Bottomonium, Charmonium and Exotic States

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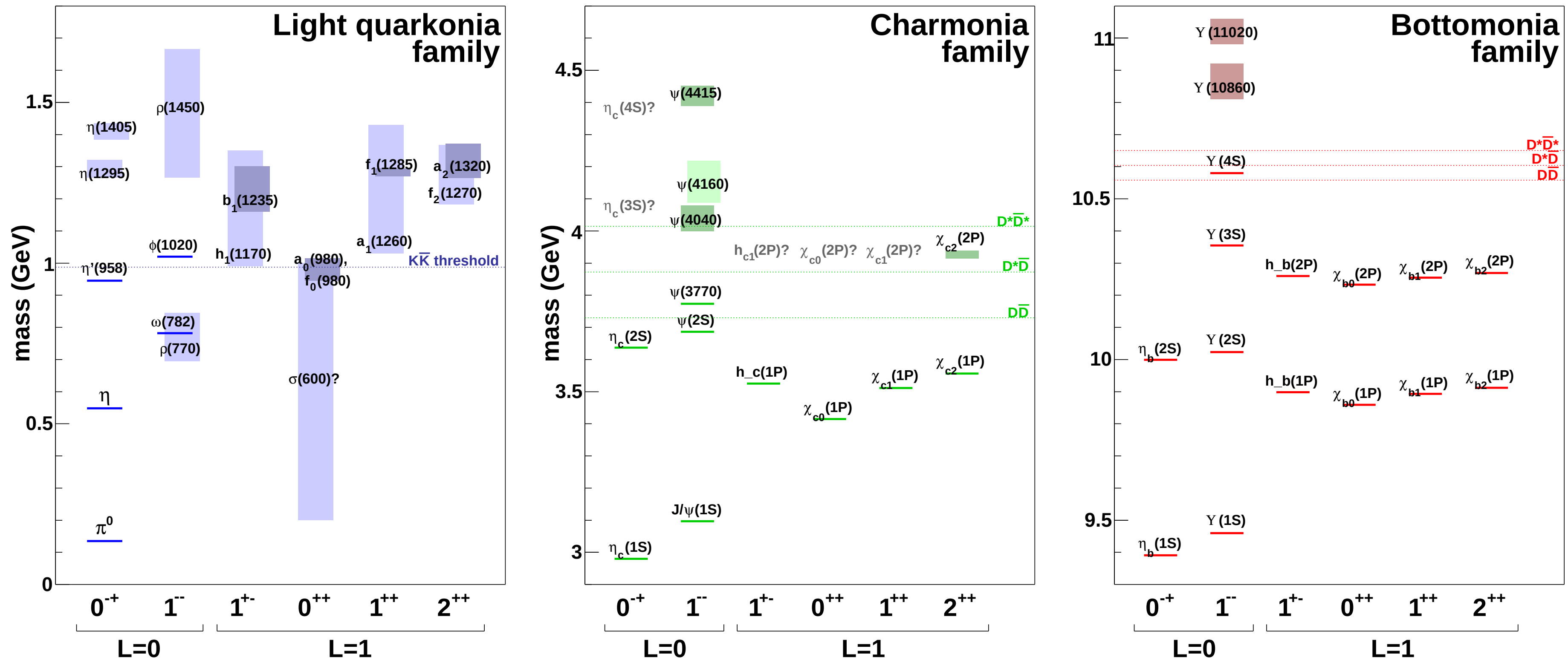
27 Mai–1 Juin, 2012,

Châteux de Blois

Annular Solar Eclipse in Tsukuba at 07:35am, 21 May 2012

Quarkonia

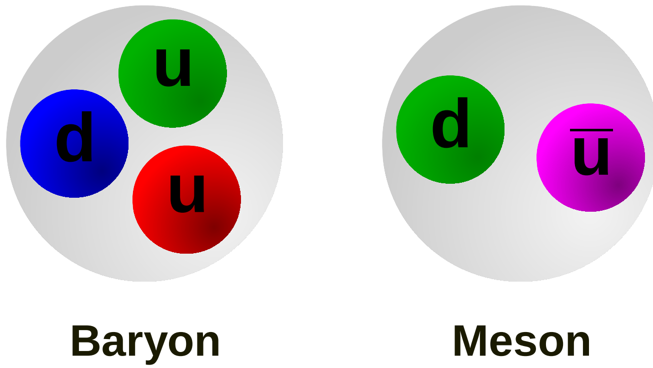
Heavy quarkonium is an ideal tool to study the "meson" which carries spin & angular momentum and described by (mostly non-relativistic) QCD (i.e., no weak decays) (e.g. Godfrey-Isgur, PRD32,169(1985))



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

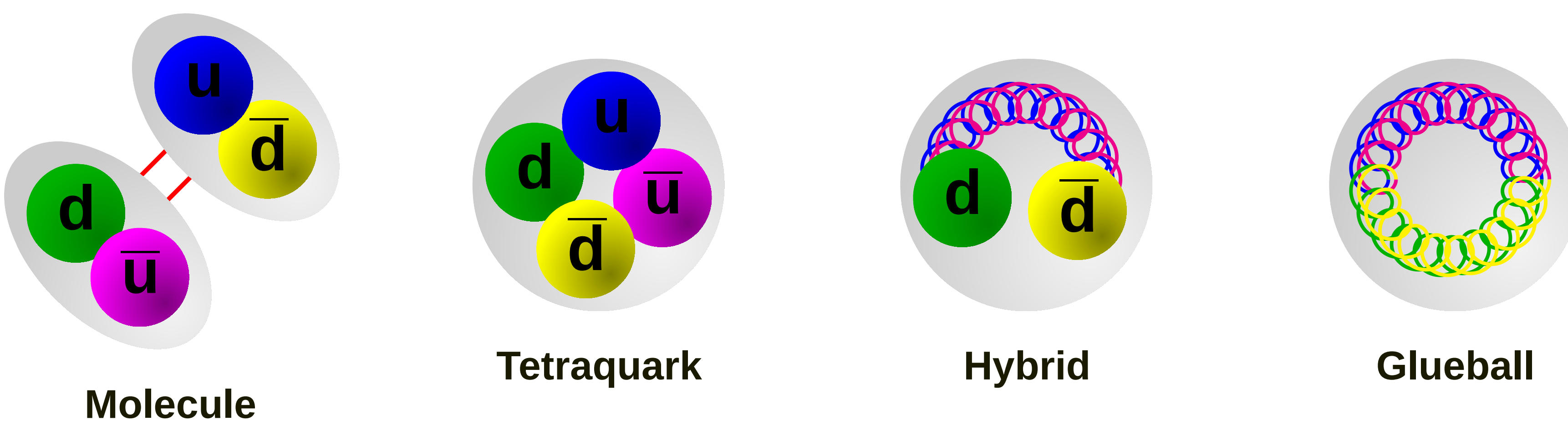
➡ ***Well, e.g., no new*** $b\bar{b}$ ***state between 1983–2004, but we learned that we don't understand the*** $X(3872)$ ***discovered in 2003. . .***

Exotics Hadrons?



- **Baryons and mesons — color SU(3) singlet**

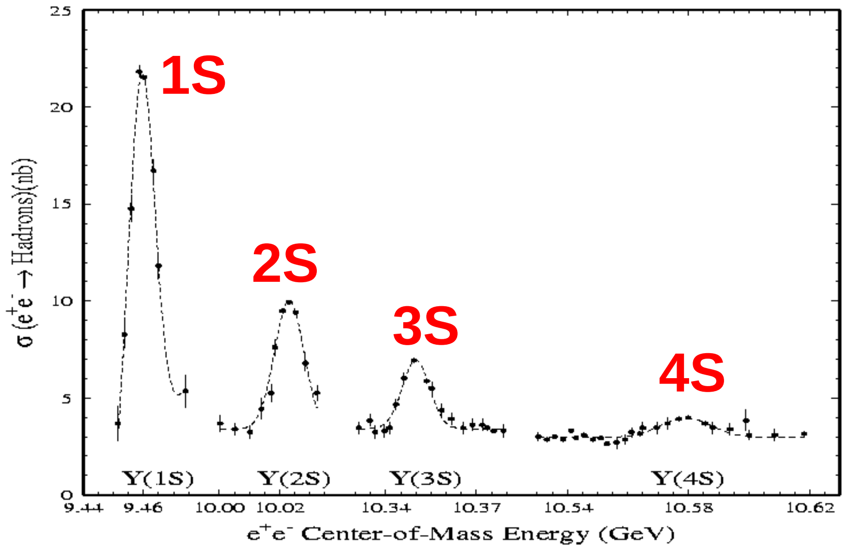
- **Other color-singlet meson-like states are possible**
  Speculated for light hadrons over decades before B-factories

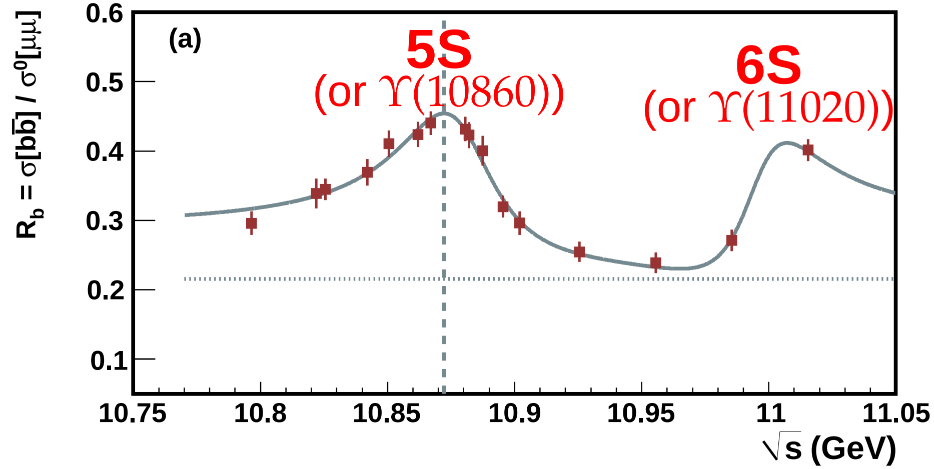


- **Today, heavy quarkonium(-like) states are shedding light**
  as they provide narrow states and are better calculable

