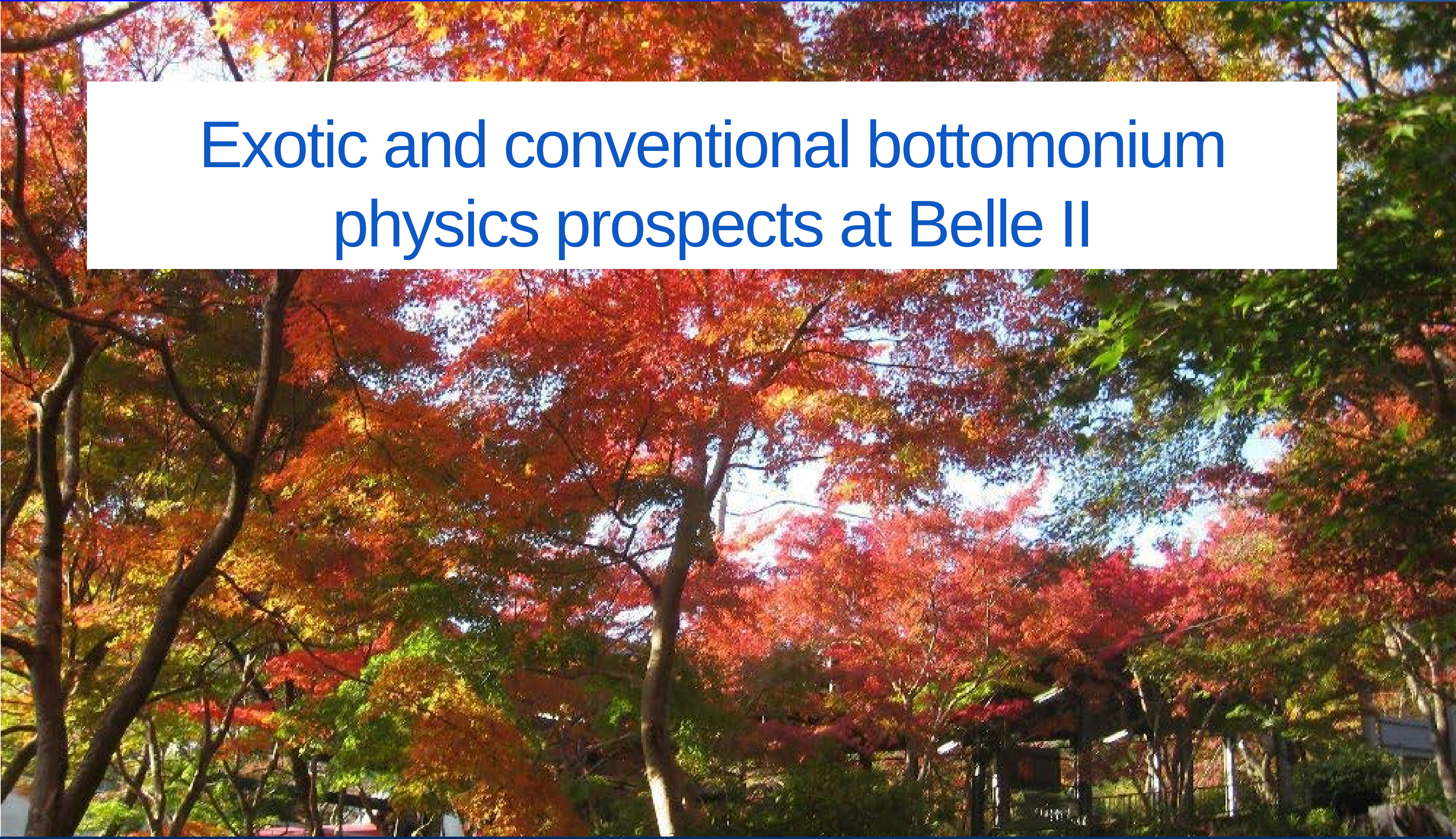
Exotic and conventional bottomonium physics prospects at Belle II



Todd Pedlar, Luther College
For the Belle II Collaboration

6th International Conference on Exotic Atoms and Related Topics
Vienna, Austria

13 September 2017

I. Introductory Remarks

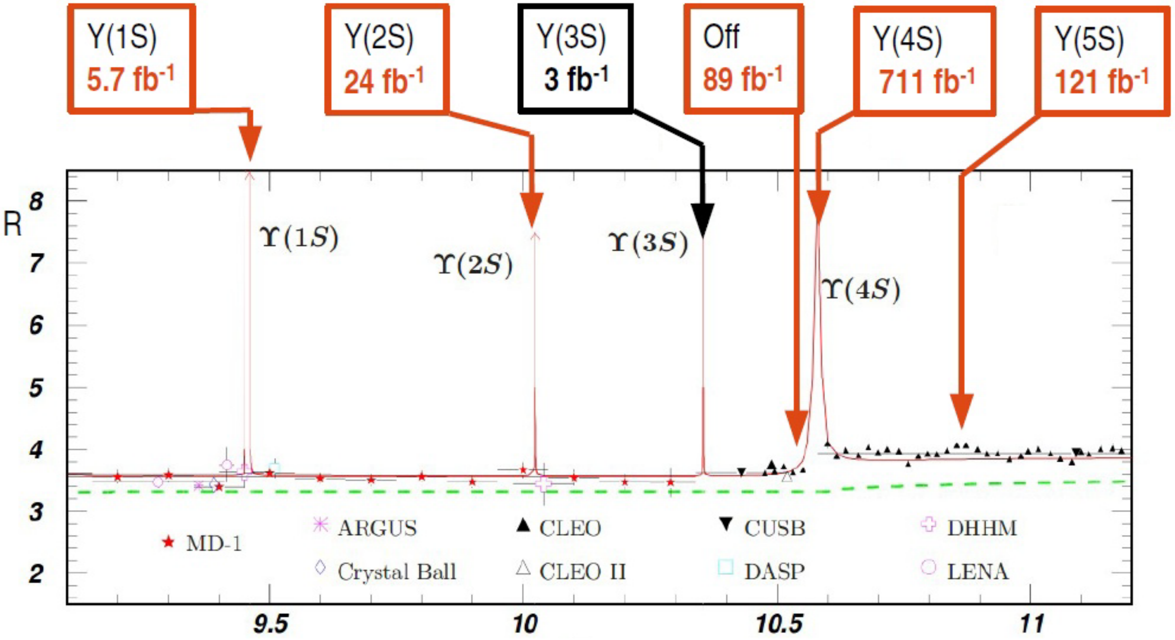
II. The Belle II Experiment

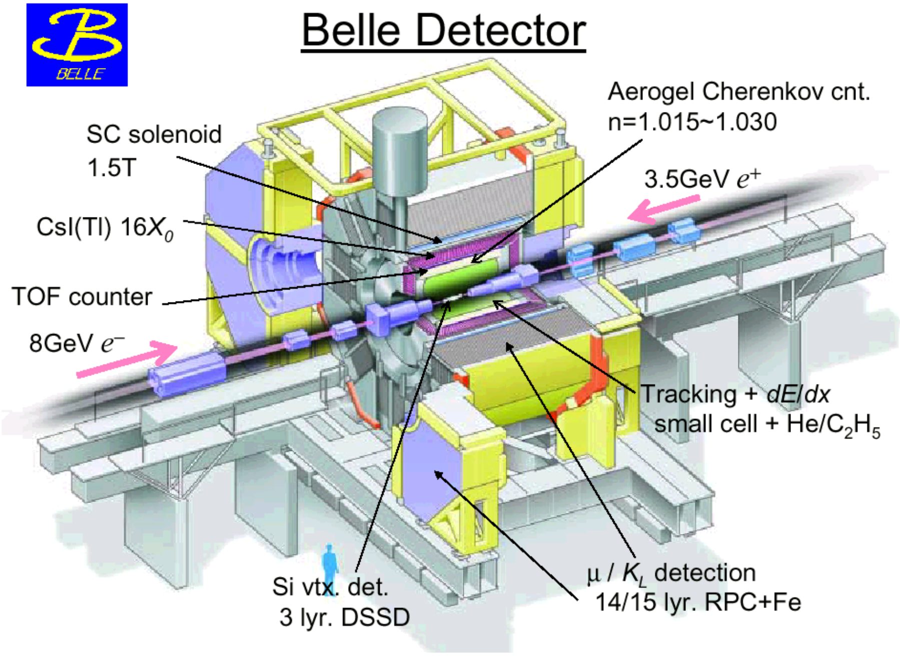
III. Belle II Prospects for Exotic Bottomonia

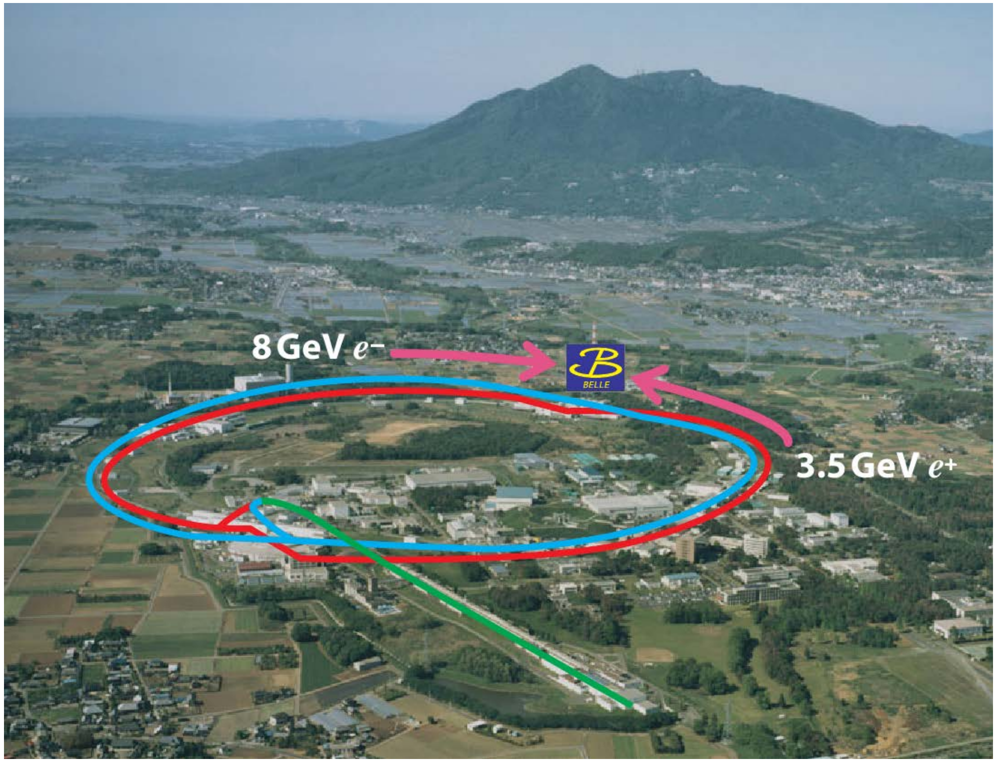
IV. Belle II Prospects for Conventional Bottomonia

