Bottomonium, Charmonium and Exotic States

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Quarkonia

Heavy quarkonium is an ideal tool to study the “meson” which carries spin & angular momentum and described by (mostly non-relativistic) QCD (i.e., no weak decays) (e.g. Godfrey-Isgur, PRD32,169(1985))

Then isn’t it a boring job to find missing pieces in heavy quarkonia?

Well, e.g., no new $b\bar{b}$ state between 1983–2004, but we learned that we don’t understand the $X(3872)$ discovered in 2003...
Exotics Hadrons?

- Baryons and mesons — color SU(3) singlet

Baryon

Meson

- Other color-singlet meson-like states are possible
  Speculated for light hadrons over decades before B-factories

Molecule

Tetraquark

Hybrid

Glueball

- Today, heavy quarkonium(-like) states are shedding light as they provide narrow states and are better calculable
Bottomonia
\[ {^1P_1} (1^{--}) = \Upsilon(1S, 2S, 3S, 4S, 5S, 6S) \]

- In 1977, discovery of hidden beauty \( \Upsilon \), or \( \Upsilon(1S) \) and subsequent discoveries of \( \Upsilon \) series at \( e^+e^- \) colliders
- Belle and BaBar collected large dataset at \( \Upsilon \) peaks
  - Huge dataset at \( \Upsilon(4S) \) for \( B \) physics
    - \( B \) decays as the source of charmonium(-like) states
  - BaBar collected largest dataset of \( \Upsilon(3S) \)
    - Below \( B\bar{B} \) threshold, clean source for rich bottomonium spectrum
  - Belle collected largest dataset of \( \Upsilon(5S) \)
    - Above \( B^*\bar{B}^* \) threshold, for \( B_s \) physics, unexpectedly rich source
$^3P_{0,1,2} \ (0^{++}, 1^{++}, 2^{++}) = (\chi_{b0}, \chi_{b1}, \chi_{b2})$ triplets

- Radiative (E1, electric-dipole) transitions from and to $\gamma$
  Peak in photon energy from $\gamma$ at rest
- $\chi_b(1P)$ and $\chi_b(2P)$ discovered in 1982–3 (CUSB)
  $\Upsilon(2S) \rightarrow \chi_b(1P)\gamma$, $\Upsilon(3S) \rightarrow \chi_b(2P)\gamma$
$3^3P_J = \chi_b(3P)$ by ATLAS/D0

- $\chi_b(3P) \rightarrow \Upsilon(1S, 2S)\gamma$, $\Upsilon \rightarrow \mu^+\mu^-$, $\gamma$ conversion to $e^+e^-$
- Observed by ATLAS, confirmed by D0
- Spin-averaged mass: (triplet states are merged together)

| ATLAS: | $M(\chi_b(3P)) = 10530 \pm 9 \pm 5$ MeV |
| D0: | $M(\chi_b(3P)) = 10551 \pm 14 \pm 17$ MeV |

(Theory $10525$ MeV)

[ATLAS PRL108,152001(2012)]

[D0 arXiv:1203.6034]
$^1P_1 \ (1^{+-}) = h_b(1P) \text{ and } h_b(2P)$

- $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$ (BaBar) $\Rightarrow$ only weak signal
- $\Upsilon(5S) \rightarrow \pi^+\pi^- h_b(1P, 2P)$ (Belle) $\Rightarrow$ very strong signal

Recoil mass (= missing mass): $M(h_b) = \sqrt{[P(\Upsilon(5S)) - P(\pi^+\pi^-)]^2}$

Hyperfine splitting: $\Delta M_{HF} = M(h_b) - \frac{[M(\chi_{b0}) + 3M(\chi_{b1}) + 5M(\chi_{b2})]}{9} \approx 0$

$h_b(1P) \quad M = 9898.2^{+1.1}_{-1.0}^{+1.0} \text{ MeV} \quad \Delta M_{HF} = +1.7^{+1.5}_{-1.1} \text{ MeV}$

$h_b(2P) \quad M = 10259.8^{+0.6}_{-1.0}^{+1.4} \text{ MeV} \quad \Delta M_{HF} = +0.5^{+1.6}_{-1.2} \text{ MeV}$

