



PRL108,122001



Mass and Γ measured in 5 different final states agree

Angular analysis suggests $J^P = 1^+$

$Z_b(10610)$

$M = 10608 \pm 2.0 \text{ MeV}$

$\Gamma = 15.6 \pm 2.5 \text{ MeV}$

$Z_b(10650)$

$M = 10653 \pm 1.5 \text{ MeV}$

$\Gamma = 14.4 \pm 3.2 \text{ MeV}$

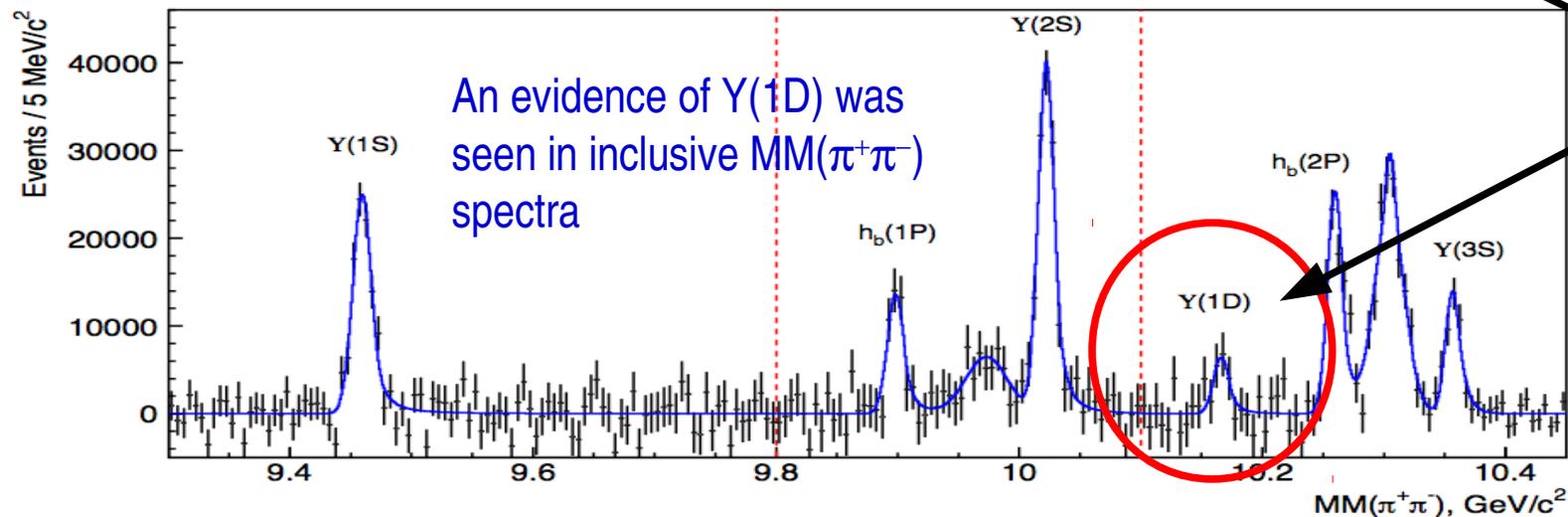
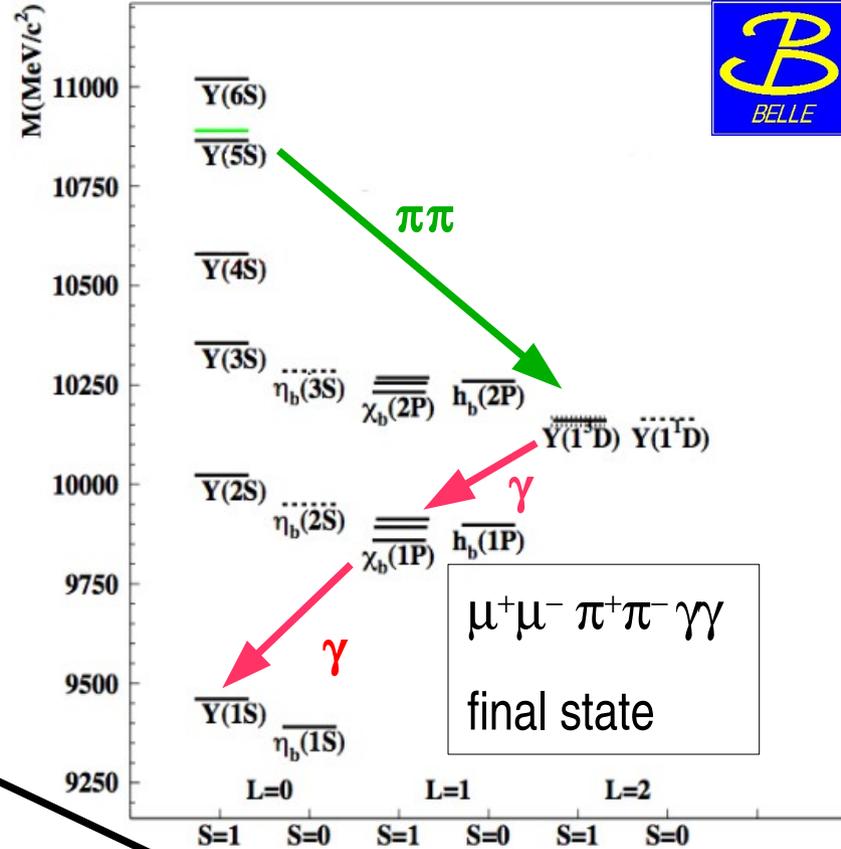
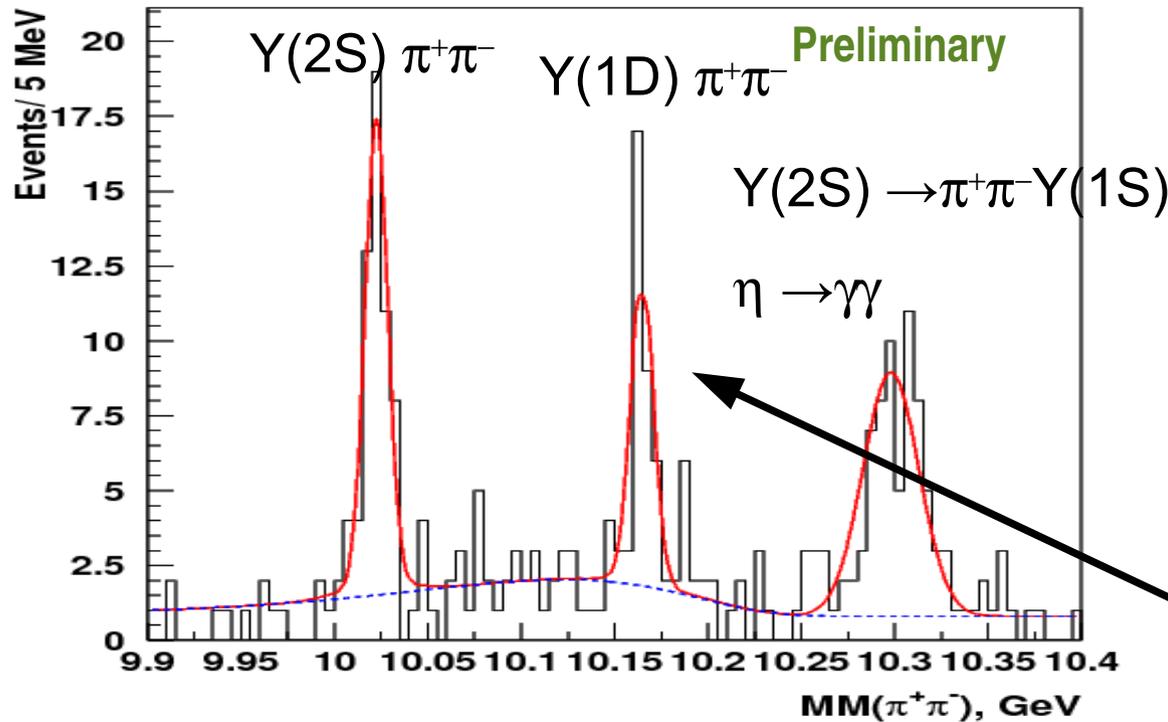
The Di Pion transitions from the Y(5S) proceed via the intermediate charged state Z_b

The transition does not imply spin flip

Masses are close to B^*B and B^*B^* thresholds
Molecules?

The Y(5S) is an unexpected source of h_b

$Y(5S) \rightarrow Y(1D) \pi^+ \pi^-$



Significance 9σ

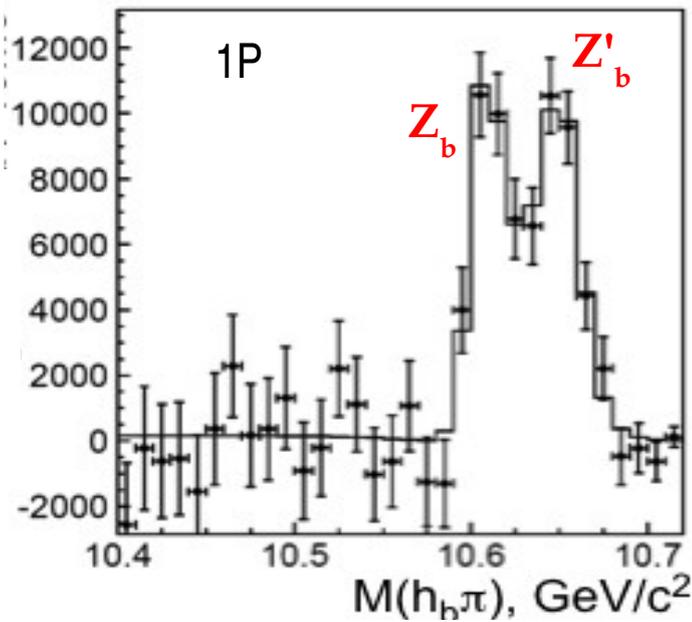
Significance 2.9σ

$$B[Y(5S) \rightarrow Y(1D) \pi^+ \pi^-] B[Y(1D) \rightarrow \chi_b(1P) \gamma \rightarrow Y(1S) \gamma \gamma] = (2.0 \pm 0.4 \pm 0.3) 10^{-4}$$

$\pi h_b(1,2P)$ mass: Z_b

PRL108,122001

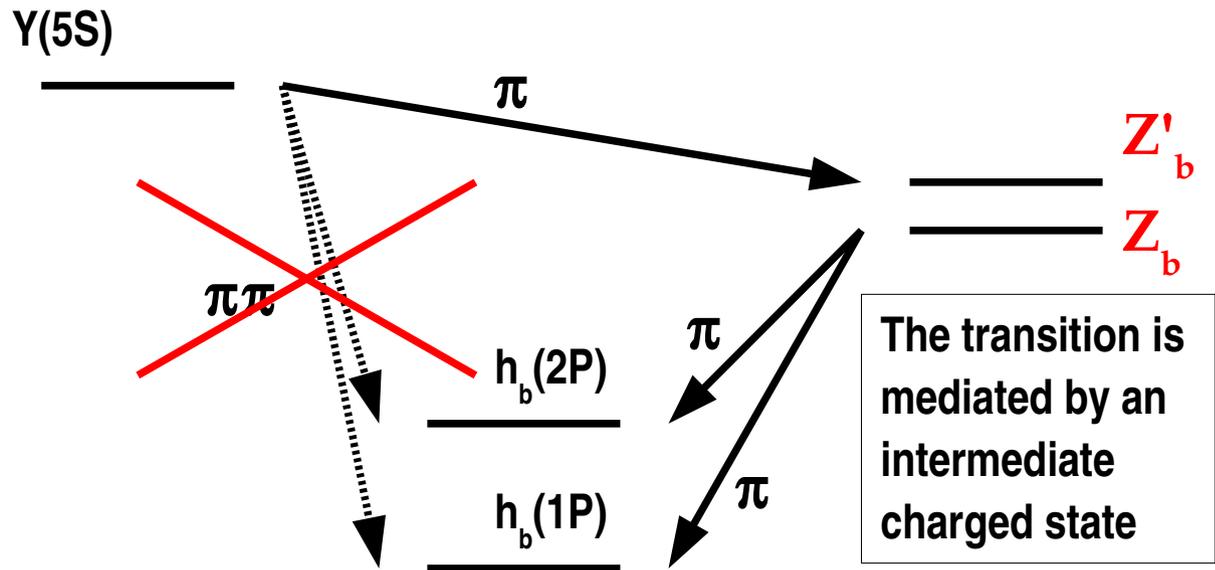
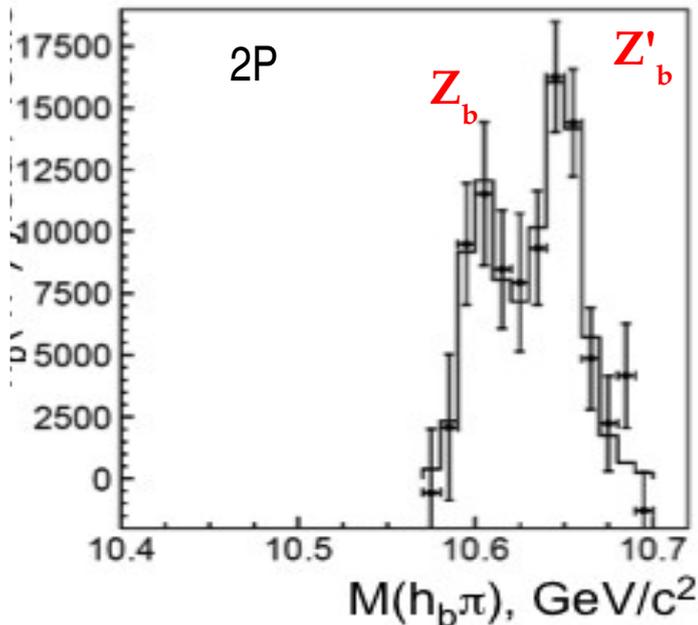
The heavy quark spin flip is predicted to suppress the $\pi\pi h_b$ transition



