Spectroscopy and New Physics Searches in Bottomonium Decays

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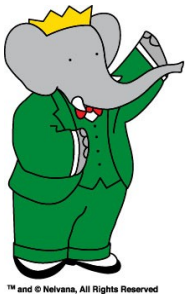
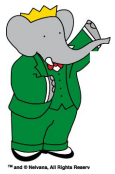
Rainer Bartoldus

SLAC



Representing the BaBar Collaboration

SLAC
NATIONAL ACCELERATOR LABORATORY

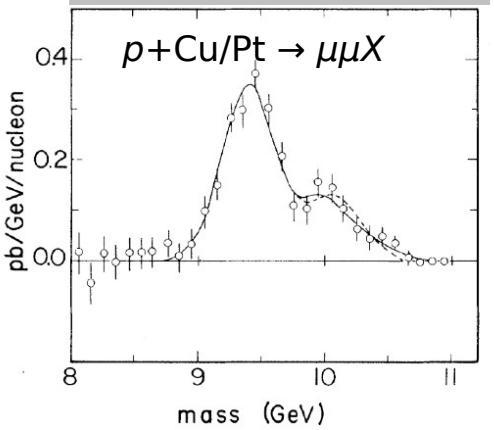


Outline

- Introduction: Bottomonium and NP
- Observation of the η_b in $Y(3S)$ decays, and evidence for the η_b in $Y(2S)$ decays NEW
- Search for the lepton-flavor violating decays $Y(3S) \to e^{\pm}\tau^{\mp}$ and $Y(3S) \to \mu^{\pm}\tau^{\mp}$
- Search for a light CP-odd Higgs A^0 in radiative $Y(3S)$ decays
- Measurement of the $e^+e^- \to b\bar{b}$ cross section between $\sqrt{s}$ = 10.54 and 11.20 GeV
- Conclusions

Bottomonium

PRL 39, 1240 (1977)



$b\bar{b}$ bound states:

Heavy quarks, non-relativistic

Radial quantum number — Spin multiplicity — Orbital angular momentum — Total angular momentum

$$n\,^{2S+1}L_J \quad \longleftrightarrow \quad I^G(J^{PC})$$

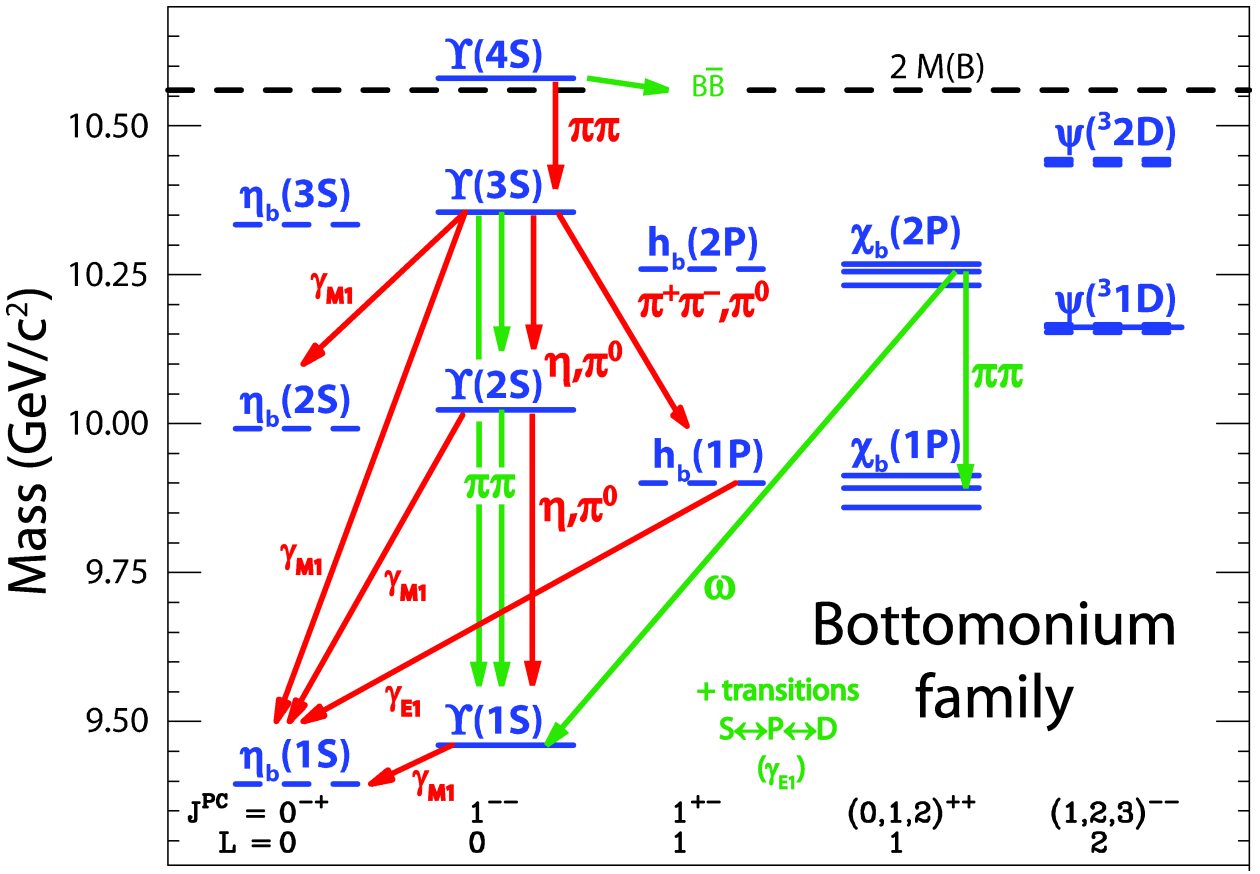
Spectroscopy notation ⟷ PDG notation

Fermion/anti-fermion: $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{L+S+I}$

Quarkonia: $I = 0, G = C$ $\quad |L-S| \le J \le L+S$

L=0	$\Upsilon(nS) = n\,^3S_1$ (1^{--})	$\eta_b(nS) = n\,^1S_0$ (0^{-+})
L=1	$\chi_{b\,0,1,2}(nP) = n\,^3P_{0,1,2}$ $(0,1,2)^{++}$	$h_b(nP) = n\,^1P_1$ (1^{+-})
⋮	*quark-spin triplet*	*quark-spin singlet*

Bottomonium Spectrum



Eichten, Godfrey, Mahlke, Rosner, RMP 80, 1161 (2008)

Complete spectrum of $L=0$ and $L=1$ spin-triplets below the $B\bar{B}$ threshold has been observed

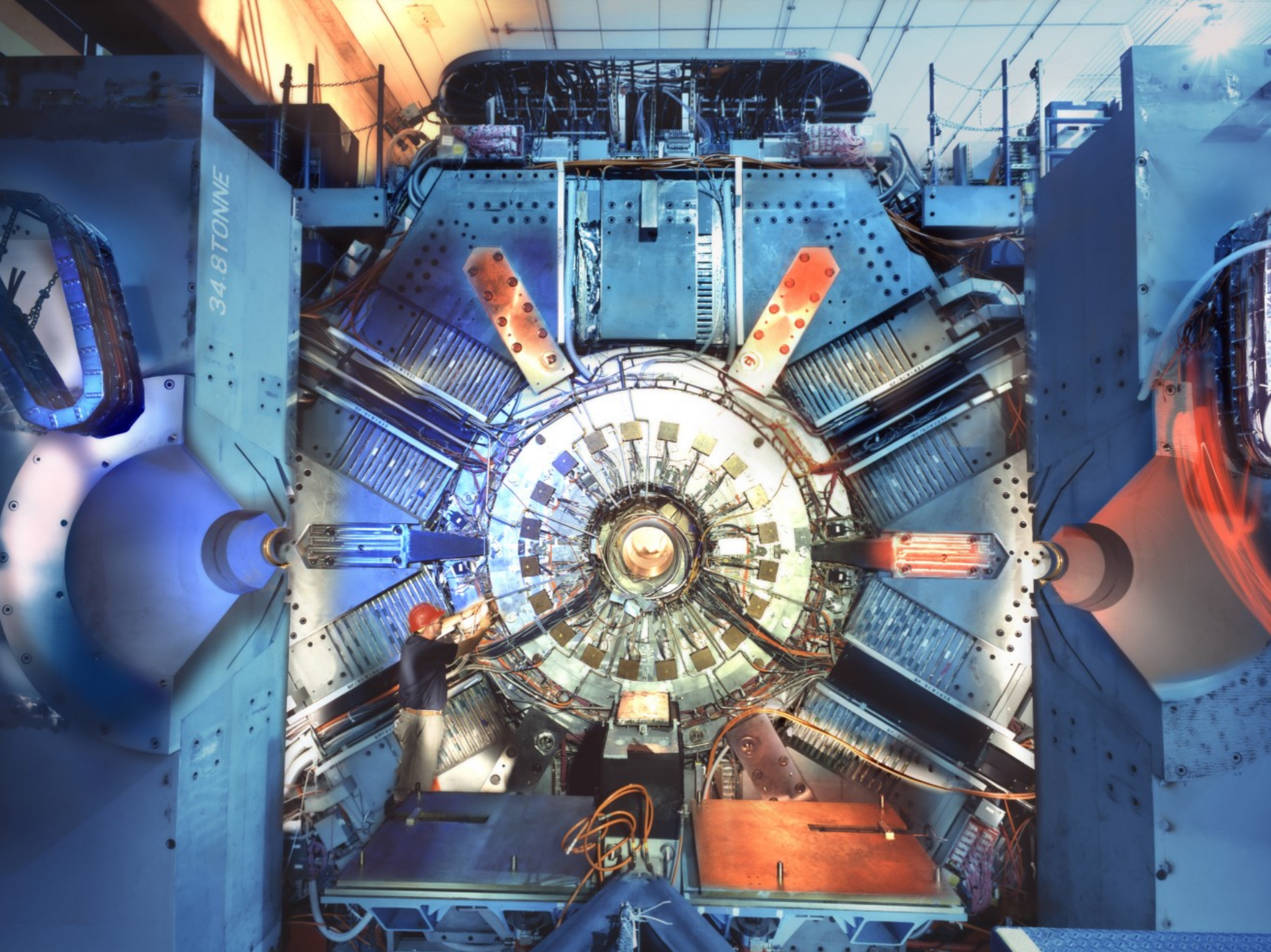
As of this summer, none of the spin-singlet states had been seen: η_b , h_b ...

