Conventional Bottomonium Experimental Overview

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Belle and Belle II Collaborations

Snowmass RF7
Rare and Precision Frontier
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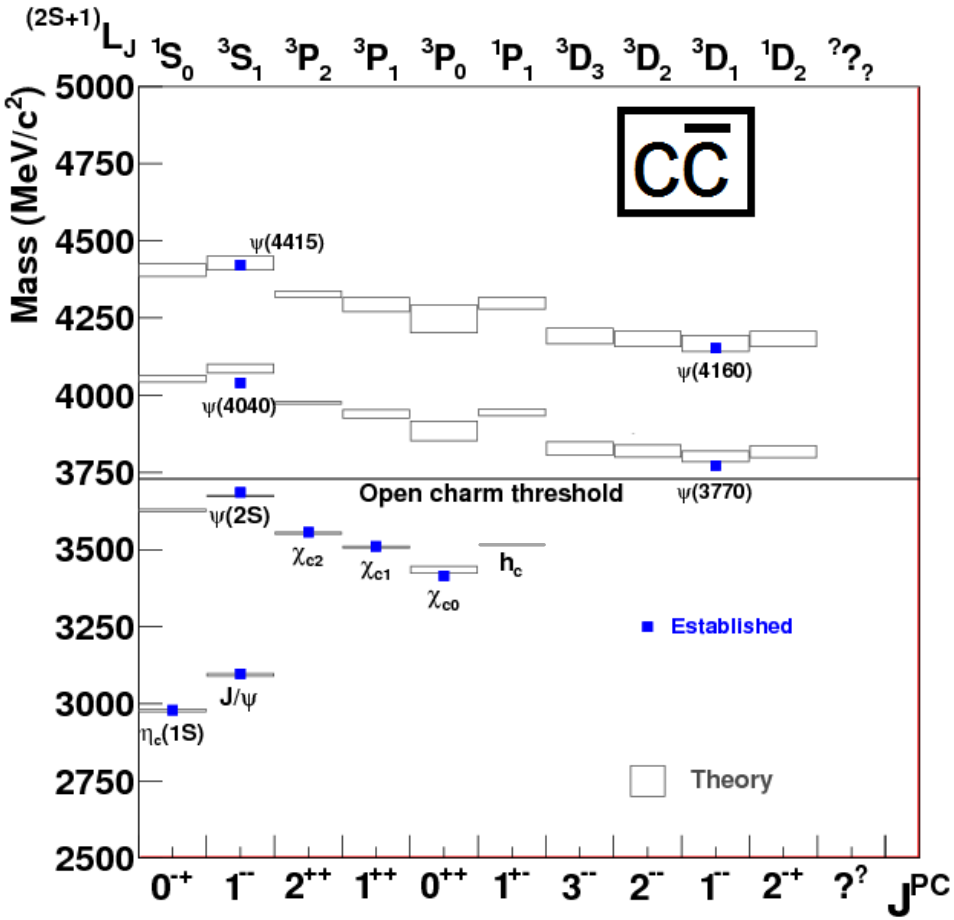
Heavy Quarkonium Spectroscopy

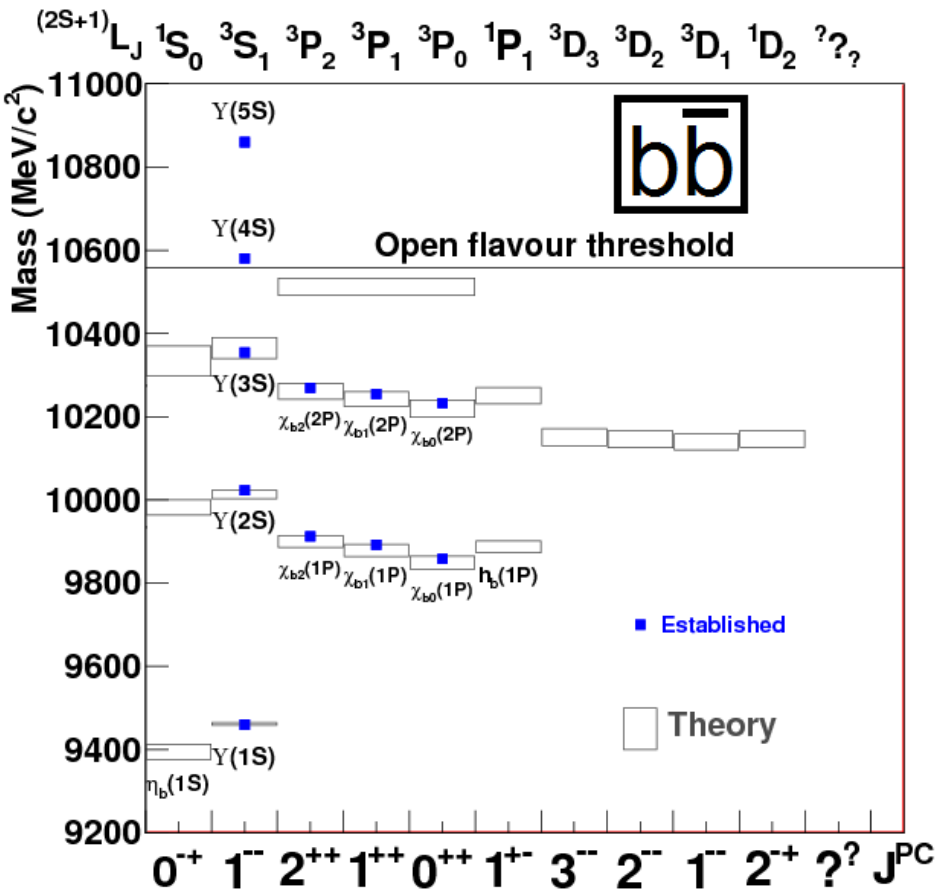
- Both charmonium and bottomonium systems
  - Saw an early period of discovery of several principal states
  - Experienced significant expansion of understanding with spectroscopy results from BES II/III, CLEO, Belle, BaBAR, and the LHC experiments
  - Excellent future prospects with much yet to learn
- Ryan Mitchell discussed charmonium this morning, and in this talk I hope to convey similar things concerning bottomonium
  1. Some of the history, focused on results from the past decade
  2. Prospects for answering some of the open questions which remain over the course of the next decade

Caveat Emptor

Concentration here is on spectroscopy/decays, (and only a few of them, for lack of time!) so several experimental bottomonium-related topics are left out (*e.g.* elliptic flow studies from ALICE, cross sections and polarization measurements in hadronic production from the LHC, RHIC, etc.)

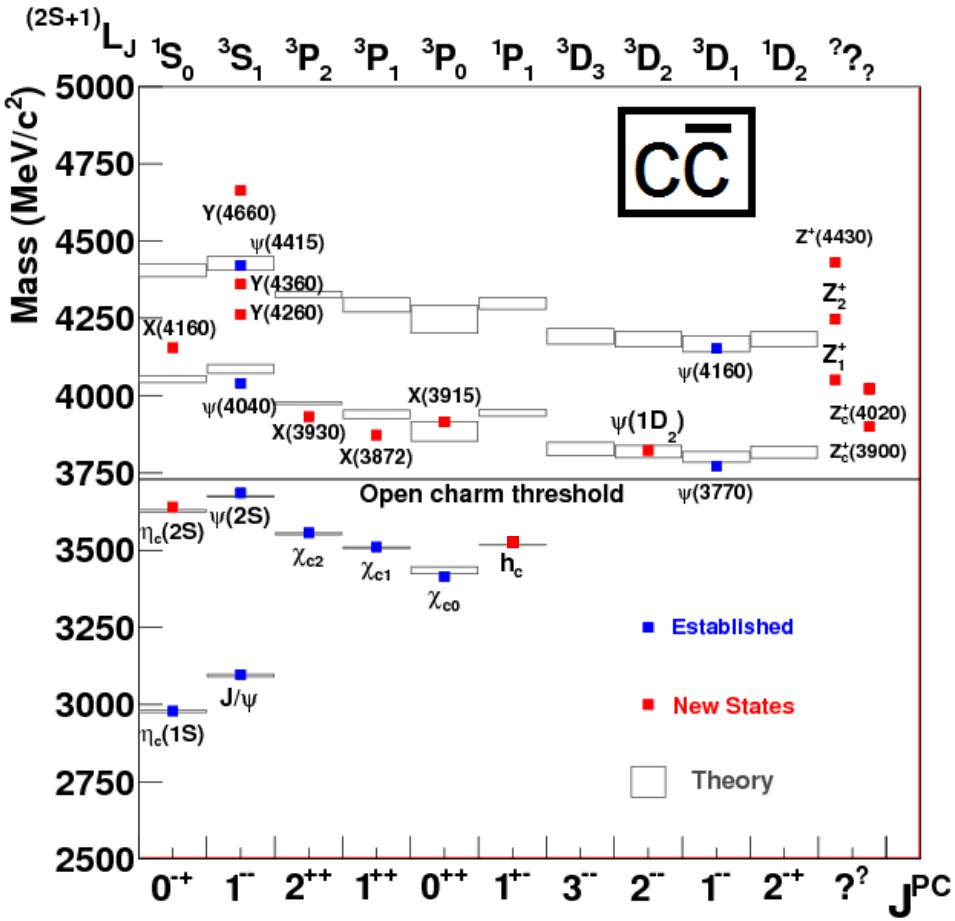
20th century Quarkonium Spectroscopy …

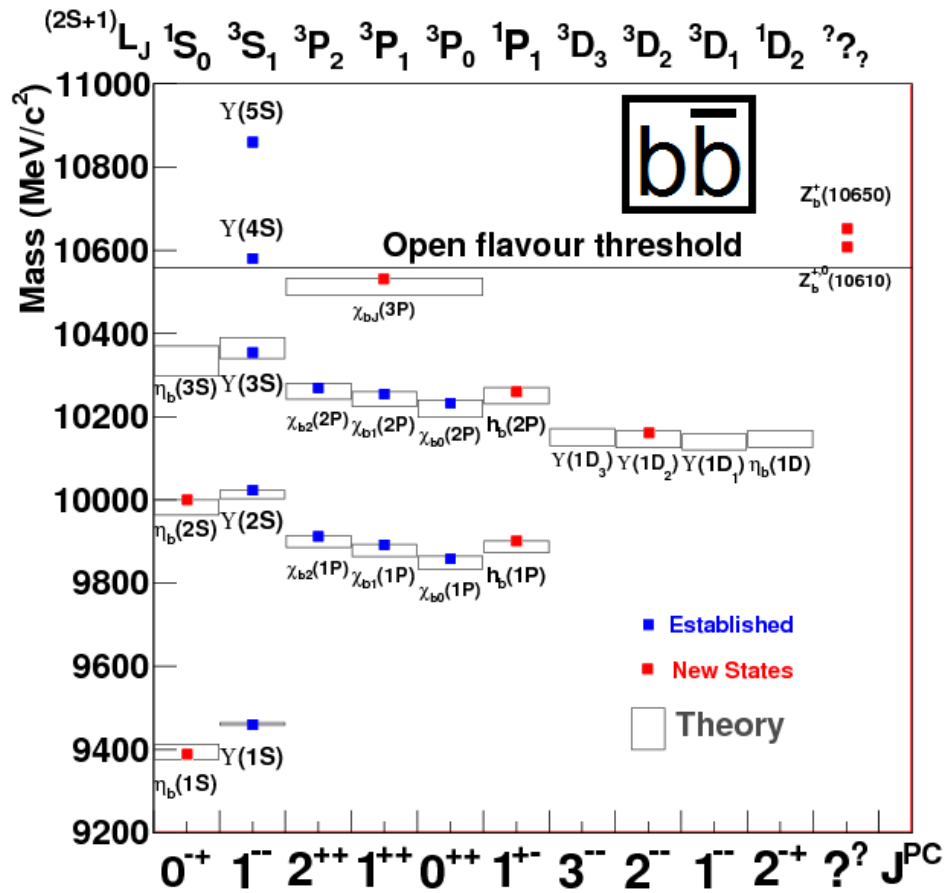




Status of the spectra circa 1998 – prior to the B-factories, CLEO-c, BES II/III

21st century Quarkonium Spectroscopy …



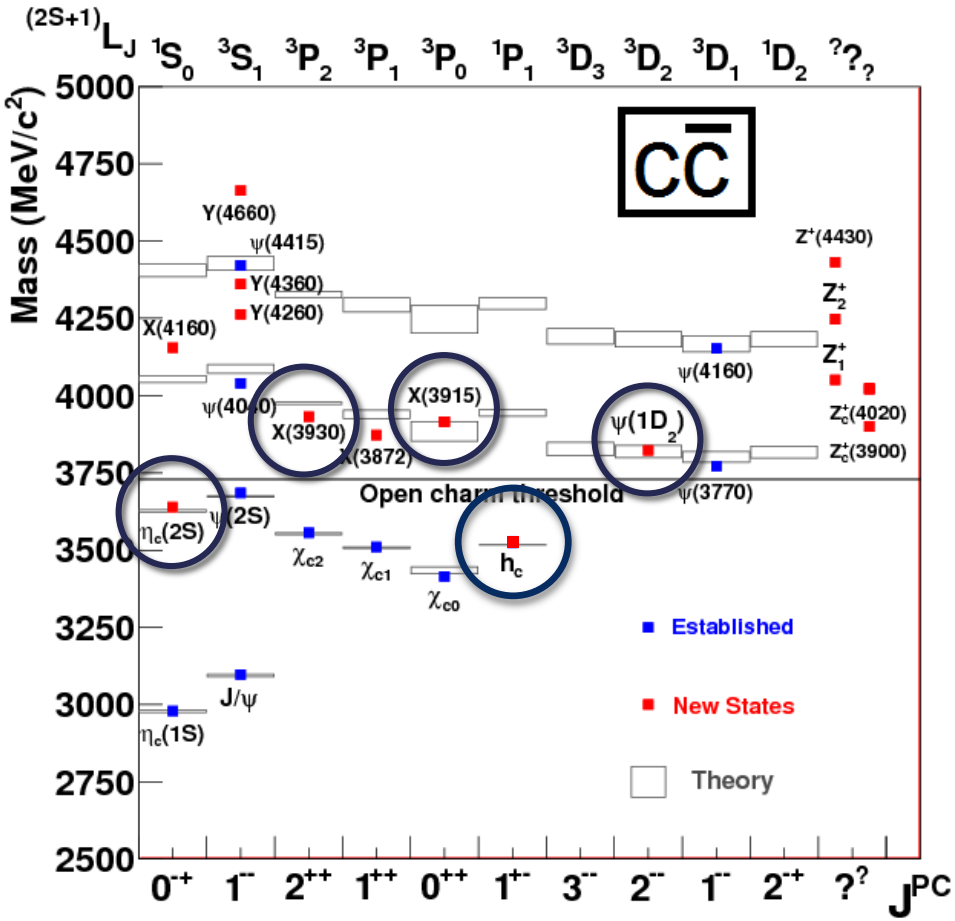


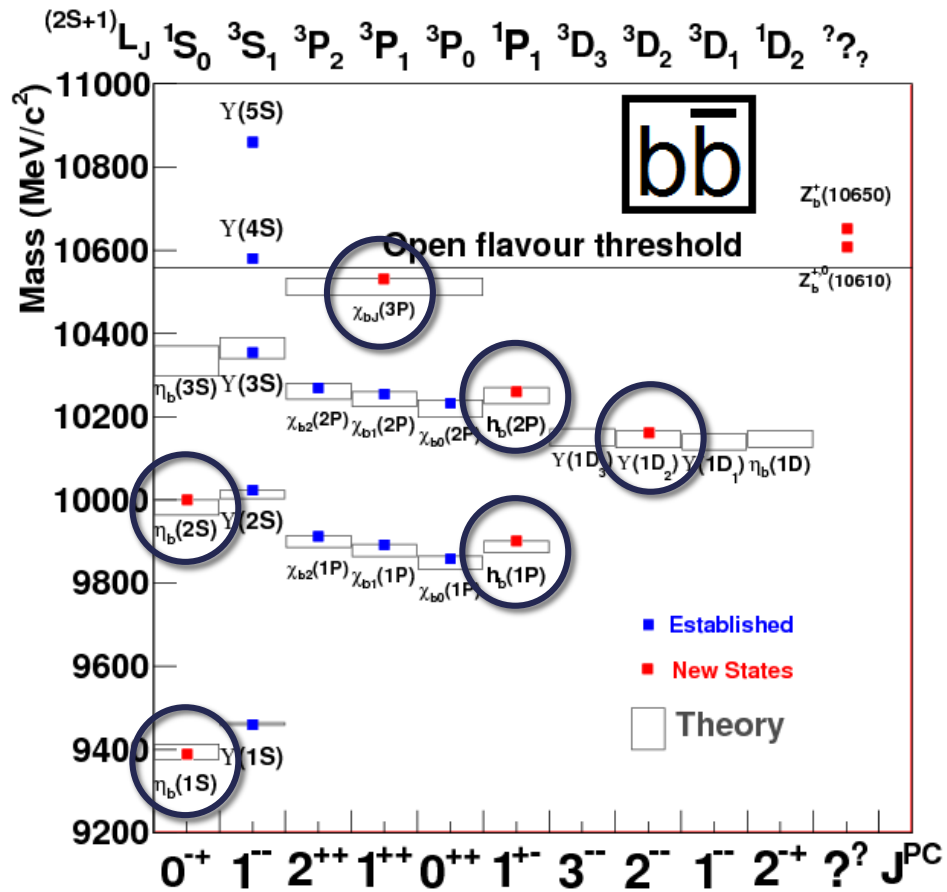
Since 1999…

If I could remember the names of all these particles, I'd be a botanist.

