SLAC-WP-093

Bottomonium Results by *BaBar*

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Summary:

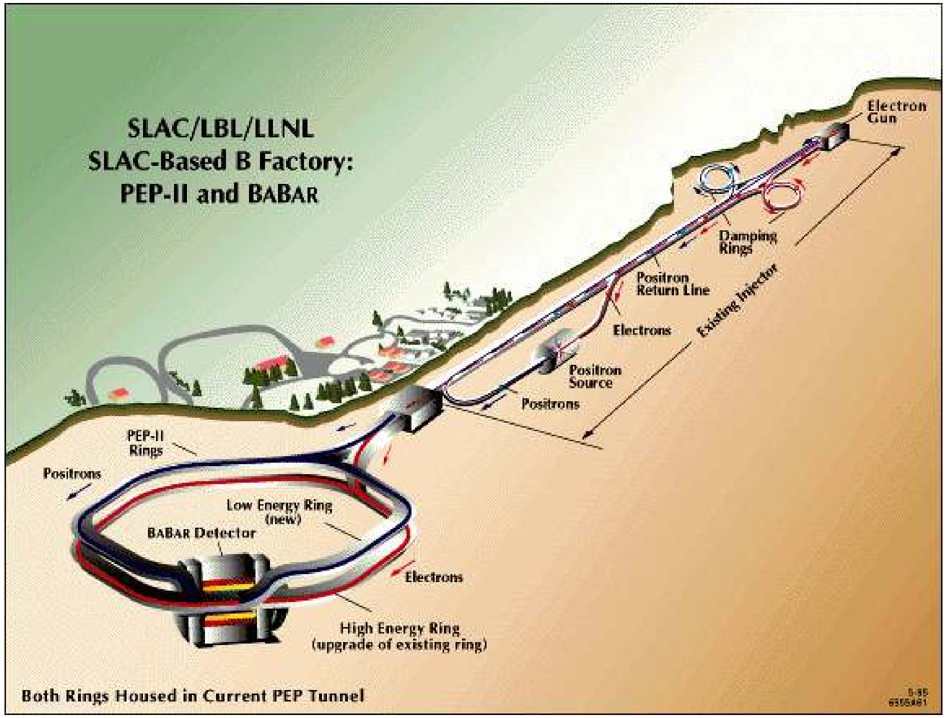
- Observation of η_b
- Energy scan above $\Upsilon(4S)$
- Search for $\Upsilon \to \gamma A^0$, $A^0 \to invisible$
- Hadronic transitions $\Upsilon(4S) \to \Upsilon(nS)$

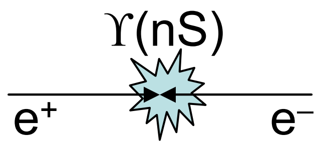
PANIC 2008, November 9-14th Eilat, Israel

Work supported in part by US Department of Energy contract DE-AC02-76SF00515.

