Novel Observations in charmonium Decays

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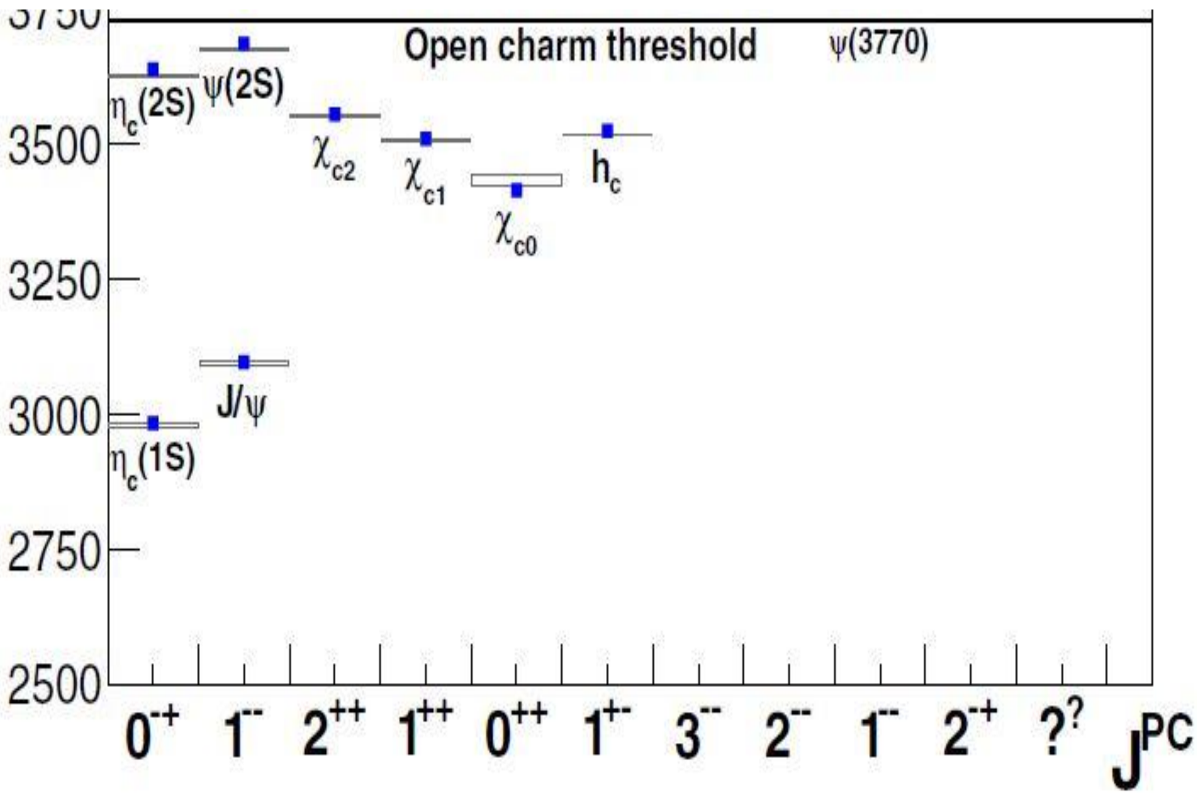
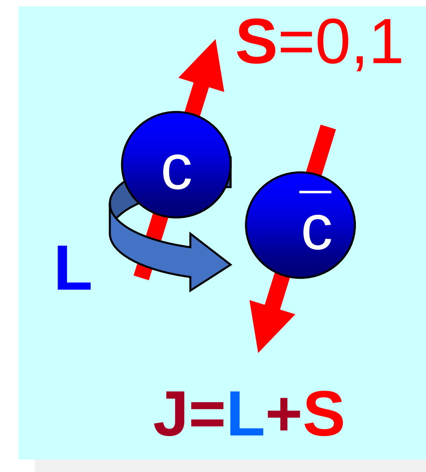
BESIII

Outline

- **Introduction**
  - ✓ Physics motivation
  - ✓ BESIII experiment
- **Recent observations on charmonium decays**
  - $\psi(3686) \to \phi\phi\phi$
  - Search for $\eta_c(2S) \to \pi^+\pi^-\eta_c, \pi^+\pi^-K_S^0K^\pm\pi^\mp$
  - Observation of $\psi(3686) \to K^+\Omega^-\bar{\Xi}^0 + c.c.$
  - Observation of $\chi_{c0,1,2} \to 3(K^+K^-)$
- **Summary**

