Exotic Hadrons

(奇特强子态)

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“XXIX Physics in Collision”
Kobe, Aug.31-Sep.2, 2009
Hadrons: normal & exotic

• Hadrons are composed from 2 (meson) or 3 (baryon) quarks

Quark model

• QCD allows hadrons with $N_{\text{quarks}} \neq 2, 3$
  – glueball: $N_{\text{quarks}} = 0$ (gg, ggg, ...)
  – hybrid: $N_{\text{quarks}} = 2$ + excited gluon
  – Multiquark state: $N_{\text{quarks}} > 3$
  – molecule: bound state of more than 2 hadrons
A bit of history on exotics hunting

• “The absence of exotics is one of the most obvious features of QCD” – R. L. Jaffe, 2005
• Deuteron $\rightarrow$ H state, $d'$, $d^*$, $\Omega^-$-$\Omega^-$ bound state
• No solid signature of glueballs
• Pentaquark state appeared and disappeared
  (“The story of pentaquark shows how poorly we understand QCD” – F. Wilczek, 2005)
• Do we still have hope?
  Yes!
Outline

The XYZ states at B-factories + other experiments

XYZ $\rightarrow$ charmonium + light meson

- $X(3872)$ – molecular state?
- XYZ(3940) & X(3915) – charmonia?
- Y(4140) & X(4350) – tetraquark states?
- Y states in ISR – hybrids?
- $Z^+(4430)/Z^+(4050)/Z^+(4250)$ – cannot be charmonia!
Most of the XYZ from B-factories

+ BES, CDF, D0
Charmonium spectroscopy

We were very proud:
Potential models worked well for charmonium.

No big progress in last century!
Then we found lots of XYZ states

What are they?
Charmonium? Hybrid? Tetraquark? Molecule?

Not all XYZ states are charmonia!
X(3872)

first and most puzzling state
(observed in 2003 at Belle)
$X(3872) \rightarrow \pi^+\pi^- J/\psi$

**recent results**

- $B^\pm \rightarrow XK^\pm$
  - $N_S = 132 \pm 15$
  - $(12.8\sigma)$

- $B^0 \rightarrow XK^0$
  - $N_S = 27.2 \pm 6.6$
  - $(5.9\sigma)$

- $B^\pm \rightarrow XK^\pm$
  - $N_S = 93 \pm 17$
  - $8.6\sigma$

- $B^0 \rightarrow XK^0$
  - $N_S = 9 \pm 5$
  - $2.3\sigma$

$$\delta M_X = M(X \text{ from } B^\pm) - M(X \text{ from } B^0)$$
$$= (0.18 \pm 0.89 \pm 0.26) \text{ MeV}$$
$$= (2.7 \pm 1.6 \pm 0.4) \text{ MeV}$$
$X(3872) \rightarrow \pi^+\pi^- J/\psi$ in CDF

recent results

Recent results from CDF have reported an observation of the $X(3872)$ decay to $\pi^+\pi^- J/\psi$. The analysis includes the determination of the mass and width of the resonance. The mass of the resonance, $M_X$, is given by:

$$M_X = 3871.61 \pm 0.16 \pm 0.19 \text{ MeV}$$

The mass is determined to be $3871.61$ MeV with uncertainties of $0.16$ and $0.19$ MeV. The mass difference, $\delta M_X$, is constrained to be less than $3.6$ MeV at the 95% confidence level (CL):

$$\delta M_X < 3.6 \text{ MeV} \text{ at 95\% CL}$$

The analysis also considers fits for two nearby states, as indicated in the graph.
M(X(3872)) π⁺π⁻J/ψ mode only

<MX> = 3871.46 ± 0.19 MeV

No sign of a mass doublet a la Maiani et al

Δm(deuteron) = -2.2 MeV

Δm = -0.35 ± 0.41 MeV
Mass in $X_{3872} \rightarrow D^{*0}D^0$

Belle 2006, 414/fb
$X_{3872} \rightarrow D^0D^0\pi^0$

BaBar 2006, 347/fb
$X_{3872} \rightarrow D^0D^{*0}(\pi^0D^0,\gamma D^0)$

Fit with truncated BW in both exps.