Belle @ KEK

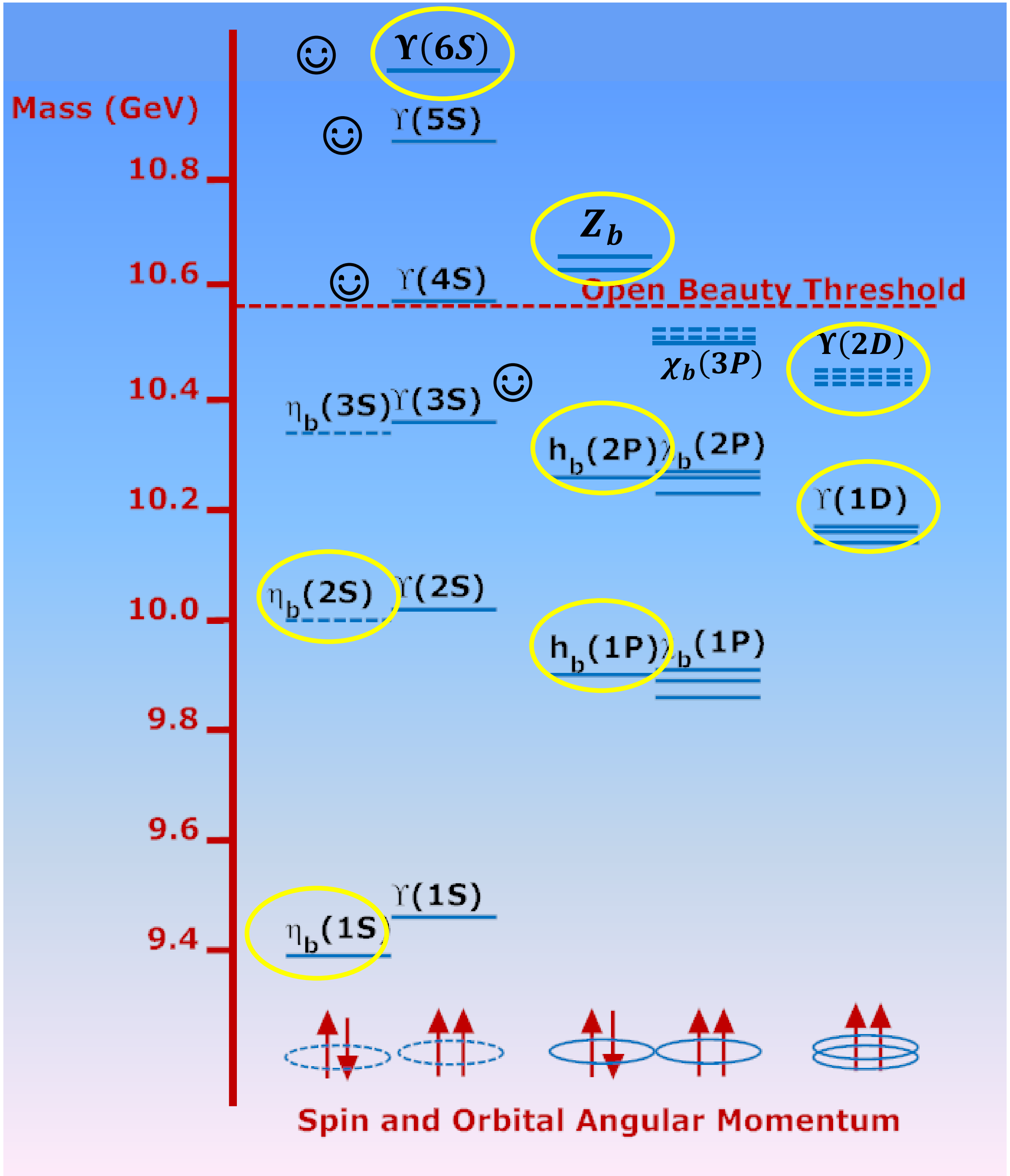
- Asymmetric e+e- collider
- Mainly operated at $\Upsilon(4S)$
- World's largest data samples at most bottomonium S-wave resonances
- In addition - 20 fb^{-1} of scan data from about 10.6 to 11.0 GeV







