Charmonium studies at BaBar

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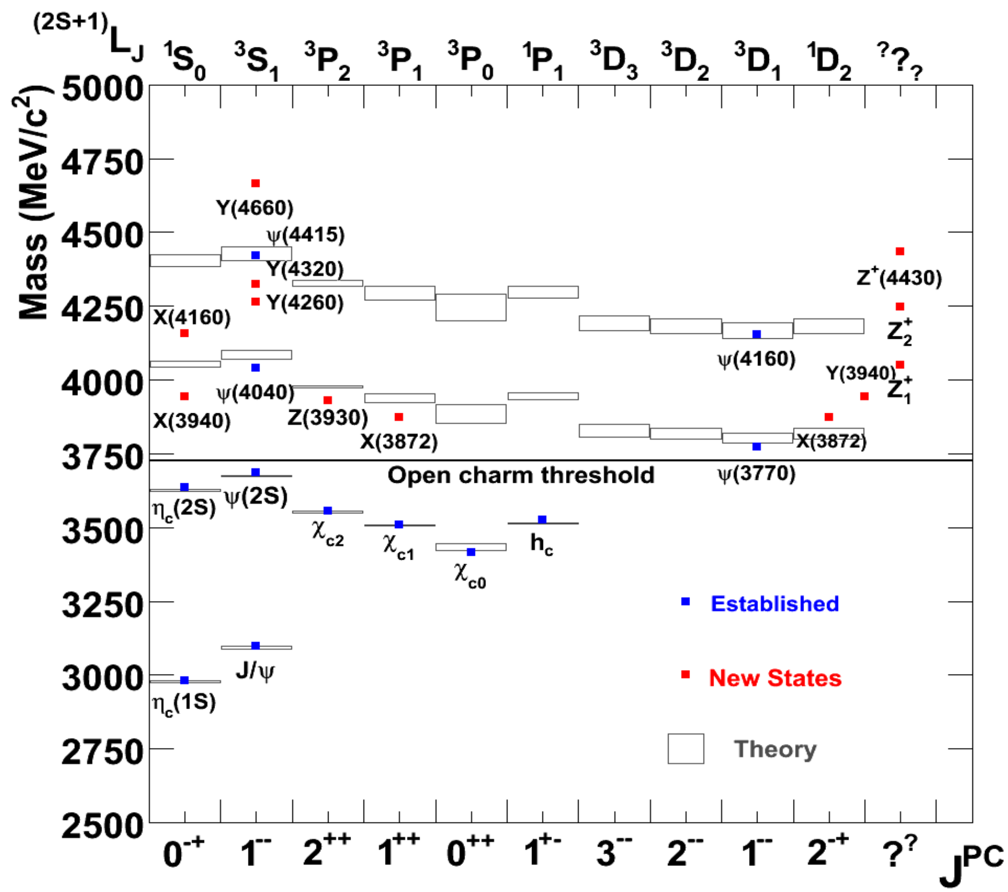
BaBar

- BaBar collected 465M $B\bar{B}$ pairs at the Υ(4S) from 1999 – 2007 at the PEP-II e^+e^- collider located at the SLAC national laboratory.
- Also collected Υ(2S) and Υ(3S) data in 2008. See "Recent BaBar Studies of Bottomonium States" by V. Ziegler in this morning's Hadron Spectroscopy session.
- Total of 519 fb^{-1}.
- Analysis of this data continues.

Charmonium ($c\bar{c}$ meson) spectrum

- Very active area of research at the B-factories and elsewhere.
- Many new states discovered, some expected, many not.



Analyses presented in this talk

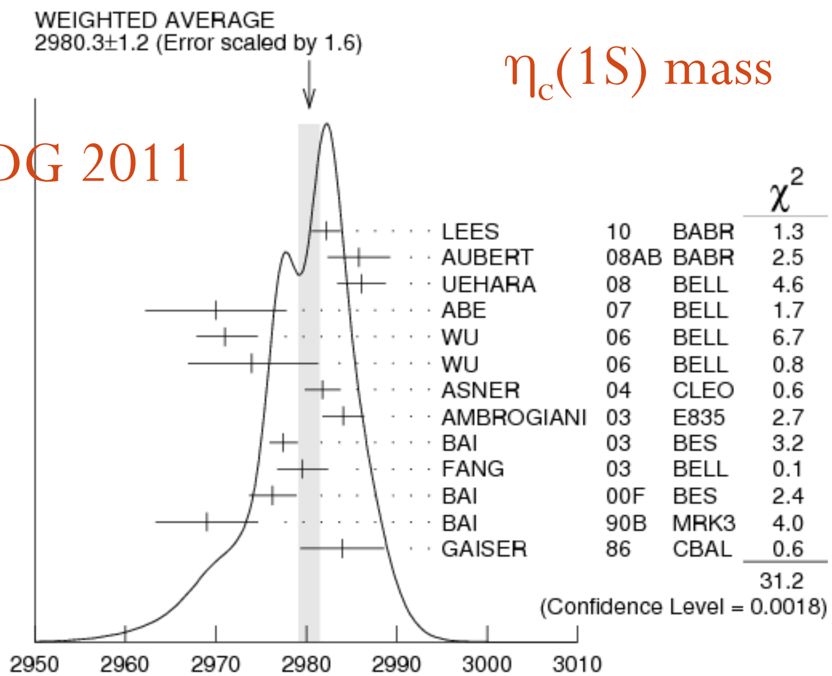
- Observation of $\eta_c(1S)$ and $\eta_c(2S)$ decays to $K^+ K^- \pi^+ \pi^- \pi^0$ in two-photon interactions
  - Phys. Rev. D **84**, 012004 (2011).

