Study of $\Upsilon(3S) \to \gamma\chi_{b1,2}(2P)$, $\chi_{b1,2}(2P) \to \omega\Upsilon(1S)$ decays at *BABAR*

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On behalf of the *BABAR* collaboration

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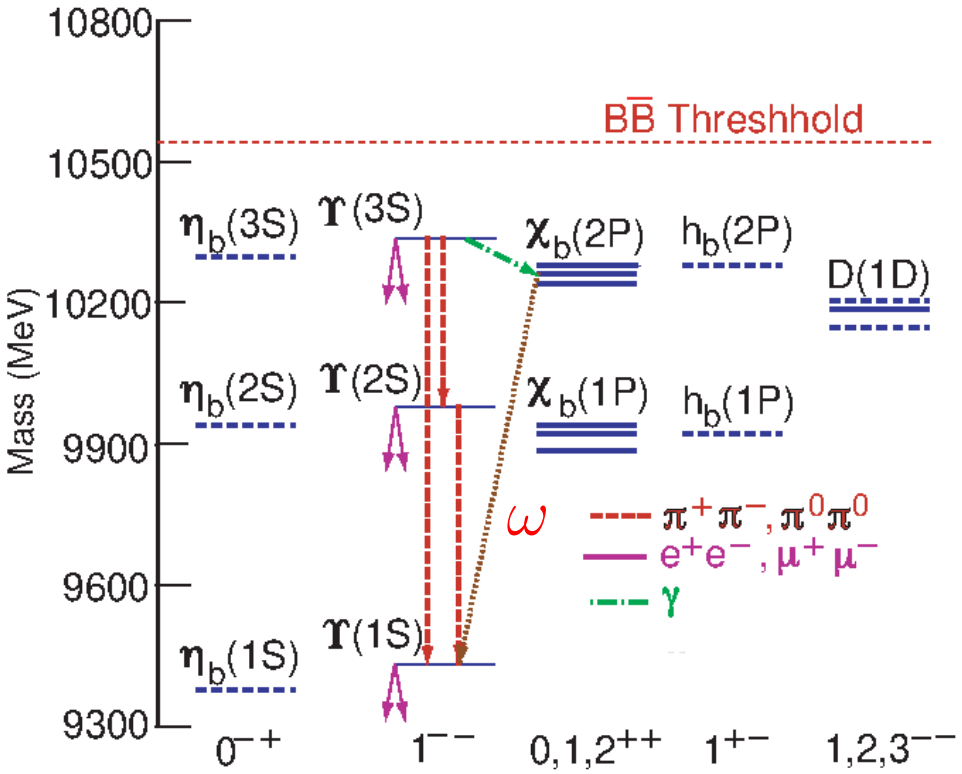
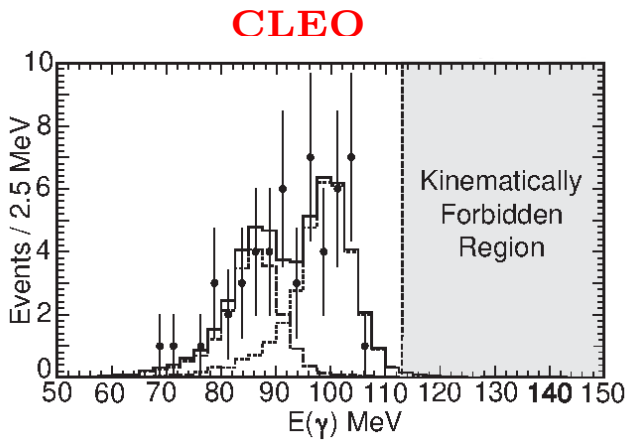
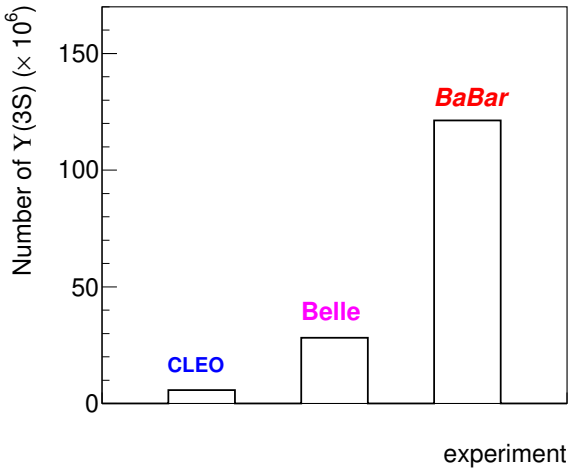
Introduction

