XYZ particles at \textit{BaBar}

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On behalf of the BABAR collaboration
Outline

- Introduction
- Motivation
- \( B \rightarrow X(3872)K \)
- \( B \rightarrow Y(3940)K \)
- \( B \rightarrow Z(4430)K \)
- \( e^+e^- \rightarrow \gamma_{\text{ISR}} Y(4260) \)
- \( e^+e^- \rightarrow \gamma_{\text{ISR}} Y(4350) \)
- Summary
Recent observations of (unexpected) new states have been performed.

Several resonances do not fit theoretical predictions.

Many subsequent interpretations of these new states and methods were suggested to analyse their structure (HQT, chiral symmetries, 4-quark models, bag model, Lattice...).
Motivations

**BaBar** is a B-factory:

- The spectrum of Heavy Quarkonium states is an ideal place to provide precision tests of QCD.
- Very accurate calculations are possible using Lattice techniques. $M_c \sim 1.5 \text{ GeV}/c^2$ is high enough to try to describe QCD in terms of NRPM.

The main goal of the BaBar Physics has been the measurement of the sides and angles of the Unitarity Triangle, and rare decays.

B-factories have been demonstrated to be also a huge source of $c\bar{c}$ production. $[\sigma(e^+e^- \rightarrow c\bar{c}) = 1.30 \text{ nb}]$.

The spectrum of Heavy Quarkonium states is an ideal place to provide precision tests of QCD.

1999-2007 $\sim 433 \text{ fb}^{-1}$ @ Y(4S) (on-peak data)
end of Dec07 - end of Feb08 $\sim 30 \text{ fb}^{-1}$ @ Y(3S)
end of Feb08 - 6th of April08 $\sim 15 \text{ fb}^{-1}$ @ Y(2S)
scan around Y(4S) (25pb$^{-1}$ every 5 MeV)

**BaBar** is a B-factory:

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The spectrum of Heavy Quarkonium states is an ideal place to provide precision tests of QCD.

Very accurate calculations are possible using Lattice techniques. $M_c \sim 1.5 \text{ GeV}/c^2$ is high enough to try to describe QCD in terms of NRPM.
Spectroscopy

- Production in continuum:
  - $e^+e^- \rightarrow J/\psi X$ (C$_X^+ = +$)
  - $e^+e^- \rightarrow \gamma_{ISR} X$ (only J$^{PC} = 1^{--}$)

- Production B decays:
  - $b \rightarrow c$ (color suppressed decay)
  - open-charm and charmonium
    (c$\bar{s}$ and c$c$ meson, cqq baryons; c$c$ +...)

charm and charmonium spectroscopy

- Transition $Y(4S) \rightarrow Y(2S)\pi^+\pi^-$, $Y(4S) \rightarrow Y(1S)\pi^+\pi^-$, $Y(4S) \rightarrow Y(1S)\eta$

bottomonium spectroscopy

The main goal of the physics @ $Y(3S)$ and @ $Y(2S)$ is the search of bottomonium states and light Higgs.
$B \rightarrow XK$

$X(3872)$
**X(3872)**

- **Final result from BABAR on the study:**
  - $B \to XK, \ X \to J/\psi \pi^+ \pi^-$

  - $R(B^0/B^\pm) = 0.41 \pm 0.24 \pm 0.05$

  - $\Delta M = (2.7 \pm 1.6 \pm 0.4) \text{ MeV/c}^2$

  - $\Gamma < 3.3 \text{ MeV @ 90\% CL}$

- **BF**($B^+ \to XK^+, \ X \to J/\psi \pi^+ \pi^-$) = $(8.4 \pm 1.5 \pm 0.7) \times 10^{-6}$

- **BF**($B^0 \to XK^0, \ X \to J/\psi \pi^+ \pi^-$) = $(3.5 \pm 1.9 \pm 0.4) \times 10^{-6}$

  - $< 6.0 \times 10^{-6} @ 90\% \text{ C.L.}$

- **Belle:** PRL 91, 262001 (2003), cited 412


  - **D0:** PRL 93, 162002 (2004)

  - **BABAR:** PRD 72, 054026(2005) PRD 73, 014014(2006)

- **Belle:** PRD 77, 111101(2008)

- **What is this state?**

  - Narrow resonance!