SLAC National Accelerator Laboratory, Menlo Park, CA 94025

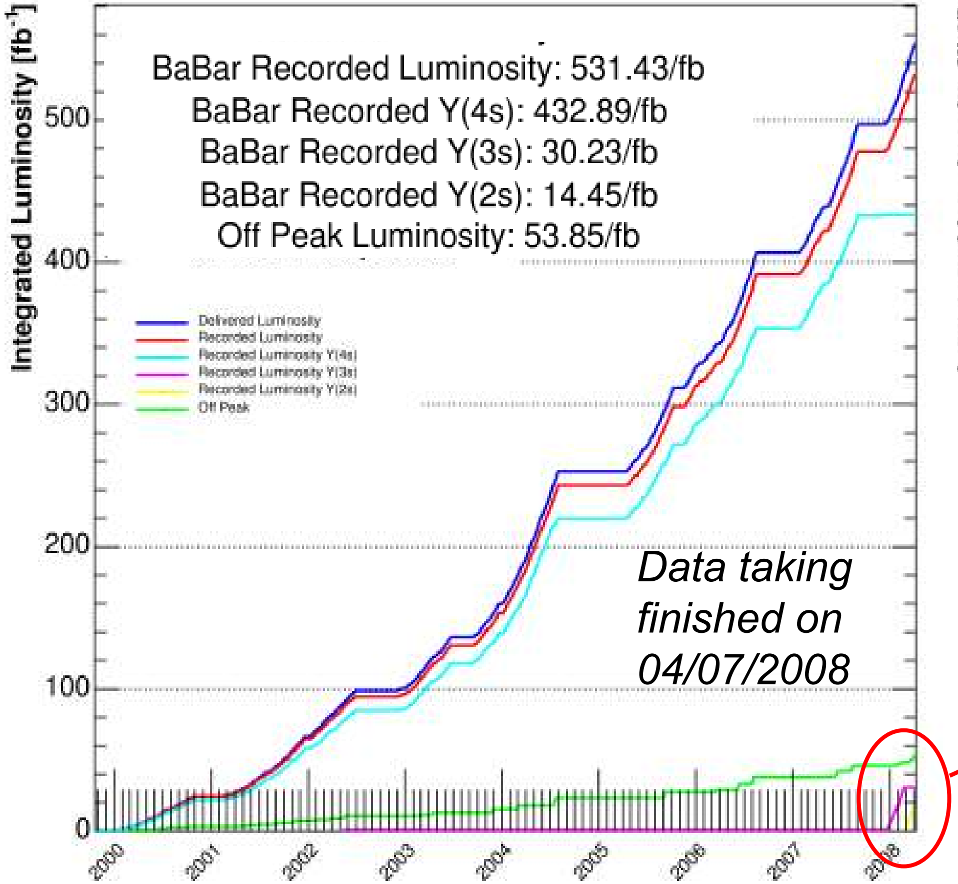
The *B*-Factory PEP-II at SLAC

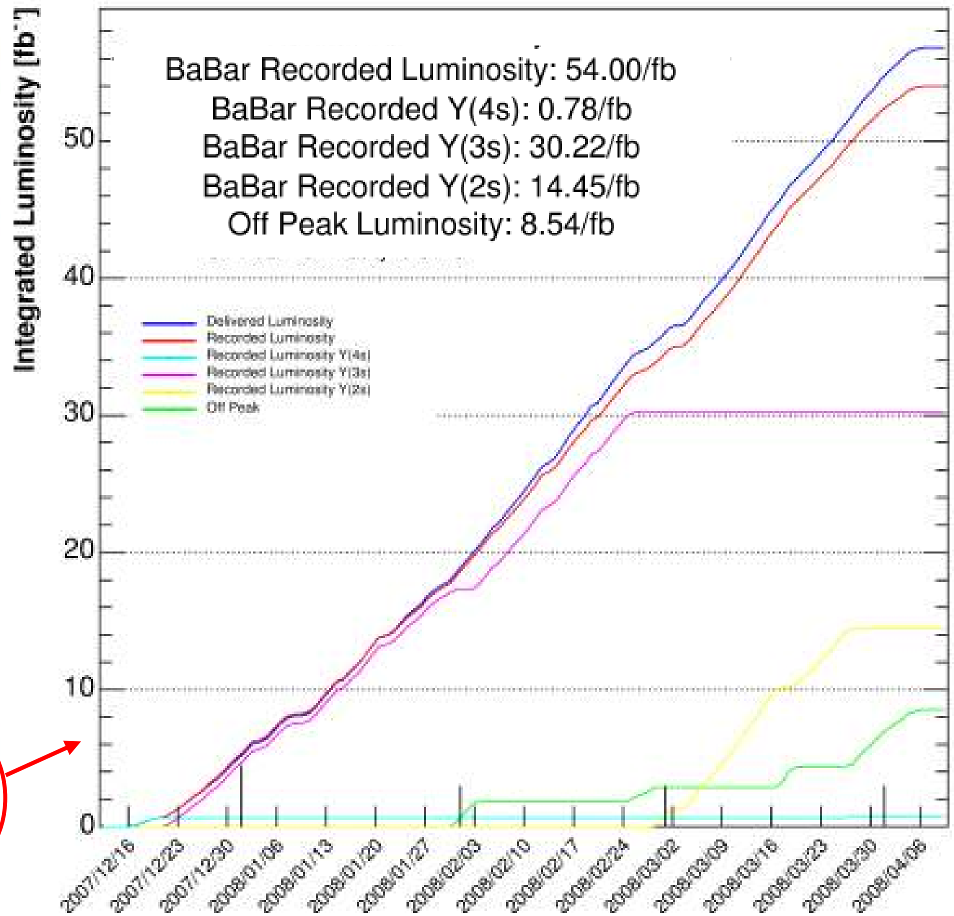


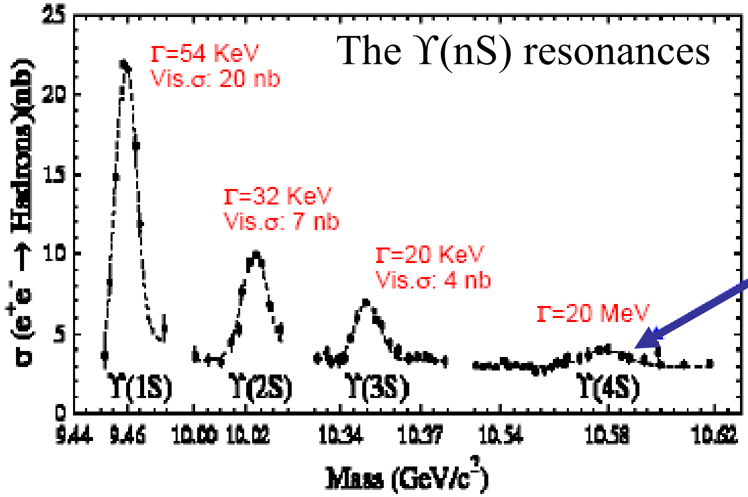


ϒ(nS): $b\bar{b}$ resonances

- Beam energies (at the ϒ(4S)): 9 GeV e^- / 3.1 GeV e^+
  - the center-of-mass energy is changed by changing the energy of the e^- beam.
- Instantaneous luminosity: $L_{peak} \approx 12 \times 10^{33}$ cm^{-2} s^{-1}
  - ~4 times the design luminosity.







- Also at the 4S the other Υ are produced, via initial state radiation $e^+e^- \to \gamma\Upsilon(nS)$: σ~20pb. For inclusive measurements or studies of final states with missing particles, runs at the resonance peaks are necessary.

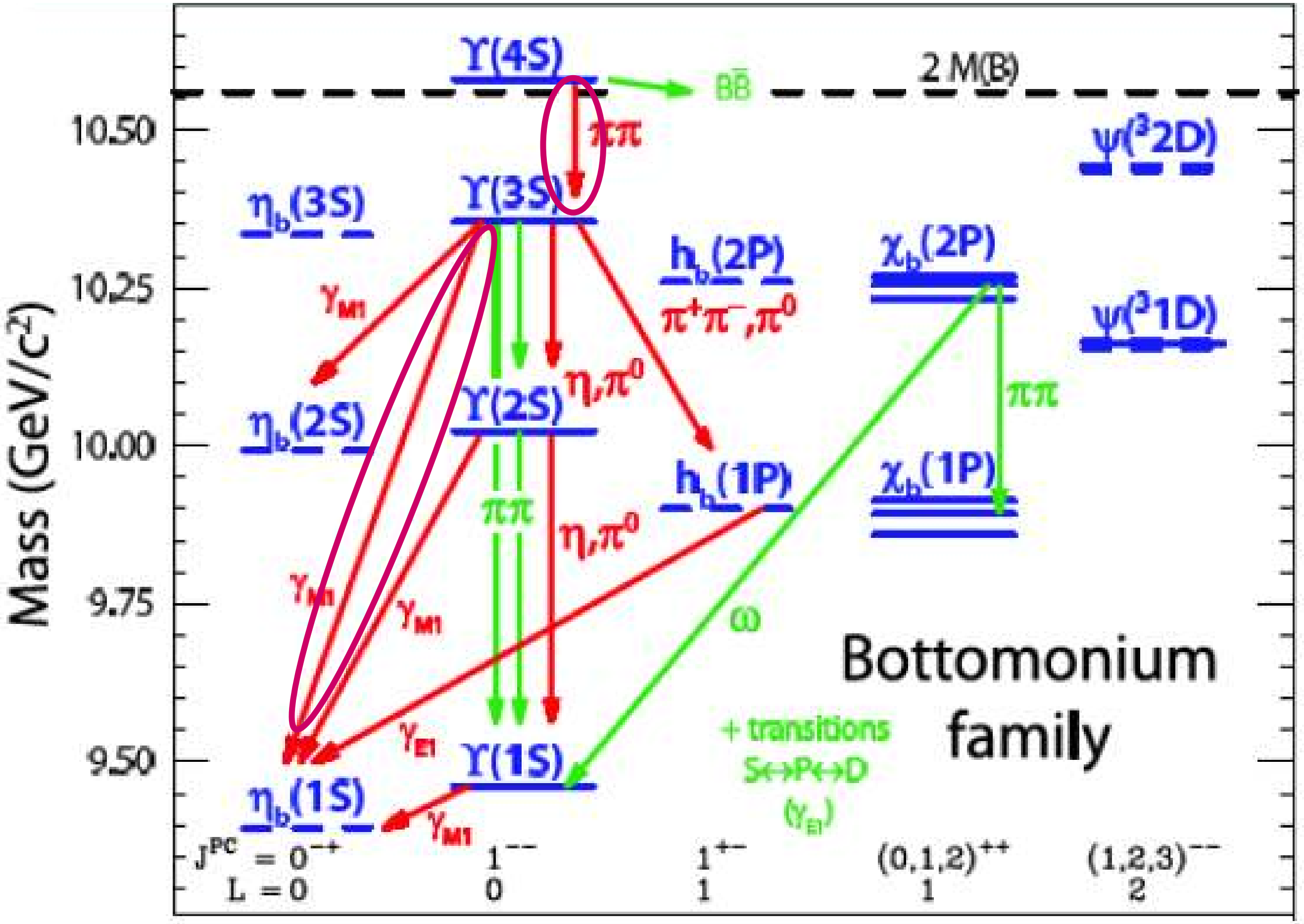
~ 4.8×10^8 $\Upsilon(4S)$

~ 1.2×10^8 $\Upsilon(3S)$

~ 1.1×10^8 $\Upsilon(2S)$

($\times 10^8$)	1S	2S	3S
CLEO:	0.2	0.09	0.06
Belle:	1	/	0.11

Spectrum of Bottomonium States



- Bound states $b\bar{b}$:
  - Spectrum described with potential models: Coulomb potential + linear term.
- 30 years after the discovery of bottomonium, all singlet states (and many D-wave states) were missing, including the ground state, η_b(1S).
  - Hyperfine splitting m(Υ(1S)) – m(η_b) gives information on the spin-spin potential
  - Sensitive to α_s.

