Recent Bottomonium Results from BaBar

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SLAC National Accelerator Laboratory

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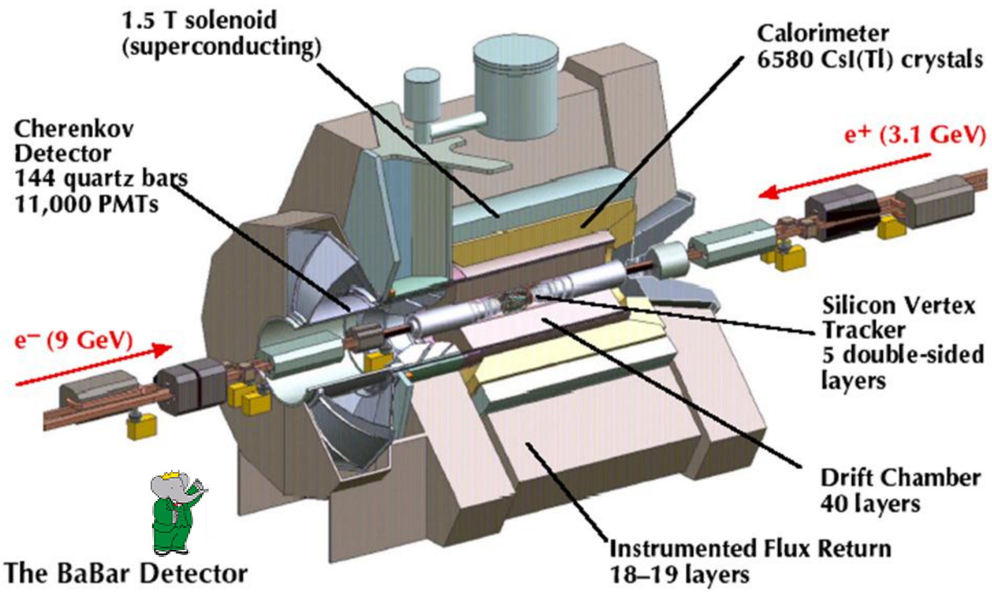
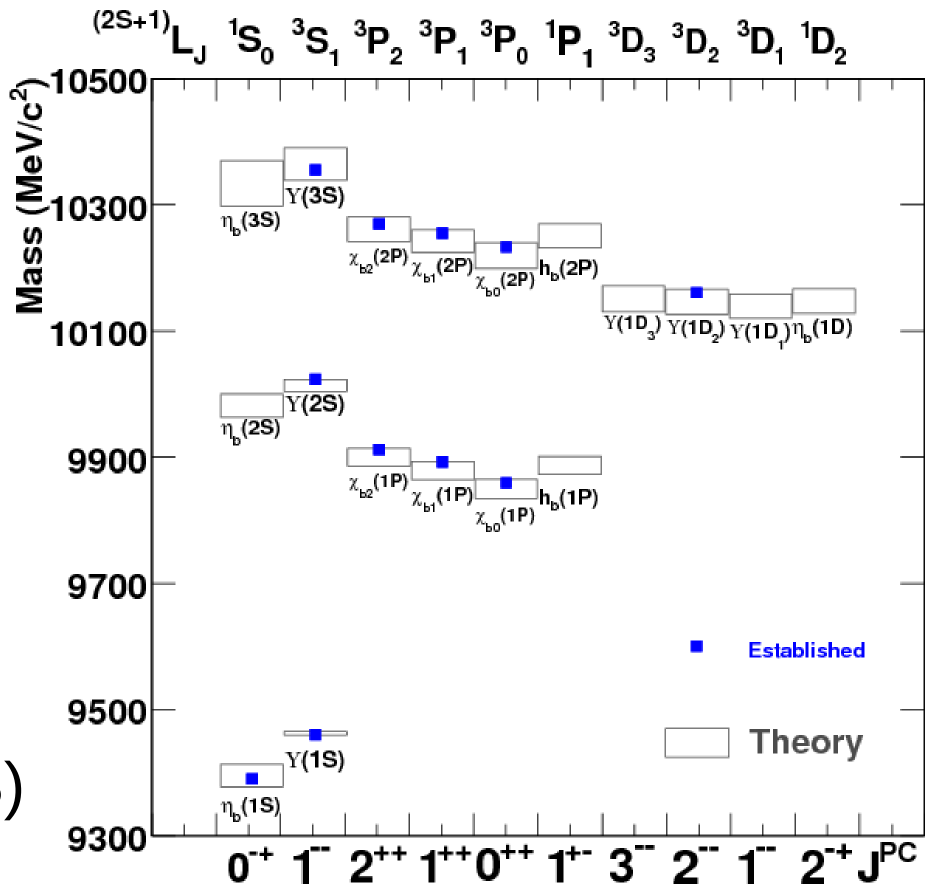
Overview



- BaBar: 1999-2008
- 122M $\Upsilon(3S)$ / 100M $\Upsilon(2S)$



- This talk:
  - $\Upsilon(1D_J) \rightarrow \pi^+ \pi^- \Upsilon(1S)$
  - $\Upsilon(nS) \rightarrow \gamma_{(e^+e^-)}\, \eta_b(1S)$
  - $\Upsilon(3S) \rightarrow \pi^+ \pi^- h_b(1P)$
  - $\Upsilon(3S) \rightarrow \pi^o h_b(1P) \rightarrow \gamma\, \eta_b(1S)$

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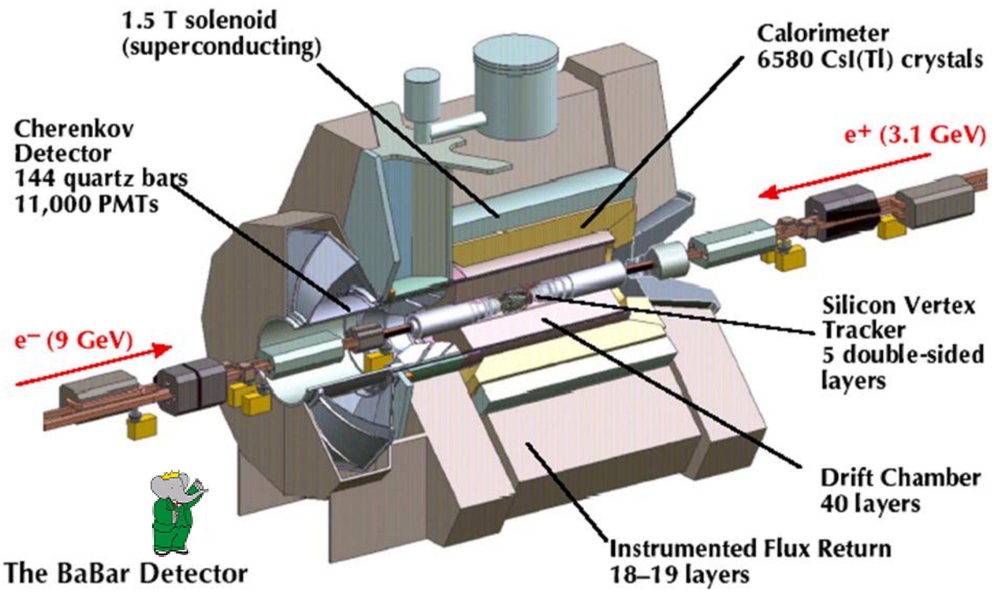

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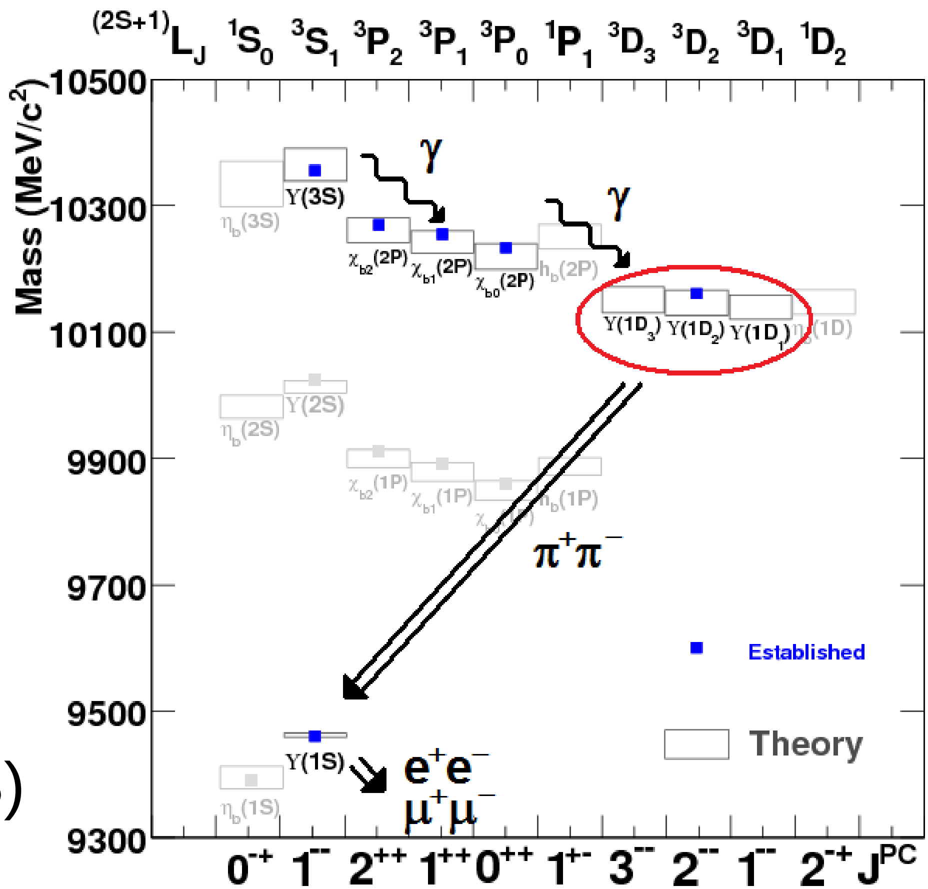

