Studies of charmonium decays at BESIII

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On behalf of the BESIII Collaboration

VIII International Workshop on Charm Physics
September 5 - 9, 2016 Bologna, Italy
Outline

- The BESIII experiment and detector
- The BESIII physics program
- Measurement of the leptonic decay width of $J/\psi$ using initial state radiation
  PLB 761, 98-103 (2016)
- Observation of $h_c$ radiative decay $h'_c \rightarrow h_c\gamma$ and evidence for $h_c \rightarrow \gamma\eta$
  PRL 116, 251802 (2016)
- Study of $\chi_{cJ}$ decaying into $\phi K^*(892)\bar{K}$
  PRD 91, 112008 (2015)
- Conclusions
Studies of charmonium decays at BESIII

2004: BEPCII/BESIII Construction
Double ring
Beam energy: 1-2.3 GeV
Designed Luminosity $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
2008: test run
2009-today: BESIII physics run
The BESIII detector

Studies of charmonium decays at BESIII
BESIII physics program

- Light hadron Physics
  - Meson and baryon spectroscopy
  - Multiquark states
  - Threshold effects
  - Glueballs and hybrids
  - Two-photon physics
  - Form factors
- QCD and $\tau$
  - Precision R measurement
  - $\tau$ decay
- Charmonium physics
  - Precision spectroscopy
  - Transitions and decays
- XYZ meson physics
  - $Y(4260), Y(4360)$ properties
  - $Z_c(3900)^+, \ldots$
- Charm physics
  - Semi-leptonic form factors
  - Decay constants $f_D$ and $f_{D_s}$
  - CKM matrix: $|V_{cd}|$ and $|V_{cs}|$
  - $D^0$-$\bar{D}^0$ mixing, CPV
  - Strong phases
- Precision mass measurements
  - $\tau$ mass
  - $D$, $D^*$ mass
BESIII physics program

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- Charm physics
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## Data samples

<table>
<thead>
<tr>
<th>Data sample</th>
<th>$E_{cm}$</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.3 \times 10^9$</td>
<td>$J/\psi$ at 3.097 GeV</td>
<td>2009 (0.225$\times 10^9$) + 2012</td>
</tr>
<tr>
<td>$0.5 \times 10^9$</td>
<td>$\psi(2S)$ at 3.686 GeV</td>
<td>2009 (0.106$\times 10^9$) + 2012</td>
</tr>
<tr>
<td>2.92 fb$^{-1}$</td>
<td>$\psi(3770)$ at 3.773 GeV</td>
<td>2010+2011</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>$\psi(4040)$ at 4.009 GeV</td>
<td>2011</td>
</tr>
<tr>
<td>0.024 fb$^{-1}$</td>
<td>$\tau$ mass scan at around 3.554 GeV</td>
<td>2011</td>
</tr>
<tr>
<td>1.9 fb$^{-1}$</td>
<td>Y(4260) at 4.23 GeV and 4.26 GeV</td>
<td>2013</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>Y(4360) at 4.36 GeV</td>
<td>2013</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>Y(4260) and Y(4360) scan</td>
<td>2013</td>
</tr>
<tr>
<td>0.8 fb$^{-1}$</td>
<td>R scan, 104 energy points between 3.85 and 4.59 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>1.0 fb$^{-1}$</td>
<td>at 4.42 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>0.1 fb$^{-1}$</td>
<td>at 4.47 GeV and 4.53 GeV for line shape</td>
<td>2014</td>
</tr>
<tr>
<td>0.04 fb$^{-1}$</td>
<td>at 4.575 GeV (around the threshold of Lambda Charm)</td>
<td>2014</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>at 4.60 GeV</td>
<td>2014</td>
</tr>
</tbody>
</table>
Measurement of the leptonic decay width of $J/\psi$ using initial state radiation

PLB 761, 98-103 (2016)
The electronic width of the $J/\psi$, $\Gamma_{ee}$ has been measured by BABAR (PRD69,011103R(2004)) and CLEO-c (PRD73,051103R(2006)).

Also KEDR experiment measured the electronic width with improved precision using a different method (PLB685,134-140(2010))

BESIII studied the process $e^+e^- \rightarrow \mu^+\mu^-\gamma$ using the ISR method, analyzing 2.93 fb$^{-1}$ of data taken at $\sqrt{s} = 3.773$ GeV.