  - Molecular model predicts $R(B^0/B^\pm) < 0.1$
Final result from BaBar on the analysis:

\[ B^+ \rightarrow X(3872)K^+ , \quad X(3872) \rightarrow J/\psi \gamma \]

\[ BF(B^+ \rightarrow X(3872)K^+) \times (X(3872) \rightarrow J/\psi \gamma) = (2.8 \pm 0.8 \pm 0.2) \times 10^{-6} \]

23.0 ± 6.4 events measured

PRD 74, 071101 (2006)
PRL 102, 132001 (2009)

First evidence for \( B^+ \rightarrow X(3872)K^+ \), \( X(3872) \rightarrow \psi(2S) \gamma \)

\[ BF(B^+ \rightarrow X(3872) K^+) \times (X(3872) \rightarrow \psi(2S) \gamma) = (9.5 \pm 2.7 \pm 0.9) \times 10^{-6} \]

\[ BF(X(3872) \rightarrow \psi(2S) \gamma) / BF(X(3872) \rightarrow J/\psi \gamma) = 3.4 \pm 1.4 \]

C-parity: 1⁺
ππ invariant mass study (X → J/ψππ):

- ππ inv. mass compatible with ρ
- I = 1; but:
  - forbidden J/ψπ0π0, J/ψπ0, J/ψη
- Decay X(3872)J/ψρ against charmonium hypothesis
- I=0 favored for X(3872) → J/ψππ

No evidence of charged partners
BaBar studied additional 8 channels:

\[ \begin{align*}
B^+ \rightarrow D^0 \bar{D}^0 K^+ + D^0 \bar{D}^0 K^+ \\
B^0 \rightarrow D^0 \bar{D}^0 K^+ + D^0 \bar{D}^0 K^0
\end{align*} \]

\[ \begin{align*}
D^* \rightarrow D^0 \gamma \text{ and } D^0 \pi
\end{align*} \]

\[ \begin{align*}
\psi(3770) \\
X(3872)
\end{align*} \]

<table>
<thead>
<tr>
<th>experiment</th>
<th>mass (MeV/c^2)</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BABAR</strong></td>
<td>( D^0 \pi + D^0 \gamma )</td>
<td>( 3875.1 \pm 1.1 \pm 0.5 ) [ \times 10^{-4} \text{B}^+ ]</td>
</tr>
</tbody>
</table>
| **BELLE**      | Only \( D^0 \pi \) \( D^0 \pi + D^0 \gamma \) | \( \begin{align*}
&3875.2^{+0.3}_{-1.6} \pm 0.8 \\
&3872.6^{+0.5}_{-0.4} \pm 0.4
\end{align*} \) \[ \times 10^{-4} \text{B}^0 + \text{B}^+ \] |

[arXiv:0810.0358]: Belle has recently reported a new mass value.

**BABAR** and **Belle** disagree on this analysis!
Remarks on the $X(3872)$

- $X(3872) \rightarrow \psi \gamma \Rightarrow C=+1$

No charged partner found for $X(3872) \Rightarrow I=0$

- $X(3872)$ quantum numbers
  - Belle: $J^{PC}=1^{++}$ favored ($\omega-\rho$ interference is not included)
  - CDF: $\pi\pi$ mass distribution analysis and the angular distribution study $\Rightarrow J^{PC}=1^{+}$ or $2^{+}$

What is the nature of $X(3872)$?
- Hybrid?.... BUT $m(c\bar{c}g)>4.2\text{GeV}/c^2$
- Tetraquark?... BUT
  - No evidence for charged $X(3872)^{\pm}$
- Charmonium?... mass is OK for $2^{+}$ state ($\eta_c^2$, the $^1D_2$ cc ground state)
- Molecular?
  - $m(D^0) + m(D^{0*}) = 3871.8 \pm 0.4 \text{MeV}/c^2$
  - Decays to $X(3872) \rightarrow J/\psi \rho$, $D^0D^{0*}$, $J/\psi \omega$ expected; but we observe $X \rightarrow \psi(2S)\gamma$
  - Compatible with $J^{PC} = 1^{++}$ assignment

