Charmonium & Bottomonium @ e^+e^- colliders

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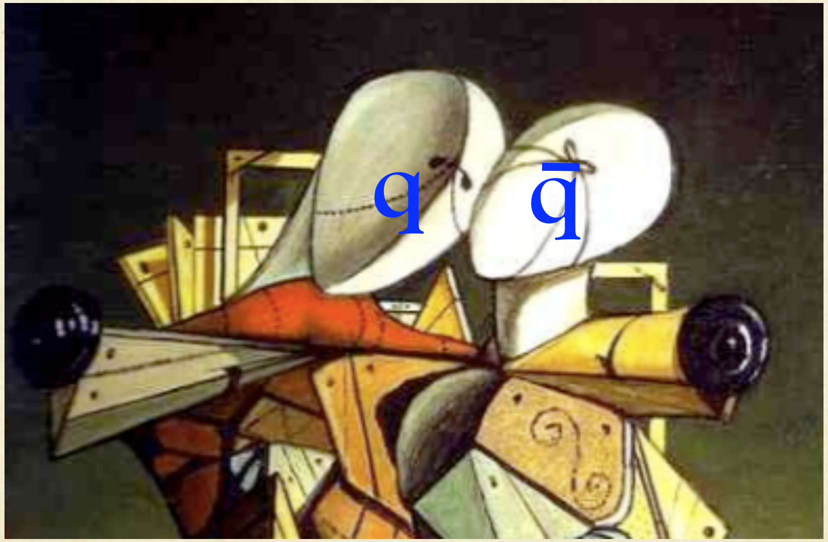
INFN Ferrara
Representing the BaBar Collaboration



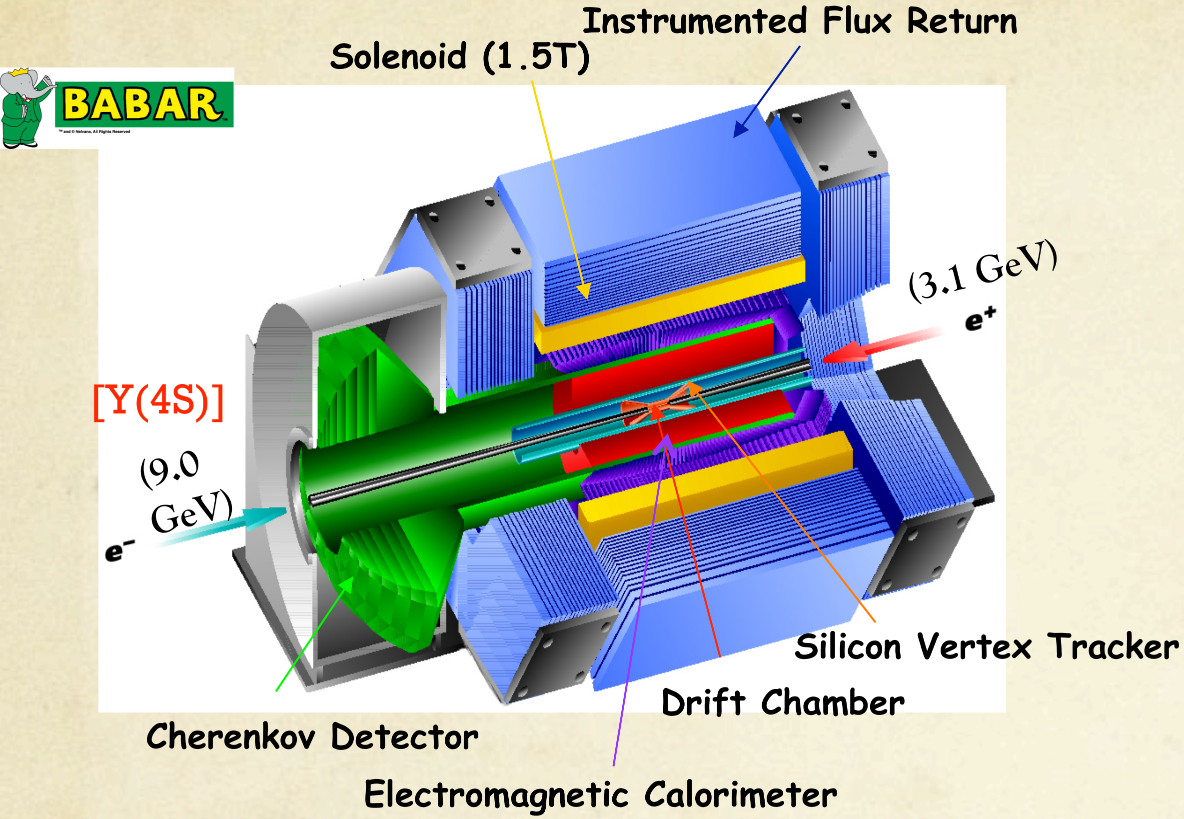
Giorgio de Chirico.
Hector and Andromache. (1917)

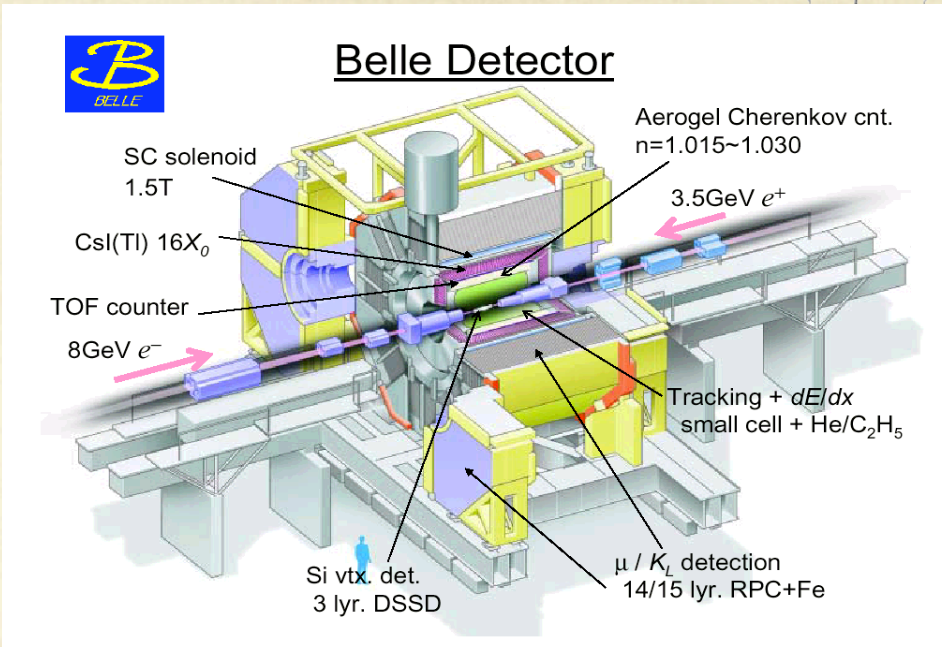
Flavor Physics and CP Violation 2011, May 23-27
Kibbutz Maale Hachamisha, Israel

Outline

- Introduction to the B-factories
- Charmonium
  - New Charmonium-like States — See Wolfgang Gradl talk
  - $\eta_c(1S)$ & $\eta_c(2S)$ measurements at the B-factories
  - Search for charmonium in $\Upsilon(1S)$ radiative decays
- Bottomonium
  - Radiative transitions from $\Upsilon(2S,3S)$ with converted photons
  - Inclusive dipion transitions in $\Upsilon(3S)$ Decays [excluding the h_b search] — See Alexander Bondar talk
  - Observation of the $\Upsilon(1^3D_J)$ bottomonium state via decay to $\pi^+\pi^-\Upsilon(1S)$

The BaBar and Belle detectors



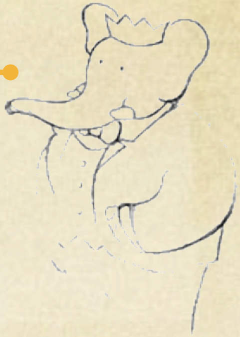


	BELLE	BaBar
Υ(5S)	121 fb^{-1}	
Υ(4S)	711 fb^{-1}	433 fb^{-1}
Υ(3S)	3.0 fb^{-1}	30 fb^{-1}
Υ(2S)	24 fb^{-1}	14 fb^{-1}
Υ(1S)	5.7 fb^{-1}	
Off-resonance	87 fb^{-1}	54 fb^{-1}
Scan	68fb^{-1}	
Total	1020fb^{-1}	531fb^{-1}

471×10^6 $B\overline{B}$ pairs

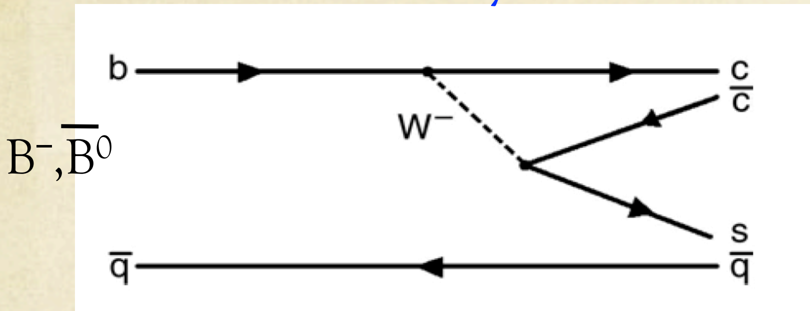
Charmonium

Salvador Dali'.
Mae West. (1934)
Come up and c c me sometime



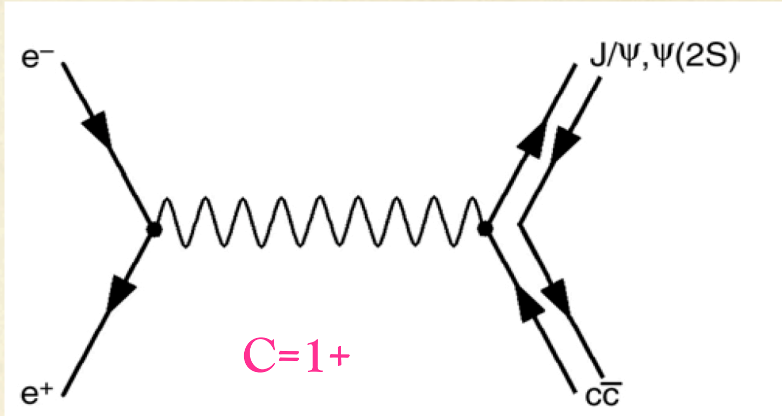
Charmonium production at the B-factories

B decays

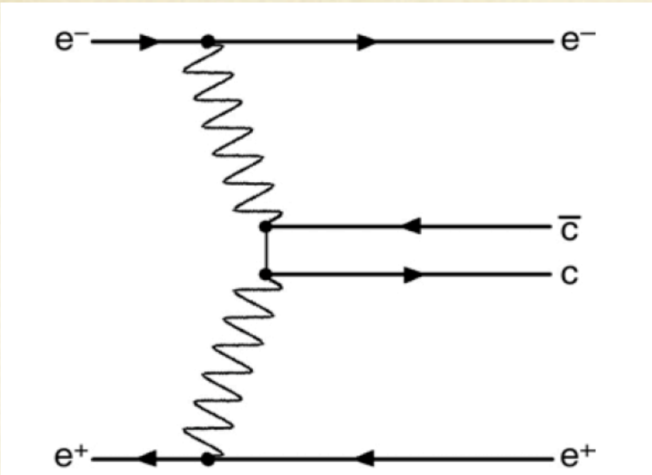


States of any quantum number can be formed

Double charmonium production

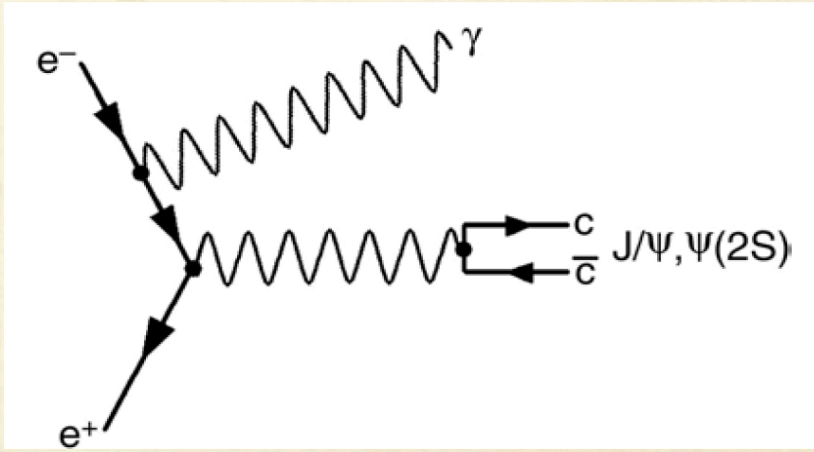


2 γ production



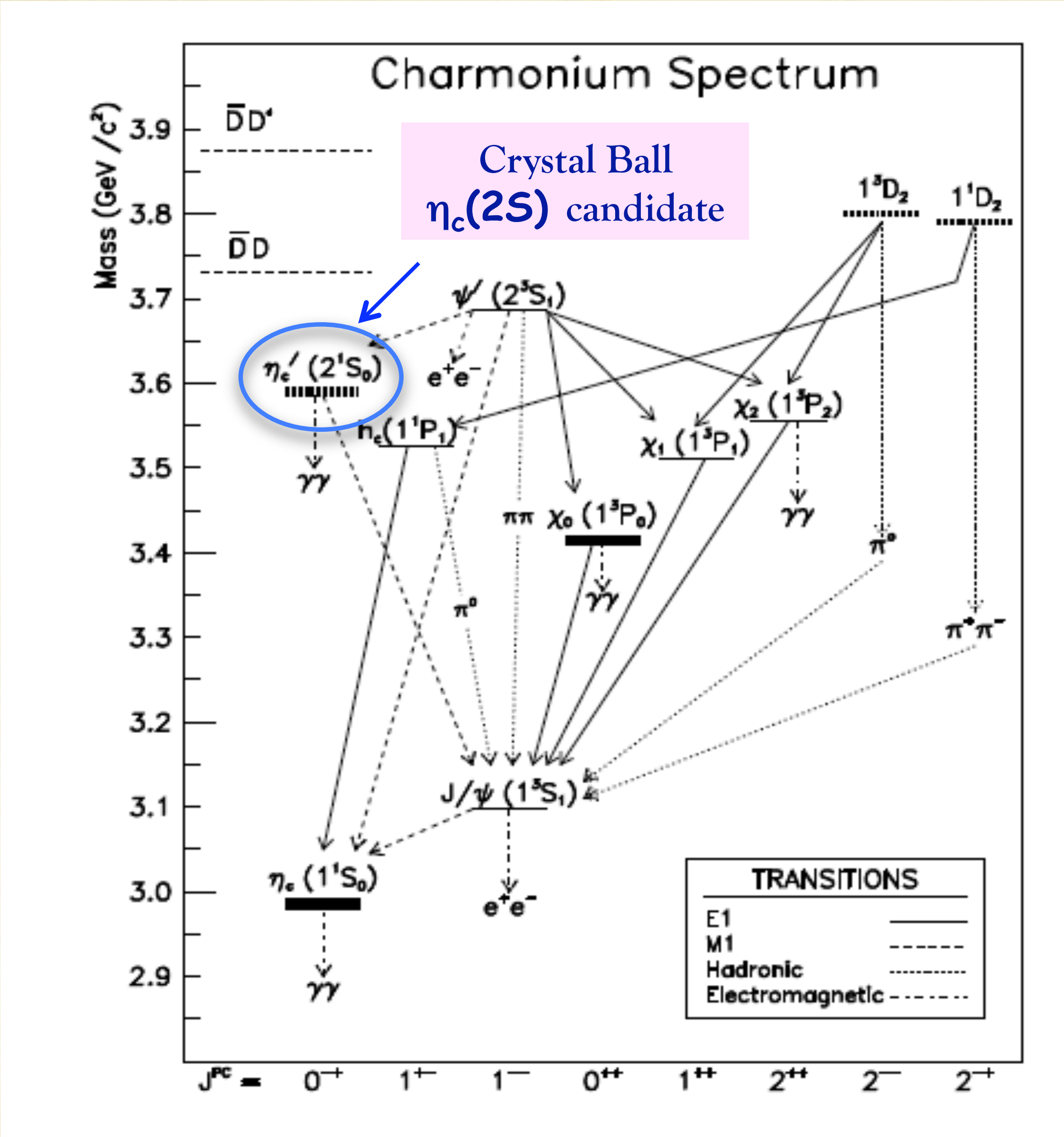
$J^{PC}=0^{\pm+}, 2^{\pm+}...$

Initial State Radiation (ISR)