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

No suppression

Intermediate state? Look at h_b yield in bins of $M(\pi h_b)$
(1 point \rightarrow 1 fit)



$h_b(1P,2P) \rightarrow \gamma \eta_b(1S,2S)$



PRL109 (2012) 232002

$h_b(1,2P)$ is predicted to have large BF for radiative decays to η_b

$$\text{BF}[h_b(1P) \rightarrow \gamma \eta_b(1S)] = 41\%$$

$$\text{BF}[h_b(2P) \rightarrow \gamma \eta_b(1S)] = 63\%$$

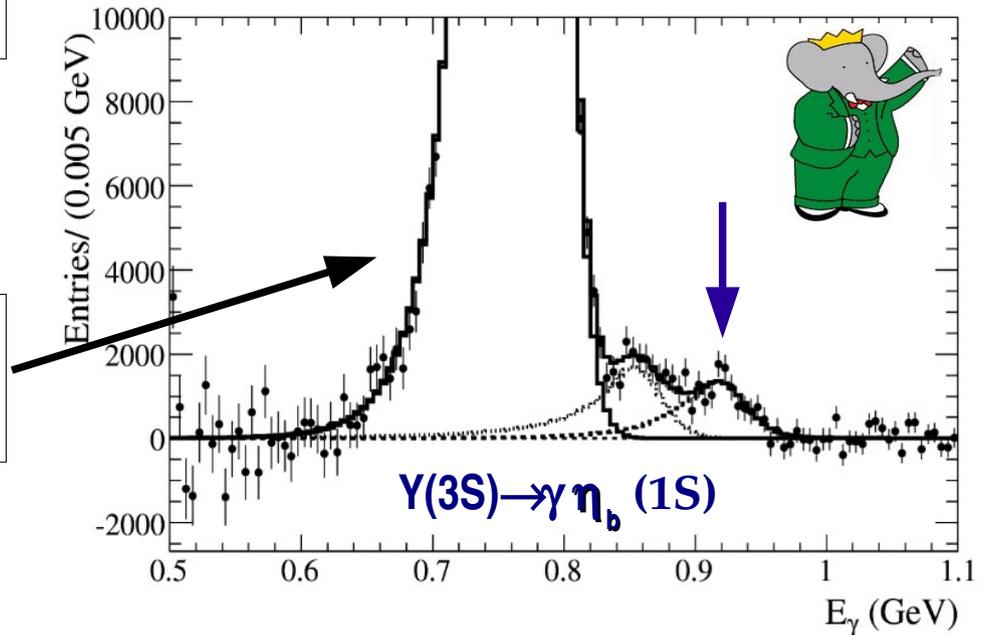
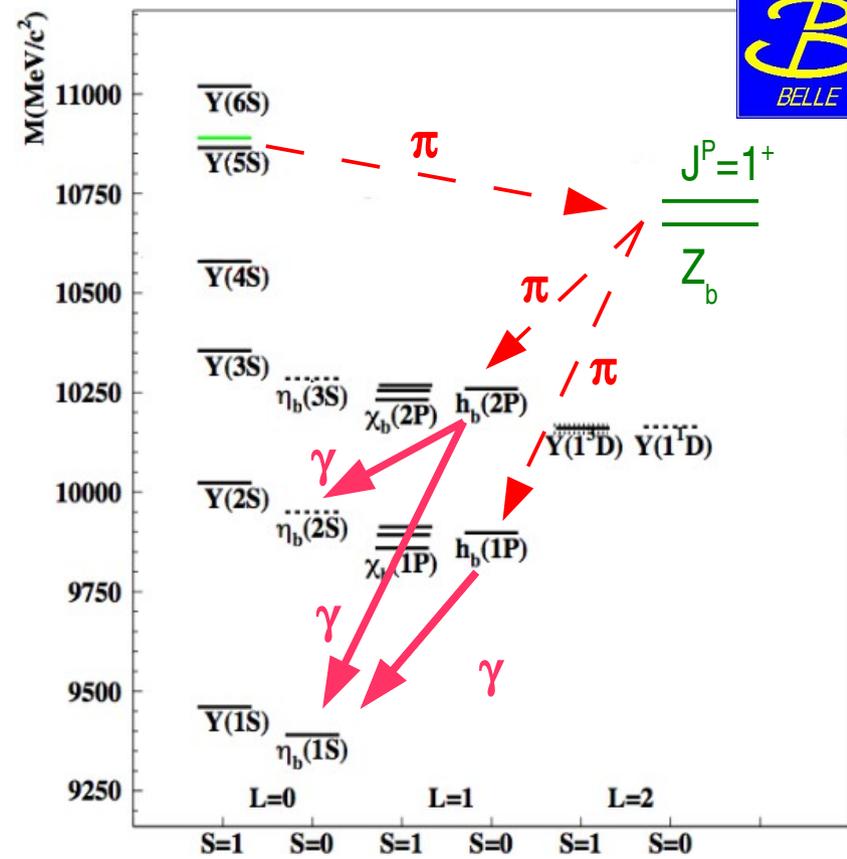
$$\text{BF}[h_b(2P) \rightarrow \gamma \eta_b(2S)] = 13\%$$

$O(10^4)$ larger than in the $Y(nS)$ system

Clean experimental signature with the $h_b(1,2P)$ and Z_b tagging

Means

Less background than in the inclusive searches from $Y(2,3S)$



Search for the $\eta_b(1S)$



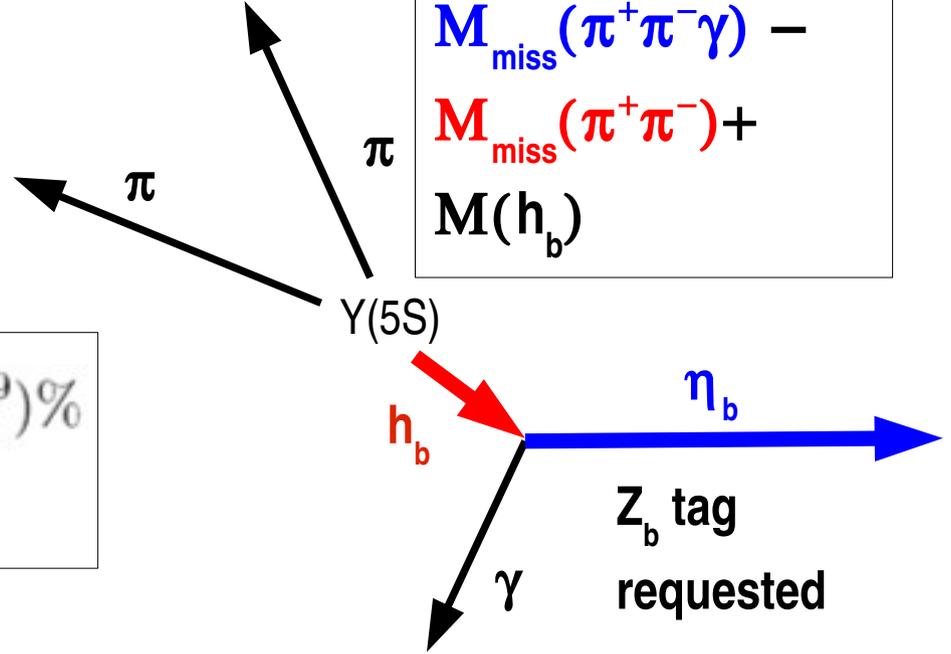
PRL109 (2012) 232002

$M[\eta_b(1S)] \quad (9401.0 \pm 1.9_{-2.4}^{+1.4}) \text{ MeV}/c^2$

$\Gamma[\eta_b(1S)] \quad (12.4_{-4.6}^{+5.5+11.5}) \text{ MeV}$

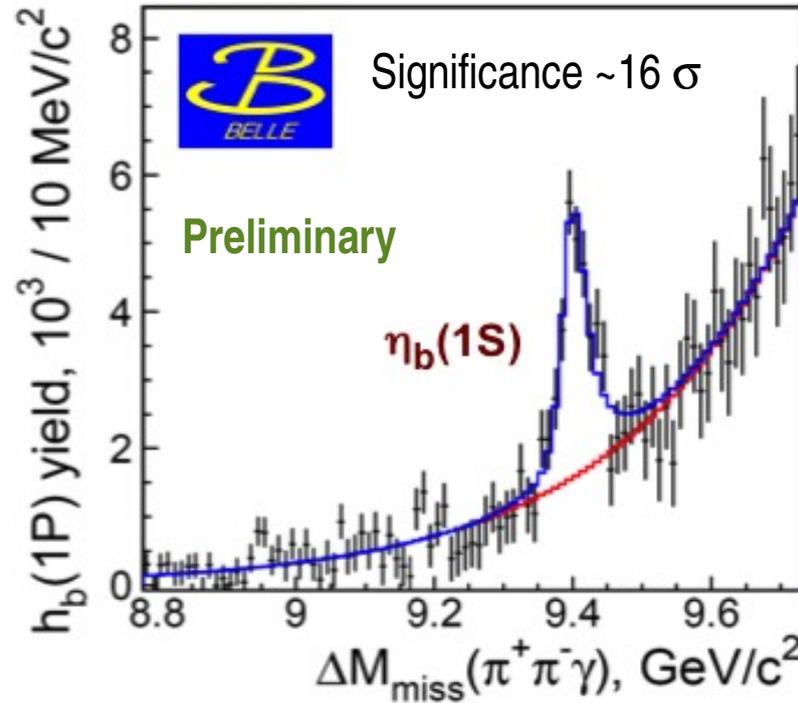
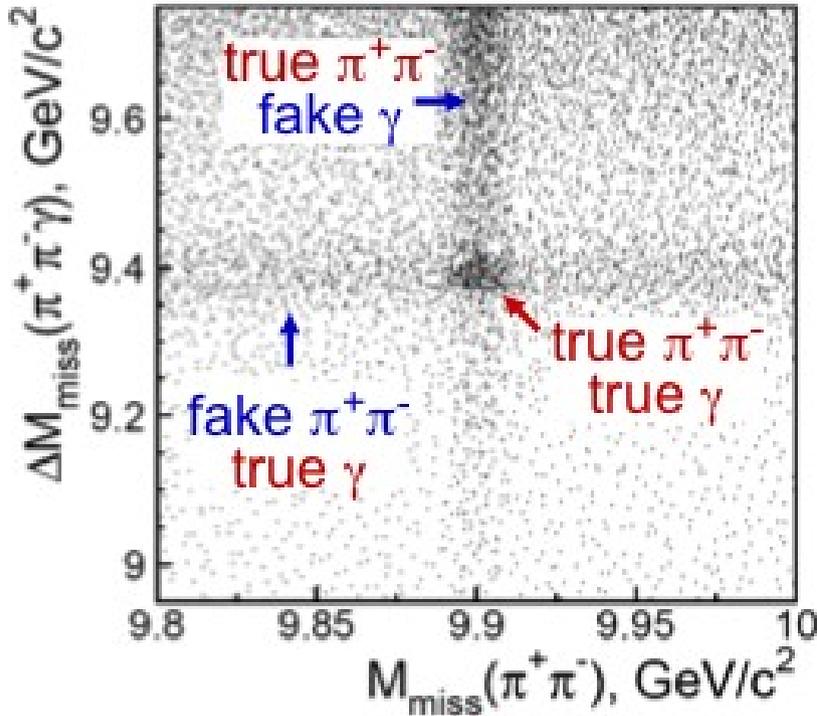
$\mathcal{B}[h_b(1P) \rightarrow \eta_b(1S)\gamma] = (49.8 \pm 6.8_{-5.2}^{+10.9})\%$

Discrepancy with theory (41%)



$$\Delta M_{\text{miss}}(\pi^+\pi^-\gamma) = M_{\text{miss}}(\pi^+\pi^-\gamma) - M_{\text{miss}}(\pi^+\pi^-) + M(h_b)$$

