Study of XYZ states in B decays and two-photon production at *BABAR*

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9th International Workshop on Heavy Quarkonium – QWG2013
Beijing, April 22-26, 2013

Outline

- Search for resonances decaying to $\eta_c \pi^+ \pi^-$ in $\gamma\gamma$ reactions
- Study of $X(3915) \to J/\psi\omega$ observed in $\gamma\gamma$ reactions
- Search for $Z_1(4050)^+$ and $Z_2(4250)^+$ in $B^0 \to \chi_{c1}\pi^+ K^-$ and $B^+ \to \chi_{c1}\pi^+ K_S$

The *BABAR* experiment

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

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

Asymmetric:

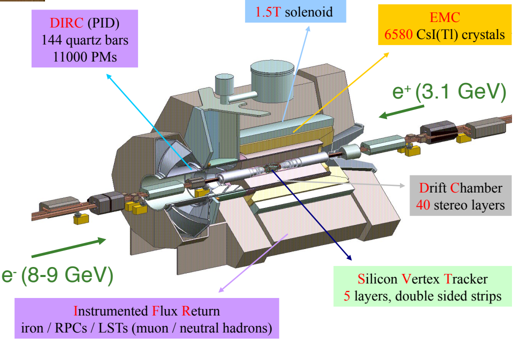
$$-0.9 < \cos\theta^* < 0.85$$

wrt electron beam

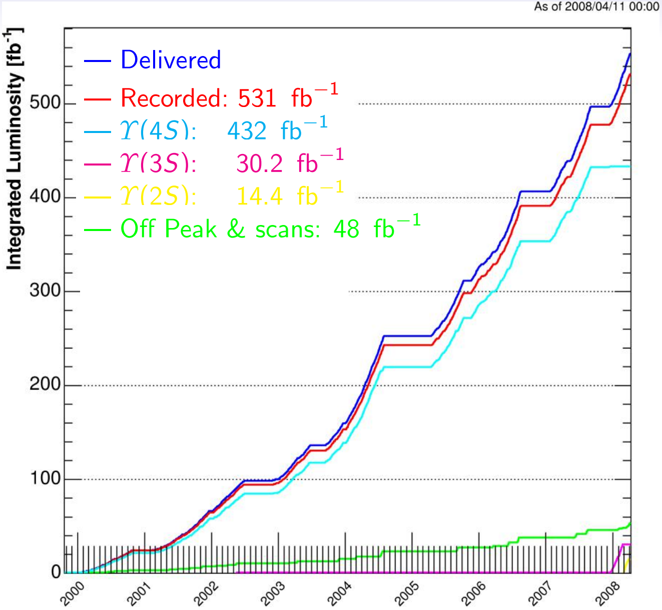
excellent performance:

- vertexing
- tracking
- PID
- calorimeter

General-purpose detector

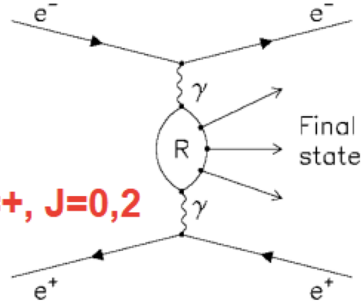


Data samples



$\gamma\gamma$ reactions

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 $4^{\pm+}, 3^{++}, 5^{++}, ...$)
- low p_t with respect to beam axis

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

- $\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-)$ predicted to be large

$$\frac{\Gamma(\eta_c(2S) \to \eta_c\pi^+\pi^-)}{\Gamma(\psi(2S) \to J/\psi\pi^+\pi^-)} \approx 2.9$$

Voloshin, Mod.Phys.Lett. A17, 1533 (2002)

thus $\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) = (2.2^{+1.6}_{-0.6})\%$

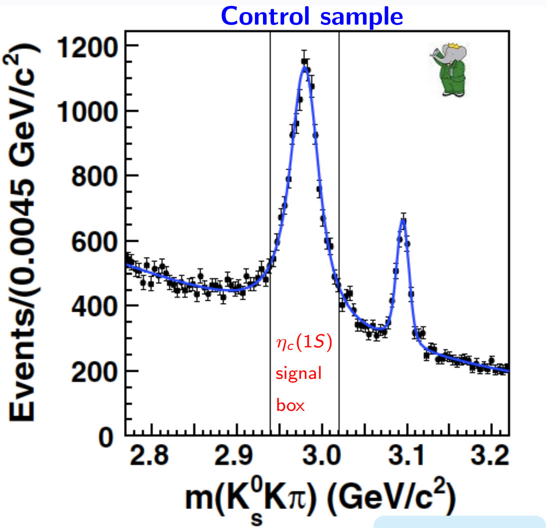
- Many new resonances observed in $J/\psi\pi^+\pi^-$
  - there could be others in $\eta_c\pi^+\pi^-$ **unexplored!**
  - 0^{-+} instead of 1^{--} allows access to "new states" with different quantum numbers

