

# Bottomonium physics in Phase II

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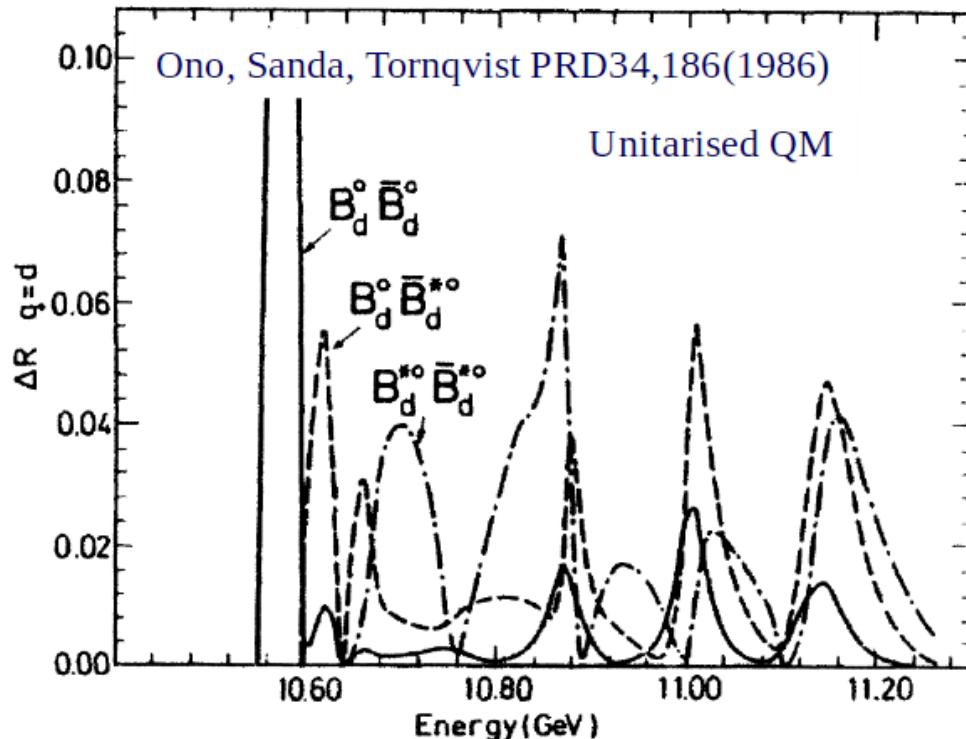
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*INFN, Sezione di Torino  
University of Torino*

VI Italian BelleII collaboration Meeting,  
Roma, 14/12/2016

# Bottomonia above threshold

R. Mizuk, MIAAP B2TiP meeting



## Open flavor channels:

oscillations  $\Leftrightarrow$  nodes of  $\Upsilon(5S,6S)$  w.f.  
almost saturate total  $\sigma_{bb}$

## Hidden flavor channels:

$\Upsilon(nS) \pi^+ \pi^-$ ,  $h_b(nP) \pi^+ \pi^-$ ,  $\Upsilon(nS) \eta$ , ...  
a few % of total  $\sigma_{bb}$

Exclusive cross sections : complete information about  $\Upsilon(4S)$ ,  $\Upsilon(5S)$ ,  $\Upsilon(6S)$  states  
Coupled channel analysis: pole positions,  $\Gamma_{e+e-}$ , couplings to various channels.

Hidden flavor cross sections : search for new states

compact tetraquarks and hadrobottomonia : decays to open flavor are suppressed

Belle:  $1\text{fb}^{-1}$  per point, Belle-II  $\rightarrow 10\text{fb}^{-1}$ . Energy smearing  $\sigma = 5 \text{ MeV} \Rightarrow$  step 10 MeV.

Belle:  $E_{\max} = 11.02 \text{ GeV}$ , Belle-II :  $E_{\max} = 11.24 \text{ GeV}$ .

# Exotica

Voloshin PRD84, 031502 (2011)

$$\left| Z_b \right\rangle = \frac{1}{\sqrt{2}} \mathbf{0}_{bb}^- \otimes \mathbf{1}_{Qq}^- - \frac{1}{\sqrt{2}} \mathbf{1}_{bb}^- \otimes \mathbf{0}_{Qq}^-$$

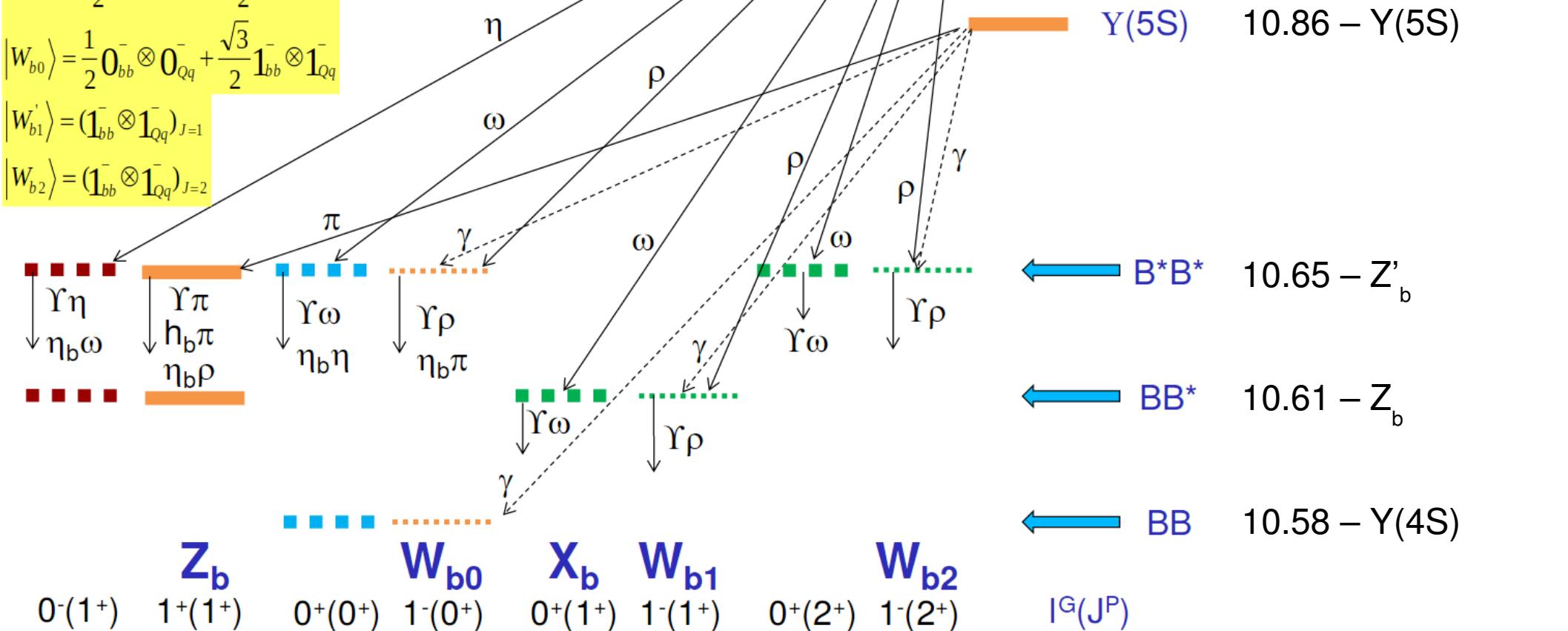
$$\left| Z_b' \right\rangle = \frac{1}{\sqrt{2}} \mathbf{0}_{bb}^- \otimes \mathbf{1}_{Qq}^- + \frac{1}{\sqrt{2}} \mathbf{1}_{bb}^- \otimes \mathbf{0}_{Qq}^-$$

$$\left| W_{b0}' \right\rangle = \frac{\sqrt{3}}{2} \mathbf{0}_{bb}^- \otimes \mathbf{0}_{Qq}^- - \frac{1}{2} \mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-$$

$$\left| W_{b0} \right\rangle = \frac{1}{2} \mathbf{0}_{bb}^- \otimes \mathbf{0}_{Qq}^- + \frac{\sqrt{3}}{2} \mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-$$

$$\left| W_{b1}' \right\rangle = (\mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-)_{J=1}$$

$$\left| W_{b2}' \right\rangle = (\mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-)_{J=2}$$

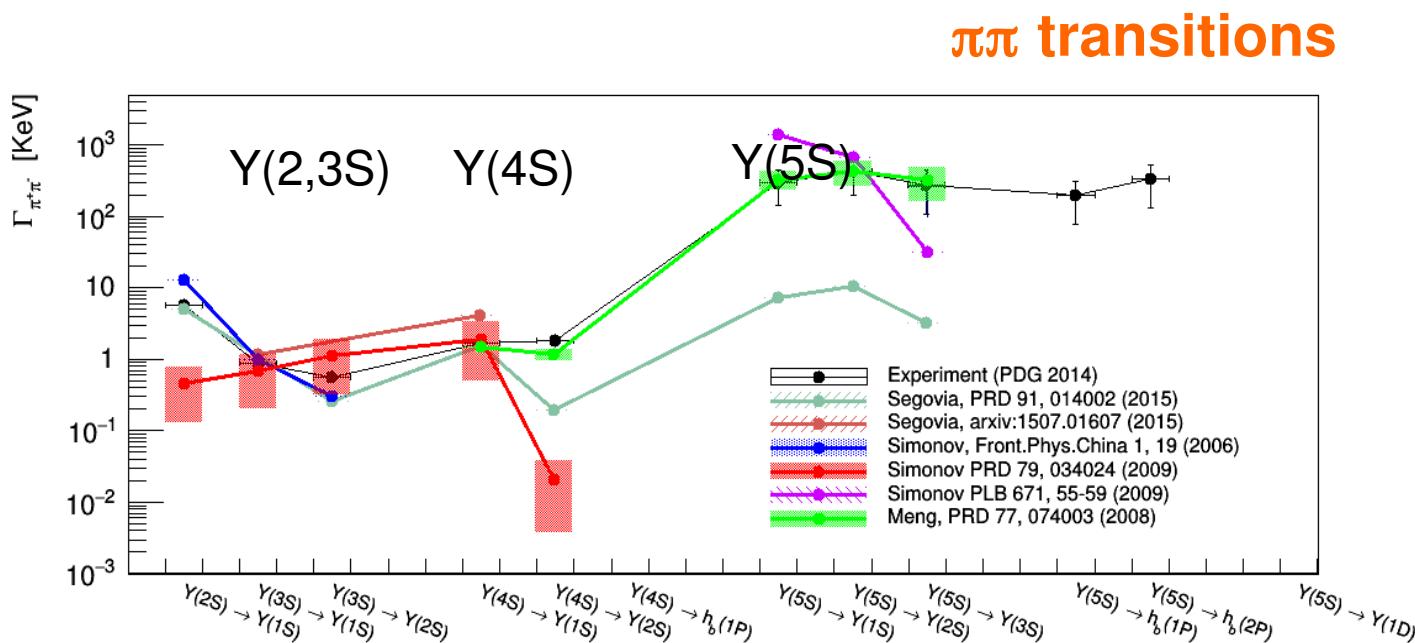


To search for exotica in hadronic transition we need data at Ecm  $\sim 11.5$  GeV

