Recent BABAR Studies of Bottomonium States

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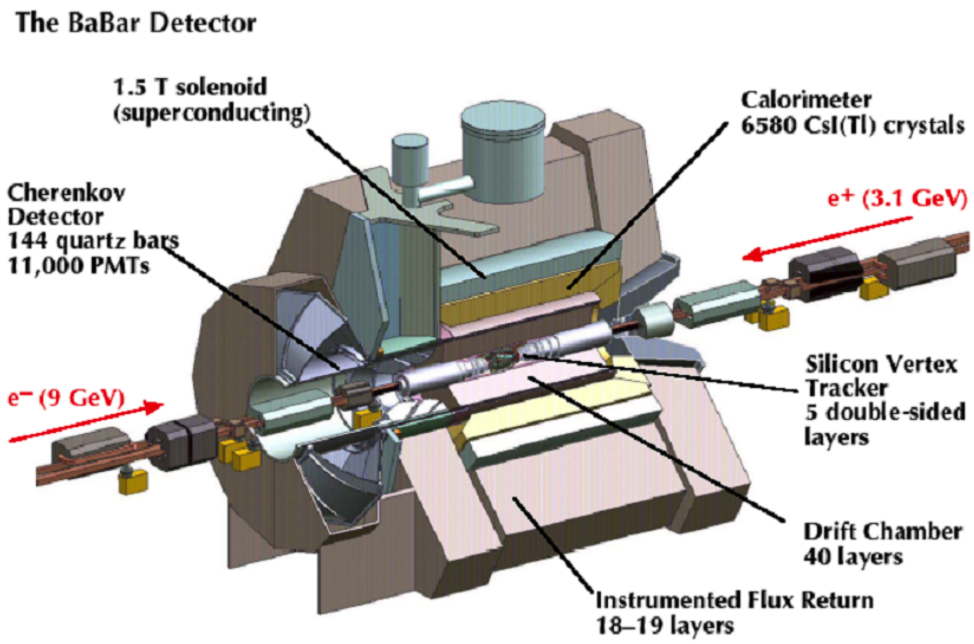
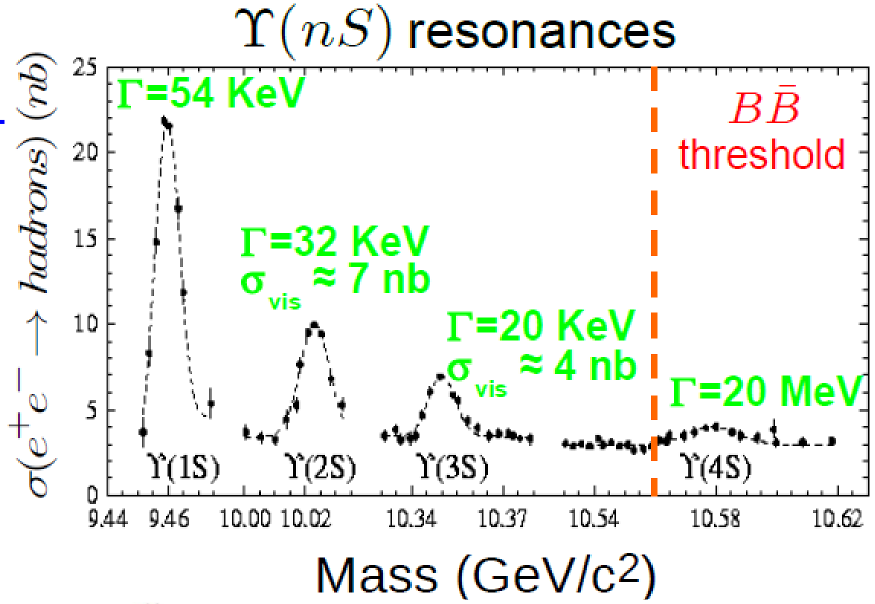
HADRON 2011
XIV International
Conference on Hadron Spectroscopy
13-17 June 2011 – München (Germany)

- Inclusive searches for the $h_b(1P)$ in
  - ✓ $\Upsilon(3S)\to\pi^+\pi^- X$
  - ✓ $\Upsilon(3S)\to\pi^0 X$
- radiative $\Upsilon(3S)$ and $\Upsilon(2S)$ transitions using converted photons

BaBar experiment



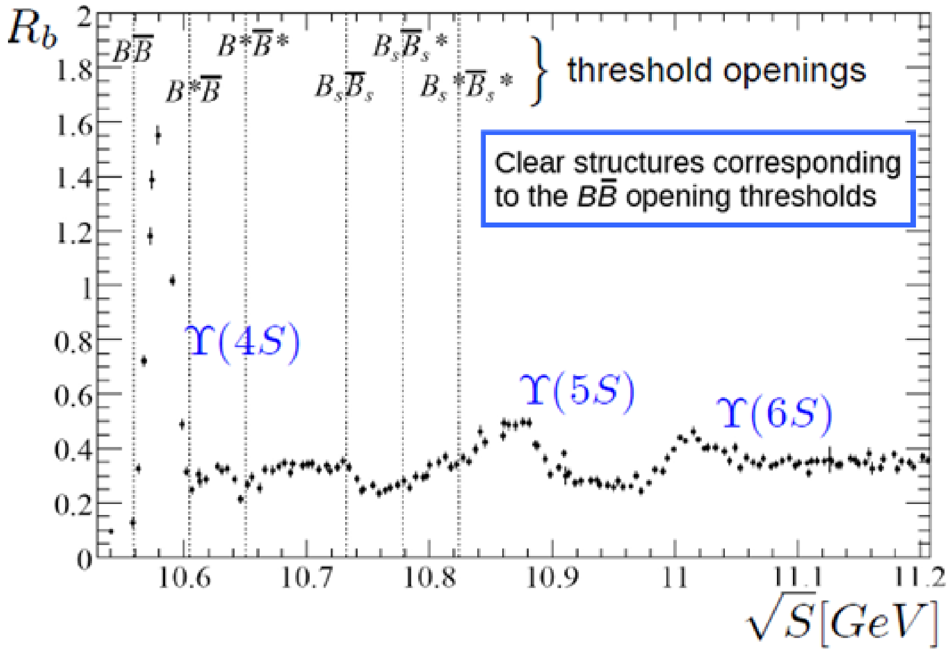


e^+e^- Cross Section Scan

PRL 102, 012001 (2009)

Precision scan in E_{CM} from 10.54 GeV to 11.20 GeV

- 5 MeV steps with 25 pb^{-1} at each step ($\int \mathcal{L} \approx 3.3\, fb^{-1}$)
- 8 steps at Υ(6S) ($\int \mathcal{L} \approx 0.6\, fb^{-1}$)



Clear structures corresponding to the $B\overline{B}$ opening thresholds

Most data taken at the Υ(4S)

dedicated running at the narrow Υ resonances

- 100 M Υ(2S)
- 122 M Υ(3S)

and a scan above the Υ(4S)

Search for $h_b(1P)$

- Expected mass: $m_{h_b(1P)} = (m_{\chi_{b0}(1P)} + 3m_{\chi_{b1}(1P)} + 5m_{\chi_{b2}(1P)}) / 9 \approx 9900\ \mathrm{MeV}/c^2$

- Predicted production mechanisms
  - $\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- h_b(1P)) \sim 10^{-3} - 10^{-2}$
  - $\mathcal{B}(\Upsilon(3S) \to \pi^0 h_b(1P)) \sim 10^{-3}$
  - $R(\pi^0 h_b (1P) / \pi^+\pi^- h_b (1P)) = 0.05 - 20$

Kuang et al., PRD 37,1210(1988)

Voloshin, Sov, J. Nucl. Phys 43,1011(1986)

- Expected decay modes
  - $h_b(1P) \to ggg\ (57\%),\ \gamma\eta_b(1S)\ (41\%),\ \gamma gg\ (2\%)$

