Measurement of $e^+e^- \rightarrow \gamma\chi_{cJ}$ via ISR at Belle Experiment

Yanliang Han

Shandong University

June 11, 2015
Motivation

Data Sample and Selection Rules

Backgrounds

Efficiency

$\psi(2S)$ branching fractions

High mass region study

Summary
Motivation

Data Sample and Selection Rules

Backgrounds

Efficiency

$\psi(2S)$ branching fractions

High mass region study

Summary
Motivation

The potential models predict five vector states

Figure: The charmonium $c\bar{c}$ [1]

Motivation

- The potential models predict five vector states
- Six vector states are discovered at Experiments.

Figure: The charmonium $c\bar{c}$ [1]

Motivation

- The potential models predict five vector states
- Six vector states are discovered at Experiments.
- The conventional $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$

Figure: The charmonium $c\bar{c}$ [1]

Motivation

▶ The potential models predict five vector states

Figure: The charmonium $c\bar{c}$ [1]

▶ Six vector states are discovered at Experiments.
▶ The conventional $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$


Figure: Invariant mass of $\pi^+\pi^- J/\psi$, Y(4260) [2]
Motivation

- The potential models predict five vector states

Figure: The charmonium $c\bar{c}$ [1]

- Six vector states are discovered at Experiments.
- The conventional $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$


Figure: Invariant mass of $\pi^+\pi^-\psi(2S)$, $Y(4360)$ $Y(4660)$ [3]
Motivation

- The potential models predict five vector states
- Six vector states are discovered at Experiments.

Some of these states show unusual properties: Maybe exotic states.

\[
e^+ e^- \rightarrow \gamma \chi_c J \text{ via ISR, } \chi_c J \rightarrow \gamma J/\psi, \quad J/\psi \rightarrow \mu^+ \mu^-\]

\[
\frac{5}{32}
\]
Motivation

- The potential models predict five vector states
- Six vector states are discovered at Experiments.

Some of these states show unusual properties: Maybe exotic states.
- Y(4260), Y(4360) did not show up in hadronic R inclusive scan
Motivation

- The potential models predict five vector states
- Six vector states are discovered at Experiments.

Some of these states show unusual properties: Maybe exotic states.
- Y(4260), Y(4360) did not show up in hadronic R inclusive scan
- Large dipion transitions rate than conventional charmonium.
Motivation

- The potential models predict five vector states
- Six vector states are discovered at Experiments.

Some of these states show unusual properties: Maybe exotic states.

- $Y(4260), Y(4360)$ did not show up in hadronic R inclusive scan
- Large dipion transitions rate than conventional charmonium.

It is important to investigate them using much larger data samples and new decay channels.
Motivation

- The potential models predict five vector states
- Six vector states are discovered at Experiments.

Some of these states show unusual properties: Maybe exotic states.
- Y(4260), Y(4360) did not show up in hadronic R inclusive scan
- Large dipion transitions rate than conventional charmonium.

It is important to investigate them using much larger data samples and new decay channels.
- Full Belle data sample
Motivation

- The potential models predict five vector states
- Six vector states are discovered at Experiments.

Some of these states show unusual properties: Maybe exotic states.
- Y(4260), Y(4360) did not show up in hadronic R inclusive scan
- Large dipion transitions rate than conventional charmonium.

It is important to investigate them using much larger data samples and new decay channels.
- Full Belle data sample
- Radiative transitions: $e^+ e^- \rightarrow \gamma \chi_{cJ}$ via ISR, $\chi_{cJ} \rightarrow \gamma J/\psi$, $J/\psi \rightarrow \mu^+ \mu^-$
Motivation

Data Sample and Selection Rules

Backgrounds

Efficiency

\( \psi(2S) \) branching fractions

High mass region study

Summary
Data and MC Samples

DATA
- Full Belle data sample, integrated luminosity is 980 fb$^{-1}$.

