Seminario Generale INFN
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Bottomonium physics: state of the art and perspectives at the Belle II experiment

BELLE

Belle II

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Outline

- Main achievements of the B-factories in bottomonium spectroscopy
  - Discovery of new resonances
  - Exotic states
  - Study of transitions between bottomonium states, and problematic theoretical interpretations
- What is left to do for the 2nd generation of B-factories?

What is bottomonium?

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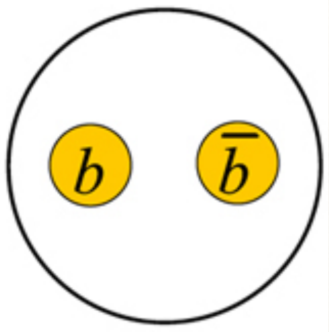

- A bound state of a b and an anti-b quark

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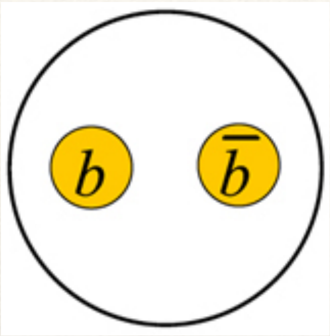

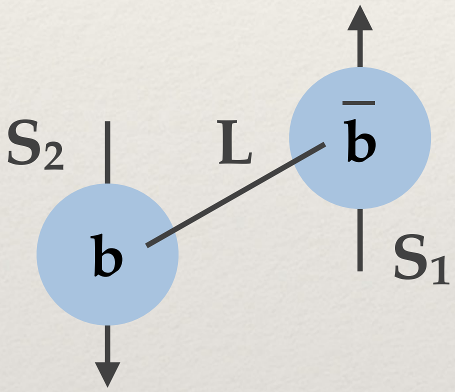

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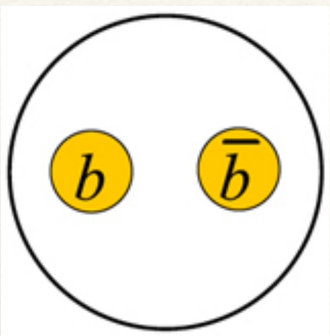
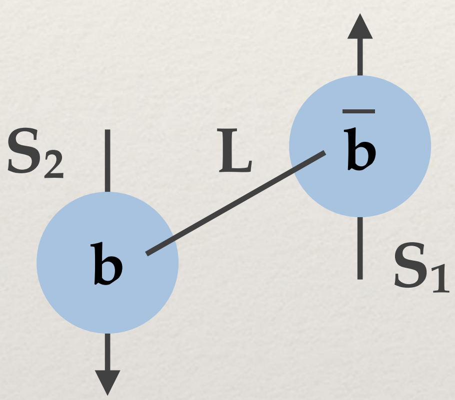
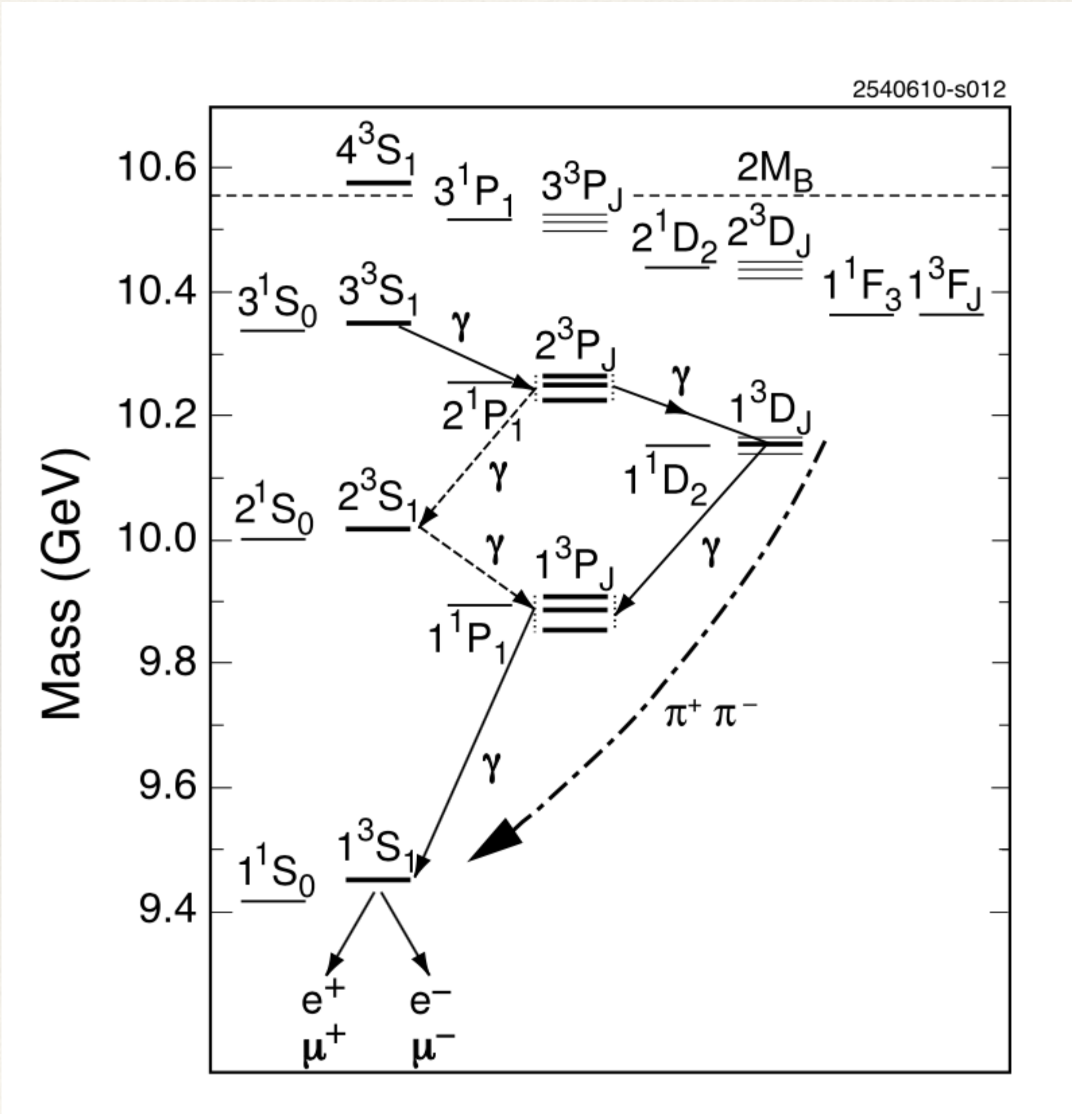


- A bound state of a b and an anti-b quark
  - Access to energy levels below, near and above the BB threshold
  - Narrow resonances: $\Gamma < \Delta M << M$





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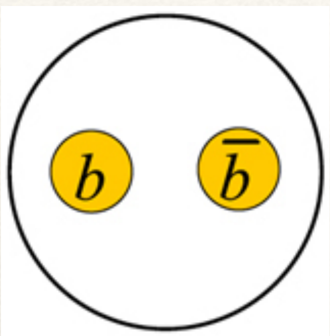

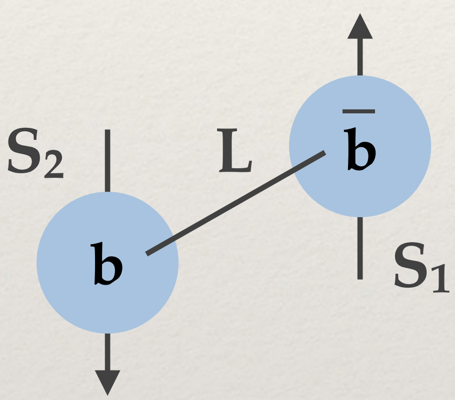

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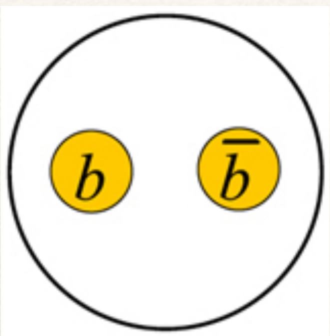
  - at high energies: perturbative approach (expansion in $\alpha_S(Q^2)$)
  - at low energies: non-perturbative effects dominate
  - in between, more complex approaches needed: interplay between perturbative and non-perturbative QCD

What is bottomonium?



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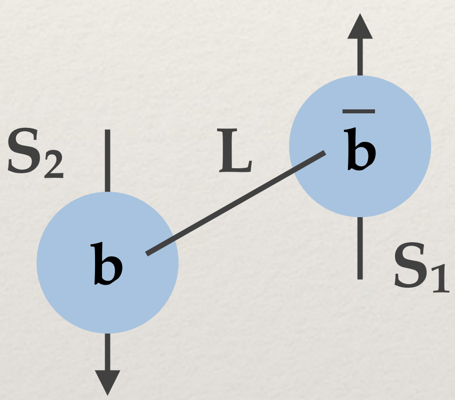
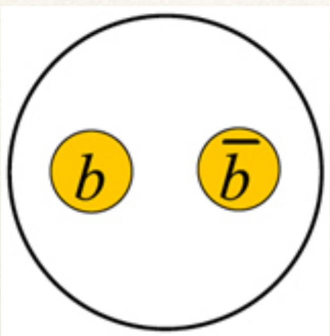
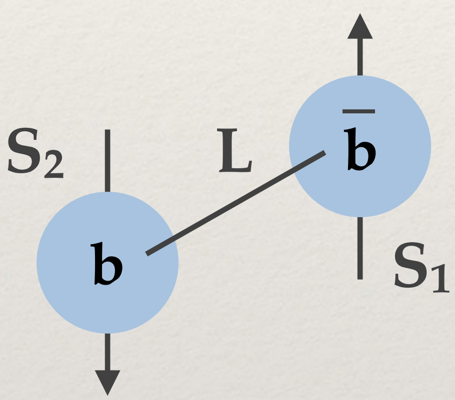


- A window to look at the different regimes of QCD: multiscale system
  - at high energies: perturbative approach (expansion in $\alpha_S(Q^2)$)
  - at low energies: non-perturbative effects dominate
  - in between, more complex approaches needed: interplay between perturbative and non-perturbative QCD
- Different sectors of interest:
  - **spectroscopy**: which level exist and why? masses, widths, quantum numbers. Are all the observed states expected and compatible with a bb content? Unconvential quarkonia?
  - **decays:** increasing precision in the dominant modes, measurement of the rarest ones: is theory able to predict their branching fractions?
  - **production** and behaviour **in media**

What is bottomonium?





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  - in bet… ed: interplay between pertu…

Interplay between theory and experiment is vital!

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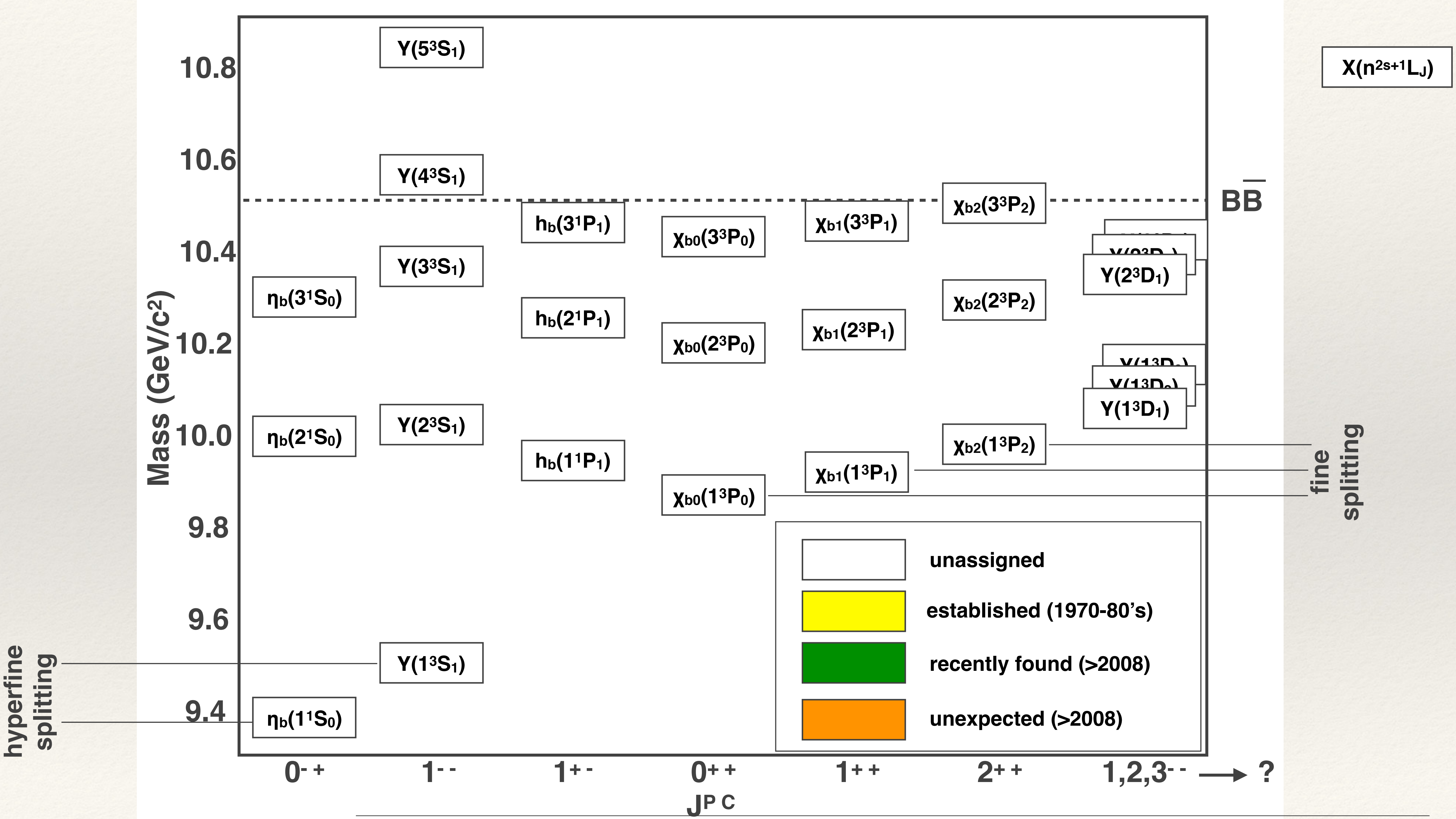
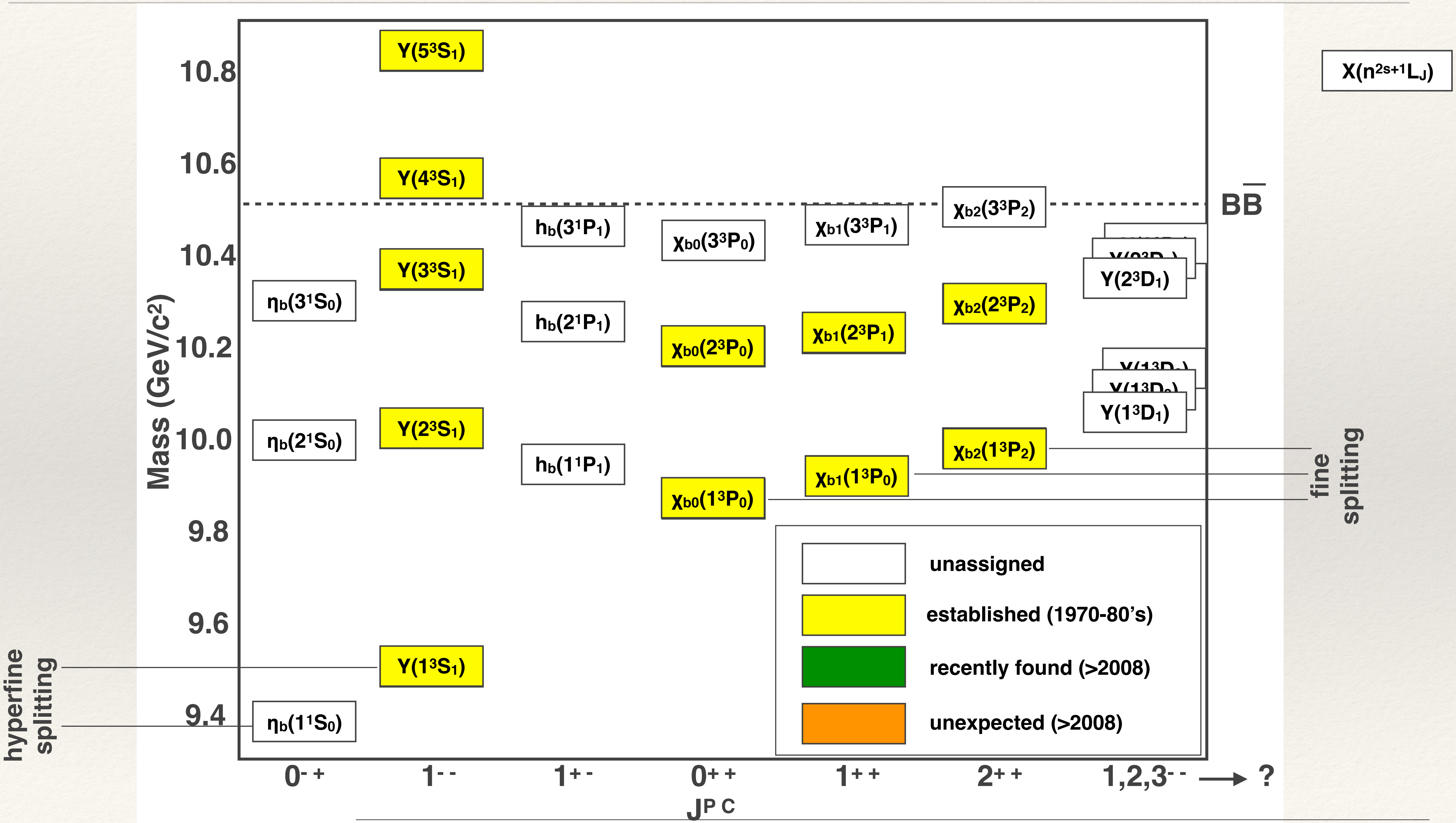
Bottomonium history in one page



Bottomonium history in one page



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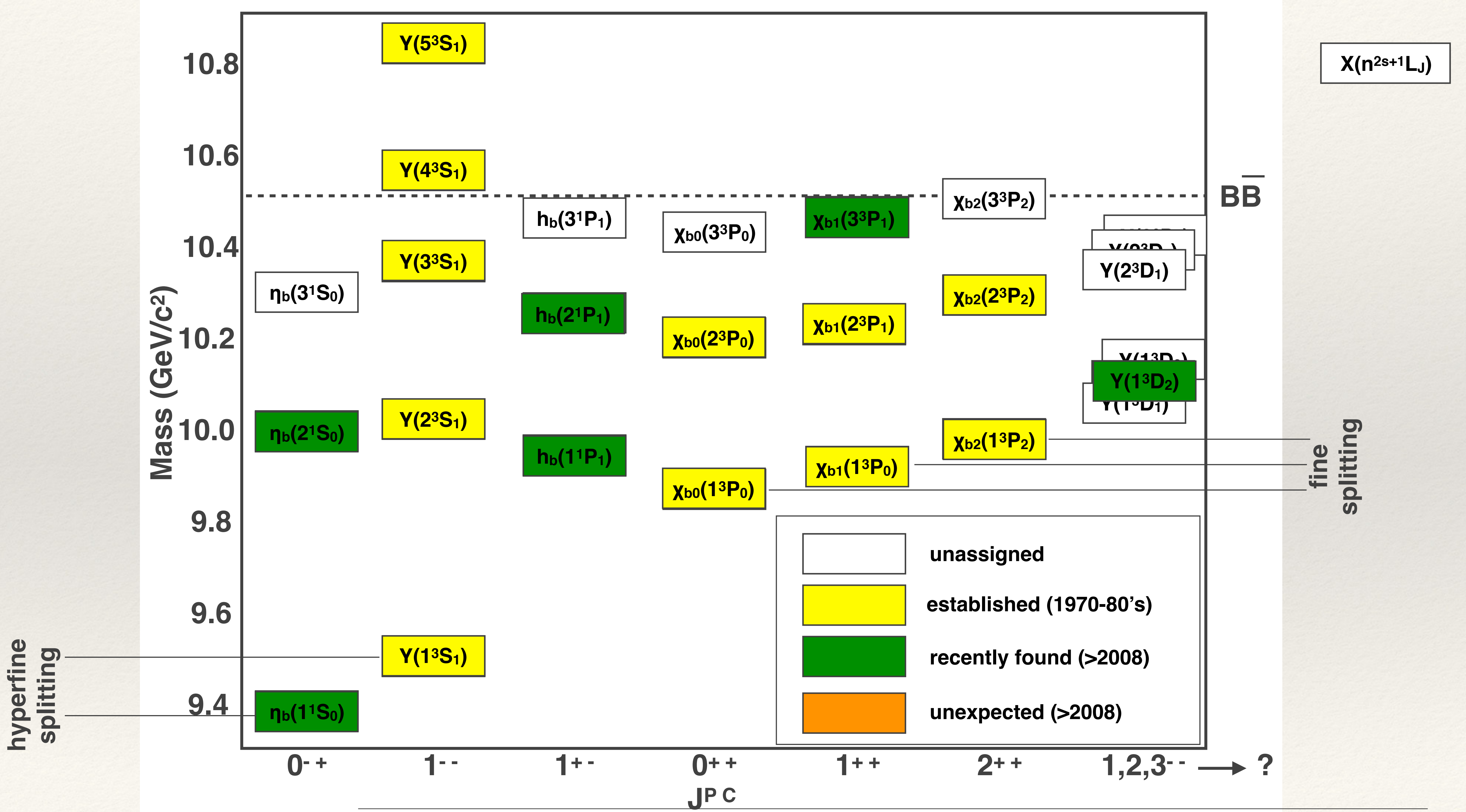
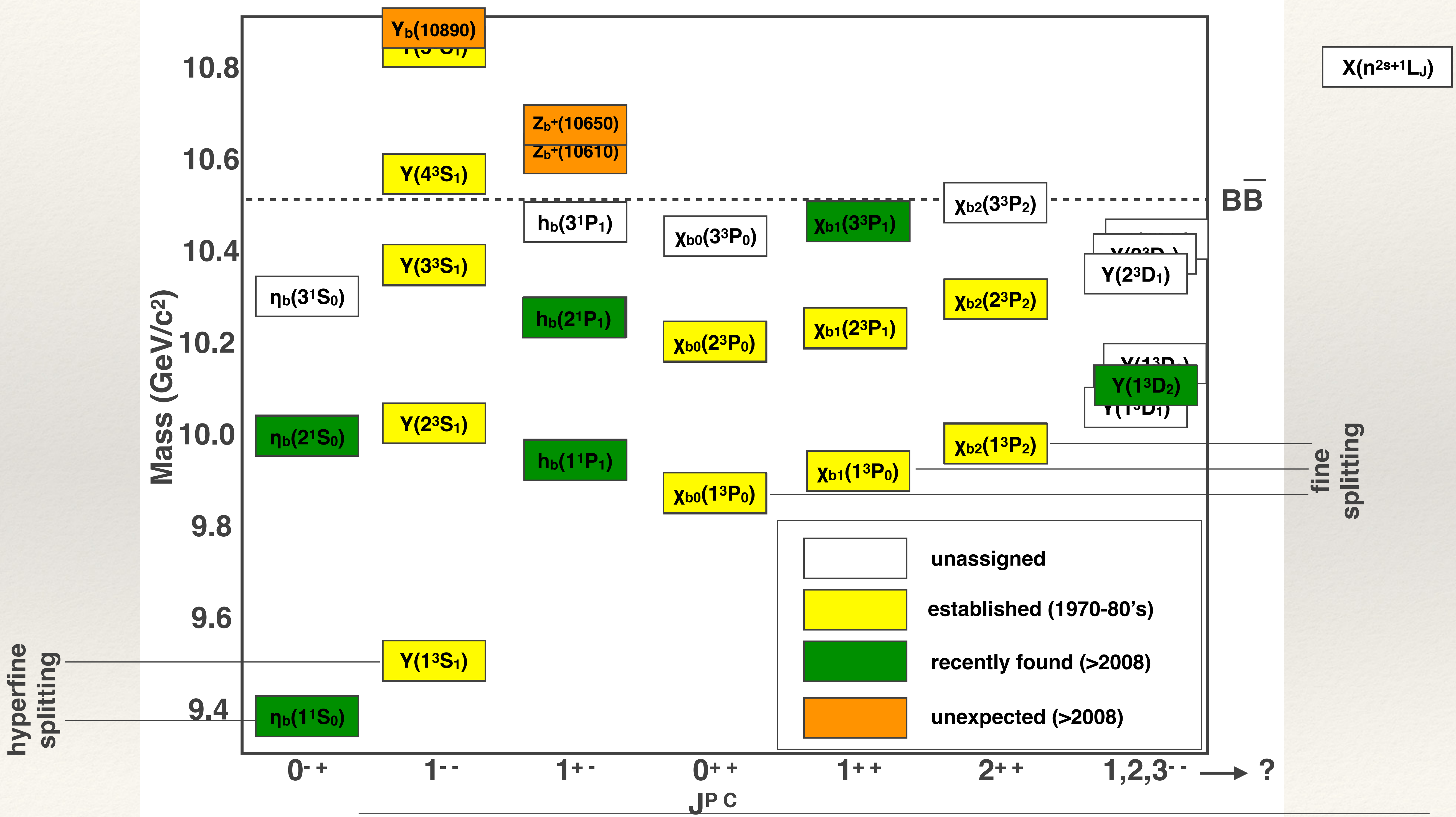
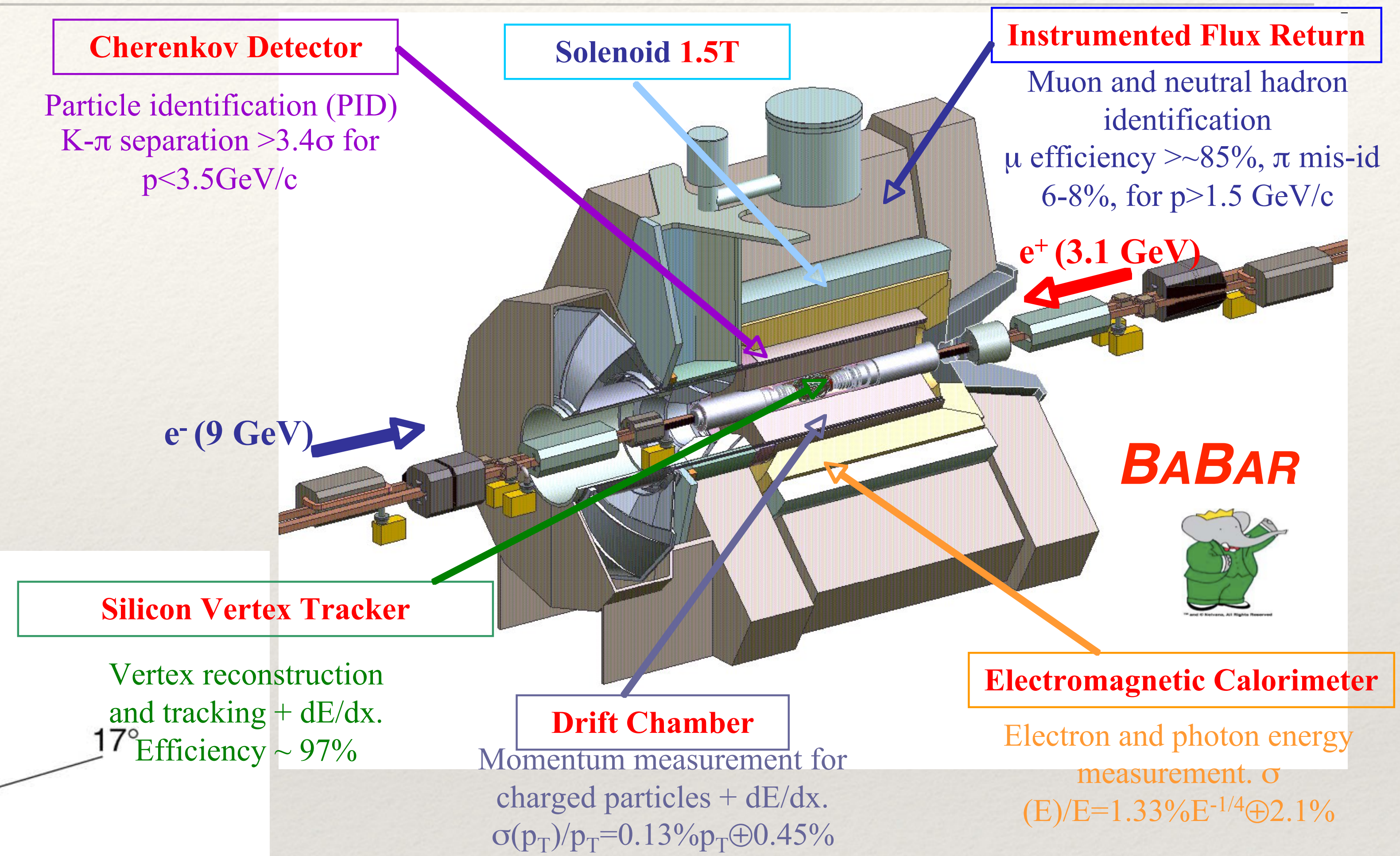


