Prompt $\chi_{c1}, \chi_{c2}$ and $X(3872)$ Production in $e^+e^-$ Annihilation

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Introduction

- We’ve heard a lot of exciting news about charmonium production in $e^+e^-$ annihilation so far from B-factories:
  - Prompt $J/\psi$ and $\psi(2S)$ production is observed.
  - Double charmonium production observed with $M_{\text{rec}}$ against $J/\psi$.
  - $X(3872)$, $Z(3930)$, $Y(3940)$, $Z(3940)$, and $Y(4260)$ observed
  - These are great tools to test NRQCD.

- Question:
  Why have $\chi_{c1}$ and $\chi_{c2}$ not been observed yet in the continuum?
  - In B decay, inclusive BF is 1.09% ($J/\psi$), 0.31% ($\psi(2S)$), 0.39%($\chi_{c1}$), 0.14%($\chi_{c2}$).
  - In $e^+e^-$ annihilation, $J/\psi$, $\psi(2S)$, $\chi_{c0}$ found but not $\chi_{c1}$, $\chi_{c2}$ yet.
  - Search for $\chi_{c1,2}$ with the dominant BF process $\gamma J/\psi$
    $\Rightarrow$ 36% for $\chi_{c1}$ and 20% for $\chi_{c2}$.

  **BELLE PRL2002 (33fb$^{-1}$)**

  $\sigma(e^+e^- \to \chi_{c1}X) < 0.35$ pb

  $\sigma(e^+e^- \to \chi_{c2}X) < 0.66$ pb

- Search for $X(3872) \rightarrow \gamma J/\psi$ in continuum.
  - $X(3872)$ observed in B-decay.
  - Take advantage of the machinery for $\chi_c$. 
**BaBar Data**

- **Peak Luminosity:** $1.21 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
- **Recorded:** 391 fb\(^{-1}\)
- **This talk based on:** 386 fb\(^{-1}\)

Data taking will resume in Jan 2007

(as of Oct 13, 2006)
• Double-charmonium MC ($\gamma^* \rightarrow \chi_c J/\psi$ or $\psi(2S)$) is used as our signal MC.

• To estimate signal detection efficiency inclusively, we use single $\chi_c$ and $X(3872)$ MC generated flat distribution over $\cos\theta^*$ and $p^*$ up to 5 GeV/c.

• The $\chi_c$ from B decays are used as a control sample to validate data-to-MC comparison.

• BB MC is used to estimate BB background.

• For the $X(3872)$ search, we take advantage of the $\chi_c$ study because of similar kinematics.
Event Selection (I)

- $N_{\text{ch}} > 4$ and $R_2 < 0.8$ to suppress QED type of backgrounds: ISR $\psi(2S)$ and two-photon fusion events.

- Qualified photon candidate must satisfy:
  - $A_{42} < 0.1$: $A_{42}$ measures the azimuthal asymmetry of the cluster about its peak, distinguishing electromagnetic from hadronic showers.
  - $0.01 < \text{LAT} < 0.5$: LAT is a measure of the radial energy profile of the cluster and is used to suppress clusters from electronic noise or hadronic interactions.
  - $0.41 < \theta < 2.41$: Photons in electromagnetic calorimeter fiducial volume (polar angle to the beam axis).
  - Reject $\gamma$ from $\pi^0$ if $M_{\pi^0} \in [0.114, 0.146]$ GeV with $E_{\gamma} = 30$ MeV, LAT < 0.8
  - Splitoff rejection by requiring at least 9° from any charged track.
Event Selection (II)

- $p^*(\chi_c, J/\psi) > 2.0$ GeV/c to suppress B-decay contribution.
- Electron id with radiation recovery. Muon identification.
- Geometric constraint on the $J/\psi$ vertex and $J/\psi$ mass constraint.
- $-0.05 < M_{ee} - M_{J/\psi} < 0.03$ GeV and $-0.03 < M_{\mu\mu} - M_{J/\psi} < 0.03$ GeV.
- $|\cos \theta_H(J/\psi)| < 0.9$

- $0.25 < \Delta M (M_{\chi\ell\ell} - M_{\ell\ell}) < 0.60$ GeV for the $\chi_c$ search
  - More efficient variable than $M_{\chi\ell\ell}$ to discriminate $\chi_{c1}$ from $\chi_{c2}$.