Bottomonia

$^1P_1\ (1^{--}) = \Upsilon(1S, 2S, 3S, 4S, 5S, 6S)$

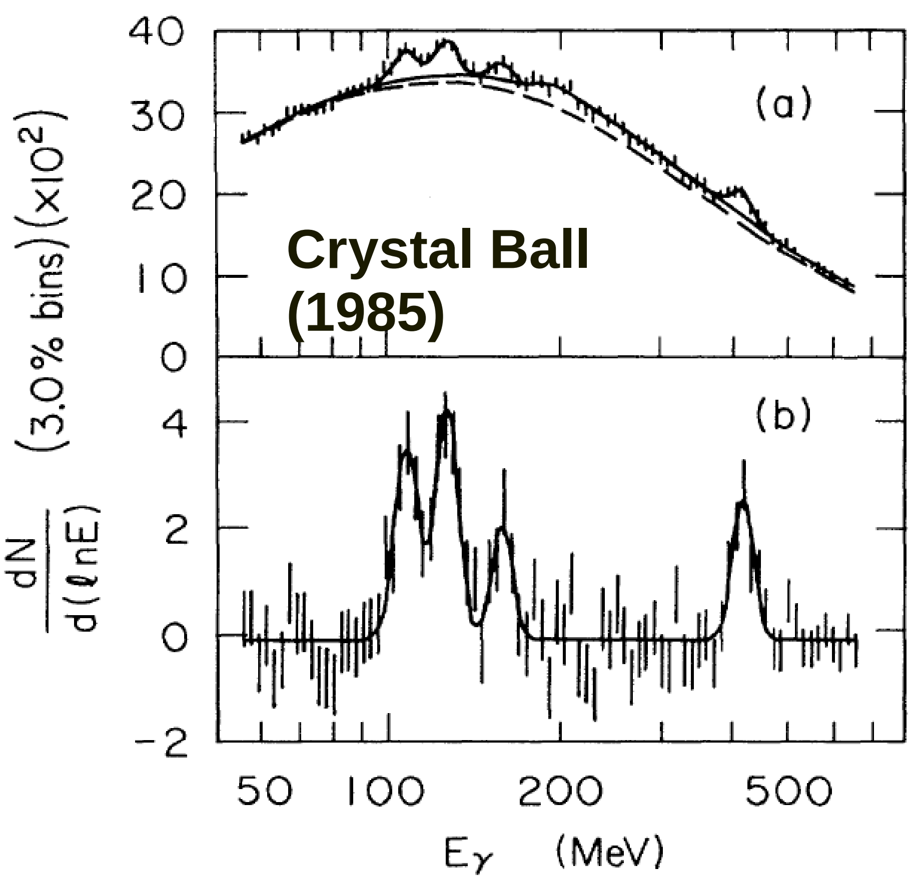


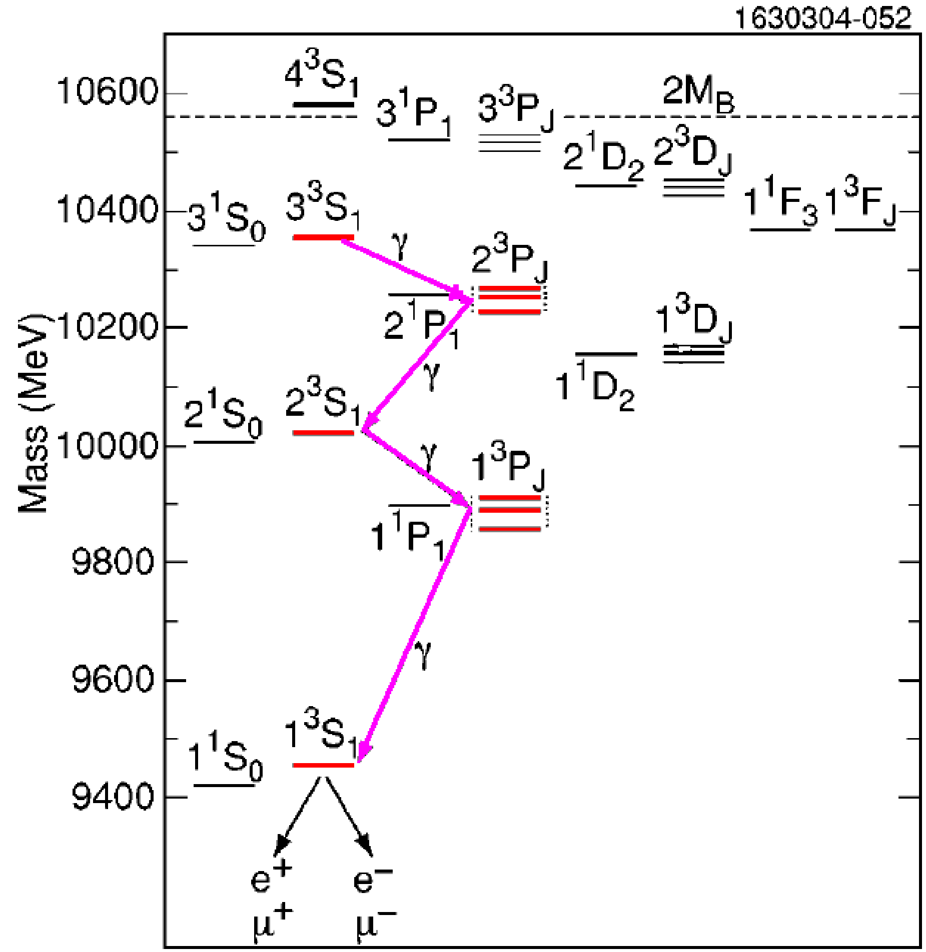


- **In 1977, discovery of hidden beauty Υ, or $\Upsilon(1S)$**
  and subsequent discoveries of Υ series at e^+e^- colliders
- **Belle and BaBar collected large dataset at Υ peaks**
  - **Huge dataset at $\Upsilon(4S)$ for B physics**
    B decays as the source of charmonium(-like) states
  - **BaBar collected largest dataset of $\Upsilon(3S)$**
    Below $B\overline{B}$ threshold, clean source for rich bottomonium spectrum
  - **Belle collected largest dataset of $\Upsilon(5S)$**
    Above $B^*\overline{B}^*$ 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 Υ**
  Peak in photon energy from Υ at rest
- **$\chi_b(1P)$ and $\chi_b(2P)$ discovered in 1982–3** (CUSB)
  $\Upsilon(2S) \to \chi_b(1P)\gamma$, $\Upsilon(3S) \to \chi_b(2P)\gamma$





$3^3P_J = \chi_b(3P)$ by ATLAS/D0

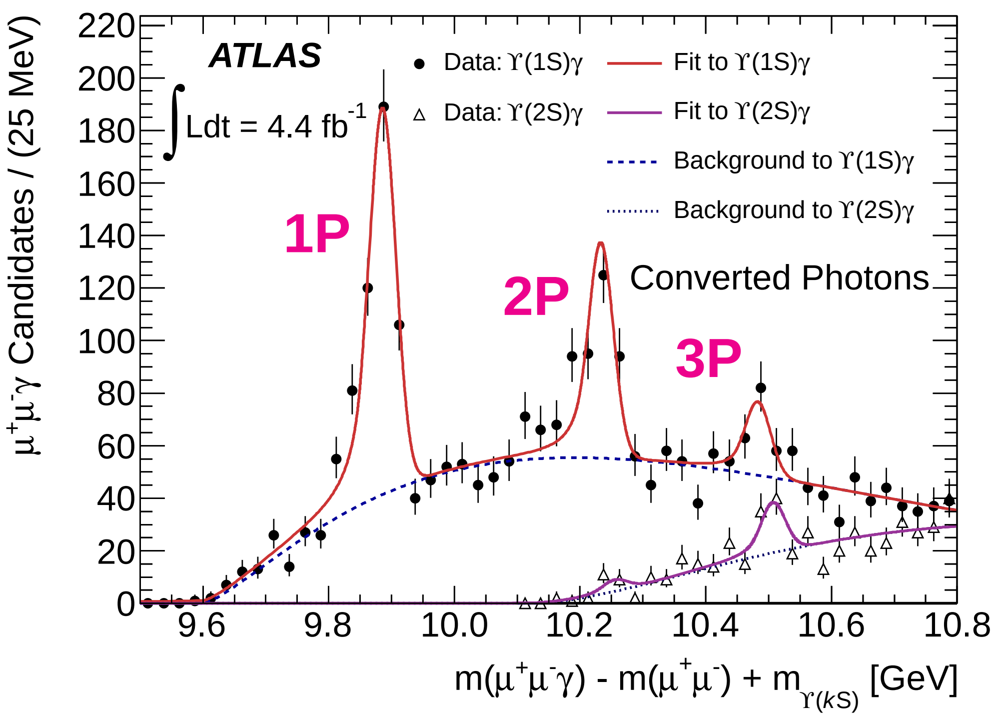
- $\chi_b(3P) \to \Upsilon(1S, 2S)\gamma$, $\Upsilon \to \mu^+\mu^-$, γ conversion to e^+e^-
- Observed by ATLAS, confirmed by D0
- Spin-averaged mass: (triplet states are merged together)

ATLAS: $M(\chi_{bJ}(3P)) = 10530 \pm 9 \pm 5$ MeV

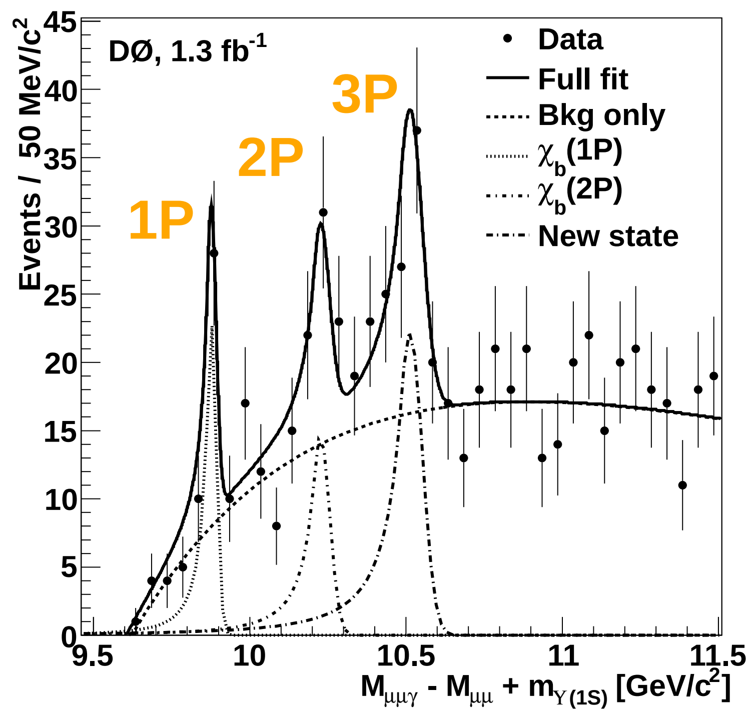
D0: $M(\chi_{bJ}(3P)) = 10551 \pm 14 \pm 17$ MeV

(theory 10525 MeV)

[ATLAS PRL108,152001(2012)]



[D0 arXiv:1203.6034]



$^1P_1$ (1^{+-}) = $h_b(1P)$ and $h_b(2P)$

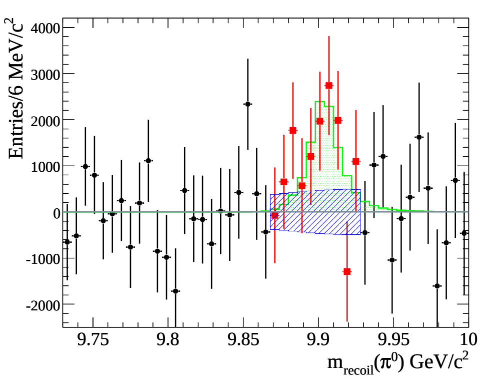
- $\Upsilon(3S) \to \pi^0 h_b(1P)$ (BaBar) $\Rightarrow$ only weak signal
- $\Upsilon(5S) \to \pi^+\pi^- h_b(1P, 2P)$ (Belle) $\Rightarrow$ **very strong signal**