$J^{PC}=1^{--}$

Charmonium Spectrum before the B-factories

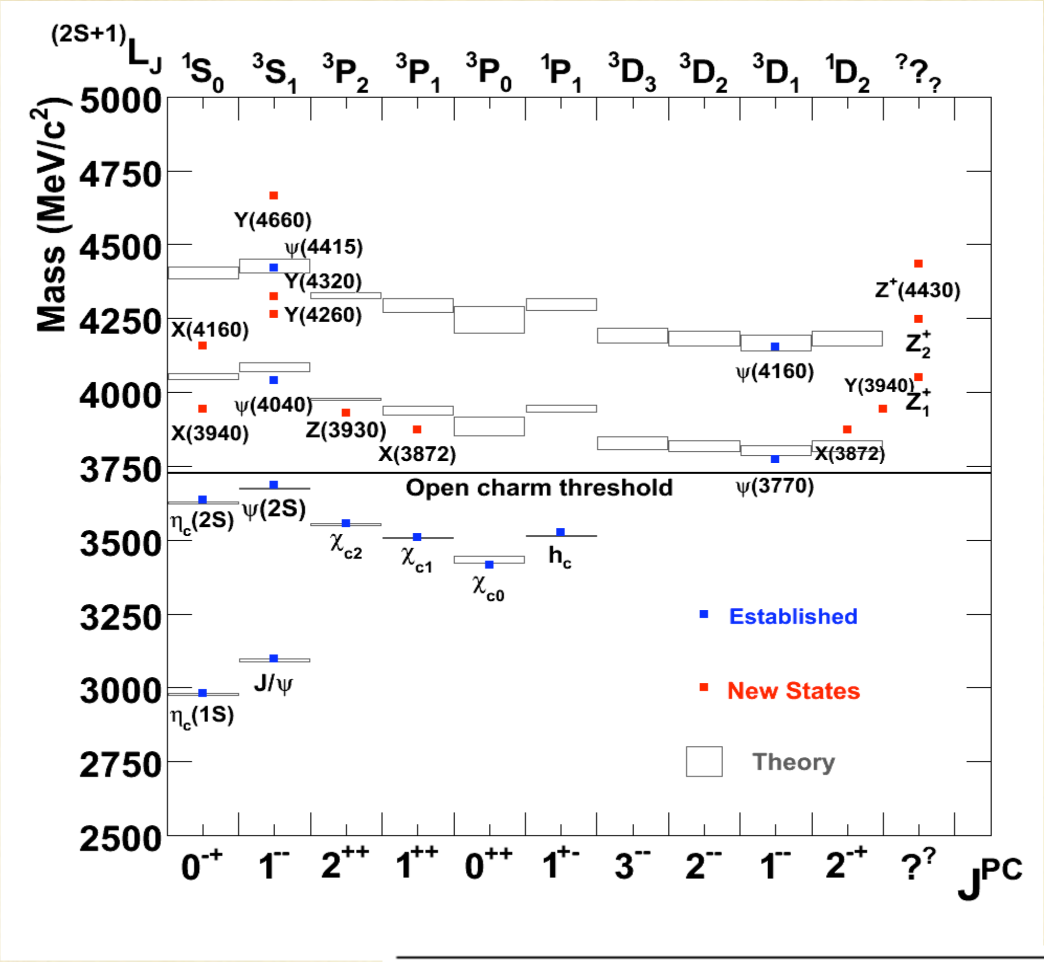


- Charmonium properties were well understood up to $\psi(3770)$ (i.e. about the $D\bar{D}$ threshold) with some missing pieces (like the $\eta_c(2S)$)
- No new $c\bar{c}$ states were discovered between 1980 to 2002
- $c\bar{c}$ states above open charm threshold are expected to have significant width values and to decay mainly to open charm channels

(E835 experiment - year 2000) in the same year -B factories started to take data

Charmonium spectrum

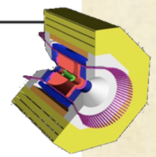
(May 2011)



- In a few years the situation changed rapidly
- There were discoveries of new charmonium states like the $h_c(1P)$, $\eta_c(2S)$ and $\chi_{c2}(2P)$
- And several new "charmonium –like" states

Eur. Phys.J.C71, 1534 (2011)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$h_c(1P)$	3525.45 ± 0.15	0.73 ± 0.53 (<1.44)	1^{+-}	$\psi(2S) \to \pi^0(\gamma\eta_c(1S))$ $\psi(2S) \to \pi^0(\gamma\ldots)$ $p\bar{p} \to (\gamma\eta_c) \to (\gamma\gamma\gamma)$ $\psi(2S) \to \pi^0(\ldots)$
$\eta_c(2S)$	3637 ± 4	14 ± 7	0^{-+}	$B \to K(K_S^0 K^- \pi^+)$ $e^+e^- \to e^+e^-(K_S^0 K^- \pi^+)$ $e^+e^- \to J/\psi\ (\ldots)$
$\chi_{c2}(2P)$	3927.2 ± 2.6	24.1 ± 6.1	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$



Z(3930)

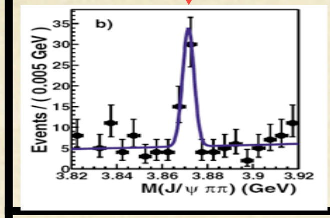
Charmonium-like States at the B Factories

QWG report: **Eur. Phys.J.C71, 1534 (2011)**

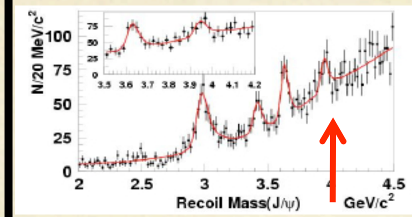
State	M, MeV	Γ, MeV	J^{PC}	Process
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$
		(< 2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$
				$B \to K(\omega J/\psi)$
				$B \to K(D^{*0} D^0)$
				$B \to K(\gamma J/\psi)$
				$B \to K(\gamma \psi(2S))$
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$
				$\gamma\gamma \to (\omega J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
				$e^+e^- \to J/\psi\ (\ldots)$
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi')$
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$

All in all

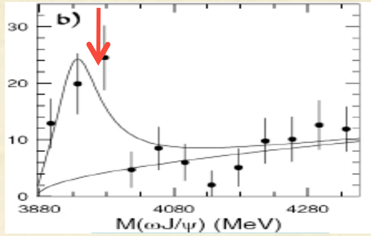
X(3872)
PRL 91, 262001 (2003)



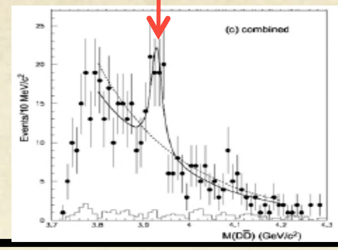
X(3940)
PRL 98, 082001 (2007)



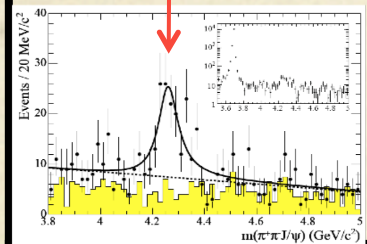
Y(3940)
PRL 94, 182002 (2005)



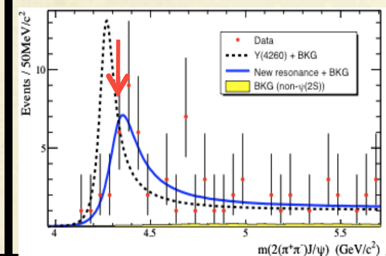
χ_{c2}(2P)
PRL 96, 082003 (2006)



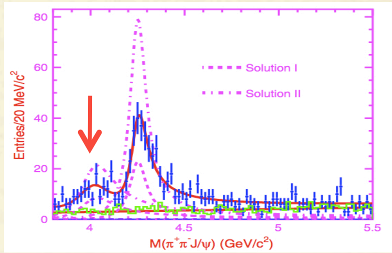
Y(4260)
PRL 95, 142001 (2005)



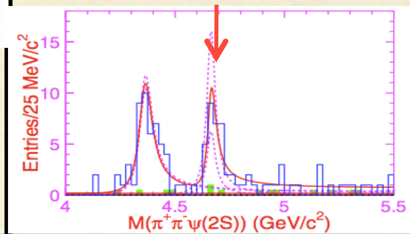
Y(4350)
PRL 98, 212001 (2007)



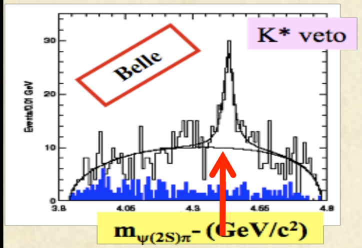
Y(4008)
PRL 99, 182004 (2007)



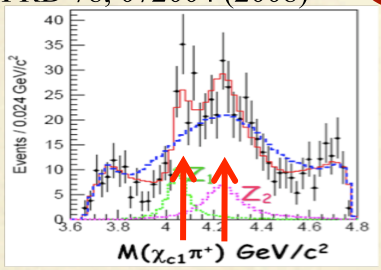
Y(4660)
PRL 99, 142002 (2007)



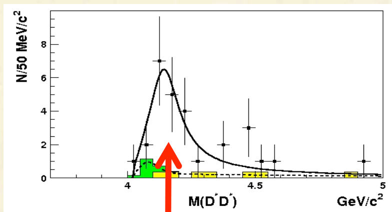
Z(4430)$^+$
PRL 100, 142001 (2008)



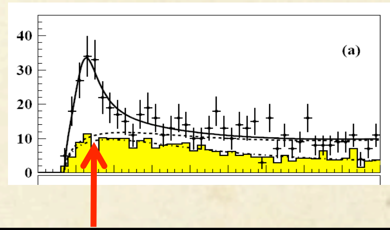
Z_1^+ and Z_2^+
PRD 78, 072004 (2008)



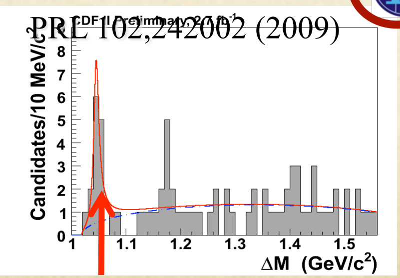
X(4160)
PRL 100,202001 (2008)



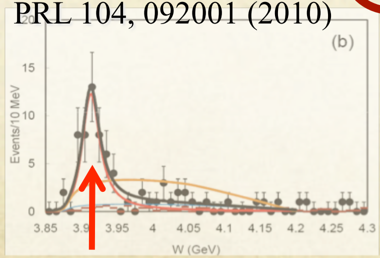
X(4630)
PRL 101, 172001 (2008)



Y(4140)
PRL 102,242002 (2009)



X(3915)
PRL 104, 092001 (2010)



$\eta_c(1S)$ & $\eta_c(2S)$ current status

$\eta_c(1S)$

Discovered by Crystal Ball 1980

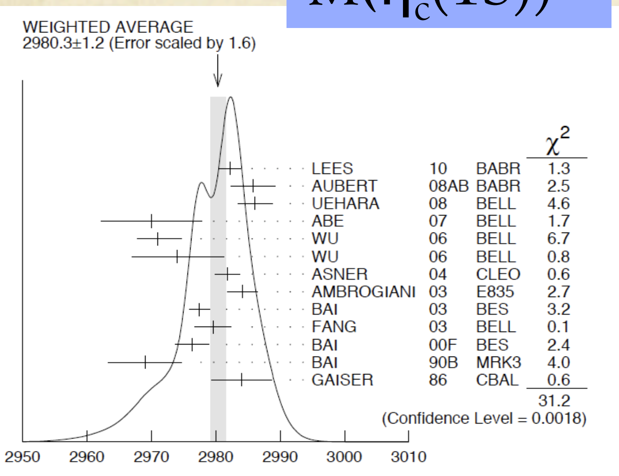
Phys. Rev. Lett. 45, 1150-1153 (1980)

$\eta_c(2S)$

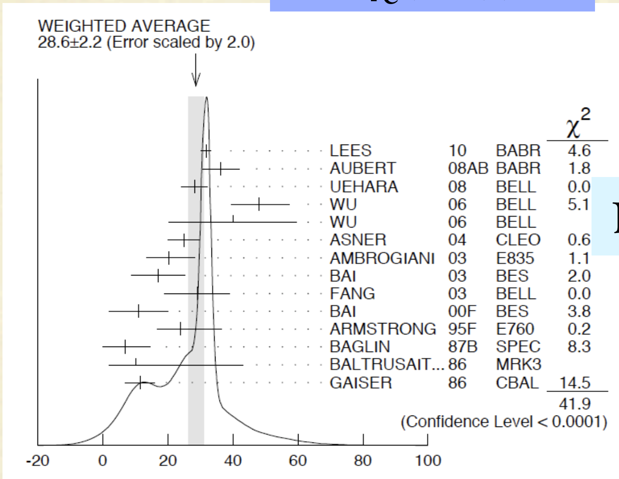
Discovered by BELLE 2002

Phys. Rev. Lett. 89 102001 (2002)

$M(\eta_c(1S))$

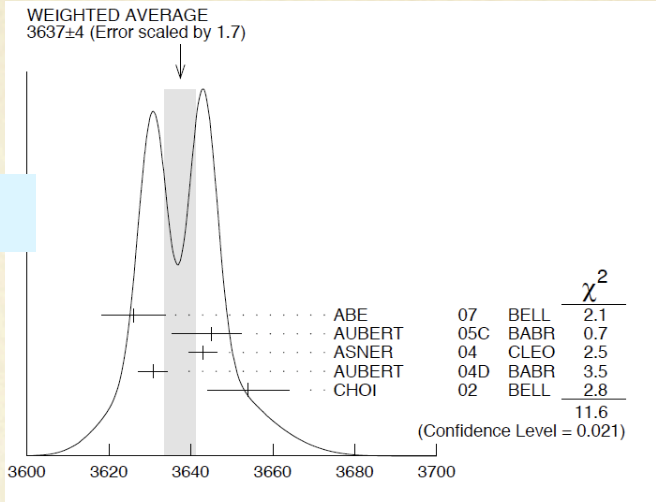


$\Gamma(\eta_c(1S))$



PDG 2010

$M(\eta_c(2S))$



$\eta_c(1S)$ observed by several experiments but there is a large spread in mass and width measurements

