Recent results from BABAR

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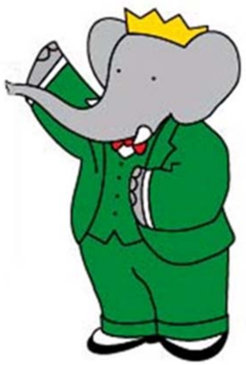
I) Bottomonium spectroscopy: ➔ $\Upsilon(3S)$ *sample*

- **Radiative transitions** using **converted γ** & **search** for $\eta_b(1S,2S)$ (+$\Upsilon(2S)$ sample)

- **Search for $h_b(1P)$** in $\Upsilon(3S)\to(\pi^0/\pi^+\pi^-)h_b(1P)$ [$h_b(1P)\to\gamma\,\eta_b(1S)$]

II) Search for the decay $D^0\to\gamma\gamma$
& measurement of $D^0\to\pi^0\pi^0$ ➔ *$\Upsilon(4S)$ sample and below "off-peak"*

III) $\mathcal{B}(B_s\to X\, l\, \nu_l)$ & B_s fraction: f_s ➔ *scan above the $\Upsilon(4S)$*



All results are preliminary

25th RENCONTES DE PHYSIQUE
DE LA VALLEE D'AOSTE
La Thuile - March 2, 2011

BaBar dataset

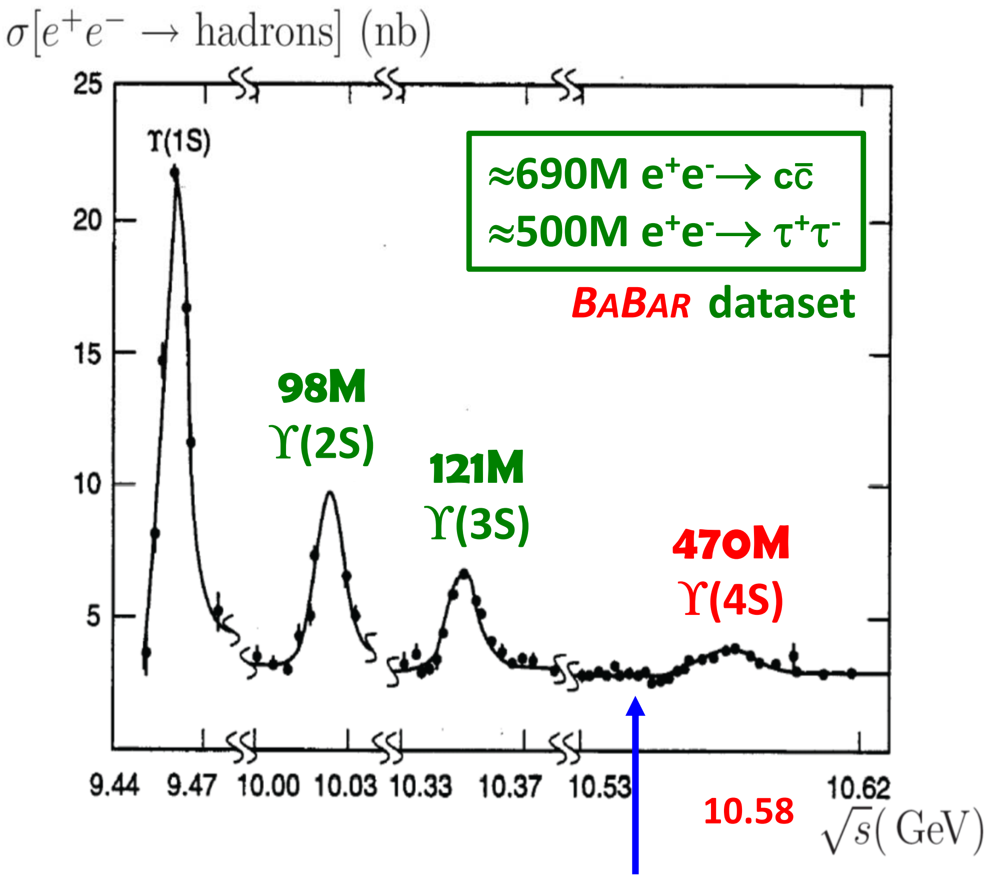
- **PEP-II rings: asymmetric e^+e^- collider@SLAC**
- **BaBar Collected 530/fb data 1999-2008**
- **data analysis still very active with rich physics program: >455 publi./submitted**

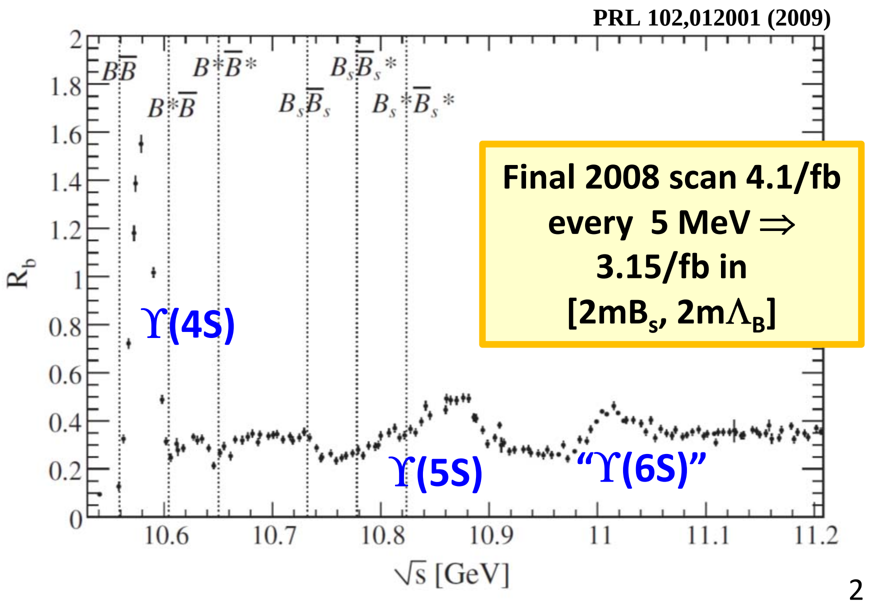
Υ(4S)	Υ(3S)	Υ(2S)	Other*
430/fb	30.2/fb	14.5/fb	54/fb

* **Mostly @Υ(4S)-40MeV**

Events	Υ(3S)	Υ(2S)
BaBar	121 M	98 M
Belle	11 M	175 M
CLEO	6 M	9 M

→used here



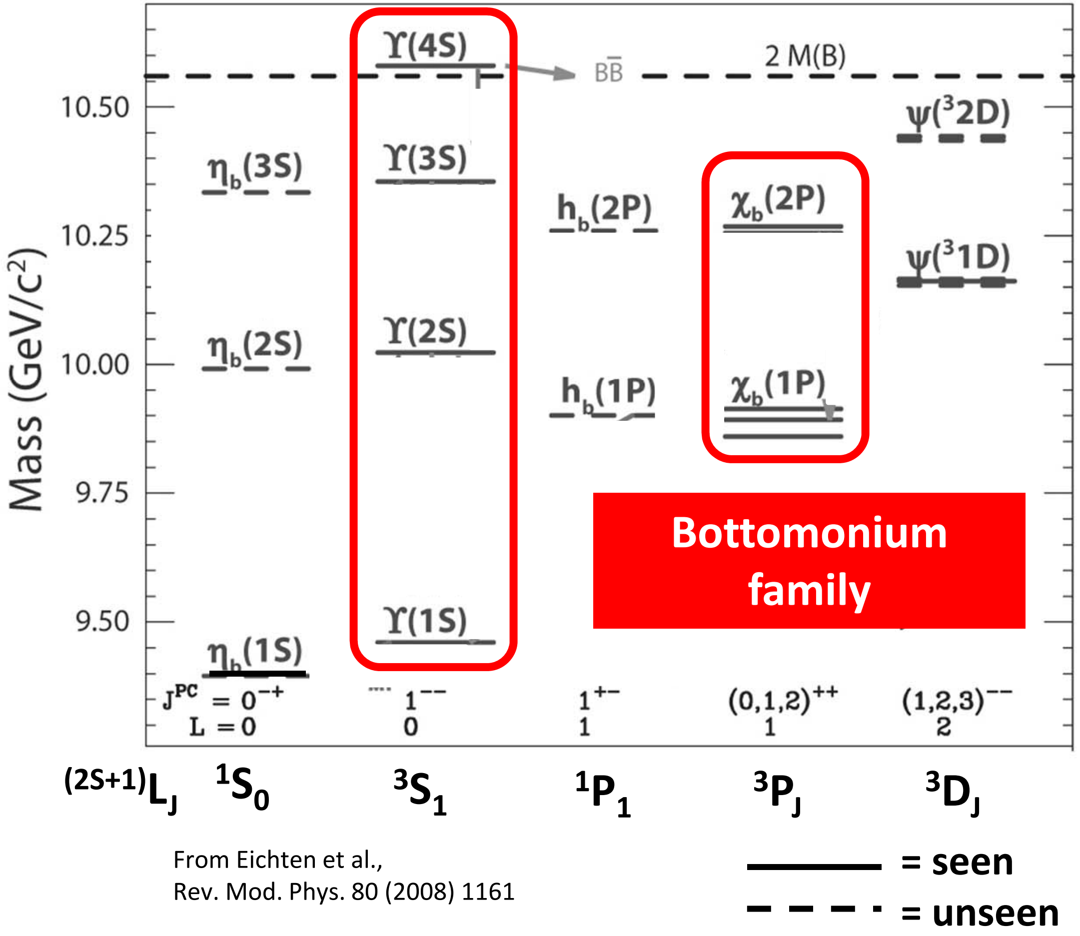


Bottomonium spectroscopy

- ➔ Spectrum below open-flavor threshold richer than charmonium
- ➔ Masses & BFs important to test heavy $q\bar{q}$ potential models and lattice QCD and pNRQCD
- ➔ Hadronic transitions probe non-perturbative QCD

- Bottomonium states with L=0, 1 & S=1 → known since 1977⇒ 1990's

- no spin-singlet observed?
- $\Upsilon(1D_{J=2})$ observed by CLEO (2004) $\gamma\gamma\Upsilon(1S)$ & BaBar (2010) $\pi\pi\Upsilon(1S)$
- η_b by BaBar (2008)
- $h_b(1P)$ state not yet observed



From Eichten et al., Rev. Mod. Phys. 80 (2008) 1161

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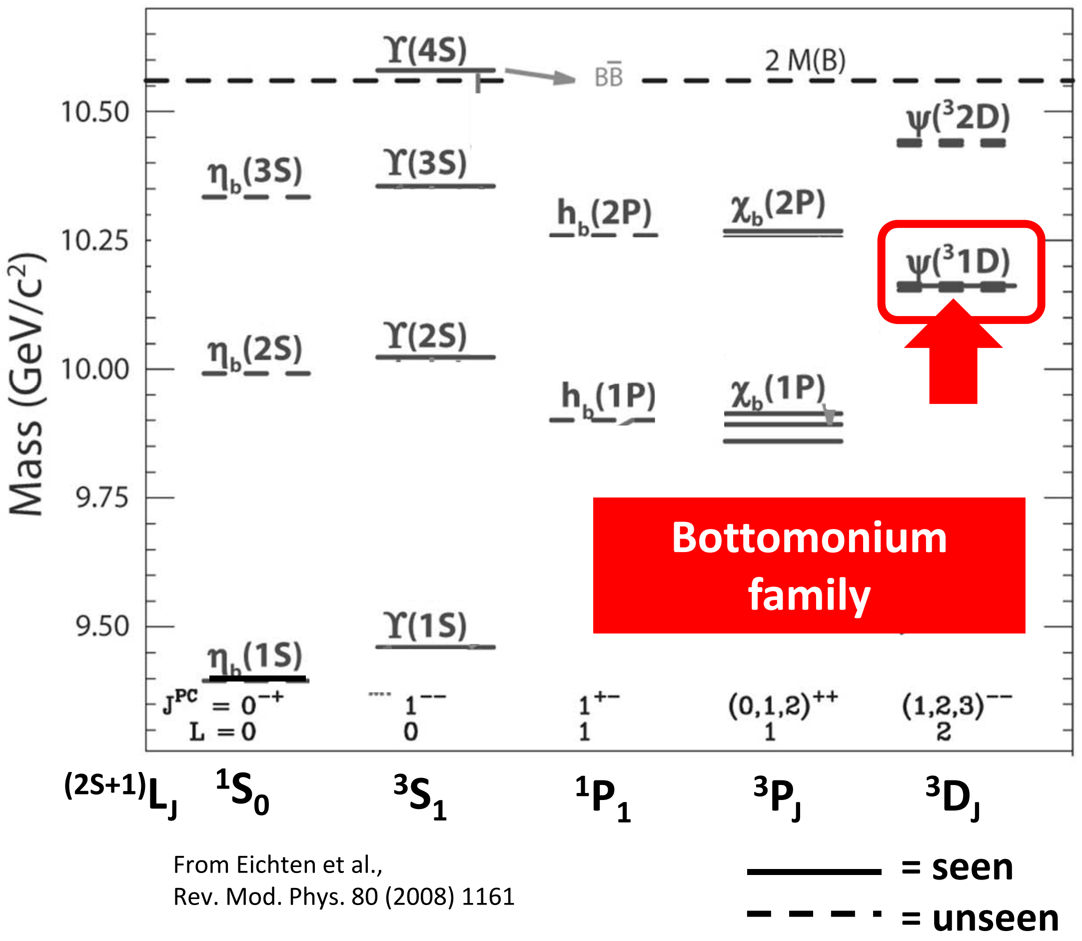

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Rev. Mod. Phys. 80 (2008) 1161

Bottomonium spectroscopy

= the states discussed here

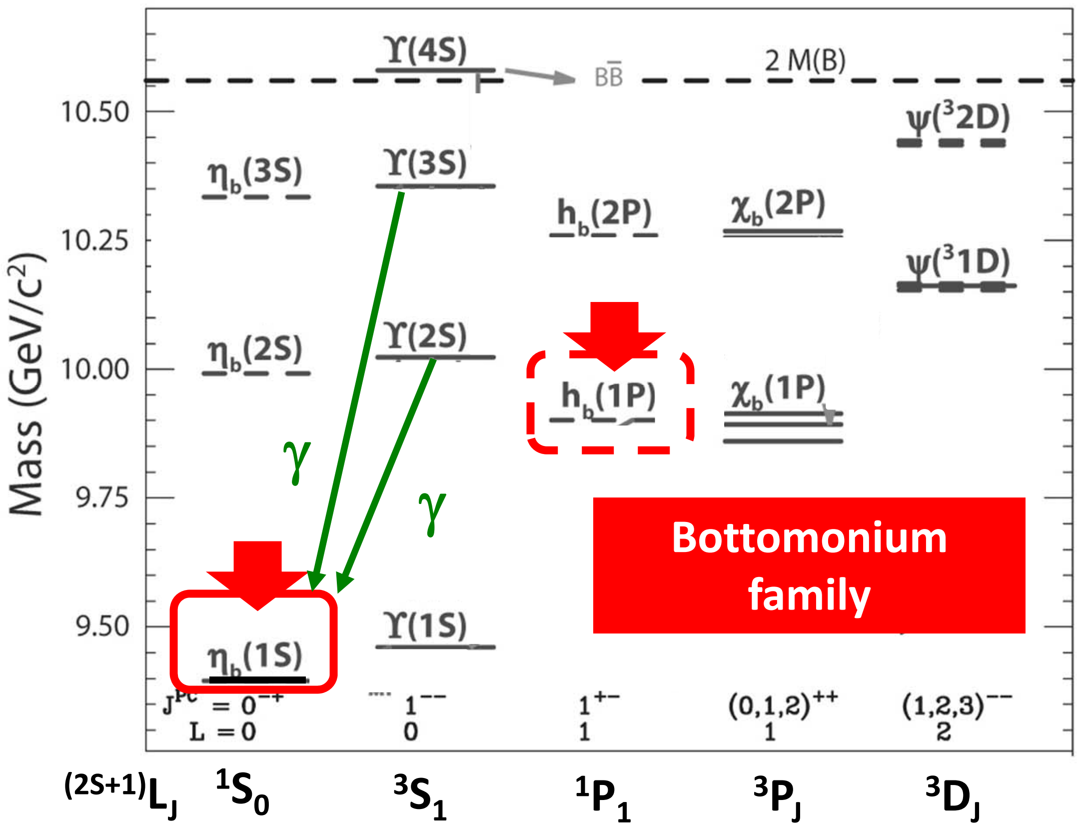
η_b and h_b : hyperfine mass splitting
→ spin dependence of the $q\bar{q}$ potential

- Bottomonium states with L=0, 1 & S=1 → known since 1977⇒ 1990's

- spin-singlet observed?

- η_b by BaBar (2008 Υ(3S), 2009 Υ(2S)) + CLEO (2010 Υ(3S)) from radiative decays

- h_b(1P) state not yet observed



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= seen
= unseen

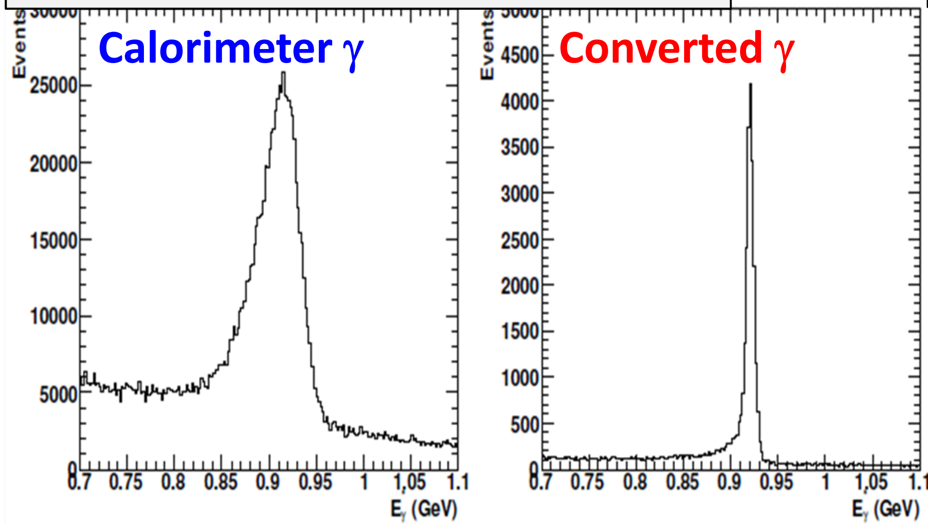
Inclusive photon spectrum for $\Upsilon(2S,3S)$ decays with converted photons $\gamma\rightarrow e^+e^-$

➔ Monochromatic γ (in init. part. CM): $E^*_{\gamma\,(\text{initial}\rightarrow\text{final})} = (m^2_{\text{init.}} - m^2_{\text{fin.}})/2m_{\text{init.}}$

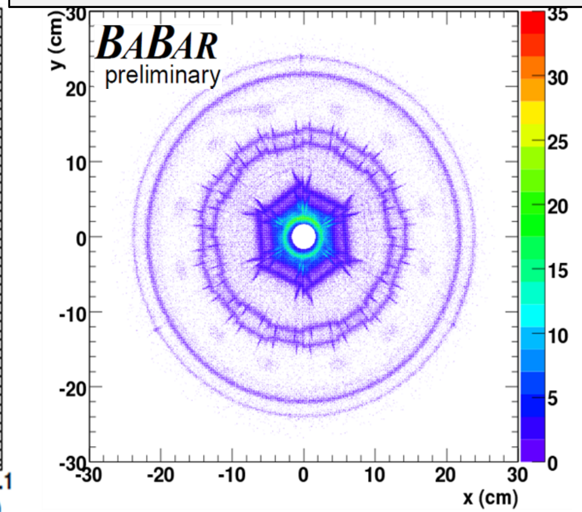
➔ Use Converted photons ($\gamma\rightarrow e^+e^-$): improves resolution (25 $\Rightarrow$ 5 MeV) and helps to resolve overlapping γ rays, but lower reconstruction efficiency ($\approx$1/20)

- Fit pair of tracks, selected with χ^2_{fitter}, m_γ, ρ_γ
- Additional cuts: $|\cos\theta_{\text{thrust}}|$, N_{tracks}, π^0 veto, R_2(sphericity)

E^*_γ in $\Upsilon(3S)\rightarrow\gamma\eta_b$ MC events (CM frame)

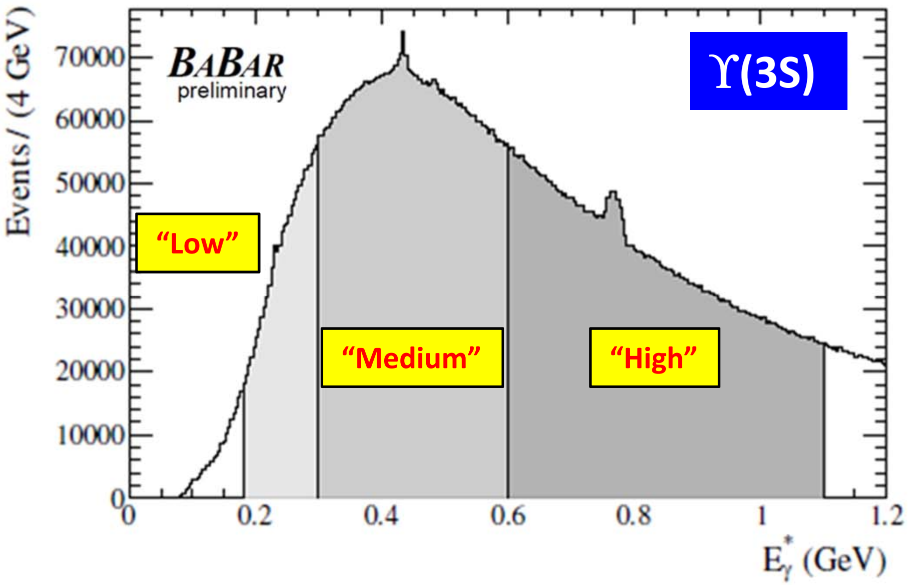


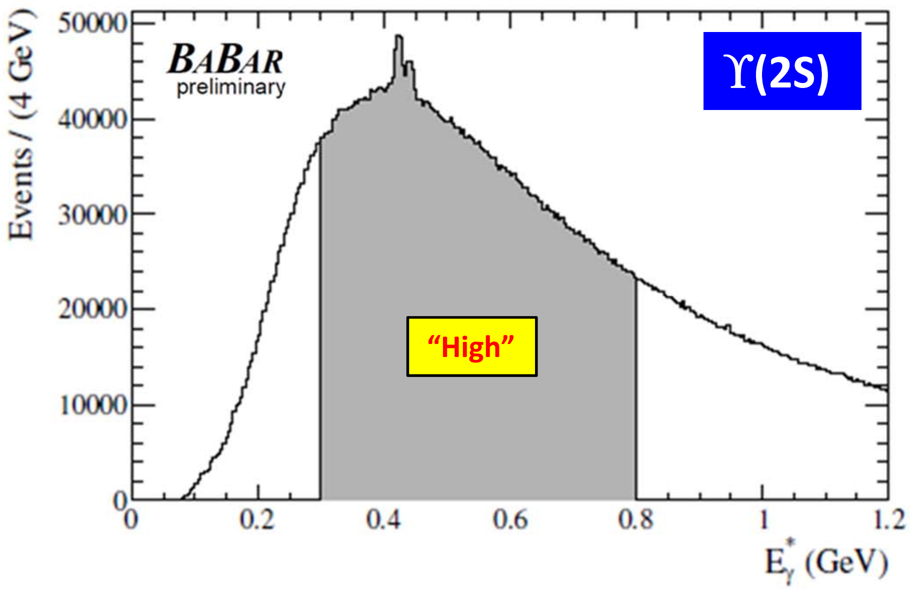
γ-ray "photograph" of innermost *BABAR* part