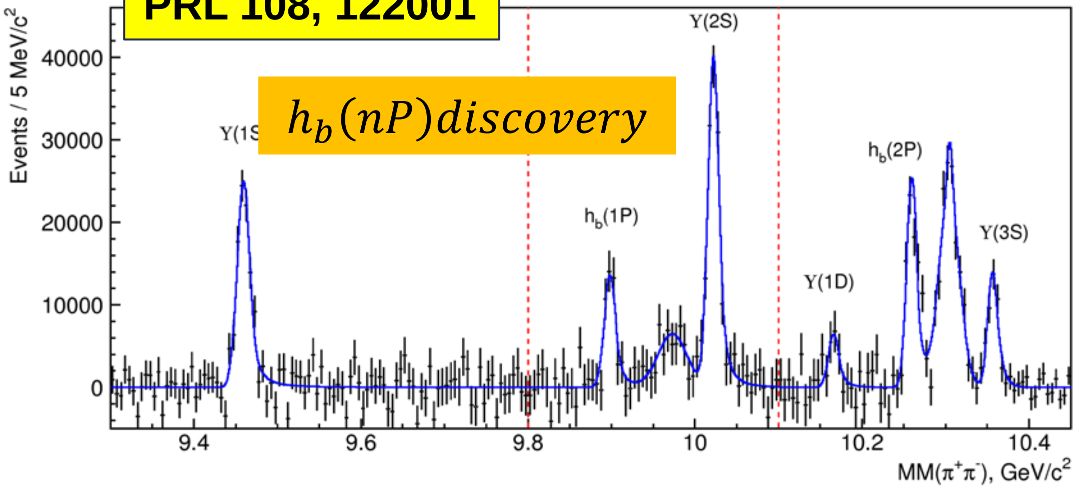
The Bottomonium Spectrum



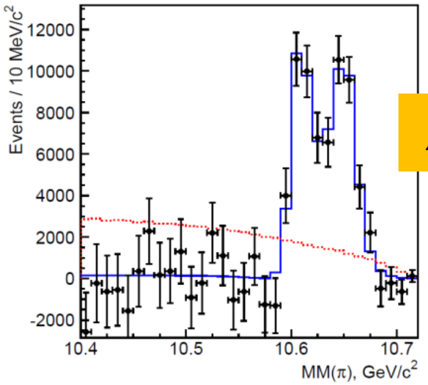
Bottomonium highlights from Belle

PRL 108, 122001

$h_b(nP) discovery$

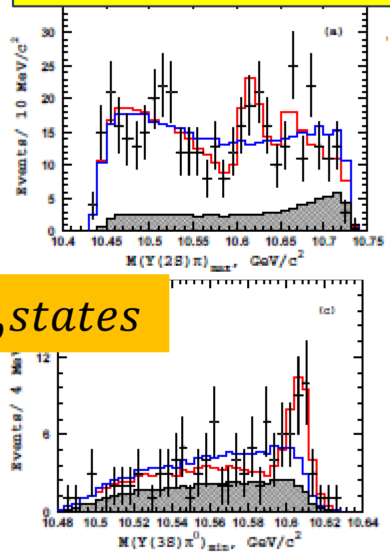


PRL 108, 032001

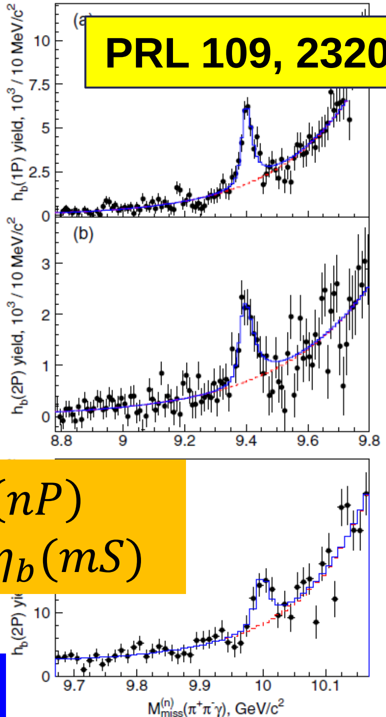


PRD 88, 052016

$Z_b states$



PRL 109, 232002



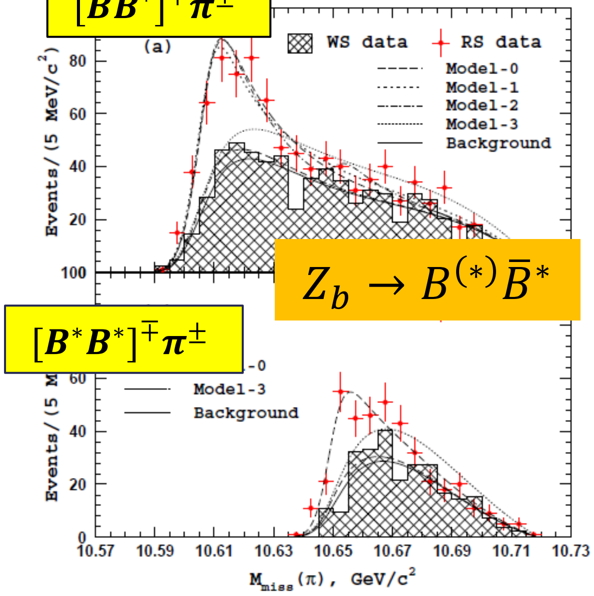
$h_b(nP)$
$\to \eta_b(mS)$

PRL 116, 212001

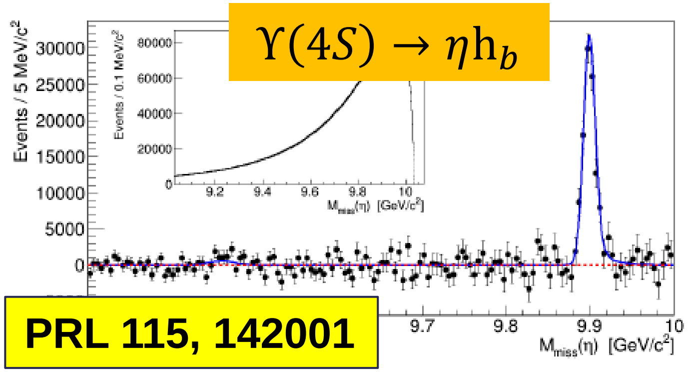
$[BB^*]^{\mp}\pi^{\pm}$

$[B^*B^*]^{\mp}\pi^{\pm}$

$Z_b \to B^{(*)}\bar{B}^*$

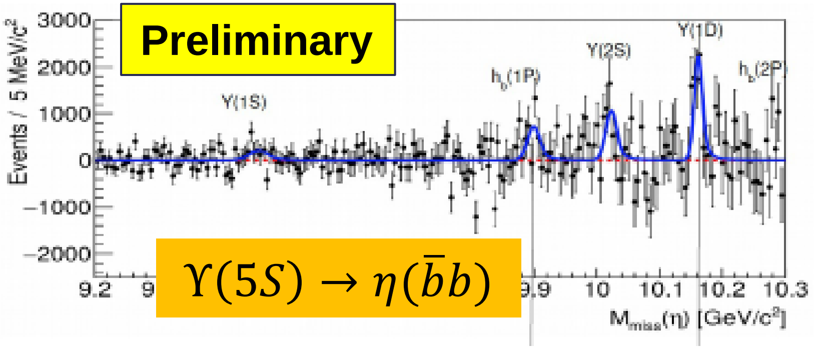


$\Upsilon(4S) \to \eta h_b$

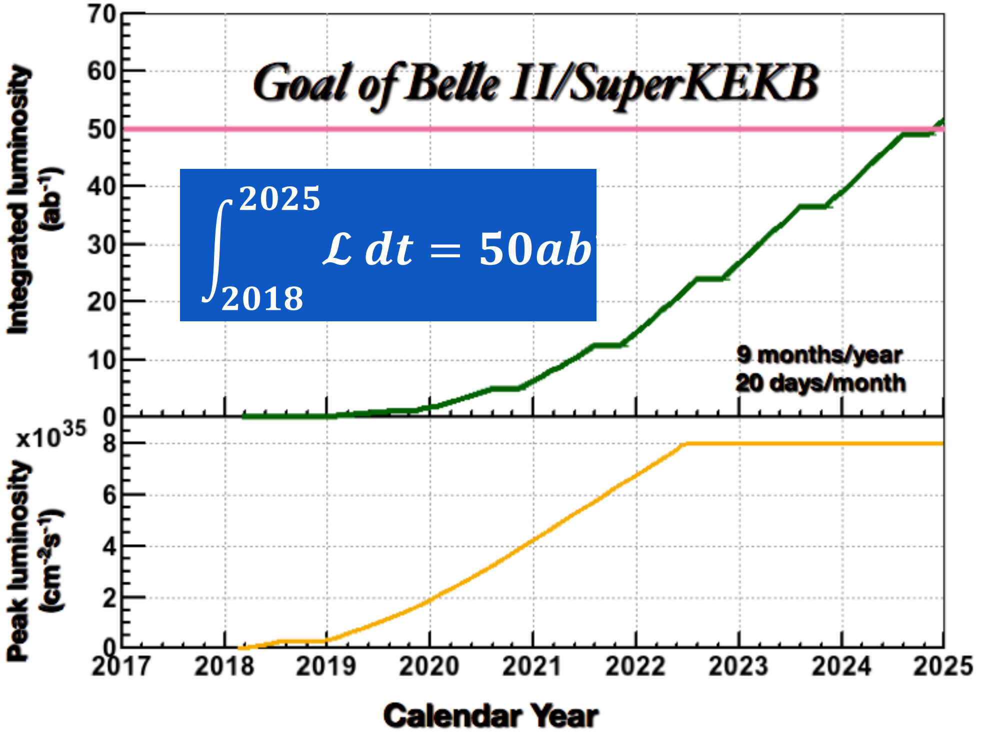


PRL 115, 142001

Preliminary



$\Upsilon(5S) \to \eta(\bar{b}b)$

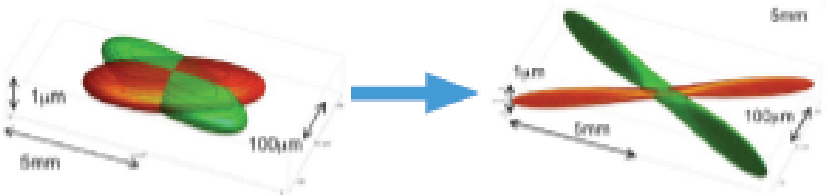


$$\int_{2018}^{2025} \mathcal{L}\, dt = 50ab$$

$$\mathcal{L}_{Belle} \rightarrow 2.1 \times 10^{34} cm^{-2} s^{-1}$$

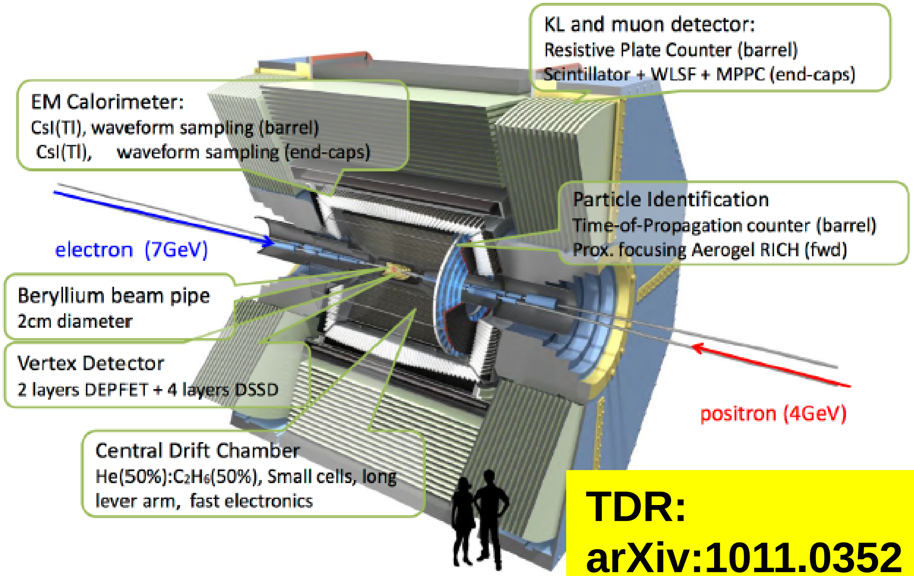
$$\mathcal{L}_{Belle\ II} \rightarrow 8 \times 10^{35} cm^{-2} s^{-1}$$

To get 40x luminosity of Belle



Reduce beam size to a few 100 atomic layers!

Belle II Detector



KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
CsI(Tl), waveform sampling (end-caps)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electron (7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positron (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

TDR: arXiv:1011.0352

Recent Progress Toward Belle II and Future Milestones

- **Oct 2016 – Mar 2017: Phase 1 Commissioning**
  - **Single beams in new SuperKEKB**
  - **Study beam backgrounds w/ BEAST, *c.f.* simulations**
- **Apr 2017: Belle II Roll-in**
  - **Fully Instrumented barrel detectors, no VXD**
- **Summer 2017: Global Cosmic Run**
- **Sept 2017: ARICH + ECL, BEAST Vertex installed**
- **Nov 2017-Jul 2018: Phase 2 Commissioning**
  - **Main goals:**
    - **Tune SuperKEKB with nano-beams – reach Belle I luminosity**
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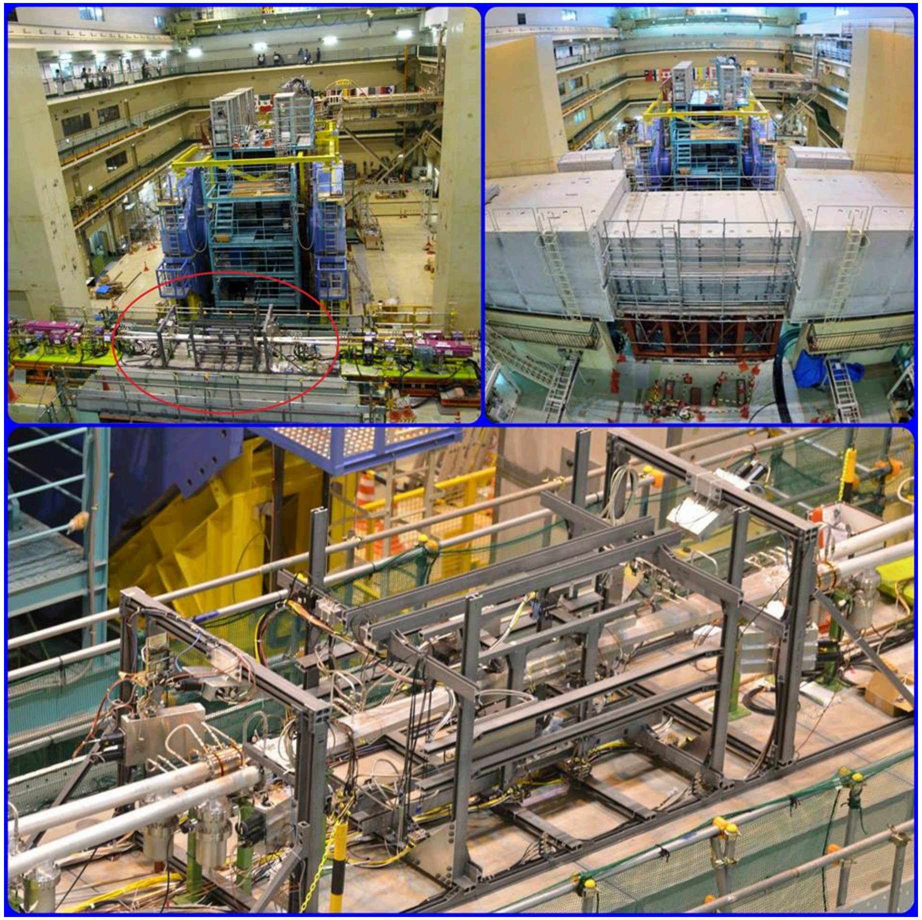
- **Summer 2018: Install VXD**
- **Late 2018: Full detector operations: start of Physics Run**



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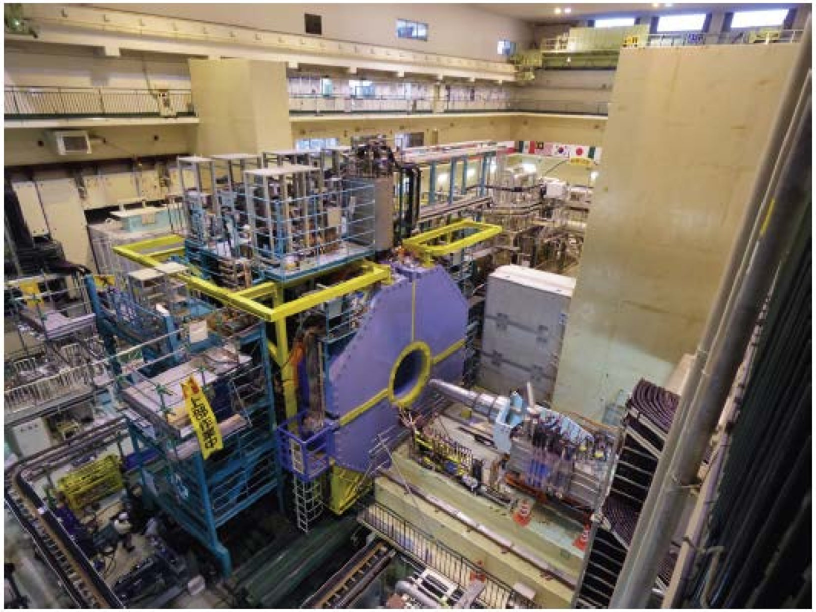

