Charmonium & Charmonium-like States with BaBar

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Representing the BaBar Collaboration

Outline

- Introduction and Overview

- Evidence for the decay $X(3872) \to J/\psi\omega$

PRD (RC) 82, 0111101 (2010)

- Observation of $\chi_{c2}(2P)$ meson in the reaction $\gamma\gamma \to D\bar{D}$

PRD 81, 092003 (2010)

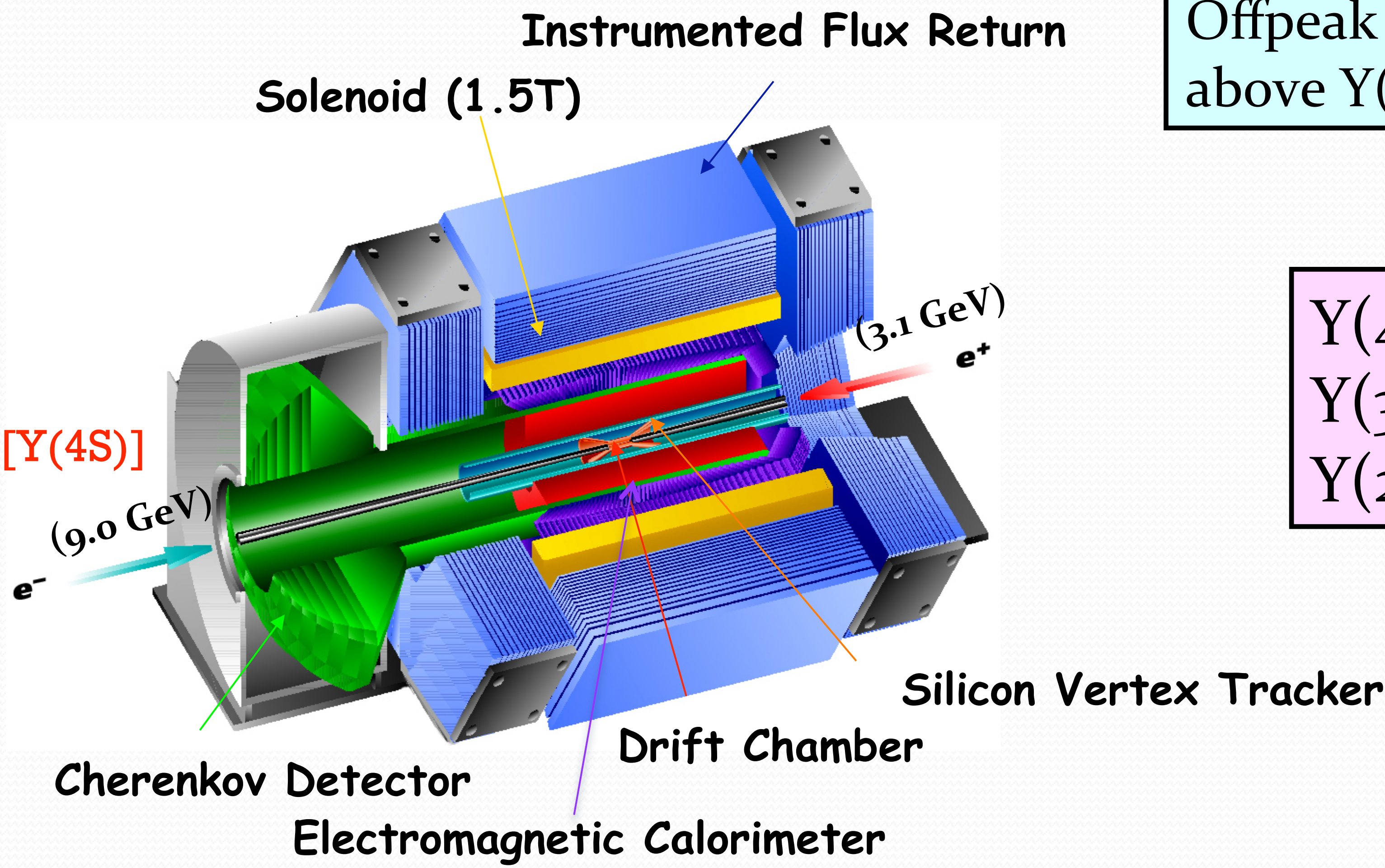
- Observation of $\eta_c(1S)$ and $\eta_c(2S)$ decays to $K^+K^-\pi^+\pi^-\pi^0$ in two photon interactions

arXiv:1103.3971v2

The BaBar detector and data sample

BaBar is a powerful *b* factory: 467 million $B\bar{B}$ pairs in the total data sample

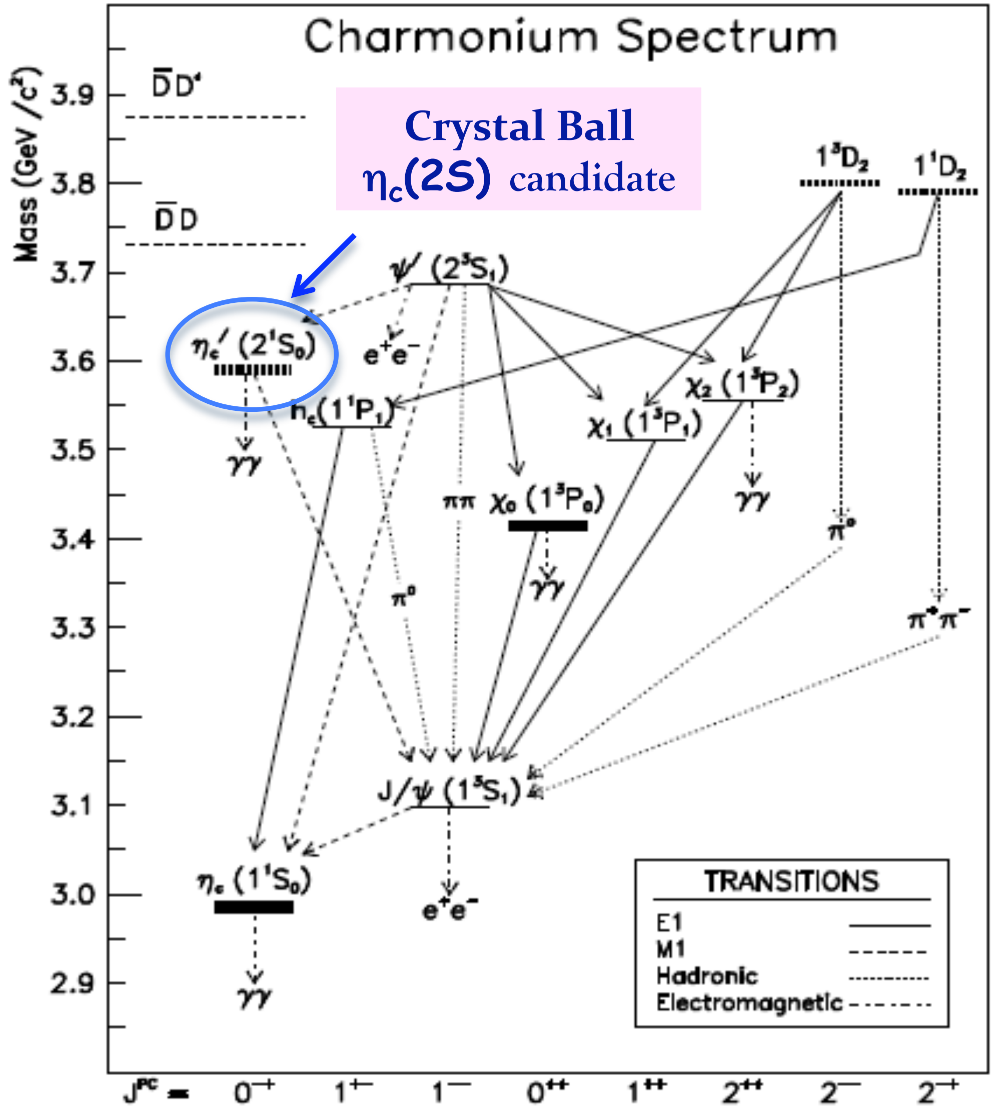
BaBar is also a *c* factory: 1.3 million Charm events per fb^{-1}



Offpeak (10.54GeV) + Scan above $\Upsilon(4S)$: 53.9 fb^{-1}

$\Upsilon(4S)$: 432 fb^{-1}
$\Upsilon(3S)$: 30.2 fb^{-1}
$\Upsilon(2S)$: 14.5 fb^{-1}

Charmonium Spectrum before the B-factories

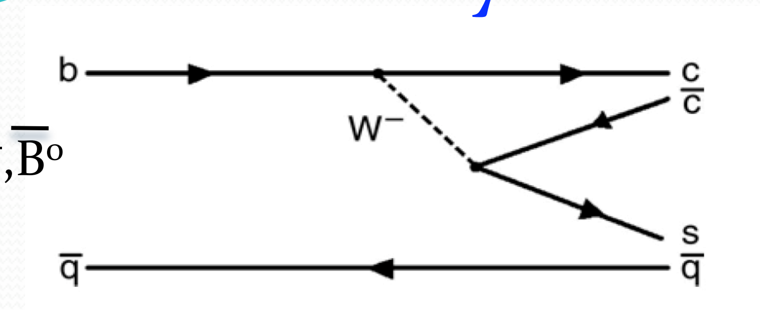


- Charmonium properties were well understood up to $\psi(3770)$ (i.e. about the $D\bar{D}$ threshold) with some missing pieces (like the $\eta_c(2S)$)
- No new $c\bar{c}$ states were discovered between 1980 to 2002
- $c\bar{c}$ states above open charm threshold are expected to have significant width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

