Recent results on conventional and exotic charmonium at BaBar

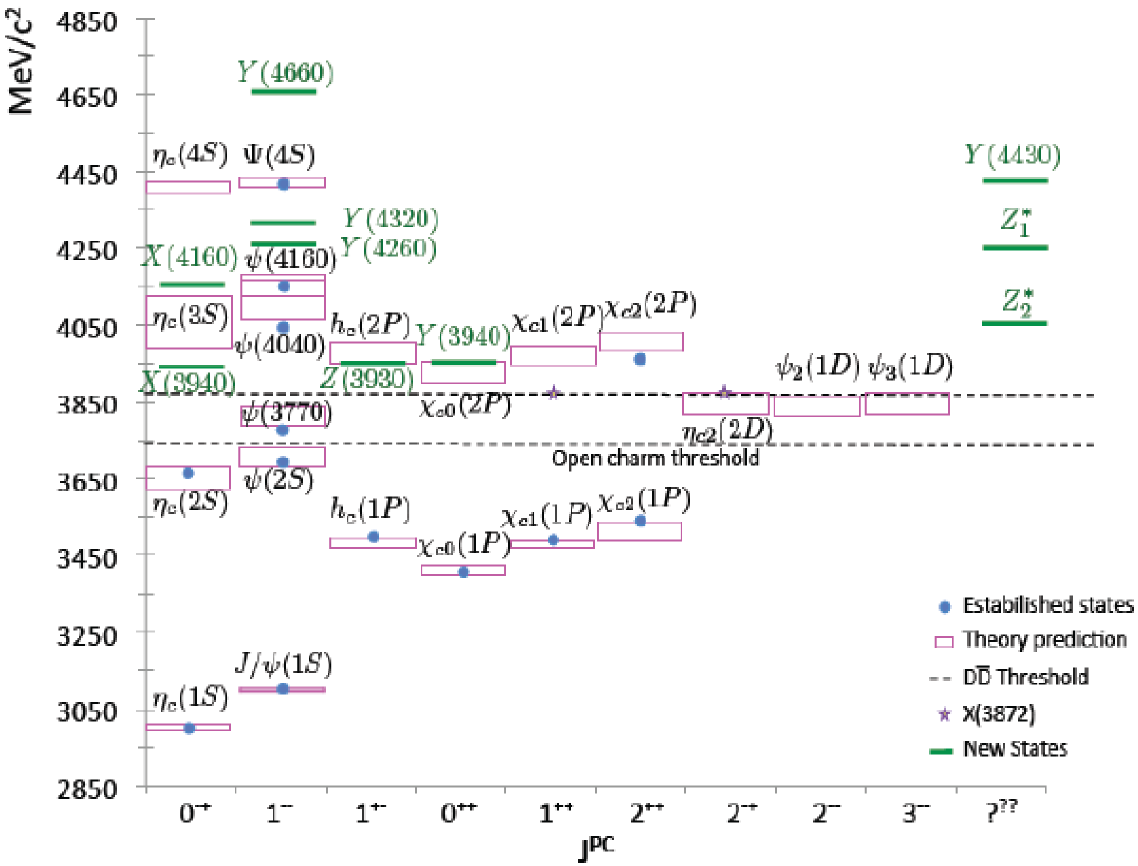
Guy Wormser

LAL Orsay

on behalf of BABAR Collaboration

Introduction

Charmonium spectrum



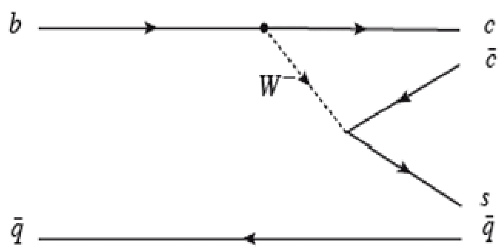
- Below the $D\bar{D}$ threshold, all expected states have been observed, with properties in good agreement with theory; there are no additional states.

- Many unexpected states have been reported above the $D\bar{D}$ threshold, seemingly too many with $J^{PC} = 1^{--}$.
Several exotic hypotheses about their nature: tetraquarks, hadronic molecules, hybrids, glueballs, hadro-quarkonia.

Running at ~Υ(4S) energy is a very good observatory for charmonium

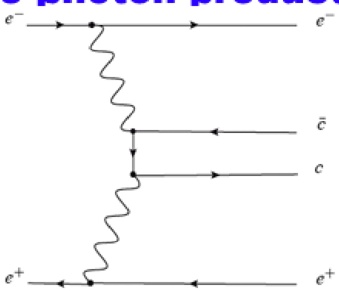
Experimental methods for charmonium production at the B-factories

B meson decays



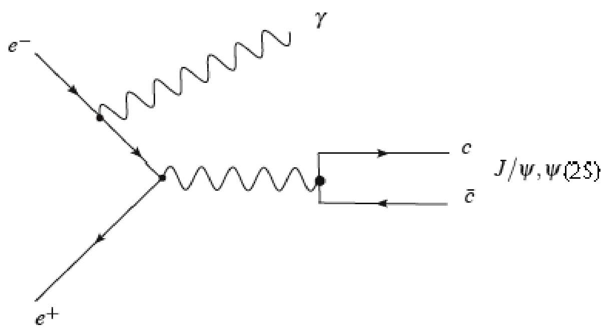
States of any quantum numbers can be produced

Two-photon production



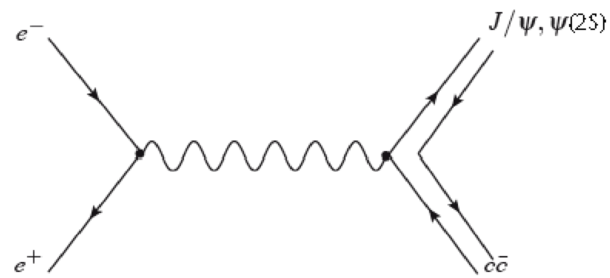
Only states with J^{PC} = $0^{\pm+}$, $2^{\pm+}$, $4^{\pm+}$,……, 3^{++}, 5^{++},……. can be produced

Initial State Radiation (ISR)



Only states with $J^{PC} = 1^{--}$ can be produced

Double charmonium production



Only charmonium states with C=+1 are allowed to be produced in association with the J/ψ or the ψ(2S)

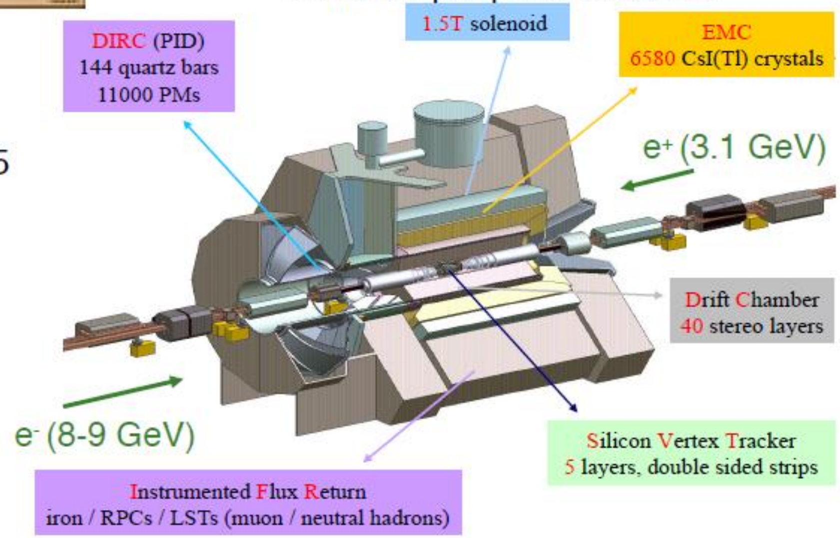
Short overview of the BABAR experiment

The *BABAR* experiment

PEP-II asymmetric e^+e^- collider operating at center of mass energies near the $\Upsilon(4S)$ (for most of the time)

