New results on h_c and $\eta_c(2S)$ decays at BESIII

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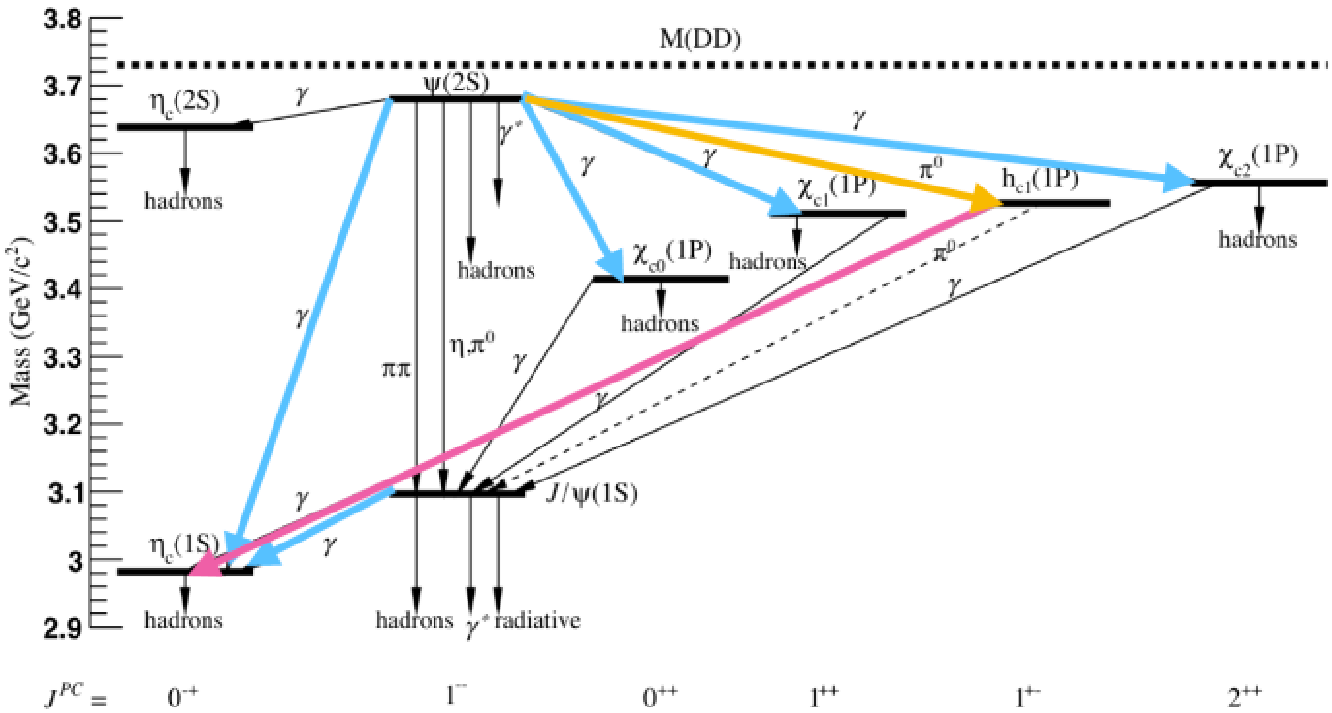
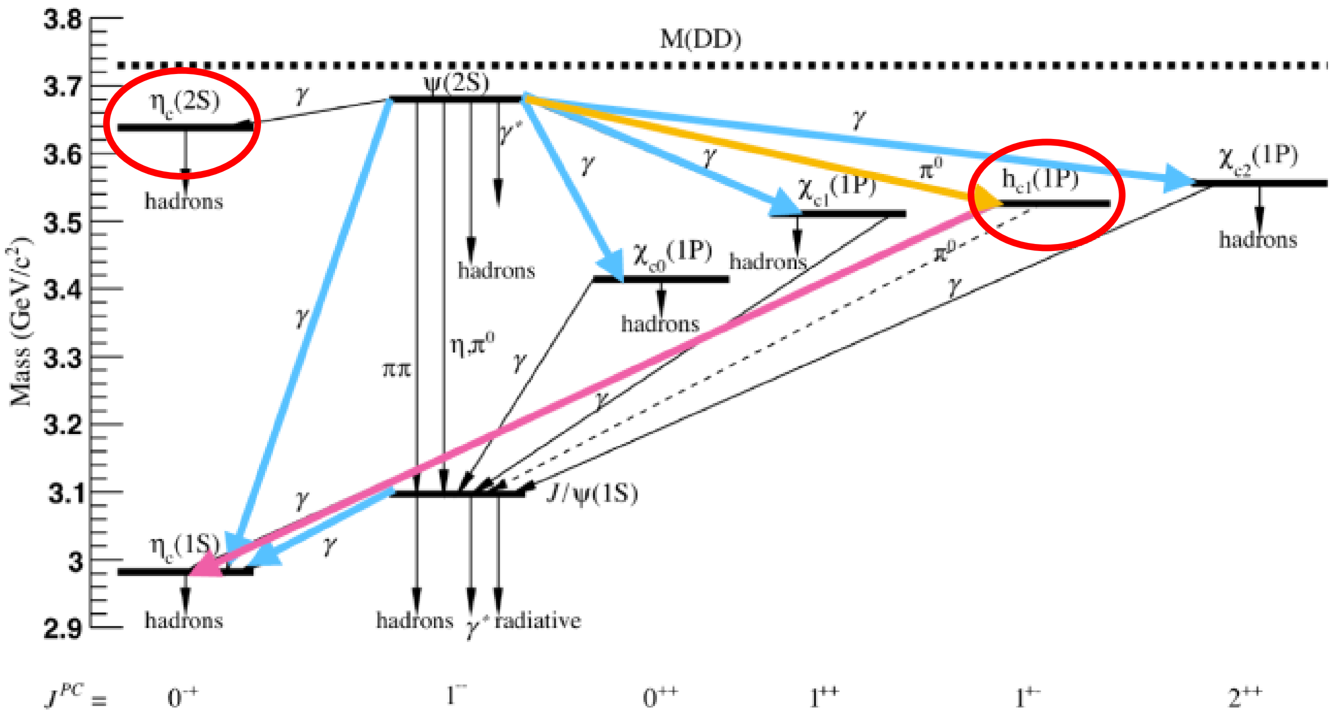
Charmonium spectrum