Rich cascades from the $Y(3S)$ and $Y(2S)$

Including magnetic dipole transitions(*) to the η_b ground state

(*) flip the quark spin

Hyperfine splitting between $Y(1S)$ and η_b very sensitive to α_s


34.8TONNE

BaBar

σ(E)/E ~ 2.5%
at 1 GeV

1.5 T Solenoid

Instrumented Flux Return
18 layers steel/brass,
barrel LST, endcaps RPC

DIRC
144 quartz bars
11000 PMTs

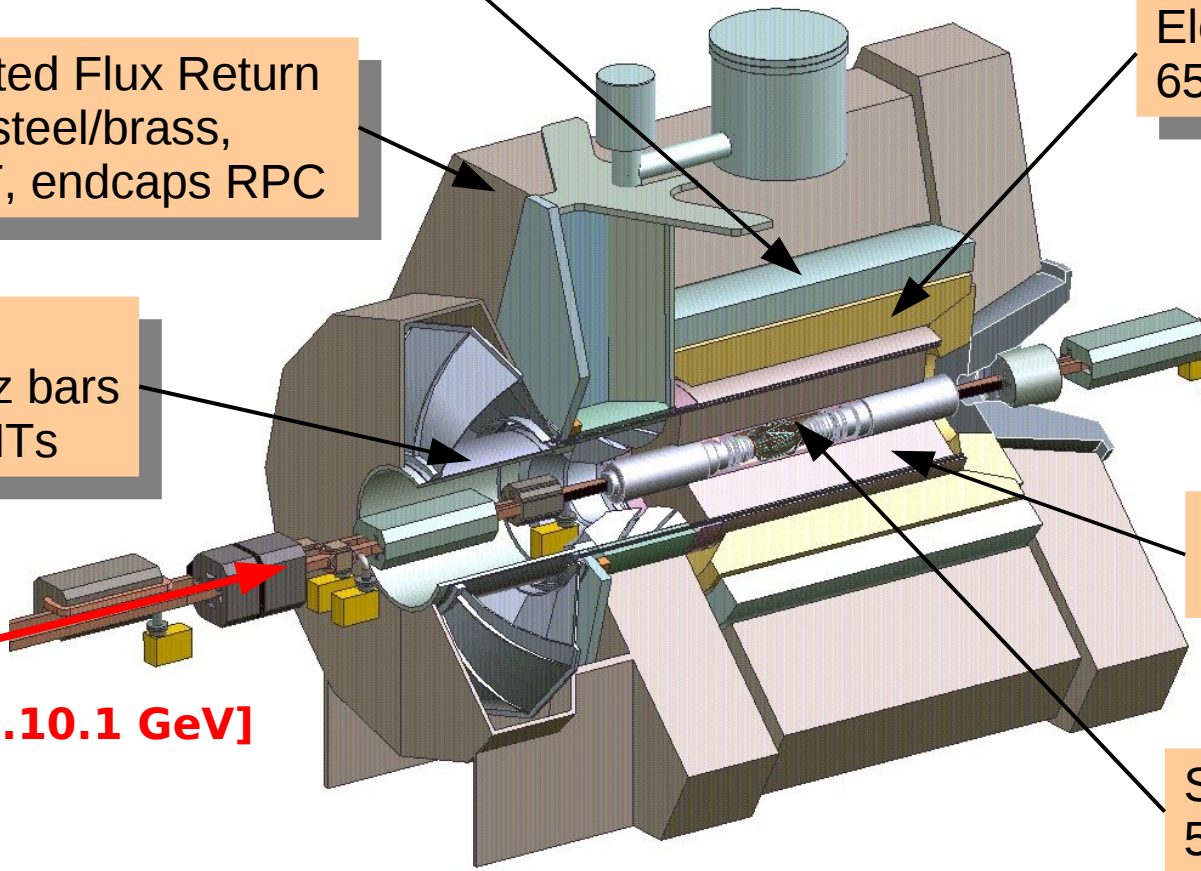
Electromagnetic Calorimeter
6580 CsI(Tl) crystals

e^+ [3.1 GeV]

Drift Chamber
40 layers axial/stereo wires

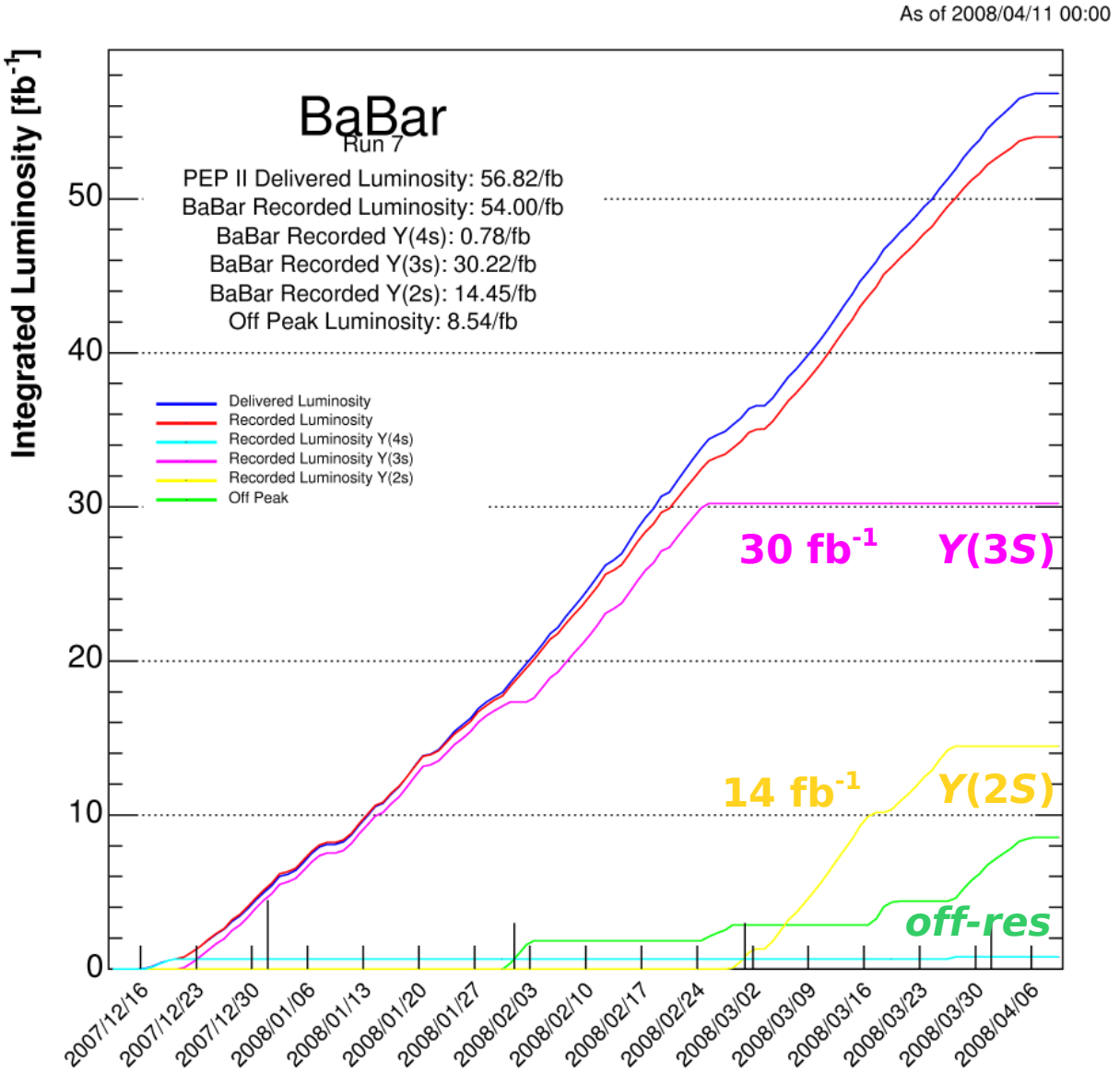
Silicon Vertex Tracker
5 layers double-sided strips

e^- [8.0...10.1 GeV]