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

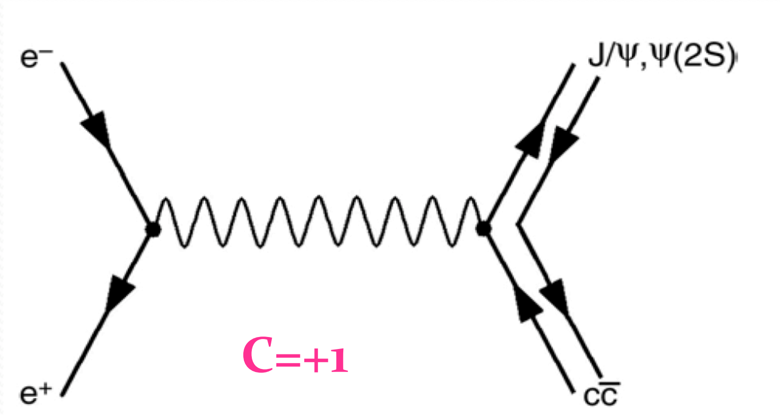
B decays

$B^-, \overline{B}^0$



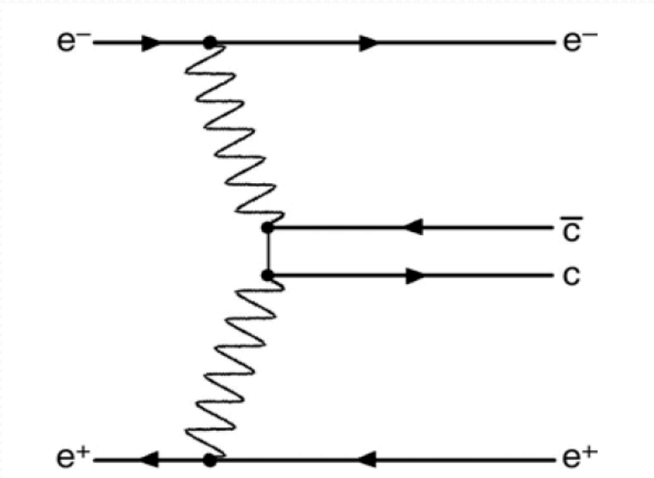
States of any quantum numbers can be formed

Double charmonium production



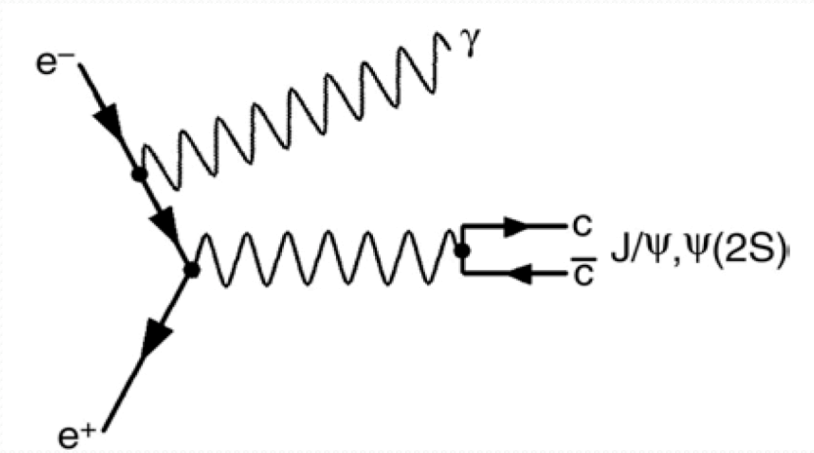
C=+1

2 γ production



$J^{PC}=0^{\pm+}, 2^{\pm+}$…

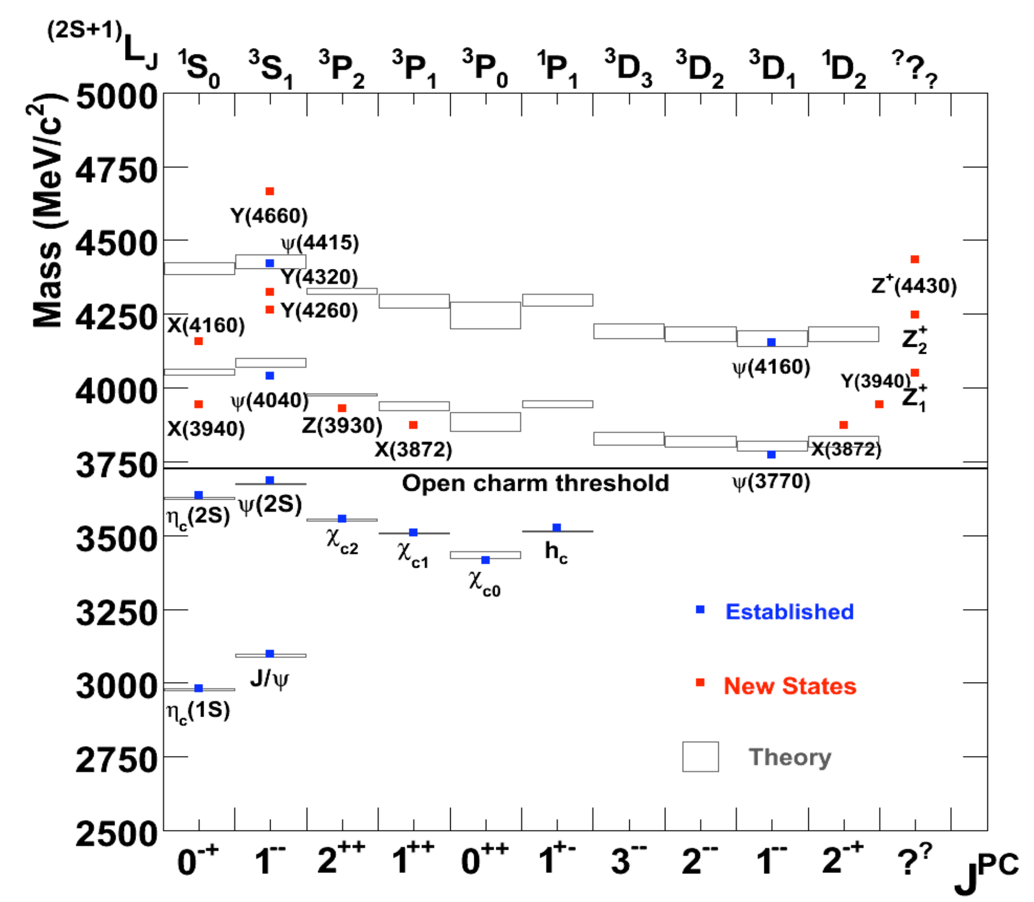
Initial State Radiation (ISR)



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

Charmonium spectrum

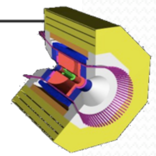
(June 2011)



- 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^{+-}	$\psi(2S) \to \pi^0(\gamma\eta_c(1S))$ $\psi(2S) \to \pi^0(\gamma ...)$ $p\bar{p} \to (\gamma\eta_c) \to (\gamma\gamma\gamma)$ $\psi(2S) \to \pi^0(...)$
$\eta_c(2S)$	3637 ± 4	14 ± 7	0^{-+}	$B \to K(K^0_S K^- \pi^+)$ $e^+e^- \to e^+e^-(K^0_S K^- \pi^+)$
				$e^+e^- \to J/\psi\ (...)$
$\chi_{c2}(2P)$	3927.2 ± 2.6	24.1 ± 6.1	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$



Z(3930)

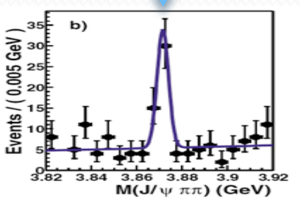
Charmonium-like States at the B Factories

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

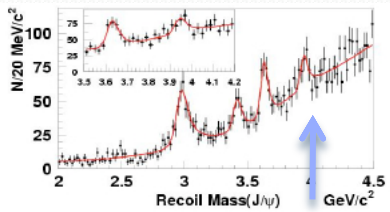
State	M, MeV	Γ, MeV	J^{PC}	Process
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$
		(< 2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$
				$B \to K(\omega J/\psi)$
				$B \to K(D^{*0}D^0)$
				$B \to K(\gamma J/\psi)$
				$B \to K(\gamma\psi(2S))$
$X(3915)$	3915.6 ± 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

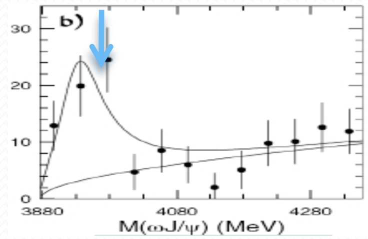
X(3872)
PRL 91, 262001 (2003)



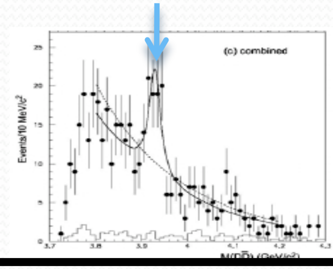
X(3940)
PRL 98, 082001 (2007)



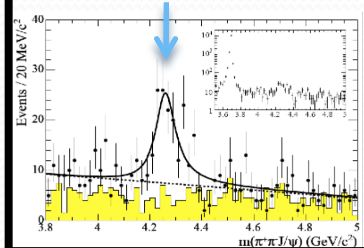
Y(3940)
PRL 94, 182002 (2005)



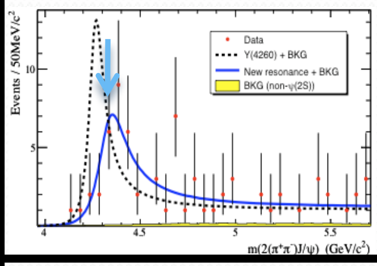
χ_{c2}(2P)
PRL 96, 082003 (2006)



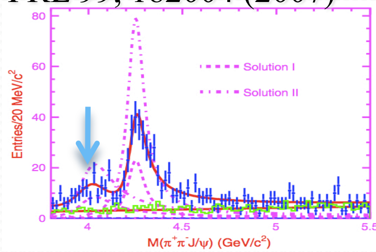
Y(4260)
PRL 95, 142001 (2005)