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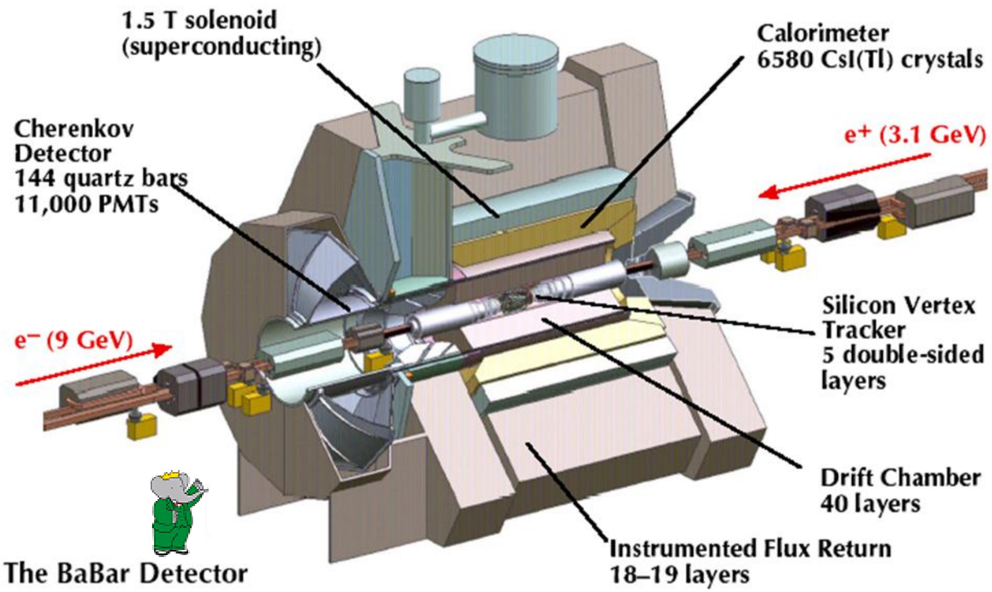

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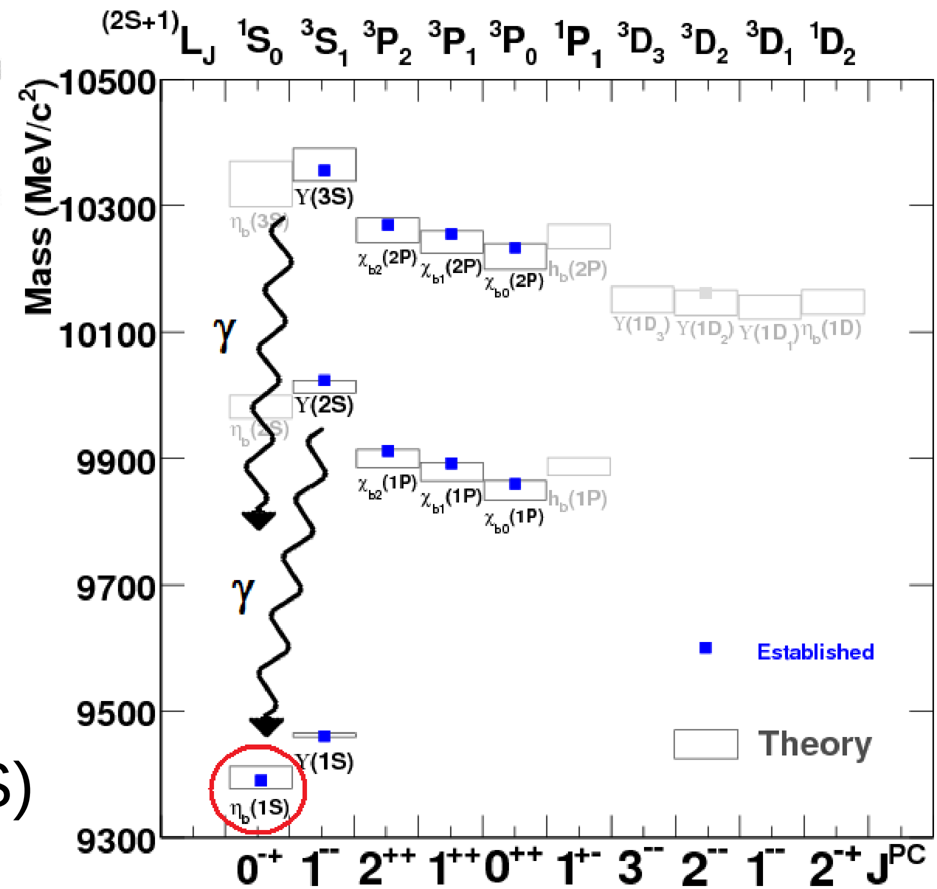

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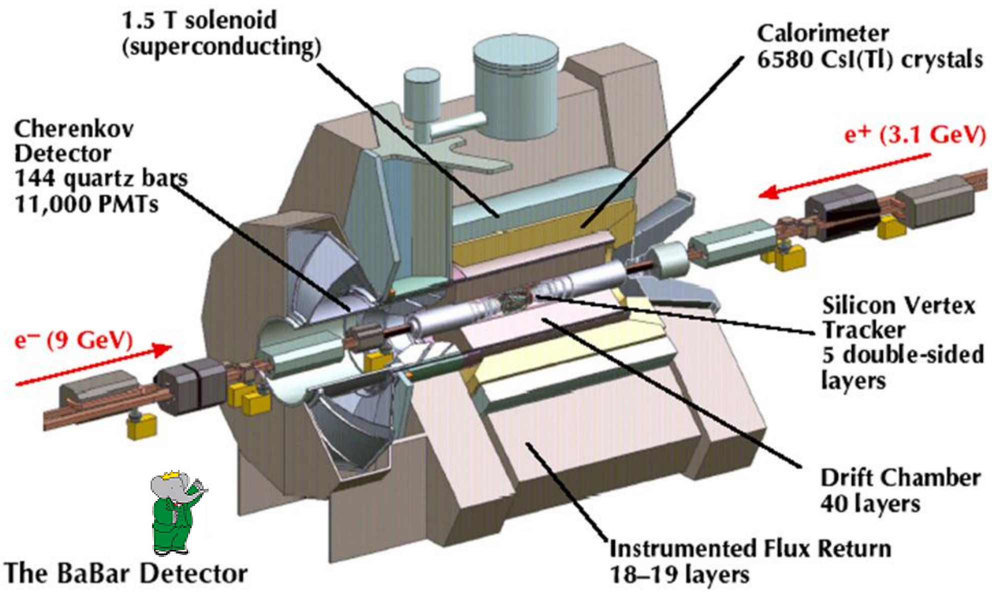

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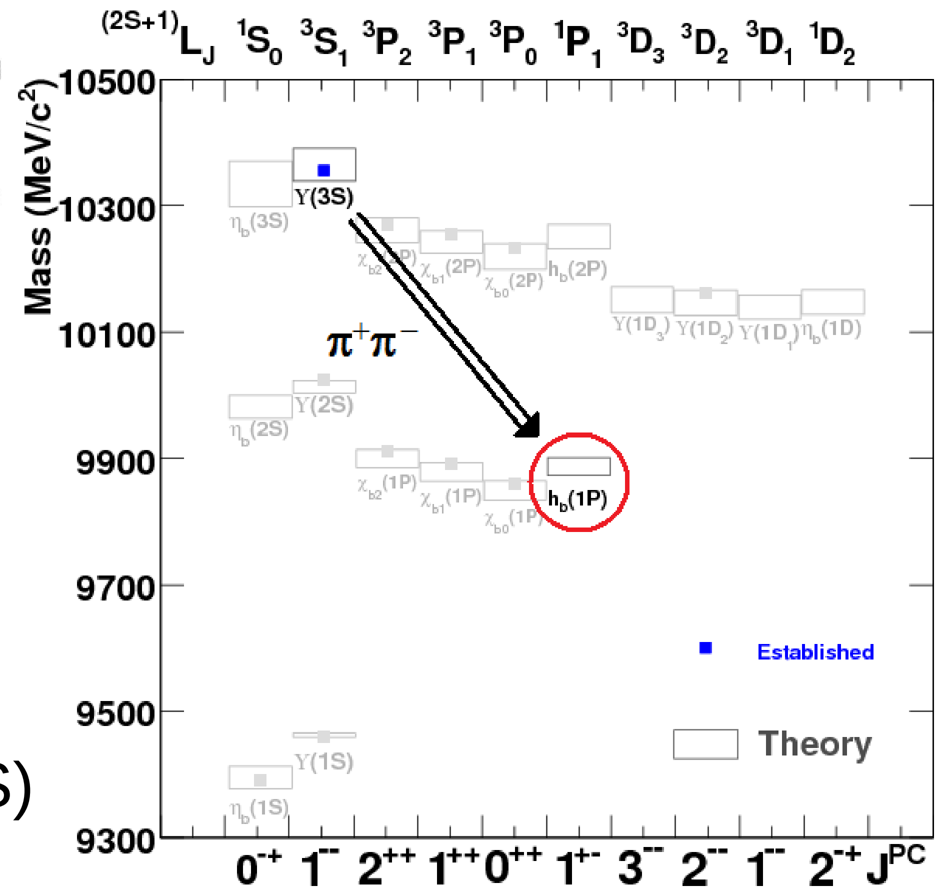

