Vincent Poireau  
CNRS-IN2P3, LAPP Annecy, Université de Savoie, France  
On behalf of the BaBar collaboration

RESULTS ON EXOTIC CHARMONIUM STATES

OUTLINE

- A few words on charmonium  
- Charmonium(-like) states: X, Y, Z states
  - Z(3930)  
  - X(3872)  
  - Y(4260) and Y(4350)  
  - Z(4430)
The experiment ran from 1999 to 2008
- 531 fb\(^{-1}\) recorded in total
  - Including 433 fb\(^{-1}\) at the \(\Upsilon(4S)\)

- Cross sections at \(\sqrt{s} = 10.58\) GeV
  - \(\sigma(e^+e^- \rightarrow b\bar{b}) = 1.1\) nb
    - 475\(\times10^6\) B\(\bar{B}\) pairs
  - \(\sigma(e^+e^- \rightarrow c\bar{c}) = 1.3\) nb
    - 633\(\times10^6\) c\(\bar{c}\) pairs

- BaBar is a B factory…
- …but BaBar is also a charm factory!
A FEW WORDS ON CHARMONIUM

- Charmonium spectrum:

- Basically all states below open-charm threshold are observed and explained.
A FEW WORDS ON CHARMONIUM

- Charmonium spectrum:

- Basically all states below open-charm threshold are observed and explained

- BUT many new states discovered since 2003!

- Let’s investigate a few of them...

---

Increasing $L$ →

Pot. model

$Y(4140)$

$Y(4100)$

$Y(4260)$

$Y(4660)$

$\psi(4415)$

$\psi(4260)$

$\chi(3872)$

$\chi(3930)$

$\psi(3770)$

$\psi(4040)$

$\psi(3940)$

$\psi(4160)$

$Z(4430)$

$Z_1(4430)$

$Z_2(4430)$

$Z_0(4430)$

$\eta_c(2S)$

$\psi(2S)$

$\chi_c(2S)$

$\chi_c(1S)$

$\chi_c(0S)$

$\chi_c(0P)$

$\chi_c(1P)$

$\chi_c(2P)$

$\chi_c(3P)$

$\eta_c(1S)$

$J/\psi$

$\psi(3770)$

$\psi(4040)$

$\psi(3940)$

$\psi(4160)$

$Z(4430)$

$Z_1(4430)$

$Z_2(4430)$

$Z_0(4430)$

$\eta_c(2S)$

$\psi(2S)$

$\chi_c(2S)$

$\chi_c(1S)$

$\chi_c(0S)$

$\chi_c(0P)$

$\chi_c(1P)$

$\chi_c(2P)$

$\chi_c(3P)$

$\eta_c(1S)$

$J/\psi$
NEW STATES OVERVIEW

X(3872)
PRL 91, 262001 (2003)

X(3940)
PRD 98, 082001 (2007)

Y(3940)
PRL 94, 182002 (2005)

Z(3940)
PRD 96, 082003 (2006)

Y(4260)
PRL 95, 142001 (2005)

Y(4350)
PRL 98, 212001 (2007)

Y(4008)
PRL 99, 182004 (2007)

Y(4660)
PRL 99, 142002 (2007)

Z(4430)+
PRL 100, 142001 (2008)

Z1+ and Z2+
PRD 78, 072004 (2008)

Y(4140)
arXiv:0903.2229

X(3915)
presented at CHARM09
BEYOND CHARMONIUM

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

- **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
CHARMONIUM PRODUCTION

- **B-meson decay**
  - Color-suppressed $b \to c$ decay
  - Penguin diagram also possible

- **$e^+e^-$ Initial State Radiation (ISR)**
  - $e^+e^-$ collision below nominal c.m. energy
  - $J^{PC} = 1^{--}$

- **Double charmonium production**
  - Typically one $J/\psi$ or $\psi$, plus second $c\bar{c}$ state

- **Two-photon production**
  - Access to $C=+1$ states
Z(3930): NEW BABAR RESULT
Z(3930)