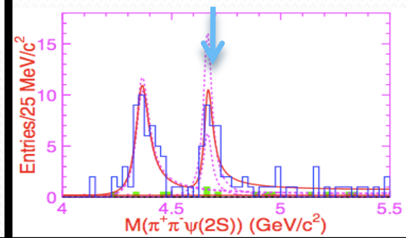
Y(4350)
PRL 98, 212001 (2007)



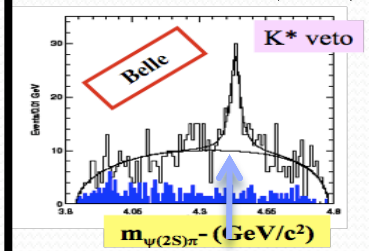
Y(4008)
PRL 99, 182004 (2007)



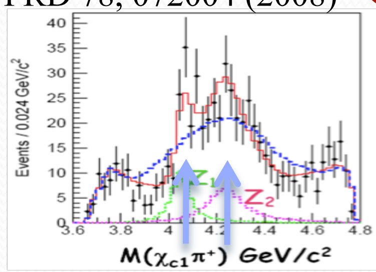
Y(4660)
PRL 99, 142002 (2007)



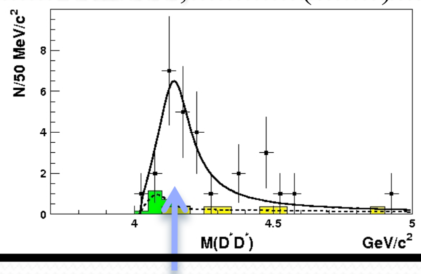
Z(4430)$^+$
PRL 100, 142001 (2008)



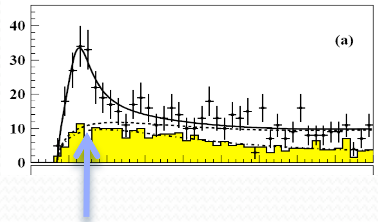
Z_1^+ and Z_2^+
PRD 78, 072004 (2008)



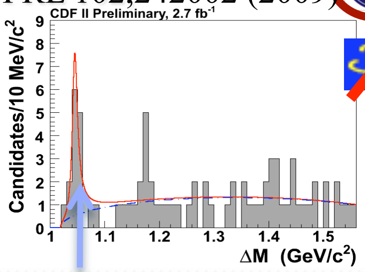
X(4160)
PRL 100,202001 (2008)



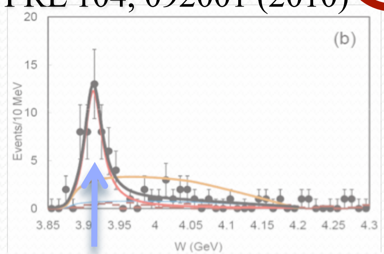
X(4630)
PRL 101, 172001 (2008)



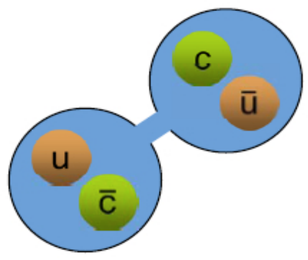
Y(4140)
PRL 102,242002 (2009)



X(3915)
PRL 104, 092001 (2010)

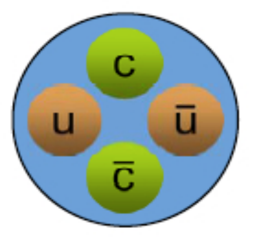


Exotic charmonium-like states interpretation



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 as if they were free.

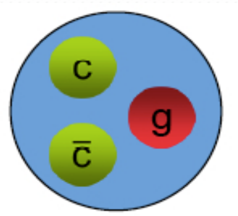
NA Tornqvist PLB 590, 209 (2004)
ES Swanson PLB 598,197 (2004)
E Braaten & T Kusunoki PRD 69 074005 (2004)
CY Wong PRC 69, 055202 (2004)
MB Voloshin PLB 579, 316 (2004)
F Close & P Page PLB 578,119 (2004) …..



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

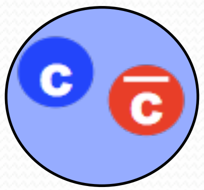
L Maiani et al PRD 71,014028 (2005)
T-W Chiu & TH Hsieh PRD 73, 111503 (2006)
D Ebert et al PLB 634, 214 (2006)
…

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.



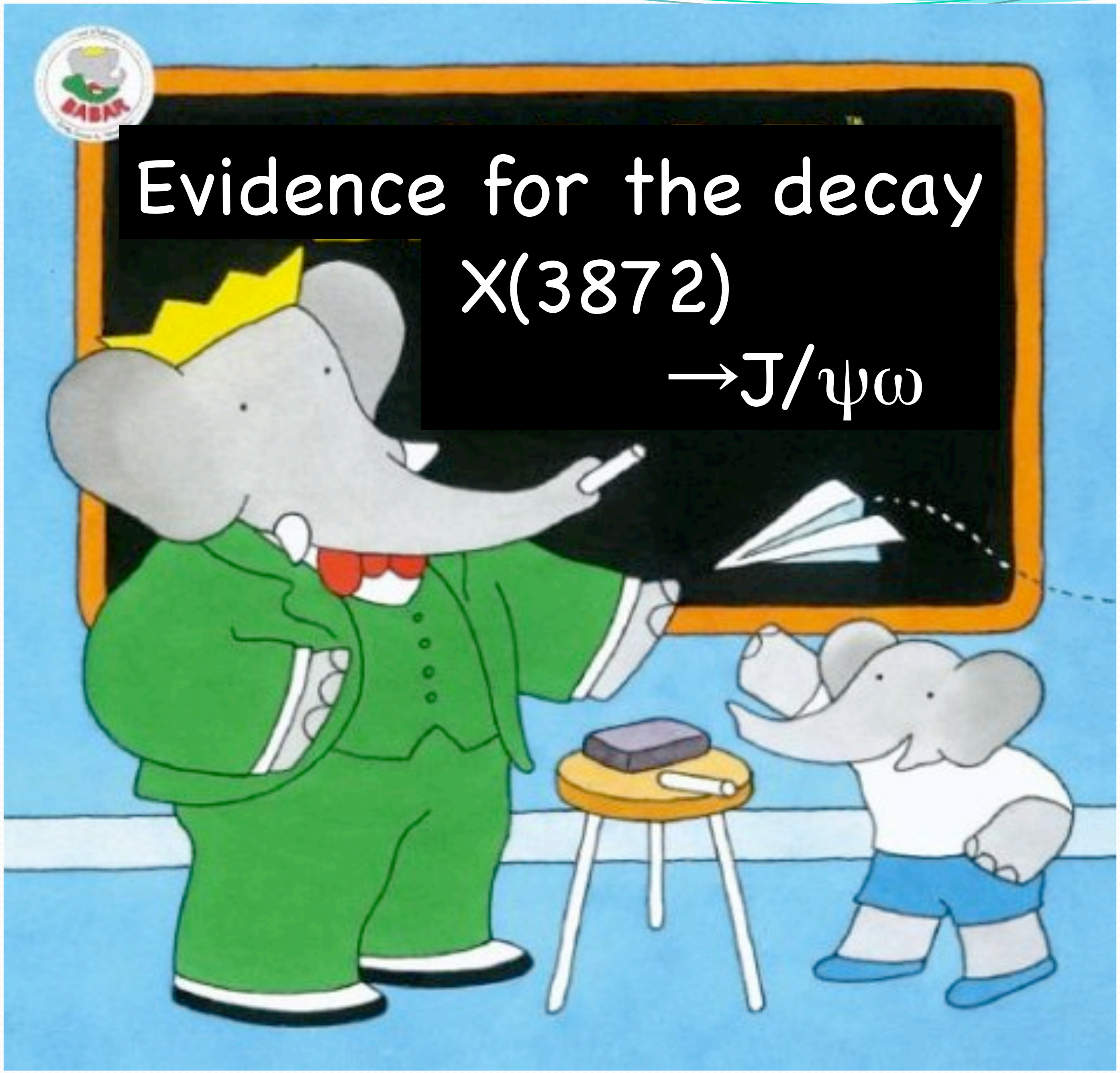
Charmonium hybrids
States with an excited gluonic degree of freedom
Lattice and model predictions for the lowest lying hybrid:
m ~4200 MeV

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
…


Evidence for the decay
X(3872)
→J/ψω

The X(3872)

X(3872) Properties

Narrow ($\Gamma \leq 2.3$ MeV according to PDG 2010) with mass m(X)=3871.61±0.25 MeV/c^2

Observed in X(3872) $J/\psi\pi^+\pi^-$, dipion mass is "ρ-like" but possible "ρ−ω" interference

Also seen in decays X(3872) → $D^0\overline{D}^{*0}$ and X(3872) → J/ψ γ,

X(3872) → ψ(2S)γ seen by BaBar but not by Belle

C is positive, spin-parity identified as either $J^{PC} = 1^{++}$ or 2^{-+}; isospin I=0

Conventional Charmonium interpretation

$\chi_{c1}(2^3P_1)$ (1^{++}) or $\eta_{c2}(1^1D_2)$ (2^{-+})

X(3872) is narrow and for unnatural spin-parity cannot decay to →$D\overline{D}$

Not expected to violate isospin, X→ J/ψ ρ;

Near $D^{*0}\overline{D}^0$ and J/ψω threshold, → isospin violating decay could be significant

Mass inconsistent with predicted $\chi_{c1}(2P)$

$D^0\overline{D}^{*0}$ Molecular interpretation:

$m(D^0) + m(\overline{D}^{*0}) = 3871.73 \pm 0.29$ MeV/c^2

Decays to X(3872) → J/ψ ρ, $D^0\overline{D}^{*0}$, J/ψω expected

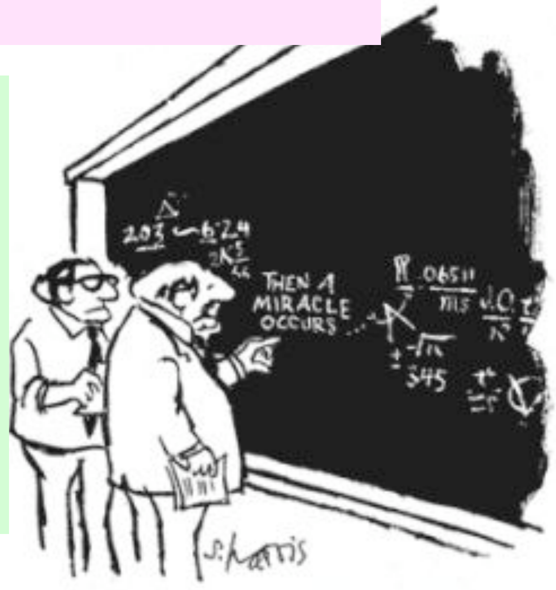
Compatible with $J^{PC} = 1^{++}$ assignment;

Mass shift ~ 3.5 MeV/c^2 [BaBar and Belle] not expected;

favors $J^P = 2^-$

PRL 100, 062006 (2008)

Successful predictions vary by model



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

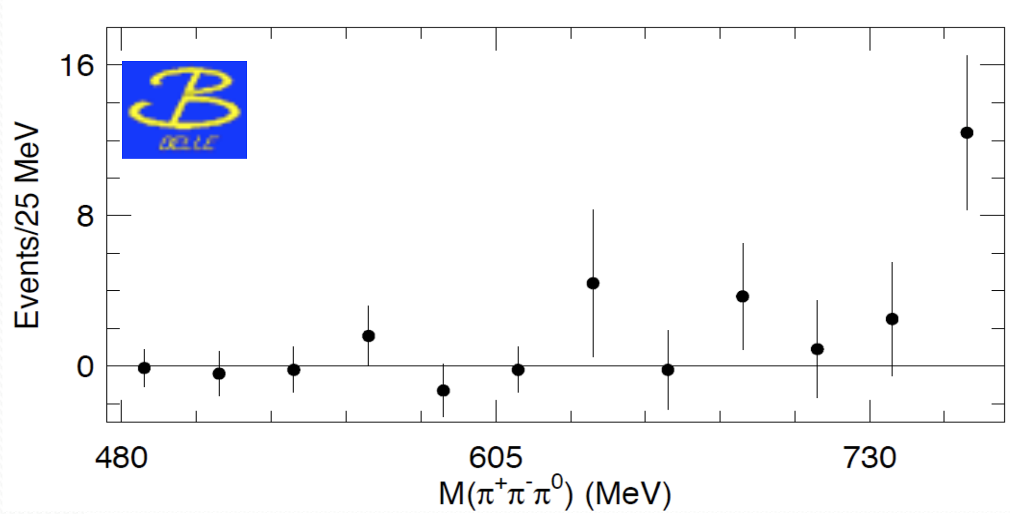
$X(3872) \to J/\psi\omega$ (Motivation)

- Belle reported an excess of events in $m_{3\pi}$ above 750 MeV/c² in the decay $B \to J/\psi 3\pi K$

  for $|m_{J/\psi 3\pi}-3872|<16.5$ MeV/c² interpreted as $X \to J/\psi\omega$

  (but unpublished)

hep-ex/0505037

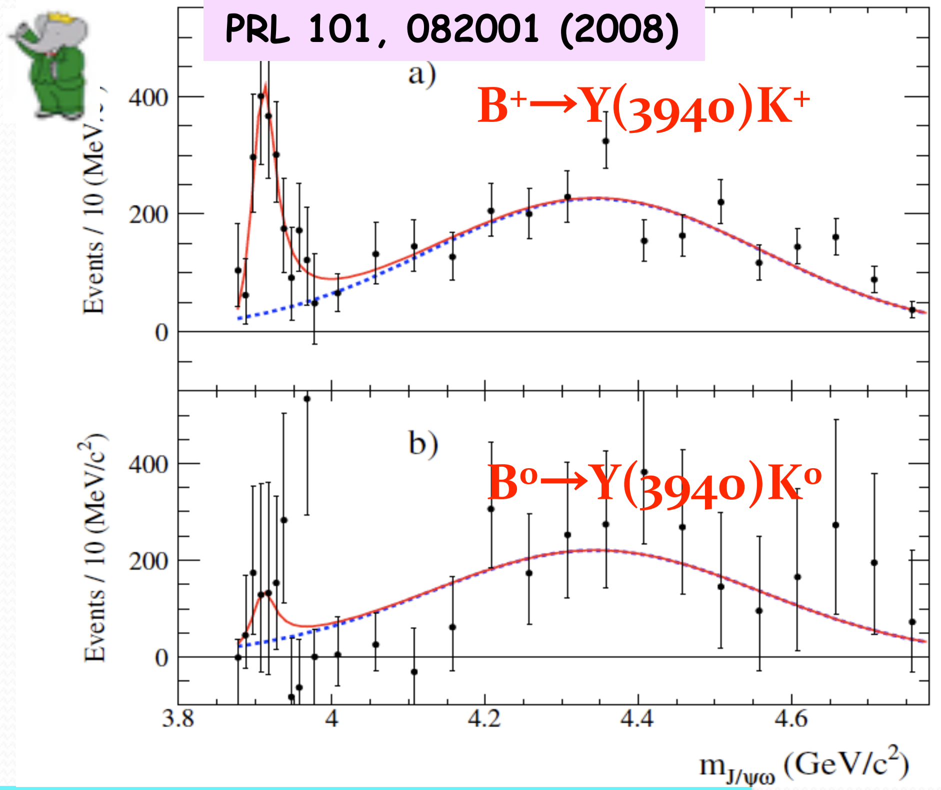


BABAR, confirmed the existence of the Y(3940) in $B \to Y(J/\psi\omega)K$ but did not observe the $X(3872) \to J/\psi\omega K$ signal when requiring

$0.7695 < m_{3\pi} < 0.7965$ GeV/c²

From optimized selection; but assumes all dynamical features of interest have access to the entire ω lineshape

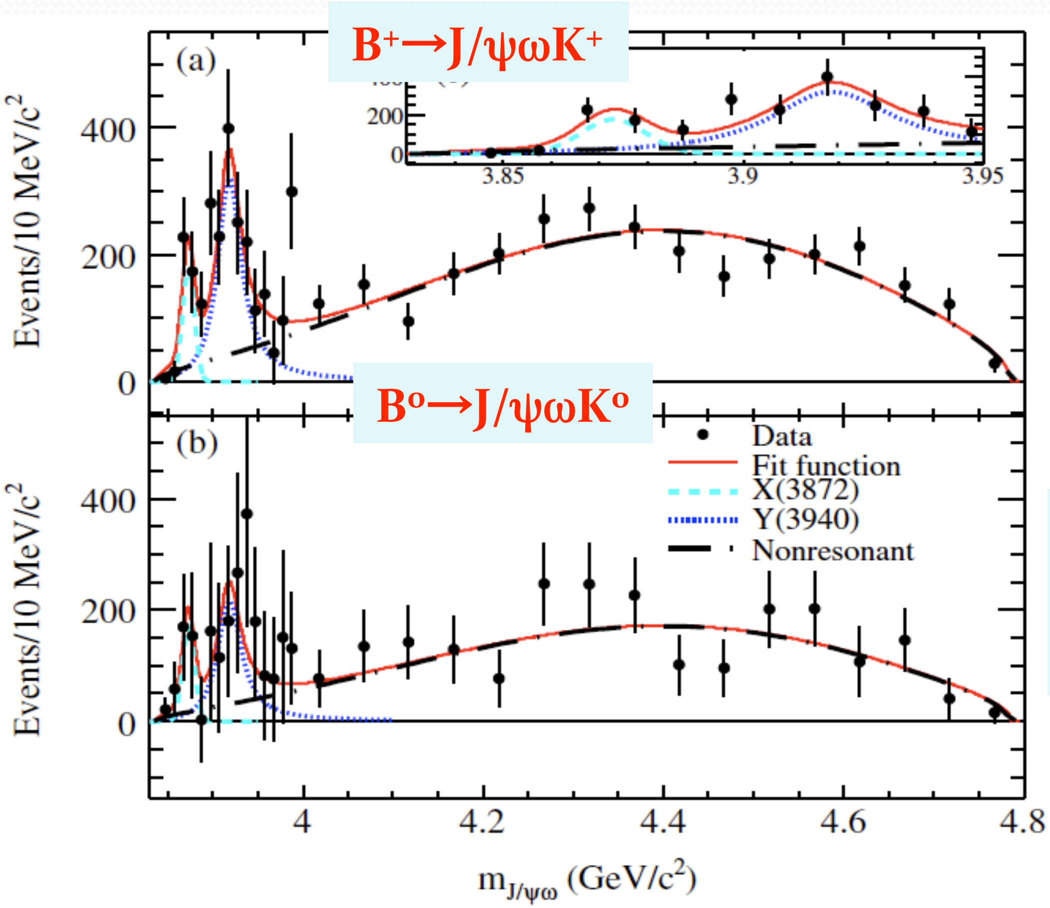
PRL 101, 082001 (2008)



X(3872) →J/ψω (New BaBar Analyis)

Same selection criteria used in the previous BABAR analysis, **except that on the lower mass limit of the ω signal region**

OLD BaBar analysis	NEW BaBar analysis
$0.7695<m_{3\pi}<0.7965$ Mev/c² (B⁺)	**0.7400**$<m_{3\pi}<0.7965$ MeV/c² (B⁺)
$0.7605<m_{3\pi}<0.8055$ Mev/c² (B⁰)	**0.7400**$<m_{3\pi}<0.8055$ MeV/c² (B⁰)
PRL 101, 082001 (2008)	PRD (RC) 82, 0111101 (2010)



X(3872): Gaussian function (resolution)

