Charmonium and charmonium-like results from $\textit{BaBar}$

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On behalf of the $\textit{BaBar}$ Collaboration

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Introduction

Search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ states in $\bar{B}^0 \rightarrow \chi_{c1} K^- \pi^+$ and $B^+ \rightarrow \chi_{c1} K^0_s \pi^+$ PRD 85, 052003 (2012)

Study of the $J/\psi \omega$ final state in two-photon collisions

Search for resonances decaying into $\eta_c \pi^+ \pi^-$ using two-photon interactions

Study of the reaction $e^+ e^- \rightarrow J/\psi \pi^+ \pi^-$ via initial-state radiation

Summary
Experimental methods for charmonium production at the B-factories

**B meson decays**

\[ b \rightarrow c \bar{c} \]

States of any quantum numbers can be produced

**Two-photon production**

\[ e^- \rightarrow \bar{c} \]

J-even charmonium states can be produced

**Initial State Radiation (ISR)**

\[ e^- \rightarrow J/\psi, \psi' \]

Only states with \( J^{PC} = 1^- \) can be produced

**Double charmonium production**

\[ e^- \rightarrow J/\psi, \psi' \]

Only charmonium states with \( C = +1 \) are allowed to be produced in association with the \( J/\psi \) or the \( \psi(2S) \)
Below the $D\bar{D}$ threshold, all expected states have been observed, with properties in good agreement with theory; there are no additional states.

Many unexpected states have been reported above the $D\bar{D}$ threshold, seemingly too many with $J^{PC} = 1^{--}$

These result mainly from Belle and BABAR, with significant contributions also from CDF, D0 and CLEO.
Search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ states in

$\bar{B}^0 \rightarrow \chi_{c1} K^- \pi^+$ and $B^+ \rightarrow \chi_{c1} K_s^0 \pi^+$ (429 fb$^{-1}$)

PRD 85, 052003 (2012)
Search for the $Z_1(4050)^+$ and $Z_2(4250)^+ - $ Motivation

- Belle reported $Z_1(4050)^+$ and $Z_2(4250)^+$ decay to $\chi_{c1}\pi^+$ in $\bar{B}^0 \to \chi_{c1}K^-\pi^+$ (PRD 78, 072004 (2008))
- Belle reports of $Z(4430)^- \to \psi(2S)\pi^-$ in $B^{-,0} \to \psi(2S)\pi^-K^{0,+}$ (PRL 100, 142001 (2008), PRD 80, 031104(R) (2009)) were not confirmed by BABAR (PRD 79, 112001 (2009)); in the latter, no structure was observed in the $J/\psi\pi^-$ system for the corresponding $B^{-,0} \to J/\psi\pi^-K^{0,+}$ decay processes.
- These reports have generated much theoretical, and experimental, discussion since such charged charmonium-like states must have four-quark content at minimum.

As a consequence, we search for $Z_1(4050)^+$ and $Z_2(4250)^+$ decay to $\chi_{c1}\pi^+$ in $\bar{B}^0 \to \chi_{c1}K^-\pi^+$ and also in $B^+ \to K_s^0\chi_{c1}\pi^+$ where $\chi_{c1} \to J/\psi\gamma$

- We project the $K\pi$ mass distribution and its Legendre polynomial angular dependence in terms of S-, P-, and D-wave amplitudes onto the $\chi_{c1}\pi^+$ mass distribution and search for corroboration of the Belle report of additional resonant structure(s).
Search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ - Analysis procedure I

- The $K\pi$ data are background-subtracted and efficiency-corrected → interference terms absent from mass projection.
- Fit with a sum of S-, P-, and D-wave intensity contributions.

<table>
<thead>
<tr>
<th>Channel</th>
<th>S-wave</th>
<th>P-wave</th>
<th>D-wave</th>
<th>$\chi^2$/NDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{B}^0 \to \chi_{c1}K^-\pi^+$</td>
<td>40.4 ± 2.2</td>
<td>37.9 ± 1.3</td>
<td>11.4 ± 2.0</td>
<td>58/54</td>
</tr>
<tr>
<td>$B^+ \to \chi_{c1}K^0_S\pi^+$</td>
<td>42.4 ± 3.5</td>
<td>37.1 ± 3.2</td>
<td>10.1 ± 3.1</td>
<td>55/54</td>
</tr>
</tbody>
</table>

- Very good agreement between the $\bar{B}^0$ and $B^+$ fractions.
- Much larger S-wave contribution than for $J/\psi$ and $\psi(2S)$.
- Fits improved by the inclusion of a $K_1^*(1680)$ contribution (2nd row in P-wave column); not present for $J/\psi$ and $\psi(2S)$.