- The $b\bar{b}$ meson system is a laboratory for testing perturbative and nonperturbative QCD calculations.
- The spectrum of bottomonium states below the open bottom threshold:







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

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

Event reconstruction

- We reconstruct the decay:

$$
\begin{aligned}
e^+e^- \rightarrow \Upsilon(3S) \rightarrow \gamma_s \chi_b(2P) & \\
& \rightarrow \Upsilon(1S) \qquad \omega \\
& \qquad \rightarrow l^+l^- \qquad \rightarrow \pi^+\pi^-\pi^0 \\
& \qquad\qquad\qquad\quad \rightarrow \gamma\gamma
\end{aligned}
$$

where $l^+l^- \equiv \mu^+\mu^-/e^+e^-$ and γ_s indicates the γ candidate for the transition $\Upsilon(3S) \rightarrow \gamma_s \chi_b(2P)$.

- All pairs of γ's with energy > 30 MeV are fitted to mass constrained π^0's.
- Using signal MC information: require $E(\gamma_s) > 50$ MeV.
- Allow $N_{\gamma_s} < 7$, $N_{\pi^0} < 6$.
- Require the two higher momentum tracks to have $p > 2.9$ GeV/c and give a lepton assignment, require the two lower momentum tracks to have $p < 0.7$ GeV/c and give a pion assignment.
- Particle identification is used only to tag $\Upsilon(1S) \rightarrow \mu^+\mu^-$ and $\Upsilon(1S) \rightarrow e^+e^-$ candidates. Tagging efficiency $\approx 100\%$.

Background suppression

- Significant backgrounds come from the $\Upsilon(3S)$ cascades (rates:≈3% and ≈0.3%):

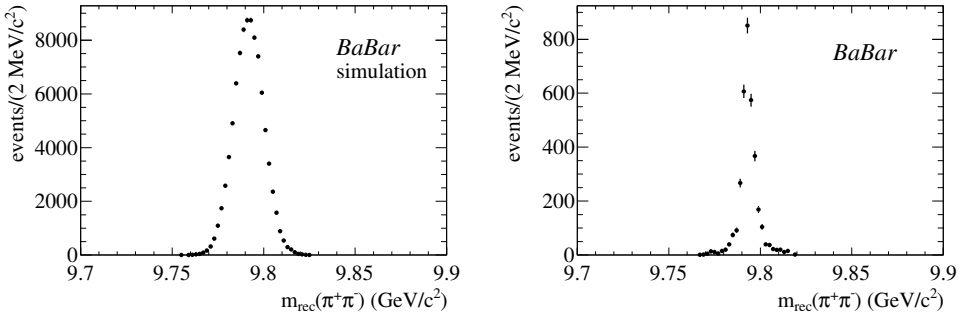
$$\Upsilon(3S)\to\gamma_1\chi_b(2P)$$
$$\to\gamma_2\Upsilon(2S)$$
$$\to\pi^+\pi^-\Upsilon(1S)$$

adding one spurious γ from the calorimeter.

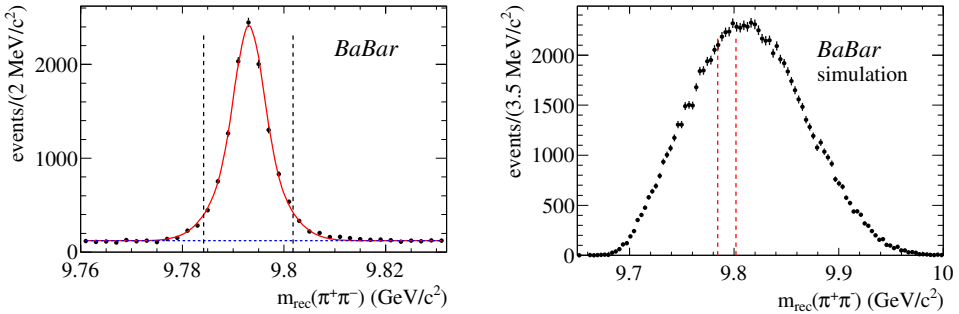
$$\Upsilon(3S)\to\pi^0\pi^0\Upsilon(2S)$$
$$\to\pi^+\pi^-\Upsilon(1S)$$

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.



