Observation of $\chi_b(2P) \to \omega\Upsilon(1S)$ decays

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On behalf of the BABAR collaboration

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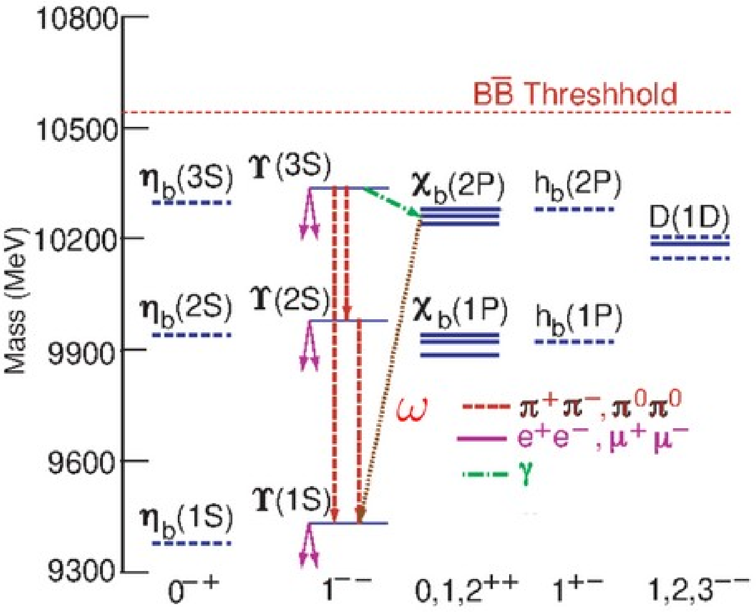
Motivation

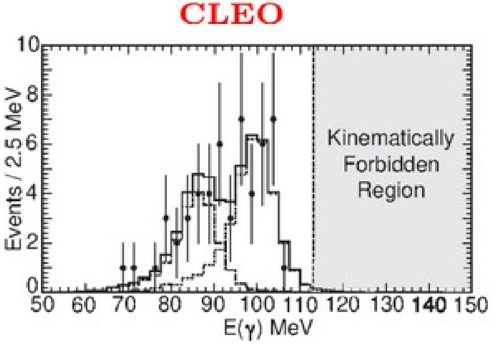
- The X(3872) now called χ_{c1}(3872) is known to decay to **$\omega J/\psi$** with a significant BR: (1.16±0.24)xBR($\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-$) although it sits 8 MeV below the on-shell mass limit (PDG)
- It is interesting to look at the same decay channel for the Υ system to look for similar objects
- Theory predictions exist for relative contributions of the χ_b states to these decays:
  - BR($\Upsilon(3S) \rightarrow \gamma(\chi_{b2} \rightarrow \omega\Upsilon(1S))$)/BR($\Upsilon(3S) \rightarrow \gamma(\chi_{b1} \rightarrow \omega\Upsilon(1S))$)=1.3±0.3

    M.B. Voloshin (Mod.Phys.Lett.A18:1067,2003)
- On the experimental side, BABAR has the world largest sample of Υ(3S) decays which allow to tag χ_b states by a radiative cascade

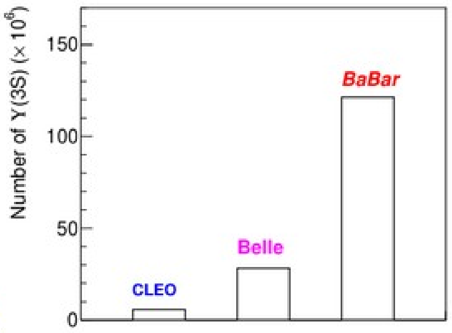
The bottomonium spectrum

- The spectrum of bottomonium states below the open bottom threshold:





- $\chi_{b1,2}(2P)\rightarrow\omega\Upsilon(1S)$ first measured by CLEO (hep-ex/0311043,2003).
- Distribution of the γ energy in the $\Upsilon(3S)\rightarrow\gamma\chi_{b1,2}(2P)$ rest frame.



- Recent analysis from Belle experiment (arXiv:2407.00879,2025).
- 3.2σ evidence for a $\chi_{b0}(2P)\rightarrow\omega\Upsilon(1S)$ decay.