MC simulation



h_b yield from fits in bins of ΔM_{miss}
1 point = 1 fit

$Y(nS) \rightarrow \eta Y(mS)$



$$Y(nS) \rightarrow \pi \pi Y(mS)$$

E1E1 transition

No Spin Flip

$$Y(nS) \rightarrow \eta, \pi^0 Y(mS)$$

E1M2 transition

Spin Flip

The η transition is predicted to be suppressed with respect to the di pion one

The η transition requires a spin flip

QCD multipole expansion:

spin flip amplitude
proportional to $(m_b)^{-2}$

Kuang Front.Phys.China 1, 19 (2006)

$$BF(2S \rightarrow 1S) = 2.1 \times 10^{-4} \quad [\text{CLEO}], \quad 2.39 \times 10^{-4} \quad [\text{BaBar}]$$

$$\sim 8 \times 10^{-4} \quad [\text{Theory}]$$

$$BF(3S \rightarrow 1S) < 1 \times 10^{-4} \quad [\text{BaBar}],$$

$$\sim 6 \times 10^{-4} \quad [\text{Theory}]$$

$$BF(4S \rightarrow 1S) = 1.96 \times 10^{-4} \quad [\text{BaBar}] \quad \text{Orders of magnitude higher (2.5x } \pi\pi \text{ transition)}$$

$Y(5S) \rightarrow \eta Y(1,2S)$

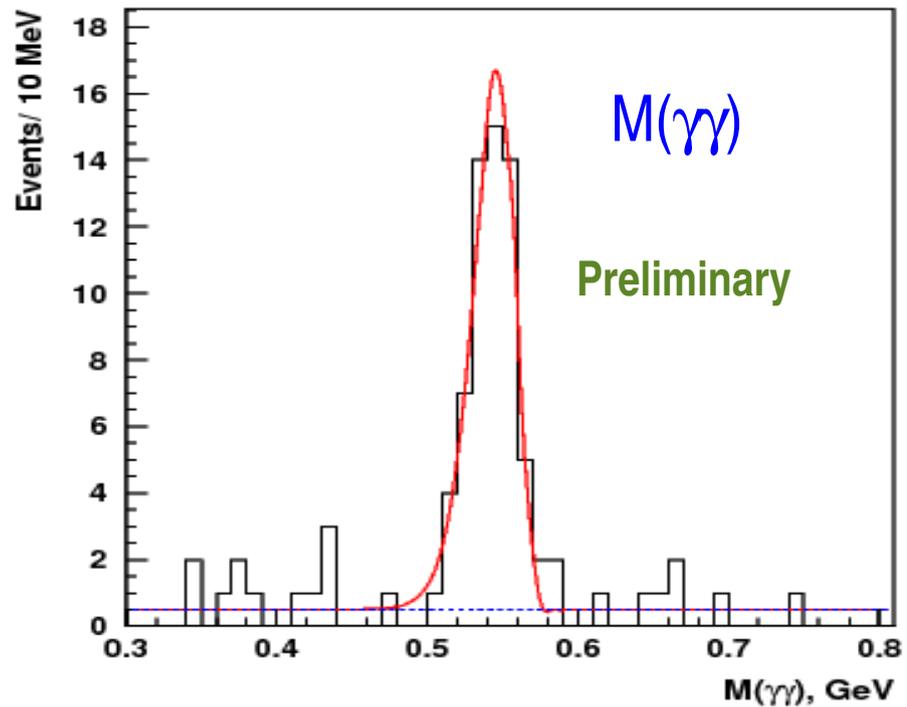
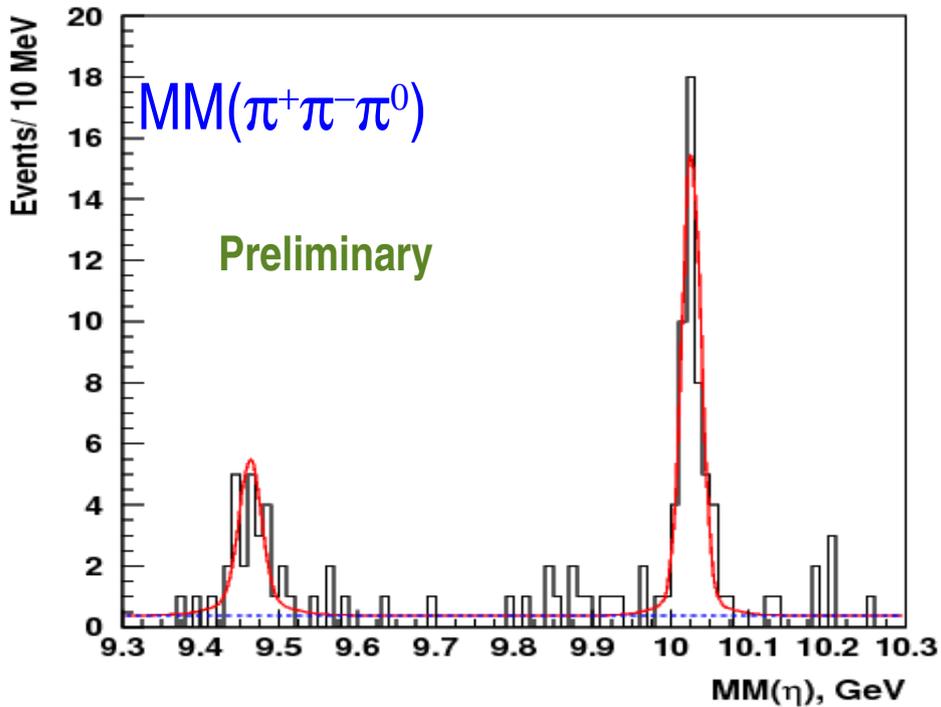
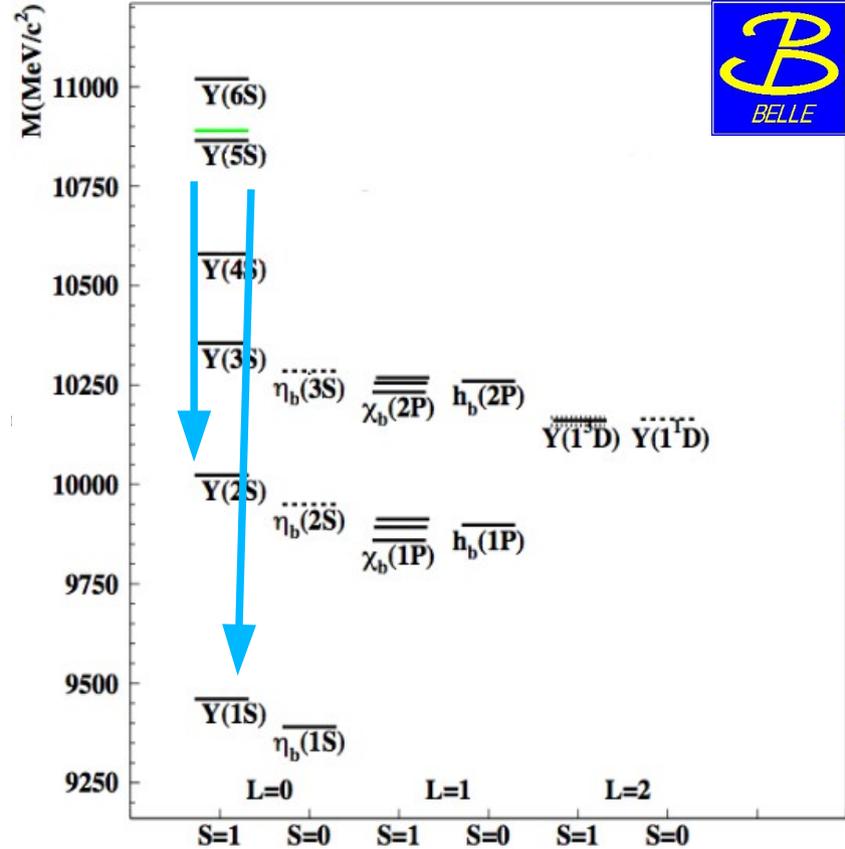
Exclusive reconstruction

$$\begin{cases} Y(1,2S) \rightarrow \mu^+\mu^- + \eta \rightarrow \pi^+\pi^-\pi^0 \\ Y(2S) \rightarrow Y(1S)\pi^+\pi^- + \eta \rightarrow \gamma\gamma \end{cases}$$

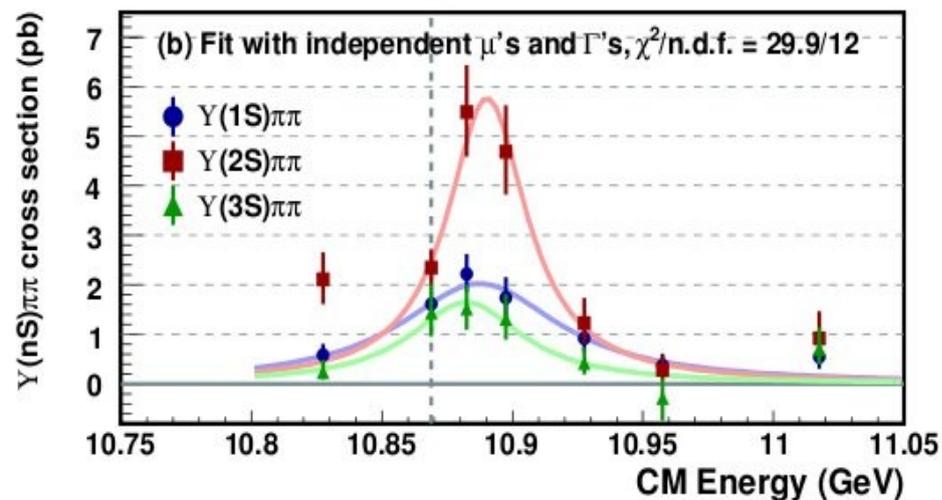
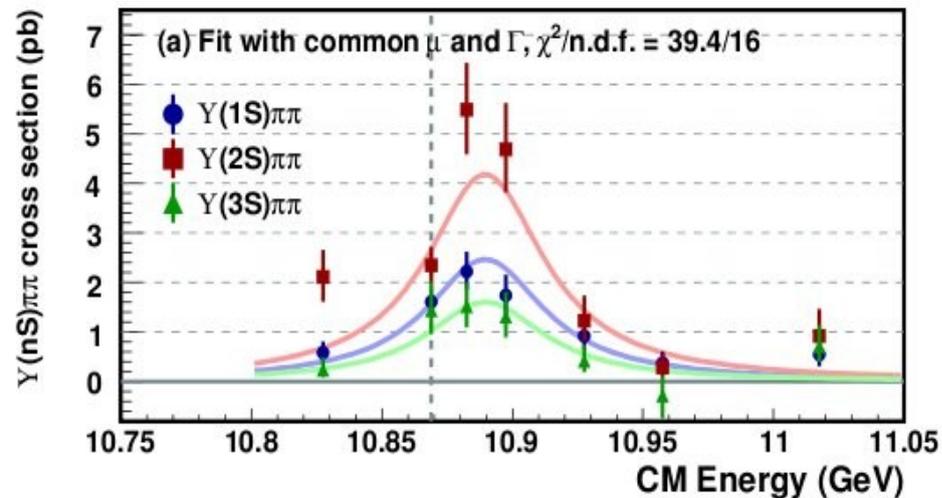
$$B[Y(5S) \rightarrow Y(1S)\eta] = (7.3 \pm 1.6 \pm 0.8) \cdot 10^{-4}$$