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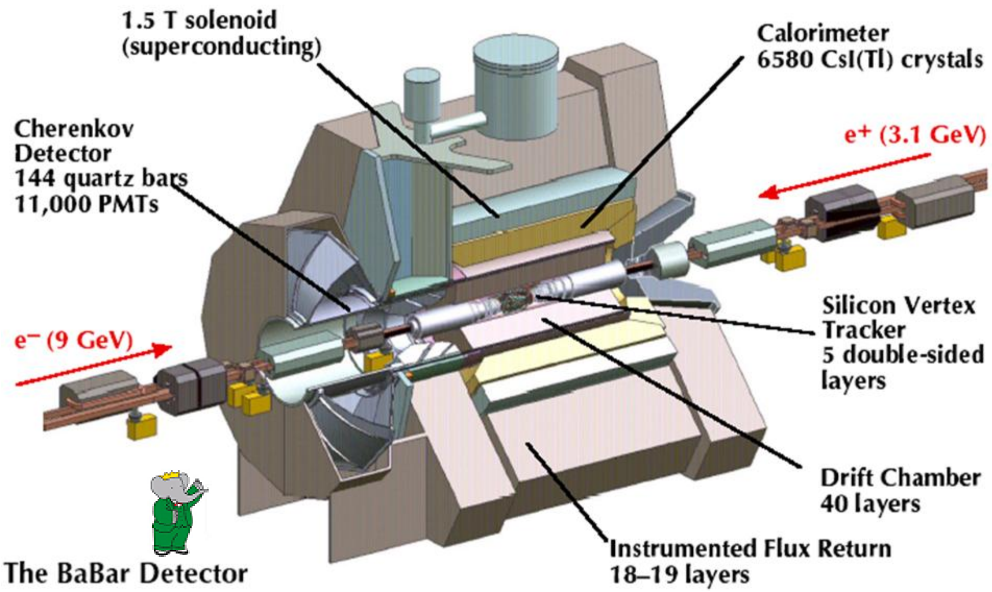

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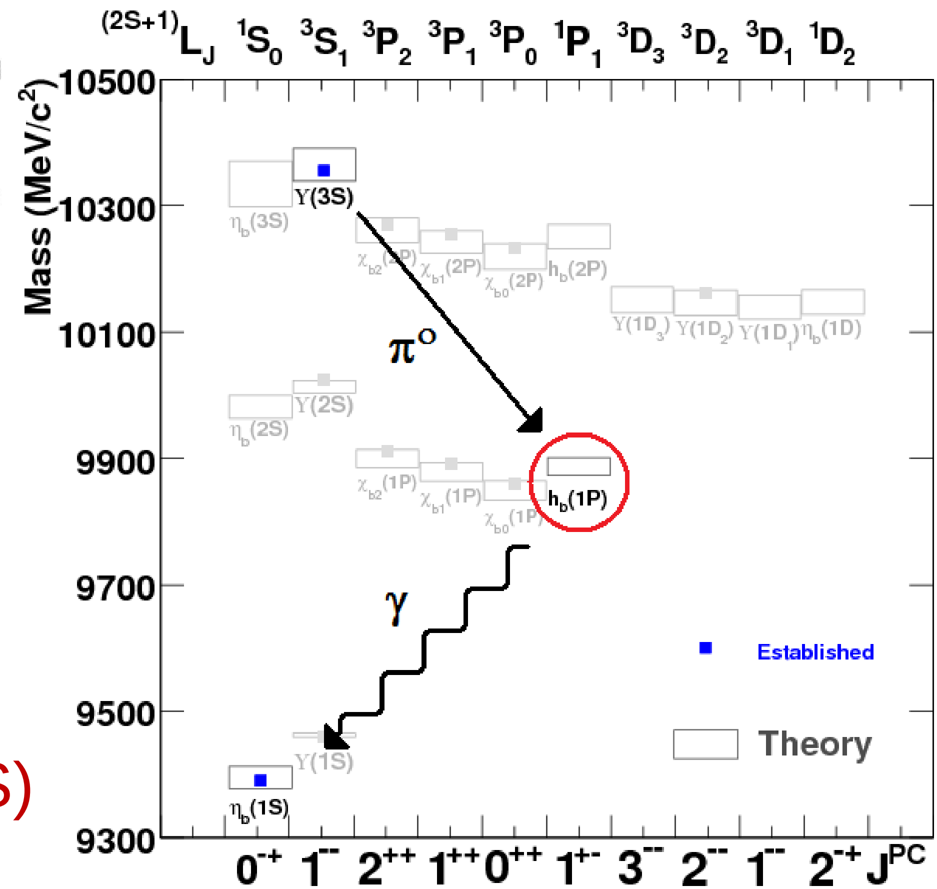

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$\Upsilon(1D_J)$

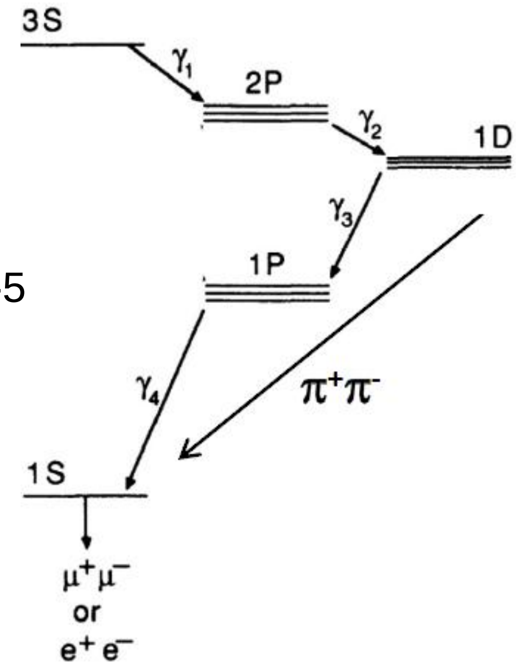
$\Upsilon(1D_J)$: General Information

- Expected $\Upsilon(1D_{J=1,2,3})$ properties
  - $m_{\Upsilon(1D_J)}$ ~10160 MeV/c^2, $m_{\Upsilon(1D_{\Delta J})}$ ~5-12 MeV/c^2, $\Gamma_{\Upsilon(1D_J)}$ ~30 keV

Godfrey & Rosner, PRD 64 097501 (2001)

- Experimental observation
  - $\Upsilon(3S) \to \gamma\gamma\Upsilon(1D_{2?}) \to \gamma\gamma\gamma\gamma\Upsilon(1S) \to \gamma\gamma\gamma\gamma\ell^+\ell^-$
  - $\mathcal{B}(\Upsilon(3S) \to \gamma\gamma\gamma\gamma\ell^+\ell^-) = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$
  - $m_{\Upsilon(1D_{2?})} = 10161.1 \pm 0.6 \pm 1.6$ MeV/c^2

CLEO, PRD 70 032001 (2004)

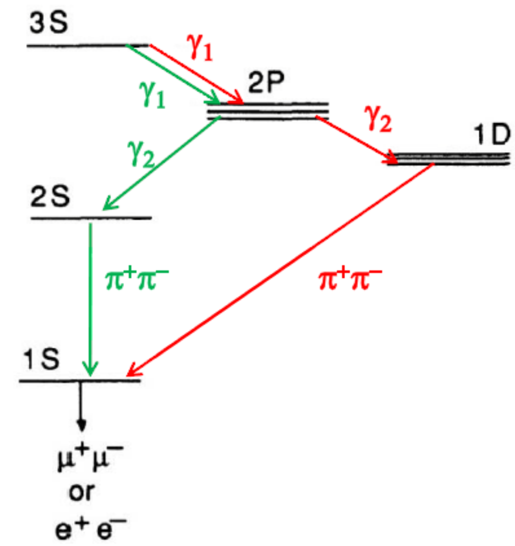


- No evidence for $\Upsilon(1D_J) \to \pi^+\pi^-\Upsilon(1S)$
  - Limit: $\mathcal{B}(\Upsilon(1D_J) \to \pi^+\pi^-\Upsilon(1S)) < 4\%$ CLEO, PRD 70 032001 (2004)
  - Theory: Kuang & Yan ~40%, Ko ~2%, Moxhay ~0.25%

Kuang-Yan, PRD 24 2874 (1981) | Ko, PRD 47 208 (1993) | Moxhay, PRD 37 2557 (1988)

