Spectroscopy of the XYZ states at BABAR.

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Introduction.

□ Belle claims for the discovery of exotic charged charmonium states in B decays.
$Z^+(4430) \to \psi(2S)\pi^+$ observed the decay $B \to \psi(2S)K\pi$ (Phys. Rev. Lett. 100, 142001, (2008)),(Phys. Rev. D 80, 031104(R) (2009)), $Z_1(4050)^+$ and $Z_2(4250)^+$ observed in the decay to $\chi_{c1}\pi^+$ in $B \to \chi_{c1}K\pi$ (Phys.Rev.D 78, 072004, (2008))

□ BaBar published the search for $Z^+(4430) \to \psi(2S)\pi^+$ with negative results (Phys. Rev. D 79, 112001 (2009)).
□ No signal was also observed in the $J/\psi\pi$ system in the study of the $B \to J/\psi K\pi$ decay.

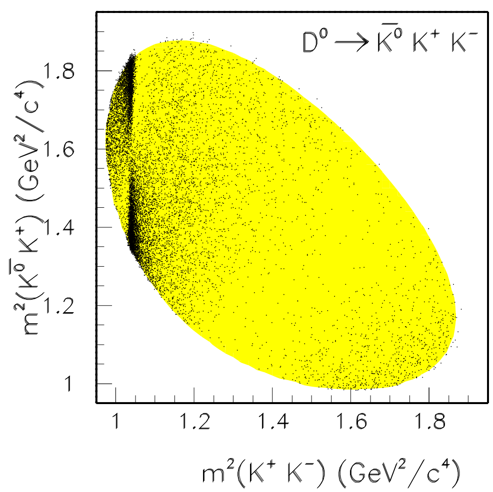
□ A lot of theoretical and experimental discussion. A charged charmonium state is not a simple $q\bar{q}$ meson.

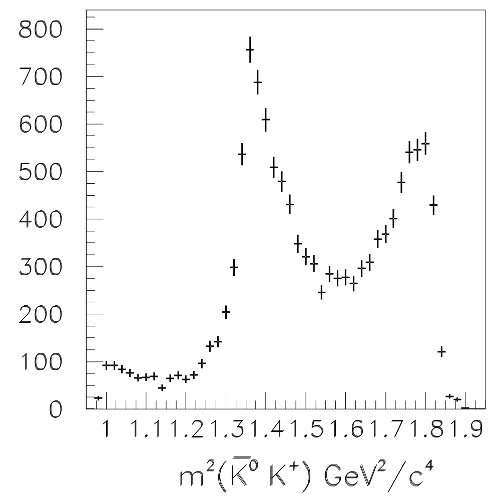
The use of charge conjugate reactions is implied throughout.

Introduction.

□ Main points of discussion are:

- Interference effects between amplitudes in 3-body B decay Dalitz plots produce peaks in quasi-two-body mass projections which may not be due to real states.
  A dramatic demonstration comes from charm decays. Dalitz plot of $D^0 \to \bar{K}^0 K^+ K^-$ and projection along the $\bar{K}^0 K^+$ axis: structures are not due to resonances.





- The angular structures in $B \to \psi(2S) K\pi$ and $B \to \chi_{c1} K\pi$ decays are very complex and cannot be described by only two variables as it is done in a simple Dalitz plot analysis.

□ The present analysis from BABAR searches for $Z_1(4050)^+$ and $Z_2(4250)^+$ in $B \to \chi_{c1} K\pi$ decays.

Reconstructed B decay modes.

☐ We reconstruct the following B decays:

$$\bar{B}^0 \to \pi^+ K^- \chi_{c1}$$
$$\to J/\psi\gamma$$

$$B^+ \to \pi^+ K^0_S \chi_{c1}$$
$$\to J/\psi\gamma$$

☐ We also make use of the following B decays:

$$\bar{B}^0 \to \pi^+ K^- J/\psi$$
$$B^+ \to \pi^+ K^0_S J/\psi$$

☐ where $J/\psi \to \mu^+\mu^-$ or $J/\psi \to e^+e^-$

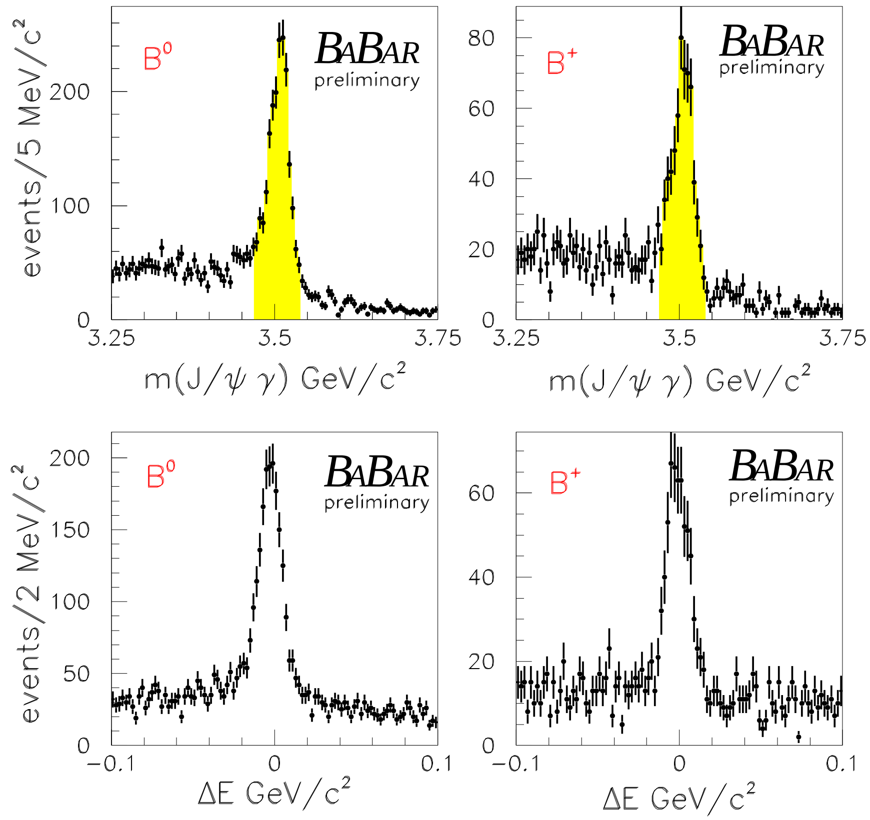
☐ Particle identification applied to all the tracks, except for the K^0_S daughters. For electrons Bremsstrahlung recovery is applied. J/ψ and K^0_S fitted with mass constraint. Geometrical vertex fit performed to the B meson. Require 0.2 cm flight distance for K^0_S. In the $\chi_{c1} \to J/\psi\,\gamma$ decay, $E_\gamma > 190$ MeV. Require vertex probabilities $> 0.1\%$

☐ Experimental $J/\psi\,\pi^+$ mass resolution: 2-3 MeV/c^2 in the region of the Z resonances.

☐ Integrated luminosity: 429 fb^{-1}.

Reconstruction of $B \to \chi_{c1} K \pi$.

□ Signals of $\chi_{c1} \to J/\psi\gamma$ after $\pm 2\sigma$ selection on m_{ES} and ΔE.



□ ΔE after $\pm 2\sigma$ selection on m_{ES} and $m(J/\psi\gamma)$.

$\Delta E \equiv E_B^* - \sqrt{s}/2$,
$m_{\mathrm{ES}} \equiv \sqrt{((s/2 + \vec{p}_i \cdot \vec{p}_B)/E_i)^2 - \vec{p}_B^{\,2}}$,
$(E_i, \vec{p}_i)$ is the initial state e^+e^- four-momentum vector in the lab. and $\sqrt{s}$ is the c.m. energy.
E_B^* is the B meson energy in the c.m., $\vec{p}_B$ is its lab. momentum.

□ Parameters from fits to the ΔE distributions.

Channel	$\sigma_{\Delta E}$	events	Purity %
$\overline{B}^0 \to \pi^+ K^- \chi_{c1}$	7.3 ± 0.3	1863	78.3 ± 0.9
$B^+ \to \pi^+ K_S^0 \chi_{c1}$	7.0 ± 0.4	628	79.7 ± 1.6

□ Background estimated from the ΔE sidebands.

Efficiency.

□ Use signal Phase Space Monte Carlo simulations.

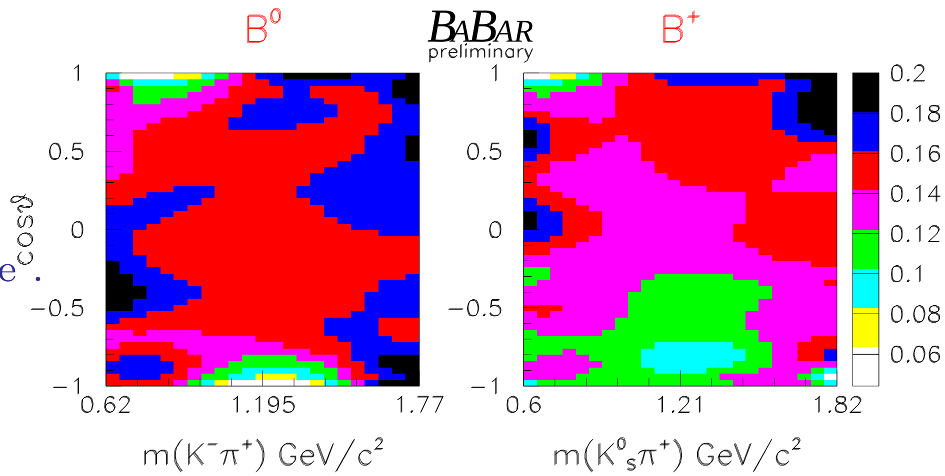
□ Parametrize the efficiency as a function of $m(K\pi)$ and $cos\theta$, where θ is the K helicity angle.

□ Divide into slices of $m(K\pi)$ and fit the efficiency dependence in $cos\theta$ using $L = 0, 12$ Legendre polynomials.

$$\epsilon(cos\theta) = \sum_{L=0}^{12} a_L Y_L^0(cos\theta)$$

□ Fit the $a_L(m(K\pi))$ using 5^{th} order polynomials.