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

Select candidates

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

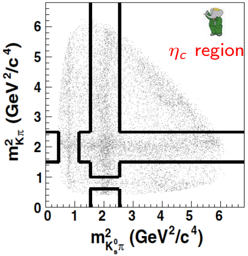
"standard" cuts on PID, p_t, missing mass,...



PRD 86, 092005 (2012)

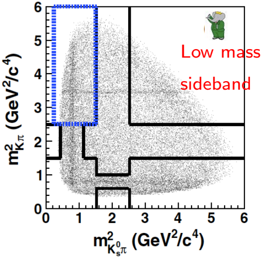
Dalitz plot cut

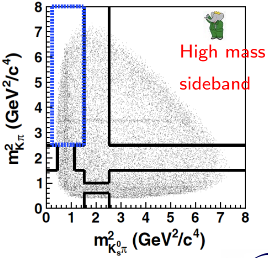
Control sample



In the control sample, the Dalitz plot of events in the η_c mass window shows different substructures than events in the low-mass or high-mass sidebands

Enhance η_c in main sample by requiring intermediate $K^*(1430)$





Further reduce non-η_c component with a NN trained to reject events in blue regions of low and high sidebands

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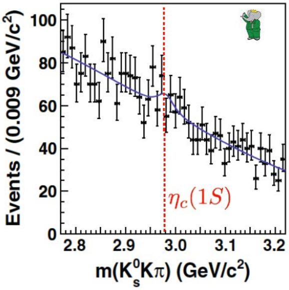
Event yield for $\gamma\gamma \to \eta_c\pi^+\pi^-$

The total signal yield for $\gamma\gamma \to \eta_c\pi^+\pi^-$ (resonant or non-resonant) is determined from the 1-D fit to the $K^0_S K^\pm\pi^\mp$ invariant mass distribution integrated over $M\left((K^0_S K^\pm\pi^\mp)\pi^+\pi^-\right) > 3.5\ \mathrm{GeV}/c^2$

$\eta_c\pi^+\pi^-$ **sample**



Only 50±37 inclusive η_c in the sample

- No evidence for $\gamma\gamma \to \eta_c\pi^+\pi^-$ signal in the main sample

  i.e.

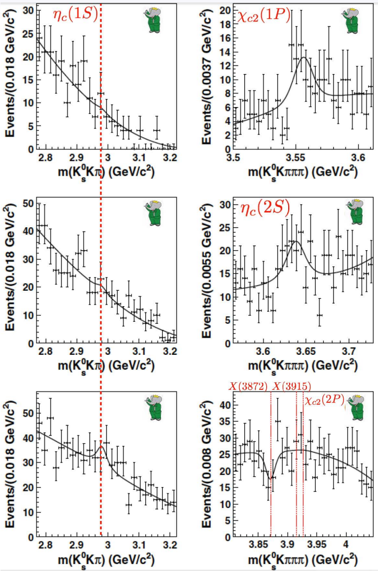
- No evidence for $\eta_c\pi^+\pi^-$ decay of resonances with $M > 3.5\ \mathrm{GeV}/c^2$

PRD 86, 092005 (2012)

Search for $\chi_{c2}(1P), \eta_c(2S) \to \eta_c\pi^+\pi^-$

PRD 86, 092005 (2012)

Perform a 2-D fit to the $M(K_0^S K^\pm \pi^\mp)$ vs $M\left((K_0^S K^\pm \pi^\mp)\pi^+\pi^-\right)$ distribution to determine the signal yield at each resonance



- No evidence for $\chi_{c2}(1P), \eta_c(2S) \to \eta_c\pi^+\pi^-$
  Peaking background from known $K_S^0 K^\pm \pi^\mp \pi^+\pi^-$ (non resonant) decays not peaking at η_c mass
- No evidence for other resonances:

90%CL

Resonance	$\Gamma_{\gamma\gamma}\mathcal{B}$(eV) Central value	UL
$\chi_{c2}(1P)$	$7.2^{+5.5}_{-4.4} \pm 2.9$	15.7
$\eta_c(2S)$	$65^{+47}_{-44} \pm 18$	133
$X(3872)$	$-4.5^{+7.7}_{-6.7} \pm 2.9$	11.1
$X(3915)$	$-13^{+12}_{-12} \pm 8$	16
$\chi_{c2}(2P)$	$-16^{+15}_{-14} \pm 6$	19

- derive using PRD 84, 012004 (2011) and PDG

$$\frac{\mathcal{B}(\chi_{c2}(1P) \to \eta_c\pi^+\pi^-)}{\mathcal{B}(\chi_{c2}(1P) \to K_S^0 K^\pm \pi^\pm)} < 32.9 \quad \mathcal{B}(\chi_{c2}(1P) \to \eta_c\pi^+\pi^-) < 2.2\%$$

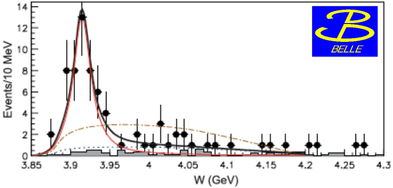
$$\frac{\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-)}{\mathcal{B}(\eta_c(2S) \to K_S^0 K^\pm \pi^\pm)} < 10.0 \quad \mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) < 7.4\%$$

compatible with Voloshin's prediction

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

$X(3915)$ decaying to $J/\psi\omega$ observed by Belle in $\gamma\gamma$ PRL 104, 092001 (2010)

$$M = 3915 \pm 3 \pm 2 \text{ MeV}/c^2$$
$$\Gamma = 17 \pm 10 \pm 3 \text{ MeV}$$
$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 61 \pm 17 \pm 8 \text{ eV} \quad (J=0)$$
$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 18 \pm 5 \pm 2 \text{ eV} \quad (J=2)$$



but there are other resonances in the same final state or mass range

- $Y(3940)$ decaying to $J/\psi\omega$ has been observed in B decays

  PRL 94, 182002 (2005) PRL 101, 082001 (2008) PRD 82, 011101 (2010)

- $Z(3930)$ decaying to $D\bar{D}$ observed in $\gamma\gamma$

  PRL 96, 082003 (2006) PRD 81, 092003 (2010)

  angular distribution supports $J=2$, identified with $\chi_{c2}(2P)$

Are they all the same or not?

Also, until recently, the assignment 2^{-+} for the X(3872) was not ruled out arXiv:1302.6269

Study of $X(3915) \to J/\psi\omega$ in $\gamma\gamma$ reactions at BABAR

$X(3915)$ confirmed by BABAR

PRD 86, 072002 (2012)

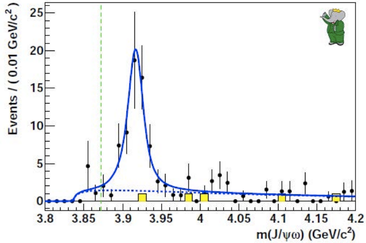
Resonance parameters in agreement with Belle:

$$M = 3919.4 \pm 2.2 \pm 1.6 \text{ MeV}/c^2$$

$$\Gamma = 13 \pm 6 \pm 3 \text{ MeV}$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 52 \pm 10 \pm 3 \text{ eV} \qquad (J = 0)$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 10.5 \pm 1.9 \pm 0.6 \text{ eV} \qquad (J = 2)$$



If $\Gamma_{\gamma\gamma} = \mathcal{O}(1 \text{ keV})$ (typical $c\bar{c}$), then $\mathcal{B}(J/\psi\omega) > (1-6)\%$

(Limit for $J = 2$ hypothesis of $X(3872)$: $\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) < 1.7 \text{ eV}$)

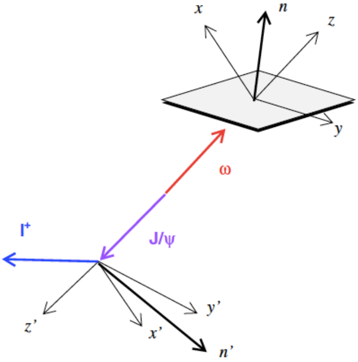
Angular distribution for $\gamma\gamma \to J/\psi\omega$

Angular analysis follows J. L. Rosner, PRD 70, 094023 (2004)

Since events have low p_t the $\gamma\gamma$ collision axis is approximately along the beam axis.