Charmonium and charmonium-like results from BABAR

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- The moments are background-subtracted and efficiency-corrected.
- The moments are for $\bar{B}^0$ and $B^+$ data combined since the intensity fractions agree and the $\bar{B}^0$ and $B^+$ moments are consistent.
- The combined data sample contains about the same number of events as the Belle $\chi_{c1}$ sample from $\bar{B}^0$ decay.
- The $<Y_L^0>$ moments for $L \geq 6$ are consistent with zero; the presence of narrow structure(s) in the $\chi_{c1}\pi^+$ mass distribution would be expected to result in higher $<Y_L^0>$ moment contributions (from MC studies).
We use a linear interpolation of the $< Y^0_L >$ moments for $L \leq 5$ to describe the $K\pi$ angular structure and, in conjunction with the fit to the $K\pi$ mass distribution, create the reflection onto the $\chi_{c1}\pi^+$ mass distribution.

- The dashed curve indicates the projection for a flat $K\pi$ angular distribution.
- The solid curve is obtained by using the interpolation of the moments up to $< Y^0_5 >$; the excellent description of the data indicates that there is no need for additional narrow structure(s) in the mass distribution.
- We quantify the latter by adding $Z_1$ and $Z_2$ Breit-Wigner intensity contributions (or a $Z$ BW intensity contribution) to our unnormalized $K\pi$ reflection, in a fit to the data; the $Z$ parameter values are fixed to those in the Belle paper.
Search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ - Results

In every case, low ($\leq 2\sigma$) significance is obtained.

Upper limits at 90% C.L.

\[ B(\bar{B}^0 \rightarrow Z_1^+ K^-) \times B(Z_1^+ \rightarrow \chi_{c1} \pi^+) < 1.8 \times 10^{-5} \]

\[ B(\bar{B}^0 \rightarrow Z_2^+ K^-) \times B(Z_2^+ \rightarrow \chi_{c1} \pi^+) < 4.0 \times 10^{-5} \]

\[ B(\bar{B}^0 \rightarrow Z^+ K^-) \times B(Z^+ \rightarrow \chi_{c1} \pi^+) < 4.7 \times 10^{-5} \]

Charmonium and charmonium-like results from BABAR
Study of the $J/\psi\,\omega$ final state in two-photon collisions (519 fb$^{-1}$)
Confirm the $X(3915)$ and search for the $X(3872)$.

<table>
<thead>
<tr>
<th>$X(3915)$</th>
<th>$X(3872)$</th>
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</table>
| - The $X(3915)$ was seen by both Belle [1] and [2] in $B \rightarrow X(3915)K$, with $X(3915) \rightarrow J/\psi \omega$
| - The $X(3872) \rightarrow J/\psi \omega$ was seen in $B$ decays by both BABAR and Belle experiment. |
| - Belle also observed the $X(3915)$ in $\gamma \gamma \rightarrow X(3915) \rightarrow J/\psi \omega$ [3]
| - The possible $X(3872)$ quantum numbers could be $J^{PC}=1^{++}$ or $J^{PC}=2^{--}$ [4]. |
| - Interpretation of $X(3915)$ as the $\chi_{c0}(2P)$ or $\chi_{c2}(2P)$ state has been suggested.
| - $\gamma \gamma \rightarrow X(3872)$ would imply $J^{PC}=2^{--}$ 
| - $\gamma \gamma \rightarrow X(3872)$ is not seen in Belle’s spectrum. |

γγ → J/ψ ω - Results

Results are consistent with Belle's:
(PRL 104, 092001 (2010))

New limit: \( \Gamma_{γγ}(X(3872)) × B(X(3872) → J/ψ ω)(J = 2) < 1.7 \text{ eV} \)

The mass and width values are slightly smaller than those obtained by Belle and BABAR for the \( \chi_{c2}(2P) \) from \( γγ → D̄D \).
Search for resonances decaying into $\eta_c \pi^+ \pi^-$ using two-photon interactions (474 fb$^{-1}$)
γγ → η_c π^+ π^- - Motivation

