Double ccbar Production at Belle

SooKyung Choi
Gyeongsang University
(For Belle collaboration)

Heavy Quarkonium 2006, June 29, BNL
\( e^+e^- \rightarrow J/\psi + (c\bar{c}) \)

- Reconstruct \( J/\psi \rightarrow l^+l^- \)
- the recoil mass against reconstructed \( J/\psi \) using two body kinematics with a known initial energy
  \[
  M_{\text{recoil}} = \sqrt{(E_{\text{cms}} - E_{J/\psi})^2 - P_{J/\psi}^2}
  \]
- \( X \) likely contains \( c\bar{c} \)
Belle’s first result

- 2002, Belle found large cross-sections for:
  (PRL89 142001 (2002))

- $e^+e^- \rightarrow J/\psi \ \eta_c$
- $e^+e^- \rightarrow J/\psi \ \chi_{c0}$
- $e^+e^- \rightarrow J/\psi \ \eta_c'$
Belle’s first result continued

- In addition, also observed associated production
  - $e^+e^- \rightarrow J/\psi \ D^{(*)+} \ X$
  - $e^+e^- \rightarrow J/\psi \ D^0 \ X$
- Immediately demonstrates large $e^+e^- \rightarrow J/\psi \ cc$ unlike theory prediction
- Based on LUND $cc \rightarrow D^{*+}/D^0$ fragmentation rates, calculated:

\[
\frac{\sigma(e^+e^- \rightarrow J/\psi cc)}{\sigma(e^+e^- \rightarrow J/\psi X)} = 0.59 \pm 0.14 \pm 0.12
\]
Theoretical predictions

- **Color-Singlet** $e^+e^- \rightarrow J/\psi$ $cc$ was estimated to be very small by *Kiselev et al.* (1994)
  - $\sigma \sim 0.05$ pb $\Rightarrow$ should be unobservable even at high luminosity B-factories

- **Color-octet** $e^+e^- \rightarrow (cc)^8$ g $\rightarrow J/\psi$ g (with $\langle O_n cc \rangle$ fixed to Tevatron and others data) should not be large as well (but can be significant around the end-point of $J/\psi$ momentum) *Braaten-Chen* (1996)

- **Color-Singlet** $e^+e^- \rightarrow J/\psi$ gg dominates! Predicted $\sigma_{CS} \sim 1-2$ pb *Cho-Leibovich* (1996)
Using more data

- Belle 2004: Full analysis of double charmonium production (PRD70 071102 (2004))
- Reconstructed charmonium:
  - $J/\psi$
  - $\psi(2S)$

$\mathcal{L} \sim 140 \text{fb}^{-1}$
Cross-sections

• Born cross-sections:

\[ \sigma^* \text{BR (recoil charmonium} \rightarrow \text{>2charged)} \]

<table>
<thead>
<tr>
<th>Reconstructed</th>
<th>( \eta_c )</th>
<th>( J/\psi )</th>
<th>( \chi_{c0} )</th>
<th>( \chi_{c1} + \chi_{c2} )</th>
<th>( \eta_c(2S) )</th>
<th>( \psi(2S) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J/\psi )</td>
<td>25.6±2.8±3.4</td>
<td>&lt;9.1</td>
<td>6.4±1.7±1.0</td>
<td>&lt;5.3</td>
<td>16.5±1.7±0.4</td>
<td>&lt;9.1</td>
</tr>
<tr>
<td>( \psi(2S) )</td>
<td>16.3±4.6±3.9</td>
<td>&lt;16.9</td>
<td>12.5±3.8±3.1</td>
<td>&lt;8.6</td>
<td>16.3±4.6±3.9</td>
<td>&lt;16.9</td>
</tr>
</tbody>
</table>

• Interesting:
  – Orbital excitations are not suppressed!
  – Only S,P states are seen recoiling to \( J/\psi \) (spin=1)!
Can theory accommodate this result