$$B[Y(5S) \rightarrow Y(2S)\eta] = (38 \pm 4 \pm 5) \cdot 10^{-4}$$

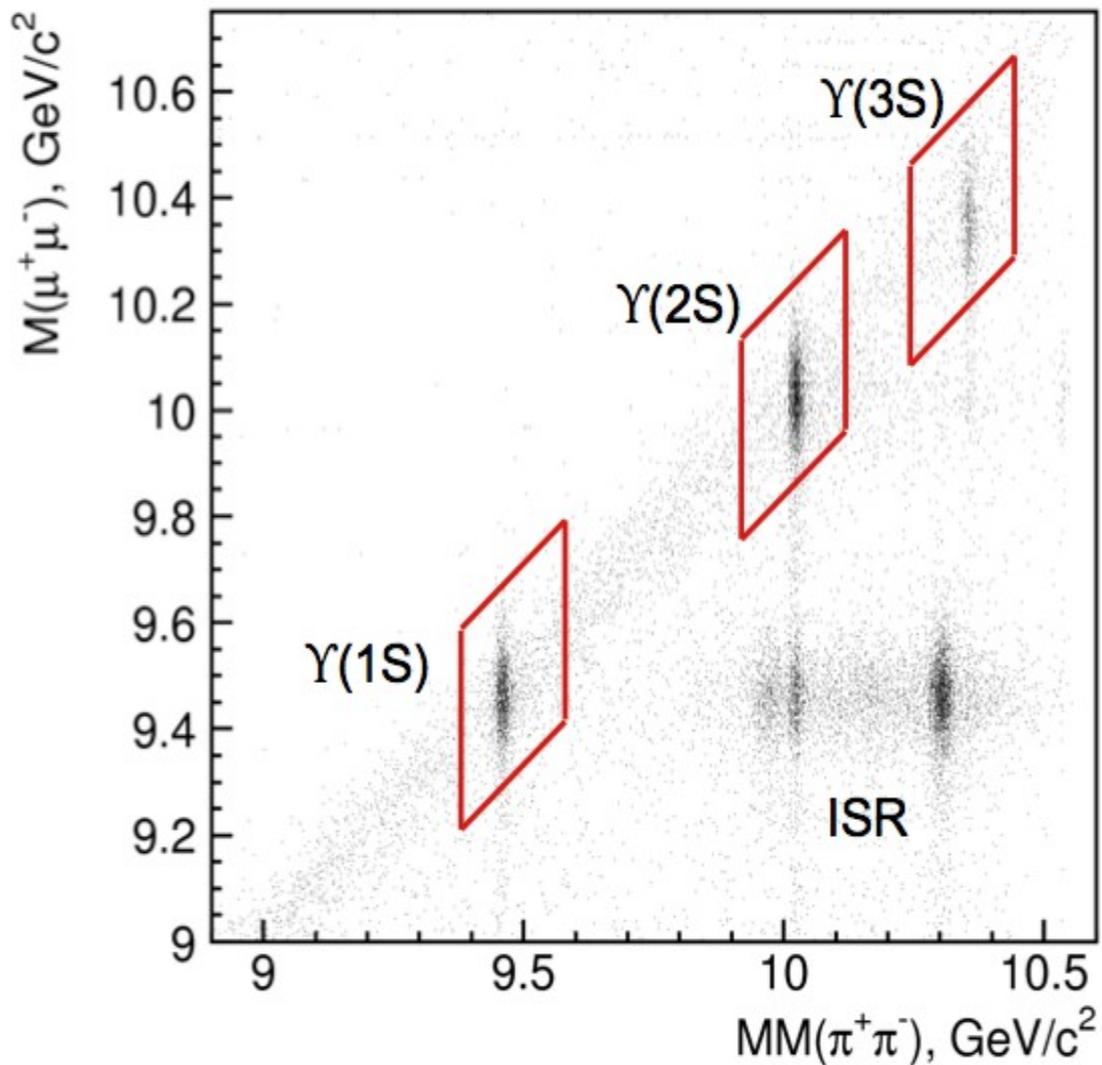
Preliminary



$\pi^+\pi^-$ transitions @ $Y(5S)$



$$Y(5S) \rightarrow Y(nS) \pi^+\pi^- \quad (n = 1,2,3)$$
$$Y(nS) \rightarrow \mu^+\mu^-$$



$\pi^+\pi^-$ transitions @ $Y(5S)$

PRL100,112001(2008)

$\Gamma(\text{MeV})$

$$\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^- \quad 0.59 \pm 0.04 \pm 0.09$$

$$\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^- \quad 0.85 \pm 0.07 \pm 0.16$$

$$\Upsilon(5S) \rightarrow \Upsilon(3S)\pi^+\pi^- \quad 0.52^{+0.20}_{-0.17} \pm 0.10$$

$$\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^- \quad 0.0060$$

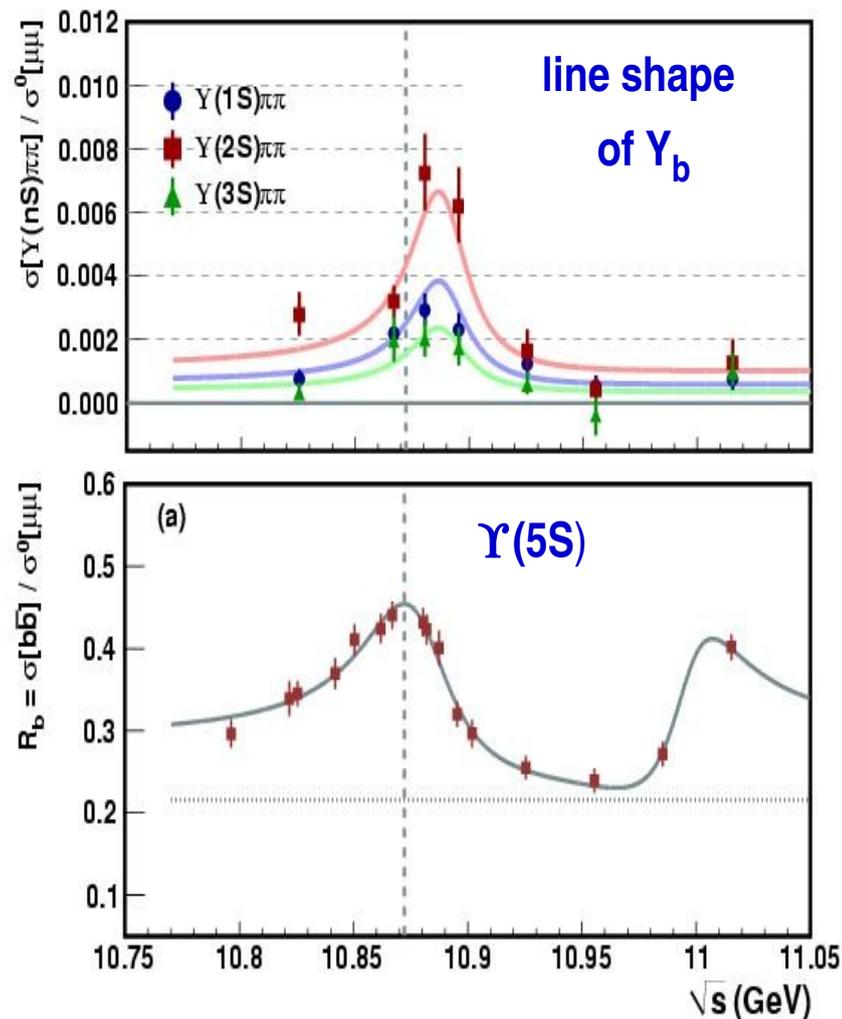
$$\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^- \quad 0.0009$$

$$\Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^- \quad 0.0019$$

Simonov JETP Lett 87,147(2008)

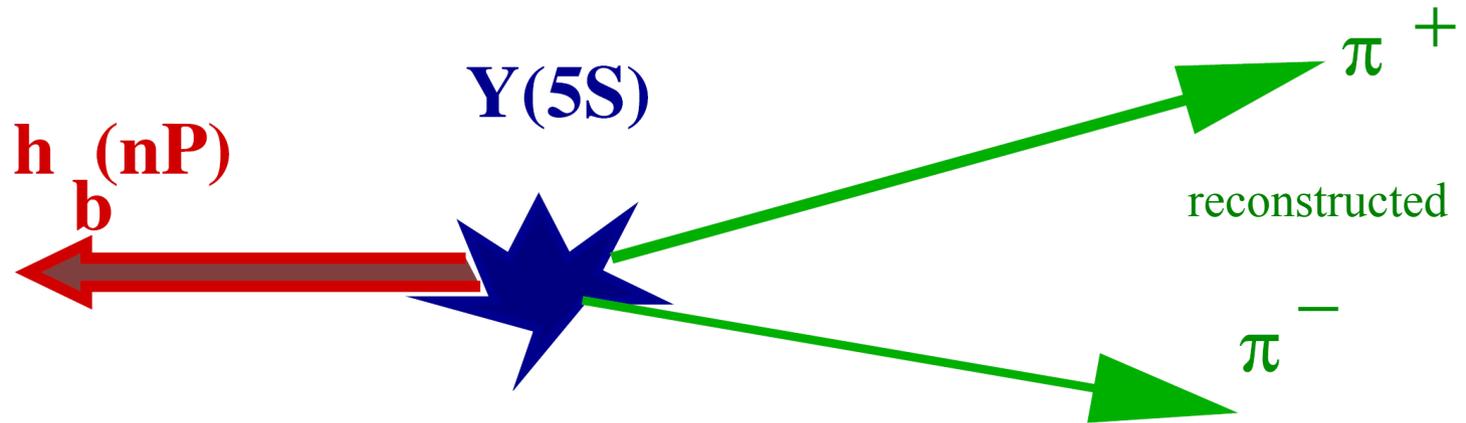
Rescattering $Y(5S) \rightarrow BB\pi\pi \rightarrow Y(nS)$?

PRD82,091106R(2010)



Missing Mass technique

Y(5S) produced at rest in the colliding e^+e^- frame



$$\mathbf{M}(h_b) = (E_{\text{c.m.}} - E_{\pi^+\pi^-}^*)^2 - \mathbf{p}_{\pi^+\pi^-}^2 \equiv \mathbf{M}_{\text{miss}}(\pi^+\pi^-)$$

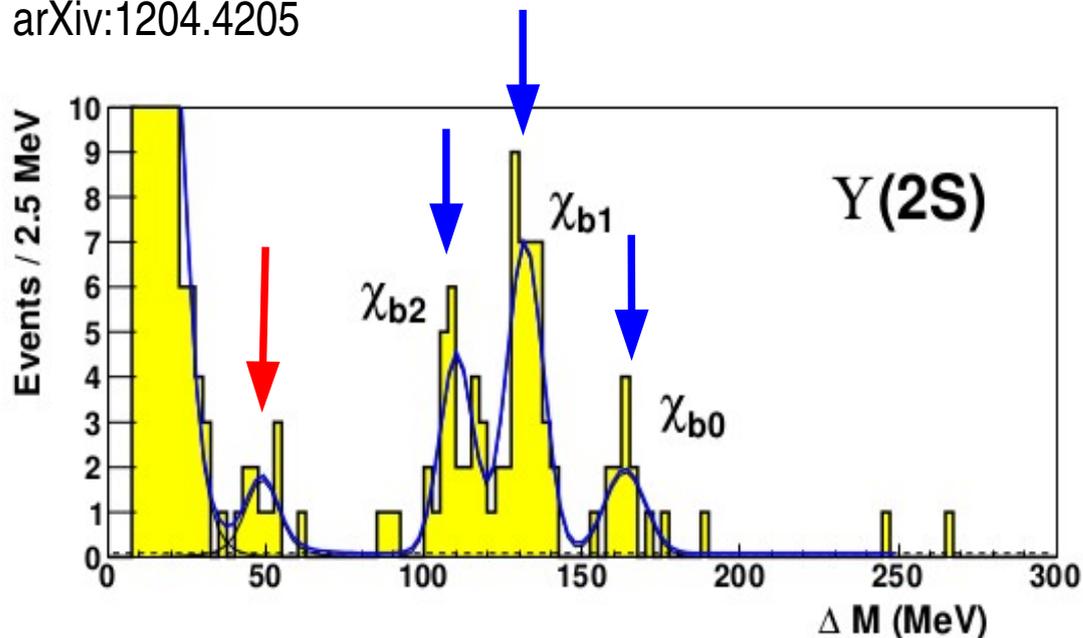
Known

Measured

$\eta_b(2S)$ claim



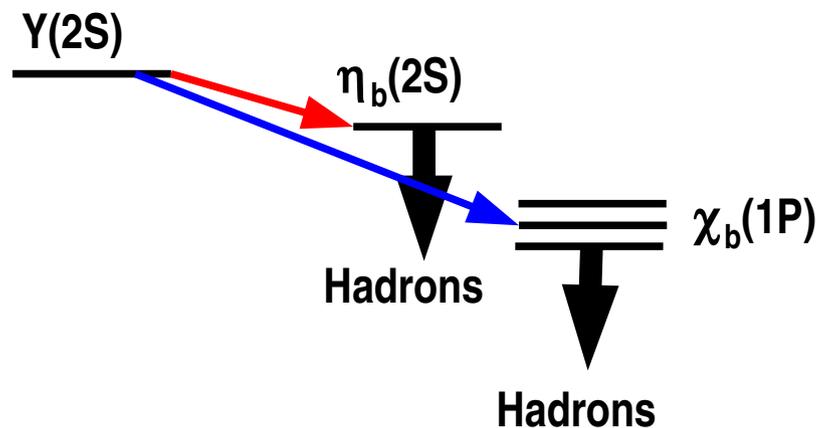
arXiv:1204.4205



Dobbs et. Al analyzed the data from CLEO-III searching for $Y(2S) \rightarrow \gamma (b\bar{b})$ with exclusive reconstruction of $(b\bar{b}) \rightarrow X$ in **26 different hadronic modes**