- $0.60 < \Delta M (M_{\chi\ell\ell} - M_{\ell\ell}) < 0.95$ GeV for the $X(3872)$ search
$\cos \theta_H(\chi_c) < 0.40$
- The figure of merit is $N_{\text{sig}}^2/(N_{\text{cont}}+N_{\text{BB}})$ for the individual cut.
- The optimized cut is not sensitive to the scale of $N_{\text{sig}}$. 

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Unbinned ML Fit

CBL Parameterization from MC.

<table>
<thead>
<tr>
<th>$e^+e^- \rightarrow \chi_c X$</th>
<th>$m$ (MeV)</th>
<th>$\sigma$ (MeV)</th>
<th>$\alpha$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c1}$</td>
<td>412.5</td>
<td>14.0</td>
<td>1.079</td>
<td>4.130</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>458.7</td>
<td>15.3</td>
<td>1.056</td>
<td>4.843</td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>773.0</td>
<td>20.5</td>
<td>0.984</td>
<td>5.003</td>
</tr>
</tbody>
</table>

- **Signal PDF**
  - Crystal Ball Line shape (CBL).
  - Mass difference between $\chi_c$ is constrained to PDG 2006 value, 45.5 MeV.
  - To account for possible energy scale or resolution difference between data and MC, mean is shifted by an offset and resolution is scaled by scale factor. It's tuned by our control sample (see the next page).

- **Background PDF**
  - 3rd order Chebyshev polynomial with all parameters floated.
  - For the purpose of systematic error study, Exponential function is used.

$$e^{-[p_0 + p_1(\Delta M) + p_2(\Delta M)^2]}$$
Control Sample

• To tune offset and scale, we performed an UML fit for the control sample, $\chi_c$ from B decays ($p^* < 1.7$ GeV/c).

• To cross check, $N(\chi_{c2})$ to $N(\chi_{c1})$ ratio is calculated and it is consistent with PDG2006.

• These values (offset and scale) will be used and fixed in the UML fit to search for $\chi_c$ and $X(3872)$ in continuum ($p^* > 2.0$ GeV/c).
Efficiency

\[ \epsilon = \epsilon_r \cdot \epsilon_v \cdot \epsilon_s \cdot f_{N_{trk}} \]

\( \epsilon_r \) : Reconstruction efficiency is estimated by single \( \chi_c \) MC.

\( \epsilon_v \) : Survival rate under \( \pi^0 \) veto

\( \epsilon_s \) : Survival rate under splitoff rejection

\( f_{N_{trk}} \) : Fraction of signal events that pass \( N_{trk} > 4 \) cut

(we assume \( f_{N_{trk}} = 1.0 \))
Reconstruction Efficiency ($\varepsilon_r$)

- The $\varepsilon_r$ depends on $p^*$ and $\cos\theta^*$ of $\chi_c$ because of $p^*(J/\psi) > 2.0$ GeV/c and lower coverage in endcap.