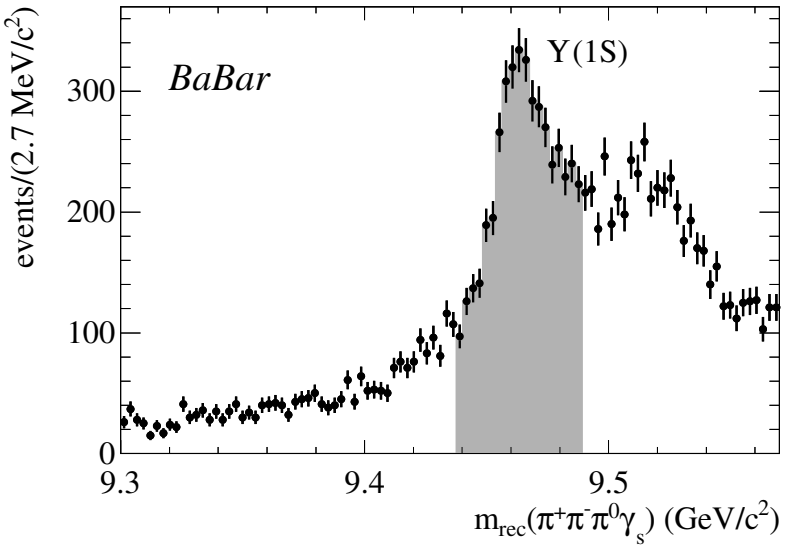
- Veto the dashed regions. Suppression of background by $\approx 2\times10^{-3}$ with 12% signal loss.

Signal selection (I)

- Loop over γ_s candidates and π^0 candidates.
- Apply momentum balance.

$$\Delta \mathbf{p}_i = \mathbf{p}_i(e^+) + \mathbf{p}_i(e^-) - \sum_{j=1}^{6} \mathbf{p}_i(j).$$

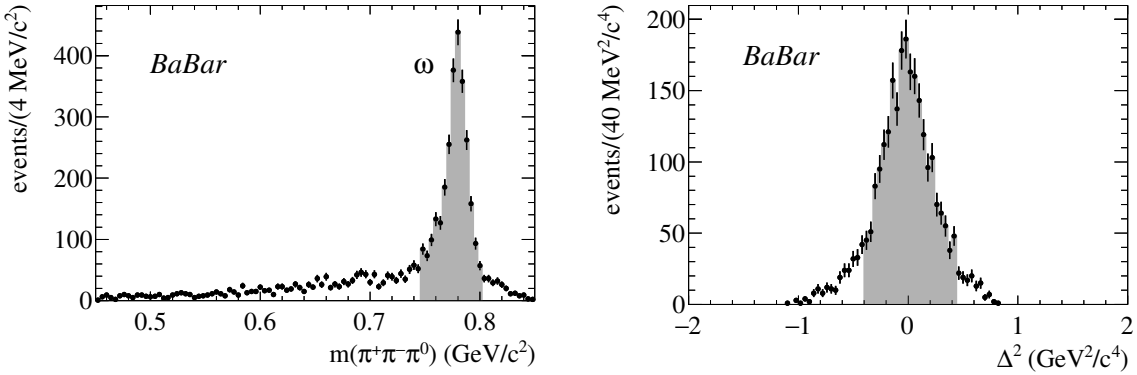
- $\Delta \mathbf{p}_i$ distributions fitted using Gaussian functions.
- Fitted values are $\sigma_{xy} = 75$ MeV/c and $\sigma_z = 85$ MeV/c.
- Events are selected within $\pm 3\sigma$.
- Distribution of $m_{rec}(\pi^+\pi^-\pi^0\gamma_s)$: $\Upsilon(1S)$ signal on significant combinatorial background.



- Fitted $\Upsilon(1S)$ parameters are $m = 9.4623$ GeV, $\sigma = 10.0$ MeV. Selected within $\pm 3\sigma$.

