Studies of radiative $X(3872)$ decays at Belle

Charm 2012
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(on behalf of Belle)
Outline

• Charmonium at Belle

• Radiative decays of $X(3872)$.

• Search for $X(3872)^{C^-}$ in $\chi_{c1,c2}^{\gamma}$

• First evidence of $\Psi_2$

• Result and Conclusion
Charmonium spectrum

Contribution to new states:

$\eta_c(2S), \Psi_2, X(3872), X(3915), Z(3930), X(3940), Y(3940), Z_1(4050)^+, Z_2(4250)^+, Y(4260), Z(4430)^+, Y(4660), \ldots$
In this talk

Production of $c\bar{c}$ (-like) in B-factory

A few % of B mesons decay into $c\bar{c}$ and $K^{(*)}$

$B$-decays

Easy to study.
Low background.
$J^{PC}$ using angular studies.

$J/\psi$, $\psi'$, $\eta_c$, $\chi_c$, ...

Reconstruct $J/\psi$ and look at recoil mass

Annihilation at smaller energy.

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

Initial state radiation

Clean and ideal place to carry charmonium spectroscopy related business.

Double Charmonium

$C = +1$

$J even$

Two photon production

$c\bar{c}$ states produced without additional hadrons.

$C = +1$
Radiative decays of X(3872)

Belle found evidence for $X(3872) \rightarrow J/\psi \gamma$ in $B^+ \rightarrow X(3872) K^+$. Also seen by BaBar

$$\text{BR}(B^+ \rightarrow XK^+) \cdot \text{BR}(X \rightarrow J/\psi \gamma) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$$

BaBar, PRL 102, 132001 (2009)

$$\text{BR}(X(3872) \rightarrow \psi' \gamma) / \text{BR}(X(3872) \rightarrow J/\psi \gamma) = 3.5 \pm 1.4$$

Update from Belle, established $X(3872) \rightarrow J/\Psi \gamma$ with 5.5σ observation*

$$\text{BR}(B^+ \rightarrow XK^+) \times \text{BR}(X \rightarrow J/\psi \gamma) = (1.78 \pm 0.46 \pm 0.12) \times 10^{-6}$$


PLB 697, 3, 233-237 (2011)

However, Belle didn’t see any signal in $X(3872) \rightarrow \psi' \gamma$

$$\frac{\text{BR}(X \rightarrow \psi' \gamma)}{\text{BR}(X \rightarrow J/\psi \gamma)} < 2.1 \text{ (@90\% CL)}$$

No Belle evidence for $X(3872) \rightarrow \psi' \gamma$

* combining $B^+ \rightarrow XK^+ \& B^0 \rightarrow XK^0$
Search for $X(3872)^\text{c-}$ in $\chi_{c1,c2}\gamma$

- Earlier search for tetraquark partner (charged $X(3872)$), no signal was seen.
- However, many tetraquark models predict $X(3872)^+$ to be broad and non-observed yet due to low statistics (?).
- $X(3872)$ C-even parity prohibit it to decay into $\chi_{c1,c2}\gamma$.
- If $X(3872)$ is tetraquark than its’ C-odd partner can decay into $\chi_{c1,c2}\gamma$.
- In Belle previous searches (with less data), no signal was seen and UL was provided.

With 5 x more data either we can observe or provide much tighter constraint to C-odd partner of $X(3872)$
Search for $c\bar{c}$ (-like) states

- Many conventional states still awaiting confirmation and B decays provide a gateway to study them.
- Theory predicts $^3D_2$ $c\bar{c}$ state to lie around $\sim 3810$-$3840$ MeV/c$^2$ mass and should be narrow.
  
  Partial width, $\Gamma(\psi_2 \rightarrow \chi_{c1}\gamma) = 260$ keV.
- Along with this, there should be $^3D_3$ $c\bar{c}$ state lying around $\sim 3830$-$3880$ MeV/c$^2$ mass and will decay into $\chi_{c2}\gamma$.
  
  Partial width, $\Gamma(\psi_3 \rightarrow \chi_{c2}\gamma) = 286$ keV.

✓ With current statistics, we expect to find some hint of $\Psi_2$ and $\Psi_3$.
✓ Along with this, we may also find some other C-odd $c\bar{c}$ - like resonance.