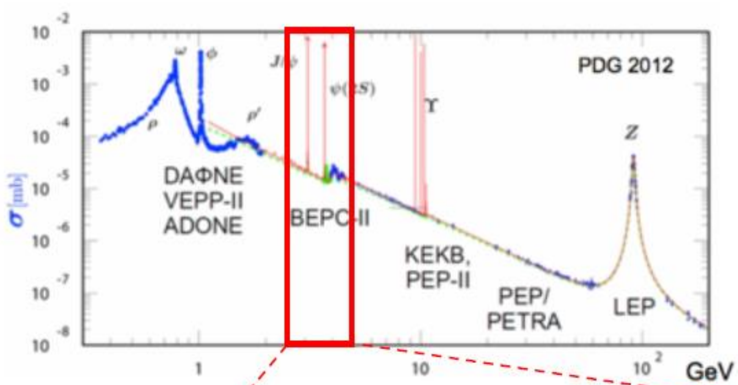
- ➢ **Charmonium states located in the transition region between non-perturbative and perturbative quantum chromodynamics (QCD), so the charmonium decays are important probes of strong interaction.**
- ➢ **Various theoretical models make predictions for charmonium decays, precise experimental measurements are needed to test models.**
- ➢ **New observed charmonium decays can provide more new information for theory.**