Signal selection (II)

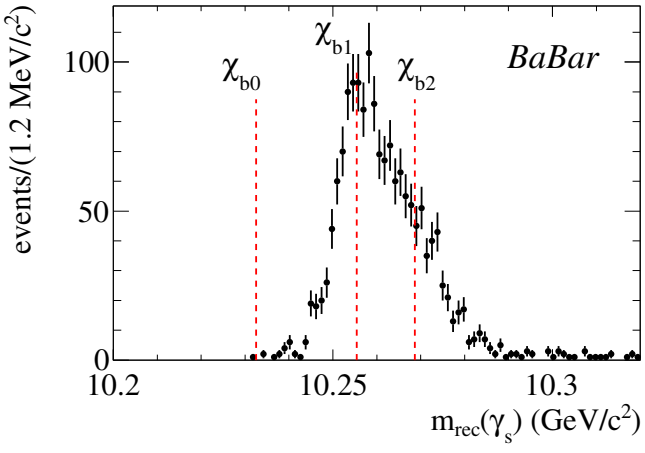
- $\pi^+\pi^-\pi^0$ mass distribution, showing the ω signal selected in the (0.75-0.80) GeV mass region.



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

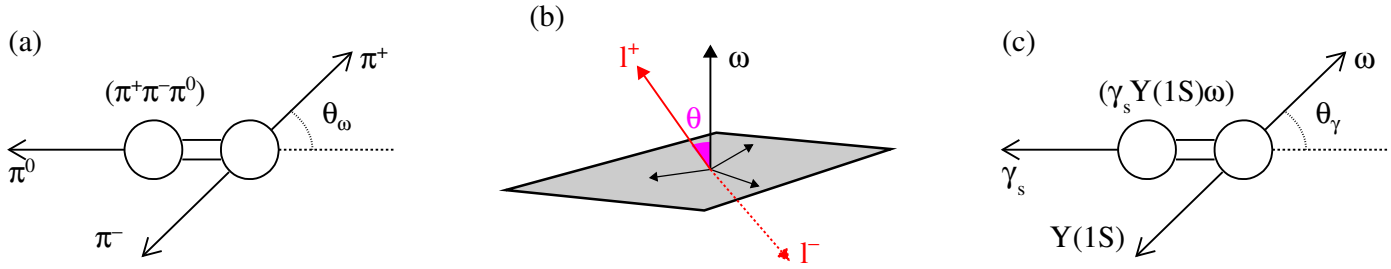
$$\Delta^2 = m^2_{rec}(\gamma_s) - m^2(\Upsilon(1S)\omega)$$

- 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 $\chi_{b0}(2P)$.

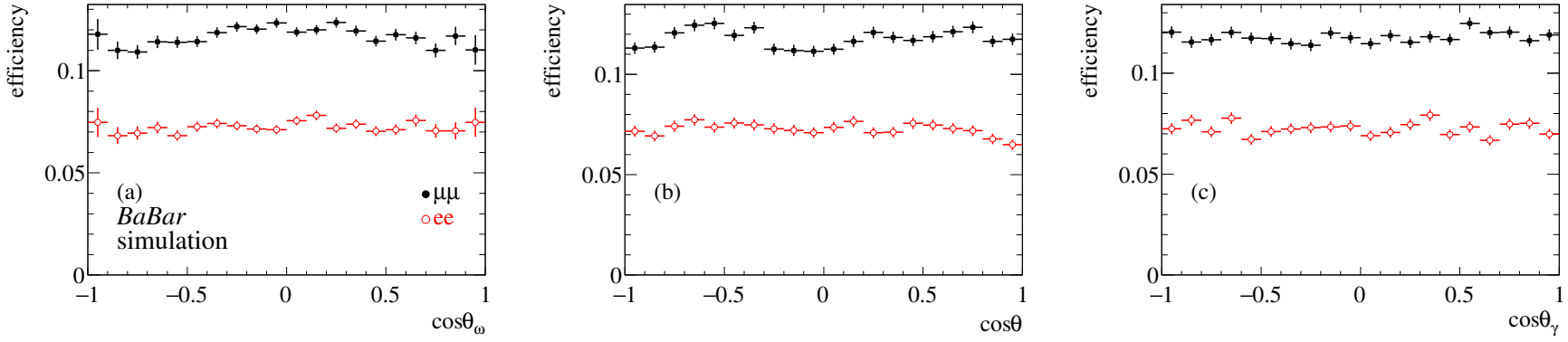


Efficiency

- We define the angles θ_ω, θ and θ_γ.
- θ is the angle between the lepton in the $\Upsilon(1S)$ rest frame and the normal to the $\pi^+\pi^-\pi^0$ plane in the ω rest frame.