Inclusive photon spectrum for $\Upsilon(2S,3S)$ decays with converted photons $\gamma \to e^+e^-$

➔ **Define 4 E^*_γ regions of interest:**

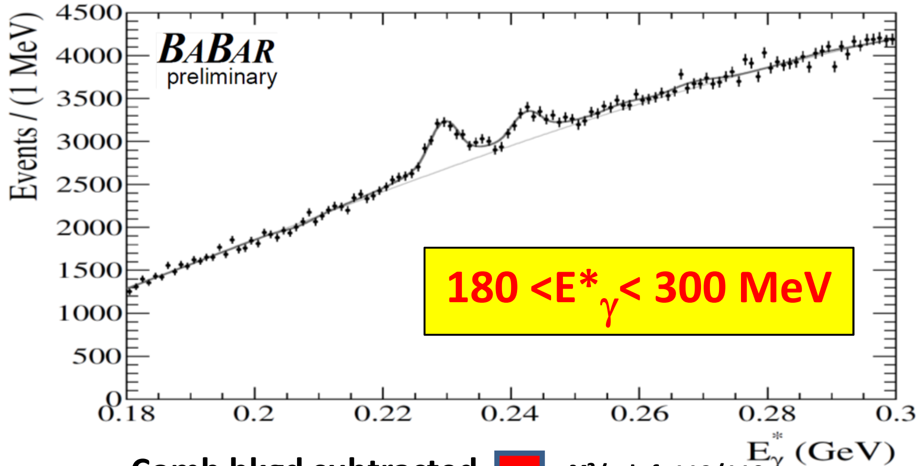




➔ **χ^2 fits to recoil E^*_γ spectrum in $\Upsilon(3S)$ and $\Upsilon(2S)$ datasets (rich phenomenology):**

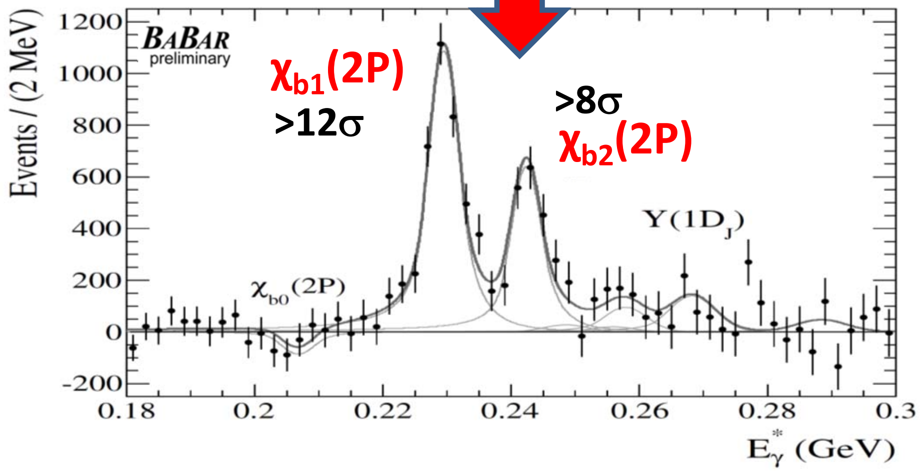
- **$\Upsilon(3,2S) \to \gamma\, \eta_b(1S)$ & $\Upsilon(3S) \to \gamma\, \eta_b(2S)$:** alternate $\eta_b(1S,2S)$ search + mass measurement
- **$e^+ e^-_{E=m_{\Upsilon(nS)}} \to \gamma_{ISR}\, \Upsilon(1S)$**
- **$\chi_{bJ}(1,2P) \to \gamma\, \Upsilon(1S)$, $\chi_{bJ}(2P) \to \gamma\, \Upsilon(2S)$, $\Upsilon(3S) \to \gamma\, \chi_{bJ}(1P)$**
- **Combinatorial background**

"Low" $E^*\gamma$ for $\Upsilon(3S)$ data

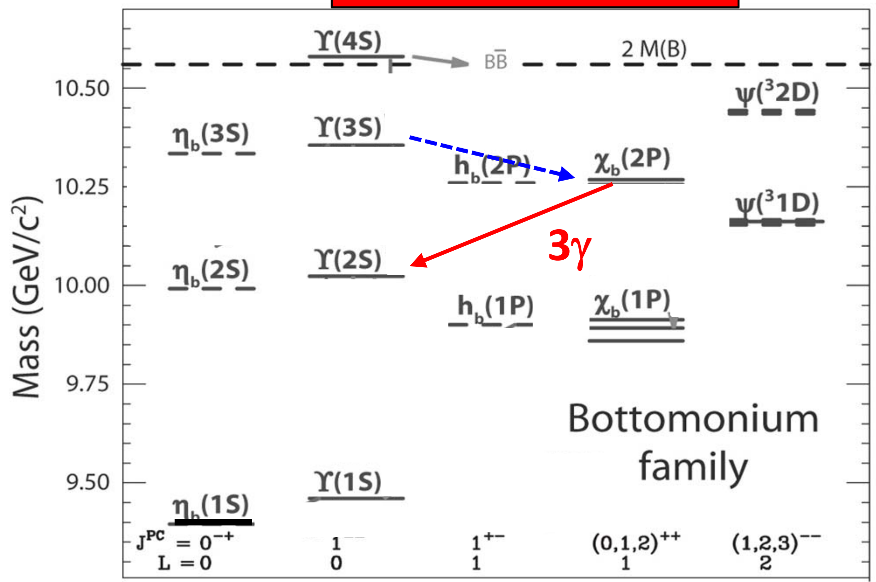


Comb bkgd subtracted

χ^2/ndof=119/110



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



- Fixed predict contrib. from $\Upsilon(^31D_J) \to \gamma\,\chi_{bJ}(1P)$
- $\chi_{b1,2}(2P) \to \gamma\,\Upsilon(2S)$ seen
- $\chi_{b0}(2P) \to \gamma\,\Upsilon(2S)$ not seen
- Consistent with CLEO and CUSB (92)
- Most precise measurement

Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) BABAR	CUSB	CLEO
$\chi_{b0}(2P) \to \gamma\Upsilon(2S)$	205.0	-347 ± 209	0.105	$-4.9 \pm 2.9^{+0.7}_{-0.8} \pm 0.5$ (< 2.9)	3.6 ± 1.6	< 5.2
$\chi_{b1}(2P) \to \gamma\Upsilon(2S)$	229.7	4294 ± 251	0.152	$19.5 \pm 1.1^{+1.1}_{-1.0} \pm 1.9$	13.6 ± 2.4	21.1 ± 4.5
$\chi_{b2}(2P) \to \gamma\Upsilon(2S)$	242.3	2462 ± 243	0.190	$8.6^{+0.9}_{-0.8} \pm 0.5 \pm 1.1$	10.9 ± 2.2	9.9 ± 2.7

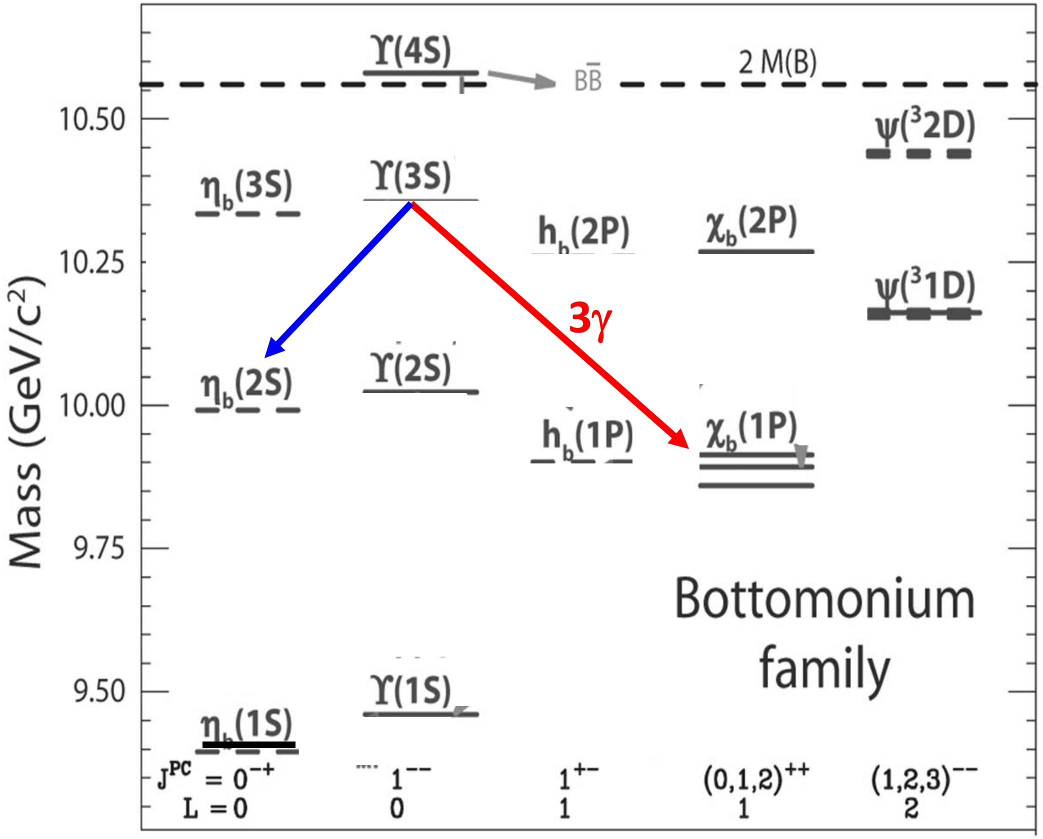
U.L.@90% of CL & $\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{bJ}(2P))$ from PDG

"Medium" E*γ for ϒ(3S) data

300 < E^*_γ < 600 MeV

(6 + 1?) pathways:

- $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \gamma\gamma\Upsilon(2S) \to \gamma\gamma\gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \gamma\gamma\Upsilon(1D_J) \to \gamma\gamma\gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \pi\pi\Upsilon(2S) \to \pi\pi\gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \gamma\chi_{bJ}(2P) \to \gamma\pi\pi\chi_{bJ}(1P)$
- $e^+e^- \to \gamma_{ISR}\Upsilon(2S) \to \gamma_{ISR}\gamma\chi_{bJ}(1P)$
- **$\Upsilon(3S) \to \gamma\, \eta_b(2S)$** expect $E^*\gamma$=335 –375MeV



"Medium" E*γ for $\Upsilon(3S)$ data

(6 + 1?) pathways:

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- $\Upsilon(3S) \to \gamma\gamma\Upsilon(2S) \to \gamma\gamma\gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \gamma\gamma\Upsilon(1D_J) \to \gamma\gamma\gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \pi\pi\Upsilon(2S) \to \pi\pi\gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \gamma\chi_{bJ}(2P) \to \gamma\pi\pi\chi_{bJ}(1P)$
- $e^+e^- \to \gamma_{ISR}\Upsilon(2S) \to \gamma_{ISR}\gamma\chi_{bJ}(1P)$
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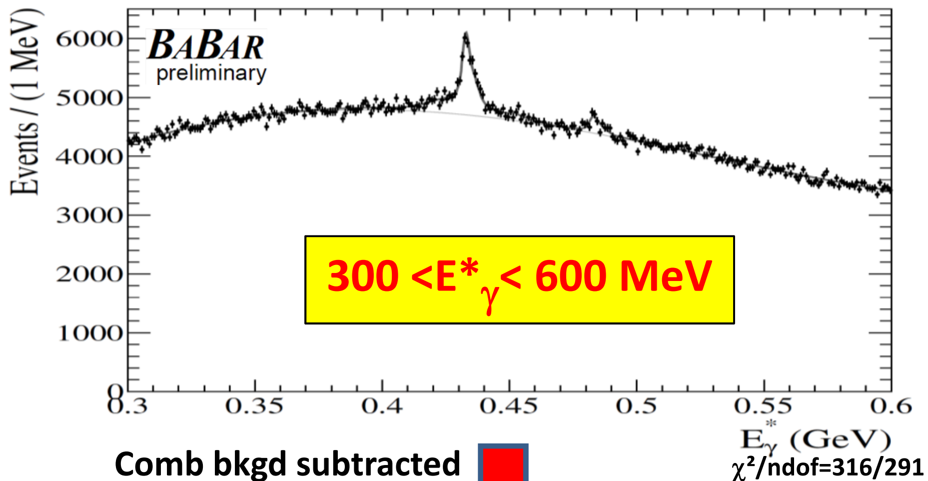
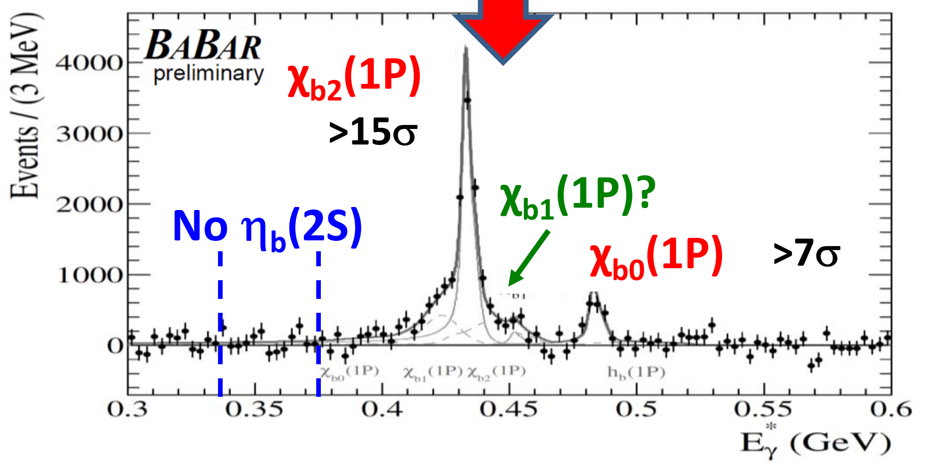


Comb bkgd subtracted



- $\Upsilon(3S) \to \gamma\,\chi_{b0,2}(1P)$ observed
- $\Upsilon(3S) \to \gamma\,\chi_{b1}(1P)$ not seen
- Consistent with CLEO 2010 arXiv:1012.0589
- $\mathcal{B}(\Upsilon(3S) \to \gamma\,\eta_b(2S))<1.9\times10^{-3}$ 90%CL

(scan (335<E*γ<375Mev) CLEO 2005 : 0.62 ×10^{-3}

Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction ($\times10^{-3}$) *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

U.L.@90% of CL

"High" $E^*\gamma$ for $\Upsilon(3S)$ data

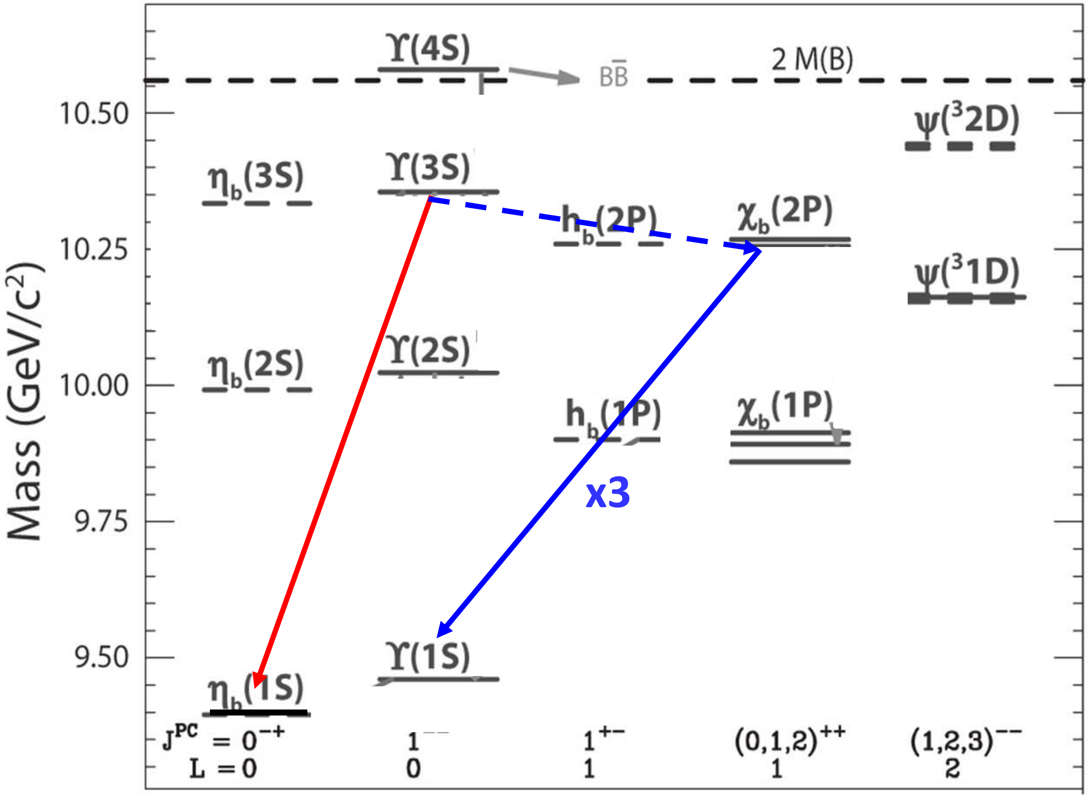
$600 < E^*_\gamma < 1100$ MeV

<u>5 monochromatic γ:</u>

1-3) $\chi_{bJ}(2P) \to \gamma\, \Upsilon(1S)$; J=0,1,2

4) $e^+e^- \to \gamma_{ISR}\, \Upsilon(1S)$: not from $\Upsilon(3S)$!

5) Signal $\eta_b(1S)$



"High" $E^*\gamma$ for $\Upsilon(3S)$ data

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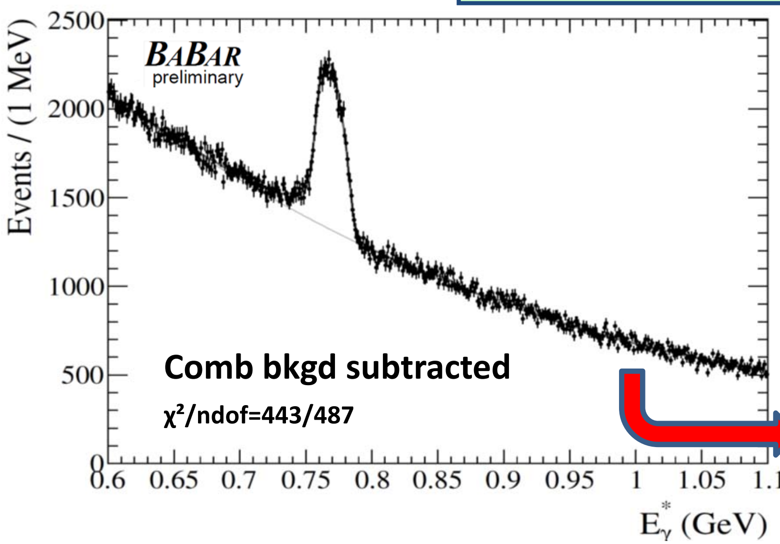
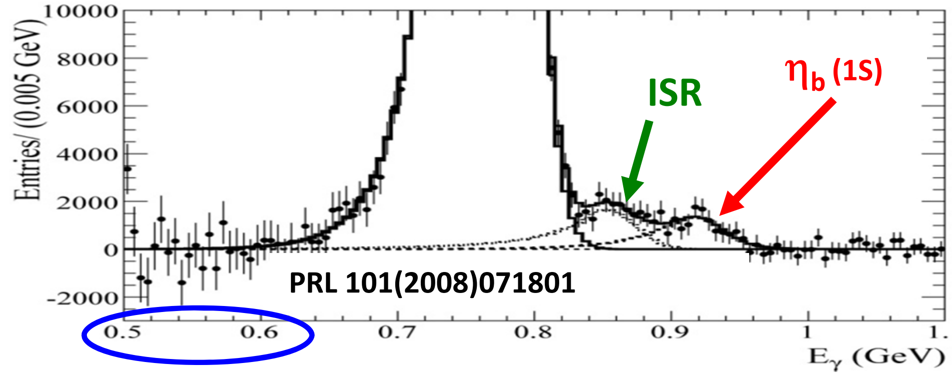
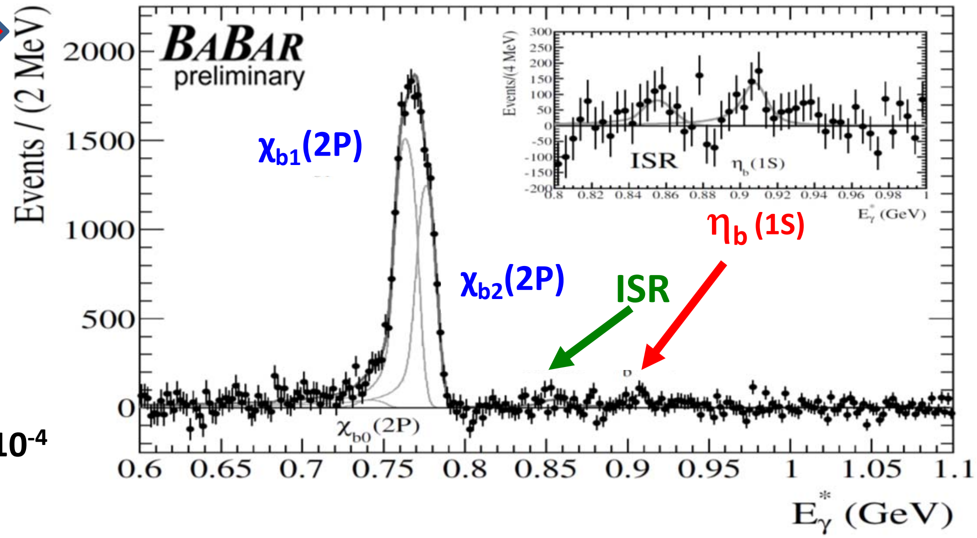