Designed to study *CP* violation in the *B* system, yet produced a diverse portfolio of results in many areas

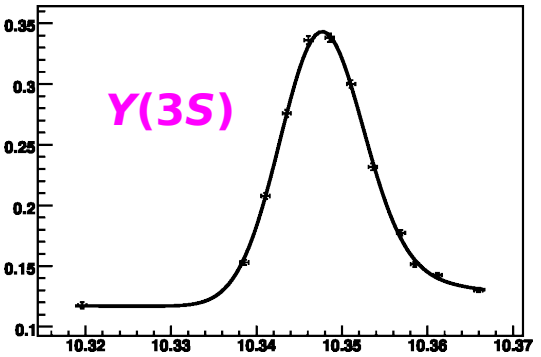
BaBar Run 7



Changed the experiment last December after decision to move off the $\Upsilon(4S)$ for the remainder of the running

Rapidly retuned the machine, reconfigured and added new triggers (L1 and L3)

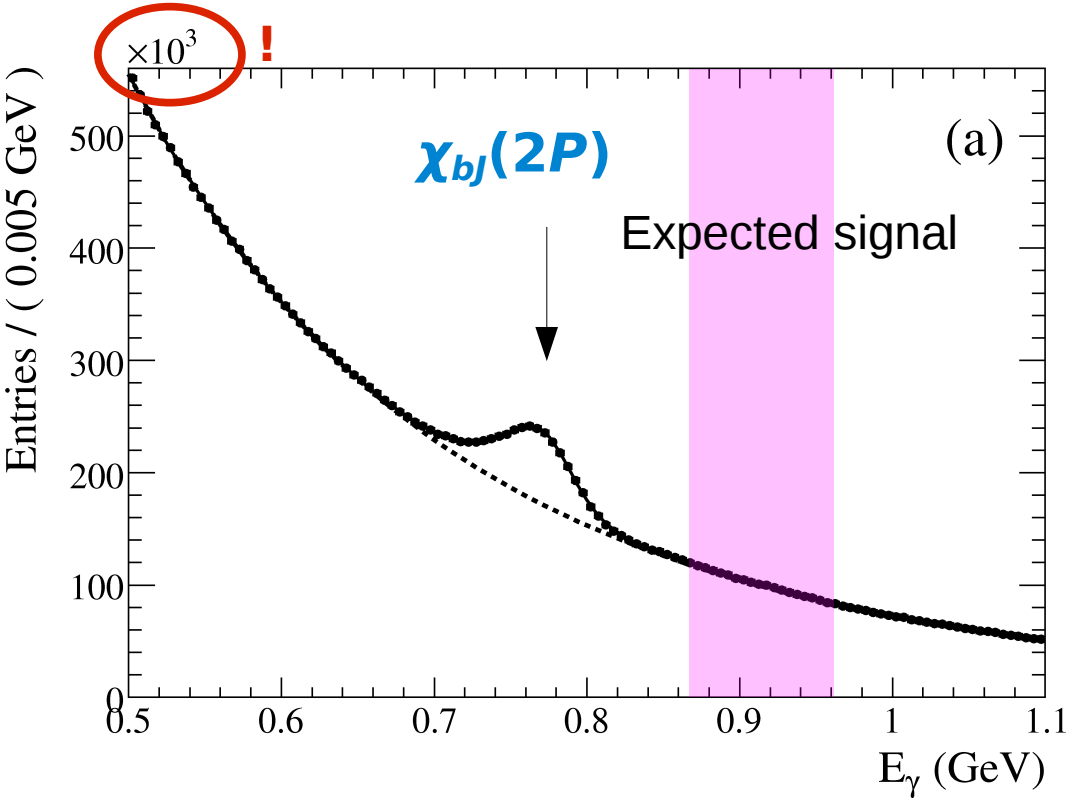
Took largest samples to-date on the $\Upsilon(3S)$ and $\Upsilon(2S)$, followed by a fine-grained scan above the $\Upsilon(4S)$



Search for $\Upsilon(3S) \to \gamma\, \eta_b$

Inclusive search: η_b decays mostly via two gluons, exclusive modes not known

Signal monochromatic: look for bump in photon energy spectrum, $E_\gamma = \frac{s - m^2_{\eta_b}}{2\sqrt{s}}$



Fit to full dataset of 109M $\Upsilon(3S)$ in 30 fb^{-1}

Huge background, determine shape from 10% of dataset = 10M $\Upsilon(3S)$ (excluded in final result)

Non-peaking background fit with an exponential shape

Signal fit with Breit-Wigner convolved with Crystal Ball function

Analysis with expected signal region “blinded”

$\Upsilon(3S) \rightarrow \gamma\, \eta_b$ Backgrounds

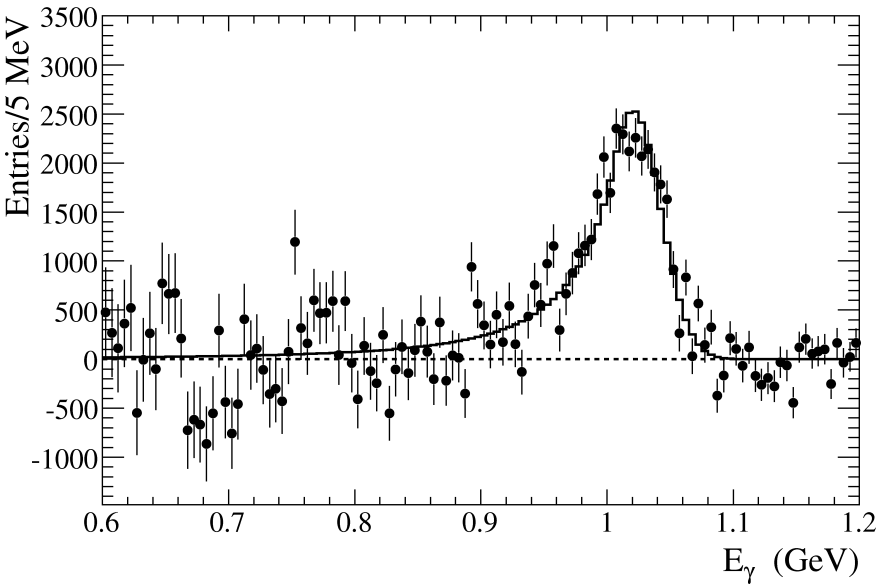
Peaking background from initial state radiation

Radiative return to $\Upsilon(1S)$:
$\Upsilon(3S) \rightarrow \gamma_{ISR}\, \Upsilon(1S)$

Yield estimated from high statistics off-resonance data (Run 1-6), taken 40 MeV below $\Upsilon(4S)$ peak

Extrapolated to $\Upsilon(3S)$; cross-check with $\Upsilon(3S)$ off-resonance: shows good agreement