E. Fermi (quoted in Hyperspace, M. Kaku)

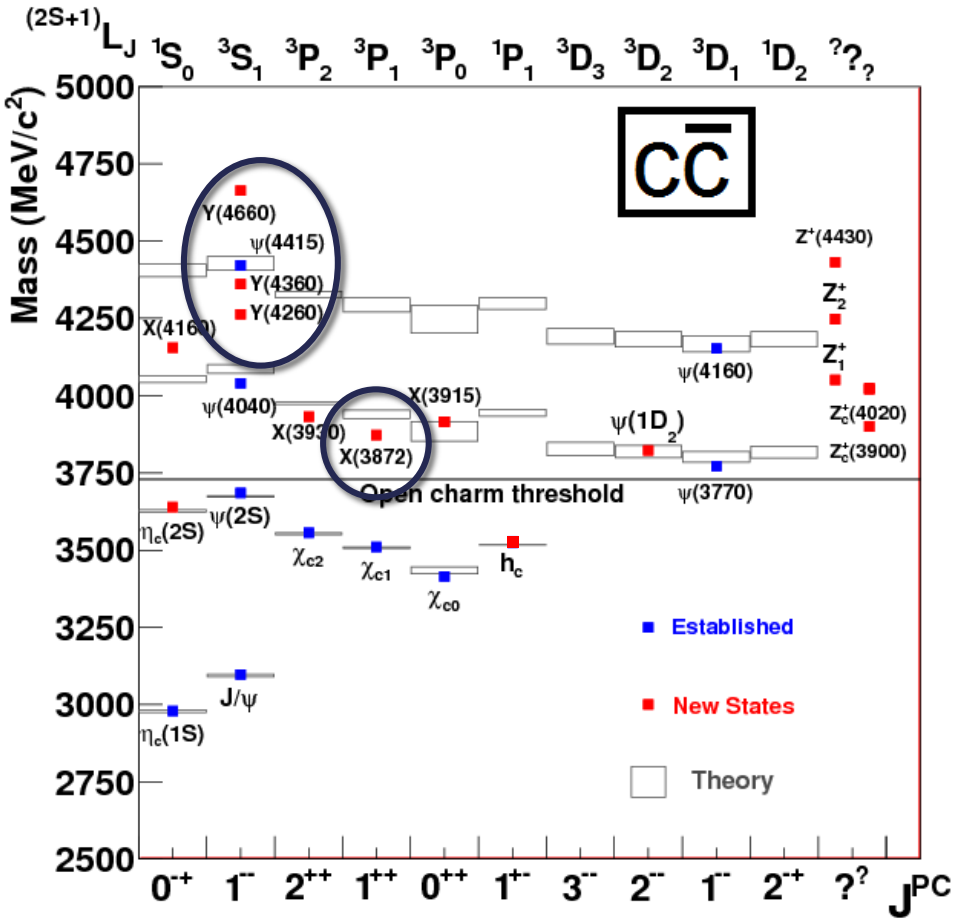
Quarkonium Spectroscopy: What we have learned

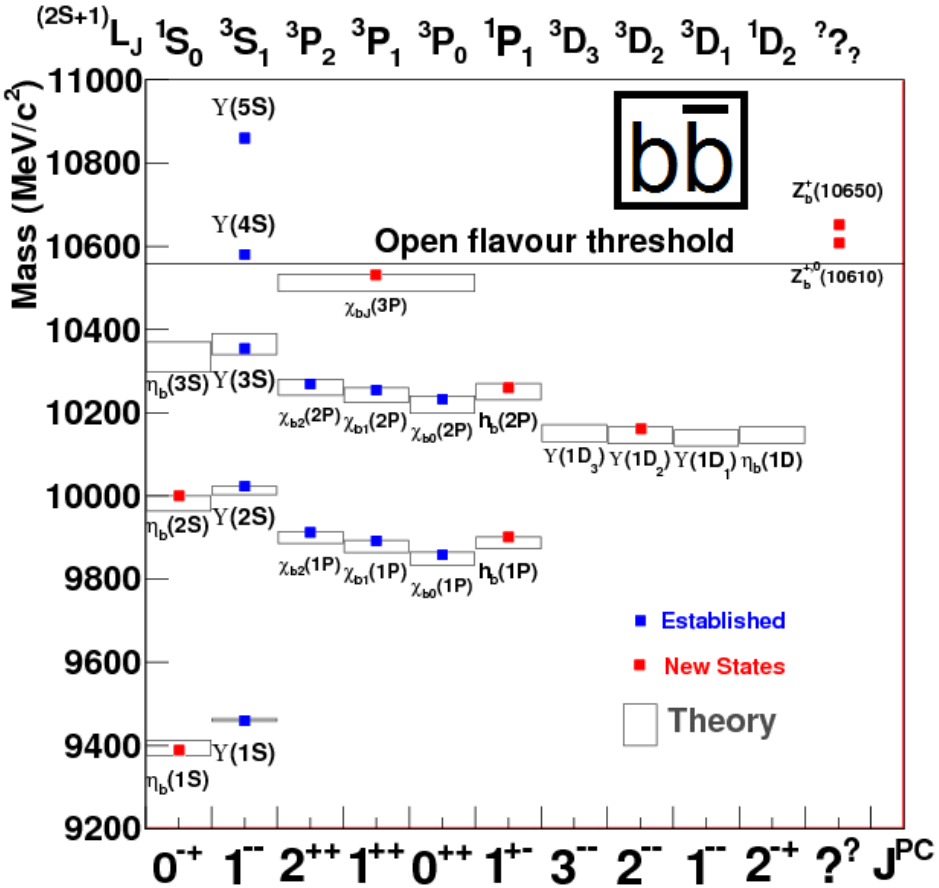




- **First discoveries of long-predicted conventional quarkonia**

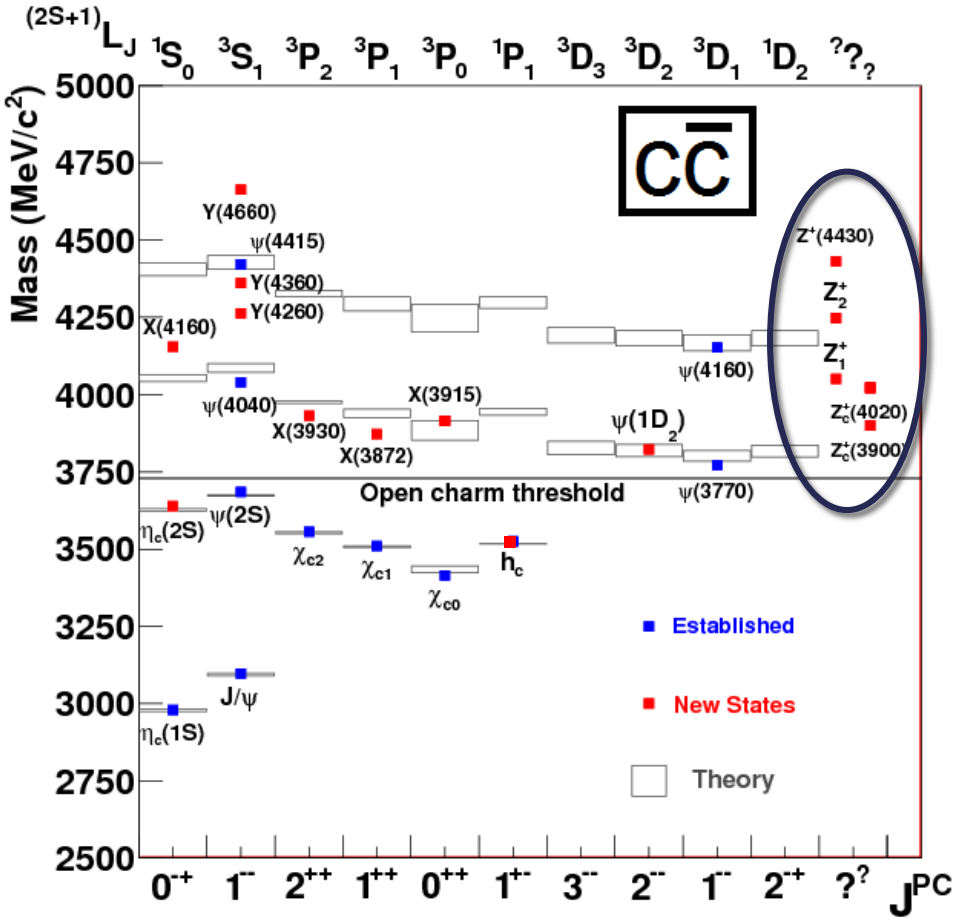
Quarkonium Spectroscopy: What we have learned

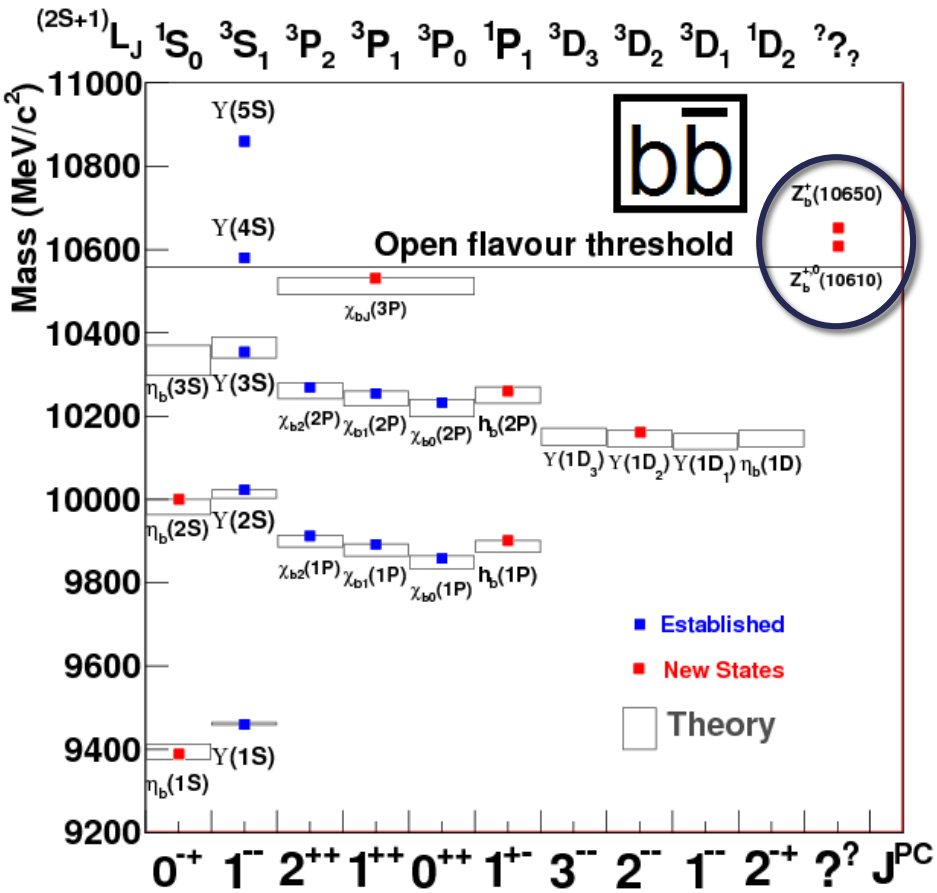




- First discoveries of long-predicted conventional quarkonia
- Many discoveries are difficult to explain by quarkonium model

Quarkonium Spectroscopy: What we have learned



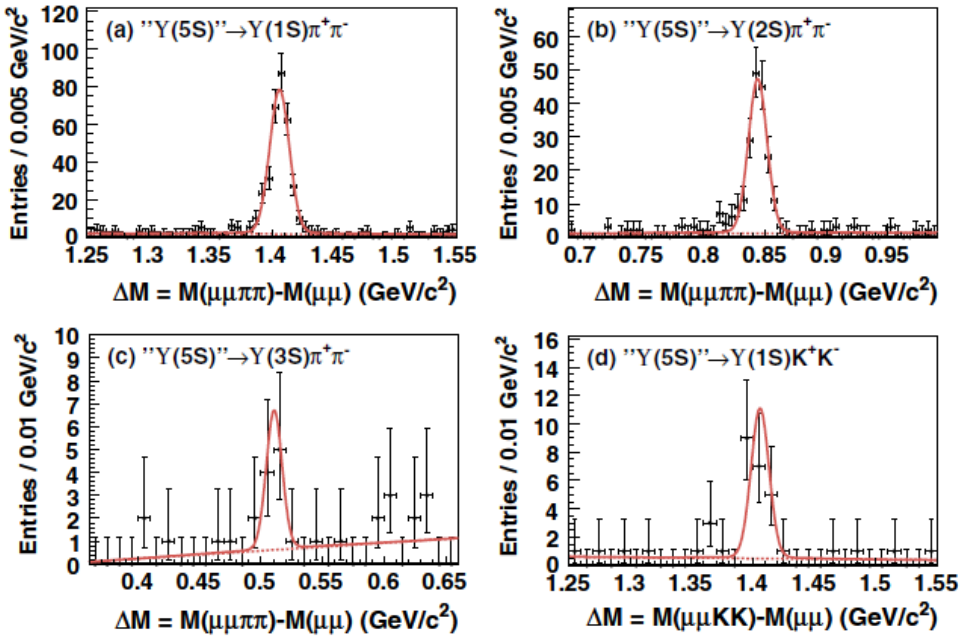


- First discoveries of long-predicted conventional quarkonia
- Many discoveries are difficult to explain by quarkonium model
- Several discoveries are simply impossible to explain by quarkonium model

A Transition in Heavy Quarkonium Spectroscopy

- The first twenty years or so:
  - States principally discovered and studied through radiative decays
  - A few hadronic transitions known: ππ, η
- The most recent decade: the rise of these very hadronic transitions
  - As a subject of study themselves and, surprisingly,
  - As a prolific production mechanism for lower quarkonium states, both known and not yet known

2008: Anomalously Large ππ Transition Rates



	Γ (MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

10^2

Totally unexpected rates prompts much speculation about something unusual about the Υ(5S) or perhaps the existence of some unconventional state nearby.