- **$\chi_{b1,2}(2P) \to \gamma\,\Upsilon(1S)$ improved**
- **$\chi_{b0}(2P) \to \gamma\,\Upsilon(1S)$ not seen**
- **$\eta_b(1S)$ result:**

- Fitted mass = (9403.6±2.8±0.9) MeV/c^2 is inconsistent with PDG (9390.9±2.8) by ≈3.1σ

- Consistent with PDG: $\mathcal{B}(\Upsilon(3S)\to\gamma\eta_b(1S))$ = (5.1±0.7) x 10^{-4}

- Syst. uncertainty dominated by width assumption

- Significance: 2.9σ stat., 2.7σ +syst

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	$0.7 \pm 0.4^{+0.2}_{-0.1} \pm 0.1$ (< 1.2)	< 1.9	< 2.2
$\chi_{b1}(2P) \to \gamma\Upsilon(1S)$	764.1	14965^{+381}_{-383}	1.039	$9.9 \pm 0.3 \pm 0.4 \pm 0.9$	7.5 ± 1.3	10.4 ± 2.4
$\chi_{b2}(2P) \to \gamma\Upsilon(1S)$	776.4	11283^{+384}_{-385}	1.056	$7.1 \pm 0.2 \pm 0.3 \pm 0.9$	6.1 ± 1.2	7.7 ± 2.0
$\Upsilon(3S) \to \gamma\eta_b(1S)$	$907.9 \pm 2.8 \pm 0.9$	933^{+263}_{-262}	1.388	$0.059 \pm 0.016^{+0.014}_{-0.016}$	-	-

U.L.@90% of CL & & $\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{bJ}(2P))$ from PDG

“High” $E^*\gamma$ for $\Upsilon(2S)$ data

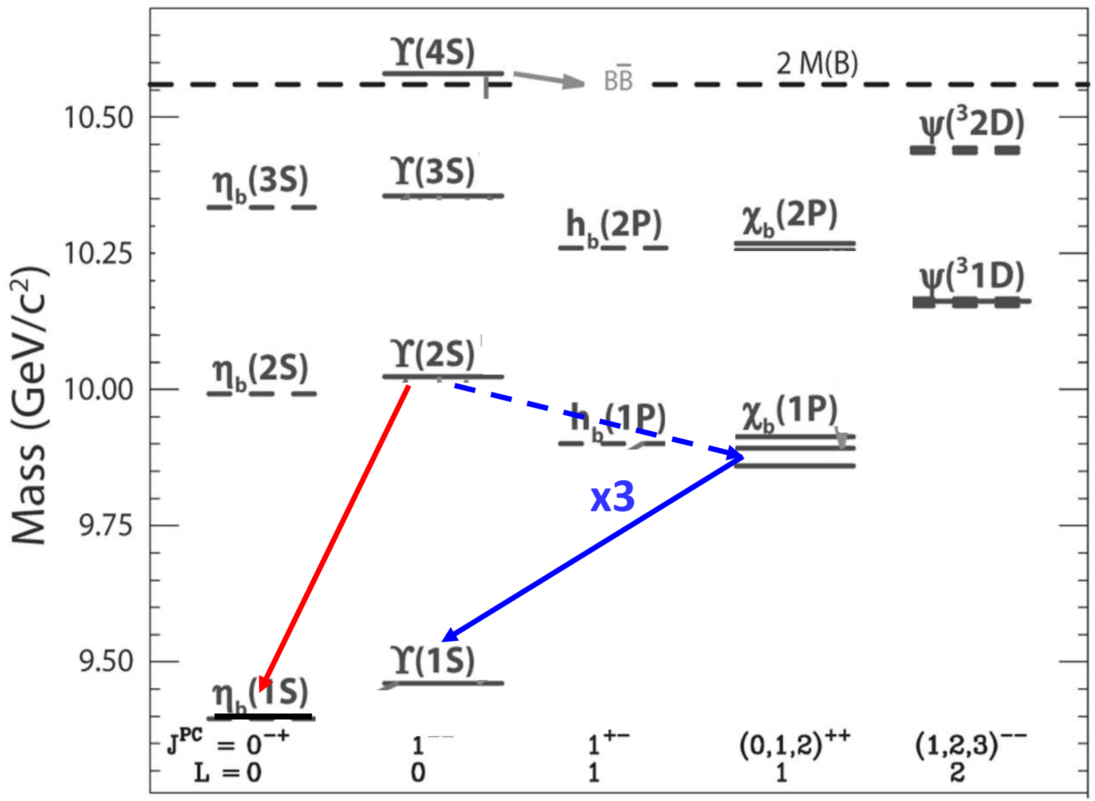
$300 < E^*_\gamma < 800$ MeV

<u>5 monochromatic γ:</u>

1-3) $\chi_{bJ}(1P) \to \gamma\, \Upsilon(1S)$; J=0,1,2

4) $e^+e^- \to \gamma_{ISR}\, \Upsilon(1S)$: not from $\Upsilon(2S)$!

5) Signal $\eta_b(1S)$



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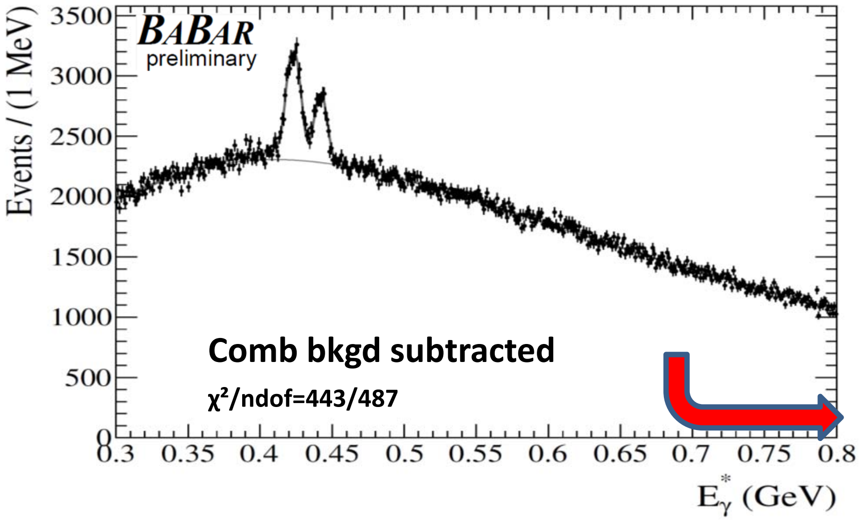
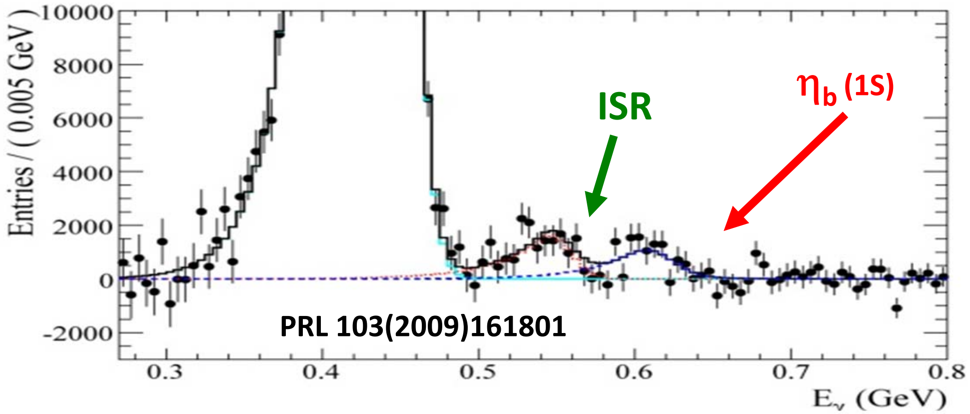
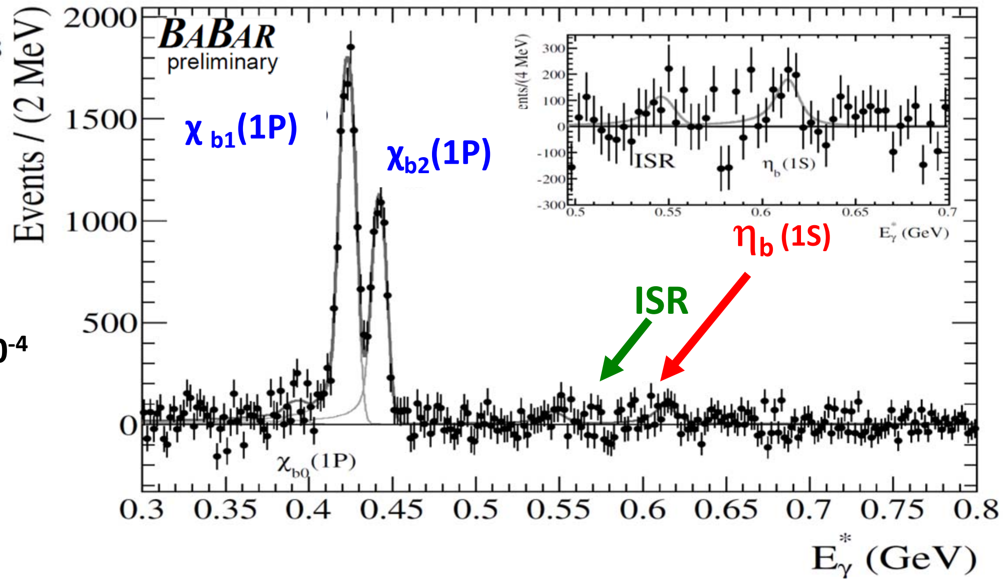






- $\chi_{b1,2}(1P) \to \gamma\,\Upsilon(1S)$ improved
- $\chi_{b0}(1P) \to \gamma\,\Upsilon(1S)$ not seen
- $\eta_b(1S)$ result:

- E*$_\gamma$ offset is ok: $(-0.6^{+0.5}_{-0.4})$ MeV
- Consistent with PDG: $\mathcal{B}(\Upsilon(2S)\to\gamma\eta_b(1S)) = (3.9\pm1.5) \times 10^{-4}$

-Syst. uncertainty on yield is large (>50%) dominated by bkgd. shape, PDG masses, MC params.

- BUT low significance: 2.5σ stat., 1.7σ + syst.

Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) BABAR	CB	CUSB	CLEO
$\chi_{b0}(1P) \to \gamma\Upsilon(1S)$	391.5	391 ± 267	0.496	$2.3 \pm 1.5^{+1.0}_{-0.7} \pm 0.2$ (< 4.6)	< 5	< 12	1.7 ± 0.4
$\chi_{b1}(1P) \to \gamma\Upsilon(1S)$	423.0	12604 ± 285	0.548	$36.2 \pm 0.8 \pm 1.7 \pm 2.1$	34 ± 7	40 ± 10	33.0 ± 2.6
$\chi_{b2}(1P) \to \gamma\Upsilon(1S)$	442.0	7665^{+270}_{-272}	0.576	$20.2 \pm 0.7^{+1.0}_{-1.4} \pm 1.0$	25 ± 6	19 ± 8	18.5 ± 1.4
$\Upsilon(2S) \to \gamma\eta_b(1S)$	$613.7^{+3.0+0.7}_{-2.6-1.1}$	1109 ± 348	1.050	$0.11 \pm 0.04^{+0.07}_{-0.05}$	-	-	-

U.L.@90% of CL & & $\mathcal{B}(\Upsilon(2S) \to \gamma\chi_{bJ}(1P))$ from PDG

Summary on inclusive photon spectrum for $\Upsilon(2,3S)$ decays with converted γ

- **Best $\mathcal{B}(\chi_{bJ}(nP) \to \gamma\Upsilon(mS))$**
  - First direct measurements
  - Good agreement with theory

  (Kwong & Rosner, PRD 38 279 (1988))

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

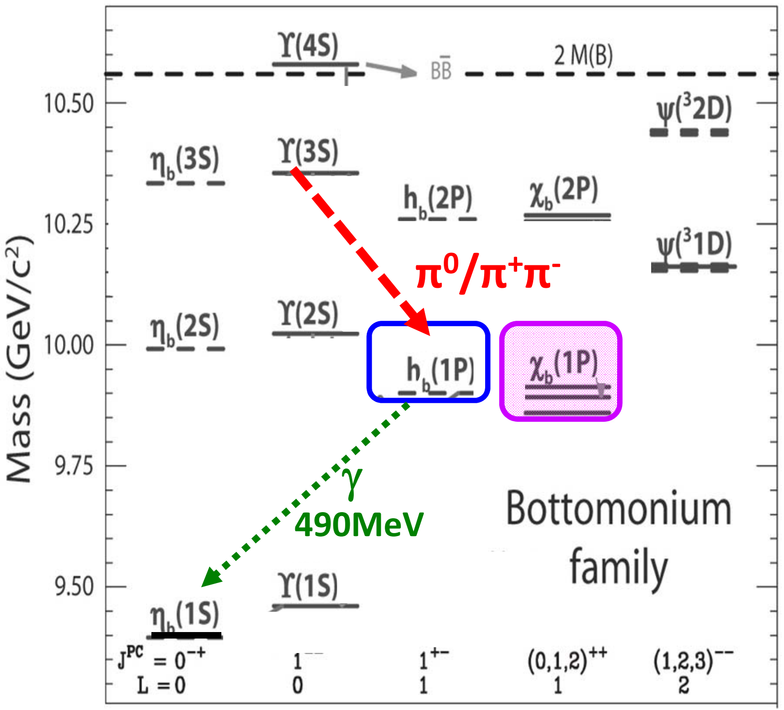
- **Observation: $\Upsilon(3S) \to \gamma\, \chi_{b0,2}(1P)$ not $\gamma\, \chi_{b1}(1P)$**
  - Inconsistent with any theory

  (~ok with CLEO 2010 arXiv:1012.0589)

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

- **New information on $m_{\eta_b(1S)}$?**
  - significance ~2.7σ for $\Upsilon(3S)$ only
  - BTW disagrees with prev. expt.

Search for $h_b(1P)$ in $\Upsilon(3S)$



$^1P_1$

- axial vector partner of 3 P-wave $\chi_{bJ}(1P)$ states
  → expected $m_{h_b(1P)}$ as spin-averaged $\Sigma[(2J+1)\, m_J]/\Sigma(2J+1)$:

$(m\chi_{b0(1P)} + 3\, m\chi_{b1(1P)} + 5\, m\chi_{b2(1P)})\,/9 \approx (9900 \pm \mathcal{O}(3))$ MeV/c^2

- **Production mechanisms:** (Kuang,Tuan,Yan (81-92), Voloshin (86), Godfrey(05)) $\Upsilon(3S) \to \gamma h_b(1P)$ forbidden (C-Parity)

$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- h_b(1P)) \sim 10^{-5} - 10^{-3}$

$\mathcal{B}(\Upsilon(3S) \to \pi^0 h_b(1P)) \sim 10^{-3}$

$R(\pi^0 h_b(1P) / \pi^+\pi^- h_b(1P)) \sim 0.05 - 20$

- **Decays (width<1Mev):** (Godfrey, Rosner (02-05)) $h_b(1P) \to ggg$ (~57%), $\gamma\eta_b(1S)$ (40-50%), γgg (~2%)

⇒ Charmonium $h_c(1P)$ observed in analogous decay chain: $\psi(2S) \to \pi^0 h_c$; $h_c \to \gamma\eta_c$ [CLEO 2005; BES 2010]
and also $e^+e^- \to \pi^+\pi^- h_c$ at 4170 MeV (CLEO-C arXiv:1102.3424)

- Previous searches by CLEO (91-94) (90% CL):

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

$\mathcal{B}(\Upsilon(3S) \to \pi^0 h_b(1P)) < 2.7 \times 10^{-3}$

Search for $\Upsilon(3S)\to\pi^0 h_b(1P)\to\pi^0\gamma\eta_b$: analysis strategy

NEW: arXiv:1102.4565
submitted to Phys. Rev. D RC

- **Reconstruct $\pi^0(\gamma_1\gamma_2)$ and γ:**

- $E^*(\gamma)$ consistent with $h_b\to\gamma\,\eta_b$ transition: [420, 540] MeV
- Cuts on N_{tracks}, R_2 (event shape), π^0 veto (all γ candidates), π^0 $\cos\theta_{heli}$

$\Rightarrow$ efficiency=(15.8±0.2)%

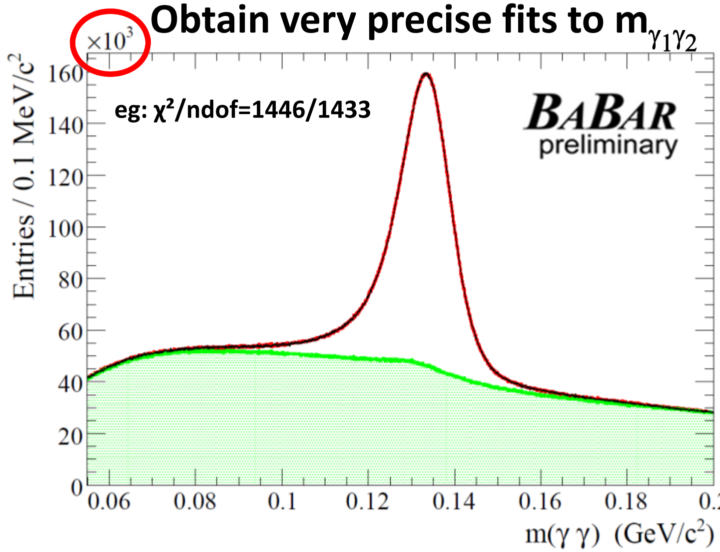
- **Search for a peak near 9.9 GeV/c² in the π^0 recoil mass spectrum** (in the Υ(3S) frame):

$$m_{recoil}(\pi^0) \equiv \sqrt{(E^*_{\Upsilon(3S)} - E^*_{\pi^0})^2 - (\vec{p}^{\,*}_{\pi^0})^2}$$

(±25MeV/c²)

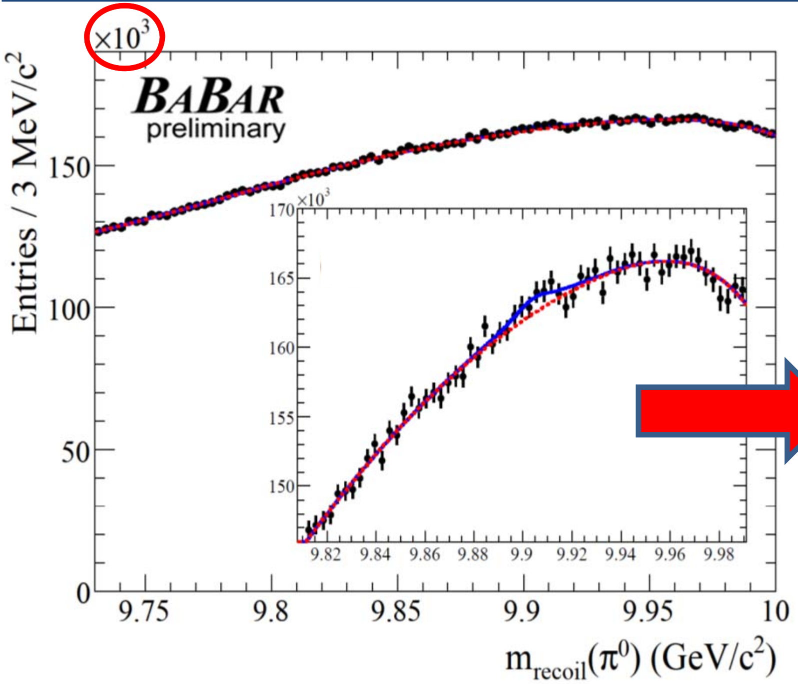
- Constrain $m\pi^0$ to improve resolution.
- $N\pi^0$ from $m_{\gamma_1\gamma_2}$ fit in each of the 90 $m_{recoil}(\pi^0)$ bin of the spectrum (3 MeV/c²).
average χ^2/ndof=0.98±0.03

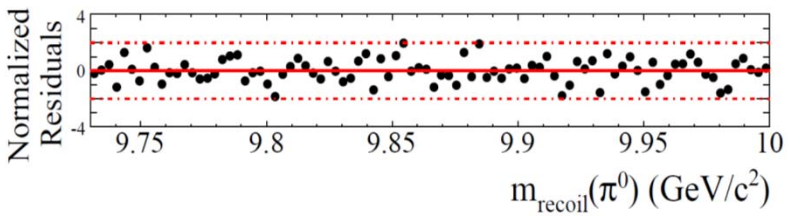
Obtain very precise fits to $m_{\gamma_1\gamma_2}$

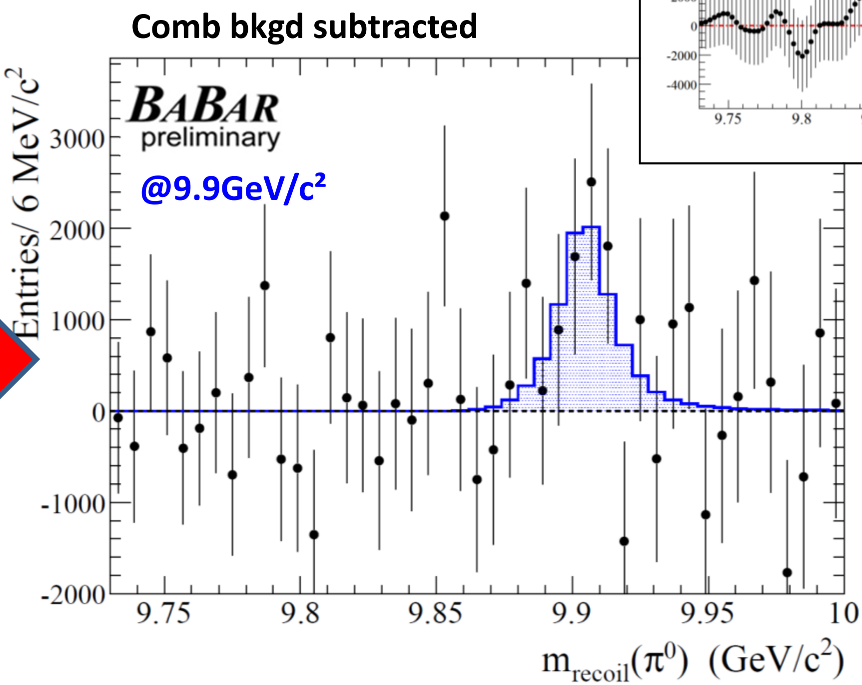


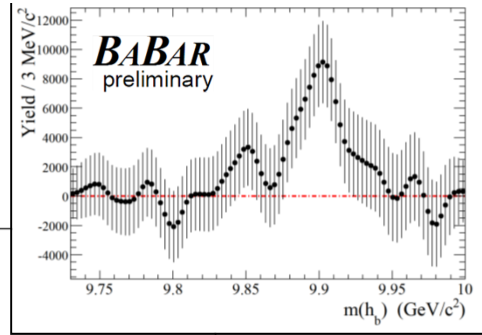
- **χ^2 fit of $m_{recoil}(\pi^0)$ distribution**
  - **h_b(1P) signal: sum 2 Crystal Ball PDF**
  - **Background: 5th order polynomial, from reweighted MC** (excluding signal region)