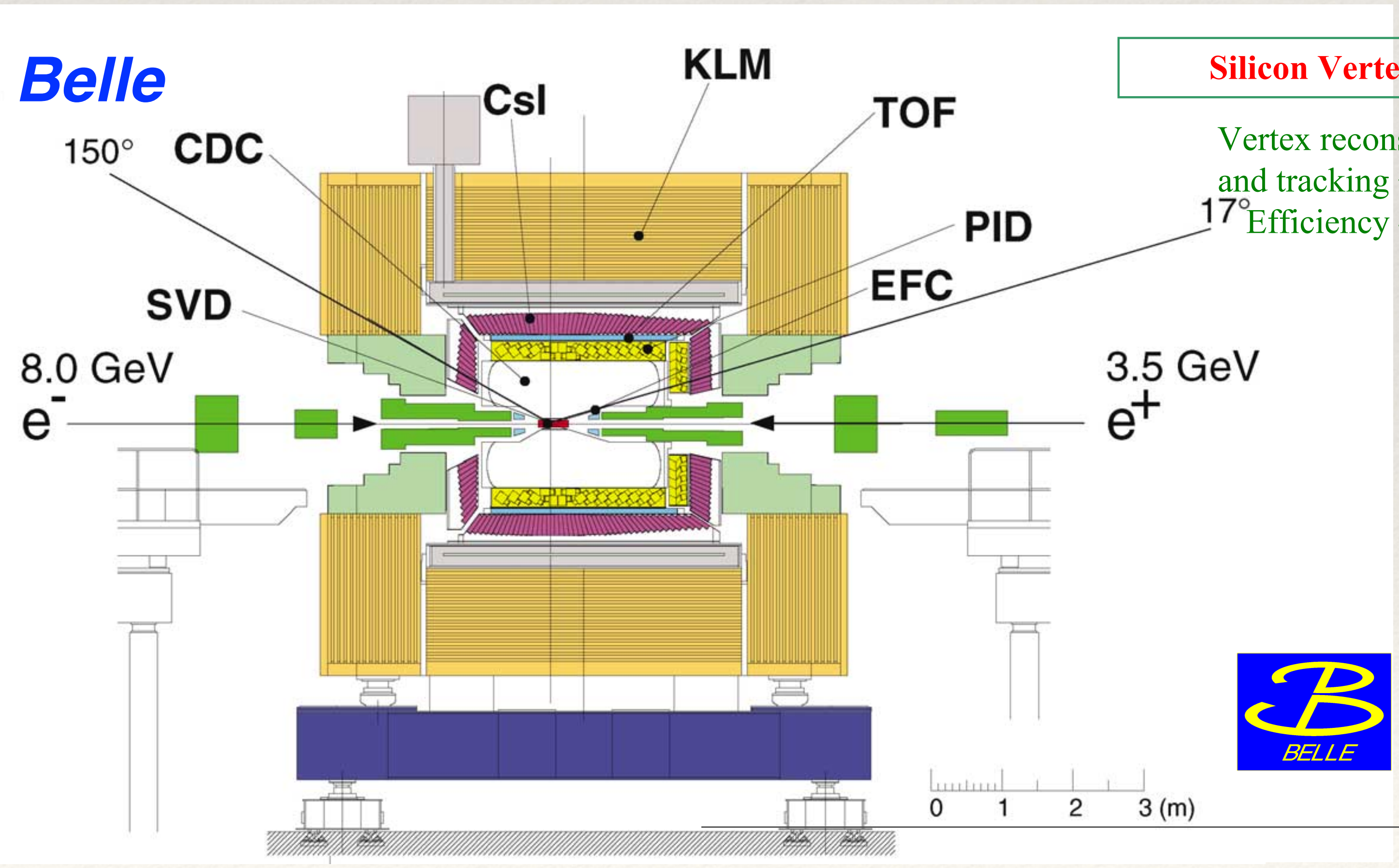
Bottomonium history in one page



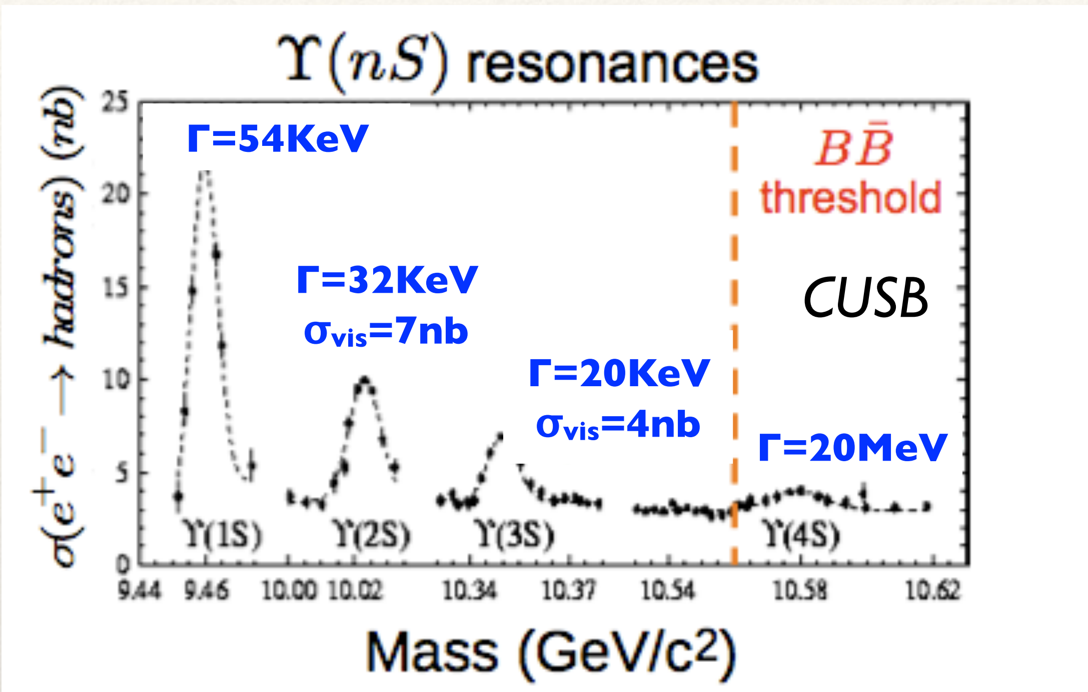
BaBar and Belle

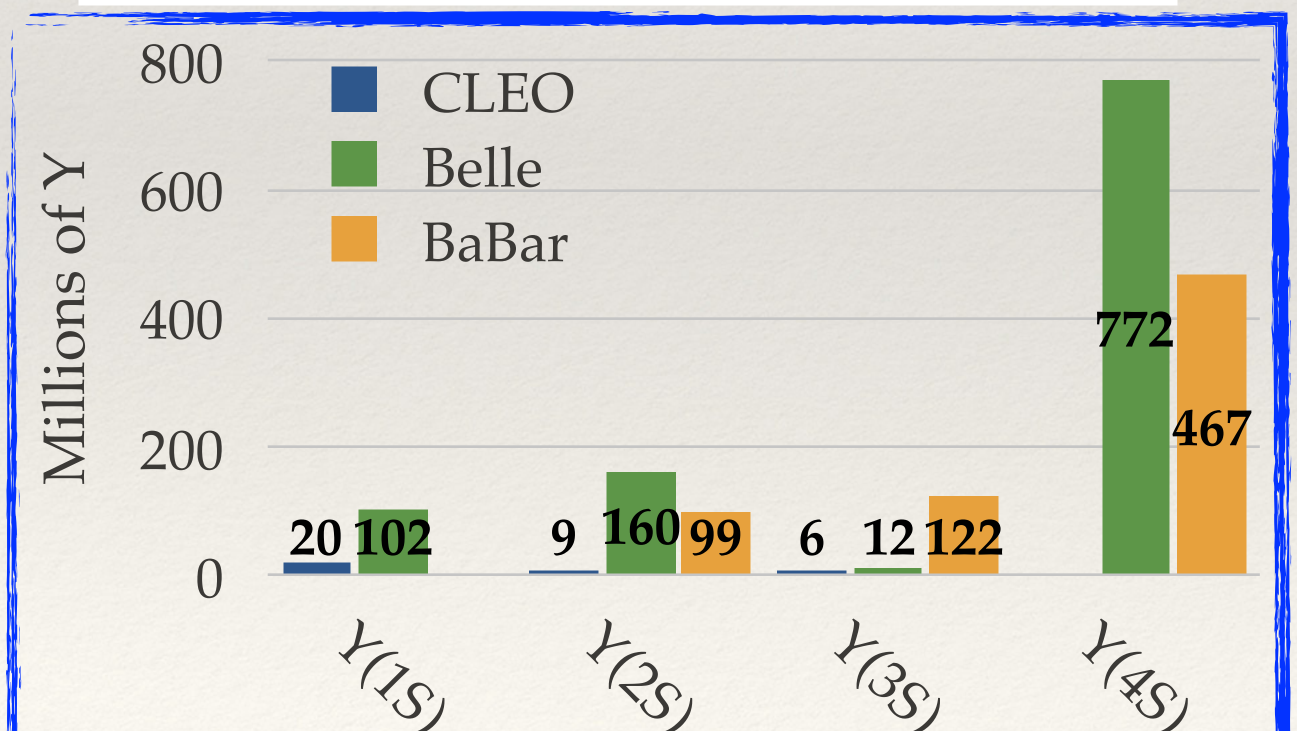
- BaBar & Belle: experiments at asymmetric e^+e^- colliders, run at the energies of the different Υ resonances (or above open-bottom threshold) for ~ a decade



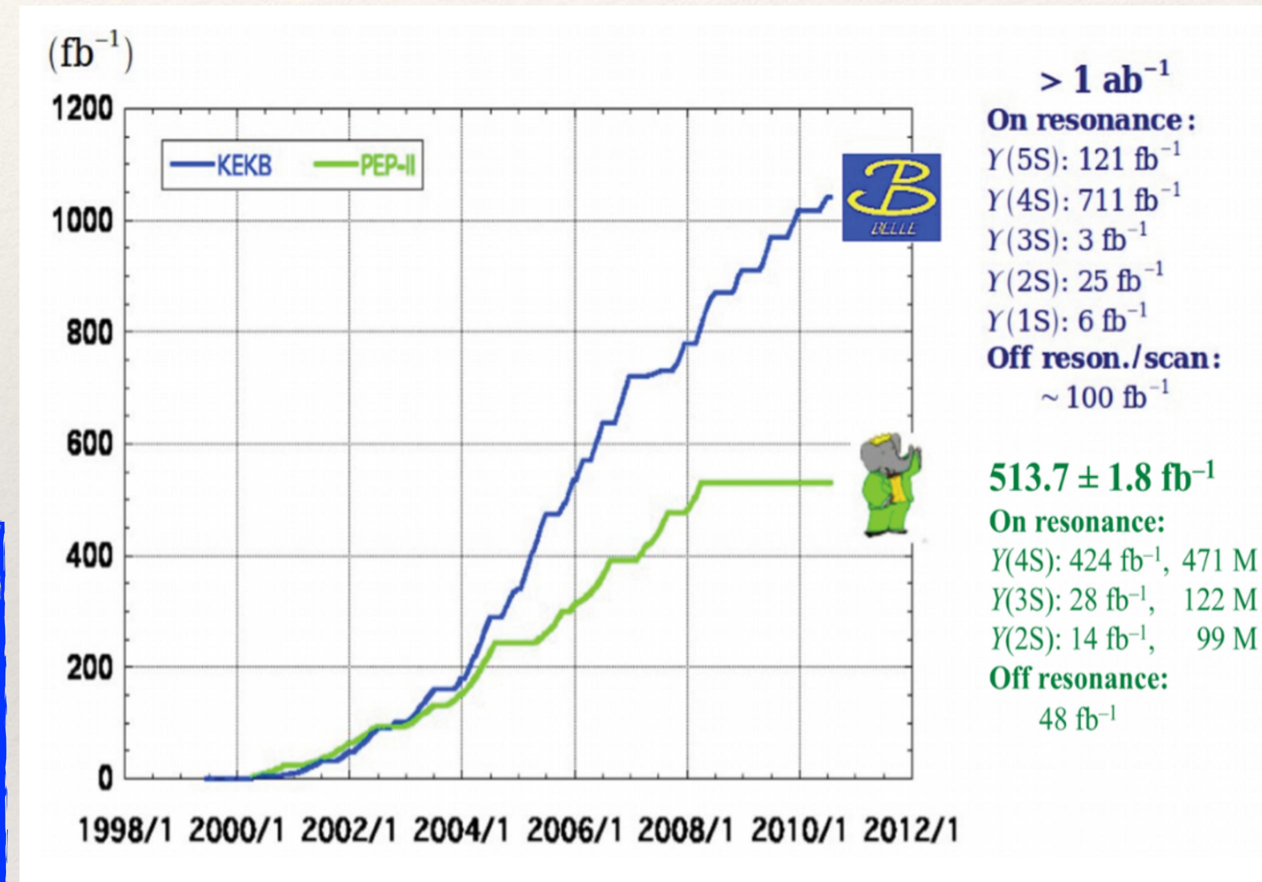


B-factories data samples



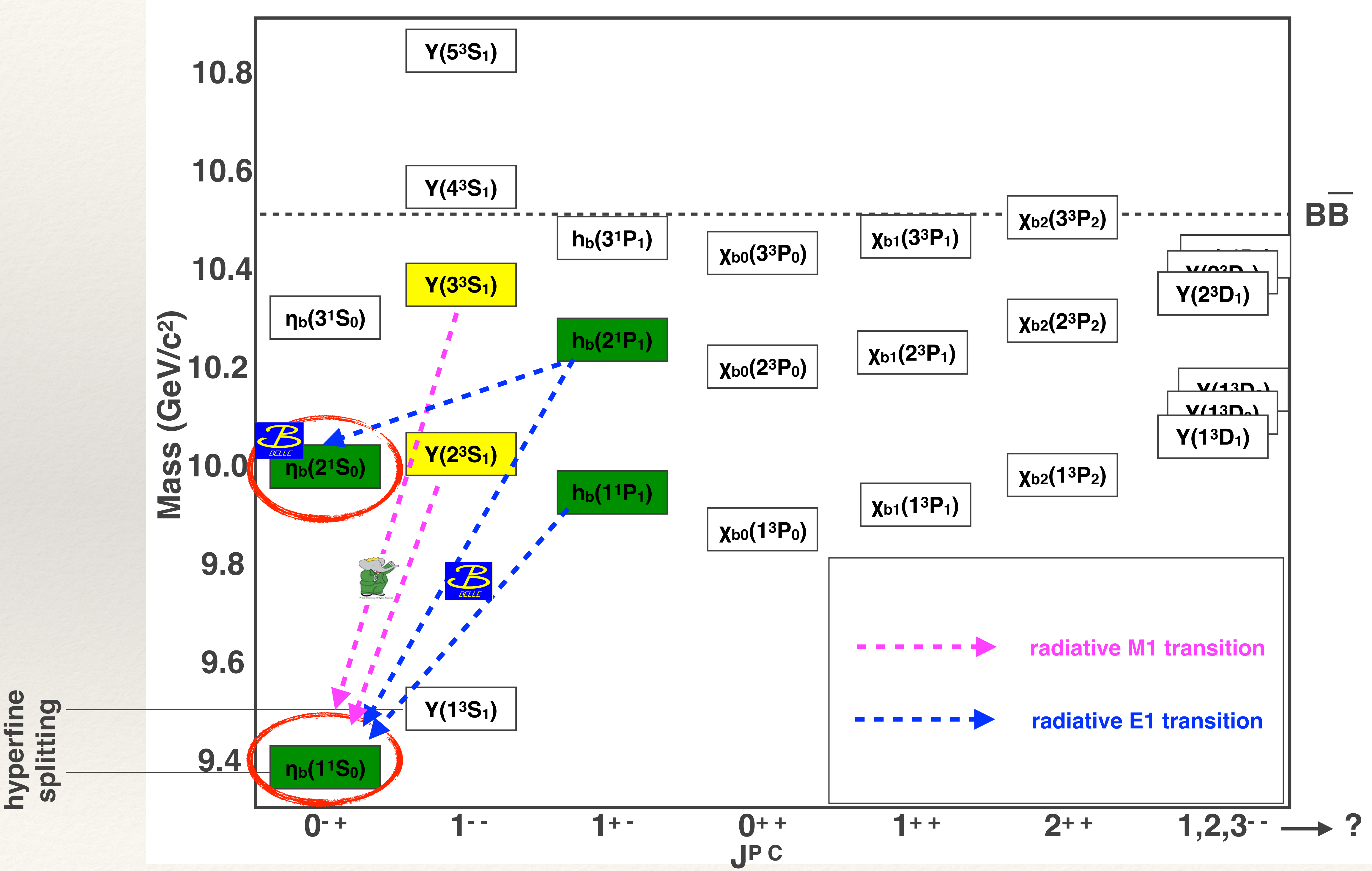


- Collected by far the largest data samples at these energies: a total of more than 1.5 ab^{-1} among the two experiments



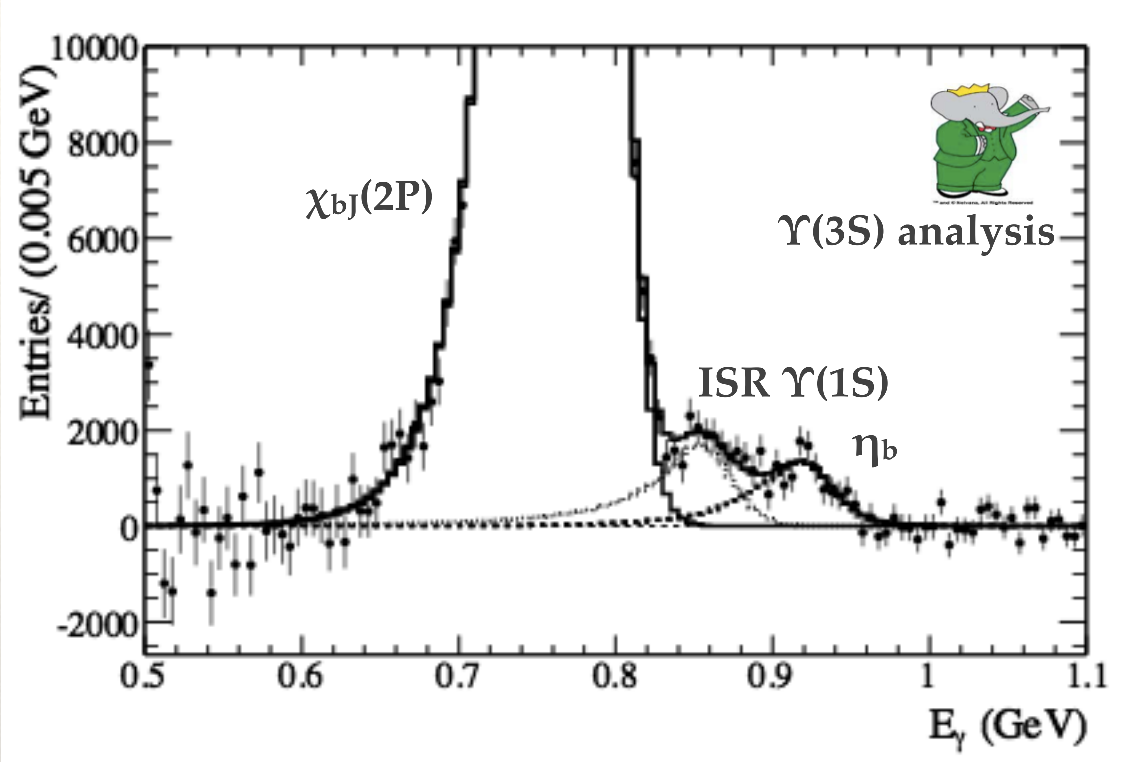
- Belle: 1 fb^{-1} scan of [10.77,11.02] GeV/c^2 in 19 steps
- BABAR: 3.3 fb^{-1} scan of [10.54,11.20] GeV/c^2 in 132 steps + 0.6 fb^{-1} scan of [10.96,11.10] GeV/c^2 in 8 steps

The ground state and its excitation



The ground state and its excitation

- Observation of **Υ(3S,2S) —> γη_b(1S)** by BABAR (2008-2009) + re-analysis of previous data by CLEO (2010)
- Fit to the inclusive photon CM energy spectrum, searching for monochromatic photon above the smooth non-peaking bkg



Combined Y(3S,2S):
m(η_b(1S))=(9390.8±3.2)MeV/c^2
From the Y(2S): ΔM_{hf}=(66.1±5.4)MeV/c^2

BABAR Coll. PRL 101 (2008) 071801
BABAR Coll. PRL 103 (2009) 161801
CLEO Coll. PRD 81 (2010) 031104
Belle Coll. PRL 109 (2012) 232002

The ground state and its excitation

- Observation of Υ(3S,2S) —> $\gamma\eta_b$(1S) by BABAR (2008-2009) + re-analysis of previous data by CLEO (2010)
- Fit to the inclusive photon CM energy spectrum, searching for monochromatic photon above the smooth non-peaking bkg
- A new unpredicted pathway to access the η_b(1S) and η_b(2S) from Υ(5S) by Belle (2012)
- **Access via E1 transitions from the h_b(nP) states:**
  - Evidence of η_b(2S)
  - Improved η_b(1S) mass measurement wrt the M1 transitions, and first measurement of the width

Transition	$h_b(1P) \to \eta_b(1S)$	$h_b(2P) \to \eta_b(1S)$
Yield$\times 10^{-3}$	23.5 ± 2.0	10.3 ± 1.3
$\mathcal{B} \times 10^2$	$49.2 \pm 5.7^{+5.6}_{-3.3}$	$22.3 \pm 3.8^{+3.1}_{-3.3}$
Significance	15σ	9σ
$m_{\eta_b(1S)}$ (MeV/c^2)	$9402.4 \pm 1.5 \pm 1.8$	(joint fit)
Δm_{hf} (MeV/c^2)	57.9 ± 2.3	(joint fit)
$\Gamma(\eta_b(1S))$ (MeV)	11^{+6}_{-4}	(joint fit)