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



- Weak dependence on angular variables.
- e^+e^- events suppressed by the trigger prescaling of Bhabha events.

Measurement of the $\chi_{b1,2}(2P)$ fractions

□ To measure the $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ fractions we use the method of the Channel Likelihood (P.Condon and P.Cowell,Phys. Rev. D **9**, 2558 (1974))

□ The total pdf ($\mathcal{L}$) is described by

$$\mathcal{L} = c_1 \cdot f(\chi_{b1}(2P)) + c_2 \cdot f(\chi_{b2}(2P)) + ps$$

where c_1 and c_2 are the fractional contributions for $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$.

□ $ps = 1 - c_1 - c_2$ indicates the residual (background) contribution.

□ The $\chi_{b1,2}(2P)$ lineshapes are described by Breit-Wigner functions with $\Gamma = 0.1$ MeV, in the range of the small expected width of the χ_b states, convolved with the resolution functions and the m_0 values fixed to $\chi_{b1,2}(2P)$ known values.

□ The resolution functions are fitted by the sum of a Gaussian function (G) and a Crystal-Ball function (CB)

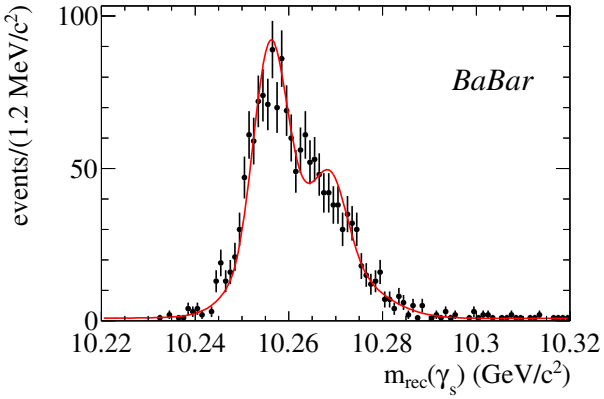
$$f(\chi_b(x)) = BW(x) \otimes [(1-c) \cdot CB(x) + c \cdot G(x)],$$

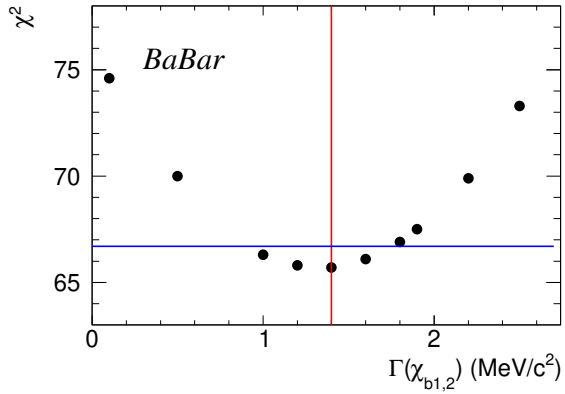
where $x = m_{rec}(\gamma_s)$.

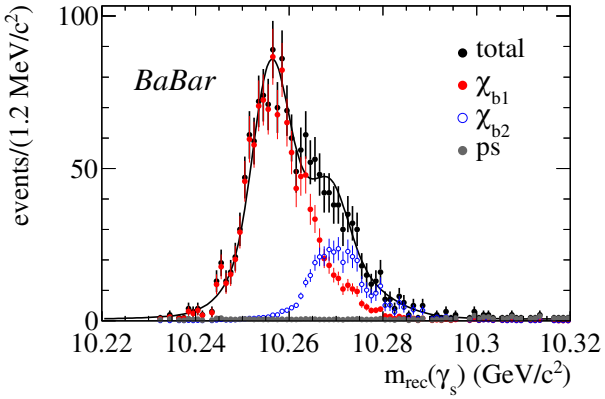
□ The method assigns weights $w(\chi_{b1}(2P))$, $w(\chi_{b2}(2P))$ and $w(ps)$ to each event to belong to the different components included in the definition of the likelihood function.