3σ evidence $\Upsilon(3S)\to\pi^0 h_b(1P)\to\pi^0\gamma\eta_b$: $m_{recoil}(\pi^0)$









Fitted yield vs. $m(h_b)$ scan

(9145 ± 2804 ± 1082) sig. evts : 3.0σ (stat + syst)

(Syst. dominated by [bkgd+signal] line shapes +$m(\gamma\gamma)$ fits & 3.2σ w/o syst)

Δ_{HF}=(+2 ± 4 ± 1) MeV/c²

$m(h_b)$=(9902 ± 4 ± 1) MeV/c² ⇒ consistent with predicted value within few MeV

$\mathcal{B}(\Upsilon(3S)\to\pi^0 h_b(1P)\to\pi^0\gamma\eta_b(1S))$ = (3.7 ± 1.1 ± 0.4)×10⁻⁴

$\mathcal{B}(\Upsilon(3S)\to\pi^0 h_b(1P)\to\pi^0\gamma\eta_b(1S))$ < 5.8×10⁻⁴ @ 90% CL

Voloshin(86):4×10⁻⁴

CLEO(94)<2.7×10⁻³

assume $\mathcal{B}(h_b)\to\gamma\eta_b)$=(45±5)%

NEW: arXiv:1102.4565

submitted to Phys. Rev. D RC

Search for $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$: analysis strategy

- **Combine pairs of oppositely charged tracks**:

- Remove K^0_s (+Λ and γ convert.): vertex in beam spot +π-PID
- Cuts on N_{tracks}, R_2 (event shape), E_{total}

⇒ efficiency=41.8%

- **Search for a peak near 9.9 GeV/c²** in the $\pi^+\pi^-$ recoil mass spectrum (in the $\Upsilon(3S)$ frame):

$$m_{recoil}(\pi\pi) \equiv \sqrt{(M_{\Upsilon(3S)} - E^*_{\pi\pi})^2 - (\vec{p}^{\,*}_{\pi\pi})^2}$$

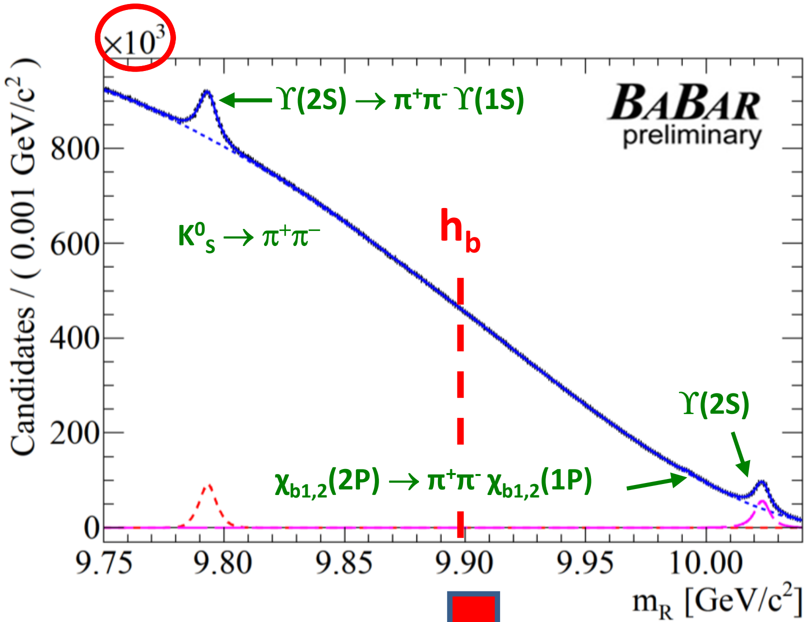
(resolution: 9MeV/c²)

- **1D χ^2 fit** of $m_{recoil}(\pi^+\pi^-)$ distribution with 7 components:

  - h_b signal: Symmetric two-sided Crystal Ball (TCB) PDF
  - $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$: Asymmetric TCB + Bifurcated Gaussian ➔ used for mass calibration $\Upsilon(2S)$:
    δ_M=(+0.42±0.01(stat)±0.59(syst)) MeV/c²
  - $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$: same, with fixed feed-down components
  - $\chi_{b1,2}(2P) \to \pi^+\pi^- \chi_{b1,2}(1P)$: TCB, with fixed peak position
  - $K^0_s \to \pi^+\pi^-$: MC-determined phase space
  - Non-peaking background (including ISR $e^+e^- \to \pi^+\pi^-\Upsilon(1S)$): 6th order Chebychev polynomial

➔ 2 steps W/O (bkgd components) and scan for h_b

Search for $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$: $m_{recoil}(\pi^+\pi^-)$



χ^2 fit @m_{hb}=9900MeV/c^2:

NO SIGNAL: -1106±2432(stat) sig. evts

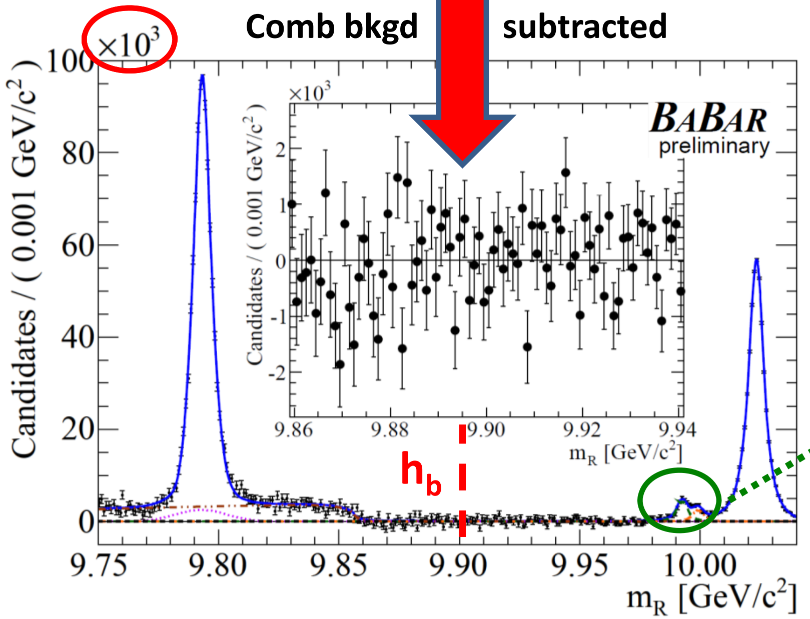
$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- h_b(1P))$ = (0.0± 0.5 ± 0.3)×10^{-4}

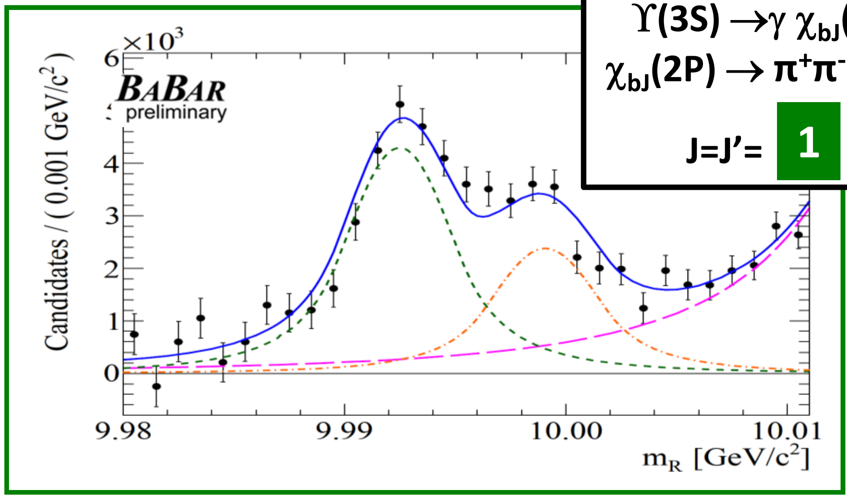
<1.0×10^{-4} 90% CL

$R(\pi^0 h_b(1P) / \pi^+\pi^- h_b(1P))$ > [3.7,5.8]

(< 2.5×10^{-4} (90% CL) over scanned range: max signif. 2σ) (Syst. dominated by decay of light charmless mesons + model continuum and residual Ks and ISR)

Comb bkgd subtracted





$\Upsilon(3S) \to \gamma\, \chi_{bJ}(2P)$ &

$\chi_{bJ}(2P) \to \pi^+\pi^- \chi_{bJ'}(1P)$

J=J'= 1 or 2

Measure $\mathcal{B}$ (J=J'=1,2): (1.16±0.07±0.12)×10^{-3} & (0.64±0.05±0.08)×10^{-3}

$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- \Upsilon(2S))$ = (3.00 ±0.02±0.14)%
improved (wrt PDG) and
$\mathcal{B}(\Upsilon(3S) \to X\Upsilon[(2S) \to \pi^+\pi^- \Upsilon(1S)])$=(1.78± 0.02 ± 0.11)%

Search for $D^0 \to \gamma\gamma$: Theory & Motivation

➔ **FCNC Decay:**

- **Forbidden at the tree-level**
- **1-loop GIM suppressed in charm**

➔ **SM Dominated by long distance effects**

PRD 66,014009 (2002)

- **Short-range (mainly 2-loops):**

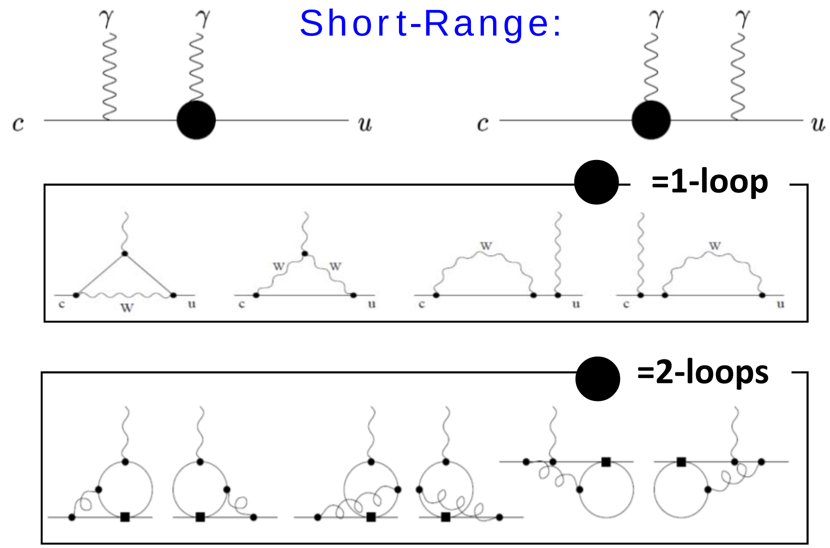
$$\mathcal{B}(D^0 \to \gamma\gamma) \approx 3 \times 10^{-11}$$

- **Long-range by Vector Meson Dominance (VMD):**

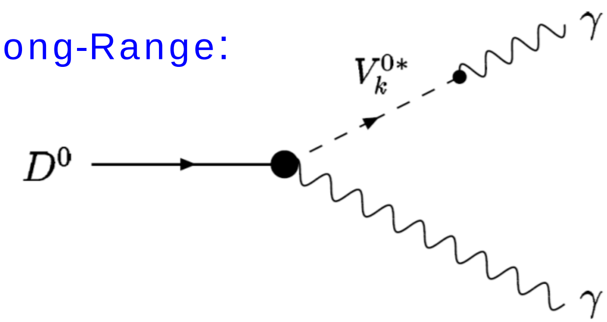
$$\mathcal{B}(D^0 \to \gamma\gamma) \approx (3.5^{+4.0}_{-2.6}) \times 10^{-8}$$

HQχPT $\Rightarrow$ $(1.0\pm0.5) \times 10^{-8}$ *PRD 64 074008 (2001)*

Short-Range:



Long-Range:



➔ **Possible ×200 enhancement from long distance new physics (NP):** $\mathcal{B}(D^0 \to \gamma\gamma) \approx 6 \times 10^{-6}$

(gluino-exchange@MSSM) *PLB 500, 304 (2001)*

➔ **Within the range of *BABAR* sensitivity: 470.5/fb near $\Upsilon(4S)$ $\Rightarrow$ >610×10^6 $c\bar{c}$ pairs**

$\Rightarrow$ **Excellent (but difficult) mode for NP search.**

Search for $D^0 \to \gamma\gamma$ and measurement of $D^0 \to \pi^0\pi^0$

$\mathcal{B}$ Mode	Experimental results Value	
$D^0 \to \gamma\gamma$	$< 2.7 \times 10^{-5}$	PDG'10 mainly CLEO
$D^0 \to \pi^0\pi^0$	$(8.0 \pm 0.8) \times 10^{-4}$	PDG'10 mainly CLEO
$D^0 \to K^0_s\pi^0$	$(1.22 \pm 0.05) \times 10^{-2}$	CLEO'08

- Largest bkgd is from $\pi^0\pi^0$ $\Rightarrow$ Measure $\mathcal{B}(D^0 \to \pi^0\pi^0)$ wrt $\mathcal{B}(D^0 \to K^0_s\pi^0)$
  - $\Rightarrow$ abundant, precise and pure reference channel ($\Delta\mathcal{B}$~4%) + some systematic cancel in ratio
  - $\Rightarrow$ main bkgd for $\pi^0\pi^0$: $D^0 \to K^0/\overline{K}^0\pi^0$ & $K\pi\pi^0$
  - $\Rightarrow$ Use $\pi^0\pi^0$ result in $\gamma\gamma$ background

- Use $D^{*+} \to D^0\pi^+$ tagged events : P_{D*} >2.4-2.85 GeV/c to remove $B\overline{B}$ bkgd (remove QED: $N_{(tracks,\ neutrals)}$>4 note that $D^{*0} \to D^0\pi^0/\gamma$ is the main bkgd for $K^0_s\pi^0$)

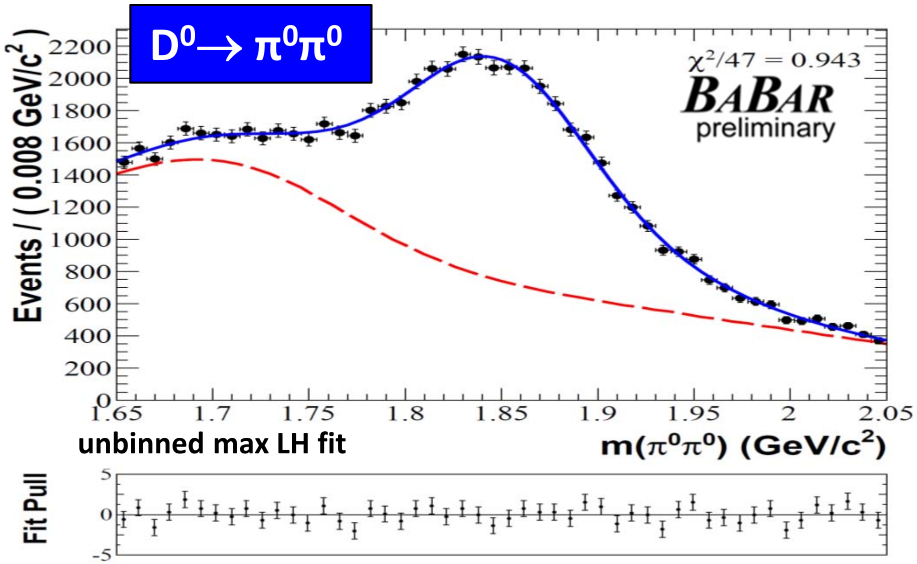
- veto against π^0 (66%(5%) efficient for signal(bkgd))

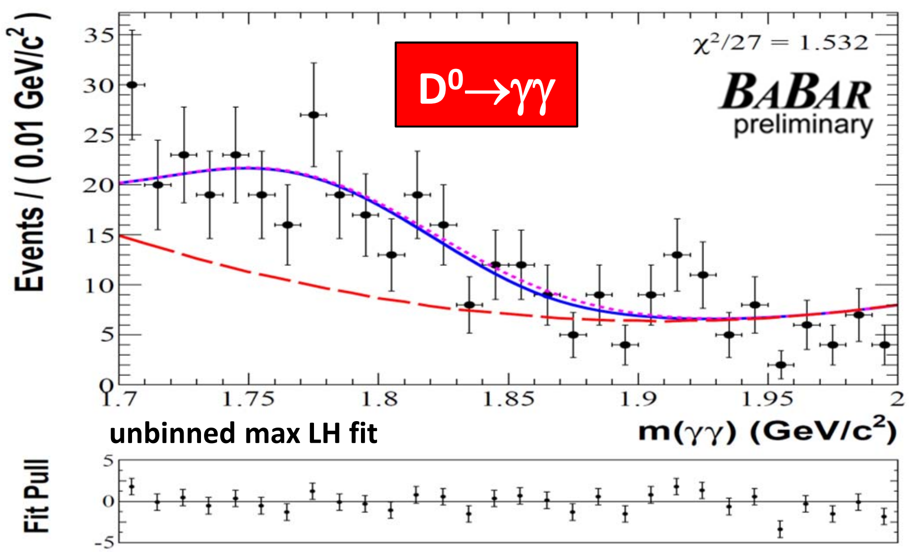
analysis	$D^0 \to \pi^0\pi^0$	$D^0 \to \gamma\gamma$
ε for signal	15.2%	6.1%
ε for norm. $K^0_s\pi^0$	12.0%	7.6%

Measure $\mathcal{B}(D^0 \to \gamma\gamma)$ wrt $\mathcal{B}(D^0 \to K^0_s\pi^0)$

Search for $D^0 \to \gamma\gamma$ and measurement of $D^0 \to \pi^0\pi^0$

Signal
Comb bkgd
$D^0 \to \pi^0\pi^0$





26010±304 $D^0 \to \pi^0\pi^0$ wrt 103859±392 $D^0 \to K^0_s\pi^0$

$\mathcal{B}(D^0 \to \pi^0\pi^0) = (8.4 \pm 0.1_{stat} \pm 0.4_{syst} \pm 0.3_{\mathcal{B}(K^0_s\pi^0)}) \times 10^{-4}$

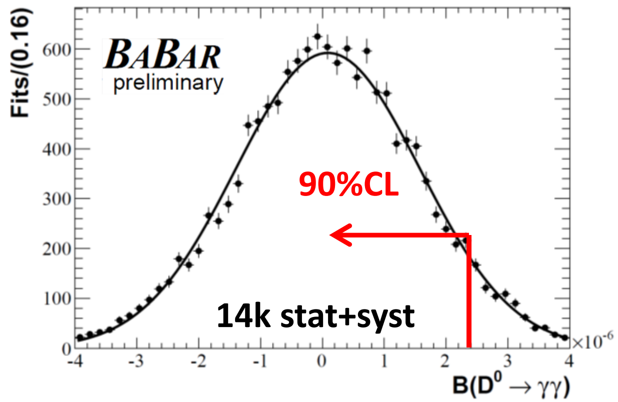
40% improvement/PDG

(-6±15) $D^0 \to \gamma\gamma$ (< 25.1 cands 90%CL)

$\mathcal{B}(D^0 \to \gamma\gamma) < 2.4 \times 10^{-6}$ 90%CL
(<2.06 stat only)

×10 improvement/PDG (& in the NP region)

Systematic	$\sigma(D^0 \to \pi^0\pi^0)$ (%)
Tracking (K^0_S) and Vertexing	0.96
Photon Reconstruction	3.00
π^0 Veto	-
D^{*+} Fragmentation	0.03
Signal Shape	0.20
Background Shape	0.80
Cut selection	2.50
$D^0 \to K^0_s\pi^0$ Signal Shape	0.17
$D^0 \to K^0_s\pi^0$ Background Shape	0.63
$D^0 \to K^0_s\pi^0$ Cut selection	0.76
Total Systematic Uncertainty	4.23

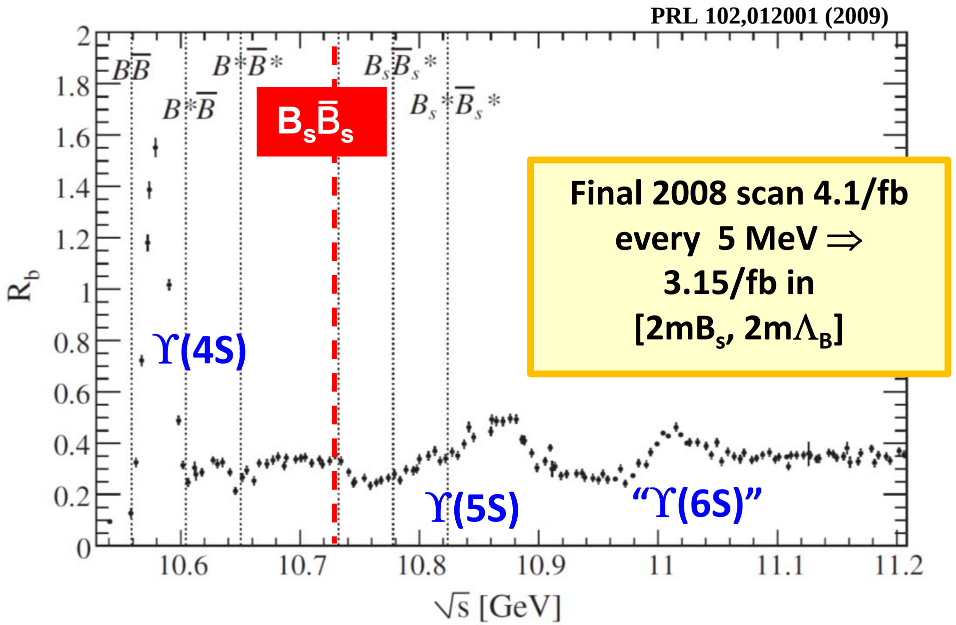


$\mathcal{B}(B_s \to X\, l\, \nu_l)$ & B_s fraction: f_s above $\Upsilon(4S)$

- **semi-leptonic $B_{u,d}$: $\mathcal{B}(B_{u,d} \to X\, l\, \nu_l)$=(10.99-10.33±0.28)% well-known**
- **Semi-leptonic B_s: $\mathcal{B}(B_s \to X\, l\, \nu_l)$ not well-known**
  - **(7.9±2.4)%** (PDG from LEP@Z^0 includes $P(b \to B_s)$=(10.5±0.9)%)
  - **(10.2±0.8±0.9)%** (Belle unpublished arXiv:0710.2548)
  - **LHCb measures ratios** of semi-exclusive decays to total inclusive (arXiv:1102.0348):

$$\mathcal{B}(B_s \to (D_{s2}^{*}/D_{s1})^{+} X\mu\nu_\mu) \,/\, \mathcal{B}(B_s \to X\mu\nu_\mu)$$