$\Gamma(\eta_c(1S))$~15 MeV (J/ψ and $\psi(2S)$) radiative decays

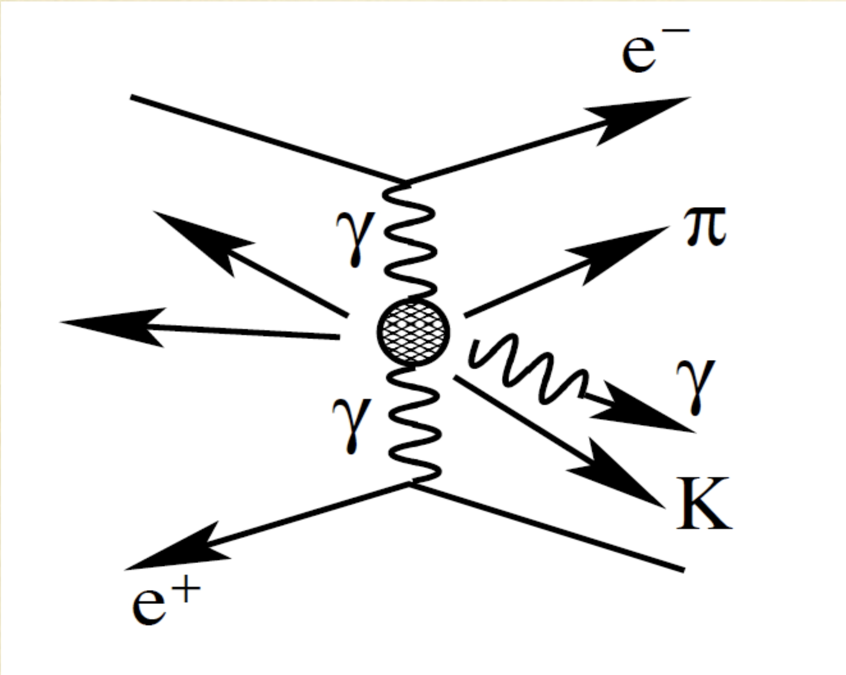
$\Gamma(\eta_c(1S))$~30 MeV (B-decays and $\gamma\gamma$ production)

Until recently has only been observed in exclusive decay to $K\bar{K}\pi$
Precise measurement of $m(\eta_c(2S))$ will help discriminate among different charmonium models

519.2 fb^{-1} collected at the $\Upsilon(4S)$, $\Upsilon(3S)$, $\Upsilon(2S)$

arXiv:1103.3971v1

Production: $e^+e^- \rightarrow \gamma\gamma e^+e^-$



Only states with even $J^{\pm+}$ or odd J^{++} with J>1 are allowed

Final states are :

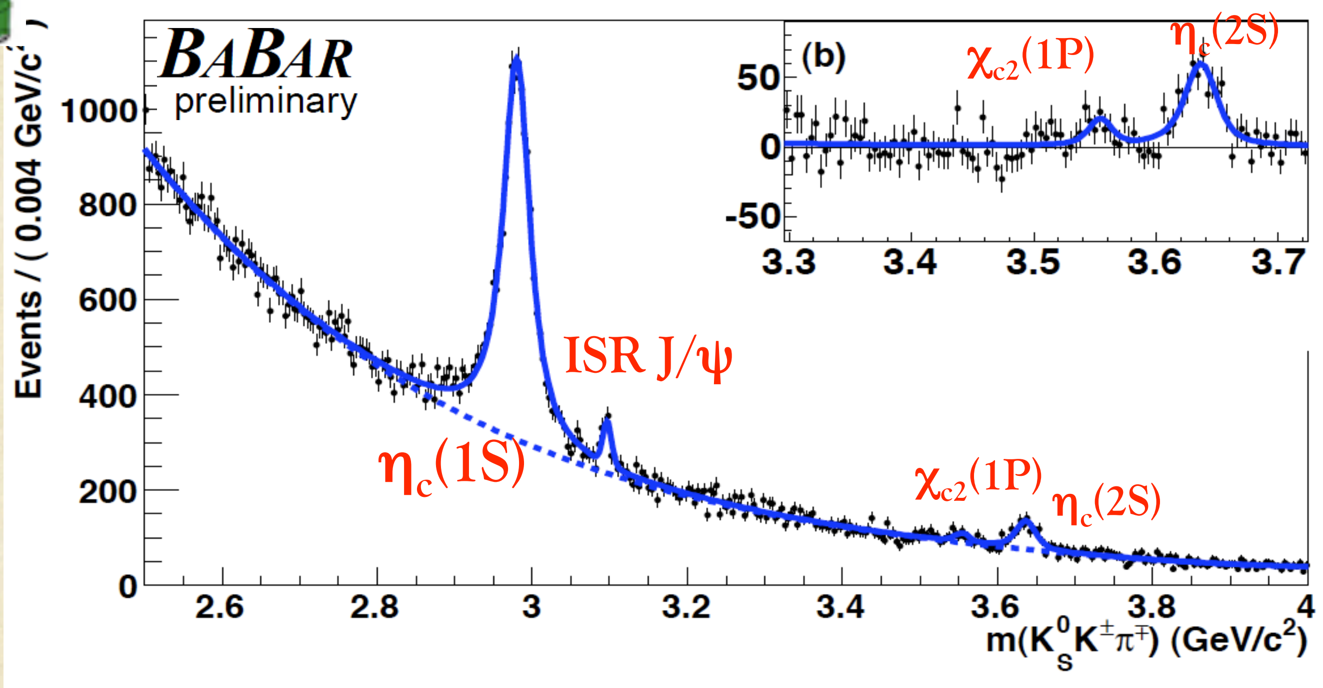
$$\gamma\gamma e^+e^- \longrightarrow K^+K^-\pi^+\pi^-\pi^0 e^+e^-$$

$$\gamma\gamma e^+e^- \longrightarrow K_S^0 K^\pm \pi^\mp e^+e^-$$

For this final state $J^P=0^+$ is not allowed

Outgoing e^+ and e^- are not detected

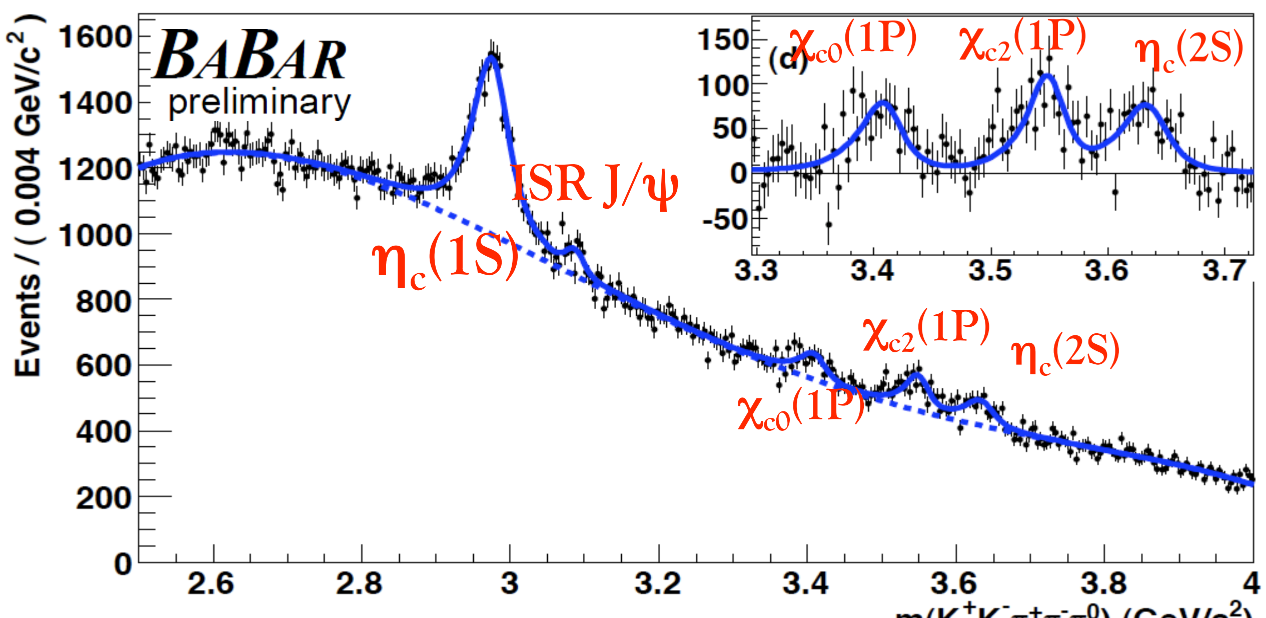
$\eta_c(1S)$ & $\eta_c(2S)$ new BaBar results(2)



Inset: Background-subtracted distribution

Signal for
$\eta_c(1S)$,$\chi_{c2}(1P)$,$\eta_c(2S)$
No signal for the $\chi_{c2}(2P)$

arXiv:1103.3971v1



Inset: Background -subtracted distribution

Signal for
$\eta_c(1S)$,$\chi_{c0,2}(1P)$,$\eta_c(2S)$
No signal for the $\chi_{c2}(2P)$

$\eta_c(1S)$ & $\eta_c(2S)$ Final Results

$m(\eta_c(1S))=2982.5\pm0.4\pm1.4$ MeV/c^2
$\Gamma(\eta_c(1S))=32.1\pm1.1\pm1.3$ MeV

$m(\eta_c(2S))=3638.5\pm1.5\pm0.8$ MeV/c^2
$\Gamma(\eta_c(2S))=13.4\pm4.6\pm3.2$ MeV

Measurement more precise than the world average

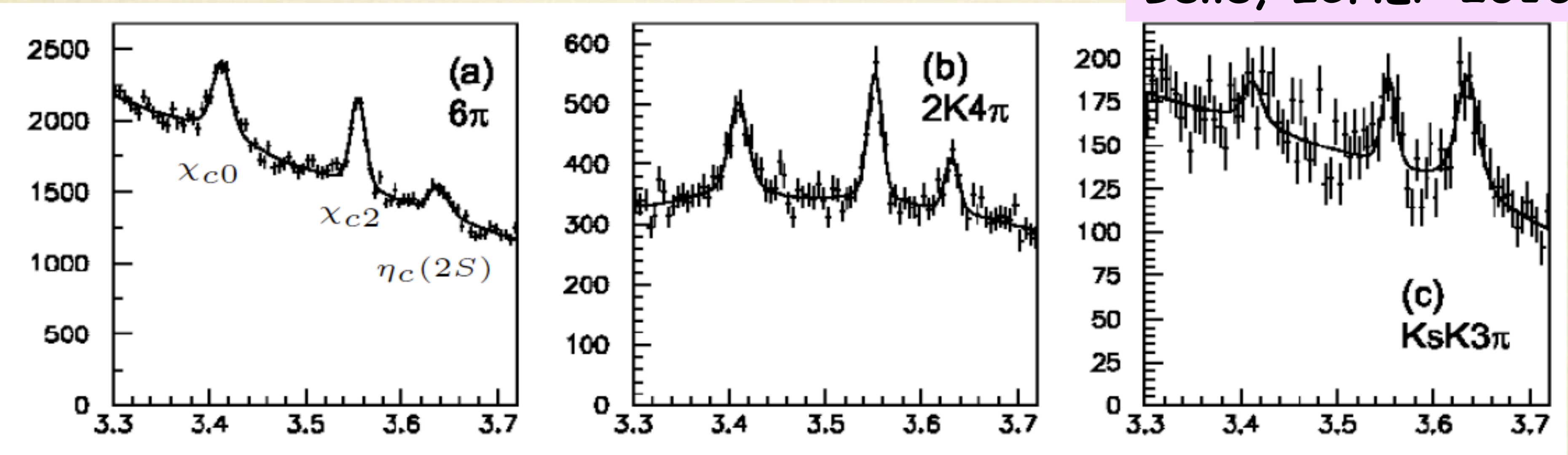
Process	$\Gamma_{\gamma\gamma}\times\mathcal{B}$ (keV)
$\eta_c(1S)\to K\overline{K}\pi$	$0.386\pm0.008\pm0.021$
$\chi_{c2}(1P)\to K\overline{K}\pi$	$(1.8\pm0.5\pm0.2)\times10^{-3}$
$\eta_c(2S)\to K\overline{K}\pi$	$0.041\pm0.004\pm0.006$
$\chi_{c2}(2P)\to K\overline{K}\pi$	$<2.1\times10^{-3}$
$\eta_c(1S)\to K^+K^-\pi^+\pi^-\pi^0$	$0.190\pm0.006\pm0.028$
$\chi_{c0}(1P)\to K^+K^-\pi^+\pi^-\pi^0$	$0.026\pm0.004\pm0.004$
$\chi_{c2}(1P)\to K^+K^-\pi^+\pi^-\pi^0$	$(6.5\pm0.9\pm1.5)\times10^{-3}$
$\eta_c(2S)\to K^+K^-\pi^+\pi^-\pi^0$	$0.030\pm0.006\pm0.005$
$\chi_{c2}(2P)\to K^+K^-\pi^+\pi^-\pi^0$	$<3.4\times10^{-3}$

Study of the $\gamma\gamma \to \eta_c(2S)$ at Belle

BELLE studied the process $\gamma\gamma \to \eta_c(2S) \to$ 6 charged tracks:
6π ($\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$), $2K4\pi$ ($K^+K^-\pi^+\pi^-\pi^+\pi^-$), $4K2\pi$ ($K^+K^-K^+K^-\pi^+\pi^-$), $K_SK3\pi$ ($K_SK^+\pi^-\pi^+\pi^-$)

923 fb^{-1}

Belle, ICHEP 2010



	M, MeV	Γ, MeV	Signif.	$\Gamma_{\gamma\gamma}\mathcal{B}$, eV
6π	$3638.9 \pm 1.6 \pm 2.3$	10.7 ± 4.9	8.5σ	$20.1 \pm 3.7 \pm 3.2$
$2K4\pi$	$3634.7 \pm 1.6 \pm 2.8$	< 13 @ 90% CL	6.2σ	$10.2 \pm 2.3 \pm 3.4$
$K_SK3\pi$	$3636.5 \pm 1.8 \pm 2.4$	15.9 ± 5.7	8.7σ	$30.7 \pm 3.9 \pm 3.7$

$M(\eta_c(2S)) = 3636.9 \pm 1.1 \pm 2.5 \pm 5.0$ MeV/c^2
$\Gamma(\eta_c(2S)) = 9.9 \pm 3.2 \pm 2.6 \pm 2.0$ MeV