BaBar 122M $\Upsilon(3S)$

arXiv:1102.4565

Belle 121.4 fb$^{-1}$
PRL108,032001
$1^1S_0 (0^{-+}) = \eta_b(1S)$

Radiative transition from $\Upsilon(3S)$

$$\mathcal{B}(\Upsilon(3S) \to \eta_b(1S)\gamma) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$$

[PRL101,071801(2008) BaBar 109M $\Upsilon(3S)$]

(also weakly confirmed by CLEO with 6M $\Upsilon(3S)$ [PRD81,031104(2010)])

$$M(\eta_b) = 9390.9 \pm 2.8 \text{ MeV} \quad \text{(BaBar+CLEO)}$$

$$\Delta M_{\text{HF}} = 69.3 \pm 2.8 \text{ MeV}$$

$$[\Delta M_{\text{HF}} \equiv M(\Upsilon(1S)) - M(\eta_b)]$$

$$\Delta M_{\text{HF}} = 60 \pm 8 \text{ MeV} \quad \text{(Lattice)}$$

$$\Delta M_{\text{HF}} = 41 \pm 14 \text{ MeV} \quad \text{(NRQCD)}$$

More promising? — radiative transition from $h_b$

- expected to be large, 41% from $h_b(1P)$, 13% from $h_b(2P)$, and also $h_b(2P) \to \eta_b(2S)\gamma$, 19% [Godfrey-Rosner, PRD66,014062(2002)]

- Belle has found strong $h_b(1P)$ and $h_b(2P)$ sample!
$1^1S_0 = \eta_b(1S)$ from $h_b(1P)$

[Belle $\Upsilon(5S) 121.4 \text{ fb}^{-1}$, arxiv:1110.3934]

- $\Upsilon(5S) \rightarrow h_b(1P) \pi^+ \pi^-$,
  $\rightarrow \eta_b(1S) \gamma \pi^+ \pi^-$

- $M_{\text{miss}}(\pi^+ \pi^-)$ to tag $h_b$,
  and $M_{\text{miss}}$ difference to tag $\eta_b$
  $M_{\text{miss}}(\pi^+ \pi^- \gamma) - M_{\text{miss}}(\pi^+ \pi^-)$

$M(\eta_b(1S)) = 9401.0 \pm 1.9^{+1.4}_{-2.4}$ MeV

$\Gamma(\eta_b(1S)) = 12.4^{+5.5}_{-4.6}^{+11.5}_{-3.4}$ MeV

$\Delta M_{\text{HF}} = 59.3 \pm 1.9^{+2.4}_{-1.4}$ MeV

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

First measurement of $\eta_b(1S)$ width,
Mass in a better agreement with theory,
Large branching fraction as expected
$2^1S_0 = \eta_b(2S)$ from $h_b(2P)$

[Belle $\Upsilon(5S)$ and scan data 133.4 fb$^{-1}$, IWHSS2012]

- Same analysis method:
  $\Upsilon(5S) \rightarrow h_b(2P) \pi^+ \pi^-$,
  $\rightarrow \eta_b(2S) \gamma \pi^+ \pi^-$,

- First $\eta_b(2S)$ evidence ($> 4\sigma$), with “look-elsewhere-effect”

\[
M(\eta_b(2S)) = 9999.0 \pm 3.5^{+2.8}_{-1.9} \text{ MeV} \\
(\text{width fixed to expectation})
\]

\[
\Delta M_{HF} = 24.3 \pm 3.5^{+2.8}_{-1.9} \text{ MeV}
\]

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

**HF splitting in agrees with theory (23.5 ± 4.7 MeV),**

**Large branching fraction as expected**

We consider the excess reported by Dobbs et al. using CLEO data (arxiv:1204.4205) is not $\eta_b(2S)$, since $\Delta M_{HF} = 48.7 \pm 2.7 \text{ MeV}$ is too high and production rate is anomalously large
$1^3D_J = \Upsilon(1D)$

- First and only one $L = 2$ state found in radiative decay chain [CLEO(2004)]
  \[
  \Upsilon(3S) \rightarrow \chi_b(2P)\gamma \rightarrow \Upsilon(1D)\gamma\gamma \\
  \rightarrow \chi_b(1P)\gamma\gamma\gamma \rightarrow \Upsilon(1S)\gamma\gamma\gamma\gamma
  \]

- Belle measured a new production chain
  \[
  \Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^- \\
  \rightarrow \chi_b(1P)\gamma\pi^+\pi^- \rightarrow \Upsilon(1S)\gamma\gamma\pi^+\pi^-
  \]

**CLEO**

\[ M = 10161.1 \pm 0.6 \pm 1.6 \text{ MeV} \]

Product $B = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$

**Belle preliminary [LaThuile2012]**

Product $B = (2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$
Exotic Bottomonia-like States
\( \Upsilon(5S) \) or \( \Upsilon_b \)?