Fits to the data

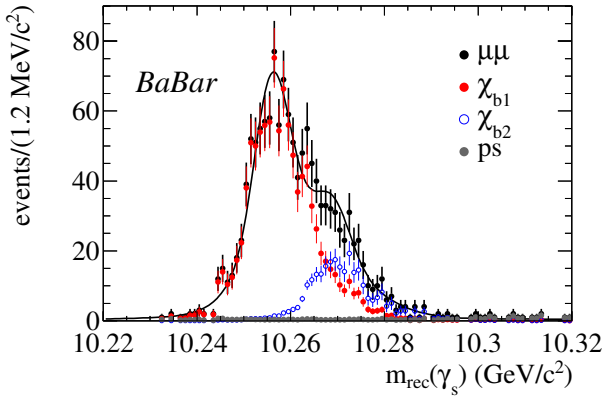
- Combined $\mu^+\mu^-$ and e^+e^- data are first processed through the channel likelihood fit with $\Gamma = 0.1$ MeV.

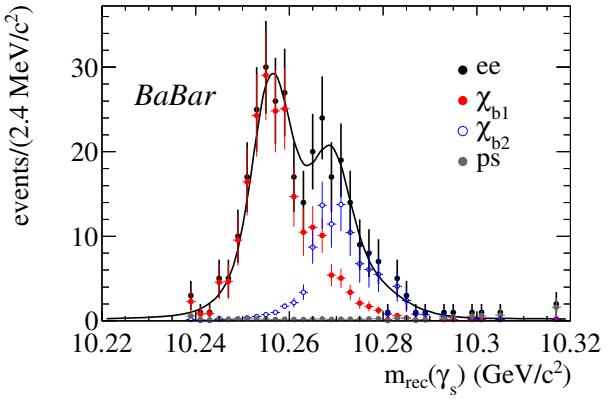






- The fit quality is assessed using a χ^2 evaluation and we obtain χ^2/ndf=75/77.
- We relax the condition on the BW width and scan the χ^2 as function of Γ.
- The distribution shows a well defined minimum for $\Gamma = 1.4 \pm 0.5$ MeV with χ^2/ndf=66/77
- Fit projections for the $\mu^+\mu^-$ and e^+e^-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





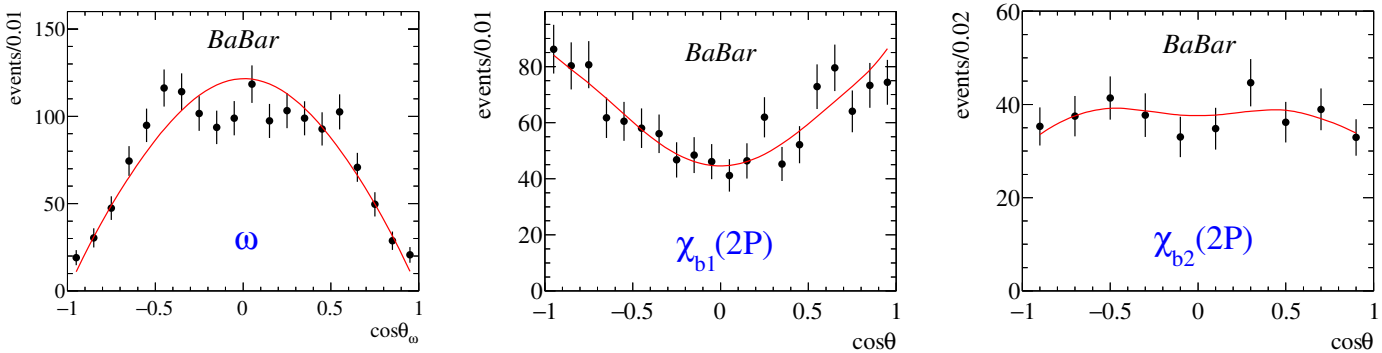
Angular analysis

- Distribution of $cos\theta_\omega$, weighted by $w(\chi_{b1}(2P)) + w(\chi_{b2}(2P))$.
- The superimposed curve is evaluated as

$$f_\omega = (1 - \cos^2\theta_\omega) \cdot \varepsilon(\theta_\omega)$$

where $\varepsilon(\theta_\omega)$ indicate the total efficiency.