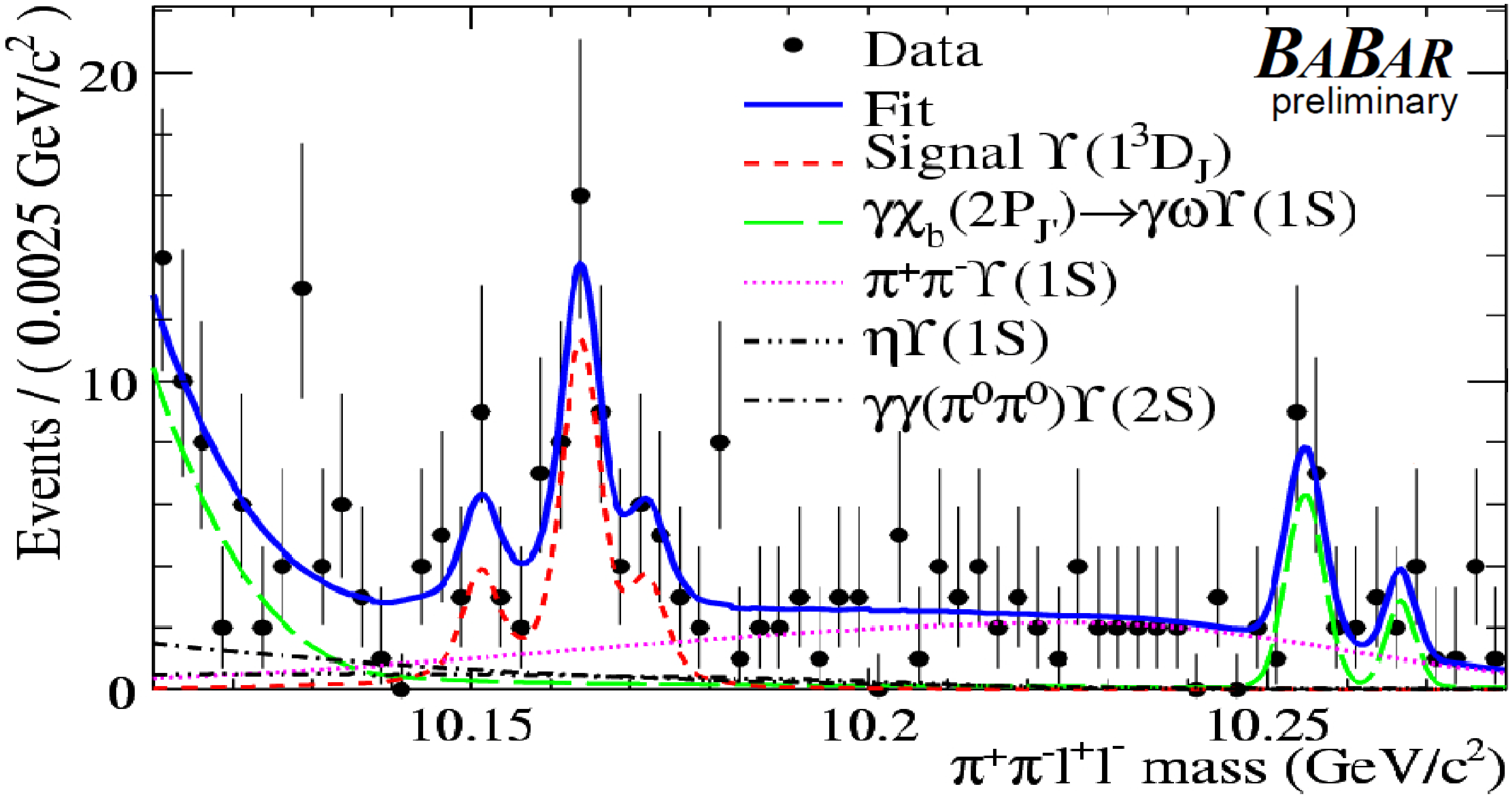
$\Upsilon(1D_J)$: BaBar Analysis

- Reconstruct $\Upsilon(3S) \rightarrow \gamma\gamma\Upsilon(1D_J) \rightarrow \gamma\gamma\pi^+\pi^-\Upsilon(1S) \rightarrow \gamma\gamma\pi^+\pi^-\ell^+\ell^-$
  - Require exactly 4 tracks
  - $m_{\ell^+\ell^-}$ consistent with / constrained to $m_{\Upsilon(1S)}$
  - Minimize E_γ χ^2 to select best candidate
  - $m_{\Upsilon(1D_J)}$ resolution ~ 3 MeV/c^2



- Maximum Likelihood fit to $m_{\pi^+\pi^-\ell^+\ell^-}$ spectrum
  - $\Upsilon(1D_J)$ signals: Double Gaussian + Crystal Ball
  - Monte Carlo (MC)-determined backgrounds:
    - $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P) \rightarrow \gamma\omega$ ($\pi^+\pi^-$ or $\pi^+\pi^-\pi^o$) $\Upsilon(1S)$
    - $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S) + \gamma_{FSR}$
    - $\Upsilon(3S) \rightarrow \eta$ ($\pi^+\pi^-\pi^o$) $\Upsilon(1S)$
    - $\Upsilon(3S) \rightarrow \gamma\gamma/\pi^o\pi^o$ $\Upsilon(2S)$ ($\pi^+\pi^-\Upsilon(1S)$)

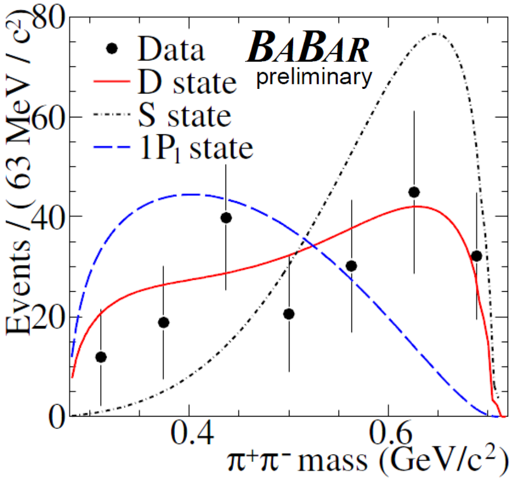
$\Upsilon(1D_J)$: Fit Results



J	Yield	σ (w. syst.)	$\mathcal{B}(\Upsilon(1D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$	90% CL Limit
1	$10.6^{+5.7}_{-4.9}$	2.0 (1.8)	$(0.42^{+0.27}_{-0.23} \pm 0.10)\%$	$(< 0.82\%)$
2	$33.9^{+8.2}_{-7.5}$	6.5 (5.8)	$(0.66^{+0.15}_{-0.14} \pm 0.06)\%$	-
3	$9.4^{+6.3}_{-5.2}$	1.7 (1.6)	$(0.29^{+0.22}_{-0.18} \pm 0.06)\%$	$(< 0.62\%)$

$$m_{\Upsilon(1D_2)} = 10164.5 \pm 0.8 \pm 0.6 \text{ MeV}/c^2$$

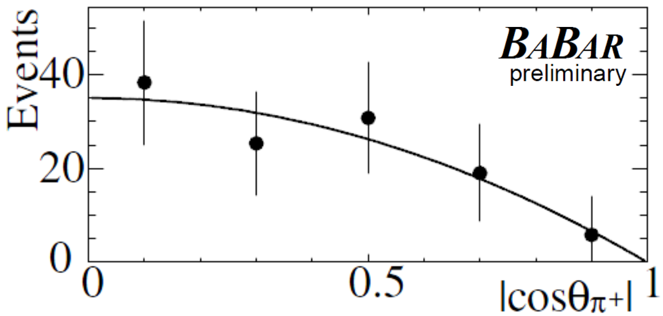
$\Upsilon(1D_J)$: Quantum Numbers



– L: $\pi^+\pi^-$ invariant mass

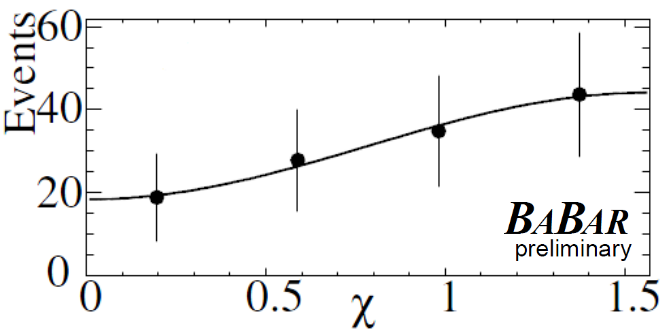
Yan, PRD 22 1652 (1980) Kuang et al. PRD 37 1210 (1988)

- $P(\chi^2)$ for $m_{\pi^+\pi^-}$ distribution
- D(84.6%), S(3.1%), P(0.3%)



– J: π Helicity Angle

- $dN/d(\cos\theta_\pi) \sim 1 + \xi(3\cos^2\theta_\pi-1)/2$
- $\xi = -1.0\pm0.4\pm0.1$ consistent w. J = 2



– J^P: Angle between $\pi^+\pi^-$ and $\ell^+\ell^-$ planes

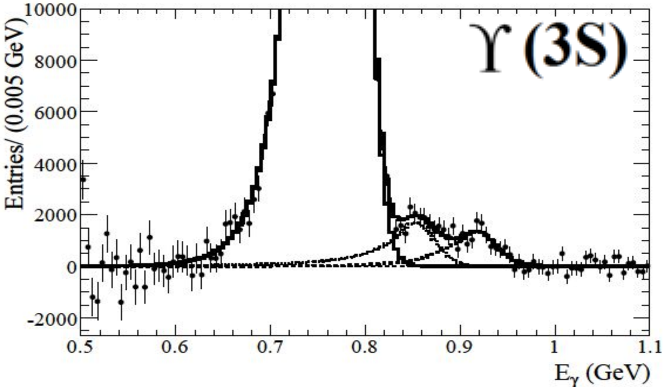
Dell'Aquila & Nelson, PRD 33 80 (1986)

- $dN/d\chi \sim 1 + \beta\cos(2\chi)$, $\text{sign}(\beta) = (-1)^J P$
- $\beta = -0.4\pm0.3\pm0.1$ consistent w. $J^P = 2^-$