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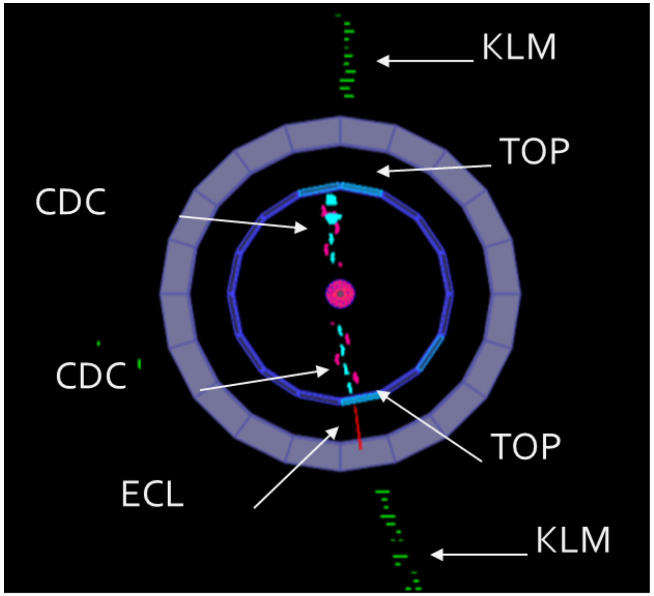

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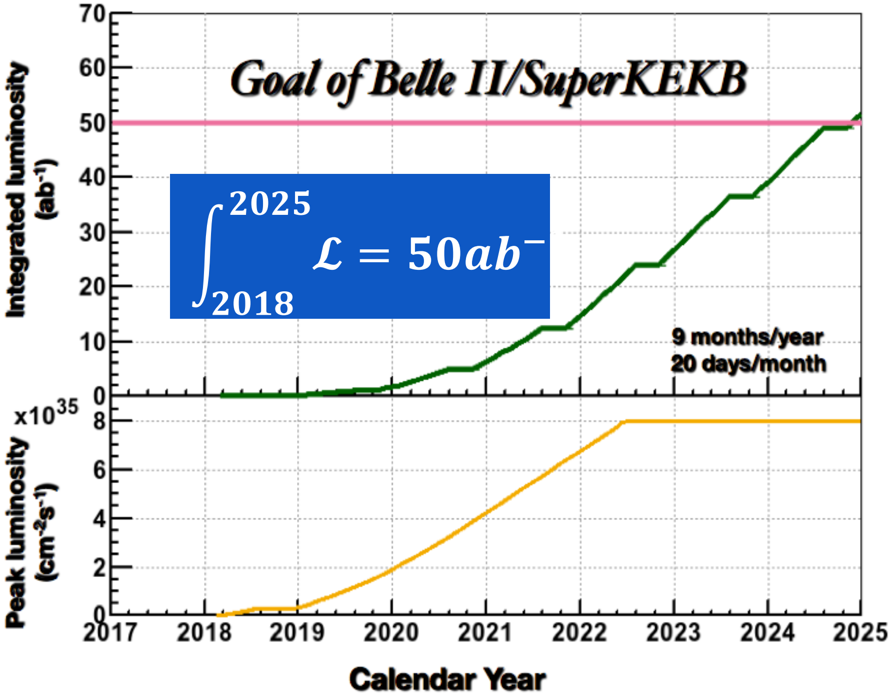


MENU

- Studies of the exotic charged and neutral $Z_b(10610)$ and $Z_b(10650)$ states
- Studies of $\Upsilon(6S)$ - decays to $h_b(nP), \Upsilon(nS)$, and others
- Studies of the $\Upsilon(1D, 2D)$ states which are either poorly resolved or unobserved
- Studies of the known $h_b(1P, 2P)$ and $\eta_b(1S, 2S)$ states
- Other things for dessert?

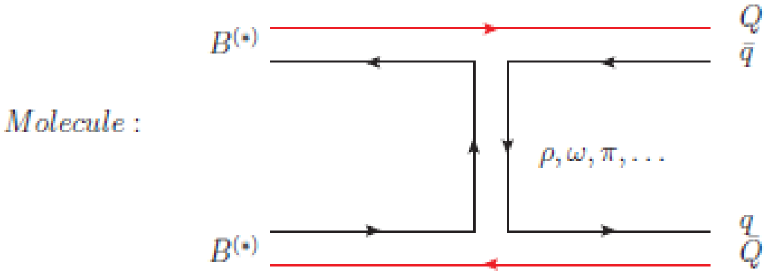
$Z_b(10610)$ and $Z_b(10650)$ states observed in $\Upsilon(5S, 6S)$ decays

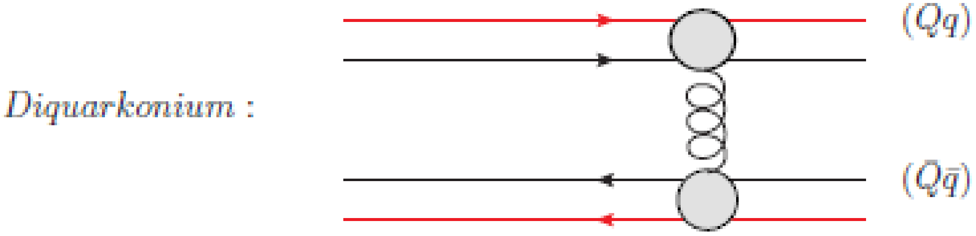
- The Z_b states are responsible for the large rates of production of the $h_b(1P, 2P)$ states seen in $\Upsilon(5S)$ decays

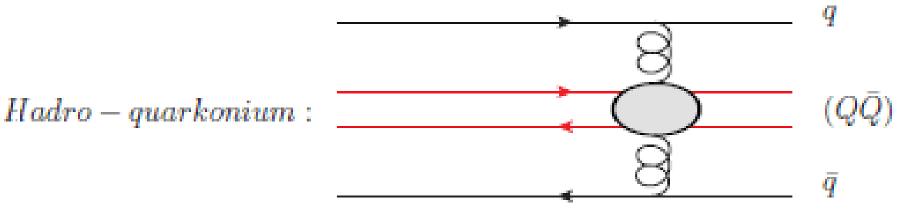
✔ $Z_b^\pm(10610)$ and $Z_b^\pm(10650)$ discovered in $\Upsilon(nS)\,\pi^\pm$ and $h_b(mP)\,\pi^\pm$ at $\Upsilon(5S)$
PRL 108, 122001 (2012)

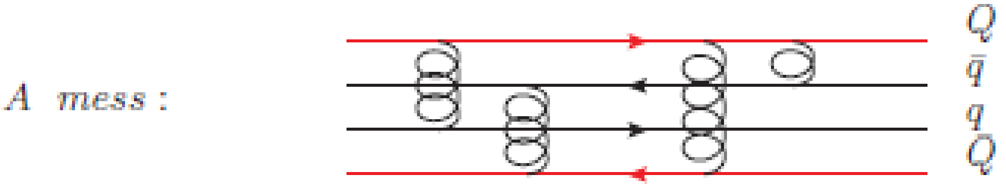
✔ $Z_b^0(10610)$ discovered in $\Upsilon(nS)\,\pi^0$ at $\Upsilon(5S)$ PRD 88, 052016 (2013)

✔ $Z_b^\pm(10610) \to B^*B$ and $Z_b^\pm(10650) \to B^*B^*$ observed at $\Upsilon(5S)$ (dominant)
PRL 116, 212001 (2016)

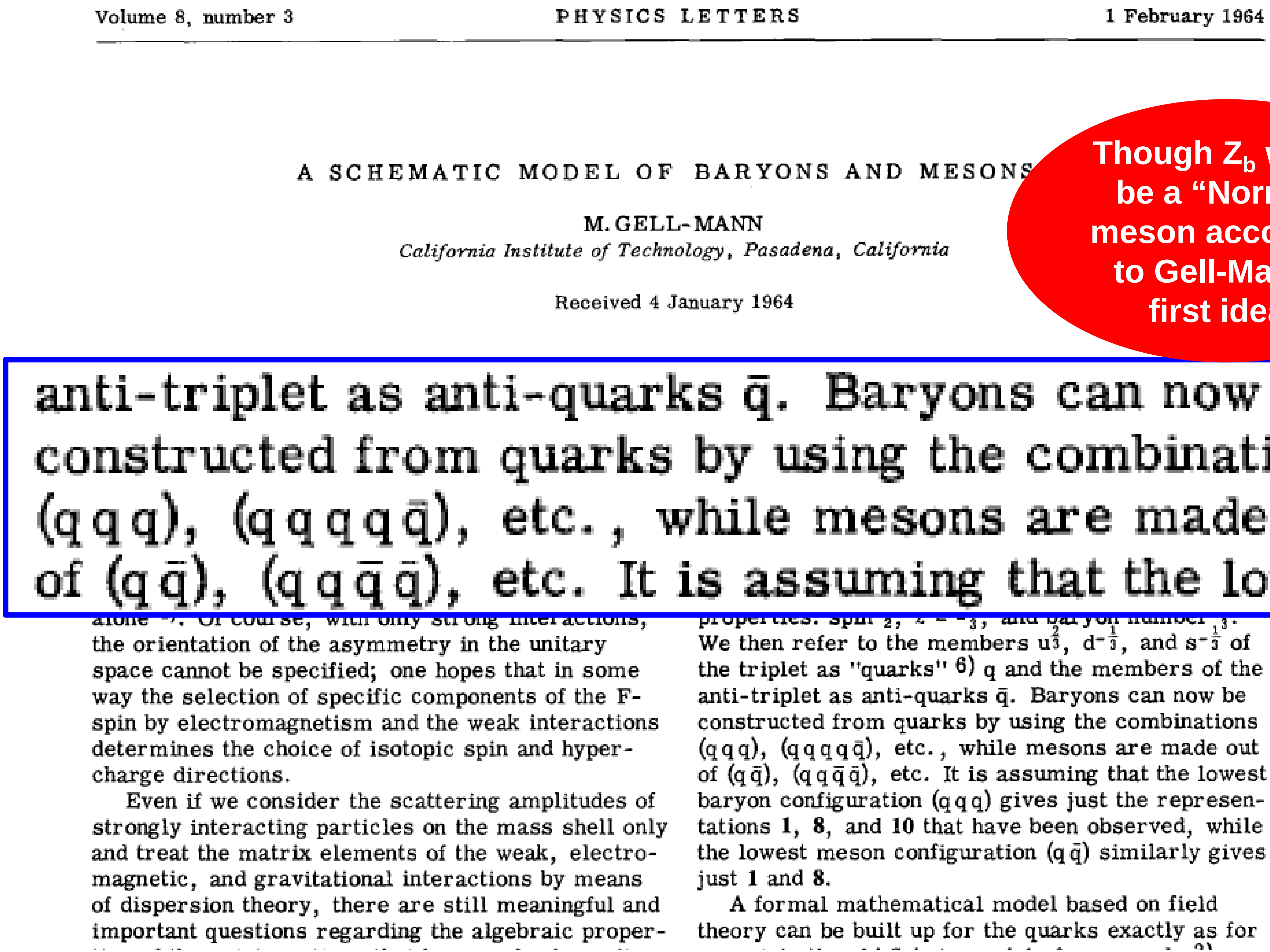








Though Z_b would be a "Normal" meson according to Gell-Mann's first ideas



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

alone 5). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means of dispersion theory, there are still meaningful and important questions regarding the algebraic proper-