MC Samples
- EVTGEN with the VECTORISR model is used to simulate the signal process $e^+e^- \rightarrow \gamma_{ISR} V \rightarrow \gamma_{ISR} \gamma \chi_{cJ} \rightarrow \gamma_{ISR} \gamma \gamma J/\psi$
- Background MC samples are generated with PHOKHARA
Event selection

- Two good charged tracks with zero net charge
Event selection

- Two good charged tracks with zero net charge
- Muon identification is required
Event selection

- Two good charged tracks with zero net charge
- Muon identification is required
- Two highest energy photons (Non ISR) in the lab. system

\[ \eta(\pi^0) J/\psi \] events are rejected

\[ M(\gamma\gamma) > 0.20 \text{ GeV}/c^2 \] to reject \( \pi^0 \) and other low invariant mass events
Event selection

- Two good charged tracks with zero net charge
- Muon identification is required
- Two highest energy photons (Non ISR) in the lab. system
- Reject $\eta(\pi^0)J/\psi$ events
  - $M(\gamma\gamma)$ are not in the $\eta$ mass region $[0.50, 0.58]$ GeV/$c^2$
  - $M(\gamma\gamma) > 0.20$ GeV/$c^2$ to reject $\pi^0$ and other low invariant mass events
Missing Mass Square

Defined as $M_{\text{rec}}^2 = (P_{e^+e^-} - P_{\gamma\gamma\mu^+\mu^-})^2$

Figure: MMS distribution with $M(\gamma_l\gamma_h J/\psi) < 5.56$ GeV/$c^2$

Here $M(\gamma_l\gamma_h J/\psi) = M(\gamma_l\gamma_h \mu^+\mu^-) - M(\mu^+\mu^-) + m_{J/\psi}$

We require: $-1$ (GeV/$c^2)^2 < M_{\text{rec}}^2 < 2$ (GeV/$c^2)^2$
Invariant mass of $\mu^+\mu^-$

**Figure:** Invariant mass distribution of $\mu^+\mu^-$. The shaded area in the middle is the $J/\psi$ signal region, and the shaded regions on both sides are the $J/\psi$ mass sidebands.

- **$J/\psi$ signal region:** Within $\pm 45$ MeV/$c^2$ of the $J/\psi$ mass
Invariant mass of $\gamma J/\psi$

Including $M(\gamma_h J/\psi)$ and $M(\gamma_l J/\psi)$, two entries per event

Figure: Invariant mass distribution of $\gamma J/\psi$ for candidate events with
$M(\gamma_l, \gamma_h J/\psi) < 5.56 \text{ GeV}/c^2$. The shaded histograms show the
$\chi_{c1}$ ([3.48, 3.535] GeV$/c^2$) and $\chi_{c2}$ ([3.535, 3.58] GeV$/c^2$) regions.
Motivation

Data Sample and Selection Rules

Backgrounds

Efficiency

\( \psi(2S) \) branching fractions

High mass region study

Summary
Potential background

▶ Non $J/\psi$ background. This can be estimated by $J/\psi$ sideband
Potential background

- Non $J/\psi$ background. This can be estimated by $J/\psi$ sideband
- $e^+ e^- \rightarrow \gamma_{\text{ISR}} J/\psi$
  - This cross section can be calculated theoretically
Potential background

- Non $J/\psi$ background. This can be estimated by $J/\psi$ sideband

- $e^+ e^- \rightarrow \gamma_{\text{ISR}} J/\psi$
  - This cross section can be calculated theoretically

- $e^+ e^- \rightarrow \gamma_{\text{ISR}} \pi^0 \pi^0 J/\psi$
  - $\sigma(e^+ e^- \rightarrow \pi^0 \pi^0 J/\psi) = \frac{1}{2} \sigma(e^+ e^- \rightarrow \pi^+ \pi^- J/\psi)$
  - $\sigma(e^+ e^- \rightarrow \pi^+ \pi^- J/\psi)$ can be got from [1]

