Recent Charmonium Results at BESIII Experiment

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Outline

➢ BEPCII and BESIII

➢ Observation of $h_c$ at BESIII

➢ Precision measurement of the $\eta_c$ properties at BESIII

➢ The first observation of the M1 transition $\psi' \rightarrow \gamma\eta_c(2S)$

➢ Observation of $\chi_{cJ} \rightarrow VV$ and $\gamma V$

➢ Evidence of $\psi' \rightarrow \gamma P (P=\pi^0, \eta, \eta')$

➢ Summary
BEPCII storage rings

Beam energy: 1.0-2.3 GeV
Design Luminosity: $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
Optimum energy: 1.89 GeV
Energy spread: $5.16 \times 10^{-4}$
No. of bunches: 93
Bunch length: 1.5 cm
Total current: 0.91 A
Circumference: 237 m
BESIII

- First collisions: March 2008
- First collisions in BESIII: July 2008
- Physics in BESIII: March 2009
- Record luminosity (April 2011): 6.9x10^{32}cm^{-2}s^{-1}

- BESIII will also collect:
  - more J/ψ, ψ', ψ(3770)
  - data at higher energies
    (for XYZ searches, R scan and Ds physics)

So far world largest data samples:
- ~225 Million J/Ψ
- ~106 Million Ψ'
- ~2.9 fb^{-1} Ψ(3770)
- ~0.5 fb^{-1} @Ψ(4010)
Observation of $h_c$ at BESIII
$h_c(^1P_1)$ in charmonium family

- Spin singlet P wave ($S=0$, $L=1$)

- Potential model if non-vanishing spin-spin interaction:
  \[ \Delta M_{hf}(1P) = M(h_c) - \frac{1}{9}(M(\chi_{c0}) + 3M(\chi_{c1}) + 5M(\chi_{c2})) \neq 0 \]

- E835 found evidence for $h_c$ in $pp \rightarrow h_c \rightarrow \gamma \eta_c$

- CLEO-c observed $h_c$ in $ee \rightarrow \psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$
  \[ \Delta M_{hf}(1P) = 0.08 \pm 0.18 \pm 0.12 \text{MeV/c}^2 \]
Observation of $h_c$ at BESIII (inclusive)


- Select inclusive $\pi^0 (\psi' \rightarrow \pi^0 h_c)$
- Select E1-photon in $h_c \rightarrow \gamma \eta_c$ (E1 tagged) or not (E1 untagged)

E1-tagged selection gives:

$M(h_c) = 3525.40 \pm 0.13 \pm 0.18 \text{MeV}$
($\Delta M_{hf}(1P) = 0.10 \pm 0.13 \pm 0.18 \text{MeV}/c^2$)

$\Gamma(h_c) = 0.73 \pm 0.45 \pm 0.28 \text{MeV}$
(<1.44\text{MeV at 90\% CL})

$\text{Br}(\psi' \rightarrow \pi^0 h_c) \times \text{Br}(h_c \rightarrow \gamma \eta_c) = (4.58 \pm 0.40 \pm 0.50) \times 10^{-4}$

E1-untagged together with tagged selection gives the first measurement:

$\text{Br}(\psi' \rightarrow \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$

$\text{Br}(h_c \rightarrow \gamma \eta_c) = (54.3 \pm 6.7 \pm 5.2)\%$
Measurements of the $h_c$ properties at BESIII (exclusive)

- 16 decay modes are studied:
  - $\gamma \to p_0 h_c$, $h_c \to g h_c$, $h_c \to X_i$: ppbar, 4p, 4K, 2p2K, ppbar
  - $h_c \to X_i$: pp, 6p, 2K4p, KK $p_0$, ppbar $p_0$, KsK
  - $h_c \to 4p$, 2p2p0, 4p2p0

Simultaneous fit to $\pi^0$ recoiling mass $M(h_c) = 3525.31 \pm 0.11 \pm 0.15$ MeV
$\Gamma(h_c) = 0.70 \pm 0.28 \pm 0.25$ MeV
$N = 832 \pm 35$
$\chi^2/\text{d.o.f.} = 32/46$

Consistent with BESIII inclusive results PRL104, 132002(2010)
CLEOc exclusive results
$M(h_c) = 3525.21 \pm 0.27 \pm 0.14$ MeV/$c^2$
$N = 136 \pm 14$
PRL101, 182003(2008)
Precision measurement of the $\eta_c$ properties

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Introduction

- The lowest lying S-wave spin singlet charmonium \( \eta_c \) was discovered in 1980 by MarkII.