⇒ Use the 4.1/fb scan above $\Upsilon(4S)$ ((25.500±6200) $B_s^{(*)}\bar{B}_s^{(*)}$) to measure both the inclusive semi-leptonic $\mathcal{B}_{sl}$ and the B_s production rate f_s



➔ Inclusive yields of ϕ mesons & ϕ+lepton are more abundant in B_s decays : used here to measure $\mathcal{B}_{sl}$ and f_s

**Here results only (details in Lake Louise Winter Institute 2011 talk by B. Hamiton)*

$\mathcal{B}(B_s \to X\, l\, \nu_l)$ & B_s fraction: f_s above $\Upsilon(4S)$

➔ **Measure number of events as a function of CM energy:**

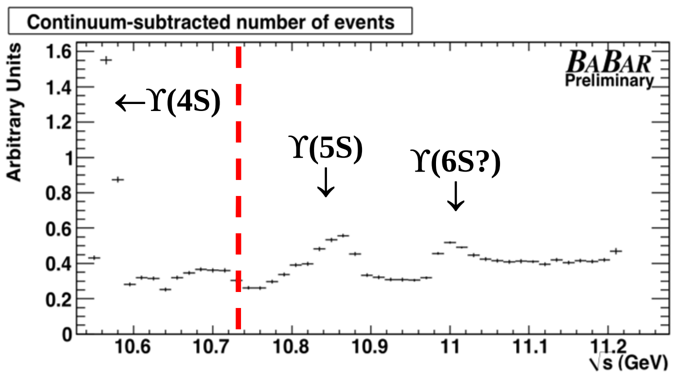
- **B-Hadron events =** $R_b\,[f_s\epsilon_{1s} + (1-f_s)\epsilon_1]$
- **Inclusive ϕ rate =** $R_b\left[f_s P(B_s\bar{B}_s \to \phi X)\epsilon_{2s} + (1-f_s)P(B\bar{B} \to \phi X)\epsilon_2\right]$
- **ϕ rate in correlation with a high-momentum lepton =**

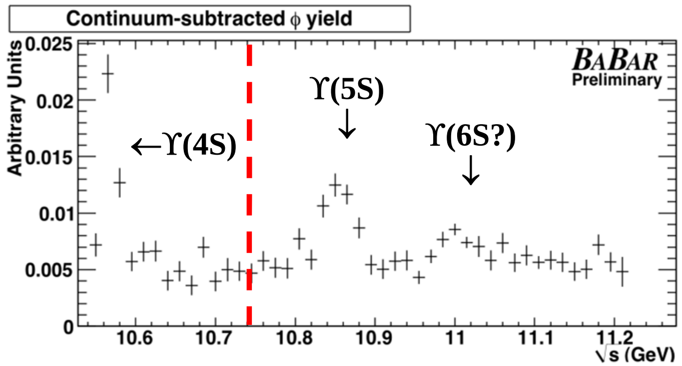
$$R_b\left[f_s P(B_s\bar{B}_s \to \phi\ell\nu X)\epsilon_{3s} + (1-f_s)P(B\bar{B} \to \phi\ell\nu X)\epsilon_3\right]$$

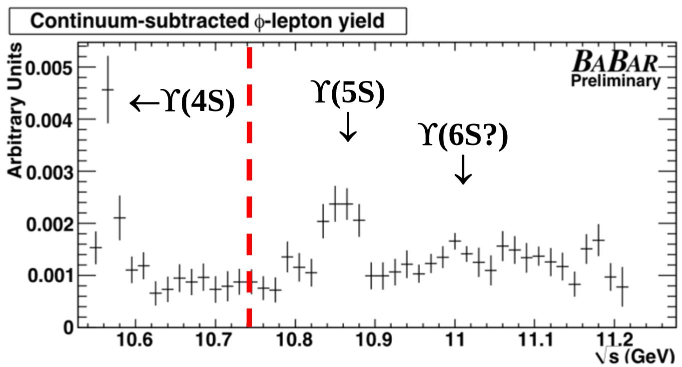
➔**Subtract light $q\bar{q}$** (q=u,d,s,c) **continuum from off $\Upsilon(4S)$ peak and account for $B_{u,d}$ contributions from $\Upsilon(4S)$ data**

➔ **B_s contributions depend on:**

$\mathcal{B}(B_s \to D_s X_i)$ (PDG $\mathcal{B}$=(93±25)%), $\mathcal{B}(B_s \to l\nu_l X_j)$,
$\mathcal{B}(D_s \to l\nu_l X_k)$ (PDG), $\mathcal{B}(D_s \to \phi X_l)$ (PDG),
$\mathcal{B}(D_s \to \phi l\nu_l X_m)$ (PDG) and others…
(⇒account for semi-leptonic AND secondary/fake leptons)



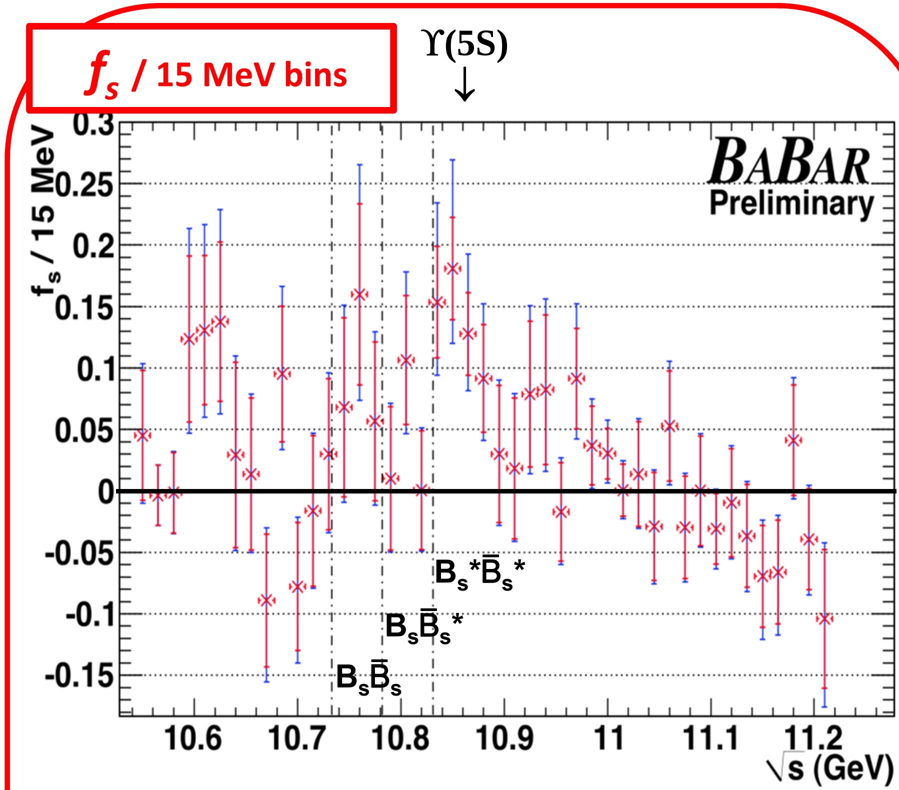




events yields/15 MeV bins

$\mathcal{B}(B_s \to X\, l\, \nu_l)$ & B_s fraction: f_s above $\Upsilon(4S)$

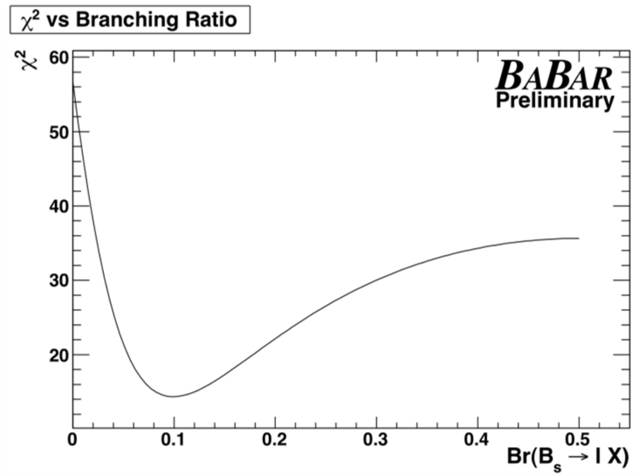
➔ **extract B_s production fraction f_s** at each CM energy point and perform a global χ^2 fit to the various yields to **extract the semi-leptonic $\mathcal{B}(B_s \to X\, l\, \nu_l)$**



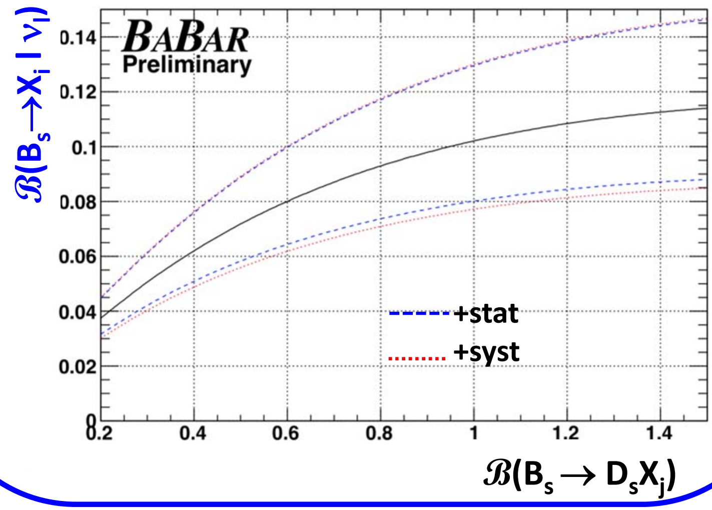
⇒ Bins near $\Upsilon(5S)$ consistent/previous ON peak results:

- Belle: (19.3 ±2.9)% PRD 76, 012002 (2007)
- CLEO: (16.8 ±2.6)% PRD 75, 012002 (2007)

+see theory : N. A. Törnqvist, PRL 53, 878 (1984)



$$\mathcal{B}(B_s \to X\, l\, \nu_l) = (9.9^{+2.6}_{-2.1}\,(\text{stat})^{+1.3}_{-2.0}\,(\text{syst}))\%$$



Conclusions

I) Bottomonium spectroscopy: ➔ *$\Upsilon(3S)$ sample*

- Radiative transitions using converted γ & search for $\eta_b(1,2S)$ (+$\Upsilon(2S)$ sample)

➔ RICH PHENOMENOLOGY and MANY NEW PRECISE RESULTS for $\chi_{bJ}(1,2P)$

- Search for $h_b(1P)$ in $\Upsilon(3S) \to (\pi^0/\pi^+\pi^-)h_b(1P)$ [$h_b(1P) \to \gamma\, \eta_b(1S)$]

➔ 3.0σ EVIDENCE in $\pi^0 h_b(1P)$ MODE

NEW: arXiv:1102.4565
submitted to Phys. Rev. D RC

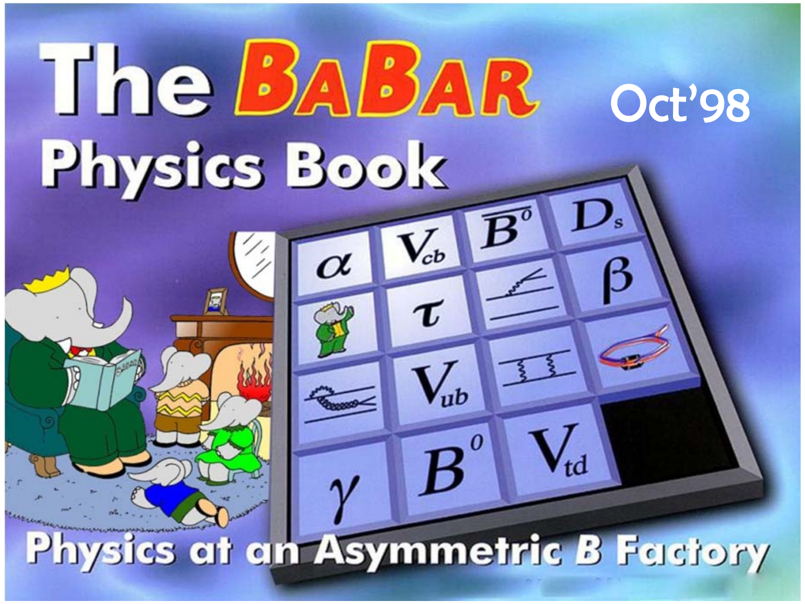
II) Search for the decay $D^0 \to \gamma\gamma$
& measurement of $D^0 \to \pi^0\pi^0$ ➔ *$\Upsilon(4S)$ sample and below "off-peak"*

➔ IMPROVED MEASUREMENTS and $\mathcal{B}(\gamma\gamma)$ LIMIT in PREDICTED NP REGION

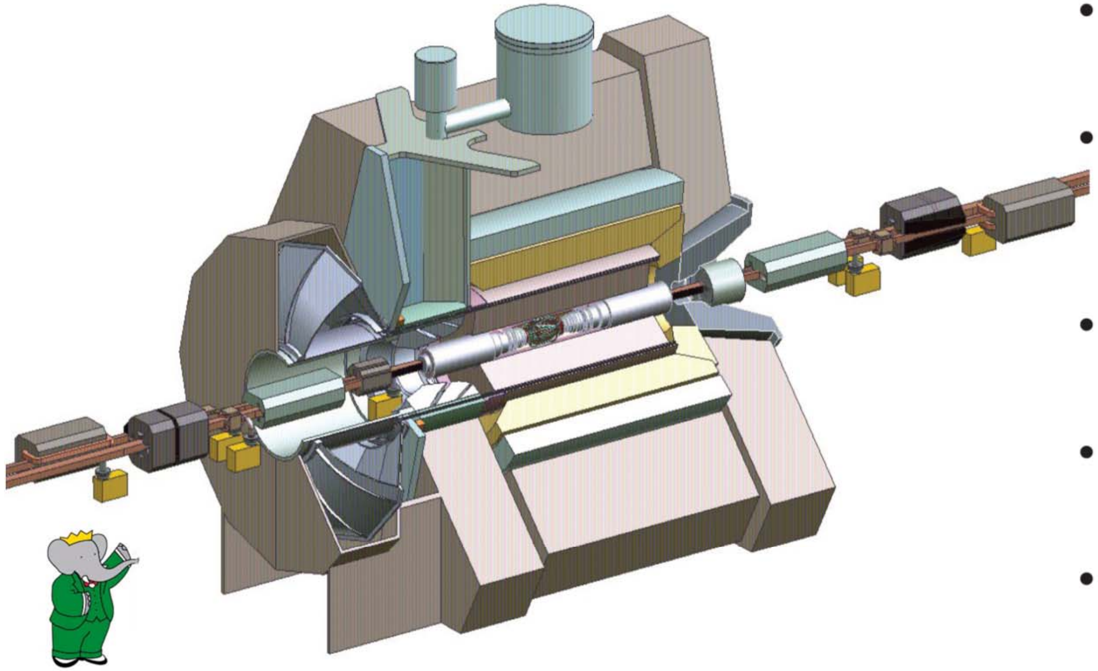
III) $\mathcal{B}(B_s \to X\, l\, \nu_l)$ & B_s fraction: f_s ➔ *scan above the $\Upsilon(4S)$*

➔ YES B_s STUDIED by BaBar ! : INTERESTING CROSS-CHECK MEASUREMENTS

BACKUP SLIDES

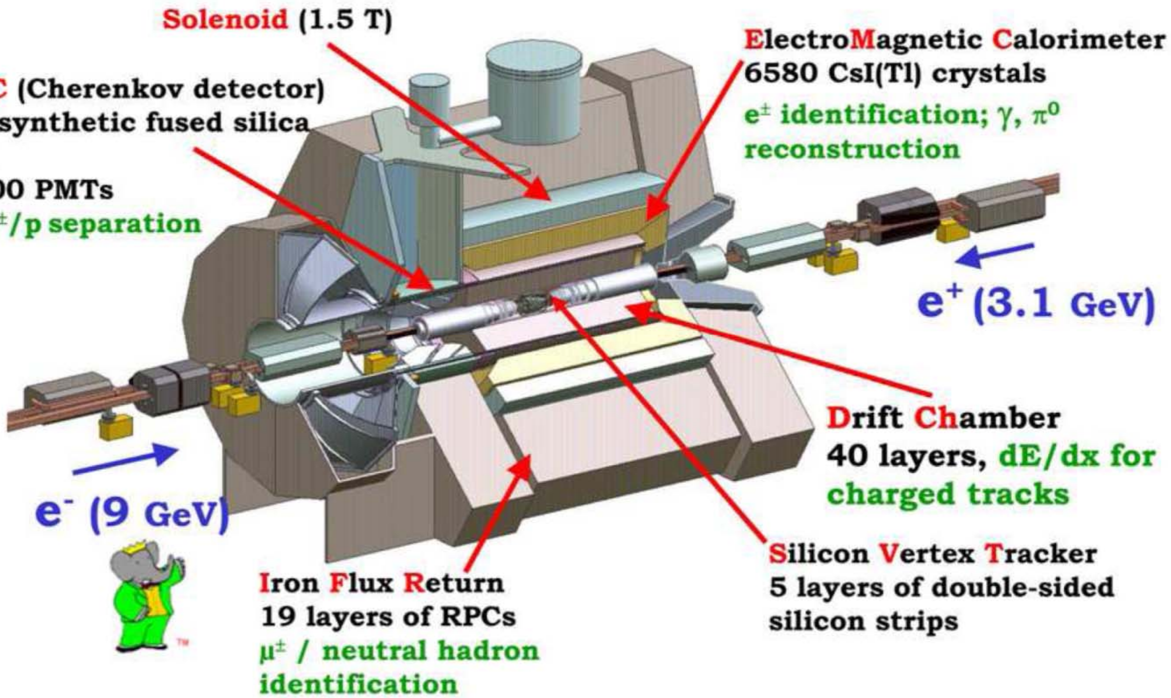


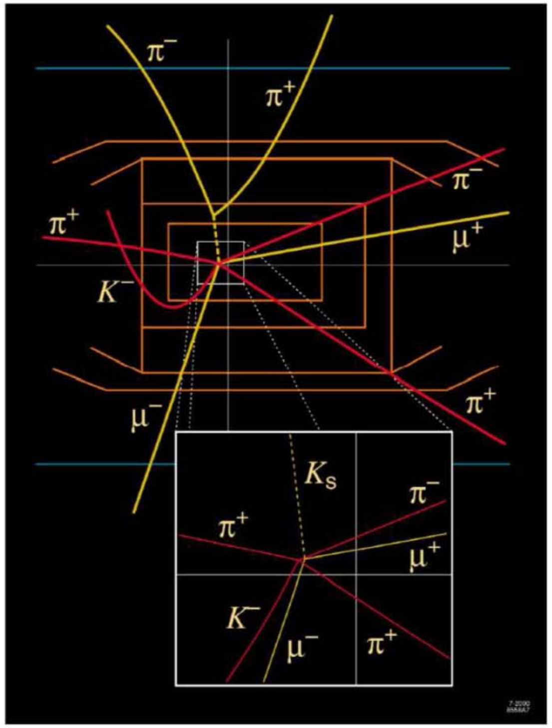
BABAR at SLAC

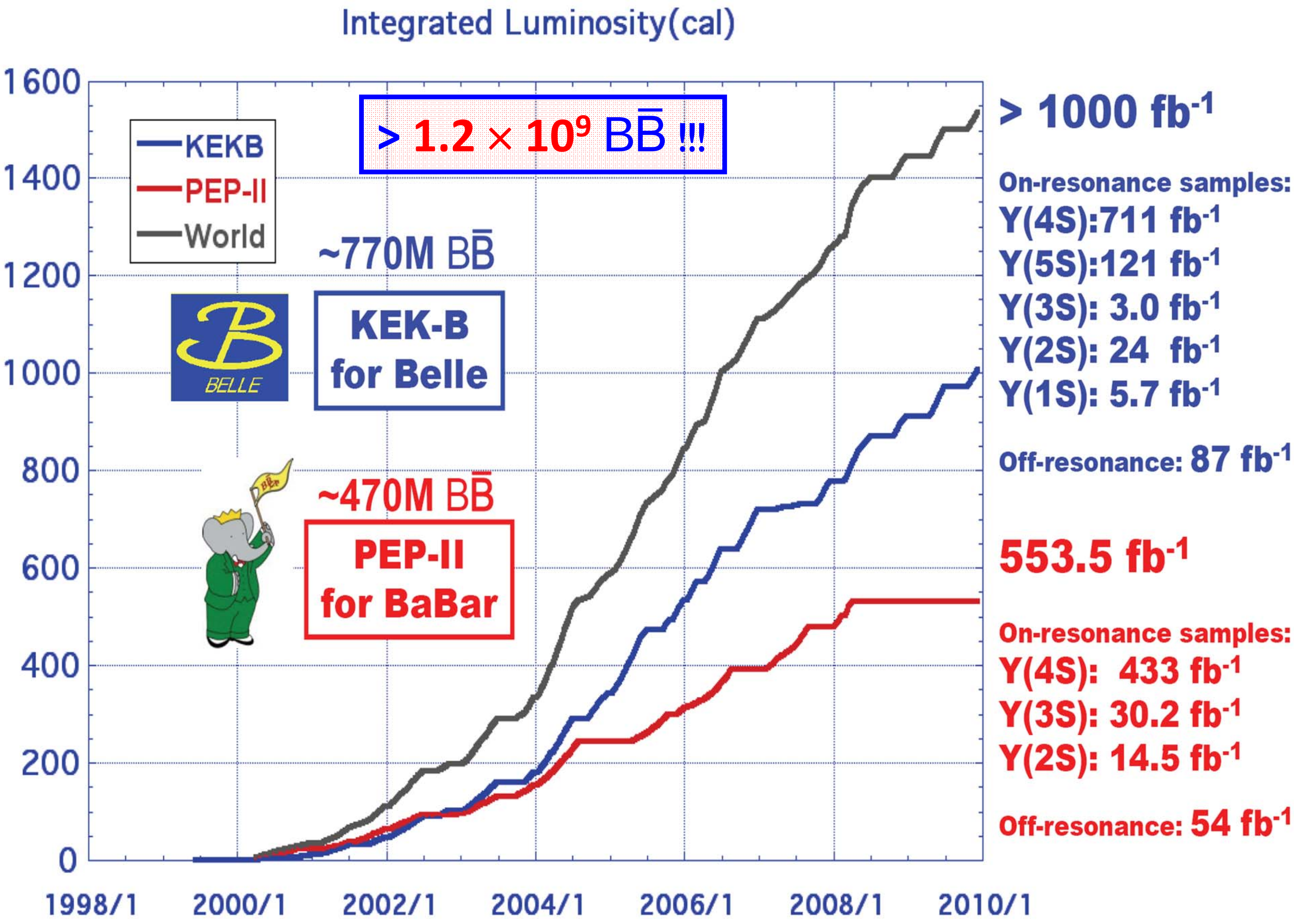


- 1.5 T solenoid
- Silicon vertex tracker
  - 5 layer, double-sided
- Drift chamber
  - Tracking + dE/dx
  - 40 stereo layers
- DIRC particle ID
  - Quartz bars, 11000 PMTs
- CsI(Tl) calorimeter
  - 6580 crystals
- Instrumented Flux Return
  - Iron + resistive plate chambers and limited streamer tubes