- $R(B^0/B^+) = 0.50 \pm 0.30 \pm 0.05$ in $J/\psi \pi \pi$
- $R(B^0/B^+) = 1.33 \pm 0.69 \pm 0.52$ in $D^0\overline{D}^{*0}$

- $\Delta m = 2.7 \pm 1.3 \pm 0.2 \text{MeV}/c^2$ in $J/\psi \pi \pi$
- $\Delta m = 0.7 \pm 1.9 \pm 0.3 \text{MeV}/c^2$ in $D^0\overline{D}^{*0}$

- $M_X = 3871.4 \pm 0.6 \text{MeV}/c^2$ in $J/\psi \pi \pi$
- $M_X = 3875.1 \pm 1.1 \text{MeV}/c^2$ in $D^0\overline{D}^{*0}$
$B \rightarrow YK$

$e^+ e^- \rightarrow \gamma_{ISR} Y$

- $Y(3940)$
- $Y(4260)$
- $Y(4350)$
Discovered from BaBar in ISR events $e^-e^+ \rightarrow \gamma_{\text{ISR}} Y(4260) \rightarrow J/\psi \pi^+ \pi^-$

$B_{\text{ABAR}}$ preliminary:

$454 \text{ fb}^{-1}$

$J^{PC} = 1^{--}$

$m_Y = 4259 \pm 8^{+2}_{-6} \text{ MeV/c}^2$

$\Gamma_Y = 88 \pm 23^{+6}_{-4} \text{ MeV}$

Confirmed by CLEO-c (scan), CLEO III (ISR), and Belle

(PRL 95, 142001 (2006), PRD 73, 011101(2005),
PRL 96, 162003 (2006), PRD 74, 091104 (2006),
PRL 99, 142002 (2007))

No evidence for $Y(4260) \rightarrow \pi^+ \pi^- \phi$, D$\bar{D}$, p$\bar{p}$

(PRD 74, 091103 (2006), PRD 76, 111105 (2007),
PRD 73, 012005 (2006))

$B_{\text{ABAR}}$ update on $Y(4260)$ (preliminary):

$m = 4252 \pm 6(\text{stat})^{+2}_{-3} (\text{syst}) \text{ MeV/c}^2$

$\Gamma_Y = 105 \pm 18(\text{stat})^{+4}_{-6} (\text{syst}) \text{ MeV}$

No evidence for enhancement at $\sim 4050 \text{ MeV/c}^2$

reported by Belle (PRL 99, 182004 (2007))
Search for $Y(4260) \rightarrow \bar{D}D, D^*\bar{D},$ and $D^*\bar{D}^*$

If $Y(4260)$ is charmonium, it should decay mainly to $\bar{D}D$, $D^*\bar{D}$ and $D^*\bar{D}^*$. No evidence found!

What is $Y(4260)$?
- Hybrid?
- Baryonium?
- Tetraquark?
- Molecular state?

Limits on $Y(4260)$

- $B(D\bar{D})/B(J/\psi \pi\pi) < 1.0$
- $B(D^*\bar{D})/B(J/\psi \pi\pi) < 34$
- $B(D^*\bar{D}^*)/B(J/\psi \pi\pi) < 40$

at 90% C.L.

PRD 72, 054026(2005), PRD 73, 014014(2006), arXiv:0808.1543
Evidence for $Y(4350) \rightarrow \psi(2S)\pi^+\pi^-$ in ISR

It was natural to search for the decay $Y(4260) \rightarrow \psi(2S)\pi^+\pi^-$

e$^+e^-$ requires this state to be $J^{PC} = 1^{-} \rightarrow$ overpopulated

Seems impossible to assign both as charmonium; but, there are two $c\bar{c}$ $1^{-}$ states which might mix to yield the observed spectrum

$Y(4350)$ has been confirmed by Belle (PRL 99, 142002 (2007))

