New results on X, Y, Z states at *BABAR*

Wolfgang Gradl
representing the *BABAR* collaboration

Institut für Kernphysik

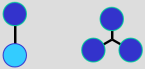
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

17th May 2012
Charm 2012
Honolulu, Hawai'i

Motivation

We know

mesons and baryons

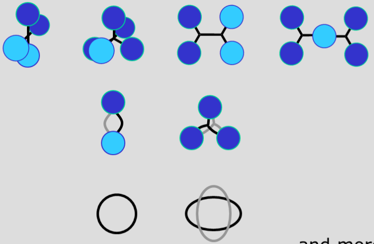


QCD also allows

molecules/multi-quarks

hybrids

glueballs



and more

Everything not forbidden is compulsory

'…while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, *etc.*'

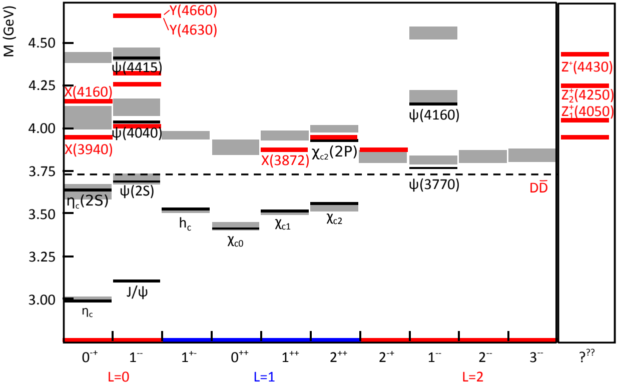
Gell-Mann, Phys. Lett. **8**, 214 (1964)

Charmonium spectrum — new states

Search for non-qqq or non-$q\bar{q}$ hadrons: so far no compelling candidates

Charmonium and charmonium-like states useful for this search:

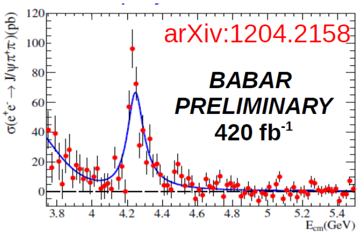
- separation between states larger
- states presumably less mixed than in light quark sector
- Exciting possibility to find exotics among new states



Godfrey & Isgur,
Phys. Rev. D **32**, 189 (1985)

Charmonia and charmonium-like resonances

See E. Prencipe's talk (Wednesday, Spectroscopy 1) for new *BABAR* results



$e^+e^- \to \gamma_{\text{ISR}} J/\psi\,\pi^+\pi^-$: $Y(4260)$

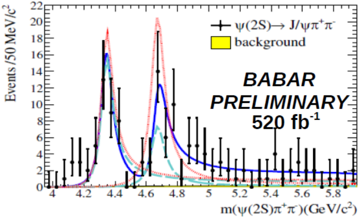
$$m = 4244 \pm 5 \pm 4\,\text{MeV}$$

$$\Gamma = 114^{+16}_{-15} \pm 7\,\text{MeV}$$

No hint for $Y(4008)$ as seen by Belle

$\pi^+\pi^-$ consistent with *S*-wave

arXiv:1204.2158 [hep-ex]



$e^+e^- \to \gamma_{\text{ISR}}\psi(2S)\pi^+\pi^-$:

$Y(4360)$, $Y(4660)$

Charmonia and charmonium-like resonances

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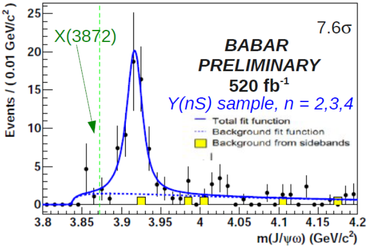


$\gamma\gamma \to J/\psi\,\omega$
$X(3915)$ seen;
spin-parity analysis ongoing
No hint for $X(3872)$ in this reaction

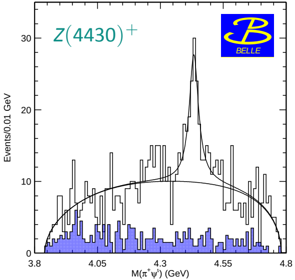
Generally very good agreement (except $Y(4008)$) between Belle and *BABAR*

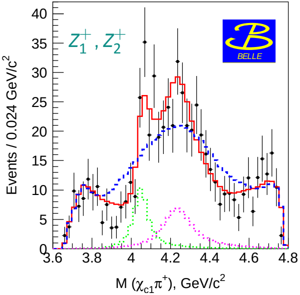
Charged charmonium-like states: a Z^+ family?