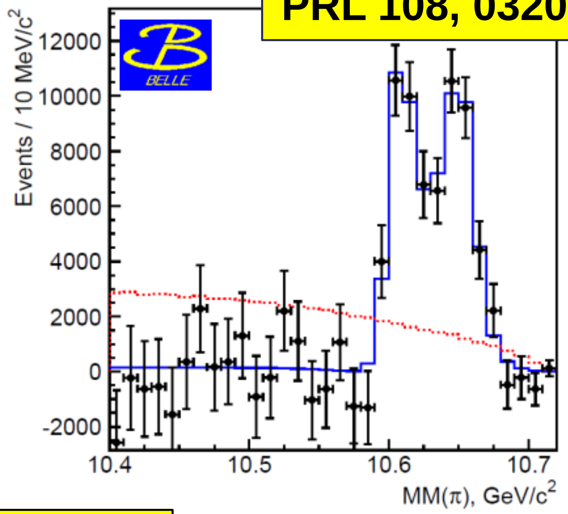
properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

A formal mathematical model based on field theory can be built up for the quarks exactly as for

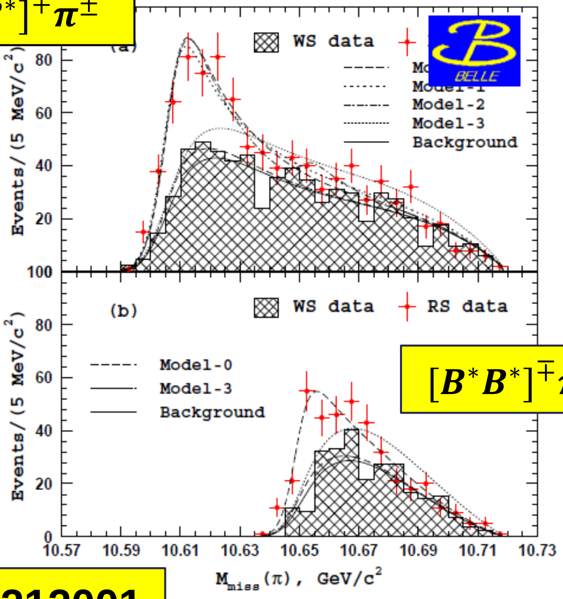
$Z_b(10610)$ and $Z_b(10650)$ states

- Minimum four quark content
- Proximity to $B\overline{B^*}$ and $B^*\overline{B^*}$ thresholds – and their being the dominant decay modes strongly suggests *molecule*
- $Z_b(10650)$ does not decay **at all** to $B\overline{B^*}$? Further – and stronger – evidence
- Spin-parity measurement, total widths, production rates also consistent with expectations for molecular states

PRL 108, 032001



$[BB^*]^{\mp}\pi^{\pm}$



$[B^*B^*]^{\mp}\pi^{\pm}$

PRL 116, 212001

$Z_b(10610)$ and $Z_b(10650)$ states

- A very interesting analog: $Z_c(3900)$ and $Z_c(4025)$ (that lie near $D\overline{D^*}$ and $D^*\overline{D^*}$ thresholds)
  - $Z_c(3900)$ Observed in $Y(4260)$ and $Y(4360)$ decays to $J/\psi\pi\pi$, and a hint of $\mathrm{h}_c\pi\pi$
  - $Z_c(4025)$ Observed in $Y(4260)$ and $Y(4360)$ decays to $J/\psi\pi\pi$, $\mathrm{h}_c\pi\pi$, $\psi(2S)\pi\pi$
- Nagging question – masses of molecules should be < M(daughters)
  - Reported masses of $Z_c(3900)$, $Z_c(4025)$, $Z_b(10610)$, and $Z_b(10650)$ are greater by 7.8, 6.7, 2.7, and 1.8 MeV.
  - A re-analysis of the Z_b fits (PRD 93, 074013), gave smaller deviations (and put the higher state below threshold)
- Still – calls clearly for more data and systematic understanding of these charged states

$Z_b(10610)$ and $Z_b(10650)$ states

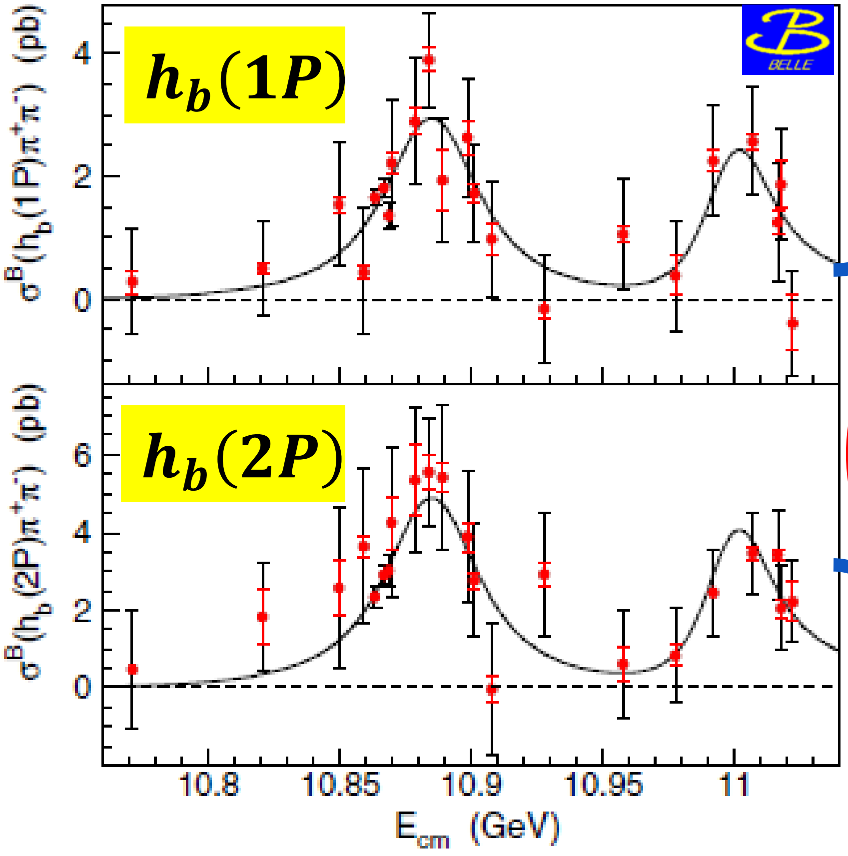
- Produced in both $\Upsilon(5S, 6S)$ decays, and it's important that we study production from both resonances in Belle II
  - At first - $20fb^{-1}$ of $\Upsilon(6S)$ in Phase 2 or early Phase 3 – and much more later
  - We also hope to collect at some point a large $\Upsilon(5S)$ sample, increasing its statistics by 10-20 or thereabouts ($\sim 1-2ab^{-1}$)

- Significantly improve the understanding of $Z_b(10610)$ and $Z_b(10650)$ masses and branching fractions

- (similar improvements in charged charmonium-like states will be made, though this is beyond the bounds of this talk)

PRL 117, 142001 (2016)

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

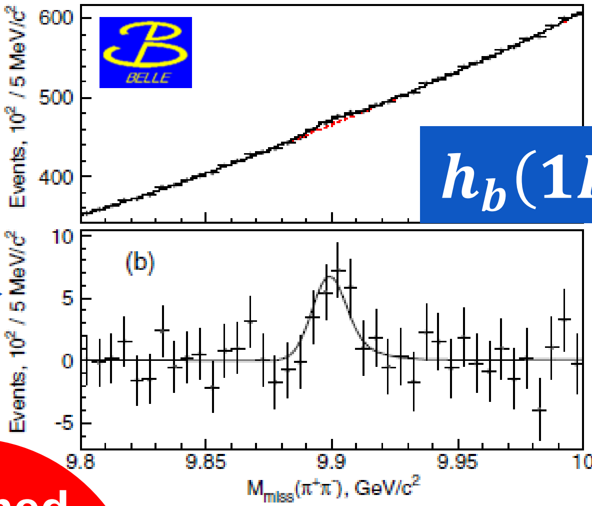


$h_b(1P)$

$h_b(2P)$

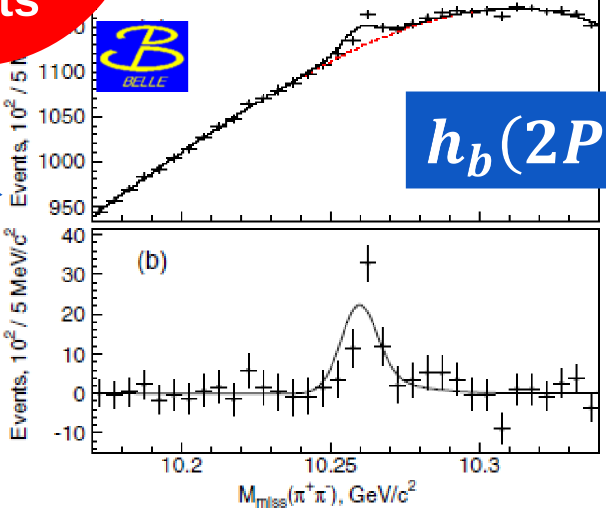
$h_b(nP)$ yield vs. E_{cm}

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



$h_b(1P)$ yield

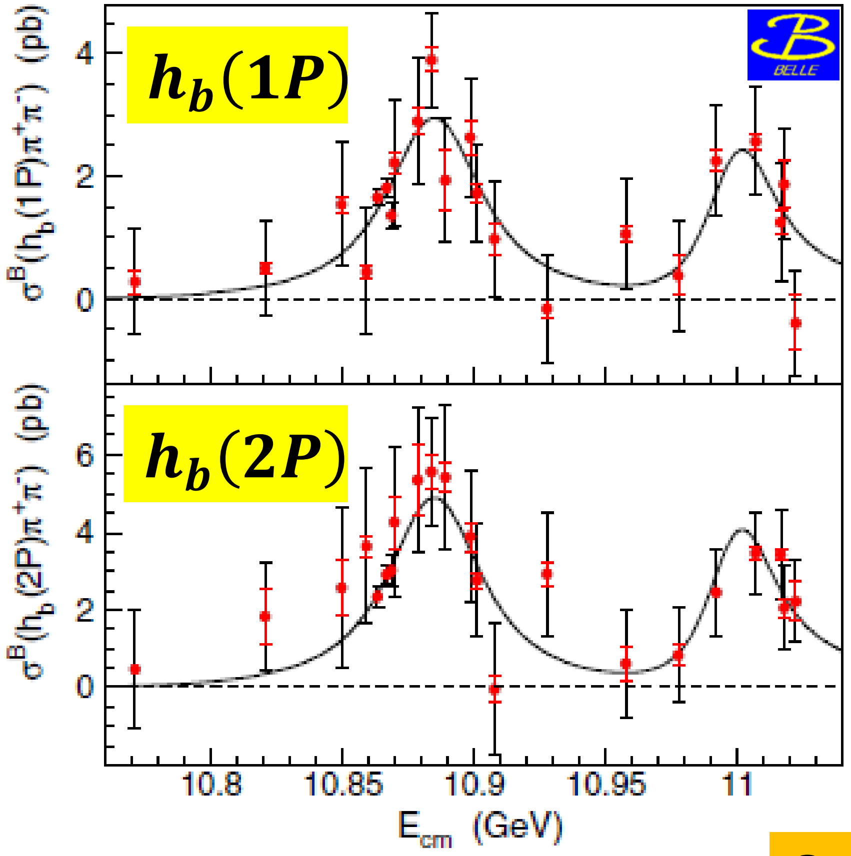
in $\pi\pi$ missing mass



$h_b(2P)$ yield

PRL **117**, 142001 (2016)