Charmonium Spectrum





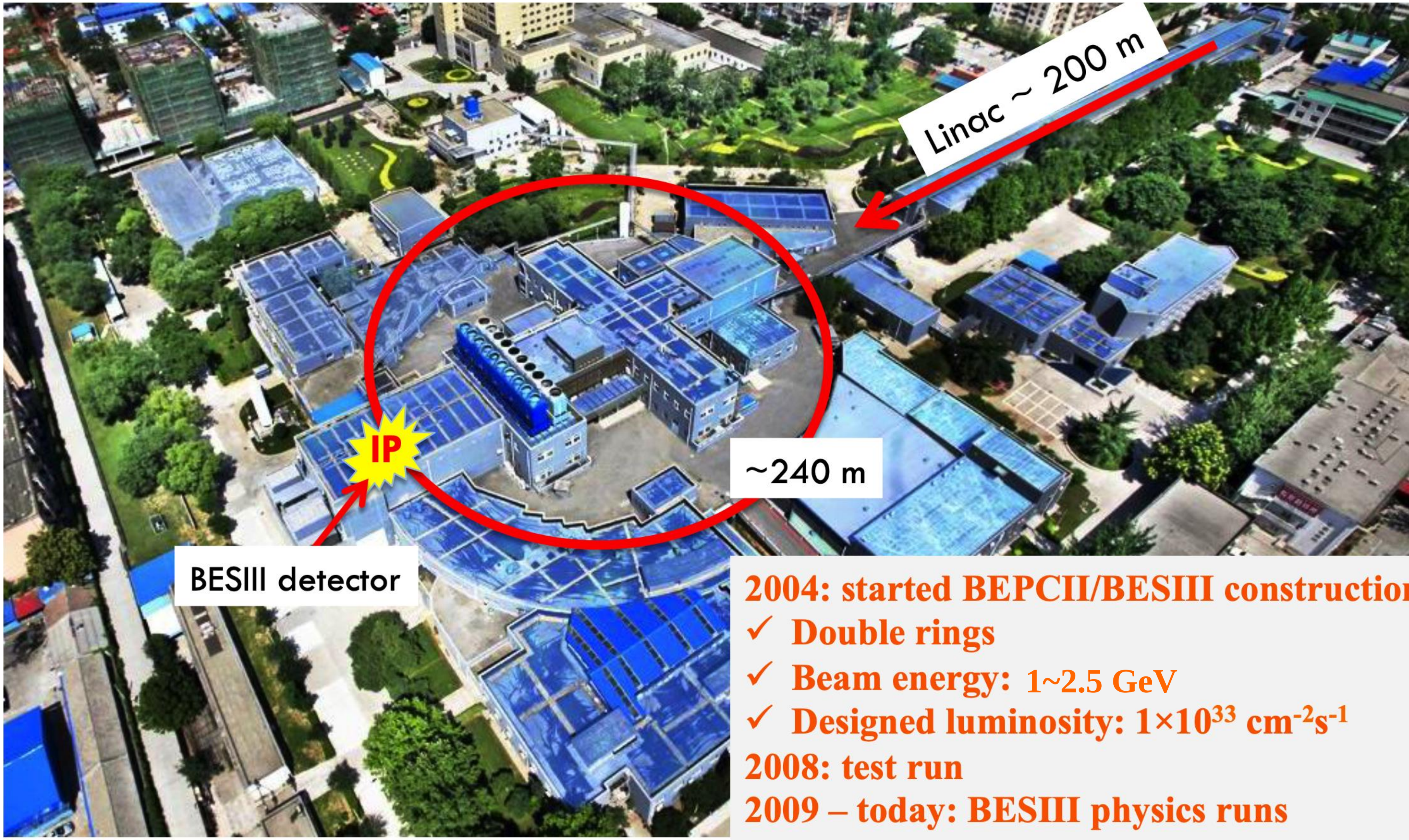
Traditional charmonium states are named as η,ψ,h_c,χ_c……