Belle reports another state: $m=4660\pm12$ MeV/$c^2$, $\Gamma=48\pm15$ MeV
Confirmed by \textit{BABAR} in $B \to J/\psi \omega K$ (347 fb$^{-1}$)

- $B^+$ and $B^0$ BF’s measured separately

- $B^0/B^+$ in the $Y$-resonant region:
  - $R_Y = 0.27^{+0.28}_{-0.23}^{+0.04}_{-0.01}$

  **3σ below the isospin expectation**

  - The ratio is consistent with isospin expectation in the non-resonant region

Similar to $X(3872)$ from \textit{BABAR}:

\[ R_X = 0.41 \pm 0.24 \pm 0.05 \]

To compare with...

cf. $R_{\psi(2S)} = 0.81 \pm 0.05 \pm 0.01$; $R_{J/\psi} = 0.865 \pm 0.044$ (PDG)
**BABAR** | **BELLE**
---|---
Mass (MeV/c²) | $3914.6^{+3.8}_{-3.4} \pm 2.0$ | $3943 \pm 11 \pm 13$
Width (MeV) | $34^{+12}_{-8} \pm 5$ | $87 \pm 22 \pm 26$
$BF$: $B^+ \rightarrow YK^+$, $Y \rightarrow J/\psi \omega$ ($\times 10^{-5}$) | $4.9^{+1.8}_{-0.9} \pm 0.5$ | $7.1 \pm 1.3 \pm 3.1$
$BF$: $B^0 \rightarrow YK^0$, $Y \rightarrow J/\psi \omega$ ($\times 10^{-5}$) | $1.3^{+1.3}_{-1.1} \pm 1.1$ | combined

$BF$: $B^+ \rightarrow J/\psi \omega K^+ \ (\times 10^{-4})$ | $3.5 \pm 0.2 \pm 0.4$ | $-$
$BF$: $B^0 \rightarrow J/\psi \omega K^0 \ (\times 10^{-4})$ | $3.1 \pm 0.6 \pm 0.3$ | $-$

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**M**: $3914 \pm 3 \pm 2$ MeV  
**Γ**: $23 \pm 10^{+2}_{-8}$ MeV  
$N_{res} = 55 \pm 14^{+2}_{-14}$ events  
Signif. = 7.7σ,  

$N = 55 \pm 14^{+2}_{-14} \ (7.7σ)$

Preliminary

694 fb⁻¹
$B \rightarrow ZK$

$Z(4430)$
**Observation of Z(4430)**

- Belle has reported a new charged charmonium-like state in the decay:
  \[ B \rightarrow Z \rightarrow K, \ Z \rightarrow \psi(2S)\pi^- \] (PRL 100, 142001 (2008))

- The reported mass and width are:
  \[ M = 4433 \pm 4 \text{(stat)} \pm 2 \text{(syst)} \text{ MeV}/c^2 \]
  \[ \Gamma = 45^{+18}_{-13} \text{(stat)}^{+30}_{-13} \text{(syst)} \text{ MeV} \]

- Significance: 6.5(σ)

- If this result is confirmed ⇒ first observation of a genuine c\bar{c}u\bar{d} “tetraquark” state, since it is charged and carries hidden charm

\[ M = (4443^{+15}_{-12} +17_{-13}) \text{ MeV}/c^2 \]
\[ \Gamma = (109^{+86}_{-43} +57_{-52}) \text{ MeV} \]
Search for the $Z(4430)^-$ in the decay modes $B^0 \rightarrow \psi \pi K^{0+}$ (*)

Describe the $K\pi^-$ system in detail, since structure in the $K\pi^-$ mass and angular distributions dominates each Dalitz plot.

Correct the data for efficiency event-by-event across the Dalitz plot, and describe using only S-, P-, and D-wave intensity contributions.