The cross section $\sigma_{J/\psi\gamma} = \sigma(e^+e^- \rightarrow J/\psi\gamma \rightarrow \mu^+\mu^-\gamma)$ is proportional to $\Gamma_{ee} \times B_{\mu\mu}$, where $B_{\mu\mu} = B(J/\psi \rightarrow \mu^+\mu^-)$.

With the precise measurement of $B_{\mu\mu}$ from BESIII, we have the opportunity to obtain $\Gamma_{ee}$ with high precision.
Results

Our measurement of $\Gamma_{ee} \times B_{\mu\mu}$ is consistent with results from BABAR, CLEO-c and KEDR. The measured value for $\Gamma_{ee}$ is more precise.
Observation of $h_c$ radiative decay $h'_c \rightarrow h_c \gamma$ and evidence for $h_c \rightarrow \gamma \eta$

PRL 116, 251802 (2016)
Many unexpected states have been reported above the $D\bar{D}$ threshold, seemingly too many with $J^{PC} = 1^{--}$. Several exotic hypotheses as to their nature: tetraquarks, hadronic molecules, hybrids, glueballs, hadro-quarkonia.

Below the $D\bar{D}$ threshold, all expected states have been observed, with properties in good agreement with theory. However, knowledge is still sparse on the $P$-wave spin-singlet state, $h_c(1P_1)$.
Only a few decay modes of $h_c$ have been observed, $h_c \rightarrow \gamma \eta_c$ (BR\(\sim\)50%) and $h_c \rightarrow 2(\pi^+\pi^-)\pi^0$ (BR\(\sim\)2%).

Searches for the new $h_c$ decay modes are useful for providing constraints to theoretical models in the charmonium region.

The ratio of the branching fraction $\mathcal{B}(h_c \rightarrow \gamma \eta) / \mathcal{B}(h_c \rightarrow \gamma \eta')$ can also be used to study the $\eta - \eta'$ mixing angle, which is important to test SU(3)-flavor symmetries in QCD.

We report the observation of the $h_c$ radiative decay $h_c \rightarrow \gamma \eta'(\eta)$, where $h_c$ is produced in the decay $\psi' \rightarrow \pi^0 h_c$.

The $h_c \rightarrow \gamma \eta'$ is reconstructed by using $\eta' \rightarrow \pi^+\pi^-\eta$ and $\eta' \rightarrow \gamma\pi^+\pi^-$ with $\eta \rightarrow \gamma\gamma$.

The $h_c \rightarrow \gamma \eta$ is reconstructed from decays $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ with $\pi^0 \rightarrow \gamma\gamma$.

The analyses are based on a data sample of $4.48 \times 10^8 \ \psi'$ events.
Studies of charmonium decays at BESIII

### Results

**PRL 116, 251802 (2016)**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{h_c \to \gamma' (\eta)}$</th>
<th>$B[h_c \to \gamma' (\eta)]$</th>
<th>Significance</th>
<th>[\frac{B(h_c \to \gamma)}{B(h_c \to \gamma')}\text{%}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_c \to \gamma'$</td>
<td>$44.3 \pm 7.8\text{(stat)}$</td>
<td>$[1.52 \pm 0.27\text{(stat)} \pm 0.29\text{(sys)}] \times 10^{-3}$</td>
<td>$8.4\sigma$</td>
<td>$30.7 \pm 11.3\text{(stat)} \pm 8.7\text{(sys)}$</td>
</tr>
<tr>
<td>$h_c \to \gamma$</td>
<td>$18.1 \pm 5.8\text{(stat)}$</td>
<td>$[4.7 \pm 1.5\text{(stat)} \pm 1.4\text{(sys.)}] \times 10^{-4}$</td>
<td>$4.0\sigma$</td>
<td></td>
</tr>
</tbody>
</table>

**Elisa Fioravanti**

14
Study of $\chi_{cJ}$ decaying into $\phi K^*(892)\bar{K}$

PRD 91, 112008 (2015)
Unlike the \( J/\psi \) and the \( \psi' \), the \( P \)-wave charmonia states \( \chi_{cJ} \) are not directly produced in \( e^+e^- \) collisions and, thus, are less well understood.