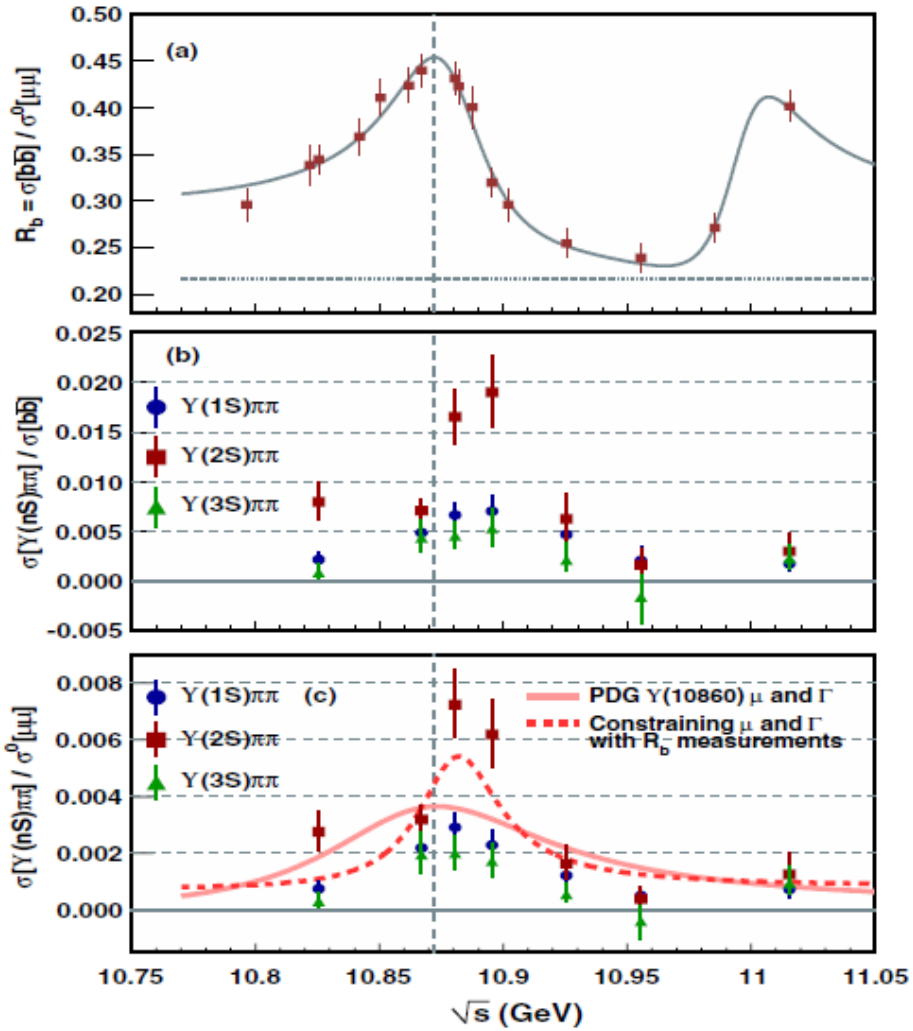
PRL 100, 112001 (2008)

Scan of ϒ(5S) region to study these anomalies

- A discrepancy observed between the peak of cross sections for bb vs ϒ ππ

R_b: $M = 10879 \pm 3\ MeV$
$R_{\Upsilon\pi\pi}$: $M = 10888 \pm 3\ MeV$

- Only 2σ difference, but led to suggestions of a Y_b analogous to the Y(4260) in the charmonium region

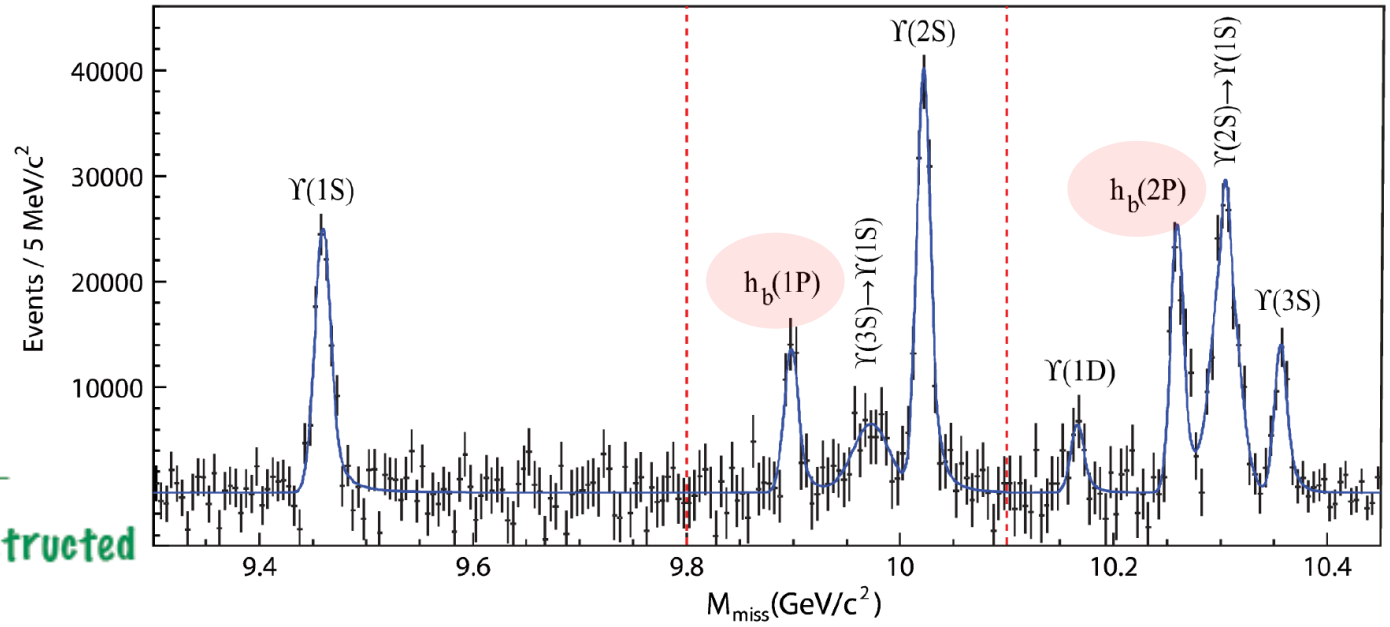


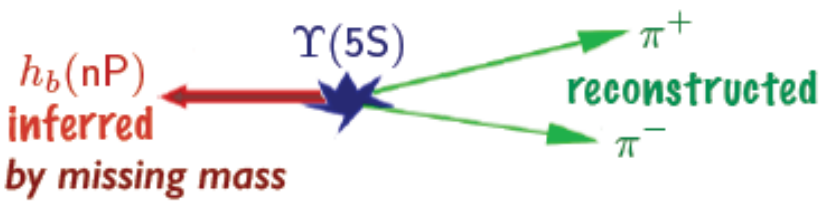
These anomalies motivated a much increased data sample in the ϒ(10860) region (121.4 fb^{-1} plus scan data)

PRD 82, 091106 (2010)

Discovery of $h_b(nP)$

Motivated by CLEO's result of observing h_c in dipion transitions from above open flavor threshold...





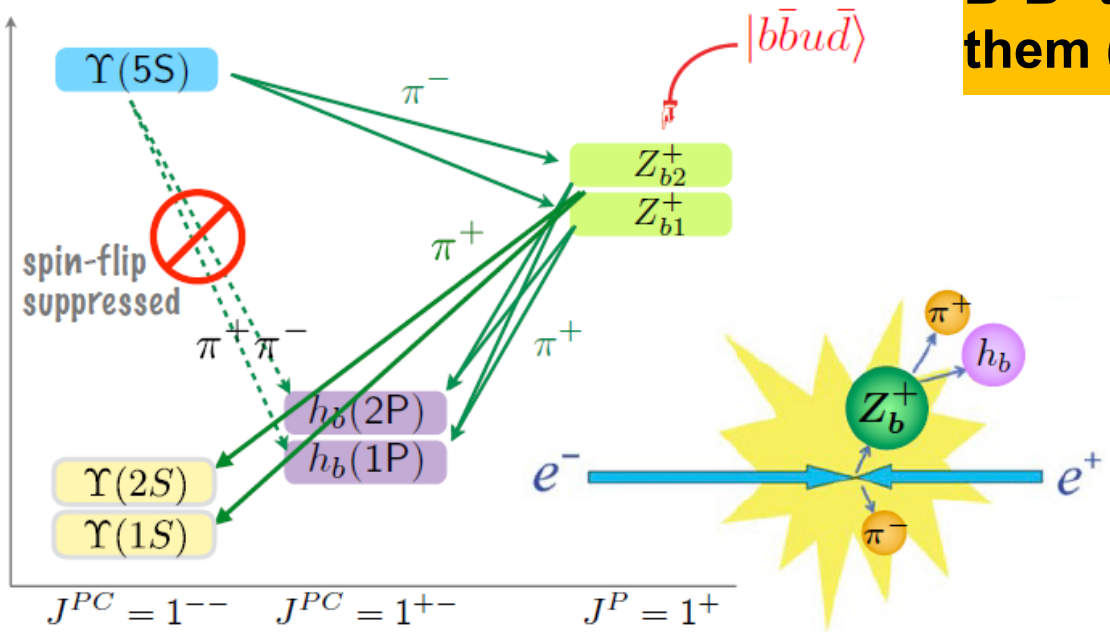
$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-]} = \begin{cases} 0.46 \pm 0.08 \pm {}^{0.07}_{0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08 \pm {}^{0.22}_{0.17} & \text{for } h_b(2P) \end{cases}$$

not suppressed as $\sim (\Lambda_{QCD}/m_b)^2$??

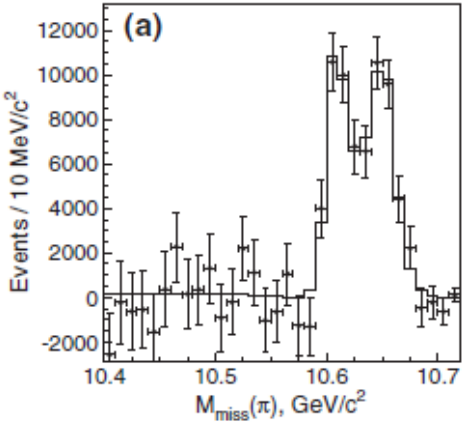
PRL 107, 041803 (2011)

Z_b intermediate states

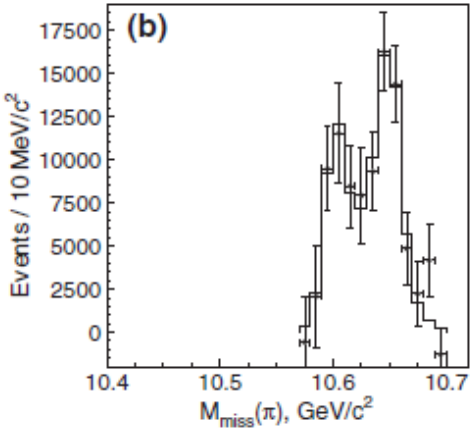
Min. 4-quark content (inferred from mass and charge). Masses very near BB* and B*B* thresholds! Suggests relationship to them (Molecules?)



$h_b(1P)\pi\pi$



$h_b(2P)\pi\pi$



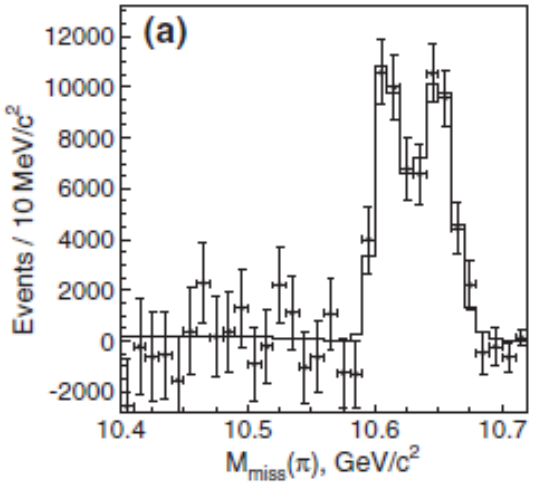
$$\langle M_1 \rangle = 10607.2 \pm 2.0 \text{ MeV}$$
$$\langle \Gamma_1 \rangle = 18.4 \pm 2.4 \text{ MeV}$$

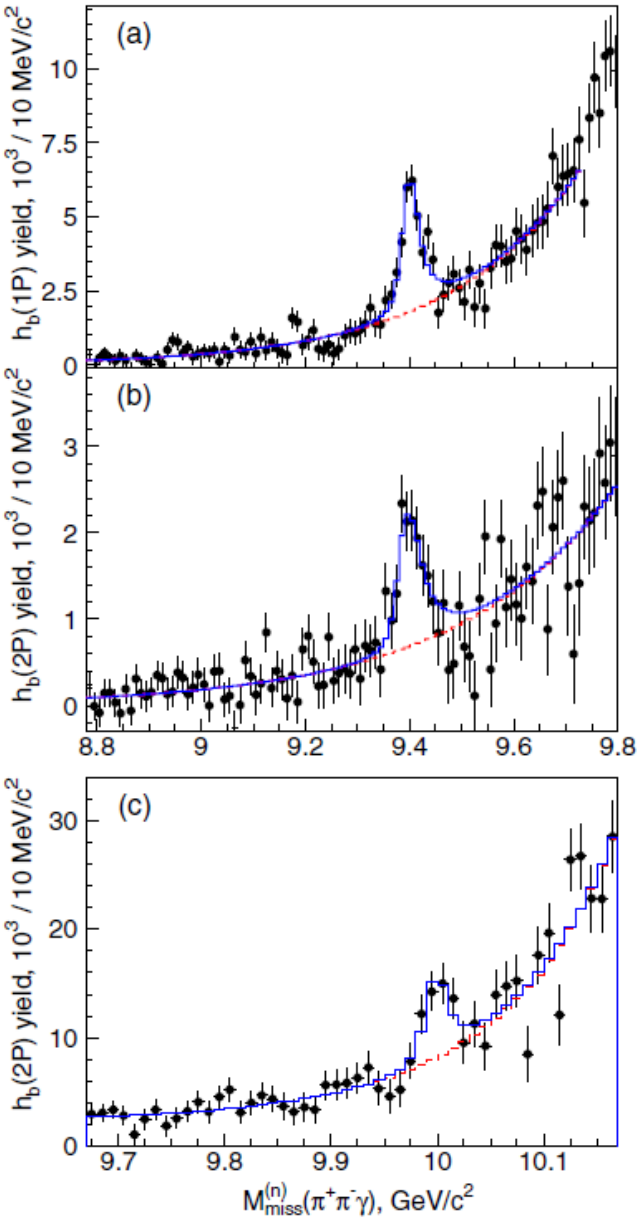
$$\langle M_2 \rangle = 10652.2 \pm 1.5 \text{ MeV}$$
$$\langle \Gamma_2 \rangle = 11.5 \pm 2.2 \text{ MeV}$$

PRL 109, 122001 (2012)

Z_b intermediate states help select h_b production

Cleaner selection of h_b enables study of their radiative decays





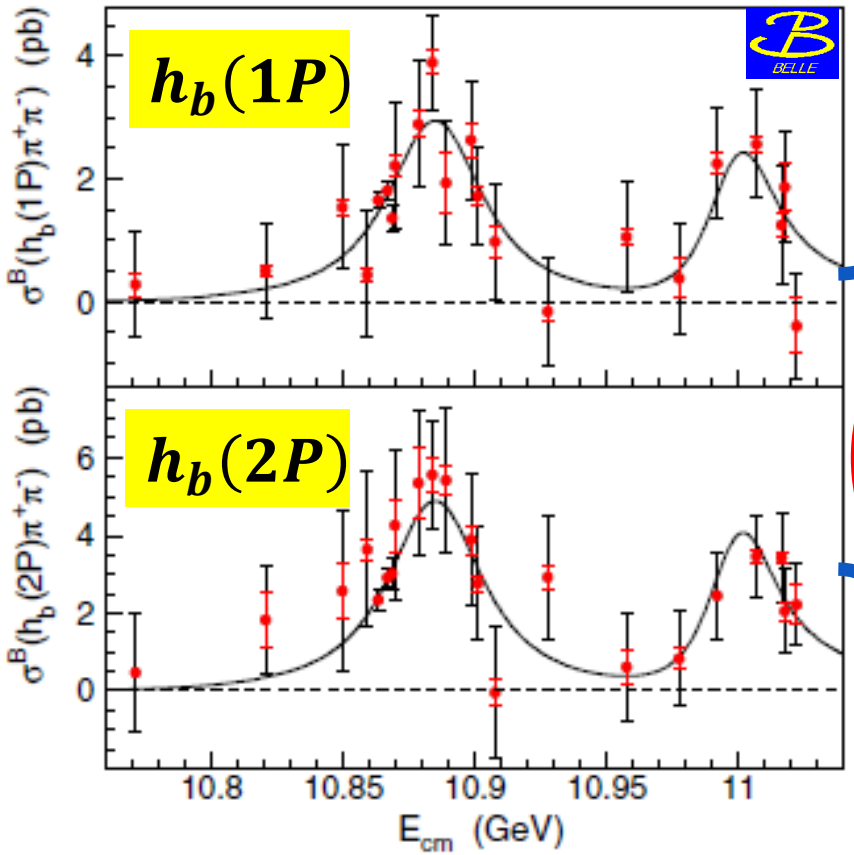
$$\mathcal{B}[h_b(1P) \to \eta_b(1S)\gamma] = (49.2 \pm 5.7^{+5.6}_{-3.3})\%$$

$$\mathcal{B}[h_b(2P) \to \eta_b(1S)\gamma] = (22.3 \pm 3.8^{+3.1}_{-3.3})\%$$

$$\mathcal{B}[h_b(2P) \to \eta_b(2S)\gamma] = (47.5 \pm 10.5^{+6.8}_{-7.7})\%$$

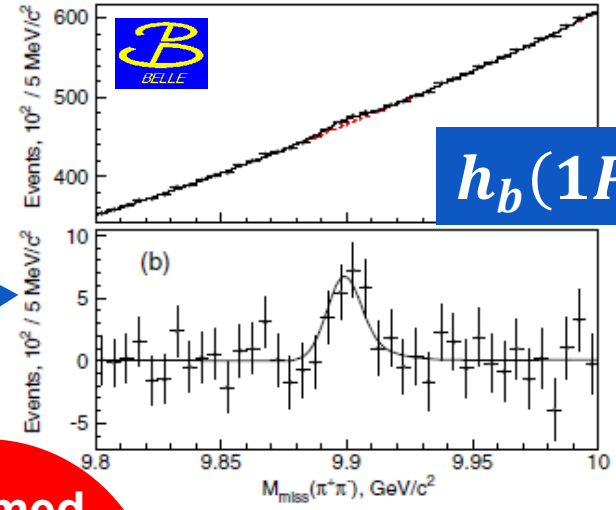
PRL 109, 232002 (2012)