Belle observes broad, **charged** charmonium-like states in $(c\bar{c})K\pi$ Dalitz plots

- $Z(4430)^+$ in $B \to \psi(2S)\pi^+ K$ — Phys. Rev. Lett. **100**, 142001 (2008)
- $Z_1(4050)^+$ and $Z_2(4250)^+$ in $B \to \chi_{c1}\pi^+ K$ — Phys. Rev. D **78**, 072004 (2008)

Quark content at least $|c\bar{c}u\bar{d}\rangle$ ➠ No simple $q\bar{q}$ meson!





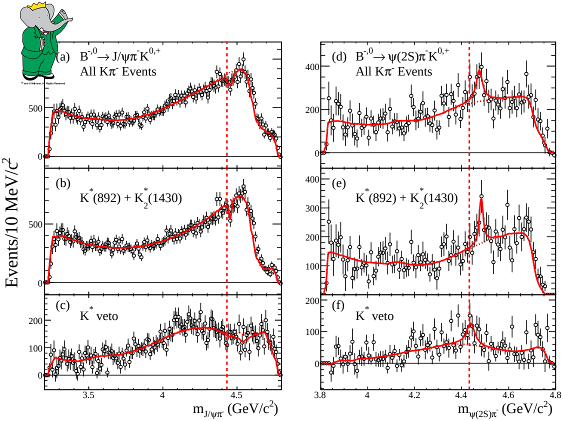
- 2-Z^+ favoured over 1-Z^+
- most clearly seen in $1.0 < m^2_{K\pi} < 1.75\ \mathrm{GeV}^2$

Charged charmonium-like states: a Z^+ family?

BABAR Phys. Rev. D **79**, 112001 (2009) :

- No significant evidence for $Z(4430)$ found in $B \to \psi(2S)\pi^+ K$
- No resonant behaviour in $J/\psi\,\pi^+$ seen in $B \to J/\psi\,\pi^+ K$

Belle: no significant $Z \to J/\psi\,\pi$; K. Chilikin, Wed. Spectroscopy 1



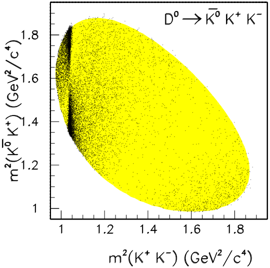
Z states decaying to χ_{c1}: reconstruction difficult in hadron machines

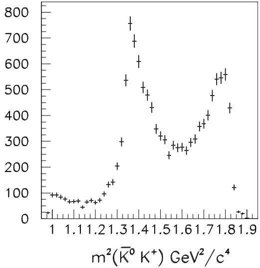
➠ Search for Z_1 and Z_2 in BABAR data

Reflections

Interference effects in three-body B decay can produce peaks in mass projections (reflections)

Striking example provided by $D^0 \to \bar{K}^0 K^+ K^-$ *BABAR*, Phys. Rev. D **72**, 052008 (2005)





No resonances in $K^+ \bar{K}^0$ channel.
Structures visible in projection created from resonances in $K^+ K^-$.

Note: $B \to \psi(2S) K\pi$ more complicated: Two kinematic variables of Dalitz plot not sufficient to describe angular structure

e.g. *BABAR* $B \to J/\psi K\pi$, Phys. Rev. D **71**, 032005 (2005)

BABAR's search for $Z_1(4050)^+$, $Z_2(4250)^+$

Obtain good **and simple** description of $K\pi$ system:

- □ mass (resonance model)
- □ and angular distribution (determined directly from data)

Use this model to predict distribution of $m_{\chi_{c1}\pi^+}$

Search for any excess in $m_{\chi_{c1}\pi^+}$

BABAR, Phys. Rev. D **85**, 052003 (2012)

B decay modes

Reconstruct B decays (+ charge conjugate)

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

Control studies performed on

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

Reconstruct $J/\psi \to e^+e^-, \mu^+\mu^-$ and $K^0_S \to \pi^+\pi^-$

Positive PID required on all tracks
except $K^0_S \to \pi^+\pi^-$ which is identified by mass and displaced vertex

$J/\psi\,\pi^+$ mass resolution around $m \sim 4\,\text{GeV}$: $\sigma(m) \sim 2-3\,\text{MeV}$

Integrated luminosity at $\Upsilon(4S)$: $429\,\text{fb}^{-1}$

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

Kinematic variables to select signal events:

$$\Delta E \equiv E_B^* - \frac{\sqrt{s}}{2}$$

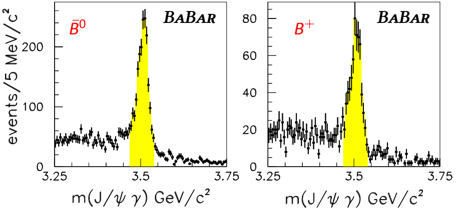
$$m_{ES} \equiv \sqrt{E_{\rm beam}^{*2} - \vec{p}_B^{*2}} = \sqrt{((s/2 + \vec{p}_i \cdot \vec{p}_B)/E_i)^2 - \vec{p}_B^2}$$