$M = 3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8 \text{ MeV}/c^2$

Is this the higher mass partner state predicted by Maiani et al?
Belle update

N_{signal} = 48 \pm 11 \text{ evts}
Signif. = 8.8\sigma

\[
\text{mass} \ (\text{MeV}/c^2) = 3872.6 \pm 0.5 \pm 0.4
\]

Agree with \pi\pi J/\psi \text{ mode.}

Fit with a phase-space modulated BW
Can also use other parameterizations to do the fit
**X(3872) → γJ/ψ & γψ’ from BaBar**

**PRL 102, 132001 (2009)**

\[ X(3872) \rightarrow J/\psi \gamma \] 3.0σ

**K+**

\[ 23.0^{+/-6.4}_{-6.4} \text{ events} \]

**BABAR**

**m_X (GeV/c^2)**

- Events / (5 MeV/c^2)

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

- C-parity = +1

- \( J^{PC} = 2^- \) disfavored \( \leftrightarrow \) multipole suppression

- \( Bf(X_{3872} \rightarrow \gamma \psi') > Bf(X_{3872} \rightarrow \gamma J/\psi) \leftrightarrow \text{bad for molecules} \)

**X(3872) → ψ(2S) γ** 3.5σ

**K+**

\[ 25.4^{+/-7.3}_{-7.3} \text{ events} \]

**BABAR**

**m_X (GeV/c^2)**

\[ Bf(B^+ \rightarrow X_{3872}K^+) \times (X_{3872} \rightarrow \psi' \gamma) = (9.5 \pm 2.7 \pm 0.9) \times 10^{-6} \]

- (Belle also measured \( \gamma J/\psi \): 0505037)

- Swanson PLB 598, 197 (2004)
$B \to K\pi X(3872)$ from Belle

$\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-) < 3.4 \times 10^{-6}$

$\mathcal{B}(B^0 \to X(3872)(K^+ \pi^-)_{NR}) \times \mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$

$\text{Bf}(B \to J/\psi K^{*0})/\text{Bf}(B \to J/\psi K_{\pi_{NR}}) \sim 4.$

Similar ratios for $\chi_{c1}, \psi(2S)$!

$X$ is very different from other charmonia. Pure 3-body $B$ decays? Check Dalitz plot!
Production of $X(3872)$ in $B$ decays

$Bf\left( B^- \rightarrow X(3872)K^- \right) < 3.2 \times 10^{-4}$ at 90% C.L.

PRL 96, 052002 (2006)
Babar (2008) and Belle (2008) average:

\[ Bf\left( B^- \rightarrow X(3872)K^- , \ X \rightarrow J/\psi \pi^+ \pi^- \right) = (8.20 \pm 0.93) \times 10^{-6} \]

Together with Babar upper limit on

\[ Bf\left( B^- \rightarrow X(3872)K^- \right) < 3.2 \times 10^{-4} \]

one gets

\[ Bf\left( X \rightarrow J/\psi \pi^+ \pi^- \right) > 2.3\% \]
Decay of $X(3872)$

\[
Bf(B^- \rightarrow XK^-)Bf(X \rightarrow J / \psi \pi^+ \pi^-) = (8.20 \pm 0.93) \times 10^{-6}
\]
\[
Bf(B^- \rightarrow XK^-)Bf(X \rightarrow J / \psi \pi^+ \pi^- \pi^0) = (8.2 \pm 4.2) \times 10^{-6}
\]
\[
Bf(B^- \rightarrow XK^-)Bf(X \rightarrow J / \psi \gamma) = (2.8 \pm 0.8 \pm 0.2) \times 10^{-6}
\]
\[
Bf(B^- \rightarrow XK^-)Bf(X \rightarrow \psi(2S)\gamma) = (9.5 \pm 2.7 \pm 0.9) \times 10^{-6}
\]
\[
Bf(B^- \rightarrow XK^-)Bf(X \rightarrow D^0 \overline{D}^{0*} + c.c.) = (1.67 \pm 0.36 \pm 0.47) \times 10^{-4}
\]