Project each $K\pi^-$ description onto the relevant $\psi \pi^-$ mass distribution to investigate the need for $Z(4430)^-$ signal above this “$K\pi^-$ background”

Mass resolution at $m_\pi$: ~ 7 MeV/c$^2$ for $J/\psi \pi^-$ and ~4 MeV/c$^2$ for $\psi(2S)\pi^-$

\[ \text{no significant effect on any } Z(4430)^- \text{ signal} \]

(*) We use “$\psi$” to denote “$J/\psi$ or $\psi(2S)$” unless otherwise indicated.
Dalitz plots & Kπ mass distribution

B^+ → J/ψπK^0_S

B^+ → ψ(2S)πK^0_S

B^0 → J/ψπK^+  

B^0 → ψ(2S)πK^+

Fitted with S- (LASS), P-, and D-wave intensity

Good descriptions of the m_{Kπ} distributions are obtained
The Legendre Polynomial moments

\[ \frac{dN}{d \cos \theta_K} = N \sum_{i=0}^{4} \langle P_i \rangle P_i(\cos \theta_K) = \frac{N}{2} + \sum_{i=1}^{4} (N \langle P_i \rangle) P_i(\cos \theta_K) \]

Unnormalized moment \( \langle P_i^U \rangle \)

Clear backward-forward asymmetry
The $Z(4430)^-$ and the $K\pi$ reflections

$m_{\psi\pi}$ peaks at high values because of the asymmetry in the $\cos\theta_K$ distributions

The $K^*$ regions dominate, and affect different regions of $\cos\theta_\psi$ for $J/\psi$ and $\psi(2S)$

The $K^*$ veto removes approximately half of the angular distribution at the $Z(4430)^-$
The corrected \( m_{\psi\pi} \) distributions

All K\(\pi\) mass values

The \( K\pi \) reflections reproduce the data;

no need for additional structure
Fits to the corrected $m_{\psi\pi}$-distributions

Four free parameters: $m_Z$, $\Gamma_Z$, $N_Z$, and $N_{K\pi}$, bkg

$m=4476^{+8}_{-8}$
$\Gamma=32^{+16}_{-16}$
2.7σ

$m=4483^{+3}_{-3}$
$\Gamma=17^{+12}_{-12}$
2.5σ

$m=4439^{+8}_{-8}$
$\Gamma=41^{+33}_{-33}$
1.9σ

No significant Z(4430)$^-$ signal on 413fb$^{-1}$…
**Summary**

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P C$</th>
<th>Mass (MeV/c$^2$)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>$1^{++}$ or $2^{--}$</td>
<td>3871.80±0.25</td>
<td>&lt;2.3</td>
</tr>
<tr>
<td>$Y(3940)$</td>
<td>$??^+$</td>
<td>3916±6</td>
<td>40±22</td>
</tr>
<tr>
<td>$Y(4260)$</td>
<td>$1^{--}$</td>
<td>4264±12</td>
<td>83±22</td>
</tr>
<tr>
<td>$Y(4350)$</td>
<td>$1^{--}$</td>
<td>4361±13</td>
<td>74±18</td>
</tr>
<tr>
<td>$Z(4430)$</td>
<td>$??^+$</td>
<td>$4443^{+15}_{-12}$</td>
<td>$109^{+86}_{-43}$</td>
</tr>
</tbody>
</table>

What about $Y(4143)$? BaBar analysis is ongoing...
Backup slides
Center of mass: 10.58 GeV
\( e^+ e^- \rightarrow \Upsilon(4S) (b\bar{b}) \rightarrow B\bar{B} \)

Peak luminosity:
\[ L = 12.1 \times 10^{33} \text{ cm}^2\text{s}^{-1} \]
The BaBar detector

Silicon Vertex Tracker
Precision vertex reconstruction, dE/dx

Drift Chamber
Momentum, dE/dx

EM Calorimeter
low energy reach for $\pi^0$, $\gamma$
e- ID, neutral hadron detection

9 GeV e-

1.5 T Solenoid

3.1 GeV e+

Instrumented Flux Return
$\mu$ ID, neutral hadron detection

DIRC
PID, K/$\pi$

E. Prencipe, PhiPsi09
Hadron spectroscopy at the B-Factory

- **Two photons production**
  - $e^+ + e^- \rightarrow \gamma \gamma^* \rightarrow c \bar{c}$

