\( \eta_c \) Decays at BESIII

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On behalf of BESIII collaboration

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• Introduction

• $Br(\eta_c \rightarrow VV)$
  - $\eta_c \rightarrow \phi\phi, \omega\phi$
  - $\eta_c \rightarrow \omega\omega$

• Search for $\psi(3686) \rightarrow \gamma\eta_c \rightarrow \gamma\pi^+\pi^-\pi^0$

• $e^+e^- \rightarrow \pi^+\pi^- h_c, h_c \rightarrow \gamma\eta_c, \eta_c \rightarrow$ hadrons with XYZ data

• Summary
Introduction

- $\eta_c$ is the lowest lying charmonium state
- $\eta_c$ can’t be generated directly from $e^+ e^-$ annihilation
- $\eta_c$ can be generated from the radiative transition of $J/\psi$, $\psi'$ or $h_c$

BESIII data samples:
- $J/\psi$: 0.225Billion (2009), 1.09B (2012), 8.5B (2018)
- $\psi(3686)$: 106M (2009), 341M (2012)
- XYZ: 12fb$^{-1}$ (Ecms $>$ 3.8 GeV)
- $\eta_c$ mainly decay through the 2 gluons.
- $\eta_c \rightarrow VV$ is suppressed (forbidden) by pQCD at the leading-twist order because it violates the Helicity Selection Rule (HSR)

$$
\text{BR} \left( J_{c\bar{c}}(\lambda) \rightarrow h_1(\lambda_1) h_2(\lambda_2) \right) \sim \left( \frac{\Lambda_{\text{QCD}}^2}{m_c^2} \right)^{|\lambda_1 + \lambda_2| + 2},
$$

Or $\sigma_c \neq \sigma_1 \sigma_2$, where $\sigma = P(-1)^J$ is the naturalness of the particle

- When higher order correction is taken into consideration in pQCD, the decay branching fraction can become significant

$$
\text{Br}(\eta_c \rightarrow VV) \approx 10^{-4}
$$

References:
- PRD 81, 014017 (2010)
- PLB 702 (2011) 49–54
Introduction

- The experimental result for $Br(\eta_c \rightarrow VV) \approx 10^{-2}, 10^{-3}$ which is 1 or 2 orders larger than pQCD predication.

- Some non-perturbative mechanism is proposed to explain this, such as:
  - The intermediate meson loop (IML)  
    \[ \text{PLB 711 (2012) 364–370} \]
  - The charmonium light fork component admixture model $(\eta_c, \eta, \eta')$  
    \[ \text{PLB 702 (2011) 49–54} \]
  - The $^3P_0$ quark creation mechanism $(\eta_c \rightarrow (\eta, \eta') \rightarrow VV)$  
    \[ \text{PRD71, 114002 (2005)} \]

They can give predicated $Br(\eta_c \rightarrow VV)$ closer to experimental result.
Branching fractions for $\eta_c \rightarrow \phi \phi, \omega \phi$

PRD95, 092004 (2017)

- Based on $(223.7 \pm 1.4) \times 10^6 J/\psi$ events.
- $J/\psi \rightarrow \gamma \eta_c, \quad \eta_c \rightarrow \phi \phi, \omega \phi$ signal are selected

- Clear $\phi \phi$ and $\omega \phi$ clusters can be seen
PWA for $J/\psi \rightarrow \gamma \eta_c$, $\eta_c \rightarrow \phi \phi$

- PWA with helicity-covariant formalism is performed.
- $\eta_c$ is parameterized with the following formula,

$$f(s) = \frac{1}{M^2 - s - i\Gamma M} \mathcal{F}(E_\gamma),$$

$$\mathcal{F}(E_\gamma) = \exp\left(-\frac{E_\gamma^2}{16\beta^2}\right) \text{ with } \beta = 0.065 \text{ GeV}$$

- And the mass and width are fixed to previous BESIII measurement, $M=2.984 \text{ GeV}$, $\Gamma=0.032 \text{ GeV}$

- The interference is considered, however PWA also bring larger uncertainty.