- Earlier experiments using J/\( \psi \) radiative transition gives \( M(\eta_c) \approx 2978.0 \text{MeV}/c^2, \Gamma(\eta_c) \approx 10 \text{MeV} \).

- Recent studies using the two-photon processes gives \( M(\eta_c) = 2983.1 \pm 1.0 \text{MeV}/c^2, \Gamma(\eta_c) = 31.3 \pm 1.9 \text{MeV} \).

- The most recent study from CLEO-c pointed out the distortion of the \( \eta_c \) line shape in \( \psi' \) decays.

Measurement of the \( \eta_c \) properties at BESIII

- Data sample: 1.06*10^8 \( \psi' \) events, 45pb^{-1} continuum data at 3.65 GeV
- Decay modes (X_i): KsK\( \pi \), K^+K^-\( \pi^0 \), \( \eta\pi^+\pi^- \), KsK3\( \pi \), K^+K^-\( \pi^+\pi^-\pi^0 \), 3(\( \pi^+\pi^- \)), where Ks\( \rightarrow \pi^+\pi^- \), \( \eta \rightarrow \gamma\gamma \), \( \pi^0 \rightarrow \gamma\gamma \)

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The simultaneous fit

Simultaneous fit by considering the interference between $\eta_c$ and non-$\eta_c$ decays: an universal phase for different modes is used and assume all non-$\eta_c$ is $0^{-+}$

- mass = $2984.4 \pm 0.5_{\text{stat}} \pm 0.6_{\text{sys}}$ MeV/c$^2$
- width = $30.5 \pm 1.0_{\text{stat}} \pm 0.9_{\text{sys}}$ MeV
- $\phi = 2.35 \pm 0.05_{\text{stat}} \pm 0.04_{\text{sys}}$ rad

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Comparison of BESIII preliminary results with other measurements

BESIII results include both stat. and syst. errors, which is the most precision measurement, the interference between $\eta_c$ decay and non-resonance is important.

The world average in PDG2010 was using earlier results.

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The first observation of the M1 transition $\psi' \rightarrow \gamma \eta_c(2S)$
**Introduction**

- First “observation” by Crystal Ball in 1982 (M=3.592, B=0.2%-1.3% from $\psi' \rightarrow \gamma X$, never confirmed by other experiments.)

- Published results about $\eta_c(2S)$ observation:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle [1]</td>
<td>3654 ± 6 ± 8</td>
<td>—</td>
<td>$B^\pm \rightarrow K^\pm \eta_c(2S)$, $\eta_c(2S) \rightarrow K_S K^\pm \pi^\mp$</td>
</tr>
<tr>
<td>CLEO [2]</td>
<td>3642.9 ± 3.1 ± 1.5</td>
<td>6.3 ± 12.4 ± 4.0</td>
<td>$\gamma \gamma \rightarrow \eta_c(2S)$ $\rightarrow K_S K^\pm \pi^\mp$</td>
</tr>
<tr>
<td>BaBar [3]</td>
<td>3630.8 ± 3.4 ± 1.0</td>
<td>17.0 ± 8.3 ± 2.5</td>
<td>$\gamma \gamma \rightarrow \eta_c(2S)$ $\rightarrow K_S K^\pm \pi^\mp$</td>
</tr>
<tr>
<td>BaBar [4]</td>
<td>3645.0 $+5.5^{-4.9}_{-7.8}$</td>
<td>—</td>
<td>$e^+ e^- \rightarrow J/\psi c\bar{c}$</td>
</tr>
<tr>
<td>PDG [5]</td>
<td>3638 ± 4</td>
<td>14 ± 7</td>
<td>—</td>
</tr>
</tbody>
</table>

Combined with the results based on two-photon processes from BaBar and Belle reported at ICHEP 2010, the world average $\Gamma(\eta_c(2S))=12 \pm 3$ MeV

- The M1 transition $\psi' \rightarrow \gamma \eta_c(2S)$ has not been observed. (experimental challenge : search for real photons ~50MeV, )

- Better chance to observe $\eta_c(2S)$ in $\psi'$ radiative transition with ~1.06*10^8 $\psi'$ data at BESIII.