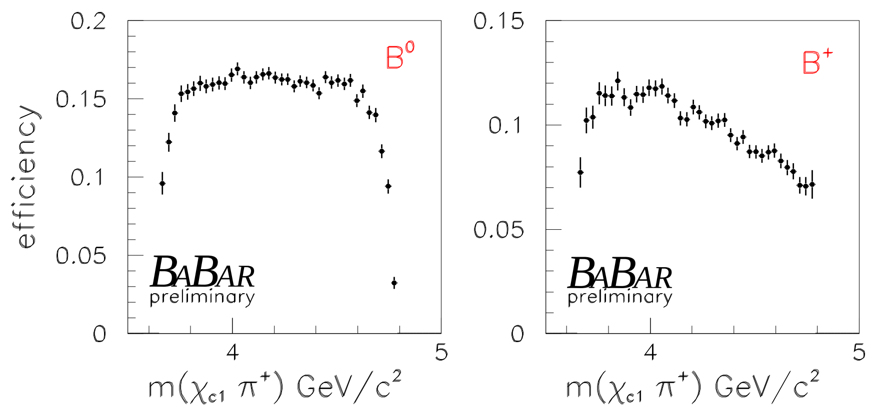
□ Plot fitted efficiencies in the $(m(K\pi), cos\theta)$ plane.



□ Efficiency as a function of the $\chi_{c1}\pi$ mass.

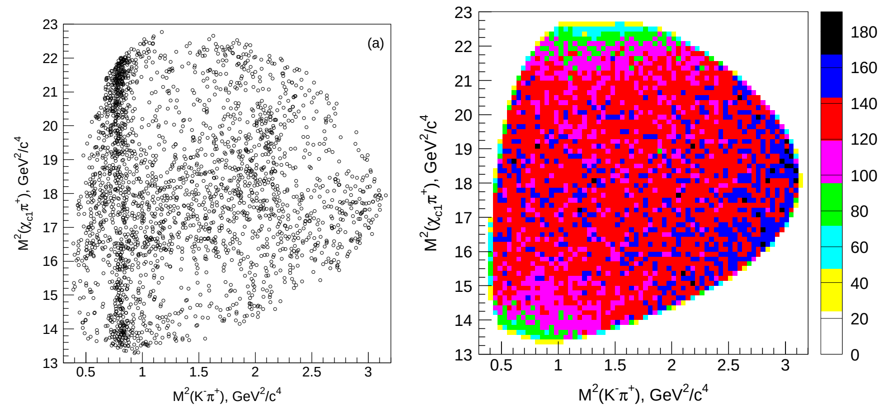
□ Decrease at the edges due to the loss of slow pions and kaons.

□ No problem with efficiency at the Z masses.

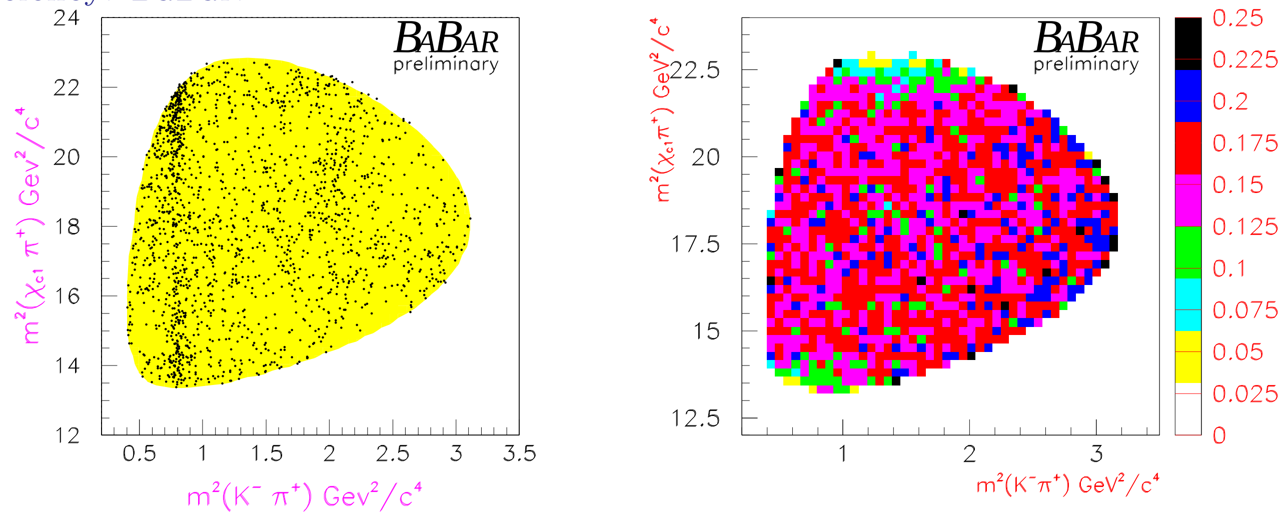


Comparison between BaBar and Belle data.