Charmonium spectrum

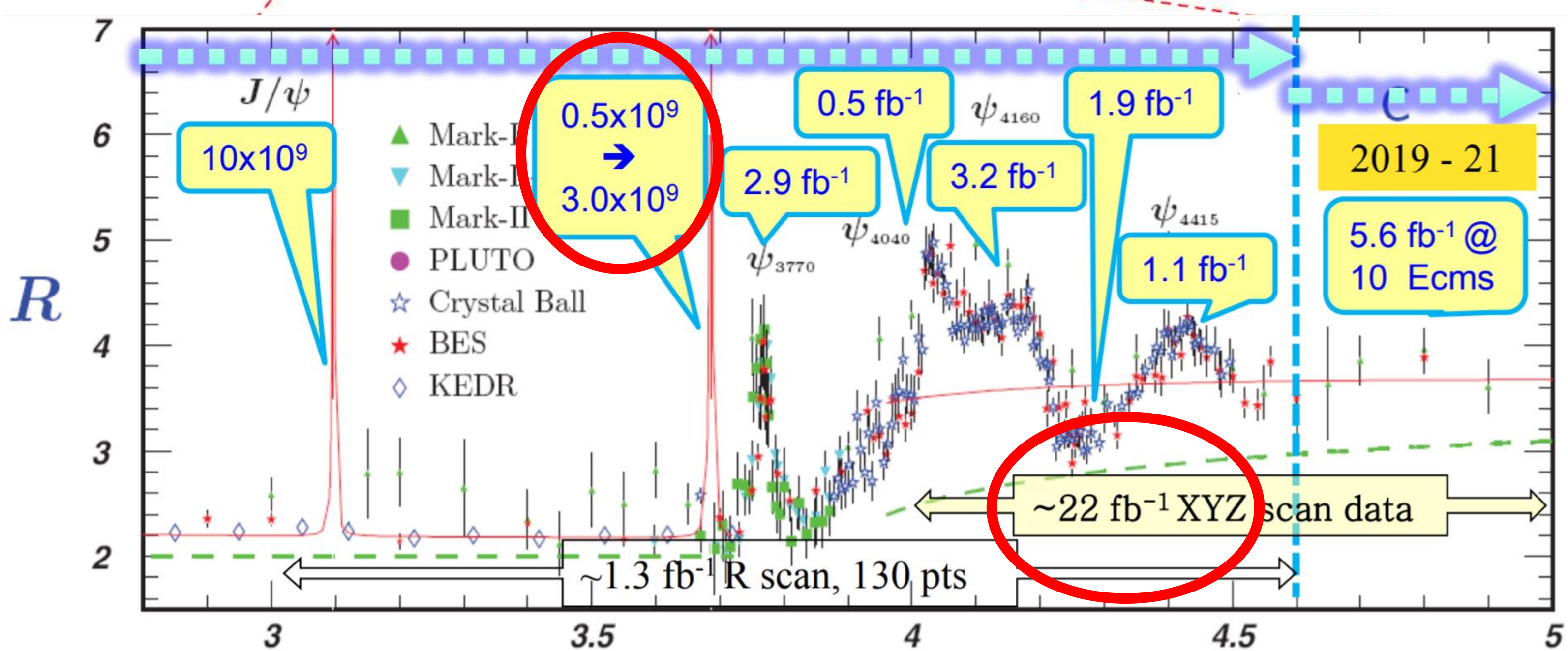


- **Among them, knowledge is very sparse on the P-wave spin-singlet h_c and S-wave spin-singlet $\eta_c(2S)$. They are generally obtained by $\psi(3686) \to \pi^0 h_c$ and $\psi(3686) \to \gamma\eta_c(2S)$, so the yield is low.**
- **Only a few decay modes of h_c and $\eta_c(2S)$ have been observed. Search for new decays of them can provide useful information to constrain theoretical models in the charmonium region.**

BESIII data samples



BESIII has collected the largest data samples of the J/ψ and $\psi(3686)$ in the world, and $> 20\ \mathrm{fb}^{-1}$ above $4.0\ \mathrm{GeV}$ in total.



Recent results on h_c and $\eta_c(2S)$ decays

h_c decays

- $h_c \to p\bar{p}\pi^+\pi^-\pi^0$
- $h_c \to p\bar{p}\eta$
- $h_c \to p\bar{p}\pi^0$
- $h_c \to \pi^0 J/\psi$