Possible interference with the background

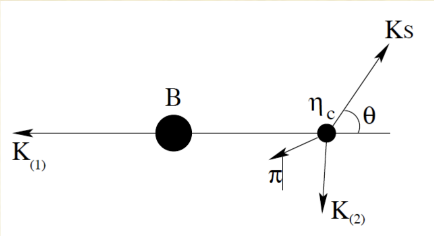
Study of the $B^{\pm} \to K^{\pm}\eta_c$ and $B^{\pm} \to K^{\pm}\eta_c(2S)$

$$B^{\pm} \to K^{\pm}\eta_c \to K^{\pm}(K_S K\pi)^0,$$
$$B^{\pm} \to K^{\pm}\eta_c(2S) \to K^{\pm}(K_S K\pi)^0.$$

arXiv:1105.0978v2

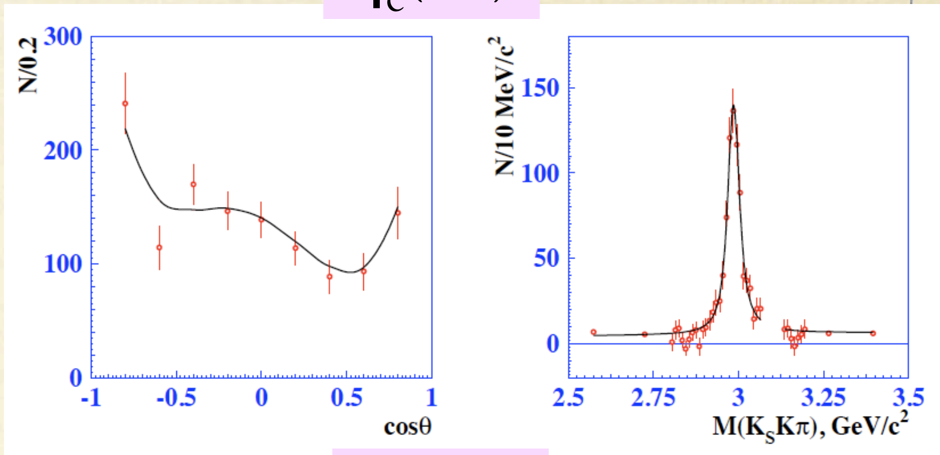
429 fb^{-1}

BELLE considered the interference with the non resonant component $B^+ \to K^+(K_S K\pi)^0$
2D fit in $\cos\theta$ and $m(K_s K\pi)$

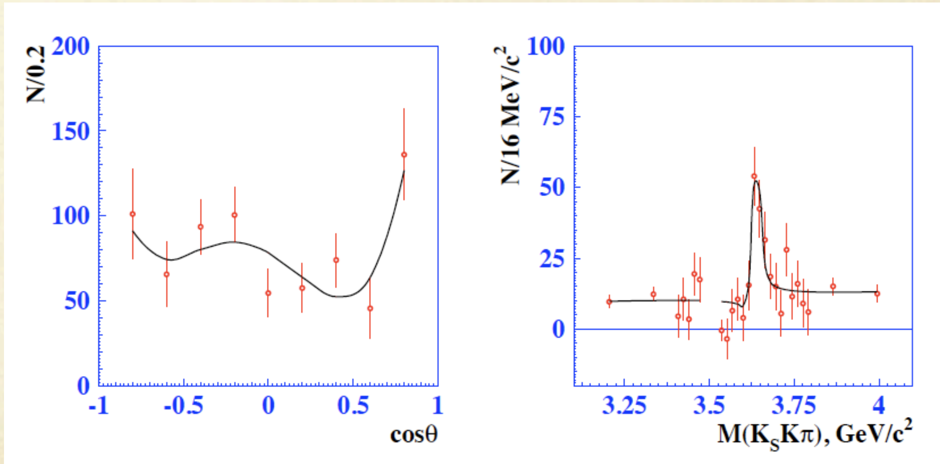


The interference effect is important

$\eta_c(1S)$



$\eta_c(2S)$



$$m(\eta_c(1S)) = 2985.4 \pm 1.5^{+0.2}_{-2.0}\ \text{MeV}/c^2$$
$$\Gamma(\eta_c(1S)) = 35.1 \pm 3.1^{+1.0}_{-1.6}\ \text{MeV}$$

$$m(\eta_c(2S)) = 3636.1^{+3.9}_{-4.1}{}^{+0.5}_{-2.0}\ \text{MeV}/c^2$$
$$\Gamma(\eta_c(2S)) = 6.6^{+8.4}_{-5.1}{}^{+2.6}_{-0.9}\ \text{MeV}$$

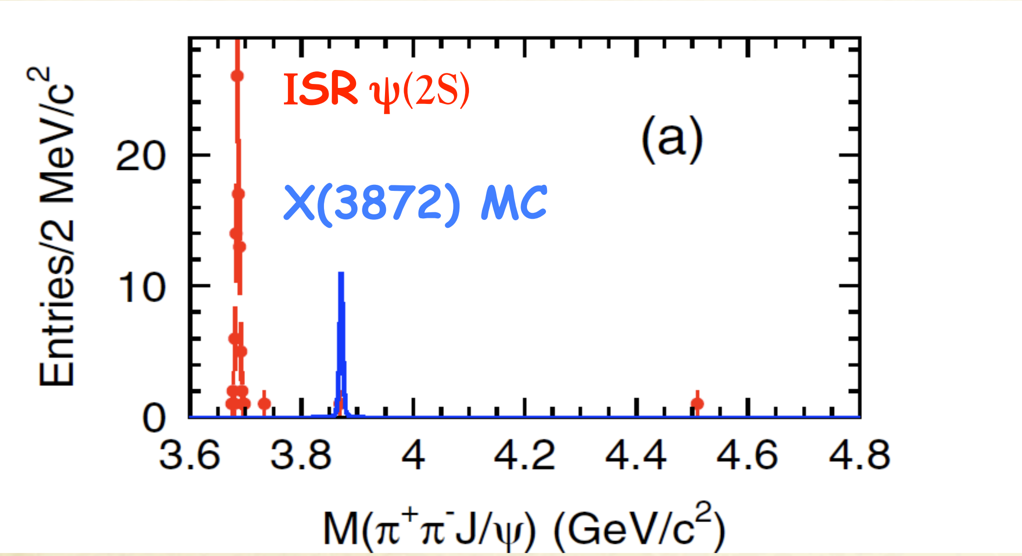
No interference has significant effect for $\eta_c(2S)$ width

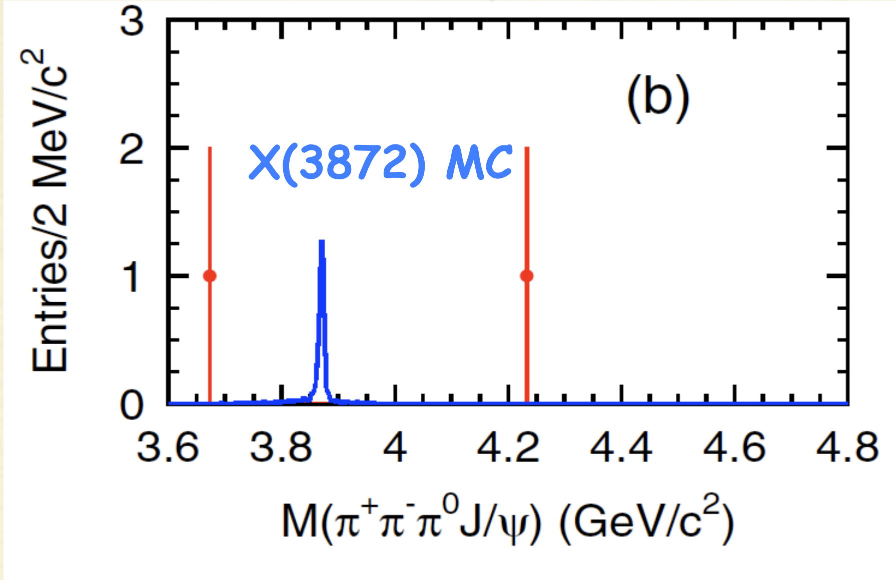
$$\Gamma(\eta_c(2S)) = 41.1 \pm 12.0^{+6.4}_{-10.9}\ \text{MeV}$$

Search for charmonium in Υ(1S) radiative decays

5.7 fb^{-1} Υ(1S)
1.8 fb^{-1} in the continuum

PRD 82, 051504(R) 2010





BELLE searched for charge parity-even charmonium and charmonium like states in Υ(1S) radiative decay $(b\bar{b}) \rightarrow c\bar{c}\gamma$ process

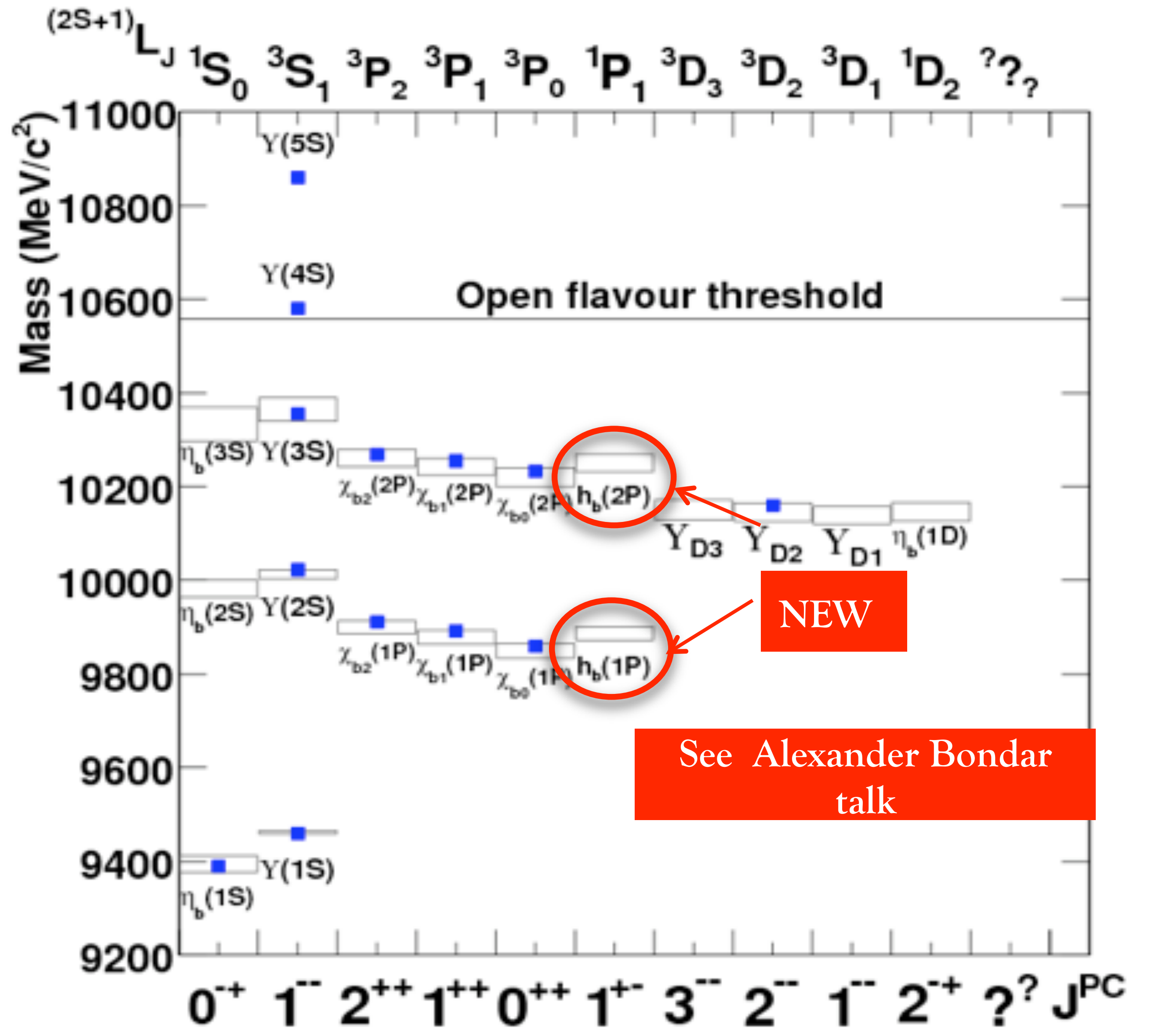
State (R)	N_{sig}^{UP}	ε (%)	σ_{sys} (%)	$\mathcal{B}_R(10^{-5})$
χ_{c0}	11.5	15.1	11	65
χ_{c1}	13.8	17.0	11	2.3
χ_{c2}	2.4	15.8	11	0.76
η_c	72	25.1	23	5.7
$X(3872) \to \pi^+\pi^- J/\psi$	3.9	23.2	7.6	0.16
$X(3872) \to \pi^+\pi^-\pi^0 J/\psi$	2.3	7.6	9.7	0.28
$X(3915) \to \omega J/\psi$	2.3	8.1	9.7	0.30
$Y(4140) \to \phi J/\psi$	2.3	19.4	7.7	0.22

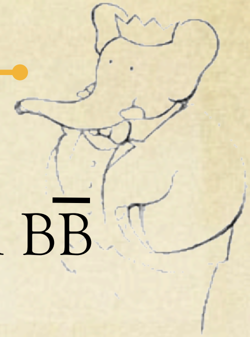
No evidence for excited charmonium states below 4.8 GeV/c²

Bottomonium

Magritte, Okapi, 1958

Bottomonium Spectrum



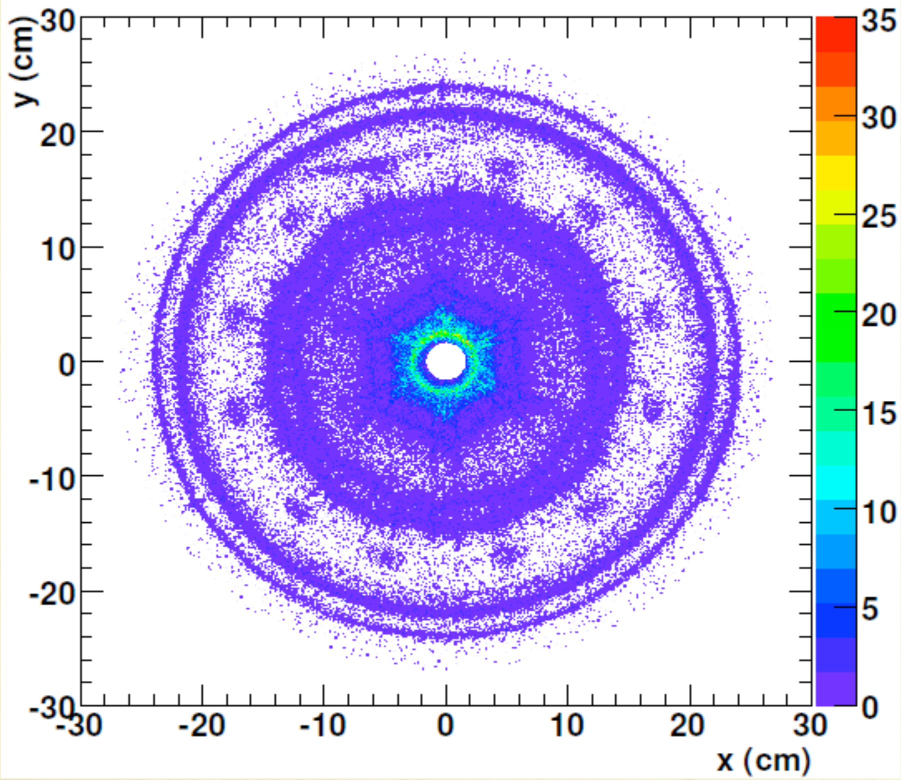


- ✓All the states below open $B\bar{B}$ threshold conform to the predicted level structure
- ✓Very little exploration of the region above the Υ(4S)
- ✓So far no analogues to the X,Y,Z states have been established
- ✓Information about the bottomonium sector in the region above the Υ(4S) will most likely come from SuperB, LHCb and BELLE-II

Radiative transitions from the Υ(2S,3S) with converted photons (1)

BaBar inner detector as seen by converted photons

arXiv:1104.5254v1



- ✓Using converted photons $\gamma \rightarrow e^+e^-$ greatly improves energy resolution
- ✓The signal yield is diminished due to small conversion rate
- ✓Each photon is reconstructed from a pair of e^+e^- tracks
- ✓The signals appear as peaks in the inclusive photon energy spectra