- $\bar{B}^0 \to \chi_{c1} K^- \pi^+$ Dalitz plot and efficiency: Belle.



- $\bar{B}^0 \to \chi_{c1} K^- \pi^+$ Dalitz plot and efficiency: BaBar.

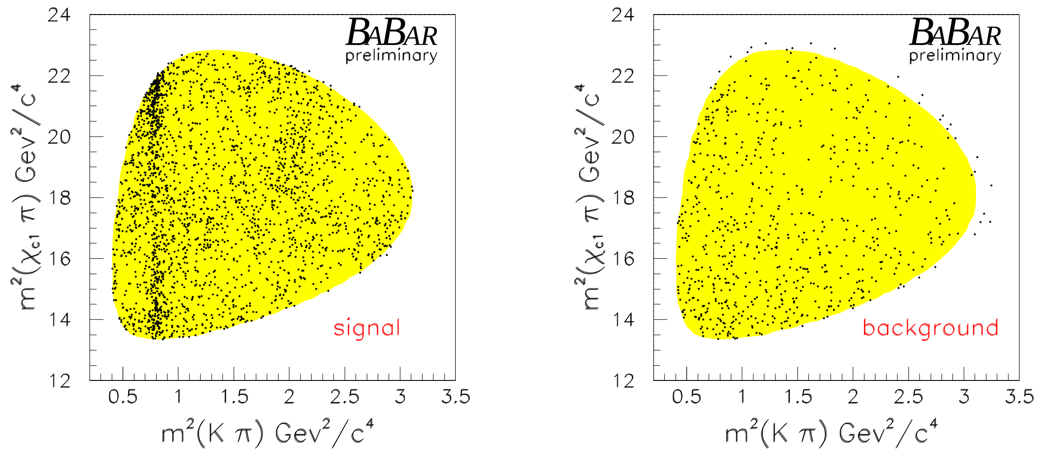


- Efficiency and resolution similar in the two experiments.
- **BaBar data do not show any horizontal strong enhancements.**
- $\bar{B}^0$ data. BaBar: Total 1458 events, Belle: 2126 events. Scaling by the different luminosities (0.71) expect: 1509 events. In addition, 499 B^+ events.

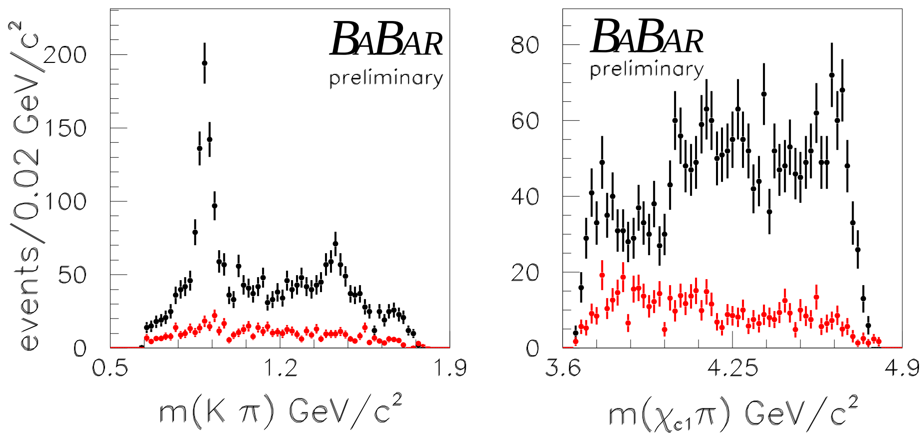
- Total: 1957 events. Almost the same statistics as Belle.

Signal and Background.

- Within statistics $\bar{B}^0$ and B^+ Dalitz plots are similar and have been combined.
- $B \to \chi_{c1} K\pi$ total Dalitz plot for signal and background.



- Uncorrected total Dalitz plot projections for signal and background.



- We obtain background-subtracted and efficiency-corrected distributions by subtracting the sideband distributions and weighting each event by: $1/\epsilon(m(K\pi), cos\theta)$.

Branching fractions.

□ To estimate the relative Branching Fractions we obtain the yields from fits to the ΔE experimental distributions and correct for efficiency.

□ We obtain:

$$\frac{\mathcal{B}(\overline{B}^0 \to \chi_{c1} K^- \pi^+)}{\mathcal{B}(\overline{B}^0 \to J/\psi K^- \pi^+)} = 0.474 \pm 0.013 \pm 0.062 \qquad \frac{\mathcal{B}(B^+ \to \chi_{c1} K^0 \pi^+)}{\mathcal{B}(B^+ \to J/\psi K^0 \pi^+)} = 0.501 \pm 0.024 \pm 0.090$$

□ $\overline{B}^0$ and B^+ ratios are consistent.