- Z(3930) discovered by Belle in 2005 in $\gamma\gamma\rightarrow Z\rightarrow D\bar{D}$
- Preliminary result in Nov. 2009 by BaBar
  - Fit signal with a Breit-Wigner
  - $N = 76 \pm 17$ events ($5.8\sigma$)
- $M = (3926.7 \pm 2.7 \pm 1.1)$ MeV/c$^2$
- $\Gamma = (21.3 \pm 6.8 \pm 3.6)$ MeV
- $\Gamma_{\gamma\gamma}\cdot\text{BF}(Z(3930)\rightarrow D\bar{D}) = 0.241 \pm 0.054 \pm 0.043$ keV
- Belle found (395 fb$^{-1}$)
  - $M = (3929 \pm 5 \pm 2)$ MeV/c$^2$
  - $\Gamma = (29 \pm 10 \pm 2)$ MeV
- Angular distribution and spin
  - Spin 0: $\chi^2/\text{nordf} = 15.6/9$
  - Spin 2, helicity 2: $\chi^2/\text{nordf} = 5.6/9$
  - $\Rightarrow$ Probably spin 2
- Consistent with $\chi_{c2}(2P)$ ($J^{PC} = 2^{++}$ and mass value)
X(3872): WHERE IT ALL BEGAN
X(3872)

- First observation by Belle in B decays $B^\pm \rightarrow X(3872)K^\pm$ with $X(3872) \rightarrow J/\psi \pi^+\pi^-$
  - Confirmed by BaBar, CDF, D0
  - $M = (3871.4 \pm 0.6)$ MeV/c$^2$
  - $\Gamma < 2.3$ MeV at 90% CL

- This state is above $D\bar{D}$ threshold
  - Should have large width! (if natural parity)

- This state is very close to the $D^*0\bar{D}^0$ threshold (affects width if unnatural parity)
  - $m(D^0) + m(\bar{D}^0*) = (3871.8 \pm 0.4)$ MeV/c$^2$
  - Is this a coincidence?

- Quantum numbers: $\pi^+\pi^-$ invariant mass distribution + angular analyses
  - Belle: $J^{PC} = 1^{++}$ favored
  - CDF: either $J^{PC} = 1^{++}$ or $2^{-}$

- BaBar: search for a charged partner (decaying to $J/\psi \pi^0\pi^-$)
  - No signal

References:
- D0: PRL 93, 162002 (2004)
- BaBar: PRD 72, 054026 (2005), PRD 73, 014014 (2006)
Recent update of BaBar for $X(3872) \rightarrow J/\psi\pi^+\pi^-$

Main results

- $\text{BF}(B^+ \rightarrow XK^+, X \rightarrow J/\psi\pi^+\pi^-) = (8.4 \pm 1.5 \pm 0.7) \times 10^{-6}$
- $\text{BF}(B^0 \rightarrow XK^0, X \rightarrow J/\psi\pi^+\pi^-) = (3.5 \pm 1.9 \pm 0.4) \times 10^{-6}$, $\leq 6.0 \times 10^{-6}$ @ 90% C.L.
- $R(X) = \frac{\text{BF}(B^0)}{\text{BF}(B^+)} = 0.41 \pm 0.24 \pm 0.05$
- $\Gamma(X) < 3.3 \text{ MeV} @ 90\% \text{ CL}$
X(3872) → J/ψ γ, ψ(2S) γ

- Find 3.6σ evidence for
  B⁺ → X(3872)K⁺, X(3872) → J/ψ γ
  - BF(B⁺ → X(3872)K⁺)×(X(3872) → J/ψγ) = (2.8 ± 0.8 ± 0.2) × 10⁻⁶

- First evidence for B⁺ → X(3872)K⁺,
  X(3872) → ψ(2S) γ
  - 3.5σ significance
  - BF(B⁺ → X(3872) K⁺)×(X(3872) → ψ(2S)γ) = (9.5 ± 2.7 ± 0.9) × 10⁻⁶

- BF(X(3872) → ψ(2S) γ) / BF(X(3872) → J/ψ γ) = 3.4 ± 1.4

- These observations imply C-parity = +1
  - Dipion has C-parity = -1
  - Odd angular momentum
  - I = 1
  - Decay to J/ψπ⁺π⁻ violates isospin conservation, and dipion is most probably in a P-wave state

BaBar: PRL 102, 132001 (2009)
THE $X(3872) \to D^0\bar{D}^{*0}$ SAGA

- **Belle in 2006:** excess in the $D^0D^0\pi^0$ invariant mass in $B \to D^0D^0\pi^0K$, with a shifted mass with respect to $X(3872) \to J/\psi\pi^+\pi^-$
  - $M = (3875.2 \pm 0.7^{+1.2}_{-2.0})$ MeV/c²
  - $2\sigma$ away from the $X(3872) \to J/\psi\pi^+\pi^-$