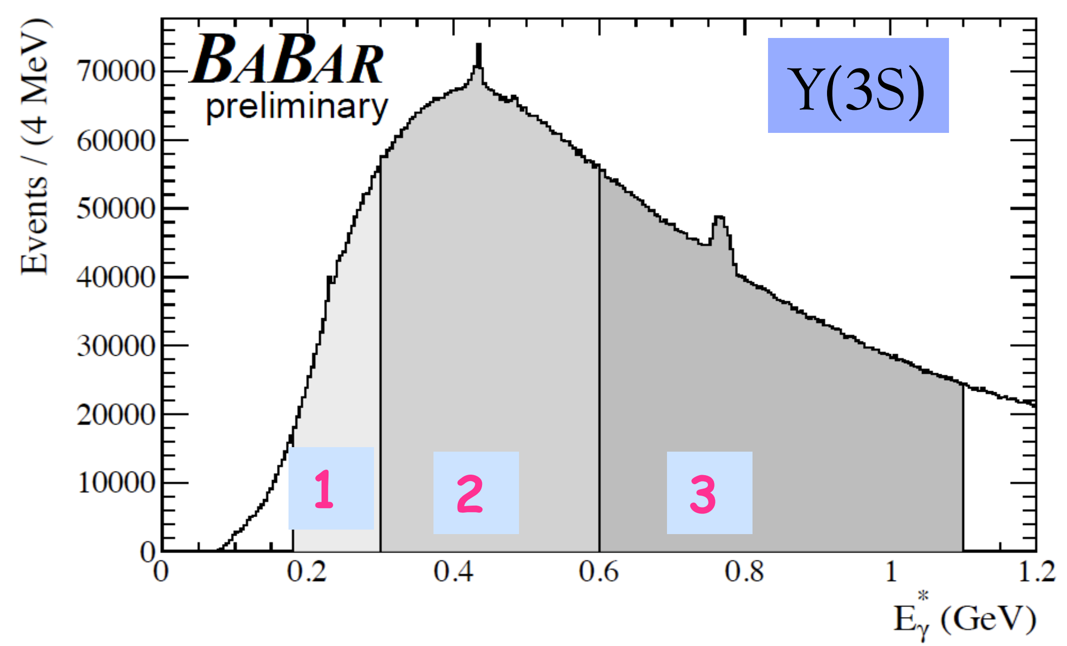
$$E(\gamma)_{CM} = ((\sqrt{s})^2 - m^2_{final\ \ state})/(2\sqrt{s})$$

The analysis involves:

- ✓Measurement of $B(\chi_{bJ}(2P) \rightarrow \gamma\ \Upsilon(2S))$, $B(\chi_{bJ}(1P,2P) \rightarrow \gamma\ \Upsilon(1S))$
- ✓ Observation of $\Upsilon(3S) \rightarrow \gamma\ \chi_{b0,2}(1P)$
- ✓Search for $\eta_b(1S)$ and $\eta_b(2S)$

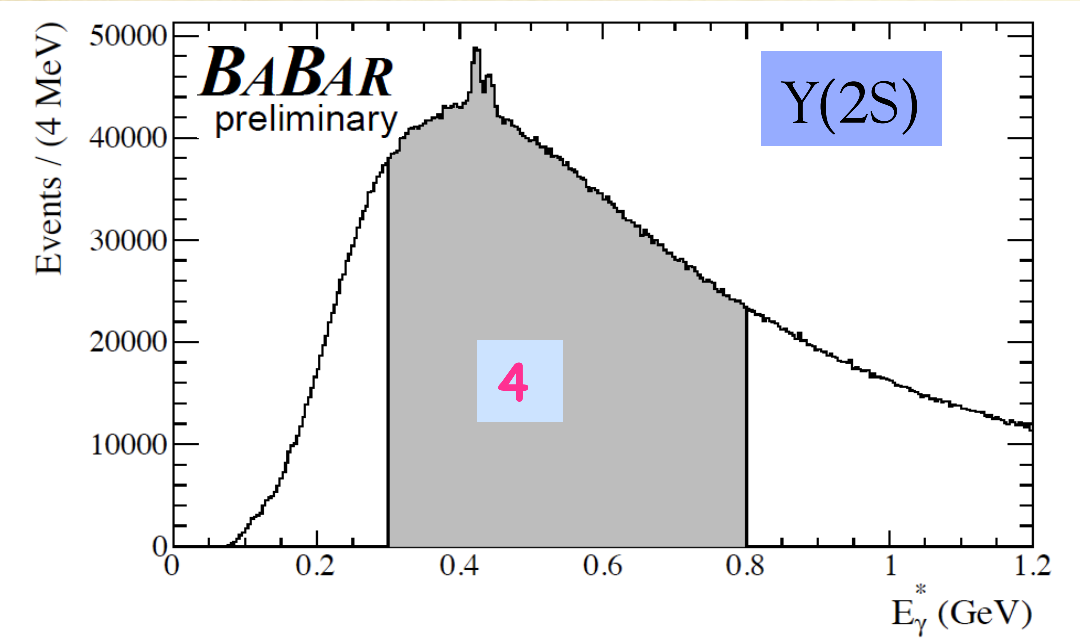
Radiative transitions from the Υ(2S,3S) with converted photons (2)

Inclusive converted photon energy spectrum



Shaded areas of interest Υ(3S)

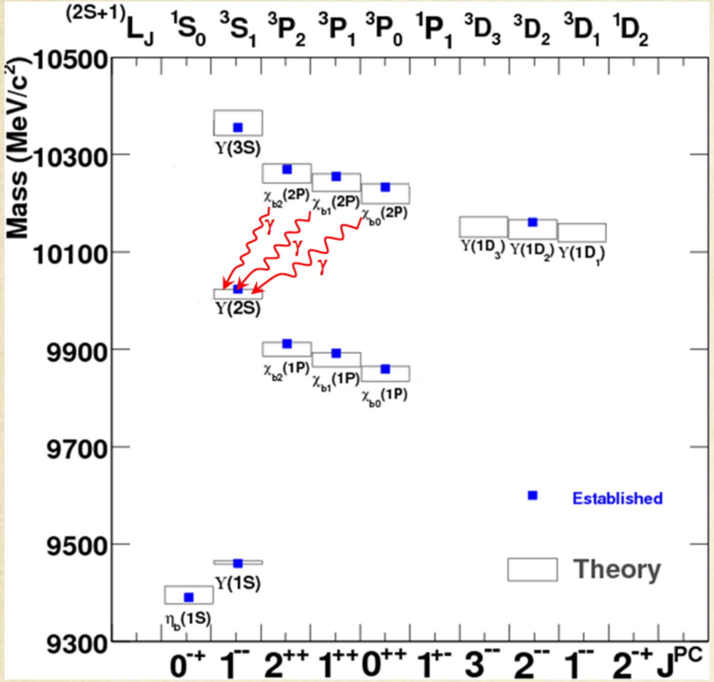
✓1) 180 < $E_{cm}(\gamma)$ < 300 MeV
✓2) 300 < $E_{cm}(\gamma)$ < 600 MeV
✓3) 600 < $E_{cm}(\gamma)$ < 1100 MeV

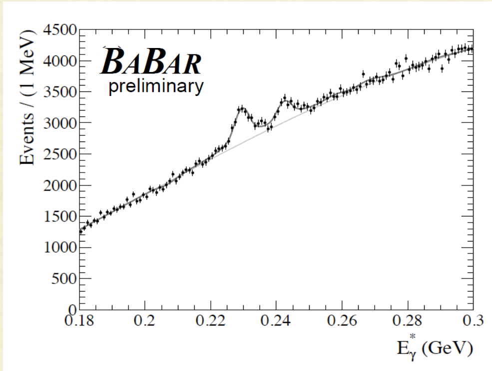


Shaded area of interest Υ(2S)

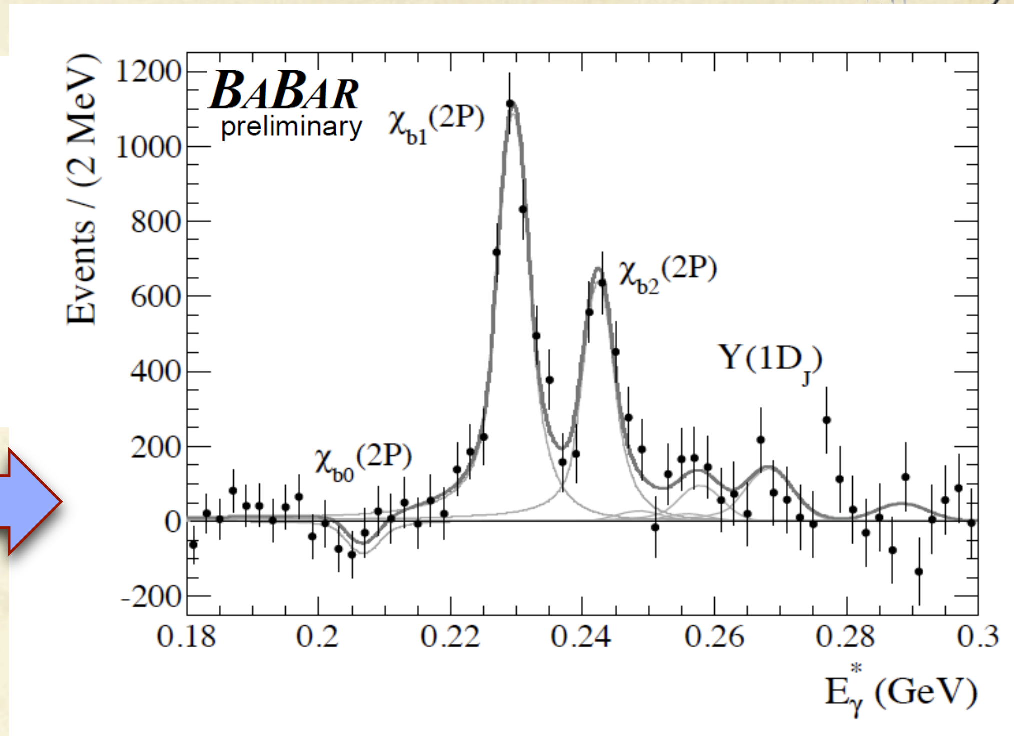
✓4) 300 < $E_{cm}(\gamma)$ < 800 MeV

First region of interest: Υ(3S) data: 180 < $E_{cm}(\gamma)$ < 300 MeV





Background-subtracted

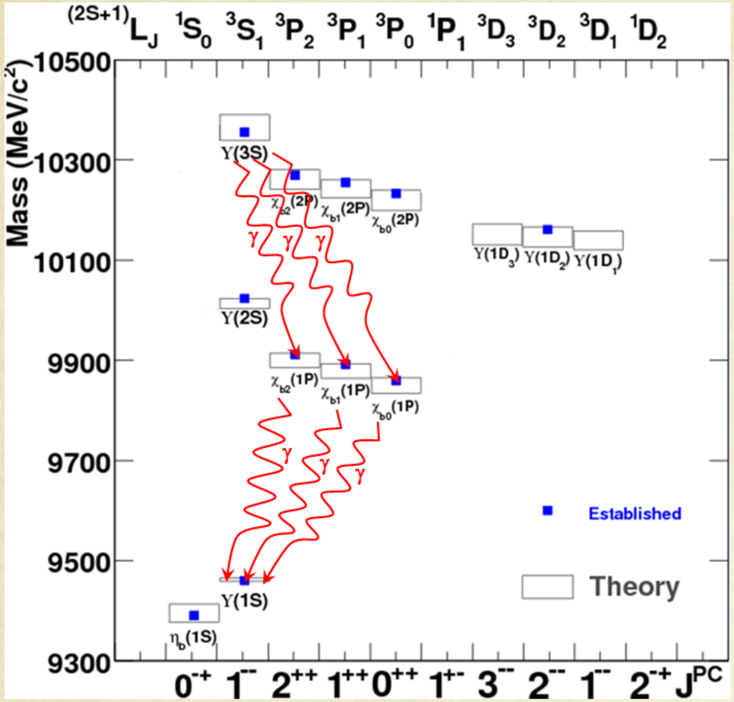


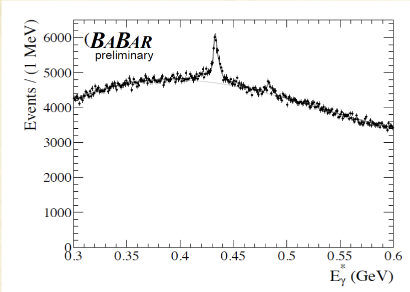
The main purpose of the fit to this region is to study the transitions $\chi_{bJ}(2P) \rightarrow \gamma \Upsilon(2S)$

Clear peaks for $\chi_{bJ}(2P)$ and even a hint for Υ(1D)

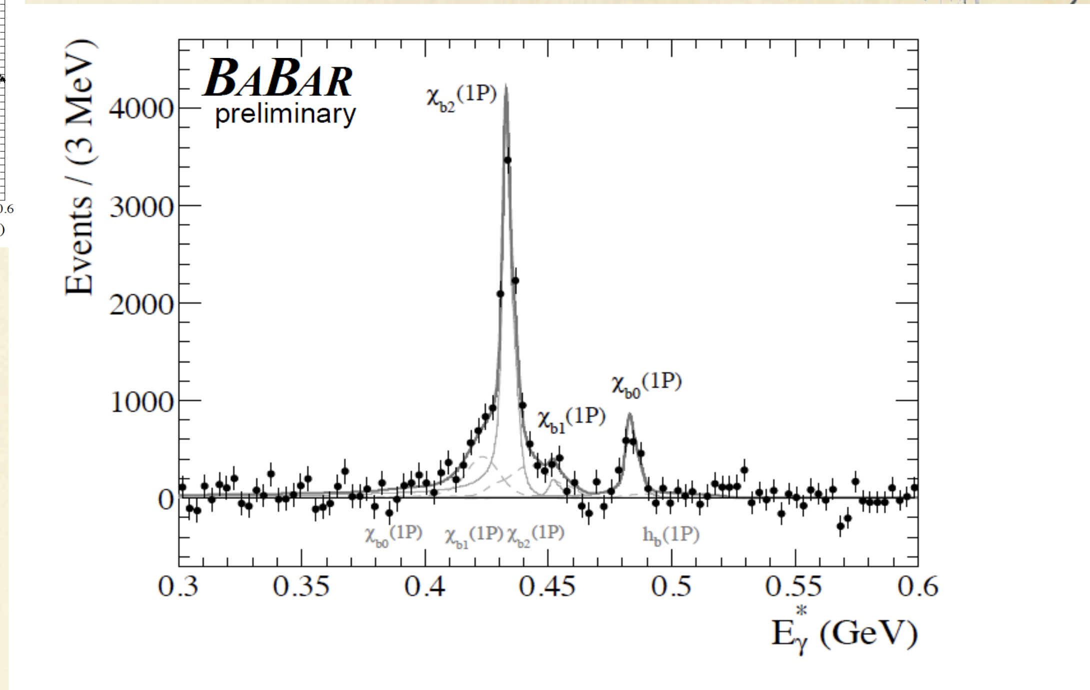
Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) BABAR	CUSB	CLEO
$\chi_{b0}(2P) \rightarrow \gamma\Upsilon(2S)$	205.0	-347 ± 209	0.105	$-4.9 \pm 2.9^{+0.7}_{-0.8} \pm 0.5$ (< 2.9)	3.6 ± 1.6	< 5.2
$\chi_{b1}(2P) \rightarrow \gamma\Upsilon(2S)$	229.7	4294 ± 251	0.152	$19.5 \pm 1.1^{+1.1}_{-1.0}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