- Evidence for the decay $X(3872) \to J/\psi\ \omega$
  - Phys. Rev. D **82**, 011101(R) (2010).

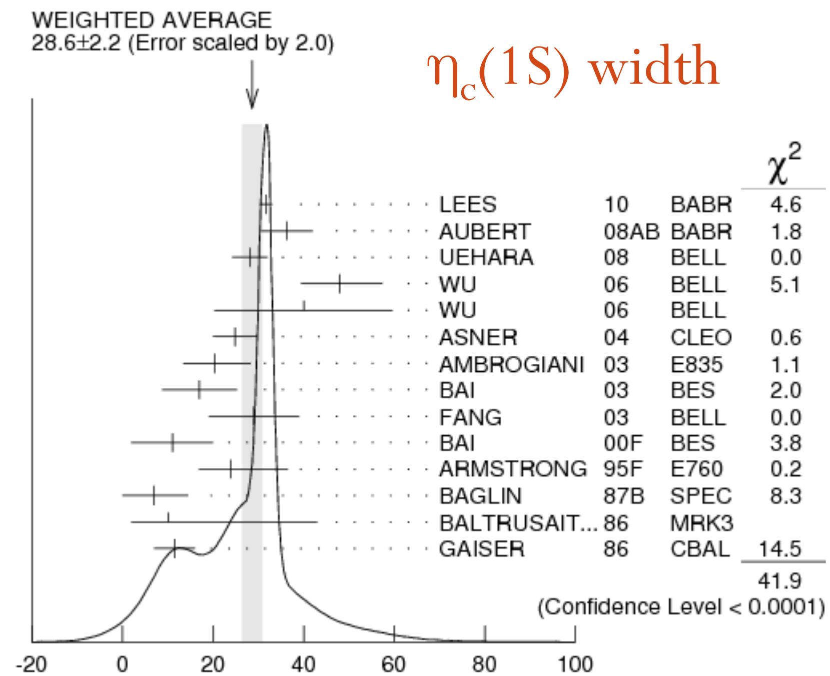
Current status of $\eta_c(1S)$

PDG 2011

$\eta_c(1S)$ mass



$\eta_c(1S)$ width

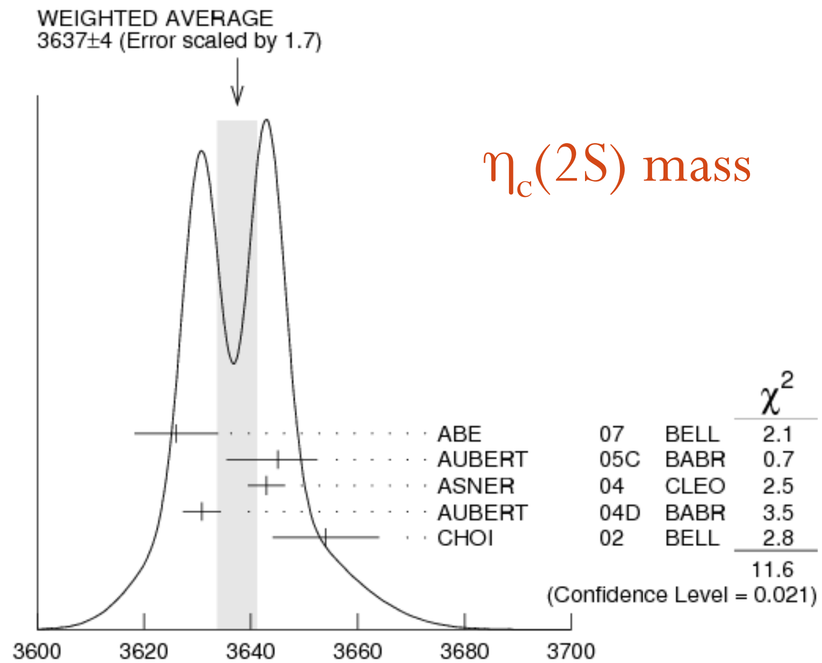


- Large spread in $\eta_c(1S)$ mass and width measurements.
- $\Gamma \sim 15$ MeV in J/ψ and $\psi(2S)$ radiative decays.
- $\Gamma \sim 30$ MeV in B decays and $\gamma\gamma$ production.

Current status of $\eta_c(2S)$

PDG 2011

$\eta_c(2S)$ mass



- Discovered by Belle in 2002.
- $\eta_c(2S)$ observed in exclusive decay only to $K\,\overline{K}\,\pi$.
- Precise measurement of mass will help discriminate among charmonium models.