# Hadronic transitions

Hadronic transitions are challenging all the theoretical models

Transition	Partial width (keV)
$\Upsilon(2S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$	$5.7 \pm 0.5$
$\Upsilon(1S) \eta$	$(9.3 \pm 1.5) \times 10^{-3}$
$\Upsilon(3S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$	$0.89 \pm 0.08$
$\Upsilon(1S) \eta$	$< 2 \times 10^{-3}$
$\Upsilon(2S) \pi^+ \pi^-$	$0.57 \pm 0.06$
$\Upsilon(4S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$	$1.7 \pm 0.2$
$\Upsilon(1S) \eta$	$4.0 \pm 0.8$
$\Upsilon(2S) \pi^+ \pi^-$	$1.8 \pm 0.3$
$h_b(1P) \eta$	$45 \pm 7$
$\Upsilon(5S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$	$238 \pm 41$
$\Upsilon(1S) \eta$	$39 \pm 11$
$\Upsilon(1S) K^+ K^-$	$33 \pm 11$
$\Upsilon(2S) \pi^+ \pi^-$	$428 \pm 83$
$\Upsilon(2S) \eta$	$204 \pm 44$
$\Upsilon(3S) \pi^+ \pi^-$	$153 \pm 31$
$\chi_{b1}(1P) \omega$	$84 \pm 20$
$\chi_{b1}(1P) (\pi^+ \pi^- \pi^0)_{\text{non-}\omega}$	$28 \pm 11$
$\chi_{b2}(1P) \omega$	$32 \pm 15$
$\chi_{b2}(1P) (\pi^+ \pi^- \pi^0)_{\text{non-}\omega}$	$33 \pm 20$
$\Upsilon_J(1D) \pi^+ \pi^-$	$\sim 60$
$\Upsilon_J(1D) \eta$	$150 \pm 48$
$Z_b(10610)^\pm \pi^\mp$	$2070 \pm 440$
$Z_c(10650)^\pm \pi^\mp$	$1200 \pm 300$
$\Upsilon(6S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$	$137 \pm 32$
$\Upsilon(2S) \pi^+ \pi^-$	$183 \pm 43$
$\Upsilon(3S) \pi^+ \pi^-$	$77 \pm 28$
$Z_b(10610, 10650)^\pm \pi^\mp$	$1300 - 6600$



The transitions carry information about  
 → intermediate exotic states  
 → structure of the decaying resonance

Almost no information on transitions form  $\Upsilon(6S)$

# Why an early $\Upsilon(6S)$ run

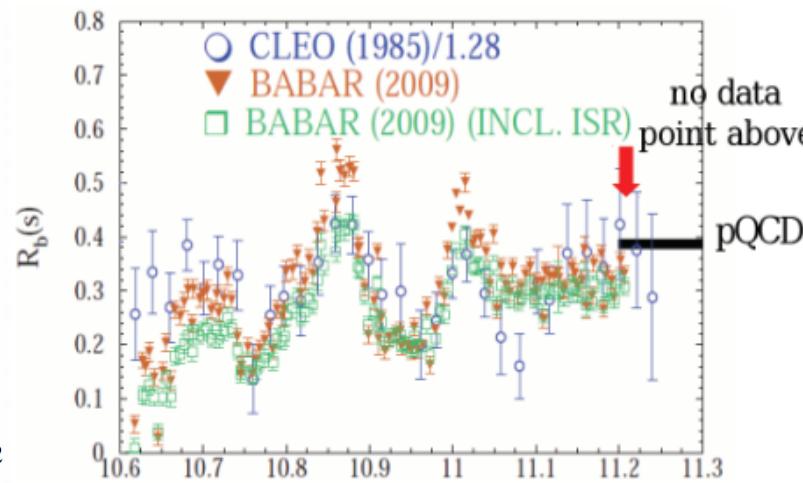
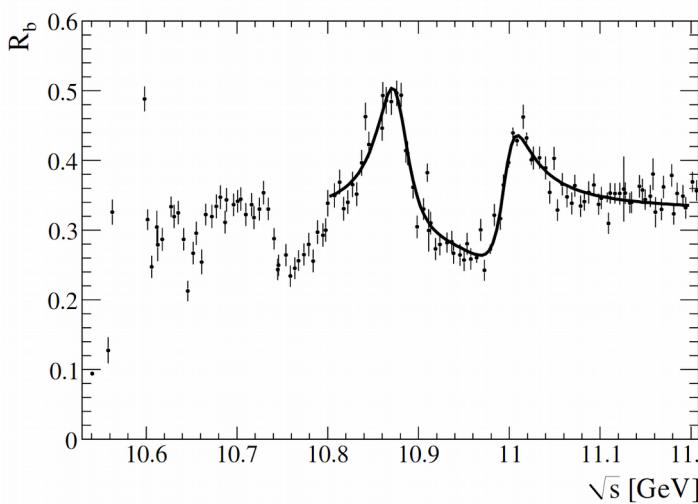
Phase-I (on-going): Beast detector to measure backgrounds

Phase-II (late 2017 – early 2018): no vertex detector,  $20 \pm 20 \text{ fb}^{-1}$ .

Phase-III (late 2018): with full Belle-II detector.

Experiment	Scans	$\Upsilon(6S)$ $\text{fb}^{-1}$	$\Upsilon(5S)$ $\text{fb}^{-1}$	$\Upsilon(4S)$ $\text{fb}^{-1}$	$\Upsilon(3S)$ $\text{fb}^{-1}$	$\Upsilon(2S)$ $\text{fb}^{-1}$	$\Upsilon(1S)$ $\text{fb}^{-1}$	$\text{fb}^{-1}$
	Off. Res.		$10^6$	$10^6$	$10^6$	$10^6$		$10^6$
CLEO	17.1	-	0.1	0.4	16	17.1	1.2	5
BaBar	54	$R_b$ scan		433	471	30	122	14
Belle	100	3	36	121	711	772	3	12