- Number of Υ(3S) per experiment

Experimental reconstruction

$$e^+e^- \rightarrow \Upsilon(3S) \rightarrow \gamma_s \;\; \chi_b(2P)$$

$$\hookrightarrow \Upsilon(1S) \qquad \omega$$

$$\Upsilon(1S) \hookrightarrow \ell^+ \ell^- \qquad \omega \hookrightarrow \pi^+\pi^-\pi^0 \qquad \pi^0 \hookrightarrow \gamma\,\gamma$$

$\ell^+ \ell^-$ = e^+e^- or $\mu^+\mu^-$ γ_s is initial photon

Selections:

- 4 charged tracks with $p_T > 0.1$ GeV/c², net charge 0, fit to common vertex
- $p_\ell^\pm > 2.9$ GeV/c, $p_\pi^\pm < 0.7$GeV/c (2 hi p trks are leptons, 2 low p trks are pions)
- $E_{\gamma_s} > 50$ MeV/c², $E_\gamma >$ 30 MeV/c² mass constrained fit to π^0's
- $<$ 7 γ_s candidates, $<$ 6 π^0 candidates

The main background sources

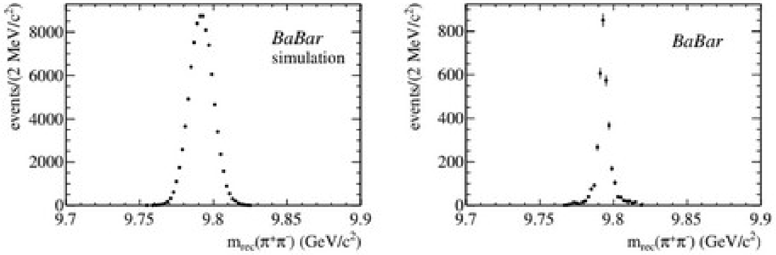
$$\Upsilon(3S) \to \gamma_1 \chi_b(2P) \to \gamma_2 \Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$$

adding one spurious γ from the calorimeter.

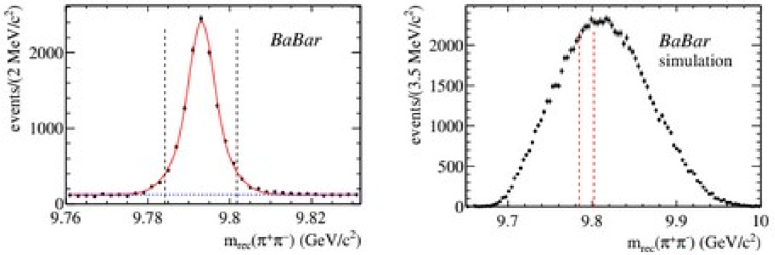
$$\Upsilon(3S) \to \pi^0\pi^0 \Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$$

where one of the γ's from π^0 decays is lost.

- Plot the recoil mass to the $\pi^+\pi^-$ system:

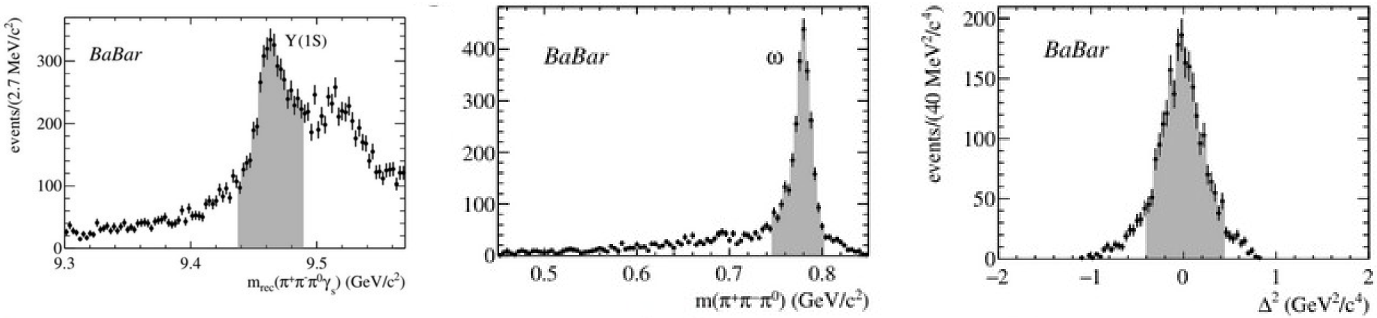


- Both backgrounds accumulate in the 9.79 GeV mass region.
- $m_{rec}(\pi^+\pi^-)$ for data and signal MC.