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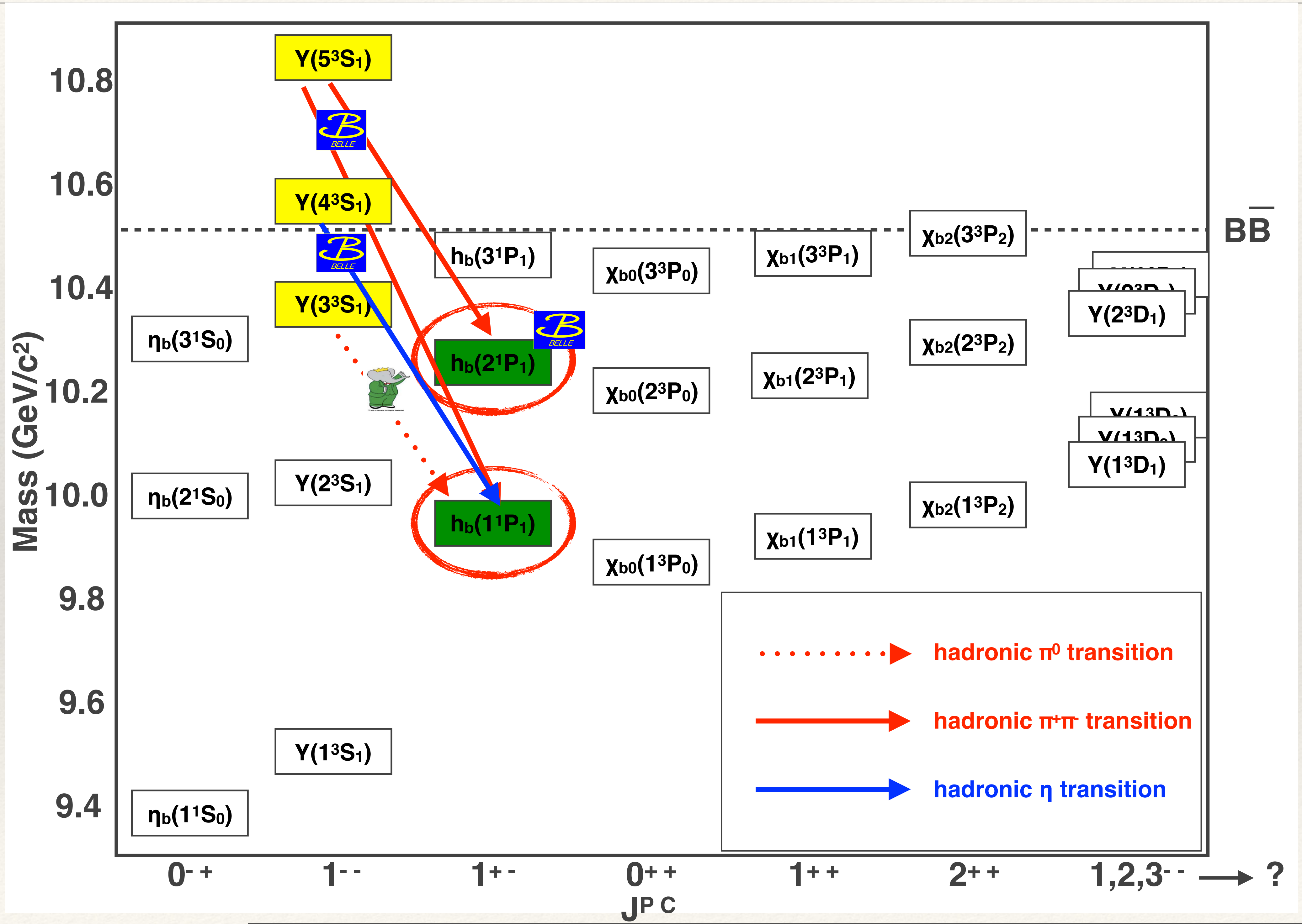
Transition	$h_b(2P) \to \eta_b(2S)$
Yield$\times 10^{-3}$	25.8 ± 4.9
$\mathcal{B} \times 10^2$	$49.2 \pm 5.7^{+5.6}_{-3.3}$
Significance	4.2σ
$m_{\eta_b(2S)}$ (MeV/c^2)	$9999.0 \pm 3.5^{+2.8}_{-1.9}$
Δm_{hf} (MeV/c^2)	$24.3^{+4.0}_{-4.5}$

BABAR Coll. PRL 101 (2008) 071801
BABAR Coll. PRL 103 (2009) 161801
CLEO Coll. PRD 81 (2010) 031104
Belle Coll. PRL 109 (2012) 232002

$h_b(1P,2P)$



Υ(5³S₁)
Υ(4³S₁)
Υ(3³S₁)
Υ(2³S₁)
Υ(1³S₁)
ηb(3¹S₀)
ηb(2¹S₀)
ηb(1¹S₀)
hb(3¹P₁)
hb(2¹P₁)
hb(1¹P₁)
χb0(3³P₀)
χb0(2³P₀)
χb0(1³P₀)
χb1(3³P₁)
χb1(2³P₁)
χb1(1³P₁)
χb2(3³P₂)
χb2(2³P₂)
χb2(1³P₂)
Υ(2³D₁)
Υ(1³D₁)
BB̄
10.8
10.6
10.4
10.2
10.0
9.8
9.6
9.4
Mass (GeV/c²)
0-+
1--
1+-
0++
1++
2++
1,2,3-- → ?
JPC
hadronic π⁰ transition
hadronic π⁺π⁻ transition
hadronic η transition

h_b(1P,2P)

- BABAR **Υ(3S)—>π^0 h_b(1P), h_b(1P)—> $\gamma\eta_b$(1S)**, using the η_b mass measurement to constrain the expected energy of the photon
- 3.3σ evidence for a resonance recoiling against the π^0, with a mass of **(9902 ± 4 ± 2) MeV/c²**, consistent with the prediction of the h_b mass from spin-weighted average of the χ_{bJ}(1P) states

BABAR Coll. PRD 84 (2011) 112007
Belle Coll. PRL 108 (2012) 032001

h_b(1P,2P)

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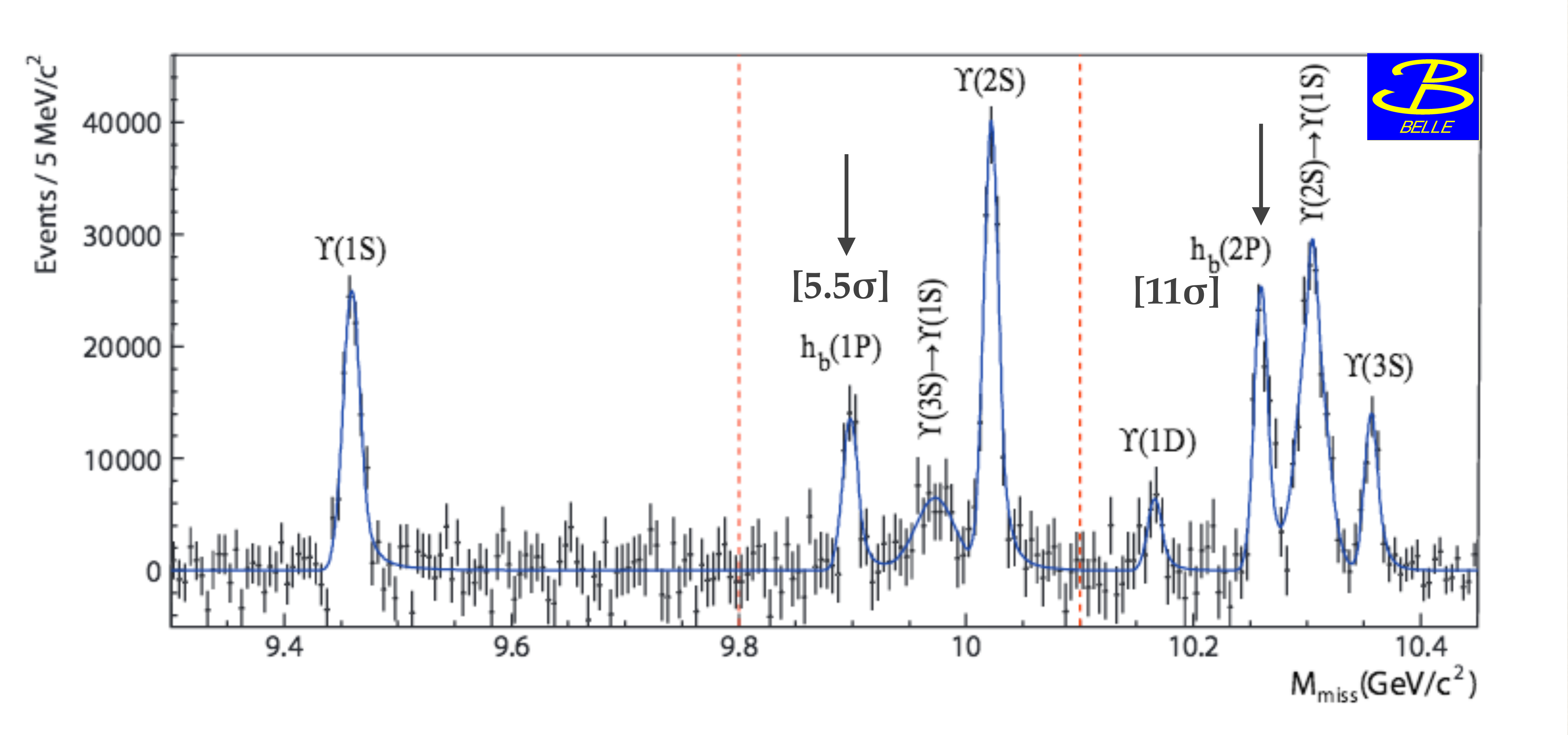
- Belle observed both h_b(1P) and h_b(2P) in **e^+e^- —> h_b(nP)$\pi^+\pi^-$** using data at Υ(5S), prompted by:
  - CLEO e^+e^- —> $h_c\pi^+\pi^-$ at a rate compatible to e^+e^- —> J/ψ $\pi^+\pi^-$ in data above open charm threshold (unexpected due to the fact that the production of h_c requires a c-spin flip, while J/ψ does not)
  - anomalously large rates for e^+e^- ->Υ(nS)$\pi^+\pi^-$ at Υ(5S) energy

BABAR Coll. PRD 84 (2011) 112007
Belle Coll. PRL 108 (2012) 032001

$h_b(1P,2P)$

- inclusive search in the recoiling mass against $\pi^+\pi^-$:



BABAR Coll. PRD 84 (2011) 112007
Belle Coll. PRL 108 (2012) 032001

Belle Coll. PRL 115 (2015) 142001

- Following a similar approach: Belle (2015) first observation of the transition **$\Upsilon(4S) \rightarrow \eta h_b(1P)$**

- Analysis of the η missing mass spectrum:

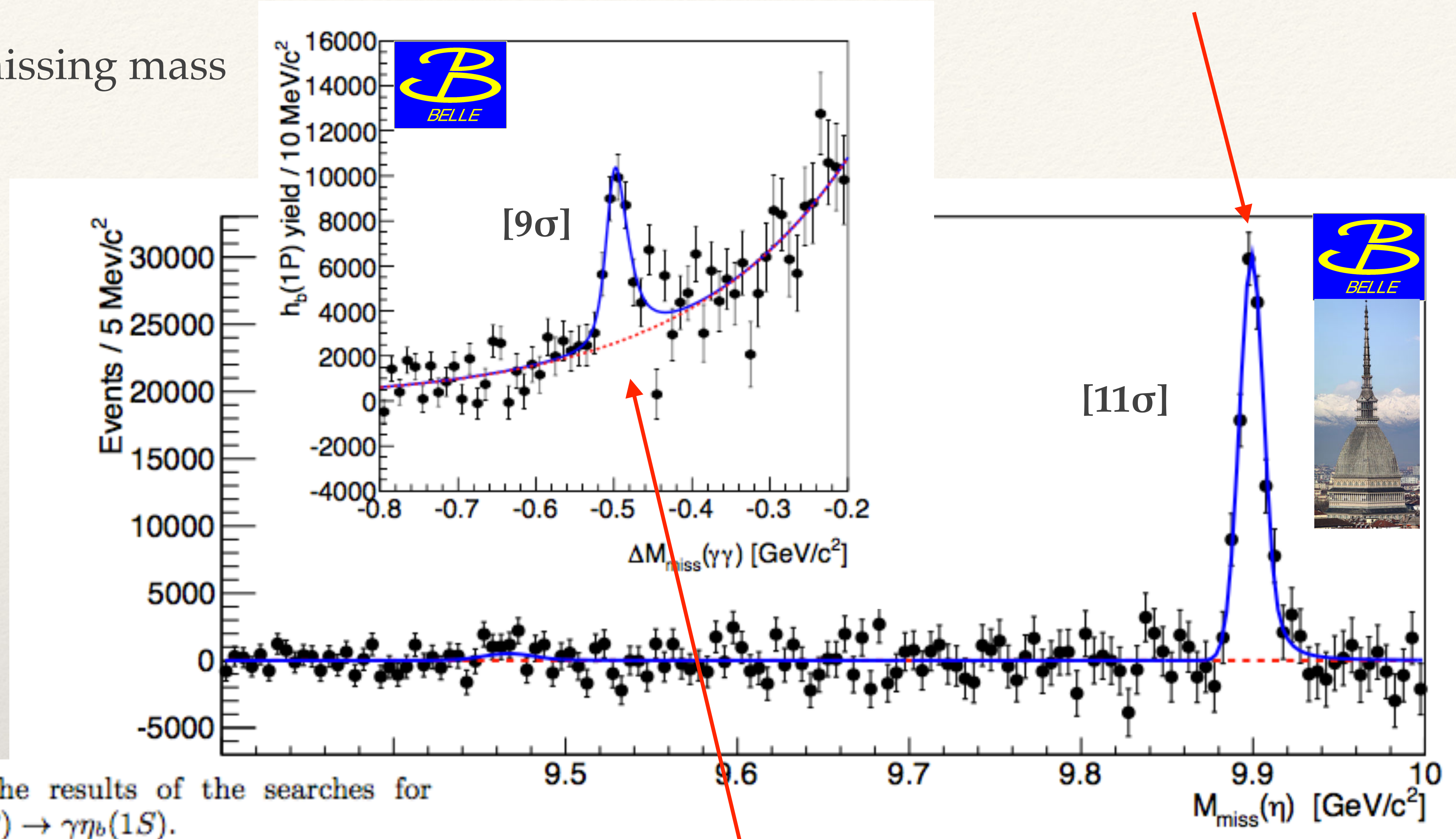


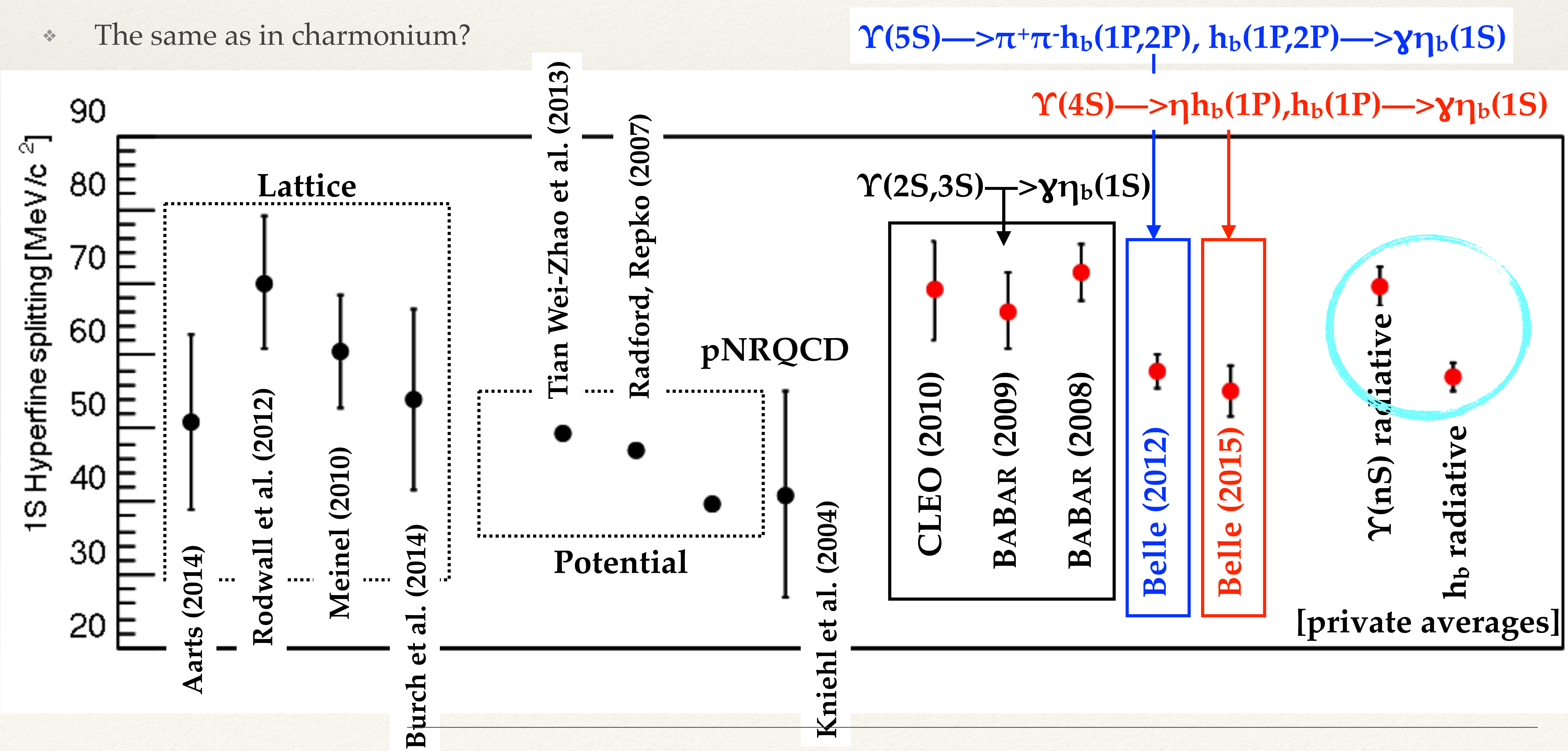
TABLE III. Summary of the results of the searches for $\Upsilon(4S) \rightarrow \eta h_b(1P)$ and $h_b(1P) \rightarrow \gamma\eta_b(1S)$.

Observable	Value
$\mathcal{B}[\Upsilon(4S) \rightarrow \eta h_b(1P)]$	$(2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$
$\mathcal{B}[h_b(1P) \rightarrow \gamma\eta_b(1S)]$	$(56 \pm 8 \pm 4)\%$
$M_{h_b(1P)}$	$(9899.3 \pm 0.4 \pm 1.0)$ MeV/c^2
$M_{\eta_b(1S)} - M_{h_b(1P)}$	$(-498.6 \pm 1.7 \pm 1.2)$ MeV/c^2
$\Gamma_{\eta_b(1S)}$	$(8^{+6}_{-5} \pm 5)$ MeV/c^2
$M_{\eta_b(1S)}$	$(9400.7 \pm 1.7 \pm 1.6)$ MeV/c^2
$\Delta M_{HF}(1S)$	$(+59.6 \pm 1.7 \pm 1.6)$ MeV/c^2
$\Delta M_{HF}(1P)$	$(+0.6 \pm 0.4 \pm 1.0)$ MeV/c^2

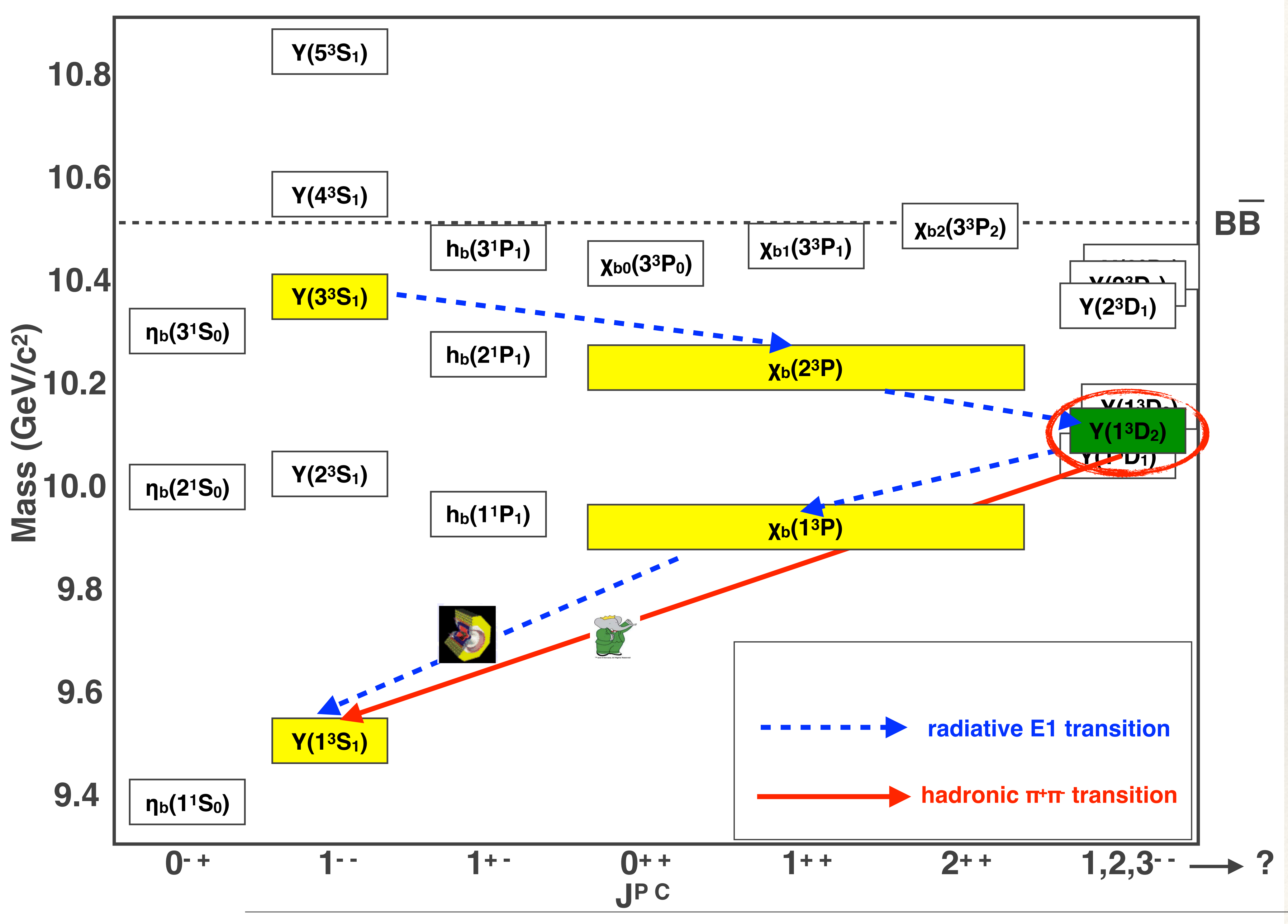
- Measurement of the $h_b(1P)$ and $\eta_b(1S)$ resonance parameters, via **$h_b(1P) \rightarrow \gamma\, \eta_b(1S)$**

Hyperfine mass splitting

- Hyperfine mass-splitting of singlet-triplet states related to the spin structure of the resonances
- A discrepancy of >3σ for the 1S-HF splitting between measurements from E1 and M1 transitions
- The same as in charmonium?



Accessing the D-wave states



Accessing the D-wave states

- CLEO (2004) **$\Upsilon(1^3D_2)$** observed one single member of the D-wave triplet, using the decay to 2 γ. Corresponding to mass and BR expected by theoretical predictions, but not able to experimentally verify the quantum numbers assignment

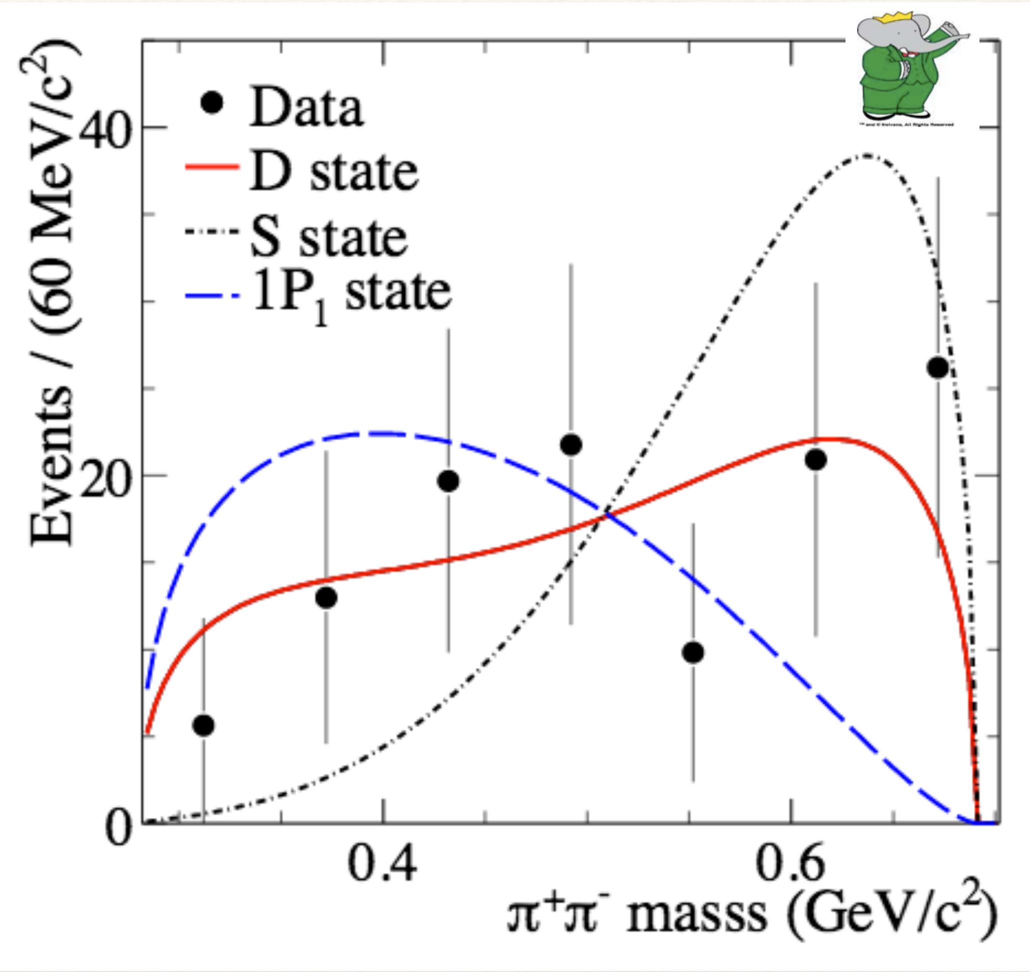
- BABAR (2010) observation of $\Upsilon(3S) \rightarrow \gamma\gamma\Upsilon(1^3D_2)$, $\Upsilon(1^3D_2) \rightarrow \pi^+\pi^-\Upsilon(1S)$ with $\Upsilon(1S)$ leptonically decaying

- An intermediate $\chi_{bJ}(2P)$ state is produced between the radiation of the two γ —> pattern of energies used to reject bkg

- 5.8σ significance

- quantum numbers determined by studying the $\pi^+\pi^-$ mass distribution after bkg subtraction —> compatible with D-wave hypothesis