The angles are defined in three different center of mass frames: $J/\psi\omega$, J/ψ, and ω.

The normal to the ω decay plane defines the axis orientation



No background subtraction:

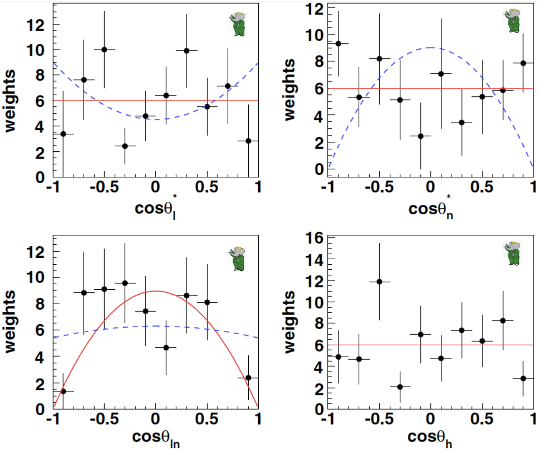
assume that all events in $3890 < M(J\psi\omega) < 3950\ \mathrm{MeV}/c^2$ are from $X(3915)$ decay

$X(3915)$: J=0 or J=2?

The efficiency corrected distributions for events in the $X(3915)$ signal region in each of the three discriminating angles favors $J = 0$ over $J = 2$

Angle	$J^P = 0^{\pm}$	$J^P = 2^{+}$
θ_l^*	1	$1 + \cos^2\theta_l^*$
χ^2	11.2	16.9
θ_n^*	1	$\sin^2\theta_n^*$
χ^2	6.9	65.9
θ_{ln}	$\sin^2\theta_{ln}$	$7 - \cos^2\theta_{ln}$
χ^2	12.5	18.0
θ_h	1	
χ^2	12.2	

(NDOF=9)

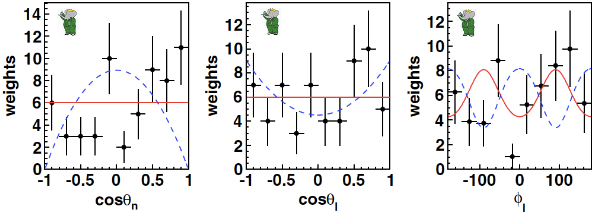


Overall J=0 strongly preferred over J=2

PRD 86, 072002 (2012)

$X(3915)$: 0^- or 0^+?

The efficiency corrected distributions for events in the $X(3915)$ signal region in three discriminating angles favors 0^+ over 0^-



Angle	$J^P = 0^-$	$J^P = 0^+$
θ_n	$\sin^2\theta_n$	1
χ^2	77.6	16.3
θ_l	$1 + \cos^2\theta_l$	1
χ^2	8.7	8.3
ϕ_l	$2 - \cos(2\cos\phi_l)$	$2 + \cos(2\cos\phi_l)$
χ^2	21.7	9.6

(NDOF=9)

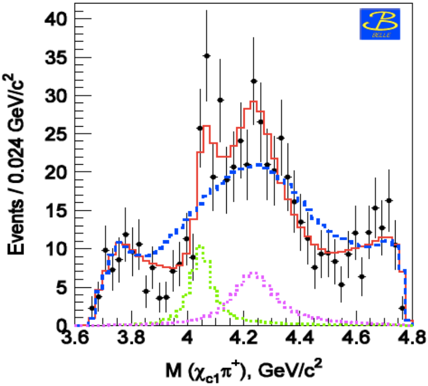
PRD 86, 072002 (2012)

$\chi_{c0}(2P)$ candidate?