Belle: $\Delta M_{HF}(2S) = 23.4^{+4.0}_{-4.5}$ MeV

Dobbs et al.: $\Delta M_{HF}(2S) = 48.7$ MeV



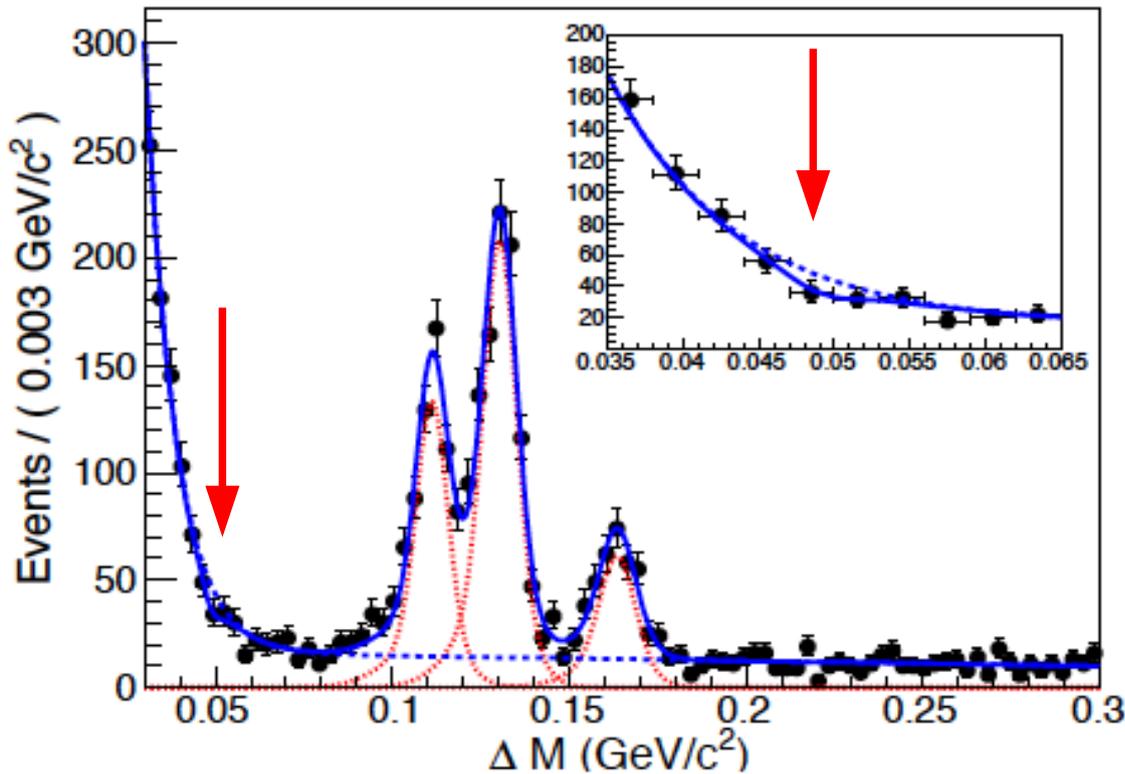
	N	ΔM_{hf} (MeV)	M (MeV)	$\chi^2/d.o.f.$	signif. (σ)	$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^6$
$\eta_b(2S)$	$11.4^{+4.3}_{-3.5}$	$48.7 \pm 2.3 \pm 2.1$	$9974.6 \pm 2.3 \pm 2.1$	91.8/103	4.9	$46.2^{+29.7}_{-14.2} \pm 10.6$
$\eta_b(1S)$	$10.3^{+4.9}_{-4.1}$	$67.1 \pm 3.4 \pm 2.3$	$9393.2 \pm 3.4 \pm 2.3$	114.6/107	3.1	$30.1^{+33.5}_{-7.4} \pm 7.5$

$BF[Y(2S) \rightarrow \gamma \eta_b(2S)] \times BF[\gamma \eta_b(2S) \rightarrow \text{hadrons}] = (46.2^{+29.2}_{-14.2} \pm 10.6) \times 10^{-6}$

Exclusive $\eta_b(2S)$ at Belle



arXiv:1306.6212

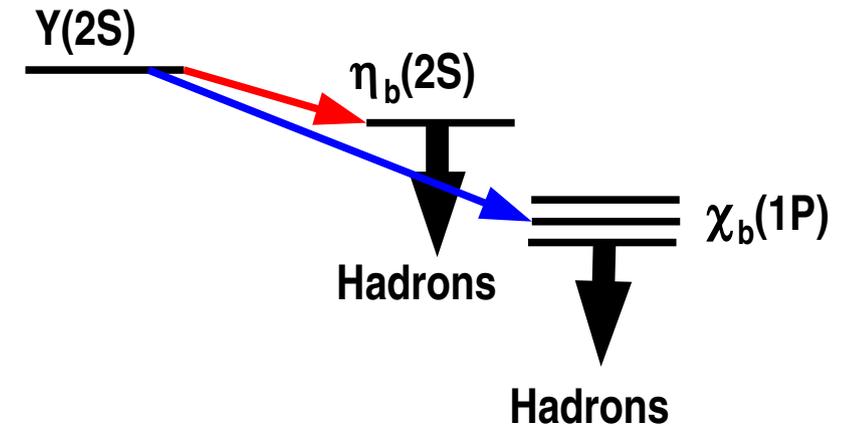


25 fb⁻¹ at Y(2S) energy
(158 M Y(2S) decays, 16x CLEO)

87 fb⁻¹ below Y(4S) energy
for the study of the continuum
background study

$$\text{BF}[Y(2S) \rightarrow \gamma\eta_b(2S)] \times \text{BF}[\gamma\eta_b(2S) \rightarrow \text{had}] < 4.9 \times 10^{-6}$$

Identical reconstruction modes



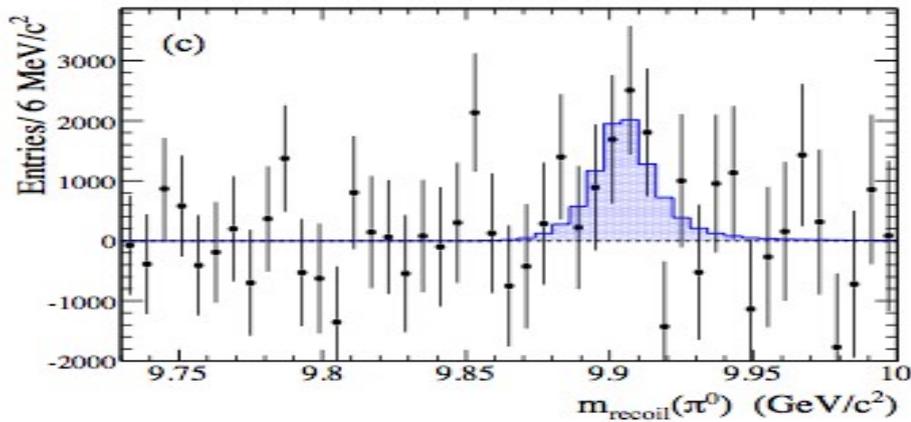
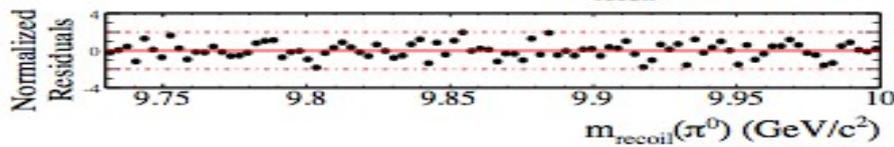
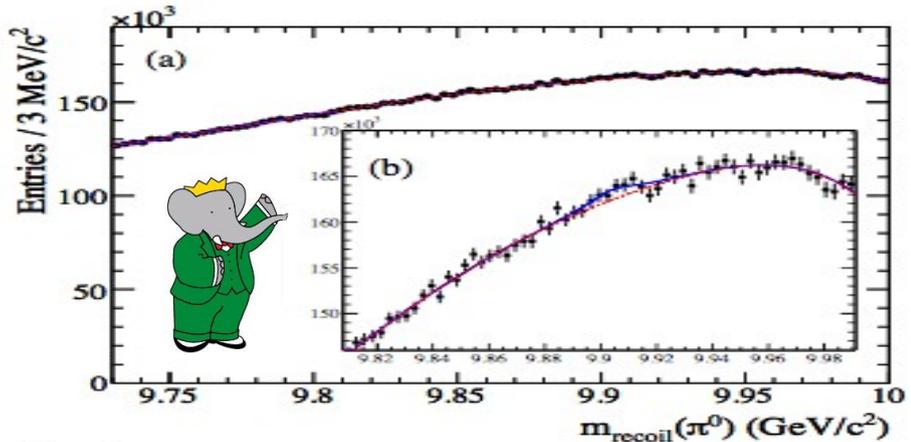
$\eta_b(2S)$ claim by
Dobbs et Al. is
disconfirmed by Belle.

~ one order of magnitude
below the claim by
Dobbs et at

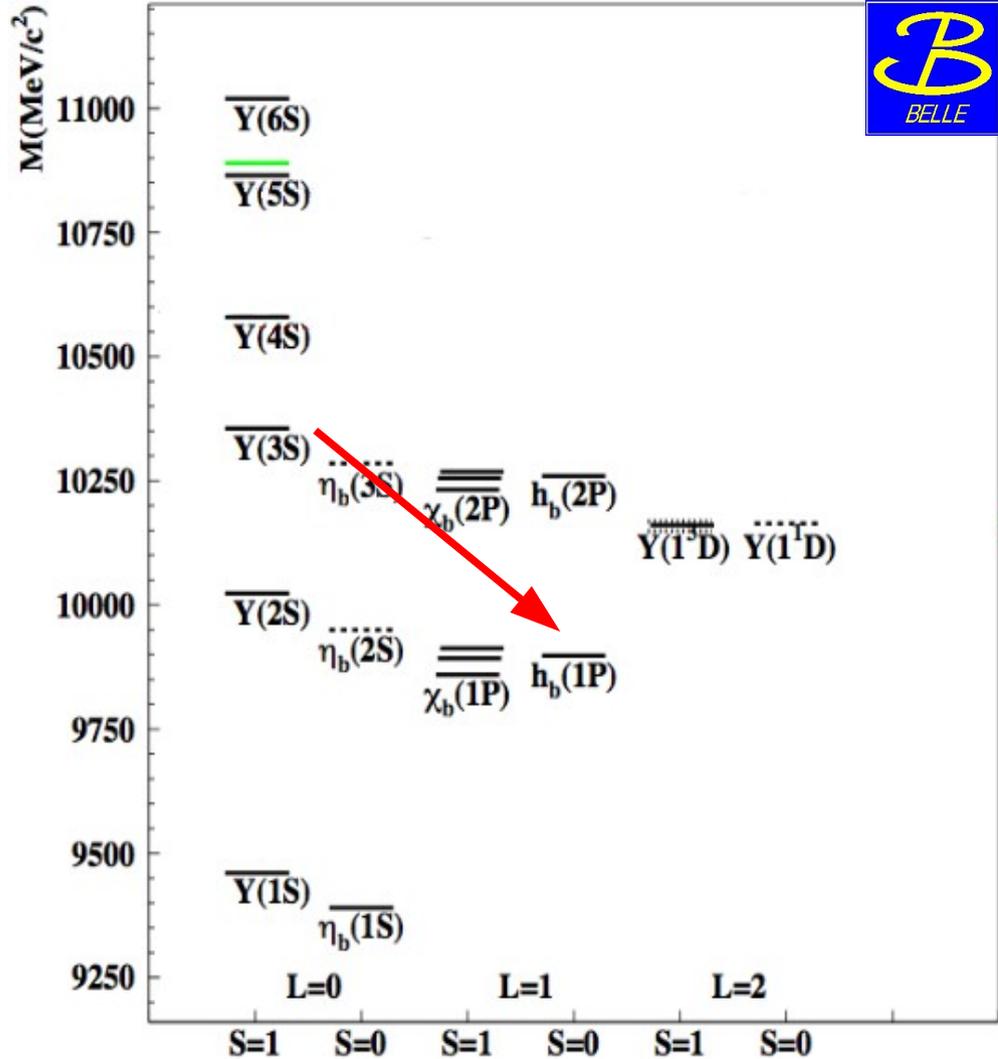
$h_b(1P)$ at BaBar

3 sigma evidence:

$$e^+e^- \rightarrow Y(3S) \rightarrow \pi^0 h_b$$



π^0 recoil mass (GeV/c^2)



Phys.Rev.D 84 091101(R)

$\Upsilon(1,2S) \rightarrow \text{exclusive } \Lambda\bar{\Lambda} + X$



Preliminary

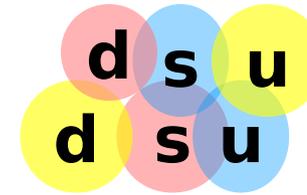
Dynamical interaction within the $\Lambda\bar{\Lambda}$ pair

→ Low threshold enhancement in $M(\mathcal{B}\bar{\mathcal{B}})$ is a common feature in B meson baryonic decays