□ Systematic uncertainties:

Contribution	Fractional error $\overline{B}^0 \to \chi_{c1} K^- \pi^+$	Fractional error $B^+ \to \chi_{c1} K^0_S \pi^+$
1. Background subtraction	0.037	0.063
2. Efficiency	0.015	0.039
3. Efficiency binning	0.011	0.019
4. χ_{c1} branching fraction	0.044	0.044
5. γ reconstruction	0.018	0.018
6. ΔE and m_{ES} selections	0.010	0.010
Total	0.062	0.090

□ Multiplying by the $B \to J/\psi K \pi$ branching fractions measured by the same experiment (Phys. Rev. D 79, 112001 (2009)), we obtain:

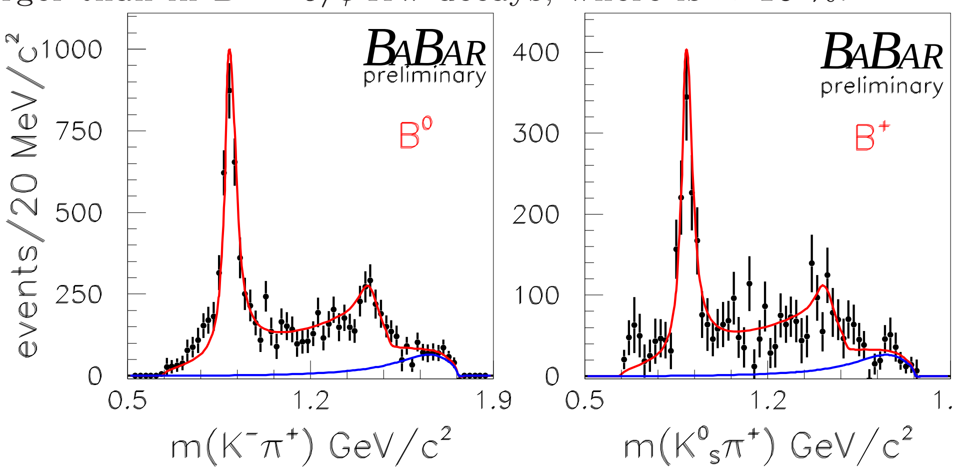
$$\mathcal{B}(\overline{B}^0 \to \chi_{c1} K^- \pi^+) = (5.11 \pm 0.15 \pm 0.67) \times 10^{-4}, \qquad \mathcal{B}(B^+ \to \chi_{c1} K^0 \pi^+) = (5.52 \pm 0.28 \pm 0.99) \times 10^{-4}$$

Fits to the $K\pi$ mass spectra.

- Binned χ^2 fits to the background-subtracted and efficiency-corrected $K\pi$ mass spectra in terms of S, P, and D wave amplitudes.
- Fitting function: $\frac{dN}{dm_{K\pi}} = N \times \left[f_S \left(\frac{G_S}{\int G_S dm_{K\pi}} \right) + f_P \left(\frac{G_P}{\int G_P dm_{K\pi}} \right) + f_D \left(\frac{G_D}{\int G_D dm_{K\pi}} \right) \right]$
- where the fractions f are such that: $f_S + f_P + f_D = 1$.
- The P- and D-wave intensities are expressed in terms of relativistic Breit-Wigner with parameters fixed to the PDG values for $K^*(892)$ and $K_2^*(1430)$ respectively.
- For S-wave contribution we make use of the LASS parametrization.
- Results from the fit.

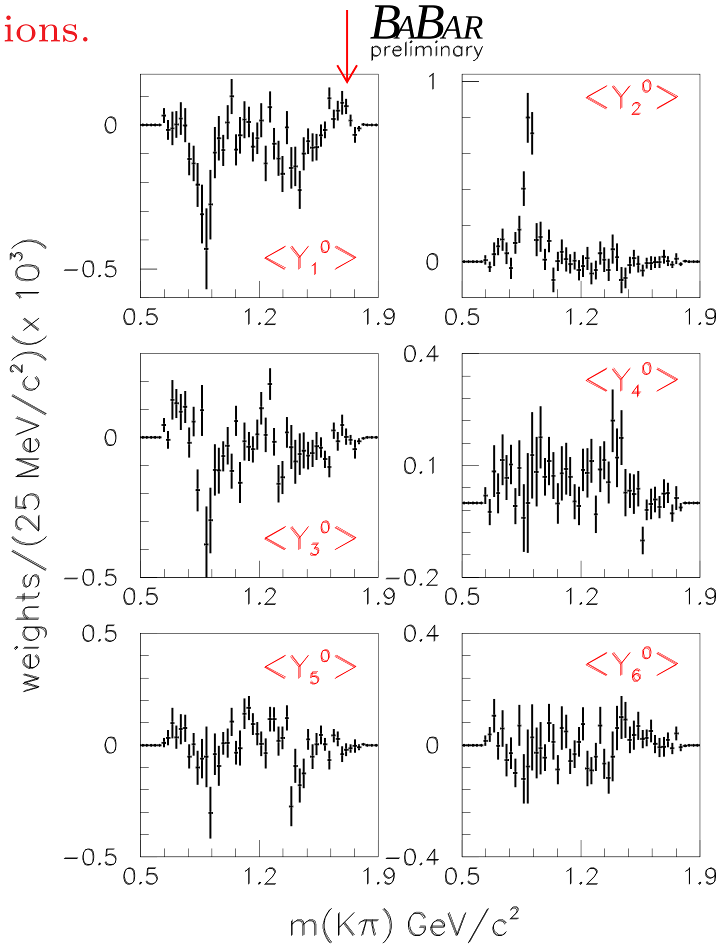
Channel	S-wave	P-wave	D-wave	χ^2/NDF
$\bar{B}^0 \to \pi^+ K^- \chi_{c1}$	40.4 ± 2.2	37.9 ± 1.3	11.4 ± 2.0	58/54
		10.3 ± 1.5		
$B^+ \to \pi^+ K_S^0 \chi_{c1}$	42.4 ± 3.5	37.1 ± 3.2	10.1 ± 3.1	55/54
		10.4 ± 2.5		