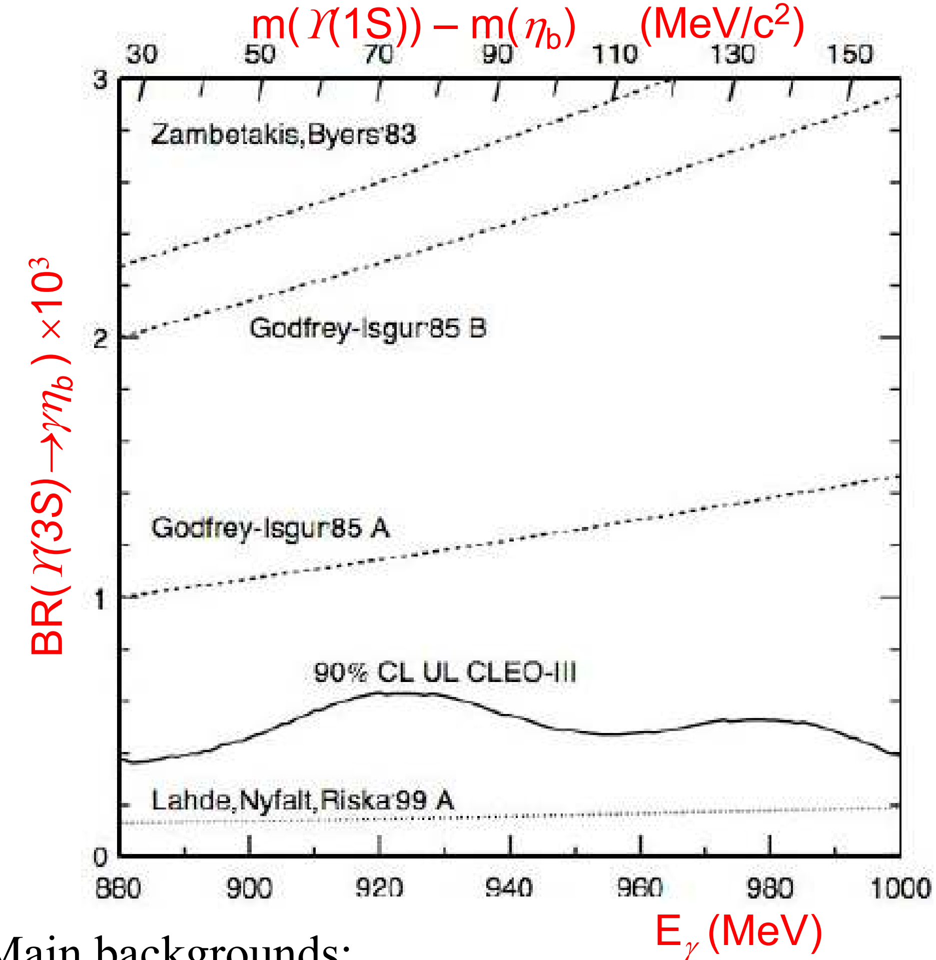
- Many transitions still to be observed.

observed
recently observed
not yet seen

Search for η_b

- Using the process $e^+e^- \to \Upsilon(3S) \to \gamma\eta_b$
  - Predictions: BR($\Upsilon(3S) \to \gamma\eta_b$) ~ $10^{-4} \div 2 \times 10^{-3}$
  - CLEO[1]: BR($\Upsilon(3S) \to \gamma\eta_b$) < 4.3×10^{-4}

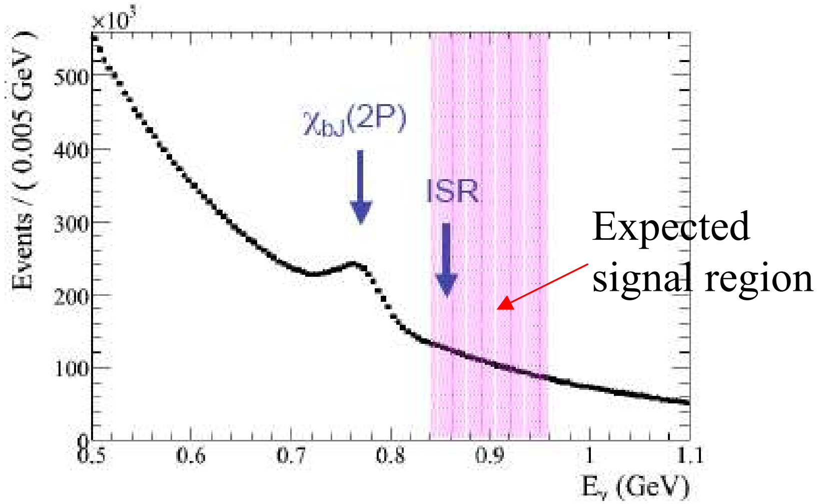
  [1] PRL 94, 032001 (2005)



- Hyperfine splitting: 35 ÷ 100 MeV ⇒ m(η_b) ~ 9400 MeV/c^2

- Total width: 4 ÷ 20 MeV/c^2.

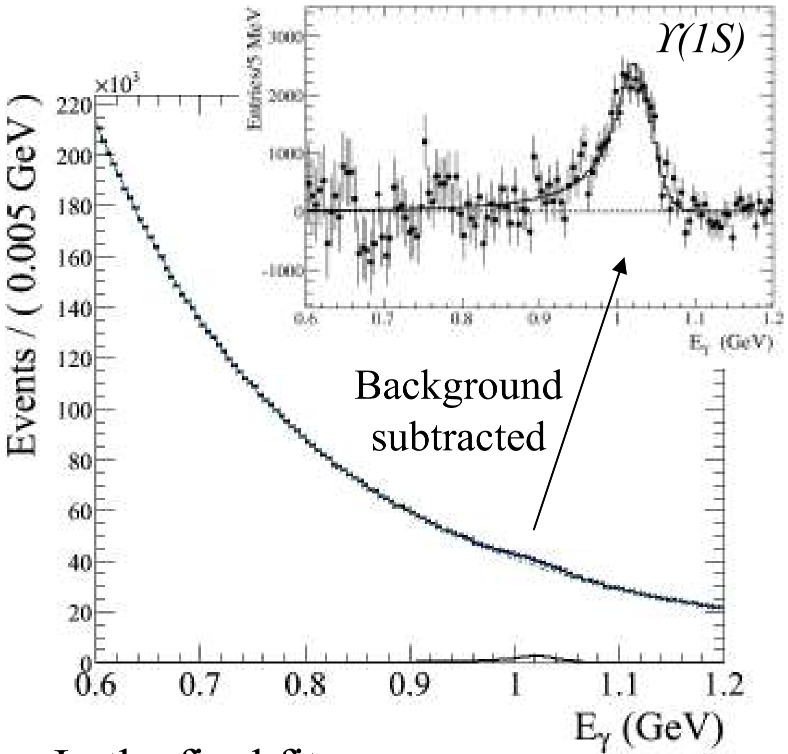
- Decays of η_b are not known:
  - study of the inclusive photon spectrum: $E_\gamma = (s - m^2) / 2\sqrt{s}$



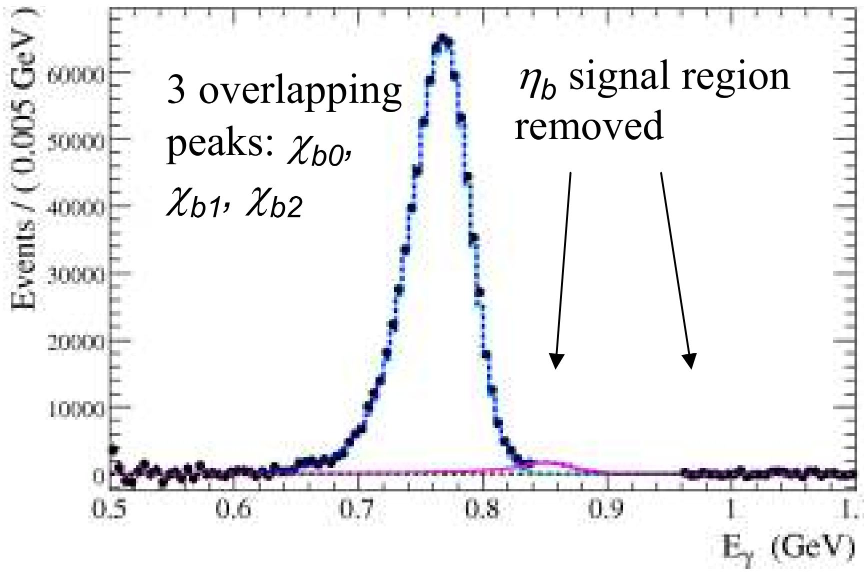
- Main backgrounds:
  - $e^+e^- \to q\bar{q}$, other Υ decays: exponential shape.
  - $\Upsilon(3S) \to \chi_{bJ}(2P)\gamma \to \Upsilon(1S)\gamma\gamma$: peak at ~ 760 MeV
  - $e^+e^- \to \gamma_{ISR}\ \Upsilon(1S)$: peak at ~ 850 MeV

- Study of peaking backgrounds

$e^+e^- \to \gamma_{ISR}\ \Upsilon(1S)$: data taken at ~40 MeV below the Y(4S).