CM boost $\beta\gamma \cong 0.56$
9 GeV e^-, 3.1 GeV e^+

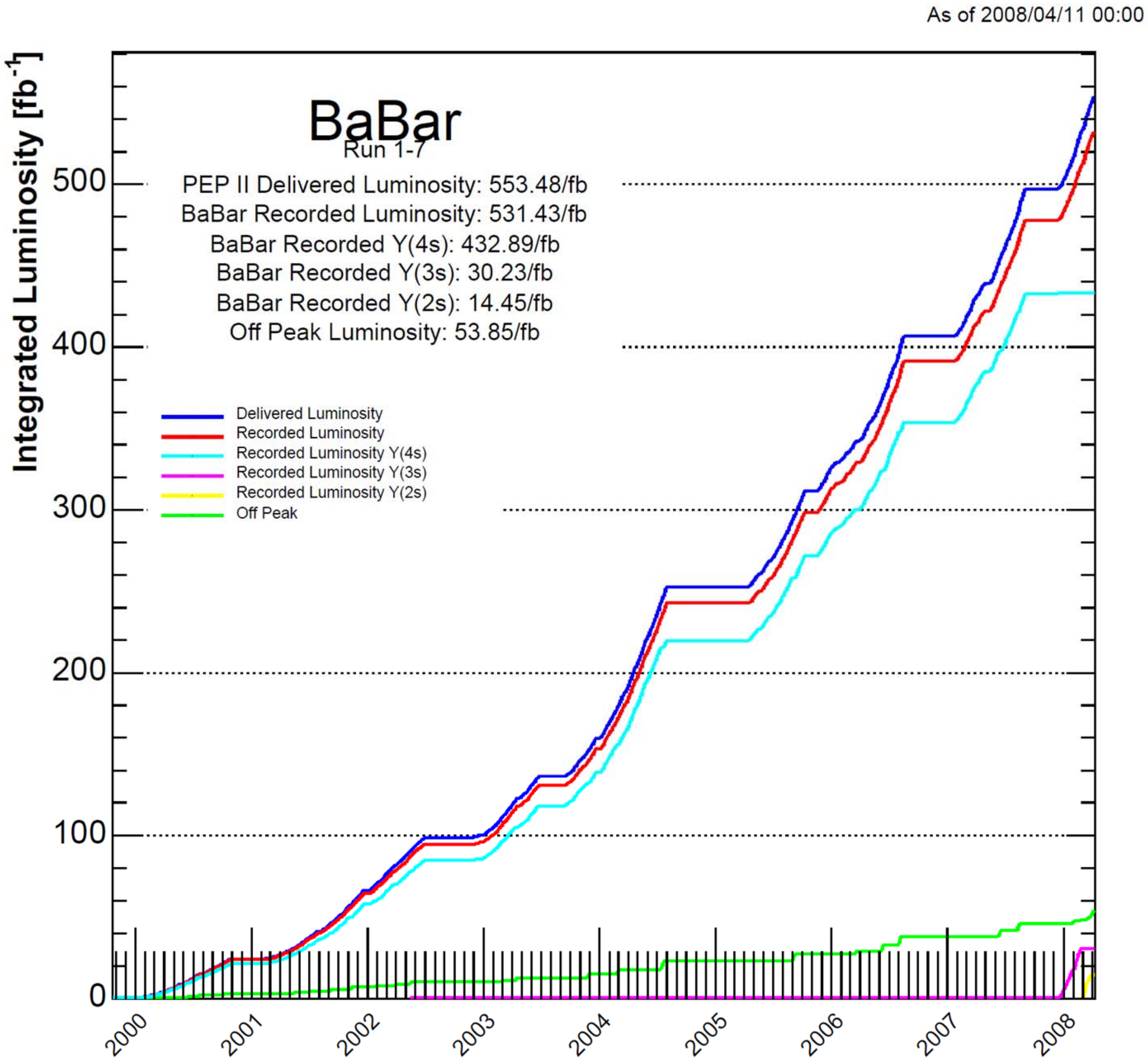

Solenoid (1.5 T)
DIRC (Cherenkov detector)
144 synthetic fused silica bars
11000 PMTs
$K^{\pm}/\pi^{\pm}/p$ separation
ElectroMagnetic Calorimeter
6580 CsI(Tl) crystals
$e^{\pm}$ identification; γ, π^0 reconstruction
e^+ (3.1 GeV)
e^- (9 GeV)
Drift Chamber
40 layers, dE/dx for charged tracks
Silicon Vertex Tracker
5 layers of double-sided silicon strips
Iron Flux Return
19 layers of RPCs
$\mu^{\pm}$ / neutral hadron identification


π^-
π^+
π^-
π^+
μ^+
K^-
μ^-
π^+
K_S
π^-
π^+
μ^+
K^-
μ^-
π^+



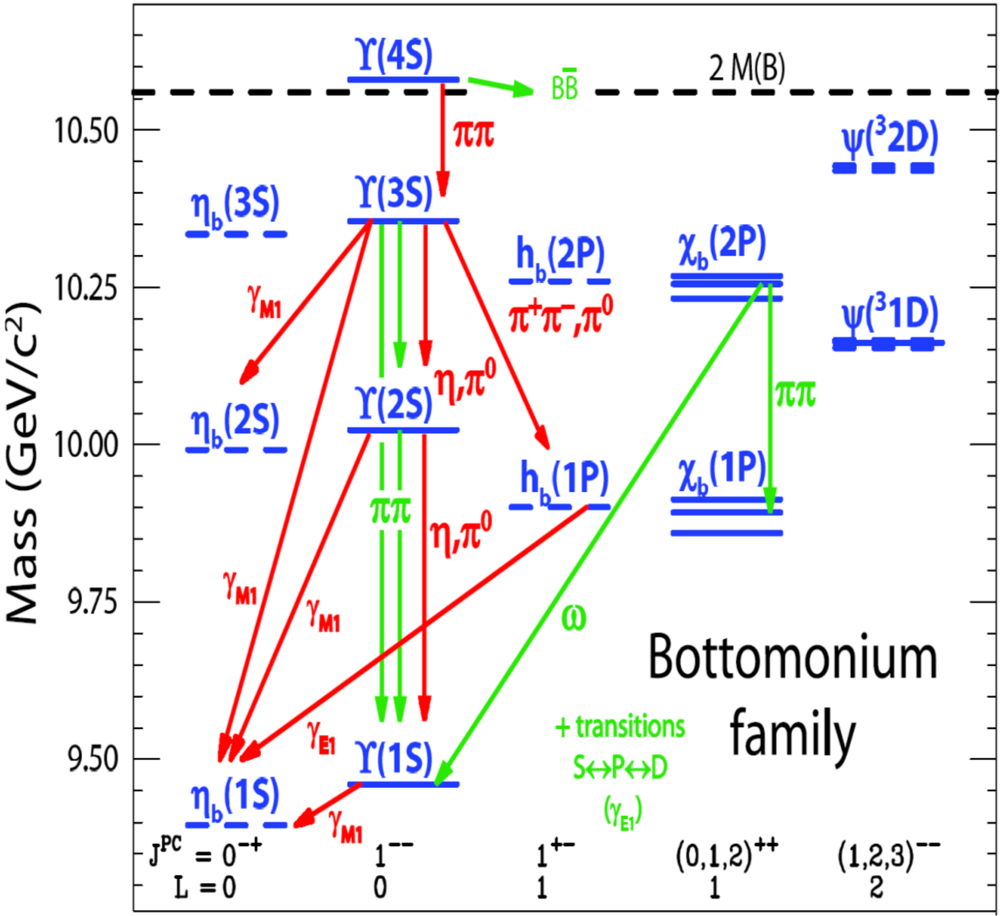
Integrated Luminosity(cal)
1600
1400
1200
1000
800
600
400
200
0
1998/1
2000/1
2002/1
2004/1
2006/1
2008/1
2010/1
KEKB
PEP-II
World
> 1.2 × 10⁹ BB̄ !!!
~770M BB̄
KEK-B for Belle
BELLE
~470M BB̄
PEP-II for BaBar
> 1000 fb-1
On-resonance samples:
Υ(4S):711 fb-1
Υ(5S):121 fb-1
Υ(3S): 3.0 fb-1
Υ(2S): 24 fb-1
Υ(1S): 5.7 fb-1
Off-resonance: 87 fb-1
553.5 fb-1
On-resonance samples:
Υ(4S): 433 fb-1
Υ(3S): 30.2 fb-1
Υ(2S): 14.5 fb-1
Off-resonance: 54 fb-1

BABAR Dataset



Integrated Luminosity(cal)

Bottomonium family



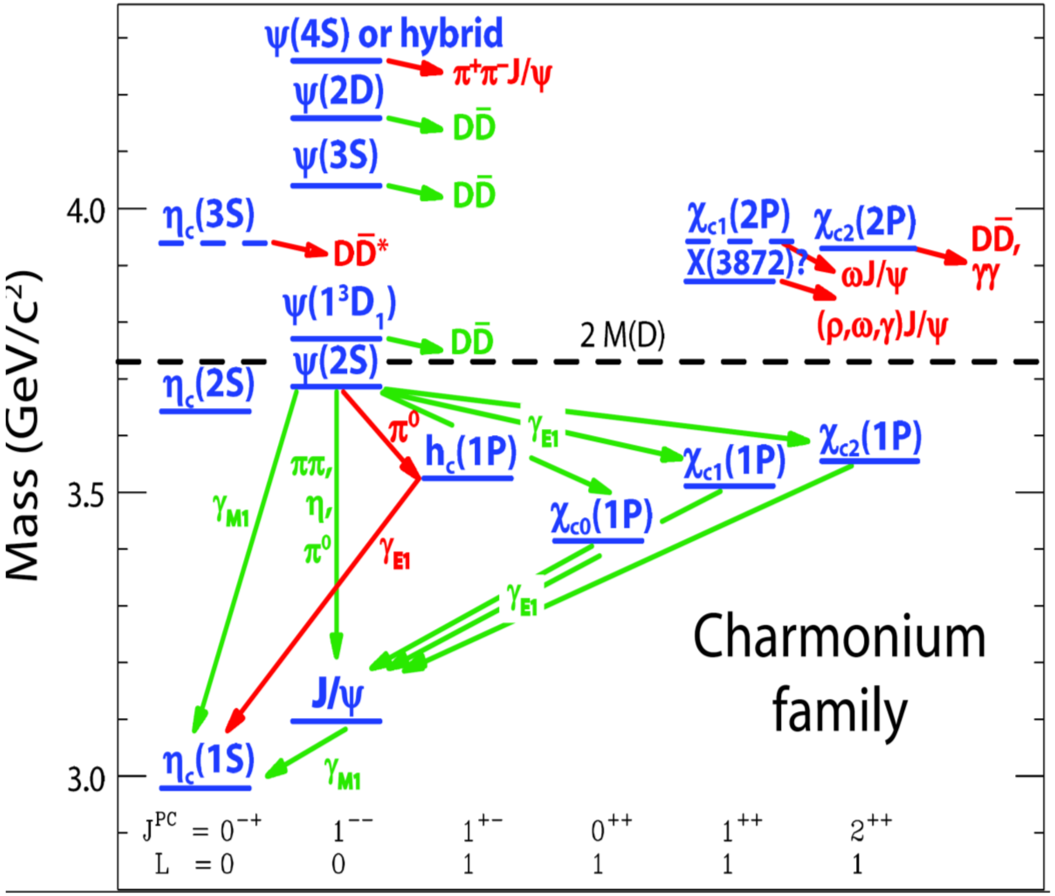
Quantum numbers					Mass	Width
n	L	J^{PC}	$n^{2S+1}L_J$	Name	(MeV)	
1	0	1^{--}	1^3S_1	$\Upsilon(1S)$	9460.30 ± 0.26	54.02 ± 1.25 keV
1	1	0^{++}	1^3P_0	$\chi_{b0}(1P)$	9859.44 ± 0.52	Unknown
1	1	1^{++}	1^3P_1	$\chi_{b1}(1P)$	9892.78 ± 0.40	Unknown
1	1	2^{++}	1^3P_2	$\chi_{b2}(1P)$	9912.21 ± 0.40	Unknown
1	2	2^{--}	1^3D_J[a]	$\Upsilon(1D)$	10161.1 ± 1.7	Unknown
2	0	1^{--}	2^3S_1	$\Upsilon(2S)$	10023.26 ± 0.31	31.98 ± 2.63 keV
2	1	0^{++}	2^3P_0	$\chi_{b0}(2P)$	10232.5 ± 0.6	Unknown
2	1	1^{++}	2^3P_1	$\chi_{b1}(2P)$	10255.46 ± 0.55	Unknown
2	1	2^{++}	2^3P_2	$\chi_{b2}(2P)$	10268.65 ± 0.55	Unknown
3	0	1^{--}	3^3S_1	$\Upsilon(3S)$	10355.2 ± 0.5	20.32 ± 1.85 keV
4	0	1^{--}	4^3S_1	$\Upsilon(4S)$	10579.4 ± 1.2	20.5 ± 2.5 MeV

[a]Probably all or mostly $J=2$.

Before summer 2008

From Eichten et al.,
Rev. Mod. Phys. 80 (2008) 1161

Charmonium family



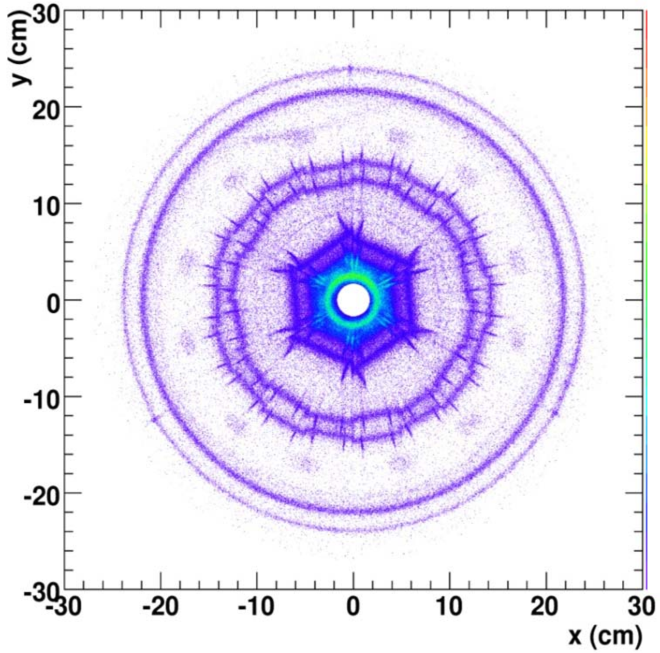
Quantum numbers					Mass	Width
n	L	J^{PC}	$n^{2S+1}L_J$	Name	(MeV)	(MeV[a])
1	0	0^{-+}	1^1S_0	$\eta_c(1S)$	2980.4 ± 1.2	25.5 ± 3.4
1	0	1^{--}	1^3S_1	J/ψ	3096.916 ± 0.011	93.4 ± 2.1 keV
1	1	0^{++}	1^3P_0	$\chi_{c0}(1P)$	3414.76 ± 0.35	10.4 ± 0.7
1	1	1^{++}	1^3P_1	$\chi_{c1}(1P)$	3510.66 ± 0.07	0.89 ± 0.05
1	1	2^{++}	1^3P_2	$\chi_{c2}(1P)$	3556.20 ± 0.09	2.06 ± 0.12
1	1	1^{+-}	1^1P_1	$h_c(1P)$	3525.93 ± 0.27	<1
1	2	1^{--}	1^3D_1	$\psi(3770)$	3771.1 ± 2.4	23.0 ± 2.7
2	0	0^{-+}	2^1S_0	$\eta_c(2S)$	3638 ± 4	14 ± 7
2	0	1^{--}	2^3S_1	$\psi(2S)$	3686.093 ± 0.034	337 ± 13 keV
2	1	2^{++}	2^3P_2	$\chi_{c2}(2P)$	3929 ± 5	29 ± 10

From Eichten et al.,
Rev. Mod. Phys. 80 (2008) 1161

η_b search using $\gamma \rightarrow e^+e^-$ conversions

- Identify $\gamma \rightarrow e^+e^-$ conversions (χ^2 test; require $m_\gamma < 30$ MeV)
- Veto $\gamma \rightarrow e^+e^-$'s that form a π^0 candidate with any other γ
- Other cuts: thrust, multiplicity
- χ^2 fit to γ recoil energy spectrum
  - → Combinatoric background
  - → "peaking" components

γ-ray "photograph" of Babar



γ conversions in inner region

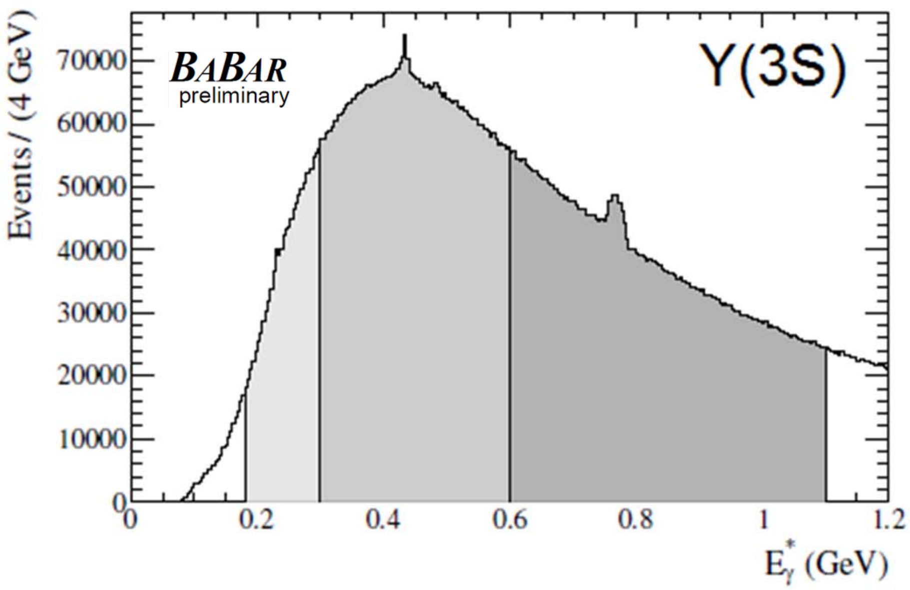
→ Fits to the $\Upsilon(3S)$ & $\Upsilon(2S)$ samples with the $\chi_{bJ}(1,2P)$ and η_b mass/yields fitted parameter

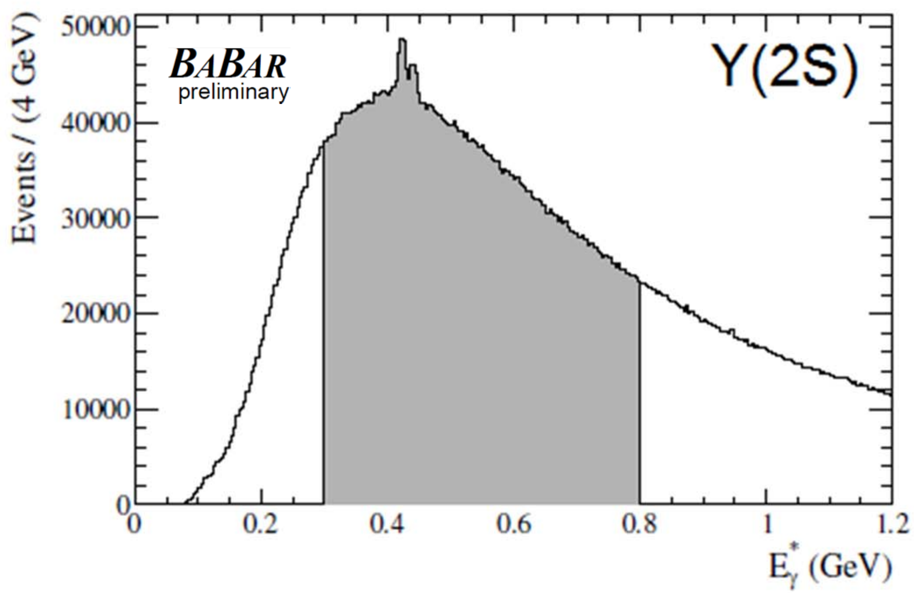
Selection criteria for using $\gamma \rightarrow e^+e^-$ conversions

- Optimize $S/\sqrt{(S+B)}$ for η_b signal MC vs. 1/10th data sample

Variable	E^*_γ Range (MeV)		
	$\Upsilon(3S)$ [180, 600]	$\Upsilon(3S)$ [600, 1100]	$\Upsilon(2S)$ [300, 800]
$nTRK$	≥ 8	≥ 8	≥ 8
$\lvert\cos\theta_T\rvert$	< 0.85	< 0.75	< 0.85
$\lvert m_{\gamma\gamma} - m_{\pi^0}\rvert$ (MeV/c^2)	> 10	> 20	> 20
$E_{\gamma 2}$ (MeV)	> 90	> 75	> 70
R_2	< 0.98	< 0.98	< 0.98