- **D-wave triplet still unresolved**

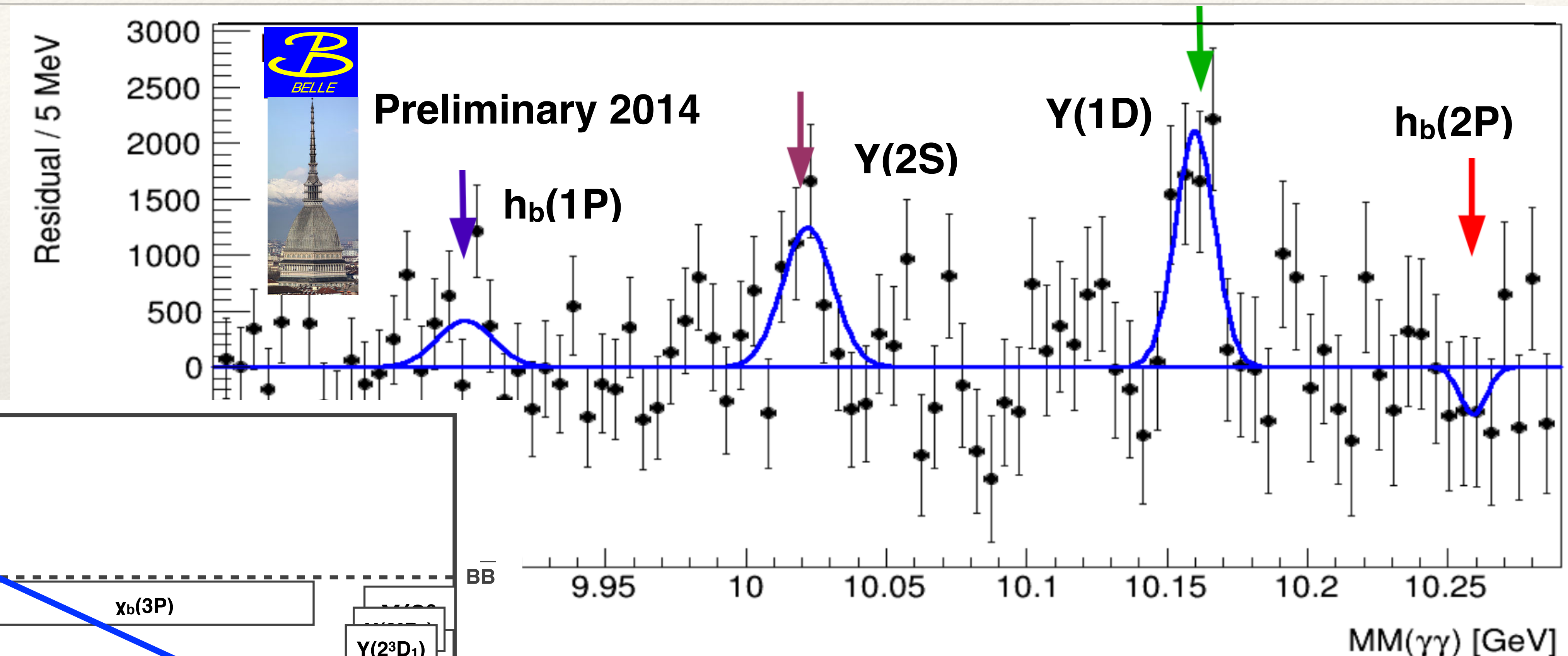


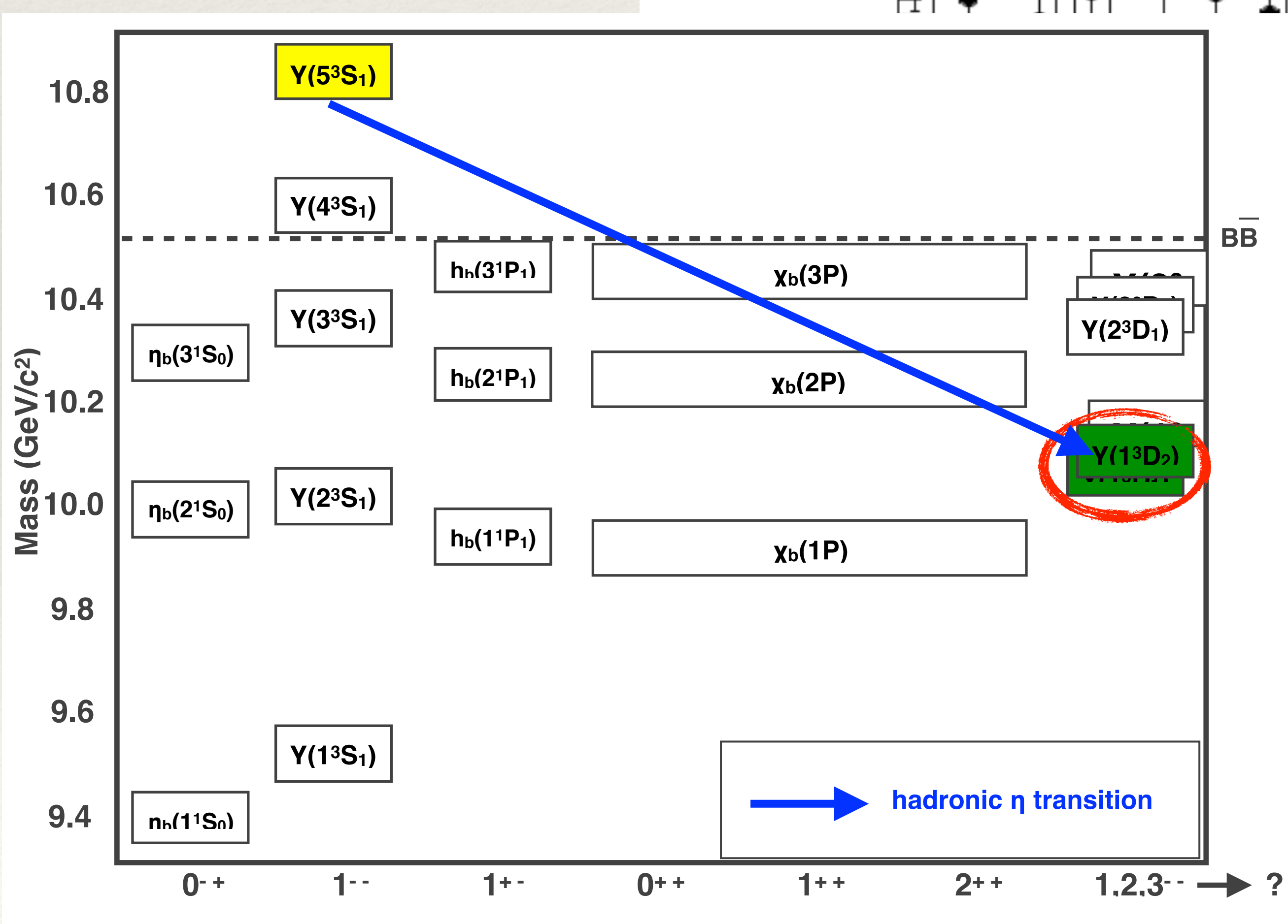
CLEO Coll. PRD 70 (2004) 032001
BABAR Coll. PRD 82 (2010) 111102

Accessing the D-wave states

Belle Coll. preliminary @DIS2014

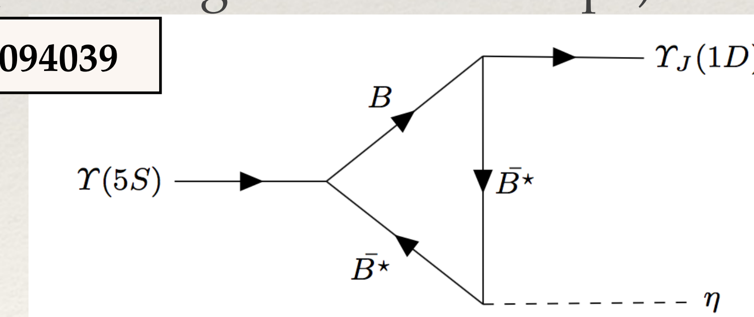
- $\Upsilon(5S)$—>$\eta\Upsilon(1D)$ observed!





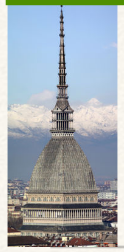
- In particular, BR($\Upsilon(5S)$ —>$\eta\Upsilon(1D)$) is compatible with the prediction (via triangular meson loops)

Wang et al. PRD 94 (2016) 094039



- Now finalizing the result on the branching fractions (to be published soon)

U.Tamponi, E.G. et al [Belle Coll.] preliminary @Hadron2017



NEW!

Investigations on the Y(1D) triplet

- Not resolving the Υ(1D) triplet (resolution ~mass splitting)

$$\mathcal{F}_{1D} = \frac{N_{1D}}{1+f_1+f_3} \cdot [\mathcal{C}_2(m_2) + f_1\mathcal{C}_1(m_1) + f_3\mathcal{C}_3(m_3)]$$

- Signal in MM(ɣɣ): 3 Crystal Ball functions, with free relative fractions f_1, f_3 that are precisely predicted in: **Wang et al. PRD 94 (2016) 094039**

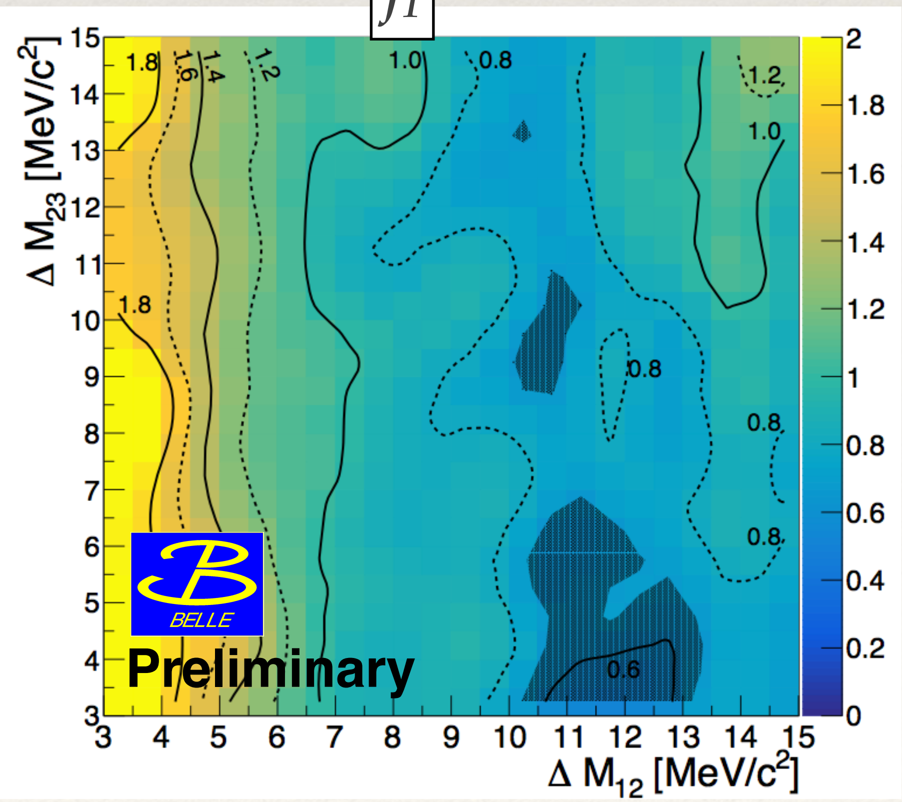
$$f_1 = \frac{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(1D_1)]}{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(1D_2)]} = 0.68$$

and

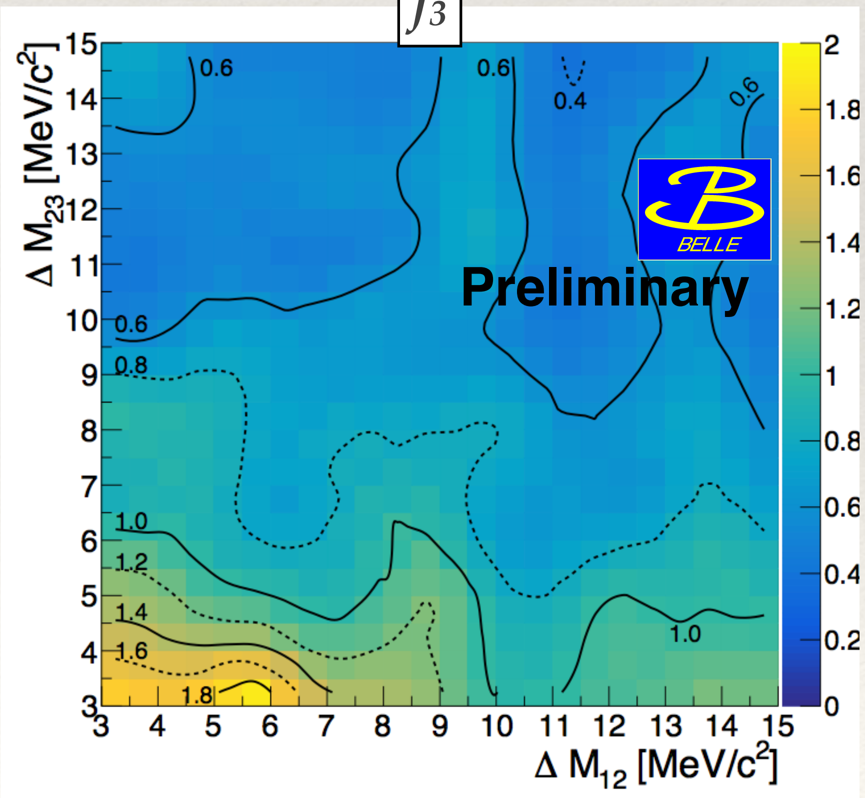
$$f_3 = \frac{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(1D_3)]}{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(1D_2)]} = 0.13.$$

- m_2 fixed to world average, ΔM_{ij} fixed to different values between 3 and 15 MeV / c² (reasonable according to calculations and observations)
- Values returned by the fit in any of these configurations are compatible with 0
- 90% CL ULs on f_1, f_3 as a function of ΔM_{12} and ΔM_{23}
- f_1 favored value excluded in 3 regions where **$10 < \Delta M_{12} < 13$ MeV/c²**

f_1



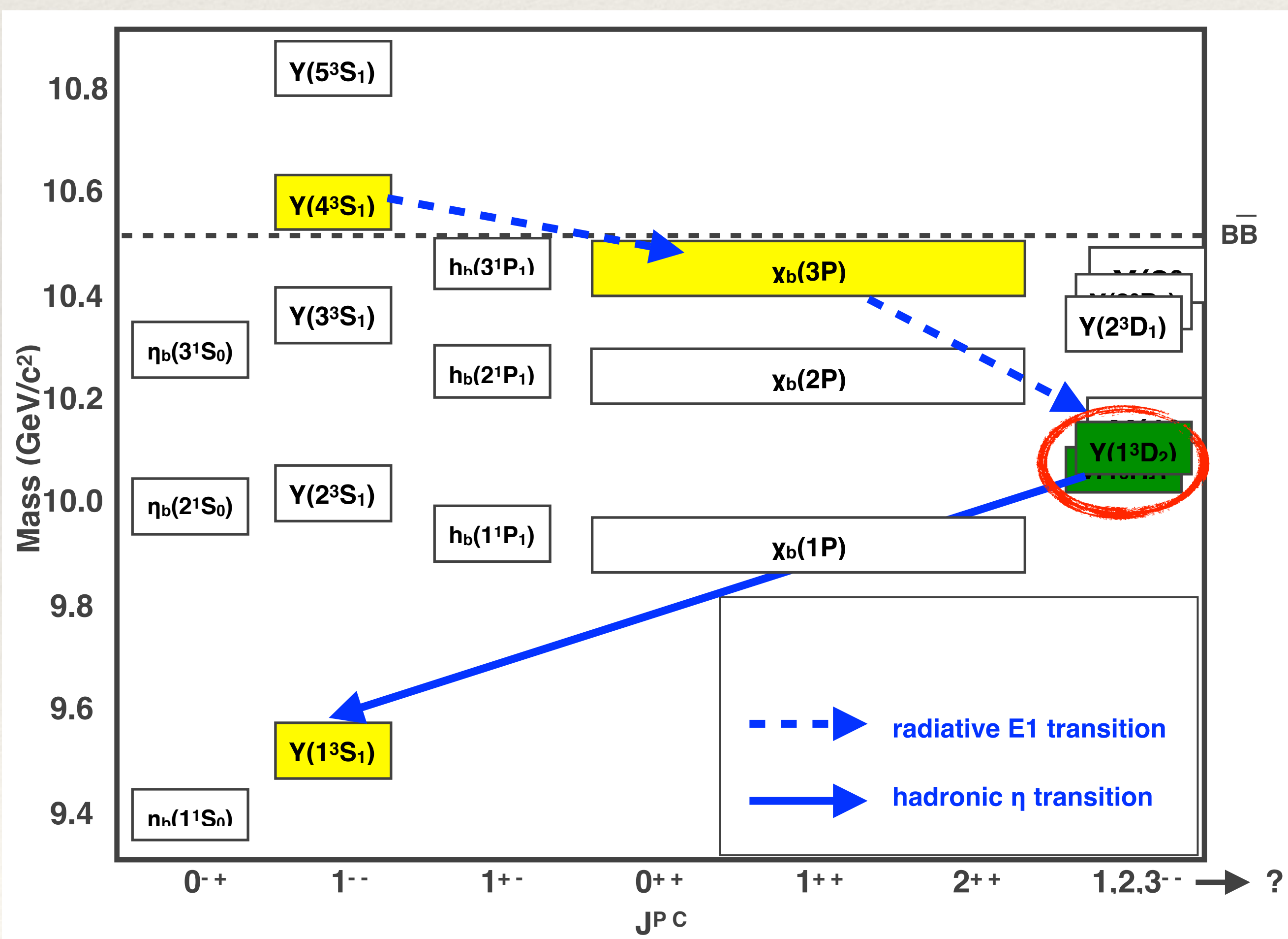
f_3

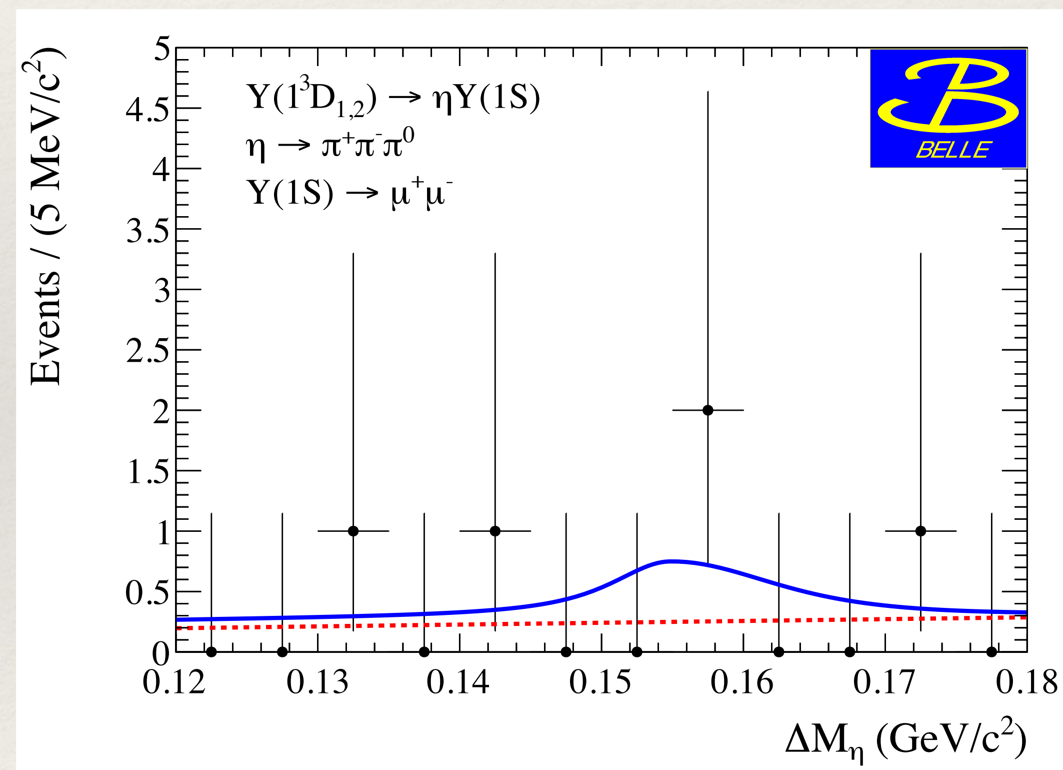


NEW!

Accessing the D-wave states

- Predicted enhancement of Υ(1D)—>ηΥ(1S) with respect to Υ(1D)—>$\pi^+\pi^-$Υ(1S) due to a contribution of the anomaly in the flavour singlet axial current in QCD (Voloshin, 2003)
- Look at this possible transition in Belle data at the Υ(4S) —> challenge to observe Υ(1D)
  - no significant indication



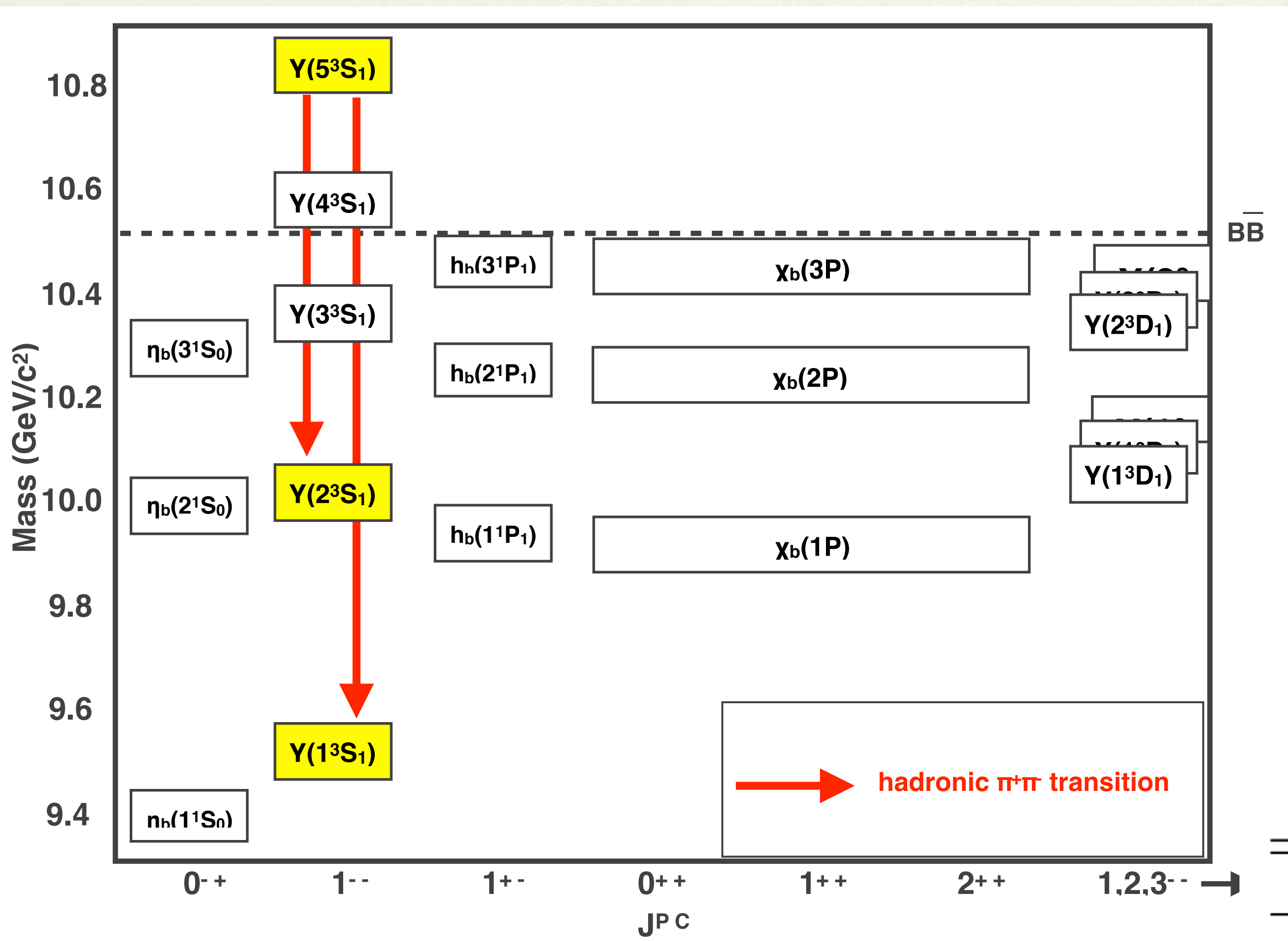


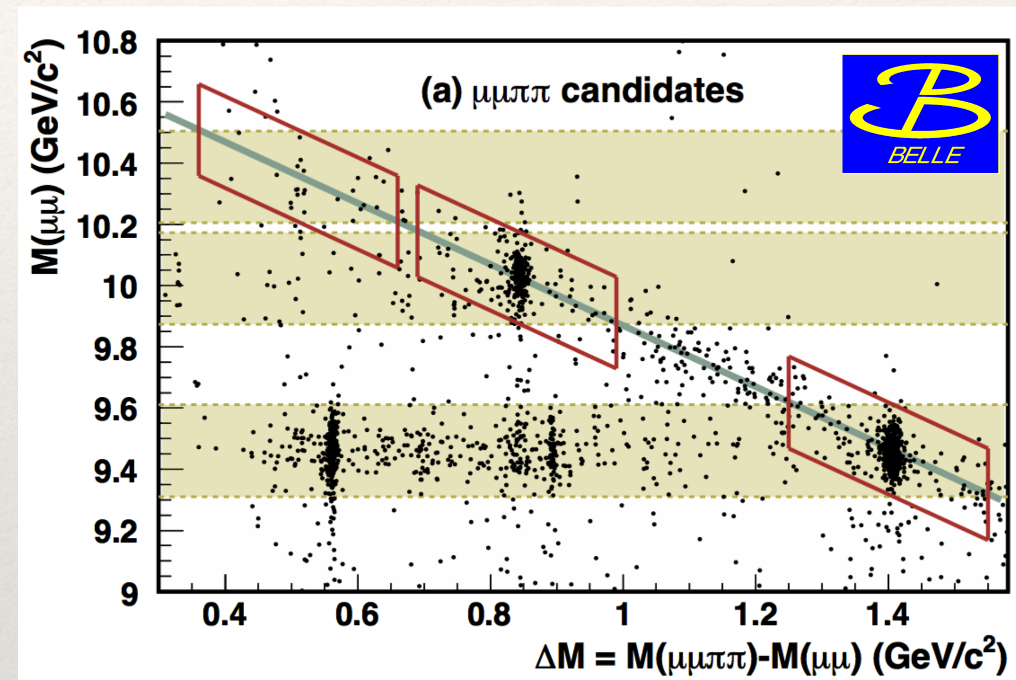
Voloshin Phys. Lett. B 562, 68 (2003)
E.G. et al [Belle Coll.] Phys. Rev. D96, 052005 (2017)

Towards the Z_b's

- Anomalous rate of $\Upsilon(5S) \longrightarrow \pi^+\pi^-\Upsilon(1S,2S)$, Belle (2008)