- We need to correct the single particle MC $\varepsilon_r$ using the weight matrix of $p^*$ and $\cos\theta^*$ and an efficiency matrix in bins of $p^*$ and $\cos\theta^*$.

$$\varepsilon_r = W_{1i}^{p^*} \varepsilon_{ij} W_{j1}^{\cos\theta^*} \quad i = 1, 6 \\
\quad j = 1, 5$$
\( \pi^0 \) veto efficiency \((\varepsilon_v)\)

- The \( \varepsilon_v \) is dependent on the number of photons in the event.
- We need:
  - The efficiency as a function of photon multiplicity \( \varepsilon_v (N_\gamma) \)
  - \( N_\gamma \) distribution of signal events.
- The \( \varepsilon_v \) is the weighted average of \( \varepsilon_v (N_\gamma) \) [weighted by the fraction of \( N_\gamma \)].
- Corrected by data-to-MC scale from the control sample (~ 1%).
- An alternative \( N_\gamma \) distribution (without sideband distribution) is used to estimate systematics.
Splitoff Rejection efficiency ($\varepsilon_s$)

- The $\varepsilon_s$ is dependent on the $N_{ch}$ in the event.
- We need:
  - The efficiency as a function of charged track multiplicity $\varepsilon_s(N_{ch})$
  - $N_{ch}$ distribution of signal events.
- The $\varepsilon_s$ is the weighted average of $\varepsilon_s(N_{ch})$ [weighted by the fraction of $N_{ch}$].
- Corrected by data-to-MC scale from the control sample (~ 0.4%).
- An alternative $N_{ch}$ distribution (w/o sideband distribution) is used to estimate systematics.
Systematic Error Study

ISR \( \psi(2S) \) background is estimated from MC as 9.5 ev for the \( \chi_{c1} \) and 3.0 ev for the \( \chi_{c2} \).

<table>
<thead>
<tr>
<th></th>
<th>( \chi_{c1} ) (%)</th>
<th>( \chi_{c2} ) (%)</th>
<th>( X(3872) ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p^<em>/\cos\theta^</em> ) correction</td>
<td>13.3</td>
<td>26.5</td>
<td>28.3</td>
</tr>
<tr>
<td>pdf</td>
<td>3.5</td>
<td>11.2</td>
<td>15.1</td>
</tr>
<tr>
<td>Tracking</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Charged PID</td>
<td>7.2</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Photon PID</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>( B_{\text{final}} )</td>
<td>5.4</td>
<td>5.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Background</td>
<td>7.1</td>
<td>5.4</td>
<td>-</td>
</tr>
<tr>
<td>( \pi^0 ) veto</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Splitoff rejection</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>18.1</td>
<td>30.7</td>
<td>33.1</td>
</tr>
</tbody>
</table>
Yields

UML fit for the continuum data (p* > 2.0 GeV/c)

- Offset and scale are fixed to the values from the control sample.
- For the $\chi_c$ search:
  \[ N_{\chi_{c1}} = 134^{+23}_{-22} \text{ with 6.6 } \sigma \text{ statistical significance} \]
  \[ N_{\chi_{c2}} = 56^{+19}_{-18} \text{ (< 80 @ 90% C.L.) with 3.2 } \sigma \text{ significance} \]

- For the $X(3872)$ search:
  \[ N_{X(3872)} = -8.0 \pm 11 \text{ (< 15 @ 90% C.L.)} \]

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\[ N_{\text{fit}} = \sigma \cdot \mathcal{L} \cdot \mathcal{B} \cdot \epsilon \]

\[ N_{\text{fit}}^{e^+e^-} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}(\chi_c \rightarrow \gamma J/\psi) \cdot \mathcal{B}(J/\psi \rightarrow e^+e^-) \cdot \epsilon_{e^+e^-} \]

\[ N_{\text{fit}}^{\mu^+\mu^-} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}(\chi_c \rightarrow \gamma J/\psi) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) \cdot \epsilon_{\mu^+\mu^-} \]

\[ N_{\text{fit}}^{e^+e^-} = N_{\text{fit}}^{e^+e^-} + N_{\text{fit}}^{\mu^+\mu^-} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}(\chi_c \rightarrow \gamma J/\psi) \cdot [\mathcal{B}(J/\psi \rightarrow e^+e^-) + \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)] \cdot \epsilon_{e^+e^-}^{\text{avg}} \]