New results on $\eta_c(1S)$ and $\eta_c(2S)$

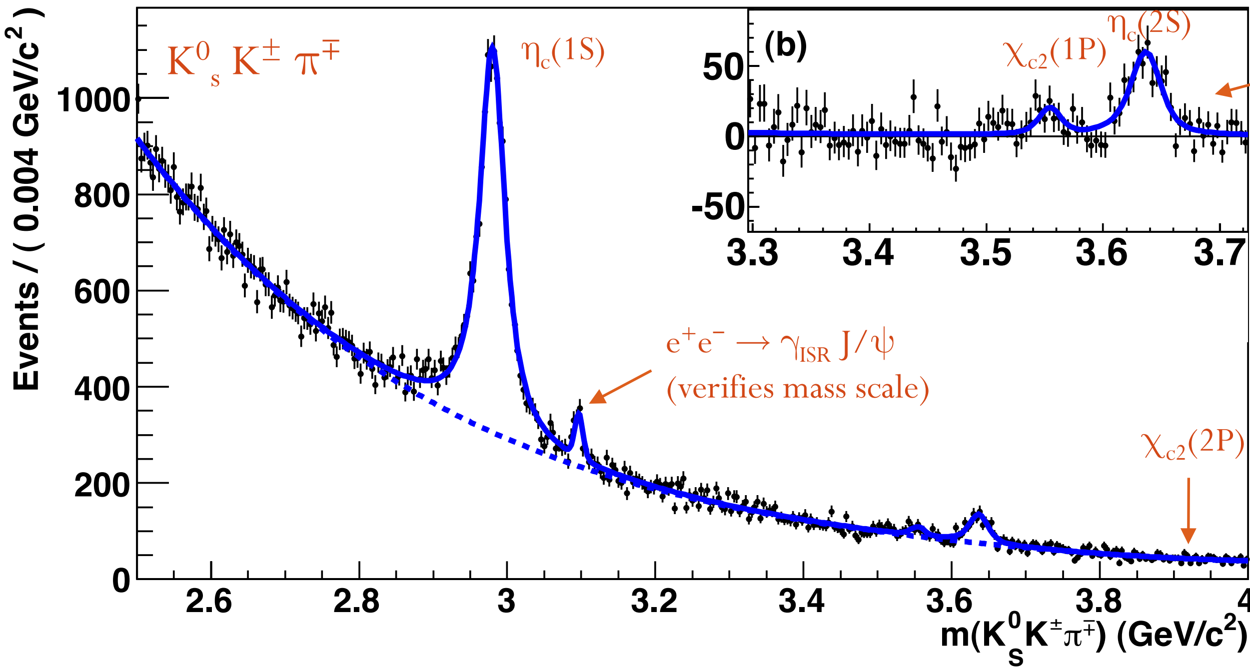
- Full BABAR data set of $\Upsilon(4S)$, $\Upsilon(3S)$ and $\Upsilon(2S)$ data of 519 fb^{-1}.
- Two photon production ($e^+e^- \rightarrow \gamma\gamma\, e^+e^-$) of final states $K^+ K^- \pi^+ \pi^- \pi^0$ and $K^0_s K^\pm \pi^\mp$.
- Outgoing e^+e^- not detected
- Almost real $\gamma\gamma \Rightarrow$ allowed quantum numbers are

$$J^{PC} = 0^{\pm +}, 2^{\pm +}, 4^{\pm +}, \ldots; \quad 3^{++}, 5^{++}, \ldots$$