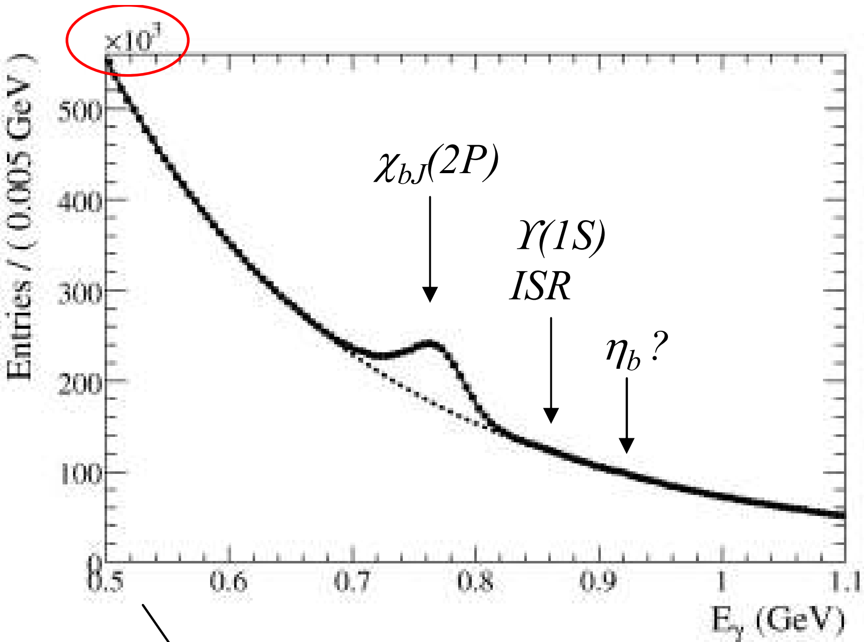


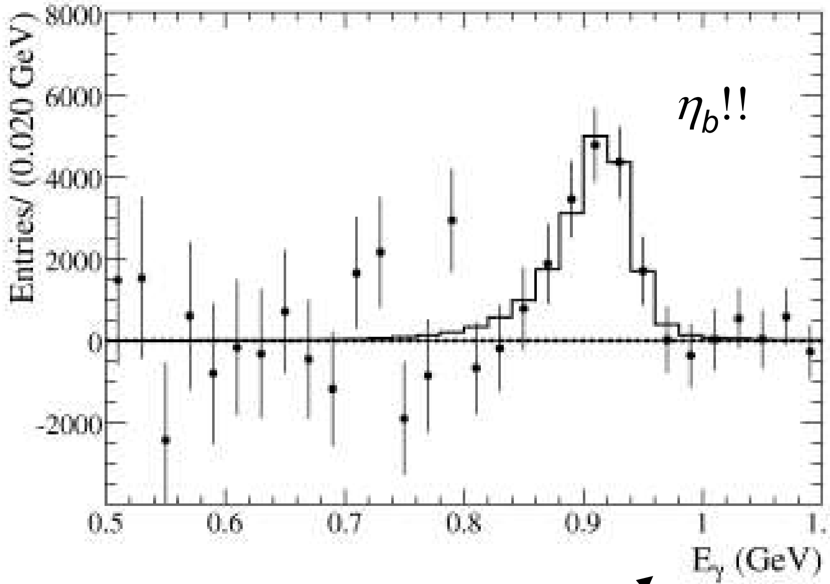
$\Upsilon(3S) \to \chi_{bJ}(2P)\gamma$: on 3S data, removing the signal region. After subtracting the exponential background:



- In the final fit:
  - exponential background: all parameters free
  - χ_{bJ}: everything fixed, but yield
  - ISR: everything fixed.
  - signal: yield and mass free.

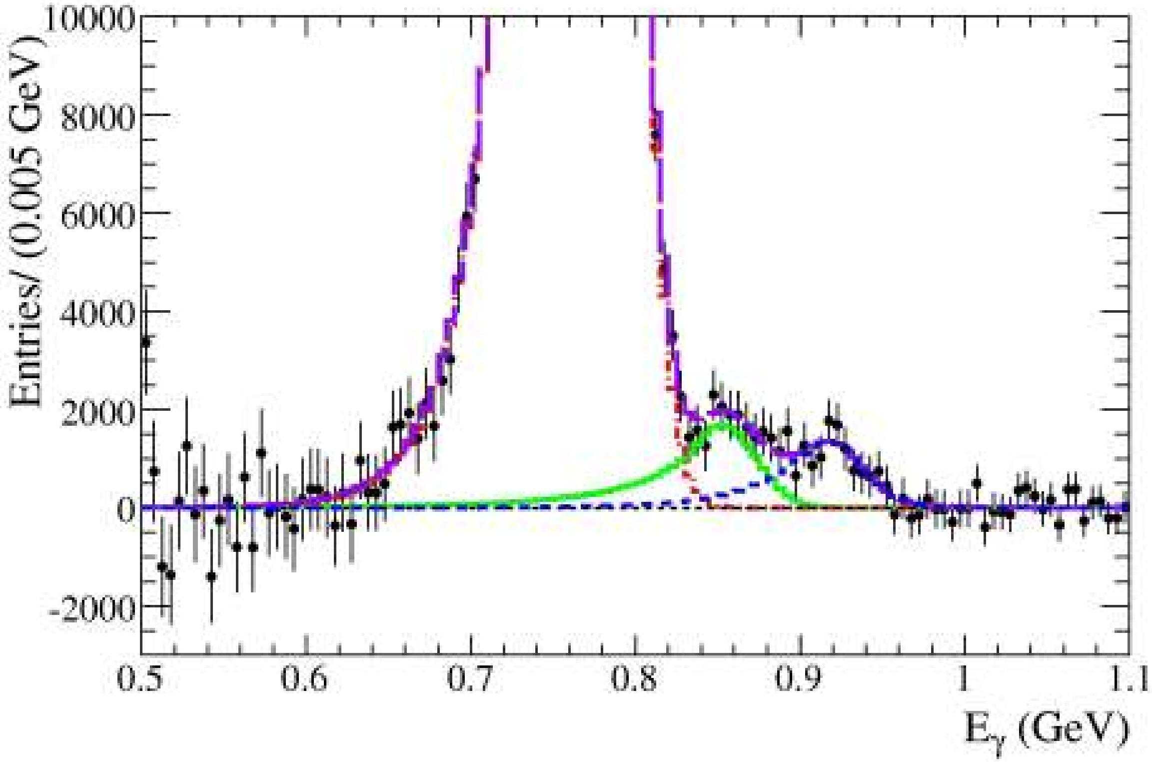
- Detailed Monte Carlo studies show that the η_b width cannot be measured in the fit.
  - Fixed to 10 MeV in the nominal fit
  - A systematic error is determined by varying the width till 20 MeV.





Subtracting also χ_b and ISR

Subtracting the exponential background



- The fit yields 19200±2000 η_b candidates. Significance 10σ.

• A significant excess of events is observed at a mass below the $\Upsilon(1S)$. The only likely candidate is the $\eta_b(1S)$. However, other interpretations cannot yet be discarded (like a light Higgs or a glueball).

• Under the bottomonium hypothesis:

Mass:

$$9388.9^{+3.1}_{-2.3}(\text{stat}) \pm 2.7(\text{syst})\ \text{MeV}/c^2$$

Hyperfine splitting:

$$71.4^{+2.3}_{-3.1}(\text{stat}) \pm 2.7(\text{syst})\ \text{MeV}/c^2$$

BR($\Upsilon(3S) \rightarrow \eta_b \gamma$):

$$[4.8 \pm 0.5(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-4}$$

Good agreement with expectations for η_b **PRL101, 071801 (2008)**

• More results are awaited soon!

– other decay chains from Υ(3S), via χ_b or h_b

– verification of bottomonium hypothesis and constraints on quantum numbers.