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

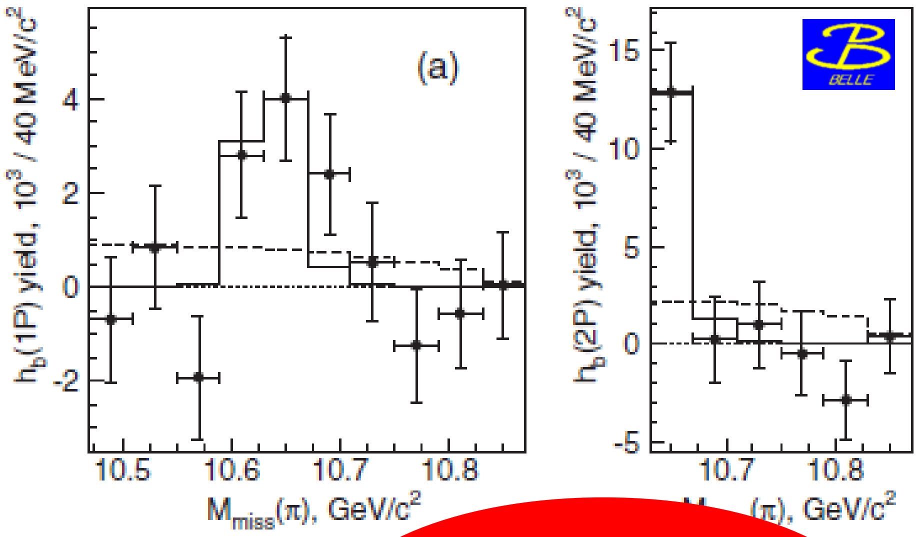


$h_b(nP)$ yield vs. E_{cm}

$h_b(1P)$ yield

$h_b(2P)$ yield

vs single π missing mass



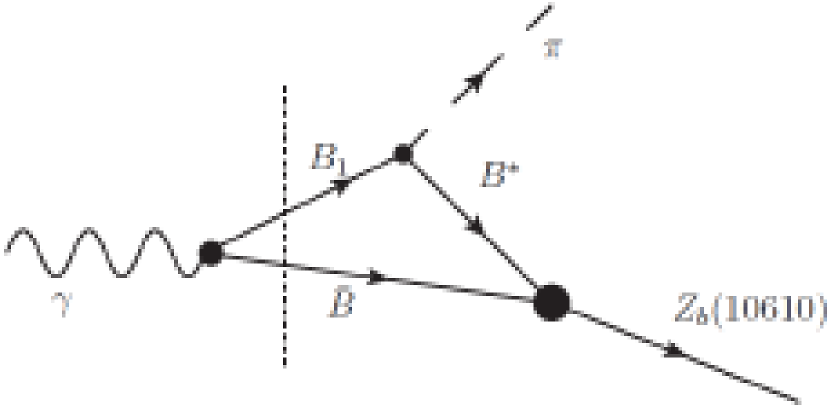
Summed over $\Upsilon(6S)$ peak points

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

Phase space hypothesis excluded at 3.6σ and 4.5σ

Which Z_b mediates $\pi\pi h_b(nP)$ transitions from $\Upsilon(6S)$ or do both?

- An interesting question! this is one place where what we know about $\Upsilon(6S)$ differs substantially from what we know about $\Upsilon(5S)$
- More interesting due to proximity of $\Upsilon(6S)$ to the threshold for $B_1\overline{B}$ at $11006\ MeV$



M. Voloshin, B2TiP Pittsburgh 2016

- A contribution of $B_1\overline{B}$ to the $\Upsilon(6S)$ wave function would imply that only $Z_b(10610)$ should be formed as an intermediate state in $\Upsilon(6S) \to \pi\pi h_b(nP)$
- Motivates taking much more data!

Which Z_b mediates $\pi\pi h_b(nP)$ transitions from $\Upsilon(6S)$ or do both?

- If $Z_b(10610)$ only, would imply a similarity of $\Upsilon(6S)$ to $Y(4260)$,
  - which has been interpreted as a possible $D_1\overline{D}$ molecule, and
  - similarly decays to lower charmonia through a charged charmonium-like state (Phys. Rev. Lett. **111**, 132003)

- Now this is getting interesting! – $Z_c\ vs.\ Z_b;\ Y(4260) vs.\ \Upsilon(6S)$

- The analogies aren't perfect, but tantalizing - thus really need more data at the $\Upsilon(6S)$ in order to tease out the similarities and differences

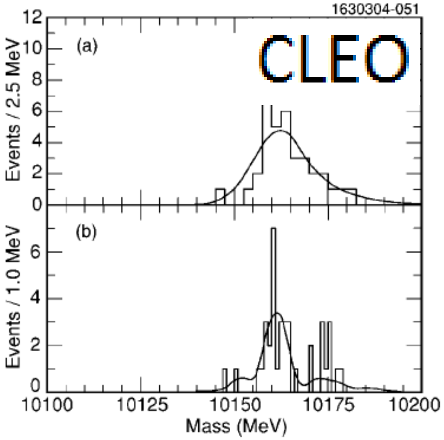
To Conclude this portion

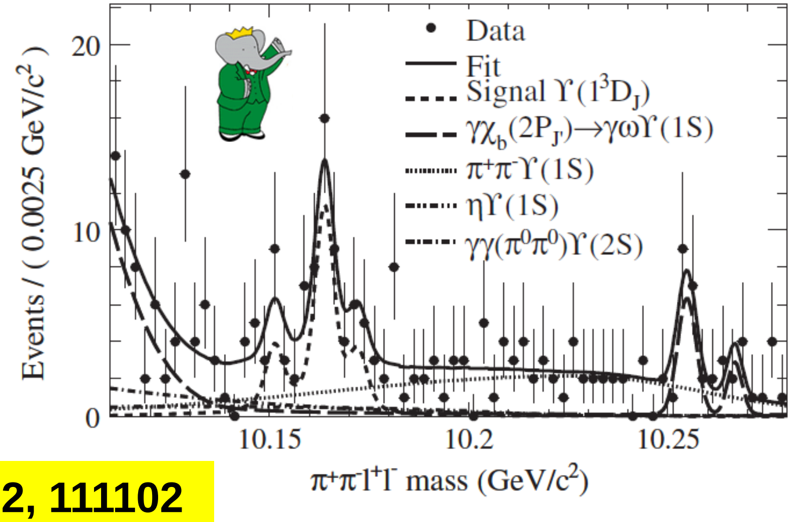
- The similarities between the charged bottomonium-like (and charged charmonium-like) states are striking
- The clear problems with a clean identification as pure $b\bar{b}$ of even the neutral vector states above open bottom threshold also invites – and even demands – much more study
- The spectroscopy of such states – and seeking a common understanding of them if possible – is is a truly important contribution towards our further understanding of QCD.
- Belle II can and will be a key player in this work over the next decade

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

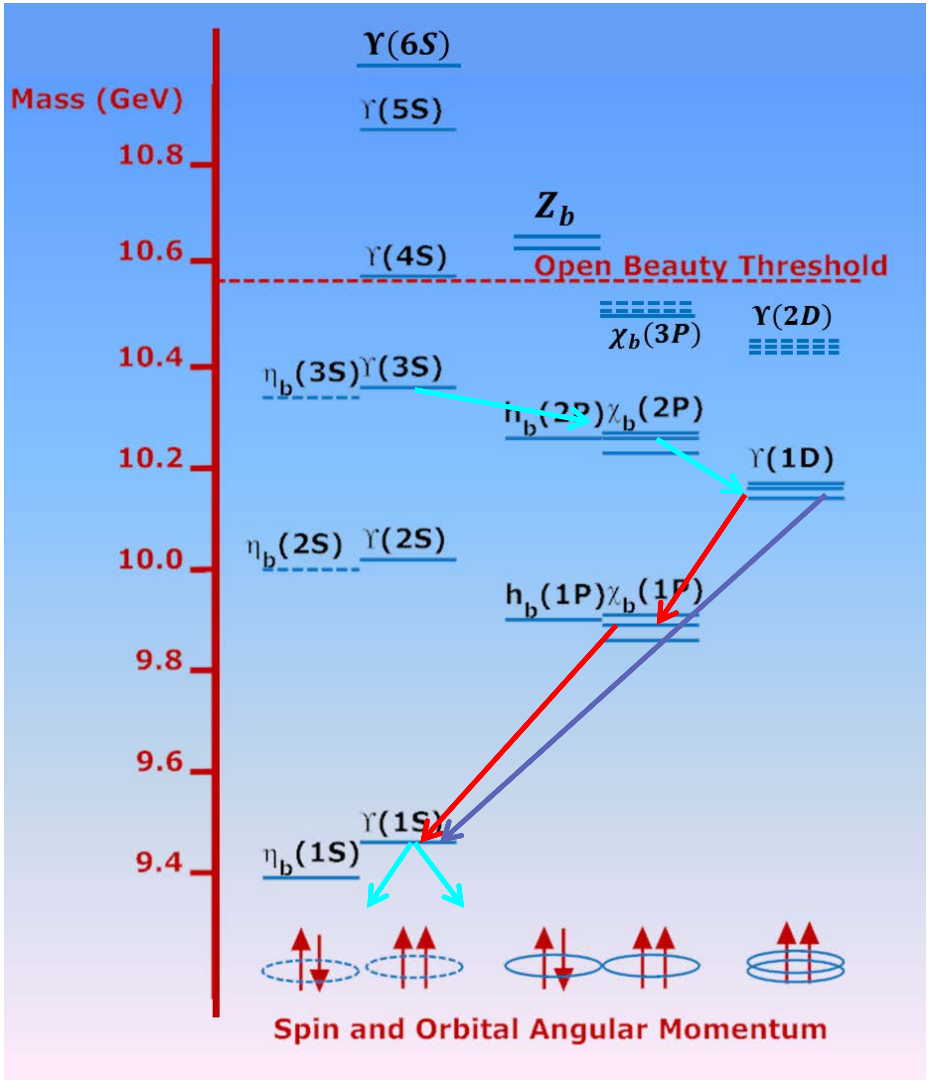
- $\Upsilon(1D)$ was originally observed by CLEO, and confirmed in a somewhat different cascade by BaBar. Neither experiment was able to resolve the 1D triplet into its three states