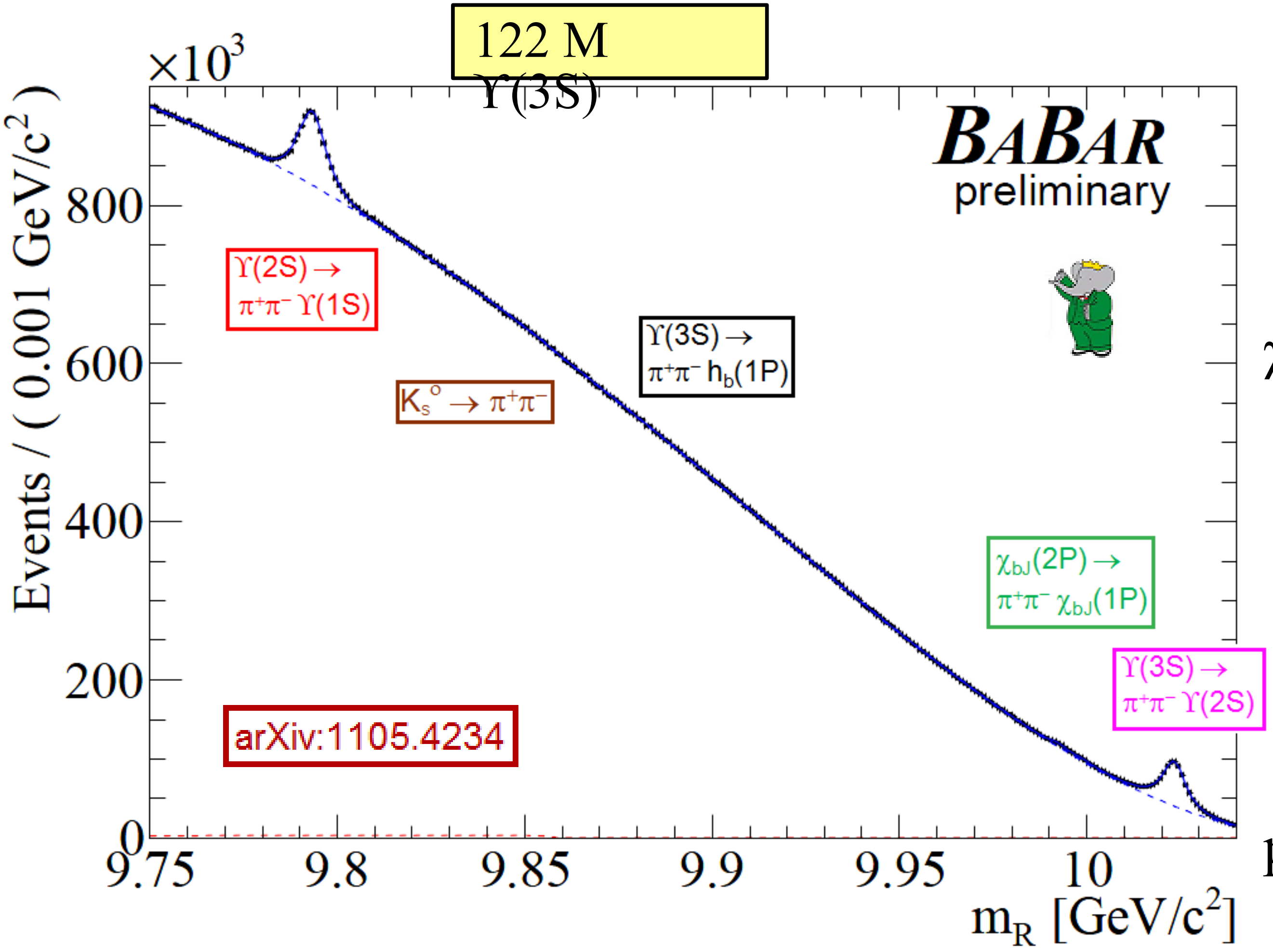
Godfrey and Rosner, PRD 66, 014012 (2002)

- Previous experimental limits
  - $\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- h_b(1P)) < 1.8 \times 10^{-3}$
  - $\mathcal{B}(\Upsilon(3S) \to \pi^0\ h_b(1P)) < 2.8 \times 10^{-3}$

CLEO, PRD 43,1448(1991)
PRD 49, 40 (1994)

Search for $h_b(1P)$ in $\Upsilon(3S)\rightarrow\pi^+\pi^-(X)$

mass recoiling against the $\pi^+\pi^-$: $m_R^2 = (m_{\Upsilon(3S)} - E_{\pi\pi})^2 - P_{\pi\pi}^2$