- The first NRQCD estimates:
  \[ R = \frac{\sigma_{J/\psi \eta_c}}{\sigma_{\mu \mu}} \sim \alpha_s^2 \left( \frac{m_c v}{E_{\text{beam}}} \right)^6 \]
  \[ \sigma(e^+e^- \rightarrow J/\psi \eta_c) = 2.3 \pm 1.1 \text{ fb.} \]
  (~10 times too low)

- Are there backgrounds from double photon annihilation \( e^+e^- \rightarrow J/\psi J/\psi \)?
  - Bodwin-Braaten-Lee 2003; confirmed by Liu-He-Chao, Brodsky-Ji-Lee

- Glueball?
  - Brodsky-Goldhabor-Lee
Calibrate recoil mass scale with $e^+e^- \rightarrow \gamma \psi' ; \psi' \rightarrow \pi^+\pi^- J/\psi$

This translates to $\delta M_x < 3 \text{ MeV}$ for $M_x \sim 3 \text{GeV}$. 

$$\Delta M^2_{\text{recoil}} = 0.010 \pm 0.009 \text{ GeV}$$

or $\Delta M^2_{\text{recoil}} < 0.024 \text{ GeV}^2/c^4$ at 90% CL (data w.r.t. MC)

$$\Delta M^2_{\text{recoil}}[\psi(2S)] = 0.025 \text{ GeV}$$ (in biased MC)
Include $e^+e^- \rightarrow J/\psi \ J/\psi$, etc in fit

\[
\begin{array}{cccc}
(c\bar{c})_{\text{res}} & N & M \ [\text{GeV}/c^2] & \text{Signif.} \ \sigma_{\text{Born}} \times B > 2 \ [\text{fb}] \\
\eta_c & 235 \pm 26 & 2.972 \pm 0.007 & 10.7 & 25.6 \pm 2.8 \pm 3.4 \\
J/\psi & -14 \pm 20 & \text{fixed} & \cdots & <9.1 \text{ at } 90\% \text{ CL} \\
\chi_{c0} & 89 \pm 24 & 3.407 \pm 0.011 & 3.8 & 6.4 \pm 1.7 \pm 1.0 \\
\chi_{c1} + \chi_{c2} & 10 \pm 27 & \text{fixed} & \cdots & <5.3 \text{ at } 90\% \text{ CL} \\
\eta_c(2S) & 164 \pm 30 & 3.630 \pm 0.008 & 6.0 & 16.5 \pm 3.0 \pm 2.4 \\
\psi(2S) & -26 \pm 29 & \text{fixed} & \cdots & <13.3 \text{ at } 90\% \text{ CL} \\
\end{array}
\]

\[\frac{\sigma(e+e- \rightarrow J/\psi cc)}{\sigma(e+e- \rightarrow J/\psi X)} = 0.82 \pm 0.15 \pm 0.14\]

Preliminary !!

(since 2003)
BaBar confirmation

- 2005, BaBar also see double charmonium events
  - $e^+e^- \rightarrow J/\psi \ \eta_c$
  - $e^+e^- \rightarrow J/\psi \ \chi_{c0}$
  - $e^+e^- \rightarrow J/\psi \ \eta_c'$

<table>
<thead>
<tr>
<th>$J/\psi \ c\bar{c}$</th>
<th>$\eta_c$</th>
<th>$\chi_{c0}$</th>
<th>$\eta_c(2S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle [PRD70, 071102]</td>
<td>$25.6 \pm 2.8 \pm 3.4$</td>
<td>$6.4 \pm 1.7 \pm 1.0$</td>
<td>$16.5 \pm 3.0 \pm 2.4$</td>
</tr>
<tr>
<td>BABAR [hep-ex/0506062]</td>
<td>$17.6 \pm 2.8^{+1.5}_{-2.1}$</td>
<td>$10.3 \pm 2.5^{+1.4}_{-1.8}$</td>
<td>$16.4 \pm 3.7^{+2.4}_{-3.0}$</td>
</tr>
<tr>
<td>Braaten, Lee [PRD 67, 054007]</td>
<td>$2.31 \pm 1.09$</td>
<td>$2.28 \pm 1.03$</td>
<td>$0.96 \pm 0.45$</td>
</tr>
<tr>
<td>Liu, He, Chao [hep-ph/0408141]</td>
<td>$5.5$</td>
<td>$6.9$</td>
<td>$3.7$</td>
</tr>
</tbody>
</table>
Angular analysis

\[ dN \left/ \frac{d\theta_{p,h}}{d\theta_{p,h}} \right. \sim (1+\alpha_{p,h} \cos^2\theta_{p,h}) \]