PRD 70, 032001





PRD 82, 111102

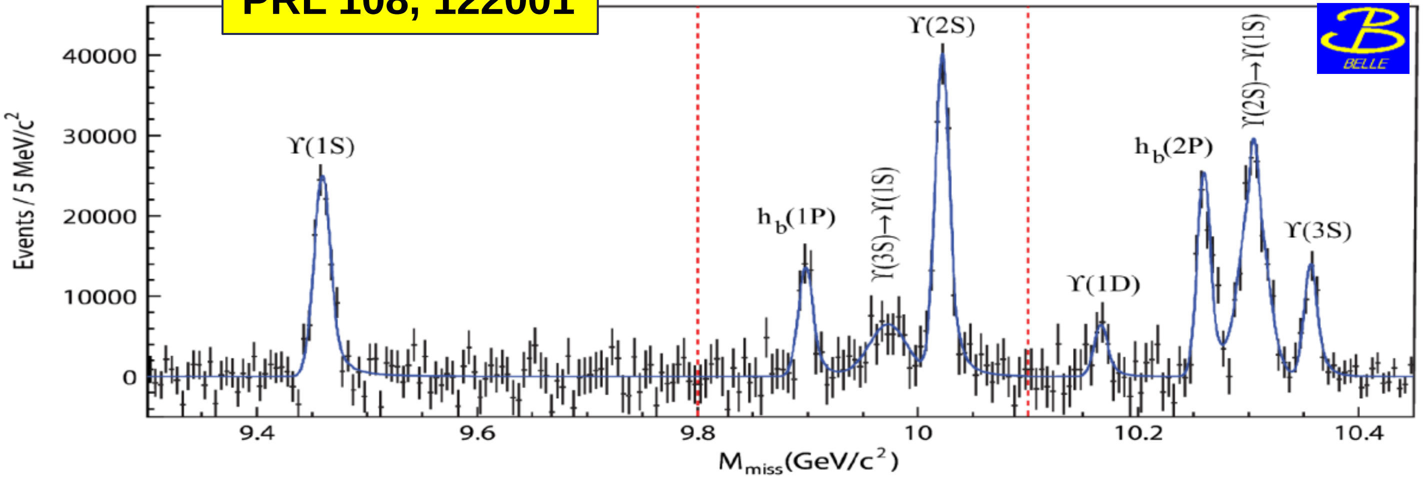


The D-wave triplets $\Upsilon(1D)$ and $\Upsilon(2D)$

- Belle has observed $\Upsilon(1D)$ in η and $\pi\pi$ transitions from $\Upsilon(5S)$, though we also do not have any clear differentiation of the three peaks

PRL 108, 122001

$$\Upsilon(5S) \rightarrow \pi\pi X$$



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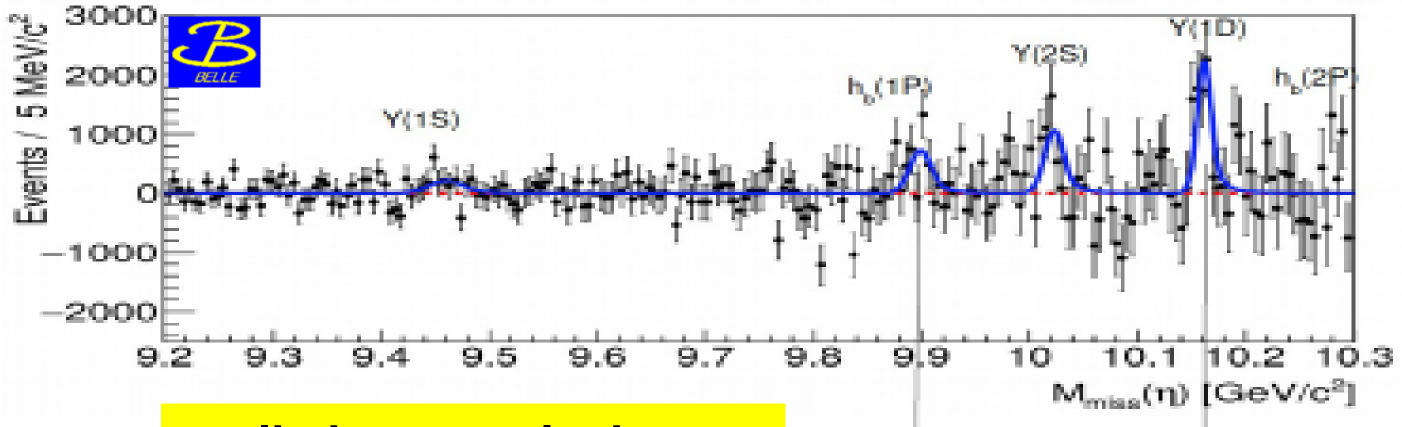

Preliminary: Inclusive η Missing Mass

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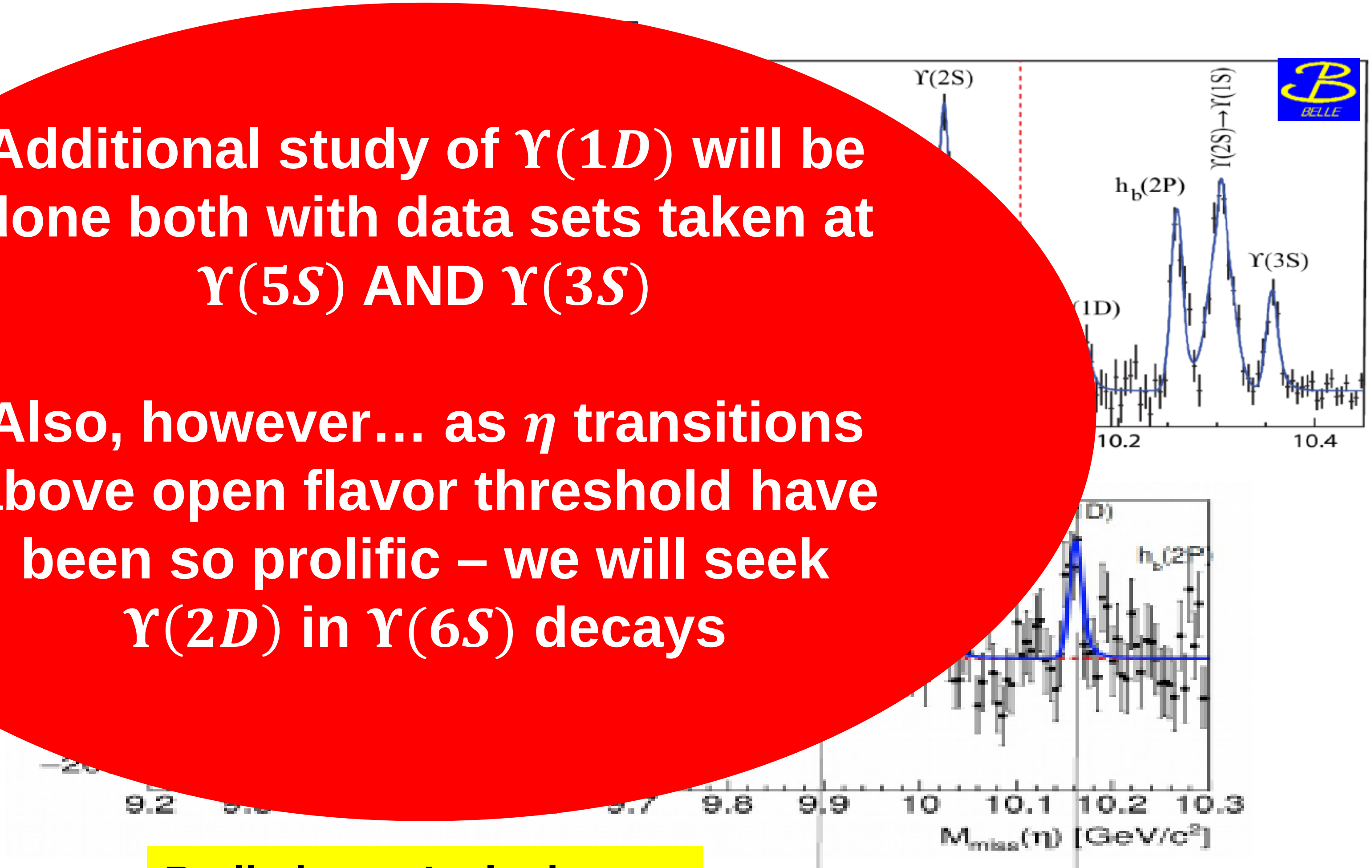
$\Upsilon(5S)$

$\Upsilon(5S)$

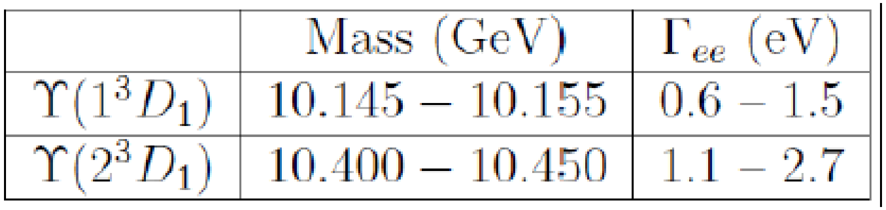


Additional study of $\Upsilon(1D)$ will be done both with data sets taken at $\Upsilon(5S)$ AND $\Upsilon(3S)$

Also, however… as η transitions above open flavor threshold have been so prolific – we will seek $\Upsilon(2D)$ in $\Upsilon(6S)$ decays

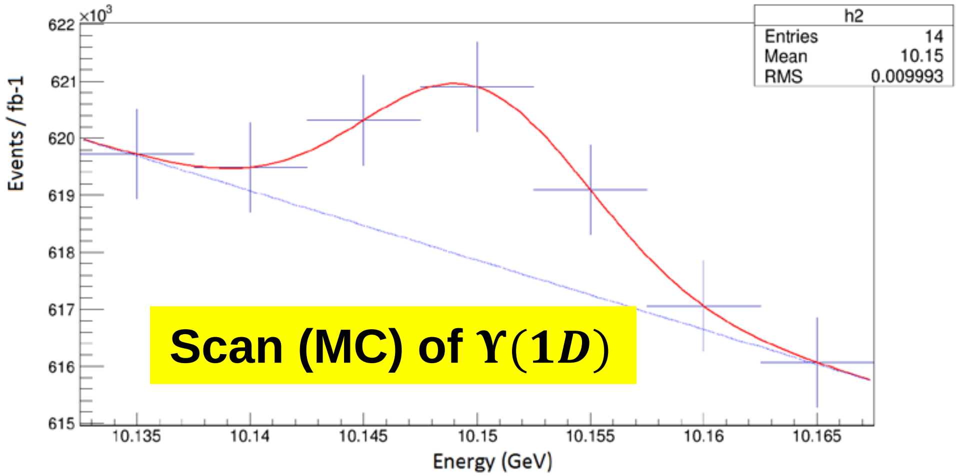
Preliminary: Inclusive η Missing Mass

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

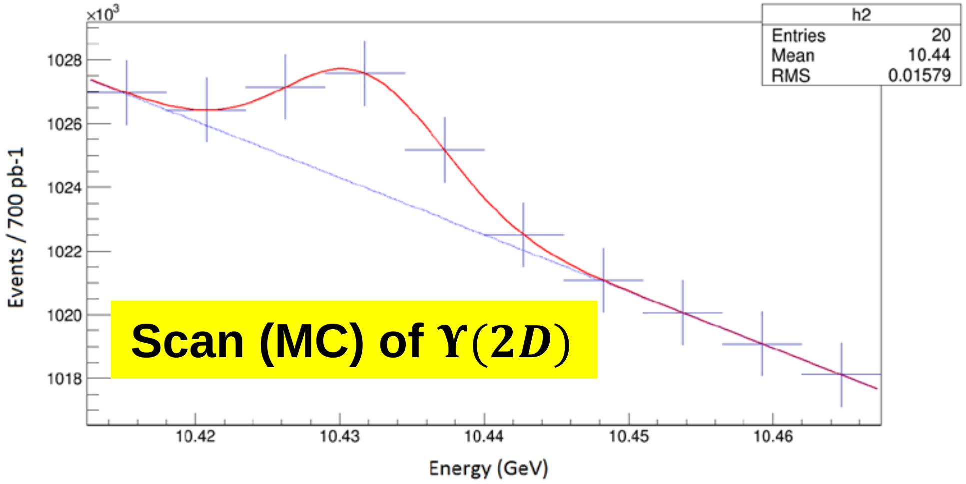


	Mass (GeV)	Γ_{ee} (eV)
$\Upsilon(1^3D_1)$	$10.145 - 10.155$	$0.6 - 1.5$
$\Upsilon(2^3D_1)$	$10.400 - 10.450$	$1.1 - 2.7$