χ^2 fit to signal components

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

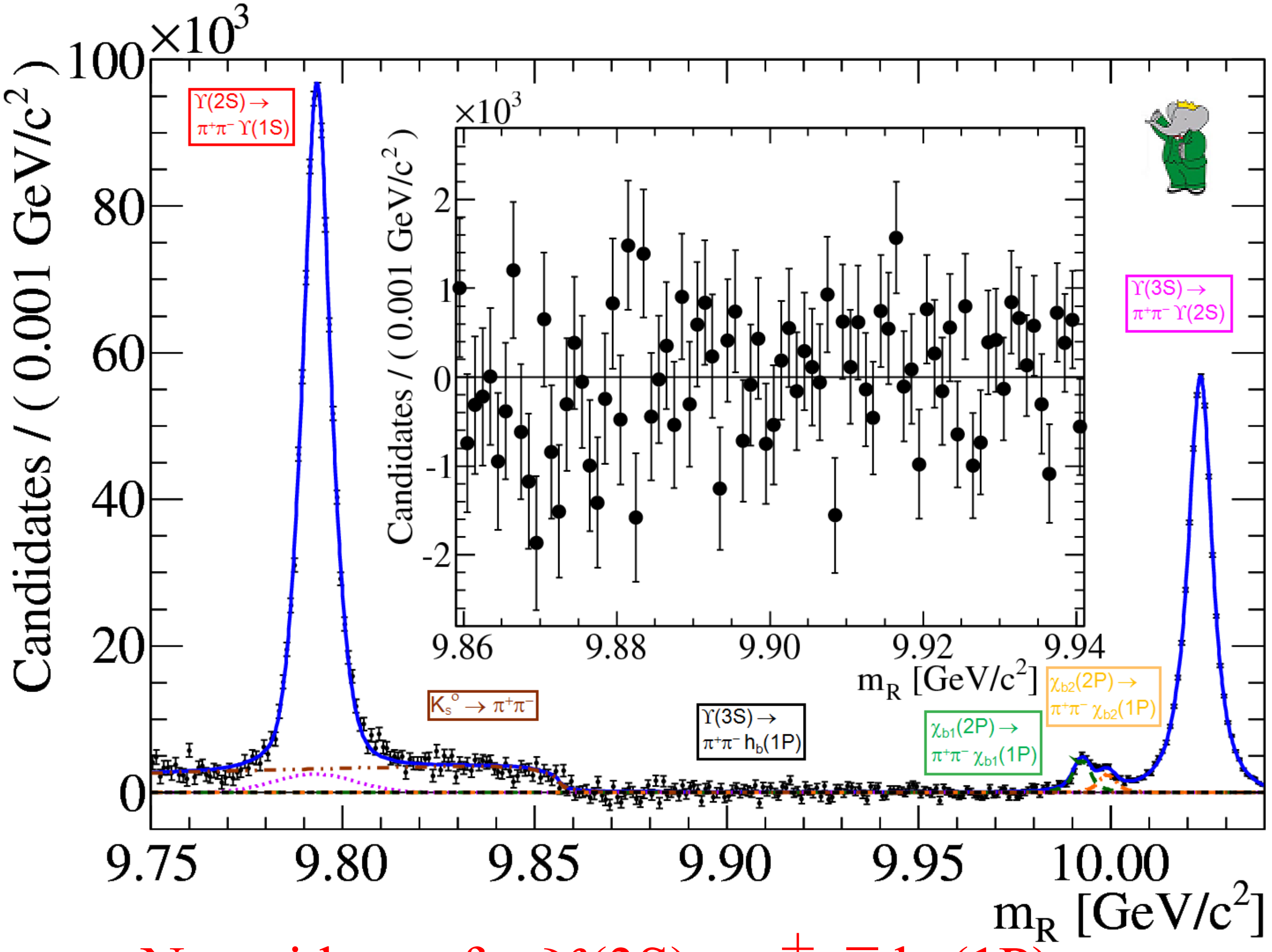
plus smooth background

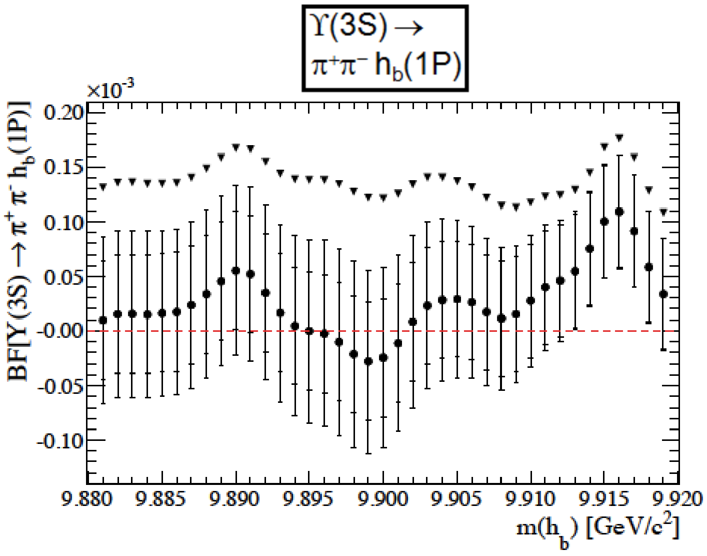
- non-peaking combinatorial
- $K^0\rightarrow\pi\pi$

Results

arXiv:1105.4234

fit result, with smooth background subtracted the inset shows the $h_b(1P)$ search region





central value and 90% CL UL as a function of h_b mass

No evidence for $\Upsilon(3S)\to\pi^+\pi^- h_b(1P)$:

$\mathcal{B}(\Upsilon(3S)\to\pi^+\pi^- h_b(1P)) < 1.2\times10^{-4}$ (90%CL)

x10 improvement over previous CLEO limit PRD 43,1448(1991)

disfavours e.g.
Kuang et al., PRD 37,1210 (1988)
Tuan, Mod. Ph.L. A7,3527 (1992)

Bottomonium dipion transitions

arXiv:1105.4234

122 M $\Upsilon(3S)$

Most precise or first measurements on other transitions

$$\mathcal{B}[\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)] = (3.00 \pm 0.02(\text{stat.}) \pm 0.14(\text{syst.}))\%$$

$$\mathcal{B}[\Upsilon(3S) \to X\chi_{b1}(2P)] \times \mathcal{B}[\chi_{b1}(2P) \to \pi^+\pi^-\chi_{b1}] = (1.16 \pm 0.07 \pm 0.12) \times 10^{-3}$$

$$\mathcal{B}[\Upsilon(3S) \to X\chi_{b2}(2P)] \times \mathcal{B}[\chi_{b2}(2P) \to \pi^+\pi^-\chi_{b2}] = (0.64 \pm 0.05 \pm 0.08) \times 10^{-3}$$

$$\mathcal{B}[\Upsilon(3S) \to X\Upsilon(2S)] \times \mathcal{B}[\Upsilon(2S) \to \pi^+\pi^-\Upsilon] = (1.78 \pm 0.02 \pm 0.11)\%$$

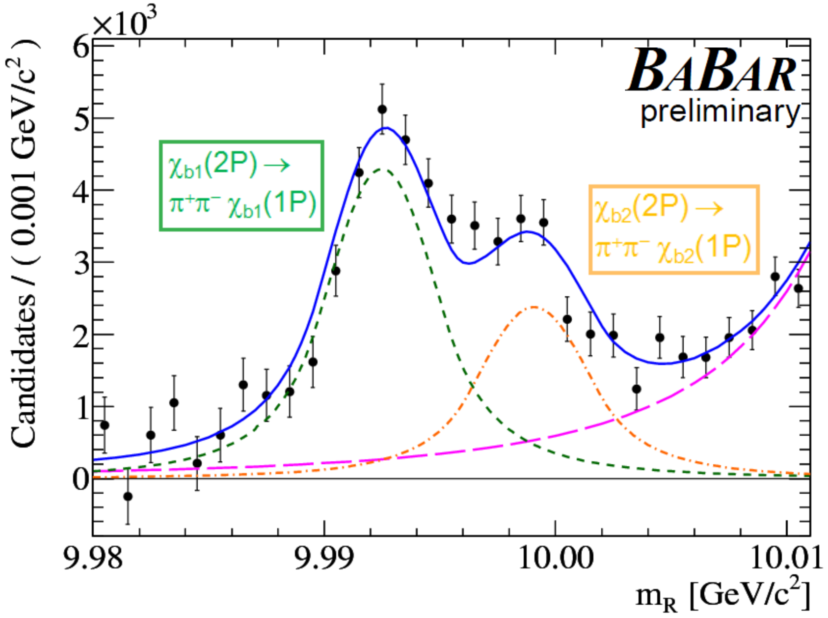
$$\Delta m[\Upsilon(3S)\text{-}\Upsilon(2S)] = 331.50 \pm 0.02(\text{stat.}) \pm 0.13(\text{syst.})\ \text{MeV}/c^2$$

dipion transitions between $\chi_{b1,2}$ states clearly separated for the first time

$\mathcal{B}(\chi_{b1}(2P) \to \pi^+\pi^-\chi_{b1}(1P)) = (9.2 \pm 0.6 \pm 0.9) \times 10^{-3}$

$\mathcal{B}(\chi_{b2}(2P) \to \pi^+\pi^-\chi_{b2}(1P)) = (4.9 \pm 0.4 \pm 0.6) \times 10^{-3}$

consistent with the CLEO measurement
(the two transitions were not resolved)
PRD 73, 012003 (2006)



Evidence for $\Upsilon(3S)\rightarrow\pi^0 h_b(1P)$

Preliminary

122 M $\Upsilon(3S)$

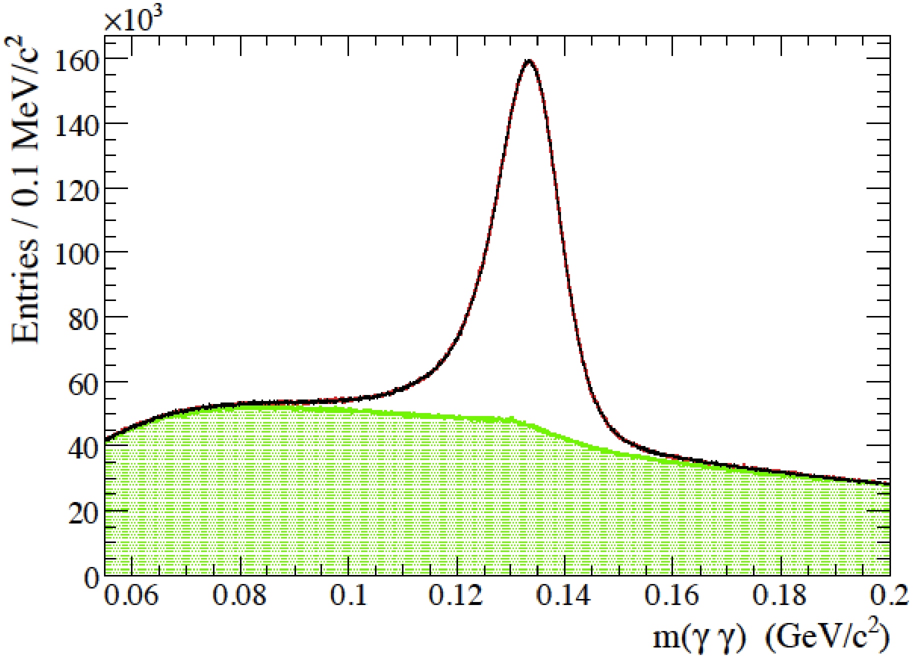
Select events with a π^0 and a photon

Require E_γ to be compatible with $h_b\rightarrow\gamma\eta_b(1S)$ (dominant decay mode)

arXiv:1102.4565

In each bin of $m_{recoil} = \sqrt{(m_{\Upsilon(3S)} - E^*_{\pi^0})^2 - P^{*2}_{\pi^0}}$