- **Look for the process**: γγ → X → η_c(1S)π^+ π^- where X stands for one of the resonances χ_{c2}(1P), η_c(2S), X(3872), X(3915) or χ_{c2}(2P), where
  η_c(1S) → K_s^0 K^\pm \pi^\mp \text{ and } K_s^0 → π^+ π^-

- **Measure branching fractions** for the decay of the states χ_{c2}(1P), η_c(2S), X(3872), X(3915) and χ_{c2}(2P) to η_c(1S)π^+ π^-

- **Prediction** for $B(η_c(2S) → η_c(1S)π^+ π^-) \sim 2.2\%$
  obtained from $Γ(η_c(2S) → η_c(1S)π^+ π^-)/Γ(ψ(2S) → J/ψπ^+ π^-) \sim 2.9$
  (M.B.Voloshin Mod.Phys.Lett A 17, 1533 (2002))
The extraction of the signal yield proceeds in two steps:

- Step 1: determine the values of the $m(K^0_s K^\pm \pi^\mp)$ distribution parameters for the combinatoric background from a one-dimensional fit to $m(K^0_s K^\pm \pi^\mp)$

- Step 2: perform a two-dimensional fit in $m(K^0_s K^\pm \pi^\mp)$ and $m(K^0_s K^\pm \pi^\mp \pi^+ \pi^-)$ in a window around each resonance of interest.

- Event types in 2D fit:
  - Signal (i.e. decay to $\eta_c(1S)\pi^+ \pi^-$)
  - Combinatoric background
  - Direct decay (i.e. signal in $m(K^0_s K^\pm \pi^+ \pi^-)$, but $K^0_s K^\pm \pi^\mp$ not from $\eta_c(1S)$ decay)
  - $\eta_c$-peaking background (peaks in $m(K^0_s K^\pm \pi^\mp)$ but no 5-body signal)
$\gamma\gamma \rightarrow \eta_c \pi^+ \pi^-$ - Results

The two-dimensional fit is carried out separately in the region of each X state
($\chi_c(1P)$, $\eta_c(2S)$, $X(3872)$, $X(3915)$, $\chi_c(1P)$)

See contribution from non-resonant
$\gamma\gamma \rightarrow X \rightarrow K_s^0 K^\pm \pi^\mp \pi^+ \pi^-$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\Gamma_{\gamma\gamma} B(\text{eV})$</th>
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<tbody>
<tr>
<td></td>
<td>Central value</td>
</tr>
<tr>
<td>$\chi_c(1P)$</td>
<td>$7.2^{+5.5}_{-4.4} \pm 2.9$</td>
</tr>
<tr>
<td>$\eta_c(2S)$</td>
<td>$65^{+47}_{-44} \pm 18$</td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>$-4.5^{+7.7}_{-6.7} \pm 2.9$</td>
</tr>
<tr>
<td>$X(3915)$</td>
<td>$-13^{+12}_{-12} \pm 8$</td>
</tr>
<tr>
<td>$\chi_c(2P)$</td>
<td>$-16^{+15}_{-14} \pm 6$</td>
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<tr>
<td></td>
<td>UL</td>
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<tr>
<td></td>
<td>$15.7$</td>
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<tr>
<td></td>
<td>$133$</td>
</tr>
<tr>
<td></td>
<td>$11.1$</td>
</tr>
<tr>
<td></td>
<td>$16$</td>
</tr>
<tr>
<td></td>
<td>$19$</td>
</tr>
</tbody>
</table>

Using $B(\chi_c(1P) \rightarrow K_s^0 K^\pm \pi^\mp)$ and $B(\eta_c(2S) \rightarrow K_s^0 K^\pm \pi^\mp)$ we obtain:

$B(\chi_c(1P) \rightarrow \eta_c(1S) \pi\pi) < 2.2\% \ @90\%CL$

$B(\eta_c(2S) \rightarrow \eta_c(1S) \pi\pi) < 7.4\% \ @90\%CL$

(consistent with the 2.2% prediction)
Study of the reaction $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ via initial-state radiation

Study of the reaction $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ via initial-state radiation (454 fb$^{-1}$)
$e^+e^- \rightarrow \gamma J/\psi \pi^+\pi^-$ - Motivation

- BABAR discovered the Y(4260) in ISR production of $J/\psi \pi^+\pi^-$ [1]; implies $J^{PC} = 1^{--}$
- Belle confirmed the Y(4260) in ISR production, and also suggested the existence of the Y(4008) [4].
- All the $1^{--}$ slots in the charmonium spectrum are already filled. The nature of the Y(4260) is still unclear.