\[
\Rightarrow Bf(X \rightarrow J / \psi \pi^+ \pi^-) < \frac{8.2 + 1\sigma}{8.2 + 8.2 + 2.8 + 9.5 + 167 - 1\sigma} \approx 6.6\% \quad @90\% \text{ C.L.}
\]

\[
2.3\% < Bf\left(X \rightarrow J / \psi \pi^+ \pi^-\right) < 6.6\% 
\]
\[
1.4 \times 10^{-4} < Bf\left(B^- \rightarrow X(3872)K^-\right) < 3.2 \times 10^{-4} \quad \text{at 90\% C.L.}
\]

\[
Bf\left(B^- \rightarrow \psi(2S)K^-\right) = (4.9 \pm 1.6 \pm 0.4) \times 10^{-4}
\]
\[
Bf\left(B^- \rightarrow \chi_{c1}K^-\right) = (8.0 \pm 1.4 \pm 0.7) \times 10^{-4}
\]
\[
Bf\left(B^- \rightarrow \eta_cK^-\right) = (8.4 \pm 1.3 \pm 0.8) \times 10^{-4}
\]
X(3872) summary

- **Mass**: Very close to $D^0D^{*0}$ threshold
- **Width**: Very narrow, $< 3$ MeV
- $J^{PC}=1^{++}$ favoured
- **Production**
  - in pp collision – similar to charmonia
  - In B decays – $KX$ similar to $cc$, $K^*X$ smaller than $cc$
- **Decay BR**: open charm $\sim 50\%$, charmonium$\sim 0\%$
- **Nature** (very likely exotic)
  - Loosely $D^0D^{*0}$ bound state (like deuteron?)?
  - Mixture of excited $\chi_{c1}$ and $D^0D^{*0}$ bound state?
  - Many other possibilities (if it is not $\chi_{c1}$, where is $\chi_{c1}$?)
The states near 3940 MeV

- circa 2005 -

\[ M = 3940 \pm 11 \text{ MeV} \]
\[ \Gamma \approx 92 \pm 24 \text{ MeV} \]
\[ \text{Nsig} = 52 \pm 24 \pm 11 \text{ evts} \]

\[ M = 3929 \pm 5 \pm 2 \text{ MeV} \]
\[ \Gamma_{\text{tot}} = 29 \pm 10 \pm 2 \text{ MeV} \]
\[ \text{Nsig} = 64 \pm 18 \text{ evts} \]
New peak in $\gamma\gamma \rightarrow \omega J/\psi$

M: $3914 \pm 3 \pm 2$ MeV,

$\Gamma$: $23 \pm 10 \pm 8$ MeV,

$N_{\text{res}} = 55 \pm 14 \pm 14$ events

Signif. = 7.7$\sigma$,

Background only fit
Could it be the Z(3930)?

\[ M = 3929 \pm 5 \pm 2 \text{ MeV} \]
\[ \Gamma_{\text{tot}} = 29 \pm 10 \pm 2 \text{ MeV} \]
\[ N_{\text{res}} = 55 \pm 14 \pm 14 \text{ evts} \]

\[ M = 3914 \pm 3 \pm 2 \text{ MeV} \]
\[ \Gamma: 23 \pm 10 ^{+2} _{-8} \text{ MeV} \]
\[ N_{\text{sig}} = 64 \pm 18 \text{ evts} \]
\[ \Gamma_{\gamma\gamma} \text{ partial width} \]

\[ \Gamma_{\gamma\gamma} B(\omega J/\psi) = 69 \pm 16^{+7}_{-18} \text{ eV (} J^P=0^+ \text{)} \]

\[ \Gamma_{\gamma\gamma} B(\omega J/\psi) = 21 \pm 4^{+2}_{-5} \text{ eV (} J^P=2^+ \text{)} \]

**For comparison:**

\[ Z(3930): \Gamma_{\gamma\gamma} B(DD) = 180 \pm 50 \pm 30 \text{ eV} \]

If \( X(3915) = Z(3930) = \chi_{c2}' \)

\[ \frac{B(\chi_{c2}' \rightarrow \omega J/\psi)}{B(\chi_{c2}' \rightarrow DD)} \geq 0.08 \]

Huge for above-open-charm-threshold charmonium
The 4 states near 3940

Mass(GeV) \quad \text{Range: } \pm (\sigma(\text{stat.}) \oplus \sigma(\text{sys.}))

\begin{itemize}
  \item X(3940)
  \item Y(3940) \quad \text{Belle}
  \item Z(3930)
  \item This X(3915)
\end{itemize}

Good overlap with BaBar “Y(3940)” values
CC assignments for X(3915), X(3940) & Y(3940)?