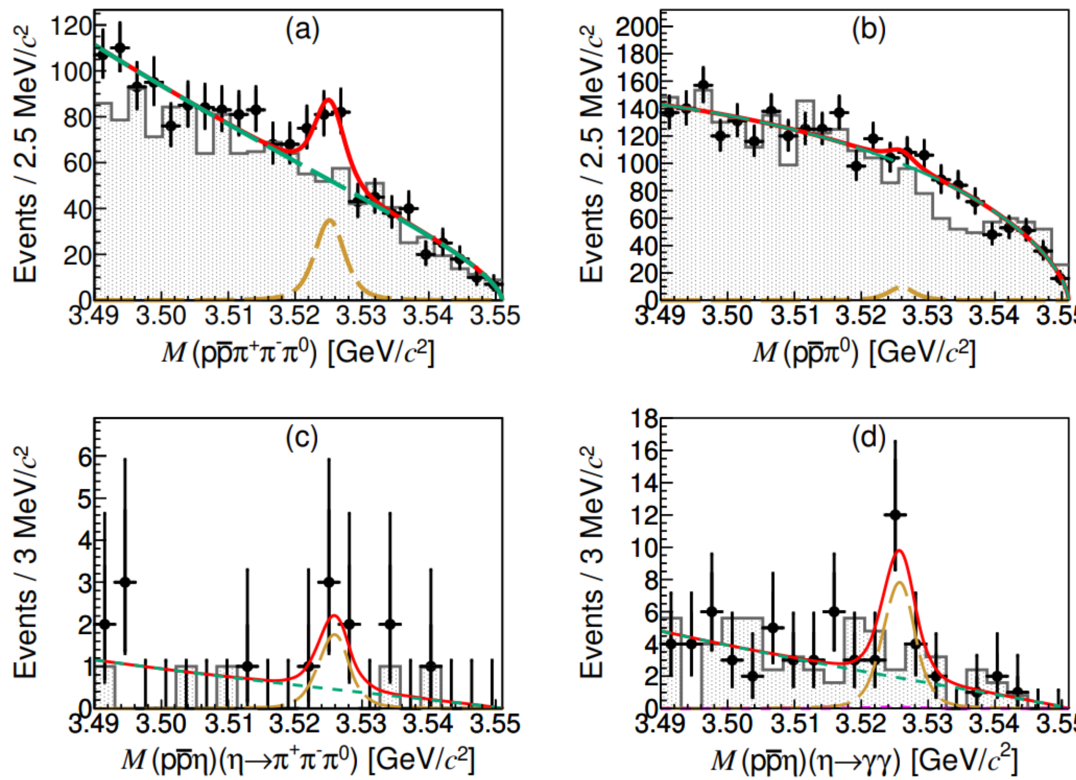
$\eta_c(2S)$ decay

- $\eta_c(2S) \to 3(\pi^+\pi^-)$

Search for new hadronic decays of h_c via $\psi(3686) \to \pi^0 h_c$

JHEP 05, 108 (2022)

- The dominant h_c decay is electric dipole (E1) transition $h_c \to \gamma\eta_c$ (~50%).
- The sum of all measured branching fractions for h_c non-E1 decays is ~3%, so there are many unknown h_c decay modes.
- About 0.4 M h_c events can be produced via $\psi(3686) \to \pi^0 h_c$ based on 448 M $\psi(3686)$ events.
- First search for $h_c \to p\bar{p}X$ ($X = \pi^+\pi^-\pi^0$, η, π^0) decays.



Search for new hadronic decays of h_c via $\psi(3686) \to \pi^0 h_c$

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Mode	I	III
$p\bar{p}X$	$p\bar{p}\pi^+\pi^-\pi^0$	$p\bar{p}\pi^0$
N_{h_c}	86.5 ± 18.7	< 57
$\mathcal{B}(h_c \to p\bar{p}X)$	$(3.84 \pm 0.83 \pm 0.69 \pm 0.58) \times 10^{-3}$	$< 6.59 \times 10^{-4}$
$\mathcal{B}(\psi(3686) \to \pi^0 h_c) \times \mathcal{B}(h_c \to p\bar{p}X)$	$(3.30 \pm 0.71 \pm 0.59) \times 10^{-6}$	$< 5.67 \times 10^{-7}$
Significance(σ)	4.9	—

Mode	II	
$p\bar{p}\eta$	$\eta \to \pi^+\pi^-\pi^0$	$\eta \to \gamma\gamma$
N_{h_c}	3.4 ± 0.9	18.1 ± 4.9
$\mathcal{B}(h_c \to p\bar{p}\eta)$	$(6.41 \pm 1.74 \pm 0.53 \pm 1.00) \times 10^{-4}$	
$\mathcal{B}(\psi(3686) \to \pi^0 h_c) \times \mathcal{B}(h_c \to p\bar{p}\eta)$	$(5.51 \pm 1.50 \pm 0.46) \times 10^{-7}$	
Significance(σ)	5.1	