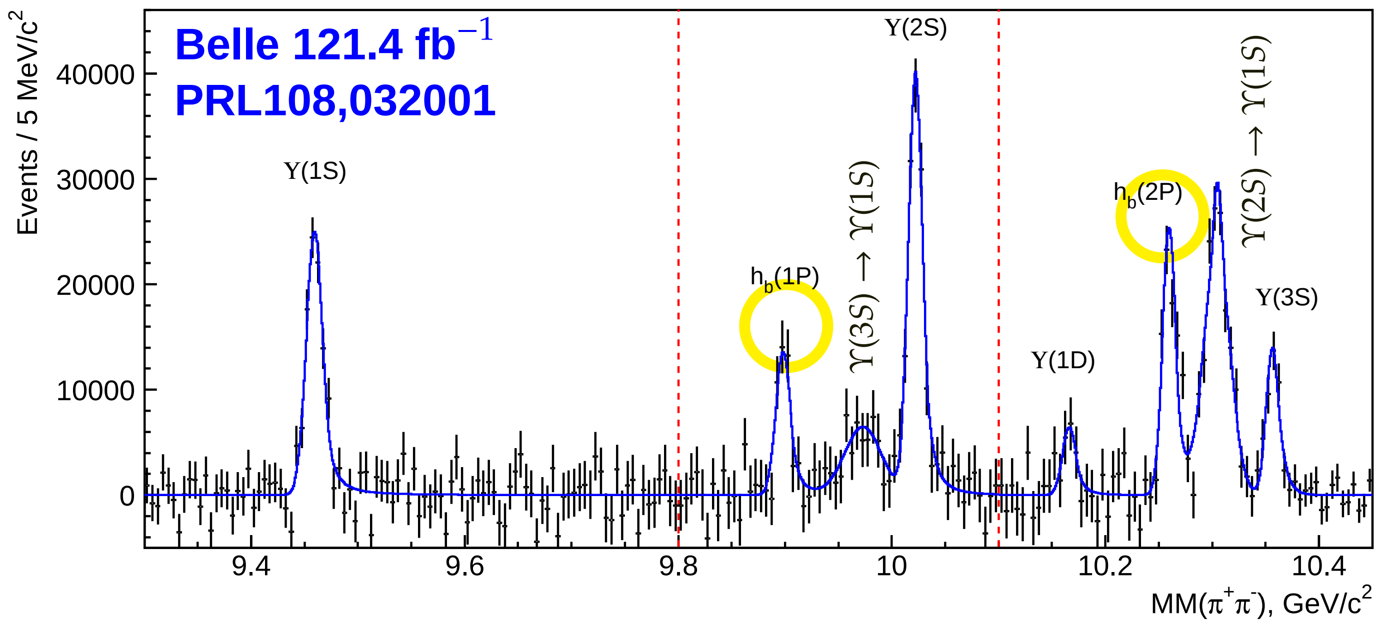
Recoil mass (=missing mass): $M(h_b) = \sqrt{[P(\Upsilon(5S)) - P(\pi^+\pi^-)]^2}$

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

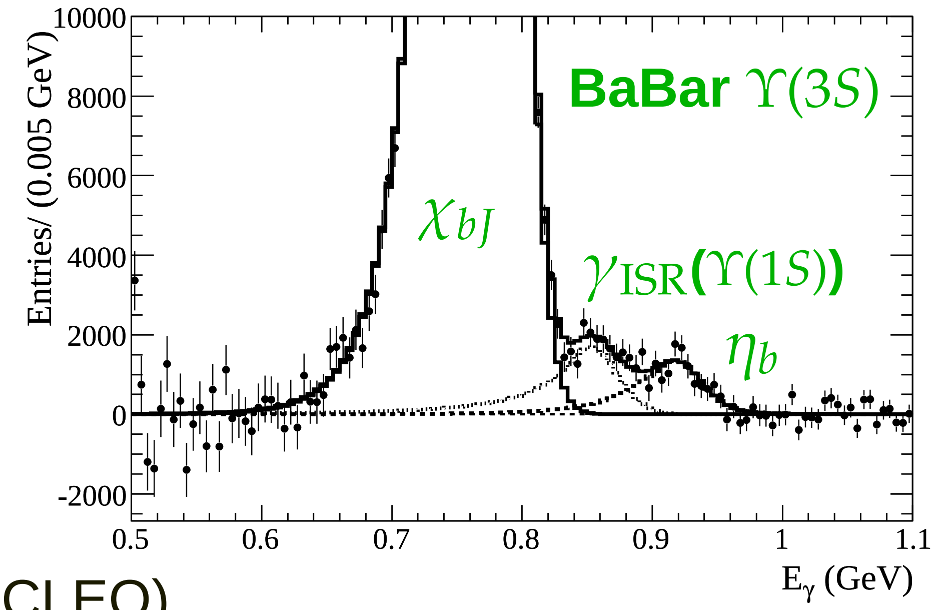
$h_b(1P)$	$M = 9898.2\,^{+1.1}_{-1.0}\,^{+1.0}_{-1.1}$ **MeV**	$\Delta M_{HF} = +1.7 \pm 1.5$ **MeV**
$h_b(2P)$	$M = 10259.8 \pm 0.6\,^{+1.4}_{-1.0}$ **MeV**	$\Delta M_{HF} = +0.5\,^{+1.6}_{-1.2}$ **MeV**

BaBar 122M $\Upsilon(3S)$
arXiv:1102.4565





$1^1S_0\ (0^{-+}) = \eta_b(1S)$



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)])

$M(\eta_b) = 9390.9 \pm 2.8$ MeV (BaBar+CLEO)

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

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

$\Leftrightarrow$

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

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

(small tension?)

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 $h_b(1P)$

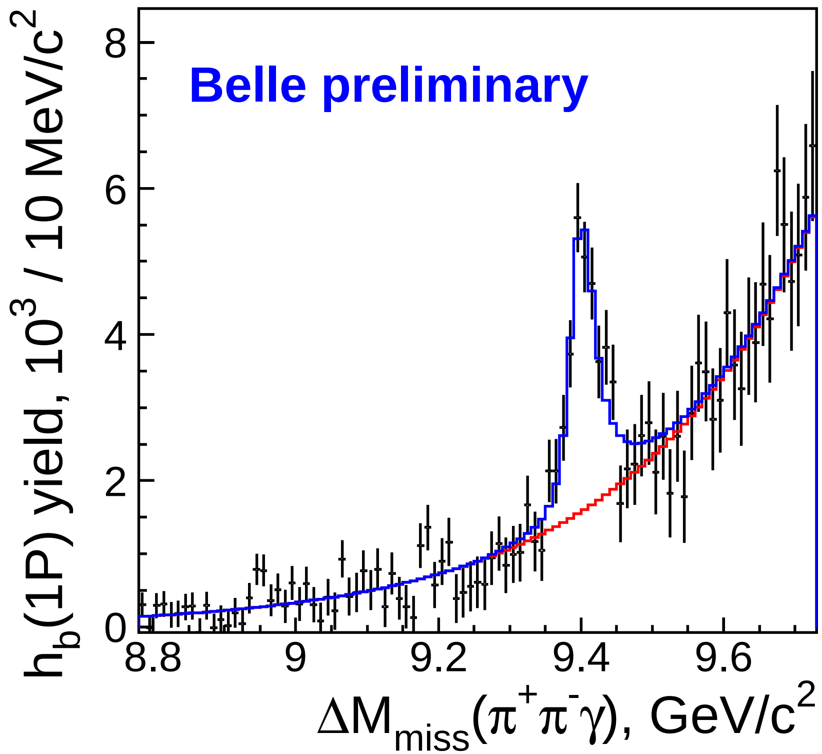
[Belle $\Upsilon(5S)$ 121.4 fb^{-1}, arxiv:1110.3934]

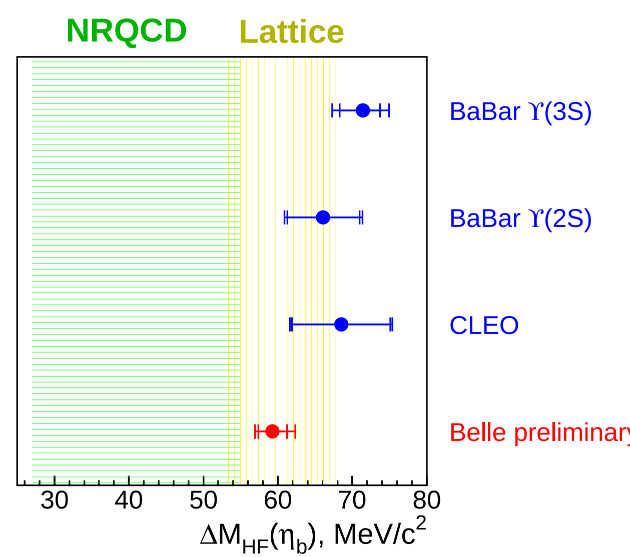
- $\Upsilon(5S) \to h_b(1P)\,\pi^+\pi^-$,
  $\to \eta_b(1S)\,\gamma\,\pi^+\pi^-$
- $M_{\rm miss}(\pi^+\pi^-)$ **to tag** h_b,
  and $M_{\rm miss}$ **difference to tag** η_b
  $M_{\rm miss}(\pi^+\pi^-\gamma) - M_{\rm miss}(\pi^+\pi^-)$

$$M(\eta_b(1S)) = 9401.0 \pm 1.9\,^{+1.4}_{-2.4}\ \text{MeV}$$
$$\Gamma(\eta_b(1S)) = 12.4\,^{+5.5}_{-4.6}\,^{+11.5}_{-3.4}\ \text{MeV}$$
$$\Delta M_{\rm HF} = 59.3 \pm 1.9\,^{+2.4}_{-1.4}\ \text{MeV}$$
$$\mathcal{B}_{h_b(1P)\to\eta_b(1S)\gamma} = (49.8 \pm 6.8\,^{+10.9}_{-5.2})\%$$

First measurement of $\eta_b(1S)$ width,
Mass in a better agreement with theory,
Large branching fraction as expected

$h_b(1P)$ **yields in $\Delta M_{\rm miss}$ bins**





$2^1S_0 = \eta_b(2S)$ from $h_b(2P)$

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

- **Same analysis method:**
  $\Upsilon(5S) \to h_b(2P)\,\pi^+\pi^-$,
  $\to \eta_b(2S)\,\gamma\,\pi^+\pi^-$,
- **First $\eta_b(2S)$ evidence ($> 4\sigma$), with "look-elsewhere-effect"**

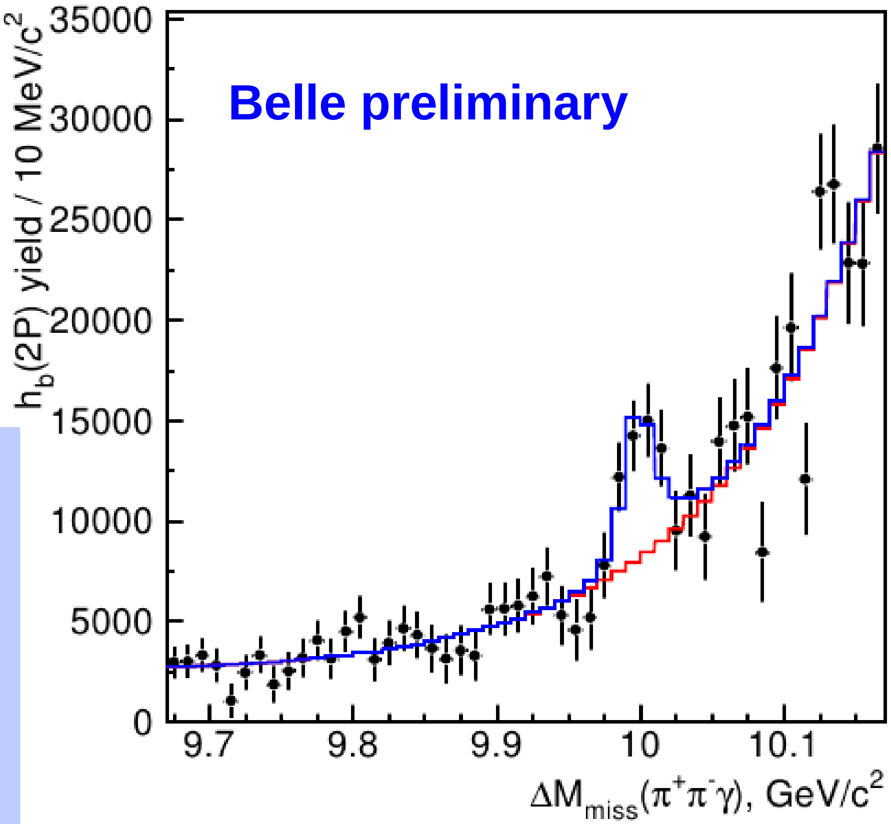
$$M(\eta_b(2S)) = 9999.0 \pm 3.5\,^{+2.8}_{-1.9}\ \text{MeV}$$