- Need for a small P-wave contribution from $K^*(1680)$ (≈ 10 %), not present in the $B \to J/\psi K\pi$ decays or $B \to \psi(2S)K\pi$.
- S-wave contribution larger than in $B \to J/\psi K\pi$ decays, where is ≈ 16 %.



The $K\pi$ Legendre polynomial moments.

- □ Add $\overline{B}^0$ and B^+ data. Weight the events by the $Y^0_L(cos\theta)$ Legendre polynomials.
- □ Efficiency-corrected and background-subtracted distributions.



- □ We observe the S-P interference in the $< Y^0_1 >$ moment.
- □ Significant enhancement in Y^0_1 at ≈ 1.7 GeV indicating the presence of a P-wave.
- □ We observe the presence of the spin-1 $K^*(890)$ in the $< Y^0_2 >$ moment.
- □ We have evidence for the spin-2 $K^*_2(1430)$ resonance in the $< Y^0_4 >$ moment.
- □ $< Y^0_6 >$ is consistent with zero.

MC simulations.

☐ A localized structure in the $\chi_{c1}\pi$ mass spectrum shows its effect in high L Legendre polynomial moments $< Y_L^0 >$.

☐ We now attempt to describe the $\chi_{c1}\pi$ mass distribution using the information from the $K\pi$ system only.

☐ *We also limit L to its minimum value.*

☐ We generate a large number of MC events according to the following model.

- $B \to \chi_{c1} K\pi$ events are generated according to phase-space. The B is generated according to a Gaussian lineshape having parameters fitted to the data.
- We label $w_{m(K\pi)}$ the weight corresponding to the fit to the $K\pi$ mass projection.
- We incorporate the measured $K\pi$ angular structure by giving weight w_L to each event according to the expression:

$$w_L = \sum_{i=0}^{L_{max}} < Y_i^N > Y_i^0(\cos\theta)$$

  where $Y_i^N = Y_i^0/n$ are the normalized moments. The Y_i^N are evaluated for the $m(K\pi)$ value by linear interpolation over consecutive $m(K\pi)$ mass intervals.

- The total weight is thus:

$$w = w_{m(K\pi)} \cdot w_L$$

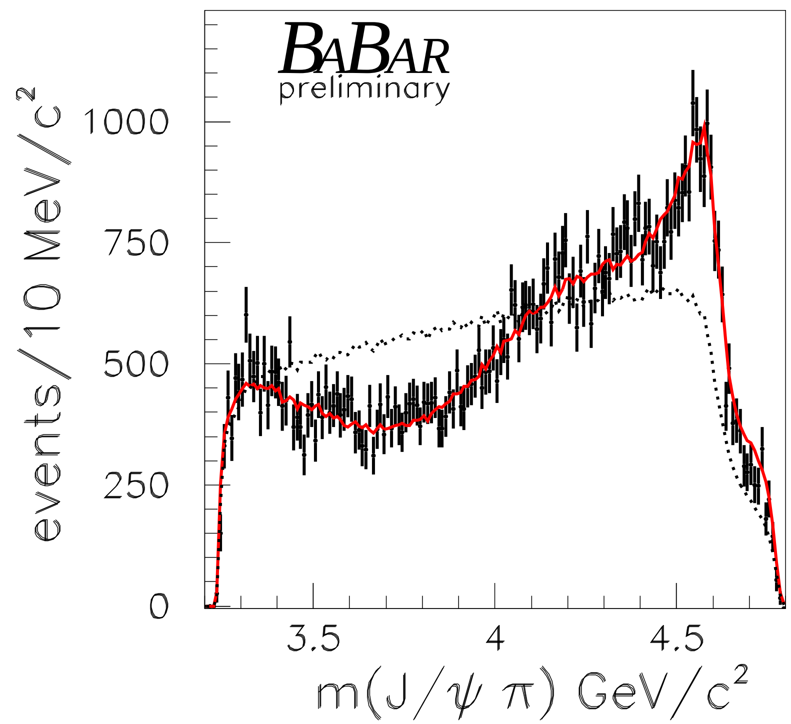
☐ The generated distributions, weighted by the total weight w, are then normalized to the number of data events after background-subtraction and efficiency-correction.

MC simulations: $B \to J/\psi K\pi$

- We test the method on $B \to J/\psi \pi K$ where there is no evidence for narrow or broad Z resonances.
- We vary L_{max} between 4 and 6 and obtain the best description of the data with $L_{max} = 5$.