Significance of the deviation from phase space flat distribution

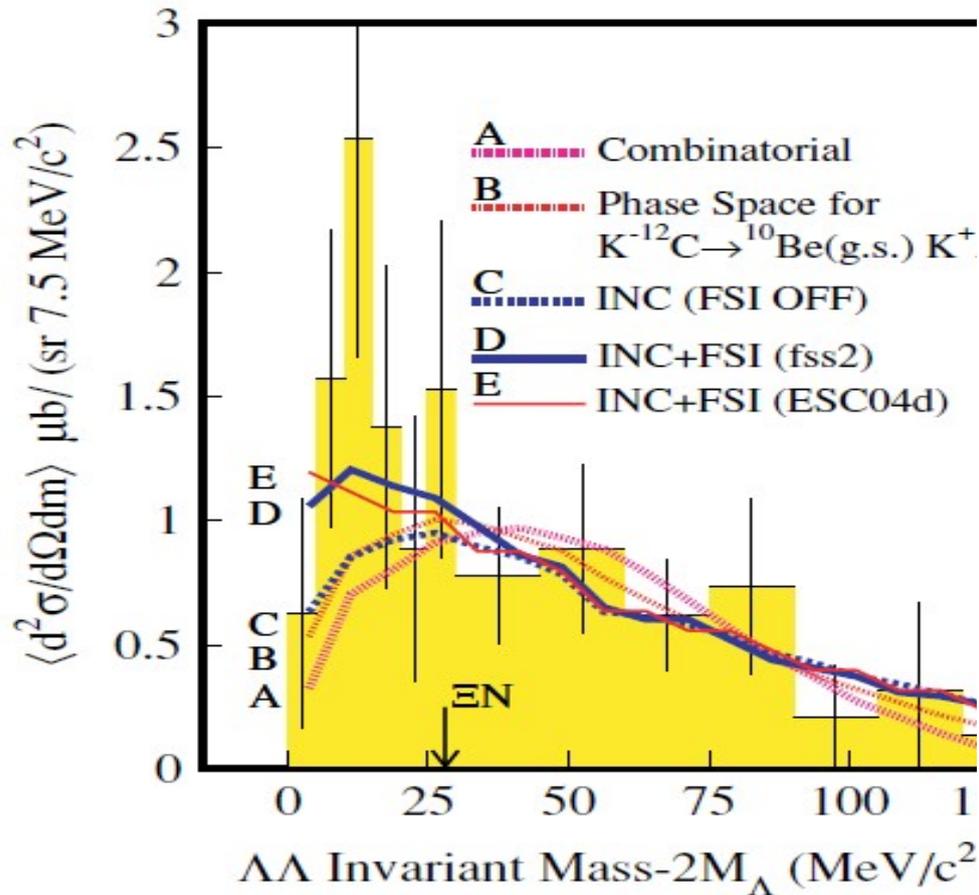
Final state X	$\Upsilon(1S) \rightarrow X$	$\Upsilon(2S) \rightarrow X$	$e^+e^- \rightarrow q\bar{q} \rightarrow X$
$\Lambda\bar{\Lambda} + \pi^+\pi^-$	2.16		1.83
$\Lambda\bar{\Lambda} + K^+K^-$	2.94	4.60	
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)$	2.96	3.07	4.23
$\Lambda\bar{\Lambda} + \pi^+\pi^-K^+K^-$	4.61		6.08
$\Lambda\bar{\Lambda} + \pi^+\pi^-p\bar{p}$	2.06		0.57
$\Lambda\bar{\Lambda} + 3(\pi^+\pi^-)$	0.31	2.97	3.76
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)K^+K^-$	0.36		3.75
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)p\bar{p}$	<0.1		0.83
$\Lambda\bar{\Lambda} + \pi^+\pi^-2(K^+K^-)$	0.50	0.29	
$\Lambda\bar{\Lambda} + \pi^+\pi^-\pi^0$	1.95		2.36
$\Lambda\bar{\Lambda} + K^+K^-\pi^0$			1.51
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)\pi^0$	<0.1	0.36	4.27
$\Lambda\bar{\Lambda} + \pi^+\pi^-K^+K^-\pi^0$	<0.1		2.33
$\Lambda\bar{\Lambda} + \pi^+\pi^-p\bar{p}\pi^0$	<0.1		
$\Lambda\bar{\Lambda} + 3(\pi^+\pi^-)\pi^0$	1.38	0.25	2.10
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)K^+K^-\pi^0$	1.28	<0.1	1.28
$\Lambda\bar{\Lambda} + 2(\pi^+\pi^-)p\bar{p}\pi^0$	<0.1		

Search for H dibaryon

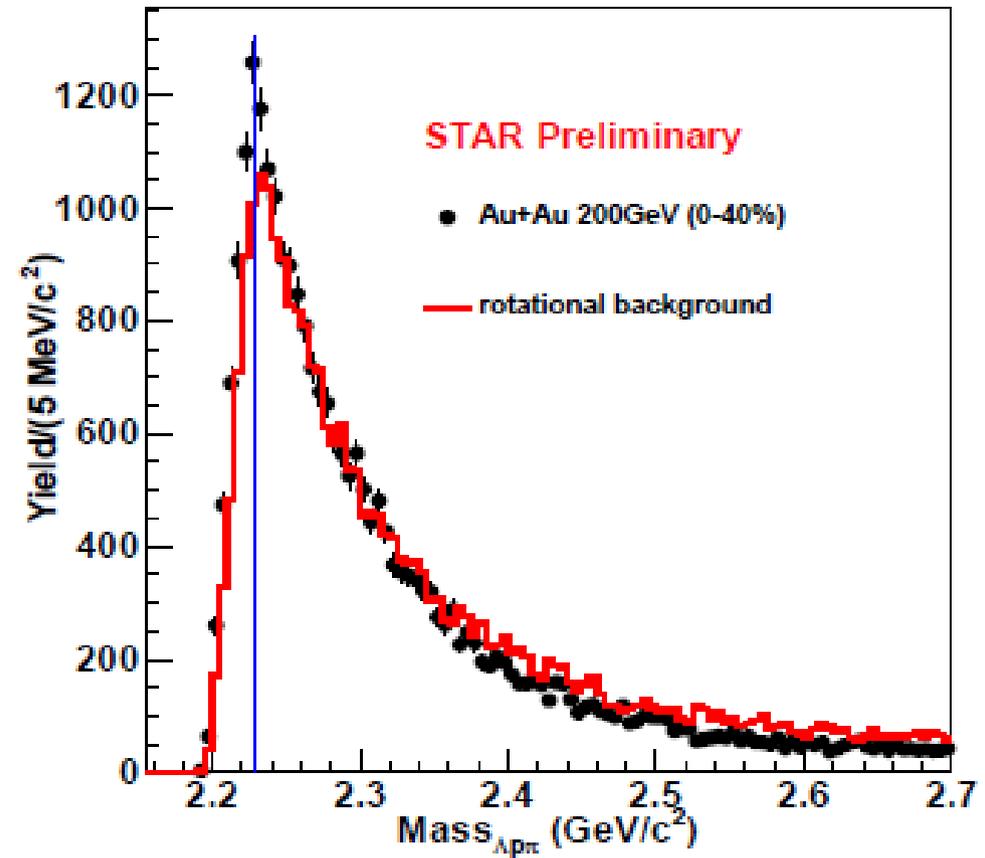


Exotic state (Jaffe, 1977)

→ completely antisymmetric arrangement of uuddss



KEK-PS
E522(2007)

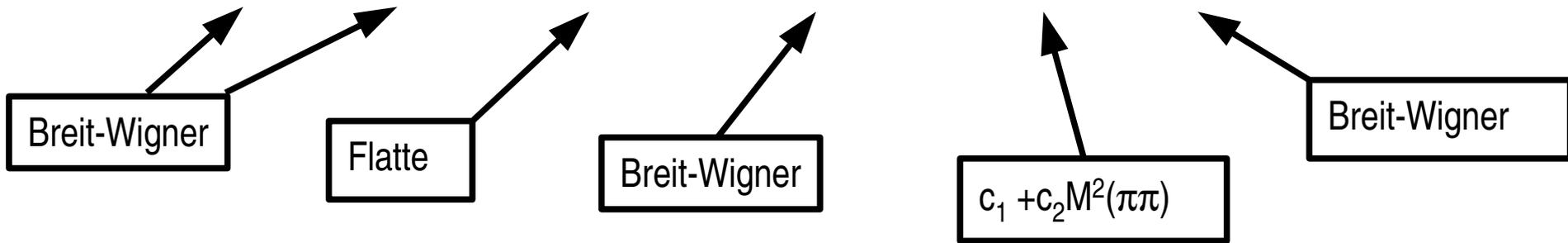


RHIC-STAR
(2011)

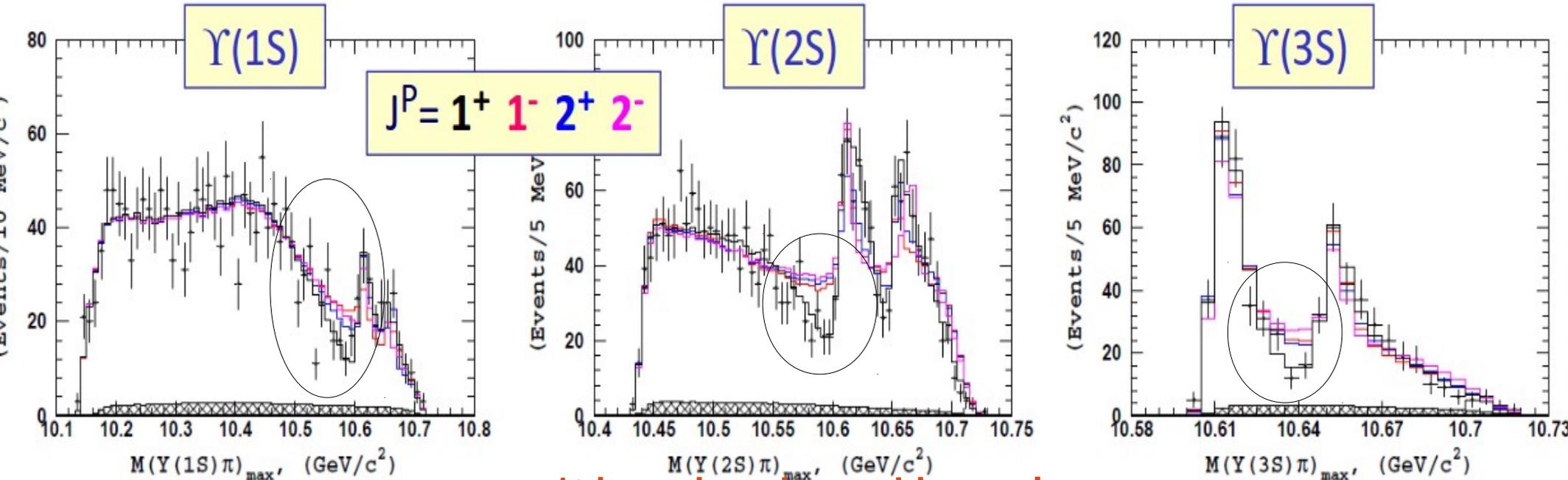
Spin-parity of the Z_b

New study of spin parity with a **6-D fit** that includes contributions from non-resonant S and D waves:

$$S(s_1, s_2) = A(Z_b) + A(Z'_b) + A(f_0(980)) + A(f_2(1275)) + A(NR) + A(\sigma)$$