$Z_1(4050)^+$ and $Z_2(4250)^+$

Fit to the Dalitz plot intensity of $\bar{B}^0 \to \chi_{c1}\pi^+K^-$ including contributions from all know $K*$

To obtain a good fit need to include two more intermediate states decaying to $\chi_{c1}\pi^+$



PRD 78, 072004 (20008)

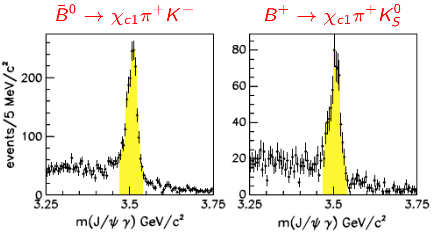
$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$
$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV},$$

with the product branching fractions of

$$\mathcal{B}(\bar{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+ \chi_{c1}) = (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5},$$
$$\mathcal{B}(\bar{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+ \chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5}.$$

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

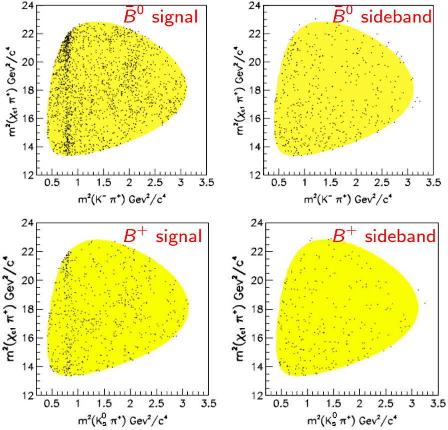
Select samples with relatively large purities



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

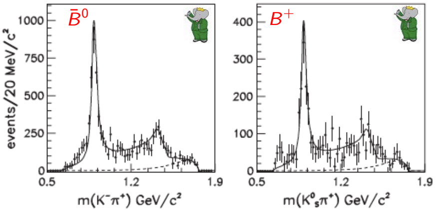
PRD 85, 052003 (2012)

and study DP for signal region and background sidebands



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

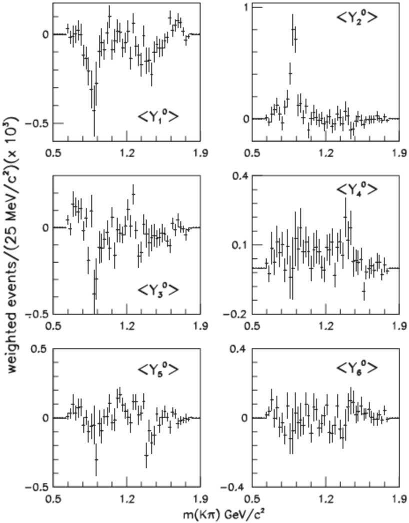
Fit the $K\pi$ invariant mass distribution to a sum of S-P-D wave



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 $Z_2(4250)^+$

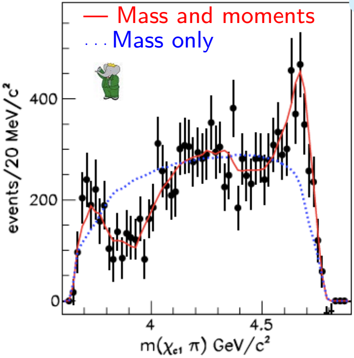
Use MC to predict reflections of $K\pi$ mass and angular structures in $\chi_{c1}\pi^+$

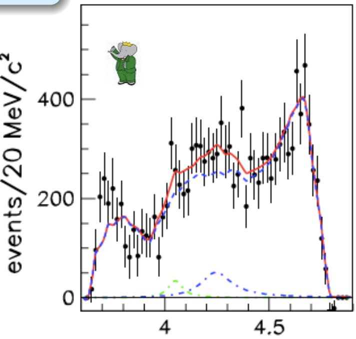
Reflections in MC using only $K\pi$ mass structures look different

No Z's

PRD 85, 052003 (2012)

with Z's





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

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

Not incompatible with Belle

Conclusions

- Search for resonances decaying to $\eta_c\pi^+\pi^-$ in $\gamma\gamma$ reactions
  - First search in this mode
  - No signal found
  - $\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) < 7.4\%$ and $\mathcal{B}(\chi_{c2}(1P) \to \eta_c\pi^+\pi^-) < 2.2\%$
- Study of $X(3915) \to J/\psi\omega$ observed in $\gamma\gamma$ reactions
  - Confirm the state observed by Belle
  - Study of angular distribution suggests 0^{++} $\chi_{c0}(2P)$**??**
- Search for $Z_1(4050)^+$ and $Z_2(4250)^+$ in $B^0 \to \chi_{c1}\pi^+K^-$ and $B^+ \to \chi_{c1}\pi^+K_S$
  - we do NOT confirm the state observed by Belle
  - nor we are able to exclude it
- Analysis still ongoing, more than 5 years after the end of the data taking, new results to come