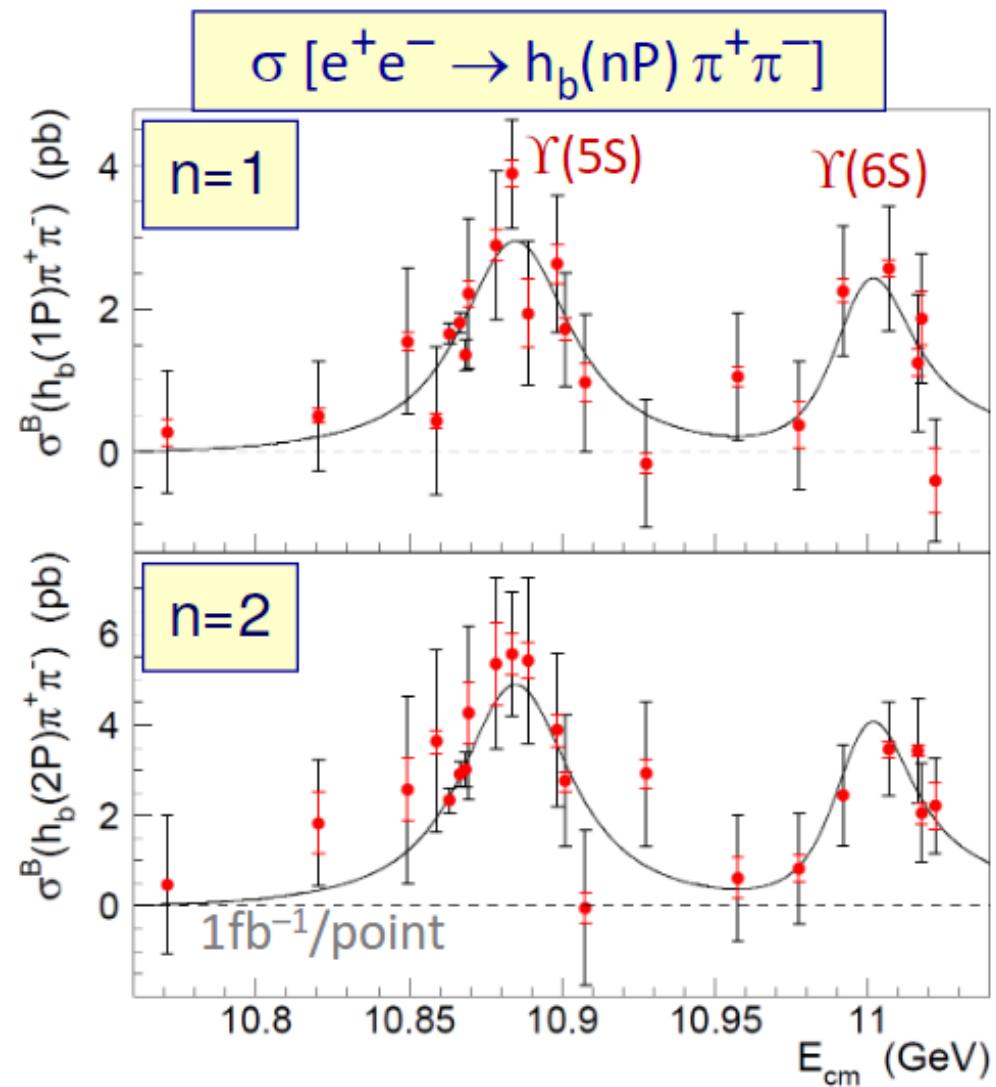
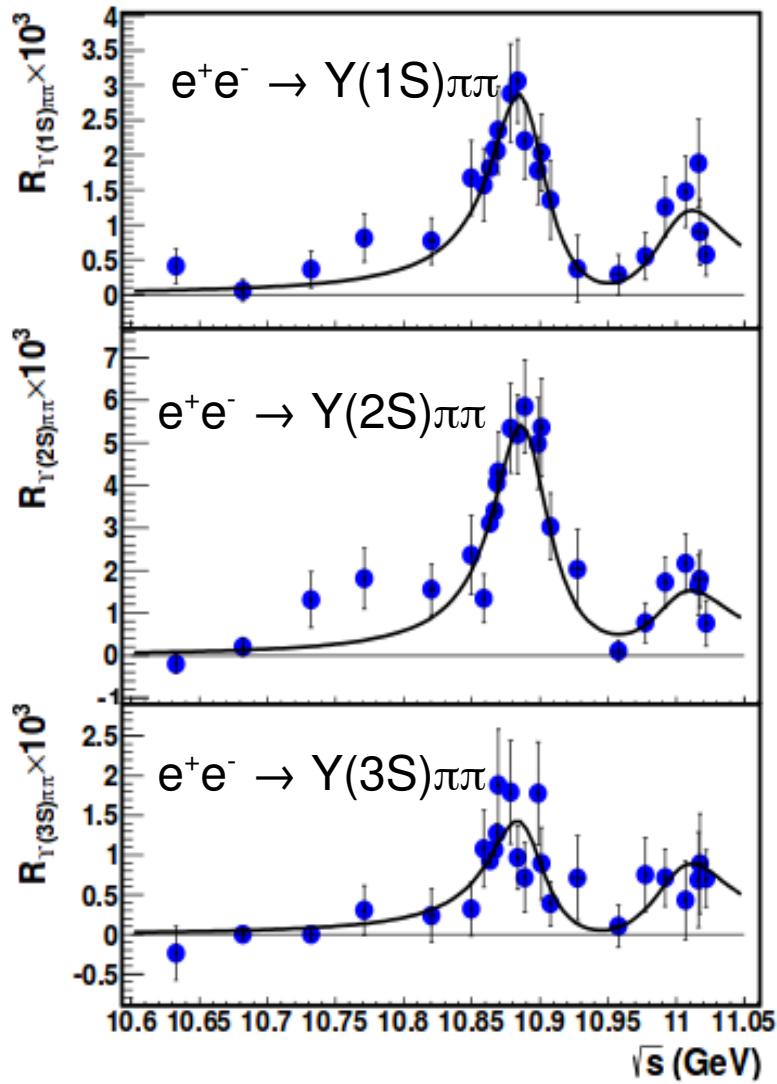
- Even 20  $\text{fb}^{-1}$  are a sizable improvement
- All our knowledge comes from low statistics energy scans



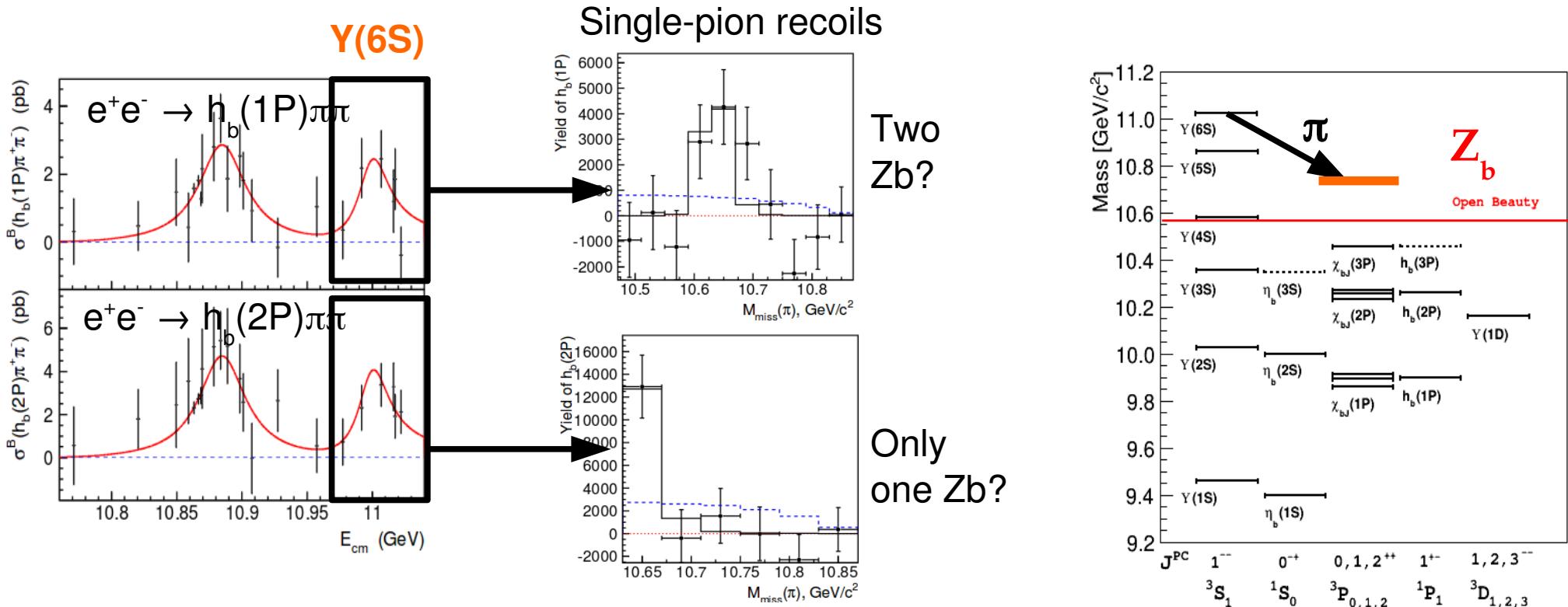
**Analysis topics:**

- Dipion transitions
- $\eta/\omega$  transitions
- radiative transitions

# Dipion cross section nearby Y(6S)



# Dipion analyses



## Analyses:

- 1) Inclusive Di-Pion recoil (search for all possible transitions).
- 2) Exclusive Y(6S) → ππ Y(nS) → ππ μμ

## Goals:

- Separate Zb and Z'b contributions
- Measure the relative phase

# $\eta/\omega$ recoil

## Analyses:

- 1) Inclusive recoil.
- 2) Exclusive  $Y(6S) \rightarrow \eta Y(nS)$  with di-muon tag

## $\eta/\pi\pi$ ratios

$$\frac{\Gamma[Y(5S) \rightarrow \eta h_b(1P)]}{\Gamma[Y(5S) \rightarrow \pi\pi h_b(1P)]} < 0.94$$

$$\frac{\Gamma[Y(5S) \rightarrow \eta h_b(2P)]}{\Gamma[Y(5S) \rightarrow \pi\pi h_b(2P)]} < 0.62$$

## $\eta/\eta$ ratios

$$\frac{\Gamma[Y(5S) \rightarrow \eta Y(1D)]}{\Gamma[Y(5S) \rightarrow \eta h_b(1P)]} > 0.92 \quad \longleftrightarrow$$

$$\frac{\Gamma[Y(5S) \rightarrow \eta Y(1D)]}{\Gamma[Y(5S) \rightarrow \eta h_b(2P)]} > 0.78 \quad \longleftrightarrow$$

$$\frac{\Gamma[Y(5S) \rightarrow \eta Y(1D)]}{\Gamma[Y(5S) \rightarrow \eta Y(2S)]} = 1.6 \pm 0.7 \quad \longleftrightarrow$$

## Goals:

- 1)  $\eta/\pi\pi$  ratio at  $Y(6S)$
- 2)  $Y(1D), Y(2D)$  ?

## The $Y(5S)$ - $Y(1D)$ anomaly:

- Transitions to  $h_b$  and  $Y(1S,2S,3S)$  have  $\Gamma[\pi\pi] > \Gamma[\eta]$
- Transitions to  $Y(1D)$  have  $\Gamma[\pi\pi] < \Gamma[\eta]$

## $\pi\pi/\pi\pi$ ratios

$$\frac{\Gamma[Y(5S) \rightarrow \pi\pi Y(1D)]}{\Gamma[Y(5S) \rightarrow \pi\pi h_b(1P)]} \approx 0.5$$

$$\frac{\Gamma[Y(5S) \rightarrow \pi\pi Y(1D)]}{\Gamma[Y(5S) \rightarrow \pi\pi h_b(2P)]} \approx 0.3$$

$$\frac{\Gamma[Y(5S) \rightarrow \pi\pi Y(1D)]}{\Gamma[Y(5S) \rightarrow \pi\pi Y(2S)]} \approx 0.3$$