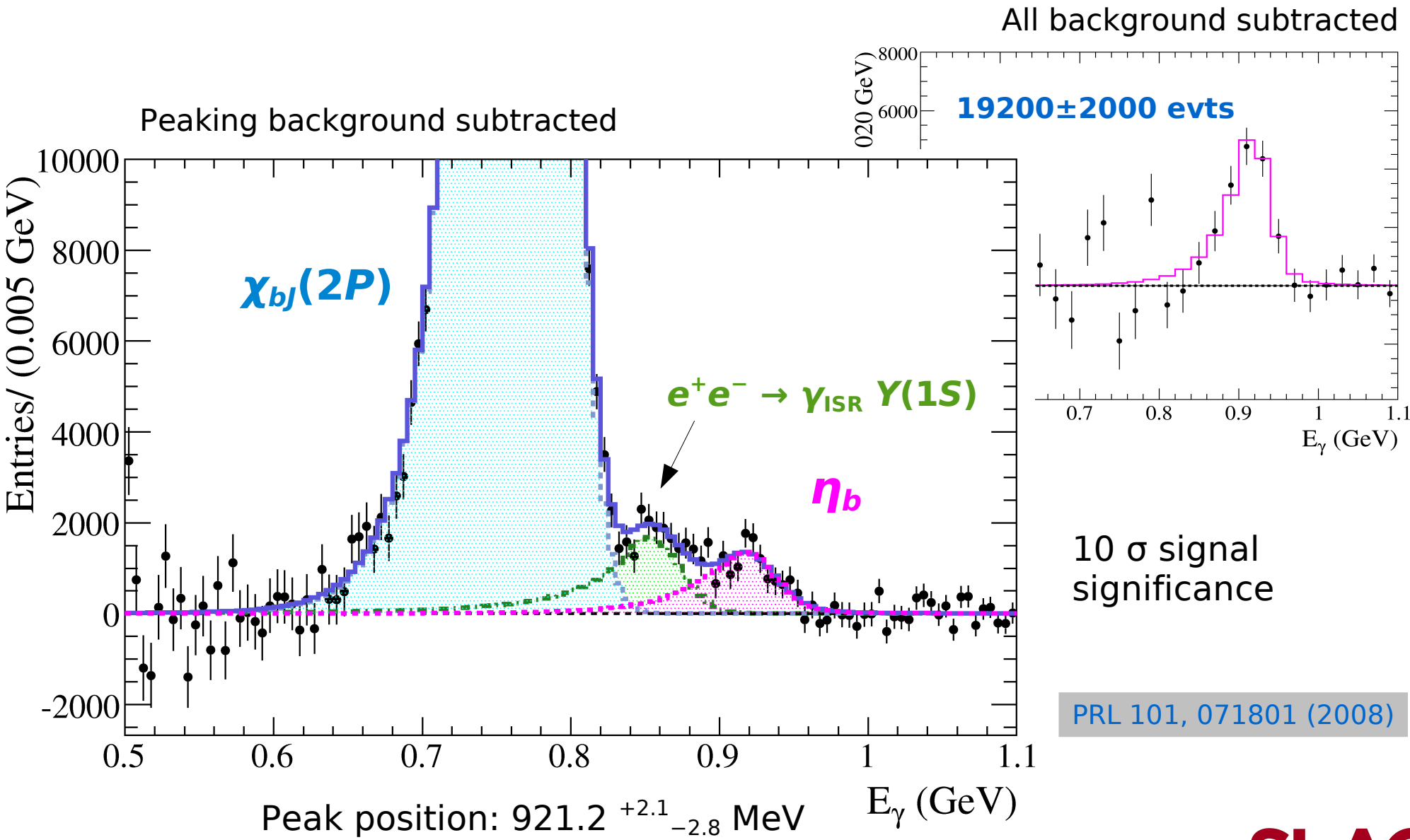
E_{CM} = 10.54 GeV (off resonance) data



Peaking background from $\chi_{bJ}(2P)$ [J=0,1,2] states

Modeling each with a Gaussian convolved with a power-law tail on both sides (Crystal Ball function)

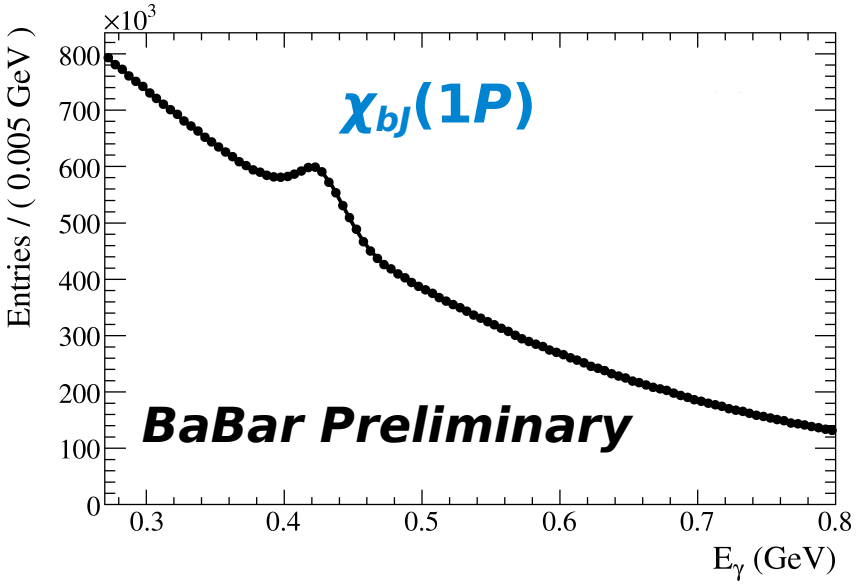
Observation of the η_b



10 σ signal significance

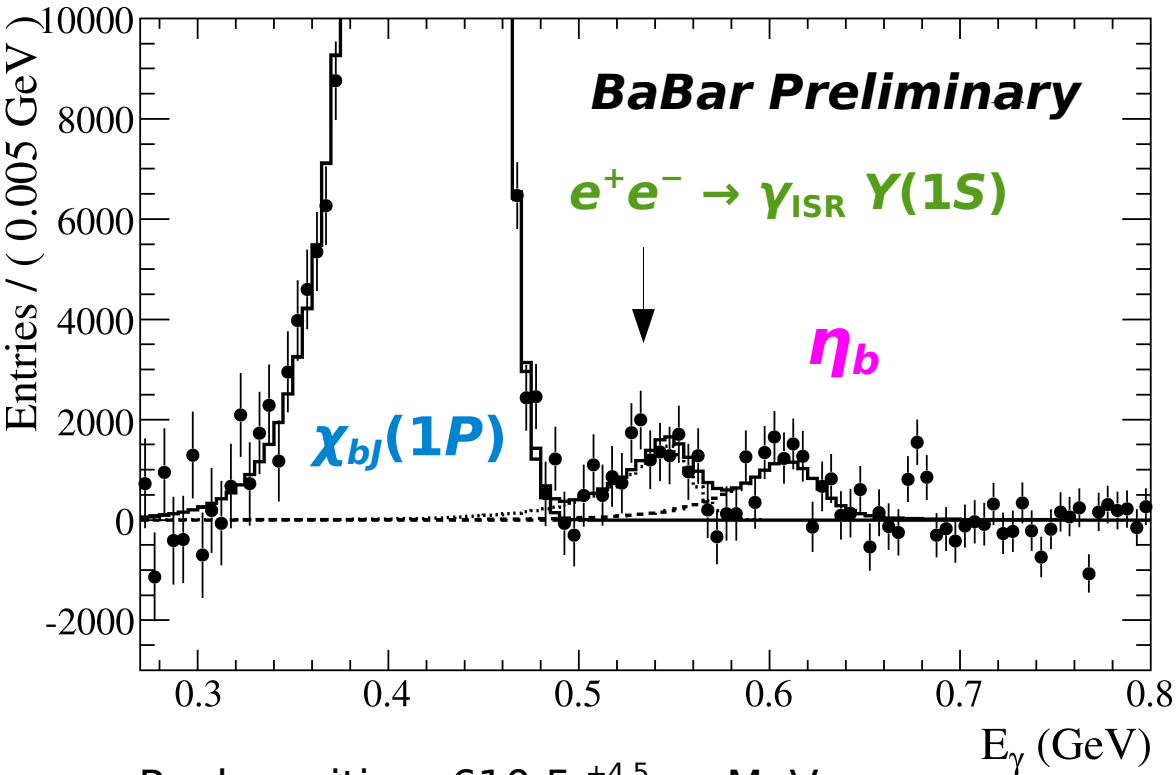
PRL 101, 071801 (2008)

Look for η_b in $Y(2S)$



Essentially the same analysis

92M $Y(2S)$ decays collected in 14 fb^{-1}



χ_b(1P) peaks again merged due to energy resolution and "Doppler broadening" (*i.e.* motion of the χ_b in the CMS)

Better separation of peaks, mainly due to better calorimeter energy resolution at lower energy

signal significance is 4 σ

Peak position: $610.5\ ^{+4.5}_{-4.3}$ MeV

η_b Results

Better statistics in $Y(3S)$ due to lower background

Better systematics in $Y(2S)$ due to better separation

η_b mass

$Y(3S) \to \gamma\, \eta_b$ $\quad 9388.9\ ^{+3.1}_{-2.3}$ (stat) ± 2.7 (syst) MeV/c^2

$Y(2S) \to \gamma\, \eta_b$ $\quad 9392.9\ ^{+4.6}_{-4.8}$ (stat) ± 1.8 (syst) MeV/c^2 (*)

$Y(1S)$-η_b hyperfine splitting

$Y(3S) \to \gamma\, \eta_b$ $\quad 71.4\ ^{+2.3}_{-3.1}$ (stat) ± 2.7 (syst) MeV/c^2