- The decay $h_c \to p\bar{p}\eta$ is observed, evidence for the decay $h_c \to p\bar{p}\pi^+\pi^-\pi^0$ is found, no significant signal for $h_c \to p\bar{p}\pi^0$ is seen.
- The branching fractions obtained in this work are at the level of $\sim 10^{-3}$, which is the same level as the previously observed decays $h_c \to 2(\pi^+\pi^-)\pi^0$, $p\bar{p}\pi^+\pi^-$, $K^+K^-\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^0\eta$ and $K_S^0 K^\pm \pi^\mp \pi^+\pi^-$.
- It is still unclear whether the hadronic decay width of the h_c is of the same order as the radiative decay width. Further experimental measurements can help us to answer the question.

Search for the decay $h_c \to \pi^0 J/\psi$ via $e^+e^- \to \pi^+\pi^- h_c$

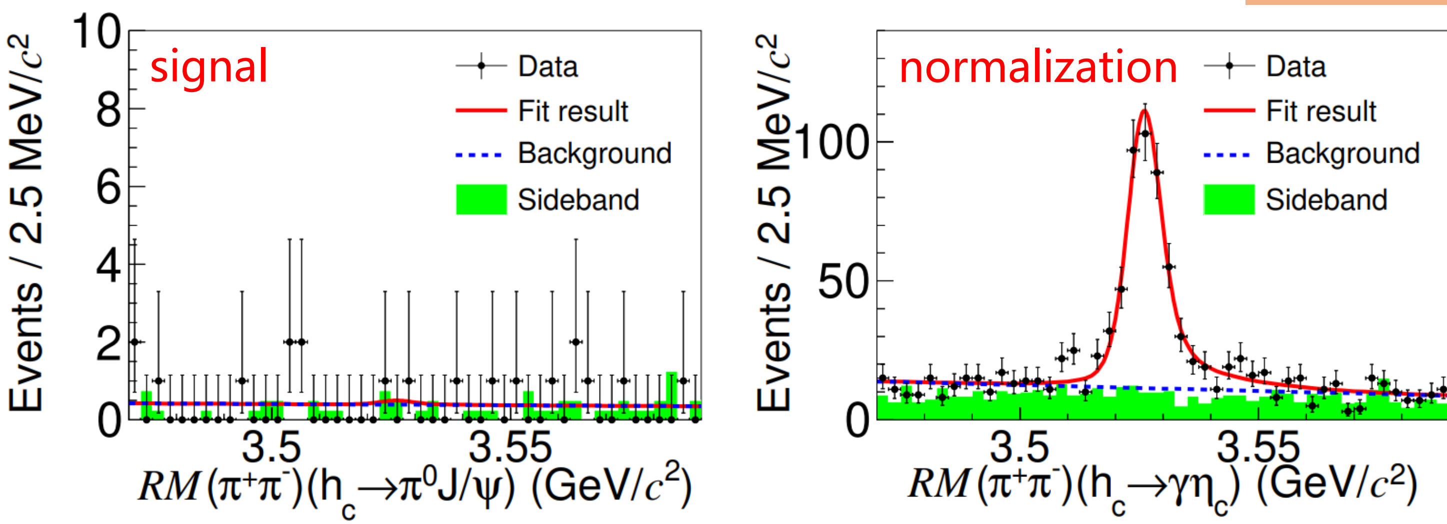
JHEP 05, 003 (2022)

- In 1992, the E760 Collaboration reported an evidence of the h_c in the $\pi^0 J/\psi$ decay, but this was not confirmed by the successor experiment E835 with higher statistics in 2005. More measurements are needed for clarification.
- Several theoretical articles have addressed the decay $h_c \to \pi^0 J/\psi$, with predictions for the partial width around several keV. Until now, there is no experimental result to confirm this.
- It is hard to search for the decay $h_c \to \pi^0 J/\psi$ using the $\psi(3686)$ data sample due to the large background from $\psi(3686) \to \pi^0\pi^0 J/\psi$. A noval method is used to avoid this, we use $e^+e^- \to \pi^+\pi^- h_c$ events from data samples collected at center-of-mass energies between 4.189 and 4.437 GeV with a luminosity of 11 fb^{-1}.
- The decay $h_c \to \gamma\eta_c$ with $\eta_c \to K^+K^-\pi^0$ is used as the normalization channel.