– $\Upsilon(2S) \rightarrow \gamma\, \eta_b(1S)$

Energy Scan Above Υ(4S)

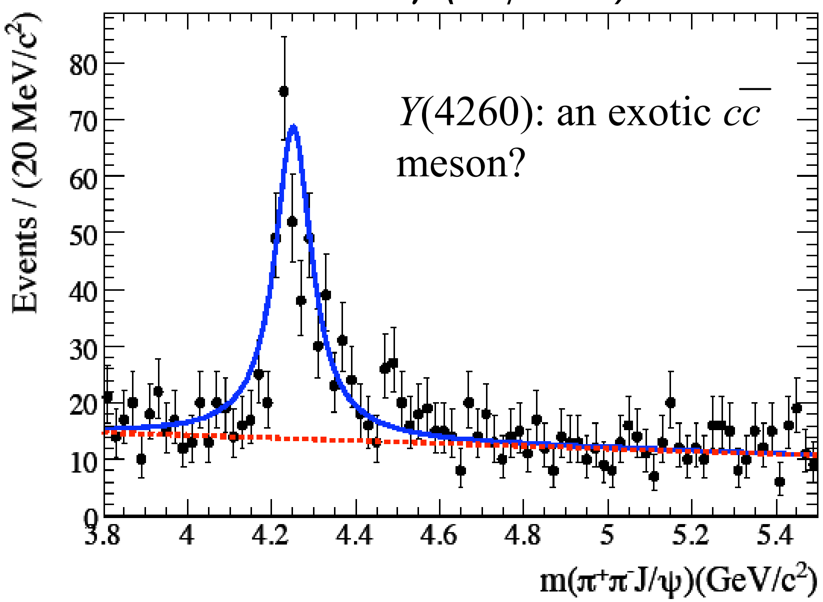
arXiv:0809.4120

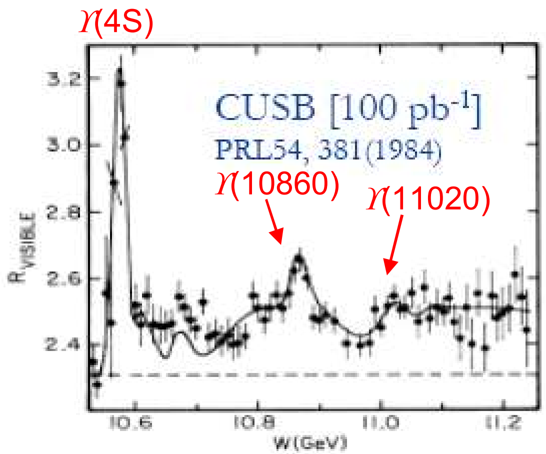
- Main motivation:
  - Search for counterparts of the exotic states with c quark.
- Scan from 10.54 to 11.20 GeV in 5 MeV steps.
  - 25/pb per step, plus 600/pb around Υ(11020)
- Hadronic cross section measurement as a function of energy
  - $R_b(s) = \sigma_b(s)/\sigma_\mu(s)$

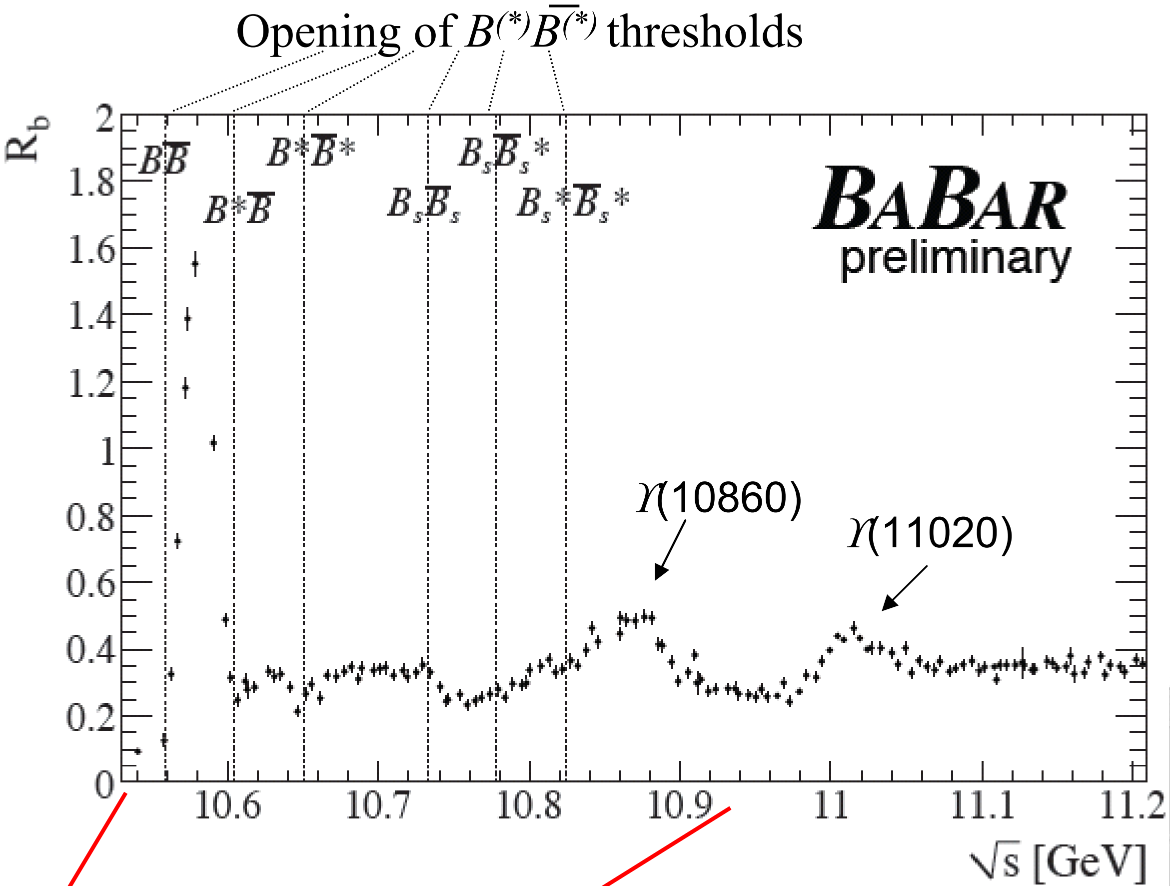
$\sigma_b(s)$: total cross section for $e^+e^- \to b\bar{b}(\gamma)$

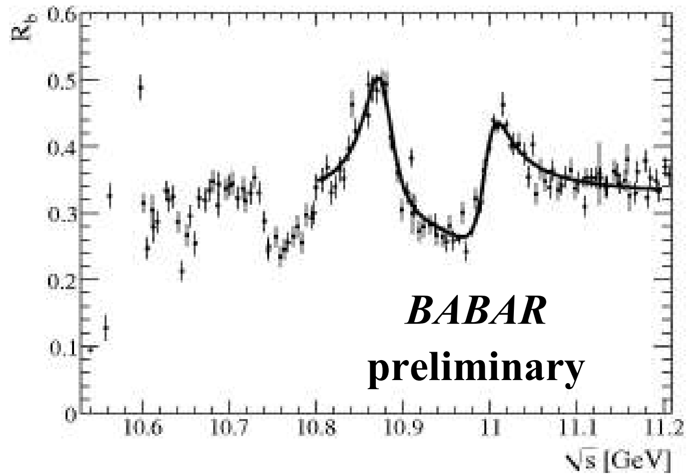
$\sigma_\mu(s)$: 0^{th} order cross section for $e^+e^- \to \mu^+\mu^-$