$Y(2S) \to \gamma\, \eta_b$ $\quad 67.4\ ^{+4.8}_{-4.5}$ (stat) ± 1.9 (syst) MeV/c^2 (*)

$\gamma\, \eta_b$ branching fraction

$Y(3S) \to \gamma\, \eta_b$ $\quad [\ 4.8 \pm 0.5$ (stat) ± 1.2 (syst) $] \times 10^{-4}$

$Y(2S) \to \gamma\, \eta_b$ $\quad [\ 4.2 \pm\ ^{+1.1}_{-1.0}$ (stat) ± 0.9 (syst) $] \times 10^{-4}$ (*)

BF ratio $Y(2S)/Y(3S)$ appears to be consistent with expectation for magnetic dipole transition (0.3 - 0.7)

PRL 101, 071801 (2008)

(*) ***BaBar Preliminary***

Lepton Flavor Violation

Search for LFV in bottomonium decays

Extremely suppressed in the SM by $(\Delta(m_\nu^2)/m_W^2)^2 < 10^{-48}$

Any evidence of LVF in the Y system would be a tell-tale sign of New Physics

If LFV mechanism is in the Higgs sector, it should preferentially couple to bottomonium

BFs in $Y(4S)$ are too small: even $Y(4S) \to \tau^+\tau^-$ not observed yet; but dramatically enhanced in the narrow resonances:

$$\Gamma(Y(4S)) / \Gamma(Y(3S)) \sim 10^3$$

BaBar Analysis

Search for decays $Y(3S) \to e^\pm\tau^\mp$, $Y(3S) \to \mu^\pm\tau^\mp$

Require one $e^\pm$ or $\mu^\pm$ with CM momentum close to the beam energy, plus a second charged lepton or $\pi^\pm$ from τ decay

Separate four signal channels:

leptonic $e^\pm\tau^\mp$, $\tau \to \mu\, \upsilon_\mu\, \upsilon_\tau$

hadronic $e^\pm\tau^\mp$, $\tau \to \pi\, \pi^0\, \upsilon_\tau$ / $\pi\, \pi^0\, \pi^0\, \upsilon_\tau$

leptonic $\mu^\pm\tau^\mp$, $\tau \to e\, \upsilon_\mu\, \upsilon_\tau$

hadronic $\mu^\pm\tau^\mp$, $\tau \to \pi\, \pi^0\, \upsilon_\tau$ / $\pi\, \pi^0\, \pi^0\, \upsilon_\tau$

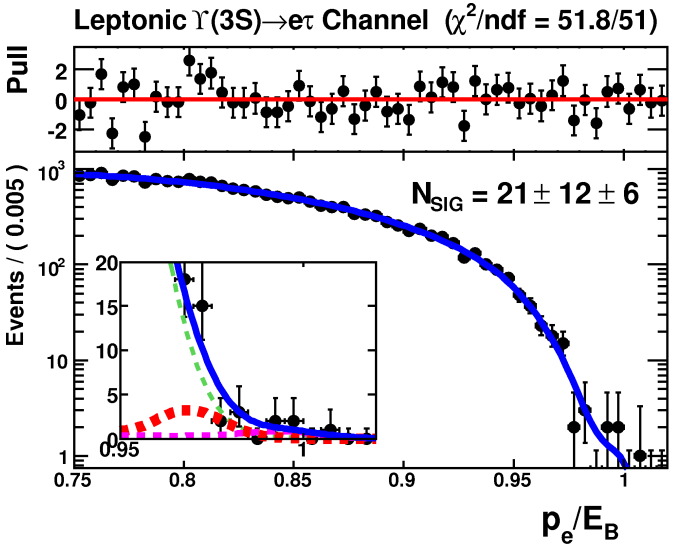
Dominant background from $\tau^+\tau^-$ production; mis-id Bhabha or μ-pair; require addtl. π^0 to suppress $\pi^\pm$ mis-id in hadronic modes

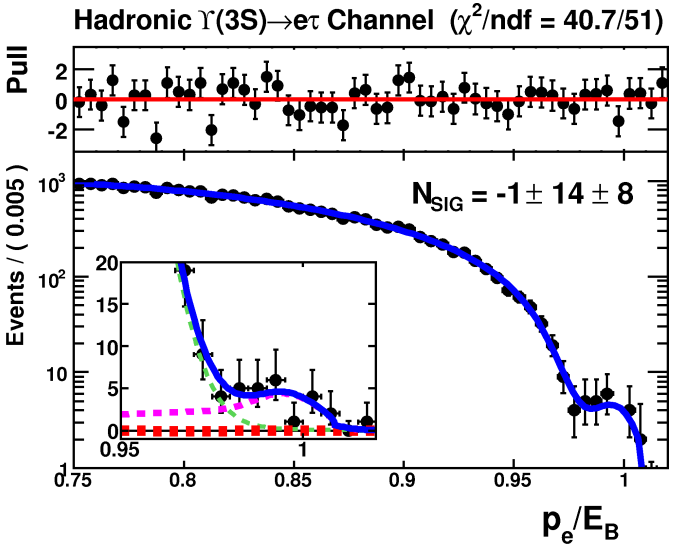
LFV in $Y(3S) \to e^{\pm}\tau^{\mp}, \mu^{\pm}\tau^{\mp}$

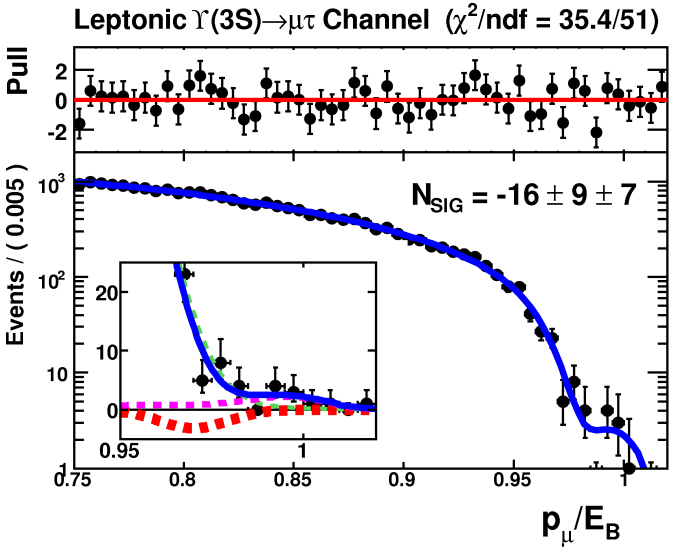
Maximum likelihood fit of signal and background

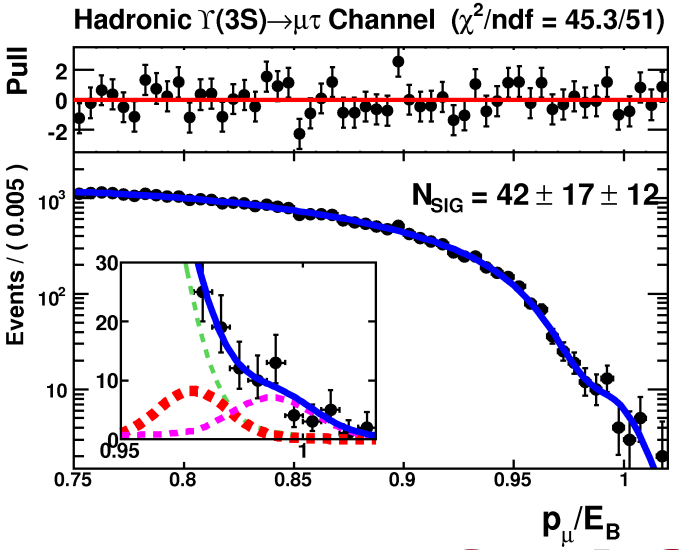
Backgrounds

green: tail from τ pair
magenta: Bhabha and di-muons, peak at 1
red: signal, peaks at ~0.97









LFV Results

All signal yiels consistent with 0 within ±2.1 σ

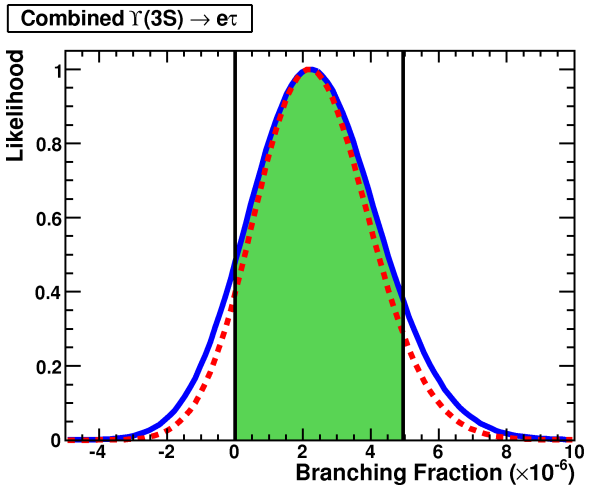
Extract limits at 90% C.L. from integrating likelihood
(equiv. Bayesian limit with flat prior)