$$\frac{\mathcal{B}(h_c \to \pi^0 J/\psi)}{\mathcal{B}(h_c \to \gamma\eta_c \to \gamma K^+K^-\pi^0)} = \frac{N_{\pi^0 J/\psi}}{N_{\gamma\eta_c}} \frac{\sum_i \mathcal{L}_i \sigma_i (1+\delta_i)\epsilon_i^{\gamma\eta_c}}{\sum_i \mathcal{L}_i \sigma_i (1+\delta_i)\epsilon_i^{\pi^0 J/\psi}} \frac{1}{\mathcal{B}(J/\psi \to \ell^+\ell^-)}$$

Search for the decay $h_c \to \pi^0 J/\psi$ via $e^+e^- \to \pi^+\pi^- h_c$

JHEP 05, 003 (2022)



- The decay $h_c \to \pi^0 J/\psi$ is searched for using the process $e^+e^- \to \pi^+\pi^- h_c$, no significant signal is observed.
- $\frac{\mathcal{B}(h_c\to\pi^0 J/\psi)}{\mathcal{B}(h_c\to\gamma\eta_c\to\gamma K^+K^-\pi^0)} < 7.5\times10^{-2}$, $\mathcal{B}(h_c \to \pi^0 J/\psi) < 4.7\times10^{-4}$ and $\Gamma(h_c \to \pi^0 J/\psi) < 0.52$ keV.
- The measured results are not consistent with the measurements by the E760 Collaboration, while in agreement with the E835 Collaboration.
- The upper limit on the partial width for $h_c \to \pi^0 J/\psi$ is one order-of-magnitude lower than the current theoretical predictions (several keV).

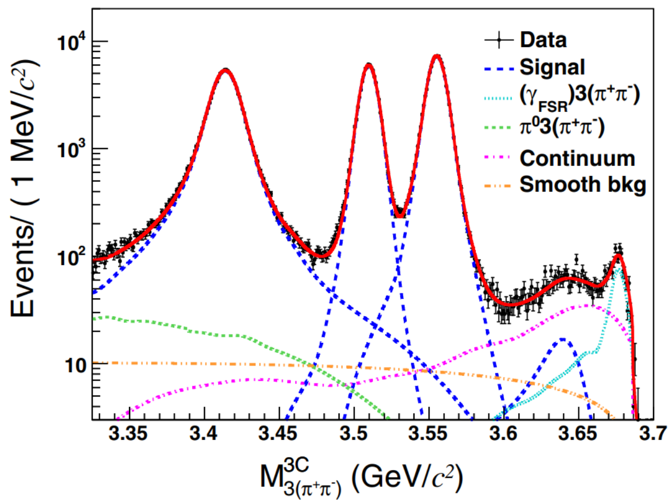
Observation of $\eta_c(2S) \to 3(\pi^+\pi^-)$ via $\psi(3686) \to \gamma\eta_c(2S)$

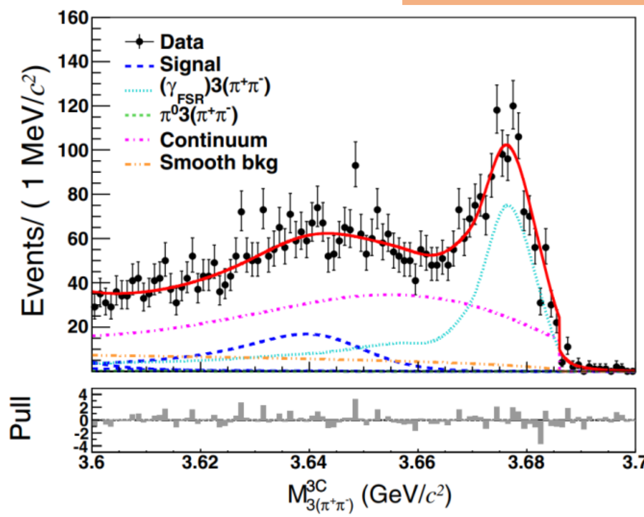
PRD 106, 032014 (2022)