$h_b(1P, 2P)$ at $\Upsilon(6S)$



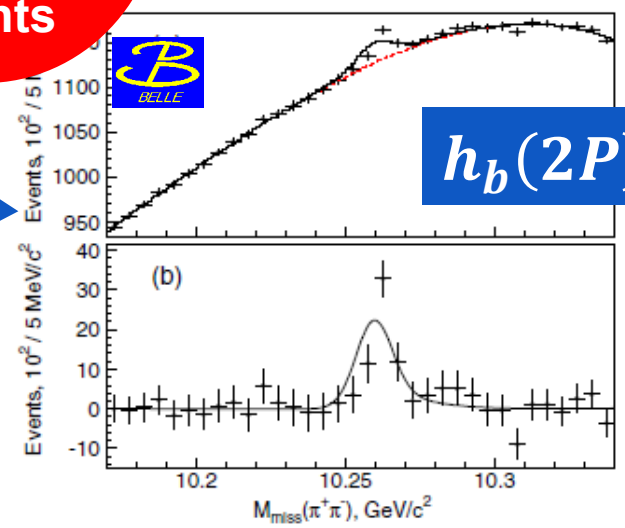
$h_b(nP)$ yield vs. E_{cm}

Summed over the $\Upsilon(6S)$ peak points



$h_b(1P)$ yield

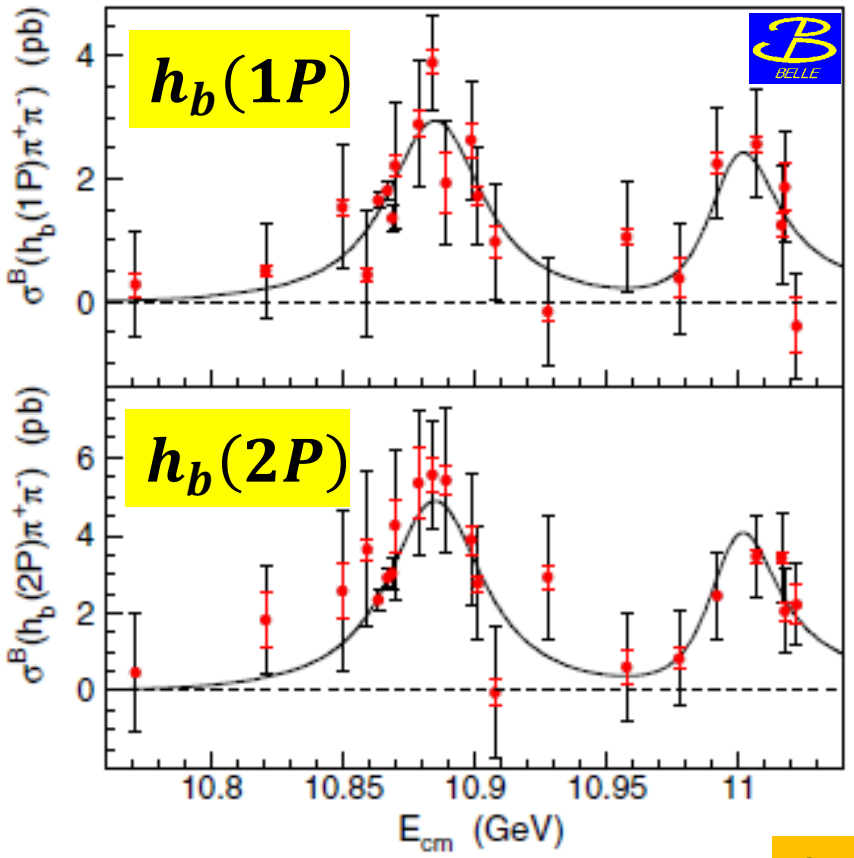
in $\pi\pi$ missing mass



$h_b(2P)$ yield

PRL 117, 142001 (2016)

Z_b at $\Upsilon(6S)$ too!

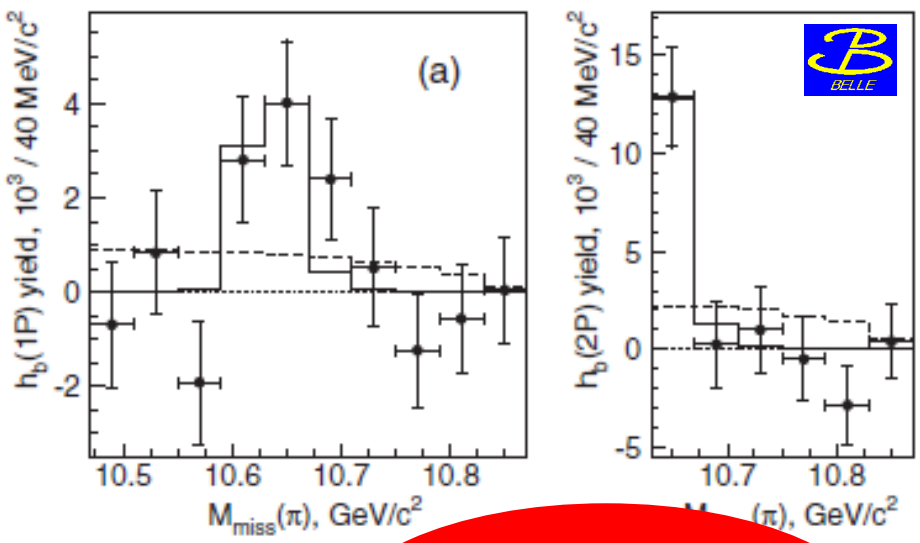


$h_b(nP)$ yield vs. E_{cm}

$h_b(1P)$ yield

$h_b(2P)$ yield

vs single π missing mass



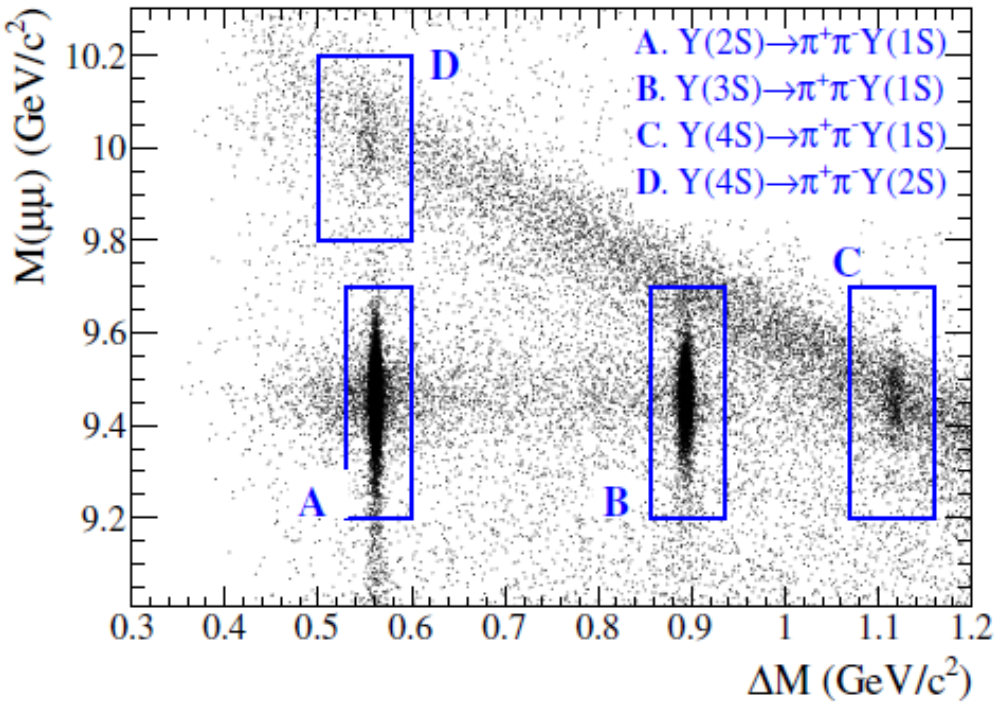
Summed over $\Upsilon(6S)$ peak points

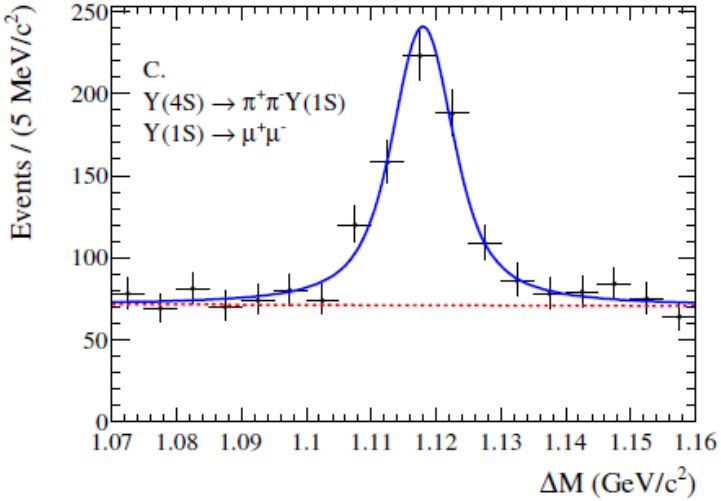
Consistent with dominance of Z_b but statistics insufficient to distinguish contributions from <u>one or both</u> states

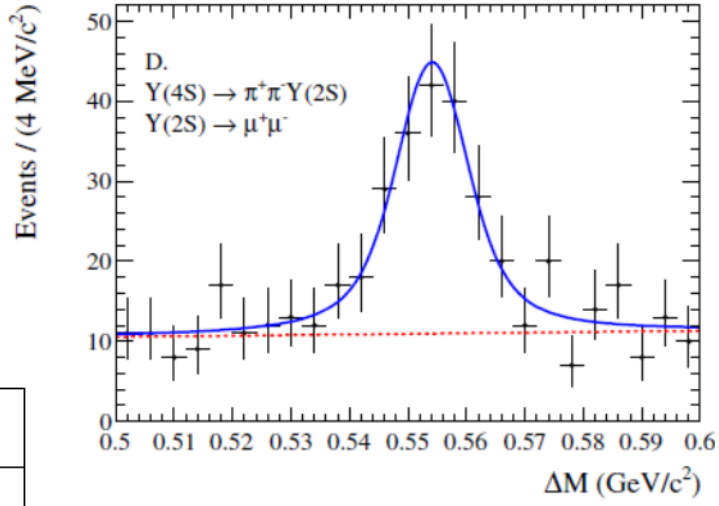
Phase space hypothesis excluded at 3.6σ and 4.5σ

PRL 117, 142001 (2016)

ππ transitions from ϒ(4S)





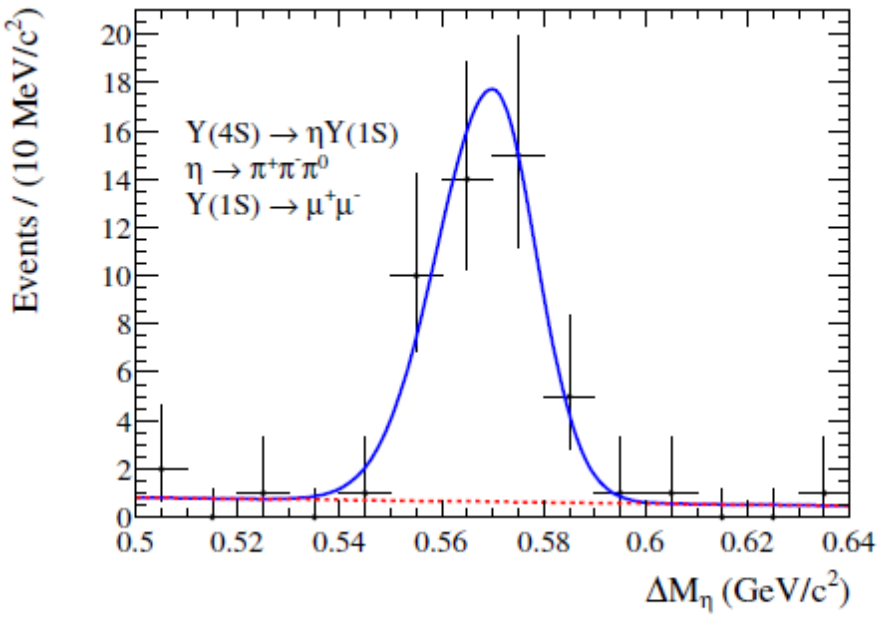


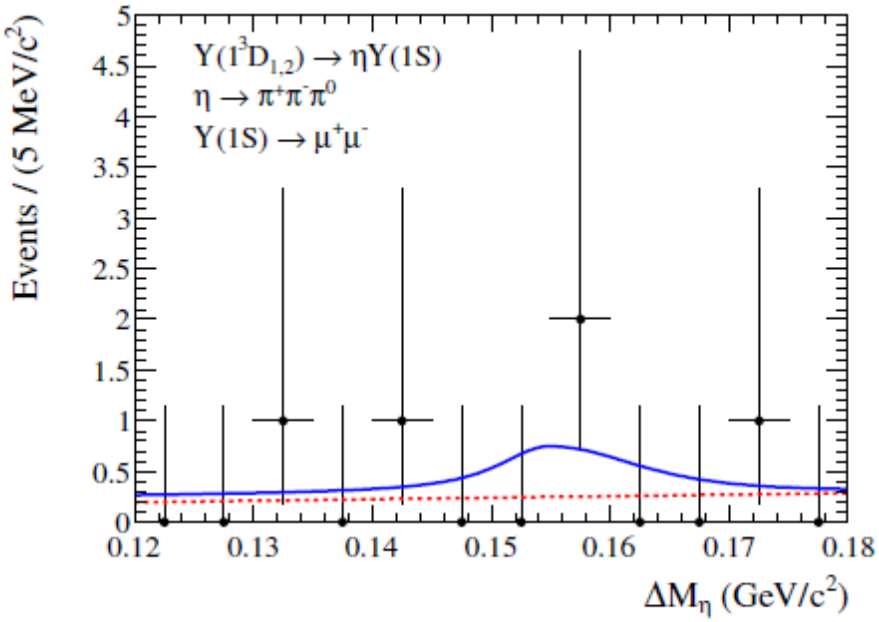
$$\Delta M = M(\pi\pi\mu\mu) - M(\mu\mu),$$

Decay	Events	$\mathcal{B}, 10^{-5}$	$\mathcal{B}_{\rm PDG}, 10^{-5}$
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$	1095 ± 74	$8.2 \pm 0.5 \pm 0.4$	8.1 ± 0.6
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$	821 ± 107	$7.9 \pm 1.0 \pm 0.4$	8.6 ± 1.3

PRD 96, 052005 (2017)

η Transitions from ϒ(4S)