Search for new exotic state in $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$ by scanning $M_{\chi_{c1,c2}\gamma}$ (mass distribution) for narrow peak.
Analysis procedure

Reconstruct $B^\pm$ (of interest)

Variable used in analysis to extract signal

$$M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$

$$\Delta E = E_B - E_{beam}$$

$$M_{\chi_{c1}\gamma} \text{ or } M_{\chi_{c2}\gamma}$$

To identify background, large sample of $B \rightarrow J/\Psi X$ (final state, here $X$ can be anything) MC is used.
Analysis procedure

Reconstruct $B^\pm$ (of interest)

To reduce background

- $\pi^0$ veto
- $\chi_{c1,c2}'\gamma$ veto

$-28\text{ MeV} < \Delta E < 30\text{ MeV}$

$E_\gamma$ scaled ($\Delta E=0$) to improve the resolution of $M_{\chi_{c1,c2}\gamma}$

- 2D UML fit to $M_{\chi_{c1,c2}\gamma}$ & $M_{bc}$ extract signal yield

- If some new resonance, it will become visible in $M_{\chi_{c1,c2}\gamma}$, in $M_{bc}$ signal region.

MC for illustration purpose

Projection in signal region

$B^\pm \rightarrow \chi_{c1}\gamma K^\pm$

$M_{bc} > 5.27\text{ GeV/c}^2$

$M_{\chi_{c1}\gamma}$ $[3.85,3.89]$
M_{\chi c_1 \gamma} distribution

- Narrow peak observed around 3820 MeV/c^2.
- No strong evidence for any discrepancy between data/MC, expect this narrow peak.

B^+ \rightarrow \psi' (\rightarrow \chi_{c1} \gamma) K^+

M_{bc} > 5.27\text{ GeV/c}^2

Combinatorial background
Signal extraction in $M_{\chi_{c1}\gamma}$ 2D UML fit

Background parameterize using large $B \to J/\Psi X$ MC sample

- $B^+ \to \Psi'(\to \chi_{c1}\gamma) K^+$
- $B^+ \to \Psi'(\to \chi_{c1}\gamma) K^+$
- $B^+ \to \Psi_2(\to \chi_{c1}\gamma) K^+$
- Combinatorial

**MC**

- Peaking background
  $(B \to \Psi K^*, \chi_{c1} K^*, \Psi K \pi, \chi_{c1} K \pi, ..)$

**Fit parameterize**

- Sum of two Gaussian (convoluted with Breit-Wigner) is used to fit $\Psi_2$ (from MC).
- Tail part Gaussian same as $\Psi'$ (tested on MC study).
- $M_{bc}$ PDF same as $\Psi'$ (from MC study).
- $\Psi_2$ width is fix to zero, resolution is estimated from $\Psi'$ peak (and scaled from MC).

For fit bias, 2000 toys and no significant bias is observed.

Maximum bias of 2% estimated and included in the systematics.

*Estimated from signal MC (for different width)
Mass of new peak

Peak at $3823.5\pm2.8$ MeV/c$^2$

Yield: $4.2\sigma$ (syst. Included)

Clear evidence of signal at 3823 MeV/c$^2$

$\Gamma = 4\pm6$ MeV if fitted, poor sensitivity
What is this peak?

\( \Psi_2 \) below D\( \bar{D} \)\( \ast \) threshold: expected to have narrow decay width of 300-400 keV

\( \Psi_2 \rightharpoonup D\bar{D} \) is forbidden due to parity. Mostly decaying into \( \chi_{c1}\gamma \).

\( 3^D_2 \) doesn't have E1 transition to \( \chi_{c1}\gamma \)

\( \Psi_2 \rightarrow \Psi_2 \rightarrow D\bar{D} \) mass is quite near and the observed peak has not been seen in D\( \bar{D} \) (\( 3^D_2 \rightarrow D\bar{D} \) is expected).

\( X(3823) \) seems to be the missing \( \Psi_2 \) from the charmonium spectrum.

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$\mathbf{B^\pm \rightarrow \chi_{c1}\gamma K^\pm}$

**X(3872)$^\text{C-}$**

**X(3872) yield : -0.9±5.1 events**

![Projection graph]

No hint of X(3872)

$\mathbf{M_{\chi_{c1}\gamma} (GeV/c^2)}$

$\mathbf{M_{bc} > 5.27 GeV/c^2}$

No signal is observed in the X(3872) region.