Kind reminder: $\psi(3686) \equiv \psi(2S) \equiv \psi'$

Physics Motivation

- The study of charmonium decays can provide valuable insights to improve the understanding of the inner charmonium structure and test phenomenological mechanisms of non-perturbative QCD
- For $\eta_c(2S)$,only few decay modes are observed ($\sum \mathcal{B}\sim 6\%$). Particularly, the transition amplitude of $\eta_c(2S) \to \pi^+\pi^-\eta_c$ decay is expected to exhibit the same linear dependence q^2 as $\psi(2S) \to \pi^+\pi^- J/\psi$.
- The study of a decay with three pairs of $s\bar{s}$ in the final state will expand our knowledge on the charmonium decay mechanism , such as the color octet and singlet contributions, the violation of helicity conservation, and SU(3) favor symmetry breaking effects.
- Theoretical studies indicate that the color octet mechanism may also influence the decays of the χ_{cJ} (J=0,1,2). Intensive measurements of χ_{cJ} (J=0,1,2) hadronic decays are highly desirable to understand the underlying their decay dynamics

BEPCII

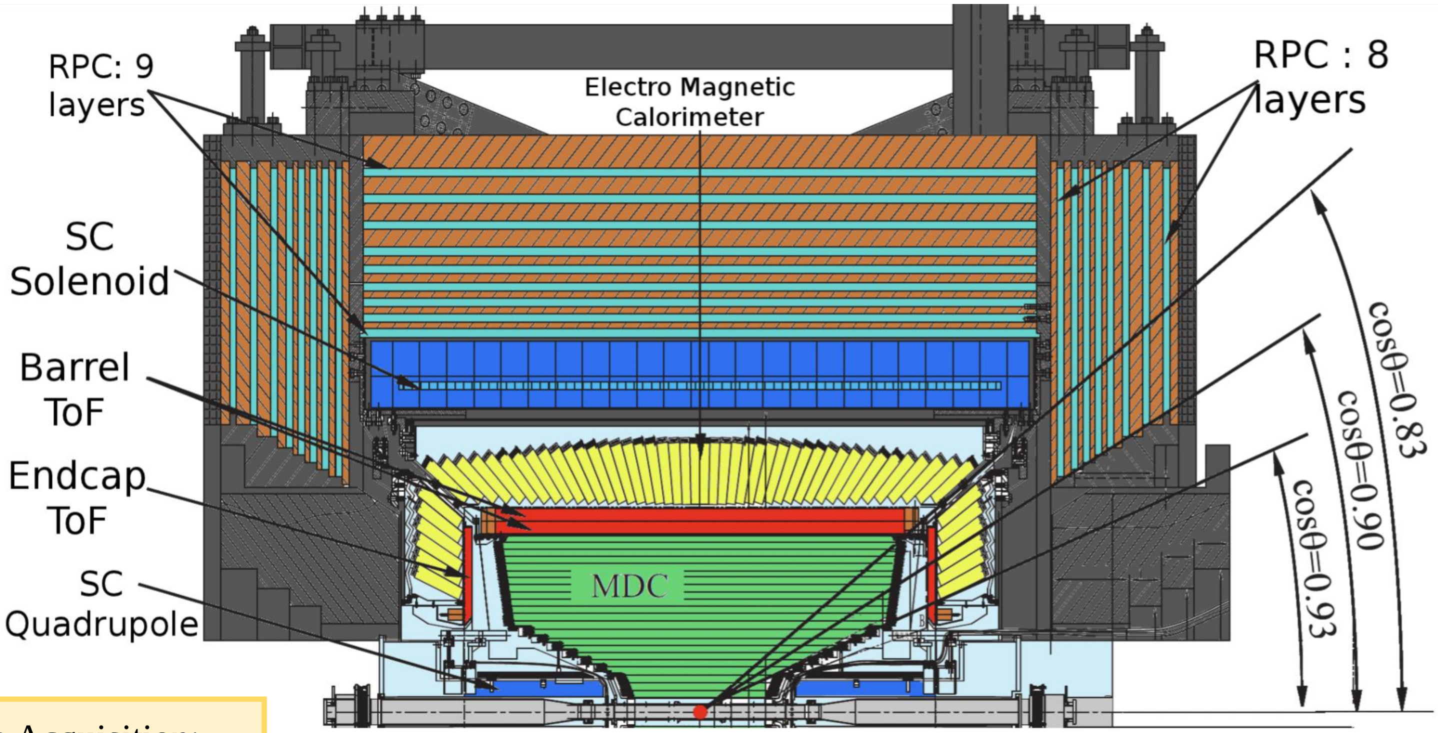


2004: started BEPCII/BESIII construction
- ✓ **Double rings**
- ✓ **Beam energy: 1~2.5 GeV**
- ✓ **Designed luminosity: 1×10^{33} $cm^{-2}s^{-1}$**

2008: test run
2009 – today: BESIII physics runs

BESIII Detector

Nucl. Instr. Meth. A614, 345 (2010)



Data Acquisition:
Event rate = 3 kHz
Throughput ~ 50 MB/s

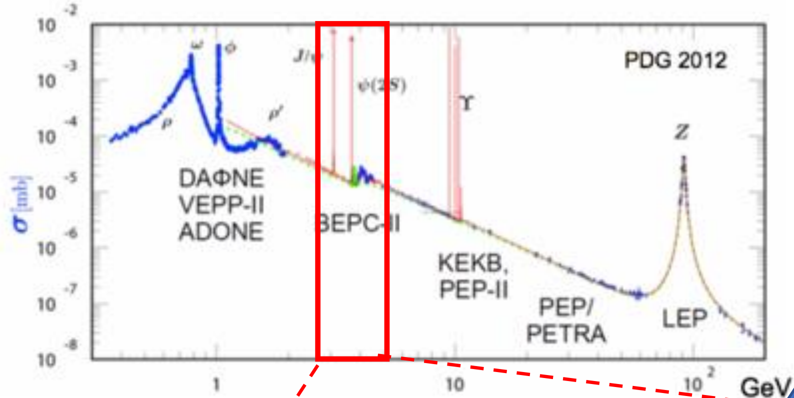
Drift Chamber
$\sigma_{r\varphi}$ ~ 130 μm (single wire)
σ_{pt}/p_t ~ 0.5 % @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
σ_E/E < 2.5% @ 1 GeV (barrel)
σ_E/E < 5% @ 1 GeV (end caps)
σ_{xy} ~ (6 mm)/$E^{1/2}$ @ 1 GeV

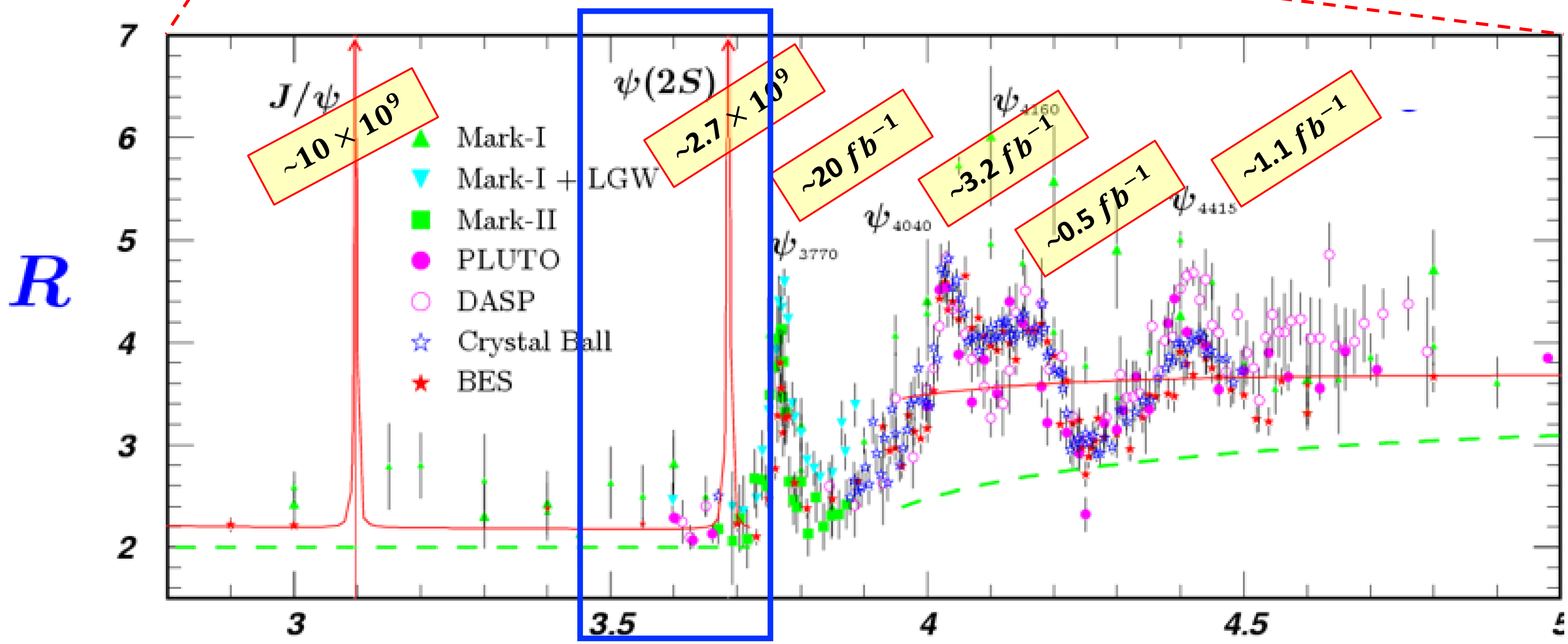
ToF
σ_t ~ 68 ps (barrel)
σ_t ~ 60ps (end caps)