- **Unexpectedly large** \( \Upsilon(5S) \to \Upsilon(1S, 2S, 3S)\pi^+\pi^- \)?
  - \( \Upsilon(2S, 3S, 4S) \to \Upsilon(1S, 2S, 3S)\pi^+\pi^- \) rates are tiny

- **Unexpectedly large** \( \Upsilon(5S) \to h_b(1P, 2P)\pi^+\pi^- \)?
  - \[ \frac{\Gamma(\Upsilon(5S) \to h_b(nP)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.407 \pm 0.079 & h_b(1P) \\ 0.78 \pm 0.09 & h_b(2P) \end{cases} \]
  - but should be suppressed because of spin-flip

- **Another exotic resonance** \( \Upsilon_b \) just nearby \( \Upsilon(5S) \)?
  - \( \Upsilon\pi^+\pi^- \) peak shifted by \( \sim 2\sigma \)? [Belle PRD82,091106R(2010)]
  - Similar to \( \Upsilon(4260) \to J/\psi\pi^+\pi^- \)?
  - \( e^+e^- \to h_c\pi^+\pi^- \) near \( \Upsilon(4260) \)
    - found by CLEO
  - \( e^+e^- \to h_b\pi^+\pi^- \) near \( \Upsilon_b \)?
Two horizontal bands in $\Upsilon \pi_\text{max}^\pm$ (charged!), fitted with:

$$A = A(Z_{b_1}^+) + A(Z_{b_2}^+) + A(f_0(980)) + A(f_2(1270)) + A(\text{NR})$$

• $f_0$ and $f_2$ to improve fit
• Slanted horizontal band due to $Z_b$–NR interference

$J^P = 1^+$ assumed, $S$-wave pion emission, consistent with uniform band (angular analysis in arxiv:1105.4583)

Relative phase between $Z_{b_1}$ & $Z_{b_2} \sim 0^\circ$ (clear gap between bands)
\[ \Upsilon(5S) \rightarrow h_b(1P, 2P)\pi^+\pi^- \text{ through } Z_b^+ \]

- \( M_{\text{miss}}(\pi^\pm) \) to look at \( h_b\pi^\mp \), fit with \( A(Z_{b1}) + A(Z_{b2}) + A(\text{NR}) \)
- \( \Upsilon(5S) \rightarrow h_b(1P)\pi^+\pi^- \) is saturated with \( Z_{b1} \) and \( Z_{b2} \) (zero-consistent non-resonant amplitude)
- \( \Upsilon(5S) \rightarrow h_b(2P)\pi^+\pi^- \) has very limited phase space, but consistent with \( Z_{b1} \) and \( Z_{b2} \)
- Phase between \( Z_{b1} \) & \( Z_{b2} \) \( \sim 180^\circ \) (constructive interference)
Charged states $Z_b(10610)$ and $Z_b(10650)$

- $\Upsilon(1S)\pi^+$
- $\Upsilon(2S)\pi^+$
- $\Upsilon(3S)\pi^+$
- $h_b(1P)\pi^+$
- $h_b(2P)\pi^+$

### Charged Bottomonia

$Z_b$ found in 5 decay channels

- Just above $B\bar{B}^*$ and $B^*\bar{B}^*$ threshold

Belle 121 fb$^{-1}$

PRL108,122001(2012)

$M = 10608.4 \pm 2.0$ MeV
$\Gamma = 15.6 \pm 2.5$ MeV

$M = 10653.2 \pm 1.5$ MeV
$\Gamma = 14.4 \pm 3.2$ MeV
What are known about $Z^+_b$