$e^+e^- \rightarrow \gamma J/\psi \pi^+\pi^-$ - $\psi(2S)$ region (3.5-4 GeV/$c^2$)

The region below 4 GeV/$c^2$ ($\psi(2S)$ and $\psi(3770)$ region) in the $J/\psi \pi^+\pi^-$ mass region is investigated in detail for the first time.

- In order to understand a possible contribution coming from the $\psi(2S)$ tail a detailed study of the $\psi(2S)$ lineshape has been performed.

- Note that BES (Phys.Lett.B 605,63(2005)) and CLEO (Phys.Lett.96 082004(2006)) reported the decay of the $\psi(3770)$ to $J/\psi \pi^+\pi^-$.  

We conclude that we cannot discount the possibility of a contribution from an $e^+e^- \rightarrow J/\psi \pi^+\pi^-$ continuum cross section in this region.
$e^+e^- \rightarrow \gamma J/\psi \pi^+\pi^- - \text{Up to } 5.5 \text{ GeV}/c^2$

- A extended-maximum-likelihood fit is performed to the signal region $J/\psi \pi^+\pi^-$ distribution and simultaneously to the background distribution in the region 3.74-5.5 GeV/$c^2$.

- The fit function incorporates the mass-dependence of efficiency and luminosity, and uses a relativistic BW for the $Y(4260)$, a third-order polynomial to describe the background from the $J/\psi$ sideband regions (yellow histogram and dashed curve); an empirical exponential function describes the excess of events below 4 GeV/$c^2$, which may result from the $\psi(2S)$ tail and a possible $J/\psi \pi^+\pi^-$ nonresonant contribution.

Mass ($Y(4260)$) = $4244\pm5\pm4$ MeV/$c^2$

$\Gamma(Y(4260))=114^{+16}_{-15}\pm7$ MeV

$\Gamma_{e^+e^-}\times B(J/\psi \pi^+\pi^-)=9.2\pm0.8\pm0.7$ eV

We see no evidence for the state at $\sim4\text{ GeV}/c^2$ reported by Belle.

Charmonium and charmonium-like results from BABAR

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Invariant mass distribution in the $\Upsilon(4260)$ decay

- For $4.15 \leq m(J/\psi \pi^+ \pi^-) \leq 4.45 \text{ GeV}/c^2$
- The distribution seems to peak around the $f_0(980)$ mass; however the peak is displaced from the indicated $f_0(980)$ position.
- The fact that the peak is displaced suggests possible interference between the $f_0(980)$ and an $m(\pi^+ \pi^-)$ continuum.

The $\pi^+ \pi^-$ system has $C=+1$ and hence even angular momentum.

Define $\theta_\pi$ as the angle between the $\pi^+$ direction and that of the recoil $J/\psi$ both in the dipion rest frame.

The distribution, which must be symmetric, is consistent with S-wave behaviour ($\chi^2/NDF = 12.3/9$; probability=$19.7\%$).

Charmonium and charmonium-like results from BABAR
Invariant mass distribution in the $Y(4260)$ decay

We use a simple model to describe the $\pi^+\pi^-$ mass distribution, namely the square of an amplitude consisting of the coherent sum of a nonresonant component motivated by a QCD multipole expansion and an $f_0(980)$ amplitude; the relative strength and phase of these components are free to vary in the fit to the data.

The mass-dependence of the $f_0(980)$ amplitude and phase is from the BABAR analysis of the decay $D_{s}^+ \rightarrow \pi^+\pi^-\pi^+$.

A good description of the $\pi^+\pi^-$ mass distribution is obtained. This indicates that there is an $f_0(980)$ contribution to the decay of the $Y(4260)$ to $J/\psi\pi^+\pi^-$ but that contribution is not dominant.

$$\frac{B(Y_{4260} \rightarrow J/\psi f_0(980), f_0(980) \rightarrow \pi^+\pi^-)}{B(Y_{4260} \rightarrow J/\psi \pi^+\pi^-)} = (17 \pm 13)\%$$
Search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ states in $\bar{B}^0 \rightarrow \chi_{c1} K^- \pi^+$ and $B^+ \rightarrow \chi_{c1} K_s^0 \pi^+$

**PRD 85, 052003 (2012)**

$B(\bar{B}^0 \rightarrow Z_1^+ K^-) \times B(Z_1^+ \rightarrow \chi_{c1} \pi^+) < 1.8 \times 10^{-5}$ No significant signal observed.