(width fixed to expectation)

$$\Delta M_{\rm HF} = 24.3 \pm 3.5\,^{+2.8}_{-1.9}\ \text{MeV}$$

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

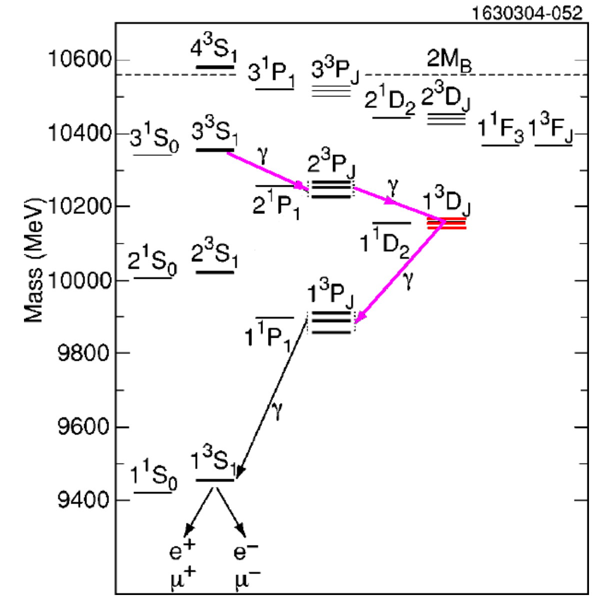
$h_b(2P)$ **yields in $\Delta M_{\rm miss}$ bins**



***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 $\Delta M_{HF} = 48.7 \pm 2.7$ MeV is too high and production rate is anomalously large

$1^3D_J = \Upsilon(1D)$



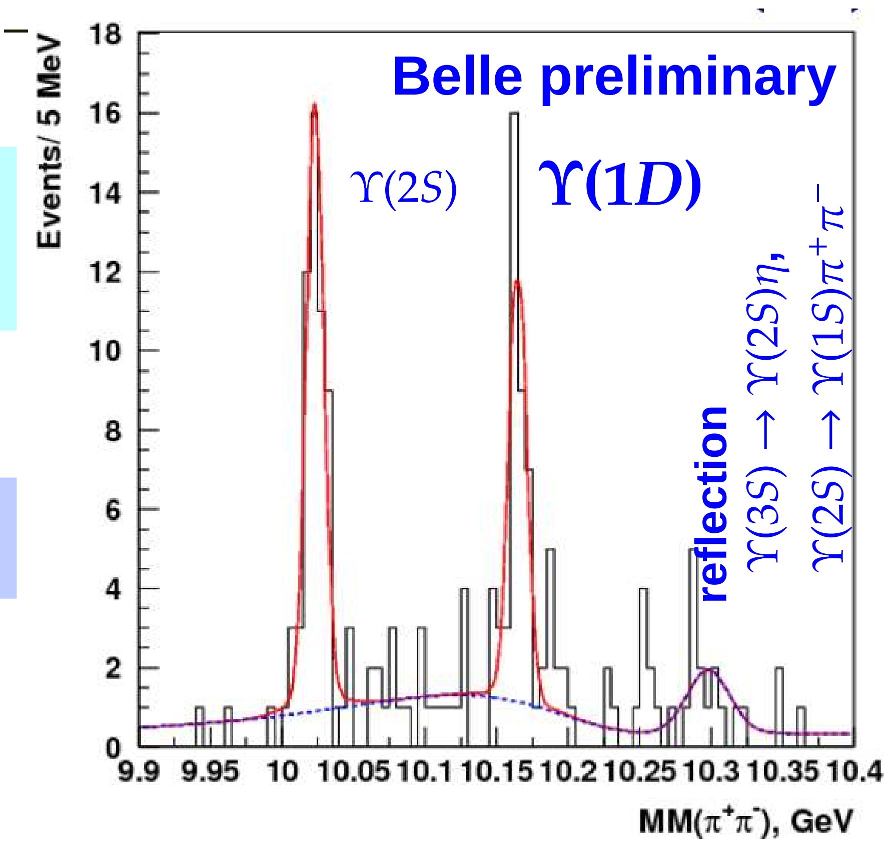
- **First and only one $L = 2$ state found in radiative decay chain** [CLEO(2004)]
  $\Upsilon(3S) \to \chi_b(2P)\gamma \to \Upsilon(1D)\gamma\gamma$
  $\to \chi_b(1P)\gamma\gamma\gamma \to \Upsilon(1S)\gamma\gamma\gamma\gamma$
- **Belle measured a new production chain**
  $\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-$
  $\to \chi_b(1P)\gamma\pi^+\pi^- \to \Upsilon(1S)\gamma\gamma\pi^+\pi^-$

CLEO

$M = 10161.1 \pm 0.6 \pm 1.6$ **MeV**
product $\mathcal{B} = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$

Belle preliminary [LaThuile2012]

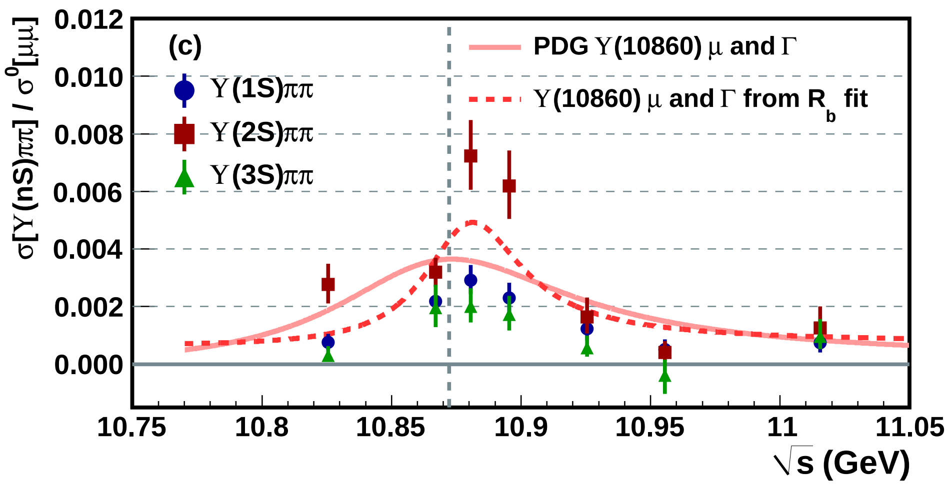
product $\mathcal{B} = (2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$



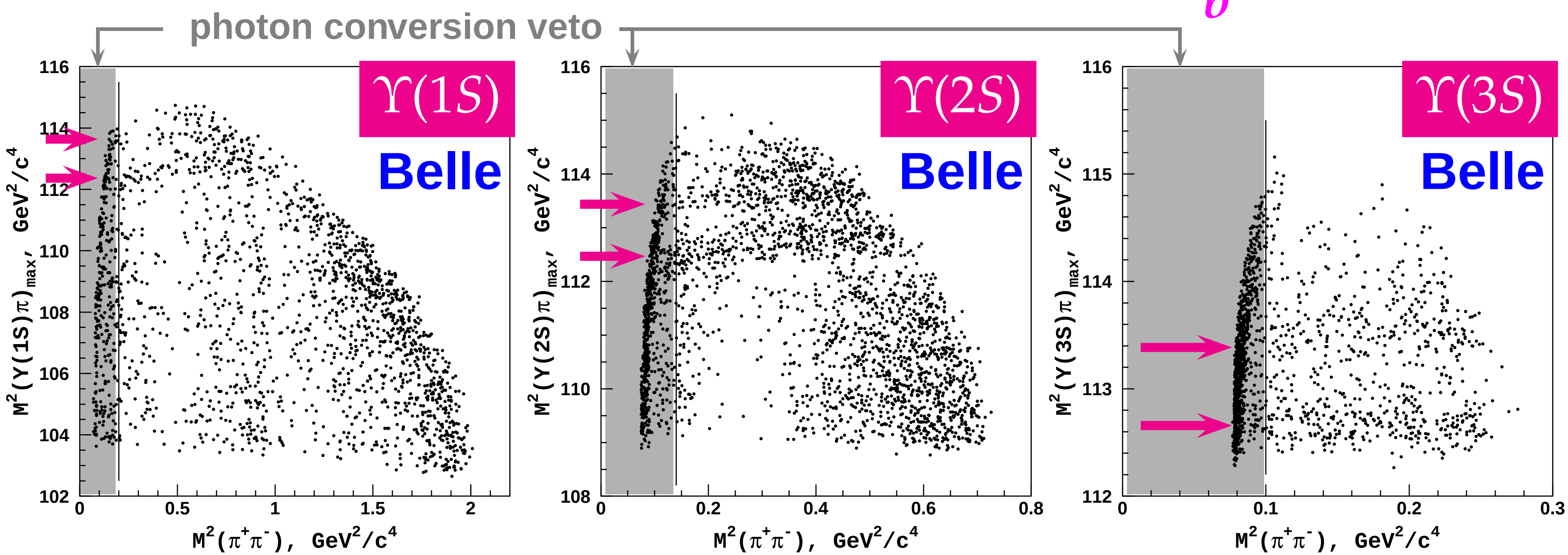
Exotic Bottomonia-like States

$\Upsilon(5S)$ or Y_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 $\Upsilon(5S) \to h_b(1P,2P)\pi^+\pi^-$?**
  - $$\frac{\Gamma(\Upsilon(5S) \to h_b(nP)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.407 \pm 0.079\,^{+0.043}_{-0.076} & h_b(1P) \\ 0.78 \pm 0.09\,^{+0.22}_{-0.10} & h_b(2P) \end{cases}$$
    but should be suppressed because of spin-flip
- **Another exotic resonance Y_b just nearby $\Upsilon(5S)$?**
  - $\Upsilon\pi^+\pi^-$ peak shifted by $\sim 2\sigma$? [Belle PRD82,091106R(2010)]
  - Similar to $Y(4260) \to J/\psi\pi^+\pi^-$?
  - $e^+e^- \to h_c\pi^+\pi^-$ near $Y(4260)$ found by CLEO
    $e^+e^- \to h_b\pi^+\pi^-$ near Y_b?