RPC Muon Counter
$\Delta\Omega/4\pi$=93%

BESIII Data Collections



- ✓ BESIII detector has collected the largest data samples in the ψ energy region in the world.
- ✓ ~30% of $\psi(3686)$ produces χ_{cJ} in its EM radiative transition decay.



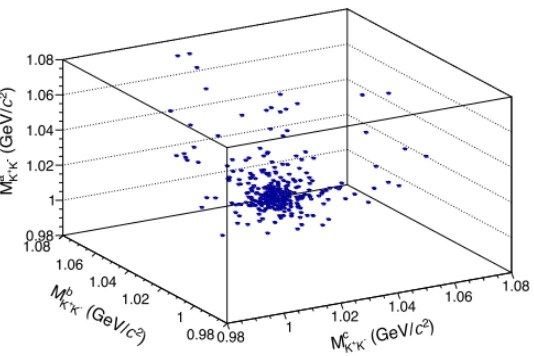
Recent Observations on charmonium decays

- Observation of $\psi(3686) \to \phi\phi\phi$
- Search for $\eta_c(2S) \to \pi^+\pi^-\eta_c, \pi^+\pi^-K_S^0K^\pm\pi^\mp$
- Observation of $\psi(3686) \to K^+\Omega^-\bar{\Xi}^0 + c.c.$
- Observation of $\chi_{cJ} \to 3(K^+K^-)$

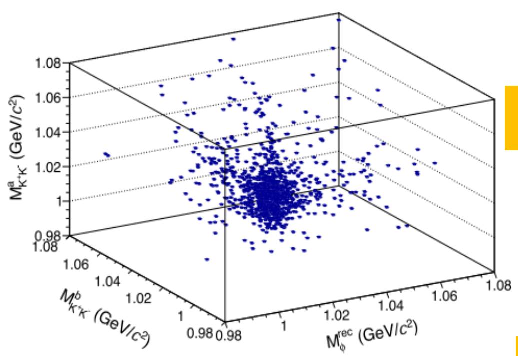
Observation of $\psi(3686) \to \phi\phi\phi$

PRD 109, 072015 (2024)

- For the decay of $\psi(3686) \to$ **3**-body, we have observed the $\psi(3686) \to$ ***PPP, PPV,VVP*** (P=pseudoscalar, V=vector) final states, but ***VVV*** mode hasn't been reported before.
- Both full and partial reconstruction techniques are employed to select signal events, and alternatively make a cross check. For partial reconstruction, one ϕ is missing and tagged by the recoil mass of another two reconstructed ϕ.