Potential background

- Non $J/\psi$ background. This can be estimated by $J/\psi$ sideband
- $e^+e^- \to \gamma_{\text{ISR}} J/\psi$
  - This cross section can be calculated theoretically
- $e^+e^- \to \gamma_{\text{ISR}} \pi^0\pi^0 J/\psi$
  - $\sigma(e^+e^- \to \pi^0\pi^0 J/\psi) = \frac{1}{2}\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$
  - $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ can be got from [1]
- $e^+e^- \to \gamma_{\text{ISR}} \eta J/\psi$
  - $\sigma(e^+e^- \to \eta J/\psi)$ can be got from [2]


Potential background

- Non $J/\psi$ background. This can be estimated by $J/\psi$ sideband
  - $e^+ e^- \rightarrow \gamma_{\text{ISR}} J/\psi$
    - This cross section can be calculated theoretically
  - $e^+ e^- \rightarrow \gamma_{\text{ISR}} \pi^0 \pi^0 J/\psi$
    - $\sigma(e^+ e^- \rightarrow \pi^0 \pi^0 J/\psi) = \frac{1}{2} \sigma(e^+ e^- \rightarrow \pi^+ \pi^- J/\psi)$
  - $\sigma(e^+ e^- \rightarrow \pi^+ \pi^- J/\psi)$ can be got from [1]
  - $e^+ e^- \rightarrow \gamma_{\text{ISR}} \eta J/\psi$
    - $\sigma(e^+ e^- \rightarrow \eta J/\psi)$ can be got from [2]
  - $e^+ e^- \rightarrow \gamma_{\text{ISR}} \psi(2S)$ at high mass region


Motivation

Data Sample and Selection Rules

Backgrounds

Efficiency

$\psi(2S)$ branching fractions

High mass region study

Summary
Efficiency

There is only one ISR photon generated in \textsc{EVTGEN}. The efficiency will be over-estimated. We need to correct this.

- \textsc{PHOKHARA} can be used to generate $e^+e^- \to \gamma_{\text{ISR}}\eta J/\psi$ with one or two ISR photons.
- \textsc{EVTGEN} can also generate $e^+e^- \to \gamma_{\text{ISR}}\eta J/\psi$
- The difference is used to correct the ISR effect

The process $\psi(2S) \to \gamma \chi_{cJ} \to \gamma \gamma J/\psi$ is dominated by ”E1” transition, with some mixing of ”M2” and ”E3”. The photon angular distribution is given in [1]. This is also considered by assuming that all ISR photons is emitted from initial electrons.

Efficiency curve and $\gamma\gamma J/\psi$ mass

Figure: Invariant mass distributions of $\gamma\chi_{cJ}$ candidates. Shown from top to bottom are $\gamma\chi_{c1}$, $\gamma\chi_{c2}$, and their sum.
Motivation

Data Sample and Selection Rules

Backgrounds

Efficiency

$\psi(2S)$ branching fractions

High mass region study

Summary
\( \psi(2S) \rightarrow \gamma \chi_{cJ} \) branching fractions

\( \psi(2S) \) signal region: \( 3.65 < M(\gamma \gamma J/\psi) < 3.72 \text{ GeV}/c^2 \).

The fit gives 340 ± 20 \( \chi_{c1} \) and 97 ± 12 \( \chi_{c2} \) signal events.