- However $K^0_s K^\pm \pi^\mp$ cannot have $J^{PC} = 0^{++}$

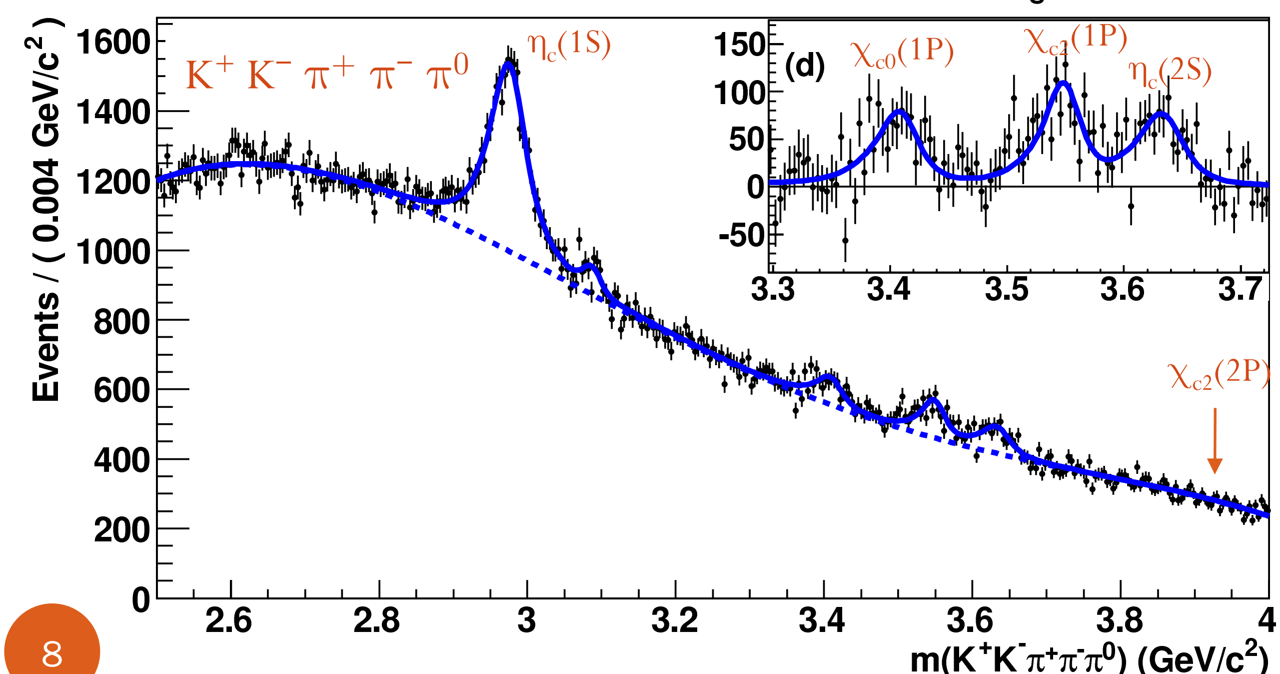
  $\Rightarrow$ $\chi_{c1}(1P)$ is not produced;

  $\chi_{c0}(1P)$ does not decay to $K^0_s K^\pm \pi^\mp$



spectrum after background subtraction

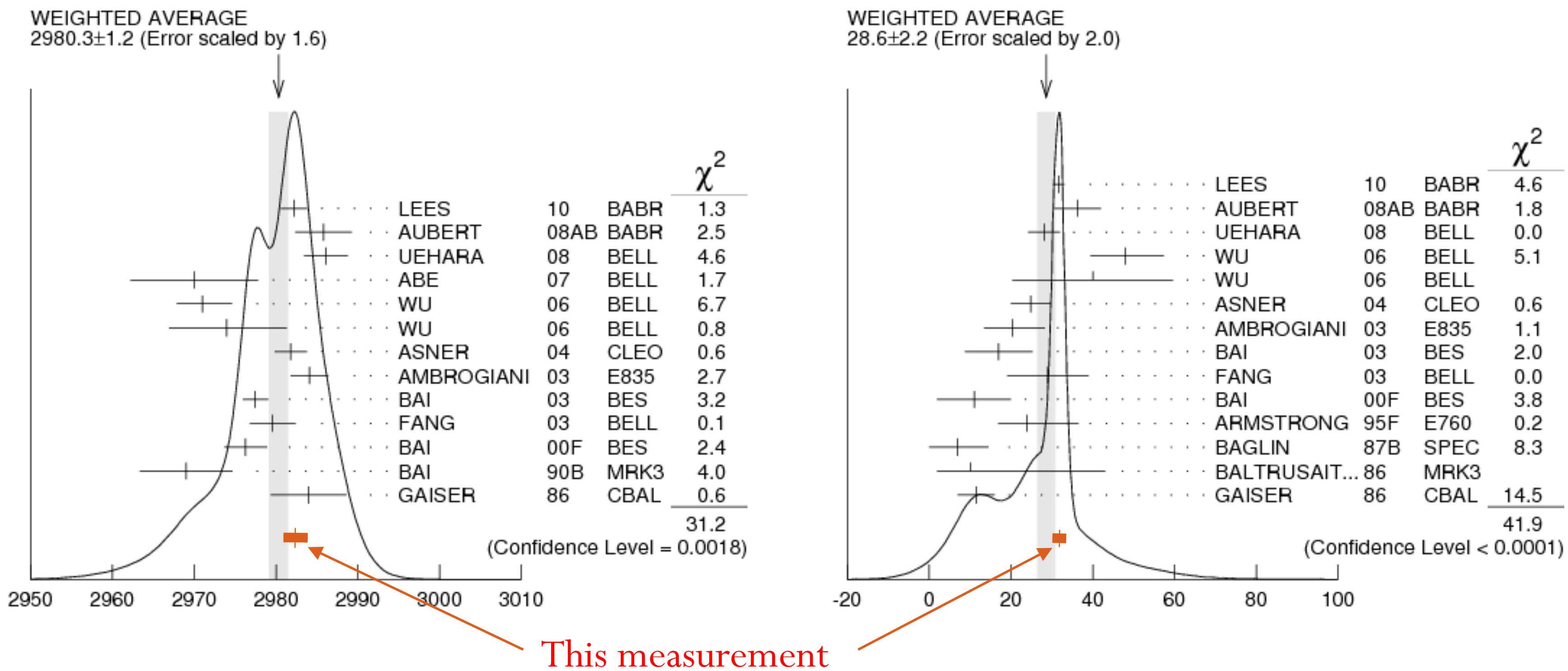
need to subtract peaking backgrounds of few % [$\eta_c(1S)$] to ~20% [$\chi_{c2}(1P)$ in $KK3\pi$]