- The ratio of branching fractions of $\psi(3686)$ and J/ψ decaying into the same light hadron final states is predicted to be around 12%. This is valid in most of the measured hadronic channels, except for the decays into pseudoscalar vector pairs and vector tensor pairs.
- $\eta_c(2S)$ and $\eta_c(1S)$ are the spin-singlet partners of $\psi(3686)$ and J/ψ, but two theoretical papers predict two different ratios for $\frac{\mathcal{B}[\eta_c(2S)\to\text{hadrons}]}{\mathcal{B}[\eta_c(1S)\to\text{hadrons}]}$, which are $\frac{\mathcal{B}[\eta_c(2S)\to\text{hadrons}]}{\mathcal{B}[\eta_c(1S)\to\text{hadrons}]} \simeq \frac{\mathcal{B}[\psi(3686)\to\text{hadrons}]}{\mathcal{B}[J/\psi\to\text{hadrons}]} \simeq 12\%$ or $\frac{\mathcal{B}[\eta_c(2S)\to\text{hadrons}]}{\mathcal{B}[\eta_c(1S)\to\text{hadrons}]} \simeq 1$.
- Currently, only a few decay modes of $\eta_c(2S)$ are observed with large uncertainty experimentally. The sum of these decay modes is around 5% of the total width of $\eta_c(2S)$.
- Among the discovered decay modes of $\eta_c(1S)$, the decay rate of $\eta_c(1S) \to 3(\pi^+\pi^-)$ is relatively large. It is promising to search for $\eta_c(2S) \to 3(\pi^+\pi^-)$.

Observation of $\eta_c(2S) \to 3(\pi^+\pi^-)$ via $\psi(3686) \to \gamma\eta_c(2S)$

PRD 106, 032014 (2022)





- Hadronic decay $\eta_c(2S) \to 3(\pi^+\pi^-)$ is observed for the first time with a significance of 9.3σ.
- $\mathcal{B}[\psi(3686) \to \gamma\eta_c(2S)] \times \mathcal{B}[\eta_c(2S) \to 3(\pi^+\pi^-)] = (9.2 \pm 1.0 \pm 1.2) \times 10^{-6}$.
  $\mathcal{B}[\eta_c(2S) \to 3(\pi^+\pi^-)] = (1.31 \pm 0.15 \pm 0.17^{+0.64}_{-0.47}) \times 10^{-2}$, the third uncertainty is from $\mathcal{B}[\psi(3686) \to \gamma\eta_c(2S)]$.
- The ratio of branching fraction is calculated to be $\frac{\mathcal{B}[\eta_c(2S)\to 3(\pi^+\pi^-)]}{\mathcal{B}[\eta_c(1S)\to 3(\pi^+\pi^-)]} = 0.77 \pm 0.59$.
- This measured ratio seems to lean slightly towards the prediction from $\frac{\mathcal{B}[\eta_c(2S)\to \text{hadrons}]}{\mathcal{B}[\eta_c(1S)\to \text{hadrons}]} \simeq 1$ over the prediction from $\frac{\mathcal{B}[\eta_c(2S)\to \text{hadrons}]}{\mathcal{B}[\eta_c(1S)\to \text{hadrons}]} \simeq 12\%$, but is compatible with both predictions.

Summary

- BESIII has collected the large data samples around charmonium energy region. 10 Billion J/ψ, 3 Billion $\psi(3686)$.
- It is an excellent laboratory to study charmonium decays:
  - High statistics
  - Low background
- Some h_c and $\eta_c(2S)$ decay channels have been studied:
  - Observation of $h_c \to p\bar{p}\eta$ and evidence for $h_c \to p\bar{p}\pi^+\pi^-\pi^0$
  - Upper limit on the decay $h_c \to \pi^0 J/\psi$
  - Observation of $\eta_c(2S) \to 3(\pi^+\pi^-)$
- Future:
  - More data will be collected
  - More detailed studies will be done

More results will come out !!!

Thanks for your attention!