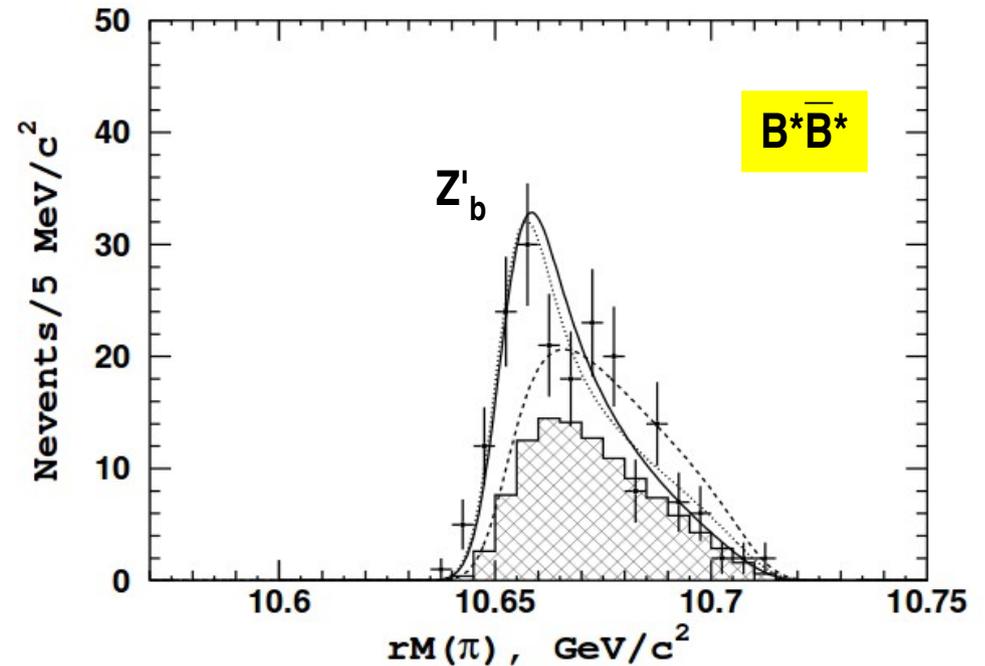
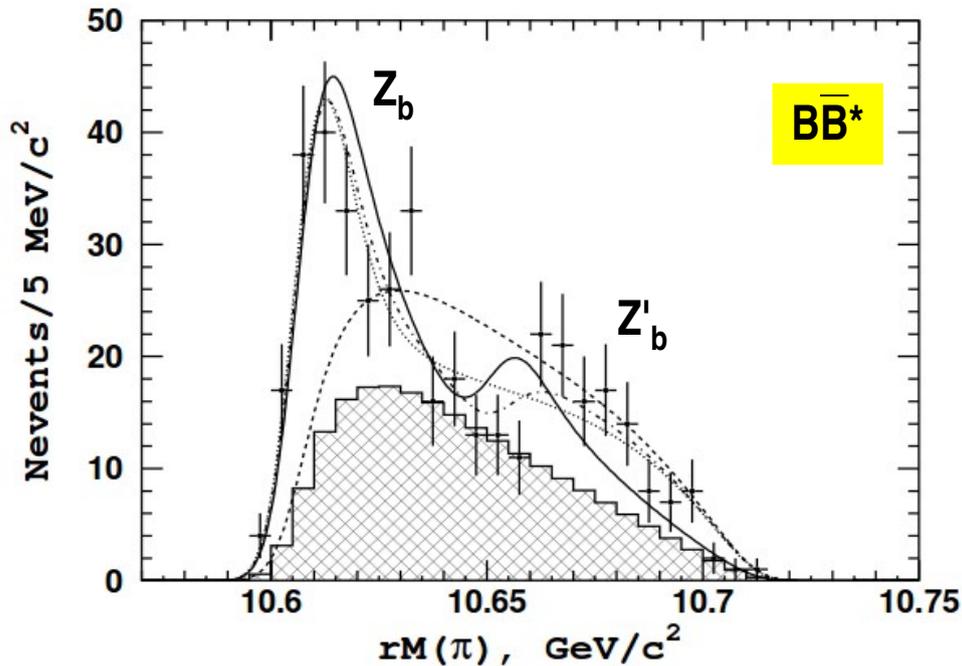
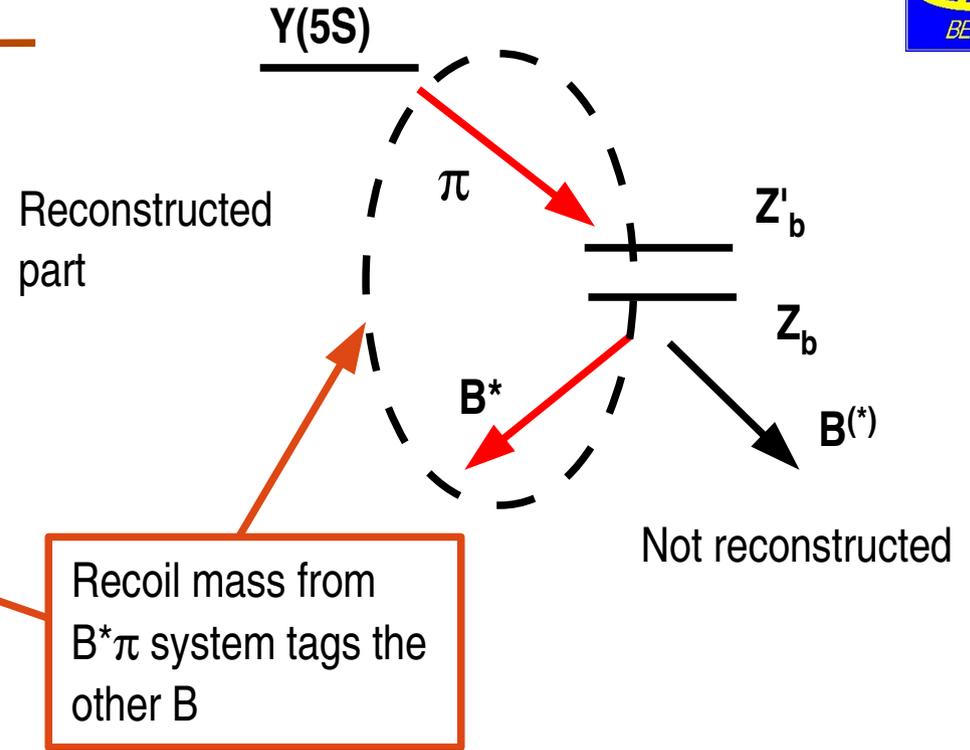
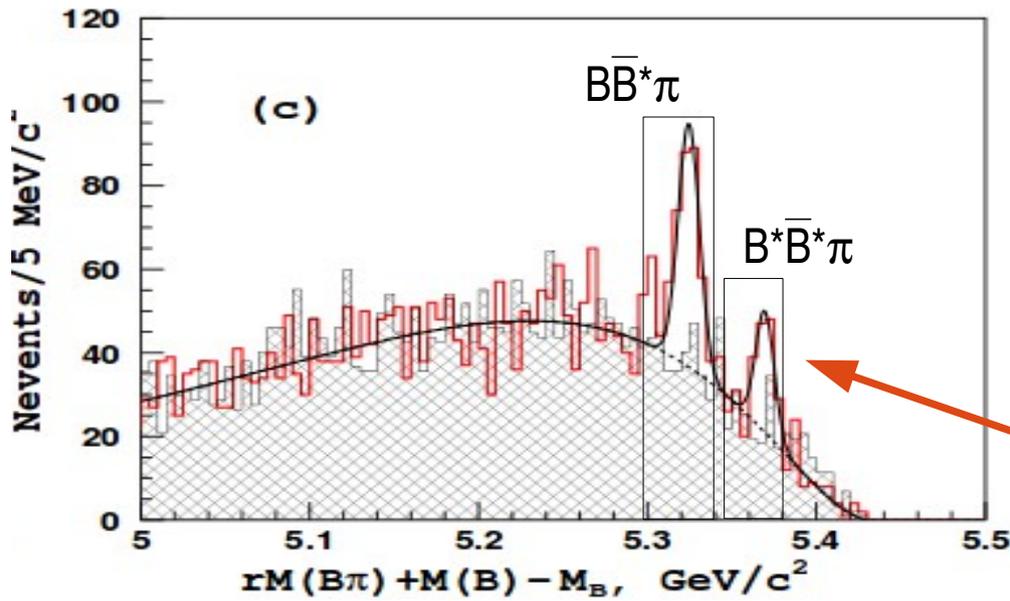
Fit projections in $M(Y(nS)\pi)$



1⁺ is assigned unambiguously

Z_b decay modes

arXiv:1209.6450v2

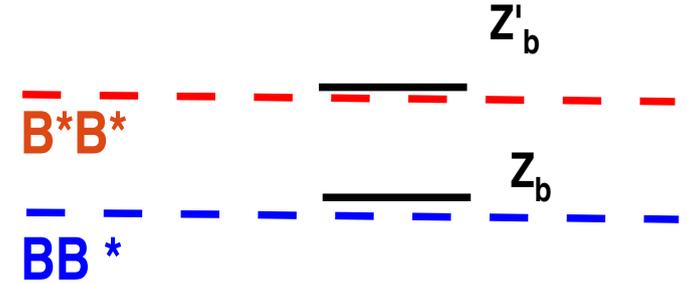


Recoil mass form single pion in selected events

Z_b decay modes

arXiv:1209.6450v2

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



From inclusive $\Upsilon(5S) \rightarrow \pi^+\pi^- + X$ decays

Kinematically favoured but absent

Why $Z_b(10650)$ should not decay in BB^* ?

$$Z_b \sim |BB^*\rangle$$

$$Z'_b \sim |B^*B^*\rangle \quad \text{with negligible } |BB^*\rangle \text{ component}$$

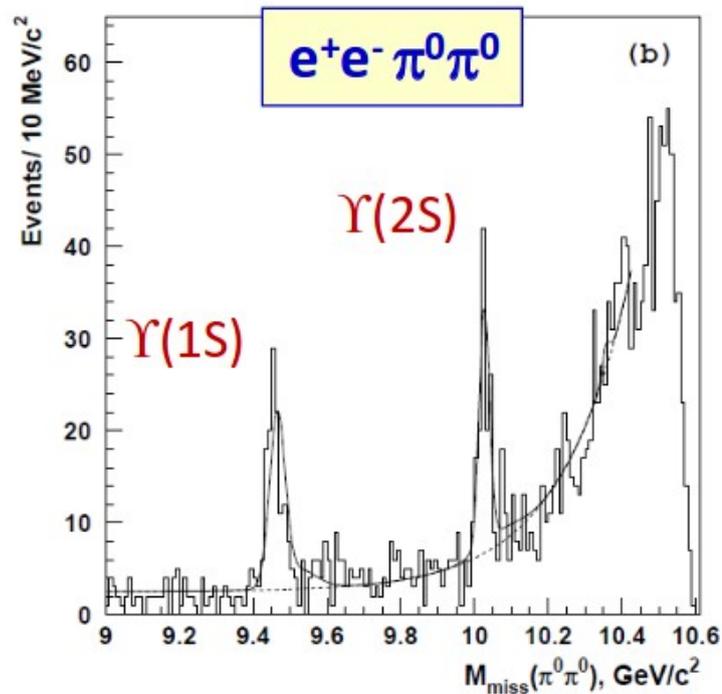
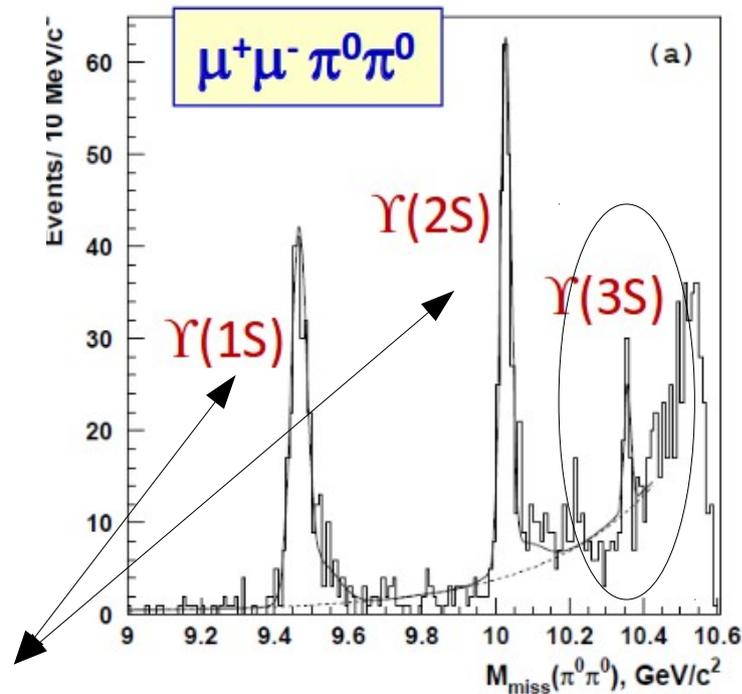
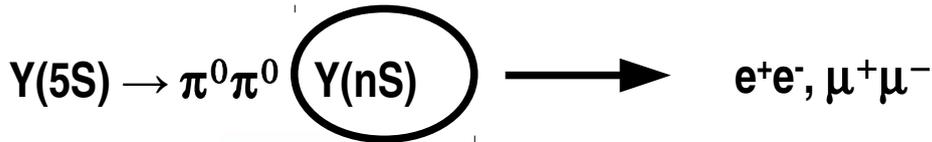
Molecular Model

Proximity to open threshold 
 $\Gamma(\text{open flavour}) \gg \Gamma(\text{narrow quarkonium})$

The Z_b are BB^* and B^*B^* molecules with $J^P = 1^+$ (?) 

Search for Z_b^0

arXiv:1318.2648



$$\text{BF}[Y(5S) \rightarrow \pi^0 \pi^0 Y(1S)] = (2.25 \pm 0.11 \pm 0.20) \times 10^{-3}$$

$$\text{BF}[Y(5S) \rightarrow \pi^0 \pi^0 Y(2S)] = (3.79 \pm 0.24 \pm 0.49) \times 10^{-3}$$

$$\text{BF}[Y(5S) \rightarrow \pi^0 \pi^0 Y(3S)] = (2.09 \pm 0.51 \pm 0.34) \times 10^{-3}$$

$$\text{BF}[\pi^+\pi^-] = (4.45 \pm 0.16 \pm 0.35) \times 10^{-3}$$

$$\text{BF}[\pi^+\pi^-] = (7.97 \pm 0.31 \pm 0.96) \times 10^{-3}$$

$$\text{BF}[\pi^+\pi^-] = (2.88 \pm 0.19 \pm 0.36) \times 10^{-3}$$

Isospin symmetry : $\text{BF}[\pi^+\pi^-] = 2 \times \text{BF}[\pi^0\pi^0]$ **OK**