$\mathbf{M_{bc} (GeV/c^2)}$

$\mathbf{3.84 < M_{\chi_{c1}\gamma} < 3.9 GeV/c^2}$

B.R.$(B^\pm \rightarrow X(3872)K^\pm) \times \text{B.R.}(X(3872) \rightarrow \chi_{c1}\gamma) < 2.0 \times 10^{-6} \text{ (@90\% CL)}$

$$\frac{\Gamma(X3872 \rightarrow \chi_{c1}\gamma)}{\Gamma(X3872 \rightarrow J/\psi\pi^+\pi^-)} < 0.26$$

Belle, PRD 85,052004 (R) (2011)

* Recent Belle result used for BR(B$\rightarrow$X3872K)$ \times $BR(X3872$\rightarrow$J/$\psi\pi^+\pi^-$).
### Fit results

<table>
<thead>
<tr>
<th>(B^\pm \rightarrow \chi_{c1}\gamma K^\pm)</th>
<th>Yield</th>
<th>(BR\ (10^{-4}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\psi' \rightarrow \chi_{c1}\gamma)</td>
<td>193±19</td>
<td>(7.74^{+0.77}_{-0.74})(stat)(+0.87)(-0.83)(syst)</td>
</tr>
</tbody>
</table>

\(BR(B^+ \rightarrow \psi' K^+)\) consistent with world average

<table>
<thead>
<tr>
<th>(B^\pm \rightarrow \chi_{c1}\gamma K^\pm)</th>
<th>Yield</th>
<th>(BR(B^+ \rightarrow X K^+)), (BR(X \rightarrow \chi_{c1}\gamma)) (10^{-6})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\psi_2 \rightarrow \chi_{c1}\gamma)</td>
<td>33.2±9.1</td>
<td>(9.70^{+2.84}_{-2.51})(stat)(+1.06)(-1.03)(syst)</td>
</tr>
<tr>
<td>(X(3872) \rightarrow \chi_{c1}\gamma)</td>
<td>-0.9±5.1</td>
<td>&lt; 2.0(@90% CL)</td>
</tr>
</tbody>
</table>

First evidence of \(\psi_2\) with 4.2 \(\sigma\) significance by Belle.
No strong evidence for any narrow peak between data/MC at current statistics.

$B^+ \rightarrow \Psi' (\rightarrow \chi_{c2} \gamma) K^+$

$B^+ \rightarrow \Psi' (\rightarrow \chi_{c2} \gamma) K^+$

$\Psi_2 / X(3823)$

$X(3872)$

Combinatorial background

$M_{bc} > 5.27$ GeV/c$^2$
Signal extraction in $M_{\chi c2\gamma}$

2D UML fit

Background parameterize using large $B \rightarrow J/\Psi X$ MC sample

- Peaking component Combinatorial
- $X(3823)$

Fit parameterize

- Sum of two Gaussian is used to fit $\Psi'$ and $\Psi_2$ shape estimated (from MC).
- Data/MC correction estimated from $B^{\pm} \rightarrow \Psi'(\rightarrow \chi_{c1}\gamma)K^{\pm}$.
- 2000 toys were used to test fitter and no significant bias is observed.
**Results**

**Belle**

**711 fb^{-1}**

- $B^+ \rightarrow X(3872)(\rightarrow \chi_{c2} \gamma) K^+$
- $B^+ \rightarrow \Psi_2(\rightarrow \chi_{c2} \gamma) K^+$
- $B^+ \rightarrow \Psi'(\rightarrow \chi_{c2} \gamma) K^+$
- Combinatorial

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Yield</th>
<th>BR $\times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \rightarrow \chi_{c2} \gamma K^\pm$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Psi' \rightarrow \chi_{c2} \gamma$</td>
<td>$56.6\pm9.3$</td>
<td>$5.82\pm0.95(stat)\pm0.61(syst)$</td>
</tr>
<tr>
<td>$\Psi_2 \rightarrow \chi_{c2} \gamma$</td>
<td>$-0.4\pm3.4$</td>
<td>$&lt;3.4$</td>
</tr>
<tr>
<td>$X(3872) \rightarrow \chi_{c2} \gamma$</td>
<td>$3.9\pm3.9$</td>
<td>$&lt;6.0$</td>
</tr>
</tbody>
</table>