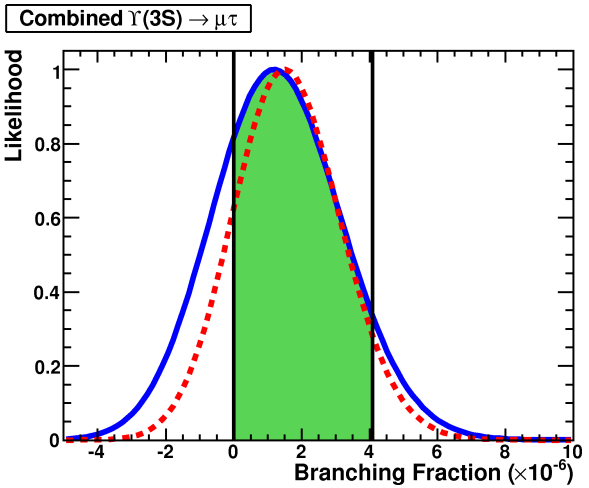
First measurement

$$BF(\,\Upsilon(3S) \to e^{\pm}\tau^{\mp}\,) < 5.0\times10^{-6}$$

$$BF(\,\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}\,) < 4.1\times10^{-6}$$

Improves previous best limit (CLEO) by factor ~4





Light Higgs in the NMSSM

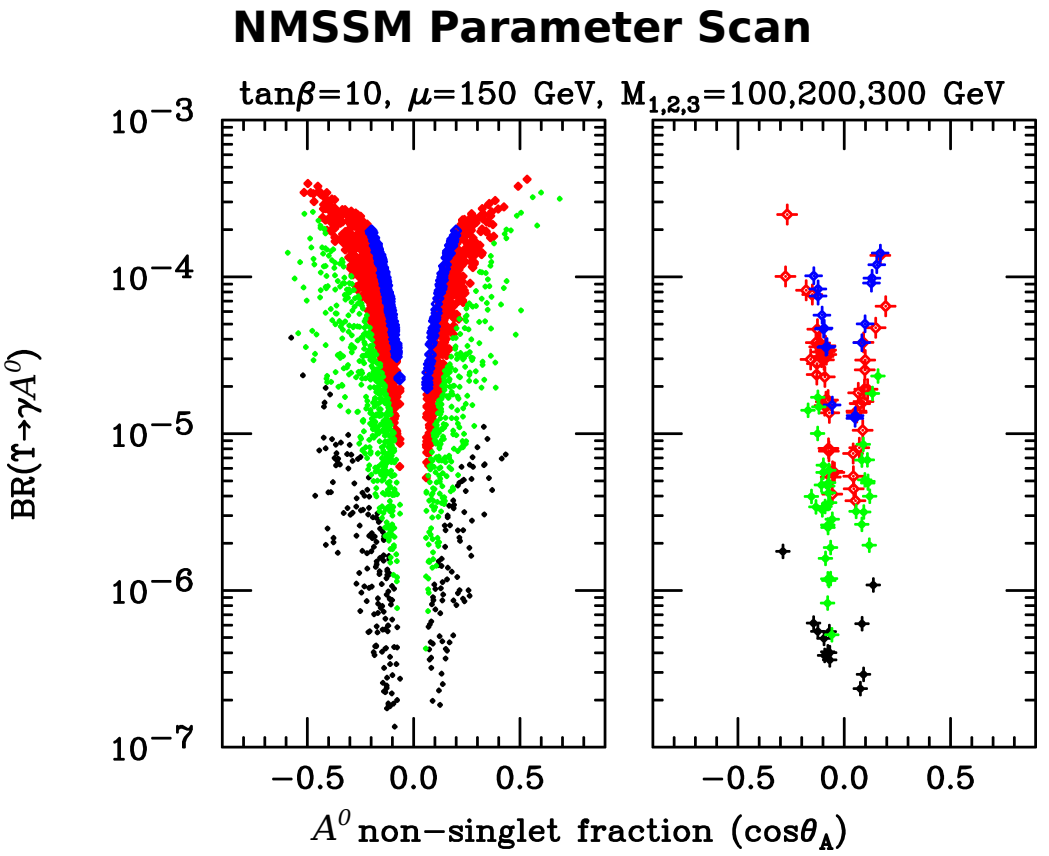
Next to minimal SUSY model (NMSSM) adds a Higgs singlet

Linear combination of this and the EW doublet produces a CP-odd Higgs boson A^0

The A^0 can be light, usually constrained to be less than $2m_b$

This makes it accessible from bottomonium decays

Dominant decay mode could be invisible, to a pair of LSPs



blue points: $m_A < 2m_\tau$

red points: $2m_\tau < m_A < 7.5$ GeV

green points: 7.5 GeV $< m_A <$ 8.8 GeV

black points: 8.8 GeV $< m_A <$ 9.2 GeV

Dermíšek, Gunion, McElrath, PRD 76, 051105 (2007)

Search for $Y(3S) \to \gamma A^0$

Analysis strategy: Search for an invisibly decaying particle recoiling against a single photon; required substantial change in the trigger to be able to record these

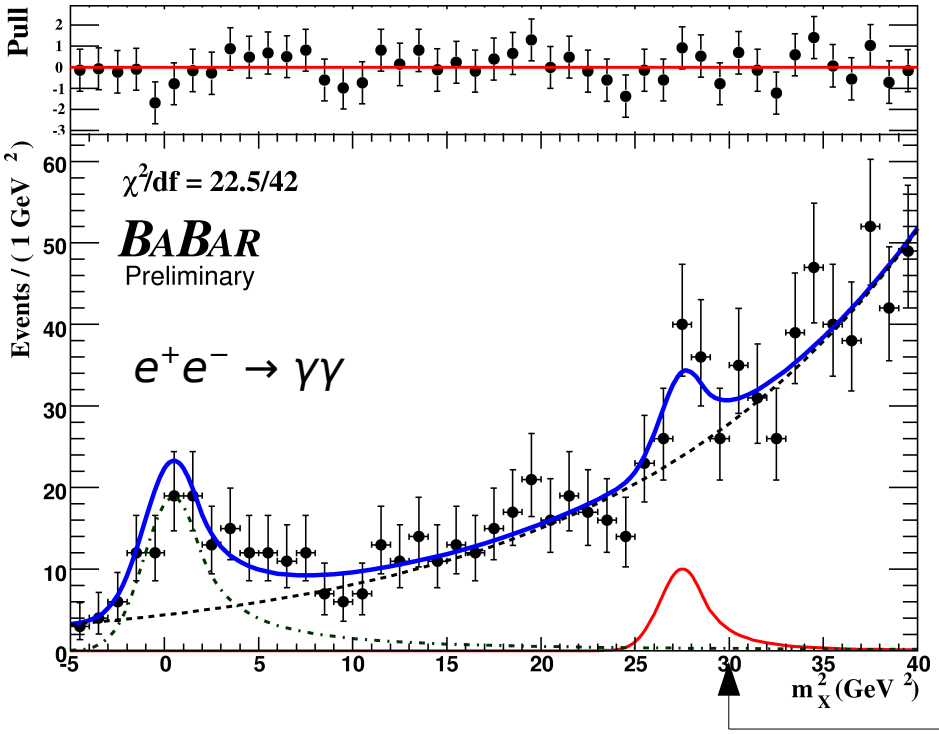
Perform an unbinned ML fit to the missing mass-squared