- **BaBar in 2008:** study of $X(3872) \to D^0\bar{D}^{*0}$
  - Confirms $X(3872)$ signal ($4.9\sigma$)
  - $M = (3875.1^{+0.7}_{-0.5} \pm 0.5)$ MeV/c²
  - $4.5\sigma$ away from the $X(3872) \to J/\psi\pi^+\pi^-$
  - Measurement of the width
    - $\Gamma = 3.0^{+1.9}_{-1.4} \pm 0.9$ MeV
  - **Angular** study inconclusive

- **In 2008, Belle redid the mass measurement for $D^0\bar{D}^{*0}$ with more statistics**
  - $M = (3872.6^{+0.5}_{-0.4} \pm 0.4)$ MeV/c²
  - In better **agreement** with $X(3872) \to J/\psi\pi^+\pi^-$
  - In **disagreement** with BaBar result
THE X(3872) → D⁰ D*⁰ SAGA

- Saga summary

<table>
<thead>
<tr>
<th>Year</th>
<th>Collaboration</th>
<th>Channel</th>
<th>Mass measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-2009</td>
<td>Belle/BaBar/CDF/D0</td>
<td>J/ψ π⁺ π⁻</td>
<td>M = (3871.4 ± 0.6) MeV/c²</td>
</tr>
<tr>
<td>2006</td>
<td>Belle</td>
<td>D⁰ D⁰ π⁰</td>
<td>M = (3875.2 ± 0.7 +1.2 -2.0) MeV/c²</td>
</tr>
<tr>
<td>2008</td>
<td>BaBar</td>
<td>D⁰ D*⁰</td>
<td>M = (3875.1 +0.7 -0.5 ± 0.5) MeV/c²</td>
</tr>
<tr>
<td>2008</td>
<td>Belle</td>
<td>D⁰ D*⁰</td>
<td>M = (3872.6 +0.5 -0.4±0.4) MeV/c²</td>
</tr>
</tbody>
</table>

- One possible explanation for the mass shift in X(3872) → D⁰ D*⁰
  - No proximity of the threshold for J/ψ π⁺ π⁻
    - Mass and width measurement correspond to the real particle
  - Proximity of the threshold for D⁰ D*⁰
    - If particle just below threshold, we see a peak above threshold NOT corresponding to the real particle

- Another possible explanation
  - If the width of the X(3872) is 2-3 MeV, peak position sensitive to the angular momentum (due to the proximity of the threshold)
  - Mass shift of ~3 MeV/c² if X(3872) is J⁰ = 2⁻ (L = 1)

J/ψ π⁺ π⁻ lineshape
D⁰ D*⁰ lineshape
D⁰ D⁰ π⁰ lineshape

PRL 100, 062006 (2008)
X(3872): INTERPRETATION

- **X(3872) likely not a charmonium state**
  - Radial excitation of $\chi_{c1}$ ($J^{PC} = 1^{++}$) expected at 3950 MeV/c$^2$
  - $\eta_{c2}$ ($J^{PC} = 2^{--}$) should have $X \rightarrow J/\psi \gamma$ suppressed
  - No satisfactory $c\bar{c}$ assignment

- **$\bar{D}^0D^*0$ molecule?**
  - Would explain proximity of the $\bar{D}^0D^*0$ threshold
  - favors $D\bar{D}^*$ decay over $J/\psi \pi\pi$ over $J/\psi \gamma$ (as observed)
  - Expect $X \rightarrow \psi(2S)\gamma$ to be suppressed (in contradiction with observation)

- **tetraquark state?**
  - Predict 2 neutral states and 2 charged states
    - Neutral states produced in $B^0$ and $B^+$ decays: $\Delta m \approx (7 \pm 2)$ MeV/c$^2$
  - Measurements:
    - $\Delta m = (2.7 \pm 1.6 \pm 0.4)$ MeV/c$^2$ in $B \rightarrow J/\psi \pi^+\pi^-$
    - No evidence for charged partners

- **Mixing of $\bar{D}^0D^*0$ and $\chi_{c1}$? Something else?...**
Y(4260) AND Y(4350)
New resonance discovered in $e^+e^- \rightarrow \gamma_{\text{ISR}}(J/\psi\pi^+\pi^-)$ by BaBar in 2005

BaBar updated the measurement in 2008

- $M = (4252 \pm 6 \, {}^{+2}_{-3})$ MeV/c$^2$
- $\Gamma = (105 \pm 18 \, {}^{+4}_{-6})$ MeV