- Decay mode studied: $\psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma K_S K\pi$ (K^+K^-\pi^0 etc. in progress)

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Mass fitting (conti.)

$\chi^2$/ndf=0.9  

- $N(\eta_c(2S)) = 50.6 \pm 9.7$
- Pure statistical significance more than 6\(\sigma\)
- Significance with systematic variations not less than 5\(\sigma\)

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Preliminary measurements from

\[ \psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma KsK\pi \]

\[ M(\eta_c(2S)) = 3638.5 \pm 2.3 \text{_{stat}} \pm 1.0 \text{_{sys}} \text{ (MeV/c}^2\text{)} \]

\[ Br(\psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma KsK\pi) = (2.98 \pm 0.57 \text{_{stat}} \pm 0.48 \text{_{sys}}) \times 10^{-6} \]

\[ Br(\eta_c(2S) \rightarrow \overline{K}\overline{K}\pi) = (1.9 \pm 0.4 \pm 1.1)\% \text{ from BaBar} \]

\[ Br(\psi' \rightarrow \gamma \eta_c(2S)) = (4.7 \pm 0.9 \text{_{stat}} \pm 3.0 \text{_{sys}}) \times 10^{-4} \]

CLEO-c: $<7.6\times10^{-4}$ \hspace{1cm} (PRD81,052002(2010))

Potential model: $(0.1-6.2)\times10^{-4}$ \hspace{1cm} (PRL89,162002(2002))

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$\chi_{c1}$ decays into Vector Meson pairs ($\phi\phi$, $\omega\omega$, $\omega\phi$)
Introduction

- $e^+e^- \rightarrow \psi' \rightarrow \gamma \chi_{cJ}$ is the clean mode for the study of $\chi_{cJ}$
- Previous measurements from BESII. Only $\chi_{c0}$ and $\chi_{c2}$ decays into $\phi \phi$ and $\omega \omega$ are observed
- $\chi_{c1}$ violate the helicity selection rule (HSR) and expected to be suppressed
- Recently, long-distance effects in $\chi_{c1}$ have been proposed to account for the HSR violation
- Decays $\chi_{cJ} \rightarrow \omega \phi$ are doubly OZI suppressed and have yet to be observed

<table>
<thead>
<tr>
<th>BR($10^{-3}$)</th>
<th>$\chi_{c0}$</th>
<th>$\chi_{c2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rightarrow \phi \phi$</td>
<td>$0.94 \pm 0.21 \pm 0.13$</td>
<td>$1.70 \pm 0.30 \pm 0.25$</td>
</tr>
<tr>
<td>$\rightarrow \omega \omega$</td>
<td>$2.29 \pm 0.58 \pm 0.41$</td>
<td>$1.77 \pm 0.47 \pm 0.36$</td>
</tr>
</tbody>
</table>

BESII, PLB 642, 197 (2006)
BESII, PLB 630, 7 (2005)
Study of $\chi_{cJ} \rightarrow \phi\phi, \omega\omega, \omega\phi$

First observation

First observation

Doubly OZI suppressed $\chi_{cJ} \rightarrow \omega\phi$ are observed for the first time
$\chi_{cJ}$ radiative decays into a Vector Meson
Introduction

- $\psi \rightarrow \gamma X \rightarrow \gamma \gamma V$ ($V$ is $\rho$, $\omega$ and $\phi$) provide information on the flavor content of the $C$-even resonance $X$

- $\chi_{cJ} \rightarrow \gamma V$

- Recent pQCD calculation includes nonperturbative QCD hadronic loop contribution to account for the discrepancy between experimental results and former theoretical predications (pQCD, NRQCD, NRQCD+QED)