Belle Coll. PRL 100 (2008) 112001



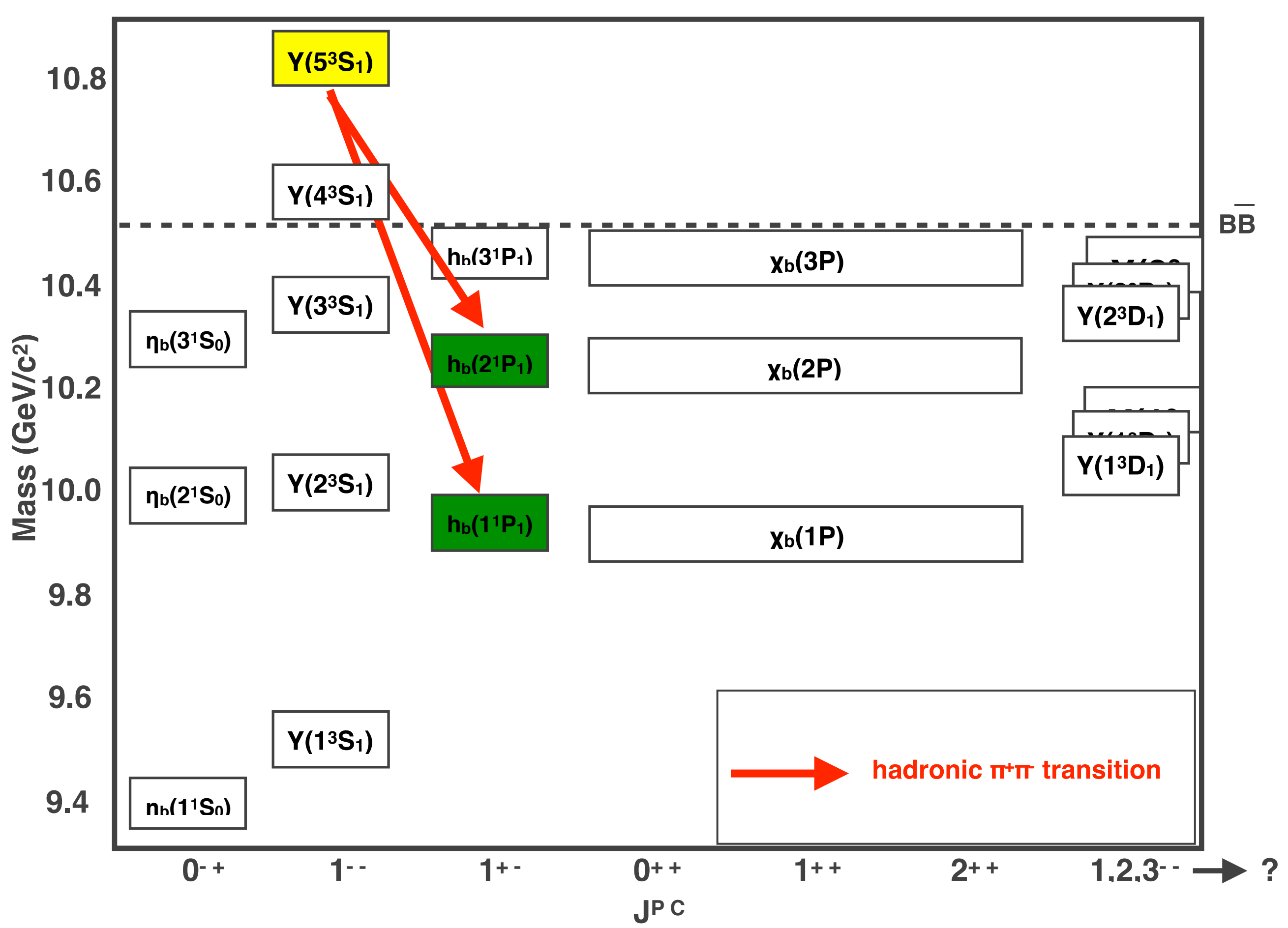


Process	Γ_{total}	$\Gamma_{e^+e^-}$	$\Gamma_{\Upsilon(1S)\pi^+\pi^-}$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.032 MeV	0.612 keV	0.0060 MeV
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.020 MeV	0.443 keV	0.0009 MeV
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	20.5 MeV	0.272 keV	0.0019 MeV
$\Upsilon(10860) \to \Upsilon(1S)\pi^+\pi^-$	110 MeV	0.31 keV	0.59 MeV

Towards the Z_b's

- Anomalous rate of $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1S,2S)$, Belle (2008)

Belle Coll. PRL 100 (2008) 112001

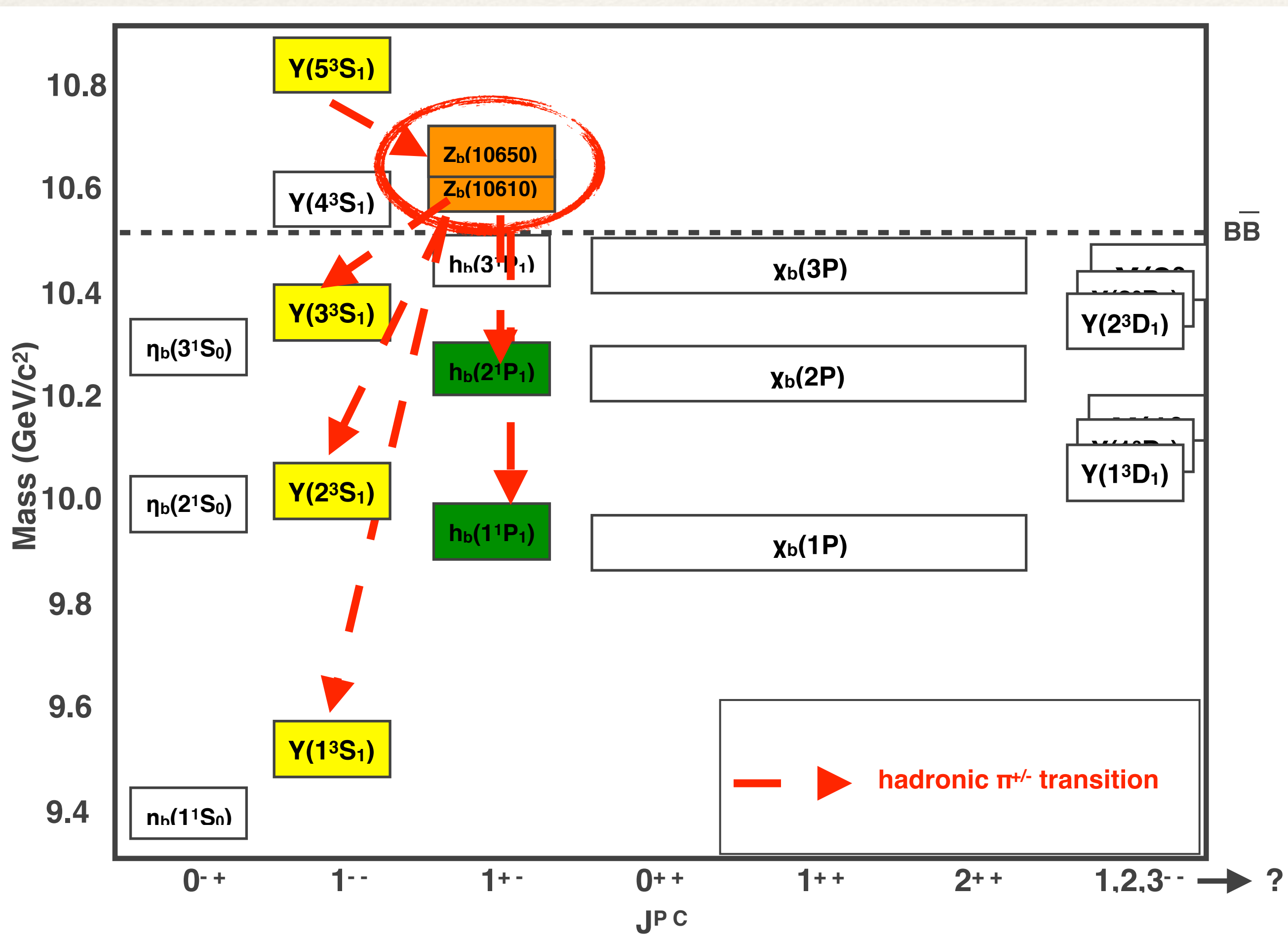


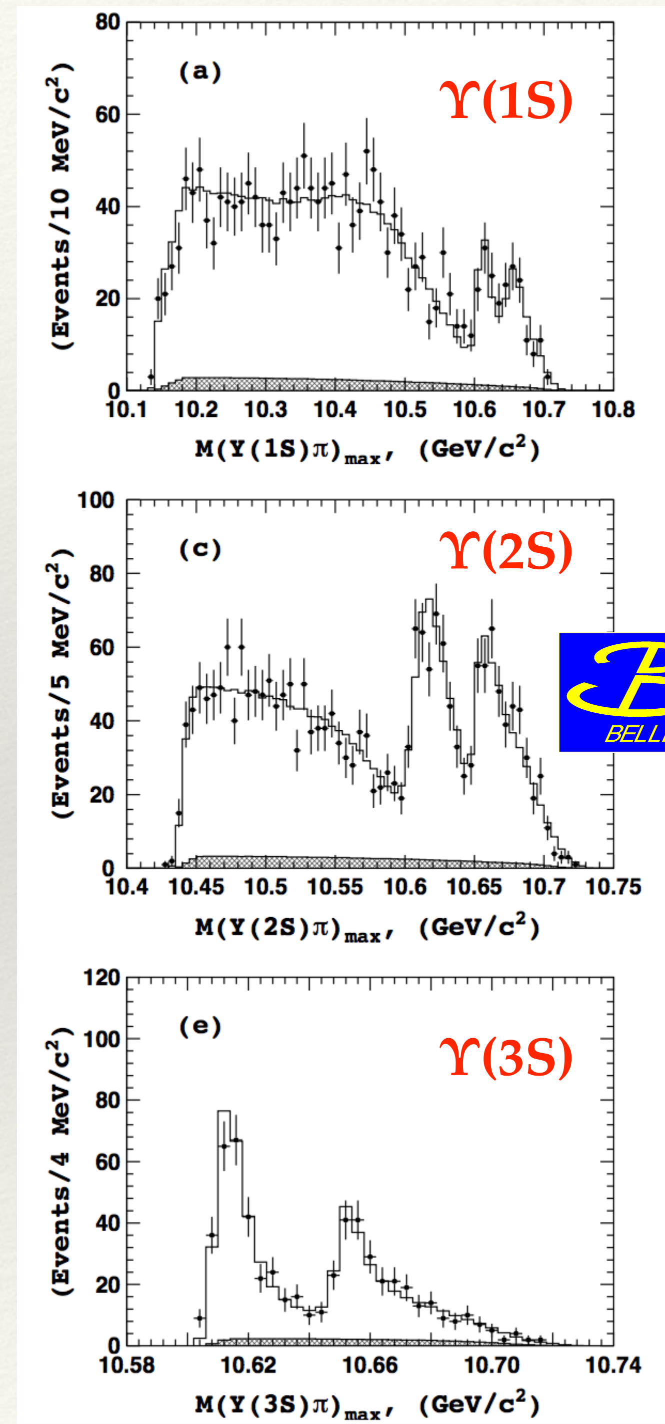
- + anomalous rate of $\Upsilon(5S) \to \pi^+\pi^- h_b(1P,2P)$, that led to h_b discovery, Belle (2012)
- magnitude comparable to $\Upsilon(5S) \to \Upsilon(nS)$ dipion transitions (despite involving a spin flip) —> exotic mechanism

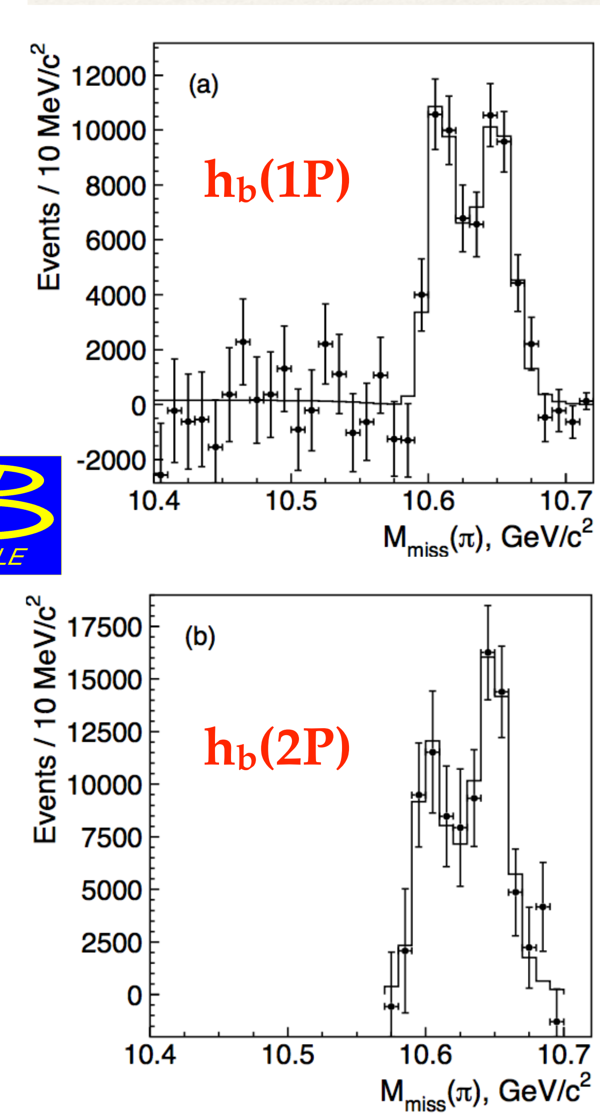
Belle Coll. PRL 108 (2012) 032001

The Z_b's

- Decays are mediated by two narrow structures:



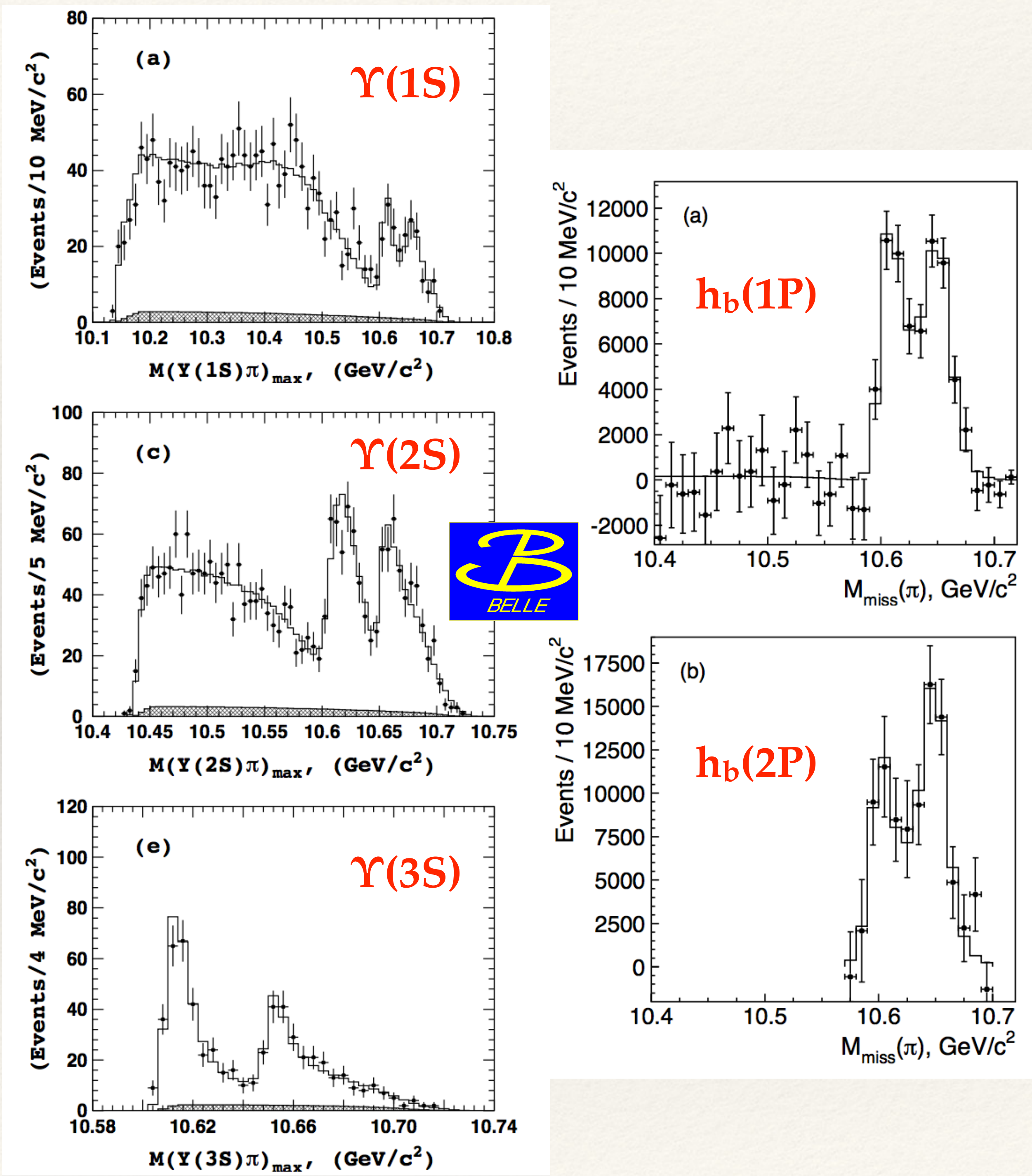




Belle Coll. PRL 108 (2012) 032001
Belle Coll. PRD 91 (2015) 072003

The Z_b's

- Decays are mediated by two narrow structures:
- 5 decay channels (Υ(3S,2S,1S) and h_b(2P,1P)), similar production rates for the 2 resonances
- $J^P = 1^+$ favored for both the resonances
- Minimal quark content is a four-quark combination
- Masses a few MeV / c^2 above the thresholds of the open-bottom channels B*B and B*B* —> suggesting a 'molecular' interpretation, but other possibilities are still open



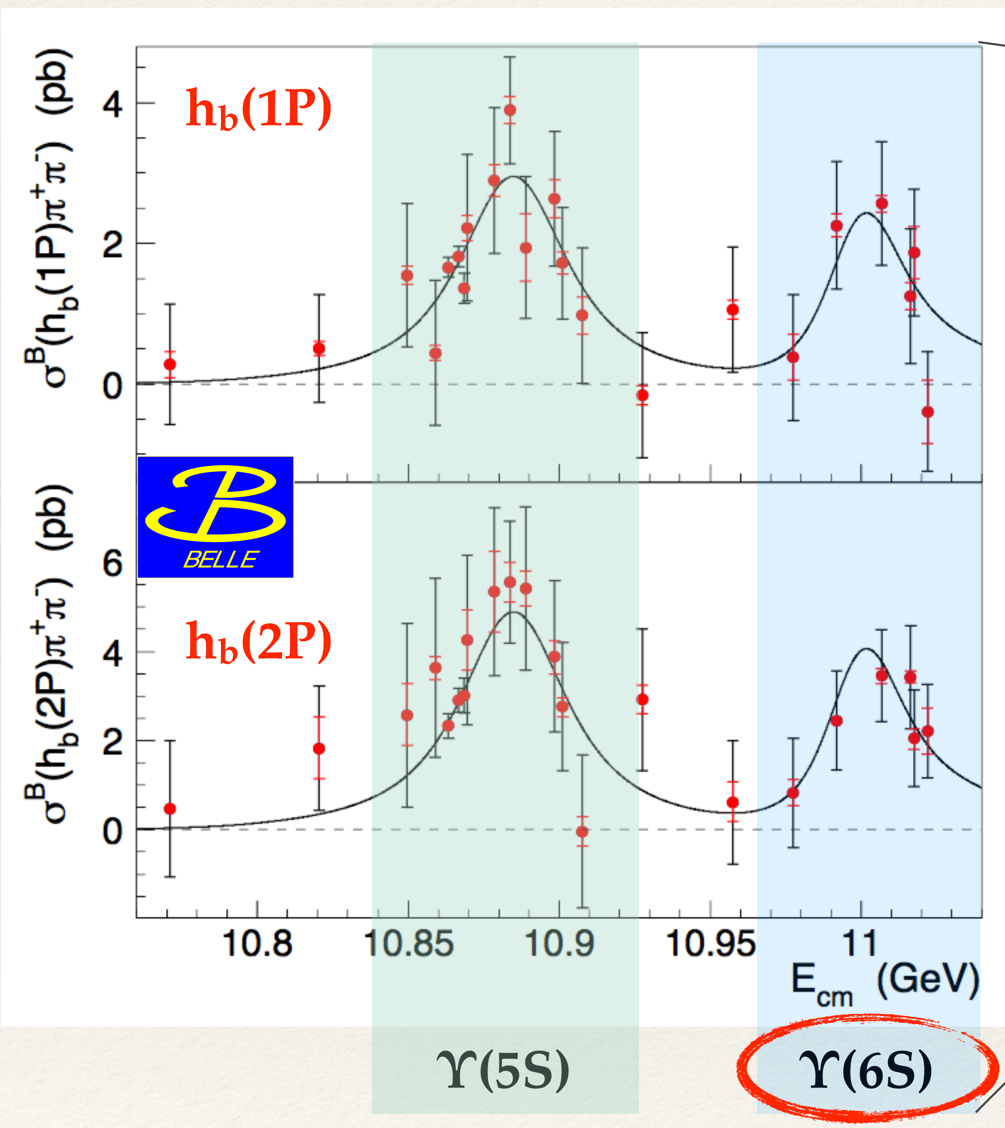
Belle Coll. PRL 108 (2012) 032001
Belle Coll. PRD 91 (2015) 072003

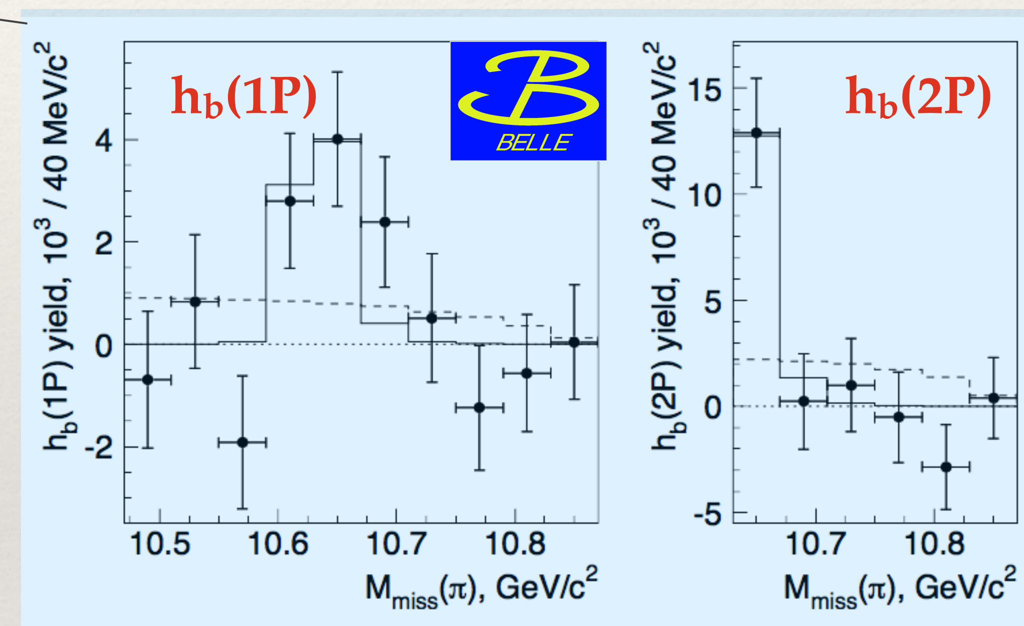
Z_b's from above the Υ(5S)?

- Are the Z_b's accessible even from higher energies?

Belle Coll. PRL 117 (2016) 142001

- Study of $e^+e^- \longrightarrow h_b(1P,2P)\pi^+\pi^-$ in the Belle energy scan above the Υ(4S)



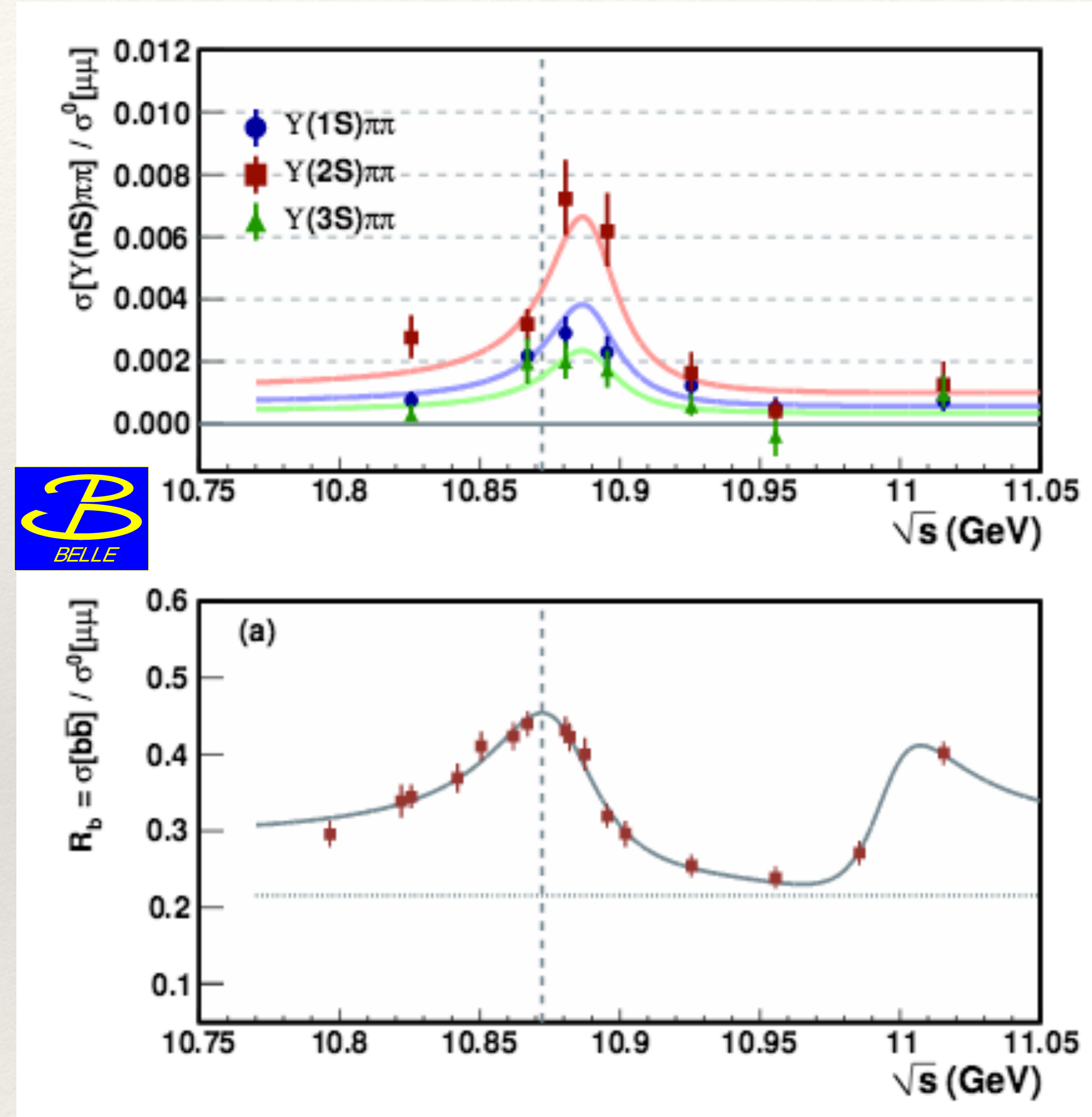


- Statistics is still too limited to separate the Z_b's contributions
- Hp. of $Z_b(10610)$ only excluded at 3.3σ, hp. of $Z_b(10650)$ only not excluded

Another exotic: $Y_b(10890)$?