$B(\bar{B}^0 \rightarrow Z_2^+ K^-) \times B(Z_2^+ \rightarrow \chi_{c1} \pi^+) < 4.0 \times 10^{-5}$ No significant signal observed.

$B(\bar{B}^0 \rightarrow Z^+ K^-) \times B(Z^+ \rightarrow \chi_{c1} \pi^+) < 4.7 \times 10^{-5}$ No significant signal observed.

Study of the $J/\psi \omega$ final state in two-photon collisions:

Confirm Belle’s results for $\gamma \gamma \rightarrow X(3915) \rightarrow J/\psi \omega$:

$\Gamma(\gamma \gamma(X(3915))) B(X(3915) \rightarrow J/\psi \omega)(J = 0)) = (52 \pm 10 \pm 3) \text{ eV}$

$\Gamma(\gamma \gamma(X(3915))) B(X(3915) \rightarrow J/\psi \omega)(J = 2)) = (10.5 \pm 1.9 \pm 0.6) \text{ eV}$

**BABAR** determines a limit on $\gamma \gamma \rightarrow X(3872) \rightarrow J/\psi \omega$:

$\Gamma(X(3872)) \times B(X(3872) \rightarrow J/\psi \omega) < 1.7 \text{ eV @ 90\% CL}$
Search for resonances decaying into $\eta_c\pi^+\pi^-$ using two-photon interactions:

New limits on decays to $\eta_c\pi^+\pi^-$:

- $B(\chi_{c2}(1P) \to \eta_c(1S)\pi\pi) < 2.2\% \text{ @90\% CL}$ No significant signal observed.
- $B(\eta_c(2S) \to \eta_c(1S)\pi\pi) < 7.4\% \text{ @90\% CL}$ No significant signal observed.

Study of the reaction $e^+e^- \to J/\psi\pi^+\pi^-$ via initial state radiation:

- $\sigma(e^+e^- \to \psi(2S)) = 14.5\pm0.7 \text{ pb}$
- $\Gamma(\psi(2S) \to e^+e^-) = 2.29\pm0.05 \text{ keV}$
- Improved precision on the $Y(4260)$ parameter values
- $\Gamma_{e^+e^-}xB(J/\psi\pi^+\pi^-) = 9.2\pm0.8\pm0.7 \text{ eV}$
- $\pi^+\pi^-$ invariant mass distribution: $\frac{B(Y_{4260} \to J/\psi f_0(980), f_0(980) \to \pi^+\pi^-)}{B(Y_{4260} \to J/\psi\pi^+\pi^-)} = (17\pm13)\%$
Future Prospects

Ongoing \textit{BABAR} charmonium analyses

- **B decay:**
  - $B \rightarrow KJ/\psi\phi$

- **ISR production:**
  - $e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$
  - $e^+e^- \rightarrow J/\psi K^+K^-$

- **$\gamma\gamma$ interactions:**
  - $\gamma\gamma \rightarrow K\bar{K}\pi$
  - $\gamma\gamma \rightarrow \eta K\bar{K}$

- **Inclusive $c\bar{c}$**
  - $e^+e^- \rightarrow J/\psi c\bar{c}$
  - $e^+e^- \rightarrow \psi(2S)c\bar{c}$

A lot of interesting results have been obtained, but much more data are required for a better understanding of the charmonium spectrum.
Charmonium and charmonium-like results from BABAR

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The $\textbf{BABAR}$ experiment and data sample

**Features**

- Asymmetric beams energies: $E_{e^-}=9$ GeV, $E_{e^+}=3.1$ GeV; $\beta=0.56$ in the CM frame.
  For $\sqrt{s}=10.58$ GeV, the $\Upsilon(4S)$ mass

- Integrated luminosity:
  - $431\ fb^{-1}$ at $\Upsilon(4S)$ resonance (On-Peak),
  - $45\ fb^{-1}$ 40 MeV below (Off-Peak).

- Data taken also at the $\Upsilon(3S)$ [30 $fb^{-1}$]
  $\Upsilon(2S)$ [14 $fb^{-1}$]

- Data taken period: 1999-2008

$\textbf{BABAR}$ is a $B$ factory: 467 million $B\overline{B}$ pairs in the total data sample.