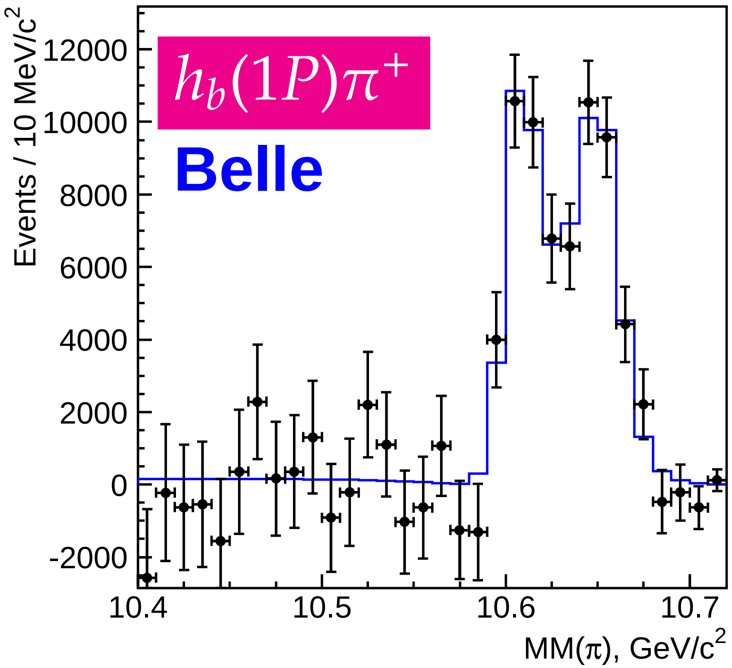


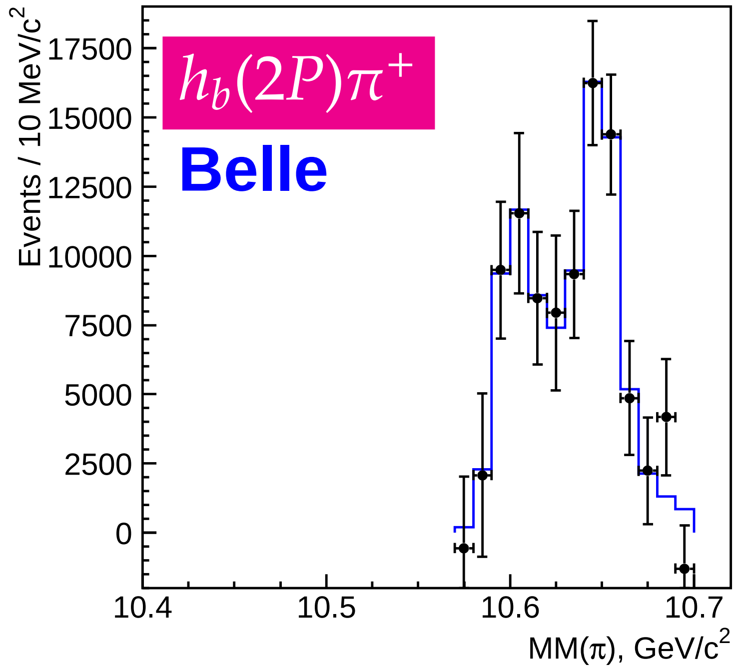
$\Upsilon(5S) \to \Upsilon(1S,2S,3S)\pi^+\pi^-$ through Z_b^+



- **Two horizontal bands in** $\Upsilon\pi^\pm_{\rm max}$ **(charged!), fitted with:**
  $A = A(Z^+_{b1}) + A(Z^+_{b2}) + A(f_0(980)) + A(f_2(1270)) + A(\textbf{NR})$
  - 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_{b1} **&** $Z_{b2} \sim 0^\circ$ (clear gap between bands)

$\Upsilon(5S) \to h_b(1P, 2P)\pi^+\pi^-$ through Z_b^+

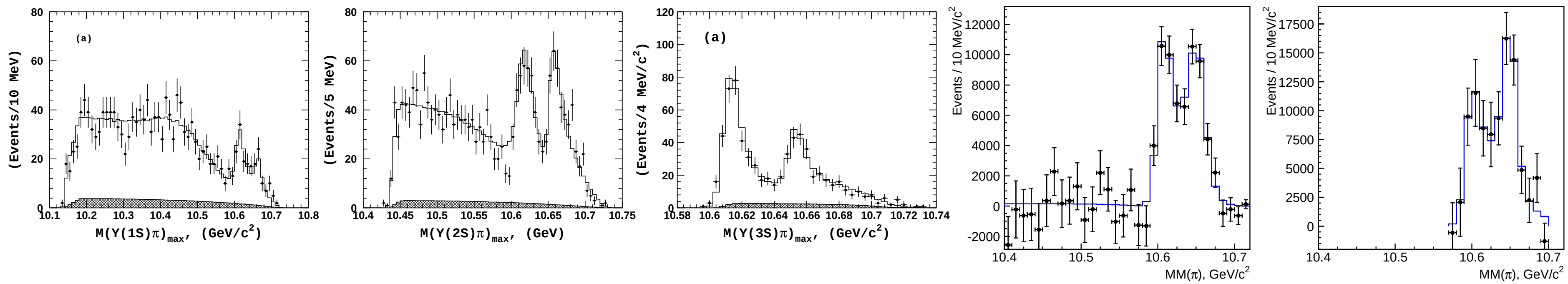


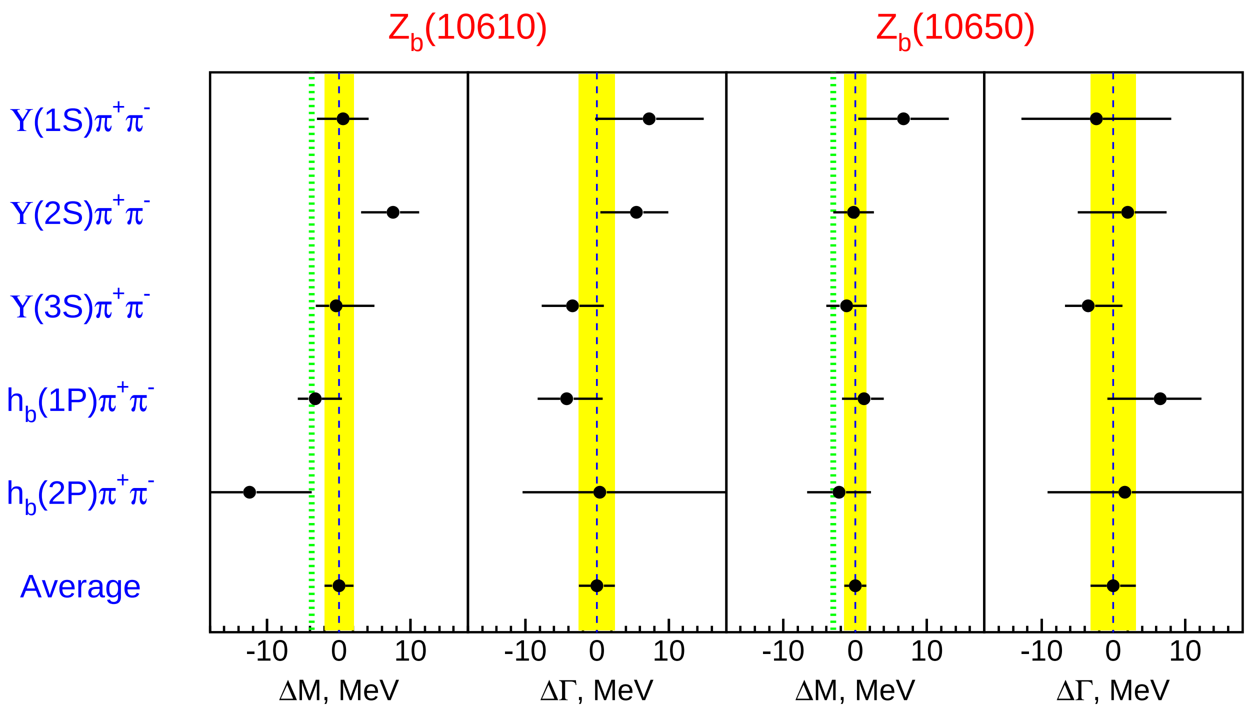


- $M_{\text{miss}}(\pi^\pm)$ **to look at** $h_b\pi^\mp$**, fit with** $A(Z_{b1}) + A(Z_{b2}) + A(\text{NR})$
- $\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$ **is saturated with** Z_{b1} **and** Z_{b2}
  (zero-consistent non-resonant amplitude)
- $\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$ **has very limited phase space, 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 BB^* and B^*B^* threshold

Belle 121 fb^{-1}
PRL108,122001(2012)

$Z_b(10610)$	$Z_b(10650)$
$M = 10608.4 \pm 2.0$ **MeV**	$M = 10653.2 \pm 1.5$ **MeV**
$\Gamma = 15.6 \pm 2.5$ **MeV**	$\Gamma = 14.4 \pm 3.2$ **MeV**

What are known about Z_b^+

- $(B^*\overline{B})^+$ **and** $(B^*\overline{B}^*)^+$ **molecule interpretation** [Bondar et al, arxiv:1105.4473]
  - Masses just above $B^*\overline{B}$ and $B^*\overline{B}^*$
  - Similar production rate for Z_{b1} and Z_{b2}
  - Similar decay width $\Gamma(Z_{b1}) \sim \Gamma(Z_{b2})$
  - Why $\Upsilon(5S) \to h_b\pi^+\pi^-$ is not suppressed
  - Relative phase: $\sim 0°$ for $\Upsilon\pi$ and $\sim 180°$ 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

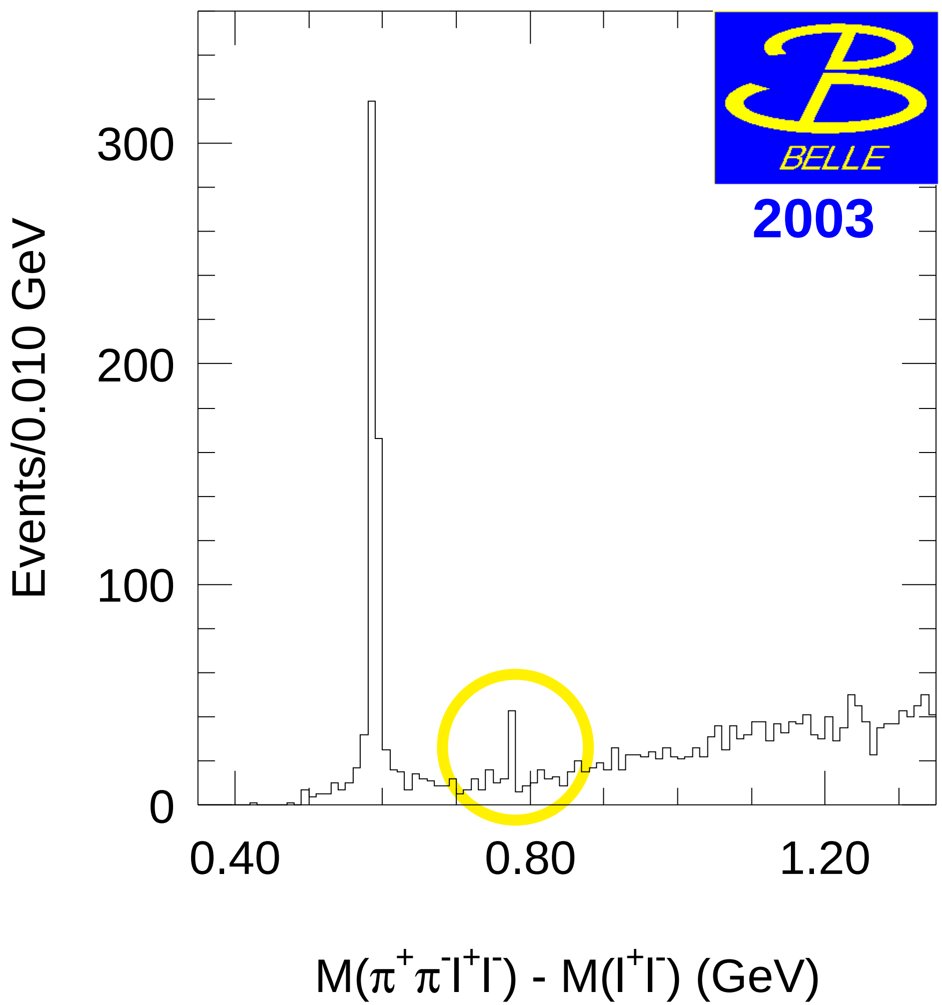
Certainly more than $b\overline{b}$, not conclusive but interesting!