- $Y(3940) = X(3915) = \chi_{c0}'$? $\iff \Gamma(\omega J/\psi)$ too large?
- $X(3940) = \eta_c''$? $\iff$ mass too low? $\psi(3S) = 4040$ MeV
- $Z(3940) = \chi_{c2}'$? $\iff (\Delta M(J=2,0) = 15 \pm 7$ MeV?)
States decaying into $J/\psi\phi$

Evidence for $Y(4140)$ and a New Resonance at 4.35 GeV
The CDF $Y(4140) \rightarrow \phi J/\psi$

- $B^+ \rightarrow Y(4140)K^+$
- 14±5 events, >3.8σ
- Mass: 4143.0 ± 2.9 ± 1.2 MeV
- Width: 11.7+8.3−5.0 ± 3.7 MeV (It is narrow!)

![Diagram of particles and reactions](image)

**PRL102, 242002 (2009)**
Y(4140) not significant at Belle

- Belle: $B \rightarrow J/\psi \phi K$ with 772M $BB$
  $M(J/\psi \phi)$ fit with $Y(4140)$ parameters fixed

[but low efficiency at $J/\psi \phi$ threshold]

$Br\left( B^+ \rightarrow Y(4140)K^+, Y \rightarrow J/\psi \phi \right) < 6 \times 10^{-6}$ @ 90% C.L

CDF result:
$Br\left( B^+ \rightarrow Y(4140)K^+, Y \rightarrow J/\psi \phi \right) = (9.0 \pm 3.4 \pm 2.9) \times 10^{-6}$

$B^+ \rightarrow J/\psi \phi K^+$
325 ± 21

\[ \Delta E = E_B - \sqrt{s}/2 \]
Searched for in $\gamma\gamma \rightarrow \phi J/\psi$

- No Y(4140)
- A few events accumulate at 4.35 GeV in both $J/\psi \rightarrow e^+e^-$ and $\mu^+\mu^-$ modes

$J^P=0^+$: $\Gamma_{\gamma\gamma} \text{Br}(Y(4140) \rightarrow \phi J/\psi) < 39 \text{ eV} \quad @ 90\% \text{ C.L.}$

$J^P=2^+$: $\Gamma_{\gamma\gamma} \text{Br}(Y(4140) \rightarrow \phi J/\psi) < 5.7 \text{ eV} \quad @ 90\% \text{ C.L.}$
Fit to $\phi J/\psi$ invariant mass

- unbinned maximum likelihood method
- BW convoluted with Double Gaussian resolution function
- mass resolution is 5.5 MeV at 4.35 GeV

$\Gamma_{\gamma \gamma} \text{ Br}(X(4350) \rightarrow \phi J/\psi) = 6.4^{+3.1}_{-2.3} \pm 1.1 \text{ eV}$

$\Gamma_{\gamma \gamma} \text{ Br}(X(4350) \rightarrow \phi J/\psi) = 1.5^{+0.7}_{-0.5} \pm 0.3 \text{ eV}$
Preliminary results

- $M(X(4350)) = 4350.6^{+4.6}_{-5.1} \pm 0.7 \text{ MeV/c}^2$
- $\Gamma = 13.3^{+17.9}_{-9.1} \pm 4.1 \text{ MeV/c}^2$
- $N(X(4350)) = 8.8^{+4.2}_{-3.2}$
- Statistical significance: $3.2-3.9\sigma$

- Excited P-wave charmonium?
- Tetraquark?
- $D^*_sD^*_s$ molecule at $4.34\pm0.09 \text{ GeV}$?