$$\sqrt{s} = 10.58\,\mathrm{GeV}/c^2$$

General-purpose detector



Asymmetric:

$$-0.9 < \cos\theta^* < 0.85$$

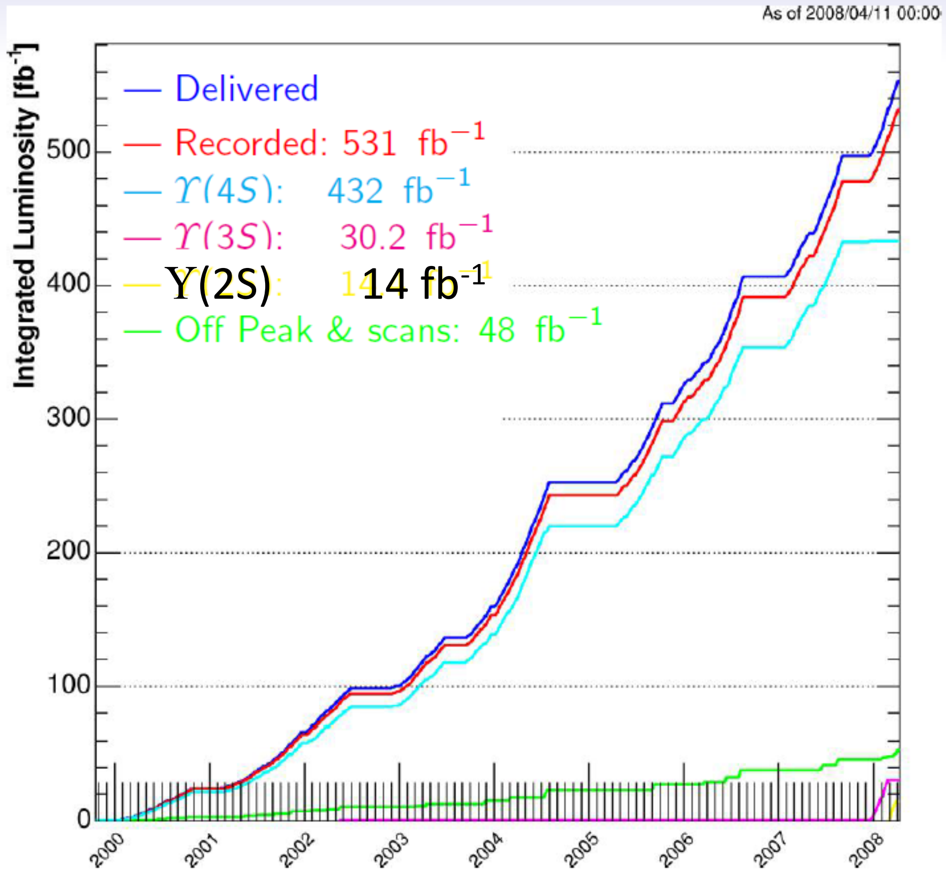
wrt electron beam

excellent performance:

- vertexing
- tracking
- PID
- calorimeter

BABAR Luminosity

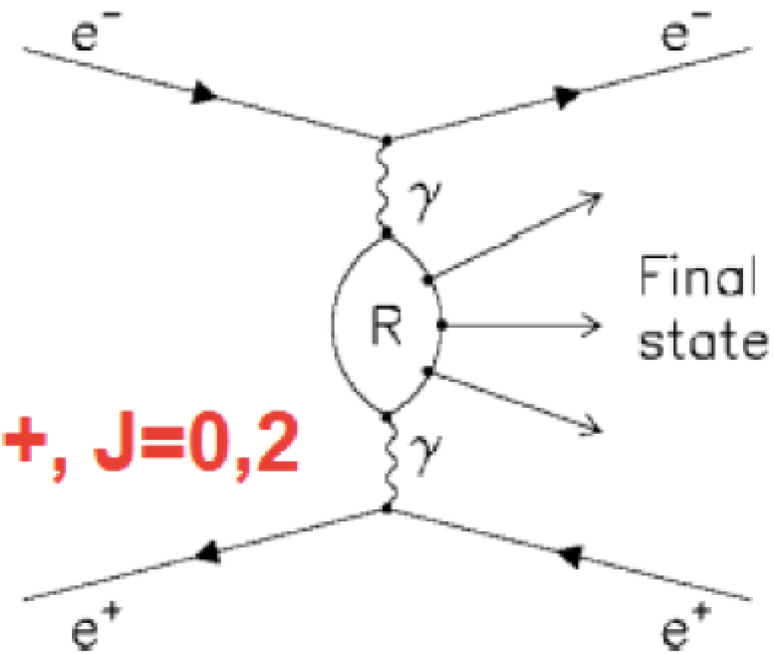
Data samples



4 physics topics covered in this talk

- Recent results on $J/\psi\ \omega$ channel through $\gamma\gamma$ production
  - PRD86,072002 (2012)
- $\gamma\gamma$ production of $\eta_c\pi\pi$
  - PRD86,092005 (2012)
- Y(4260) and related resonances (in ISR channel)
  - PRD86,051102(R) (2012)
  - arXiv:1211.6271
- Are there new charmonium-like charged states ?
  - PRD85,052003(2012)

Electron and positron beams emit (quasi-real) photons which interact and may form resonances



C=+, J=0,2

- Final state $e^{\pm}$ emitted along beam direction undetected
- allowed $J^{PC} = 0^{\pm+}, 2^{\pm+}$ (and $4^{\pm+}, 3^{++}, 5^{++}, \ldots$)
- low p_t with respect to beam axis