- $(B^*\bar{B})^+$ and $(B^*\bar{B}^*)^+$ molecule interpretation
  [Bondar et al, arxiv:1105.4473]

  - Masses just above $B^*\bar{B}$ and $B^*\bar{B}^*$
  - Similar production rate for $Z_{b1}$ and $Z_{b2}$
  - Similar decay width $\Gamma(Z_{b1}) \sim \Gamma(Z_{b2})$
  - Why $\Upsilon(5S) \rightarrow h_b\pi^+\pi^-$ is not suppressed
  - Relative phase: $\sim 0^\circ$ for $\Upsilon\pi$ and $\sim 180^\circ$ for $h_b\pi$
  - $J^P = 1^+$ assignment ($0^\pm$ forbidden, $1^-$, $2^\pm$ disfavored at $\sim 3\sigma$)

- Other possible explanations
  - Coupled channel resonances — Danilkin et al, arxiv:1106.1552
  - Cusp — Bugg, arxiv:1105.5492
  - Tetraquark — Karliner-Lipkin, arxiv:0802.0649

Certainly more than $\bar{b}b$, not conclusive but interesting!
Exotic Charmonia-like States
**X, Y, Z**

- **X(3872)** — strong signal, starting point of everything
  - Discovery by Belle (2003), followed by D0, CDF, BaBar, LHCb, CMS
  - Decays into $J/\psi \pi^+ \pi^- (\sim \rho^0)$, $J/\psi \pi^+ \pi^- \pi^0 (\sim \omega)$, $D^{*0} \overline{D}^0$, $J/\psi \gamma$, $\psi(2S)\gamma$
  - Properties still under investigation

- **Y-series in ISR (1--)** — $Y(4260)$, $Y(4360)$, $Y(4660)$, (etc?)
  - Many states in addition to $\psi$ series ($L = 0$, $n^3S_1$ or $L = 2$, $n^3D_1$)

- **Charged Z states ($Z(4430)^+, Z(4050)^+, Z(4250)^+$)**
  - At least 4 quarks (or 2 mesons): molecule, tetraquark, cusp...
  - Belle’s signal neither confirmed nor refuted by BaBar

- **Need confirmation**
  - $X(3915)$? $Y(3940)$? = $\chi_{c2}(2P)(3930)$?, or yet missing $\chi_{c0}(2P)$?
  - $X(4350)$? $Y(4630) = Y(4660)$? …?
$X(3872)$ collection

World Average

$M(X(3872)) = 3871.67 \pm 0.17$ MeV

$\Gamma(X(3872)) < 1.2$ MeV

Bottomonium, Charmonium and Exotic States — M. Nakao — p.21
What are known about $X(3872)$

- $C = +1$: $X(3872) \to J/\psi \rho$ and $X(3872) \to J/\psi \gamma$
- $C = -1$ partner so far not found (predicted for exotic case)
- $J^{PC} = 1^{++}$ or $2^{-+}$ (next slide)
- Probably $I = 0$: no charged partner $X^+$ found, Isospin violating decay $X(3872) \to J/\psi \pi^+ \pi^-$
- Mass just around $D^* \bar{D}$
  - $M_X - M_{D^*0} - M_{\bar{D}^0} = -0.12 \pm 0.35$ MeV
  - $M_X - M_{D^{*+}} - M_{D^-} = -7.74 \pm 0.35$ MeV
- Possible $c\bar{c}$ interpretation:
  - $\chi_{c1}(2^3P_1)$ for $1^{++}$, but predicted mass is too low
    - [$\chi_{c2}(2^3P_2)$ was found by Belle (confirmed by BaBar) with $M = 3927$ MeV]
  - $\eta_{c2}(1^1D_2)$ for $2^{-+}$
- Possible exotic interpretation:
  - $D^{*0}\bar{D}^0$ molecule ($J^P = 1^+$)
  - Tetraquark
**X(3872): 1^{++} vs 2^{--}**

- **CDF angular analysis:** 1^{++} or 2^{--} \[\text{[PRL98,132002(2007)]}\]

**Belle** \(X \rightarrow J/\psi \pi^+ \pi^-\) \[\text{[PRD84,052004(2011)]}\]

**BaBar** \(X \rightarrow J/\psi \pi^+ \pi^- \pi^0\) \[\text{[PRD82,011101R(2010)]}\]

(one of three angles, the others are similar)