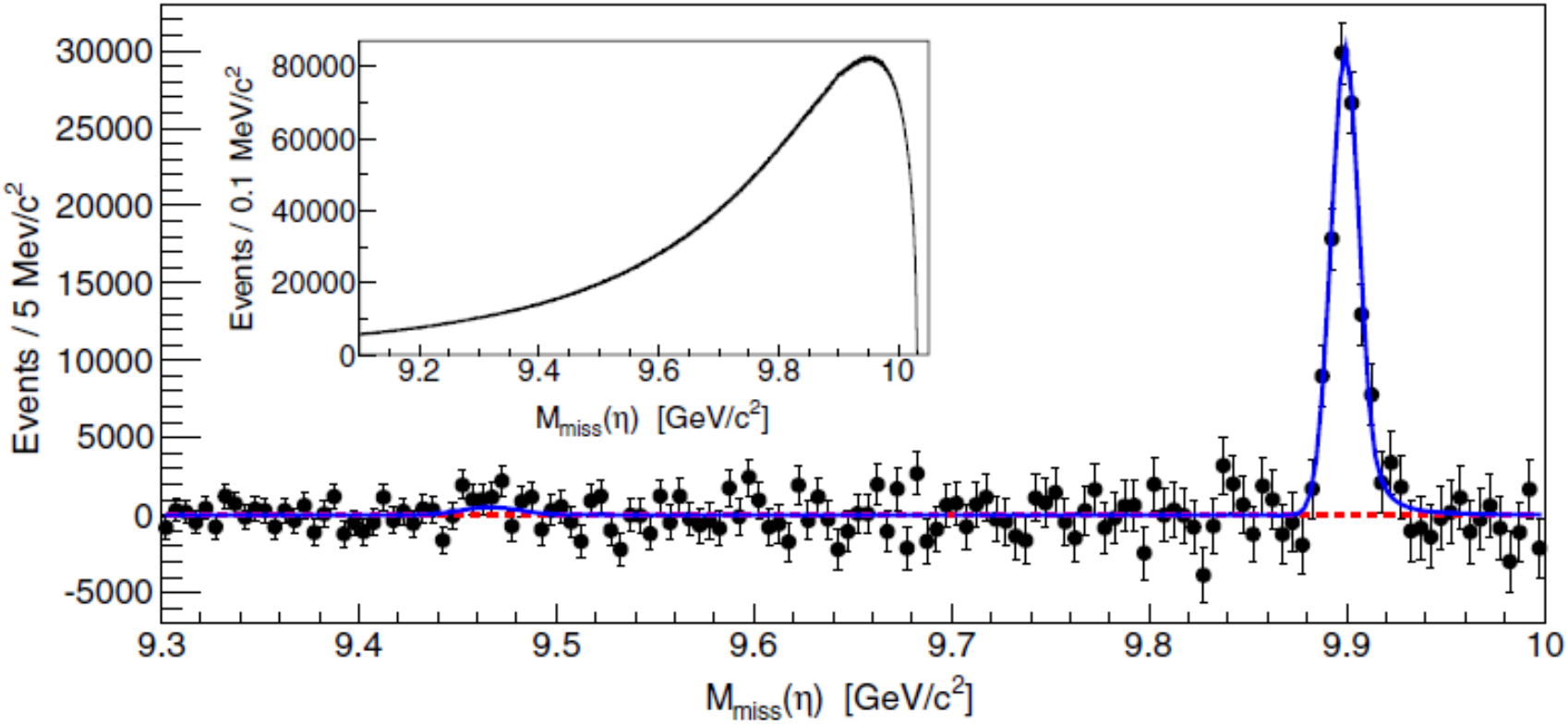


Decay	Events	$\mathcal{B}$, 10^{-4}	$\mathcal{B}_{\rm PDG}$, 10^{-4}
$\Upsilon(4S) \to \eta\Upsilon(1S)$	49 ± 7	$1.70 \pm 0.23 \pm 0.08$	1.96 ± 0.28
$\Upsilon(1^3D_{1,2}) \to \eta\Upsilon(1S)$	2.1 ± 3.0	< 0.23	–

Confirms previous result from BaBAR – what's going on here? The rate is double that of the ππ transition, whereas it should be highly suppressed

PRD 96, 052005 (2017)

$h_b(1P)$ produced in η transitions from ϒ(4S)



$\mathcal{B}[\Upsilon(4S) \to \eta h_b(1P)]$ $(2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$

This transition is the single largest non-BB branching fraction for ϒ(4S)! (and a factor 10 larger than ηϒ(1S))

PRL 115, 142001 (2015)

Bottomonium singlets produced in $\Upsilon(4S)$ decays

The large $h_b(1P)$ sample then enabled another measurement of $h_b(1P) \rightarrow \gamma\eta_b(1S)$

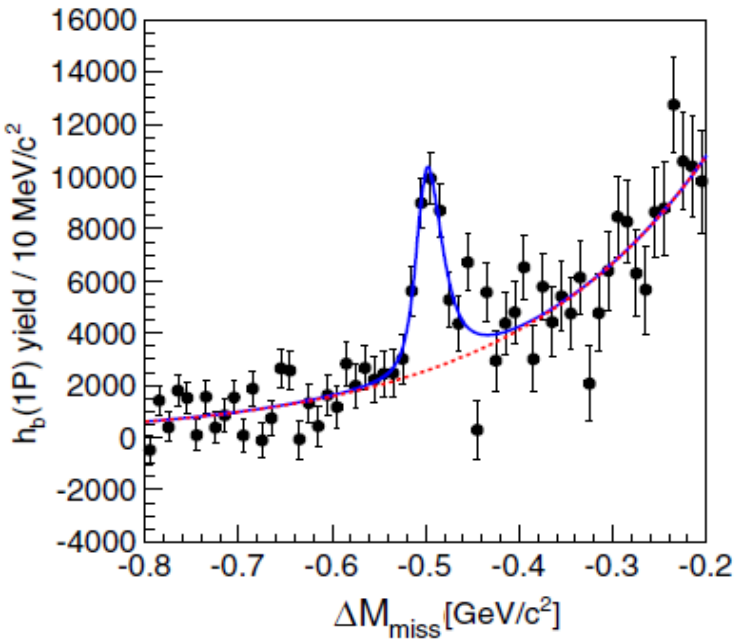


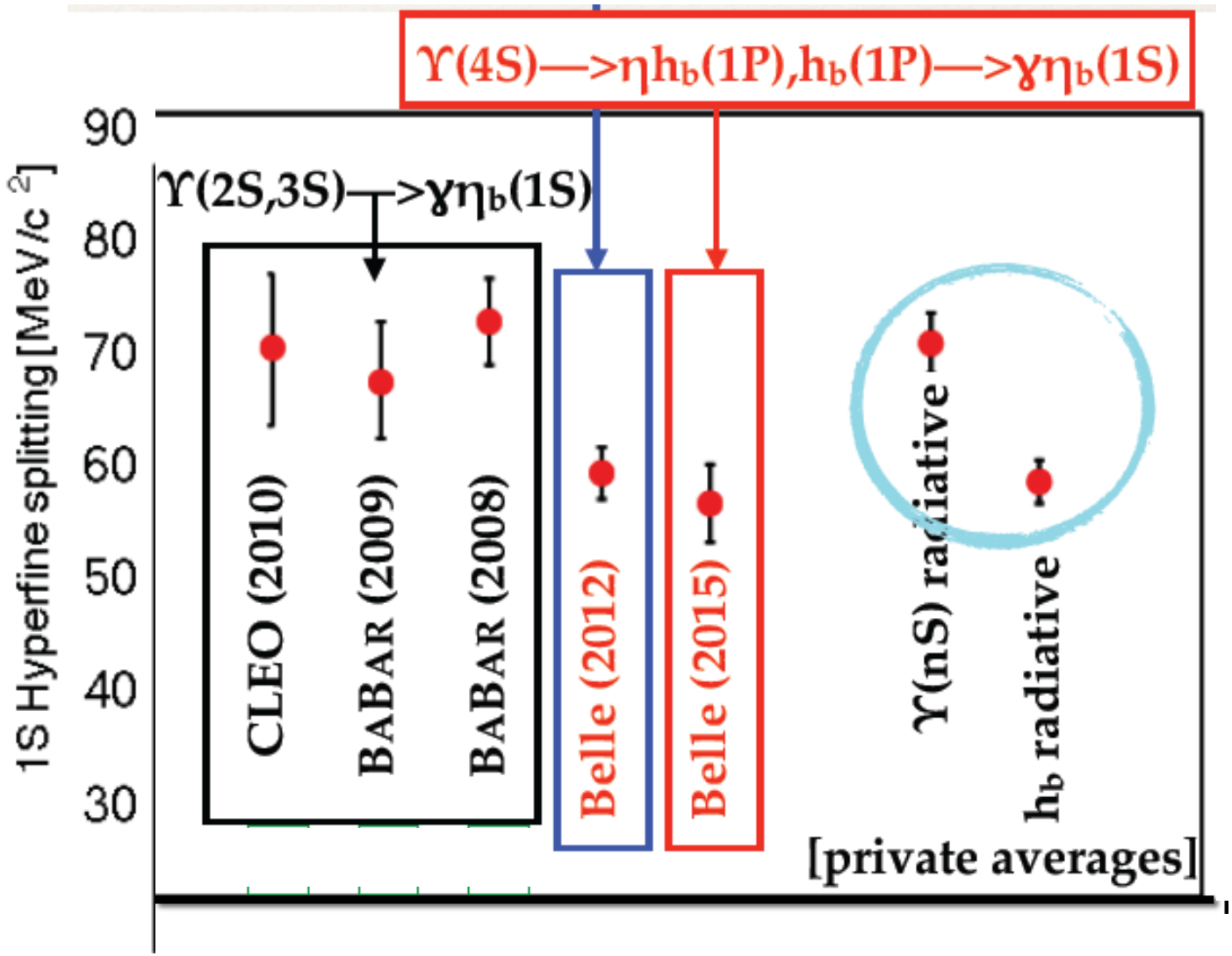
TABLE III. Summary of the results of the searches for $\Upsilon(4S) \rightarrow \eta h_b(1P)$ and $h_b(1P) \rightarrow \gamma\eta_b(1S)$.

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$/c^2$
$\Delta M_{\rm HF}(1S)$	$(+59.6 \pm 1.7 \pm 1.6)$ MeV$/c^2$
$\Delta M_{\rm HF}(1P)$	$(+0.6 \pm 0.4 \pm 1.0)$ MeV$/c^2$

η_b parameters: consistent with previous Belle results, but not consistent with BaBar, CLEO

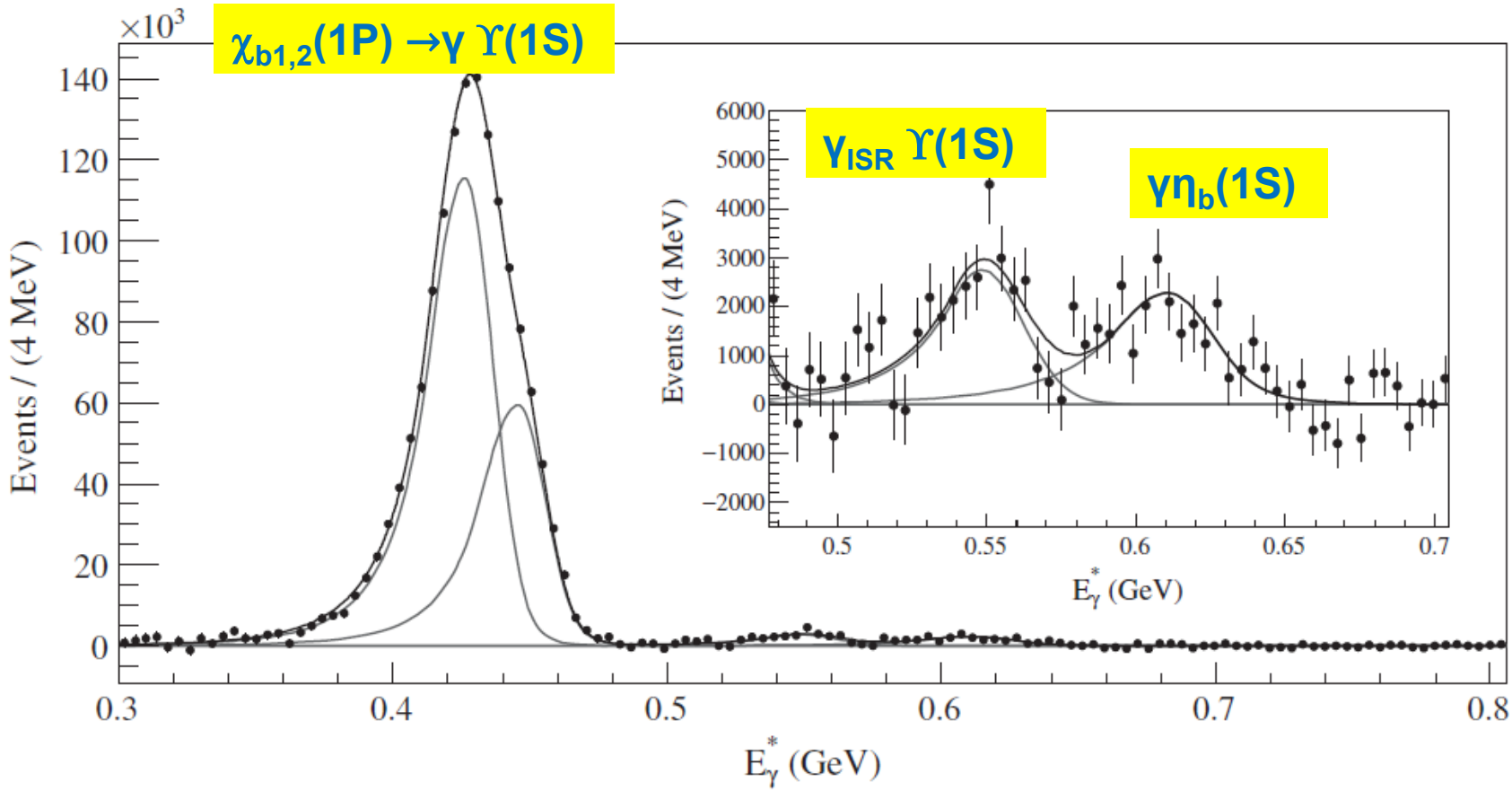
PRL 115, 142001 (2015)

1S Hyperfine Splitting



- A significant disagreement in $\eta_b(1S)$ mass between E1 and M1 production
- Reminiscent of the case of mass measurement disagreements for $\eta_c(1S)$

First observation of $\eta_b(1S)$ in $\Upsilon(2S)$ decay



Branching Fraction: $(6.1^{+0.6}_{-0.7}{}^{+0.9}_{-0.6})\times 10^4$

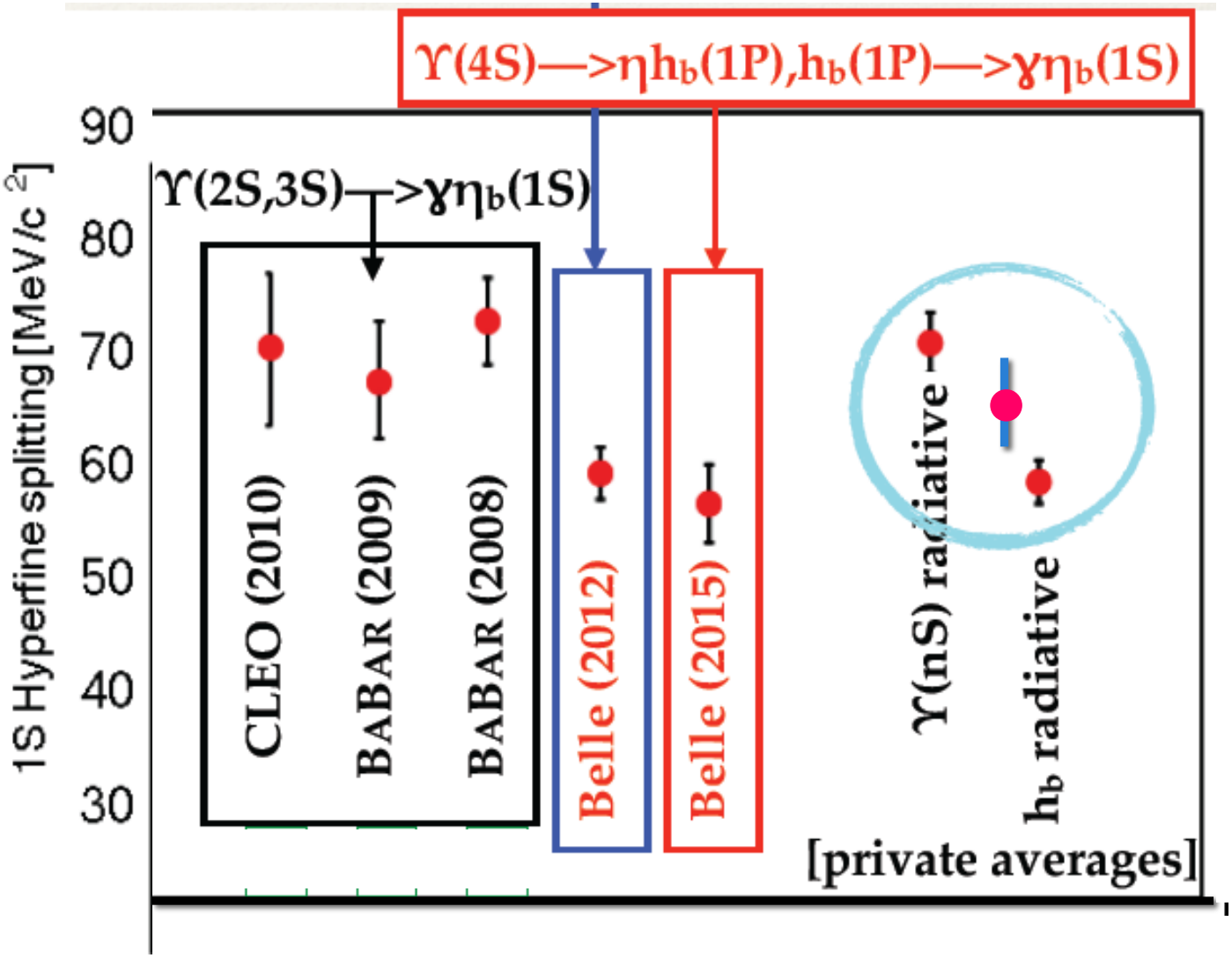
Mass: $9394.8^{+2.7}_{-3.1}{}^{+4.5}_{-2.7}$ MeV/c^2

Data sample of 158M $\Upsilon(2S)$

PRL 121, 232001 (2018)

Including the $\eta_b(1S)$ mass from $\Upsilon(2S)$ decays

1S Hyperfine Splitting



Smack dab in the middle, of course!