Charmonium in $\gamma\gamma \to J/\psi\,\omega$

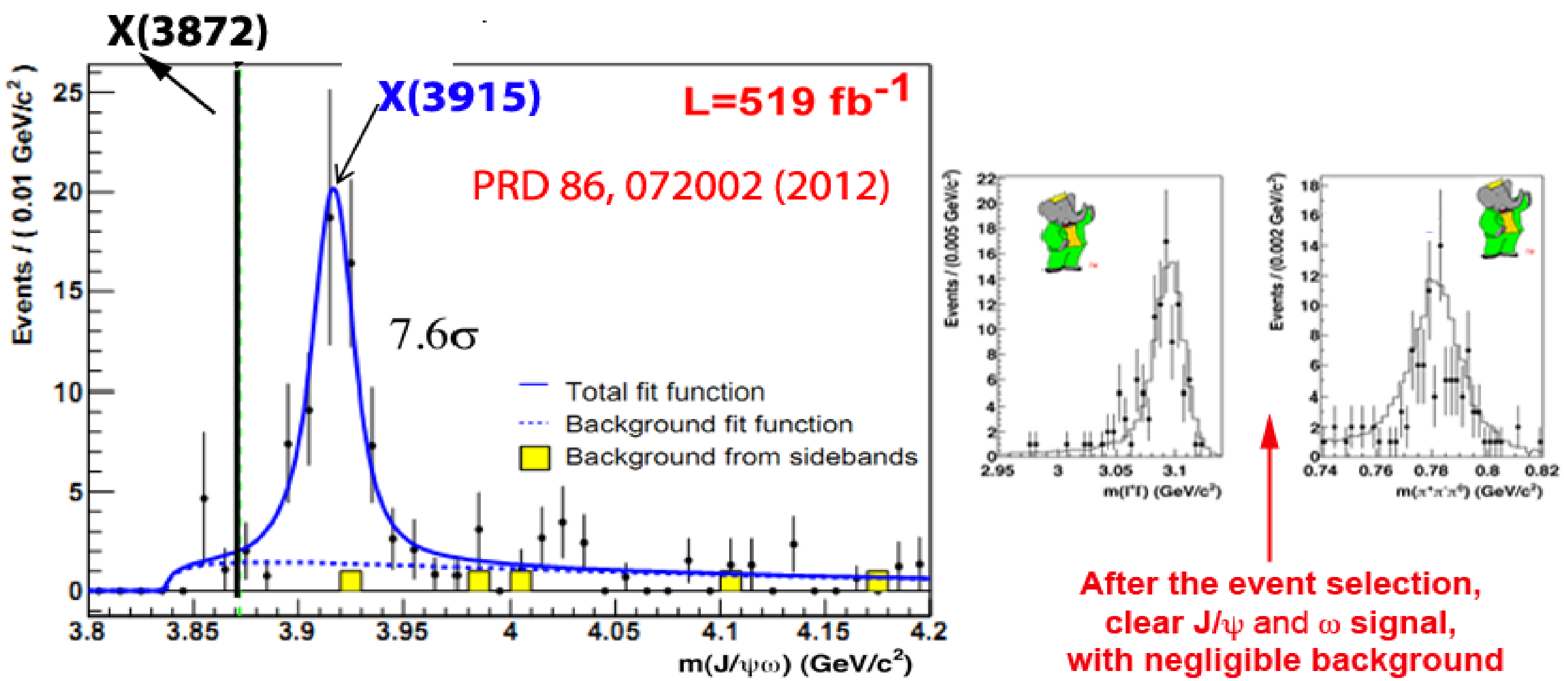
- X(3915)
  - X(3915) observed by Belle in $\gamma\gamma \to J/\psi\,\omega$; $\chi_{c0}(2P)$? $\chi_{c2}(2P)$?
  - Z(3930) observed by Belle, and BaBar, in $\gamma\gamma \to D\overline{D}$. $\chi_c 2(2P)$

  Are X(3915) and Z(3930) the same state ? measure J^{PC} of X(3915) !

- X(3872)
  - discovered in B decays, $X(3872) \to J/\psi\,\pi\pi$, Belle
  - seen in B decays, $J/\psi\,\pi\pi$, $J/\psi\,\omega$, $D^0 D^0 \pi^0$, $J/\psi\,\gamma$ $(C = +)$
  - $J^{PC} = 1^{++}$ or $J^P = 2^{-+}$, angular analysis of $J/\psi\,\pi\pi$ CDF
  - If :
    - $J^P = 2^-$, X(3872) 2-photon production allowed.
    - $J^P = 1^+$, X(3872) 2-photon production NOT allowed.

  Analysis performed before LHCb's result on X3872 spin measurement

$\gamma\gamma \to J/\psi\ \omega$ - Results

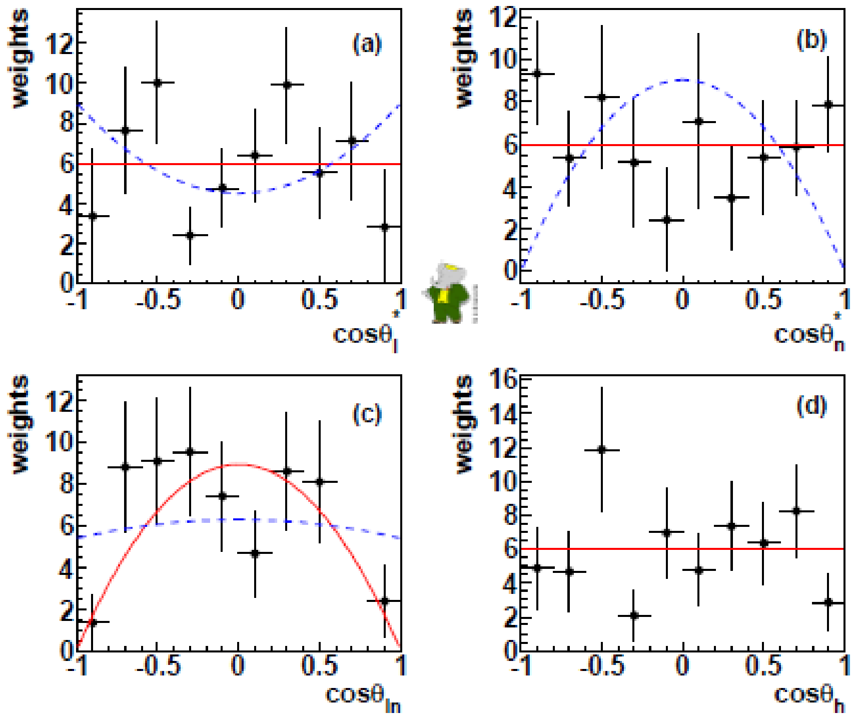


Results are consistent with Belle's:
(PRL 104, 092001 (2010))

	BABAR	Belle
Mass (MeV/c^2)	$3919.4 \pm 2.2 \pm 1.6$	$3915 \pm 3 \pm 2$
Width (MeV)	$13 \pm 6 \pm 3$	$17 \pm 10 \pm 3$
$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (J=0) (eV)	$52 \pm 10 \pm 3$	$61 \pm 17 \pm 8$
$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (J=2) (eV)	$10.5 \pm 1.9 \pm 0.6$	$18 \pm 5 \pm 2$

New limit: $\Gamma_{\gamma\gamma}(X(3872)) \times B(X(3872) \to J/\psi\ \omega)(J=2) < 1.7$ eV
X(3915) quantum number determination: $J^P = 0^+$ favored by *BABAR*

X(3915) Angular analysis-Step 1
Spin 0 or 2 ?