First observation of $\eta_c(1S)$, $\chi_{c0}(1P)$ and $\eta_c(2S)$ in this final state.
4σ evidence for $\chi_{c2}(1P)$

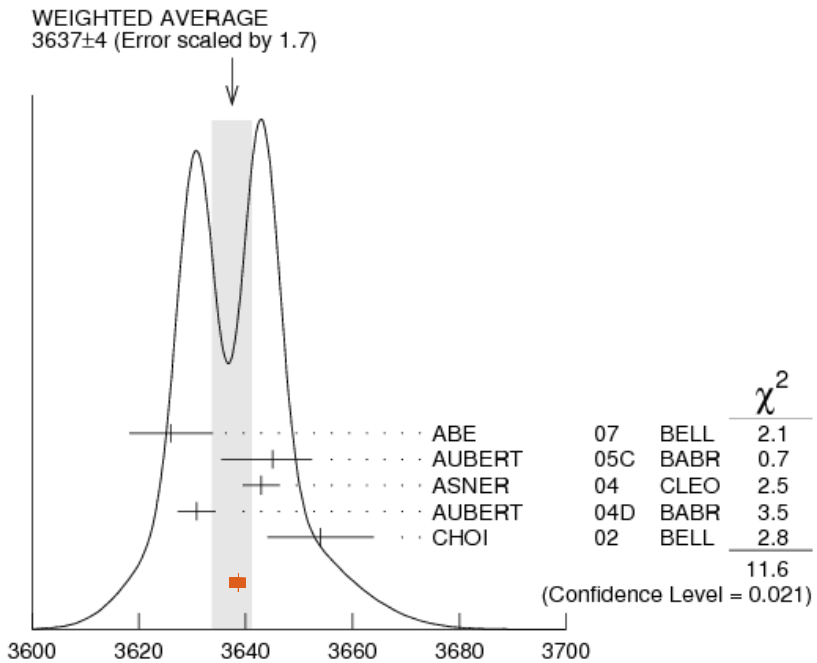
No sign of the $\chi_{c2}(2P)$, observed in $\gamma\gamma$ production of $D\bar{D}$

$\eta_c(1S)$ mass and width results



$$M[\eta_c(1S)] = 2982.5 \pm 0.4 \pm 1.4 \text{ MeV/c}^2 \qquad \text{PDG}: 2980.3 \pm 1.2$$
$$\Gamma[\eta_c(1S)] = 32.1 \pm 1.1 \pm 1.3 \text{ MeV} \qquad \text{PDG}: 28.6 \pm 2.2$$

$\eta_c(2S)$ mass and width results



More precise than world average

$$M[\eta_c(2S)] = 3638.5 \pm 1.5 \pm 0.8\ \mathrm{MeV/c^2} \quad \mathrm{PDG: 3637 \pm 4}$$
$$\Gamma[\eta_c(2S)] = 13.4 \pm 4.6 \pm 3.2\ \mathrm{MeV} \quad \mathrm{PDG: 14 \pm 7}$$

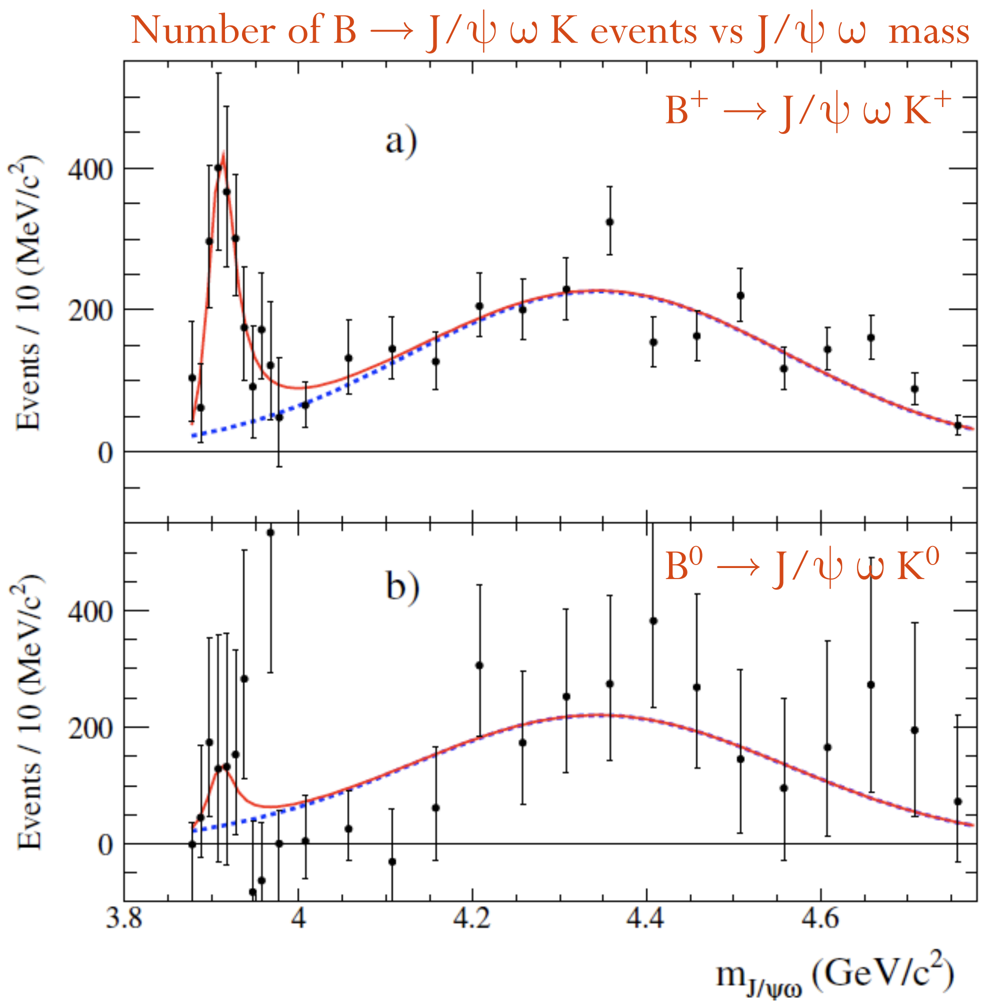
X(3872)

