Z Observation at Belle

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Representing the Belle Collaboration

- Introduction
- Observation of $Z(4430)^+ \rightarrow \pi^+ \psi'$ at Belle
- Observation of $Z_{1,2}^+ \rightarrow \pi^+ \chi_{c1}$ at Belle
- Update of $Z(4430)^+$ at Belle (NEW)
- Summary
High *Luminosity* has permitted us to obtain unexpected results on charm spectroscopy, particularly with charmonium in the final state.

This has modified our understanding of known and predicted charmonia levels.
**Z(4430)** at Belle

**Study of B → Kπ⁺ψ′:**

ψ′ → l⁺l⁻ and J/ψπ⁺π⁻ (M(ππ) > 0.44 GeV);

B-candidates inv. mass is kinematically constrained to m_B (experim. resolution for M(ψ′π⁺) ~ 2.5 MeV);

**Horizontal band**

- K*(1430)
- K*(892)

Study it
Z(4430)$^+$ at Belle

Fit: S-wave Breit-Wigner + Background with kinematic thresholds

Cross-checks: Z(4430)$^+$ is present in both $\psi'$ subsamples

Total significance: 6.5 $\sigma$

$M = (4433\pm4\pm1)$ MeV

$\Gamma = (44^{+17}_{-13}^{+30}_{-11})$ MeV

$\text{Br}(B \to KZ) \times \text{Br}(Z \to \psi(2S)\pi^+) = (4.1\pm1.0\pm1.3) \cdot 10^{-5}$
**Z(4430)** at Belle

\[ B^+ \rightarrow Z^+ K_S \quad \text{or} \quad B^0 \rightarrow Z^- K^+ \]

\[ Z^\pm \rightarrow \psi(2S) \pi^\pm \]

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**A variety of interpretations:**
- Threshold effect
  (J.L.Rosner 0708.3496, D.V.Bugg, 0709.1254);
- D* \(D_1\) molecular state
  (X. Liu and Y.R. Liu, 0711.0494);
- Radially excited tetraquark
  (L.Maiani, A.D.Polosa, V.Riquer, 0708.3997);
- Baryonium state
  (C.F.Qiao, 0709.4066);
- Hadro-charmonium
  (S.Dubinskiy, M.B.Voloshin, 0803.2224); ...

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Charged, \( I=1 \)

Cannot be a conventional charmonium or hybrid state

Should contain light quarks in addition to \( cc \).
The observation of $Z(4430)$ has motivated us to continue the study of other $B \rightarrow (c\bar{c}) \pi^+K^-$ decays.

**New charged Z’s decaying into $\pi^+\chi_{c1}$**

**PRD 78, 072004 (2008)**
Study of $B \rightarrow K^{-}\pi^{+}\chi_{c1}$

Very simple selection, then look at DP:

B-signal

Horizontal band

Study it

$K^{*}(892)$

$K^{*}(1430)$
Isobar Fit to entire Dalitz Plot:

\[ \kappa + K^*(892) + K^*(1410) + K^*_0(1430) + K^*_2(1430) + K^*(1680) + K^*_3(1780) + (Z's) + \text{Interference} \]

All known $K^*$'s below 1900 MeV
**K^{-π^+\chi_{c1}} Dalitz Plot Formalism**

The decay $B \rightarrow K\pi\chi_{c1}$ is described by 6 variables, $M(\pi\chi_{c1})$, $M(K\pi)$, helicity angles $\theta_{\chi_{c1}}$, $\theta_{J/\psi}$ and angles btw the production and decay planes $\varphi_{\chi_{c1}}$, $\varphi_{J/\psi}$.