p_{χ^2} for θ^*_n

$J^P = 0^\pm$ $p_{\chi^2} = 64.7$ %

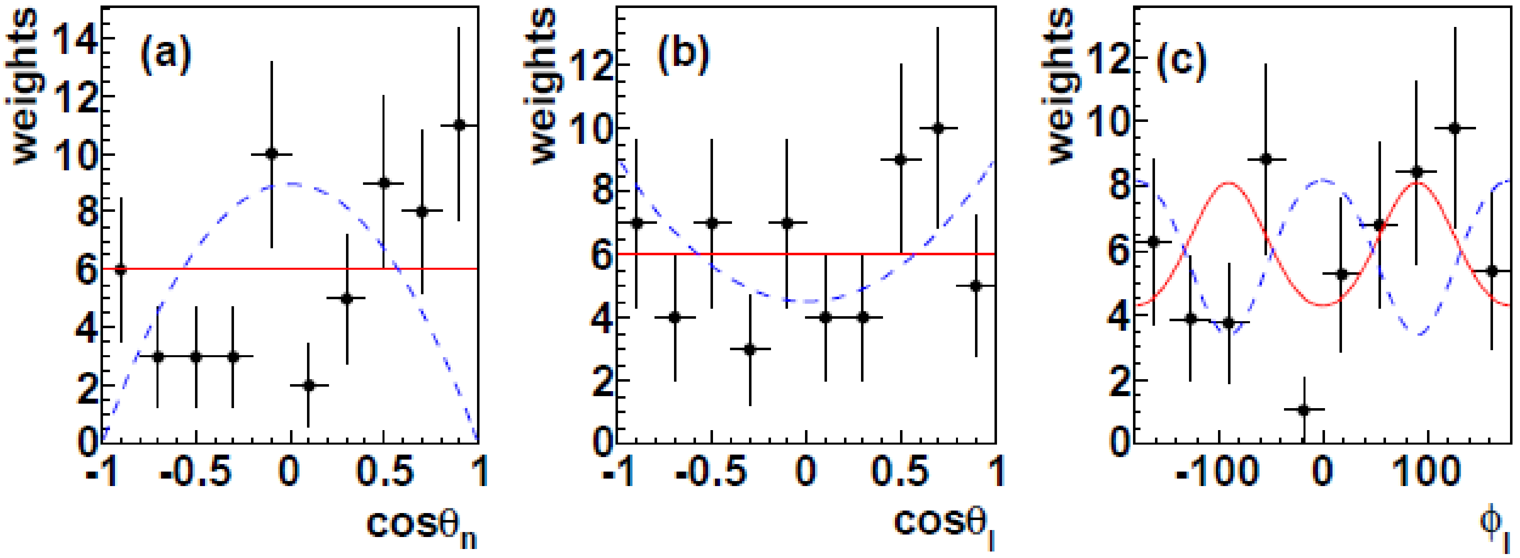
$J^P = 2^+$ $p_{\chi^2} = 9.6 \times 10^{-9}$

$J^P = 0^\pm$ preferred

Phys. Rev. D 86, 072002 (2012)

519 fb^{-1}

Scalar or pseudoscalar ?



p_{χ^2} for θ_n :

- $J^P = 0^+$ $p_{\chi^2} = 6.1$ %
- $J^P = 0^-$ $p_{\chi^2} = 4.8 \times 10^{-11}$

$J^P = 0^+$ preferred ; $\chi_{c0}(2P)$? ?

Phys. Rev. D 86, 072002 (2012) 519 fb^{-1}

Search for $\eta_c\pi\pi$ in $\gamma\gamma$ production

Predictions :

- $\Gamma(\eta_c(2S) \to \eta_c\pi^+\pi^-)/\Gamma(\psi(2S) \to J/\psi\,\pi^+\pi^-) = 2.9$
  That is $\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) = (2.2^{+1.6}_{-0.6})\%$
  M.B. Voloshin, Mod. Phys. Lett. A 17 (2002) 1533

- Then
  - If $X(3872) \equiv \eta_{c2}\ (1^1D_2,\ J^{PC} = 2^{-+})$,
  - $\mathcal{B}(X(3872) \to \eta_c\pi^+\pi^-)$ (isospin conserving) $>$ $\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-)$ (isospin violating) $> 2.6\%$[PDG]
    S. Olsen et al., (Int J. Mod. Phys A 20 240 (2005))

If $J^{PC} = 2^{-+}$, X(3872) 2-photon production would be allowed, and $\mathcal{B}(X(3872) \to \eta_c\pi^+\pi^-)$ could be sizable.

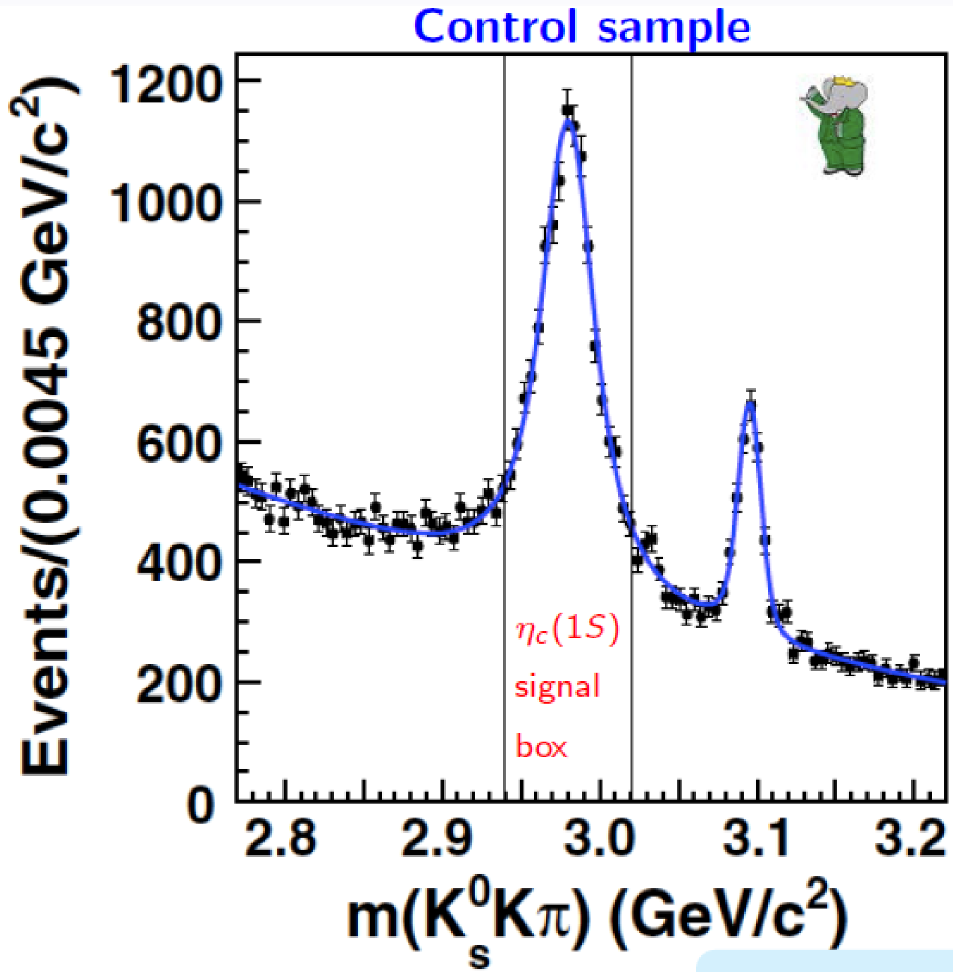
Analysis performed before LHCb's result on X3872 spin measurement

Search for $\gamma\gamma \to \eta_c \pi^+\pi^-$

Select candidates

- control sample
  $\gamma\gamma \to \eta_c \to K_S^0 K^\pm \pi^\mp$
  used to optimize the η_c selection
  (4 tracks)
- main sample of
  $\gamma\gamma \to X \to \eta_c \pi^+\pi^- \to (K_S^0 K^\pm \pi^\mp)\ \pi^+\pi^-$
  (6 tracks)