- \( \sigma[e^+e^- \rightarrow \gamma_{\text{ISR}}\psi(2S)] = (14.25 \pm 0.26) \text{ pb} \)
- \( \mathcal{L} = 980 \text{ fb}^{-1} \)
- \( \epsilon_{\chi_{c1}} = 1.4\%, \epsilon_{\chi_{c2}} = 0.7\% \)

\( B[\psi(2S) \rightarrow \gamma \chi_{c1} \rightarrow \gamma \gamma J/\psi] = (2.92 \pm 0.19)\% \)

\( B[\psi(2S) \rightarrow \gamma \chi_{c2} \rightarrow \gamma \gamma J/\psi] = (1.65 \pm 0.21)\% \)

PDG14 gives 2.93 ± 0.15 and 1.52 ± 0.15
Motivation

Data Sample and Selection Rules

Backgrounds

Efficiency

$\psi(2S)$ branching fractions

High mass region study

Summary
High mass region study

The high mass region: \( M(\gamma\gamma J/\psi) \in [3.8, 5.56] \text{ GeV}/c^2 \)

There is no obvious signals, upper limits are given.
Cross section upper limit

We first construct the likelihood function \( L(N_{\chi c_1}, N_{\chi c_2}) \) for the number of produced events. Using \( L(N_{\chi c_1}, N_{\chi c_2}) \), upper limit of \( N_{\chi c_1} \) and \( N_{\chi c_2} \) at 90% C.L. can be got. And then the upper limit of \( \sigma(e^+e^- \rightarrow \gamma\chi_{cJ}) \).

Figure: Measured upper limits on the \( e^+e^- \rightarrow \gamma\chi_{cJ} \) cross sections at the 90% C.L. for \( \chi_{c1} \) (top) and \( \chi_{c2} \) (bottom).
Transition rate of charmonium to $\gamma \chi_{cJ}$

We can fit the mass spectrum of $\gamma\gamma J/\psi$ to get transition rate of the vector charmonium to $\gamma \chi_{cJ}$.

- One Breit-Wigner function as the signal and a linear function as the background
- The mass and total width are fixed
- $\Gamma_{ee} \times B(R \rightarrow \gamma \chi_{cJ})$ is scanned to obtain the p.d.f.

<table>
<thead>
<tr>
<th></th>
<th>$\chi_{c1}$ (eV)</th>
<th>$\chi_{c2}$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{ee}[\psi(4040)] \times B[\psi(4040) \rightarrow \gamma \chi_{cJ}]$</td>
<td>2.9</td>
<td>4.6</td>
</tr>
<tr>
<td>$\Gamma_{ee}[\psi(4160)] \times B[\psi(4160) \rightarrow \gamma \chi_{cJ}]$</td>
<td>2.2</td>
<td>6.1</td>
</tr>
<tr>
<td>$\Gamma_{ee}[\psi(4415)] \times B[\psi(4415) \rightarrow \gamma \chi_{cJ}]$</td>
<td>0.47</td>
<td>2.3</td>
</tr>
<tr>
<td>$\Gamma_{ee}[Y(4260)] \times B[Y(4260) \rightarrow \gamma \chi_{cJ}]$</td>
<td>1.4</td>
<td>4.0</td>
</tr>
<tr>
<td>$\Gamma_{ee}[Y(4360)] \times B[Y(4360) \rightarrow \gamma \chi_{cJ}]$</td>
<td>0.57</td>
<td>1.9</td>
</tr>
<tr>
<td>$\Gamma_{ee}[Y(4660)] \times B[Y(4660) \rightarrow \gamma \chi_{cJ}]$</td>
<td>0.45</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Upper limits on branching fractions

Taking $\Gamma_{ee}[\psi(4040)]$ and $\Gamma_{ee}[\psi(4415)]$ from the world average values and $\Gamma_{ee}[\psi(4160)]$ from the BES II measurement.

Table: Upper limits on branching fractions $B(R \rightarrow \gamma \chi_{cJ})$ at the 90% C.L.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\gamma \chi_{c1} \ (10^{-3})$</th>
<th>$\gamma \chi_{c2} \ (10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi(4040)$</td>
<td>3.4</td>
<td>5.5</td>
</tr>
<tr>
<td>$\psi(4160)$</td>
<td>6.1</td>
<td>16.2</td>
</tr>
<tr>
<td>$\psi(4415)$</td>
<td>0.83</td>
<td>3.9</td>
</tr>
</tbody>
</table>
**Upper limits on branching fractions ratio**