**Fitting function:**

$$F(s_x, s_y) = S(s_x, s_y) \times \epsilon(s_x, s_y) + B(s_x, s_y)$$

$$A^R_{\lambda}(s_x, s_y) = F^\Lambda_B \cdot \frac{1}{M_R^2 - s_R - iM_R \Gamma(s_R)} \cdot F^\Lambda_R \cdot T_{\lambda}$$

$$\cdot \left( \frac{p_B}{m_B} \right)^{L_B} \cdot \left( \frac{p_R}{\sqrt{s_R}} \right)^{L_R}$$

**Amplitude for $B \rightarrow K\pi\chi_{c1}$ via 2-body intermediate res. R and $\chi_{c1}$ in hel. $\lambda$**

**Angle dependent term:**

$$T_{\lambda} = d^J_{0\lambda}(\theta_{Z^*})$$

**Signal event density**

$$S(s_x, s_y) = \sum_{\lambda' = -1, 0, 1} \left| \sum_{K^*} a^K_{\lambda'} e^{i\phi_{K^*}} A^K_{\lambda'}(s_x, s_y) \right|^2 + \sum_{\lambda' = -1, 0, 1} d^1_{\lambda'\lambda}(\theta) a^{Z^*}_{\lambda'} e^{i\phi_{Z^*}} A^{Z^*}_{\lambda'}(s_x, s_y)$$

Integrate over all angles; reconstruction efficiency is uniform over full angle ranges and interference terms between different $\chi_{c1}$ helicity states are negligibly small.
The fit results in DP slices without any Z’s:

Confidence level of this fit: $3 \times 10^{-10}$
The fit results in DP slices with one Z:

Confidence level of this fit: 0.5%

Try an additional Z
The fit results in vertical DP slices with two Z’s:

Confidence level of this fit: 42%
Systematics and significances (incl. d.o.f.) from various fit models:

TABLE II. Different fit models that are used to study systematic uncertainties and the significances of the single- and double-$Z^+$ hypotheses.

<table>
<thead>
<tr>
<th>Model</th>
<th>Significance of one $Z^+$</th>
<th>One $Z^+$ vs two $Z^+$</th>
<th>Significance of two $Z^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.7$\sigma$</td>
<td>5.7$\sigma$</td>
<td>13.2$\sigma$</td>
</tr>
<tr>
<td>2</td>
<td>15.6$\sigma$</td>
<td>5.0$\sigma$</td>
<td>16.6$\sigma$</td>
</tr>
<tr>
<td>3</td>
<td>13.4$\sigma$</td>
<td>5.4$\sigma$</td>
<td>14.8$\sigma$</td>
</tr>
<tr>
<td>4</td>
<td>10.4$\sigma$</td>
<td>5.2$\sigma$</td>
<td>14.4$\sigma$</td>
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<tr>
<td>5</td>
<td>13.3$\sigma$</td>
<td>5.6$\sigma$</td>
<td>14.8$\sigma$</td>
</tr>
<tr>
<td>6</td>
<td>12.9$\sigma$</td>
<td>5.6$\sigma$</td>
<td>14.4$\sigma$</td>
</tr>
<tr>
<td>7</td>
<td>9.0$\sigma$</td>
<td>5.3$\sigma$</td>
<td>10.3$\sigma$</td>
</tr>
<tr>
<td>8</td>
<td>11.3$\sigma$</td>
<td>5.1$\sigma$</td>
<td>13.5$\sigma$</td>
</tr>
<tr>
<td>9</td>
<td>11.4$\sigma$</td>
<td>5.3$\sigma$</td>
<td>13.7$\sigma$</td>
</tr>
<tr>
<td>10</td>
<td>10.8$\sigma$</td>
<td>5.4$\sigma$</td>
<td>13.2$\sigma$</td>
</tr>
<tr>
<td>11</td>
<td>9.5$\sigma$</td>
<td>5.3$\sigma$</td>
<td>10.7$\sigma$</td>
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<td>5.4$\sigma$</td>
<td>9.2$\sigma$</td>
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<td>6.2$\sigma$</td>
<td>5.6$\sigma$</td>
<td>8.1$\sigma$</td>
</tr>
<tr>
<td>14</td>
<td>12.4$\sigma$</td>
<td>5.3$\sigma$</td>
<td>13.8$\sigma$</td>
</tr>
</tbody>
</table>

The worst case, but the param’s of this new $K^*$ are far from those for all known $K^*$’s
Parameters of the new EXOTIC $Z_{1,2}^+ \rightarrow \pi^+ \chi_{c1}$ states and Mass($\pi^+ \chi_{c1}$) distribution