Signal selection

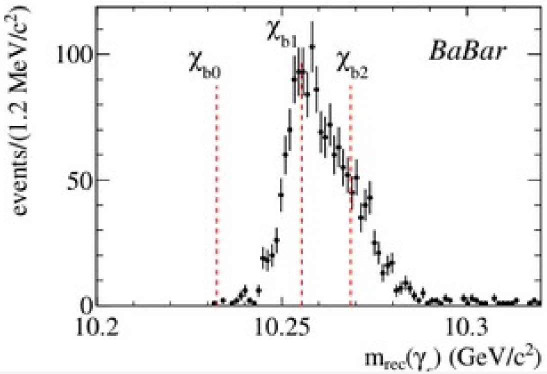
- $\pi^+\pi^-\pi^0$ mass distribution, showing the ω signal selected in the (0.75-0.80) GeV mass region.



- Recompute the energy of the $\Upsilon(1S)$ and ω using the PDG mass. Evaluate:

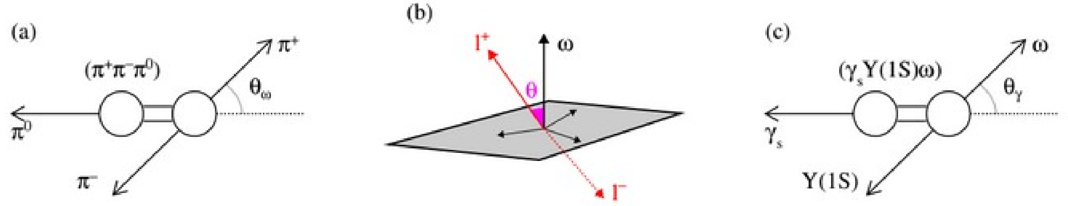
$$\Delta^2 = m^2_{rec}(\gamma_s) - m^2(\Upsilon(1S)\omega)$$

- Require $|\Delta^2| < 0.4\ GeV^2$. Choose the best value of $|\Delta^2|$ in case of two candidates.
- 78.8%, 17.6% and 3.6% have one, two or (more than two combinations: discarded).
- Total $m_{rec}(\gamma_s)$ distribution: $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ signals. No evidence for $\chi_{b0}(2P)$.

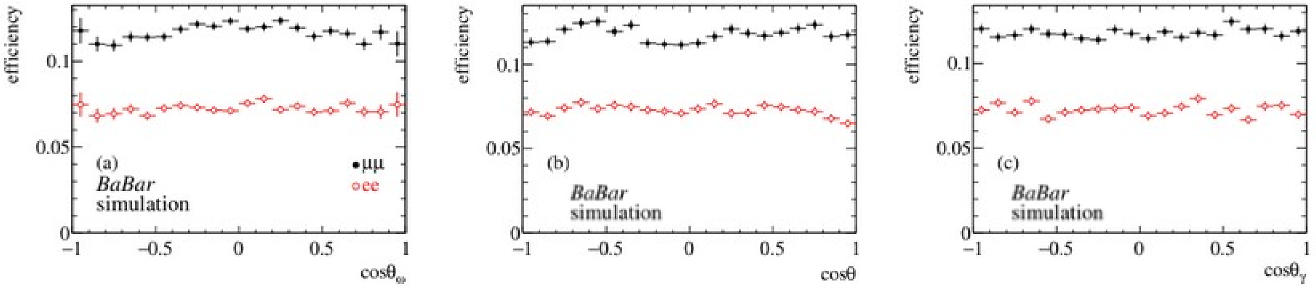


Efficiency as function of the angular variables

- θ is the angle between the lepton in the $\Upsilon(1S)$ rest frame and the normal to the $\pi^+\pi^-\pi^0$ plan in the ω rest frame.



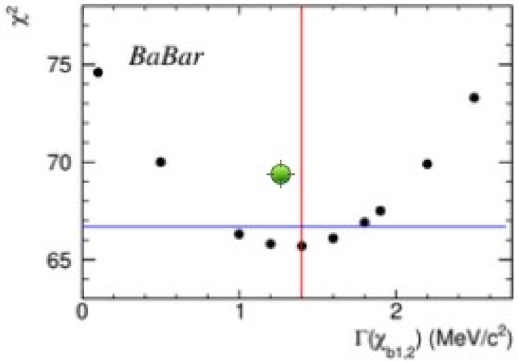
- Efficiency distributions for $\mu^+\mu^-$ and e^+e^-MC as functions of the three angles.