Backgrounds taken from ΔE sidebands

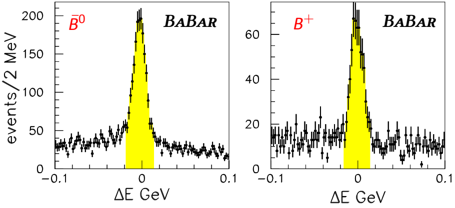
From ΔE distribution:

	Events	Purity (%)
$B^0 \to \pi^+ K^- \chi_{c1}$	1863	78.3 ± 0.9
$B^+ \to \pi^+ K_S^0 \chi_{c1}$	628	79.7 ± 1.6

$\chi_{c1} \to J/\psi\,\gamma$ after selection on ΔE, m_{ES}



ΔE after selection on m_{ES} and $m_{J/\psi\,\gamma}$



JG|U

Efficiency

Need efficiency $\varepsilon(m_{K\pi}, \cos\theta)$ to describe $K\pi$ system

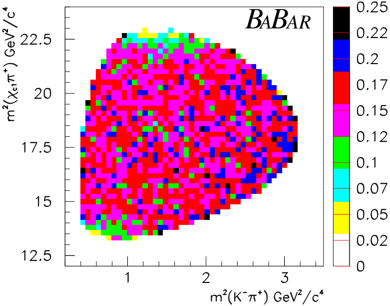
$\cos\theta$: K helicity angle: $\theta = \angle(-\vec{p}_{\chi_{c1}}, \vec{q}_K)$ in $K\pi$ rest frame

Move from 'conventional' Dalitz plot to 'rectangular DP'

$$(m^2_{K\pi}, m^2_{\chi_{c1}\pi}) \rightsquigarrow (m_{K\pi}, \cos\theta)$$
$$\mathrm{d}\rho \sim \mathrm{d}m^2_{K\pi}\,\mathrm{d}m^2_{\chi_{c1}\pi} \rightsquigarrow pq\,\mathrm{d}m_{K\pi}\,\mathrm{d}\cos\theta$$

Phase space density uniform in $\cos\theta$ at constant $m_{K\pi}$

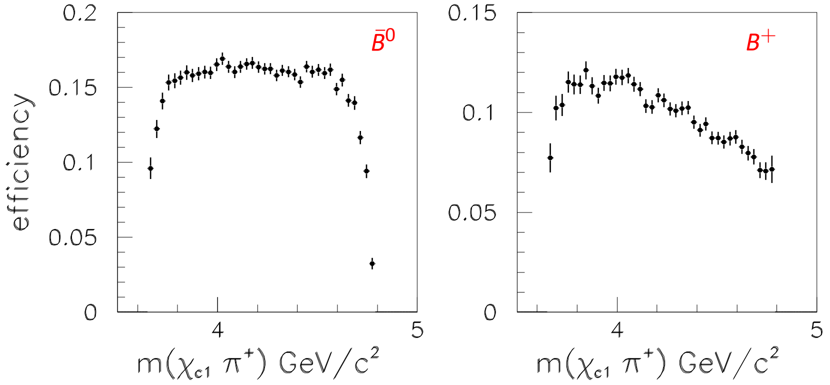
Use phase space simulated events



Efficiency in $m_{\chi_{c1}\pi}$

Project efficiency on $\chi_{c1}\pi^+$ mass:

- drop at edges due to loss of slow π and K
- smooth in the vicinity of the Z masses



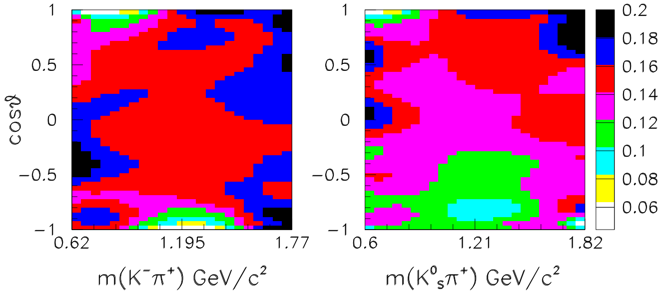
Efficiency in $(m_{K\pi}, \cos\theta)$

Procedure to smooth out statistical fluctuations:

- fit $\cos\theta$ dependence in 50 MeV wide slices of $m_{K\pi}$ with spherical harmonics:

$$\varepsilon(m_{K\pi}, \cos\theta) = \sum_{L=0}^{12} a_L(m_{K\pi}) Y_L^0(\cos\theta)$$

- fit $a_L(m_{K\pi})$ with polynomials
- use this parametrisation to interpolate



Branching fractions

Measure branching fraction $B \to \chi_{c1} K\pi^+$ relative to $B \to J/\psi K\pi^+$

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

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

Systematics dominated by background subtraction and χ_{c1} BF.
Branching fractions for $\bar{B}^0$ and B^+ consistent.