- Belle (2010) analysis of data scan around the $\Upsilon(5S)=\Upsilon(10860)$ energy
- 8.1 fb^{-1} in the range [10.83; 11.02] GeV/c^2
- Energy-dependent measurement of the $e^+e^- \longrightarrow \Upsilon(nS)\,\pi^+\pi^-$ cross section
- Peak at $(10888^{+2.7}_{-2.6}\pm1.2)$ MeV with a 30-MeV width
- This peak differs substantially from the observed maximum in the overall hadronic cross section

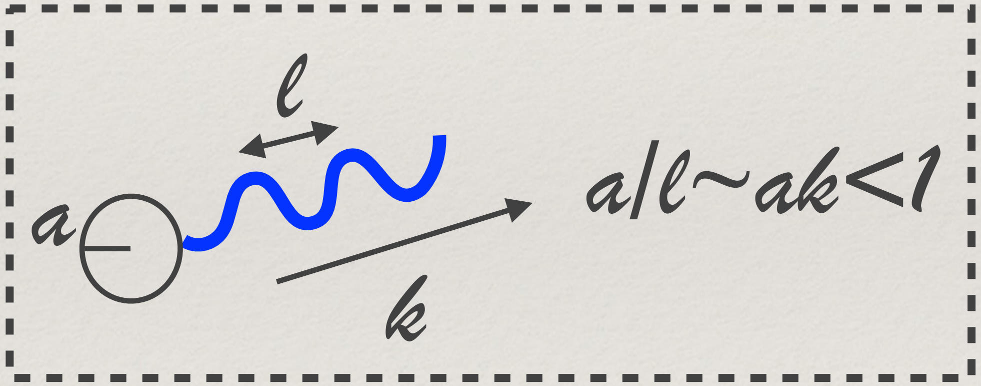
—> suggesting that may not be due to $\Upsilon(5S)$ but some exotic state (hidden-beauty counterpart of Y(4260) in charmonium?)

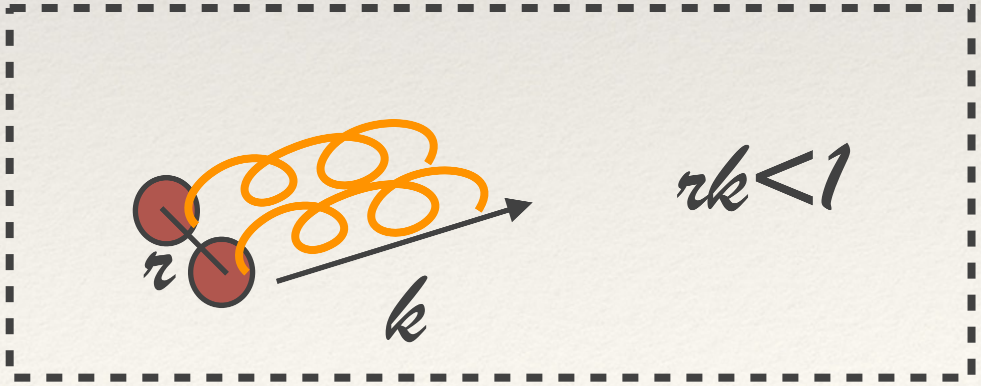


Belle Coll. PRD 82 (2010) 091106(R)

Not only new resonances…

- Important informations on bottomonium given not only by the discovery of new resonances, but also by the **study of transitions** between its states
- These transitions can be predicted by effective potential models, rather well established in the case of the dominant radiative transitions
- Some puzzling features, in particular in the 2-body hadronic transitions (η, π^0)
- In quarkonia below threshold, should be explained by **QCDME** (analogy with the QED multiple expansion) in terms of momentum of the emitted gluons
- Gluons emitted in pairs, either **E1** (no spin-flipping) or **M1** (spin-flipping)
- Expectations:
  - **suppression of spin-flipping transitions** (i.e. mS—>η nS wrt mS—>$\pi^+\pi^-$ nS, and mS—>$\pi^+\pi^-$ nP wrt mS—>$\pi^+\pi^-$ nS)
  - **further suppression of isospin-violating transitions** (i.e. mS—>π^0 nS wrt others)





η transitions: experimental status

Transition	CLEO	Year	BaBar 	Year	Belle 	Year
$\Upsilon(4S) \to \eta\Upsilon(1S)$	-		1.96±0.26±0.09	2008	1.70±0.23±0.08 [EG]	2017
$\Upsilon(3S) \to \eta\Upsilon(1S)$	<1.8 (*)	2008	<1.0 (*) [EG]	2011	-	
$\Upsilon(2S) \to \eta\Upsilon(1S)$	$2.1^{+0.7}_{-0.6}\pm0.3$	2008	2.39±0.31±0.14 [EG]	2011	3.57±0.25±0.21	2013
$\Upsilon(4S) \to \eta h_b(1P)$	-		-		21.8±1.1±1.8	2015

BaBar Coll. PRD 78 (2008) 112002
CLEO Coll. PRL 101 (2008) 192001
BaBar Coll. PRD 84 (2011) 092003
Belle Coll. PRL 115 (2015) 142001
E.G. et al [Belle Coll.] Phys. Rev. D96 (2017) 052005

[in units of 10^{-4}]

(*) ULs are at 90% CL

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$\Upsilon(4S) \longrightarrow \eta h_b(1P)$	-		-		21.8±1.1±1.8	2015

>2 times larger than dipion transition!

[B(Υ(4S)⟶π⁺π⁻Υ(1S)) = (0.81±0.06) 10⁻⁴]

⟶ no spin-flipping suppression, due to effects next to threshold?

[in units of 10^{-4}]

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BaBar Coll. PRD 78 (2008) 112002

E.G. et al [Belle Coll.] Phys. Rev. D96 (2017) 052005

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$\Upsilon(4S) \to \eta h_b(1P)$	-					2015

~2 times smaller than theoretical prediction!

CLEO Coll. PRL 101 (2008) 192001
BaBar Coll. PRD 84 (2011) 092003
Belle Coll. PRL 115 (2015) 142001

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$\Upsilon(2S) \to \eta$					3.57±0.25±0.21	2013
$\Upsilon(4S) \to \eta$					21.8±1.1±1.8	2015

yet unobserved!
But BaBar found evidence for
BR($\Upsilon(3S) \to \pi^0 h_b(1P)$) = (7.4±2.2±1.4) 10^{-4}...!
High tension with theoretical predictions

[in units of 10^{-4}]

(*) ULs are at 90% CL

CLEO Coll. PRL 101 (2008) 192001
BaBar Coll. PRD 84 (2011) 092003

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$\Upsilon(2S) \to \eta\Upsilon(1S)$	2.1 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]±0.21	2013
$\Upsilon(4S) \to \eta h_b(1P)$	-		-		21.8±1.1±1.8	2015

the largest non-BB transition from the Υ(4S)!

In agreement with prediction

Guo et al. PRL 105 (2010) 162001

[in units of 10^{-4}]

Belle Coll. PRL 115 (2015) 142001

(*) ULs are at 90% CL

η transitions from Y(5S)

- Dipion transitions from **Υ(5S)** enhanced due to the Z_b's…

Belle Coll. PRL 100 (2008) 112001
Belle Coll. PRL 108 (2012) 032001

[in units of **10^{-3}**]

Transition	Belle	Year
Υ(5S) —>ππΥ(1S)	5.3±0.6	2008
Υ(5S) —>ππΥ(2S)	7.8±1.3	2008
Υ(5S) —>ππh_b(1P)	$3.5^{+1.0}_{-1.3}$	2012
Υ(5S) —>ππh_b(2P)	$5.7^{+1.7}_{-2.1}$	2012

η transitions from Υ(5S)

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Υ(5S) —>ππh_b(2P)	$5.7^{+1.7}_{-2.1}$	2012

- …but η transitions are NOT suppressed!
- Observation of **Υ(5S)—>ηΥ(1D)!**

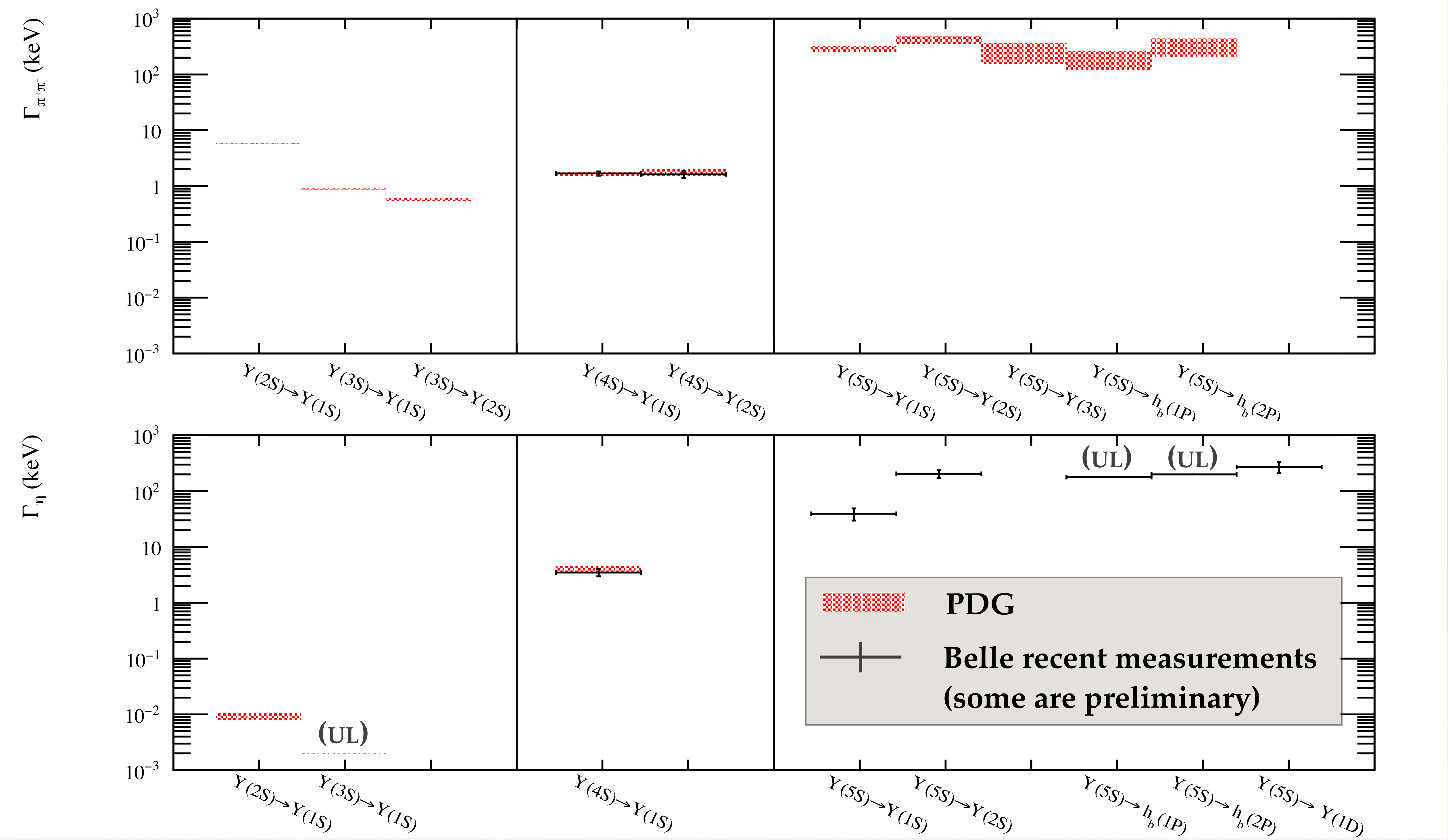
Belle Coll. preliminary @LaThuile2012
Belle Coll. preliminary @DIS2014

Belle Coll. PRL 100 (2008) 112001
Belle Coll. PRL 108 (2012) 032001

[in units of 10^{-3}] (*) ULs are at 90% CL

Transition	Belle	Year
Υ(5S) —>ηΥ(1S)	0.73±0.16±0.8	2012 (prel.)
Υ(5S) —>ηΥ(2S)	2.1±0.7±0.3	2014 (prel.)
Υ(5S) —>ηh_b(1P)	<3.3 (*)	2014 (prel.)
Υ(5S) —>ηh_b(2P)	<3.7 (*)	2014 (prel.)
Υ(5S) —>ηΥ(1D)	2.8±0.7±0.4	2014 (prel.)

A quick-view summary



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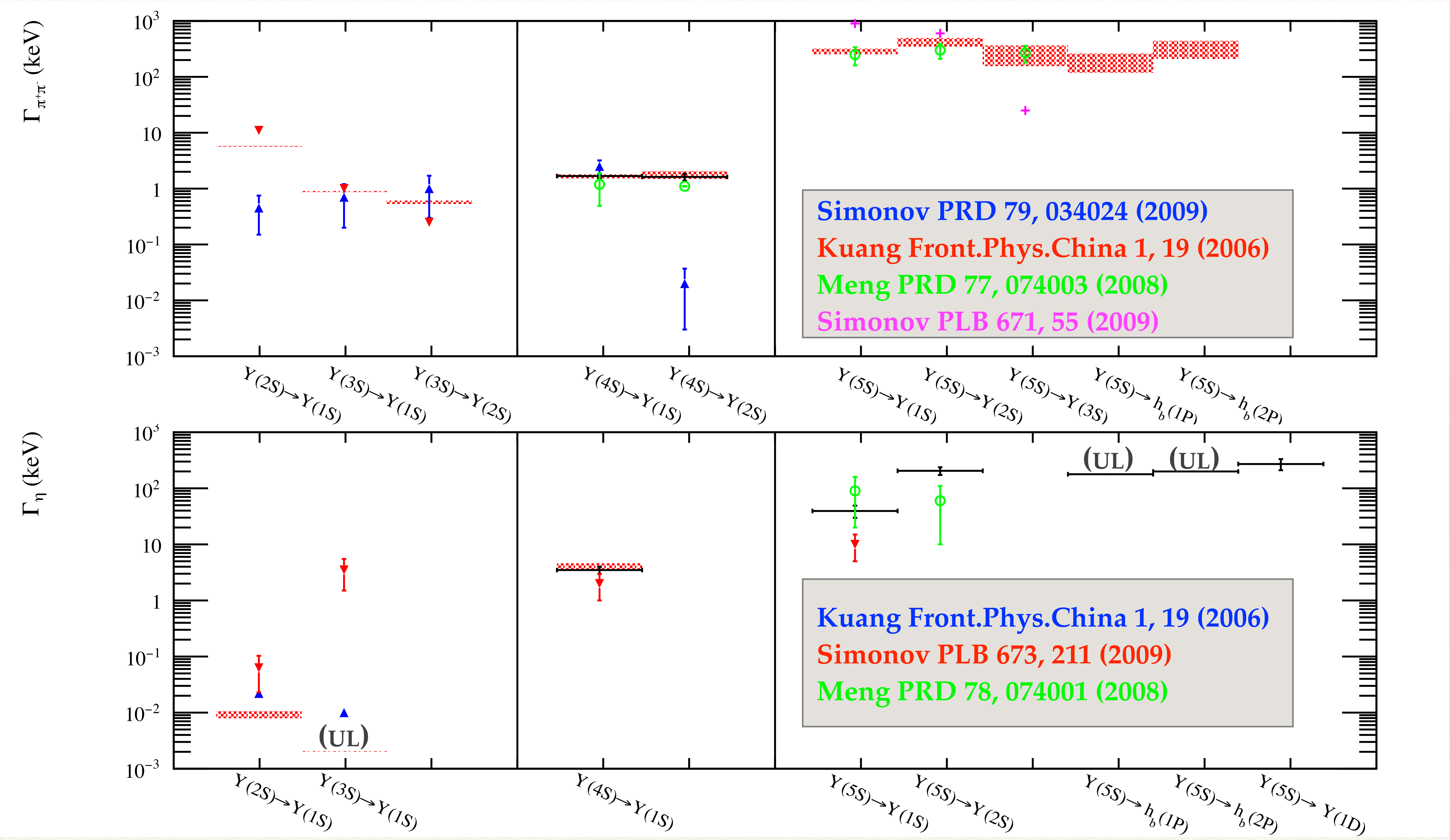
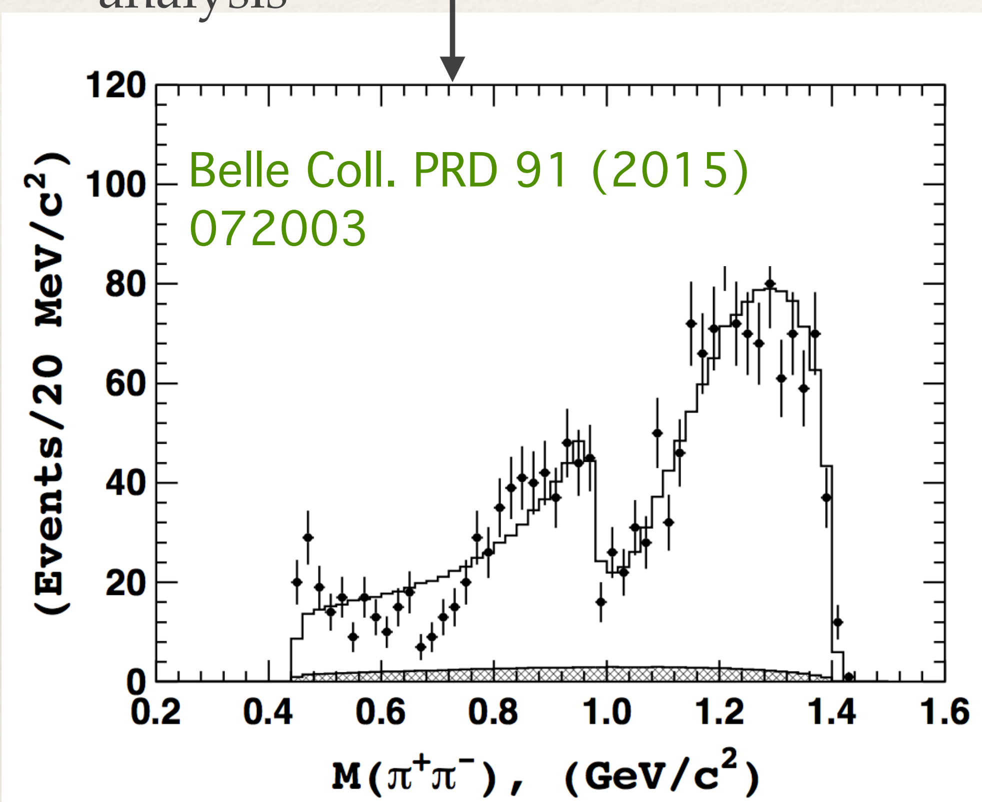


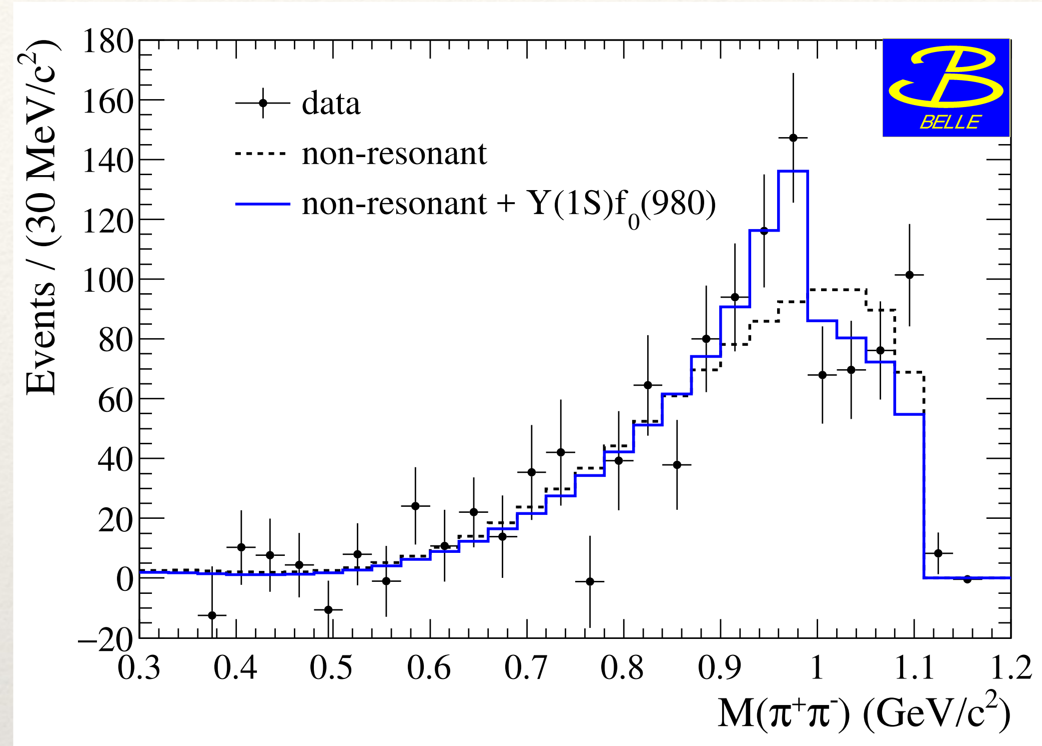
NEW!

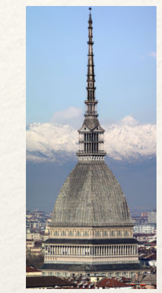
E.G. et al [Belle Coll.] Phys. Rev. D96, 052005 (2017)

Resonant contributions to dipion transitions

- **Clear dip just below 1GeV** (never seen before)
- Similar to what observed in Belle 5S analysis



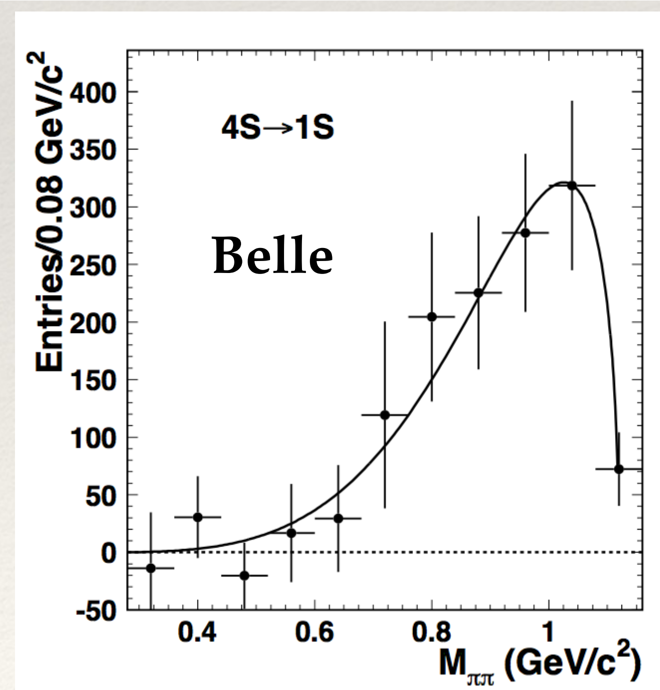


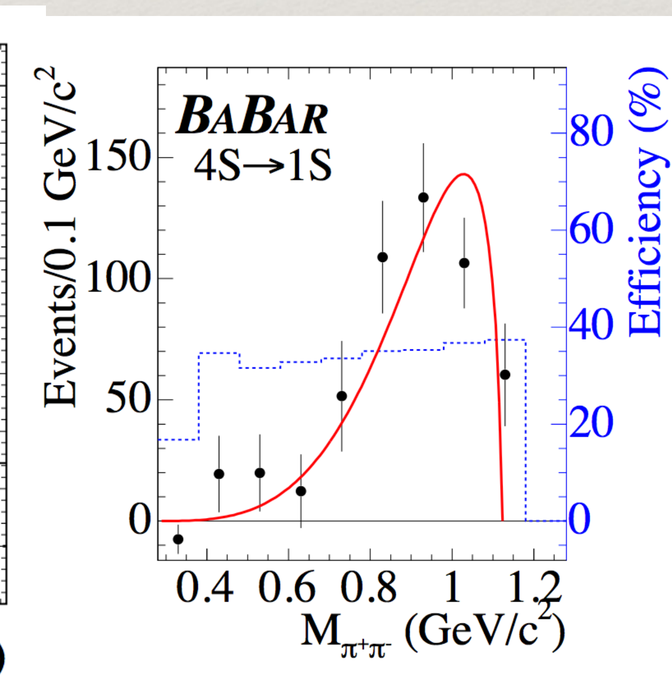


Belle Coll. PRD 79 (2009) 051103

BaBar Coll. PRL 96 (2006) 232001

- Due to interference between non-resonant and $f_0(980)$
- **Indications for $f_0(980)$ at 2.8σ**
- More data needed for a refined Dalitz analysis and study of other contributions
- First time this behaviour is seen in 4S transitions

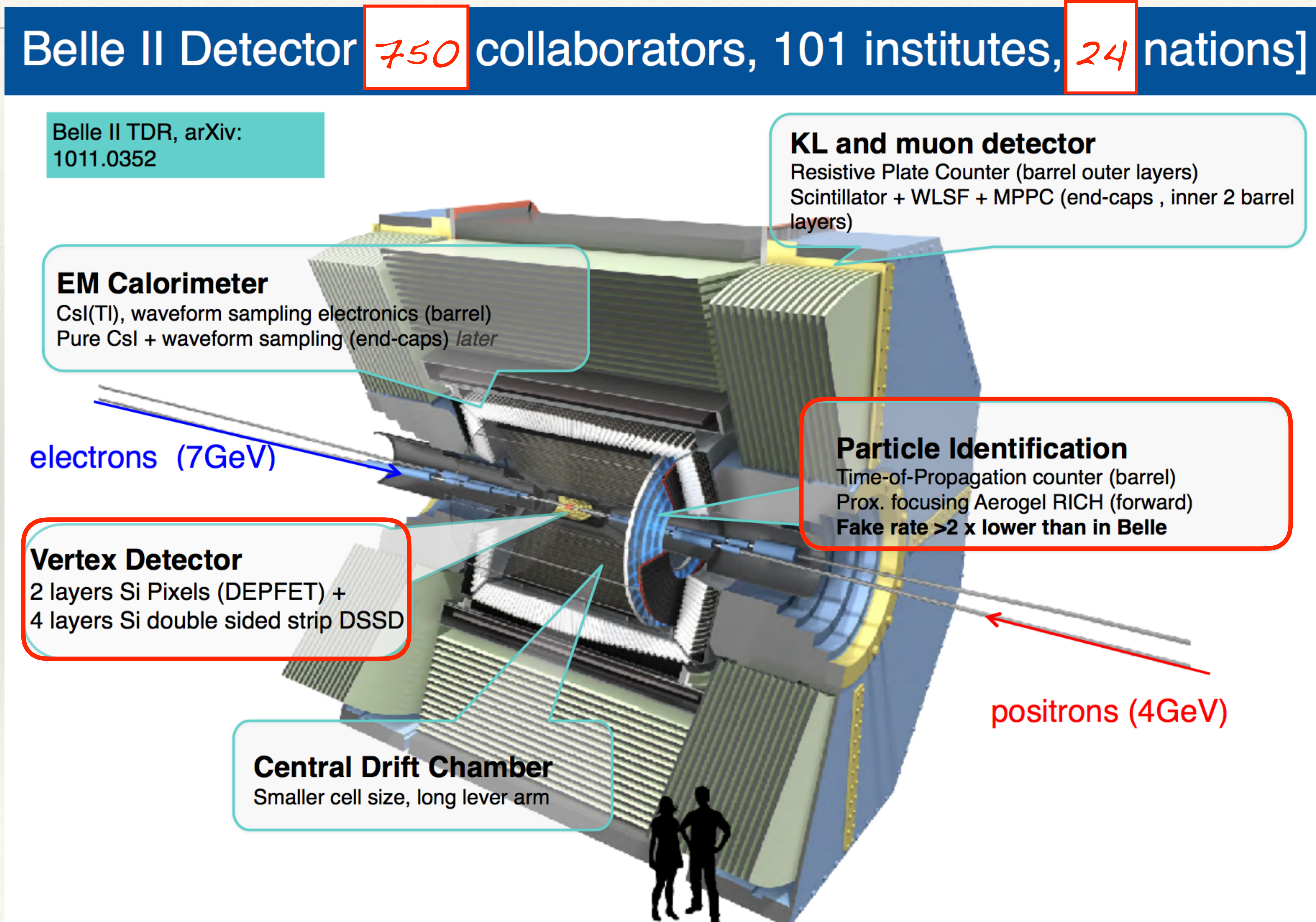




Preliminary conclusions

- An incomplete summary of the heritage of the 1st generation of B-factories in the bottomonium physics field
    - A lot of achievements
    - A lot of open items for theoretical speculation but also for further experimental investigation
- Promising territory for the next B-factory as well!