Second region of interest Υ(3S) data: 300 <$E_{cm}(\gamma)$<600 MeV





Background-subtracted

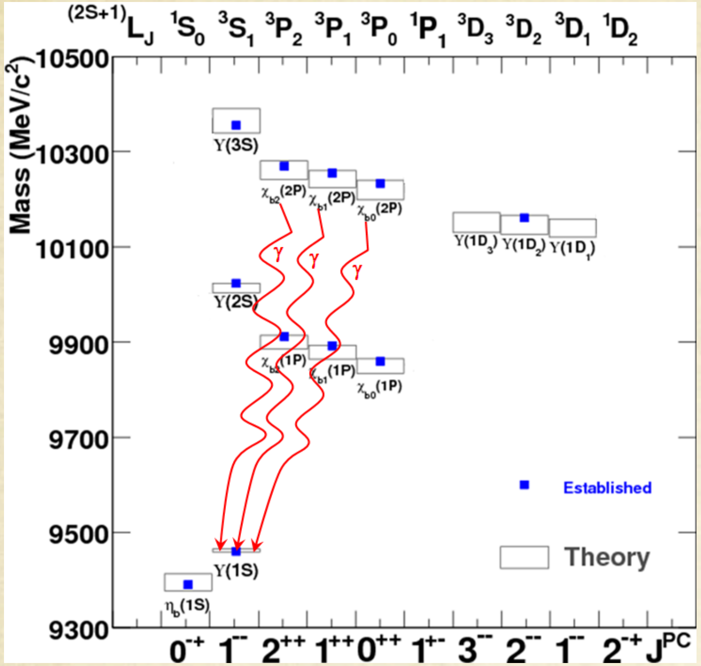


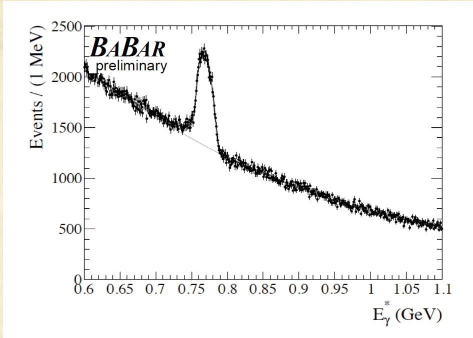
Clear peaks for χ_{bj}(1P)

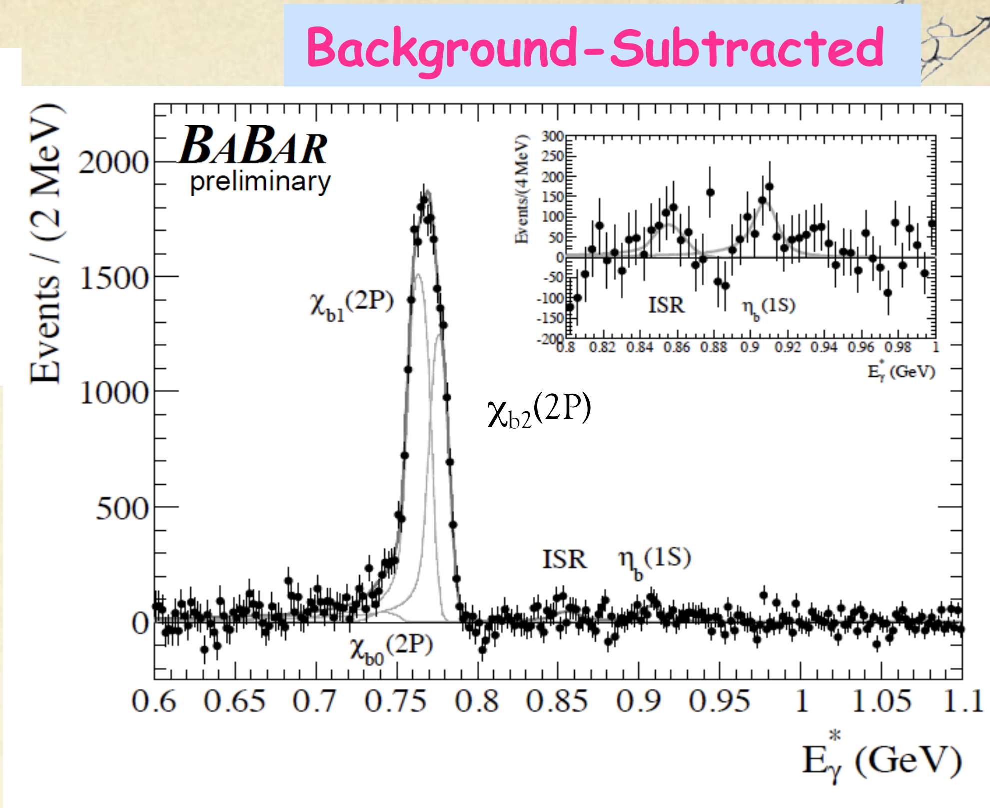
Observation and most precise measurement of Υ(3S) → $\gamma\chi_{b0,2}$(1P)

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

Third region of interest Υ(3S) data: 600 <$E_{cm}(\gamma)$<1100 MeV





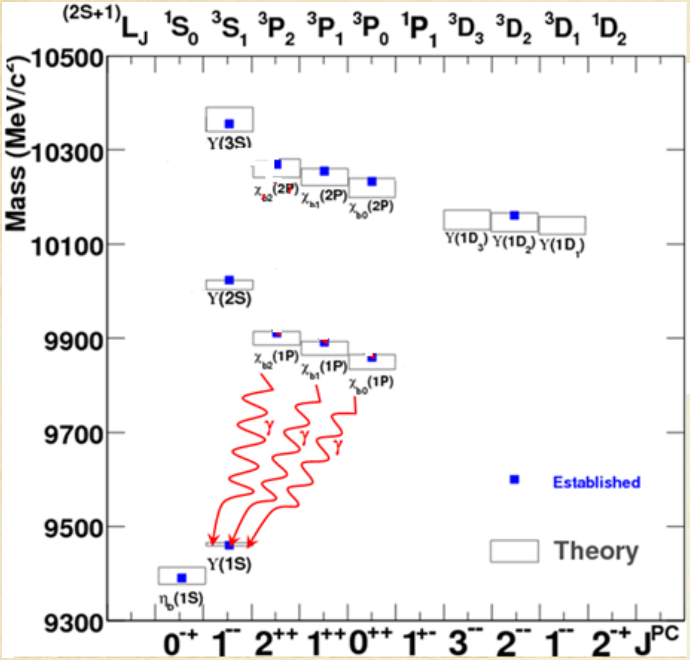


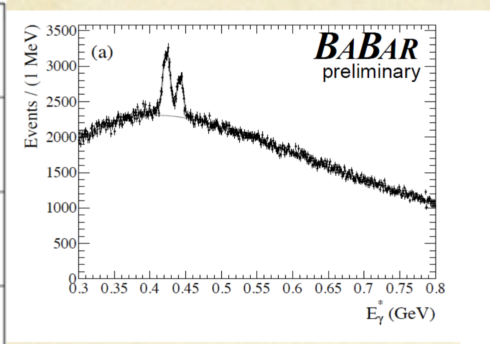
The main purpose of the fit to this region is to study the transitions $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$ and $\Upsilon(3S) \to \gamma\eta_b$

Clear peaks for $\chi_{bJ}(2P)$; no significant evidence for $\eta_b(1S)$

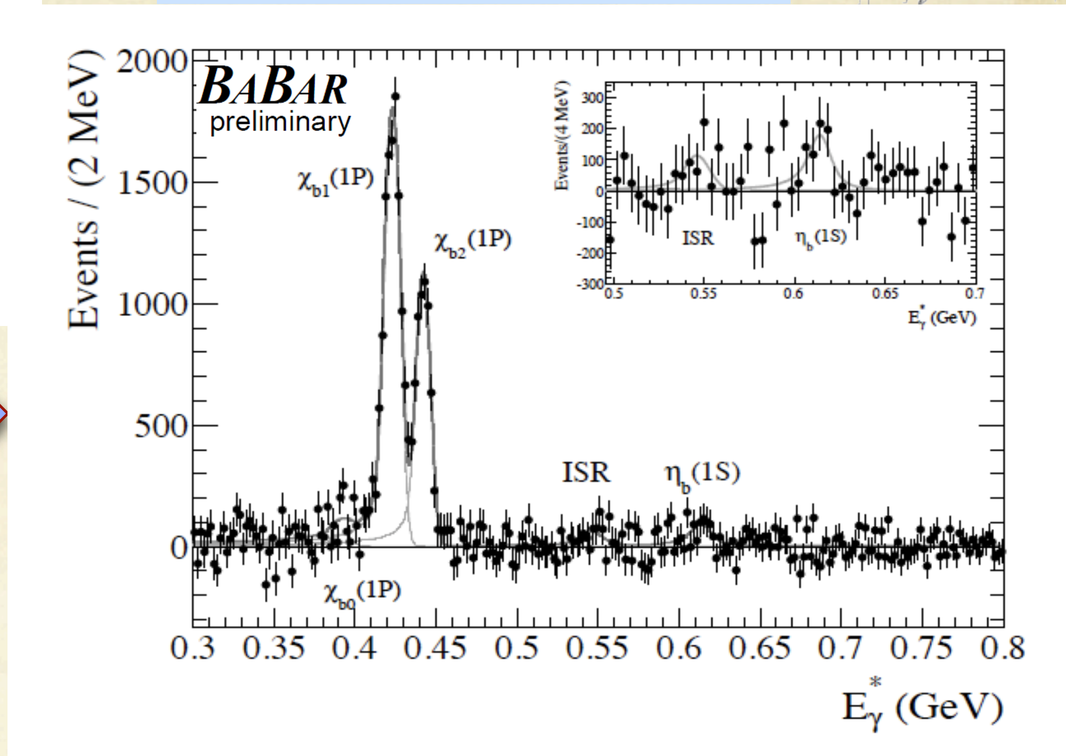
Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) BABAR	CUSB	CLEO
$\chi_{b0}(2P) \to \gamma\Upsilon(1S)$	742.7	469^{+260}_{-259}	1.025	$0.7 \pm 0.4^{+0.2}_{-0.1} \pm 0.1$ (< 1.2)	< 1.9	< 2.2
$\chi_{b1}(2P) \to \gamma\Upsilon(1S)$	764.1	14965^{+381}_{-383}	1.039	$9.9 \pm 0.3 \pm 0.4 \pm 0.9$	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	$0.059 \pm 0.016^{+0.014}_{-0.016}$	-	-

Fourth region of interest Υ(2S) data: $300<E_{cm}(\gamma)<800$ MeV





Background-Subtracted



The main purpose of the fit to this region is to study the transitions $\chi_{bJ}(1P) \rightarrow \gamma \Upsilon(1S)$ and $\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$

Clear peaks for $\chi_{bJ}(1P)$

Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) BABAR	CB	CUSB	CLEO
$\chi_{b0}(1P) \rightarrow \gamma\Upsilon(1S)$	391.5	391 ± 267	0.496	$2.3 \pm 1.5^{+1.0}_{-0.7} \pm 0.2$ (< 4.6)	< 5	< 12	1.7 ± 0.4
$\chi_{b1}(1P) \rightarrow \gamma\Upsilon(1S)$	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
$\chi_{b2}(1P) \rightarrow \gamma\Upsilon(1S)$	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
$\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$	$613.7^{+3.0+0.7}_{-2.6-1.1}$	1109 ± 348	1.050	$0.11 \pm 0.04^{+0.07}_{-0.05}$ (< 0.22)	-	-	-

Radiative transitions from the Υ(2S,3S) with converted photons

Summary of the results

Comparison of branching fractions (as measured by BABAR) with theoretical predictions;

Good overall agreement between experiment and theory;

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

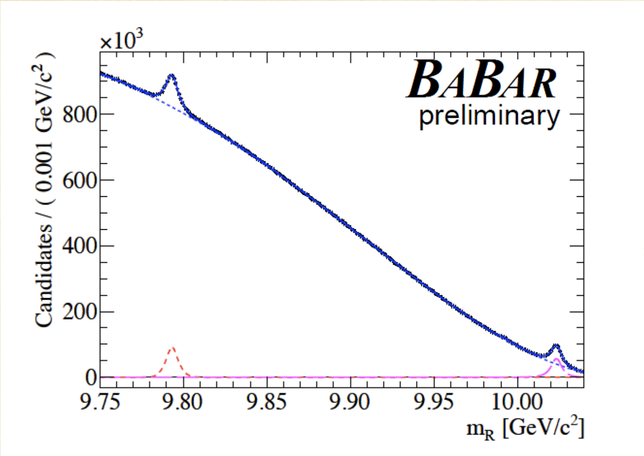
W.Kong and J.L. Rosner, Phys. Rev. D 38, 279 (1988)

The inclusive dipion transition are studied using a fit to the spectrum of the mass m_R recoiling against the $\pi^+\pi^-$ system defined as:

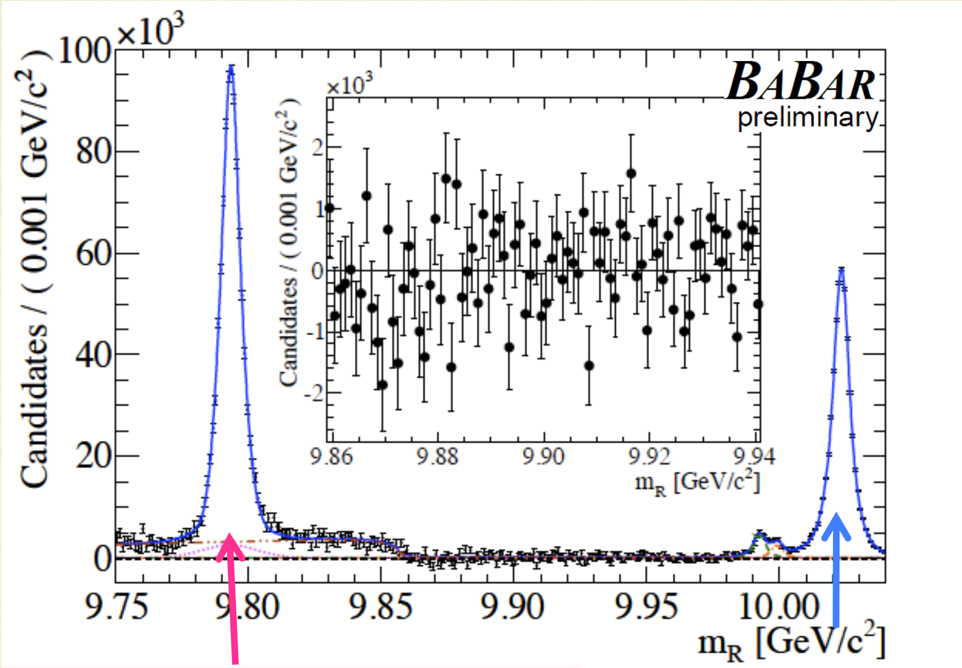
$$m_R^{\ 2} = (M_{Y(3S)} - E^*_{\pi\pi})^2 - \left|P^*_{\pi\pi}\right|^2$$

where $E^*_{\pi\pi}$ and $P^*_{\pi\pi}$ are the measured ππ energy and momentum in the c.m. frame