Using $\mathcal{B}(B \to J/\psi K\pi)$ from BABAR Phys. Rev. D **79**, 112001 (2009):

$$\mathcal{B}(\bar{B}^0 \to \chi_{c1} K^- \pi^+) = (5.11 \pm 0.15 \pm 0.67) \times 10^{-4}$$

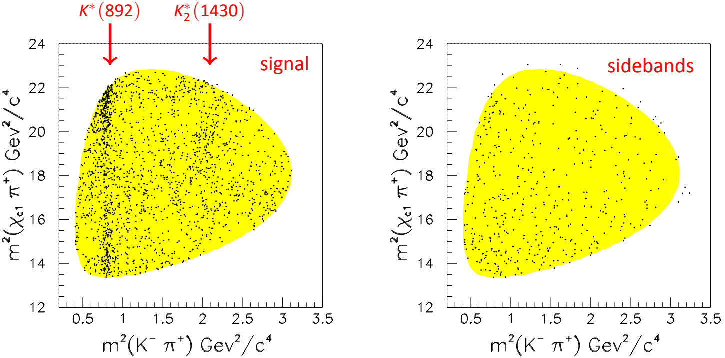
$$\mathcal{B}(B^+ \to \chi_{c1} K^0 \pi^+) = (5.52 \pm 0.28 \pm 0.99) \times 10^{-4}$$

In agreement with Belle's value

$$\mathcal{B}(\bar{B}^0 \to \chi_{c1} K^- \pi^+) = (3.83 \pm 0.10 \pm 0.39) \times 10^{-4}$$

Dalitz plots for signal and background

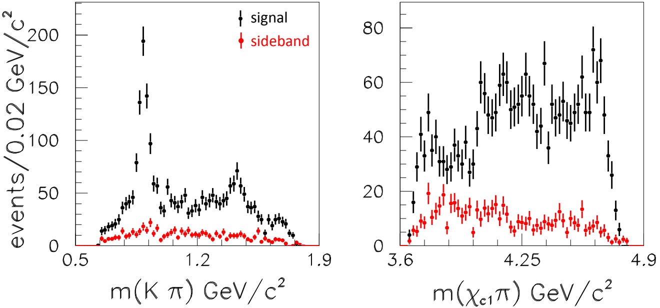
$\bar{B}^0 \to \chi_{c1} K^- \pi^+$



Band from $K^*(892)^0$
Indication for $K_2^*(1430)^0$
Within statistics, $\bar{B}^0$ and B^+ Dalitz plots are similar and can be combined.

Signal and background

Uncorrected, combined DP projections for signal and background



- Subtract sideband distributions
- weight each event by $1/\varepsilon(m_{K\pi}, \cos\theta)$

Signal yields (after background subtraction):

Belle:	2126 $\bar{B}^0 \to \chi_{c1} K^- \pi^+$
BABAR:	1453 $\bar{B}^0 \to \chi_{c1} K^- \pi^+$ + 496 $B^+ \to \chi_{c1} K^0_s \pi^+$

Modelling $K\pi$ mass distribution

Fit to background-subtracted and efficiency corrected $K\pi$ mass spectrum:

Expect *S*, *P*, *D* wave amplitudes are sufficient

Correct for $\cos\theta$-dependence of efficiency
➠ interference terms between $K\pi$ amplitudes vanish
when integrated over $\cos\theta$

Fit model:

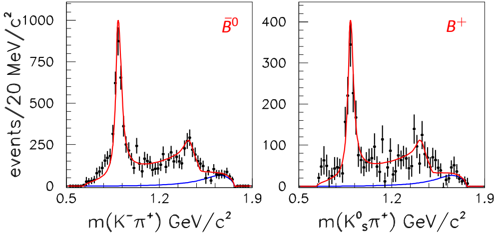
- *S*-wave: LASS parametrisation (non-resonant $K\pi$ + $K_0^*(1430)$)
  Nucl. Phys. **B296**, 493 (1988)
- *P*-wave: $K^*(892)$, $K^*(1680)$
- *D*-wave: $K_2^*(1430)$

$$\frac{\mathrm{d}N}{\mathrm{d}m_{K\pi}} = N\left[f_S \frac{G_S(m_{K\pi})}{\int G_S(m_{K\pi})\mathrm{d}m_{K\pi}} + f_P \frac{G_P(m_{K\pi})}{\int G_P(m_{K\pi})\mathrm{d}m_{K\pi}} + f_D \frac{G_D(m_{K\pi})}{\int G_D(m_{K\pi})\mathrm{d}m_{K\pi}}\right]$$

with fit fractions $f_S + f_P + f_D = 1$

Modelling $K\pi$ mass distribution

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



Good description of data

Small P-wave contribution from $K^*(1680)$ needed

S-wave contribution significantly larger than in $J/\psi K\pi$ or $\psi(2S)K\pi$ ($f_S \approx 16\%$)