The Belle II experiment



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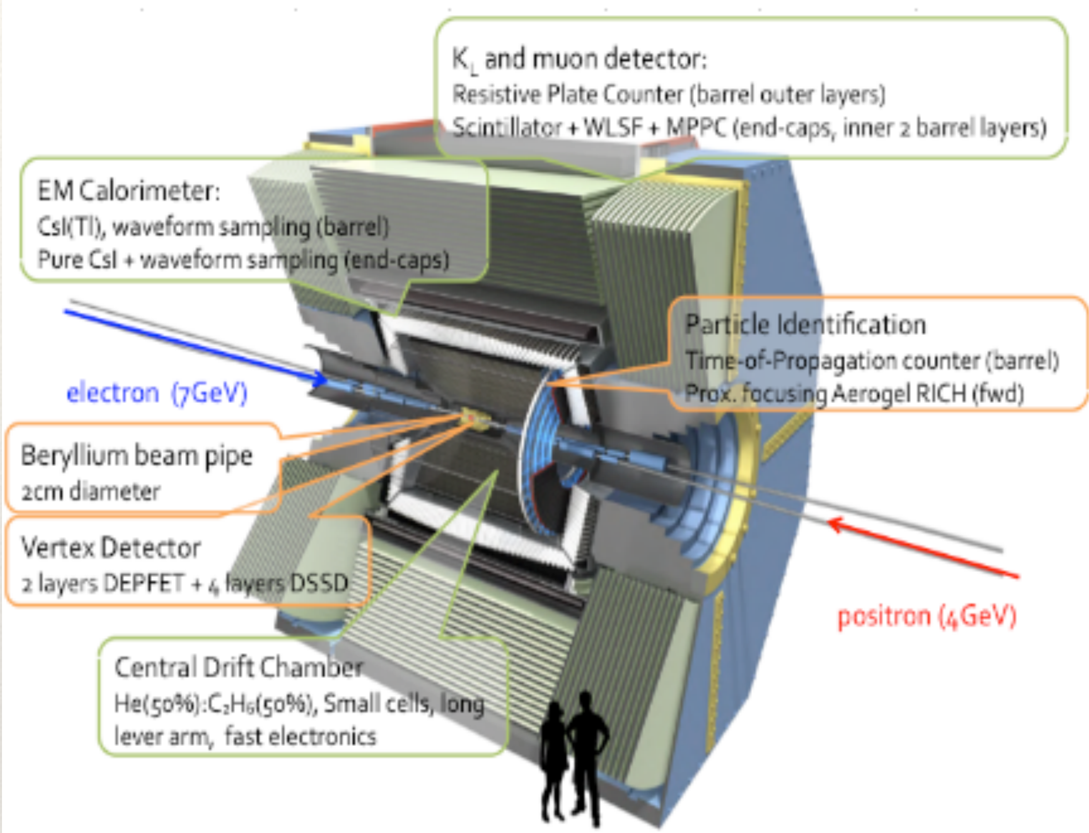
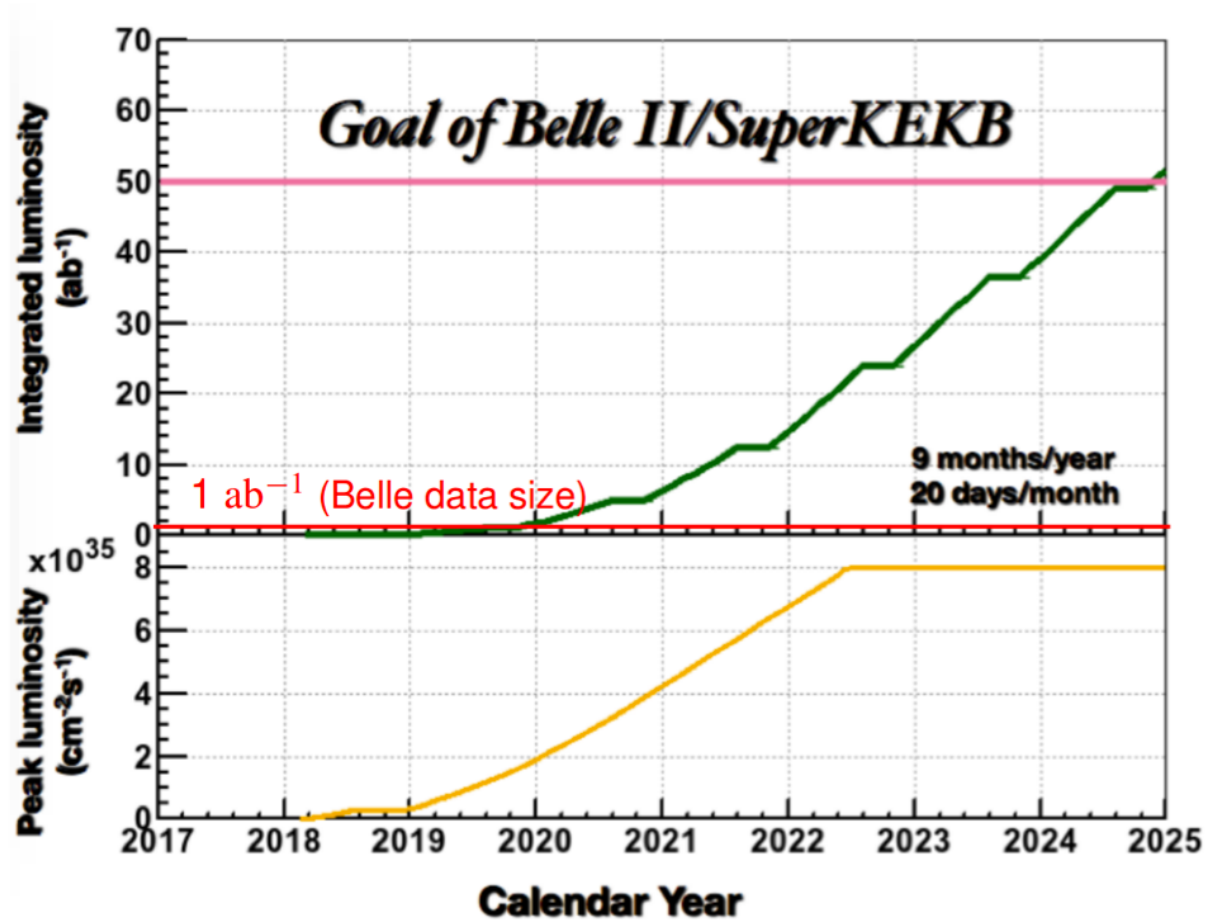
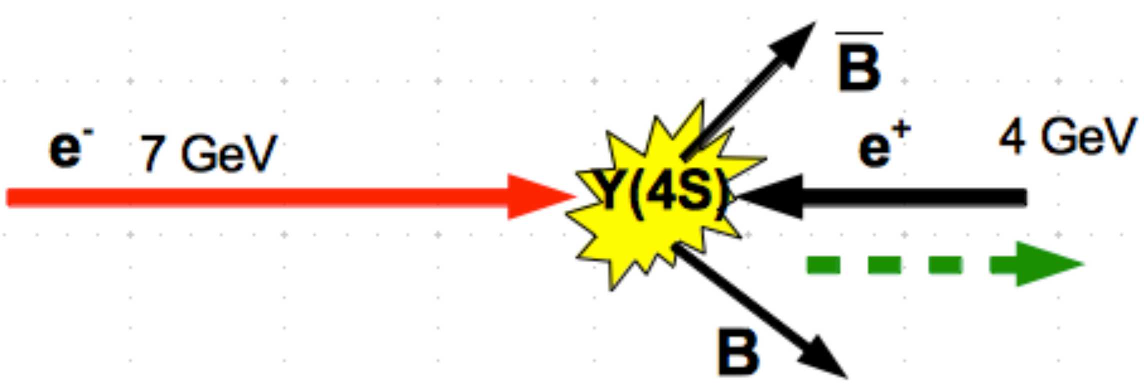




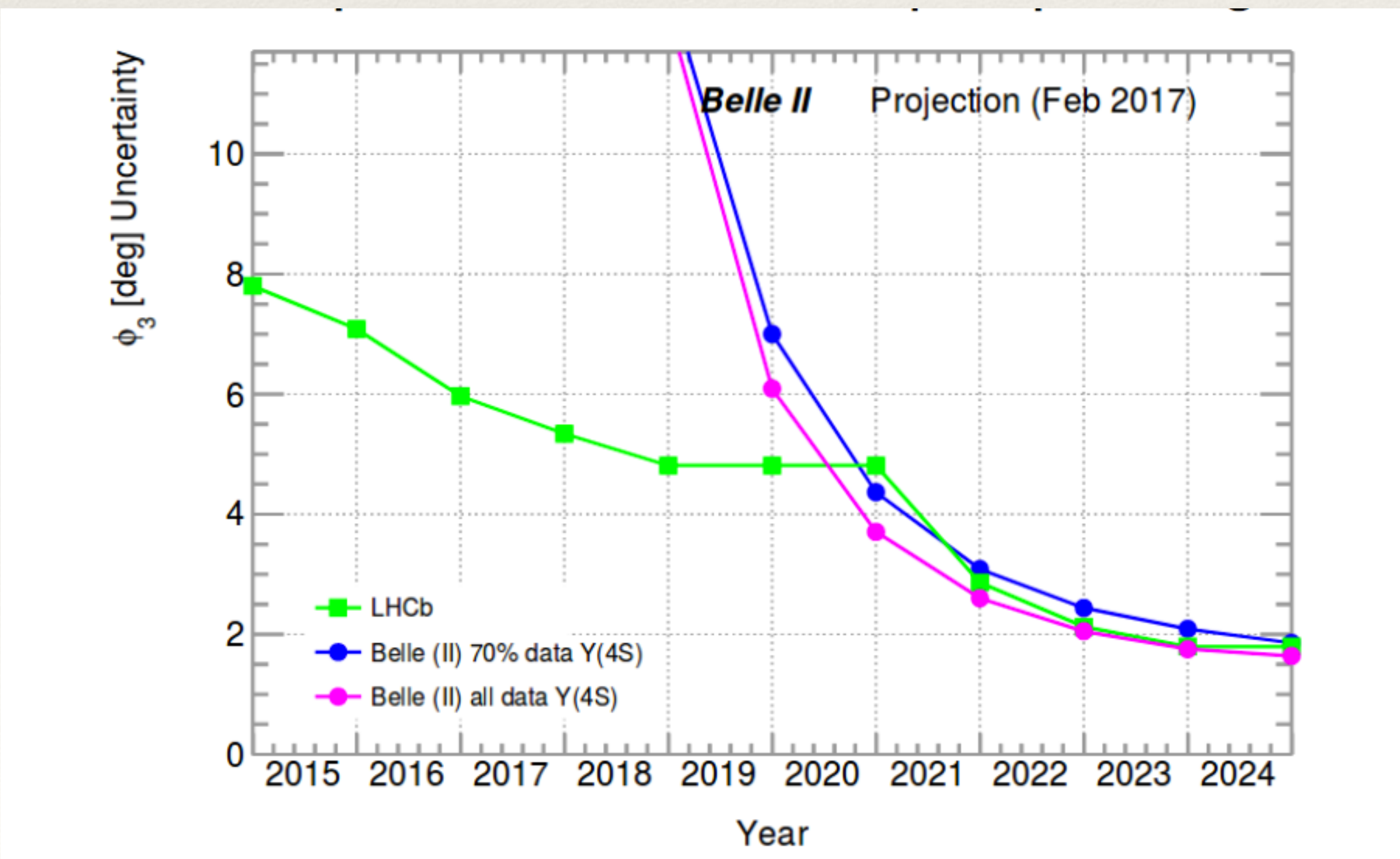


Target instantaneous luminosity:
$8 \times 10^{35} / cm^2 /s$

Target integrated luminosity:
$50\ ab^{-1}$ (50x Belle, ~100x BaBar)

First data taking phase (without vertex detector) in 2018

- Bottomonium physics program highly demands for data to be collected at the **Υ(3S) and Υ(5S,6S)**
- Option of collecting data @Υ(6S) in Phase 2: tough because at the very limit of the machine
- Competition with LHCb is quite pressing
- Even in Phase 3, the fraction of Υ(4S) data collected is a delicate matter of discussion



A reasonable non-Υ(4S) request:
- 1 ab^{-1} @Υ(5S)
- 100 fb^{-1} @Υ(6S)
- 300 fb^{-1} @Υ(3S)
- 400 fb^{-1} scan

Wish list for Belle II

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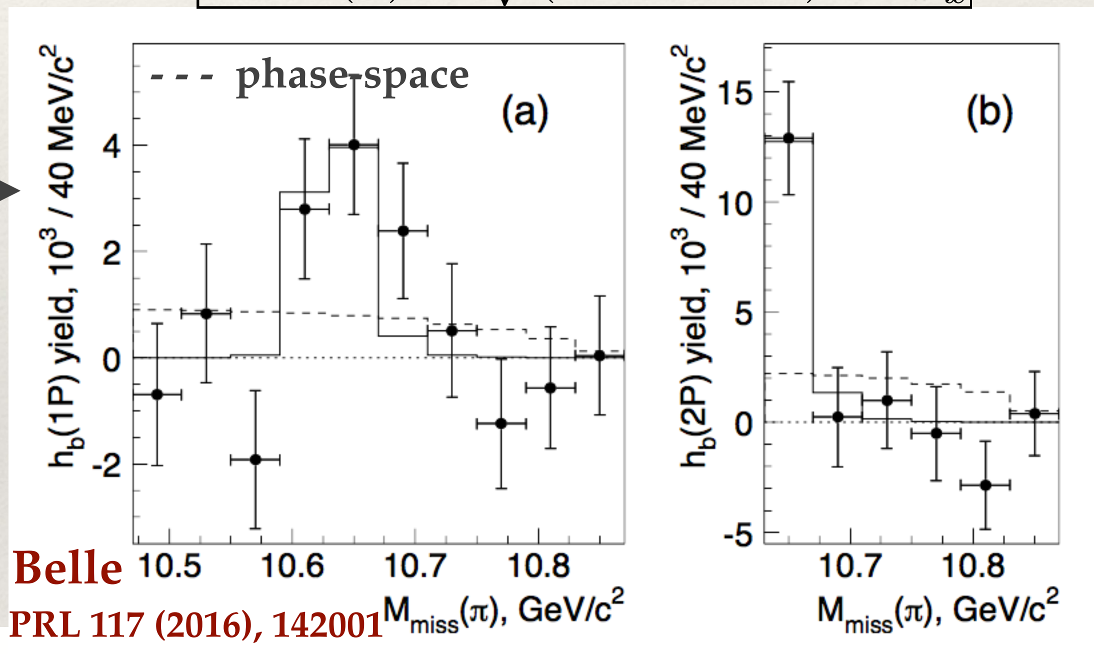
- Missing states: **D-waves**. Expected narrow widths, dominant radiative decays to χ_{bJ}
- **Hadronic transitions** still not well understood, and spin-flipping transitions below/above threshold to be interpreted: high statistics study compelling for feeding theoretical speculation
- Exotica: others apart from **Z_b's**? if so, probably accessible from data taking at higher energies. Testing tetraquark/molecular nature of Z_b's

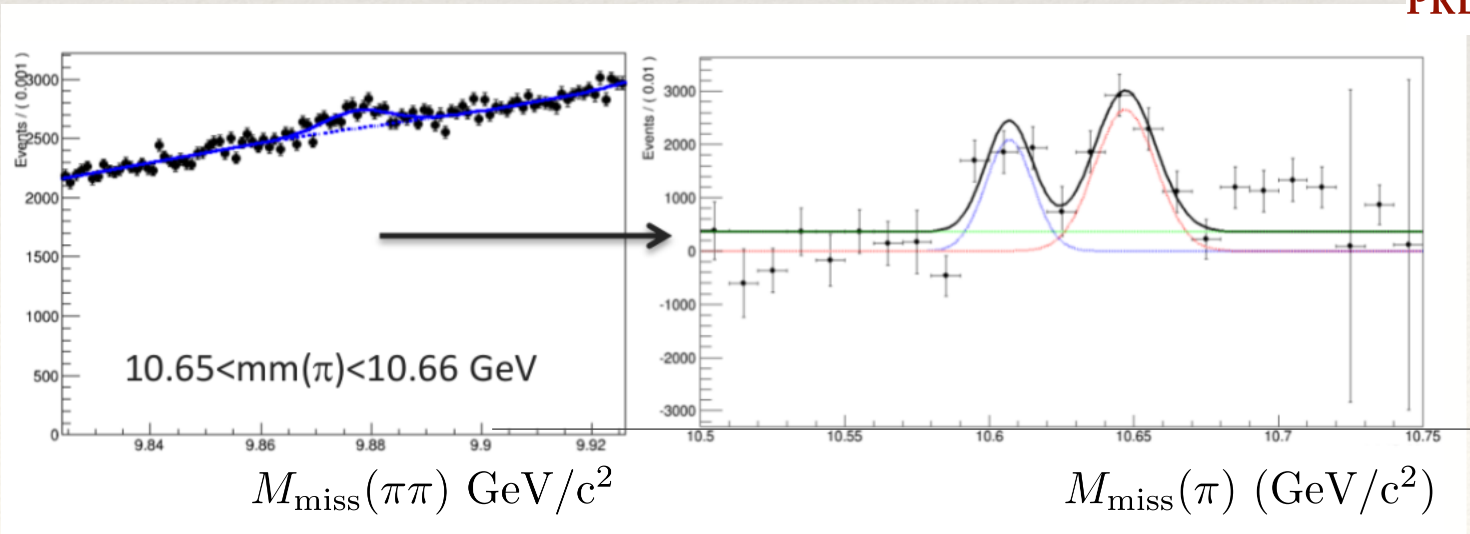
Bottomonium physics @ Y(6S)

- Important results, through some golden modes based on a possibly **unique data sample** to be collected at the **Y(6S)** energy

$$M_{\mathrm{miss}}(x) = \sqrt{(E_{\mathrm{CM}} - E_x)^2 - p_x^2}$$

- **$\Upsilon(6S)\to\pi Z_b$, $Z_b\to\pi h_b(nP)$**
  - not sufficient statistics at Belle to clearly separate the Z_b contribution
  - possibility for a data acquisition at the $\Upsilon(6S)$ energy during Phase 2 (2018)
  - according to MC studies, separation is possible already with 10 fb^{-1} of data

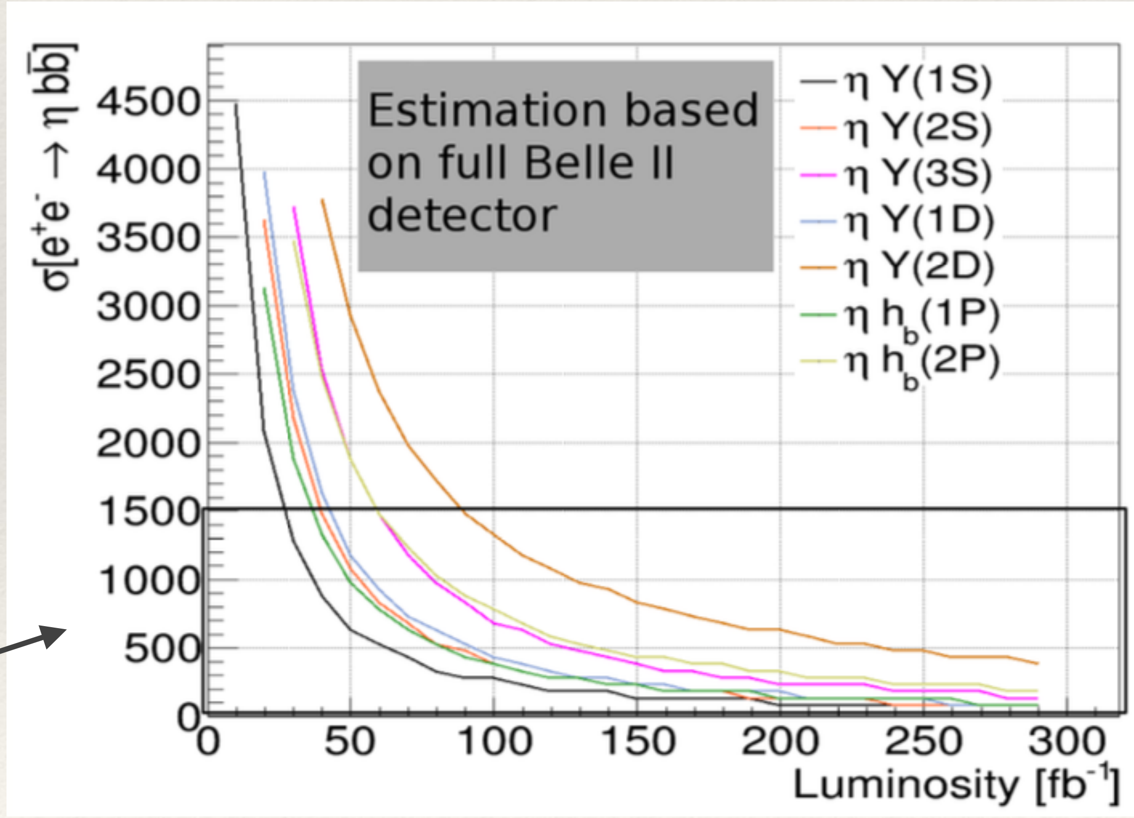




Bottomonium physics @ Y(6S)

- Important results, through some golden modes based on a possibly **unique data sample** to be collected at the **Y(6S)** energy

- **η transitions from ϒ(6S)**
  - could be used to access missing states below $B\bar{B}$ threshold (in particular Y(2D) triplet)
  - heavy quark spin symmetry violating —> comparison with QCD multipole expansion calculations
  - results with 50 fb^{-1}, but more statistics will be needed for Y(2D) discovery



from similar transitions from Y(5S) , it is reasonable to expect cross-sections < 1500 fb

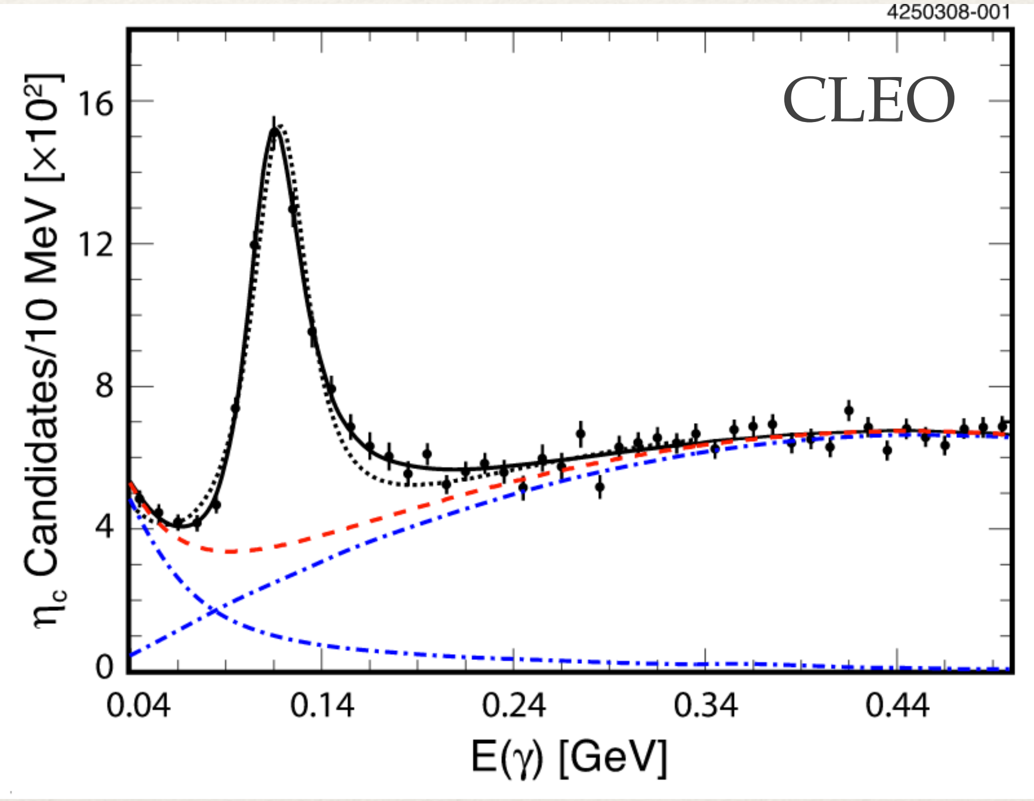
Summary

- Bottomonium physics has been one of the main successes achieved by the first generation of B-factories
  - Discovery of long-awaited resonances
  - Open room for exotic states
  - Puzzling hadronic transitions between states below and above threshold
- A fertile field also for Belle II !