Search for Z_b^0

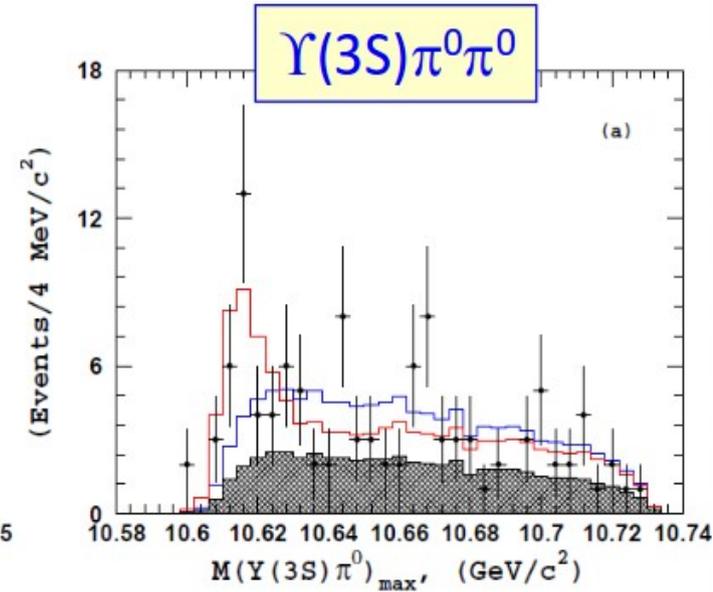
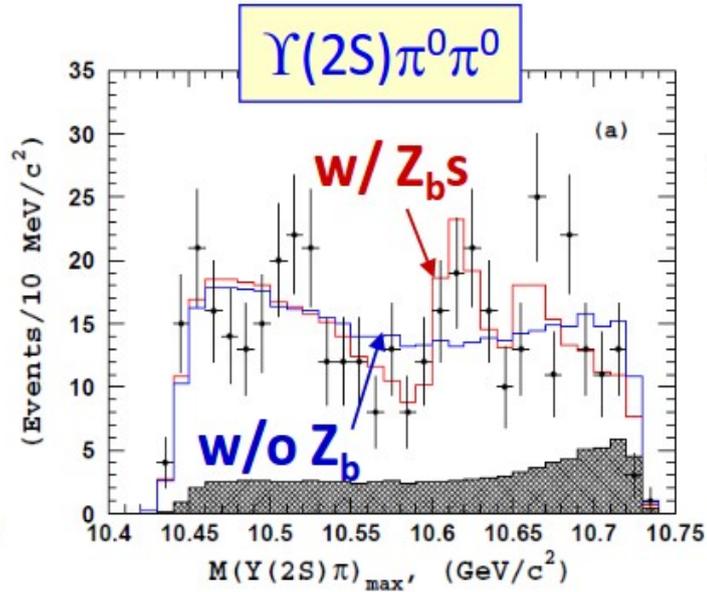
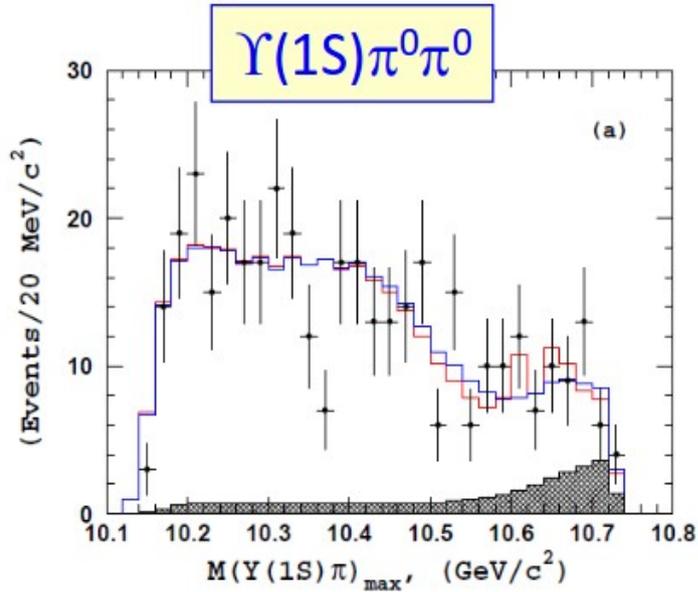


arXiv:1318.2648

Again multidimensional fit that includes contributions from non resonant S and D wave

$$S(s_1, s_2) = A(Z_b)$$

$$A(Z'_b) + A(f_0(980)) + A(f_2(1275)) + A(NR)$$



Significance is calculated from the Multi-dimensional fit

$Z_b^0(10610)$: 6.5σ [4.9σ from $\Upsilon(2S)$ + 4.3σ from $\Upsilon(3S)$]

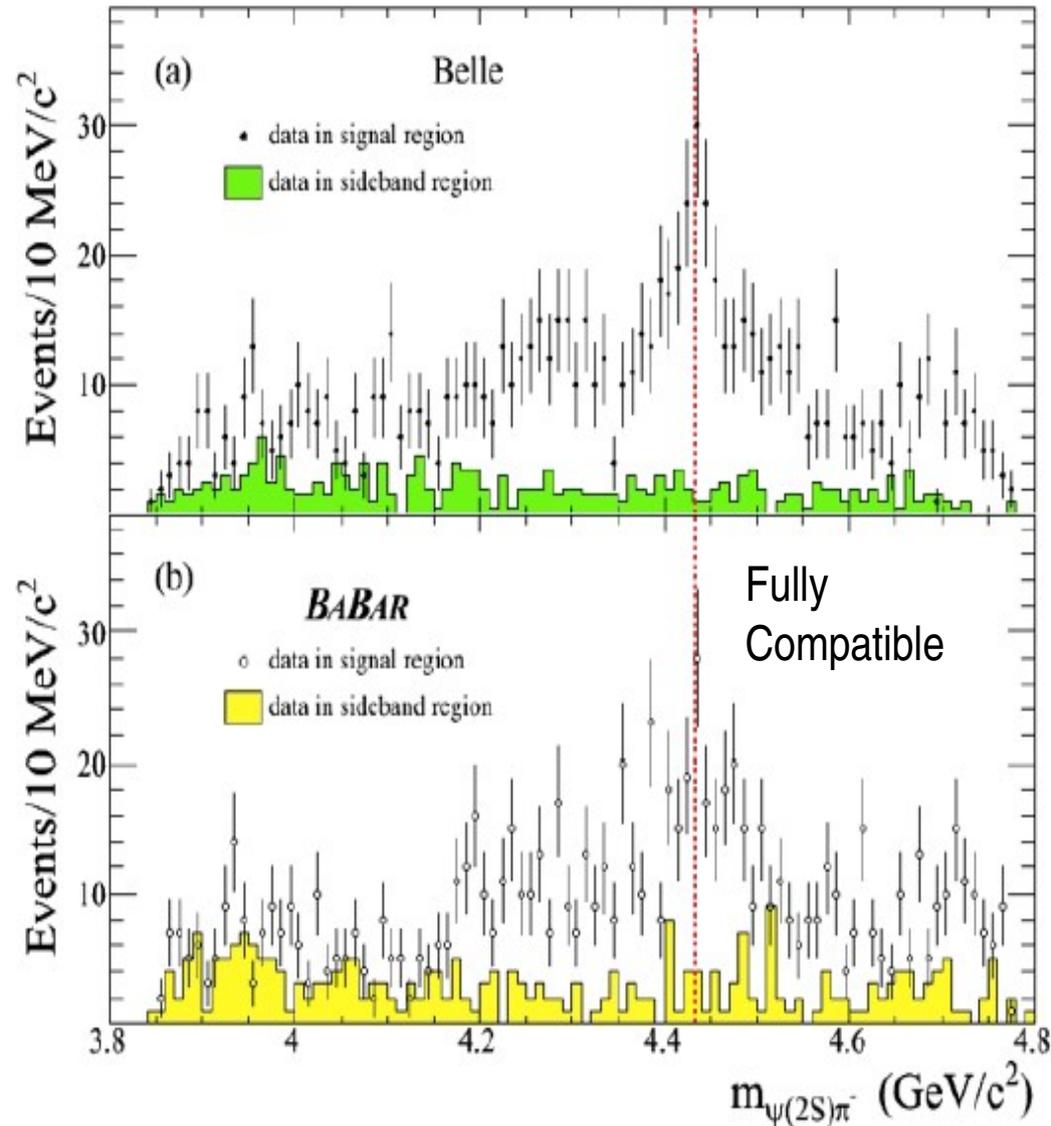
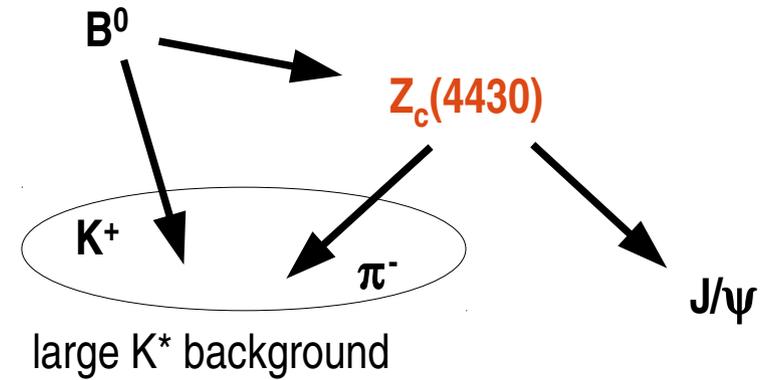
Observed

$Z_b^0(10650)$: not observed but not excluded either

Discovery of $Z_c(4430)$

Belle: PRL100, 142001 (2008)

BaBar: PRD79, 112001 (2009)



Belle:

Charged charmonium-like

$$M = 4433^{+15}_{-12} \text{ MeV}^{+19}_{-13}$$

Very close to D^*D_1 threshold

$$\Gamma = 107^{+86}_{-43} \text{ MeV}^{+74}_{-53}$$

BaBar:

Effect of highly excited K^* states

“We obtain mass and width values that are compatible with theirs [...] but only 1.9 σ ; fixing the mass and with increased this to only 3.1 σ ”

$Z_c(4430)$ quantum numbers



arXiv:1306.4894

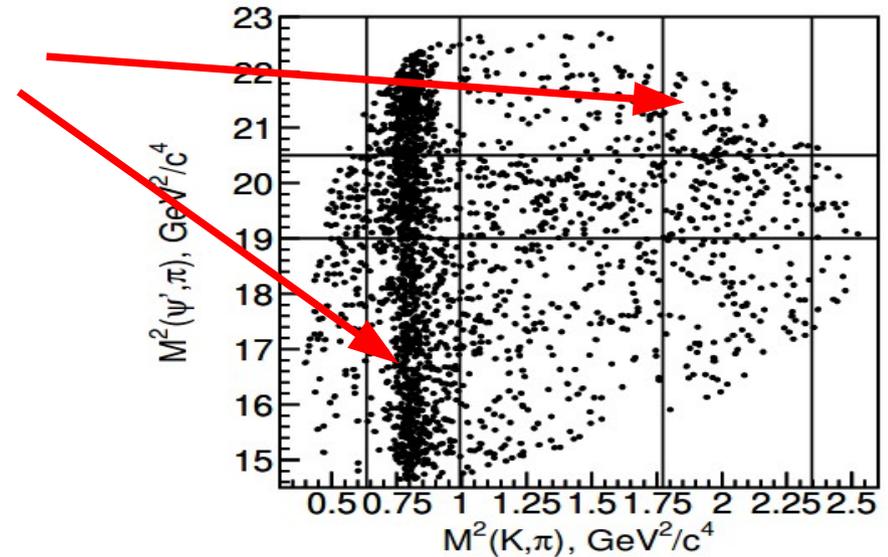
4-D dalitz plot fit

→ $M(k\pi)$, $M(\psi\pi)$, ψ elicity, $\theta(\pi\psi)$

$K^*(892)$ and $K^*(1200)$ are vetoed

broader K^* resonances are included in the fit

Vetoed regions



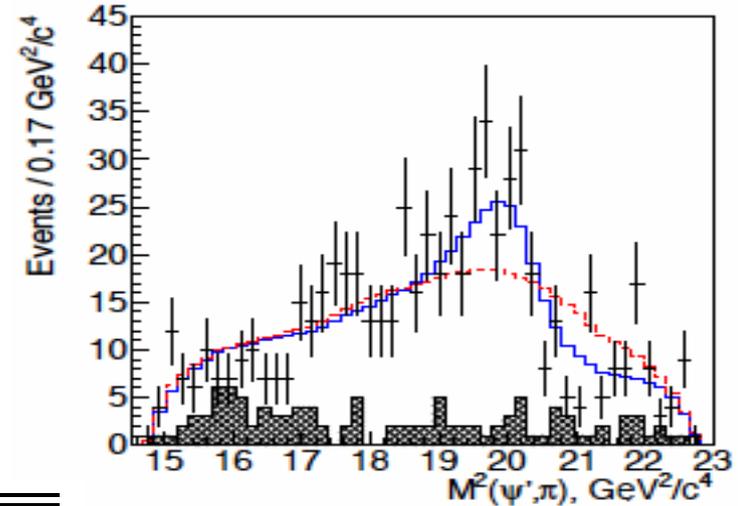
$$\mathcal{B}(\bar{B}^0 \rightarrow \psi' K^- \pi^+) = (5.80 \pm 0.36) \times 10^{-4},$$

$$\mathcal{B}(\bar{B}^0 \rightarrow \psi' K^*(892)) = (5.20_{-0.20-0.39}^{+0.28+1.45}) \times 10^{-4},$$

$$\mathcal{B}(\bar{B}^0 \rightarrow Z(4430)^+ K^-) \times \mathcal{B}(Z(4430)^+ \rightarrow \psi' \pi^+) =$$

$$(3.5_{-0.8-1.3}^{+1.2+0.4}) \times 10^{-5} \quad \text{for } J^P = 1^+ \text{ or}$$

$$(1.5_{-0.5-0.2}^{+0.7+0.7}) \times 10^{-5} \quad \text{for } J^P = 0^-,$$



Belle confirms again the $Z(4430)$ with a slightly different mass (No more close to D^*D_1 threshold)

1^+ is preferred
 0^- cannot be excluded

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