- The fit is acceptable (χ^2/ndf=42/19). Deviations may be due to the presence of $\rho\pi$ contributions



- Distribution of $\cos\theta$ weighted by $w(\chi_{b1}(2P))$.
- The angular distributions for $\chi_{b1,2}(2P) \to \omega\Upsilon(1S)$ are predicted by (M.B.Voloshin, hep-ph/0304165)
- The superimposed curve (χ^2/ndf=15/19) is evaluated as

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

- Distribution of $\cos\theta$ weighted by $w(\chi_{b2}(2P))$.
- The $\chi_{b1}(2P)$ angular distribution is included in the definition of $f(\chi_{b1}(2P))$.
- The superimposed curve (χ^2/ndf=4/9) is evaluated as

$$f_{\chi_{b2}(2P)} = (1 - \tfrac{1}{7}cos^2\theta) \cdot \varepsilon(\theta)$$

Fit results

- 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

□ 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

$$N_{\Upsilon(3S)} = (121.3\pm1.2_{\rm sys})\times10^6.$$

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

□ We obtain:

$$\boxed{\mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1S)) = (2.56\pm0.09_{\rm stat}\pm0.18_{\rm sys}\pm0.25_{\rm pdg})\%}$$

and

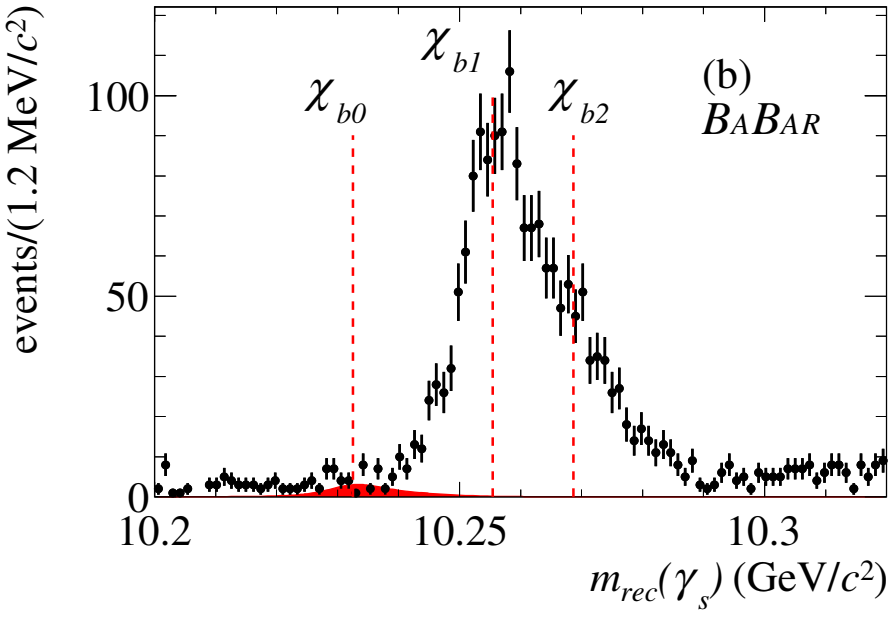
$$\boxed{\mathcal{B}(\chi_{b2}(2P)\to\omega\Upsilon(1S)) = (0.69\pm0.07_{\rm stat}\pm0.06_{\rm sys}\pm0.09_{\rm pdg})\%.}$$

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

$$\boxed{r_{2/1} = \frac{\mathcal{B}(\chi_{b2}(2P)\to\omega\Upsilon(1S))}{\mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1S))} = 0.27\pm0.03_{\rm stat}\pm0.02_{\rm sys}\pm0.04_{\rm pdg}.}$$