- **Continuum production**
  - $e^+ + e^- \rightarrow \gamma^* \rightarrow c \bar{c}$

- **Double charmonium production**
  - $e^+ + e^- \rightarrow J/\psi \rightarrow c \bar{c}$

- **Production in B decays**
  - $B \rightarrow W \rightarrow c \bar{c}$
  - $B \rightarrow K^{(*)} \rightarrow s \bar{q}$

E. Prencipe, PhiPsi09
**Beyond Charmonium**

- **Hybrids**
  - States with *excited gluonic* degrees of freedom
  - Lattice and model predictions for the *lowest-mass* hybrid
    - $M \sim 4.2 \text{ GeV/c}^2$
  - Dominant decay into $DD^*$

- **Tetraquarks**
  - Bound states of *4 quarks*
  - *Large number* of states expected
  - *Small widths* above threshold

- **Molecular states**
  - Loosely bound states of a *pair of mesons*
  - *Small number* of states
  - *Small widths* above threshold

- **Other possibilities**
  - *Threshold, cusp*, or *coupled-channel* effect
  - Give a *cross section enhancement* which may not correspond to resonance production at all
**X(3872): Discovery**

Discovered by Belle:

\[ M_X = (3871.2 \pm 0.5) \text{ MeV/c} \]

Confirmed by:
- BABAR
- CDF
- D0

Belle: PRL 91 (2003) 262003
BaBar: PRD71 (2005) 071103
BaBar: PRD74 (2006) 071101
D0: PRL93 (2004) 162002
**X(3872)**

Measured in $X \rightarrow DD$:

\[ \Delta M(B^0/B^+) = (0.2 \pm 1.6) \text{ MeV}/c^2 \]

- $1^{++}$: $DD^*$ in a S-wave $\propto q^*$
- $2^{++}$: $DD\pi$ in a D-wave $\propto q^{*5}$

$q$ is the momentum of D in the X(3872) frame

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<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$\chi^2/n.d.f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^-$</td>
<td>9.8/7</td>
</tr>
<tr>
<td>$1^+$</td>
<td>3.9/7</td>
</tr>
<tr>
<td>$1^+$</td>
<td>2.5/6</td>
</tr>
<tr>
<td>$2^+$</td>
<td>5.9/7</td>
</tr>
<tr>
<td>$2^-$</td>
<td>2.7/6</td>
</tr>
</tbody>
</table>

- Expected: 1.30 for a state proceeding only via $D^0\overline{D}^{0*}$

Low statistics in BaBar to conclude on $J^P$.

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\[ R \left( \frac{X(3872) \rightarrow D^0\overline{D}^0\pi^0}{X(3872) \rightarrow D^0\overline{D}^0\gamma} \right) = 1.37 \pm 0.56 \]
Y(4260): Discovery

- Observed in ISR events
- Confirmed by Cleo-c (scan) and Cleo III (ISR)

Study of $J/\psi \pi^+ \pi^-$ production in ISR
- $\gamma_{\text{ISR}}$ not necessarily detected
- Small mass recoiling against final state
- Low missing transverse momentum
- Good benchmark channel ISR $\psi (2s)$

$M_\gamma = 4259 \pm 8^{+2}_{-6}$ MeV/c$^2$

$\Gamma_\gamma = 88 \pm 23^{+6}_{-4}$ MeV

- $N=125 \pm 23$ $J^{PC}=1^{--}$

$\Gamma_\gamma \times B(\gamma(4260) \rightarrow \pi^+ \pi^- J/\psi) = (5.5 \pm 1.0^{+0.8}_{-0.7})$ eV

PRL 95, 142001 (2005)

E. Prencipe, PhiPsi09
• Belle-BaBar comparison

Both Belle and BaBar data are re-binned (to calculate $\chi^2$) and sideband subtracted.

The BaBar data are normalized (x1.18) to the Belle sample (luminosity ratio is 1.46).

The data distributions are statistically consistent ($\chi^2 = 54.7/58$)

⇒ Main difference is treatment of background