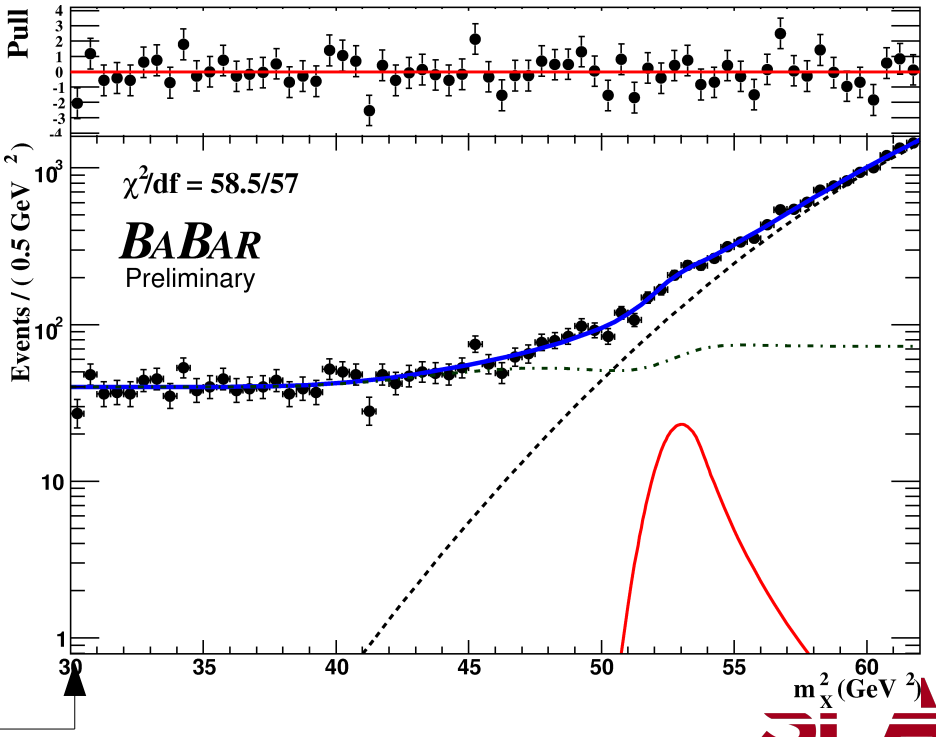
Low mass region

Background dominated by $e^+e^- \to \gamma\gamma$

High mass region

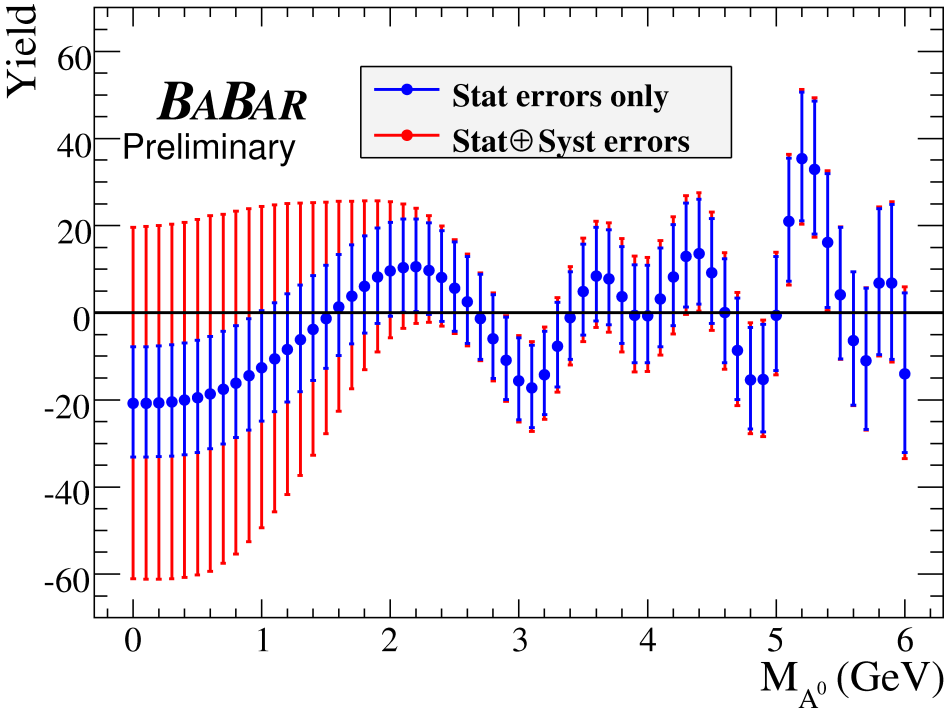
Background low-angle radiative Bhabha and tail of $e^+e^- \to \gamma\gamma$



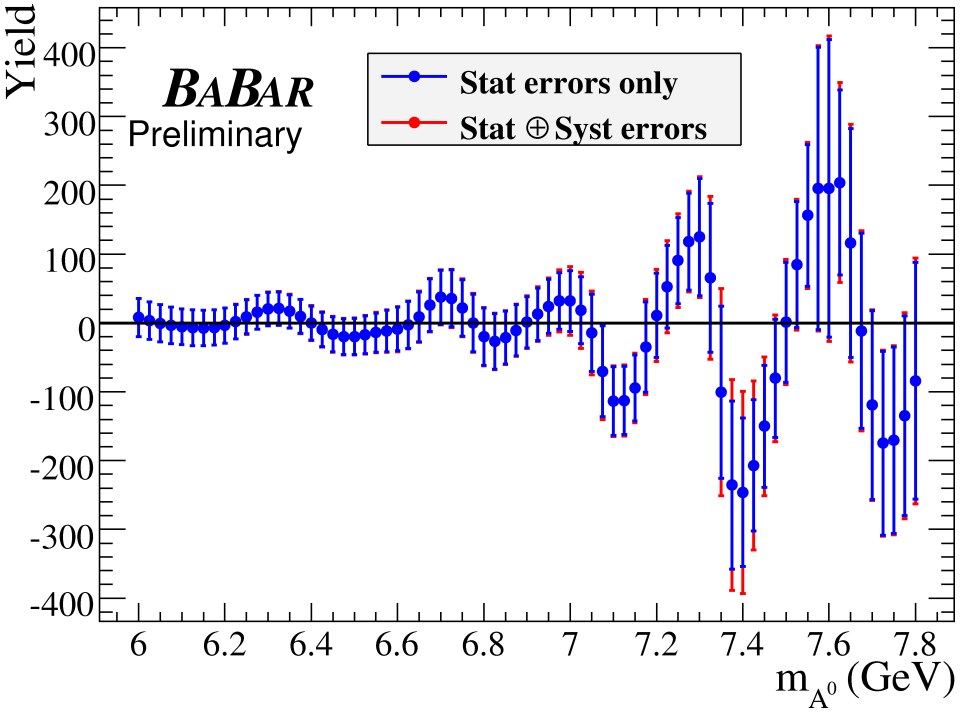


Scan of Yield versus $m(A^0)$

Low mass region



High mass region



Individual steps much finer than missing-mass resolution, *i.e.* neighboring points highly correlated

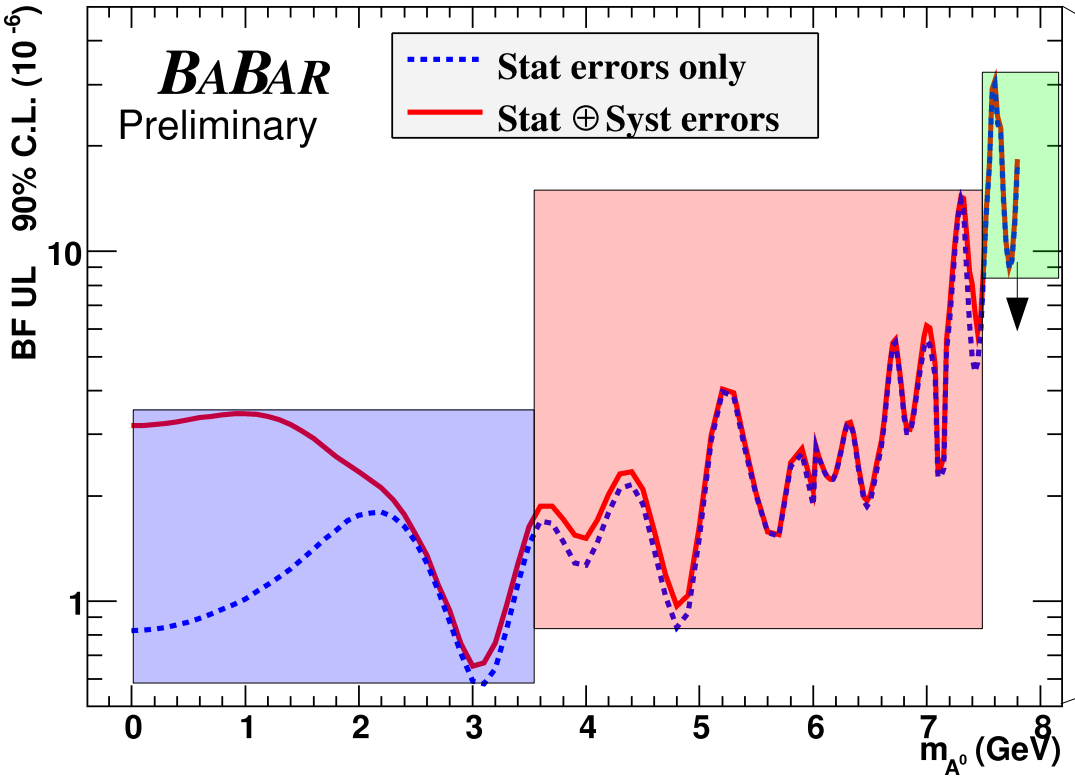
No significant excess found; largest significance 2.6 σ at 5.2 GeV