- The result is much larger than pQCD, and agree better with several non-perturbative model.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\text{Br}(J/\psi \rightarrow \gamma \eta_c)$</th>
<th>$\text{Br}(\eta_c \rightarrow \phi \phi) \times 10^{-5}$</th>
<th>$\text{Br}(\eta_c \rightarrow \phi \phi) \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESIII</td>
<td>$4.3 \pm 0.5^{+0.5}_{-1.2}$</td>
<td>$2.5 \pm 0.3^{+0.3}_{-0.7} \pm 0.6$</td>
<td></td>
</tr>
<tr>
<td>BESII [5]</td>
<td>$3.3 \pm 0.8$</td>
<td>$1.9 \pm 0.6$</td>
<td></td>
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<tr>
<td>DM2 [30]</td>
<td>$3.9 \pm 1.1$</td>
<td>$2.3 \pm 0.8$</td>
<td></td>
</tr>
<tr>
<td>Theoretical</td>
<td>Prediction</td>
<td>$\text{Br}(\eta_c \rightarrow \phi \phi) \times 10^{-3}$</td>
<td>(0.7–0.8)</td>
</tr>
<tr>
<td>pQCD [10]</td>
<td></td>
<td>(1.9–2.0)</td>
<td></td>
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<tr>
<td>$^3P_0$ quark model [13]</td>
<td></td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Charm meson loop [14]</td>
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</table>
Branching fractions for $\eta_c \to \omega\phi$

No significant $\eta_c \to \omega\phi$ events are observed, the uplimit at 90% C.L is given

$$\text{Br}(\eta_c \to \omega\phi) < \frac{N_{\text{up}}}{N_{J/\psi}\epsilon\text{Br}(1 - \sigma_{\text{sys}})}$$

$$= 2.5 \times 10^{-4},$$
Observation of $\eta_c \rightarrow \omega\omega$

BESIII Preliminary

- Based on $(1310.6 \pm 7.0) \times 10^6 J/\psi$ events

- Remove all non-$\omega\omega$ background using Q-factor method. Based on probabilistic event weights.

- 4900 $\omega\omega$ events after background subtracted.

Clear cluster of signal can be seen
PWA of $J/\psi \rightarrow \gamma \eta_c, \eta_c \rightarrow \omega \omega$

![Graph showing PWA results](image)

A similar PWA as in $\phi \phi$ channels are also performed

<table>
<thead>
<tr>
<th></th>
<th>$Br(\eta_c \rightarrow \omega \omega)$</th>
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</thead>
<tbody>
<tr>
<td>This measurement</td>
<td>$(2.88 \pm 0.1 \pm 0.46 \pm 0.68) \times 10^{-3}$</td>
</tr>
<tr>
<td>PDG</td>
<td>$&lt; 3.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>pQCD (PLB 702 (2011) 49–54)</td>
<td>$1.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>Meson loop (PLB 711 (2012) 364–370)</td>
<td>$1.76 \times 10^{-3}$</td>
</tr>
<tr>
<td>Light fork states mixing</td>
<td>$5.2 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Isospin violated process $\eta(1405) \rightarrow \pi^+\pi^-\pi^0$ was observed, what about $\eta_c \rightarrow \pi^+\pi^-\pi^0$?

BESIII has observed the $\eta(1405) \rightarrow f_0(980)\pi^0$ which is iso-spin violated process, And the width of $f_0(980)$ is very narrow $\Gamma=9.5\pm1.1$ MeV.

This can be explained dominantly by the Triangle Singularity, the f0-a0 mixing’s contribution is small.
Search for $\psi(3686) \rightarrow \gamma \eta_c \rightarrow \gamma \pi^+ \pi^- \pi^0$

PRD96, 112008(2017)

- Based on $448.1 \times 10^6 \psi(3686)$ events
- Isospin violating(G Parity)

Uplimit at 90% C.L.

$Br(\psi(3686) \rightarrow \gamma \eta_c) \times Br(\eta_c \rightarrow \pi^+ \pi^- \pi^0) < 1.6 \times 10^{-6}$
\[ e^+e^- \rightarrow \pi^+\pi^- h_c, \ h_c \rightarrow \gamma \eta_c, \ \eta_c \rightarrow \text{exclusive channels} \]

**Using XYZ data at Ecms=4.23, 4.26, 4.36 and 4.42 GeV**

**Why use \( h_c \rightarrow \gamma \eta_c \)?**

\( \text{Br}(h_c \rightarrow \gamma \eta_c) \approx 50\% \) is much larger than \( \text{Br}(\psi' \rightarrow \gamma \eta_c) \approx 0.3\% \).

\( \text{If we assume the non-}\eta_c \text{ radiative decay rate of } h_c \) and \( \psi' \) is at the same level, then the interference between \( h_c \rightarrow \gamma \eta_c \) and non-\( \eta_c \) process \( h_c \rightarrow \gamma + \text{hadrons} \) should be much smaller than \( \psi' \) or J/\( \psi \) decay.
method

• The $\eta_c$ is reconstructed **inclusively** by the recoiled mass of $(\gamma \pi^+ \pi^-)$.