- The first of the new states was the X(3872), discovered in 2003 by Belle using the $J/\psi\ \pi^+ \pi^-$ final state.
- What is it?
  - mass
  - number of states (X^+, $B^0 \rightarrow X K^0$ vs $B^+ \rightarrow X K^+$)
  - quantum numbers
  - decay branching fractions

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

- Belle presented some evidence for this decay in a 2005 (unpublished) conference paper, hep-ex/0505037.
  - $B \to [J/\psi\, \pi^+ \pi^- \pi^0\,]\, K$
- In the same final state, BABAR has previously seen clear evidence for $Y(3940) \to J/\psi\, \omega$, but not $X(3872)$.
    - Phys. Rev. Lett. 101, 082001 (2008).
  - but required $769.5 < m_{3\pi} < 796.5$ MeV/c^2 (B^+)
    - i.e $m_{3\pi} > m_\omega - 13$ MeV/c^2
    - note that $m_{J/\psi} + m_\omega$ is 8 ± 4 MeV/c^2 greater than m_X.
    - $\Gamma_\omega = 8.49$ MeV
  - The analysis presented here is similar, but with $m_{3\pi} > m_\omega - 43$ MeV/c^2

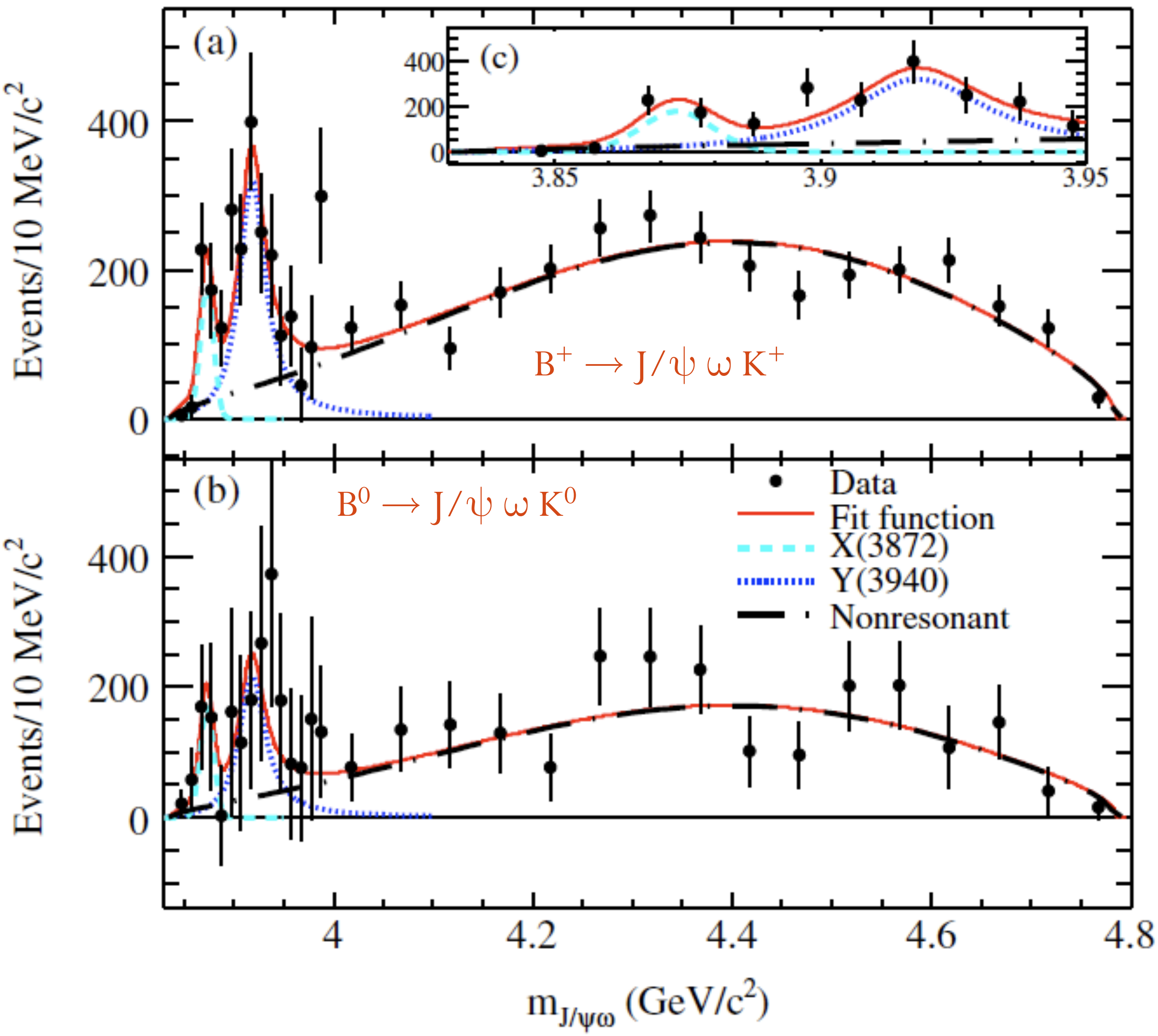
Previous result



$J/\psi\ \omega$ mass spectrum

- Fit the $B \to J/\psi\ \omega\ K$ MES mass distribution for each 10 MeV/c^2 bin in $J/\psi\ \omega$ mass to obtain the number of B decays at that mass.
- Correct for efficiency and secondary BF
- Simultaneous fit (B^+ and B^0) to $J/\psi\ \omega$ mass spectrum for X(3872), Y(3940), and non-resonant components.
- 4σ evidence for $X \to J/\psi\ \omega$
- $B(B^+ \to X K^+) \cdot B(X \to J/\psi\ \omega) = [0.6 \pm 0.2 \pm 0.1] \times 10^{-5}$
- $B(B^0 \to X K^0) \cdot B(X \to J/\psi\ \omega) = [0.6 \pm 0.3 \pm 0.1] \times 10^{-5}$

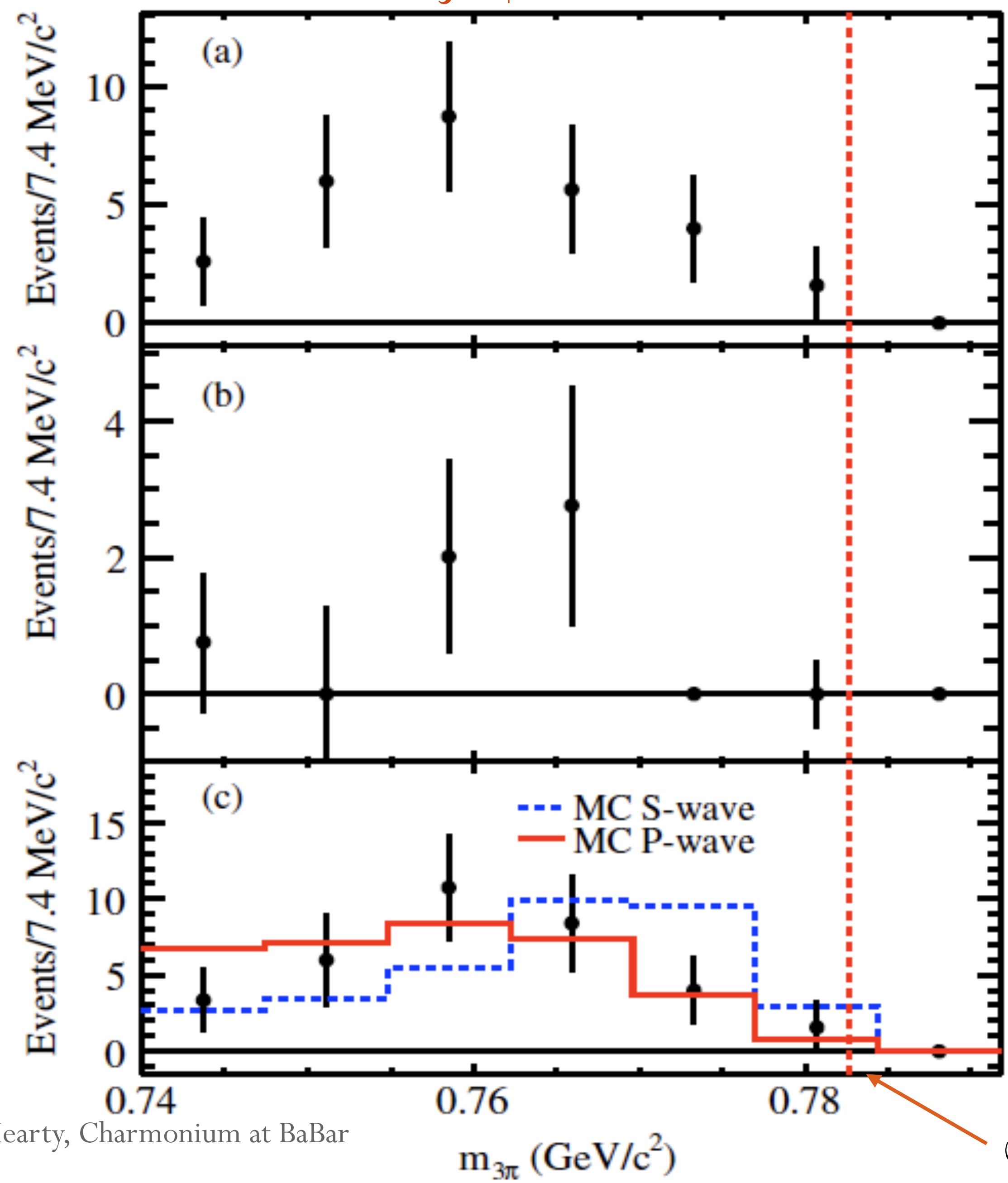
Number of B → J/ψ ω K events vs J/ψ ω mass