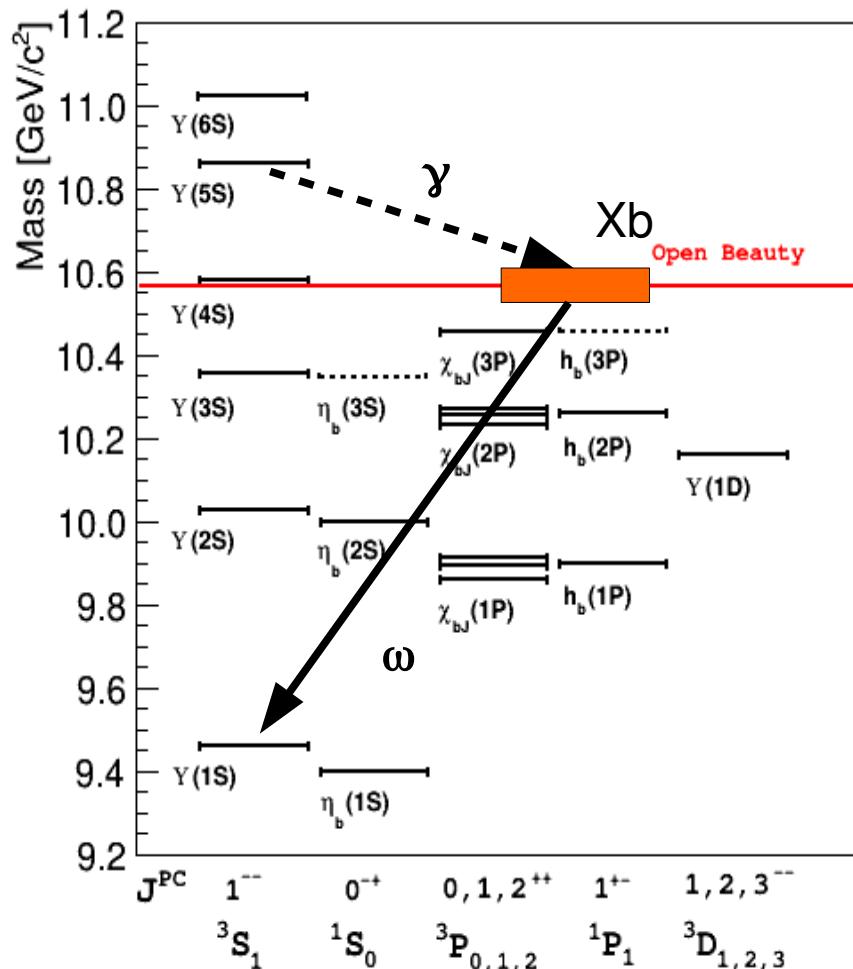
# $\eta/\omega$ recoil

## Analyses:

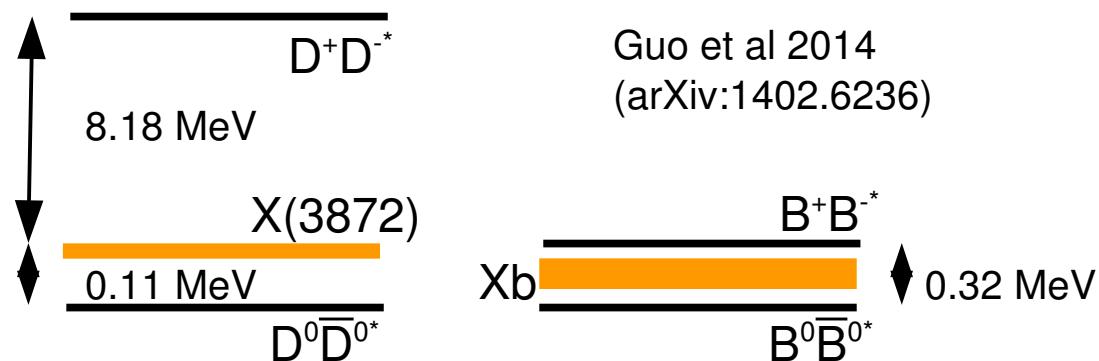
- 1) Inclusive recoil.
- 2) Exclusive  $Y(6S) \rightarrow \eta Y(nS)$  with di-muon tag
- 3) Exclusive  $Y(6S) \rightarrow \omega\gamma Y(1S)$  with di-muon tag

## Goals:

- 1)  $\eta/\pi\pi$  ratio at  $Y(6S)$
- 2)  $Y(1D)$  ?
- 3)  $X_b$



$X(3872)$  is closer to  $D^0\bar{D}^{0*}$  than to  $D^+D^{-*}$   
sizable isospin violation  $X(3872) \rightarrow \pi\pi J/\psi$



$X_b \rightarrow \omega Y(1S)$  Isospin preserving

$X_b \rightarrow \pi\pi Y(1S)$  Isospin violating

Belle searched for  $X_b$  from  $Y(5S)$ , but the production rate depends on the nature of the decaying resonance

# Radiative transitions

## Analyses:

- 1) Inclusive  $\gamma$  spectrum.
- 2) Semi-inclusive  $\gamma + \rho$  recoil

Voloshin PRD84, 031502 (2011)

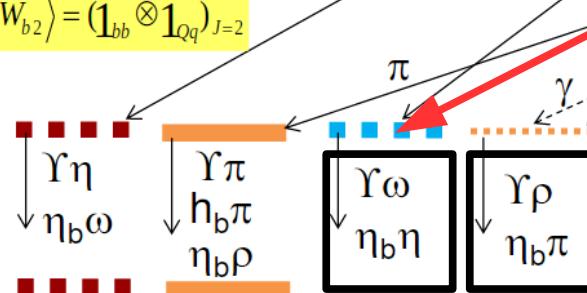
$$|Z_b\rangle = \frac{1}{\sqrt{2}} \mathbf{0}_{bb}^- \otimes \mathbf{1}_{Qq}^- - \frac{1}{\sqrt{2}} \mathbf{1}_{bb}^- \otimes \mathbf{0}_{Qq}^-$$

$$|Z_b'\rangle = \frac{1}{\sqrt{2}} \mathbf{0}_{bb}^- \otimes \mathbf{1}_{Qq}^- + \frac{1}{\sqrt{2}} \mathbf{1}_{bb}^- \otimes \mathbf{0}_{Qq}^-$$

$$|W_{b0}'\rangle = \frac{\sqrt{3}}{2} \mathbf{0}_{bb}^- \otimes \mathbf{0}_{Qq}^- - \frac{1}{2} \mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-$$

$$|W_{b1}'\rangle = (\mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-)_{J=1}$$

$$|W_{b2}'\rangle = (\mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-)_{J=2}$$



## Goals:

- 1) Exotica

Need input from Belle-II

11.5GeV

$Y(?)S$

$Y(6S)$

$Y(5S)$

$\sim 400$  MeV photon

$B^*B^*$

$BB^*$

$BB$

$|G(J^P)$

# New states discovery

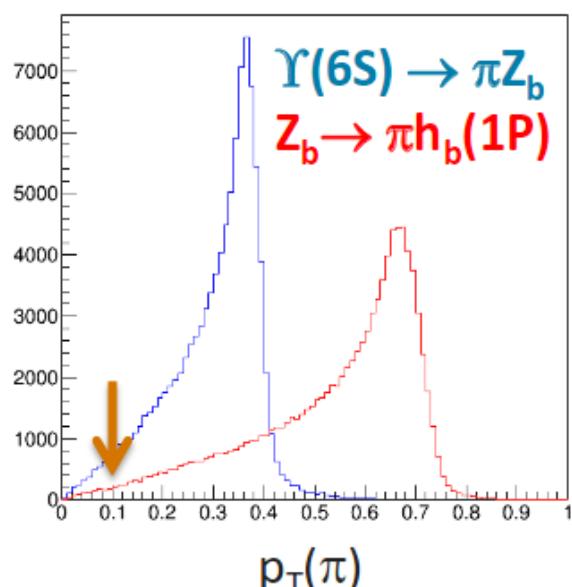
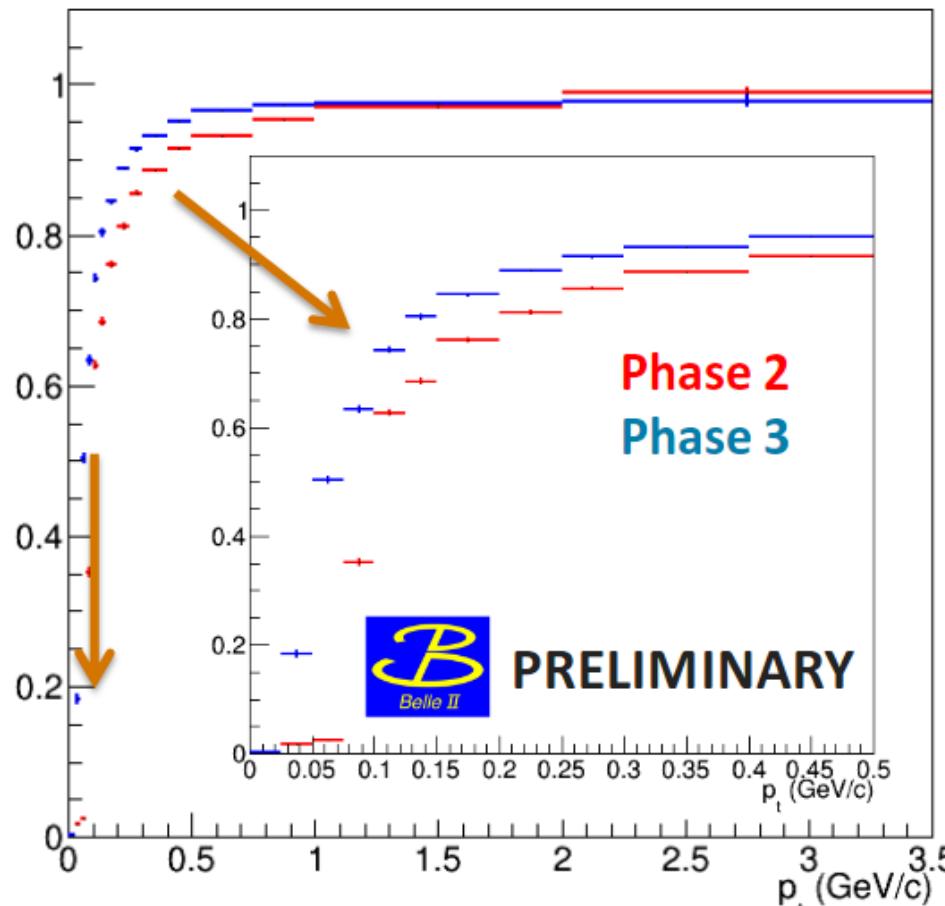
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## Conventional bottomonia states in hadronic transitions from the Y(6S)