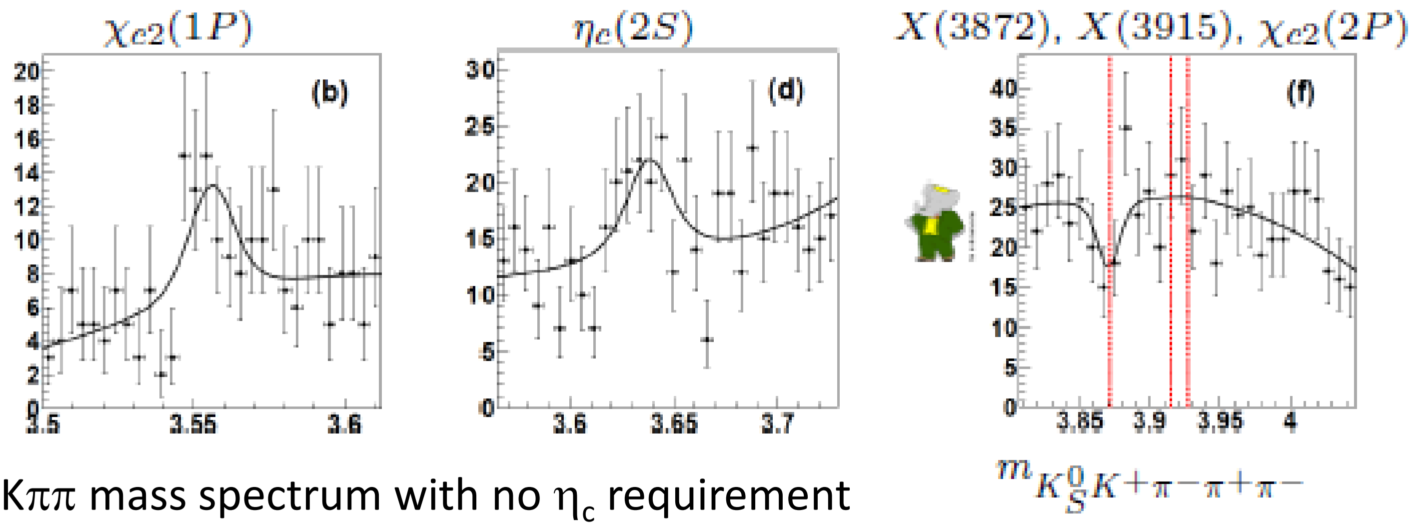
"standard" cuts on PID, p_t, missing mass,...



PRD 86, 092005 (2012)

Search for resonances in $\gamma\gamma \to \eta_c\pi^+\pi^-$

- Untagged $\quad \eta_c \to K^0_S K^+\pi^-$ $\quad$ 473.9 fb^{-1} $\quad$ Phys. Rev. D 86, 092005 (2012)



$K^0K\pi\pi$ mass spectrum with no η_c requirement

$$\frac{\mathcal{B}(\chi_{c2}(1P)\to\eta_c\pi^+\pi^-)}{\mathcal{B}(\chi_{c2}(1P)\to K^0_S K^+\pi^-)} = 14.5^{+10.9}_{-8.9} \pm 7.3 \pm 2.5 \qquad \mathcal{B}(\chi_{c2}(1P) \to \eta_c\pi^+\pi^-) < 2.2\%$$

$$\frac{\mathcal{B}(\eta_c(2S)\to\eta_c\pi^+\pi^-)}{\mathcal{B}(\eta_c(2S)\to K^0_S K^+\pi^-)} = 4.9^{+3.5}_{-3.3} \pm 1.3 \pm 0.8 \qquad \mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) < 7.4\%$$

(compatible with prediction 2.2%)

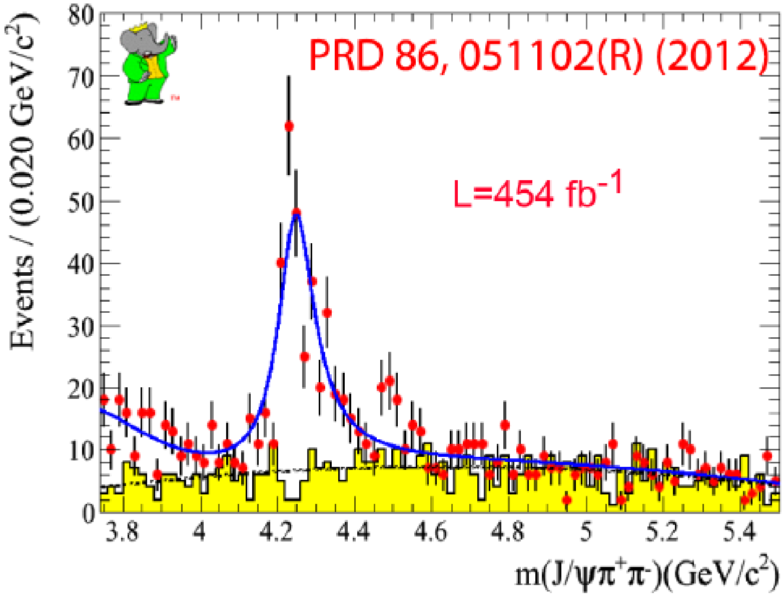
$\Gamma_{\gamma\gamma}(X) \times \mathcal{B}(X \to \eta_c\pi^+\pi^-)$	$X(3872)$	$X(3915)$	$\chi_{c2}(2P)$
	< 11.1 eV	< 16 eV	< 19 eV

- No evidence for $\gamma\gamma$ production of $X(3872)$, $X(3915)$ nor $\chi_{c2}(2P)$

Resonances in the ISR channel

Y(4260)

- New analysis from *BABAR* : more precise measurements of Y(4260) parameters in $J/\psi\pi^+\pi^-$ ISR production PRD 86, 051102(R) (2012)



An extendend-maximum-likelihood fit is performed to the signal region $J/\psi\pi^+\pi^-$ distribution and simultaneously to the background distribution in the region 3.74-5.5 GeV/c^2.

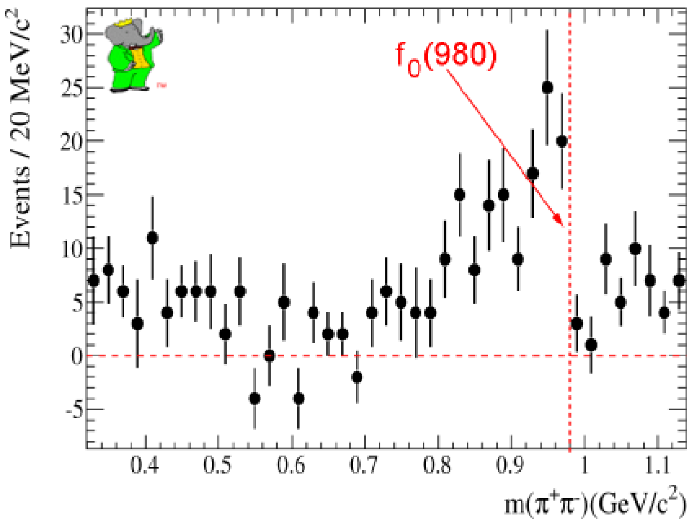
Mass (Y(4260)) = 4244$\pm$5$\pm$4 MeV/c^2

Γ(Y(4260))=$114^{+16}_{-15}\pm7$ MeV

$\Gamma_{e^+e^-}\times B(J/\psi\pi^+\pi^-)$=9.2$\pm$0.8$\pm$0.7 eV

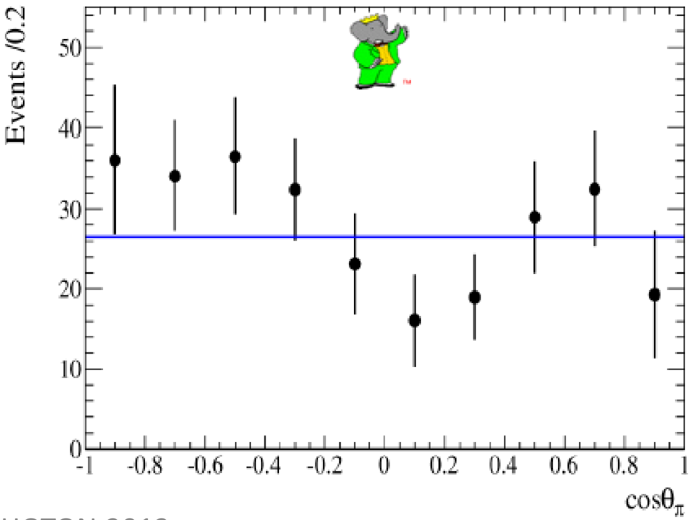
No evidence for the state at $\sim$4 GeV/c^2 reported by Belle.