- perform a fit to the γγ inv. mass distribution to determine the number of π^0 in that bin

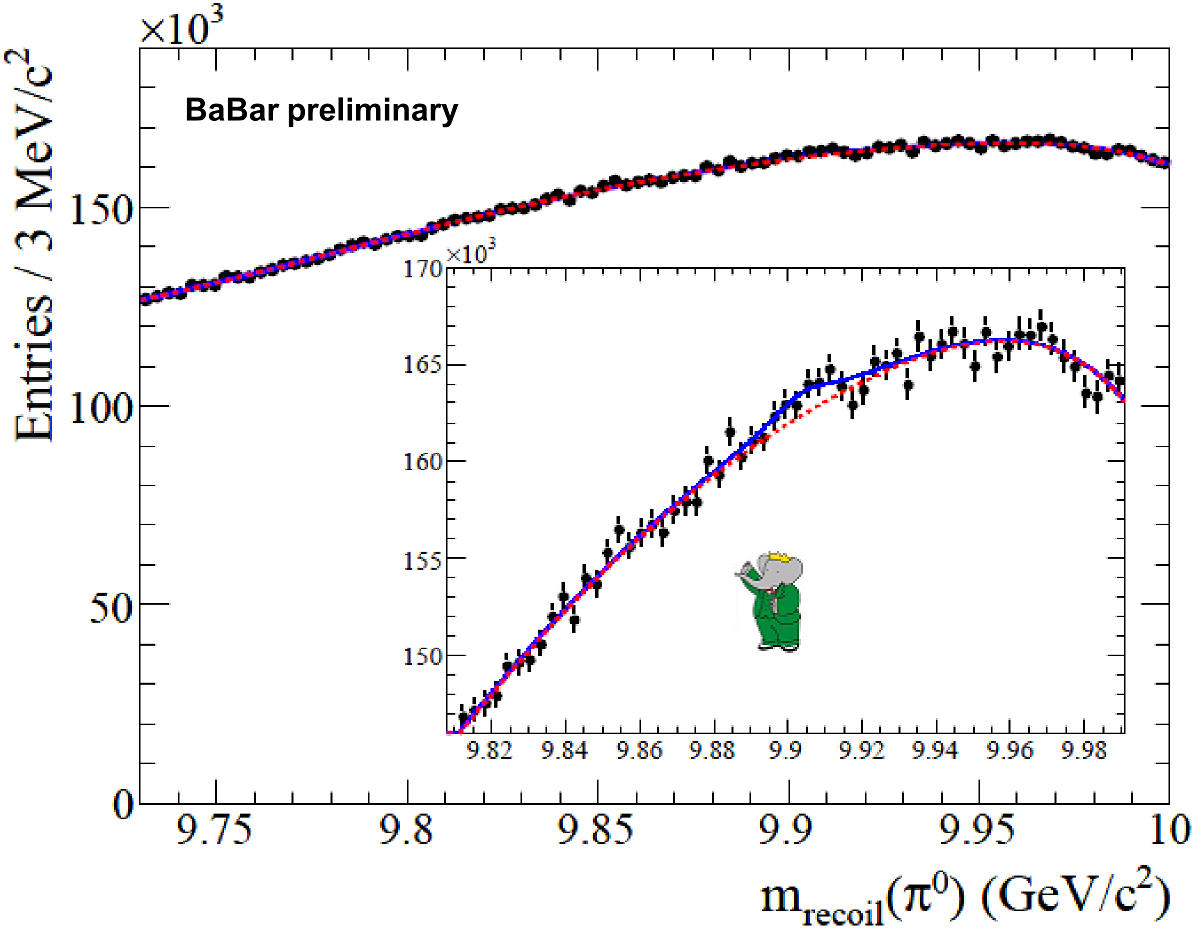


to obtain the distribution of the number of events recoiling against a π^0 as a function of m_{recoil}

Evidence for $\Upsilon(3S)\to\pi^0 h_b(1P)$

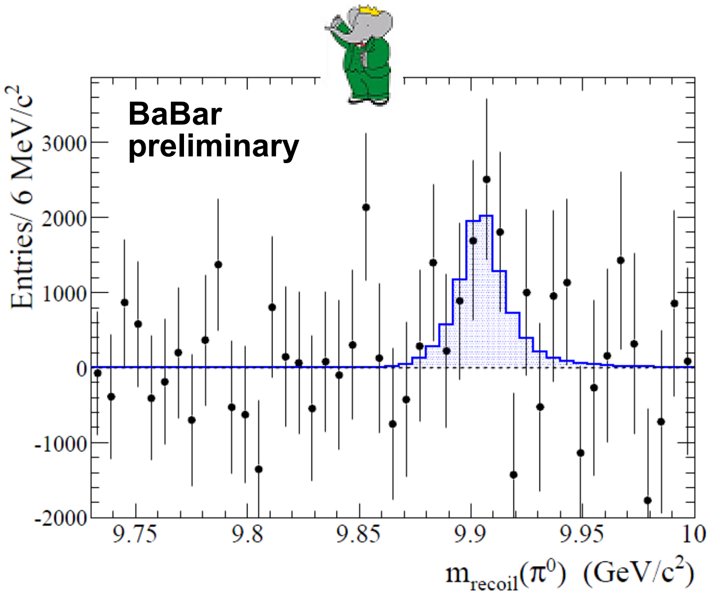
Preliminary

122 M $\Upsilon(3S)$



arXiv:1102.4565

$m_{recoil}(\pi^0)$ background subtracted



9145±2804 signal events

$M(h_b)=(\,9902\pm4_{(stat)}\pm1_{(syst)}\,)$ MeV/c^2 consistent with predictions

$\mathcal{B}(\Upsilon(3S)\to\pi^0 h_b(1P))\times\mathcal{B}(h_b(1P)\to\gamma\eta_b(1S))=(\,3.7\pm1.1\pm0.7\,)\times10^{-4}$

Statistical significance (from $\sqrt{\Delta\chi^2}$): 3.2 σ

including systematic error: 3.0 σ

evaluated at the expected mass value $M(h_b)=9900$ MeV/c^2

Bottomonium radiative transitions with converted photons

Rates generally phenomenologically well-predicted

arXiv:1104.5254

large $\mathcal{B}$ for electric dipole transitions

$\Upsilon(3S)\rightarrow\chi_{bJ}(2P)$, $\Upsilon(2S)\rightarrow\chi_{bJ}(1P)$, $\chi_{bJ}(2P)\rightarrow\Upsilon(2S)$, $\chi_{bJ}(1P)\rightarrow\Upsilon(1S)$