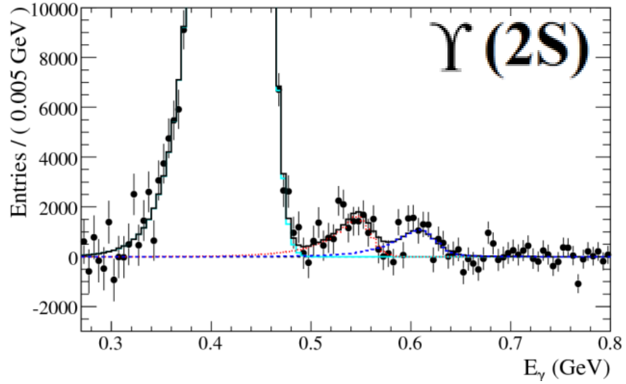
$\eta_b(1S)$

$\eta_b(1S)$: General Information

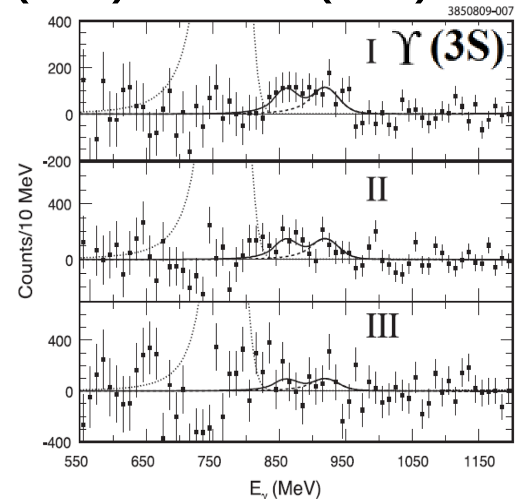
- $\eta_b(1S)$ observed in inclusive γ spectrum for $\Upsilon(3S)$ and $\Upsilon(2S)$



BaBar, PRL 101 071801 (2008)



BaBar, PRL 103 161801 (2009)



CLEO, PRD 81 031104(R) (2010)

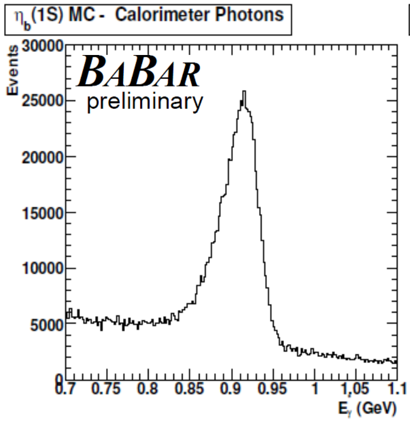
- Measured properties
  - $\mathcal{B}(\Upsilon(3,2S) \to \gamma\eta_b(1S)) = (5.1 \pm 0.7) \times 10^{-4} / (3.9 \pm 1.5) \times 10^{-4}$
  - $m_{\eta_b(1S)} = 9390.9 \pm 2.8$ MeV/c^2, $\Gamma_{\eta_b(1S)} \approx 10$ MeV
  - $(m_{\Upsilon(1S)} - m_{\eta_b(1S)}) = 69.3 \pm 2.8$ MeV/c^2
- Hyperfine splitting theoretical predictions
  - Lattice: ~50-60 MeV/c^2 NRQCD: ~40 MeV/c^2

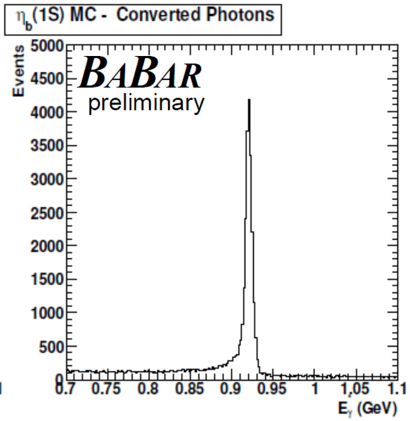
HPQCD, PRD 72 094507 (2005)
Fermilab & MILC, PRD 81 034508 (2010)

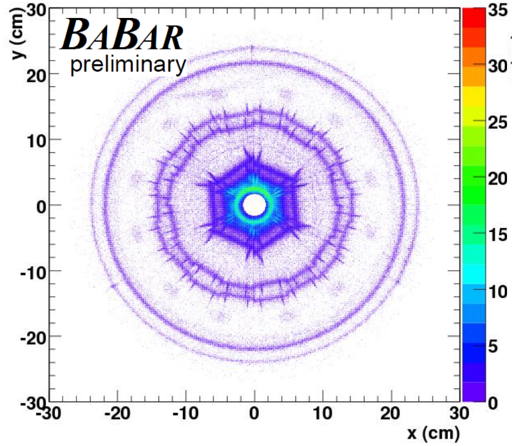
Kniehl et al., PRL 92 242001 (2004)

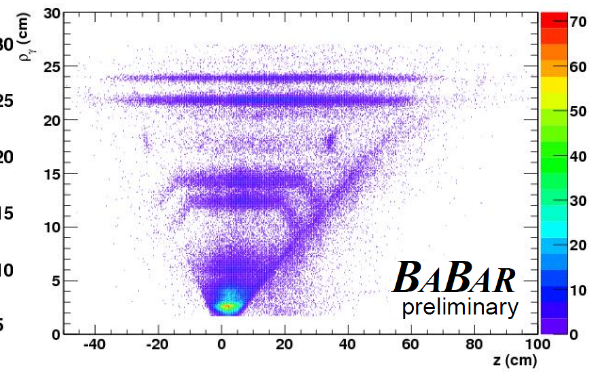
η_b(1S): Converted Photon Analysis

- Converted photons ($\gamma \to e^+e^-$) improve resolution (25 $\to$ 5 MeV)
  - Fit pair of tracks, selected with χ^2_{fitter}, m_γ, ρ_γ
  - Additional cuts: $|\cos\theta_{thrust}|$, N_{tracks}, π^o veto



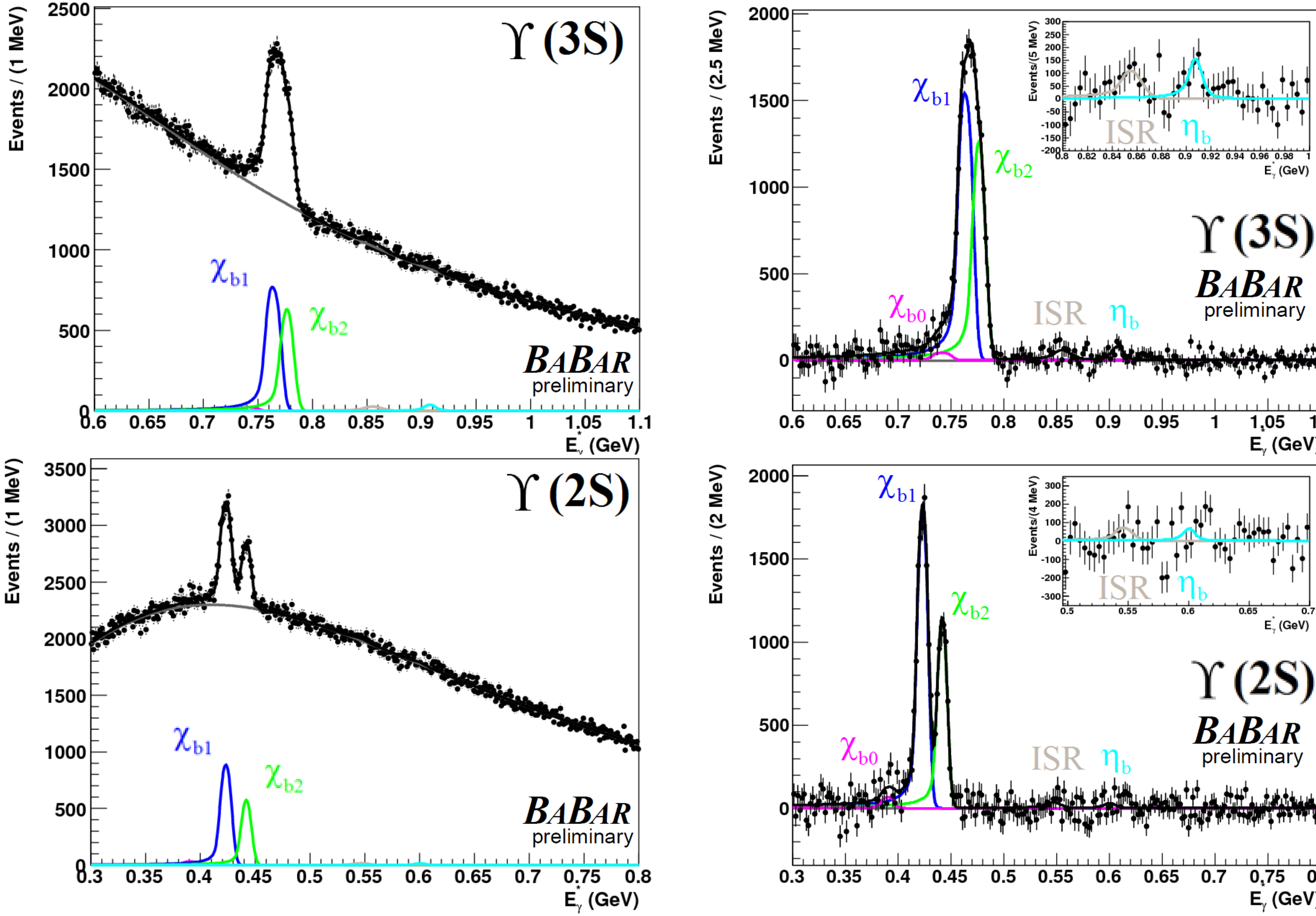






- Simultaneous fit to E_γ^* spectrum in Υ(3S) and Υ(2S) datasets
  - $\Upsilon(3,2S) \to \gamma\, \eta_b(1S)$: Breit-Wigner $*$ Crystal Ball
  - $e^+ e^-_{E=m_{\Upsilon(nS)}} \to \gamma_{ISR}\, \Upsilon(1S)$: Crystal Ball
  - $\chi_{bJ}(2,1P) \to \gamma\, \Upsilon(1S)$: Doppler broadening $*$ Crystal Ball
  - Background: 4^{th} order polynomial $\times$ exponential decay