Fl. Stancu, arXiv: 0906.2485
J.R. Zhang et al., arXiv: 0905.4672

SPECTRUM OF $c\bar{c} s\bar{s}$
The Y states should also appear in this plot (between 4.0 and 4.7 GeV)
Y family (vector states)

$e^+e^- \rightarrow J/\psi \pi^+\pi^- \gamma_{ISR}$

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

Above DD threshold, decay to open charm?

PRL 99, 182004 (2007)

550 fb$^{-1}$

$Y(4008)$

7$\sigma$

$Y(4260)$

PRL 99, 142002 (2007)

670 fb$^{-1}$

$Y(4360)$

$Y(4660)$ 6$\sigma$

arXiv:0808.1543

PRL 98, 212001 (2007)

298 fb$^{-1}$

$Y(4360)$

$Y(4660)$
Y family

- Y(4008), Y(4260), Y(4360), Y(4660) don’t match peaks in D(*)D(*) Xsection
- Widths for ψππ transition too large for conventional charmonia
- Y(4260) is DD_1 molecule/ccg hybrid?
  DD_1 [→DD*π] decay should dominate but no signal found
What are the Y states?

- Between 4 and 4.7 GeV, at most 5 states expected (3S, 2D, 4S, 3D, 5S), 7 observed
- Hybrids are expected in this mass region
- Molecular states?
- Cannot rule out threshold effect/FSI/…
- Y(4260), Y(4360), Y(4660) are all narrow and similar
Charged state with hidden charm $Z^+(4430)$ and more

Unambiguous tetraquark state?
$Z(4430)^{\pm} \rightarrow \psi(2S)\pi^{\pm}$

- Found in $\psi(2S)\pi^+$ from $B \rightarrow \psi(2S)\pi^+K$. Z parameters from fit to $M(\psi(2S)\pi^+)$
- Confirmed through Dalitz-plot analysis of $B \rightarrow \psi(2S)\pi^+K$
- $B \rightarrow \psi(2S)\pi^+K$ amplitude: coherent sum of Breit-Wigner contributions
- **Models:** all known $K^* \rightarrow K\pi^+$ resonances only
  - all known $K^* \rightarrow K\pi^+$ and $Z^+ \rightarrow \psi(2S)\pi^+$ ⇒ favored by data

**Significance:** $6.4 \sigma$

$M = 4433^{+15}_{-12}^{+19}_{-13}$ MeV

$\Gamma = 107^{+86}_{-43}^{+74}_{-53}$ MeV

- [cu][cd] tetraquark? neutral partner in $\psi'\pi^0$ expected
- $D^*D_1(2420)$ molecule? should decay to $D^*D^*\pi$
Z⁺⁻(4430) in BaBar data?

- Fits to \( M(\psi(2S)\pi^+) \): no significant Z(4430) signal

\[ M_Z = 4476 \pm 8 \text{ MeV} \]
\[ \Gamma_Z = 32 \pm 16 \text{ MeV} \]
2.7σ

\( \chi^2/\text{ndf} = 54.7/58 \)

PRD79, 112001 (2009)

- \( M(\psi(2S)\pi^+) \) is statistically consistent between BaBar & Belle

- Better to have one more experiment to examine it
Two $Z^\pm \rightarrow \chi_{c1}\pi^\pm$

- Dalitz-plot analysis of $B^0 \rightarrow \chi_{c1}\pi^+K^-$, $\chi_{c1} \rightarrow J/\psi\gamma$ with 657M $BB$
- Dalitz plot models: known $K^* \rightarrow K\pi$ only
  $K^*$'s + one $Z \rightarrow \chi_{c1}\pi^\pm$
  $K^*$'s + two $Z^\pm$ states $\Rightarrow$ favored by data

Significance: $5.7\sigma$

Waiting for experiments to confirm them!
Summary of the talk

Many XYZ states were observed in B-factories and other experiments in

\[ \text{XYZ} \rightarrow \text{charmonium} + \text{light meson} \]

They could be exotic hadrons such as molecular state, tetraquark state, or hybrids or just charmonium states, threshold effect, FSI effect or some other unknown QCD effect.