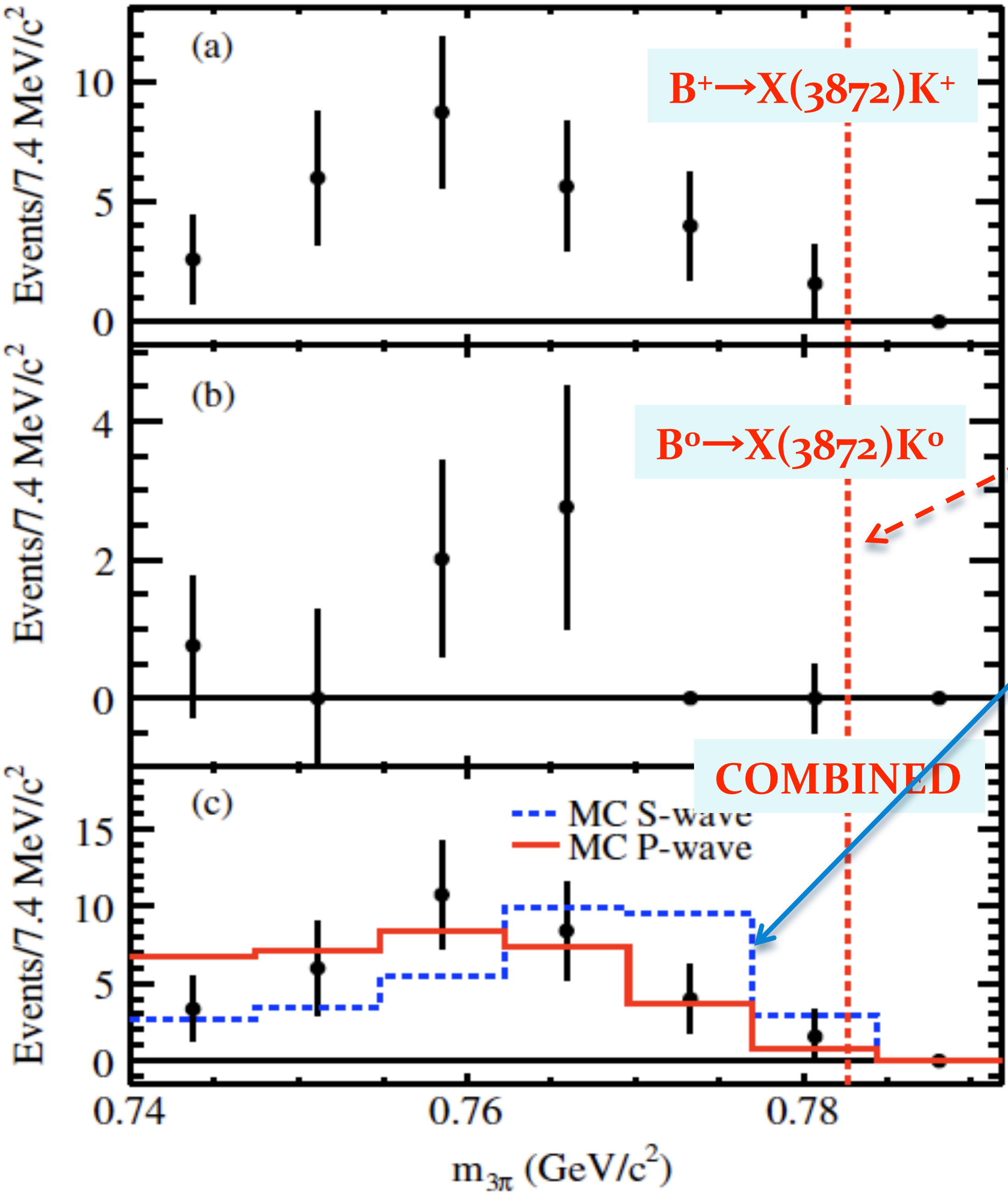
Y(3940): Breit-Wigner function x phase space

Nonresonant: phase-space x Gaussian function x $m_{J/\psi\omega}$

$m_{X(3872)}=3873.0^{+1.8}_{-1.6}$(stat)±1.3(syst) MeV/c²
$m_{Y(3940)}=3\,919.1_{-3.4}^{+3.8}$(stat) ±2(syst) MeV/c²
$\Gamma_{Y(3940)}=31_{-8}^{+10}$(stat) ±5(syst) MeV

Significance of the X(3872) ~ 4.0 σ

$m_{3\pi}$ for the X(3872) (New BaBar Analysis)



PRD (RC) 82, 0111101 (2010)

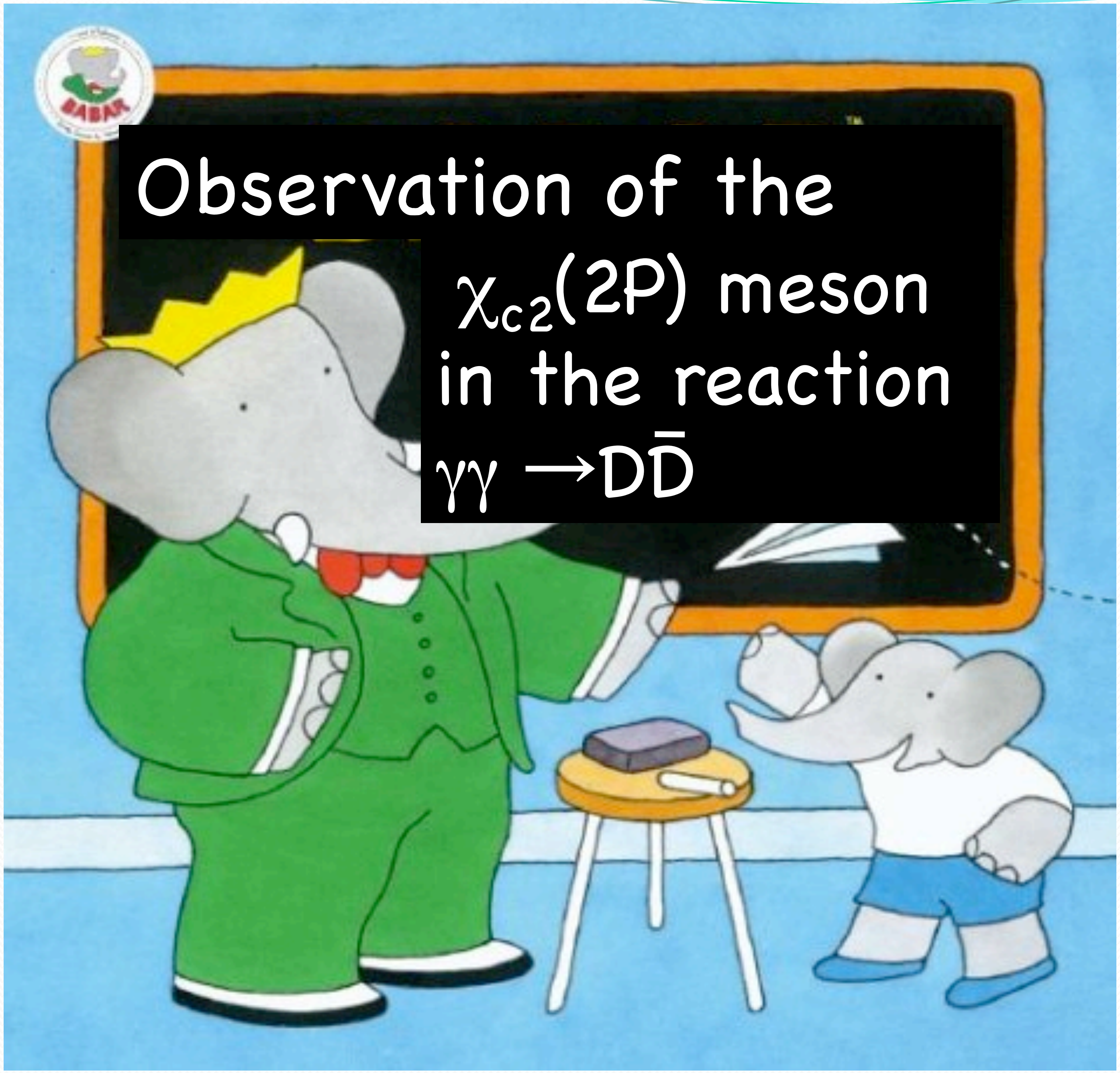
Events in X signal region $3.8625 < m_{J/\psi\omega} < 3.8825$ GeV/c²

ω PDG mass value

S-wave: χ^2/NDF=10.17/5
P(χ^2/NDF)=7%
P-wave: χ^2/NDF=3.53/5
P(χ^2/NDF)=62%

NEGATIVE Parity favored

X(3872) is more *likely to have $J^P=2^-$ than $J^P=1^+$;* **consistent with charmonium η_{c2}(1D) interpretation; similar to $D^0\bar{D}^{*0}$ see** PRL 100, 062006 (2008)

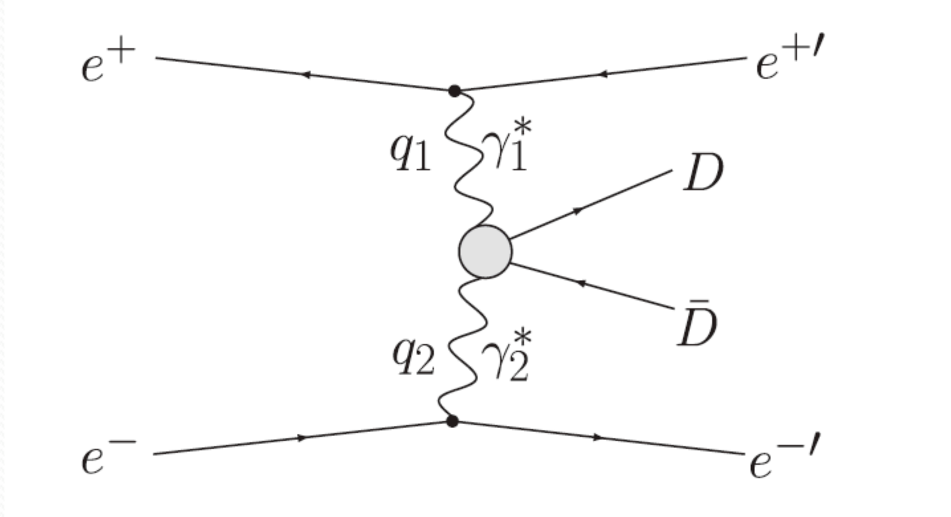

Observation of the
$\chi_{c2}(2P)$ meson
in the reaction
$\gamma\gamma \rightarrow D\bar{D}$