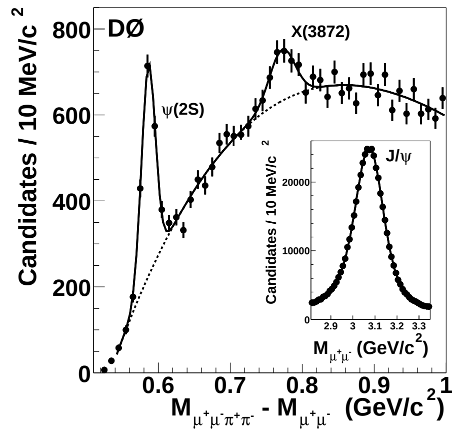
Exotic Charmonia-like States

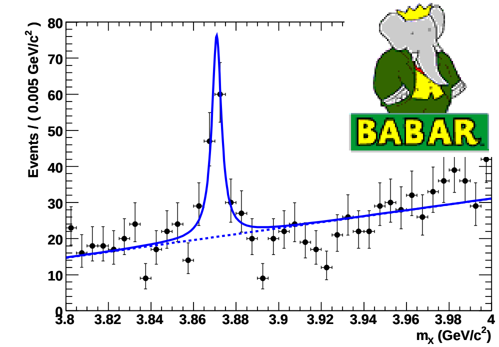
X, Y, Z

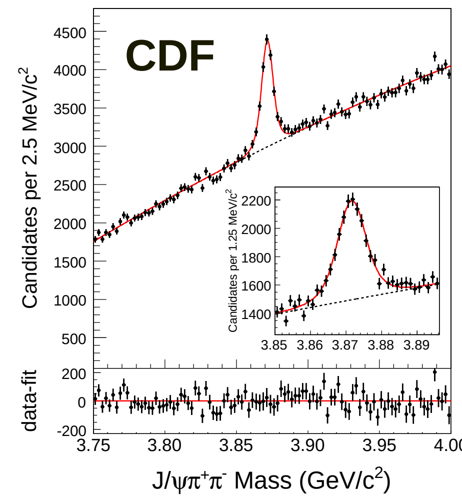
- $X(3872)$ **— strong signal, starting point of everything**
  - Discovery by Belle (2003), followed by D0, CDF, BaBar, LHCb, CMS
  - Decays into $J/\psi\pi^+\pi^-(\sim\rho^0)$, $J/\psi\pi^+\pi^-\pi^0(\sim\omega)$, $D^{*0}\overline{D}^0$, $J/\psi\gamma$, $\psi(2S)\gamma$
  - Properties still under investigation
- Y**-series in ISR (1^{--}) —** $Y(4260)$**,** $Y(4360)$**,** $Y(4660)$**,** (etc?)
  - Many states in addition to ψ 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 $\chi_{c0}(2P)$?
  - $X(4350)$? $Y(4630) = Y(4660)$? . . . ?

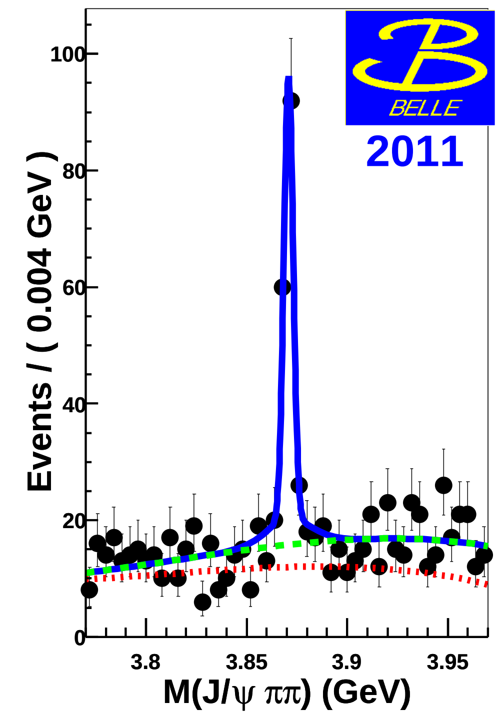
$X(3872)$ collection

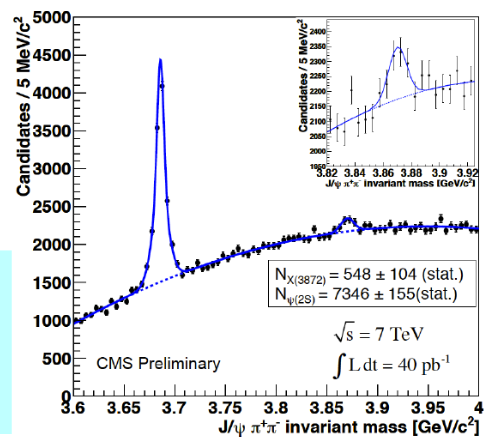


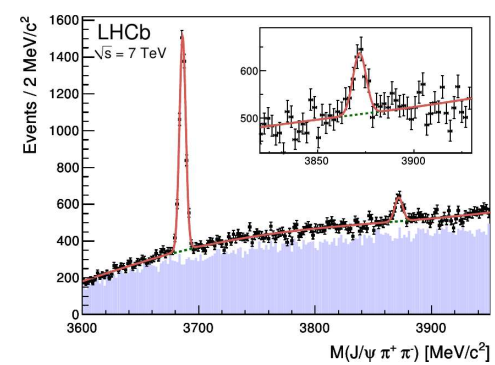












World Average

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

$$\Gamma(X(3872)) < 1.2\ \textbf{MeV}$$

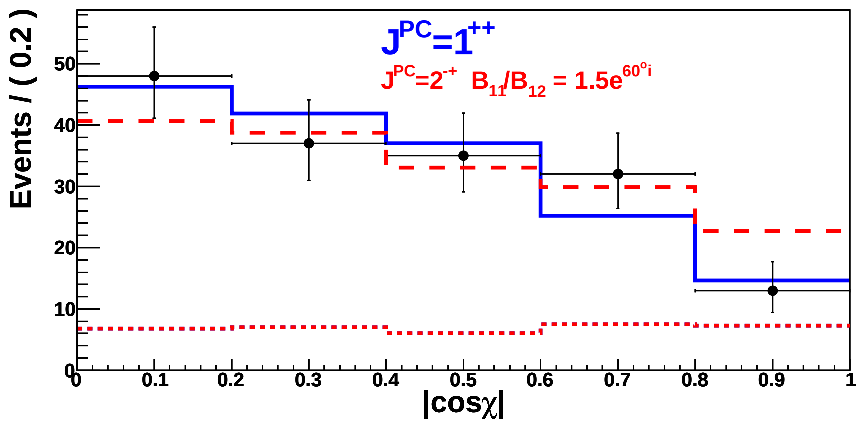
What are known about $X(3872)$

- $C = +1$: $X(3872) \to J/\psi\rho$ **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** $D^*\overline{D}$ $\left\langle \begin{array}{l} M_X - M_{D^{*0}} - M_{\overline{D}^0} = -0.12 \pm 0.35 \text{ MeV} \\ M_X - M_{D^{*+}} - M_{D^-} = -7.74 \pm 0.35 \text{ MeV} \end{array} \right.$
- **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:**
  - $D^{*0}\overline{D}^0$ molecule ($J^P = 1^+$)
  - Tetraquark

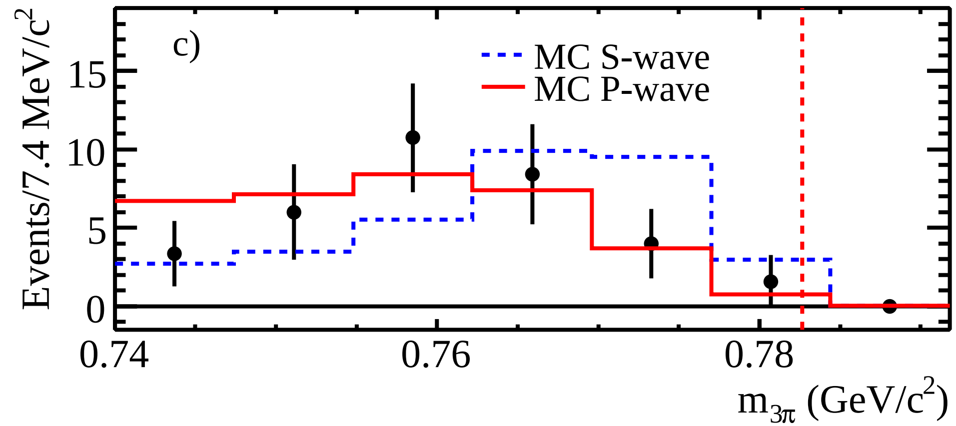
$X(3872)$: 1^{++} vs 2^{-+}

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

Belle $X \to J/\psi\pi^+\pi^-$ **[PRD84,052004(2011)]**



BaBar $X \to J/\psi\pi^+\pi^-\pi^0$ **[PRD82,011101R(2010)]**



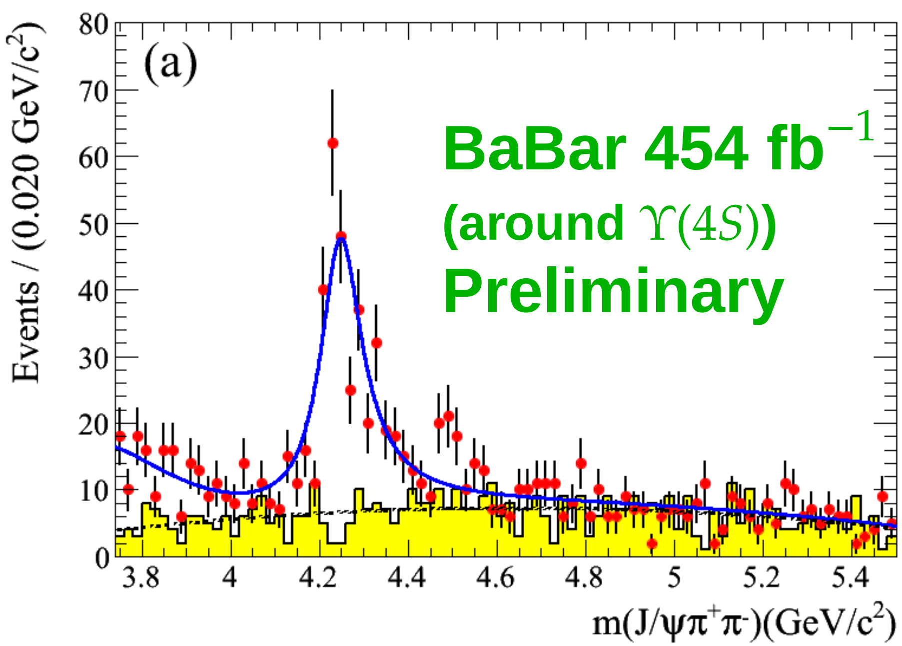
(one of three angles, the others are similar)