$\pi^+\pi^-$ Invariant mass distribution in the Y(4260) decay (1)



- For $4.15 \le m(J/\psi\pi^+\pi^-) \le 4.45$ GeV/c^2
- The distribution seems to peak around the $f_0(980)$ mass; however the peak is displaced from the indicated $f_0(980)$ position.
- The fact that the peak is displaced suggests possible interference between the $f_0(980)$ and an $m(\pi^+\pi^-)$ contribution.

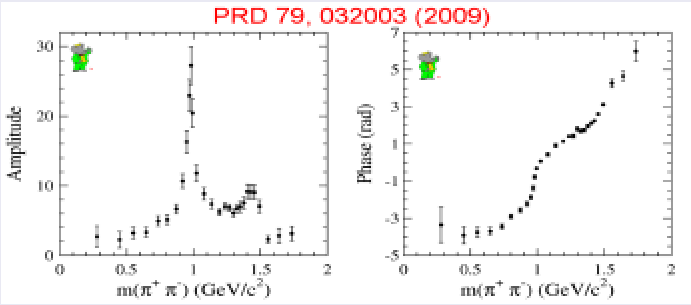
- The $\pi^+\pi^-$ system has C=+1 and hence even angular momentum.
- Define θ_π as the angle between the π^+ direction and that of the recoil J/ψ both in the dipion rest frame.
- The distribution, which must be symmetric, is consistent with S-wave behaviour (blue line) $\chi^2/NDF = 12.3/9$; probability=19.7%.

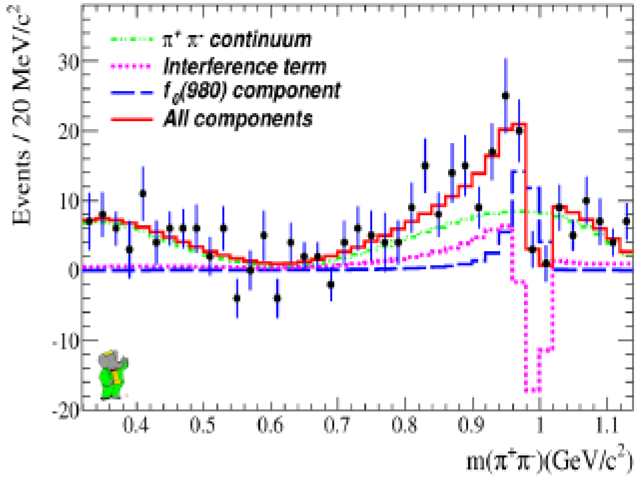


$\pi^+\pi^-$ Invariant mass distribution in the Y(4260) decay (2)

A simple model has been used to describe the $\pi^+\pi^-$ mass distribution, namely the square of an amplitude consisting of the coherent sum of a nonresonant component motivated by a QCD multipole expansion and an $f_0(980)$ amplitude; the relative strength and phase of these components are free to vary in the fit to the data.

The mass-dependence of the $f_0(980)$ amplitude and phase is from the *BABAR* analysis of the decay $D_s^+ \rightarrow \pi^+\pi^-\pi^+$





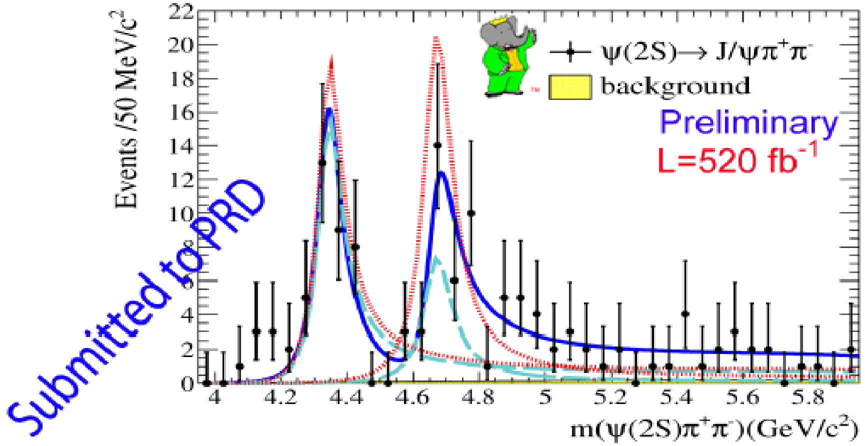
Using this simple model, a good description of the $\pi^+\pi^-$ mass distribution is obtained.
This indicates that there is an $f_0(980)$ contribution to the decay of the Y(4260) to $J/\psi\pi^+\pi^-$ but that contribution is not dominant.

$$\frac{B(Y_{4260}\rightarrow J/\psi f_0(980), f_0(980)\rightarrow\pi^+\pi^-)}{B(Y_{4260}\rightarrow J/\psi\pi^+\pi^-)} = (17\pm13)\%$$

ψ(2S) ππ channel in ISR channel

Y(4350) - Y(4660)

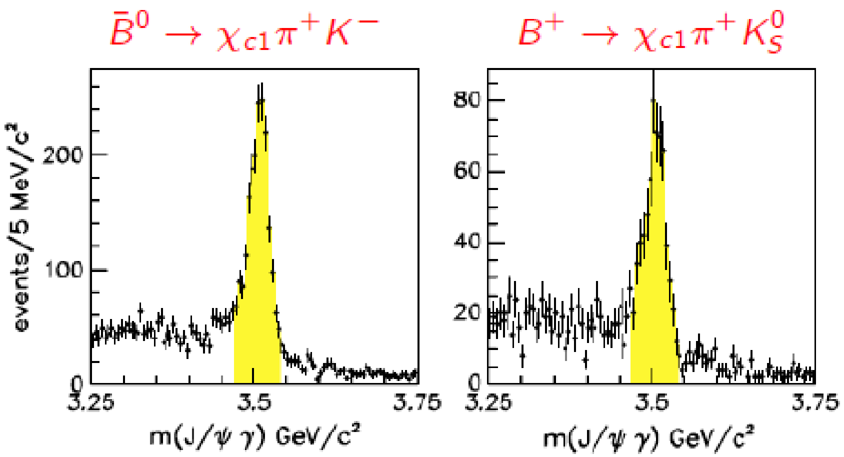
- *BABAR* update arXiv:1211.6271 using the full dataset, including $\Upsilon(2S)$ and $\Upsilon(3S)$



Parameters	First Solution [constructive interference]	Second Solution [destructive interference]
Mass Y(4360)(MeV/c^2)	$4340 \pm 16 \pm 9$	
Width Y(4360)(MeV)	$94 \pm 32 \pm 13$	
$\mathcal{B} \times \Gamma_{ee}(Y(4360))$(eV)	$6.0 \pm 1.0 \pm 0.5$	$7.2 \pm 1.0 \pm 0.6$
Mass Y(4660)(MeV/c^2)	$4669 \pm 21 \pm 3$	
Width Y(4660)(MeV)	$104 \pm 48 \pm 10$	
$\mathcal{B} \times \Gamma_{ee}(Y(4660))$(eV)	$2.7 \pm 1.3 \pm 0.5$	$7.5 \pm 1.7 \pm 0.7$
$\phi(^\circ)$	$12 \pm 27 \pm 4$	$-78 \pm 12 \pm 3$