Evaluation of the $\chi_{b0}(2P)$ branching fraction limit

- 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

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

Summary

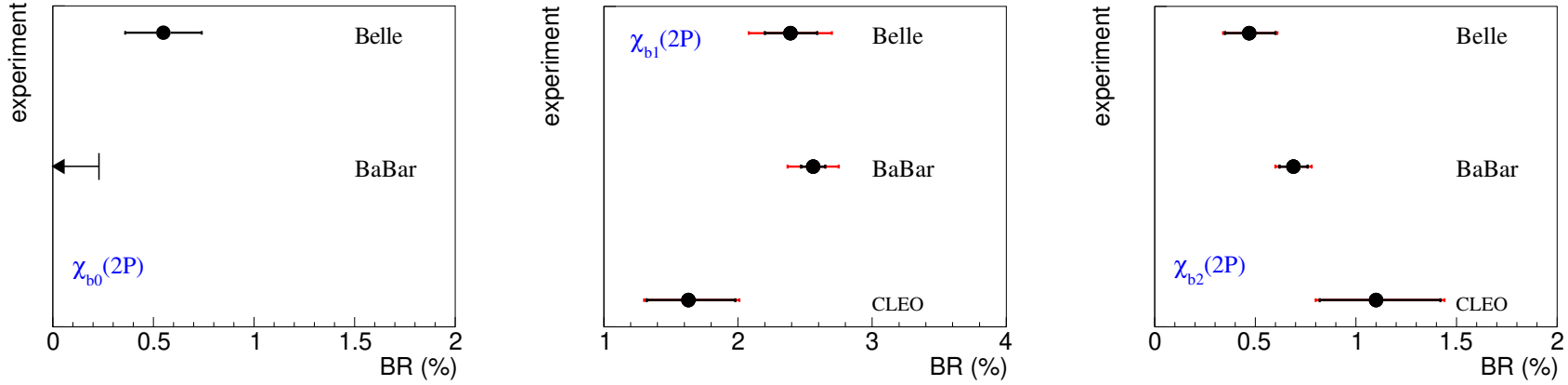
□ Results are presented on $\chi_{b1,2}(2P) \to \omega\Upsilon(1S)$ transitions from $e^+e^- \to \Upsilon(3S) \to \gamma\chi_{b1,2}(2P)$ decays at *BaBar*.

□ 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.

Backup: MC validation

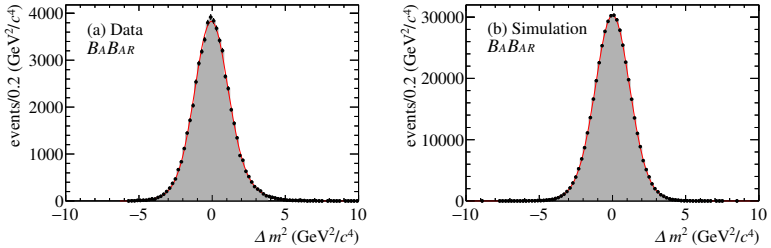
□ The validation of the performance of the MC simulation of the background γ's from final state radiation effects is performed by comparing data and simulation on the reference $\Upsilon(3S)$ decay mode

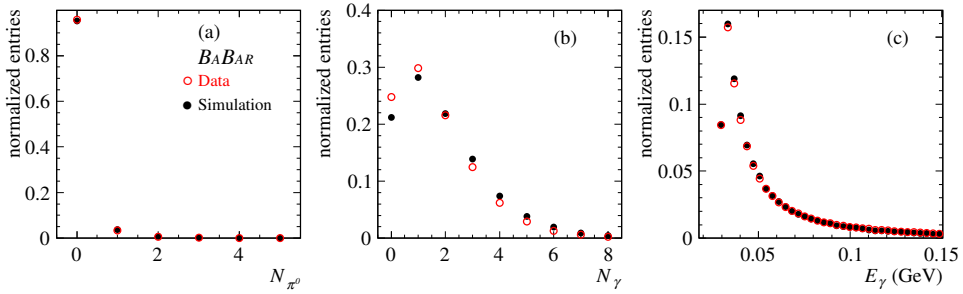
$$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S), \qquad \Upsilon(1S)\to\mu^+\mu^-$$

□ After requiring momentum balance, the final selection is performed on the variable

$$\Delta m^2 = m^2_{rec}(\pi^+\pi^-) - m^2(\mu^+\mu^-).$$

□ The distributions show consistent resolutions, with $\sigma = 1.28 \pm 0.05$ GeV$^2/c^4$ and $\sigma = 1.25 \pm 0.05$ GeV$^2/c^4$ for data and MC simulation, respectively.



□ For the selected events all the activity present in the EMC should be due to final state radiation or incident beams background.

□ Good agreement is found between the normalized distributions of (a) the number of candidate π^0's, (b) the number of candidate γ's and (c) the γ's energy distribution for data and simulation.