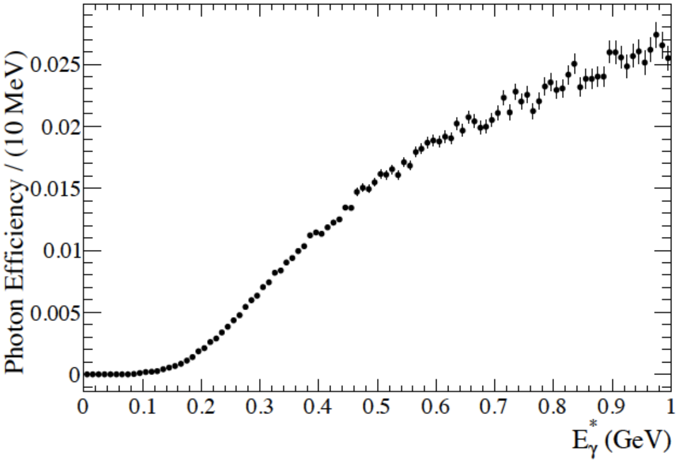
"hindered" electric dipole transitions suppressed

$\Upsilon(3S)\rightarrow\chi_{bJ}(1P)$, $\chi_{bJ}(2P)\rightarrow\Upsilon(1S)$

"hindered" M1 transitions highly suppressed: $\Upsilon(3S)\rightarrow\eta_b(1S)$, $\Upsilon(2S)\rightarrow\eta_b(1S)$

For some of these transitions the photons are in the same energy range "overlapping" due to Doppler broadening and detector resolution

Deconvolving the individual contributions has been the main difficulty in earlier measurements



Use converted photons ($\gamma\rightarrow e^+e^-$) to improve resolution (e.g.: 25 → 5 MeV)

Price: efficiency (0.1÷2.5)%

Converted photon energy spectra

arXiv:1104.5254

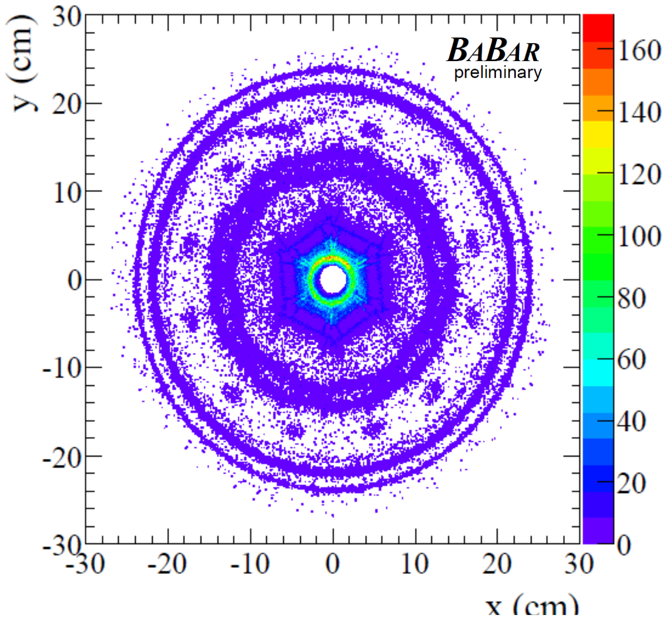
Converted photons are reconstructed from pair of tracks, selected with χ^2 fitter, m_γ, ρ_γ

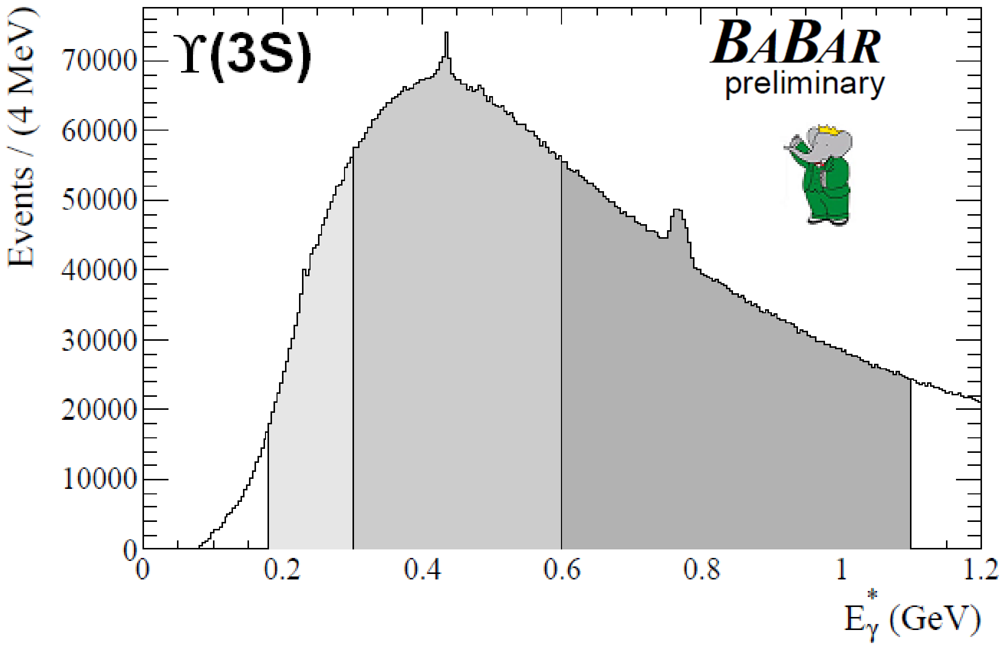
Additional cuts: $|\cos\theta_{thrust}|$, N_{tracks}, π^0 veto

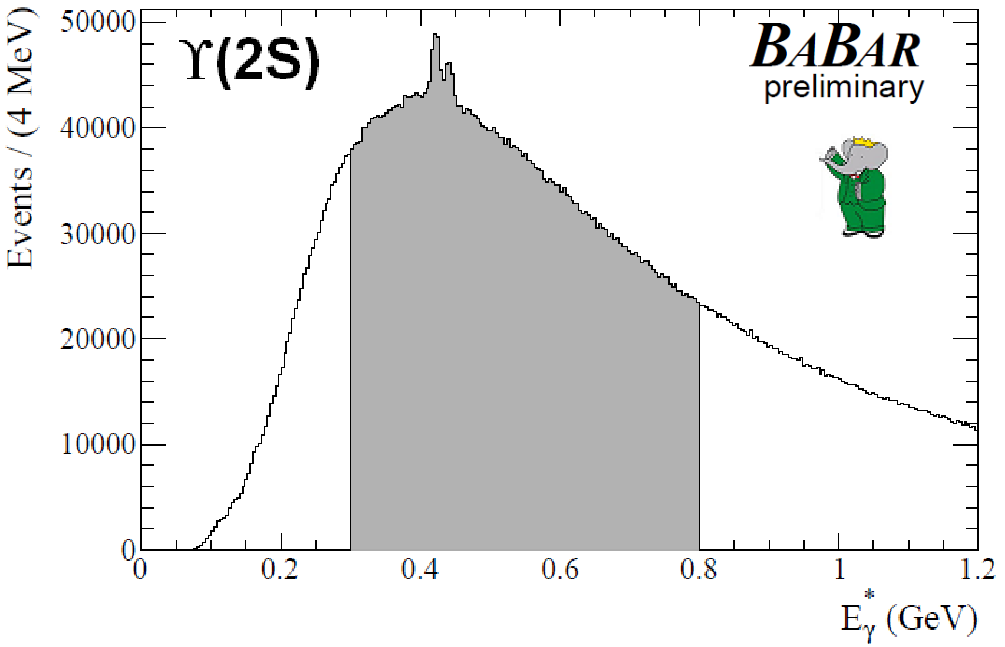
Fit E^*_γ spectrum in four regions of interest

1) $\Upsilon(3S)$: $180 < E^*_\gamma < 300$ MeV
2) $\Upsilon(3S)$: $300 < E^*_\gamma < 600$ MeV
3) $\Upsilon(3S)$: $600 < E^*_\gamma < 1100$ MeV