Observation of the $\chi_{c2}(2P)$ meson in the reaction $\gamma\gamma \to D\bar{D}$ (1)

$$e^+e^- \to e^+e^-\gamma\gamma$$

$$\gamma\gamma \to X \to D^+D^-, D^0\overline{D^0}$$

$D^0\bar{D}^0$	$D^0 \to K^-\pi^+$	$\bar{D}^0 \to K^+\pi^-$
$D^0\bar{D}^0$	$D^0 \to K^-\pi^+$	$\bar{D}^0 \to K^+\pi^-\pi^0$
$D^0\bar{D}^0$	$D^0 \to K^-\pi^+$	$\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$
$D^0\bar{D}^0$	$D^0 \to K^-\pi^+\pi^+\pi^-$	$\bar{D}^0 \to K^+\pi^-\pi^0$
D^+D^-	$D^+ \to K^-\pi^+\pi^+$	$D^- \to K^+\pi^-\pi^-$



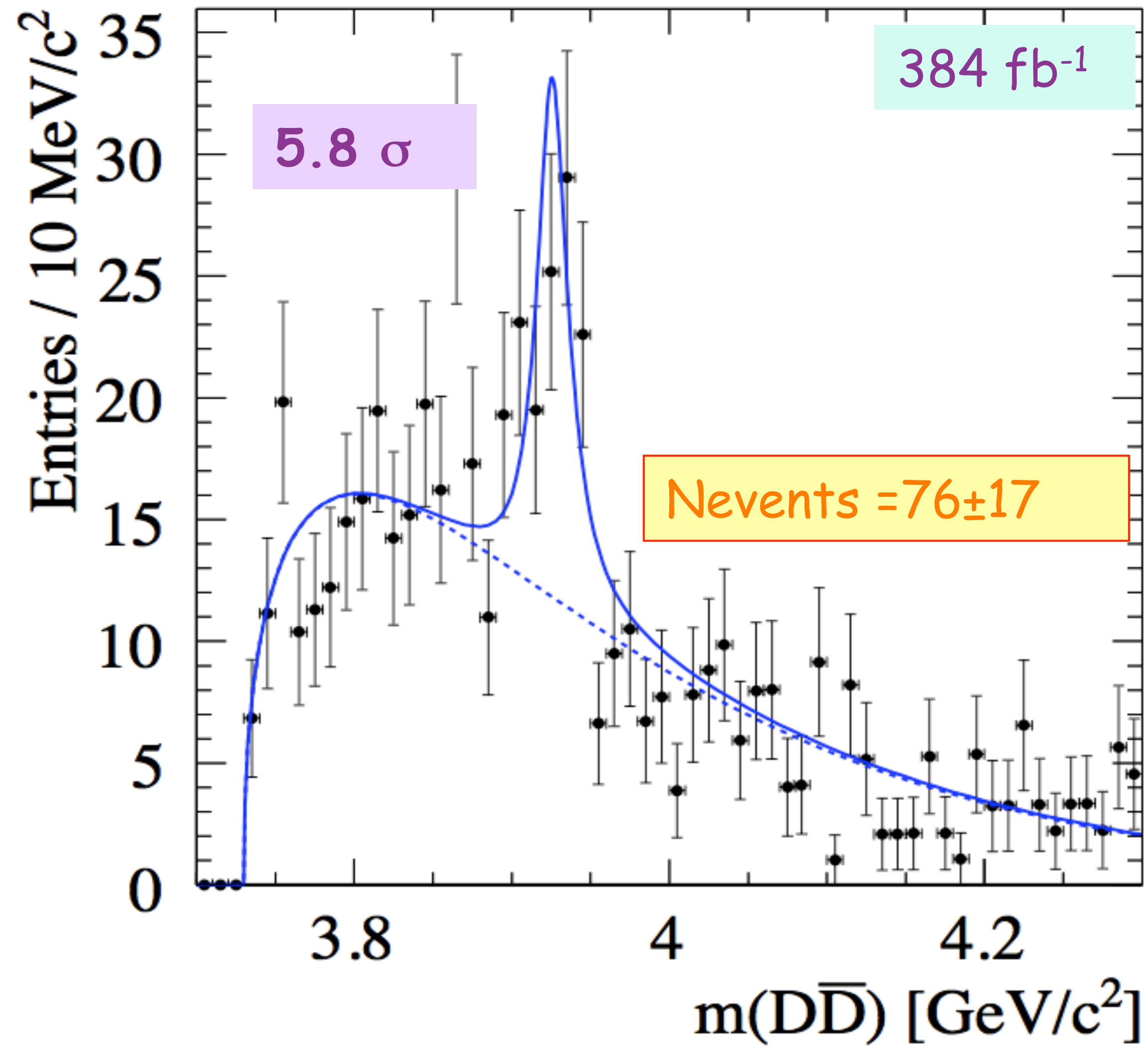
Outgoing e^+ and e^- are not detected
Small $e^\pm$ scattering angle
→quasi real γ
→large missing mass

$$m^2_{\text{miss}} = (p_{e^+} + p_{e^-} - p_D - p_{\bar{D}})^2,$$

where p_e are the four-momenta of the beam electron and positron and p_D, $p_{\bar{D}}$ are the four-momenta of the final state D and $\bar{D}$ mesons, respectively

C=(-1)^J → spin Parity $J^{PC}=J^{++}$ with J=0, 2, 4;

Observation of the $\chi_{c2}(2P)$ meson in the reaction $\gamma\gamma \rightarrow D\bar{D}$ (2)



Signal: Relativistic BW

Background:

$$D(m) \propto \sqrt{m^2 - m_t^2}\,(m - m_t)^{\alpha} \exp\left[-\beta(m - m_t)\right]$$

$m(3930)=3926.7\pm2.7\pm1.1$ MeV/c^2
$\Gamma(3930)=21.3\pm6.8\pm3.6$ MeV

PRD 81, 092003 (2010)

$m(3930)=3929\pm5\pm2$ MeV/c^2
$\Gamma(3930)=29\pm10\pm2$ MeV

PRL 96, 082003 (2006)

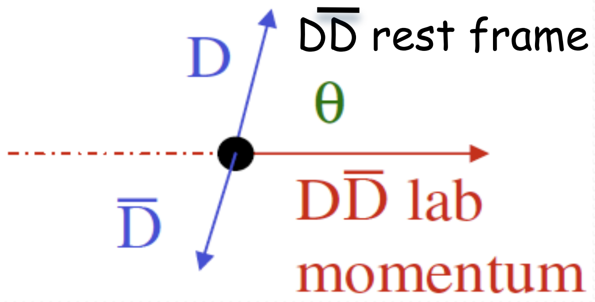
395 fb^{-1}

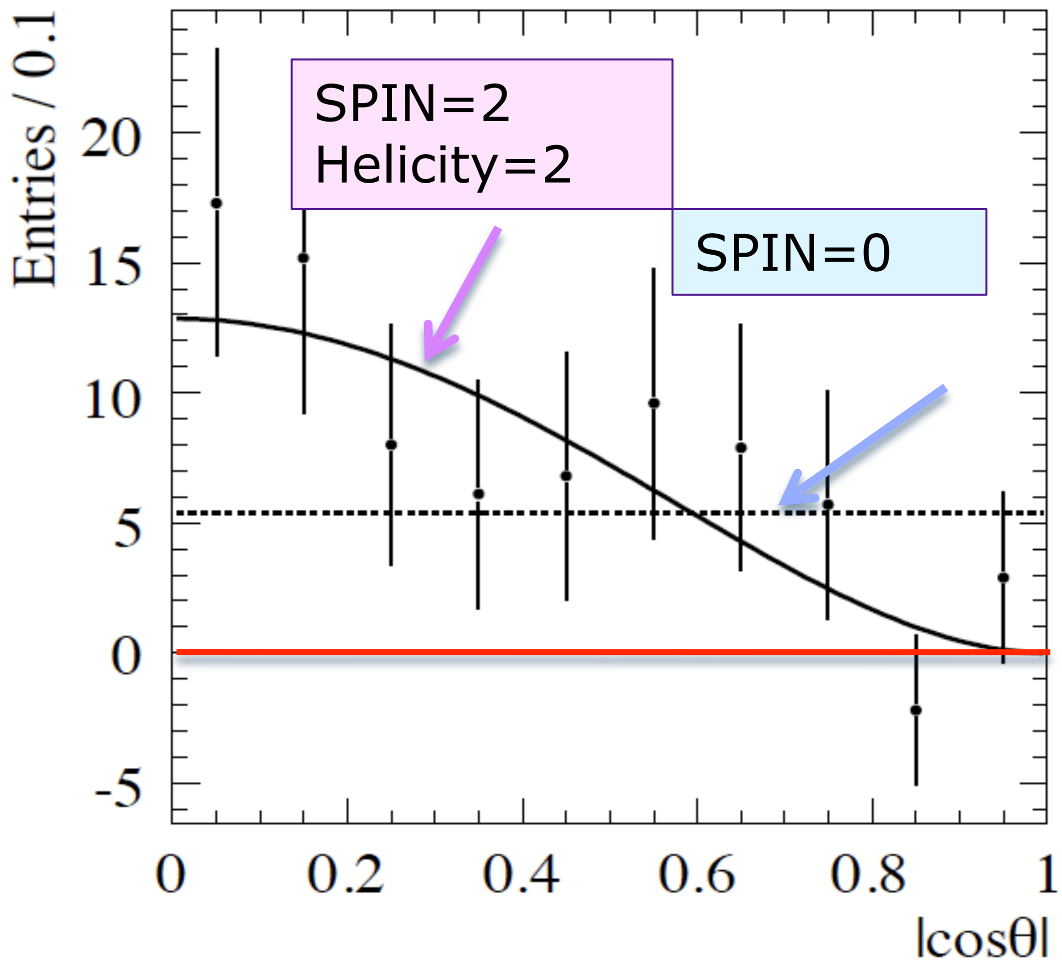
$\Gamma_{\gamma\gamma}\cdot BF(Z(3930 \rightarrow D\bar{D})=0.241 \pm0.054\pm0.043$ keV