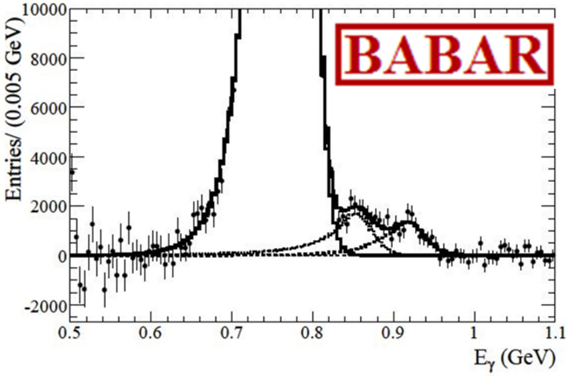
- Define 4 E^*_γ regions of interest

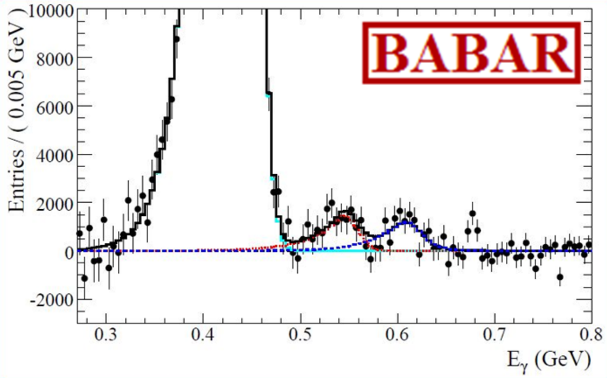


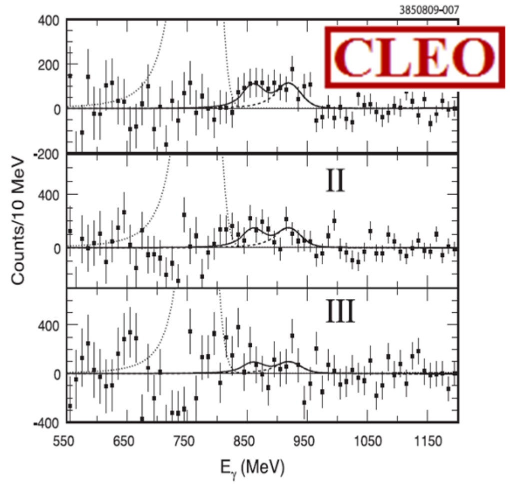


"high" $E^*\gamma$ spectrum from $\Upsilon(2,3S)$ decays

- $\eta_b(1S)$ observed in inclusive γ spectrum for $\Upsilon(3S)$ and $\Upsilon(2S)$







  - $m_{\eta b(1S)} = (9390.9 \pm 2.8)$ MeV/c^2
  - $m_{\eta b(1S)} - m_{\Upsilon(1S)} = (69.3 \pm 2.8)$ MeV/c^2
  - Lattice QCD ≈ 50-60 MeV/c^2, pNRQCD ≈ 40 MeV/c^2

- $\chi_{bJ}(1,2P) \to \gamma\Upsilon(1S)$ transitions
  - Last measured ~20 years ago
  - J=0 yet to be observed
  - ($\chi_{b0}(1P) \to \gamma\ \Upsilon(1S)$ Belle prelim.)

Mode	PDG BF
$\chi_{b2}(2P) \to \gamma\Upsilon(1S)$	$7.1 \pm 1.0\%$
$\chi_{b1}(2P) \to \gamma\Upsilon(1S)$	$8.5 \pm 1.3\%$
$\chi_{b0}(2P) \to \gamma\Upsilon(1S)$	$(9 \pm 6) \times 10^{-3}$
$\chi_{b2}(1P) \to \gamma\Upsilon(1S)$	$22 \pm 4\%$
$\chi_{b1}(1P) \to \gamma\Upsilon(1S)$	$35 \pm 8\%$
$\chi_{b0}(1P) \to \gamma\Upsilon(1S)$	$< 6\%$

Summary on inclusive photon spectrum for $\Upsilon(2,3S)$ decays with converted γ

- **Best $\mathcal{B}(\chi_{bJ}(nP) \to \gamma\Upsilon(mS))$**
  - First direct measurements
  - Good agreement with theory

  (Kwong & Rosner, PRD 38 279 (1988))

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

- **Observation: $\Upsilon(3S) \to \gamma\chi_{b0,2}(1P)$ not $\gamma\chi_{b1}(1P)$**
  - Inconsistent with any theory

  (~ok with CLEO 2010 arXiv:1012.0589)

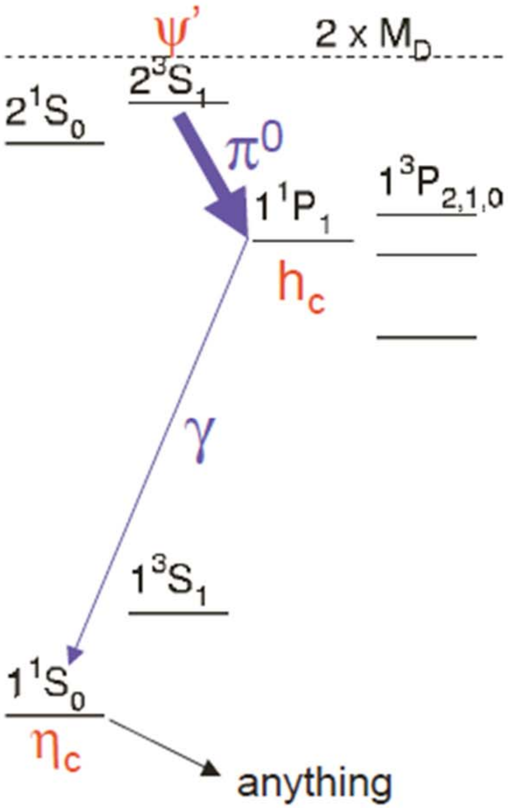
Source	$J=0$	$J=1$	$J=2$
BABAR	55 ± 10	< 22	216 ± 25
Moxhay-Rosner	25	25	150
Grotch *et al.*	114	3.4	194
Daghighian-Silverman	16	100	650
Fulcher	10	20	30
Lähde	150	110	40
Ebert *et al.*	27	67	97

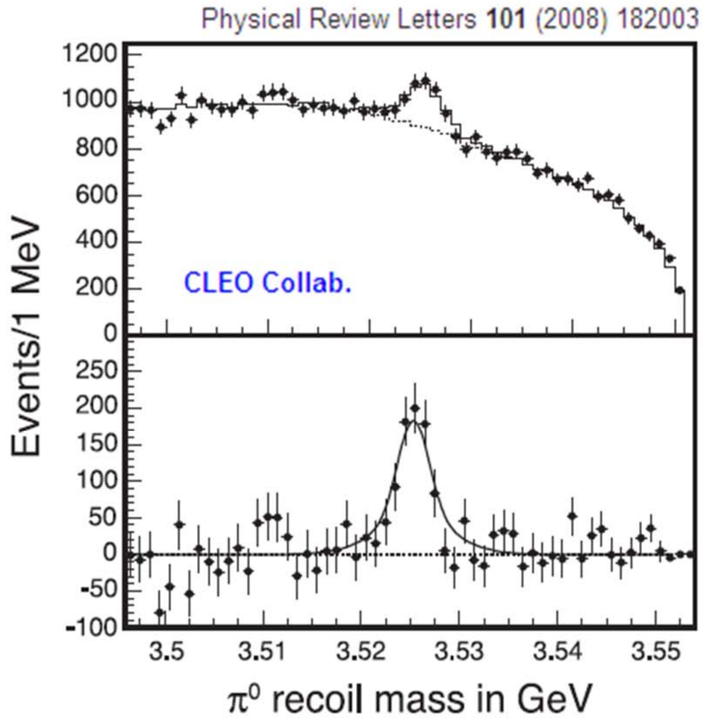
- **New information on $m_{\eta_b(1S)}$?**
  - Disagrees with prev. expt.
  - BTW significance ~2.7σ for $\Upsilon(3S)$ only

Source	$m_{\Upsilon(1S)} - m_{\eta_b(1S)}$ (MeV/c^2)
Kniehl *et al.*	41 ± 14
Recksiegel & Sumino	44 ± 11
HPQCD	61 ± 14
Fermilab & MILC	54.0 ± 12.4
Meinel	60.3 ± 7.0
PDG	69.3 ± 2.8
This work	56.6 ± 3.0

The Discovery of the $h_c(1P)$ state of charmonium at CLEO

open charm threshold



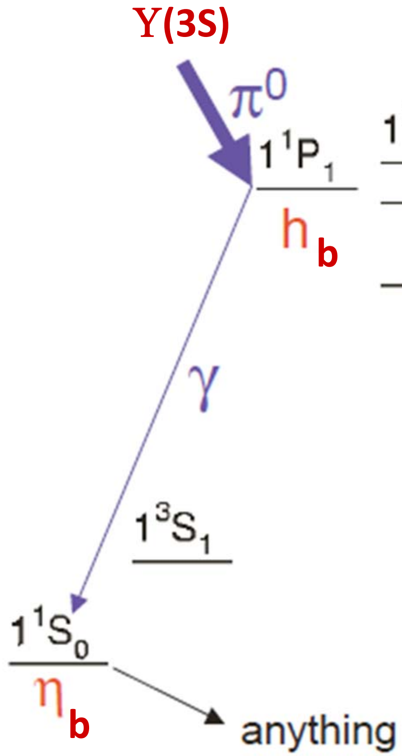


$$M(h_c) = 3525.28 \pm 0.19(\text{stat}) \pm 0.12(\text{syst})\ \text{MeV}$$

$$\Delta M_{hf}(1P) \equiv \langle M(^3P_J)\rangle - M(^1P_1)$$

$$= +0.02 \pm 0.19(\text{stat}) \pm 0.13(\text{syst})\ \text{MeV}$$

Similar strategy to look for the $h_b(1P)$ state of bottomonium

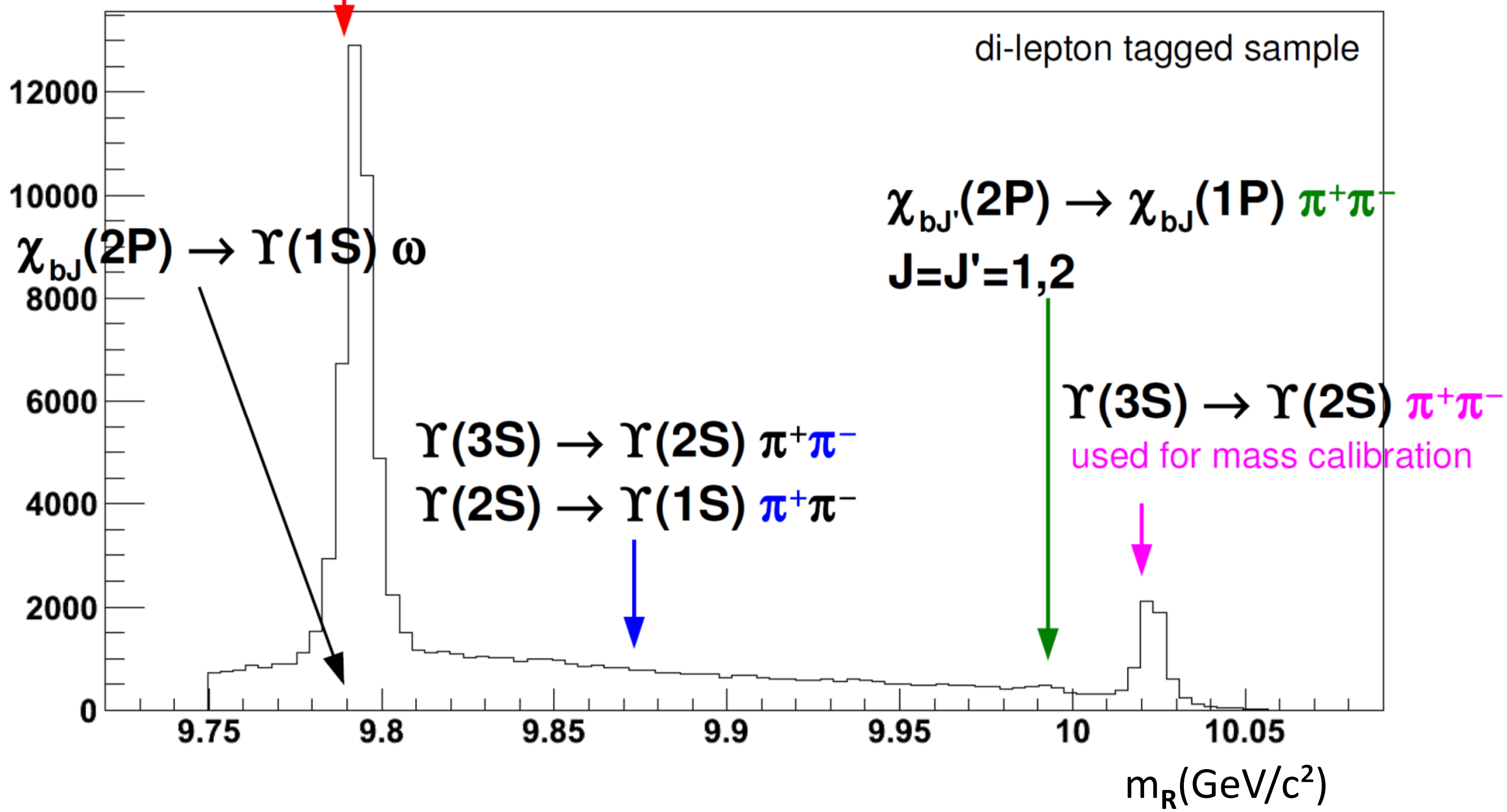


- Require $\pi^0\,\gamma$ recoil mass to be consistent with the η_c mass
- Plot π^0 recoil mass

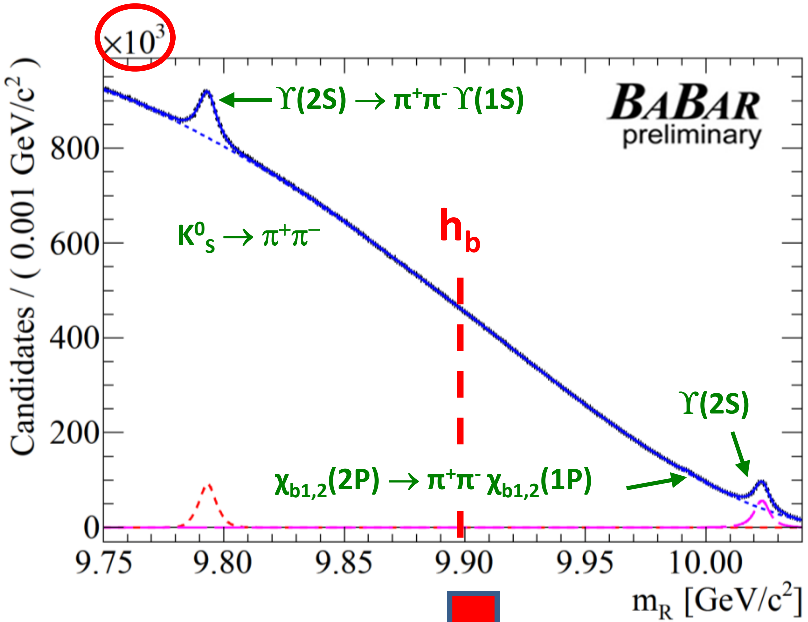
Search for $\Upsilon(3S) \rightarrow \pi^+\pi^- h_b(1P)$: Peaking Bkgd

Background	PDG (GeV)	Fit to MC (GeV)
$\Upsilon(3S) \rightarrow \Upsilon(2S)\pi^+\pi^-$	$M_{2S} = 10.02326$	10.02270
$\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$	$M_{3S} - M_{2S} + M_{1S} = 9.79224$	9.7905
$\chi_{bJ'}(2P) \rightarrow \chi_{bJ}(1P)\pi^+\pi^-$	$M_{3S} - M_{2P} + M_{1P} = 9.99252$	9.99243
$K^0_S \rightarrow \pi^+\pi^-$	...	shoulder at 9.860

$\Upsilon(3S) \rightarrow \Upsilon(2S)$ X
$\Upsilon(2S) \rightarrow \Upsilon(1S)\ \pi^+\pi^-$



Search for $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$: $m_{recoil}(\pi^+\pi^-)$



χ^2 fit @m_{hb}=9900MeV/c^2:

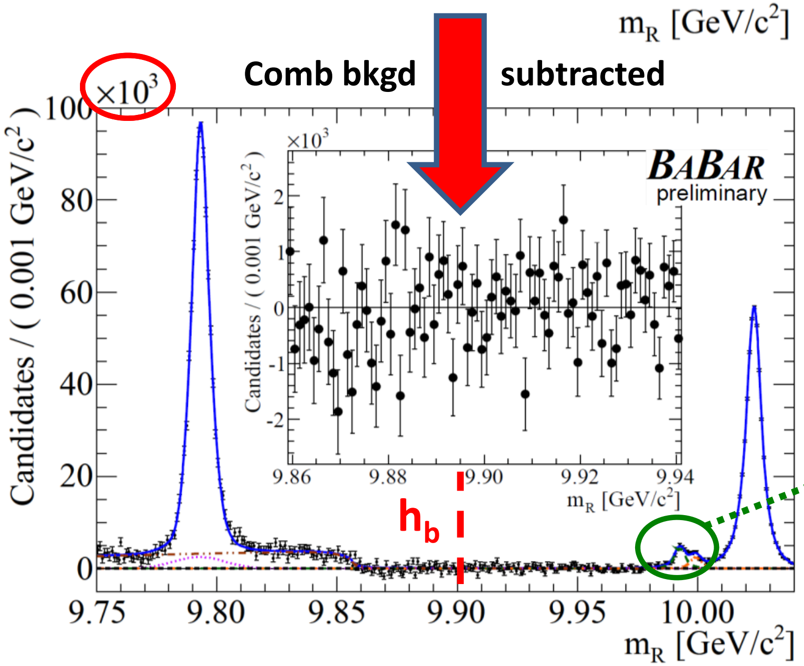
NO SIGNAL: -1106±2432(stat) sig. evts

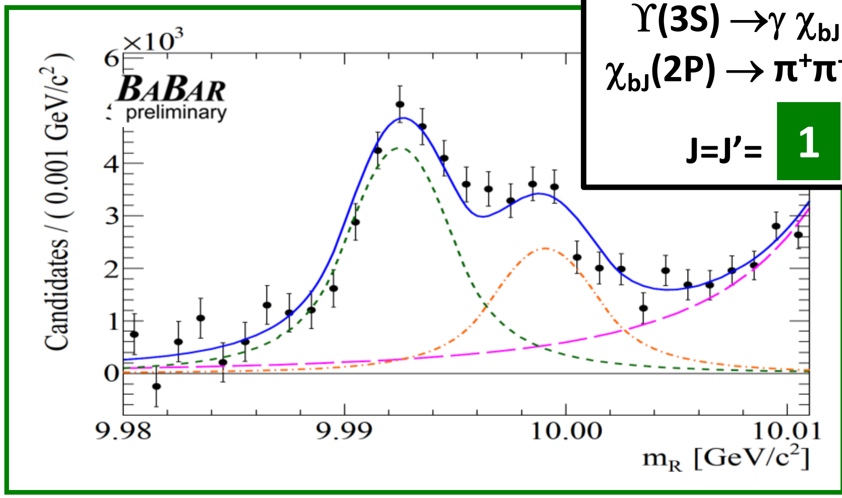
$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- h_b(1P)) = (0.0 \pm 0.5 \pm 0.3)\times10^{-4}$

$< 1.0\times10^{-4}$ **90% CL**

$R(\pi^0 h_b(1P) / \pi^+\pi^- h_b(1P)) > [3.7, 5.8]$

($< 2.5\times10^{-4}$ (90% CL) over scanned range: max signif. 2σ) (Syst. dominated by decay of light charmless mesons + model continuum and residual Ks and ISR)





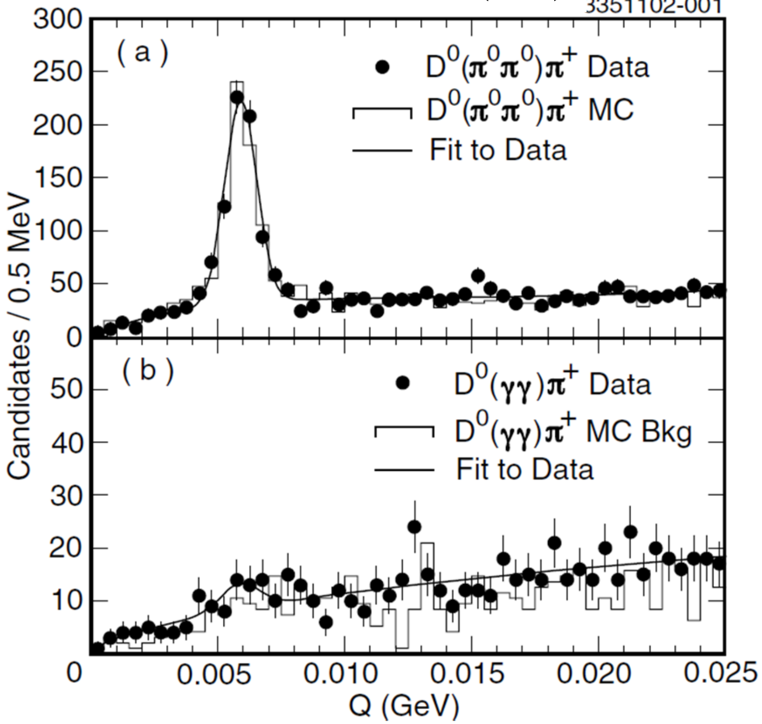
$\Upsilon(3S) \to \gamma\, \chi_{bJ}(2P)$ &

$\chi_{bJ}(2P) \to \pi^+\pi^- \chi_{bJ'}(1P)$

J=J'= **1** or **2**

Previous $D^0 \to \gamma\gamma$ and $D^0 \to \pi^0\pi^0$ measurements

PRL90, 101801 (2003)

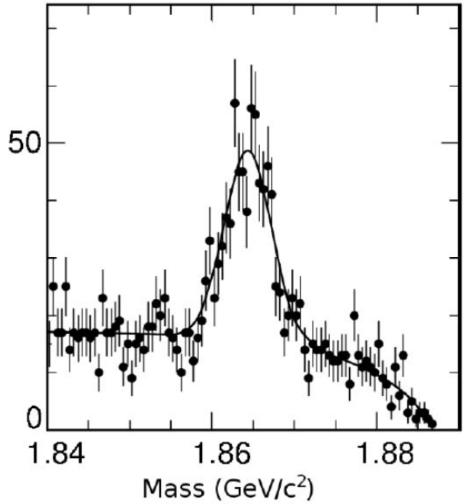


Q=m(D*)-m(D^0)-m(π_{soft})

14/fb near Υ(4S): (19.2±9.3) cands.