$K\pi$ Legendre moments

- Represent $K\pi$ angular distribution at given $m_{K\pi}$ by expansion in Legendre polynomials ➠ $\langle Y_L^0 \rangle$
- Spin-1 resonance in final state: J/ψ or χ_{c1}
  ➠ P and D wave amplitudes can be present in three helicity states
- $\langle Y_L^0 \rangle$ show complicated admixture of different partial waves and their interference terms.
  After integration over χ_{c1} decay angles:

$$\langle Y_1^0 \rangle = S_0 P_0 \cos(\delta_{S_0} - \delta_{P_0}) + \sqrt{\frac{8}{5}} P_0 D_0 \cos(\delta_{P_0} - \delta_{D_0}) + \sqrt{\frac{6}{5}} \left(P_{+1} D_{+1} \cos(\delta_{P_{+1}} - \delta_{D_{+1}}) + P_{-1} D_{-1} \cos(\delta_{P_{-1}} - \delta_{D_{-1}}) \right)$$

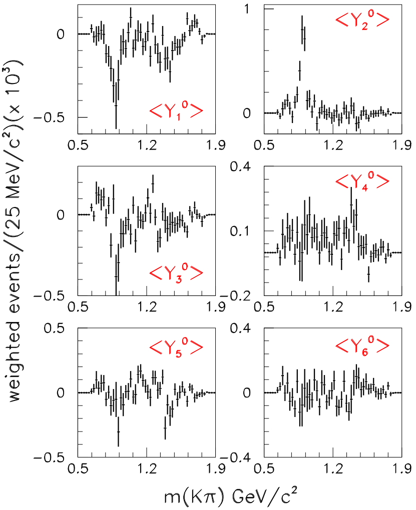
$$\langle Y_2^0 \rangle = \sqrt{\frac{2}{5}} P_0^2 + \frac{\sqrt{10}}{7} D_0^2 + \sqrt{2} S_0 D_0 \cos(\delta_{S_0} - \delta_{D_0}) - \left(\frac{1}{\sqrt{10}} (P_{+1}^2 + P_{-1}^2) + \frac{5\sqrt{10}}{28} (D_{+1}^2 + D_{-1}^2) \right)$$

...

$K\pi$ Legendre moments

- Add $\bar{B}^0$ and B^+ data; weight each event by Legendre polynomial $Y_L^0(\cos\theta)$, in bins of $m_{K\pi}$
- Efficiency corrected, background subtracted distributions

- $\langle Y_1^0 \rangle$ moment: S–P interference; enhancement at $m_{K\pi} \approx 1.7\,\text{GeV}$
- Spin-1 $K^*(892)$ in $\langle Y_2^0 \rangle$, evidence for spin-2 $K_2^*(1430)$ seen in $\langle Y_4^0 \rangle$
- $\langle Y_6^0 \rangle$ and higher moments consistent with zero



Data-driven MC simulations

- Localised structure in $\chi_{c1}\pi$ should show up especially in high $\langle Y_L^0 \rangle$
- Can $\chi_{c1}\pi^+$ mass spectrum be described using only information from $K\pi^+$ system?
- Find **minimal set** of $\langle Y_L^0 \rangle$ for adequate description of data
- Simulation:
  1. Generate $B \to \chi_{c1} K\pi^+$ according to phase space
  2. Mass-dependent weight w_m derived from fit to $m_{K\pi}$ distribution
  3. Angular structure by weight w_L as

$$w_L(m_{K\pi}, \cos\theta) = \sum_{i=0}^{L_{\max}} \langle Y_i^N \rangle (m_{K\pi}) Y_i^0(\cos\theta)$$

     where $\langle Y_i^N \rangle (m_{K\pi})$ interpolates between normalised moments $\langle Y_i^0 \rangle / n$ at particular $m_{K\pi}$ masses
  4. Total weight of event with $K\pi$ mass m_j and helicity angle θ_j:

$$w_j(m_j, \cos\theta_j) = w_m(m_j) \times w_L(m_j, \cos\theta_j)$$

Data-driven MC simulations: $B \to J/\psi K\pi^+$

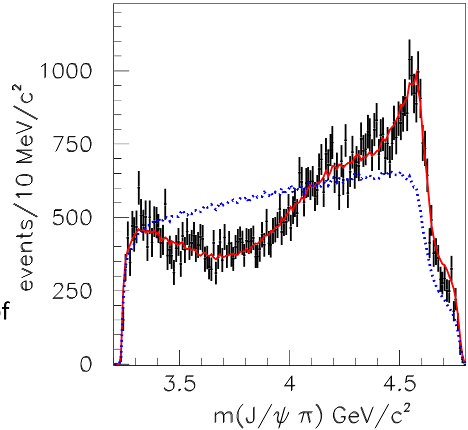
Consistency check: test method with $B \to J/\psi K\pi^+$
no evidence of (broad or narrow) resonance in $J/\psi\,\pi^+$ seen in data