| \( N_{\text{fit}} \) | \( \chi_c 1 \) & \( \chi_c 2 \) & \( X(3872) \) |
|-----------------|-----------------|-----------------|-----------------|
| \( \epsilon_r \) (%) | 10.1 & 9.3 & 8.4 |
| \( \epsilon_v \) (%) | 79.9 & 79.9 & 79.9 |
| \( \epsilon_s \) (%) | 95.8 & 95.8 & 95.8 |
| \( \epsilon \) (%) \( = \epsilon_r \cdot \epsilon_v \cdot \epsilon_s \) | 7.7 & 7.1 & 6.4 |
| \( \mathcal{B}_{\text{final}} \) (%) | 4.2 & 2.4 & 11.9 |
| \( \mathcal{L} \) \( \text{ (fb}^{-1}\) | 386 & 386 & 386 |

\[ \sigma(e^+e^- \rightarrow \chi_c X) \cdot \mathcal{B}(X \rightarrow (N_{ch} > 2)) \text{ (fb) \at90\% C.L.} \text{ (fb)} \]

107\pm18 \pm 19 & 85\pm28 \pm 26 & -2.7\pm3.7 \pm 1.0

For the \( X(3872) \), we assume BF of \( X(3872) \rightarrow \gamma J/\psi \) is 100%.
Prompt $\psi(2S)$ feed-down

For the cross-section of prompt $\chi_c$ production, we should subtract prompt $\psi(2S)$ contribution. It is

$$\begin{align*}
(58.3 \pm 11.6) \text{ fb for the } \chi_{c1} \\
(54.3 \pm 10.9) \text{ fb for the } \chi_{c2}
\end{align*}$$

compared to our measured values

$$\begin{align*}
(107 \pm 26) \text{ fb for } \chi_{c1} \text{ and } \\
(85 \pm 38) \text{ fb for } \chi_{c2}
\end{align*}$$

from

$$\begin{align*}
\sigma(e^+e^- \rightarrow \psi(2S)X) &= (0.67 \pm 0.13) \text{ pb for } p^* > 2.0 \text{ GeV/c} \\
B(\psi(2S) \rightarrow \gamma \chi_c) &= (8.7 \pm 0.4)\% \text{ for } \chi_{c1} \text{ and } (8.1 \pm 0.4)\% \text{ for } \chi_{c2}
\end{align*}$$

Belle PRL 2002

PDG 2006
Conclusion

After subtraction of prompt $\psi(2S)$ contribution, prompt $\chi_c$ production cross-sections in continuum are:

\[
\sigma(e^+e^- \rightarrow \chi_{c1,\text{direct}}X) \cdot B(X \rightarrow (N_{ch} > 2)) = (49 \pm 18 \pm 23) \text{ fb}
\]

\[
(< 86 \text{ fb} \ @90\% \ C.L.),
\]

\[
\sigma(e^+e^- \rightarrow \chi_{c2,\text{direct}}X) \cdot B(X \rightarrow (N_{ch} > 2)) = (31 \pm 28 \pm 28) \text{ fb}
\]

\[
(< 87 \text{ fb} \ @90\% \ C.L.).
\]

While $\chi_c$ production has been observed in $e^+e^-$ annihilation $\sim 10.6$ GeV, the measured cross-sections are compatible with the expected contributions from prompt $\psi(2S)$ production feed-down to $\chi_c$.

No evidence of prompt $\chi_c$ production.

Prompt $X(3872)$ production in continuum is:

\[
\sigma(e^+e^- \rightarrow X(3872)X) \cdot B(X(3872) \rightarrow \gamma J/\psi) \cdot B(X \rightarrow (N_{ch} > 2))
\]

\[
= (-2.7 \pm 3.7 \pm 1.0) \text{ fb} \quad (< 5.1 \text{ fb} \ @90\% \ C.L.).
\]

No evidence of prompt $X(3872)$ in $e^+e^-$ annihilation.