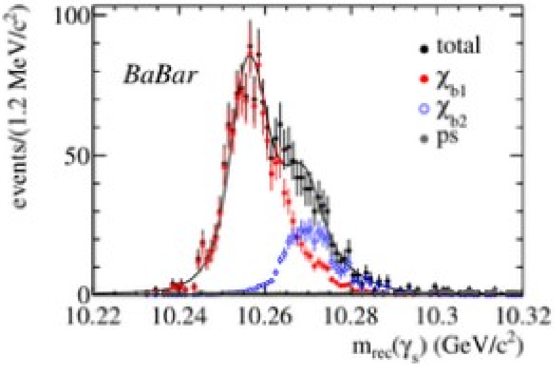


μμ

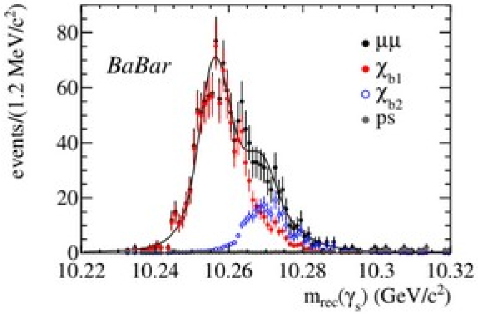
ee

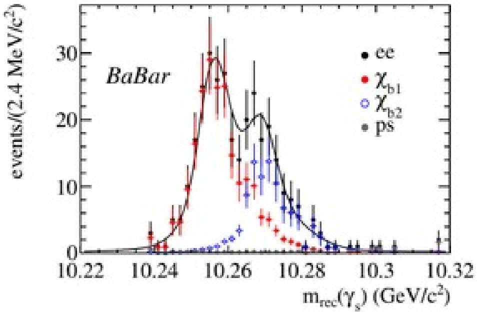
Fit results





- The fit quality is assessed using a χ^2 evaluation and we obtain $\chi^2/ndf = 75/77$.
- We relax the condition on the BW width and scan the χ^2 as function of Γ.
- The distribution shows a well defined minimum for $\Gamma = 1.4 \pm 0.5$ MeV with $\chi^2/ndf = 66/77$
- Fit projections for the $\mu^+\mu^-$ and e^+e^- datasets

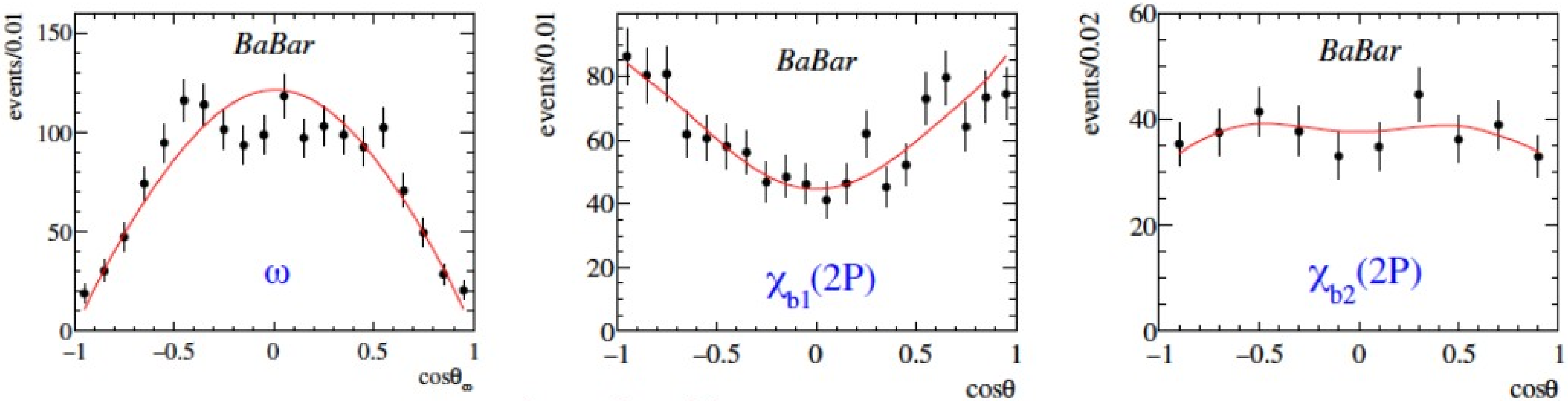




μμ **ee**

Angular distributions

Likelihood fit to find angular distributions of $\Upsilon(3S) \rightarrow \gamma_s \omega \Upsilon(1S)$