Search for missing conventional bottomonia below BB threshold

Name	$L$	$S$	$J^{PC}$	Mass, MeV/ $c^2$	Emitted hadrons [Threshold, GeV/ $c^2$ ]
$\eta_b(3S)$	0	0	$0^{-+}$	10336	$\omega$ [11.12], $\phi$ [11.36]
$h_b(3P)$	1	0	$1^{+-}$	10541	$\pi^+\pi^-$ [10.82], $\eta$ [11.09], $\eta'$ [11.50]
$\eta_{b2}(1D)$	2	0	$2^{-+}$	10148	$\omega$ [10.93], $\phi$ [11.17]
$\eta_{b2}(2D)$	2	0	$2^{-+}$	10450	$\omega$ [11.23], $\phi$ [11.47]
$\Upsilon_J(2D)$	2	1	$(1, 2, 3)^{--}$	10441 – 10455	$\pi^+\pi^-$ [10.73], $\eta$ [11.00], $\eta'$ [11.41]
$h_{b3}(1F)$	3	0	$3^{+-}$	10355	$\pi^+\pi^-$ [10.63], $\eta$ [10.90], $\eta'$ [11.31]
$\chi_{bJ}(1F)$	3	1	$(2, 3, 4)^{++}$	10350 – 10358	$\omega$ [11.14], $\phi$ [11.38]
$\eta_{b4}(1G)$	4	0	$4^{-+}$	10530	$\omega$ [11.31], $\phi$ [11.55]
$\Upsilon_J(1G)$	4	1	$(3, 4, 5)^{--}$	10529 – 10532	$\pi^+\pi^-$ [10.81], $\eta$ [11.08], $\eta'$ [11.49]

# Dipion performances



**Without SVD:**

- No tracking below  $p_t = 0.1$  GeV
- Slight decrease of efficiency for  $p_t < 0.1$  GeV
- No significant impact on dipion analyses

## ► $Z_b(10650): \pi^+ \pi^- h_b(1P)$

- Double Gaussian fit to  $mm(\pi)$  with  $9.86 < mm(\pi\pi) < 9.89$  GeV
- Phase 2: 15071 events,  $m=10651.7$  MeV,  $\Gamma=7.6$  MeV
- Phase 3: 18963 events,  $m=10652.2$  MeV,  $\Gamma=8.2$  MeV

# Bottomonium WG status

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**Conveners:**

UT (Torino) and Bryan Fulsom (PNNL)

**Confluence:**

<https://confluence.desy.de/display/BI/Physics+Bottomonium>

**Mailing List:**

[physics-bottomonium@belle2.org](mailto:physics-bottomonium@belle2.org)

**Meetings:**

Every last friday of the month, 8am – 2pm JST

Topic	Who's working on this?
Skims for bottomonium physics	<a href="#">@ Stefano Spataro</a> , <a href="#">@ Roberto Mussa</a>
Validation of Y(3S) MC5 Monte Carlo (Phase III conditions)	???
Sensitivity studies for B2TiP	<a href="#">@ Elisa Guido</a> , <a href="#">@ Umberto Tamponi</a>
Validation/development of software tools for bottomonium physics	???
Preparation of Y(6S) MC7 Monte Carlo (Phasell conditions)	<a href="#">@ Caitlin MacQueen</a> Bryan Fulsom
Triggers for Y(1S) → invisible	<a href="#">@ Gianluca Inguglia</a>

# Backup

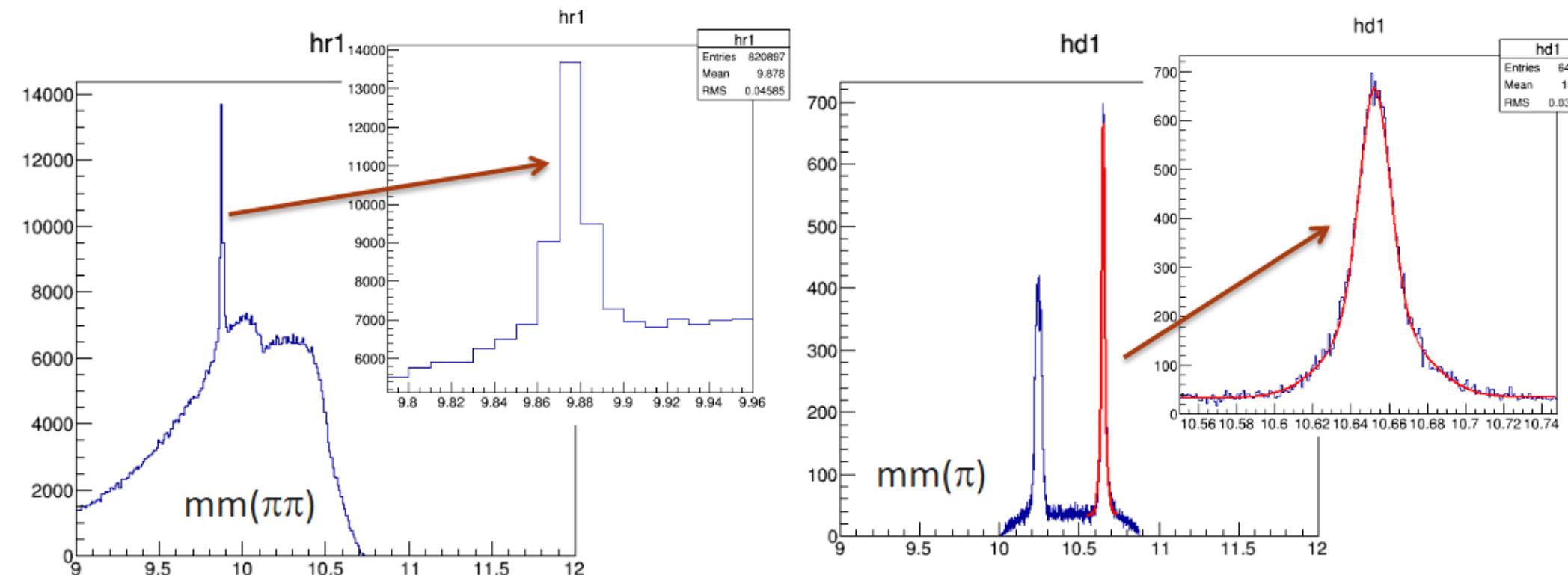
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# Dipion performances

- MC samples produced in MC7 campaign
- Validation ongoing

## ► $Z_b(10650)$ : $\pi^+\pi^-h_b(1P)$

- Double Gaussian fit to  $mm(\pi)$  with  $9.86 < mm(\pi\pi) < 9.89$  GeV
- Phase 2: 15071 events,  $m=10651.7$  MeV,  $\Gamma=7.6$  MeV
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# Hadronic transitions: $Y(4,5S)$



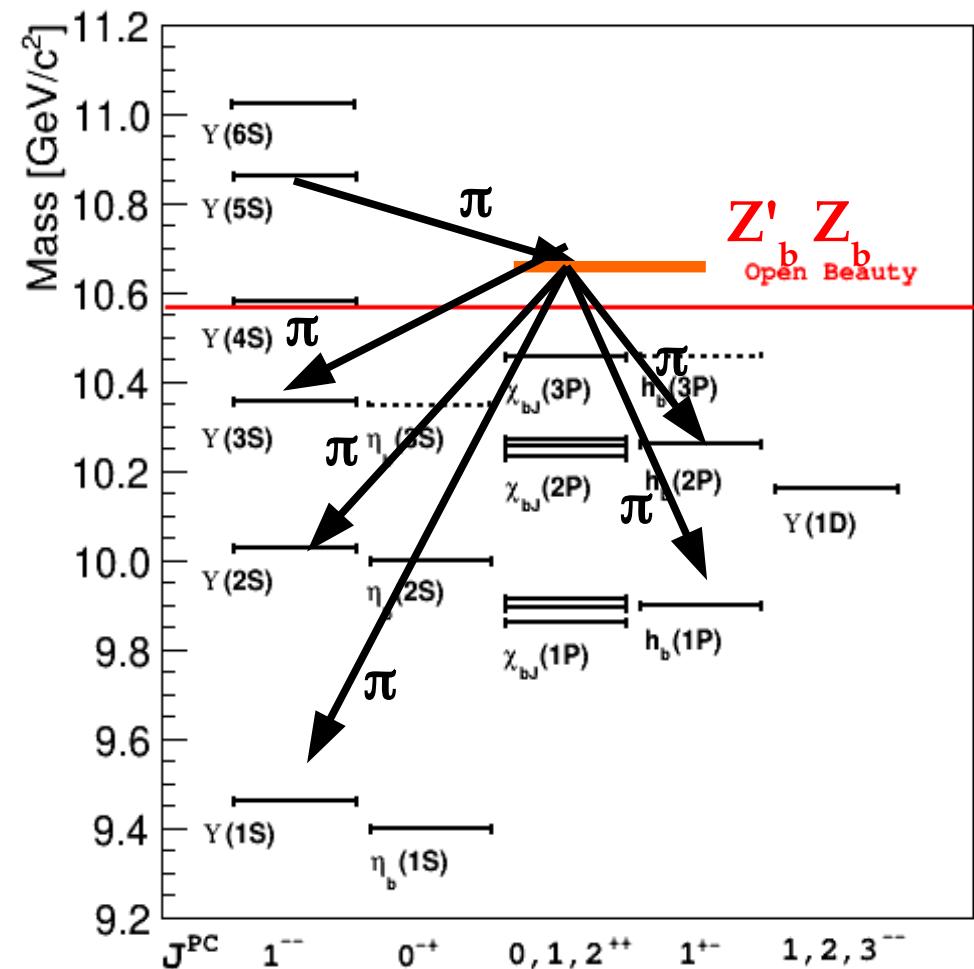
b quark spin flip

no b quark spin flip

**Spin-flip prediction**

$$\frac{\Gamma[Y(nS) \rightarrow \eta Y(mS)]}{\Gamma[Y(nS) \rightarrow \pi\pi Y(mS)]} \ll 1$$

$$\frac{\Gamma[Y(nS) \rightarrow \pi\pi h_b(mP)]}{\Gamma[Y(nS) \rightarrow \pi\pi Y(mS)]} \ll 1$$