$\eta_b(1S)$: Fit Results



$\gamma \to e^+e^-$: Results Summary

Mode	Measured	PDG Expected
$\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$		
$\chi_{b2}(2P) \to \gamma\Upsilon(1S)$	$(9.6 \pm 0.3 \pm 0.5) \times 10^{-3}$	$(9.3 \pm 1.7) \times 10^{-3}$
$\chi_{b1}(2P) \to \gamma\Upsilon(1S)$	$(13.0 \pm 0.3 \pm 0.7) \times 10^{-3}$	$(10.7 \pm 1.9) \times 10^{-3}$
$\chi_{b0}(2P) \to \gamma\Upsilon(1S)$	$(4.2 \pm 2.2^{+1.7}_{-1.8}) \times 10^{-4}$	$(5.3 \pm 3.6) \times 10^{-4}$
$\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$		
$\chi_{b2}(1P) \to \gamma\Upsilon(1S)$	$(14.4 \pm 0.5 \pm 0.8) \times 10^{-3}$	$(15.7 \pm 3.0) \times 10^{-3}$
$\chi_{b1}(1P) \to \gamma\Upsilon(1S)$	$(25.2 \pm 0.6 \pm 1.2) \times 10^{-3}$	$(24.2 \pm 5.7) \times 10^{-3}$
$\chi_{b0}(1P) \to \gamma\Upsilon(1S)$	$(1.1 \pm 0.6 \pm 1.0) \times 10^{-3}$	$< 2.3 \times 10^{-3}$
$m_{\eta_b(1S)}$ (MeV/c^2)	$9403.3 \pm 2.4^{+0.9}_{-1.5}$	9390.9 ± 2.8
$\Upsilon(3S) \to \gamma\eta_b(1S)$	$(5.1 \pm 1.5^{+1.6}_{-1.0}) \times 10^{-4}$	$(5.1 \pm 0.7) \times 10^{-4}$
$\Upsilon(2S) \to \gamma\eta_b(1S)$	$(3.1 \pm 3.0^{+3.6}_{-3.5}) \times 10^{-4}$	$(4.2 \pm 1.3) \times 10^{-4}$

- E_γ^* and branching fractions as expected

PDG, PLB 667 1 (2008)

- Mass-constrained fit:
  - No evidence for η_b (2.3σ stat.)
- Best fit result in $m_{\eta_b(1S)}$ region:
  - Differs by $+12.4^{+3.8}_{-4.0}$ MeV/c^2 (3.3σ stat., 2.6σ w. syst.)

$h_b(1P)$

h_b(1P): General Information

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

- Production mechanisms
  - $\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- h_b(1P)) \sim 10^{-3} - 10^{-2}$ Kuang et al., PRD 37 1210 (1988)
  - $\mathcal{B}(\Upsilon(3S) \to \pi^o h_b(1P)) \sim 10^{-3}$ Voloshin, Sov J Nucl Phys 43 1011 (1986)
  - $R(\pi^o h_b\,(1P) / \pi^+\pi^- h_b\,(1P)) = 0.05 - 20$

- Expected decays
  - $h_b(1P) \to ggg$ (57%), $\gamma\eta_b(1S)$ (41%), γgg (2%)

  Godfrey & Rosner, PRD 66 014012 (2002)

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

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

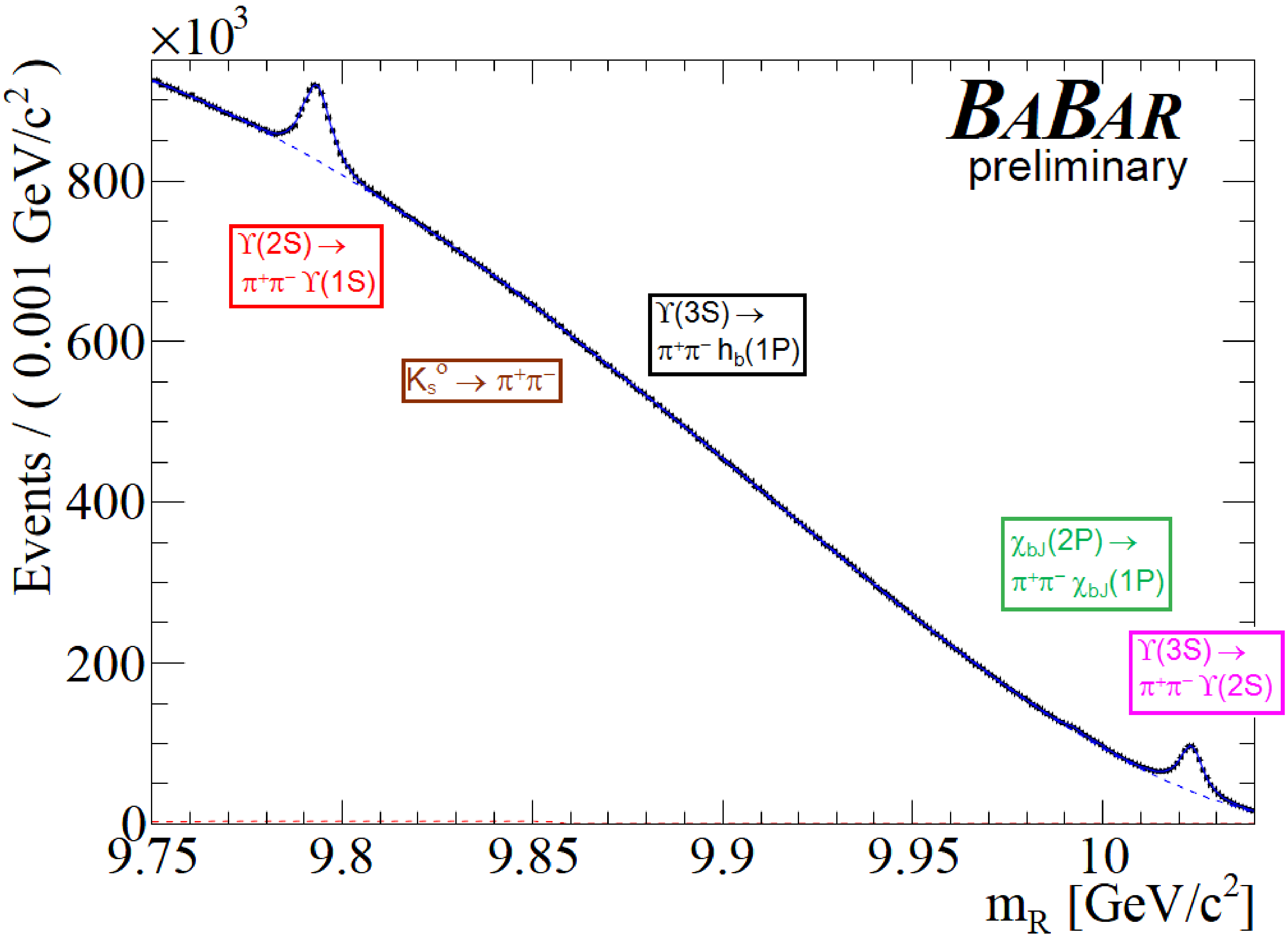
$\pi^+\pi^- h_b(1P)$: Analysis Strategy

- Reconstruct pair of oppositely charged tracks
  - Cuts on E_{total}, R_2, N_{tracks}, K_s^o veto (flight length, cos α)

- Define $\pi^+\pi^-$ recoil mass: $m_R^2 = (m_{\Upsilon(3S)} - E^*_{\pi^+\pi^-})^2 - P^{*\,2}_{\pi^+\pi^-}$

- χ^2 fit to m_R with 7 components
  - h_b signal: Symmetric two-sided Crystal Ball (TCB)
  - $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(2S)$: Asymmetric TCB + Bifurcated Gaussian
  - $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$: same, with fixed feed-down components
  - $\chi_{b1,2}(2P) \rightarrow \pi^+\pi^- \chi_{b1,2}(1P)$: TCB, with fixed peak position
  - $K_s^o \rightarrow \pi^+\pi^-$: MC-determined phase space
  - Non-peaking background: 6th order Chebychev polynomial