Vary L_{max} from 4 to 6

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

Dotted line: without angular weights w_L

Solid line: using angular weights w_L



With this method: good description of $J/\psi\,\pi^+$ mass spectrum seen in data

Angular weights required!

Data-driven MC simulations: $B \to \chi_{c1} K \pi^+$

Use same procedure on combined data $B \to \chi_{c1} K \pi^+$

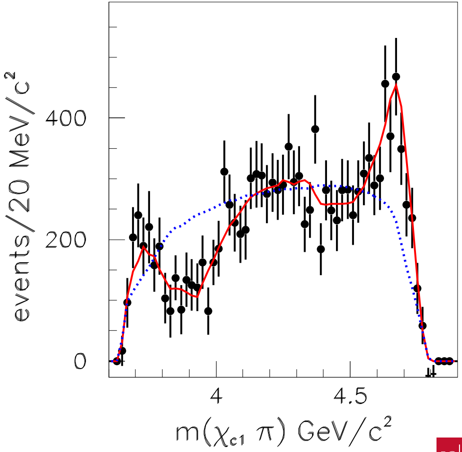
Obtain excellent description of data with $L_{\max} = 5$; $\chi^2/\mathrm{NDF} = 46/58$

Indicates that no additional resonant structure is needed to describe $\chi_{c1}\pi^+$ mass distribution

'Mixed' simulation:

- ☐ $L_{\max} = 3$ for $m_{K\pi} < 1.2$ GeV,
- ☐ $L_{\max} = 4$ above

satisfactory description



How would $Z^+ \to \chi_{c1}\pi^+$ show up?

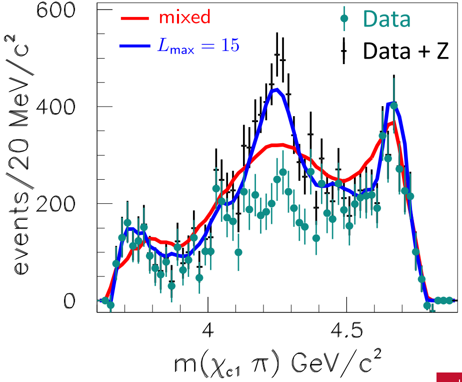
Artificially add $\approx$ 25% contribution of scalar $Z_2(4250)^+ \to \chi_{c1}\pi^+$ to data

Rel. Breit Wigner with Belle's parameters for mass and width:
$m = 4248$ MeV; $\Gamma = 177$ MeV

Repeat procedure with Legendre polynomial moments for whole sample

'mixed' simulation fails to describe MC data

Need $L_{\max} = 15$ for adequate description



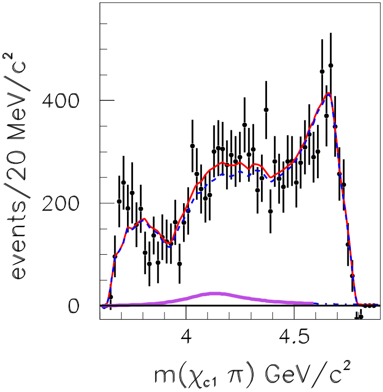
Search for Z resonances

Fit to $\chi_{c1}\pi^+$ mass spectrum using following models:

- Prediction of 'mixed' MC simulation as 'background' from $K\pi$ system
- Fit single Z^+ with $m_{Z^+} = 4150\,\text{MeV}$ and $\Gamma_{Z^+} = 352\,\text{MeV}$
- $Z_1(4050)^+$ and $Z_2(4250)^+$: scalar rel. Breit-Wigner shapes with mass and width fixed to Belle's measurement:

	m / GeV	Γ / MeV
Z_1^+	4051	82
Z_2^+	4248	177

Resonance	N_σ	Fraction (%)	χ^2 / NDF
$Z(4150)^+$	1.1	4.0 ± 3.8	61/58



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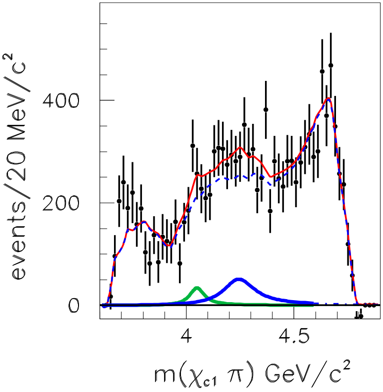
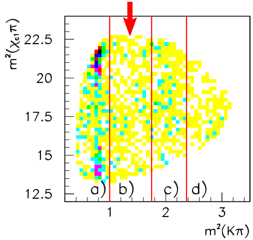
Resonance	N_σ	Fraction (%)	χ^2 / NDF
$Z(4150)^+$	1.1	4.0 ± 3.8	61/58
$Z_1(4050)^+$	1.1	1.6 ± 1.4	57/57
$Z_2(4250)^+$	2.0	4.8 ± 2.4	



Search for Z resonances

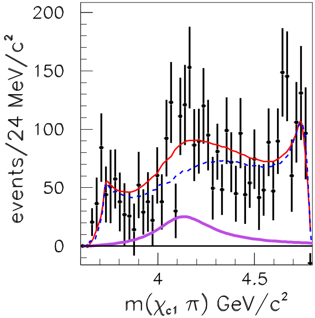
Belle: maximal resonant activity in window $1.0 < m^2_{K\pi} < 1.75\ \mathrm{GeV}^2$

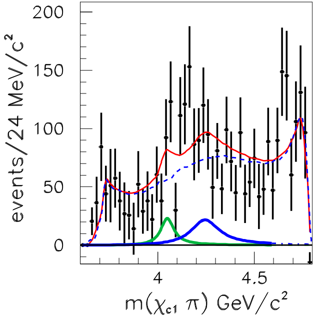


Repeat fits in this $K\pi$ mass range

Resonance	N_σ	Fraction (%)	$\chi^2\,/\,NDF$
$Z(4150)^+$	1.7	13.7 ± 8.0	53/47
$Z_1(4050)^+$ $Z_2(4250)^+$	1.2 1.3	3.5 ± 3.0 6.7 ± 5.1	53/46

In all cases low statistical significances ($\leq 2\sigma$)





Limits on Z production

Varying Z resonance parameters, repeating fits: no significant changes

Set upper limits at 90% *C.L.*:

$$\mathcal{B}(\bar{B}^0 \to Z_1^+ K^-) \times \mathcal{B}(Z_1^+ \to \chi_{c1}\pi^+) < 1.8 \times 10^{-5}$$
$$\mathcal{B}(\bar{B}^0 \to Z_2^+ K^-) \times \mathcal{B}(Z_2^+ \to \chi_{c1}\pi^+) < 4.0 \times 10^{-5}$$

For a single $Z(4150)^+$, upper limit

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

Within (large) uncertainties, limits compatible with Belle's results:

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

Belle, Phys. Rev. D **78**, 072004 (2008)

Summary

Phys. Rev. D **85**, 052003 (2012)

BABAR studied $B \to \chi_{c1} K\pi$ decays using full on-$\Upsilon(4S)$ dataset (473M $B\bar{B}$)

Resonant $K\pi$ structure, angular distributions similar in $\bar{B}^0$ and B^+ decays but different from $B \to J/\psi K\pi$: larger S-wave contribution, $K^*(1680)$

Describe $B \to \chi_{c1} K\pi$ using only resonant structure in $K\pi$ system: excellent description of the $\chi_{c1}\pi$ mass spectrum

Additional resonances required? Not statistically significant.
➠ Upper limit on Z production

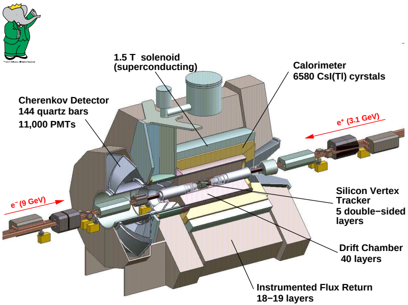
Do not statistically rule out existence of $Z_1(4050)^+$, $Z_2(4250)^+$

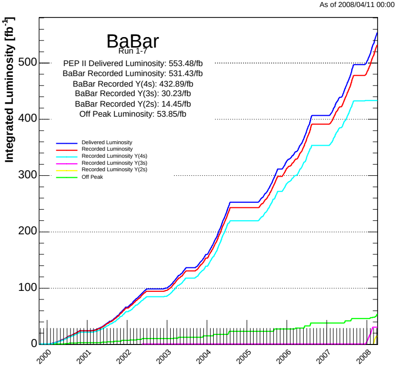
However, obtain good description of data
without additional resonances in $\chi_{c1}\pi^+$ system