4) $\Upsilon(2S)$: $300 < E^*_\gamma < 800$ MeV







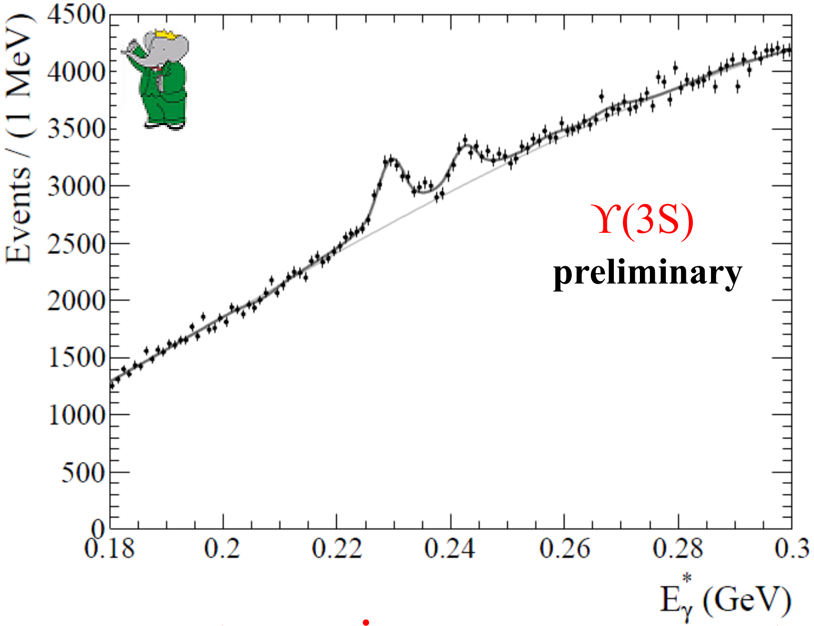
1) $\Upsilon(3S)$ - $180<E^*_\gamma<300$ MeV

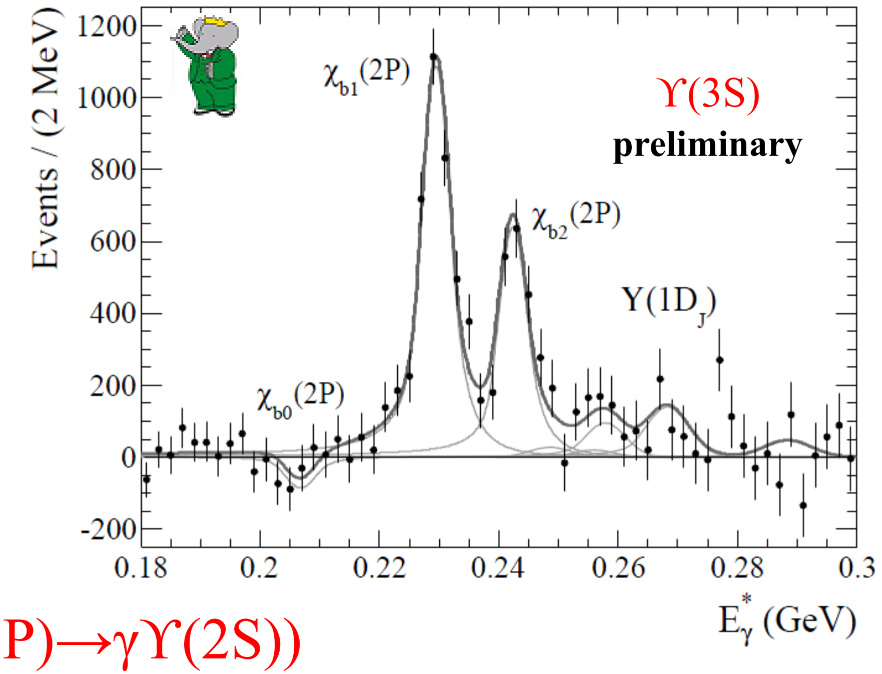
arXiv:1104.5254

expect:

3 signal transitions for $\chi_{bJ}(2P)\rightarrow\gamma\Upsilon(2S)$

possibly 6 transitions for $\Upsilon(1D_J)\rightarrow\gamma\,\chi_{bJ}(2P)$





most precise measurement of $\mathcal{B}(\chi_{bJ}(2P)\rightarrow\gamma\Upsilon(2S))$

no evidence for $\Upsilon(1D_J)\rightarrow\gamma\,\chi_{bJ}(2P)$

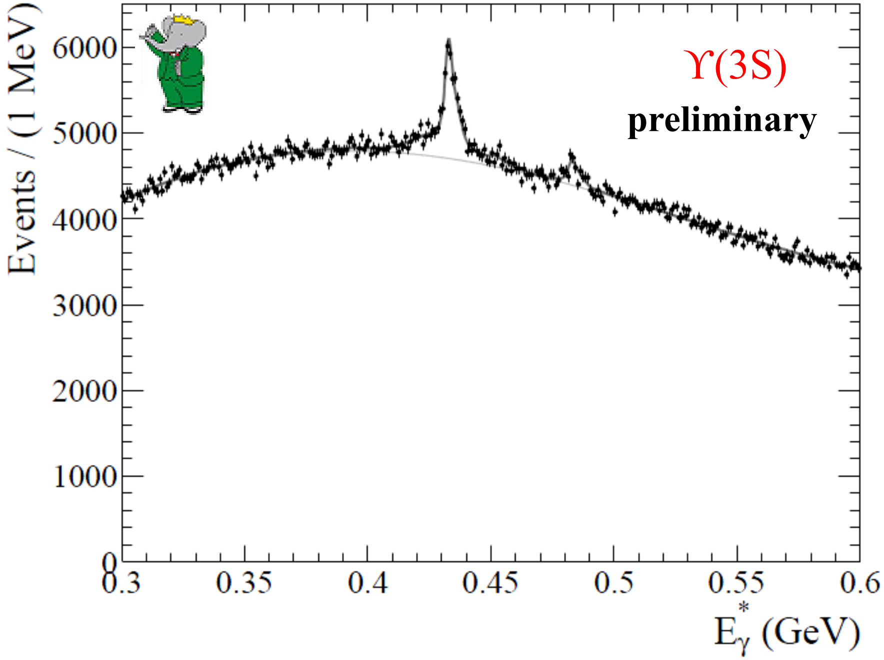
Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) *BABAR*	CUSB	CLEO
$\chi_{b0}(2P)\rightarrow\gamma\Upsilon(2S)$	205.0	-347 ± 209	0.105	$-4.9\pm2.9^{+0.7}_{-0.8}\pm0.5$ (<2.9)	3.6 ± 1.6	<5.2
$\chi_{b1}(2P)\rightarrow\gamma\Upsilon(2S)$	229.7	4294 ± 251	0.152	$19.5\pm1.1^{+1.1}_{-1.0}\pm1.9$	13.6 ± 2.4	21.1 ± 4.5
$\chi_{b2}(2P)\rightarrow\gamma\Upsilon(2S)$	242.3	2462 ± 243	0.190	$8.6^{+0.9}_{-0.8}\pm0.5\pm1.1$	10.9 ± 2.2	9.9 ± 2.7