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

with the product branching fractions of

$\mathcal{B}(\bar{B}^0 \rightarrow K^- Z_{1}^+) \times \mathcal{B}(Z_{1}^+ \rightarrow \pi^+ \chi_{c1}) = (3.0^{+1.5}_{-0.8}^{+3.7}_{-1.6}) \times 10^{-5},$

$\mathcal{B}(\bar{B}^0 \rightarrow K^- Z_{2}^+) \times \mathcal{B}(Z_{2}^+ \rightarrow \pi^+ \chi_{c1}) = (4.0^{+2.3}_{-0.9}^{+19.7}_{-0.5}) \times 10^{-5},$

are the same order as obtained for other, possibly exotic X,Y,Z states.

No discrimination between J=0 or 1
Dalitz analysis of $B \rightarrow K^{-}\pi^{+}\psi'$

Data sample from original analysis is used

The same fitting technique as in $B \rightarrow K\pi\chi_{c1}$ is used

New results on $Z(4430)^+$

Submitted to PRD(RC), arXiv:0905.2869
Dalitz Plot slices:

Fit without a Z resonance: CL=0.1%

Introduce Z
NEW results on Z(4430)$^+$ from Dalitz plot fit

The results of the DP fit in its slices with Z:
Confidence Level of the fit WITH Z(4430)$^+$ is 36%

Significance of Z is 6.4$\sigma$
Different fit models and the significance of Z(4430)$^+$

<table>
<thead>
<tr>
<th>Model</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>default</td>
<td>6.4$\sigma$</td>
</tr>
<tr>
<td>no $K_0^*(1430)$</td>
<td>6.6$\sigma$</td>
</tr>
<tr>
<td>no $K^*(1680)$</td>
<td>6.6$\sigma$</td>
</tr>
<tr>
<td>release constraints on $\kappa$ mass &amp; width</td>
<td>6.3$\sigma$</td>
</tr>
<tr>
<td>new $K^*$ ($J = 1$)</td>
<td>6.0$\sigma$</td>
</tr>
<tr>
<td>new $K^*$ ($J = 2$)</td>
<td>5.5$\sigma$</td>
</tr>
<tr>
<td>add non-resonant $\psi'K^-$ term</td>
<td>6.3$\sigma$</td>
</tr>
<tr>
<td>add non-resonant $\psi'K^-$ term, release constraints on $\kappa$ mass &amp; width</td>
<td>5.8$\sigma$</td>
</tr>
<tr>
<td>add non-resonant $\psi'K^-$ term, new $K^*$ ($J = 1$)</td>
<td>5.5$\sigma$</td>
</tr>
<tr>
<td>add non-resonant $\psi'K^-$ term, new $K^*$ ($J = 2$)</td>
<td>5.4$\sigma$</td>
</tr>
<tr>
<td>add non-resonant $\psi'K^-$ term, no $K^*(1410)$</td>
<td>6.3$\sigma$</td>
</tr>
<tr>
<td>add non-resonant $\psi'K^-$ term, no $K^*(1680)$</td>
<td>6.6$\sigma$</td>
</tr>
<tr>
<td>LASS parameterization of S-wave component</td>
<td>6.5$\sigma$</td>
</tr>
</tbody>
</table>

Assume $J_{Z(4430)} = 0$. No fit improvement for $J_{Z(4430)} = 1$. Significance of Z(4430)$^+$ in different fit models is always larger than 5$\sigma$.
Updated parameters of $Z(4430)^+$ from Dalitz plot fit

Sum of 3 slices (K*’s veto)

Belle confirms the original result on $Z(4430)^+$

$$M = (4443^{+15}_{-12}^{+17}_{-13}) \text{ MeV}/c^2$$

$$\Gamma = (109^{+86}_{-43}^{+57}_{-52}) \text{ MeV}$$

$$\mathcal{B}(B^0 \to K^- Z(4430)^+) \times \mathcal{B}(Z(4430)^+ \to \pi^+ \psi’) = (3.2^{+1.8}_{-0.9}^{+5.3}_{-1.6}) \times 10^{-5}$$