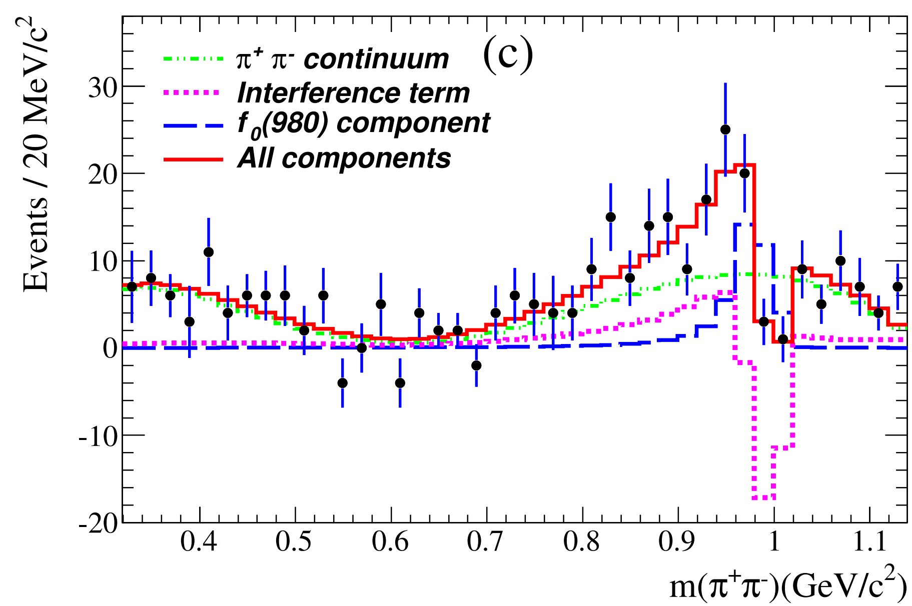
- **Neither fit has significant discrimination**
  Distinguishable with more statistics
- **A few remarks for** 1^{++}
  - Molecule predicts $J = 1$
  - Belle's $J = 2$ fit requires some parameter tuning
  - Not found in $\gamma\gamma \to X$ (allowed if $J = 2$)

$Y(4260)$ update & $Y(4005)$ refutation

- **BaBar found** $Y(4260)$ **in ISR** $e^+e^- \to J/\psi\pi^+\pi^-$ **(2005)**
- **CLEO-c/CLEO III/Belle confirmed,**
  Belle might have found another peak $Y(4005)$
- **New BaBar result does not confirm** $Y(4005)$

$M = 4244 \pm 5 \pm 4$ **MeV;** $\Gamma = 114\,^{+16}_{-15} \pm 7$ **MeV** **[arxiv:1204.2158]**



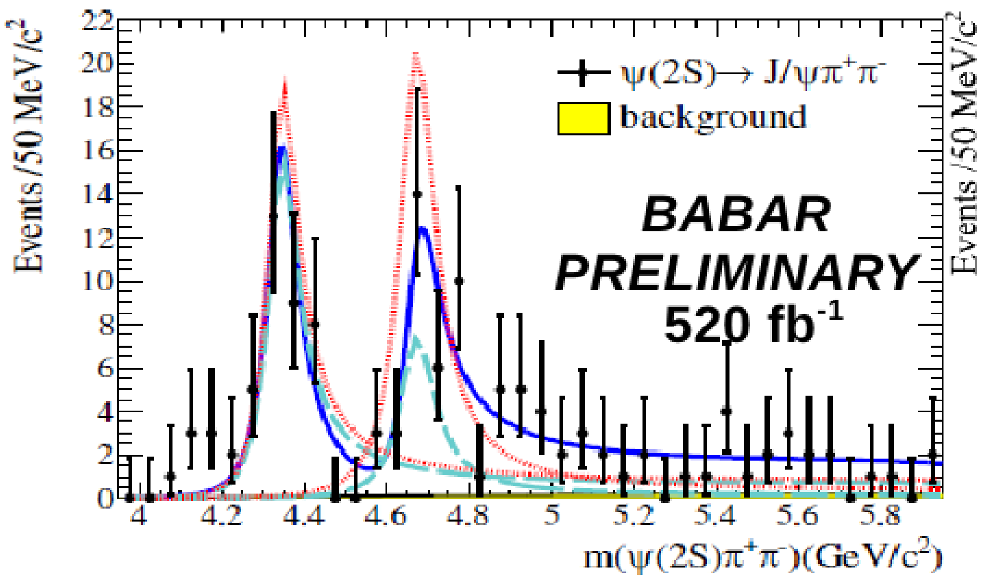


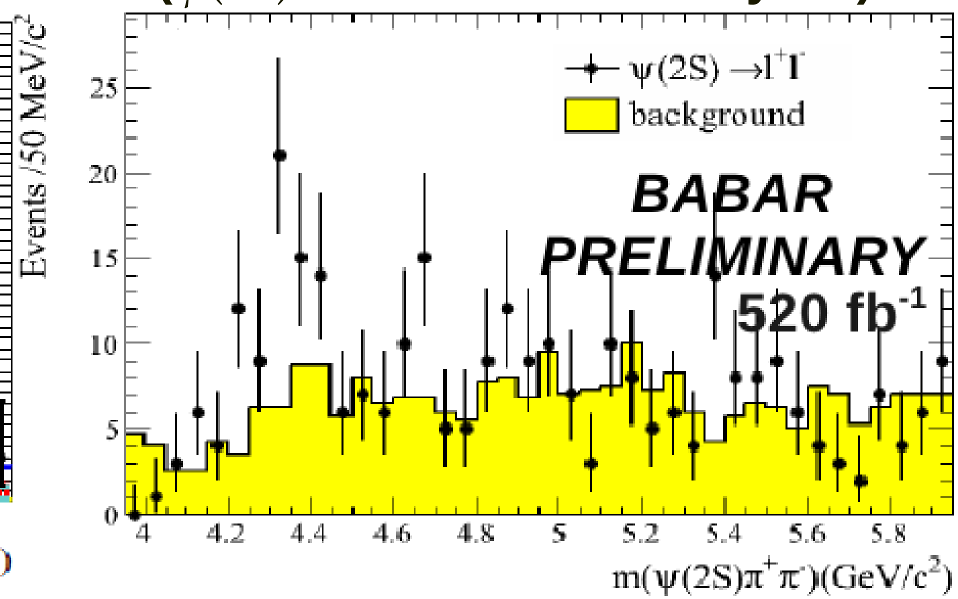
- 17 ± 13**% goes via** $f_0(980)$**, interfering with continuum** $\pi^+\pi^-$

$\Upsilon(4360)$ update & $\Upsilon(4660)$ confirmation

- **BaBar found** $\Upsilon(4360)$ **in ISR** $e^+e^- \to \psi(2S)\pi^+\pi^-$ (2007)
- **Belle confirmed** $\Upsilon(4360)$ **in ISR,**
  and have found another peak $\Upsilon(4660)$
- **New BaBar result confirms** $\Upsilon(4660)$ **[QNP2012/Charm2012]**

($\psi(2S) \to \ell^+\ell^-$ is also analyzed)





(unit in MeV)	$M(\Upsilon(4360))$	$\Gamma(\Upsilon(4360))$	$M(\Upsilon(4660))$	$\Gamma(\Upsilon(4660))$
Belle 673 **fb**$^{-1}$	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$
BaBar 520 **fb**$^{-1}$	$4340 \pm 16 \pm 9$	$94 \pm 32 \pm 13$	$4669 \pm 21 \pm 3$	$104 \pm 48 \pm 10$

What are known about Y

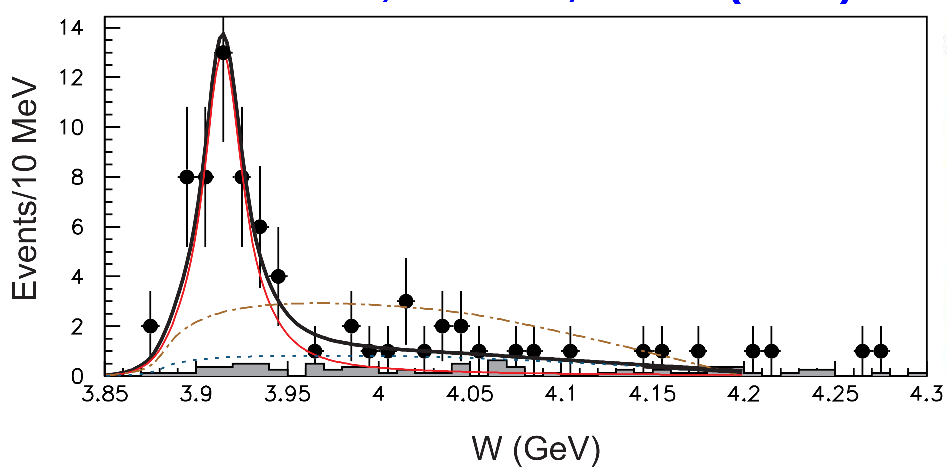
- **At least three Y states of 1^{--}**
  - $Y(4260) \to J/\psi\pi^+\pi^-$
  - $Y(4360) \to \psi(2S)\pi^+\pi^-$
  - $Y(4660) \to \psi(2S)\pi^+\pi^-$
- **Above $D\overline{D}$ threshold and not** (dominantly?) **decaying to open charm, $D^{(*)}_{(s)}\overline{D}^{(*)}_{(s)}$**
  - CLEO-c run at $\sqrt{s} = 4.26$ GeV [PRD80,072001(2009)]
  - CLEO-c found large $Y(4260) \to h_c\pi^+\pi^-$ rate [PRL107,041803(2011)]
- **Overpopulated 1^{--} entries, Y states not likely to be $c\bar{c}$ states**
  - 1^{--} below $D\overline{D}$ threshold: $L = 0$ charmonia, J/ψ and $\psi(2S)$
  - 1^{--} above $D\overline{D}$ threshold: $\psi(3770)$, $\psi(4040)$, $\psi(4140)$, $\psi(4415)$ ...
  - Candiate for hybrid states, tetraquark or other possibilities?