$e^+e^- \to \gamma\,(J/\psi\pi^+\pi^-)$

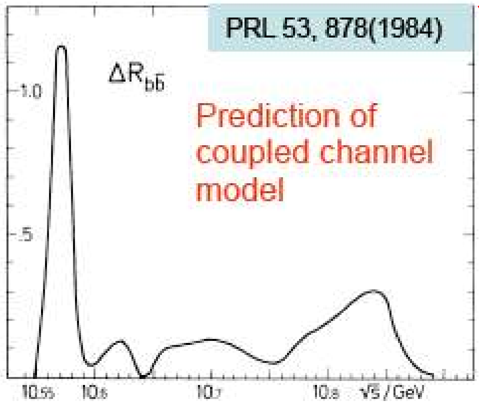








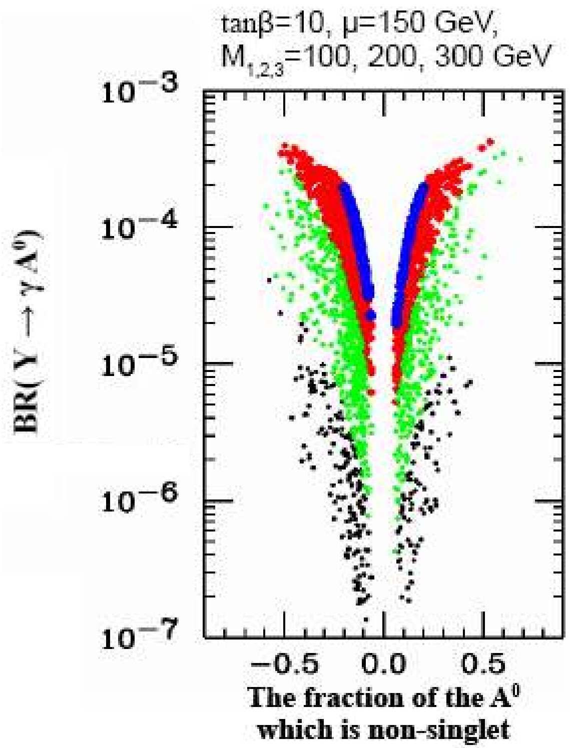
	$\Upsilon(10860)$	$\Upsilon(11020)$
mass (GeV)	10.876 ± 0.002	10.996 ± 0.002
width (MeV)	43 ± 4	37 ± 3
ϕ (rad)	2.11 ± 0.12	0.12 ± 0.07
PDG mass (GeV)	10.865 ± 0.008	11.019 ± 0.008
PDG width (MeV)	110 ± 13	79 ± 16



- Many structures above Υ(4S)
- Interpretation in terms of resonances complicated by the opening of many thresholds.
  - preliminary fit including interference with continuum $b\bar{b}$ states.
  - refined fit with threshold effects included is ongoing.
- Next steps: study of exclusive final states.

Search for Invisible Light Scalar Particles

- In extensions of the Standard Model (SM) like Next to Minimal Supersymmetric Standard Model a Higgs singlet is added.
- So there is an additional Higgs boson (A^0), (pseudo)scalar, CP odd, that can be light.
  - The SM Higgs boson can decay to A^0A^0
  - For masses below ~10 GeV, A^0 can be accessible in decays of the Υ, with BR ~ 10^{-4}.
  - A dominant decay, especially if $m(A^0) < 2m(\tau)$, could be $A^0 \to \chi\bar{\chi}$, with χ light dark matter component.
  - A Higgs boson with such properties might have eluded the LEP searches.
  - CLEO[1]: $BR(\Upsilon(1S) \to \gamma A^0) \times BR(A^0 \to \text{invisible}) < 3 \times 10^{-5}$ for $m(A^0) < 7.2\ \text{GeV}/c^2$



Scan parameters: (2)

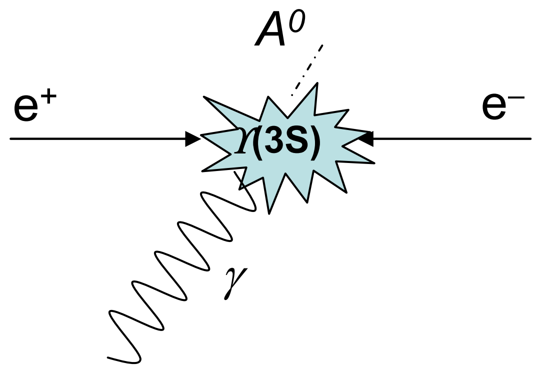
$m(A^0)<2m(\tau)$

$2m(\tau)<m(A^0)<7.5\ \text{GeV}/c^2$

$7.5<m(A^0)<8.8\ \text{GeV}/c^2$

$8.8<m(A^0)<9.2\ \text{GeV}/c^2$

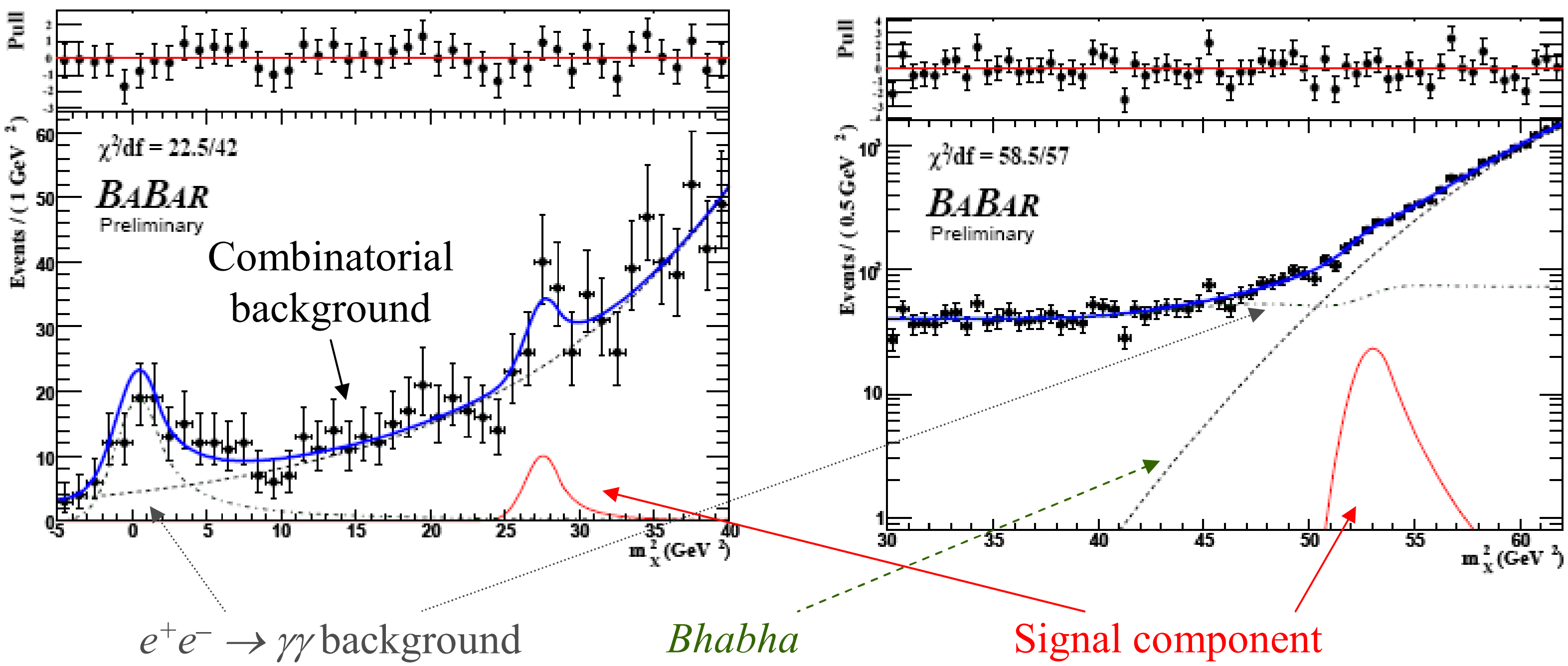
(1) PRD 51, 2053 (1995), (2) PRL 95, 041801 (2005)