## Experiment

$$\frac{\Gamma[Y(5S) \rightarrow \pi\pi h_b(2P)]}{\Gamma[Y(5S) \rightarrow \pi\pi Y(2S)]} = 0.77 \pm 0.08^{+0.22}_{-0.17}$$

PRL108,  
122001

$$\frac{\Gamma[Y(5S) \rightarrow \pi\pi h_b(1P)]}{\Gamma[Y(5S) \rightarrow \pi\pi Y(2S)]} = 0.46 \pm 0.08^{+0.07}_{-0.12}$$

No suppression

$$\frac{\Gamma[Y(5S) \rightarrow \eta Y(1S)]}{\Gamma[Y(5S) \rightarrow \pi\pi Y(1S)]} = 0.16$$

Belle  
preliminary

$$\frac{\Gamma[Y(5S) \rightarrow \eta Y(2S)]}{\Gamma[Y(5S) \rightarrow \pi\pi Y(2S)]} = 0.48$$

No suppression

$$\frac{\Gamma[Y(4S) \rightarrow \eta Y(1S)]}{\Gamma[Y(4S) \rightarrow \pi\pi Y(1S)]} = 2.41 \pm 0.40 \pm 0.20$$

Spin flipping-enhanced  
transition

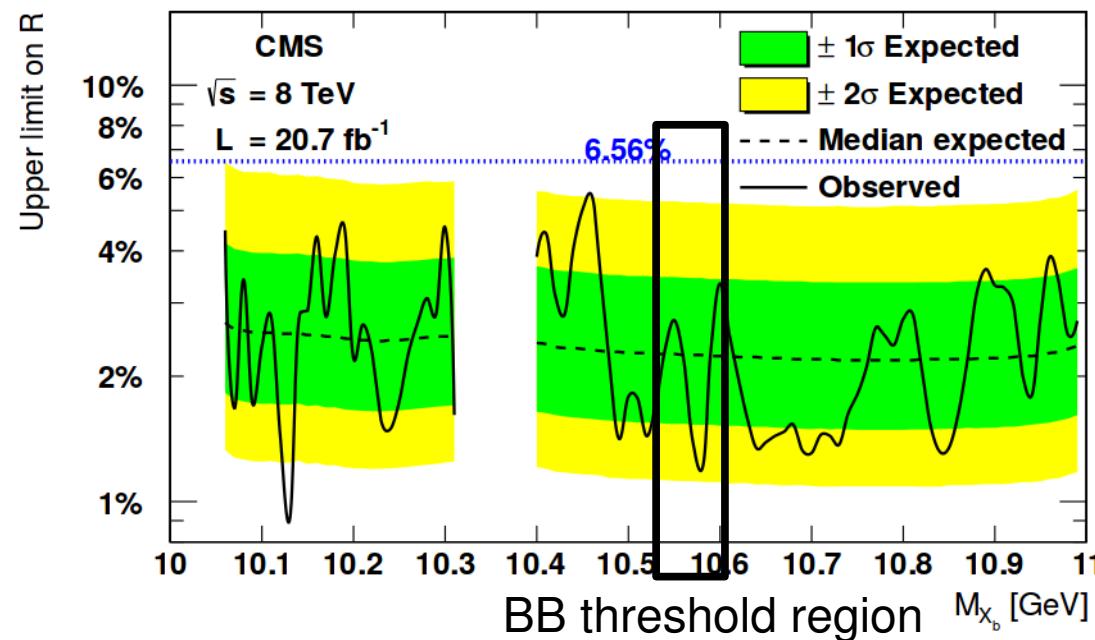
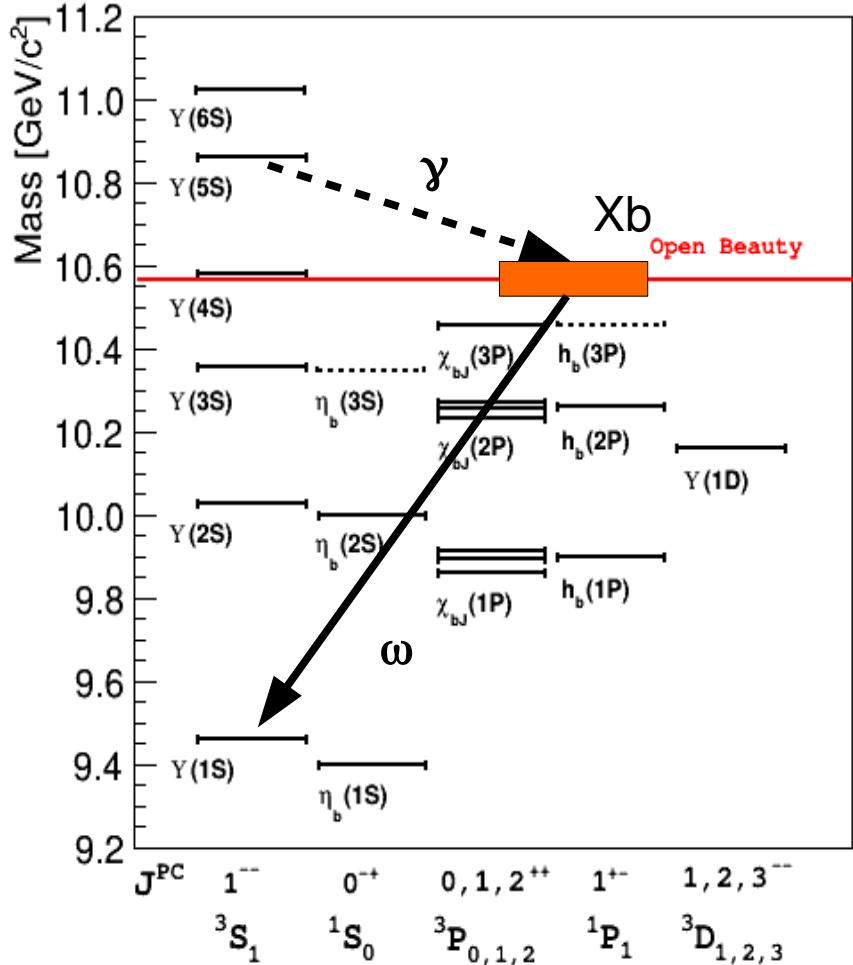
PRD 78, 112002

# Exotics in $\Upsilon(5S)$ decays

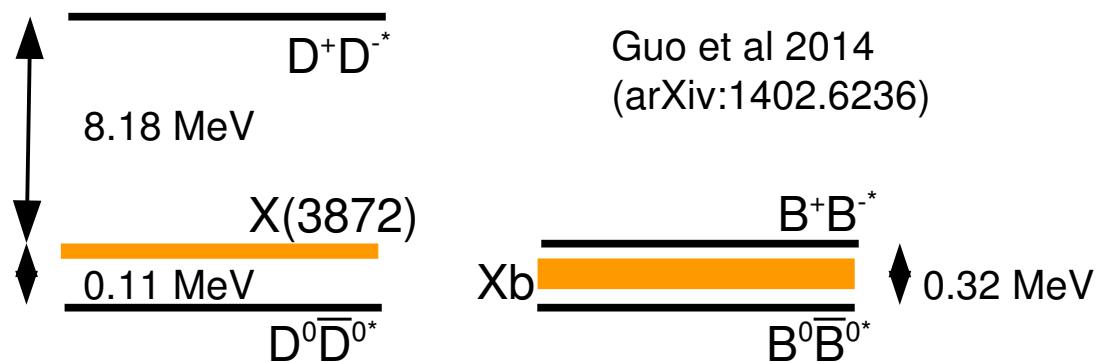
Bottomonium equivalent of  $X(3872)$

**CMS:** inclusive search for    PLB 727 (2013) 57  
 $X_b \rightarrow \pi\pi \Upsilon(1S)$  in pp collisions

**Belle:** exclusive  $\Upsilon(5S)$  decay  
 $\Upsilon(5S) \rightarrow \gamma X_b \rightarrow \gamma \omega \Upsilon(1S)$  arXiv:1408.0504



$X(3872)$  is closer to  $D^0\bar{D}^{0*}$  than to  $D^+\bar{D}^{-*}$   
sizable isospin violation  $X(3872) \rightarrow \pi\pi J/\psi$



$X_b \rightarrow \omega \Upsilon(1S)$  Isospin preserving

$X_b \rightarrow \pi\pi \Upsilon(1S)$  Isospin violating

Guo et al 2014  
(arXiv:1402.6236)