L_{max}	χ^2/NDF
4	223/152
5	162/152
6	180/152

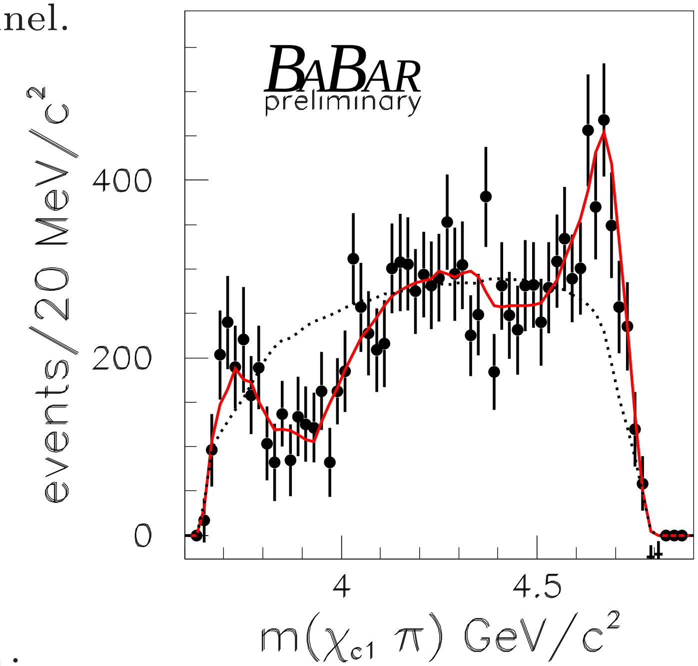
- MC/data comparison, the dotted line shows the effect of removing the angular w_L weight.



MC simulations: $B \to \chi_{c1} K\pi$

□ Similar results are obtained for the $B \to \chi_{c1} K\pi$ channel.

L_{max}	χ^2/NDF
4	53/58
5	46/58
6	49/58
"mixed"	63/58



□ *$B \to J/\psi K\pi$ and $B \to \chi_{c1} K\pi$ data can be described using a similar approach.*

□ **This indicates that there is no need for additional resonant structure in order to describe the $\chi_{c1}\pi$ mass distribution.**

□ We also use a "mixed" Legendre polynomial composition, using $L_{max} = 3$ for $m(K\pi) < 1.2$ GeV and $L_{max} = 4$ above.

□ This is justified by the fact that only spin 0 and spin 1 resonances are present in the low mass region.

□ This representation also gives an excellent description of the $\overline{B}^0 \to \chi_{c1} K\pi$ data.

□ *We will use this "mixed" representation for computing upper limits on Z production.*

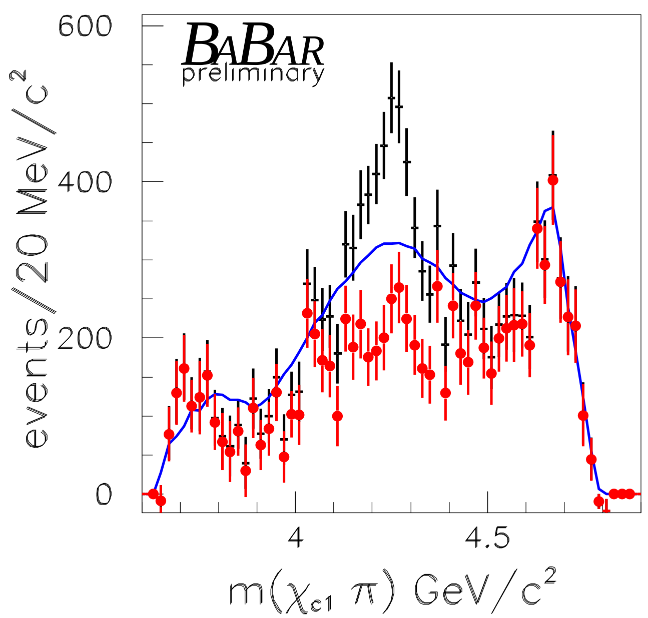
How would a Z resonance show up?

□ We artificially add a ≈ 25% contribution of a scalar $Z_2(4250)^+ \to \chi_{c1}\pi$ resonance in the $\overline{B}^0 \to \pi^+ K^- \chi_{c1}$ data.

□ These MC toy events are obtained from MC data, weighted by a Breit-Wigner.

□ We then compute Legendre polynomial moments for the whole sample and predict the $\chi_{c1}\pi$ mass spectrum using the same algorithm as for real data.