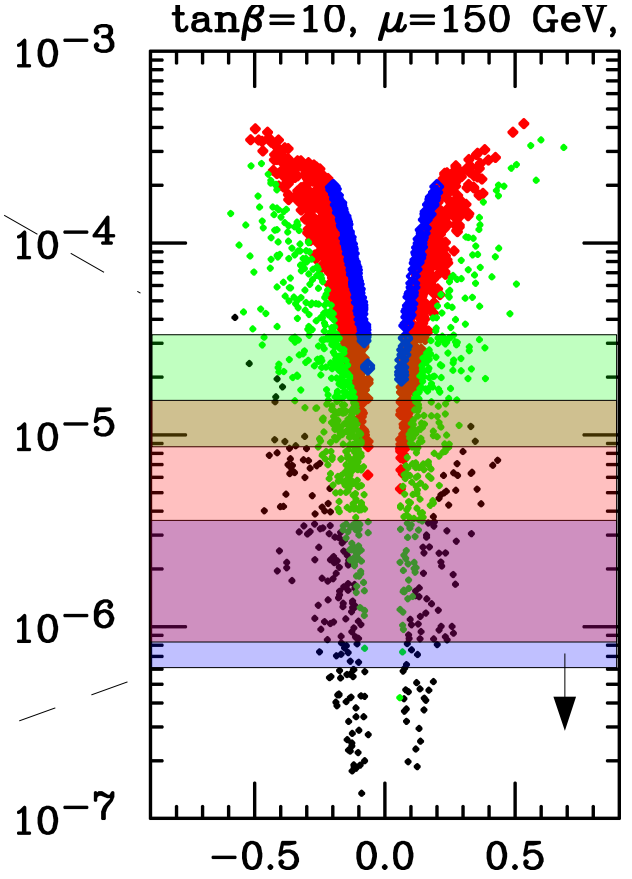
Combine to extract upper limits on BF as a function of A^0 mass

Upper Limit on $\Upsilon(3S) \to \gamma A^0$

($A^0 \to$ *invisible*)

As an illustration pick three mass ranges:





Improves previous limits by an order of magnitude

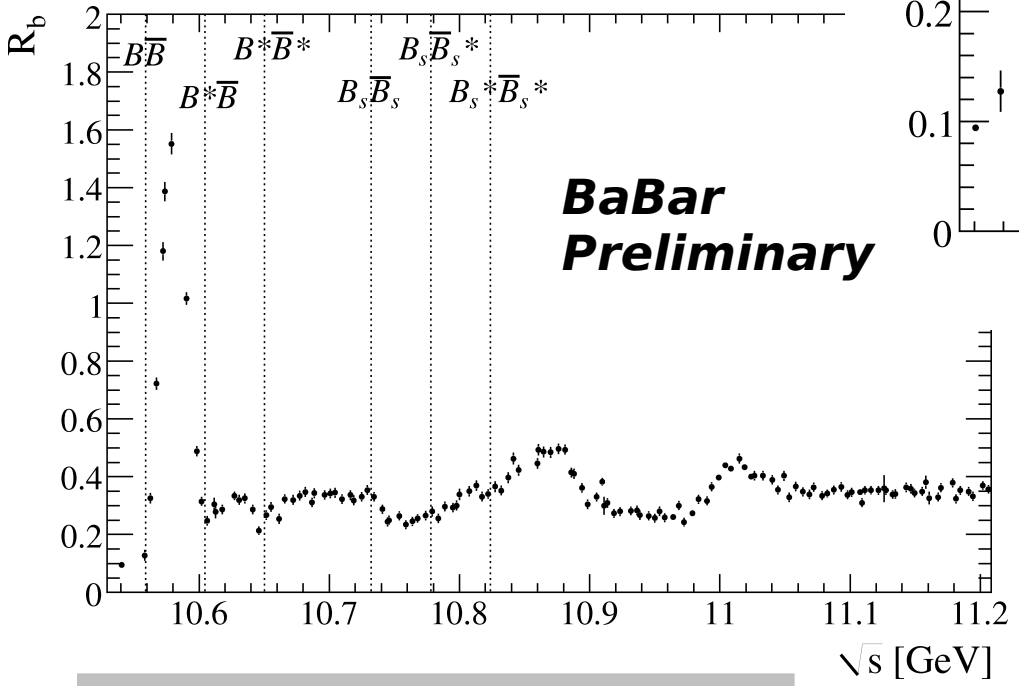
hep-ex/0808.0017

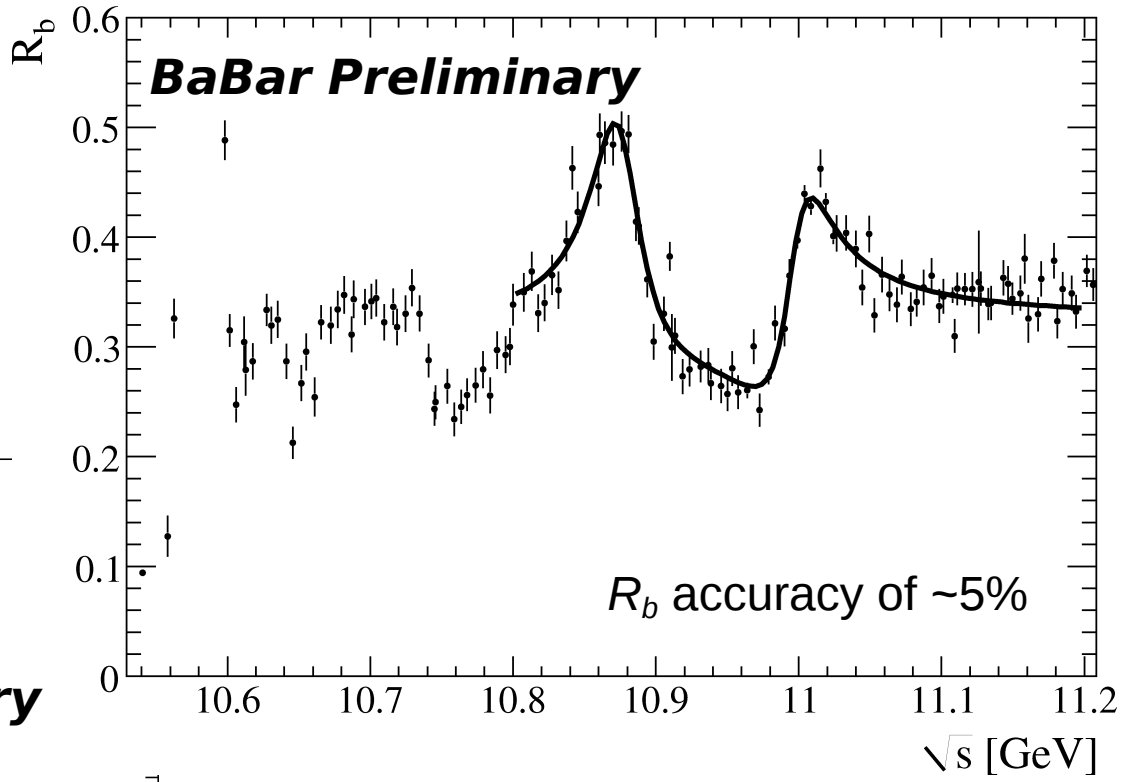
$e^+e^- \to b\bar{b}$ Cross Section Scan

Final program of PEPII+BaBar!

Took data at more than 300 center-of-mass energies, separated by about 5 MeV

Clear structures corresponding to the $B^{(*)}\bar{B}^{(*)}$ opening thresholds



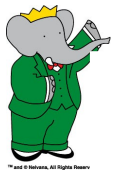


Simple model fit with flat component plus two intefering relativistic BW

May indicate much narrower width than PDG values for Y(10860), Y(11020)

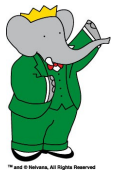
More proper fit might change this; very complex

hep-ex/0809.4120, *accepted by* PRL

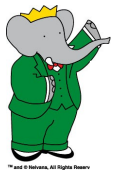


Summary

- BaBar made the first observation of the bottomonium ground state η_b at 10 σ in radiative $Y(3S)$ decays; 3.5 σ evidence now also in $Y(2S)$ transitions; measured mass, hyperfine splitting with $Y(1S)$ and branching fraction
- Search for LFV decays of $Y(3S)$ to $e\tau$ (and $\mu\tau$) set new (improved) limits on the BF of 5.0×10^{-6} and 4.1×10^{-6}
- We looked for an invisibly decaying light Higgs in $Y(3S)$ data and put limits on the product BF between 0.7×10^{-6} and 31×10^{-6} for m_{A^0} from 3 to 7.6 GeV
- A fine-grained scan of the $b\bar{b}$ cross section up to 11.2 GeV yields a ~5% measurement of R_b, revealing a rich structure that promises information on bottomonium spectroscopy and possible exotic extensions



Backup Slides



World Data Samples

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
CLEO	22M	9M	6M
Belle			11M
BaBar		90M	120M