<table>
<thead>
<tr>
<th>Mode</th>
<th>CLEO$^1$</th>
<th>pQCD$^2$</th>
<th>QCD$^3$</th>
<th>QCD+QED$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c0} \rightarrow \gamma \rho^0$</td>
<td>$&lt; 9.6$</td>
<td>1.2</td>
<td>3.2</td>
<td>2.0</td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow \gamma \rho^0$</td>
<td>$243 \pm 19 \pm 22$</td>
<td>14</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow \gamma \rho^0$</td>
<td>$&lt; 50$</td>
<td>4.4</td>
<td>13</td>
<td>38</td>
</tr>
<tr>
<td>$\chi_{c0} \rightarrow \gamma \omega$</td>
<td>$&lt; 8.8$</td>
<td>0.13</td>
<td>0.35</td>
<td>0.22</td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow \gamma \omega$</td>
<td>$83 \pm 15 \pm 12$</td>
<td>1.6</td>
<td>4.6</td>
<td>4.7</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow \gamma \omega$</td>
<td>$&lt; 7.0$</td>
<td>0.5</td>
<td>1.5</td>
<td>4.2</td>
</tr>
<tr>
<td>$\chi_{c0} \rightarrow \gamma \phi$</td>
<td>$&lt; 6.4$</td>
<td>0.46</td>
<td>1.3</td>
<td>0.03</td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow \gamma \phi$</td>
<td>$&lt; 26$</td>
<td>3.6</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow \gamma \phi$</td>
<td>$&lt; 13$</td>
<td>1.1</td>
<td>3.3</td>
<td>6.5</td>
</tr>
</tbody>
</table>
Analysis Results

**BESIII Collaboration:** Phys. Rev. D 83, 112005 (2011)

**Mode** | **BESIII** | **CLEO** | **pQCD**
--- | --- | --- | ---
$\chi_{c0} \to \gamma \rho^0$ | $< 10.5$ | $< 9.6$ | $1.2$
$\chi_{c1} \to \gamma \rho^0$ | $228 \pm 13 \pm 22$ | $248 \pm 19 \pm 29$ | $14$
$\chi_{c2} \to \gamma \rho^0$ | $< 20.8$ | $< 50$ | $4.4$
$\chi_{c0} \to \gamma \omega$ | $< 12.9$ | $< 8.8$ | $0.13$
$\chi_{c1} \to \gamma \omega$ | $69.7 \pm 7.2 \pm 6.6$ | $83 \pm 15 \pm 12$ | $1.6$
$\chi_{c2} \to \gamma \omega$ | $< 6.1$ | $< 7.0$ | $0.5$
$\chi_{c0} \to \gamma \phi$ | $< 16.2$ | $< 6.4$ | $0.46$
$\chi_{c1} \to \gamma \phi$ | $25.8 \pm 5.2 \pm 2.3$ | $< 26$ | $3.6$
$\chi_{c2} \to \gamma \phi$ | $< 8.1$ | $< 13$ | $1.1$

Br. are in unit of $10^{-6}$.

pQCD predictions too lower than experimental measurements.

See an non-pQCD explanation
“hadronic loop correction”,
D.Y Chen et al.

CLEOc: PRL 101, 151801 (2008)
pQCD: Y.J. Gao et al.,
hep-ph/0701009

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Helicity Angle

L: Longitudinal polarization, T: Transverse polarization,
θ: Helicity angle

\[ \frac{d\Gamma}{\Gamma d\cos \theta} \propto (1 - f_T) \cos^2 \theta + \frac{1}{2} f_T \sin^2 \theta \]

\[ f_T = \frac{|A_T|^2}{|A_T|^2 + |A_L|^2} \]

- Longitudinal polarization dominates in the \( \chi_{c1} \rightarrow \gamma V \)
  - As expected in axial-vector particle radiative decaying to a vector.

\[ f_T = 0.158 \pm 0.034^{+0.015}_{-0.014} \]

\[ f_T = 0.247^{+0.090}_{-0.087}^{+0.044}_{-0.026} \]

\[ f_T = 0.29^{+0.13}_{-0.12}^{+0.10}_{-0.09} \]

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Evidence for $\psi'$ decays into $\gamma\pi^0$ and $\gamma\eta$
Introduction

- Important tests for various phenomenological mechanisms:
  
  Vector meson Dominance Model (VDM); Two-gluon couplings to $qq$ states; Mixing of $\eta_c - \eta'$; Final-state radiation by light quarks.

- $R_{J/\psi} = \frac{B(J/\psi \rightarrow \gamma\eta)}{B(J/\psi \rightarrow \gamma\eta')}$, predicted by 1st order perturbation theory. $R_{\psi'} = \frac{B(\psi' \rightarrow \gamma\eta)}{B(\psi' \rightarrow \gamma\eta')} \approx R_{J/\psi}$ was expected.