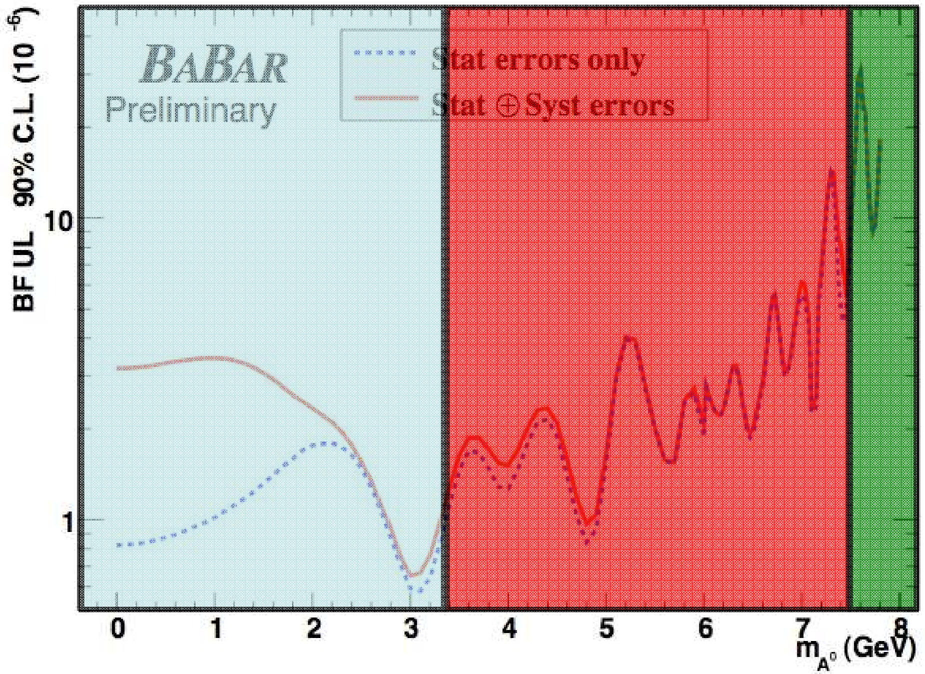
Dedicated trigger for "single photon" events

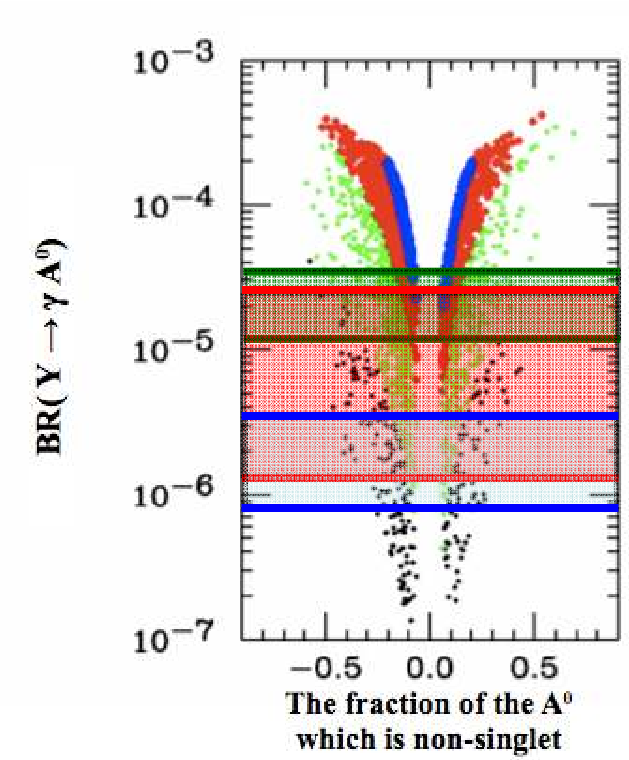
• Maximum likelihood fit to $m^2_X = m^2(\Upsilon) - 2\,E^*_\gamma\, m(\Upsilon)$ for the selected events.

• Two trigger lines in two E_γ regions: treated separately.



• Upper limit on BR($\Upsilon(3S) \rightarrow \gamma A^0$)×BR($A^0 \rightarrow$ invisible) as a function of m(A^0)





• Range: 0.7×10^{-6} (with m(A^0)=3.0 GeV/c^2) ÷ 31×10^{-6} (with m(A^0)=7.6 GeV/c^2)

• Assumption BR($A^0 \rightarrow \chi^0\bar{\chi}^0$)=1

• The models above each range of color are excluded.

Scan parameters:
m(A^0)<2m(τ)
2m(τ)<m(A^0)<7.5 GeV/c^2
7.5<m(A^0)<8.8 GeV/c^2
8.8<m(A^0)<9.2 GeV/c^2

arXiv:0808.0017 [hep-ex]

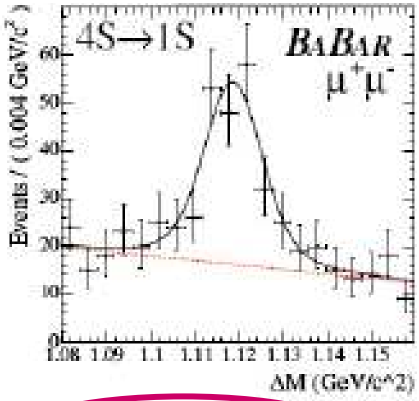
Hadronic Transitions $\Upsilon(mS)\rightarrow\Upsilon(nS)$

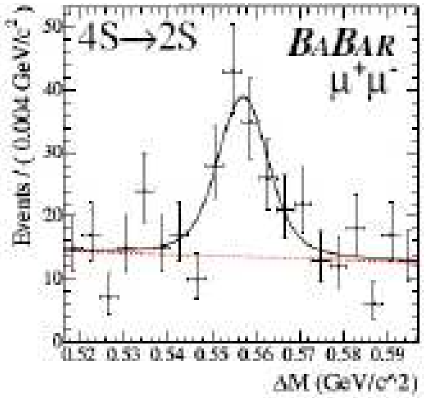
- Hadronic transitions between heavy quarkonia can be described with the QCD multipole expansion model (QCDME [1]):
  - Expansions in terms of (ak) if the radius a of the bound $q\bar{q}$ state is much smaller than the wavelength $1/k$.
  - Vicinity to threshold openings may modify the QCDME predictions.
- In the charmonium system, data agree with predictions:
  - BR($\psi(2S)\rightarrow\eta J/\psi$) / BR($\psi(2S)\rightarrow\pi\pi J/\psi$), m($\pi\pi$) in the transition $\psi(2S)\rightarrow\pi\pi J/\psi$
- In the bottomonium system, many more transitions available: more comparisons.
  - The m($\pi\pi$) distribution in the $\Upsilon(3S)\rightarrow\Upsilon(2S)\pi\pi$ and $\Upsilon(2S)\rightarrow\Upsilon(1S)\pi\pi$ transitions do agree with the QCDME expectations.
  - The m($\pi\pi$) distribution in the $\Upsilon(3S)\rightarrow\Upsilon(1S)\pi\pi$ transition is not in agreement with the QCDME model.

[1] PRD 24, 2874 (1981)

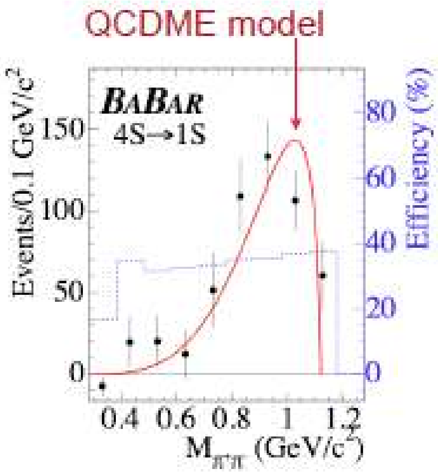
Non $B\overline{B}$ Decays of $\Upsilon(4S)$

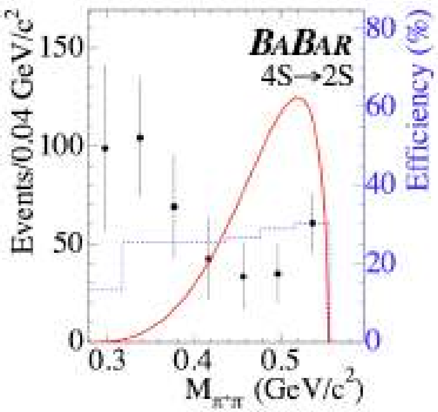
- Study of $\Upsilon(4S) \to \Upsilon(nS)\, \pi\, \pi$, with $\Upsilon(nS) \to l^+ l^-$ **PRL96, 232001 (2006)**





- Poor agreement of m($\pi\pi$) with QCDME!