New Charmonia Members

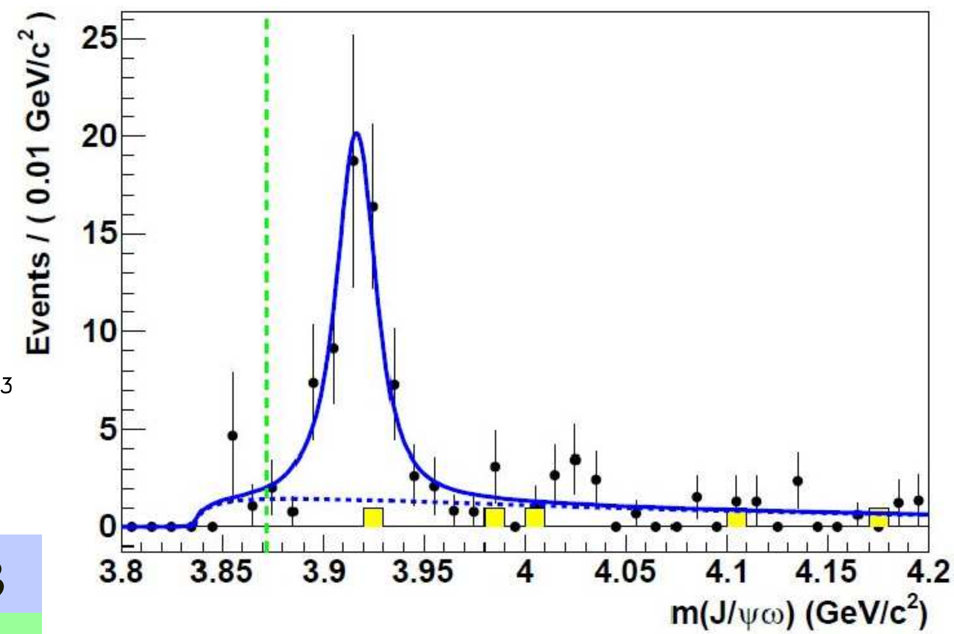
$X(3915)$

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

Belle 694 fb^{-1}, PRL104,092001(2010)



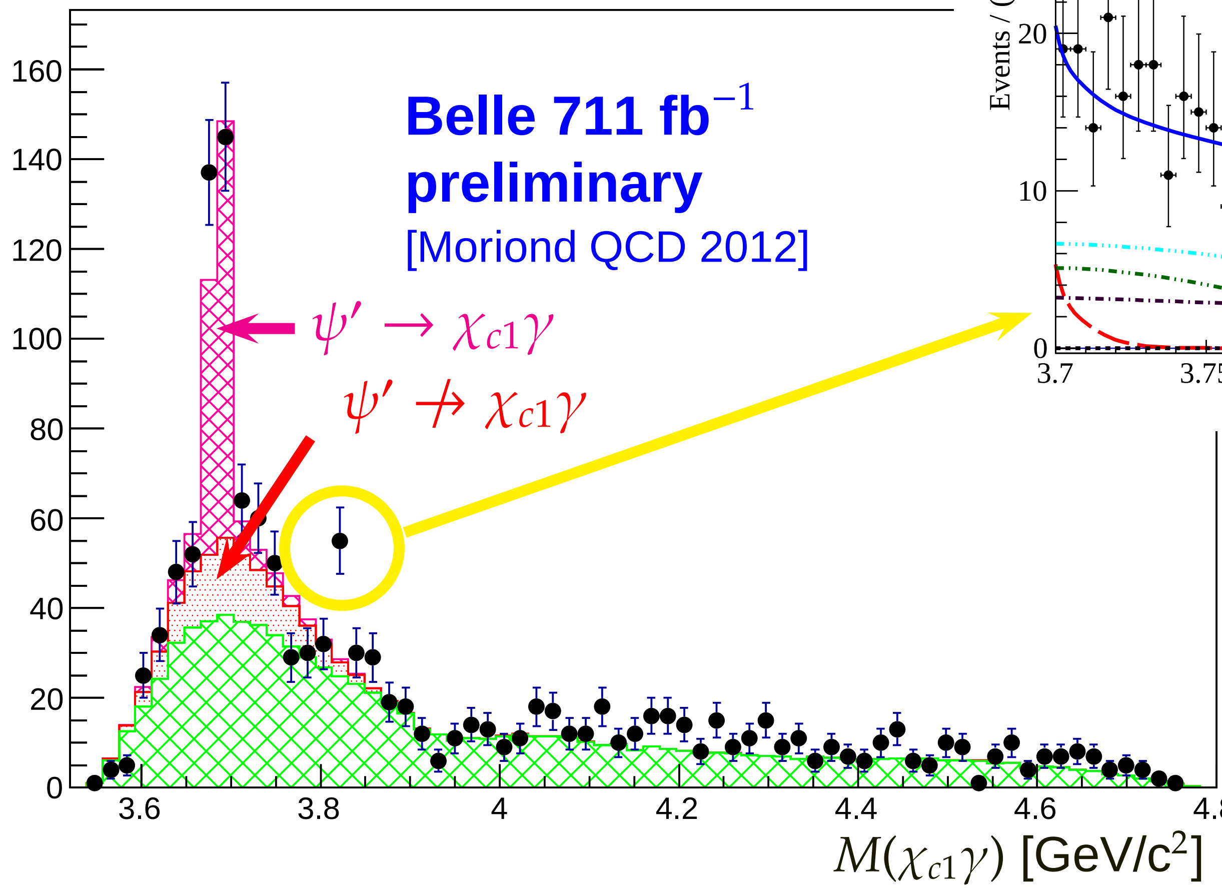
BaBar 520 fb^{-1}, preliminary (Moriond QCD)

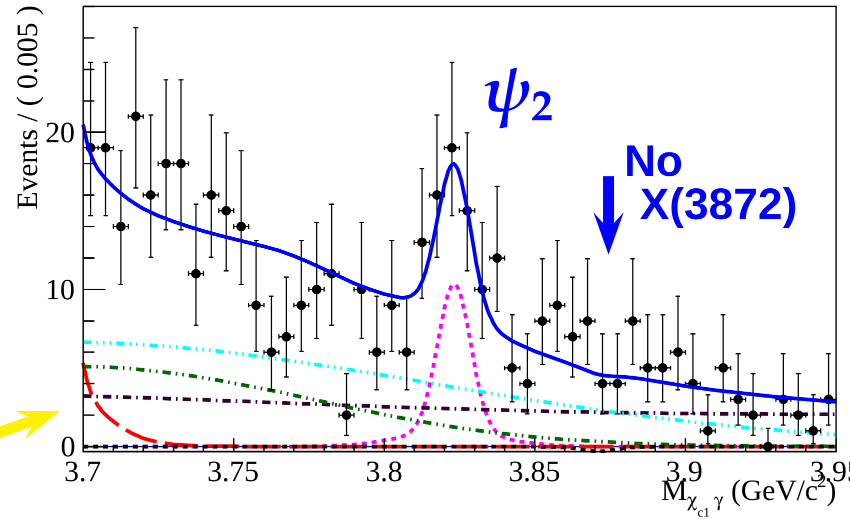


	M (MeV)	Γ (MeV)
Belle	$3915 \pm 3 \pm 2$	$17 \pm 10 \pm 3$
BaBar	$3919.4 \pm 2.2 \pm 1.6$	$13 \pm 6 \pm 3$

- **Angular analysis to assign** J^P **is on-going** (BaBar)
  (Angular distribution shown at Moriond QCD needs further checking)
- **Same state as** $Y(3940) \to J/\psi\omega$ **found in** $B \to J/\psi\omega K$**?**
  (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:** $\chi_{c0}(2P)$**?** $\chi_{c2}(2P)$**?**

$1^3D_2 = \psi_2$





4.2σ **peak in** $\chi_{c1}\gamma$ **in** $B^+ \to (\chi_{c1}\gamma)K^+$

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

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

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 ψ_2 search in $\chi_{c2}\gamma$ [Charm2012, Bhardwaj]
- **Belle,** Z_c^+ search in $B \to J/\psi\pi K$ (2.8σ, inconclusive) [Charm2012, Chilikin]

(search = negative or inconclusive result)

. . . apologies for any missing results

Summary

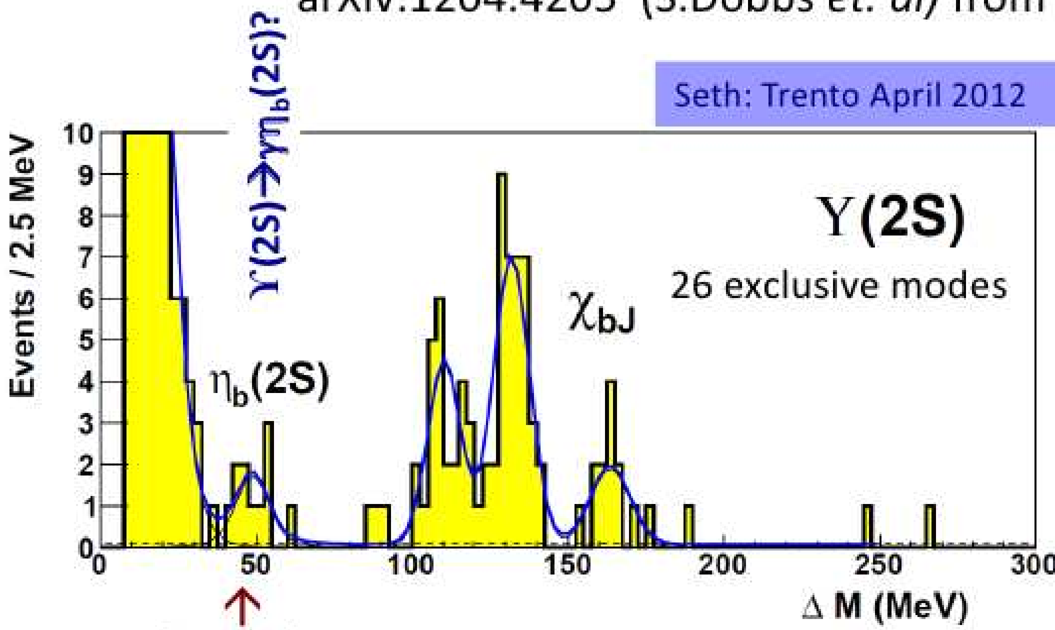
Conventional charmonia & bottomonia are well-established,
But unexpected exotics are still only vaguely understood

- **η_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**
- **ψ_2: filling the charmonia table, and still more empty seats**
- **New contributions from ATLAS/CMS/LHCb**
  More to work at Belle II / SuperB ☺

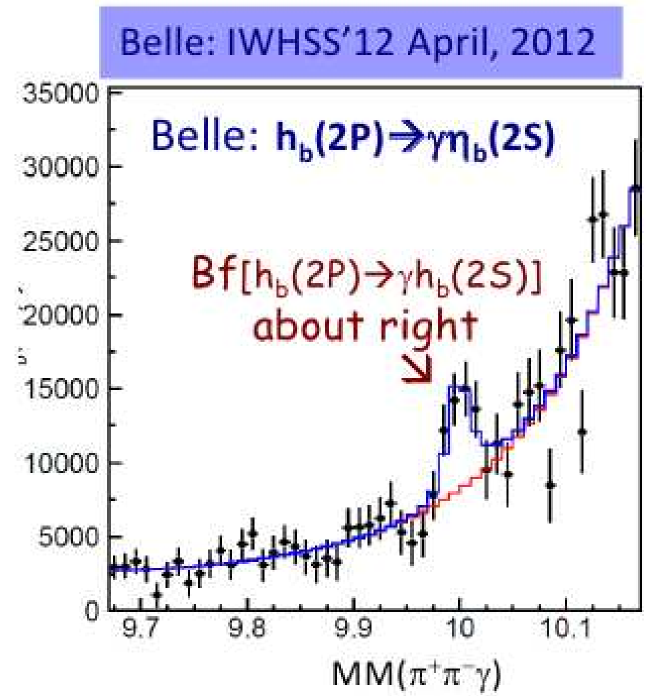
Backup

$\eta_b(2S)$ signal?

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



↑
anomalously large production rate ($\sim 0.2 \times \chi_{b1}$ rate)



Expt	ΔM_{hfs} (2S) (MeV)
S. Dobbs	48.7±2.7
Belle	24.3±4.3

← strong disagreement with theory (S. Dobbs)

← agrees with theory (Belle)

≈5σ discrepancy