- Recently, CLEOc reported on $J/\psi$, $\psi'$, $\psi'' \rightarrow \gamma P$:
  - Found no evidence for $\psi' \rightarrow \gamma\pi^0$ or $\gamma\eta$
  - Determine $B(\psi' \rightarrow \gamma\pi^0) < 5 \times 10^{-6}$
  - Obtain $R_{\psi'} < 1.8\%$ at 90\% CL and $R_{J/\psi} = (21.1 \pm 0.9)\%$

$R_{\psi'} << R_{J/\psi}$ poses a significant challenge to theory.

CLEOc, PRD 79, 111101 (2009)
\[ \psi' \rightarrow \gamma P \ (P=\pi^0, \eta \text{ and } \eta') \text{ at BESIII} \]

- \[ \psi' \rightarrow \gamma \eta \]
- \[ \eta \rightarrow \pi^+ \pi^- \pi^0, \pi^0 \pi^0 \pi^0 \]

(First observation)

- \[ \psi' \rightarrow \gamma \eta' \]
- \[ \eta' \rightarrow \gamma \pi^+ \pi^- \]
- \[ \eta' \rightarrow \pi^+ \pi^- \eta, \eta \rightarrow \gamma \gamma \]

(First observation)

\[ \psi' \rightarrow \gamma \pi^0 (\pi^0 \rightarrow \gamma \gamma) \]

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ψ'→γP (P=π⁰, η and η') at BESIII


<table>
<thead>
<tr>
<th>Mode</th>
<th>BESIII</th>
<th>Combined BESIII</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>ψ'→γπ⁰</td>
<td>1.58±0.40±0.13</td>
<td>1.58±0.40±0.13</td>
<td>≤5</td>
</tr>
<tr>
<td>ψ'→γη(π⁺π⁻π⁰)</td>
<td>1.78±0.72±0.17</td>
<td>1.38±0.48±0.09</td>
<td>≤2</td>
</tr>
<tr>
<td>→γη(π⁰π⁰π⁰)</td>
<td>1.07±0.65±0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ψ'→γη'(π⁺π⁻η)</td>
<td>120±5±8</td>
<td>126±3±8</td>
<td>121±8</td>
</tr>
<tr>
<td>→γη'(π⁺π⁻γ)</td>
<td>129±3±8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Measured branching ratios of ψ'→γη and ψ'→γπ⁰ for the first time
- The first measurement of \( R_{ψ'} = (1.10 ± 0.38 ± 0.07)\% \)
- Confirmed \( R_{ψ'} << R_{J/ψ} \)

Summary

- High luminosity by BEPCII and the good performance of BESIII give us better chance to study the charmonium spectroscopy.

- Study of $h_c$ at BESIII (inclusive & exclusive) gives the measurements of mass, width of $h_c$ as well as $\text{Br}(\psi' \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c)$.

- Precise measurement of the properties of $\eta_c$ done at BESIII. The observed distortion $\eta_c$ line shape described successfully by a interference model.

- The first observation of the M1 transition $\psi' \rightarrow \gamma \eta_c(2S)$.

- Observation of $\chi_{cJ} \rightarrow VV, \gamma V$ and $\psi' \rightarrow \gamma P (P = \pi^0, \eta, \eta')$.
Backup
\( \eta_c \) lineshape from \( \psi' \rightarrow \pi^0 h_c, \ h_c \rightarrow \gamma \eta_c \)

**BESIII Preliminary**

Sum of 16 of \( \eta_c \) decay modes

The \( \eta_c \) lineshape is not distorted in the \( h_c \rightarrow \gamma \eta_c \)
Detail analysis of \( \eta_c \) parameters is ongoing!

Symmetric lineshape in \( \gamma\gamma \) production

Asymmetric lineshape in \( \psi \) decay

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Backgrounds for $\psi' \rightarrow \gamma \eta_c \rightarrow \gamma X_i$

- $\psi' \rightarrow \pi^0 X_i$
  With the optimized selection, the mass spectra for $\pi^0 X_i$ events are measured in data and scaled according to the full simulation to estimate the contribution in $\gamma \eta_c$ candidates.

- Non-resonant contribution $\psi' \rightarrow \gamma X_i$
  the same final states, can not be removed

- Rare backgrounds
  Production rate or efficiency is very low, estimated according to the inclusive MC sample

- Continuum events
  Estimated by using the 45pb$^{-1}$ data taken at 3.65GeV
Backgrounds for $\psi' \rightarrow \gamma \eta_c \rightarrow \gamma X_i$ (conti.)