# $Z_b$ in $\Upsilon(nS)$ final states

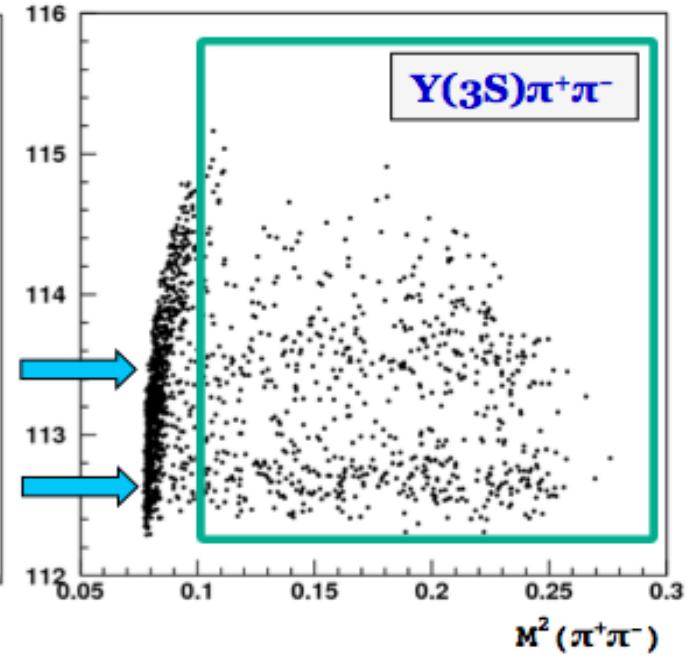
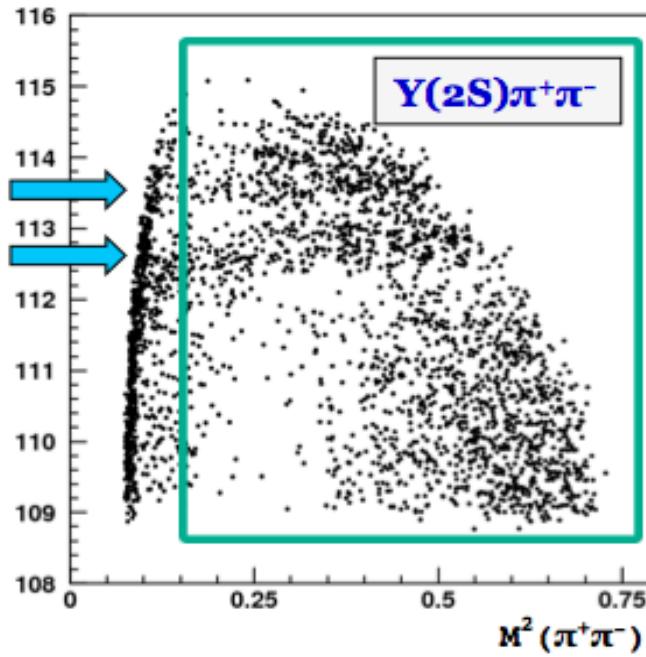
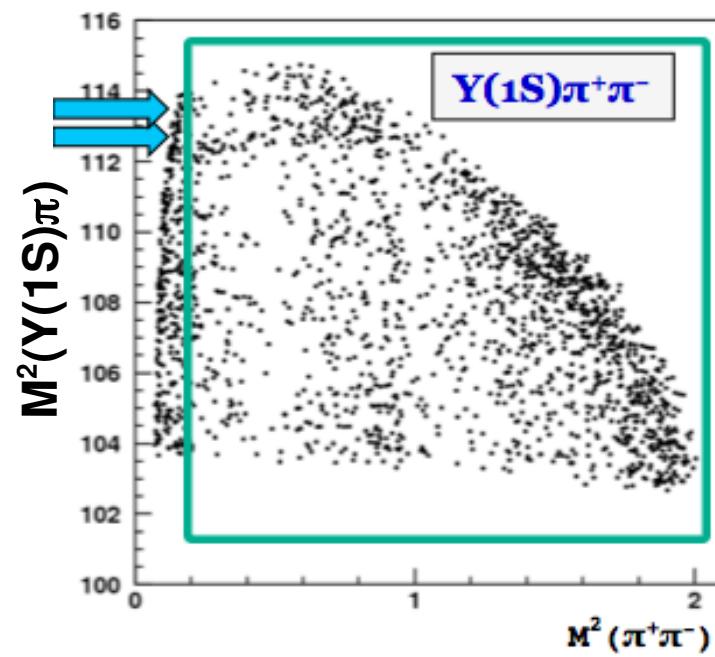
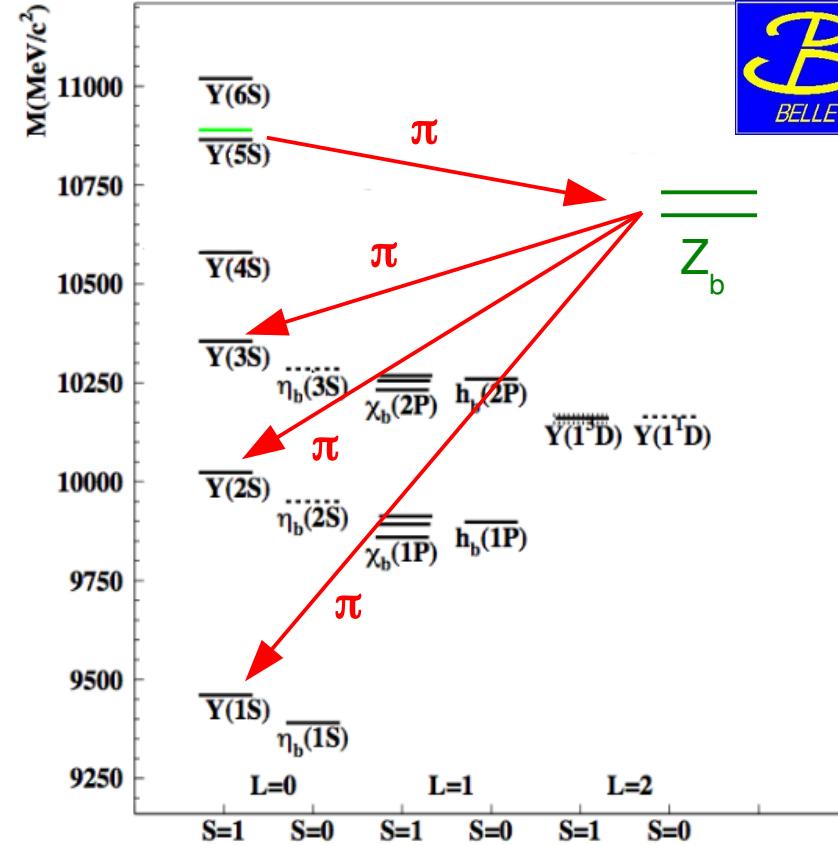
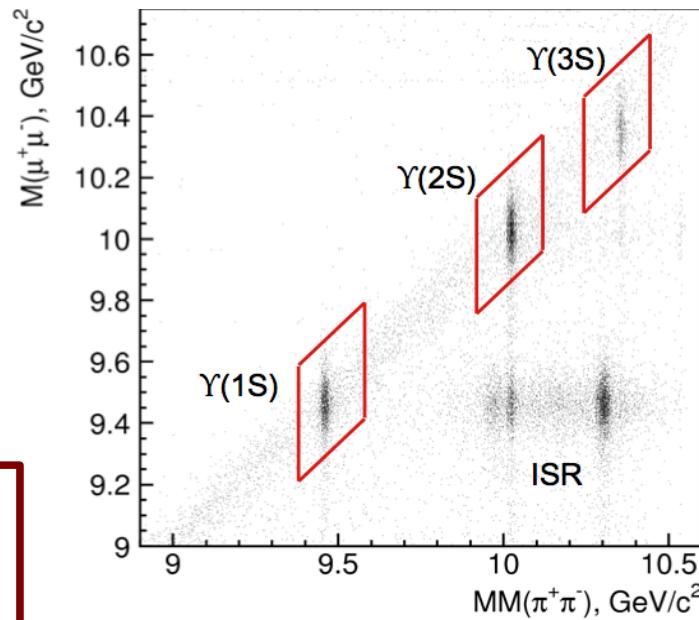