Taking $\Gamma_{ee}[Y(4260)] \times B[Y(4260) \rightarrow \pi^+\pi^- J/\psi] = (6.4 \pm 0.8 \pm 0.6) \text{ eV}$ or $(20.5 \pm 1.4 \pm 2.0) \text{ eV}$ [1]

$\Gamma_{ee}[Y(4360)] \times B[Y(4360) \rightarrow \pi^+\pi^- \psi(2S)] = (10.4 \pm 1.7 \pm 1.4) \text{ eV}$ or $(11.8 \pm 1.8 \pm 1.4) \text{ eV}$ [2]

$\Gamma_{ee}[Y(4660)] \times B[Y(4660) \rightarrow \pi^+\pi^- \psi(2S)] = (3.0 \pm 0.9 \pm 0.3) \text{ eV}$ or $(7.6 \pm 1.8 \pm 0.8) \text{ eV}$ [2]

**Table:** Upper limits on branching fraction ratios at the 90% C.L.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\gamma \chi_{c1}$</th>
<th>$\gamma \chi_{c2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B[Y(4260) \rightarrow \gamma \chi_{cJ}] / B[Y(4260) \rightarrow \pi^+\pi^- J/\psi]$</td>
<td>0.3 or 0.07</td>
<td>0.7 or 0.2</td>
</tr>
<tr>
<td>$B[Y(4360) \rightarrow \gamma \chi_{cJ}] / B[Y(4360) \rightarrow \pi^+\pi^- \psi(2S)]$</td>
<td>0.06 or 0.05</td>
<td>0.2 or 0.2</td>
</tr>
<tr>
<td>$B[Y(4660) \rightarrow \gamma \chi_{c1}] / B[Y(4660) \rightarrow \pi^+\pi^- \psi(2S)]$</td>
<td>0.2 or 0.07</td>
<td>0.9 or 0.3</td>
</tr>
</tbody>
</table>


Systematic uncertainty

- Tracking efficiency: 0.35% per track
- Particle identification: 1.9%
- $J/\psi$ and $\chi_{cJ}$ mass: 1.0% and 1.3%
  - Estimate with $\psi(2S) \rightarrow \gamma \chi_{cJ}$
- Generator
  - Corrected with $e^+e^- \rightarrow \eta J/\psi$, The difference 9.0% between measured $B$ and PDG14 is taken
    - EVTGEN: 1.0%
    - Statistical error of the MC samples: 2.0%
- Luminosity: 1.4%
- Trigger: 2%
- Branching fractions of the intermediate states: 4.5%

Assuming that all these systematic error sources are independent, the total systematic error is 13.4%. 
Motivation

Data Sample and Selection Rules

Backgrounds

Efficiency

$\psi(2S)$ branching fractions

High mass region study

Summary
Summary

- The process $e^+e^- \rightarrow \gamma_{ISR}\gamma\chi_{cJ}$ is studied using full Belle data sample
- There is no obvious $\gamma\chi_{cJ}$ signal at high mass region
- The analysis is validated with branching fraction of $B[\psi(2S) \rightarrow \gamma\chi_{cJ} \rightarrow \gamma\gamma J/\psi)]$
- Cross section upper limit of $e^+e^- \rightarrow \gamma\chi_{cJ}$ is set at 90% C.L. between $\sqrt{s} = 3.8$ to 5.56 GeV
- Upper limits on the decay rate of the vector charmonium $[\psi(4040), \psi(4160), \text{and } \psi(4415)]$ and charmoniumlike $[Y(4260), Y(4360), \text{and } Y(4660)]$ states to $\gamma\chi_{cJ}$ is also set at 90% C.L.
Thank You!
Backup
Event selection