ω mass distribution

- Plot ω mass for $3862.5 < M_{J/\psi\,\omega} < 3882.5$ MeV/c^2 $\sim M_X \pm 10$ MeV/c^2.
- Mass distribution depends on orbital angular momentum of $J/\psi\,\omega$. L = 1 suppressed at kinematic threshold by contrifugal barrier factor $q^2/(1 + R^2 \cdot q^2)$
  - q = momentum of J/ψ or ω
  - $R \sim 3$ GeV^{-1}
- L = 1 (probability χ^2 = 62%) favored over L = 0 (7%) $\Rightarrow P = -1$
- Similar analysis of threshold behavior in $X \rightarrow D^{*0}\,\overline{D}$ also favored P = −1 interpretation. PRL **100**, 062006 (2008)

Number of $B \rightarrow J/\psi\, \omega\, K$ events vs ω mass



$B^+ \rightarrow X(3872)\, K^+$

$B^0 \rightarrow X(3872)\, K^0$

Combined

ω PDG mass

$J/\psi\ \omega$ context

- Observation of $X \to J/\psi\,\gamma \Rightarrow C = +1$.
  - BABAR Phys. Rev. **D**74, 071101(R), 2006
- CDF angular analysis concluded $J^P = 1^+$ or 2^-
- Current analysis would therefore favor $J^{PC} = 2^{-+}$, which is not consistent with molecular interpretation (0^{-+} or 1^{++}), but is consistent with $\eta_{c2}(1D)$ $[^1D_2]$.
- BABAR evidence for $X \to \psi(2S)\,\gamma$ is not consistent with $\eta_{c2}(1D)$ interpretation (e.g. 1007.4541 [hep-ph])] ,
  - BaBar Phys. Rev. Lett. 102, 132001 (2009).
- But Belle did not see any evidence for this decay.

Context continued

- New Belle analysis of the angular and mass distributions in $X \to J/\psi\, \pi^+ \pi^-$ favors 1^{++}, but 2^{-+} is also possible if $\omega \to \pi^+ \pi^-$ interference with $\rho \to \pi^+ \pi^-$ occurs in $X \to J/\psi\, \pi^+ \pi^-$.
  - Belle: 1107.0163 [hep-ex] July 2011
- Story of the X(3872) is not over.

Conclusions

- First observation of $\eta_c(2S)$ in final state other than $K \bar{K} \pi$.
- New mass and width measurements for $\eta_c(1S)$ and $\eta_c(2S)$.
- X(3872) continues to be interesting. Is it really the $\eta_{c2}(1D)$?
- Examples of some other charmonium analyses that should be ready soon:
  - ISR production of $J/\psi\ \pi^+\pi^-$ and $\psi(2S)\ \pi^+\pi^-$ with full data set
  - $B \to \chi_{cJ} K\pi$ $[Z^+ \to \chi_{cJ}\pi^+]$
  - Mass spectrum recoiling against J/ψ or $\psi(2S)$ in continuum production with full data set.

Backup slides

Y(3940) results in J/ψ ω

$$M = 3919.1^{+3.8}_{-3.5}(\text{stat}) \pm 2.0(\text{sys})\ \text{MeV/c}^2$$

$$\Gamma = 31^{+10}_{-8}(\text{stat}) \pm 5(\text{sys})\ \text{MeV}$$

$$B(B^+ \to YK^+) \cdot B(Y \to J/\psi\omega) = \left[3.0^{+0.7}_{-0.6}(\text{stat})^{+0.5}_{-0.3}(\text{sys})\right] \times 10^{-5}$$

$$B(B^0 \to YK^0) \cdot B(Y \to J/\psi\omega) = \left[2.1 \pm 0.9(\text{stat}) \pm 0.3(\text{sys})\right] \times 10^{-5}$$

ω Dalitz weights

Each event has a weight of (5/2)(1-3cos$^2\theta_h$), where θ_h is the angle between the π^+ and π^0 in the $\pi^+\pi^-$ rest frame

Non-ω events gets low weight