$\pi^+\pi^- h_b(1P)$: Fit Results



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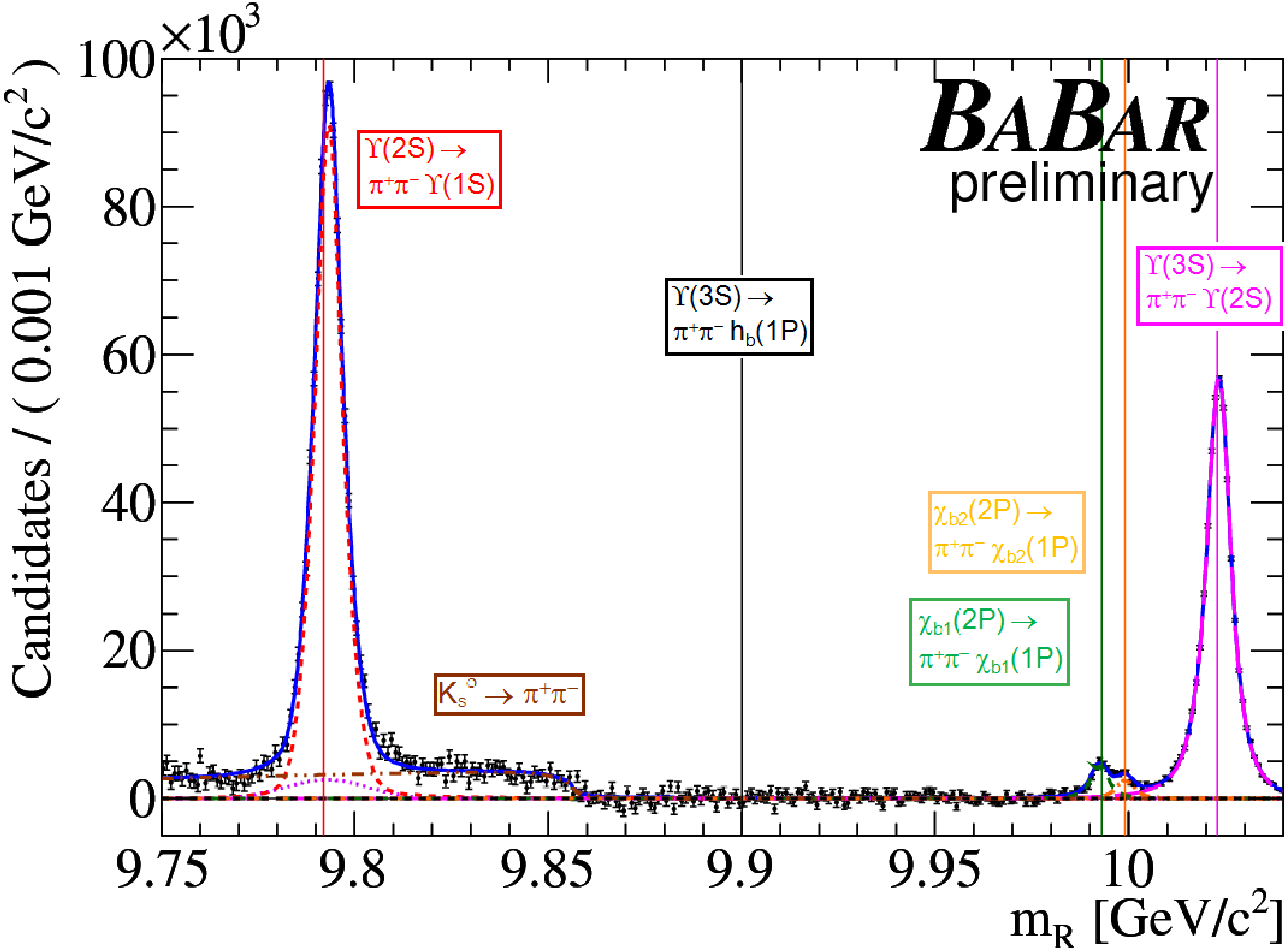

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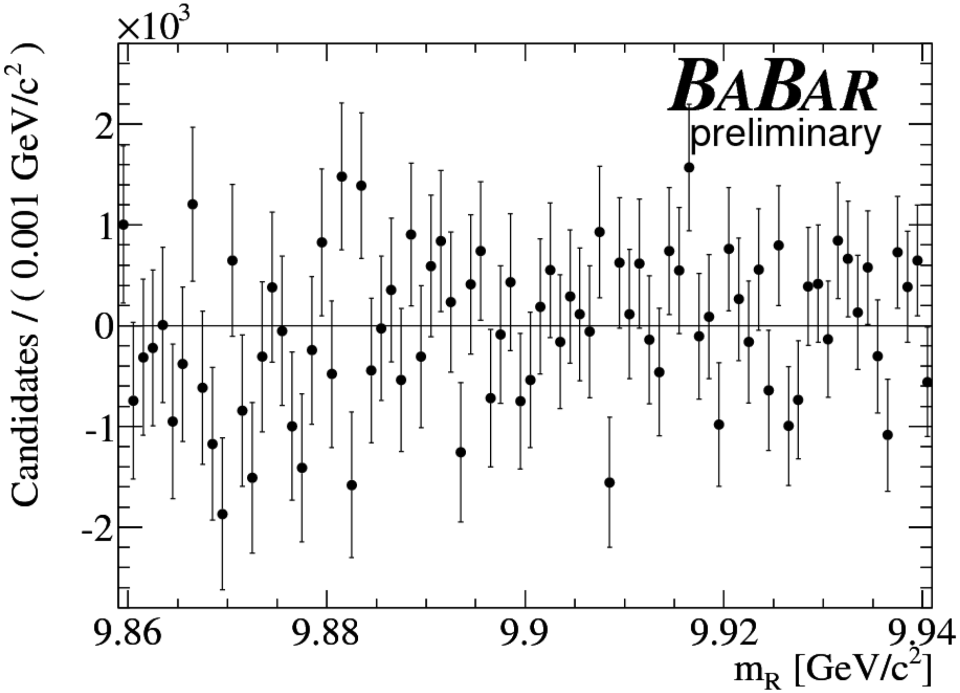
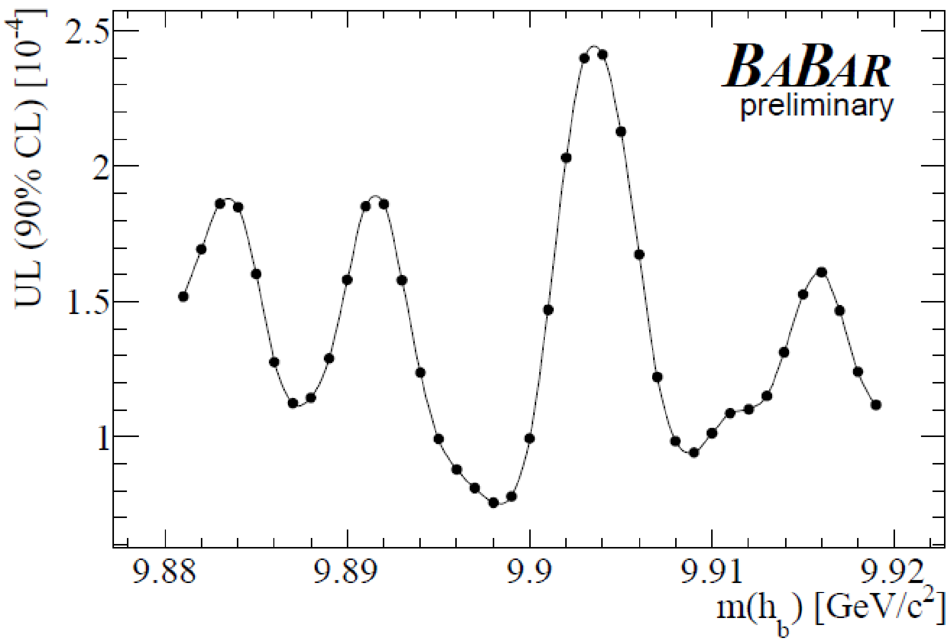
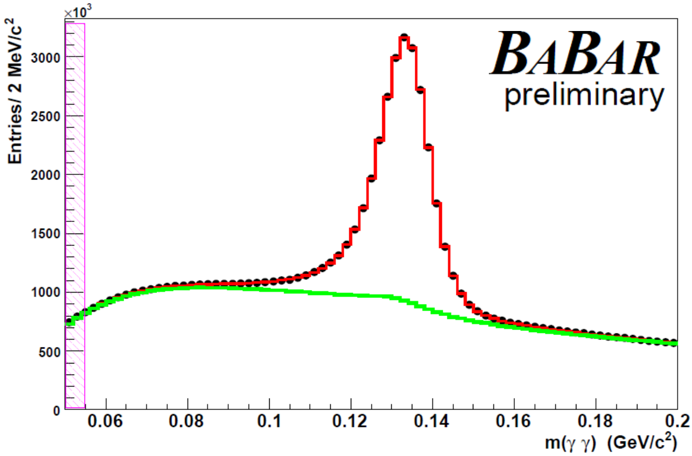




- No evidence for h_b signal at m_{h_b} = 9900 MeV/c^2
  - $\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- h_b(1P)) = (0.0 \pm 0.5 \pm 0.3)\times10^{-4}$ ($<1\times10^{-4}$ UL)
- Most significant scan point $<2\sigma$ significance
- Exclude $\mathcal{B}(\Upsilon(3S)\to\pi^+\pi^- h_b(1P)) > 2.5\times10^{-4}$ (90% CL) over range