- **Neither fit has significant discrimination**
  - Distinguishable with more statistics

- **A few remarks for 1^{++}**
  - Molecule predicts \(J = 1\)
  - Belle’s \(J = 2\) fit requires some parameter tuning
  - Not found in \(\gamma \gamma \rightarrow X\) (allowed if \(J = 2\))
**Y(4260) update & Y(4005) refutation**

- **BaBar found** $Y(4260)$ in ISR $e^+e^- \rightarrow J/\psi \pi^+\pi^-$ (2005)
- **CLEO-c/CLEO III/Belle confirmed**, Belle might have found another peak $Y(4005)$
- **New BaBar result does not confirm** $Y(4005)$
  \[ M = 4244 \pm 5 \pm 4 \text{ MeV}; \Gamma = 114^{+16}_{-15} \pm 7 \text{ MeV} \]  
  [arxiv:1204.2158]

- **BaBar 454 fb$^{-1}$** (around $\Upsilon(4S)$)
  Preliminary

- **17 ± 13% goes via** $f_0(980)$, interfering with continuum $\pi^+\pi^-$
**Y(4360) update & Y(4660) confirmation**

- **BaBar** found \( Y(4360) \) in ISR \( e^+e^- \rightarrow \psi(2S)\pi^+\pi^- \) (2007)
- **Belle** confirmed \( Y(4360) \) in ISR, and have found another peak \( Y(4660) \)
- **New BaBar result** confirms \( Y(4660) \) [QNP2012/Charm2012] \((\psi(2S) \rightarrow \ell^+\ell^- \text{ is also analyzed})\)

### Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( M(Y(4360)) ) (MeV)</th>
<th>( \Gamma(Y(4360)) ) (MeV)</th>
<th>( M(Y(4660)) ) (MeV)</th>
<th>( \Gamma(Y(4660)) ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Belle</strong></td>
<td>4361 ± 9 ± 9</td>
<td>74 ± 15 ± 10</td>
<td>4664 ± 11 ± 5</td>
<td>48 ± 15 ± 3</td>
</tr>
<tr>
<td><strong>BaBar</strong></td>
<td>4340 ± 16 ± 9</td>
<td>94 ± 32 ± 13</td>
<td>4669 ± 21 ± 3</td>
<td>104 ± 48 ± 10</td>
</tr>
</tbody>
</table>

(unit in MeV)

**Bottomonium, Charmonium and Exotic States — M. Nakao — p.25**
What are known about $\Upsilon$

- At least three $\Upsilon$ states of $1^{--}$
  - $\Upsilon(4260) \rightarrow J/\psi \pi^+ \pi^-$
  - $\Upsilon(4360) \rightarrow \psi(2S) \pi^+ \pi^-$
  - $\Upsilon(4660) \rightarrow \psi(2S) \pi^+ \pi^-$

- Above $D\bar{D}$ threshold and not (dominantly?) decaying to open charm, $D^{(*)}\bar{D}^{(*)}$
  - CLEO-c run at $\sqrt{s} = 4.26$ GeV [PRD80,072001(2009)]
  - CLEO-c found large $\Upsilon(4260) \rightarrow h_c \pi^+ \pi^-$ rate [PRL107,041803(2011)]

- Overpopulated $1^{--}$ entries, $\Upsilon$ states not likely to be $c\bar{c}$ states
  - $1^{--}$ below $D\bar{D}$ threshold: $L = 0$ charmonia, $J/\psi$ and $\psi(2S)$
  - $1^{--}$ above $D\bar{D}$ threshold: $\psi(3770), \psi(4040), \psi(4140), \psi(4415) \ldots$
  - Candidate for hybrid states, tetraquark or other possibilities?
New Charmonia Members
**X(3915)**

- **Two photon process**, $\gamma\gamma \rightarrow J/\psi\omega$, $J = 0$ or $J = 2$

  **Belle** $694 \text{ fb}^{-1}$, PRL104,092001(2010)

  **BaBar** $520 \text{ fb}^{-1}$, preliminary (Moriond QCD)

<table>
<thead>
<tr>
<th></th>
<th>$M$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>$3915 \pm 3 \pm 2$</td>
<td>$17 \pm 10 \pm 3$</td>
</tr>
<tr>
<td>BaBar</td>
<td>$3919.4 \pm 2.2 \pm 1.6$</td>
<td>$13 \pm 6 \pm 3$</td>
</tr>
</tbody>
</table>