BABAR search for $Z_1(4050)^+$ and $Z_2(4250)^+$ in $B^0 \to \chi_{c1}\pi^+K^-$ and $B^+ \to \chi_{c1}\pi^+K_S$

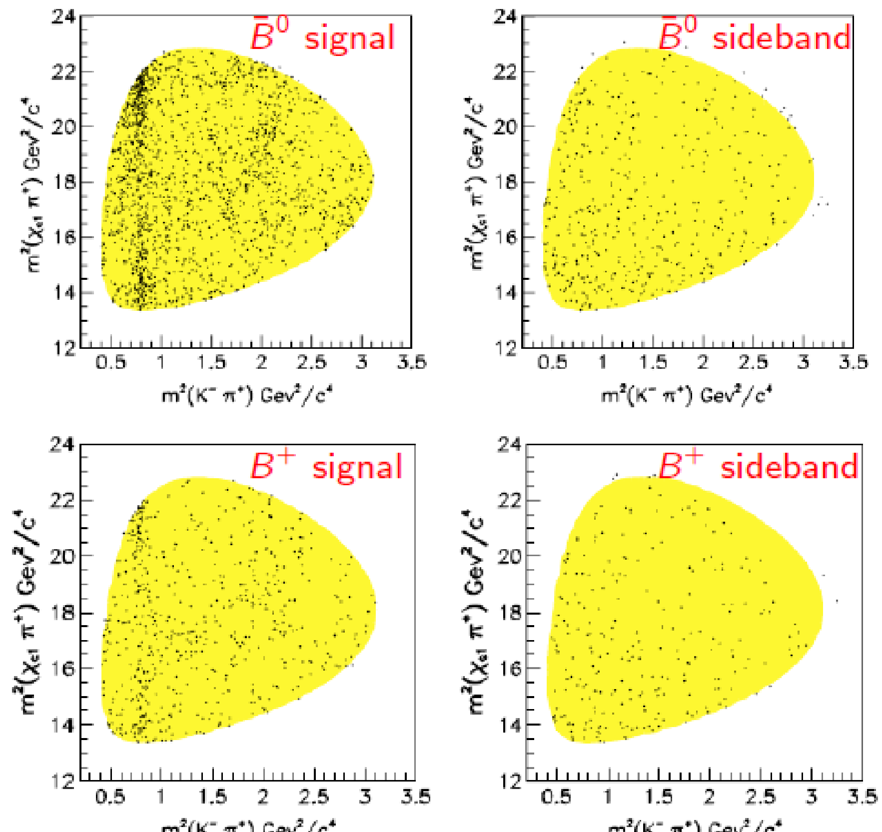
Select samples with relatively large purities



Channel	$\sigma_{\Delta E}$(MeV)	$\sigma_{m_{ES}}$(MeV/c^2)	Events	Purity %
$\bar{B}^0 \to \chi_{c1}K^-\pi^+$ $(\mu^+\mu^-)$	6.96 ± 0.34	2.60 ± 0.10	980	79.3 ± 1.3
$\bar{B}^0 \to \chi_{c1}K^-\pi^+$ (e^+e^-)	7.81 ± 0.43	2.77 ± 0.12	883	77.1 ± 1.4
$B^+ \to \chi_{c1}K^0_S\pi^+$ $(\mu^+\mu^-)$	6.65 ± 0.55	2.65 ± 0.27	299	81.7 ± 2.2
$B^+ \to \chi_{c1}K^0_S\pi^+$ (e^+e^-)	7.52 ± 0.70	2.65 ± 0.18	329	77.5 ± 2.3

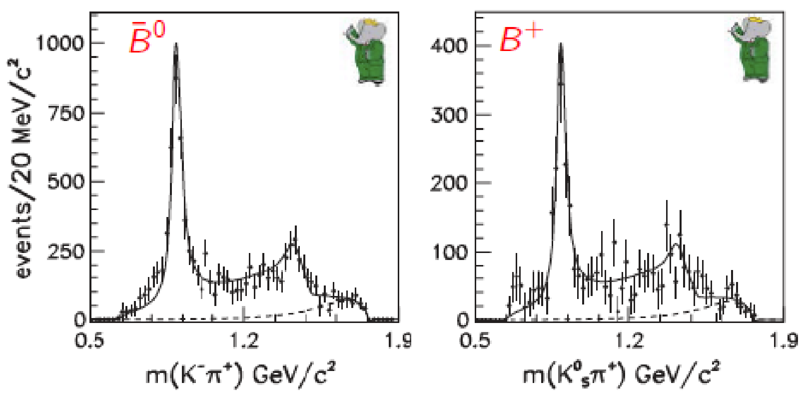
PRD 85, 052003 (2012)

and study DP for signal region and background sidebands



$K\pi$ description in $\bar{B}^0 \to \chi_{c1}\pi^+K^-$ and $B^+ \to \chi_{c1}\pi^+K^0_S$

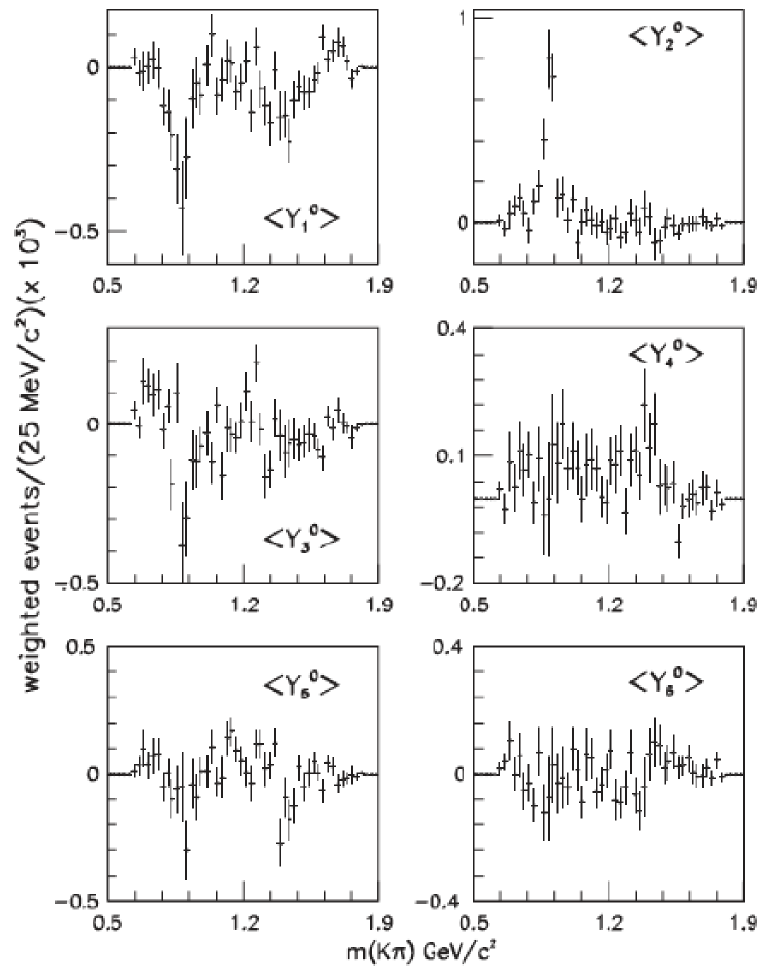
Fit the $K\pi$ invariant mass distribution to a sum of S-P-D wave