$\textbf{BABAR}$ is also a $c$ factory: 1.3 million charm events per $fb^{-1}$. 
Search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ - Analysis procedure II

Using the information from the $K\pi$ system a description of the $\chi_{c1}\pi$ mass distribution is studied. A MC simulation for $B \rightarrow \chi_{c1}K\pi$ has been performed. The best $\chi^2/NDF$ obtained is for $L_{\text{max}} = 5$.

The result of the simulation with $L_{\text{max}} = 5$ is superimposed on the data. The excellent description of the data indicates that the angular information from the $K\pi$ channel with $L_{\text{max}} = 5$ is able to account for the structures observed in the $\chi_{c1}\pi$ projection. This indicates the absence of significant structure in the exotic $\chi_{c1}\pi^+$ channel.

A 25% contribution of $Z_2^+(4250)$ in the $\bar{B}^0 \rightarrow \pi^+K^-\chi_{c1}$ is added on a MC simulation. The Legendre polynomial moments is then computed. The resulting MC simulation does not describe the MC data well.
$\gamma\gamma \rightarrow J/\psi\omega$ - Event selection

Reconstruction

- $J/\psi \rightarrow \ell^+\ell^- \ (\ell=e,\mu)$; $\omega \rightarrow \pi^+\pi^-\pi^0$, $\pi^0 \rightarrow \gamma\gamma$
- $m(e^+e^-) \in [2.95,3.14]$; $m(\mu^+\mu^-) \in [3.05,3.14]$; $m(\pi^+\pi^-\pi^0) \in [0.74,0.82] \text{ GeV}/c^2$

Main event selection

- Four charged tracks
- $M^2_{\text{miss}} = (p_{e^+e^-} - p_{J/\psi\omega})^2 > 2(\text{GeV}/c^2)^2$
- $p_T < 0.2 \text{ GeV}/c$
- $E_{\text{extra}}$ (EMC energy not associated with the final state particles) $< 0.3 \text{ GeV}$

After the event selection, clear $\omega$ and $J/\psi$ signal, with negligible background.
\[ \gamma \gamma \rightarrow \eta_c \pi^+ \pi^- \] - Event selection

### Reconstruction
- \( \eta_c \rightarrow K_s^0 K^{\pm} \pi^{\mp} ; K_s^0 \rightarrow \pi^+ \pi^- \)
- \( m(K_s^0 K^{\pm} \pi^{\mp}) \in [2.77,3.22] \);
- The sample used to search for the process \( \gamma \gamma \rightarrow X \rightarrow \eta_c \pi^+ \pi^- \) is referred to as the "main sample".
- Properties of the \( \eta_c \) and its decay into \( K_s^0 K^{\pm} \pi^{\mp} \) are studied with a separate "control sample" of \( \gamma \gamma \rightarrow \eta_c \rightarrow K_s^0 K^{\pm} \pi^{\mp} \) events.

### Main event selection
- Six charged tracks
- \( M_{\text{miss}}^2 = (p_{e^+e^-} - p_X)^2 > 10(\text{GeV} / c^2)^2 \)
- \( p_T < 1.5 \text{ GeV/c} \)
- \( E_{\text{extra}} \) (EMC energy not associated with the final state particles) \( < 0.8 \text{GeV} \)
- Study of the \( \eta_c \) Dalitz Plots to select the signal region.
- Neural Network studies in order to remove additional backgrounds, with inputs: \( p_T ; E_{\text{extra}} ; K \) and \( \pi \) ID.
\[ e^+e^- \rightarrow \gamma J/\psi \pi^+\pi^- \] - Event selection

The goal is to study the final state \( J/\psi \pi^+\pi^- \) after initial state radiation.

**Reconstruction**

- \( J/\psi \) candidates is reconstructed via its decay to \( \mu^+\mu^- \) or to \( e^+e^- \).
- \( m(e^+e^-) - m(J/\psi) \in [-75, +55] \text{ MeV/c}^2 \); \( m(\mu^+\mu^-) - m(J/\psi) \in [-55, +55] \text{ MeV/c}^2 \)
- The background is estimated using the \( J/\psi \) sidebands.

**Main event selection**

- Four charged tracks
- To select ISR events:
  - \( M^2_{\text{miss}} = (p_{e^+e^-} - p_{J/\psi \pi^+\pi^-})^2 \in [-0.50, +0.75](\text{GeV/c}^2)^2 \)
  - \( p_{T_{\text{miss}}} < 2.25 \text{ GeV/c} \)