**BR($B^+ \rightarrow X K^+$), BR($X \rightarrow \chi_{c2} \gamma$) $\times 10^{-6}$**

- $7.74^{+0.77}_{-0.74}(stat)\pm0.87(syst)$
- $9.70^{+2.84}_{-2.51}(stat)\pm1.06(syst)$

**Γ($\Psi_2 \rightarrow \chi_{c2} \gamma$) / Γ($\Psi_2 \rightarrow \chi_{c1} \gamma$) < 0.48, Expected ~ 0.2 (model dependent)**

**U.L. (@ 90% CL)**

Result & conclusion

First evidence of narrow state at 3823 MeV in $\chi_{c1}\gamma$.
• Most probable the missing $\Psi_2(c\bar{c})$ state.
• Useful for quarkonium model.
• Also, useful in understanding other resonances.

No narrow state evident in $\chi_{c2}\gamma$, at current statistics.

$\Psi_2 \rightarrow \chi_{c2}\gamma$ UL consistent with the expectation.

$X(3872)$ as tetraquark
• No signal is seen in C-odd partner of $X(3872)$ (tetraquark interpretation) in $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$.
• More stringent upper limits are provided.

Confirmation of $\Psi_2$ at other experiments.
Interesting to compare it with predicted $BR(\Psi_2 \rightarrow J/\Psi \pi\pi)$, can be measured at LHC.
Thank you
This wizard helps in keeping track of BACK-UP slides

To continue press Next >
Reconstruction

\( \chi_{c1,c2} \) reconstruct from \( J/\psi \gamma \)

- \( p_{J/\psi} < 2.0 \text{ GeV/c} \)
- Koppenberg's \( \pi^0 \) veto < 0.6 (to reject \( \gamma \) from \( \pi^0 \))
- \( 3.47 \text{ GeV/c}^2 < M_{J/\psi \gamma} < 3.54 \text{ GeV/c}^2 \) for \( \chi_{c1} \)
- \( 3.54 \text{ GeV/c}^2 < M_{J/\psi \gamma} < 3.58 \text{ GeV/c}^2 \) for \( \chi_{c2} \)

Mass constrained and vertex fit in order to improve resolution

\( \gamma \) is rejected if it is combined with another \( \gamma \) and has \( M_{\gamma \gamma} \) within \([117, 153]\) MeV/c\(^2\) (\( \pi^0 \) veto)

\( \gamma \) is veto, if it is making best \( \chi_{c1,c2} \) in that event.

- \( R_K > 0.6 \)

-28 MeV < \( \Delta E \) < 30 MeV as \( \Delta E \) window

For multiple candidate, \( \Delta E \) closest to 0.

- \( E_\gamma \) is scaled in order to improve the resolution of \( M_{\chi_{c1} \gamma} \) (\( \Delta E = 0 \)).
- Extract signal yield using fit to \( M_{\chi_{c1} \gamma} \) & \( M_{bc} \) (2D UML fit).
-198 < ΔE < -140 MeV
100 < ΔE < 158 MeV

ΔE sideband

2 x signal region

- 198 < ΔE < -140 MeV
- 100 < ΔE < 158 MeV

Rest

\( B^+ \rightarrow \Psi' K^+ \) (signal)
\( B^+ \rightarrow \Psi' K^+ \) (not signal)

No unexpected peaking background is seen.

\( B \rightarrow J/\psi X \) MC agrees quite well with data.
\[ -198 < \Delta E < -140 \text{ MeV} \]
\[ 100 < \Delta E < 158 \text{ MeV} \]

**ΔE sideband**

\[ M_{xc^2\gamma} < 3.97 \text{ GeV/c}^2 \]

\[ M_{bc} > 5.27 \text{ GeV/c}^2 \]

- No unexpected peaking background is seen.
- \( B \rightarrow J/\psi X \) MC agrees quite well with data.
There is a small bump around 3950 MeV/c² due to $\gamma$ of $\chi_{c1}$ combining with fake $\chi_{c1}$. In order to remove this bump, we need to use $\chi_{c1}' \gamma$ veto.