- $2fb^{-1}$ per scan point should yield a $> 5\sigma$ signal – of the J=1 states in each triplet
- This would likely take place early in Phase 3 when the instantaneous luminosity is still poor
- 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 $\Upsilon(1F)$



Scan (MC) of $\Upsilon(1D)$



Scan (MC) of $\Upsilon(2D)$

Studies of $h_b(1P,2P)$ and $\eta_b(1S,2S)$

The $\Upsilon(4S,5S,6S)$ all have the potential to serve as a source of $h_b(1P,2P)$

$$\boldsymbol{B[\Upsilon(5S)\to\pi\pi h_b(1P)) = (3.5\pm1.1)\times10^{-3}}$$
$$\boldsymbol{B[\Upsilon(5S)\to\pi\pi h_b(2P)) = (6.0\pm2.0)\times10^{-3}}$$
$$\boldsymbol{B[\Upsilon(4S)\to\eta h_b(1P)) = (1.83\pm0.23)\times10^{-3}}$$

$$\mathcal{B}[h_b(1P)\to\eta_b(1S)\gamma] = (49.2\pm5.7^{+5.6}_{-3.3})\%$$
$$\mathcal{B}[h_b(2P)\to\eta_b(1S)\gamma] = (22.3\pm3.8^{+3.1}_{-3.3})\%$$
$$\mathcal{B}[h_b(2P)\to\eta_b(2S)\gamma] = (47.5\pm10.5^{+6.8}_{-7.7})\%$$

And thus as a source of both $\eta_b(1S,2S)$

With samples of $50ab^{-1}$of $\Upsilon(4S)$ and $2ab^{-1}$of $\Upsilon(5S)$ we should be able to tag (with efficiencies taken into account)

~12M $h_b(1P)$ and ~1.4M $\mathrm{h}_b(2P)$

And from these, via radiative transitions,

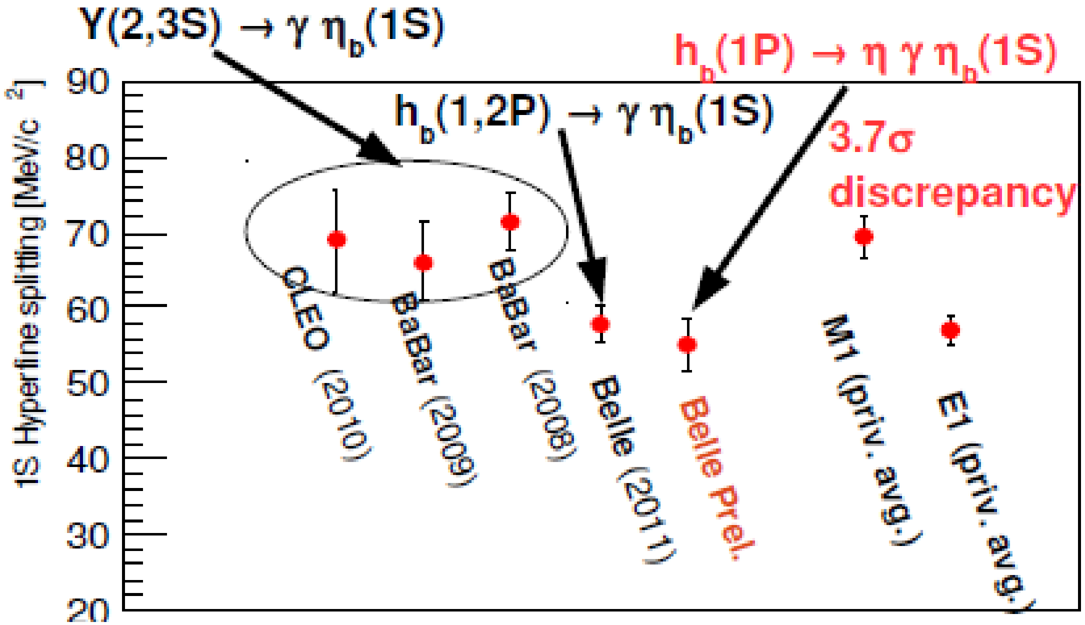
~4M $\eta_b(1S)$ and ~0.25M $\eta_b(2S)$

In addition, an expected $\mathbf{300}\boldsymbol{fb^{-1}}$ at $\boldsymbol{\Upsilon(3S)}$ will provide an additional ~0.6M $\boldsymbol{\eta_b(1S)}$ and a clear opportunity to observe the transition to $\boldsymbol{\eta_b(2S)}$ in another production mode

Studies of $h_b(1P, 2P)$ and $\eta_b(1S, 2S)$

- Hence with these immense datasets Belle II will be well positioned to address many questions re: the singlets:
  - Refined BF measurements (both on production side – of particular interest are 5S/6S comparisons – and on decay side)
  - New channels observed, for example:
    - hindered M1 decays of $h_b(2P) \to \gamma\chi_{bJ}(1P)$ [and $\chi_b(2P) \to h_b(1P)$]
    - $\eta_b(2S) \to \pi\pi\eta_b(1S)$
    - $\eta_b(nS) \to \gamma\gamma$
  - Resolving the mass discrepancy between modes of production of $\eta_b(1S)$
  - Etc.

η_b(1,2S) from Υ(3S)



$M(\eta_b)_{M1} - M(\eta_b)_{E1}$ = -12 ± 3 MeV

$M(\eta_c)_{M1} - M(\eta_c)_{E1}$ = -7.7 ± 1.4 MeV

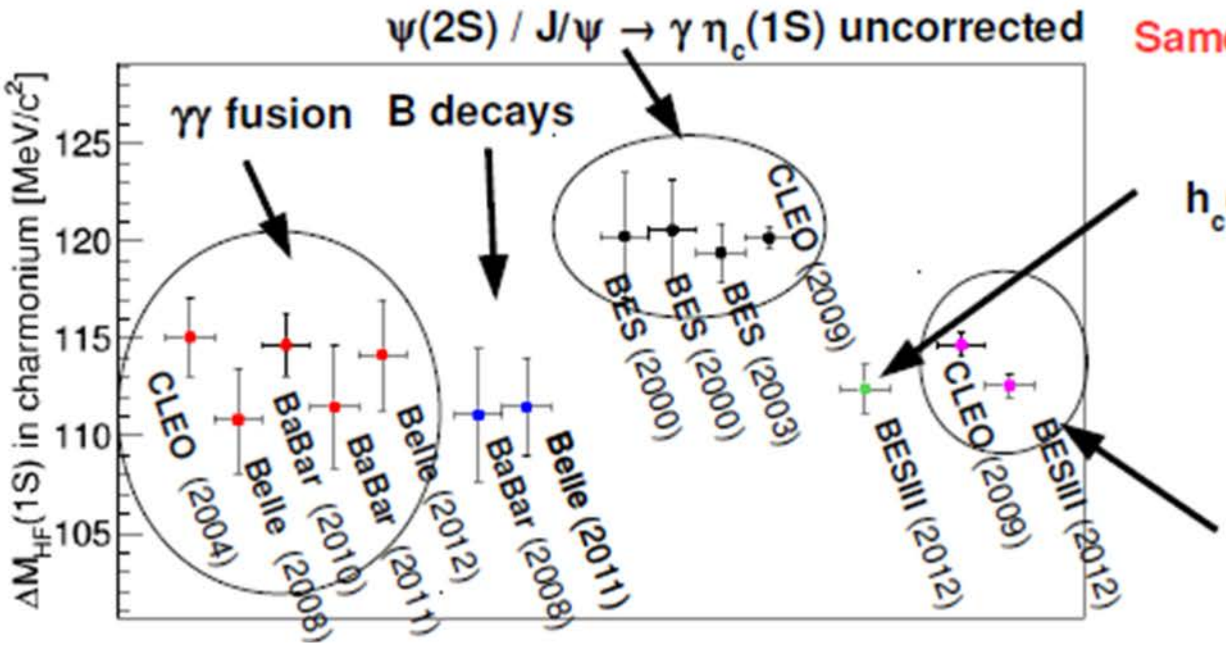
$M(\eta_c)$line shape factor:

$$E_\gamma^3 \exp\left(E_\gamma^{-2}/(8\beta^2)\right)$$

β = 65 ± 2.5 MeV

PRL 102 (2009) 011801,
Erratum-ibid. 106 (2011) 159903

Same factor for the η_b(1S)?



h_c(1P) → γ η_c(1S)

ψ(2S) / J/ψ → γ η_c(1S)
corrected

Dessert Menu

- ✓ Searches for odd-G parity molecular states (Voloshin) that are partners of the Z_b
- ✓ Observation of $\Upsilon(3S) \to \pi^0 h_b(1P)$
- ✓ Search for $\Upsilon(3S) \to \pi\pi h_b(1P)$
- ✓ Searches for $\chi_b(2P) \to \eta\eta_b$
- ✓ Resolving the $\chi_b(3P)$ into its three states
- ✓ R ratio decomposition from $\Upsilon(4S)$ to above $\Upsilon(6S)$
- ✓ Search for exotics on threshold (an X(3872) equivalent at just below $\bar{B}B$ threshold)

For more on these and other Belle II discussions of bottomonium / exotics:
R. Mussa @ PANIC
U. Tamponi @ DIS17
Belle II Physics Book (soon to be submited to PTEP)

If you find these topics inviting, please come talk at dinner tonight… perhaps over dessert!

Summary

- Belle has made significant contributions to our understanding of bottomonium and bottomonium-like states over the past decade
- With upgrades to both accelerator and detector in Belle II, our prospects for expanding the knowledge of these systems are bright
- Among the principal targets of our study:
  - **Charged and neutral four-quark Z states**
  - **Understanding the nature of $\Upsilon(6S)$ and its decay modes (c.f. $\Upsilon(5S)$)**
  - **Resolution of the $\Upsilon(1D)$, $\Upsilon(2D)$ systems and principal decays**
  - **Singlet-P and singlet-S states and their properties**
- We hope to show first results from our Phase 2 studies at Belle II in late 2018 and the 2019 winter conferences

Advertisement: Please see Kenkichi Miyabayashi's plenary talk at 15:00 tomorrow for a detailed discussion of Belle results on both bottomonium and charmonium exotics


Tak
Obrigado
감사합니다
Gracias
شكرا
Merci
شكرا لك
Thank you
Danke
謝謝
شكرا لك
Grazie
有り難う