108×10⁶ Υ(3S) Decays



After background subtraction



Background from $(e^+e^- \to q\bar{q})$

Υ(3S) → Υ(2S)X, Υ(2S) → $\pi^+\pi^-$Υ(1S)

This peak is offset from the Υ(1S) mass by approximately the Υ(3S) to Υ(2S) mass difference

Υ(3S) → $\pi^+\pi^-$Υ(2S)

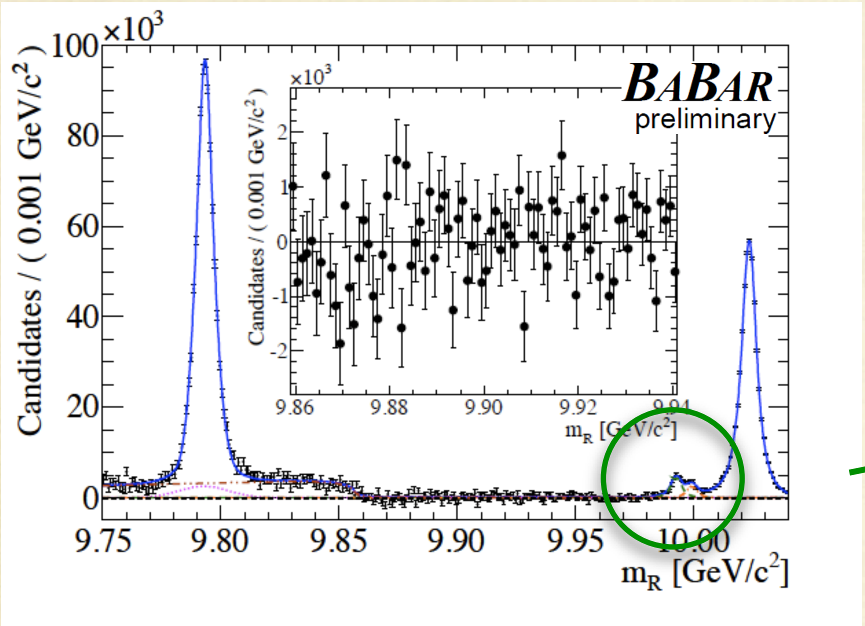
$$B\left[\Upsilon(3S) \to \pi^+\pi^- Y(2S)\right] = (3.00 \pm 0.02(stat) \pm 0.14(syst))\%$$

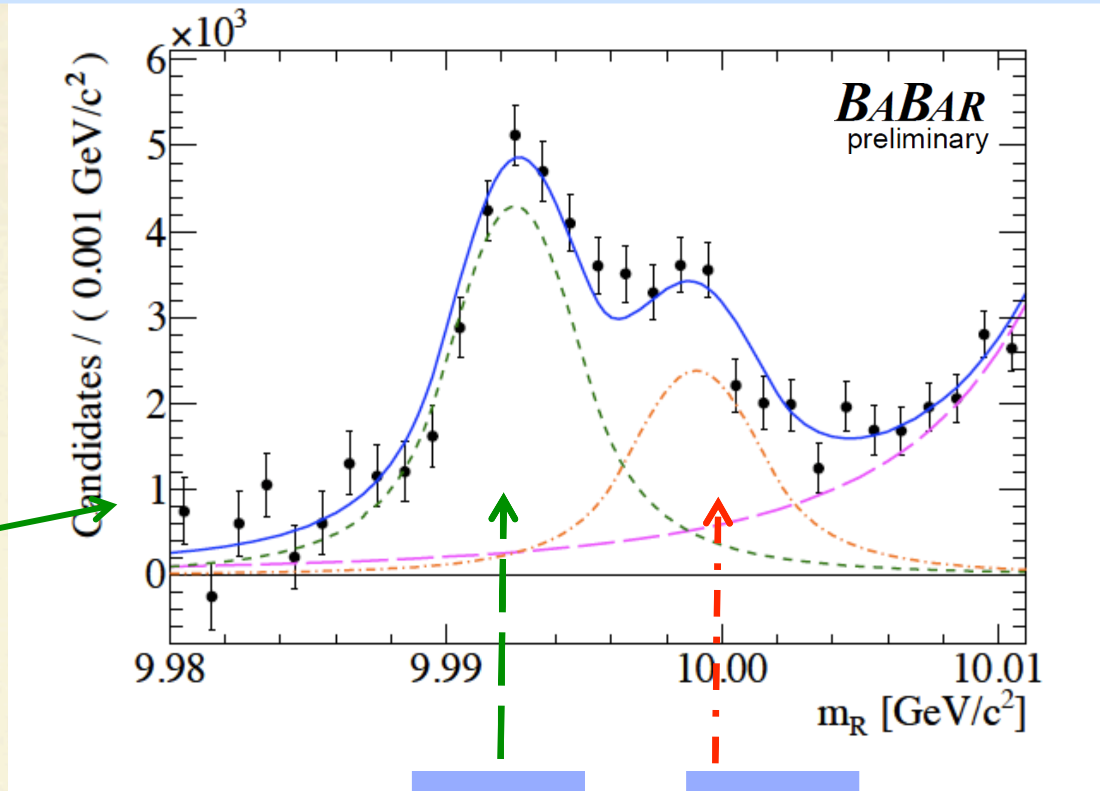
This value is more precise than the current world average

$$m(Y(3S) - Y(2S)) = 331.50 \pm 0.02(stat.) \pm 0.13(syst)\, MeV/c^2$$

Inclusive dipion transitions in Y(3S) Decays (2)

Mass spectrum in the $\chi_b^{J,J}$ region after subtraction of continuum and K_s^0 background components





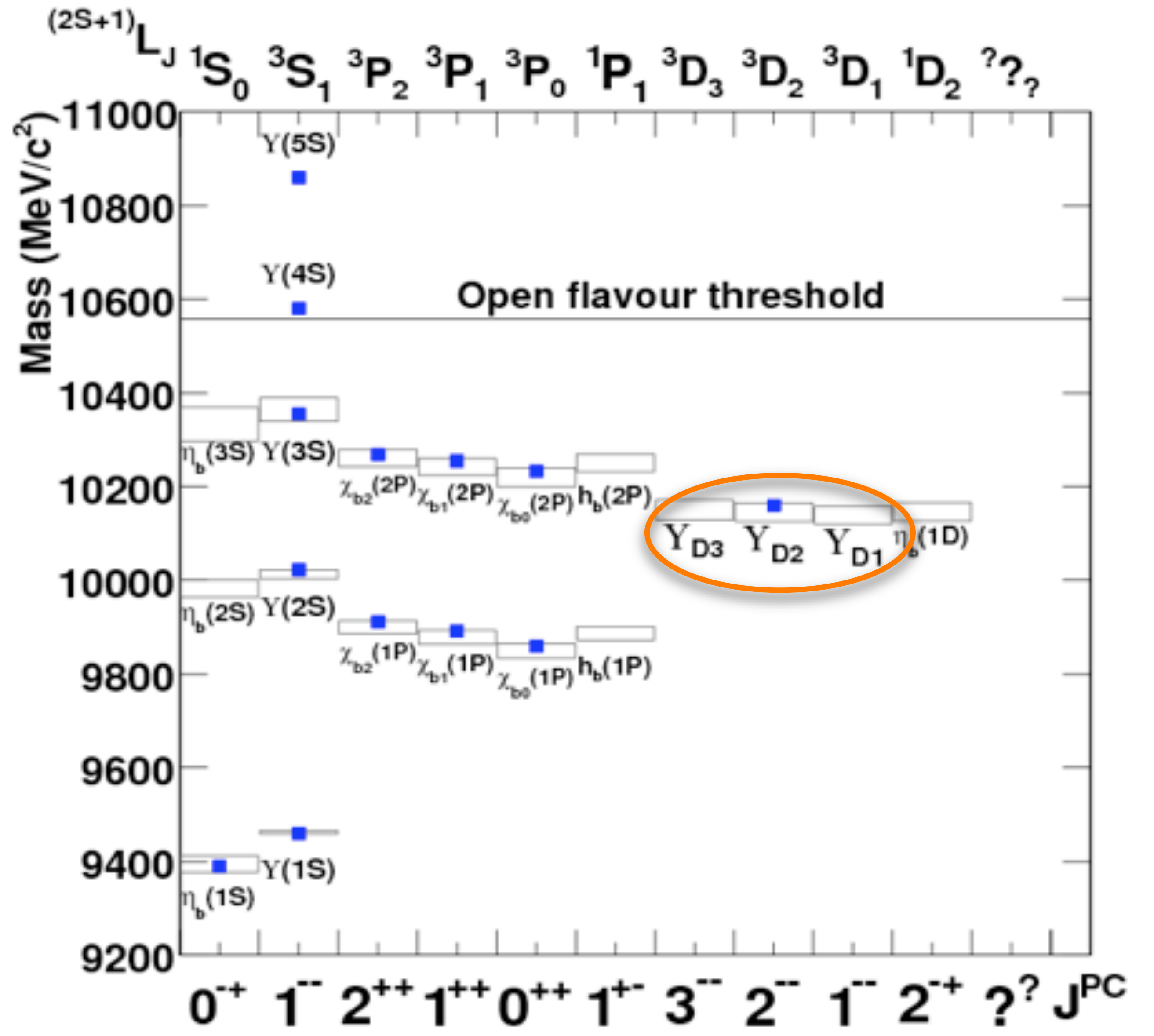
$\chi_b^{1,1}$ $\chi_b^{2,2}$

$\chi_b^{1,1}$: $B\left(\chi_{b1}(2P) \rightarrow \pi^+\pi^-\chi_{b1}(1P)\right) = 9.2 \pm 0.6 \pm 0.9 \times 10^{-3}$

$\chi_b^{2,2}$: $B\left(\chi_{b2}(2P) \rightarrow \pi^+\pi^-\chi_{b2}(1P)\right) = 4.9 \pm 0.4 \pm 0.6 \times 10^{-3}$

CLEO [PRD 73, 012003 (2006)]: the two transitions could not be separated, but the BF values obtained are consistent with the more precise BaBar measurements

Observation of the $\Upsilon(1^3D_J)$ bottomonium state through decays to $\pi^+\pi^-\Upsilon(1S)$ (1)



A single state, interpreted to be the J=2 member of the $\Upsilon(1^3D_J)$ was observed by CLEO in $\Upsilon(1^3D_2) \rightarrow \gamma\gamma\Upsilon(1S)$ but the quantum numbers L, J and P were not verified

PRD 70, 032001 (2004)

Predicted mass ≈10116.0 ± 10 MeV/c^2

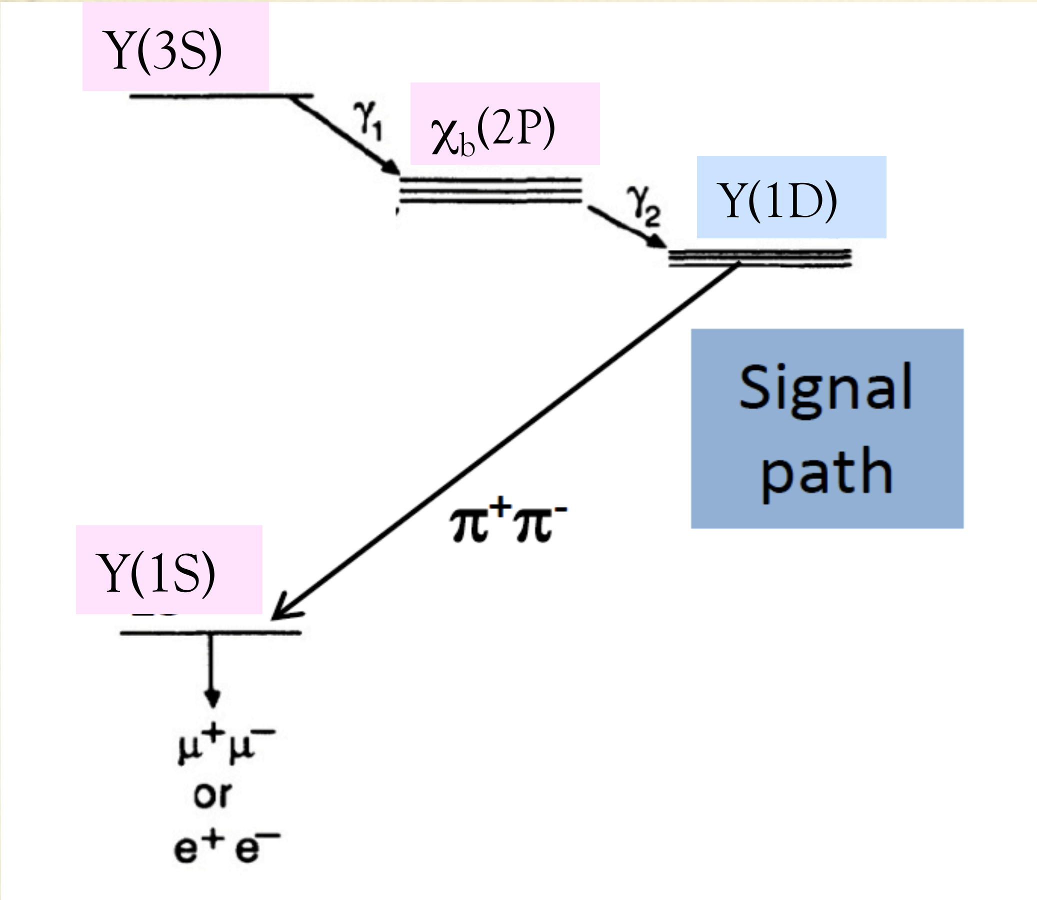
Godfrey& Rosner PRD 64 097501 (2001)

Predicted separation between Triplet states ~ 5-12 MeV/c^2

Observation of the Υ(1^3D_J) bottomonium state through decays to $\pi^+\pi^-$Υ(1S) (2)

PRD 82, 111102(R) (2010)

BaBar reported the observation of the J=2 state of the Υ(1^3D_J) in the hadronic $\pi^+\pi^-$ Υ(1S) decay channel with the Υ(1S) → l^+l^-(l=e,μ)
It provides better mass resolution than Υ(1^3D_2) → γγΥ(1S)
and allows L, J, and P to be tested through measurement of the angular distribution of the $\pi^\pm$ and $l^\pm$