- **Angular analysis to assign** $J^P$ **is on-going** (BaBar)
  (Angular distribution shown at Moriond QCD needs further checking)

- **Same state as** $\Upsilon(3940) \rightarrow J/\psi\omega$ **found in** $B \rightarrow J/\psi\omega K$?
  (BaBar finds at $3919.1^{+3.8}_{-3.5} \pm 2.0$ MeV $\Leftrightarrow$ Belle's $3943 \pm 11 \pm 13$ MeV)

- **$c\bar{c}$ interpretation:** $\chi_{c0}(2P)$? $\chi_{c2}(2P)$?
$1^3D_2 = \psi_2$

**Belle 711 fb$^{-1}$**
preliminary
[Moriond QCD 2012]

$\psi' \rightarrow \chi_{c1}\gamma$

$\psi' \not\rightarrow \chi_{c1}\gamma$

$4.2\sigma$ peak in $\chi_{c1}\gamma$
in $B^+ \rightarrow (\chi_{c1}\gamma)K^+$

$M = 3823.5 \pm 2.8$ MeV, $\Gamma$ consistent with zero

- Consistent with missing $\psi_2(1^3D_2)$ ($2^{--}$), E1 transition to $\chi_{c1}$ as expected (1$^3D_1$ state is $\psi(3770)$, 1$^3D_3$ state is still missing)
- No hint for $X(3872) \rightarrow \chi_{c1}\gamma$
Recent results omitted today

(bottomonia(-like))

- **Dobbs et al (CLEO data)**, excess in radiative decay of $\Upsilon(2S)$
  [arXiv:1204.4205]

- **BaBar**, $\Upsilon(3S) \to h_b\pi^+\pi^-$ search [arXiv:1102.4565]

- **Belle**, $\Upsilon(2S) \to \eta\Upsilon(1S)$, and $\Upsilon(2S) \to \pi^0\Upsilon(1S)$ search [QWG2011, XL.Wang]

- **Belle**, $\Upsilon(5S) \to \eta\Upsilon(1S, 2S)$, and $\Upsilon(5S) \to \eta'\Upsilon(1S)$ search [LaThuile2012, Krokovny]

(charmonia(-like))

- **BaBar**, searches in $\gamma\gamma \to \eta_c\pi^+\pi^-$ [Charm2012, Prencipe]

- **Belle**, $C = -1$ state search in $J/\psi\eta$ [Charm2012, Iwashita]

- **Belle**, $X(3872)$ and $\psi_2$ search in $\chi_{c2}\gamma$ [Charm2012, Bhardwaj]

- **Belle**, $Z_c^+$ search in $B \to J/\psi\pi K$ ($2.8\sigma$, inconclusive) [Charm2012, Chilikin]

(search = negative or inconclusive result)

... apologies for any missing results
Summary

Conventional charmonia & bottomonia are well-established, But unexpected exotics are still only vaguely understood

- $\eta_b$ & $h_b$: missing pieces of bottomonia table finally found
- Charged state $Z_b^+$ is a clear sign of something new!
- Lots of information accumulated to understand $X, Y, Z$
- $\psi_2$: filling the charmonia table, and still more empty seats
- New contributions from ATLAS/CMS/LHCb

More to work at Belle II / SuperB 😊
Backup
$\eta_b(2S)$ signal?

arXiv:1204.4205 (S. Dobbs et al.) from CLEO data

Seth: Trento April 2012

Belle: IWHSS’12 April, 2012

Belle: $h_b(2P) \rightarrow \gamma \eta_b(2S)$

Bf[$h_b(2P) \rightarrow \gamma h_b(2S)$] about right

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Expt | $\Delta M_{\text{hfs}}(2S)$ (MeV)
---|---
S. Dobbs | 48.7 ± 2.7
Belle | 24.3 ± 4.3

strong disagreement with theory agrees with theory

≈5σ discrepancy

anomalously large production rate (~0.2 × $\chi_{b1}$ rate)