Obtaining more experimental data on exclusive decays of the \( \chi_{cJ} \) states is important for a better understanding of their nature and mechanisms, as well as for testing QCD-base calculation.

Since the \( \chi_{cJ} \) states are produced copious in the E1 radiative transition of \( \psi' \), with branching fractions around 9\%, the large \( \psi' \) data sample taken at BESIII provides a unique opportunity for detailed studies of \( \chi_{cJ} \) exclusive decays.

We report the first measurement of the decay \( \chi_{cJ} \rightarrow \phi K_S^0 K^{\pm} \pi^{\mp} \) and \( \chi_{cJ} \rightarrow \phi K^+ K^- \pi^0 \) in the electric dipole E1 radiative transition \( \psi' \rightarrow \gamma \chi_{cJ} \), using \( 1.06 \times 10^8 \) \( \psi' \). The \( \phi \) is reconstructed via \( K^+ K^- \).
- Significant $\chi_{cJ}$ signals are observed.
- The dominant processes are the $\chi_{cJ} \rightarrow \phi K^*(892) \bar{K}$ three-body decays.
Branching fractions measurement

Branching fractions measured in $\phi K \bar{K} \pi$ final states:

<table>
<thead>
<tr>
<th>Decay Modes</th>
<th>$\phi K^+ K^- \pi^0$ ($\times 10^{-3}$)</th>
<th>$\phi K^+ K^- \pi$ ($\times 10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c0}$</td>
<td>$\phi K^*(892)^\pm K^\mp$</td>
<td>$1.65 \pm 0.21$ (stat) $\pm 0.22$ (sys)</td>
</tr>
<tr>
<td></td>
<td>$\phi K^*(892)^0 K^0 + c.c.$</td>
<td>$2.03 \pm 0.21$ (stat) $\pm 0.28$ (sys)</td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>$\phi K^*(892)^\pm K^\mp$</td>
<td>$1.76 \pm 0.21$ (stat) $\pm 0.26$ (sys)</td>
</tr>
<tr>
<td></td>
<td>$\phi K^*(892)^0 K^0 + c.c.$</td>
<td>$1.51 \pm 0.19$ (stat) $\pm 0.22$ (sys)</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>$\phi K^*(892)^\pm K^\mp$</td>
<td>$2.56 \pm 0.23$ (stat) $\pm 0.35$ (sys)</td>
</tr>
<tr>
<td></td>
<td>$\phi K^*(892)^0 K^0 + c.c.$</td>
<td>$2.27 \pm 0.22$ (stat) $\pm 0.32$ (sys)</td>
</tr>
</tbody>
</table>

$K^*(892)^\pm$ tagged events

$K^*(892)^0$ tagged events
The $K\bar{K}\pi$ invariant mass and $h_1(1380)$ state

- The $K\bar{K}\pi$ invariant mass distributions are studied in order to identify any intermediate states.
- A threshold enhancement, which can not be described with the phase space, is observed in both $\chi_{c1}$ and $\chi_{c2}$ signal regions and it has been identify as the $h_1(1380)$.
- In the $\chi_{c0}$ decay, a structure, the $\phi(1680)$ is observed. There is also a possible $\phi(1850)$ contribution.
The $K\bar{K}\pi$ invariant mass and $h_1(1380)$ state

- A simultaneous fit is performed to the invariant mass distributions of $K\bar{K}\pi$ for the candidate events in the $\chi_{c1,2}$ signal regions.
- The $h_1(1380)$ is observed with significance of 10$\sigma$. This is the first direct observation of this state in its decay to $K^*(892)\bar{K}$
- $m[h_1(1380)]=1412\pm4\pm8$ MeV/$c^2$; $\Gamma[h_1(1830)]=84\pm12\pm40$ MeV
- Evidence is also found for the decays $\chi_{cJ} \rightarrow \phi\phi(1680)$ and $\chi_{cJ} \rightarrow \phi\phi(1850)$ but with significances less than 5$\sigma$.
- More data and advanced analysis techniques are needed.
Conclusion

- BESIII is successfully operating since 2008, and continues to take data.
- It is an excellent laboratory to study charmonium spectroscopy:
  - High statistics
  - Low background
- Many interesting results have been obtained, only few of them are covered in this talk.
- Future:
  - More data will be collected
  - More detailed studies will be done

THANKS FOR YOUR ATTENTION!