Both theorists and experimentalists should continue work hard and patiently for possibly very rare (even non-existing) exotic hadrons! (Is exotic hadron another ether?)

Thanks a lot.
backup
### XYZ states

<table>
<thead>
<tr>
<th>Name</th>
<th>J^{PC}</th>
<th>$\Gamma$ (MeV)</th>
<th>Decay modes</th>
<th>Experiments</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(3872)</td>
<td>1^{++}</td>
<td>&lt;2.3</td>
<td>$\pi\pi J/\psi, \gamma J/\psi, DD^*, \ldots$</td>
<td>Belle/CDF/D0/BaBar</td>
<td>DD* molecule?</td>
</tr>
<tr>
<td>X(3940)</td>
<td>0^{2+}</td>
<td>~37</td>
<td>DD* (not DD, $\omega J/\psi$)</td>
<td>Belle</td>
<td>$\eta'_c$ (?)</td>
</tr>
<tr>
<td>Y(3940)</td>
<td>?^{2+}</td>
<td>~30</td>
<td>$\omega J/\psi$ (not DD*)</td>
<td>Belle/BaBar</td>
<td>ccss?</td>
</tr>
<tr>
<td>Y(4140)</td>
<td>?^{2+}</td>
<td>~11</td>
<td>$\phi J/\psi$</td>
<td>Belle</td>
<td>ccss?</td>
</tr>
<tr>
<td>X(4160)</td>
<td>0^{2+}</td>
<td>~140</td>
<td>D<em>D</em> (not DD, DD*)</td>
<td>Belle</td>
<td>$\eta'_c$ (?)</td>
</tr>
<tr>
<td>Y(4008)</td>
<td>1^{-}</td>
<td>~220</td>
<td>$\pi\pi J/\psi$</td>
<td>Belle (not Babar)</td>
<td></td>
</tr>
<tr>
<td>Y(4260)</td>
<td>1^{-}</td>
<td>~80</td>
<td>$\pi\pi J/\psi$</td>
<td>BaBar/CLEO/Belle</td>
<td>cgg hybrid?</td>
</tr>
<tr>
<td>X(4350)</td>
<td>?^{2+}</td>
<td>~13</td>
<td>$\gamma\gamma, \phi J/\psi$</td>
<td>Belle</td>
<td>ccss?</td>
</tr>
<tr>
<td>Y(4360)</td>
<td>1^{-}</td>
<td>~75</td>
<td>$\pi\pi\psi(2S)$</td>
<td>BaBar/Belle</td>
<td></td>
</tr>
<tr>
<td>Y(4660)</td>
<td>1^{-}</td>
<td>~50</td>
<td>$\pi\pi\psi(2S), \Lambda_c\Lambda_c$ (?)</td>
<td>Belle</td>
<td></td>
</tr>
</tbody>
</table>

### charged Z

| Z^{\pm}(4430) | ???? | ~100 | $\psi(2S) \pi^{\pm}$ | Belle (not Babar) | 4-quark? |
| Z^{\pm}(4050) | ???? | ~80  | $\chi^c \pi^{\pm}$   | Belle              | 4-quark? |
| Z^{\pm}(4250) | ???? | ~180 | $\chi^c \pi^{\pm}$   | Belle              | 4-quark? |
Shows up in all data subsamples

**Z(4430)**
Both Belle and $BABAR$ data are re-binned (to calculate $\chi^2$) and side-band subtracted. The $BABAR$ data are normalized (*1.18) to the Belle sample; Luminosity ratio is 1.46. The data distributions are statistically consistent ($\chi^2=54.7/58$). From J. Brodzicka, LP09.
BaBar doesn’t see a significant $Z(4430)^+$

“For the fit ... equivalent to the Belle analysis...we obtain mass & width values that are consistent with theirs,... but only $\sim1.9\sigma$ from zero; fixing mass and width increases this to only $\sim3.1\sigma$.”