Extra slides

The *BABAR* experiment at PEP-II

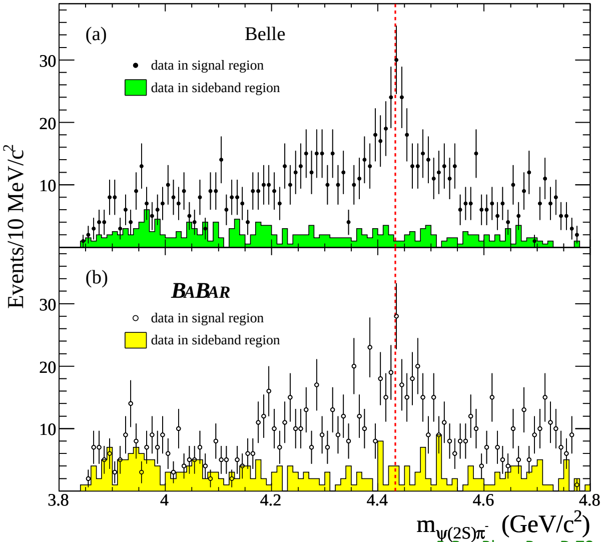
- e^+e^--collider running at $\sqrt{s} = m(\Upsilon(4S)) = 10.58\,\text{GeV}$
- Asymmetric beam energies to separate B decay vertices
- Peak luminosity $\sim 1.2 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$





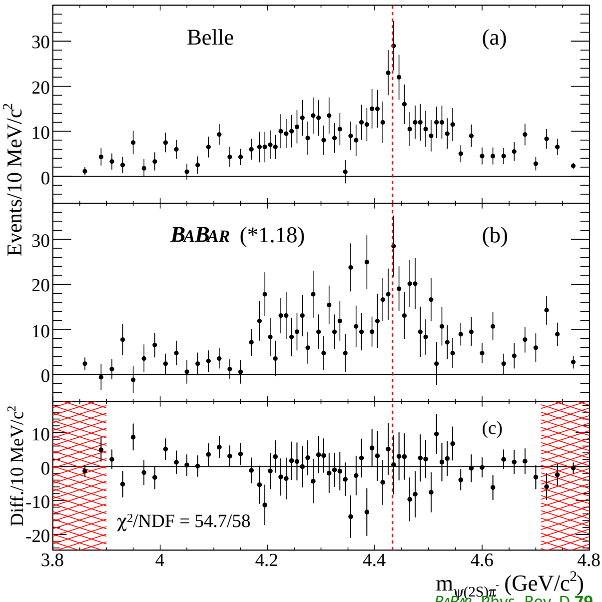
- Data taking stopped April 2008
- $\mathcal{L}_{\text{int}} = 531\,\text{fb}^{-1}$
  471 million $B\bar{B}$ pairs on-$\Upsilon(4S)$

Comparison Belle and *BABAR*: $\psi(2S)K\pi$



BABAR, Phys. Rev. D **79**, 112001 (2009)

Comparison Belle and *BABAR*: $\psi(2S)K\pi$



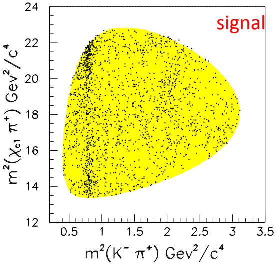
BABAR, Phys. Rev. D **79**, 112001 (2009)

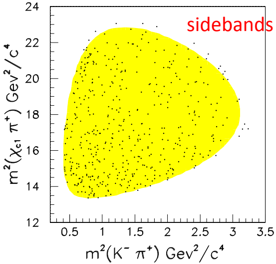
Systematics for branching fraction

Contribution	Fractional error $\bar{B}^0 \to \chi_{c1} K^- \pi^+$	Fractional error $B^+ \to \chi_{c1} K_s^0 \pi^+$
Background subtraction	0.037	0.063
Efficiency	0.015	0.039
Efficiency binning	0.011	0.019
χ_{c1} branching fraction	0.044	0.044
γ reconstruction	0.018	0.018
ΔE and m_{ES} selections	0.010	0.010
Total	0.062	0.090

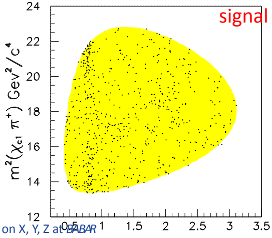
Dalitz plots for signal and background

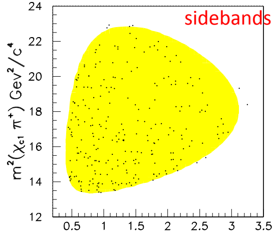
$\bar{B}^0 \longrightarrow \chi_{c1} K^- \pi^+$





$B^+ \longrightarrow \chi_{c1} K^0_s \pi^+$





Comparison: *BABAR* and Belle