$$f_{\chi_{b1}} = (1 + \cos^2\theta) \cdot \epsilon(\theta)$$

$$f_{\chi_{b2}} = (1 - \frac{1}{7}\cos^2\theta) \cdot \epsilon(\theta)$$

Confirmation of the spin assignments to $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$!!

Phys Rev D 113 052010 (2026)

Signal Yields and systematic uncertainty

- Fitted fractions and events yields.

data	total events	c_1	$\chi_{b1}(2P)$ events	c_2	$\chi_{b2}(2P)$ events	ps	χ^2/ndf
total	1651	0.748 ± 0.017	1236 ± 41	0.223 ± 0.017	369 ± 29	0.028 ± 0.007	66/77
$\mu^+\mu^-$	1334	0.769 ± 0.018	1026 ± 37	0.203 ± 0.018	270 ± 26	0.028 ± 0.008	62/74
e^+e^-	317	0.648 ± 0.038	205 ± 17	0.305 ± 0.037	97 ± 13	0.048 ± 0.019	23/31

- Due to the large systematic uncertainties and the limited e^+e^-yield we use only the $\mu^+\mu^-$ dataset to evaluate branching fractions.

- Systematic uncertainties on the evaluation of the fractions of the $\chi_{b1,2}(2P)$ contributions

Source	$\chi_{b1}(2P)$ (%)	$\chi_{b2}(2P)$ (%)
(a) Tracking efficiency	2.5	2.5
(b) γ reconstruction efficiency	1.8	1.8
(c) π^0 reconstruction efficiency	3.0	3.0
(d) Particle identification	1.0	1.0
(e) Additional γ and π^0	0.6	0.7
(f) Signal efficiency	1.9	2.9
(g) $\chi_{b1,2}(2P)$ lineshape	3.2	5.2
(h) $\chi_{b1,2}(2P)$ width	2.9	2.6
(i) $\Upsilon(2S)$ background	2.5	3.0
(j) ω selection	1.5	3.1
Total	7.1	9.0

Branching fractions

Phys Rev D 113 052010 (2026)

□ The $\chi_{bJ}(2P)\to\omega\Upsilon(1S)$ branching fractions are evaluated as

$$\mathcal{B}(\chi_{bJ}(2P)\to\omega\Upsilon(1S)) = \frac{N_{\rm corr}(\chi_{bJ}(2P)\to\omega\Upsilon(1S))}{N_{\Upsilon(3S)}\cdot\mathcal{B}(\Upsilon(3S)\to\gamma\chi_{bJ}(2P))},$$

in the decays $\Upsilon(3S)\to\gamma\chi_{bJ}(2P)$.

□ Here, for each $\chi_{bJ}(2P)$, $N_{\rm corr}(\chi_{bJ}(2P)\to\omega\Upsilon(1S))$ is the number of measured events corrected for efficiency and unseen decay modes and

$$N_{\Upsilon(3S)} = (121.3 \pm 1.2_{\rm sys}) \times 10^6.$$

□ The $\mathcal{B}(\Upsilon(3S)\to\gamma\chi_{bJ}(2P))$ branching fractions are obtained from PDG.

□ We obtain:

$$\boxed{\mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1S)) = (2.56 \pm 0.09_{\rm stat} \pm 0.18_{\rm sys} \pm 0.25_{\rm pdg})\%}$$

and

$$\boxed{\mathcal{B}(\chi_{b2}(2P)\to\omega\Upsilon(1S)) = (0.69 \pm 0.07_{\rm stat} \pm 0.06_{\rm sys} \pm 0.09_{\rm pdg})\%.}$$

□ The ratio $\tilde{r}_{2/1}$ is also evaluated, with most of the systematic uncertainties canceling out.

$$\boxed{\tilde{r}_{2/1} = \frac{\mathcal{B}(\chi_{b2}(2P)\to\omega\Upsilon(1S))}{\mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1S))} = 0.27 \pm 0.03_{\rm stat} \pm 0.02_{\rm sys} \pm 0.04_{\rm pdg}.}$$