- $KsK\pi$
- $K^+K^-\pi^0$
- $\pi^+\pi^-\eta$
- $KsK3\pi$
- $2K2\pi\pi^0$
- $6\pi$

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Mass spectrum fitting

\[ \sigma (\epsilon | e^{i\phi} f_1 S + \alpha N on|^2 f_2) + BKG \]

- **S**: signal function (BW with mass width floated)
- **Non**: PDF for the non-resonant \( \gamma X_i \) (all assumed to \( 0^{\pm} \))
- **BKG**: the sum of other backgrounds \( \pi^0 X_i + \) other rare \( \psi' \) decays + continuum, fixed in the fitting
- **\( \phi \)**: interference phase between \( \eta_c \) decay and non-resonant contribution

Fit results for individual modes:

<table>
<thead>
<tr>
<th>mode ((i))</th>
<th>signal yield (\epsilon) ((%))</th>
<th>mass ((MeV/c^2))</th>
<th>width((MeV))</th>
<th>(\phi_i)</th>
<th>(\chi^2/d.o.f)</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_S K^+ \pi^-)</td>
<td>880.4</td>
<td>35.0</td>
<td>2984.7 ± 1.2</td>
<td>32.5 ± 2.3</td>
<td>2.9 ± 0.3</td>
<td>1.1</td>
</tr>
<tr>
<td>(K^+ K^- \pi^0)</td>
<td>948.4</td>
<td>25.0</td>
<td>2980.3 ± 1.5</td>
<td>30.5 ± 2.4</td>
<td>2.4 ± 0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>(\eta \pi^+ \pi^-)</td>
<td>573.4</td>
<td>25.0</td>
<td>2982.4 ± 1.8</td>
<td>31.0 ± 3.3</td>
<td>2.2 ± 0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>(K_S K^+ \pi^+ \pi^-)</td>
<td>432.3</td>
<td>11.0</td>
<td>2986.9 ± 2.1</td>
<td>34.1 ± 3.3</td>
<td>2.3 ± 0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>(K^+ K^- \pi^+ \pi^-)</td>
<td>1033.6</td>
<td>11.0</td>
<td>2985.4 ± 1.3</td>
<td>29.1 ± 2.8</td>
<td>2.6 ± 0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>(3(\pi^+ \pi^-))</td>
<td>664.4</td>
<td>17.0</td>
<td>2986.8 ± 1.3</td>
<td>33.7 ± 3.1</td>
<td>2.5 ± 0.1</td>
<td>1.1</td>
</tr>
<tr>
<td>combined</td>
<td>4532.5</td>
<td>-</td>
<td>2984.5 ± 0.6</td>
<td>31.7 ± 1.1</td>
<td>2.5 ± 0.1</td>
<td>-</td>
</tr>
<tr>
<td>C.L.</td>
<td>-</td>
<td>-</td>
<td>1.1%</td>
<td>89%</td>
<td>28%</td>
<td>-</td>
</tr>
</tbody>
</table>

Constant fitting gives \(\chi^2/ndf=5.142/5\)

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Mass spectrum representation for $\psi' \rightarrow \gamma \eta_c(2S)$

- The 4C kinematic fitting used to select the $\gamma K_s K\pi$ candidates ($\chi^2_{4C}<50$)
- Still some $K_s K\pi$ BG events contribute the $\gamma K_s K\pi$ candidates with a fake photon.
- The invariant mass from 4C-kinematic fits make the BG $\psi' \rightarrow K_s K\pi$ contaminates the $\eta_c(2S)$ mass region (3.6~3.66 GeV).
- The mass from 3C-kinematic fits (the measured energy of the photon is free) is little biased by the fake photon.
- Difference small between 4C and 3C for signal events

So the 3C fit mass used to determine the yields and parameters
Mass fitting for $\psi' \rightarrow \gamma \eta_c(2S)$

- $\eta_c(2S)$ signal:
  
  $\Gamma(\eta_c(2S))$ fixed to 12MeV (world average)
  
  \[
  (E_\gamma^3 \times BW(m) \times \text{damping}(E_\gamma)) \otimes \text{Gauss}(0, \sigma)
  \]
  
  M1 transition

- $\chi_{cJ}$: MC shape $\otimes$ a Gaussian

- BG from $\pi^0KsK\pi$:
  