Lessens the tension a little… but …

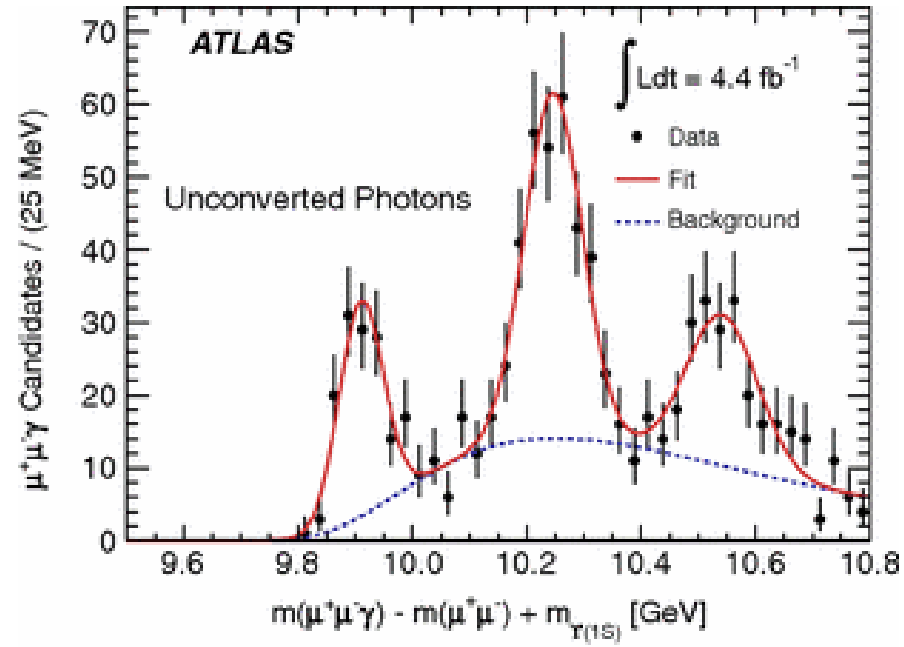
$\chi_{bJ}(3P)$ Discovery

Meanwhile, across the pond…in pp collisions at ATLAS, observing $\Upsilon(nS)$ in muon pairs and looking at $\gamma\Upsilon(nS)$ combinations, both with photons directly detected, and those in conversion

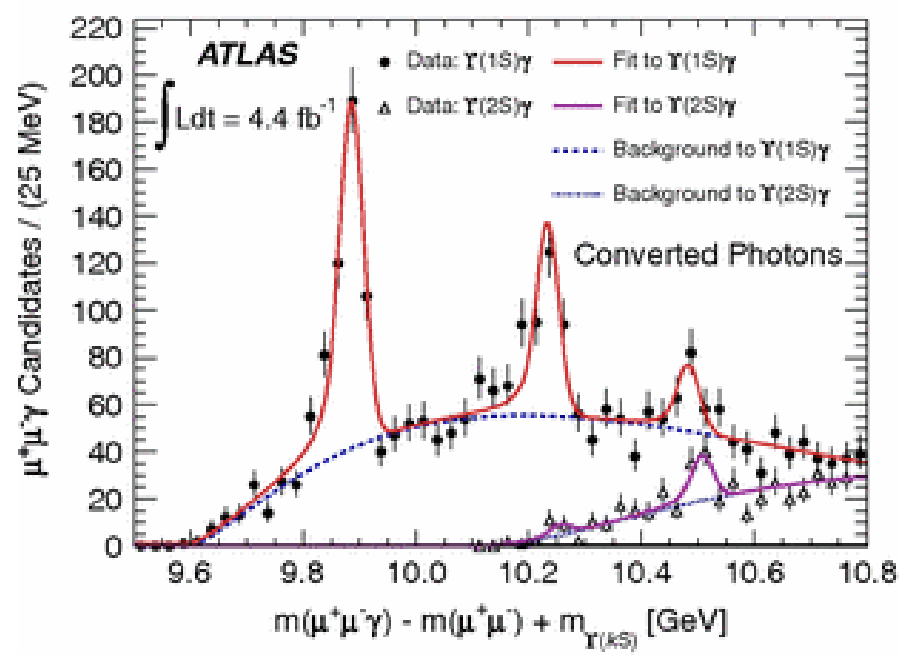
Clear observation of a third χ_{bJ} set of P-wave states

No resolution on members of the multiplet, but exciting news!

Mass: $10.530 \pm 0.005 \pm 0.009$ GeV/c^2



(a)

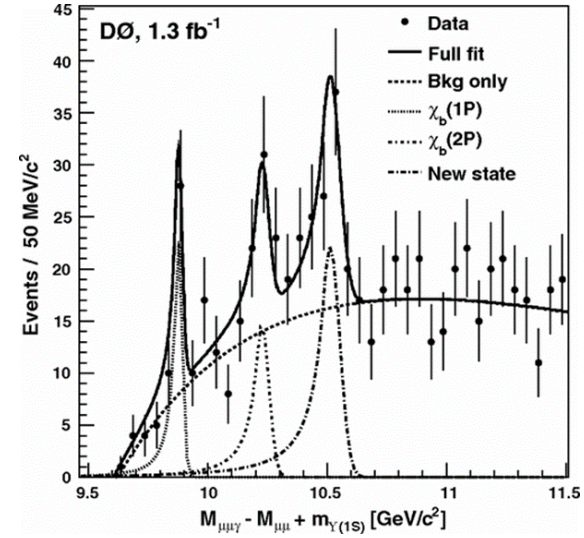


(b)

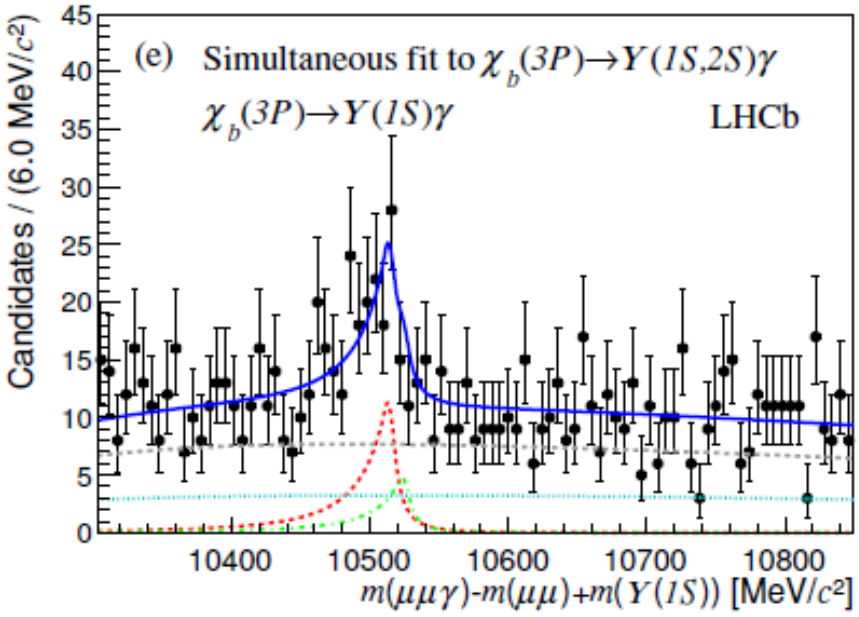
PRL 108, 152001 (2012)

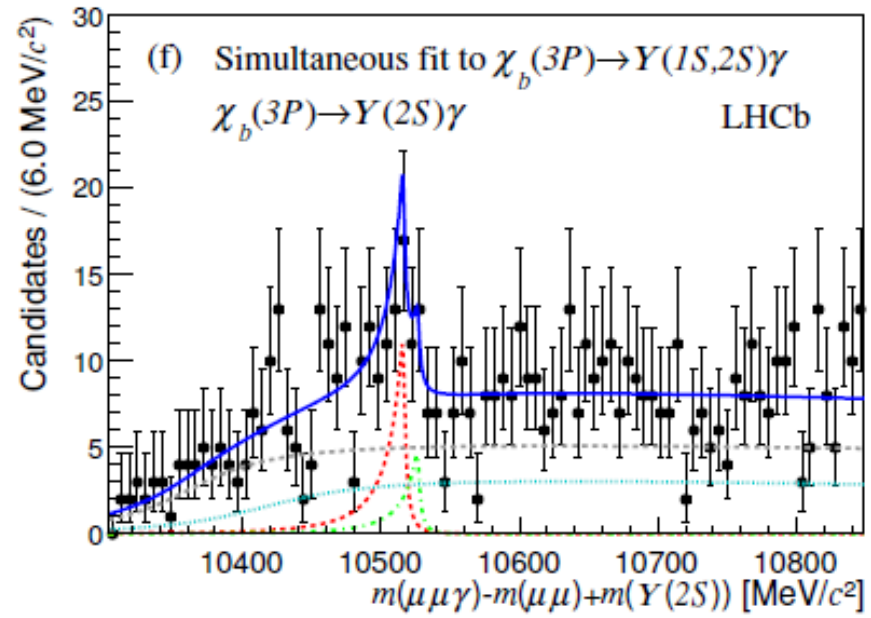
$\chi_{bJ}(3P)$ Confirmation (D0 + LHCb)

Rapid confirmation at D0 in ppbar collisions looking at $\gamma\Upsilon(nS)$ combinations



Mass: 10.551±0.014±0.017 GeV/c²



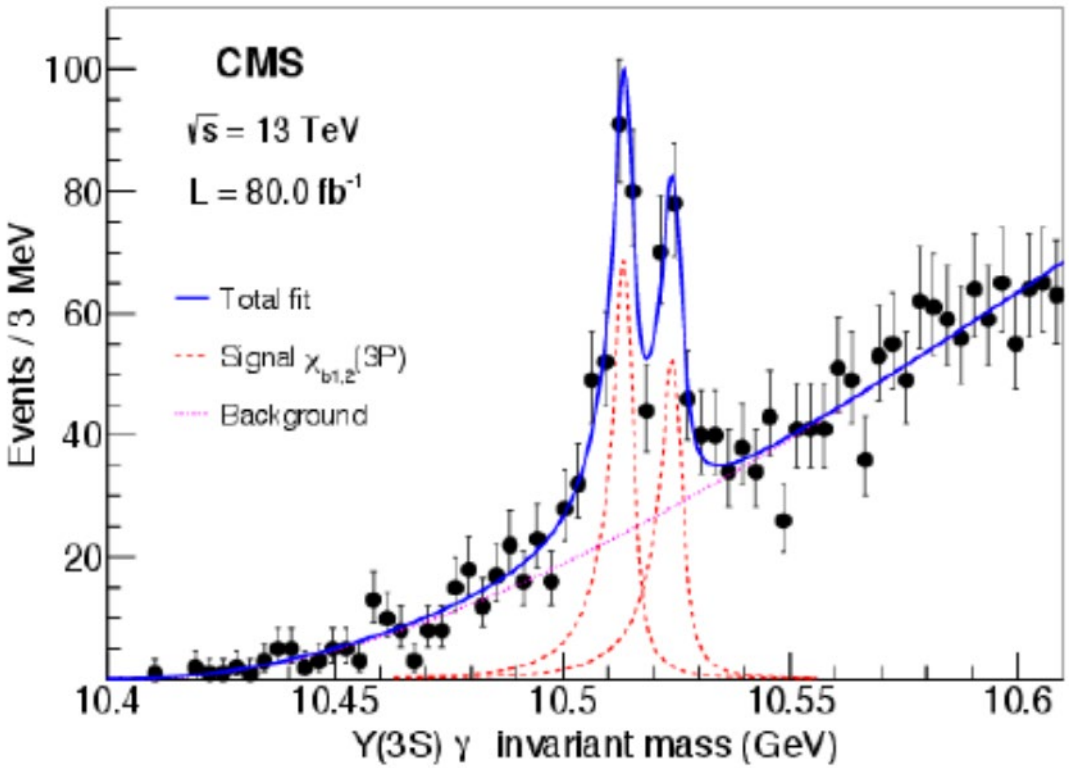


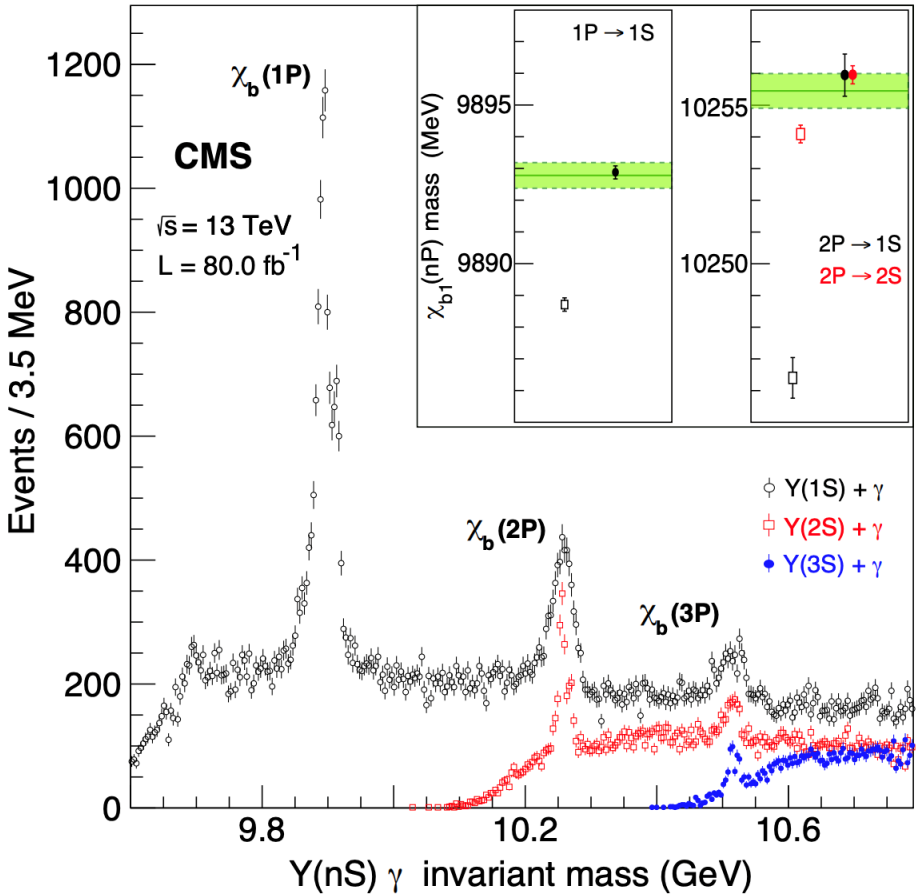
PRD 86, 031103(R) (2012)
JHEP10 (2014) 088

LHCb likewise:

$\chi_{b1}(3P)$ Mass: $10.5157^{+0.0024}_{-0.0039}{}^{+0.0015}_{-0.0021}$ GeV/c²

$\chi_{b1,2}(3P)$ Resolved





- **Using much more data at higher energy, CMS confirmed the results and split the states:**

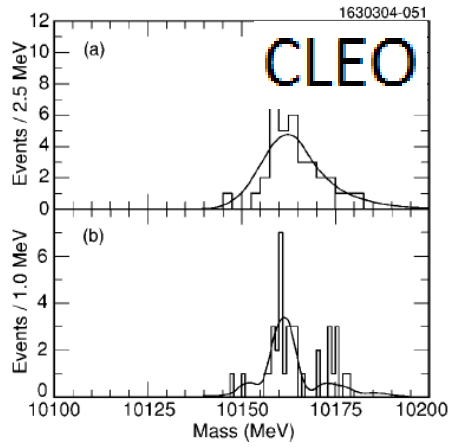
J=1 Mass = 10513.42 ± 0.41 ± 0.18 MeV/c²