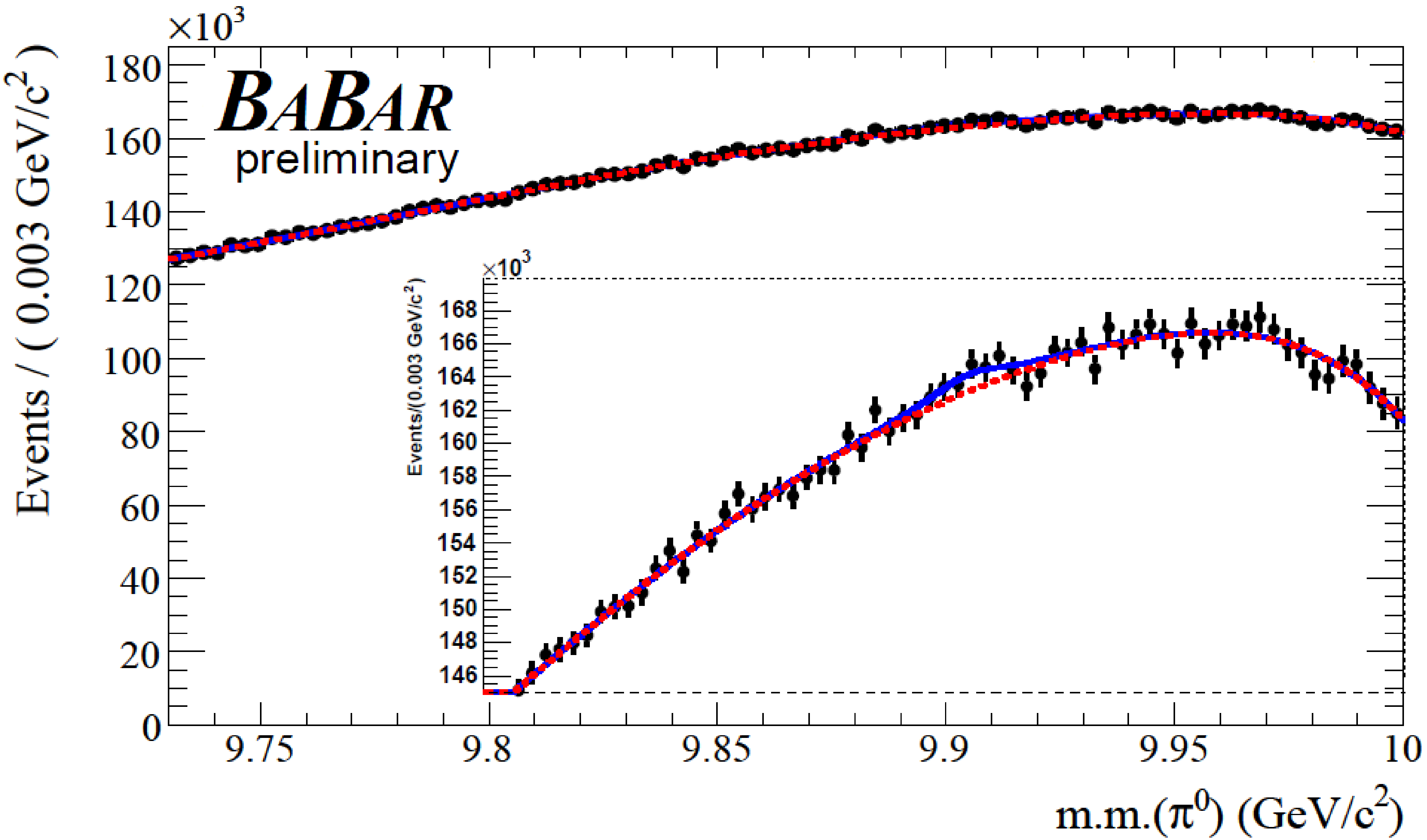
$\pi^o h_b(1P)$: Analysis Strategy

- Reconstruct $\pi^o(\gamma_1\gamma_2) + \gamma$
  - Require E_γ consistent with $h_b(1P) \rightarrow \gamma\eta_b(1S)$
  - Cuts on N_{tracks}, R_2, π^o veto (all γ candidates), π^o $\cos\theta_h$
- Define π^o missing mass: $m.m.(\pi^o)^2 = (m_{\Upsilon(3S)} - E^*_{\pi^o})^2 - P^*_{\pi^o}{}^2$
  - Constrain m_{π^o} to improve resolution
  - N_{π^o} from $m_{\gamma_1\gamma_2}$ fit in each m.m.(π^o) bin



- χ^2 fit of m.m.(π^o) distribution
  - $h_b(1P)$ signal: Double Crystal Ball
  - Background: 6th order polynomial, from reweighted MC

$\pi^o h_b(1P)$: Fit Results



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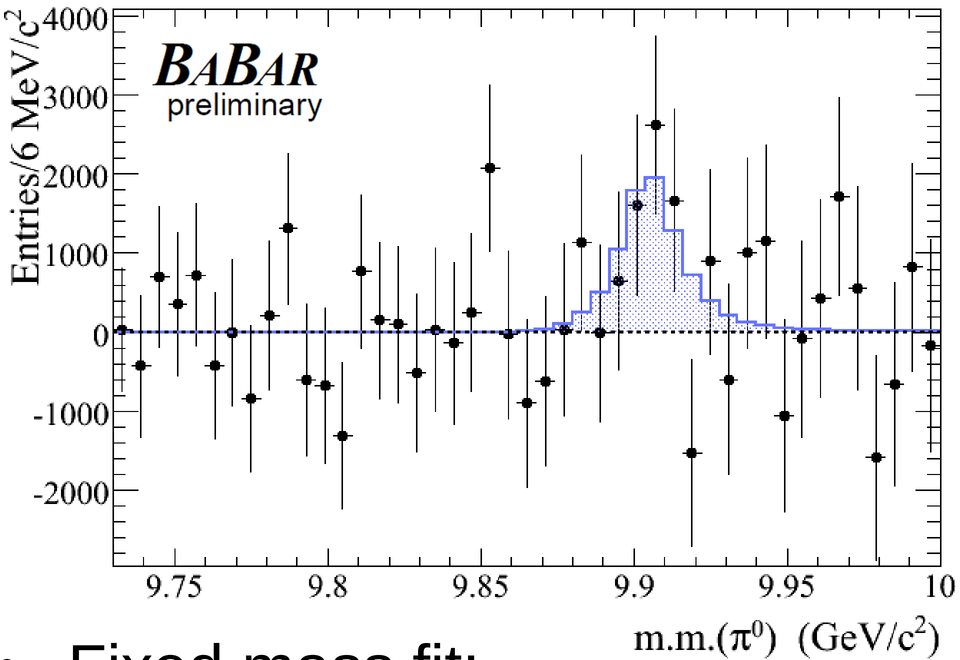

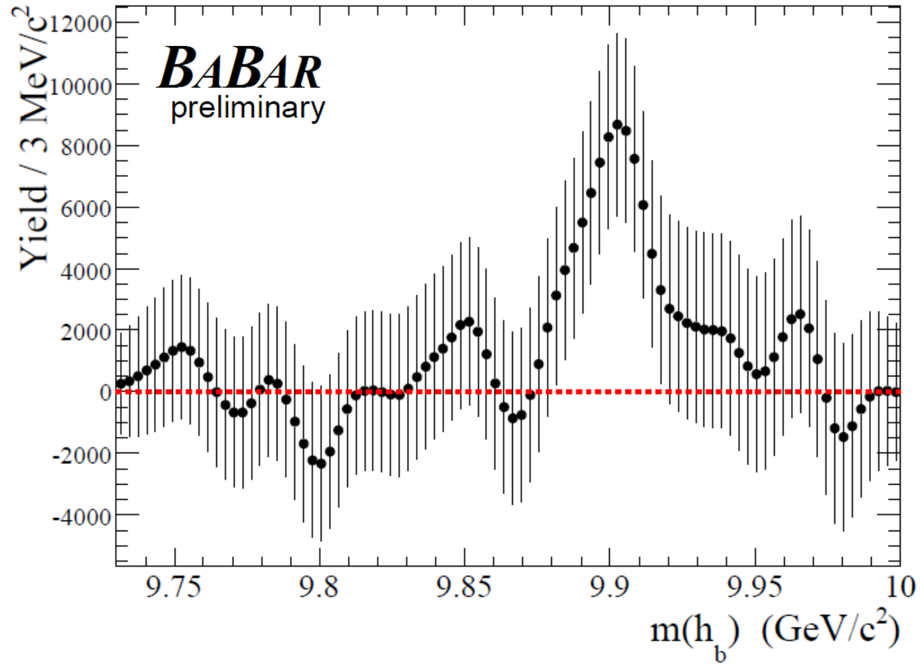

- Fixed mass fit:
  - $\mathcal{B}(\Upsilon(3S)\rightarrow\pi^o\, h_b(1P)\rightarrow\pi^o\gamma\eta_b(1S)) = (3.1\pm1.1\pm0.4)\times10^{-4}$ (2.7σ)
  - $1.5\times10^{-4} < \mathcal{B}(\Upsilon(3S)\rightarrow\pi^o\, h_b(1P)\rightarrow\pi^o\gamma\eta_b(1S)) < 4.9\times10^{-4}$
- Best fit $m_{h_b} = 9903 \pm 4 \pm 1$ MeV/c^2 consistent with predictions
- Combined results:
  - $R(\pi^o h_b(1P) / \pi^+\pi^- h_b(1P)) > 3.2$ (>1.5 for $m_{h_b} = 9903$ MeV/c^2)

Summary

- $\Upsilon(1D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$ BaBar, arXiv:1004.0175, submitted to PRL
  - First observation of $\Upsilon(1D_J)$ hadronic decays
  - Quantum numbers and precise $m_{\Upsilon(1D_2)}$ measurement

- $\Upsilon(2,3S)$ converted photon spectrum
  - Most significant (2.6σ) "η_b" signal at $9403.3\pm2.4^{+0.9}_{-1.5}$ MeV/c^2
  - Improved and first direct $\chi_{bJ}(1,2P) \rightarrow \gamma\,\Upsilon(1S)$ measurement

- $h_b(1P)$ Search
  - No evidence for $\Upsilon(3S) \rightarrow \pi^+\pi^-\, h_b(1P)$
  - Marginal evidence (2.7σ) for $\Upsilon(3S) \rightarrow \pi^o h_b(1P) \rightarrow \pi^o\gamma\eta_b(1S)$
  - $\mathcal{B}(\Upsilon(3S)\rightarrow\pi^o h_b(1P))\ /\ \mathcal{B}(\Upsilon(3S)\rightarrow\pi^+\pi^- h_b(1P)) > 1$ at 90% C.L.

FIN