Width is larger than original but uncertainties are large.
Comparison with BaBar (arXiv:0811.0564)

BaBar paper: Belle and BaBar data are statistically consistent.
⇔ peak in $M(\pi^+\psi')$ is present also in BaBar data with similar to Belle shape:

Why different significances are reported? (6.4σ Belle vs. 1.9–3.1σ BaBar)
⇔ assumption about background is crucial.
Summary of Belle results on charged Z’s

• 2007: Belle observed first charged charmoniumlike state, $Z(4430)^+$ decaying into $\psi'\pi^+$

• 2008: Belle continued the study of $B \rightarrow K\pi(c\bar{c})$ decays and observed two new charged charmoniumlike states $Z(4050)^+$ and $Z(4250)^+$, decaying into $\pi^+\chi_{c1}$

• Update on $Z(4430)^+$: Dalitz Plot analysis confirms original observation. The $Z(4430)^+$ has a significance of $6.4\sigma$. The parameters of $Z(4430)^+$ from the DP analysis agree and supersede previous Belle measurement. BaBar has not confirmed $Z(4430)^+$ production so far.

These states have similar character: have non-zero electric charge and decay into ordinary charmonia and $\pi^+$. The current options for their nature include tetraquark, molecular type states and hadro-charmonium.
Back-up slides
The mechanisms of new particle production at B-factories

From B-decays, e.g.
\[ B^+ \rightarrow X(3872)K^+ \]

In double charmonium production, e.g.
\[ e^+e^- \rightarrow J/\psi\ X(3940) \]

In \( \gamma\gamma \) fusion, e.g.
\[ \gamma\gamma \rightarrow \eta_c(2S) \text{ or } \gamma\gamma \rightarrow Z(3930) \]

In radiative return, e.g.
\[ e^+e^- \rightarrow \gamma_{\text{ISR}}\ Y(4260) \rightarrow J/\psi\ \pi^+\pi^- \]

Can charged Z be in principle produced here?

Yes

yet unknown
\( (e^+e^- \rightarrow X^+Y^- ??) \)

Since only neutrals can be produced

No
Comparison with BaBar

BaBar paper: Belle and BaBar data are statistically consistent. ⇔ peak in \( M(\pi^+\psi') \) is present also in BaBar data with similar to Belle shape:

![Belle](image1.png)

![BaBar](image2.png)

Why different significances are reported? (6.4\( \sigma \) Belle vs. 1.9–3.1\( \sigma \) BaBar) ⇔ assumption about background is crucial.

BaBar method is a simplification of amplitude analysis with a lot of (unphysical?) freedom in description of background.

Dalitz analysis is preferable.
Formalism of $B \rightarrow K^- \pi^+\chi_{c1}$ Dalitz analysis

Integrate over $\psi'$ decay angles
$\Leftrightarrow$ interference between different $\chi_{c1}$ helicity states vanish
$\Leftrightarrow$ consider $\chi_{c1}$ as stable

Amplitude = sum over quasi two-body contributions
Breit-Wigner $\times$ angular dependence

Consider intermediate resonances
$k, K^*(892), K^*(1410), K_0(1430), K_2(1430), K^*(1680), Z('s)^+$

Fit function is corrected for efficiency and background.

Use the same data sample as in $Z(4430)^+$ observation paper.

$605 fb^{-1}$
M(Kπ) description in B→Kπ⁺χc₁

\(M^2(K^+\pi^+), \text{GeV}^2/c^4\)

Events / 0.058 GeV\(^2/c^4\)
M(Kπ) description in B→Kπ⁺ψ’
Cross-Check: angular distributions of the $\chi_{c1}$ and $J/\psi$ in $B \rightarrow K\pi^+\chi_{c1}$

Data and predictions from the default fit model agree very well and little discrimination between spin 0 and 1
Dalitz Plot efficiency in B → K⁻π⁺χᶜ₁
Observed and predicted charmonia

Described well the observed spectrum of $c\bar{c}$ states

A number of unexpected exotic states above $D\bar{D}^{(*)}$ thresholds that do not fit into available $c\bar{c}$ slots