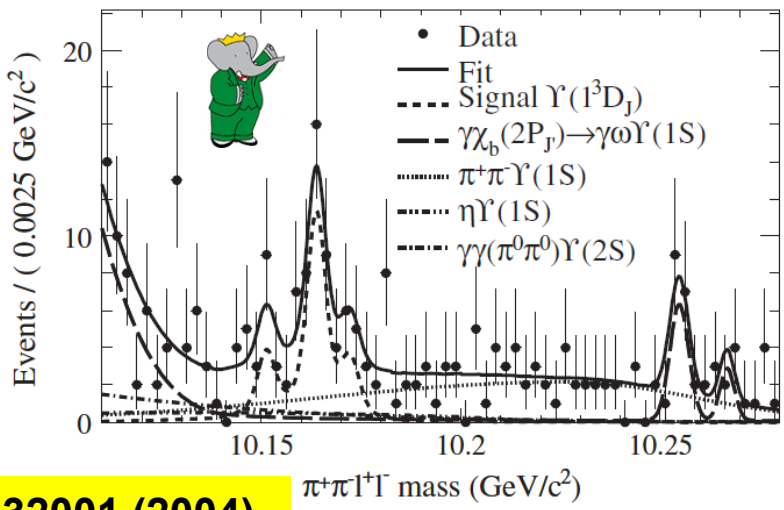
J=2 Mass = 10524.02 ± 0.57 ± 0.18 MeV/c²

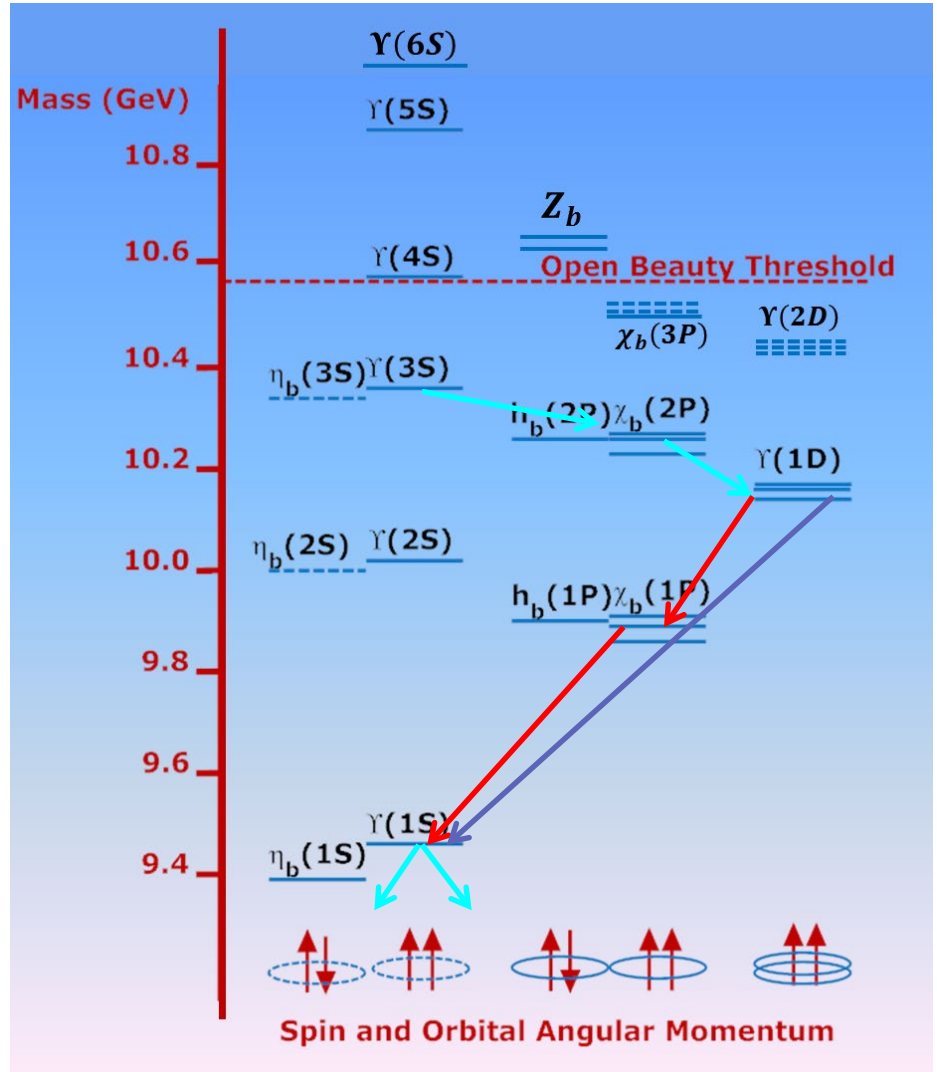
PRL 121, 092002 (2018)

The D-wave triplets $\Upsilon(1D)$ and $\Upsilon(2D)$

- $\Upsilon(1D)$ was originally observed by CLEO, and confirmed in a somewhat different cascade by BaBar. Neither experiment was able to resolve the 1D triplet into its three states



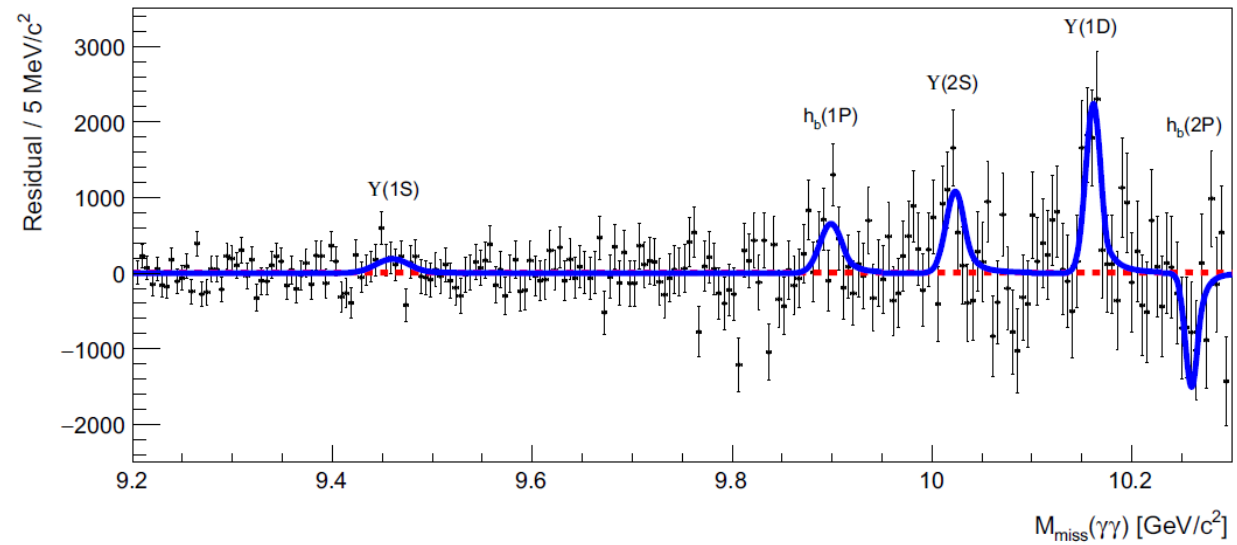




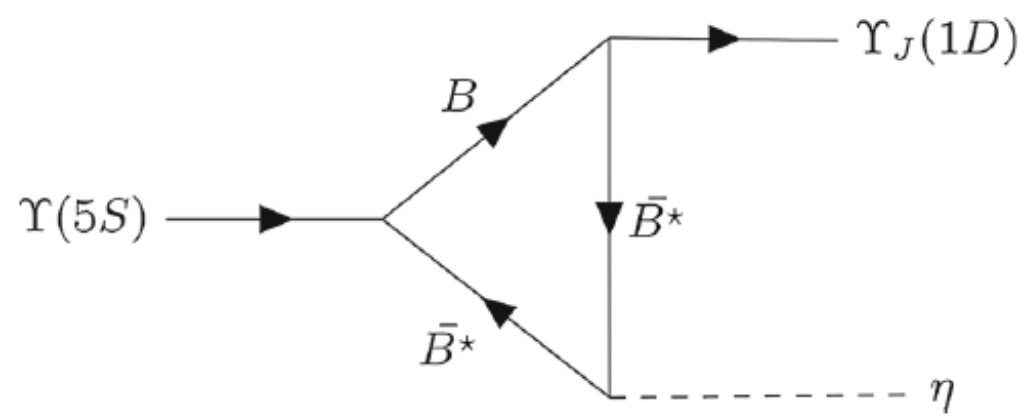
PRD 70, 032001 (2004)
PRD 82, 111102 (2011)

η transitions: from ϒ(5S)

- On their own, interesting
- Offer an additional vehicle toward higher statistics ϒ(1D) samples in future



Process	Σ	$N, 10^3$	Process	Σ	$N, 10^3$
$\eta\Upsilon(1S)$	1.5σ	1.7 ± 1.0	$\eta\Upsilon(2S)$	3.3σ	5.6 ± 1.6
$\eta\ h_b(1P)$	2.7σ	3.9 ± 1.5	$\eta\Upsilon(1D)$	5.3σ	9.3 ± 1.8



Eur. Phys. J. C78, 633 (2018)

KEY
CHANGE!!!!!

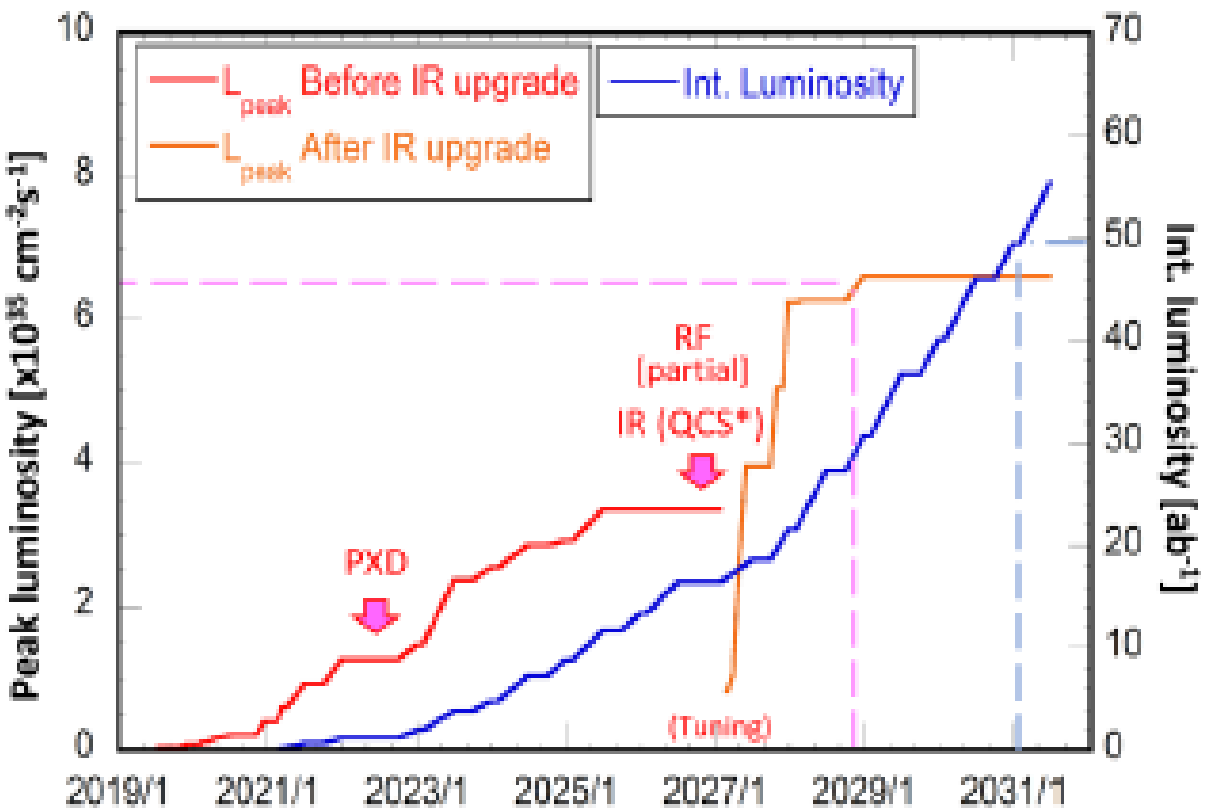
Bottomonium Spectroscopy in the 2020's

- Can expect new results from LHCb, CMS, ATLAS
  - Largely connected with things like polarization studies, reinvestigation of the 3P states with higher statistics, etc.
- Belle II offers significant possibilities for the investigation of the conventional bottomonium spectrum via
  - Production of states in decays of Υ(4S,5S,6S)
  - Production of 1^{--} states via ISR
  - Direct production of 1^{--} states on resonance Υ(3S), Υ(1D), Υ(2D)

The Bottomonium Menu @ Belle II

Current samples in fb^{-1} (millions of events) **Possible samples (same format)**

Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5	23%
BelleII			**300(1200)**	**5x10^4(5.4x10^4)**	**1000(300)**	**100+400(scan)**	**3.6%**



With data samples of order this size, a very rich program of studies in bottomonium is achievable

The Bottomonium Menu @ $\Upsilon(3S)$ [300 fb-1]

- A factor of 10 improvement over Babar – sample of 1.2B $\Upsilon(3S)$, allows these highlights (not exhaustive)
  - Observation of $\Upsilon(3S) \rightarrow \pi^0 h_b(1P) \rightarrow \pi^0 [\gamma\eta_b(1S)]$
  - Observation of $\Upsilon(3S) \rightarrow \pi^+ \pi^- h_b(1P)$
  - Observation of $\Upsilon(3S) \rightarrow \gamma\eta_b(2S)$
  - Observation of $\Upsilon(3S) \rightarrow \gamma\chi_{b0}(2P) \rightarrow \eta\eta_b(1S)$
    - Hadronic production mechanism for $\eta_b(1S)$
  - Observation of $\Upsilon(3S) \rightarrow \gamma\chi_{b2}(2P) \rightarrow \gamma\, h_b(1P)$
    - Hindered decay mode
  - Large sample of $\eta_b(1S)$ in the transition $\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$
    - New measurements of the mass and width
  - Studies of the 1D triplet:
    - Observation of $\Upsilon(3S) \rightarrow \gamma\,\gamma\, \Upsilon(1D) \rightarrow \gamma\,\gamma\, (\gamma\,\gamma, \pi\,\pi)\, \Upsilon(1S)$
    - Observation of $\Upsilon(3S) \rightarrow \gamma\,\gamma\, \Upsilon(1D) \rightarrow \gamma\,\gamma\, \eta\, \Upsilon(1S)$
  - Observation of $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P) \rightarrow \gamma\, \pi^+ \pi^- \chi_{bJ}(1P)$

The Bottomonium Menu @ $\Upsilon(4S)$ [50 ab^{-1}]

- Factor 50 improvement over Belle, corresponding to 54B $\Upsilon(4S)$, allows for these things among others
  - Huge sample of $\Upsilon(4S) \rightarrow \eta h_b(1P)$ (100M produced $h_b(1P)$)
    - Potential for observation of $h_b(1P)$ decay modes other than $\gamma\eta_b(1S)$
    - Producing a large sample of $\eta_b(1S)$ via $h_b(1P) \rightarrow \gamma\eta_b(1S)$, enabling best opportunity for $\eta_b(1S) \rightarrow \gamma\gamma$
  - Potential for confirming $\chi_{bJ}(3P)$
  - In addition, another ~1.5B ISR-produced $\Upsilon(3S)$ and ~1B ISR-produced $\Upsilon(2S)$

The Bottomonium Menu @ $\Upsilon(5S)$ [1 ab^{-1}]