- Two good charged tracks with zero net charge
  - $P_T > 0.1$ GeV/c
  - $|dr| < 0.5$ cm, $|dz| < 5.0$ cm for charged tracks
- Muon identification is required
  - One track should satisfy $R_\mu = \frac{L_\mu}{L_\mu + L_\pi} > 0.95$
  - If $R_\mu = 0$ for one track, $|\cos \theta_\mu| < 0.75$ is required for each track
- A photon candidate does not match any charged tracks
  - Photons with $E_\gamma > 3$ GeV in $e^+e^-$ CM will be labeled as ISR photon (Excluded)
  - $E_\gamma > 0.25$ GeV in lab. system
  - Two highest energy photons in the laboratory system
- Reject $\eta(\pi^0)J/\psi$ events
  - $M(\gamma\gamma)$ are not in the $\eta$ mass region [0.50, 0.58] GeV/c$^2$
  - $M(\gamma\gamma) > 0.20$ GeV/c$^2$ to reject $\pi^0$ and other low invariant mass events
Invariant mass of $\gamma_l\gamma_h J/\psi$

**Figure:** Invariant mass distribution of $\gamma_l\gamma_h J/\psi$. The background from the tail of the $\psi(2S)$ is plotted only for $M(\gamma_l\gamma_h J/\psi) > 3.75$ GeV/$c^2$ and $M(\gamma_l\gamma_h J/\psi) < 3.65$ GeV/$c^2$. 
Cross section upper limit

Maximum likelihood is used to get the upper limits.

The numbers of the expected signal events, $\nu^{\chi c_1}$ and $\nu^{\chi c_2}$

$$
\left( \begin{array}{c}
\nu^{\chi c_1} \\
\nu^{\chi c_2}
\end{array} \right) =
\left( \begin{array}{cc}
\epsilon_{11} & \epsilon_{21} \\
\epsilon_{12} & \epsilon_{22}
\end{array} \right)
\left( \begin{array}{c}
N^{\chi c_1} \times B(\chi c_1 \rightarrow \gamma J/\psi) \times B(J/\psi \rightarrow \mu^+ \mu^-) \\
N^{\chi c_2} \times B(\chi c_2 \rightarrow \gamma J/\psi) \times B(J/\psi \rightarrow \mu^+ \mu^-)
\end{array} \right)
$$

The numbers of expected events

$$
\left( \begin{array}{c}
\mu^{\chi c_1} \\
\mu^{\chi c_2}
\end{array} \right) =
\left( \begin{array}{c}
\nu^{\chi c_1} \\
\nu^{\chi c_2}
\end{array} \right) +
\left( \begin{array}{c}
 n^{\chi c_1}_{\text{bkg}} \\
 n^{\chi c_2}_{\text{bkg}}
\end{array} \right),
$$

The probability of observing $(n^{\chi c_1}_{\text{obs}}, n^{\chi c_2}_{\text{obs}})$

$$
p(N^{\chi c_1}, N^{\chi c_2}) = 
\frac{(\mu^{\chi c_1})^{n^{\chi c_1}_{\text{obs}}} e^{-\mu^{\chi c_1}}}{n^{\chi c_1}_{\text{obs}}!}
\times 
\frac{(\mu^{\chi c_2})^{n^{\chi c_2}_{\text{obs}}} e^{-\mu^{\chi c_2}}}{n^{\chi c_2}_{\text{obs}}!}
$$

Considering the uncertainty in the background estimation and systematic error

$$
L(N^{\chi c_1}, N^{\chi c_2}) = \sum_{k,l,m,n} p(N^{\chi c_1}, N^{\chi c_2}) =
\sum_{k,l,m,n} \frac{(\mu^{\chi c_1})^{n^{\chi c_1}_{\text{obs}}} e^{-\mu^{\chi c_1}_{k,l}}}{n^{\chi c_1}_{\text{obs}}!}
\times 
\frac{(\mu^{\chi c_2})^{n^{\chi c_2}_{\text{obs}}} e^{-\mu^{\chi c_2}_{m,n}}}{n^{\chi c_2}_{\text{obs}}!}
$$