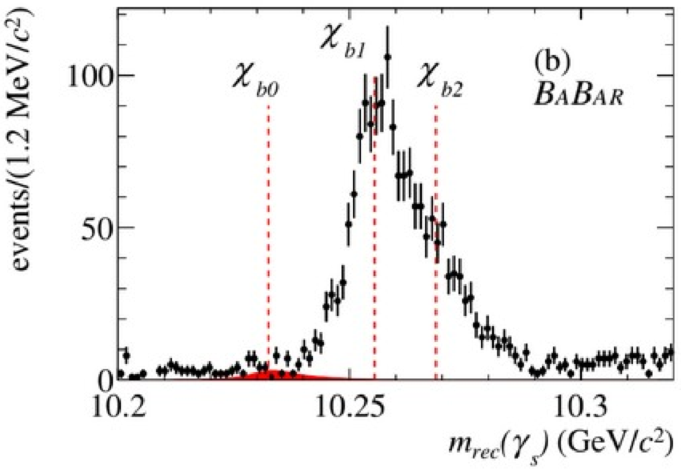
$\tilde{r}_{1,2}=(0.96\pm0.1)r_{1,2}$

IJCLab Irène Joliot-Curie

χ_{b0} BR upper limit

Phys Rev D 113 052010 (2026)

- Remove the ω selection and the method of recalculating the $\Upsilon(1S)$ and ω energies.
- Fit the data including the $\chi_{b0}(2P)$ with $\Gamma = 2.6$ MeV (arXiv:1507.00024).
- We obtain upper limits of 42 and 36 events for the total and $\mu^+\mu^-$ sample.



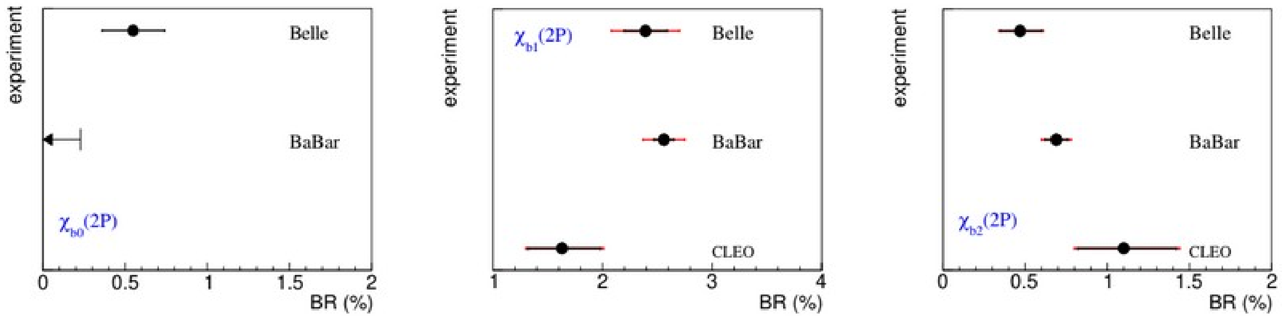
- We evaluate an upper bound of

$$\mathcal{B}(\chi_{b0}(2P)\to\omega\Upsilon(1S)) < 0.23\% \text{ at } 90\% \text{ C.L.}$$

Phys Rev D 113 052010 (2026)

Conclusion

- Clean $\chi_{b1,2}(2P)$ signals are observed and improved precision measurements of branching fractions are derived.
- The predicted value for the $r_{2/1}$ ratio is $r_{2/1} \approx 1.3 \pm 0.3$ where the quoted uncertainty arises mainly from the knowledge of total decay rates of the χ_{bJ} resonances.
- A difference of $\approx 3.4\sigma$ is found with respect to the predicted value.
- Comparison between $\chi_{b1,2}(2P)$ branching fractions measurements.



- In agreement within three standard deviations with results from CLEO and Belle experiments with significantly better precision.
- Angular distributions for $\chi_{b1}(2P)\to\omega\Upsilon(1S)$ and $\chi_{b2}(2P)\to\omega\Upsilon(1S)$ are measured for the first time and found in agreement with theoretical expectations.
- No evidence is found for the presence of a $\chi_{b0}(2P)\to\omega\Upsilon(1S)$ decay mode.