No evidence for enhancement at $\sim 4050$ MeV/c$^2$ reported by Belle

Belle measures

- $M = (4247 \pm 12 \, {}^{+17}_{-32})$ MeV/c$^2$, $\Gamma = (108 \pm 19 \pm 10)$ MeV

CLEO measures

- $M = (4284 \, {}^{+17}_{-16} \pm 4)$ MeV/c$^2$
- Also seen in $J/\psi\pi^0\pi^0 \Rightarrow$ implies $I = 0$
**Y(4260): OTHER CHANNELS**

- **Search for** $Y(4260) \rightarrow D\bar{D}, D^*\bar{D}, D^*\bar{D}^*$
  - **Dominant** decay if the $Y(4260)$ is a charmonium state
- **No evidence** in any of these channels
- **Results and combination**

**Limits on $Y(4260)$**

- $\frac{B(D\bar{D})}{B(J/\psi \pi^+\pi^-)} < 7.6$
- $\frac{B(D^*\bar{D})}{B(J/\psi \pi^+\pi^-)} < 34$
- $\frac{B(D^*\bar{D}^*)}{B(J/\psi \pi^+\pi^-)} < 40$

- **Also, no evidence for:**
  - $e^+e^- \rightarrow \gamma_{ISR}(\phi\pi^+\pi^-)$, $e^+e^- \rightarrow \gamma_{ISR}(p\bar{p})$,
  - $e^+e^- \rightarrow \gamma_{ISR}(J/\psi\gamma\gamma)$

---

19 V. Poireau Montpellier 2009 4th December 2009

BaBar: PRD 76, 111105 (2007)
BaBar: PRD 79, 092001 (2009)
Y(4260)… AND Y(4350)

- Natural to study of $Y(4260) \rightarrow \psi(2S)\pi^+\pi^-$ in ISR production

- Peak found… but not at the expected position!
  - **New resonance**: the $Y(4350)$
    - $M = (4324 \pm 24)$ MeV/$c^2$
    - $\Gamma = (172 \pm 33)$ MeV

- Confirmed by Belle
  - $M = (4361 \pm 9 \pm 9)$ MeV/$c^2$
  - $\Gamma = (74 \pm 15 \pm 10)$ MeV

- Belle also reports another state
  - $M = (4660\pm12)$ MeV/$c^2$, $\Gamma = (48\pm15)$ MeV

Y(4260): INTERPRETATION

- No $c\bar{c}$ assignment for $1^-$ state

- tetraquark state $[cs][\bar{c}\bar{s}]$?
  - Should decay dominantly to $\bar{D}_sD_s$

- Hybrid meson?
  - $\bar{D}D$, $\bar{D}^*D^*$, $\bar{D}D^*$ decays suppressed
  - $\bar{D}D_1(2420)$ decays should dominate

- hybrid + quenched lattice QCD predicts, for $1^-$
  - $M = 4380 \pm 150$ MeV/c$^2$

- Hadro-charmonium?

References:
- Phys. Rev. D72, 031502 (2005)
Z(4430): FIRST CHARGED STATE
Z(4430)⁻ DISCOVERY

- Belle has reported a new charged charmonium-like state in the decay $B \rightarrow Z'K$, $Z' \rightarrow \psi(2S)\pi^-$

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

- Significance: $6.5\sigma$
  - 121 ± 30 events

- If this result is confirmed
  - First observation of a $c\bar{c}u\bar{d}$ tetraquark state, since it is charged and carries hidden charm

- Since then, Belle confirmed this result with a Dalitz plot analysis (same data sample)
  - $M = (4443^{+15}_{-12} +17_{-13}) \text{ MeV/c}^2$
  - $\Gamma = (109^{+86}_{-43} +57_{-52}) \text{ MeV}$
BABAR SEARCH FOR $Z(4430)^-$

- Search for the $Z(4430)^-$ with 413 fb$^{-1}$ in the decay modes
  - $B^- \rightarrow J/\psi \pi^- K^0$
  - $B^0 \rightarrow J/\psi \pi^- K^+$
  - $B^- \rightarrow \psi(2S) \pi^- K^0$
  - $B^0 \rightarrow \psi(2S) \pi^- K^+$

- 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 $K\pi^-$ 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”.