Channel	S wave	P wave	D wave	χ^2/NDF
$\bar{B}^0 \to \chi_{c1}K^-\pi^+$	40.4 ± 2.2	37.9 ± 1.3 10.3 ± 1.5	11.4 ± 2.0	58/54
$B^+ \to \chi_{c1}K^0_S\pi^+$	42.4 ± 3.5	37.1 ± 3.2 10.4 ± 2.5	10.1 ± 3.1	55/54

PRD 85, 052003 (2012)

and weight each event by Legendre Y^0_L polynomials



No evidence from *BABAR* for $Z_1(4050)^+$ and $Z_2(4250)^+$

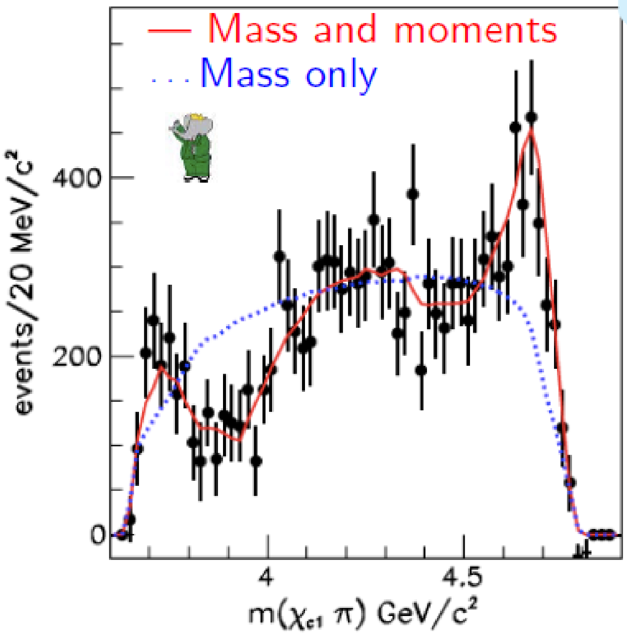
Use MC to predict reflections of $K\pi$ mass and angular structures in $\chi_{c1}\pi^+$

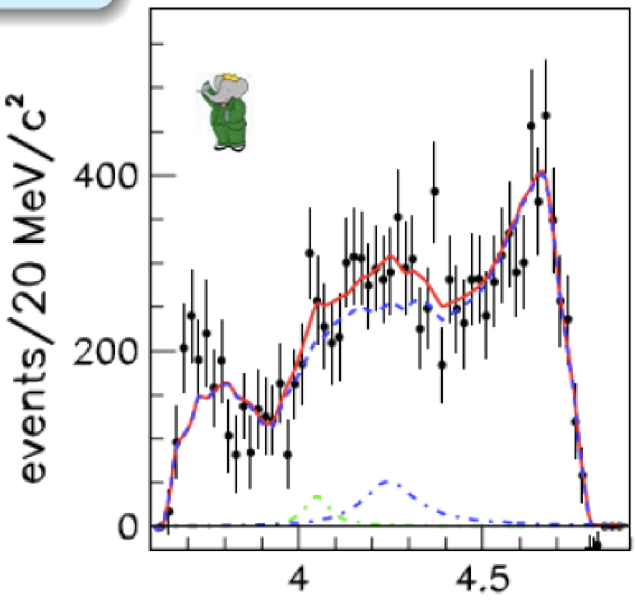
Reflections in MC using only $K\pi$ mass structures look different

No Z's

PRD 85, 052003 (2012)

with Z's





$$\mathcal{B}(\bar{B}^0 \to Z_1^+ K^-) \times \mathcal{B}(Z_1^+ \to \chi_{c1}\pi^+) < 1.8 \times 10^{-5}$$

$(3\ \ 10^{-5})$

$$\mathcal{B}(\bar{B}^0 \to Z_2^+ K^-) \times \mathcal{B}(Z_2^+ \to \chi_{c1}\pi^+) < 4.0 \times 10^{-5}$$

Not incompatible with Belle

$(4.0\ \ 10^{-5})$

Conclusions

- Confirmation of X(3915) meson seen in $J/\psi\ \omega$
  - Spin assignment 0^{++} strongly preferred: $\chi_{c0}(2P)$?
- $\gamma\gamma$ production of $\eta_c\pi\pi$
  - No X(3872) signal seen. In line with 1^{++} spin assignment
- Y(4260) and related 1^{--} resonances
  - Y(4260), Y(4350) and Y(4660) confirmed
- Are there new charmonium-like charged states ?
  - $Z(4050)^+$ and $Z(4250)^+$ NOT confirmed

  (but not incompatible with BELLE)

Summary of the Y(4260) properties

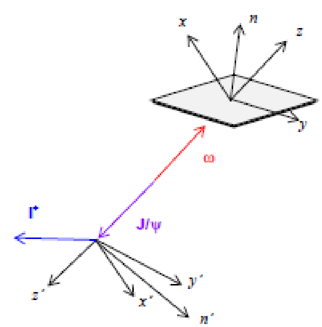
- $J^{PC} = 1^{--}$ because it is directly produced in the e^+e^- annihilation
- $Y(4260) \to J/\psi\pi^0\pi^0$ decay mode indicates I=0 PRL 96, 162003 (2006)
- Not observed in $Y(4260) \to \psi(2S)\pi^+\pi^-$ decays
- No observed decay to $D^*\bar{D}^*$ nor to $D_s^*\bar{D}_s^*$ so that its properties do not lend themselves to a simple charmonium interpretation
- BES III has reported the existence of a narrow resonant structure in the $J/\psi\pi$ sub-system at ~3.9 GeV/c^2 which would correspond to an isovector four-quark state arXiv:1303.5949
- Other interpretations:
  - four- quark state (PRD 72, 114016 (2005)). If the Y(4260) is a four-quark state it is expected to decay to $D_s^+\bar{D}_s^-$ but this has not been observed (PRD 82, 052004 (2010)).
  - baryonium state (J. Phyd. G 35, 075008 (2008))
  - hybrid state (PL B 625, 212 (2005)).

Summary of the Y(4350) - Y(4660) properties

- $J^{PC} = 1^{--}$ because they are directly produced in the e^+e^- annihilation
- They have been observed only in ISR $\psi(2S)\pi^+\pi^-$ production.
- Why are there states decaying into 2^3S_1 and not to 1^3S_1?
- One possible interpretation is hadro-charmonium states
  - M. B. Voloshin arXiv:0711.4556
  - Dubynsky & Voloshin PLB 671 (2009) 82

$J/\psi\,\omega$ *angular analysis*

- θ^*_ℓ is the angle between the direction of the positively charged lepton from J/ψ decay (ℓ^+) and the beam axis in the $J/\psi\omega$ rest frame.
- θ^*_n is the angle between the normal to the decay plane of the ω ($\vec{n}$) and the two-photon axis,
- θ_{ln} is the angle between the lepton ℓ^+ from J/ψ decay and the ω decay normal



- θ_h is the angle formed by the J/ψ momentum in the $J/\psi\omega$ rest frame with respect to the $J/\psi\omega$ direction in the laboratory frame.
- In the $J/\psi\omega$ rest frame : θ_n is the angle between the normal to the ω decay plane $\vec{n}$ and the ω direction in the $J/\psi\omega$ rest frame.
- θ_l ; first boost the ℓ^+ to the J/ψ rest frame. θ_l is the angle between the ℓ^+ and the direction of the J/ψ in the $J/\psi\omega$ frame.
- ϕ_l as the angle between the J/ψ and ω decay plane normals.