<table>
<thead>
<tr>
<th>$\chi_{c1}$</th>
<th>$J/\psi$</th>
<th>$J/\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_1$</td>
<td>blue</td>
<td></td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>yellow</td>
<td>purple</td>
</tr>
<tr>
<td>$\gamma_3$</td>
<td>blue</td>
<td></td>
</tr>
<tr>
<td>$\gamma_4$</td>
<td>blue</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

True candidates
$\gamma$ to be vetoed

$B^+ \rightarrow \chi_{c1}(\rightarrow J/\psi \gamma_a)\gamma_b K^+$

but

$B^+ \rightarrow \chi_{c1}(\rightarrow J/\psi \gamma_{\text{random}})\gamma_a K^+$

Avoid this situation by removing $\gamma_a$ from list of $\gamma_b$.
TABLE I: Thresholds for decay into open charm.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Threshold Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0\bar{D}^0$</td>
<td>3729.4</td>
</tr>
<tr>
<td>$D^+D^-$</td>
<td>3738.8</td>
</tr>
<tr>
<td>$D^0\bar{D}^{*0}$ or $D^{*0}\bar{D}^0$</td>
<td>3871.5</td>
</tr>
<tr>
<td>$D^\pm D^{\mp}$</td>
<td>3879.5</td>
</tr>
<tr>
<td>$D_s^+D_s^-$</td>
<td>3936.2</td>
</tr>
<tr>
<td>$D_s^{<em>+}D_s^{</em>-}$</td>
<td>4013.6</td>
</tr>
<tr>
<td>$D^{<em>+}D^{</em>-}$</td>
<td>4020.2</td>
</tr>
<tr>
<td>$D_s^{<em>+}D_s^{</em>-}$ or $D_s^{<em>+}D_s^{</em>-}$</td>
<td>4080.0</td>
</tr>
<tr>
<td>$D_s^{<em>+}D_s^{</em>-}$</td>
<td>4223.8</td>
</tr>
</tbody>
</table>


TABLE III: Charmonium spectrum, including the influence of open-charm channels. All masses are in MeV. The penultimate column holds an estimate of the spin splitting due to tensor and spin-orbit forces in a single-channel potential model. The last column gives the spin splitting induced by communication with open-charm states, for an initially un-split multiplet.

<table>
<thead>
<tr>
<th>State</th>
<th>Mass</th>
<th>Centroid</th>
<th>Splitting (Potential)</th>
<th>Splitting (Induced)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^3S_0$</td>
<td>2979.9$^a$</td>
<td>3067.6$^b$</td>
<td>$-90.5$</td>
<td>$+2.8$</td>
</tr>
<tr>
<td>$1^3S_1$</td>
<td>3096.9$^a$</td>
<td></td>
<td>$+30.2$</td>
<td>$-0.9$</td>
</tr>
<tr>
<td>$1^3P_0$</td>
<td>3415.3$^a$</td>
<td>$-114.9$</td>
<td>$+5.9$</td>
<td></td>
</tr>
<tr>
<td>$1^3P_1$</td>
<td>3510.5$^a$</td>
<td>$-11.6$</td>
<td>$-2.0$</td>
<td></td>
</tr>
<tr>
<td>$1^1P_1$</td>
<td>3525.3</td>
<td></td>
<td>$+1.5$</td>
<td>$+0.5$</td>
</tr>
<tr>
<td>$1^3P_2$</td>
<td>3556.2$^a$</td>
<td>$-31.9$</td>
<td>$-0.3$</td>
<td></td>
</tr>
<tr>
<td>$2^1S_0$</td>
<td>3637.7$^a$</td>
<td>3673.9$^b$</td>
<td>$-50.4$</td>
<td>$+15.7$</td>
</tr>
<tr>
<td>$2^3S_1$</td>
<td>3686.0$^a$</td>
<td></td>
<td>$+16.8$</td>
<td>$-5.2$</td>
</tr>
<tr>
<td>$1^3D_1$</td>
<td>3769.9$^{a,b}$</td>
<td></td>
<td>$-40$</td>
<td>$-39.9$</td>
</tr>
<tr>
<td>$1^3D_2$</td>
<td>3830.6</td>
<td>(3815)$^d$</td>
<td>0</td>
<td>$-2.7$</td>
</tr>
<tr>
<td>$1^1D_2$</td>
<td>3838.0</td>
<td></td>
<td>0</td>
<td>$+4.2$</td>
</tr>
<tr>
<td>$1^3D_3$</td>
<td>3868.3</td>
<td></td>
<td>$+20$</td>
<td>$+19.0$</td>
</tr>
<tr>
<td>$2^3P_0$</td>
<td>3931.9</td>
<td></td>
<td>$-90$</td>
<td>$+10$</td>
</tr>
<tr>
<td>$2^3P_1$</td>
<td>4007.5</td>
<td>3968$^d$</td>
<td>$-8$</td>
<td>$+28.4$</td>
</tr>
<tr>
<td>$2^1P_1$</td>
<td>3968.0</td>
<td></td>
<td>0</td>
<td>$-11.9$</td>
</tr>
<tr>
<td>$2^3P_2$</td>
<td>3966.5</td>
<td></td>
<td>$+25$</td>
<td>$-33.1$</td>
</tr>
</tbody>
</table>