In the following, using “$\psi$” to denote $J/\psi$ or $\psi(2S)$.
CORRECTED DISTRIBUTIONS

- Good descriptions of the $m(K\pi^-)$ distributions are obtained

- The $K\pi$- reflections reproduce the data
  - no evidence for additional structure

FITS TO THE CORRECTED $M_{\psi\pi}$ DISTRIBUTION

- No significant $Z(4430)^-$ signal in BaBar

SUMMARY AND CONCLUSIONS
CONCLUSIONS

- Almost no new resonant states in more than 20 years
- Tens of them since 1999, beginning of Belle and BaBar!
- The $Z(3930)$ could be interpreted as the $\chi_{c2}(2P)$
  - Everybody agrees it is a $c\bar{c}$ state
- Other new states not explained by usual quark content
  - However, no single explanation for all of them!
- The nature of the $X(3872)$, $Y(4260)$, $Y(4350)$ and $Z(4430)$ is still unclear
  - Probably not $c\bar{c}$
  - Maybe molecule, tetraquarks, mixed states, or…
- Experimentally
  - Update analyses with full statistics when applicable
  - Add new channels
  - Hope for LHCb and super-B/Belle II to contribute to this topic
ADDITIONAL SLIDES
Center of mass: 10.58 GeV
$e^+ e^- \rightarrow \Upsilon(4S) (b\bar{b}) \rightarrow B\Bbar$

Peak luminosity: \(\mathcal{L} = 12.1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\)

Effective cross-section

$\sigma (e^+ e^- \rightarrow \text{hadrons}) \text{(nb)}$

Mass (GeV/c$^2$): 9.44, 9.46, 10.00, 10.02, 10.34, 10.37, 10.54, 10.58, 10.62

- \(\Upsilon(1S)\)
- \(\Upsilon(2S)\)
- \(\Upsilon(3S)\)
- \(\Upsilon(4S)\)

B\Bbar threshold
THE BaBar EXPERIMENT

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

DIRC
PID, K/π

1.5 T Solenoid

3.1 GeV e+

9 GeV e−

Instrumented Flux Return
μ ID, neutral hadron detection
X(3940), Y(3940) AND Z(3930)

**X(3940)**

New state seen in $e^+e^- \rightarrow J/\psi \ X$

Also, observed $X \rightarrow \bar{D}D^*$, but not $X \rightarrow \bar{D}D$

$M = (3943 \pm 6 \pm 6) \text{ MeV}/c^2$

$\Gamma = (15.4 \pm 10.1) \text{ MeV}$

cc state $\eta_c(3S) [3^1S_0]$?

**Y(3940)**

Near threshold enhancement in $B \rightarrow J/\psi \omega K$

$M = (3943 \pm 11 \pm 13) \text{ MeV}/c^2$

$\Gamma = (87 \pm 22 \pm 26) \text{ MeV}$

cc state $\chi'_{c1} [2^3P_1]$?

**Z(3930)**

New resonance state in $\gamma\gamma \rightarrow \bar{D}D$

$M = (3929 \pm 5 \pm 2) \text{ MeV}/c^2$

$\Gamma = (29 \pm 10 \pm 2) \text{ MeV}$

cc state $\chi'_{c2} [2^3P_2]$?
Y(3940)

- Near threshold enhancement in $B \to J/\psi \omega K$ observed by Belle in 2005
- Confirmed by BaBar in 2008
- Mass and width slightly different from the one from Belle

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>BaBar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass (MeV/c²)</strong></td>
<td>3943±11±13</td>
<td>3914.6±3.8 ± 3.4 ± 2.0</td>
</tr>
<tr>
<td><strong>Width (MeV)</strong></td>
<td>87±22 ±26</td>
<td>34±12 ±5</td>
</tr>
<tr>
<td><strong>BF: $B^+ \to YK^+$</strong>, $Y \to J/\psi \omega$ ($\times 10^{-5}$)</td>
<td>7.1 ± 1.3 ± 3.1 combined</td>
<td>4.9±1.0 ±0.9±0.5</td>
</tr>
<tr>
<td><strong>BF: $B^0 \to YK^0$</strong>, $Y \to J/\psi \omega$ ($\times 10^{-5}$)</td>
<td>-</td>
<td>1.3±1.3 ±1.1±0.2</td>
</tr>
<tr>
<td>**BF: $B^+ \to J/\psi \omega K^+$ ($\times 10^{-5}$)</td>
<td>-</td>
<td>35±2±4</td>
</tr>
<tr>
<td>**BF: $B^0 \to J/\psi \omega K^0$ ($\times 10^{-5}$)</td>
<td>-</td>
<td>31±6±3</td>
</tr>
</tbody>
</table>

- New preliminary result from Belle in 2009 seems to agree now with BaBar mass and width
- **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.

**BaBar: PRD 79, 112001 (2009)**