$BF(B^0\rightarrow Z^+K) \times BF(Z^+\rightarrow \psi(2S)\pi^+) < 3.1 \times 10^{-5}$

Belle PRL: $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$
Compare with PRL results ($Z(4430)$)

$K^*$ veto applied

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

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

Signif: 6.4$\sigma$

Published results

$M = 4433 \pm 4 \pm 2$ MeV/c$^2$

$\Gamma_{\text{tot}} = 45^{+18}_{-13}^{+30}_{-13}$ MeV

$N_{\text{sig}} = 121 \pm 30$ evts

$\chi^2/\text{dof} = 80.2/94.0$ 6.5 $\sigma$

Mass & significance similar, width & errors are larger

BaBar: $\text{BF}(B^0 \rightarrow Z^+ K) \times \text{BF}(Z^+ \rightarrow \psi(2S)\pi^+) < 3.1 \times 10^{-5}$

No big contradiction

Belle: $= (3.2^{+1.8}_{0.9}^{+9.6}_{1.6}) \times 10^{-5}$
Charmonia

Quantum numbers

\[ n(2S+1)L_J \]

Many empty slots to fill
Expected broad states decaying to DD, DD*, D*D*

All states observed
Good agreement with QCD predictions

n radial quantum number
S total spin of qq
L relative orbital mom.
\[ L = 0, 1, 2 \rightarrow S, P, D \]
J = S + L
P = \((-1)^{L+1}\) parity
C = \((-1)^{L+S}\) charge conj.

 Recently measured
Charmonia above DD

- Energy scans by BESII in ‘98-99
- Refit of R spectrum: with interferences between $\psi$ 1- states

\[ R = \frac{\sigma_{had}(e^+e^- \to \gamma^* \to \text{hadrons})}{\sigma_{\mu\mu}(e^+e^- \to \gamma^* \to \mu^+\mu^-)} \]

Many decay channels allowed:

- $\psi(3770) \Rightarrow D\bar{D}$;
- $\psi(4040) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, D_s\bar{D}_s$;
- $\psi(4140) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, D_s\bar{D}_s, D_s\bar{D}_s$;
- $\psi(4415) \Rightarrow DD, D^*\bar{D}^*, D_sD_s, D_sD_s, D_s^*D_s, D_sD_s^*$;

$\Rightarrow$ fit complicated
$\Rightarrow$ model dependence

<table>
<thead>
<tr>
<th></th>
<th>$\psi(3770)$</th>
<th>$\psi(4040)$</th>
<th>$\psi(4160)$</th>
<th>$\psi(4415)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ [MeV]</td>
<td>PDG2006</td>
<td>3771.1 ± 2.4</td>
<td>4039 ± 1</td>
<td>4153 ± 3</td>
</tr>
<tr>
<td></td>
<td>BES</td>
<td>3771.4 ± 1.8</td>
<td>4038.5 ± 4.6</td>
<td>4191.6 ± 6.0</td>
</tr>
<tr>
<td>$\Gamma$ [MeV]</td>
<td>PDG2006</td>
<td>23.0 ± 2.7</td>
<td>80 ± 10</td>
<td>103 ± 8</td>
</tr>
<tr>
<td></td>
<td>BES</td>
<td>25.4 ± 6.5</td>
<td>81.2 ± 14.4</td>
<td>72.7 ± 15.1</td>
</tr>
<tr>
<td>$\delta$ [°]</td>
<td>BES</td>
<td>0</td>
<td>133 ± 68</td>
<td>301 ± 61</td>
</tr>
</tbody>
</table>

PLB660, 315 (2008)
The Y(2175) at BaBar

Babar measured $e^+e^- \rightarrow \phi\pi^{+/0}\pi^{-/0}$ and $\phi f_0(980)$ observed the $Y(2175) \rightarrow \phi f_0(980)$.