  Measurement + scaling with MC simulation

- BG from $\psi' \rightarrow KsK\pi(\gamma_{\text{FSR}})$ & continuum ($KsK\pi(\gamma_{\text{ISR}})$):
  
  Ratio of the two is fixed in the final mass fitting

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\[ \rho, \omega \text{ and } \phi \text{ Reconstruction} \]

\[ \rho \rightarrow \pi^+ \pi^- \]

\[ \phi \rightarrow K^+ K^- \]

Using 5C (energy-momentum + \pi^0 mass) kinematic fit for \(4\gamma\pi^+\pi^-\) candidates.

\[ \pi^0 \text{ reconstruction:} \]

\[ \left( \frac{M_{\gamma\gamma} - M_{\pi^0}}{\sigma_{\pi^0}} \right)^2 + \left( \frac{M_{\pi^+\pi^-\gamma\gamma} - M_{\omega}}{\sigma_{\omega}} \right)^2 \]

\[ \text{ Applying 4C kinematic fit to } \gamma\gamma\pi^+\pi^- \text{ or } \gamma\gamma K^+K^- . \]

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Study of $\chi_{cJ}\rightarrow\phi\phi$ ($\phi\rightarrow K^+K^-$)

- Using kinematic fit to select $\gamma 2(K^+K^-)$ candidates
- KK pairs reconstruction by minimizing:
  \[
  \left[M_1(K^+K^-) - M_\phi\right]^2 + \left[M_2(K^+K^-) - M_\phi\right]^2
  \]

Signal region

Sideband regions

First observation

<table>
<thead>
<tr>
<th>Channel</th>
<th>$B \times 10^{-4}$</th>
<th>PDG $\times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c0} \rightarrow \phi\phi$</td>
<td>$7.8 \pm 0.4 \pm 0.8$</td>
<td>$9.2 \pm 1.9$</td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow \phi\phi$</td>
<td>$4.1 \pm 0.3 \pm 0.4$</td>
<td>—</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow \phi\phi$</td>
<td>$10.7 \pm 0.4 \pm 1.1$</td>
<td>$14.8 \pm 2.8$</td>
</tr>
</tbody>
</table>

2011/7/20

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Study of $\chi_{cJ} \rightarrow \omega\omega$ ($\omega \rightarrow \pi^+\pi^-\pi^0$)

- Using kinematic fit to select $5\gamma 2(\pi^+\pi^-)$ candidates
- Two $\pi^0$ pair reconstruction: minimizing $\sum (M_{\gamma\gamma} - M_{\pi^0})^2$ by looping over $5\gamma$
- $\omega$ reconstruction: minimizing $\sum (M_{\pi^+\pi^-\pi^0} - M_\omega)^2$

First observation

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\mathcal{B} (\times 10^{-4})$</th>
<th>PDG $(\times 10^{-4})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c0} \rightarrow \omega\omega$</td>
<td>$9.5 \pm 0.3 \pm 1.1$</td>
<td>$22 \pm 7.0$</td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow \omega\omega$</td>
<td>$6.0 \pm 0.2 \pm 0.7$</td>
<td>—</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow \omega\omega$</td>
<td>$8.9 \pm 0.3 \pm 1.1$</td>
<td>$19.0 \pm 6.0$</td>
</tr>
</tbody>
</table>
Study of $\chi_{cJ} \rightarrow \omega \phi \rightarrow \pi^+\pi^-\pi^0K+K^-$

- Two tracks are identified as $K^+K^-$
- Using kinematic fit to select $3\gamma 2K2\pi$ candidates
- $\pi^0\omega$ are reconstructed by minimizing
  $$(M_{\gamma\gamma} - M_{\pi^0})^2 + (M_{\gamma\pi^+\pi^-} - M_\omega)^2$$

<table>
<thead>
<tr>
<th>Channel</th>
<th>$B(\times10^{-4})$</th>
<th>PDG($\times10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c0} \rightarrow \omega \phi$</td>
<td>$1.2 \pm 0.1 \pm 0.2$</td>
<td>—</td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow \omega \phi$</td>
<td>$0.22 \pm 0.06 \pm 0.02$</td>
<td>—</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow \omega \phi$</td>
<td>$&lt; 0.2$</td>
<td>—</td>
</tr>
</tbody>
</table>

Doubly OZI suppressed $\chi_{cJ} \rightarrow \omega \phi$ are observed for the first time