$\Gamma_{\gamma\gamma}\cdot BF(Z(3930 \rightarrow D\bar{D})=0.18 \pm0.05\pm0.03$ keV

Assuming J=2

Angular distribution and spin of the Z(3930)





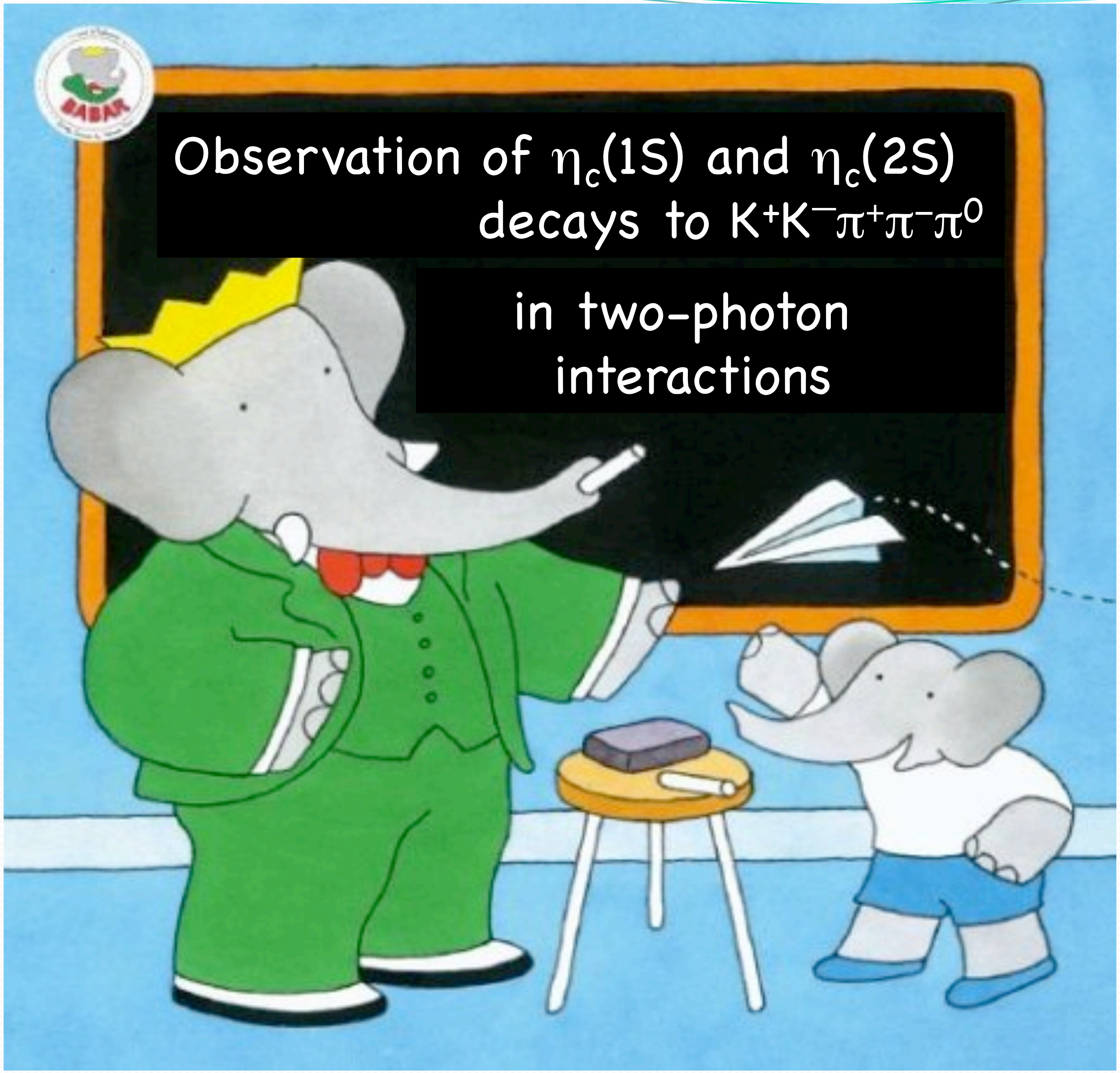
SPIN=2,
Helicity=2:

$$\frac{dN}{d\cos\theta} \propto \sin^4\theta$$

SPIN=0:
Flat distribution

Most Likely J=2

$J^{PC}=2^{++}$ and mass value (PDG 2010) → $\chi_{c2}(2P)$ interpretation


Observation of $\eta_c(1S)$ and $\eta_c(2S)$
decays to $K^+K^-\pi^+\pi^-\pi^0$
in two-photon
interactions

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

$\eta_c(1S)$

Discovered by Crystal Ball 1980

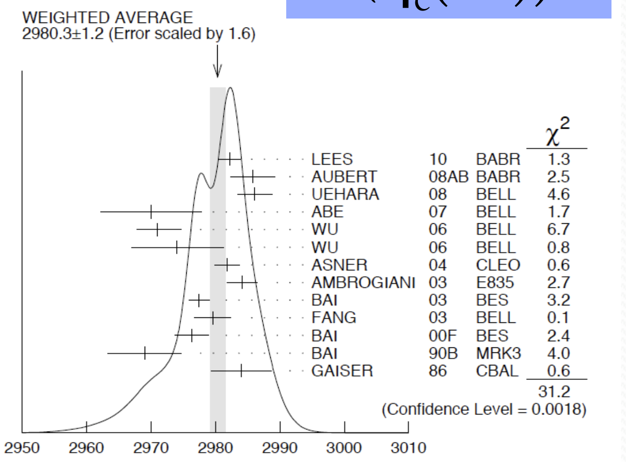
Phys. Rev. Lett. 45, 1150-1153 (1980)

$\eta_c(2S)$

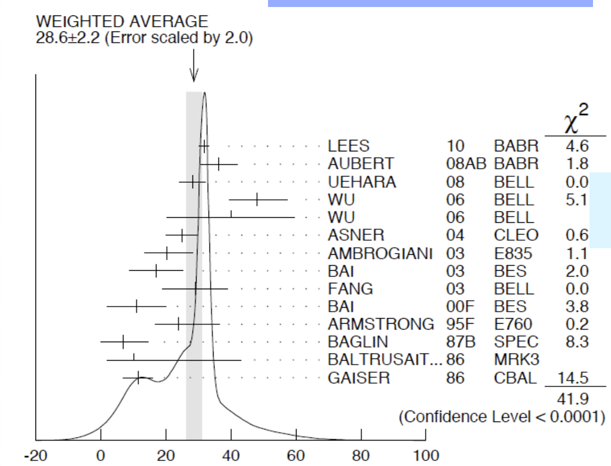
Discovered by BELLE 2002

Phys. Rev. Lett. 89 102001 (2002)

$M(\eta_c(1S))$

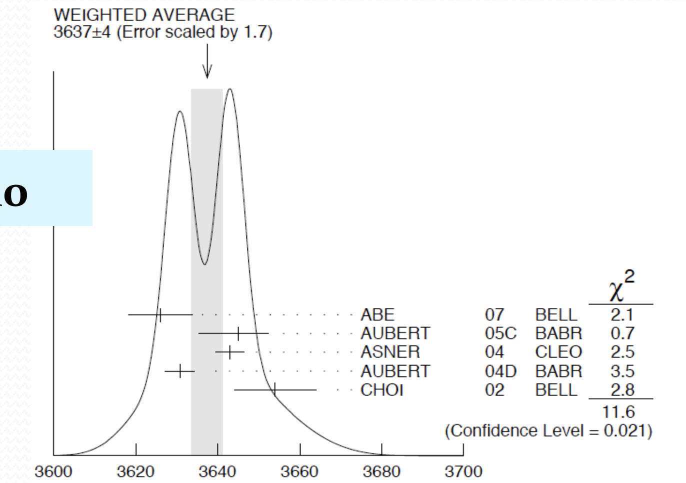


$\Gamma(\eta_c(1S))$



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**

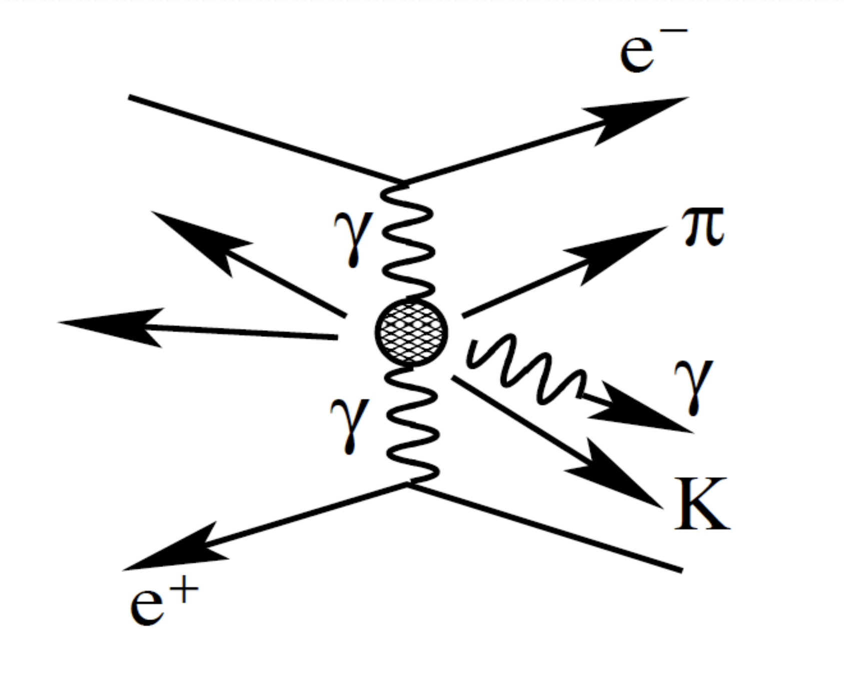
$\Gamma(\eta_c(1S))$~30 MeV **(B-decays and $\gamma\gamma$ production)**