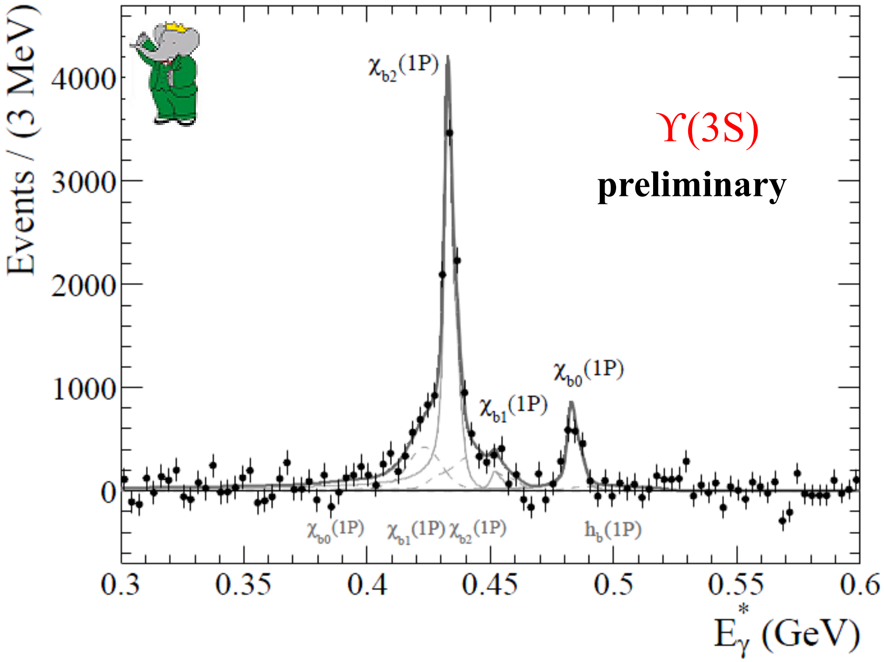
2) Υ(3S) - 300<E$^*_\gamma$<600 MeV

arXiv:1104.5254

Complicated spectrum

- 3 signal transitions for Υ(3S)→γ χ_{bJ}(1P)
- 3 overlapping Doppler-broadened transitions for χ_{bJ}(1P)→γΥ(1S), shape depends on the path to χ_{bJ}(1P)





Precise measurement of $\mathcal{B}$(Υ(3S)→γ$\chi_{b0,2}$(1P))

Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction ($\times 10^{-3}$) *BABAR*	CLEO
$\Upsilon(3S) \to \gamma\chi_{b2}(1P)$	433.1	9699 ± 318	0.794	$10.6 \pm 0.3 \pm 0.6$	7.7 ± 1.3
$\Upsilon(3S) \to \gamma\chi_{b1}(1P)$	452.2	483 ± 315	0.818	$0.5 \pm 0.3^{+0.2}_{-0.1}$ (< 1.1)	1.6 ± 0.5
$\Upsilon(3S) \to \gamma\chi_{b0}(1P)$	483.5	2273 ± 307	0.730	$2.7 \pm 0.4 \pm 0.2$	3.0 ± 1.1

disagreement(?) with CLEO exclusive anaysis Υ(3S)→γ$\chi_{b1,2}$(1P) PRD 83, 054003 (2011).

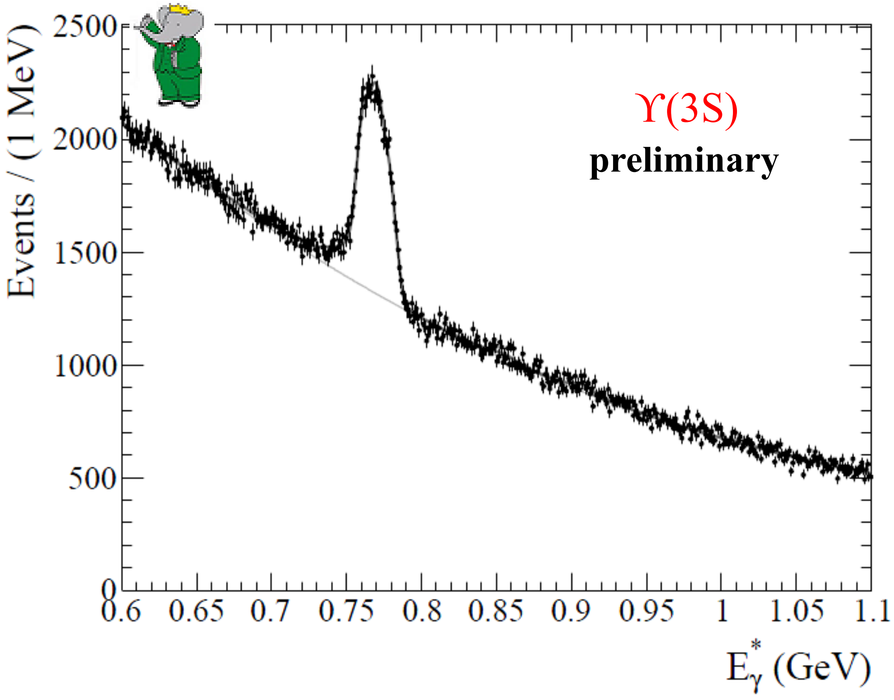
3) $\Upsilon(3S)$ - $600<E^*_\gamma<1100$ MeV

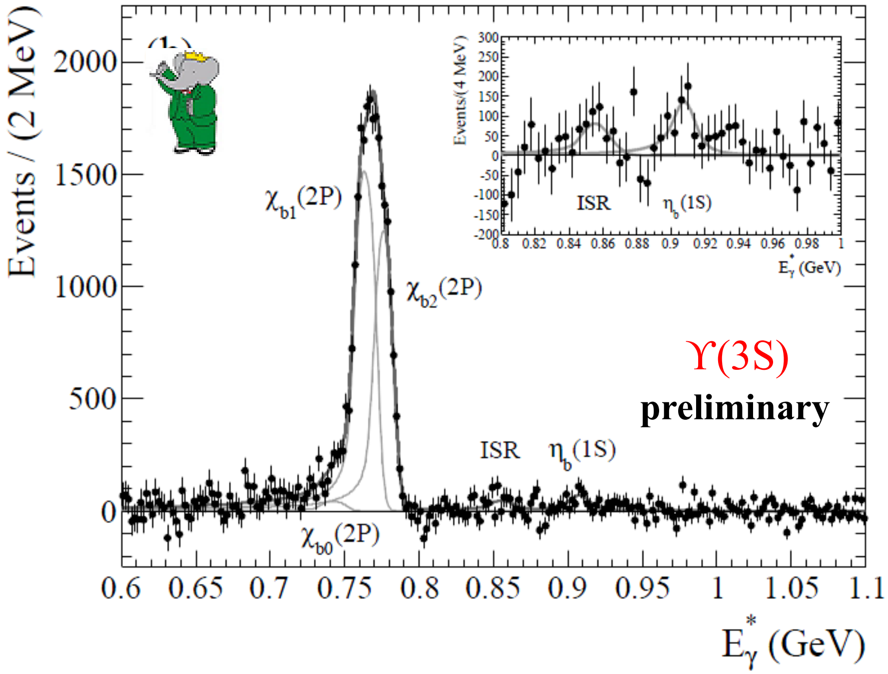
arXiv:1104.5254

Expect

3 signal overlapping transitions for $\chi_{bJ}(2P)\to\gamma\Upsilon(1S)$

$\Upsilon(3S)\to\gamma\eta_b(1S)$ and photon from ISR $\Upsilon(1S)$ production





Precise measurement of $\mathcal{B}(\chi_{b1,2}(2P)\to\gamma\Upsilon(1S))$ statistics insufficient for $\eta_b(1S)$

Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) BABAR	CUSB	CLEO
$\chi_{b0}(2P)\to\gamma\Upsilon(1S)$	742.7	469^{+260}_{-259}	1.025	$0.7\pm0.4^{+0.2}_{-0.1}\pm0.1$ (<1.2)	<1.9	<2.2
$\chi_{b1}(2P)\to\gamma\Upsilon(1S)$	764.1	14965^{+381}_{-383}	1.039	$9.9\pm0.3\pm0.4\pm0.9$	7.5 ± 1.3	10.4 ± 2.4
$\chi_{b2}(2P)\to\gamma\Upsilon(1S)$	776.4	11283^{+384}_{-385}	1.056	$7.1\pm0.2\pm0.3\pm0.9$	6.1 ± 1.2	7.7 ± 2.0
$\Upsilon(3S)\to\gamma\eta_b(1S)$	$907.9\pm2.8\pm0.9$	933^{+263}_{-262}	1.388	$0.059\pm0.016^{+0.014}_{-0.016}$	-	-