$M = 2175 \pm 10 \pm 15$ MeV
$\Gamma = 58 \pm 16 \pm 20$ MeV

$\sigma_{nr} = P(\mu) \cdot |A_{nr}(\mu)|^2$,

$A_{nr}(\mu) = \sqrt{\sigma_0} \cdot (1 - e^{-(\mu/a_1)\xi}) \cdot (1 + a_2 \mu + a_3 \mu^2)$,

$P(\mu) = \sqrt{1 - m_0^2/(m_0 + \mu)^2}$,

$\mu = E_{c.m.} - m_0$, $m_0 = 1.8$ GeV/$c^2$
$Y(2175)$ in $J/\psi \rightarrow \eta \phi f_0(980)$ at BESII

Simultaneous fit to signal and sideband events with BW+p3

$M = 2186 \pm 10 \pm 6$ MeV

$\Gamma = 65 \pm 23 \pm 17$ MeV

$B(J/\psi \rightarrow \eta Y \rightarrow \eta \phi f_0(980) \rightarrow \eta \phi \pi \pi) = (3.23 \pm 0.75 \pm 0.73) \times 10^{-4}$

BES: PRL100, 102003 (2008)
The Y(2175) at Belle

Two incoherent BWs fit as central values, $\phi f_0(980)$ fit as one source of error

$M(\phi(1680)) = 1689 \pm 7 \pm 10$ MeV
$\Gamma(\phi(1680)) = 211 \pm 14 \pm 19$ MeV

$M(Y(2175)) = 2079 \pm 13 ^{+79}_{-28}$ MeV
$\Gamma(Y(2175)) = 192 \pm 23 ^{+25}_{-61}$ MeV

- Agree with Babar’s and BES’s measurements
- Width larger than previous measurements → $Y(2175) = \text{excited } \phi$ remains a possibility

Belle: PRD80, 031101(RC) (2009)
Combined BaBar+Belle data

Two incoherent BWs: \[ \chi^2/\text{ndf}=170/111 \text{ (C.L.=0.03\%)} \]

\[
\begin{align*}
\mathcal{M}(\phi(1680)) &= 1685 \pm 5 \text{ MeV} \\
\mathcal{M}(Y(2175)) &= 2080 \pm 12 \text{ MeV} \\
\Gamma(\phi(1680)) &= 208 \pm 11 \text{ MeV} \\
\Gamma(Y(2175)) &= 182 \pm 20 \text{ MeV}
\end{align*}
\]

FIG. 2: Fit to \( e^+e^- \rightarrow \phi\pi^+\pi^- \) with two incoherent BW functions (a), and with three incoherent BW functions (b), respectively. The curves show the projections from the best fits and the contribution from each component.
Combined BaBar+Belle data

Two coherent BWs: $\chi^2/\text{ndf}=158/110$ (C.L.=0.19%)

$M(\phi(1680)) = 1677 \pm 6$ MeV  \quad $\Gamma(\phi(1680)) = 233 \pm 16$ MeV
$M(Y(2175)) = 2112 \pm 16$ MeV  \quad $\Gamma(Y(2175)) = 196 \pm 27$ MeV
$\phi_0(980)$ Combined BaBar+Belle data

$\sigma(\phi_0(980))$ (nb)

$E_{CM}$ (GeV)

$\sigma$ $2.7\sigma$

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(Y(2175))$</td>
<td></td>
<td>2163 ± 15</td>
</tr>
<tr>
<td>$\Gamma_{tot}(Y(2175))$</td>
<td></td>
<td>107 ± 25</td>
</tr>
</tbody>
</table>
Y(5S) and Y(6S)

- Energy scans above Y(4S): Belle: 7.9/fb Babar: 3.9/fb (0.13/fb from CESR)
- Motivation: new spectroscopy like in cc?
- Babar inclusive: fit to hadronic x-section
- Belle exclusive: study of di-pion transitions

Large dipion widths. For other bb: O(keV)

Pure bb state or $Y_b \rightarrow Y(nS) \pi \pi$ contributes?

Inclusive and exclusive dipion x-sections inconsistent with PDG Y(5,6S) parameters
Analogy ∼ open threshold

[CUSB: PRL 54, 377 (1985)]

[Y(5S)]

[CLEO: PRL 54, 381 (1985)]

[Y(2175)]

[Y(4260)]

[Y(10890)]
What are $\Upsilon(5S)$, $\psi(4260)$, $\phi(??)$?

We are exploring a mass region with many open-flavor threshold!
Constructive interference between amplitudes?
Need more study!