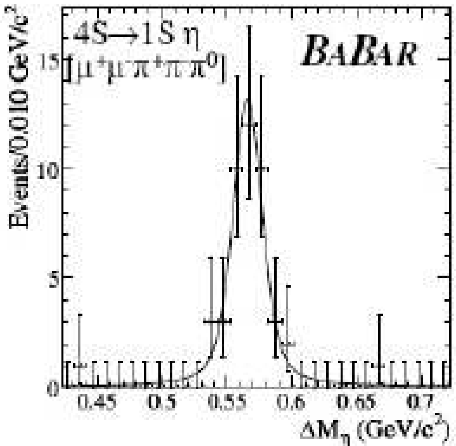


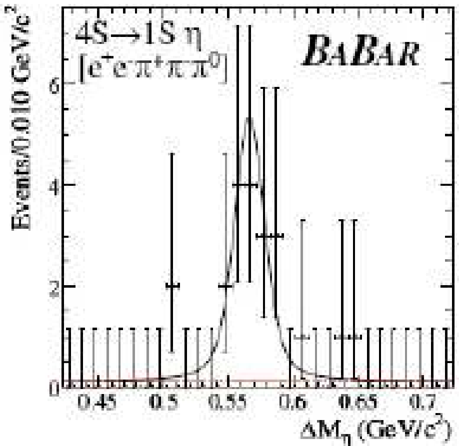


- First observation of non-$B\overline{B}$ decays of $\Upsilon(4S)$:

  BR(Υ(4S)→Υ(1S)ππ) = (0.90±0.15) × 10^{-4} ,
  BR(Υ(4S)→Υ(2S)ππ) = (1.29±0.32) × 10^{-4}

- Study of $\Upsilon(4S) \to \Upsilon(1S)\, \eta$, with $\Upsilon(1S) \to l^+ l^-$, $\eta \to \pi^+\pi^-\pi^0$ **arXiv:0807.2014]**





Δm = m(πππll)-m(ll)-m(πππ)

- First observation of $\Upsilon(4S) \to \Upsilon(1S)\, \eta$:
  - BR = (1.96±0.06±0.09) × 10^{-4}

$$\frac{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\, \eta)}{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\, \pi\, \pi)} = 2.41 \pm 0.40 \pm 0.12$$

Inconsistent with QCDME expectations (<1)!!

Conclusions

- Many interesting results on bottomonium physics.
- First measurements using data taken at energies other than the 4S were presented at the summer conferences.
- Observation of the bottomonium ground state.
- Precision measurement of the hadronic cross section above the $\Upsilon(4S)$. Study of resonances awaited soon.
- Stringent limits on invisible decays of a light scalar particle produced in bottomonium decays.
- Studies of hadronic transitions between the $\Upsilon(nS)$ reveals tension with the QCDME model.
- And many more results are awaited soon !!

Backup Slides

The *BaBar* Experiment

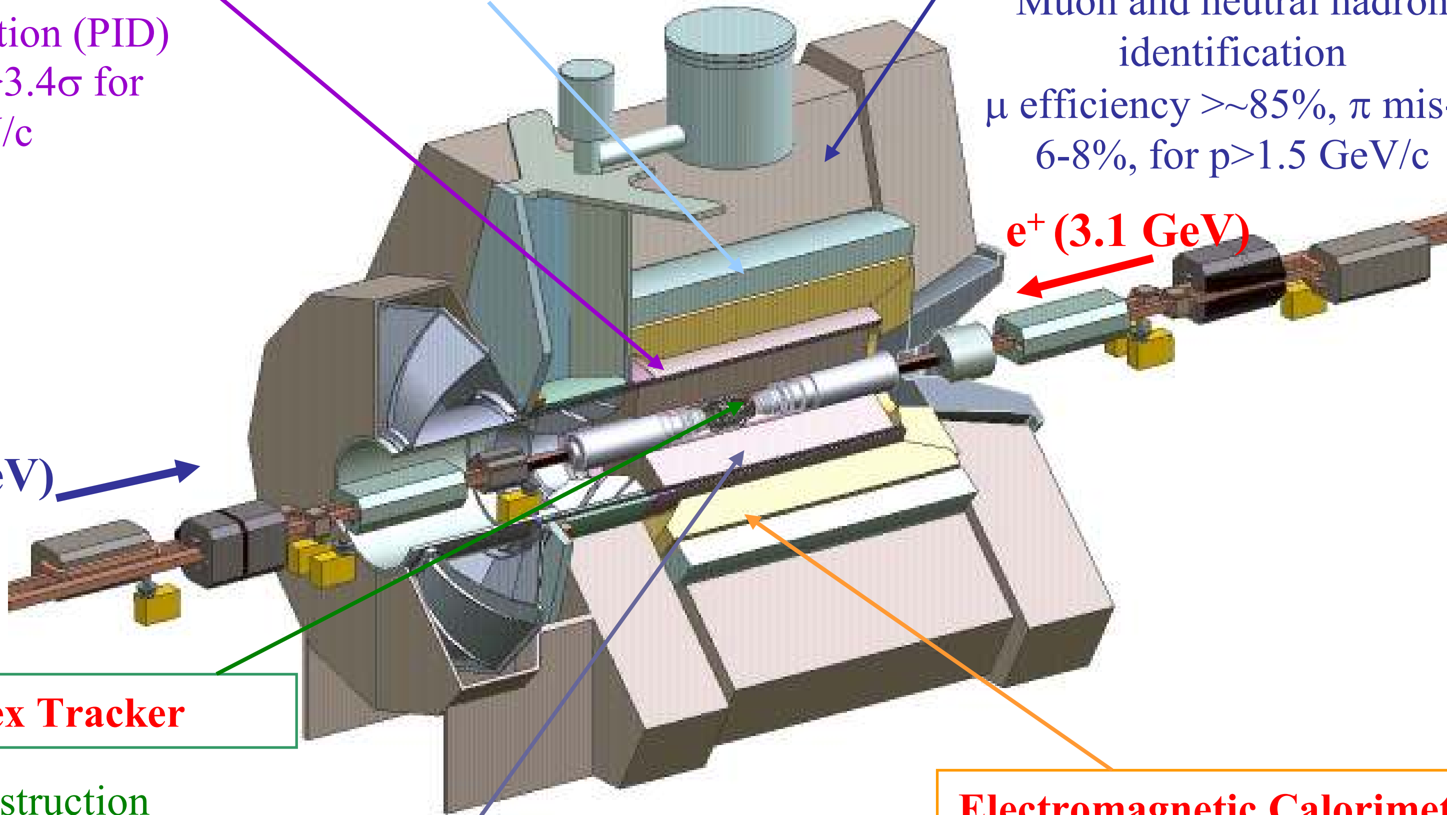
Cherenkov Detector

Particle identification (PID)
K-π separation >3.4σ for
p<3.5GeV/c

Solenoid 1.5T

Instrumented Flux Return

Muon and neutral hadron identification
μ efficiency >~85%, π mis-id 6-8%, for p>1.5 GeV/c



Silicon Vertex Tracker

Vertex reconstruction and tracking + dE/dx.
Efficiency ~ 97%

Drift Chamber

Momentum measurement for charged particles + dE/dx.
$\sigma(p_T)/p_T = 0.13\% p_T \oplus 0.45\%$

Electromagnetic Calorimeter

Electron and photon energy measurement.
$\sigma(E)/E = 1.33\% E^{-1/4} \oplus 2.1\%$

- Selection of $b\bar{b}$ events for the scan:
  - > 2 charged tracks
  - visible energy > 4.5 GeV
  - tracks vtx < 5mm (xy), 6 cm (z)
  - 2^{nd} ord FoxWolfram mom<0.2

• $e^+e^- \rightarrow \Upsilon(3S) \rightarrow \gamma A^0$: search for a particle decaying "invisibly" on the recoil of an isolated photon.

– Reconstruction of the photon as an e.m. shower in the calorimeter.

– Veto events with activity in the μ detector in direction opposite the photon (suppresses $e^+e^- \rightarrow \gamma\gamma$ background)

– No activity in the tracker

– Total energy of residual photons < 100 MeV.