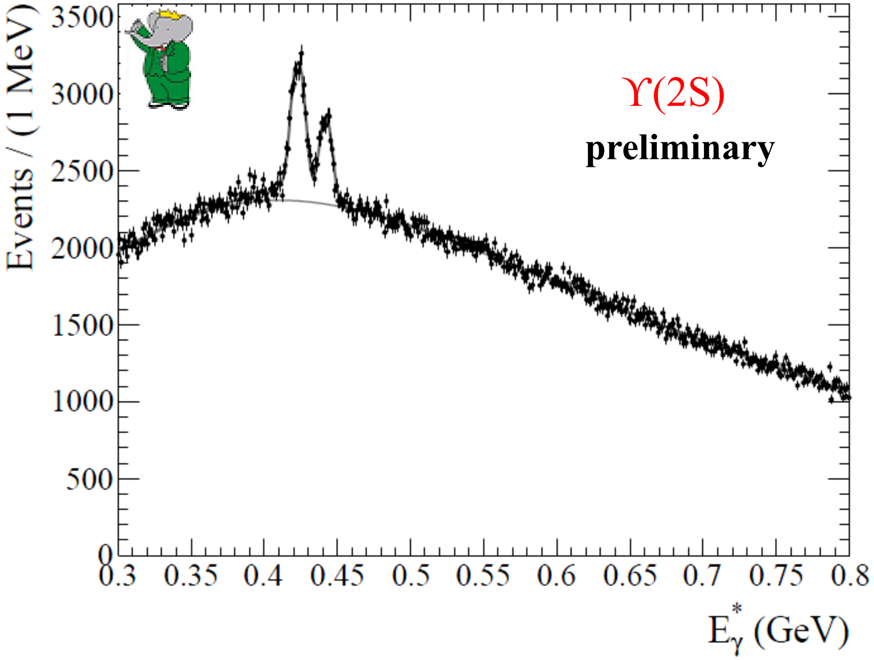
4) $\Upsilon(2S)$ - $300<E^*_\gamma<800$ MeV

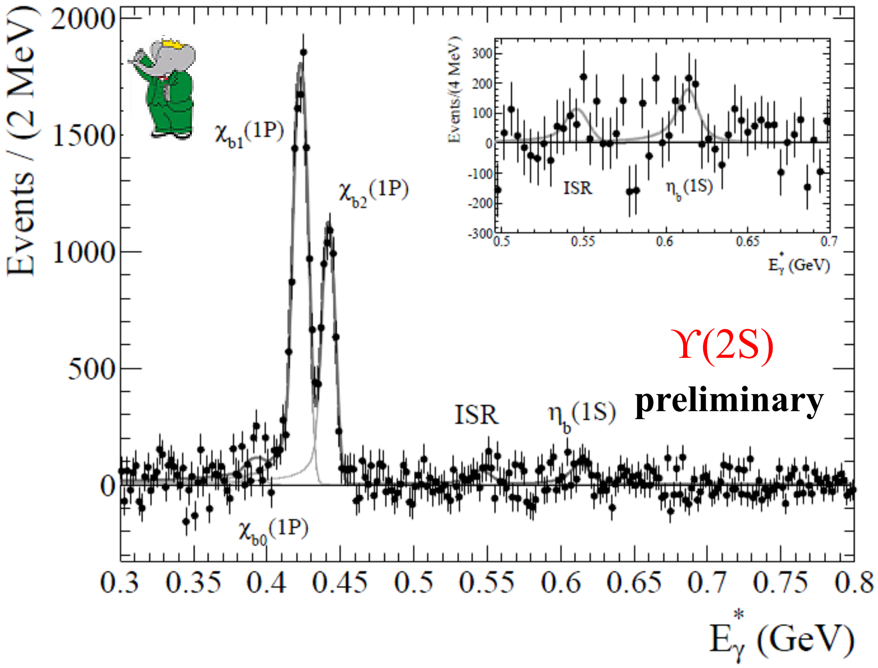
arXiv:1104.5254

Expect

3 signal transitions for $\chi_{bJ}(1P)\rightarrow\gamma\Upsilon(1S)$

$\Upsilon(2S)\rightarrow\gamma\eta_b(1S)$ and photon from ISR $\Upsilon(1S)$ production





Precise measurement of $\mathcal{B}(\chi_{b1,2}(1P)\rightarrow\gamma\Upsilon(1S))$ statistics insufficient for $\eta_b(1S)$

Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%)			
				BABAR	CB	CUSB	CLEO
$\chi_{b0}(1P)\rightarrow\gamma\Upsilon(1S)$	391.5	391 ± 267	0.496	$2.3\pm1.5^{+1.0}_{-0.7}\pm0.2\ (<4.6)$	<5	<12	1.7 ± 0.4
$\chi_{b1}(1P)\rightarrow\gamma\Upsilon(1S)$	423.0	12604 ± 285	0.548	$36.2\pm0.8\pm1.7\pm2.1$	34 ± 7	40 ± 10	33.0 ± 2.6
$\chi_{b2}(1P)\rightarrow\gamma\Upsilon(1S)$	442.0	7665^{+270}_{-272}	0.576	$20.2\pm0.7^{+1.0}_{-1.4}\pm1.0$	25 ± 6	19 ± 8	18.5 ± 1.4
$\Upsilon(2S)\rightarrow\gamma\eta_b(1S)$	$613.7^{+3.0+0.7}_{-2.6-1.1}$	1109 ± 348	1.050	$0.11\pm0.04^{+0.07}_{-0.05}\ (<0.22)$	-	-	-

Discussion of the results

Decay	*BABAR* (%)	Theory (%)
$\mathcal{B}(\chi_{b0}(2P) \to \gamma\Upsilon(2S))$	(< 2.9)	1.27
$\mathcal{B}(\chi_{b1}(2P) \to \gamma\Upsilon(2S))$	19.1 ± 2.3	20.2
$\mathcal{B}(\chi_{b2}(2P) \to \gamma\Upsilon(2S))$	8.2 ± 1.4	10.1
$\mathcal{B}(\chi_{b0}(2P) \to \gamma\Upsilon(1S))$	(< 1.2)	0.96
$\mathcal{B}(\chi_{b1}(2P) \to \gamma\Upsilon(1S))$	9.9 ± 1.1	11.8
$\mathcal{B}(\chi_{b2}(2P) \to \gamma\Upsilon(1S))$	$7.1^{+1.0}_{-0.9}$	5.3
$\mathcal{B}(\chi_{b0}(1P) \to \gamma\Upsilon(1S))$	(< 4.6)	3.2
$\mathcal{B}(\chi_{b1}(1P) \to \gamma\Upsilon(1S))$	36.2 ± 2.8	46.1
$\mathcal{B}(\chi_{b2}(1P) \to \gamma\Upsilon(1S))$	$20.2^{+1.6}_{-1.8}$	22.2

The branching fractions for

$\chi_{bJ}(1,2P) \to \gamma\Upsilon(1,2S)$

are in good agreement with predictions e.g.

Kwong,Rosner, PRD38, 279 (1988)

3S→1P rates differ from the expected $E_\gamma^3(2J+1)$ pattern and are generally poorly compatible with theory predictions

Source	$J = 0$	$J = 1$	$J = 2$
BABAR	55 ± 10	< 22	216 ± 25
Moxhay-Rosner	25	25	150
Grotch *et al.*	114	3.4	194
Daghighian-Silverman	16	100	650
Fulcher	10	20	30
Lähde	150	110	40
Ebert *et al.*	27	67	97

partial widths in eV

Conclusions

- no evidence for $\Upsilon(3S)\rightarrow\pi^+\pi^- h_b(1P)$
- evidence for $\Upsilon(3S)\rightarrow\pi^0 h_b(1P)$
  - mass compatible with expectation
  - branching ratio values marginally discriminating between different calculations
- Very precise measurements of a number of hadronic and radiative transitions

Babar continues the analysis of the large samples collected at the narrow Υ resonances. Expect more results ...