Looking at $\psi'$, here 3.836 peaks looks prominent ???

A search has been made in 300 GeV/c $\pi^\pm$- and proton-Li interactions for production of states that decay into $J/\psi$ or $\psi'$ plus one or two pions. A 2.5$\sigma$ enhancement in the $J/\psi \pi^0$ spectrum, possibly the recently reported $^1P_1$ state of charmonium, is observed at a mass of 3.527 GeV/c$^2$. In the $J/\psi$ plus two pion mass spectrum, we report, together with the expected $\psi' \rightarrow J/\psi \pi^+ \pi^-$, the tentative observation of a structure at a mass of 3.836 GeV/c$^2$. No enhancements are seen in the $J/\psi \pi^\pm \pi^\mp$, $J/\psi \pi^\pm \pi^0$, $J/\psi \pi^\pm$, or $\psi' \pi^\pm$ mass spectra.

FIG. 6. $J/\psi \pi^+ \pi^-$ mass spectra from 300 GeV/c$\pi^\pm$Li interactions; (b) $J/\psi \pi^+ \pi^-$ mass spectrum from 300 GeV/c proton Li interactions.
Interestingly $\Psi_2$ is not seen in $J/\Psi \pi \pi$ in other experiments.
Some properties of $X(3872)$

$X(3872)$ found in $J/\psi\pi\pi\pi\pi$, similar to $\psi'$

Another charmonium?

World average mass $\rightarrow 3871.6\pm 0.2\text{ MeV}/c^2$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (MeV)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF II</td>
<td>3871.61±0.16±0.19</td>
<td>PRL, 103, 152001 (2009)</td>
</tr>
<tr>
<td>Belle</td>
<td>3871.84±0.27±0.19</td>
<td>Belle, PRD 85,052004 (2011)</td>
</tr>
</tbody>
</table>

Mass near $D^0$ and $\bar{D}^*0$ threshold $\rightarrow 3871.73\pm 0.21\text{ MeV}/c^2$ PDG

How is it related to $D^0 \bar{D}^*0$? $D^0 \bar{D}^*0$ molecule or something else?

$X(3872)$ much narrower width ($\Gamma < 1.2\text{MeV} @ 90\%\text{ CL}$) than other charmonium states above $D\bar{D}$ threshold.

Observed in $D^0 \bar{D}^*0$ mode. PRL 97,162002 (2006), PRD 77,011102 (2008) and PRD 81, 031103 (2010)
**cc̄ (-like) states at Belle**

General purpose detector, built to test Standard Model mechanism for CP violation in B decays to charmonium ($B^0 \rightarrow J/\Psi, \Psi', \chi_{c1} K^0$) \cite{arXiv:1201.4643v1} accepted in PRL.

Contribution to charmonium (-like) states:
- $\eta_c(2S)$, $X(3872)$, $Y(3940)$, $Z(3930)$, $X(3940)$, $X(3915)$, $Y(4260)$, $Y(4660)$, $Z(4430)^+$, $Z_1(4050)^+$, $Z_2(4250)^+$...