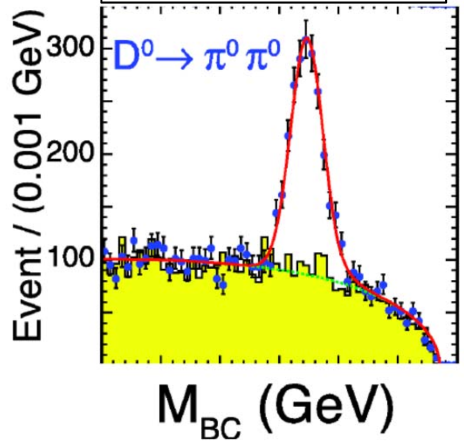
$\mathcal{B}$(D$^0 \to \gamma\gamma$)<2.4×10^{-6} 90%CL

PRL96, 081802 (2006)



CLEO-c overlapping Samples at ψ(3770)

PRD81, 052013 (2010)



Measurement	$\mathcal{B}_{mode}$ (10^{-4})
CLEO (2006) **281/pb**	$7.9 \pm 0.5 \pm 0.6 \pm 0.1 \pm 0.1$
CLEO (2009) **818/pb**	$8.1 \pm 0.3 \pm 0.4 \pm 0.2$
World Average (PDG)	8.1 ± 0.8

In BaBar use $D^0 \to K^0_s\pi^0$ as reference channel:

$$B(D^0 \to \gamma\gamma) = \frac{\frac{1}{\varepsilon_{\gamma\gamma}} N(D^0 \to \gamma\gamma)}{\frac{1}{\varepsilon_{K^0_s\pi^0}} N(D^0 \to K^0_s\pi^0)} \times B(D^0 \to K^0_s\pi^0)$$

Inclusive ϕ (+lepton) as a probe of B_s decays

- B_s decay chain leads to large ϕ yield compared to $B_{u/d}$ decays:
  - $\mathcal{B}(B_s \to D_s X) \times \mathcal{B}(D_s \to \phi X) \approx 15\%$ (PDG2010)
  - *vs* $\mathcal{B}(B \to \phi X) \approx 3.43\%$ (PDG2010)

- ϕ+lepton:
  - $B_s \to D_s l \nu X_1 \to \phi l \nu X_2 \approx 1.3\%$ (same B_s)
  - ***vs*** $B \to D l \nu X_1 \to \phi l \nu X_2 \approx 0.1\%$ (same B)

  - $B_s \to l \nu X_1$ & $B_s \to \phi X_2 \approx 1.4\%$ (different B_s)
  - ***vs*** $B \to l \nu X_1$ & $B \to \phi X_2 \approx 0.4\%$ (different B)

➔*Inclusive yields of* ϕ & ϕ+lepton can be used to measure both B_s production rate ($B_s\bar{B}_s/B\bar{B}$) and its semileptonic branching ratio

- Backgrounds sources: Continuum $e^+e^- \to q\bar{q}$ & $B_{u/d}\bar{B}_{u/d}$

Analysis Method

- Measure number of events, ϕ rate, and ϕ rate in correlation with a high-momentum lepton as a function of CM energy

- Use below $B\bar{B}$ threshold data to subtract continuum $e^+e^-\to q\bar{q}$ (q=u,d,s,c) contributions:
  - B hadron events:

$$R_b\left[f_s\epsilon_{1s} + (1-f_s)\epsilon_1\right]$$

  - Inclusive ϕ rate:

$$R_b\left[f_sP(B_s\bar{B}_s \to \phi\mathrm{X})\epsilon_{2s} + (1-f_s)P(B\bar{B} \to \phi\mathrm{X})\epsilon_2\right]$$

  - Inclusive ϕ+lepton rate:

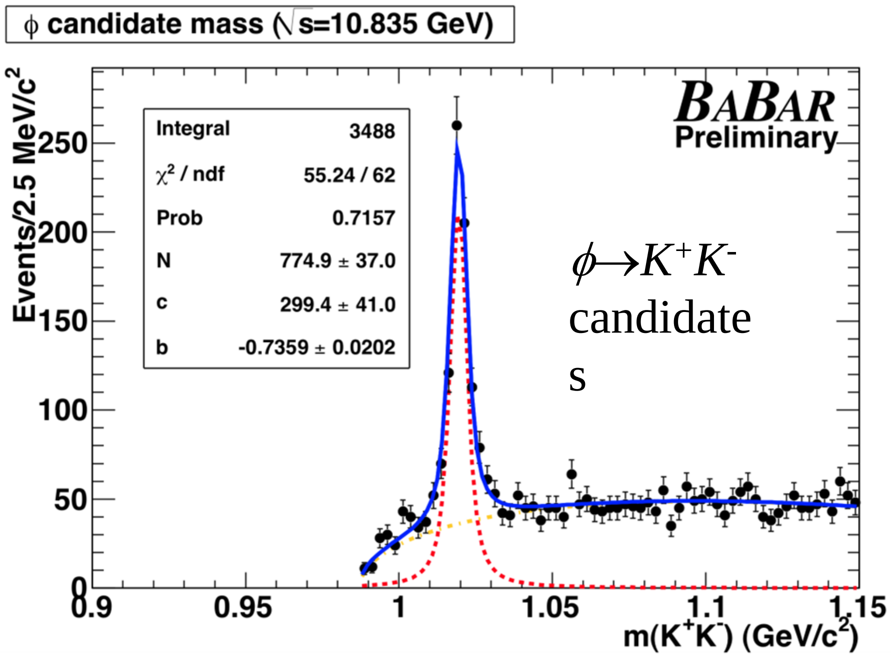
$$R_b\left[f_sP(B_s\bar{B}_s \to \phi\ell\nu\mathrm{X})\epsilon_{3s} + (1-f_s)P(B\bar{B} \to \phi\ell\nu\mathrm{X})\epsilon_3\right]$$

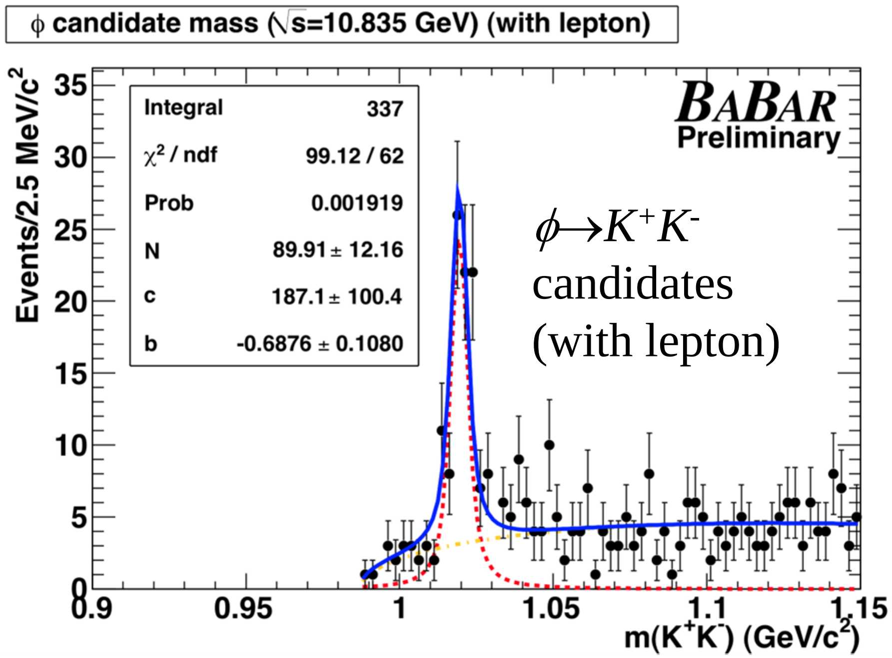
- Event rate & ϕ rate $\to f_s$

$$\bar{f}_s \equiv \frac{\#\ B_s \text{ events}}{\text{all } B \text{ hadron events}}$$

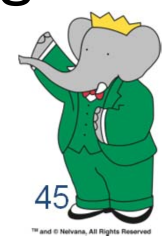
- $P(B_s\bar{B}_s \to \phi l \mathrm{X})$ contains info on $\mathcal{B}(B_s\to l\nu\mathrm{X})$

Measurement

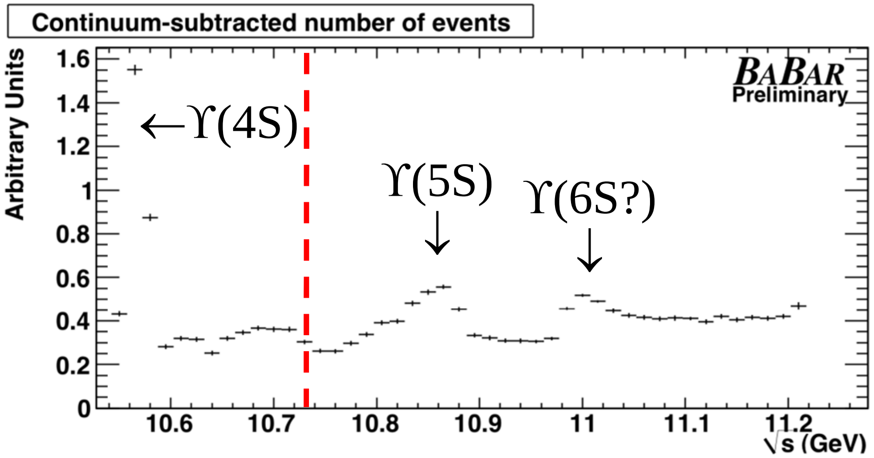


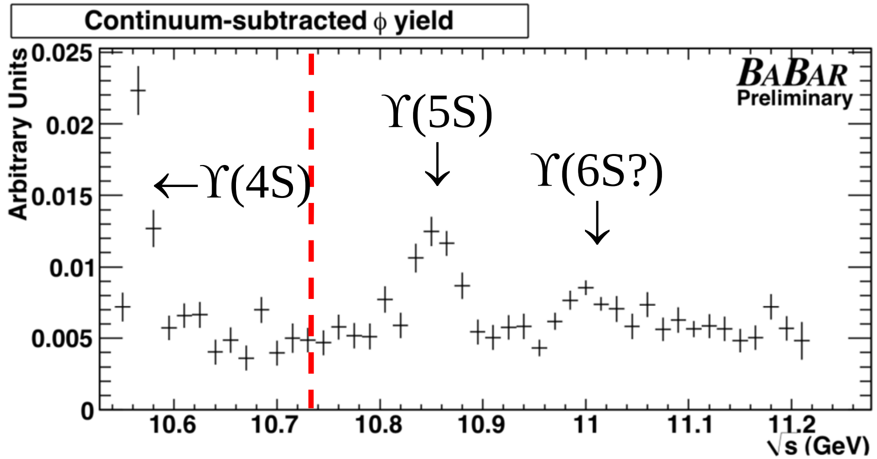


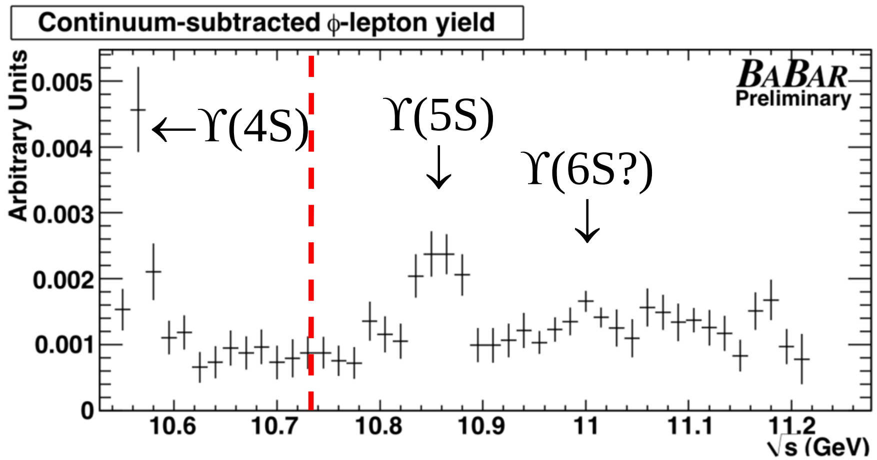
- Typical mass plots for inclusive ϕ and ϕ with lepton at $10.8225 < E_{CM} < 10.8475$ GeV
  - (At same energy, so right plot is subset of events on left)



Measurement







Relative yields as a function of energy (15 MeV bins) after continuum $e^+e^-\rightarrow q\overline{q}$ subtraction

Simultaneous Extraction of $\text{Br}(B_s \to l\nu X)$ & f_s

➢Continuum-subtracted rates given by:

$$\text{Event rate} = R_b \left[f_s \epsilon_{1s} + (1 - f_s)\epsilon_1 \right]$$

$$\phi \text{ rate} = R_b \left[f_s P(B_s \bar{B}_s \to \phi X)\epsilon_{2s} + (1 - f_s) P(B\bar{B} \to \phi X)\epsilon_2 \right]$$

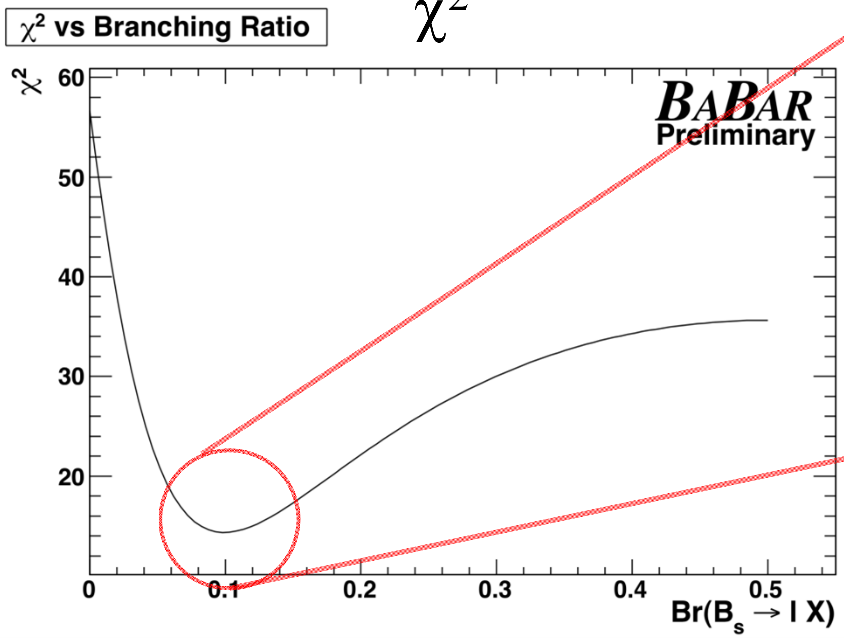
$$\phi - \ell \text{ rate} = R_b \left[f_s P(B_s \bar{B}_s \to \phi \ell \nu X)\epsilon_{3s} + (1 - f_s) P(B\bar{B} \to \phi \ell \nu X)\epsilon_3 \right]$$

- $B_{u/d}$ contributions are measured in data taken at $\Upsilon(4S)$
- f_s extracted at each energy point from number of events and ϕ yield
- B_s contributions depend on:
  - $\mathcal{B}(B_s \to D_s X_i)$ (PDG), $\mathcal{B}(B_s \to l\nu X_j)$, $\mathcal{B}(D_s \to l\nu X_k)$ (PDG), $\mathcal{B}(D_s \to \phi X_m)$ (PDG), $\mathcal{B}(D_s \to \phi l\nu X_n)$ (PDG) and others

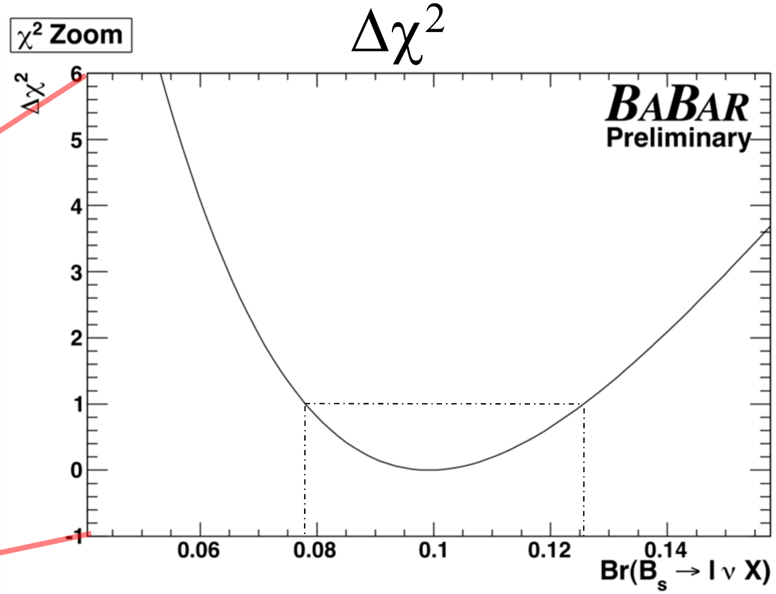
- A χ^2 fit is performed to the measured yields to extract $\text{Br}(B_s \to l\nu X)$

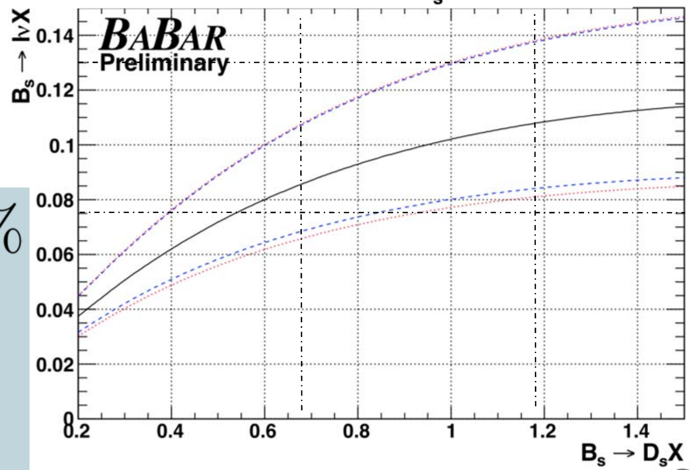
Fit to the Data in range 10.7375 GeV – 11.2 GeV

χ^2



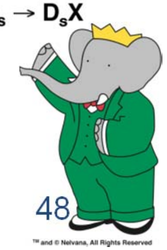
$\Delta\chi^2$





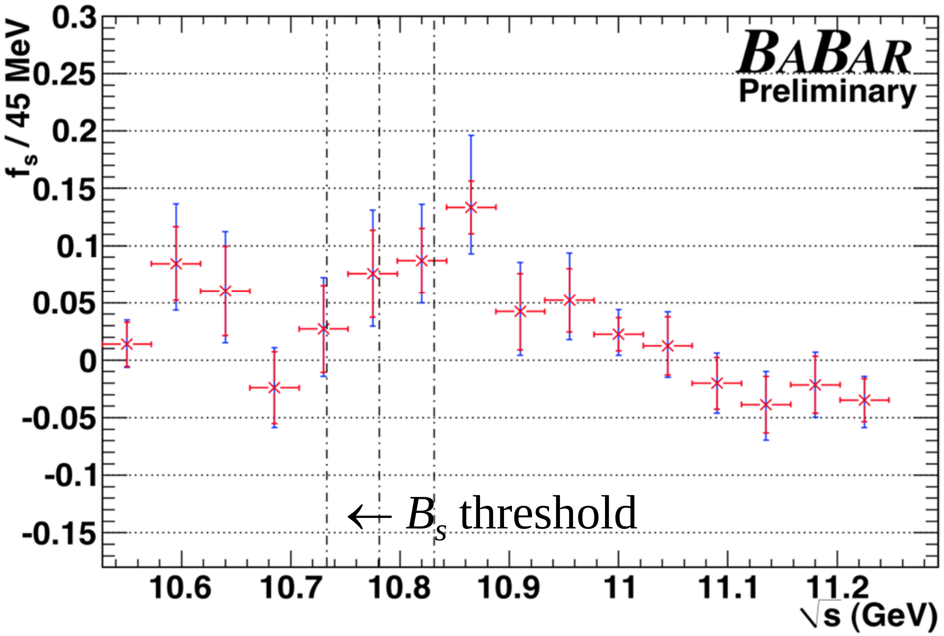
- $\text{Br}(B_s \to l \nu X) = \left(9.9^{+2.6}_{-2.1}(\text{stat})^{+1.0}_{-1.8}(\text{syst})\right)\%$

- Dominant systematic is from inclusive D_s yield per B_s = .93 ±.25 (PDG2010) (Belle & LEP)

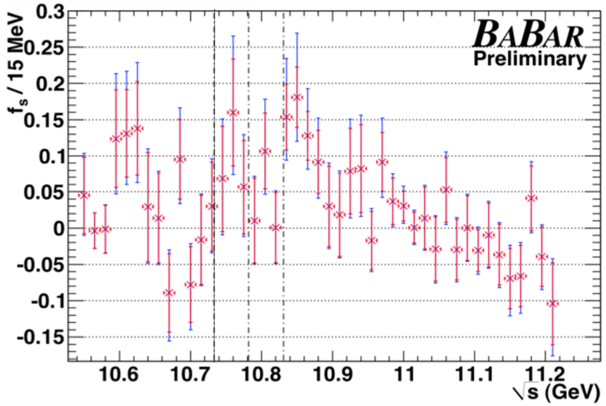


Measurement of f_s (# B_s events/# B hadron events)

f_s in 45 MeV bins



f_s in 15 MeV bins



- Bins near ϒ(5S) peak (right plot) consistent with on peak results from
  - Belle: (19.3 ±2.9)% Phys. Rev. D **76**, 012002 (2007)
  - CLEO: ($16.8 \pm 2.6^{+6.7}_{-3.4}$)% Phys. Rev. D **75**, 012002 (2007)

Comparison to theory

- Theory plot:
  N. A. Törnqvist, Phys. Rev. Lett. **53**, 878 (1984)
  - Coupled-channel analysis

- Blue arrows show the range of the theory plots on the ***BABAR*** plots