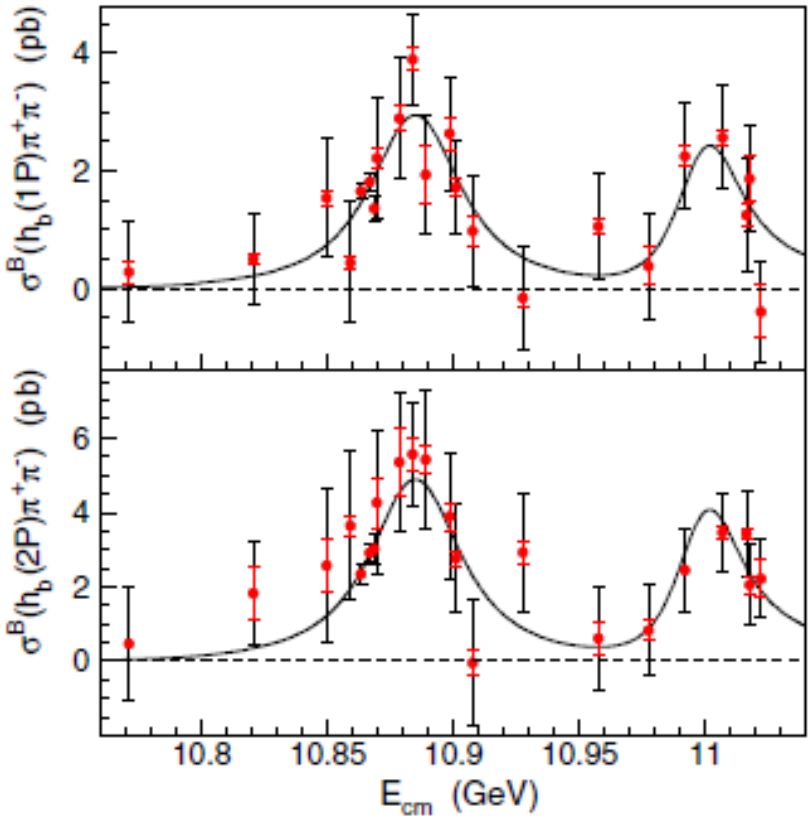
- A factor of 8 improvement over Belle, corresponding to 0.6B $\Upsilon(5S)$, allows for these and other highlights
  - Further elucidation of mix of Z_b states in transitions to lower bottomonia, as well as searches for other exotic intermediate states predicted by M Voloshin (B2TiP 2016)
  - Very large sample of $\Upsilon(5S) \rightarrow \pi\pi\, h_b(1P,2P)$ to add to the $h_b(1P)$ produced at $\Upsilon(4S)$ (2P of more interest)
    - Enables large sample of $\eta_b(1S,2S)$ via $h_b(2P) \rightarrow \gamma\eta_b(mS)$
    - Also potential for observing $\eta_b(2S) \rightarrow \gamma\Upsilon(1S)$

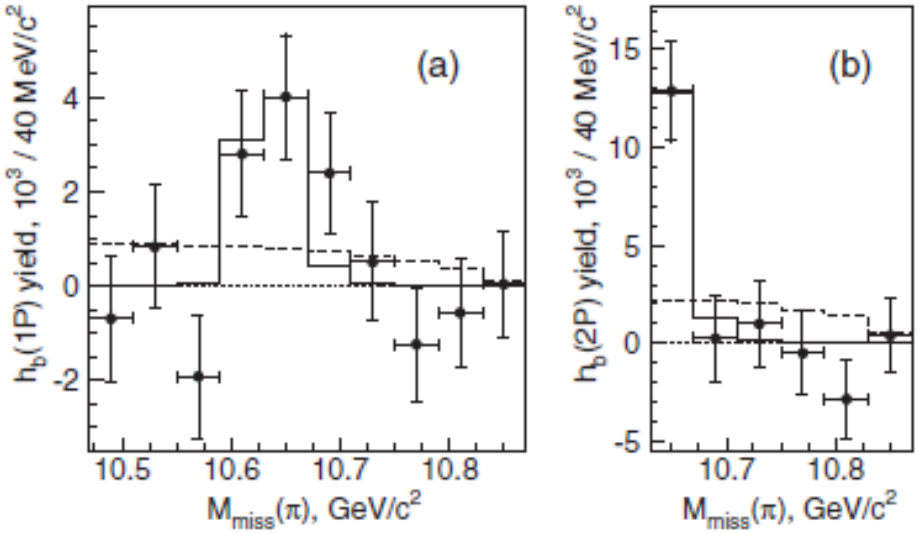
The Bottomonium Menu @ $\Upsilon(6S)$ [100 fb^{-1}]

- A factor of ~20 improvement over Belle, allows for these and other bottomonium highlights
  - Determine mixture of Z_b states produced at $\Upsilon(6S)$
    - Insights into the nature of the $\Upsilon(6S)$
  - $\Upsilon(6S) \rightarrow (\eta, \pi\pi) + h_b(nP)$
    - A second source of $h_b(2P)$
    - Discovery channel for $h_b(3P)$ and $\eta_b(3S)$?

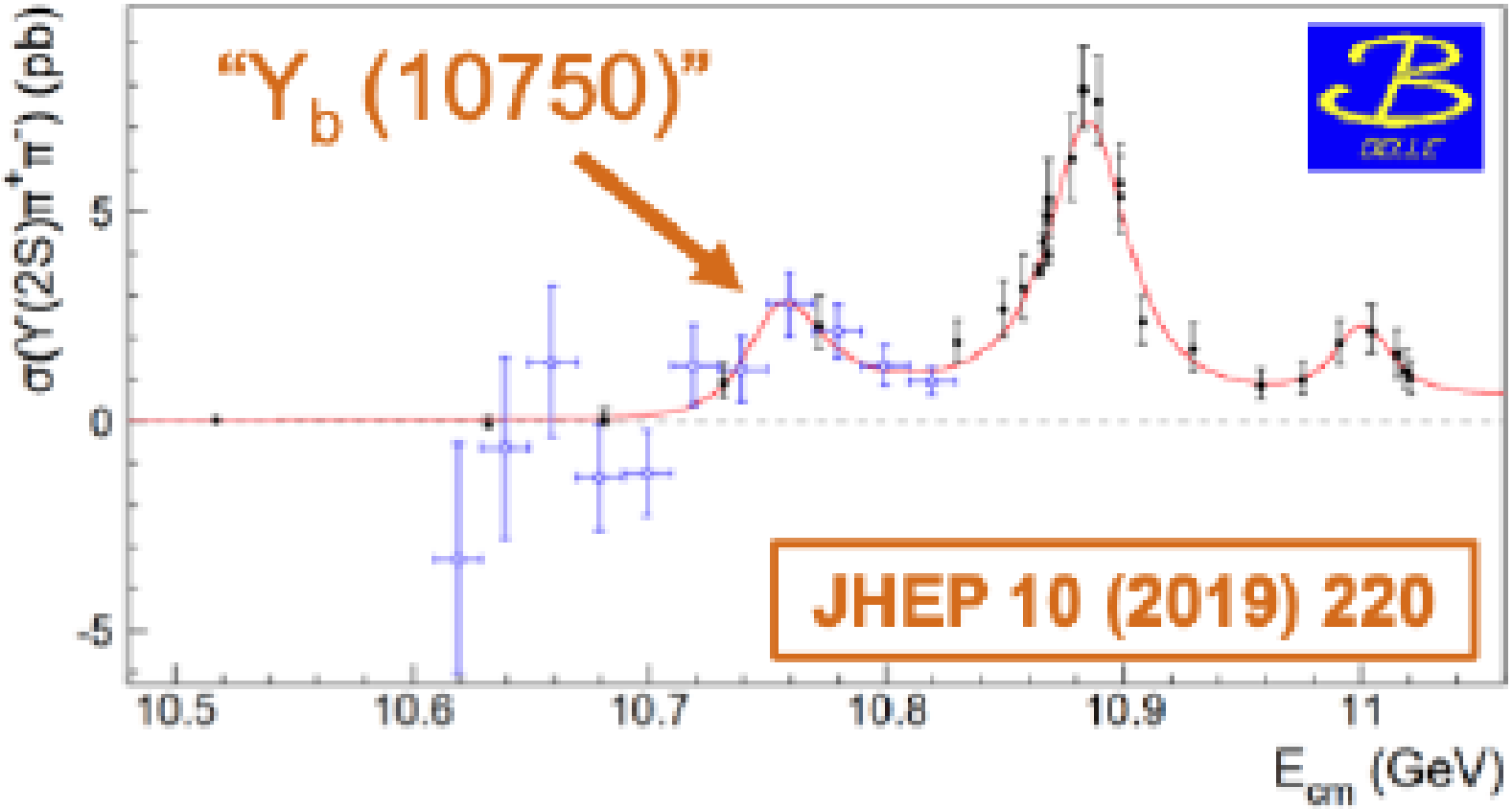
Additional Bottomonium Menu items

- Scan of 400 fb^{-1} between $\Upsilon(5S)$ and $\Upsilon(6S)$
  - Determine evolution of Z_b and other exotic states produced between $\Upsilon(5S)$ and $\Upsilon(6S)$





Scan/Study of region near 10.750 GeV

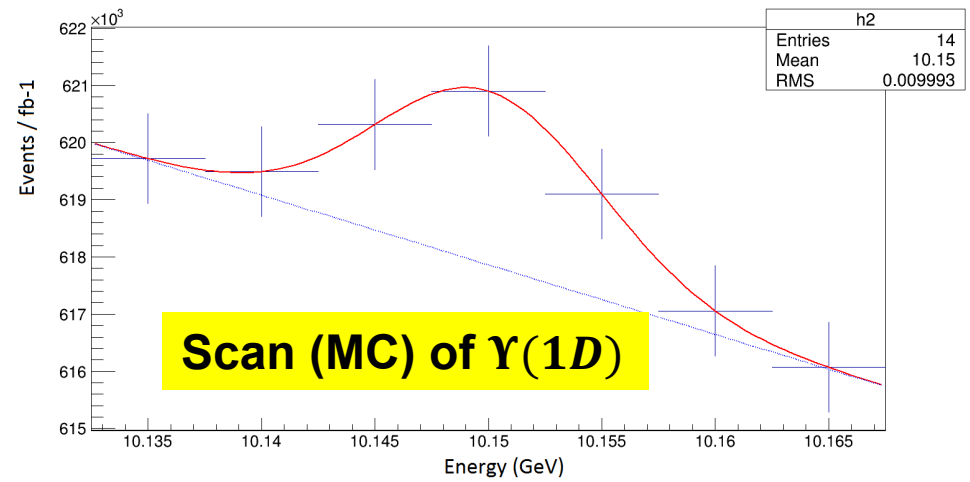


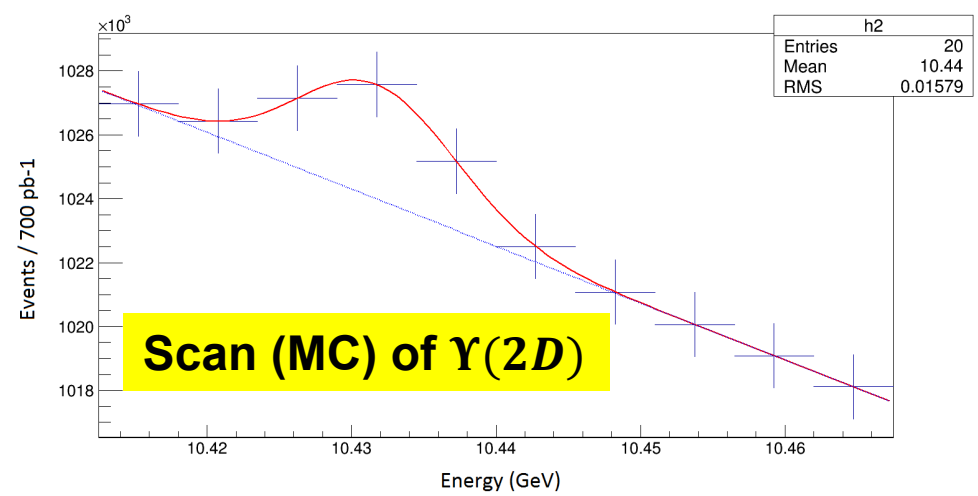
Scans of $\Upsilon(1D, 2D)$

- $2\ \mathrm{fb}^{-1}$ per scan point should yield a $> 5\sigma$ signal – of the J=1 states in each triplet

- Discovery of $\Upsilon(2D)$ could lead to a longer run later to search for $\pi\pi, \eta$ transitions to $\Upsilon(1S)$, or radiative transitions to $\Upsilon(1F)$

	Mass (GeV)	Γ_{ee} (eV)
$\Upsilon(1^3D_1)$	$10.145 - 10.155$	$0.6 - 1.5$
$\Upsilon(2^3D_1)$	$10.400 - 10.450$	$1.1 - 2.7$



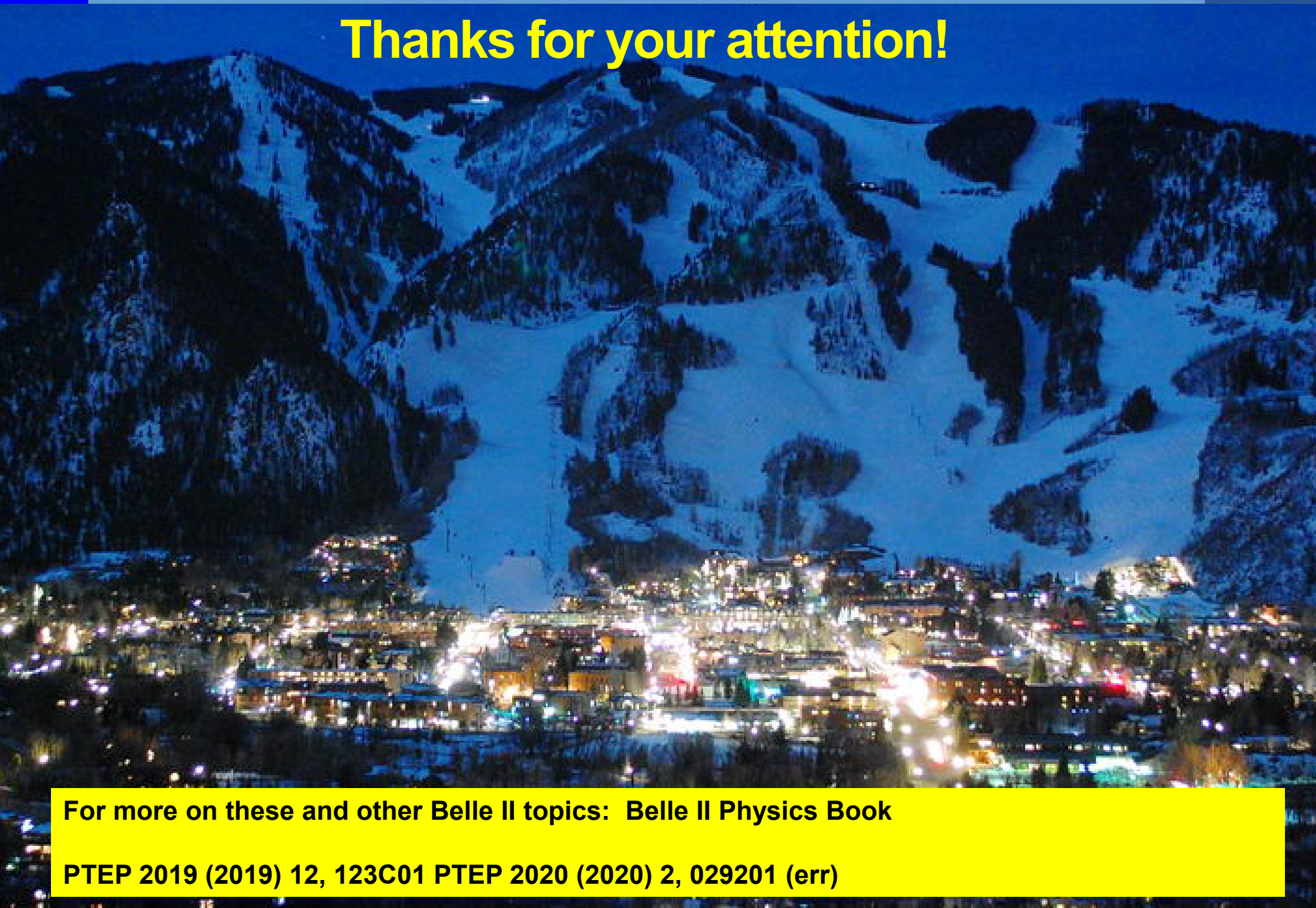


Summary

- CLEO, BaBar, Belle, and the LHC experiments have especially contributed complimentary measurements and enabled great progress in our understanding of bottomonium (and bottomonium-like) states – but the work is not done
- In the next decade, more will come from LHC, though a larger variety of possibilities to expand our understanding of bottomonium will be Belle II
- Significantly increased data samples at $\Upsilon(3S)\Upsilon(4S), \Upsilon(5S), \Upsilon(6S)$ at Belle II:
  - Greatly expanded understanding of the known singlet-P and singlet-S states
  - Resolution of the $\Upsilon(1\mathrm{D})$, $\Upsilon(2\mathrm{D})$ systems and of their principal decays
  - Understanding the nature of $\Upsilon(6S)$ and its decay modes (c.f. $\Upsilon(5S)$)
  - Charged and neutral four-quark Z states, and searches for related W and X states

Stay Tuned!

Thanks for your attention!



For more on these and other Belle II topics: Belle II Physics Book

PTEP 2019 (2019) 12, 123C01 PTEP 2020 (2020) 2, 029201 (err)