• $\eta_c$ is also reconstructed **exclusively** for four channels $\eta_c \rightarrow K^+ K^- \pi^0$, $K_S^0 K^\pm \pi^\mp$, $2(\pi^+ \pi^- \pi^0)$, $p \bar{p}$.

• Then the branching fraction of four exclusive channels can be measured to be

$$BF(\eta_c \rightarrow X) = \frac{N_i^{\text{exclusive}}}{N_i^{\text{inclusive}}} \times \frac{\epsilon_i^{\text{exclusive}}}{\epsilon_i^{\text{inclusive}}} .$$
The plots here are the sum of four energy points. A simultaneous fit is performed to all four channels and inclusive result from all four energy points.
### Branching fraction result

<table>
<thead>
<tr>
<th>Final states</th>
<th>BF (%)</th>
<th>BF (%) from Ref. [6]</th>
<th>BF (%) from PDG [7]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ K^- \pi^0$</td>
<td>1.15 ± 0.12 ± 0.10</td>
<td>1.04 ± 0.17 ± 0.11 ± 0.10</td>
<td>7.3 ± 0.5 $(K\bar{K}\pi)$</td>
</tr>
<tr>
<td>$K_S^0 K^\pm \pi^\mp$</td>
<td>2.60 ± 0.21 ± 0.20</td>
<td>2.60 ± 0.29 ± 0.34 ± 0.25</td>
<td></td>
</tr>
<tr>
<td>$2(\pi^+\pi^-\pi^0)$</td>
<td>15.3 ± 1.8 ± 1.8</td>
<td>17.23 ± 1.70 ± 2.29 ± 1.66</td>
<td>17.4 ± 3.3</td>
</tr>
<tr>
<td>$\bar{p}p$</td>
<td>0.120 ± 0.026 ± 0.015</td>
<td>0.15 ± 0.04 ± 0.02 ± 0.01</td>
<td>0.152 ± 0.016</td>
</tr>
</tbody>
</table>

**Result of this measurement**

Previous BESIII measurement with $\psi(3686) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c$

The result agree pretty well with previous measurement, with more and more XYZ Data that BESIII is still taking, better result can be expected.
The multiplicity of charged tracks from $\eta_c$ decay

The multiplicity is measured using unfolding method

$$\chi^2 = \sum_{i=1}^{8} \frac{(N_{i}^{\text{obs}} - \sum_{j=0}^{8} \epsilon_{ij} \cdot N_j)^2}{(\sigma_{i}^{\text{obs}})^2}$$
Summary

• $\eta_c \rightarrow \phi\phi, \omega\phi, \omega\omega$ are measured. $\text{Br}(\eta_c \rightarrow \gamma\gamma)$ is larger than pQCD prediction, the non-perturbative effect might be needed.
• The isospin violated process $\eta_c \rightarrow \pi^+\pi^-\pi^0$ is searched and no significant signal observed.
• $e^+e^- \rightarrow \pi^+\pi^- h_c, h_c \rightarrow \gamma\eta_c, \eta_c \rightarrow \text{hadrons}$ are measured with XYZ data
• The charged track multiplicity of $\eta_c$ is measured.
SU(3) symmetry

• By SU(3) symmetry, the branching ration between the four VV channels of $\eta_c$ decay is

$$\phi\phi: \omega\omega: \rho^0\rho^0: K^*0 \bar{K}^*0 = 1:1:1:2$$

<table>
<thead>
<tr>
<th>channel</th>
<th>Br (10^{-3})</th>
<th>Source</th>
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<tr>
<td>$\phi\phi$</td>
<td>$2.5 \pm 0.3^{+0.3}_{-0.7} \pm 0.6$</td>
<td>BESIII</td>
</tr>
<tr>
<td>$\omega\omega$</td>
<td>$2.88 \pm 0.1 \pm 0.46 \pm 0.68$</td>
<td>BESIII</td>
</tr>
<tr>
<td>$\rho^0\rho^0$</td>
<td>$6 \pm 1.7$</td>
<td>PDG</td>
</tr>
<tr>
<td>$K^*0 \bar{K}^*0$</td>
<td>$4.55 \pm 1.3$</td>
<td>PDG</td>
</tr>
</tbody>
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