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 Υ(4S), Υ(3S), Υ(2S)

arXiv:1103.3971v2

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 :

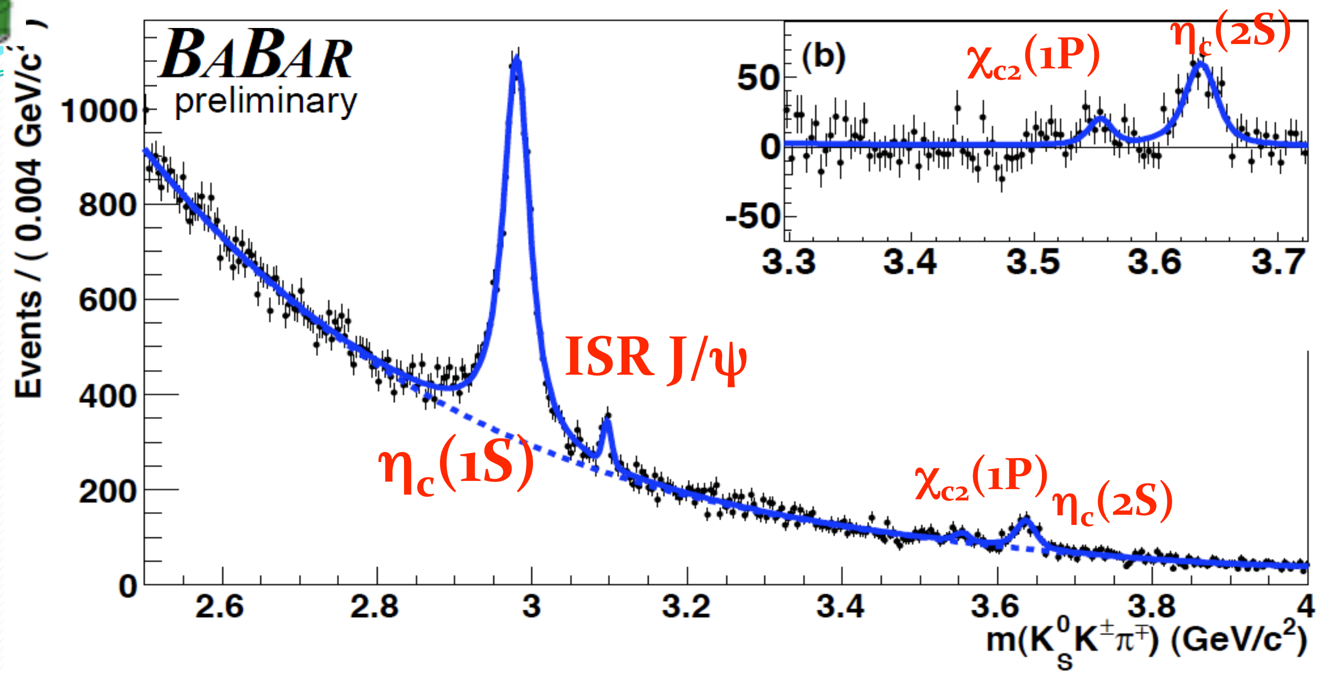
$$\gamma\gamma e^+e^- \longrightarrow K^+K^-\pi^+\pi^-\pi^0 e^+e^-$$

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

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

Outgoing e^+ and e^- are not detected

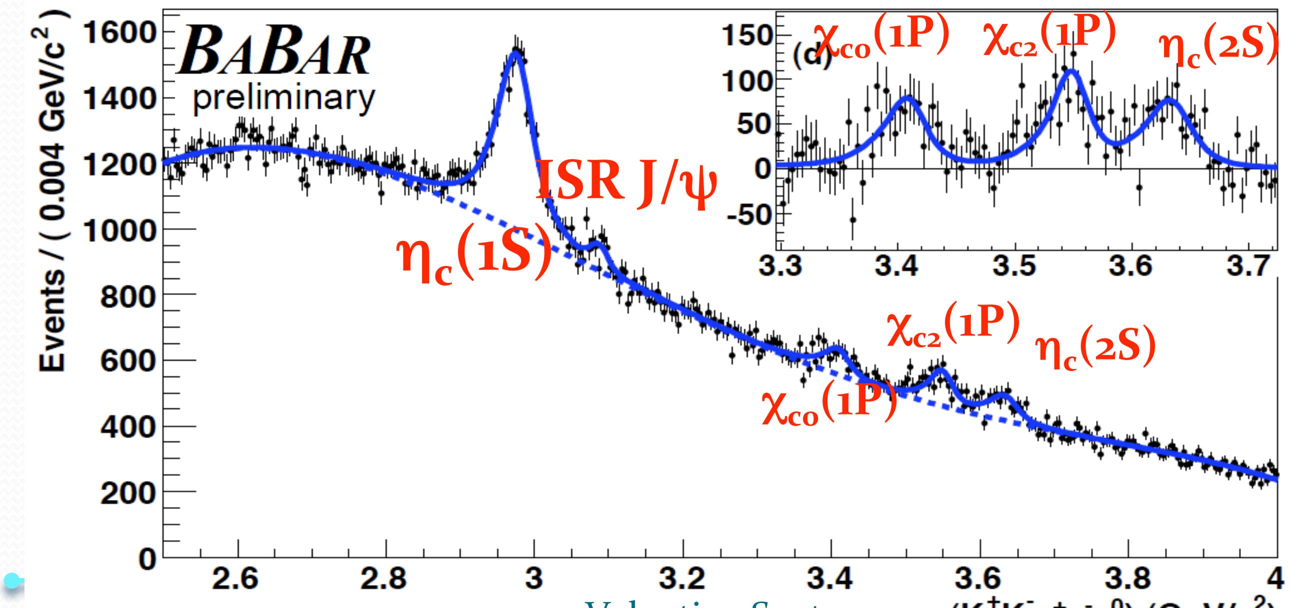
$\eta_c(1S)$ & $\eta_c(2S)$ new BaBar results(2)



Inset: Background-subtracted distribution

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

arXiv:1103.3971v2 Submitted to PRD (RC)



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

$m(\eta_c(1S)) = 2982.5 \pm 0.4 \pm 1.4$ MeV/c^2
$\Gamma(\eta_c(1S)) = 32.1 \pm 1.1 \pm 1.3$ MeV

arXiv:1103.3971v2

$m(\eta_c(2S)) = 3638.5 \pm 1.5 \pm 0.8$ MeV/c^2
$\Gamma(\eta_c(2S)) = 13.4 \pm 4.6 \pm 3.2$ MeV

Measurement more precise than the world average

BABAR preliminary

Process	$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (keV)
$\eta_c(1S) \to K\overline{K}\pi$	$0.386 \pm 0.008 \pm 0.021$
$\chi_{c2}(1P) \to K\overline{K}\pi$	$(1.8 \pm 0.5 \pm 0.2) \times 10^{-3}$
$\eta_c(2S) \to K\overline{K}\pi$	$0.041 \pm 0.004 \pm 0.006$
$\chi_{c2}(2P) \to K\overline{K}\pi$	$< 2.1 \times 10^{-3}$
$\eta_c(1S) \to K^+K^-\pi^+\pi^-\pi^0$	$0.190 \pm 0.006 \pm 0.028$
$\chi_{c0}(1P) \to K^+K^-\pi^+\pi^-\pi^0$	$0.026 \pm 0.004 \pm 0.004$
$\chi_{c2}(1P) \to K^+K^-\pi^+\pi^-\pi^0$	$(6.5 \pm 0.9 \pm 1.5) \times 10^{-3}$
$\eta_c(2S) \to K^+K^-\pi^+\pi^-\pi^0$	$0.030 \pm 0.006 \pm 0.005$
$\chi_{c2}(2P) \to K^+K^-\pi^+\pi^-\pi^0$	$< 3.4 \times 10^{-3}$

- ✓ **B decay:**
  - ✓ $B \to K\chi_{c1}\pi$ –search for $Z_1, Z_2 \to K\chi_{c1}\pi$
  - ✓ $B \to KJ/\psi\phi$ -search for $Y(4140) \to J/\psi\phi$
- ✓ **ISR production:**
  - ✓ $e^+e^- \to J/\psi\pi^+\pi^-$
  - ✓ $e^+e^- \to \psi(2S)\pi^+\pi^-$
  - ✓ $e^+e^- \to J/\psi K^+K^-$
  - ✓ $e^+e^- \to \Lambda_c\bar{\Lambda}_c$
- ✓ **$\gamma\gamma$ interactions**
  - ✓ $\gamma\gamma \to J/\psi\omega$
- ✓ **Inclusive $c\bar{c}$**
  - ✓ $e^+e^- \to J/\psi c\bar{c}$
  - ✓ $e^+e^- \to \psi(2S)\, c\bar{c}$

→ update to full BaBar data sample

Conclusions

- ✓ Charmonium spectroscopy has been revitalized by the discovery of many new states above the open charm threshold. A review of some of these new states has been presented.
- ✓ Many experimental results have been shown, with just enough data to whet the appetite, but at a statistical level which does not permit a clear understanding of the observed signals
- ✓ More data are required, possibly from LHCb, but also from the SuperB or BELLE-II projects, should they materialize in the future

BACK-UP SLIDES