PRL108,122001

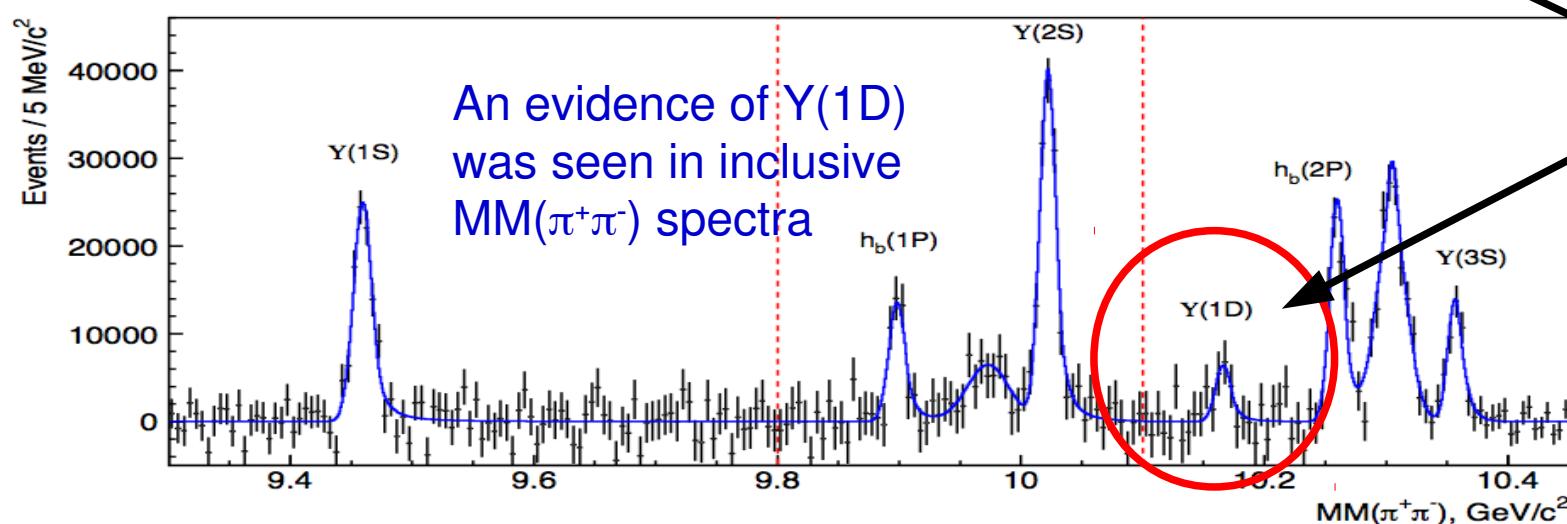
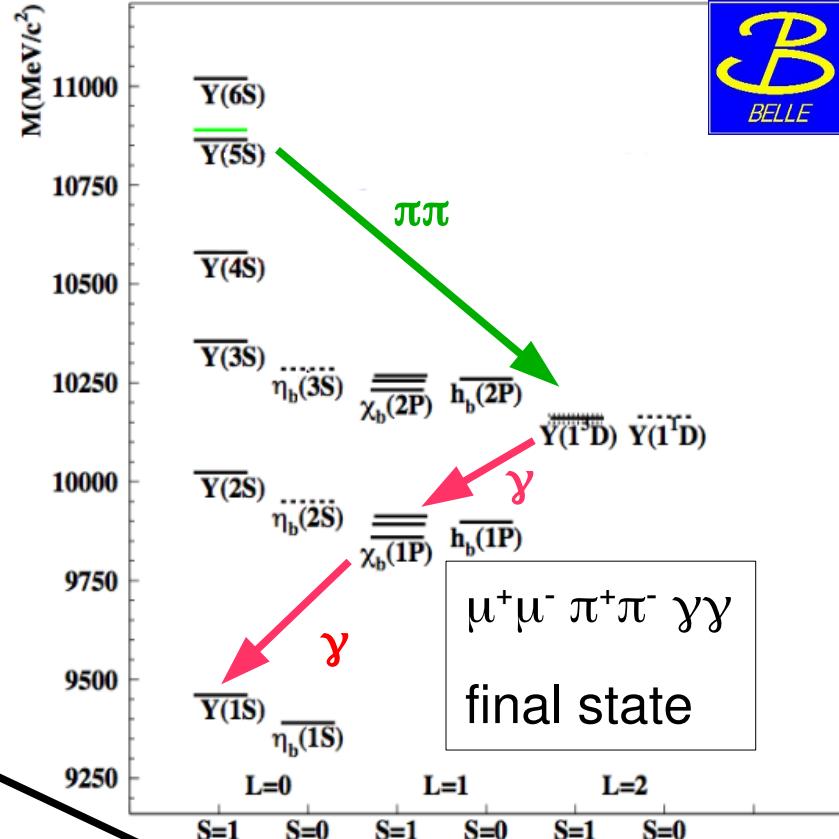
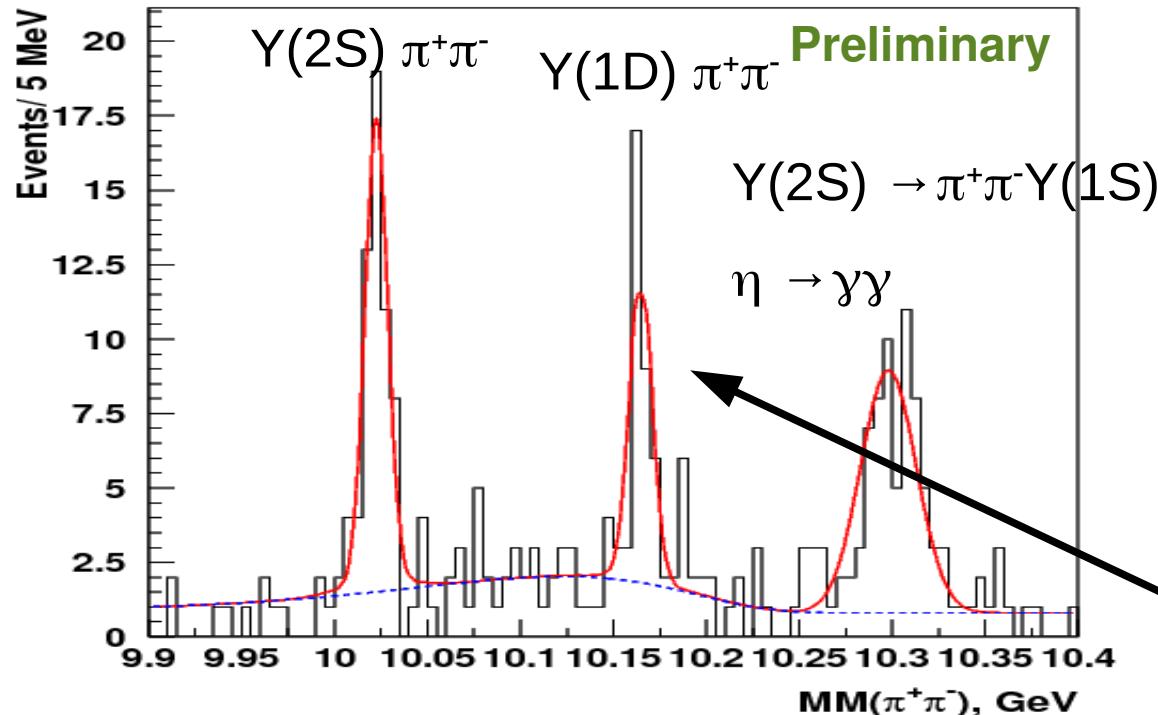
$$\Upsilon(nS) \rightarrow \mu^+ \mu^-$$

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

3 other observation  
of  $Z_b$ 's !



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

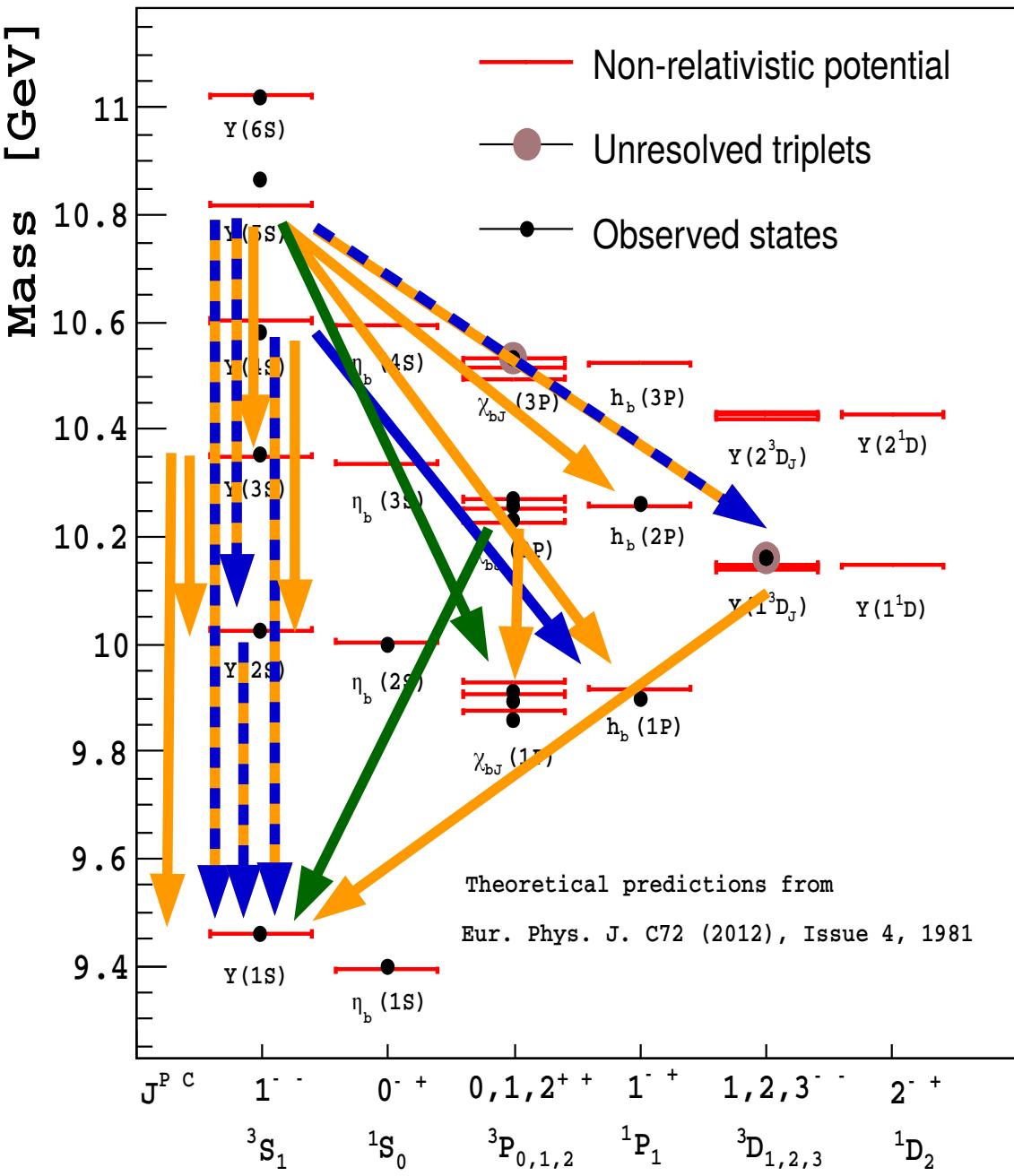


Significance 9  $\sigma$

Significance 2.9  $\sigma$

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

# Missing hadronic transitions



**What we have measured:**

$\Upsilon(5S) \rightarrow \eta/\pi\pi \Upsilon(1S)$   
 $\Upsilon(5S) \rightarrow \eta/\pi\pi \Upsilon(2S)$   
 $\Upsilon(5S) \rightarrow \pi\pi \Upsilon(3S)$   
 $\Upsilon(5S) \rightarrow \pi\pi \text{hb}(1P)$   
 $\Upsilon(5S) \rightarrow \pi\pi \text{hb}(2P)$   
 $\Upsilon(5S) \rightarrow \eta/\pi\pi \Upsilon(^31D)$   
 $\Upsilon(5S) \rightarrow \omega \chi_b(1P)$

$\Upsilon(4S) \rightarrow \eta/\pi\pi \Upsilon(1S)$   
 $\Upsilon(4S) \rightarrow \pi\pi \Upsilon(2S)$   
 $\Upsilon(4S) \rightarrow \eta \text{hb}(1P)$

$\chi_b(2P) \rightarrow \pi\pi \chi_b(1P)$   
 $\chi_b(2P) \rightarrow \omega \Upsilon(1S)$

$\Upsilon(2S) \rightarrow \eta/\pi\pi \Upsilon(1S)$   
 $\Upsilon(3S) \rightarrow \pi\pi \Upsilon(1S)$   
 $\Upsilon(3S) \rightarrow \pi\pi \Upsilon(2S)$   
 $\Upsilon(1D) \rightarrow \pi\pi \Upsilon(1S)$

**Only Triplet  $\rightarrow$  Triplet/Singlet**