- Fit \( M_{\text{recoil}}(J/\psi) \) in bins of \( J/\psi \) production and helicity angles
- Correct efficiency
- Fit with \( \sim(1+\alpha \cos^2\theta) \)
No significant $J/\psi$ $J/\psi$ contamination to $J/\psi$ $\eta_c$ signal peak

• Mass scale correct
  – within +- 3MeV

• Angular distribution consistent with VP
New ideas?

- Need to solve an order of magnitude disagreement
  - *Kaydalov 2003*. NRQCD is wrong! Use instead Regge trajectories approach – tune free parameters from D meson production ⇒ get reasonable agreement for $e^+e^- \rightarrow J/\psi cc$ ($\sigma \sim 1$ pb) and **predict** ~10% of $J/\psi cc$ are double charmonium ($M_{cc} < 2M_D$)
  - *Bondar Chernyak 2005*. Try to save NRQCD! Light cone expansion formalism. Use wider wave functions. Manage to “predict” $\sigma (e^+e^- \rightarrow J/\psi \eta_c ) \sim 30$ fb
  - *Braguta Likhoded Luchinsky 2006*. Similar approach to *BC* applied for all final states: reasonable agreement

- All approaches are phenomenological. Need to predict something that can be checked.
New state
(hep-ex/0507019)

- Add more data and extend searching region above DD threshold
- New peak at $M \sim 3.9$ GeV, Temporary called $X(3940)$
- Two peaks are not excluded, but the second is not significant with the present statistics
- Significance $5.0 \sigma$
- $\Gamma = 39 \pm 26$ MeV ($< 93$ MeV @ 90% C.L.)
- $\sigma \times \text{Br}(X(3940) \rightarrow >2$ charged tracks) $= 10.6 \pm 2.5 \pm 2.4$ fb
X(3940) decays

- $X \rightarrow DD$ or $DD^*$?
  - Reconstruct $J/\psi$ & one $D$
  - See the $M_{\text{recoil}}(D J/\psi)$
  - Observe an unreconstructed $D$ & $D^*$
  - $D$ and $D^*$ are well separated $\sim 2.5\sigma$
$X(3940) \rightarrow DD^\ast$

- $X (3940) \rightarrow DD^\ast$:
  Clear peak
- $N = 24.5 \pm 6.9 \ (5.0\sigma)$
  $\Gamma = 15.1 \pm 10.1 \ \text{MeV}$
  $M = 3.943 \pm 0.006 \ \text{GeV}$

$B \ (X(3940) \rightarrow DD^\ast)$
$= (96^{+45}_{-32} \pm 22)\%$

- $X(3940) \rightarrow DD$: no signal
- $N = 0.2^{+4.4}_{-3.5} < 8.1$

$B \ (X(3940) \rightarrow DD) < 41\% @ 90 \ \text{C.L.}$
$X(3940) \rightarrow \omega J/\psi$

- **Reconstruct** $\omega$ & one $J/\psi$
- $N = 1.9^{+3.2}_{-2.4} < 7.6$ @90% C.L
- $B (X(3940) \rightarrow DD) < 41\%$ @ 90 C.L.
- $X(3940)$ doesn’t decay into $J/\psi$ $\omega$
Summary

• $e^+e^- \rightarrow J/\psi$ cc much higher than NRQCD predictions
• $e^+e^- \rightarrow J/\psi \, \eta_c$: NRQCD predicts 2.3 pb, Expt > 25.6 pb
• “Post”dictions from Bondar-Chernyak & Braguta Likhoded Luchinsky Seem to work
• Are these reasonable? Does NRQCD need modification
• New state seen @ $M=3943$ MeV
  – decays to DD*; not seen in DD or $\omega J/\psi$