□ Using the "mixed" method, the resulting MC simulation does not describe the MC data well: $\chi^2/NDF = 140/58$

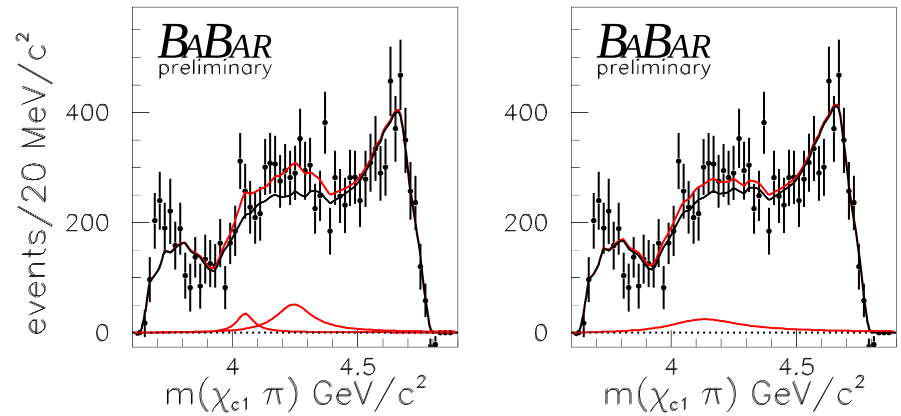


□ *red dots indicate the $B^0 \to \pi^- K^+ \chi_{c1}$ data, crosses indicate the total sample.*

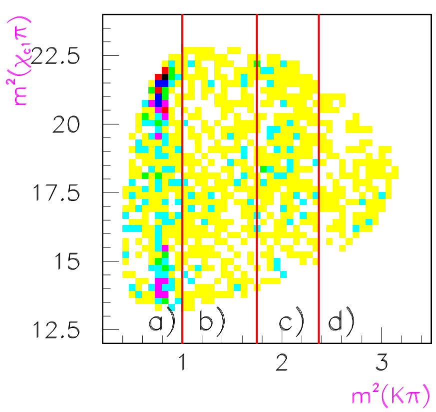
Search for Z resonances.

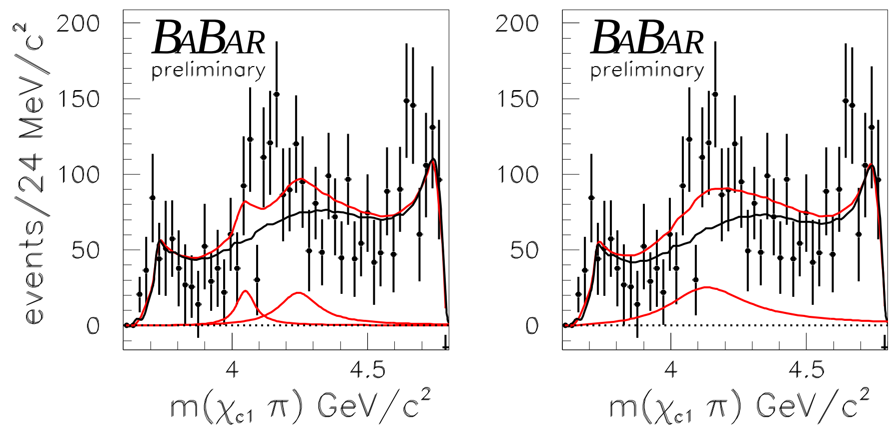
- We now fit the $\chi_{c1}\pi$ mass spectrum using the following model:
- *Assume the prediction from the MC simulation ("mixed") as background.*
- *Include two scalar Breit-Wigner with parameters fixed to the Belle measurements.*
- Fit the full data set (Total).

Data	Resonance	N_σ	Fraction (%)
a) Total	$Z_1(4050)^+$	1.1	1.6 ± 1.4
	$Z_2(4250)^+$	2.0	4.8 ± 2.4
b) Total	$Z(4150)^+$	1.1	4.0 ± 3.8
c) Window	$Z_1(4050)^+$	1.2	3.5 ± 3.0
	$Z_2(4250)^+$	1.3	6.7 ± 5.1
d) Window	$Z(4150)^+$	1.7	13.7 ± 8.0



- Repeat the fits in the $b)1.0 < m^2(K\pi) < 1.75\ GeV^2/c^4$ window, where Belle reports the maximum resonant activity (25 % of the dataset).





- **In all cases we obtain very low ($\leq 2\sigma$) statistical significances.**

Limits on Z production.

□ Significances do not change significantly if we modify the Z parameters within their statistical errors.

□ We obtain the following 90 % C.L. upper limits:

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

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

□ To be compared with Belle values of $(3^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5}$ and $(4^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5}$ respectively.

□ For only one Z we obtain:

$$\mathcal{B}(\overline{B}^0 \to Z^+ K^-) \times (\mathcal{B}(Z^+ \to \chi_{c1}\pi^+) < 4.7 \times 10^{-5}$$

Conclusions.

□ We have studied the decays $B \to \chi_{c1} K\pi$ with charged and neutral B mesons and measured their branching fractions.

□ The $K\pi$ resonant structure and angular distributions of $\overline{B}^0$ and B^+ are similar.

□ The resonant structure and angular distributions for $B \to \chi_{c1} K\pi$ are different from that of $B \to J/\psi K\pi$.

□ We model the $B \to \chi_{c1} K\pi$ decay using only the information on the resonant structure and angular distributions from the $K\pi$ system and obtain an excellent description of the $\chi_{c1}\pi$ mass distribution.

□ We test if additional resonant structures are able to improve the data description but obtain very low statistical significances.

□ We measure limits on Z production.

□ These limits do not rule out statistically the existence of Z resonances.

□ **However, we obtain a good description of the data without the need for additional resonances decaying to $\chi_{c1}\pi$.**