On-resonance:
- $4S : 711 \text{ fb}^{-1}$
- $5S : 121 \text{ fb}^{-1}$
- $3S : 3 \text{ fb}^{-1}$
- $2S : 25 \text{ fb}^{-1}$
- $1S : 6 \text{ fb}^{-1}$

Off-resonance/scan:
- $\sim 100 \text{ fb}^{-1}$
$X(3872)$  Most famous $c\bar{c}$ (-like) state  
Discovered by Belle in $J/\psi\pi\pi$ decay mode  

$B^+ \rightarrow X(3872) K^+$,  
$X(3872) \rightarrow J/\psi\pi^+\pi$  
$\Gamma < 2.5$ MeV  
(90%CL)

34±7 events  
10σ  

Confirmed by CDF, DO, BaBar, CMS and LHCb.

Difficult to assign to a conventional charmonium state.
Update on properties of $X(3872)$

$\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow J/\psi \pi \pi) = (8.61 \pm 0.82 \pm 0.52) \times 10^{-6}$

$M_{X(3872)} = (3871.84 \pm 0.27 \pm 0.19)$ MeV

$\Gamma_{X(3872)} < 1.2$ MeV (90% C.L.)

Mass diff. b/w charged and neutral B decay is

$\Delta M_{X(3872)} = (-0.69 \pm 0.97 \pm 0.19)$ MeV

Prediction: $\Delta M(M_{X(B^+)} - M_{X(B^0)}) = (8 \pm 3)$ MeV

$X(3872) \rightarrow J/\psi \rho(\rightarrow \pi^+ \pi^-)$

$J^{PC}$ through angular analysis

- $1^{++}$
- $2^+$ a free complex parameter; one value gives an acceptable fit

$\rho \rightarrow \pi^+ \pi^-$ (with $\rho - \omega$ interference)
**X(3872)^+** existence?

Tetraquark model predicts the existence of isospin triplet: $X(3872)^+$

$$BR(B^+ \rightarrow X(3872)^+K^0) = 2 \times BR(B^0 \rightarrow X(3872)K^0)$$

- Reconstruct $X(3872)^+ \rightarrow J/\psi\pi^+\pi^0$
- No signal is seen
- UL (@90% CL) is provided

$$BR(B^0 \rightarrow X^+K^-) \times BR(X^+ \rightarrow \pi^+\pi^0J/\psi) < 3.9 \times 10^{-6}$$

No charged partner

$$BR(B^+ \rightarrow X^+K^0) \times BR(X^+ \rightarrow \pi^+\pi^0J/\psi) < 4.5 \times 10^{-6}$$

Rule out isospin triplet model?

Few tetraquark models predict $X(3872)^+$ to be broad, non-observed yet because of low statistics (?). If $X(3872)$ is tetraquark, then $X(3872)$ has C-odd partner which can dominantly decay into

$\checkmark \ X(3872)^c \rightarrow \chi_{c1}\gamma$

K. Terasaki, arXiv: 1107.5868v2

With full data sample

Maiani et al., PRD71, 014028(2005)

Belle, PRD 85,052004 (2011)

Maiani et al., PRD71, 014028(2005)
Belle Babar comparison

- BaBar used 1d UML fit to $m_{\text{miss}}$ and use $s$Plot to project signal in $m_X$
- We use 1d UML fit to $M_{\psi'\gamma}$ to extract yield

Raw distribution from Fulsom’s thesis

Plot projection in $m_X$ bins
Comparison of inclusive MC (+ non-ψ data sideband) with DATA

B^0 → ψ' K^{*0} 
B^+ → ψ' K^{*+} 

MC agrees quite well with Data.. No sign of signal........
Angular analysis carried by Belle and CDF suggest, \(X(3872)\)'s \(J^{PC}\) to be 1\(^{++}\) or 2\(^{--}\).

\(J^{PC} = 2^{+}\) hypothesis:
- \(BR(X(3872) \rightarrow \psi'\gamma)\) is expected to be suppressed (consistent with our U.L.).
- Disagrees with the BaBar’s measured \(BR(X(3872) \rightarrow \psi'\gamma)\).

\(J^{PC} = 1^{++}\) hypothesis:
- Our result can be explained using molecular or using c\(\bar{c}\) admixture (less in our case).
- In BaBar’s case, sizeable admixture of c\(\bar{c}\) is necessary in order to explain large \(BR(X(3872) \rightarrow \psi'\gamma)\).