Backup

Analogy with η_c lineshape?

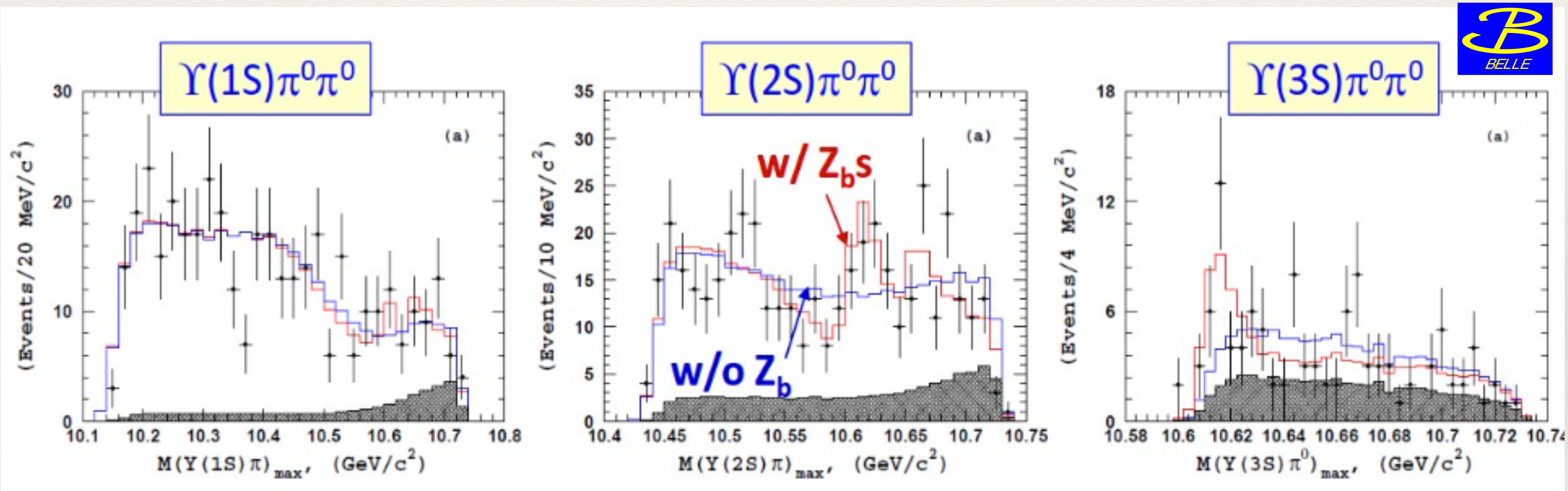
- CLEO (2009) observed a distortion in the η_c line shape due to the photon-energy dependence of the magnetic dipole transition rate ($J/\psi \longrightarrow \gamma\, \eta_c$ and $\psi(2S) \longrightarrow \gamma\, \eta_c$)
- Background that decreases with E(γ) from $J/\psi \longrightarrow X_i$, where a spurious cluster is found in the calorimeter + a rising background from both $J/\psi \longrightarrow \pi^0 X_i$ and non-signal $J/\psi \longrightarrow \gamma X_i$
- Taking into account this, a mass value (2982.2±0.6 MeV/c^2) compatible with the result from $\gamma\gamma$ fusion and $p\bar{p}$ annihilation; without ~7 MeV lower
- A similar factor for η_b?



CLEO Coll. PRL 102 (2009) 011801
Erratum ibid. 106 (2011) 159903

Search for Z_b^0

- If molecular interpretation, search for a 'natural' neutral partners of $Z_b^{\pm}$ in $\Upsilon(10860) \longrightarrow \Upsilon(nS)\pi^0\pi^0$ decays, with $\Upsilon(nS)$ going to leptons

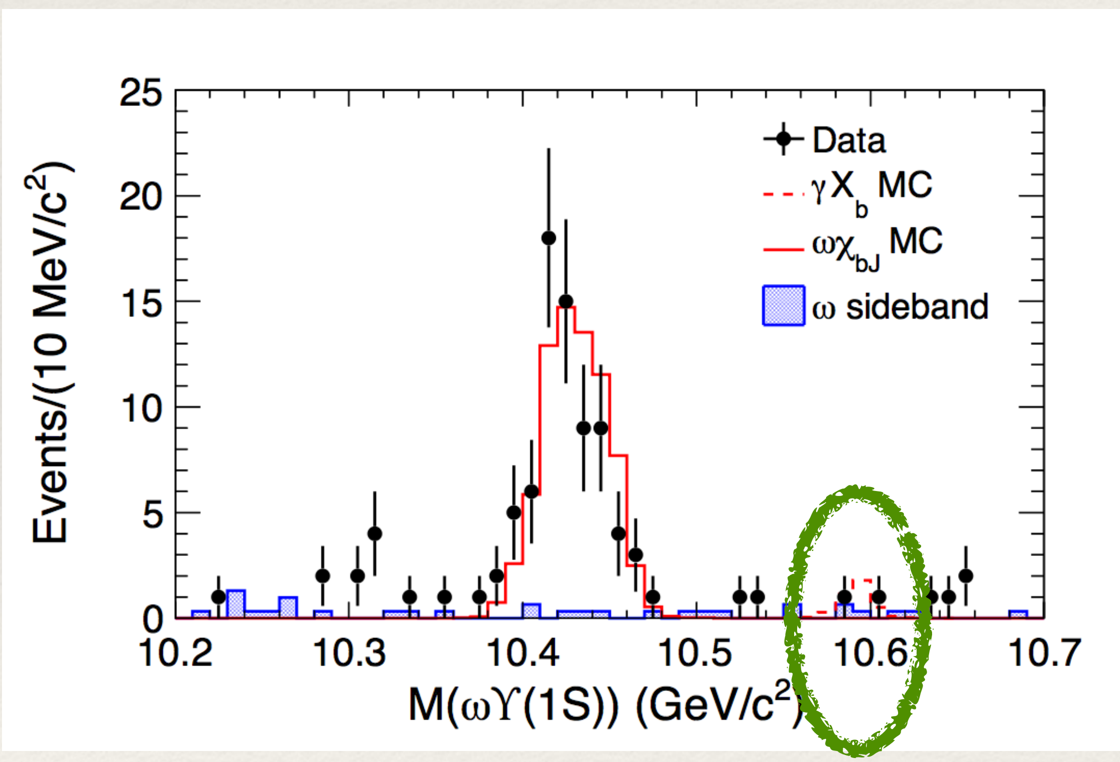


- $Z_b^0(10610)$: 6.5σ (4.9σ from $\Upsilon(2S)$ + 4.3σ from $\Upsilon(3S)$)
- $Z_b^0(10650)$: not observed, but not excluded

Belle Coll. PRD 88 (2013) 052016

More exotica?

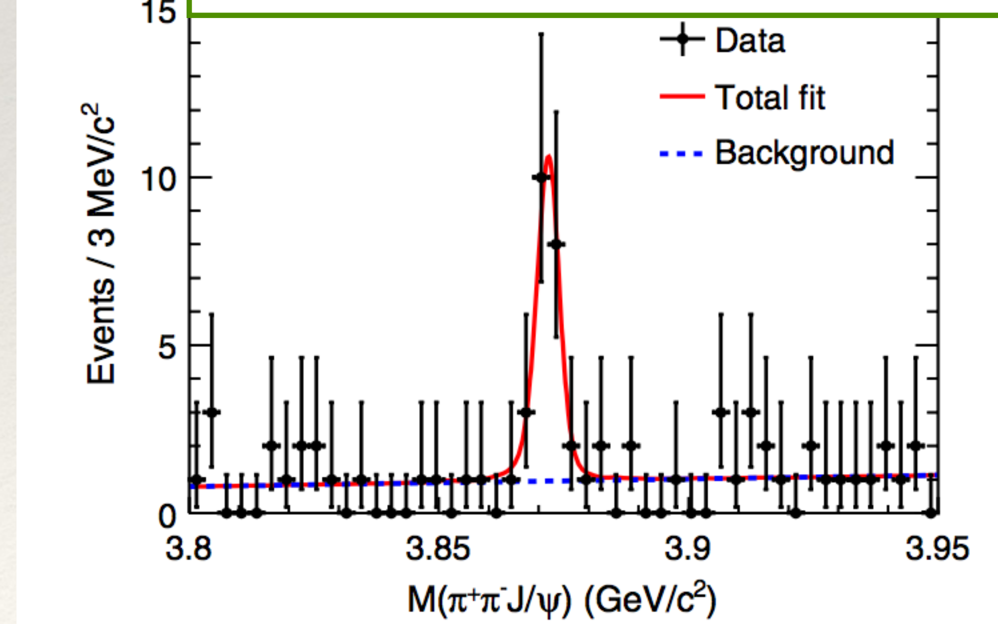
- X_b? counterpart of X(3872), $J^{PC} = 1^{++}$
- Predicted in both tetraquark model and molecular interpretations
- Searched for in the Υ(5S) data sample, through $X_b \rightarrow \omega\Upsilon(1S)$ decays (large isospin violation in $\pi^+\pi^-\Upsilon(1S)$)



Belle Coll. PRL 113 (2014) 142001

- Similarly to $e^+e^- \rightarrow \gamma X(3872)$ observation by BESIII at 4.26 GeV
- As a counterpart of $X(3872) \rightarrow \pi^+\pi^- J/\psi$

BESIII Coll. PRL 112 (2014) 092001



- More statistics needed!

Possible solutions for hadronic transitions?

- Some very recent theoretical insights:
- Eichten (B2TIP meeting 2015):
  - Above heavy flavor production threshold the usual QCDME fails (transitions rates much larger than expected, large SU(3) violations). New mechanisms for hadronic transitions required
  - light quarks dynamics should be factorized differently
- Segovia et al. (arXiv:1507.01607):
  - Starting from the large rates of $\Upsilon(4S) \to \eta h_b(1P)$ and $\Upsilon(4S) \to \eta\Upsilon(1S)$
  - Same physical origin
  - Not negligible role by M1-M1 transitions and large L=0 hybrid mesons contributions
  - Normalizing to $\Upsilon(2S)$ transitions, good agreement with $\Upsilon(4S)$ measured rates. Not completely with $\Upsilon(3S)$ though…

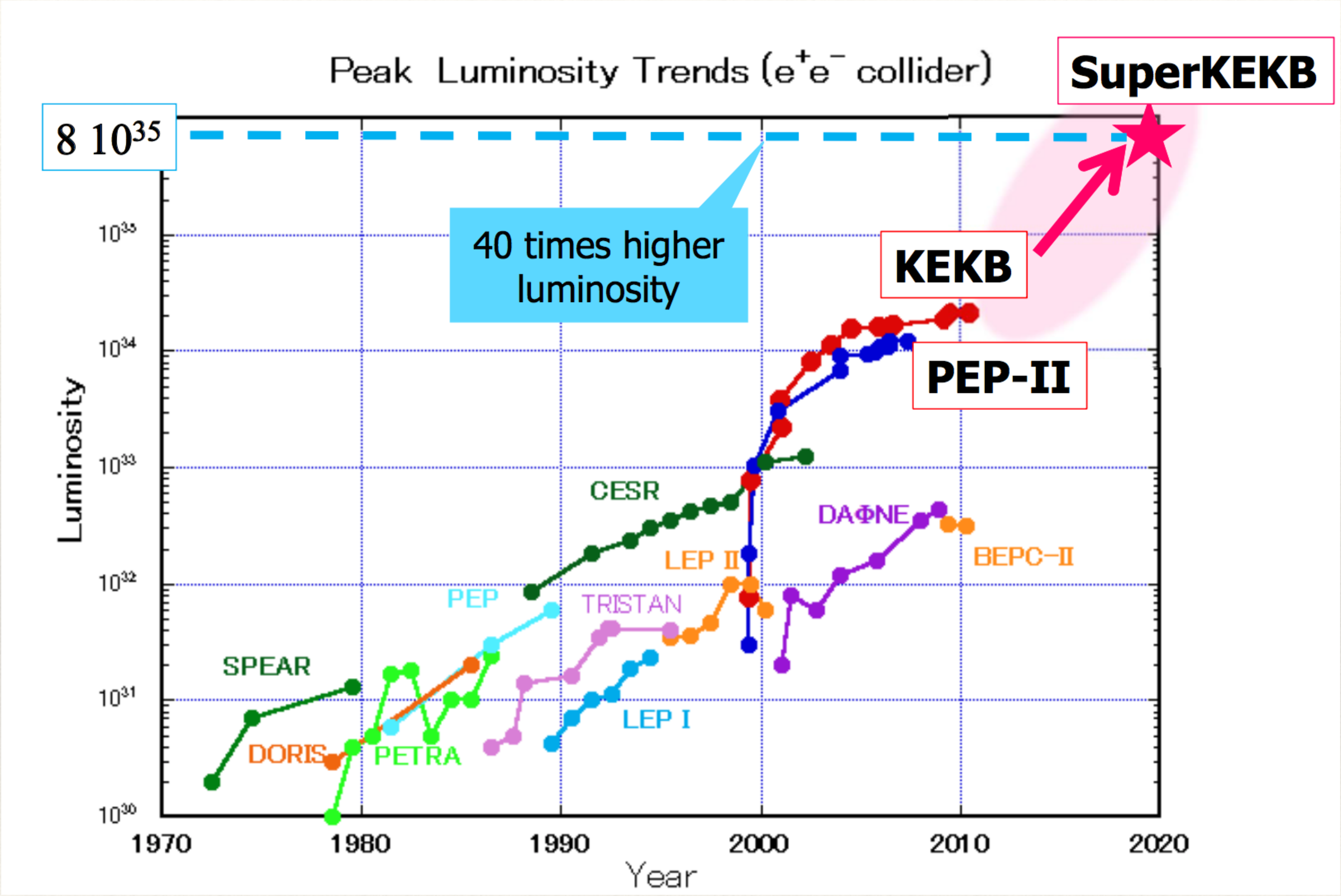
Bottomonium @ Hadron colliders

- **ATLAS**:
  - Observation of a New χ_b State in Radiative Transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ at ATLAS, **PRL 108 (2012) 152001**
  - Search for the X_b and other hidden-beauty states in the $\pi^+\pi^-\Upsilon(1S)$ channel at ATLAS, **PLB 740 (2015) 199-217**
- **CMS**:
  - Search for a new bottomonium state decaying to $\Upsilon(1S)\ \pi^+\pi^-$ in pp collisions at sqrt(s) = 8 TeV, **PLB 727 (2013) 57**
- **LHCb**:
  - Study of χ_b meson production in pp collisions at sqrt(s) = 7 and 8 TeV and observation of the decay $\chi_b(3P)$—>$\Upsilon(3S)\gamma$, **EPJ C74 (2014) 3092**
  - Measurement of the fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays in pp collisions at sqrt(s) = 7 TeV, **JHEP 11 (2012) 031**
- **D0**:
  - Observation of a narrow mass state decaying into $\Upsilon(1S)+\gamma$ in pp collisions at sqrt(s)=1.96 TeV, **PRD 86 (2012) 031103**

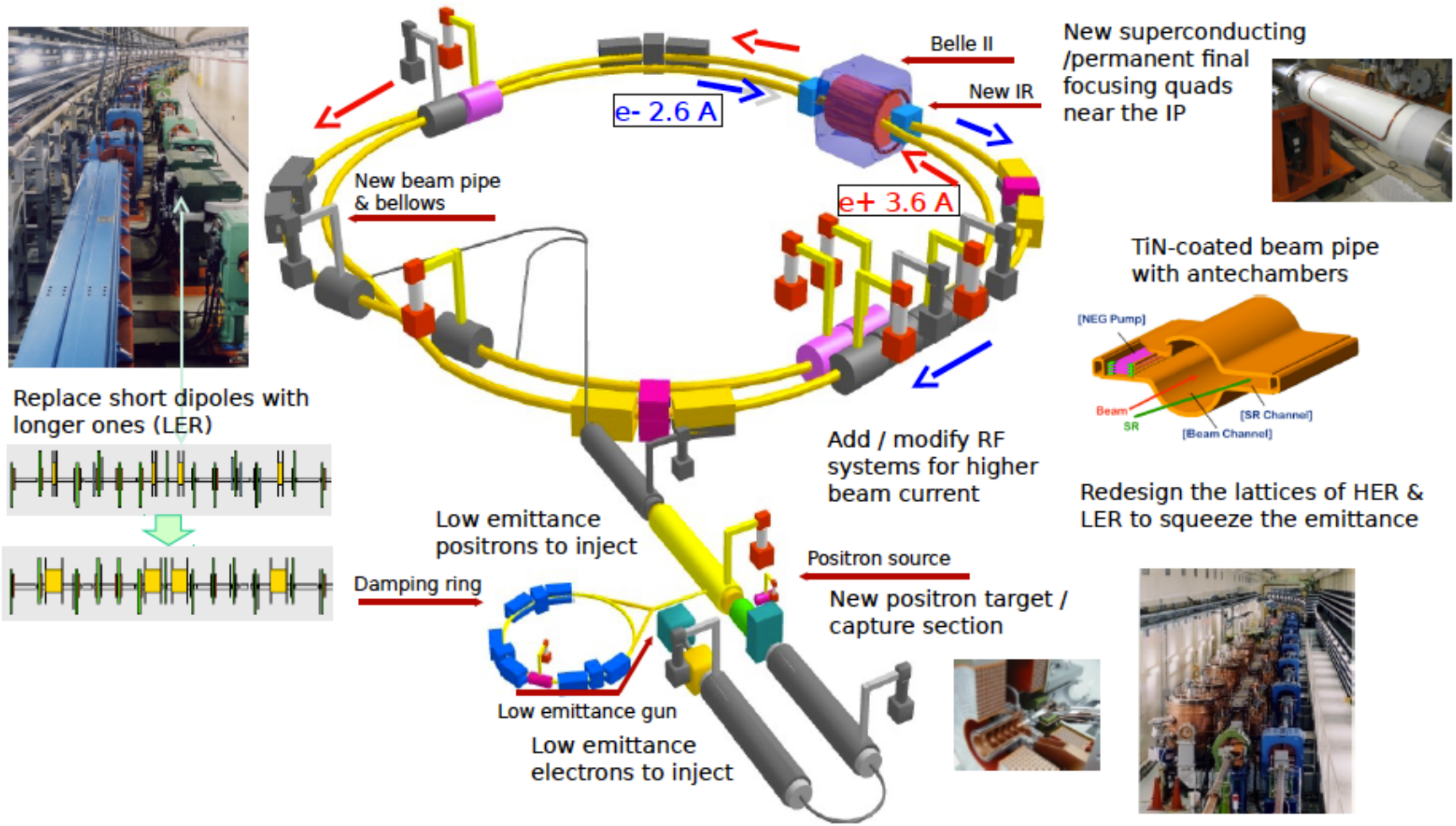
π^0 transitions: experimental status

Transition	CLEO	Year	BABAR	Year	Belle	Year
$\Upsilon(3S) \longrightarrow \pi^0 h_b(1P)$	-		7.4±2.2±1.4	2011b	-	
$\Upsilon(2S) \longrightarrow \pi^0 \Upsilon(1S)$	<1.8	2008	-		<0.41	2013

CLEO Coll. PRL 101 (2008) 192001
BABAR Coll. PRD 84 (2011) 112007
Belle Coll. PRD 87, 011104(R) (2013)

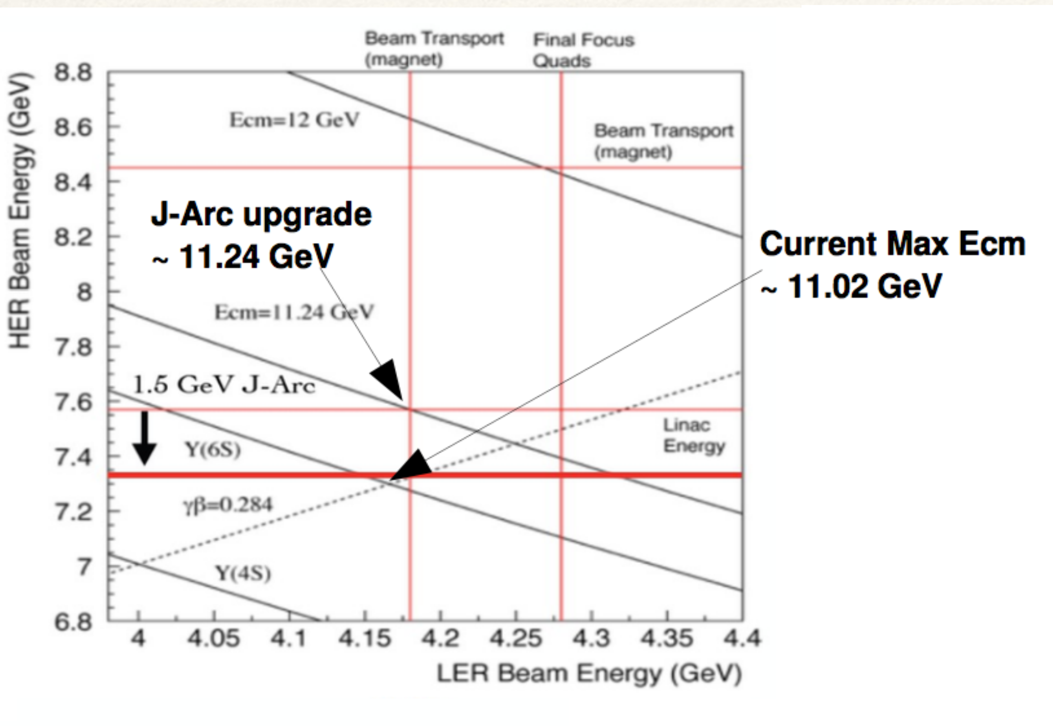

Peak Luminosity Trends (e+e− collider)
SuperKEKB
8 10^35
40 times higher luminosity
KEKB
PEP-II
CESR
DAΦNE
BEPC-II
LEP II
PEP
TRISTAN
SPEAR
LEP I
DORIS
PETRA
Luminosity
Year
1970
1980
1990
2000
2010
2020

SuperKEKB
The next generation B-factory

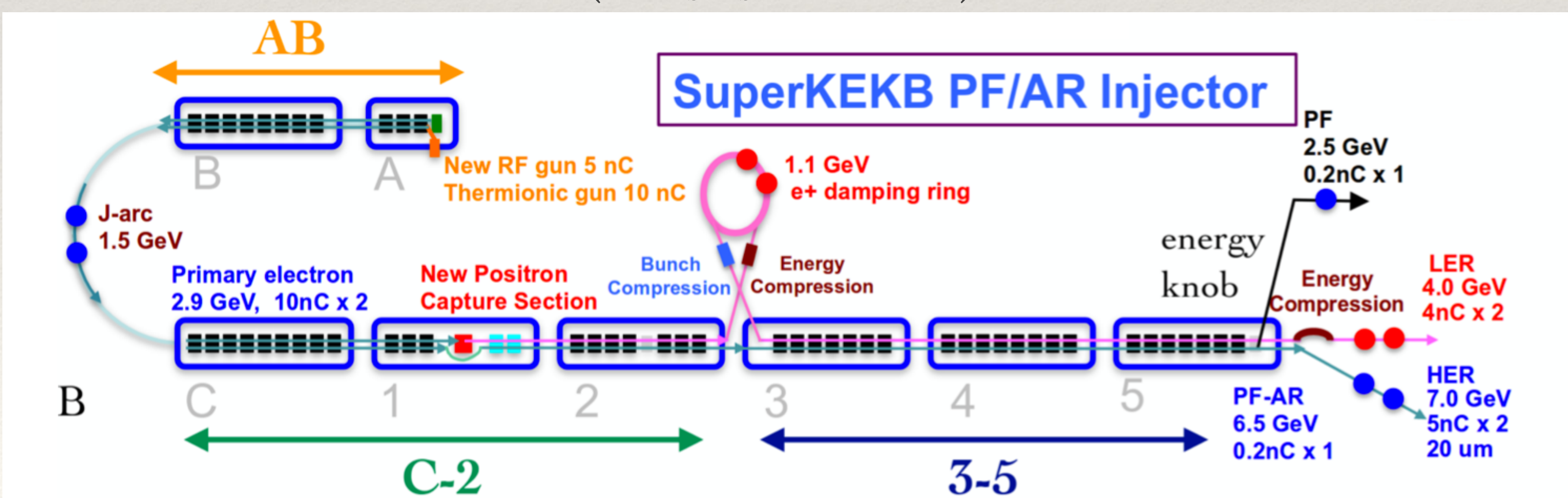


*gray - recycled, color - new

Super-KEKB: energy and limitations



- Super-KEKB is an accumulation ring
  - The acceleration stage is done in the LINAC
  - RF only to sustain the beams (with continuous injection)
- Current max E_{CM} ~11.02 GeV (slightly above Y(6S))
- Max E_{CM} achievable upon J-arc upgrade E_{CM}~11.24 GeV (at $\Lambda_b\Lambda_b$ threshold)



Time-of-Propagation Cherenkov Detector