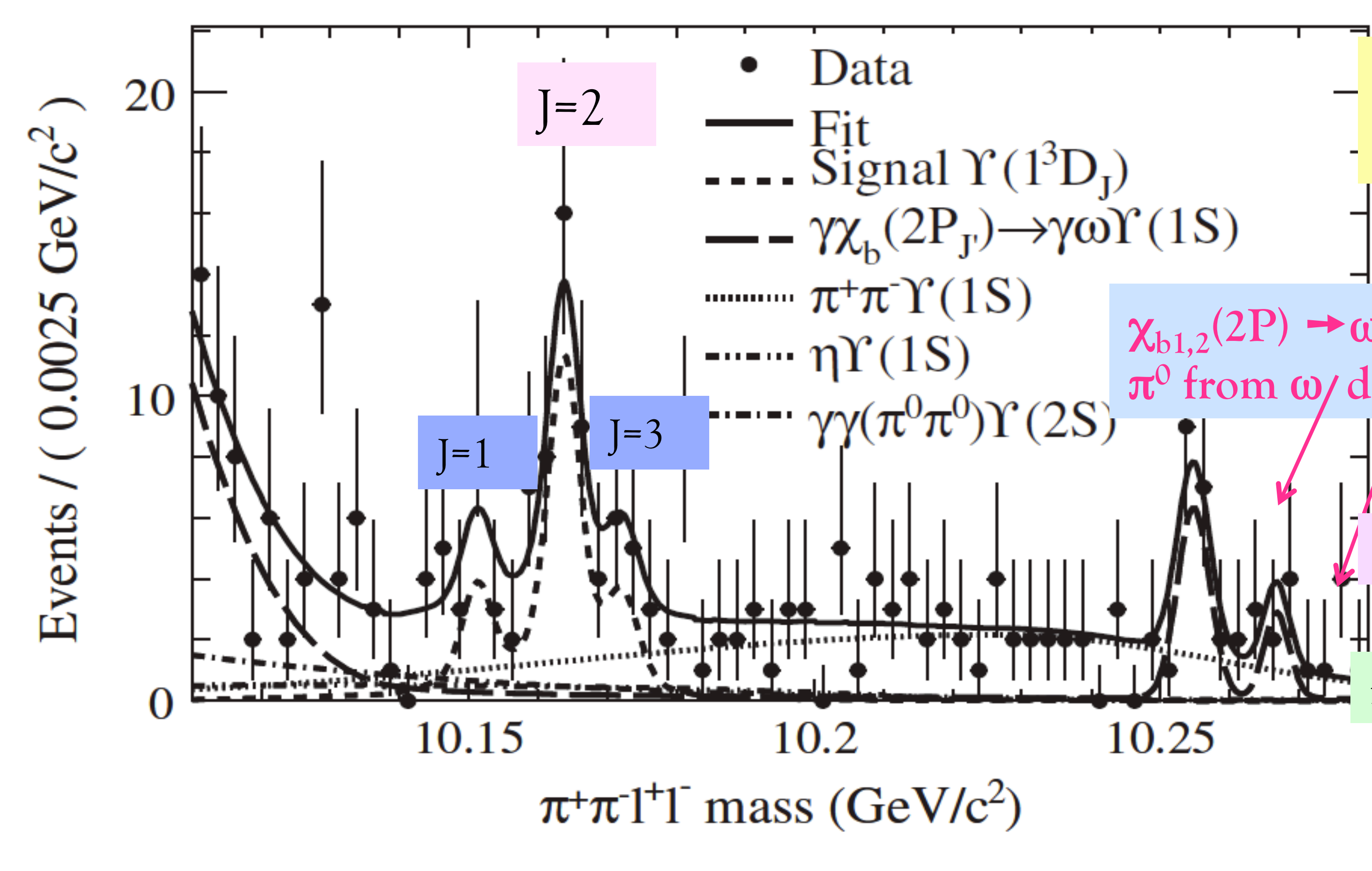
(121.8±1.2)×10⁶ Υ(3S) decays

$$Y(3S) \rightarrow \gamma\chi_{bJ'}(2P) \rightarrow \gamma\gamma Y(1^3D_J)$$

$$Y(3S) \rightarrow \gamma\gamma\pi^+\pi^- l^+ l^-$$

Complete reconstruction of the final state

Observation of the $\Upsilon(1^3D_J)$ bottomonium state through decays to $\pi^+\pi^-\Upsilon(1S)$ (2)



First observation of hadronic $\Upsilon(1^3D_J)$ decays

$\chi_{b1,2}(2P) \to \omega(\to \pi^+\pi^-)\Upsilon(1S)$ the π^0 from ω decay is not found

$m(\Upsilon(1^3D_J) = 10164.5 \pm 0.8 \pm 0.5)$ MeV/c^2

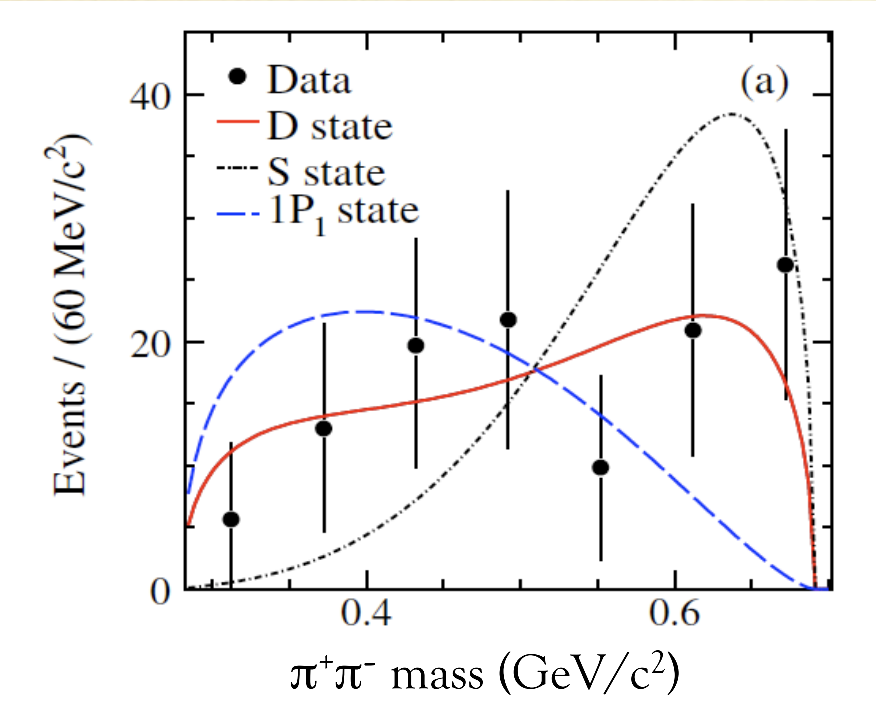
$m(\Upsilon(1^3D_J) = 10161.1 \pm 0.6 \pm 1.6)$ MeV/c^2

PRD 70, 032001 (2004)

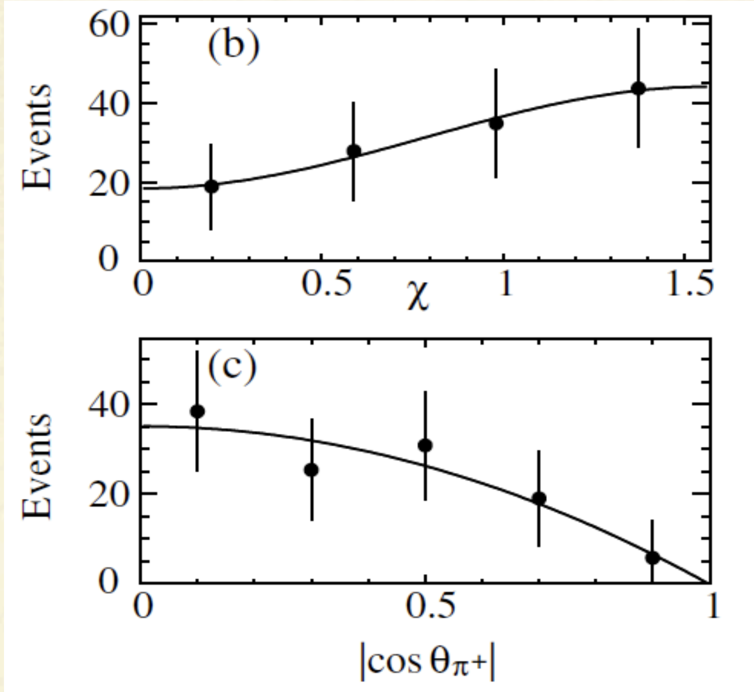
Measured BF's compared to Theory Predictions

1^3D_J	σ	Branching Fraction	90% CL UL	Ko (1993)	Moxhay (1988)
J=1	1.8σ	$(0.42^{+0.27}_{-0.23} \pm 0.10)\%$	<0.82%	1.6%	0.20%
J=2	5.8σ	$(0.66^{+0.15}_{-0.14} \pm 0.06)\%$		2.0%	0.25%
J=3	1.7σ	$(0.29^{+0.22}_{-0.18} \pm 0.06)\%$	<0.62%	2.2%	0.27%

$\pi^+\pi^-$ mass distribution for events in the Y(1^3D_2) signal region after background subtraction. The fit favors the D state hypothesis



χ is the angle between the l^+l^- and $\pi^+\pi^-$ planes



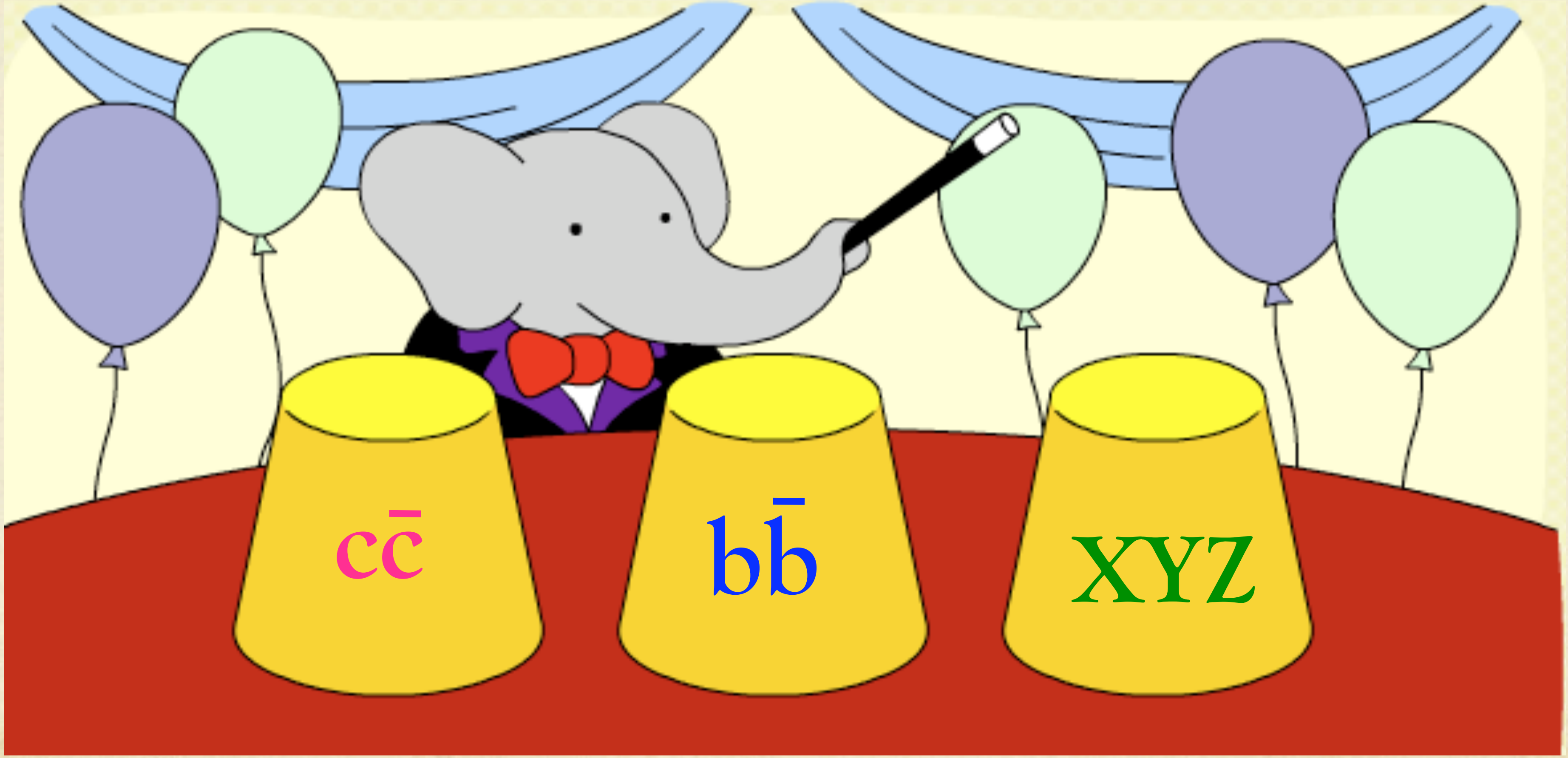
π^+ helicity angle

The χ distribution is expected to have the form of
$1+\beta\cos 2\chi$ with $\text{sgn}(\beta)=(-1)^J P$. J.R. Dell'Aquila & C.C. Nelson, PRD 33 (1986) 80
A fit to the data yield $\beta=-0.41\pm0.29(\text{stat})\pm0.10\ (\text{syst})$ ➔ J=2, P=−1

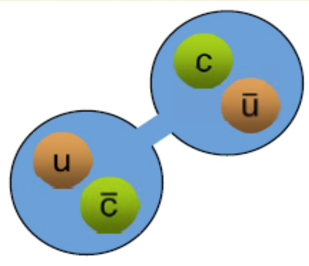
Conclusions

- ✓ Charmonium and Bottomonium spectroscopy has been revitalized by the B-factories discoveries made possible by their very large data samples
- ✓ With 1.6 ab^{-1} five missing pieces in the charmonium and bottomium spectrum ($\eta_c(2S)$,$\chi_{c2}(2P)$,$\eta_b(1S)$,$h_b(1P)$, $h_b(2P)$) snd several unexpected new states, have been found and many precise measurements have been performed
- ✓ New exciting results are still coming from BaBar and Belle
- ✓ After the lessons learned from BaBar and Belle, and given that the next generation of B-factoriesis being realized, even more exciting new results can be anticipated in the not-too-distant future

BACK-UP SLIDES

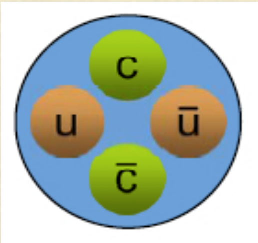


Exotic charmonium-like states interpretatations



Molecular state:
loosely bound state of a pair of mesons.
The dominant binding mechanism should be pion exchange. Being weakly bound, mesons tend to decay they were free.

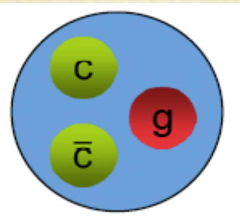
NA Tornqvist PLB 590, 209 (2004)
ES Swanson PLB 598,197 (2004)
E Braaten & T Kusunoki PRD 69 074005 (2004)
CY Wong PRC 69, 055202 (2004)
MB Voloshin PLB 579, 316 (2004)
F Close & P Page PLB 578,119 (2004) …..



Tetraquark:
Bound state of four quarks, i.e. diquark-antidiquark
Strong decays proceed via rearrangement processes.

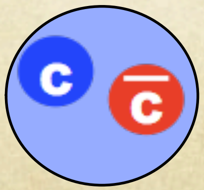
L Maiani et al PRD 71,014028 (2005)
T-W Chiu & TH Hsieh PRD 73, 111503 (2006)
D Ebert et al PLB 634, 214 (2006)
…

Distinctive features of multi-quark picture with respect to charmonium:
- prediction of many new states
- possible existence of states with non-zero charge, strangeness or both.



Charmonium hybrids
States with an excited gluonic degree of freedom
Lattice and model predictions for the lowest lying hybrid:
m ~4200 MeV

P Lacock et al (UKQCD) PLB 401, 308 (1997)
SL Zhu PLB 625, 212 (2005)
FE Close, PR Page PLB 628, 215 (2005)
E Kou, O Pene PLB 631, 164 (2005)
…



Conventional charmonium

C Meng & KT Chao PRD 75, 114002 (2007)
W Dunwoodie & V Ziegler PRL 100 062006 (2008)
O Zhang, C Meng & HQ Zheng arXiv:0901.1553
…