full



partial

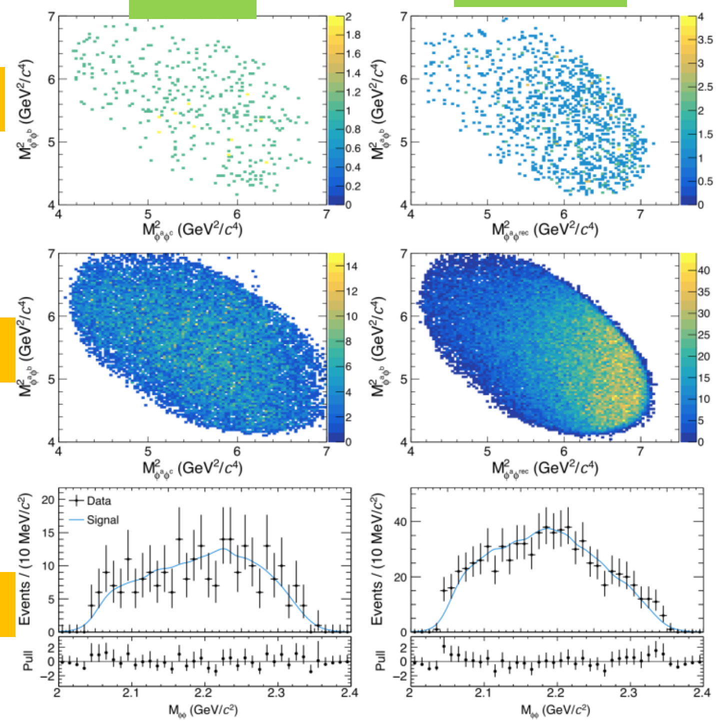
- The continuum background is estimated by the data at $\sqrt{s}$=3.773 GeV

full **partial**

data

MC

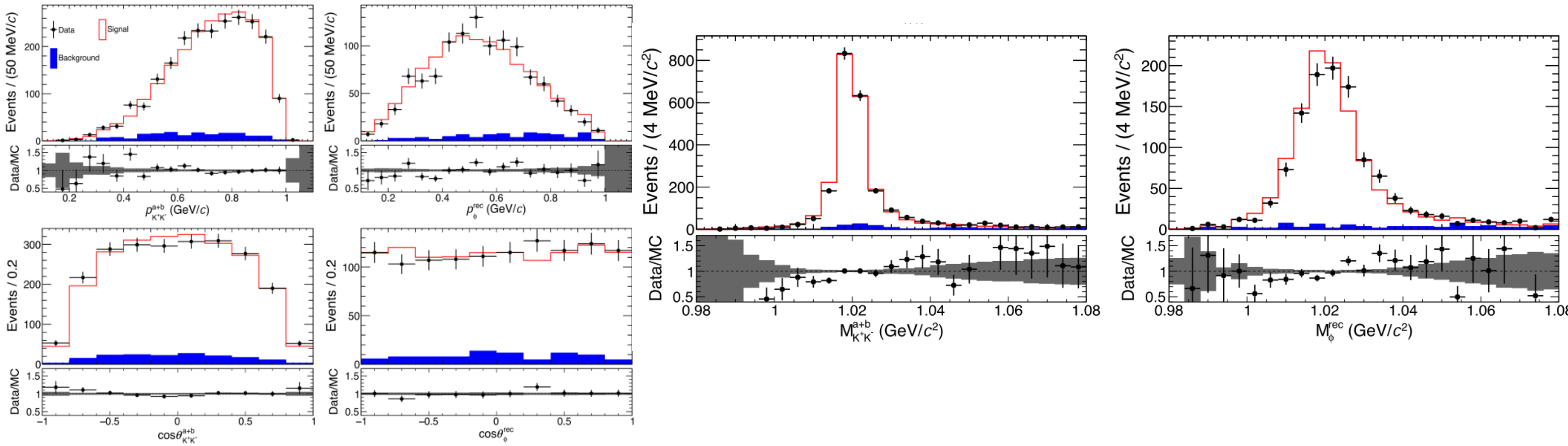
1-D



Observation of $\psi(3686) \to \phi\phi\phi$

PRD 109, 072015 (2024)

- Some comparisons between data and MC simulation are made, e.g., momentum, angular distribution, invariant mass. Good consistencies are found.



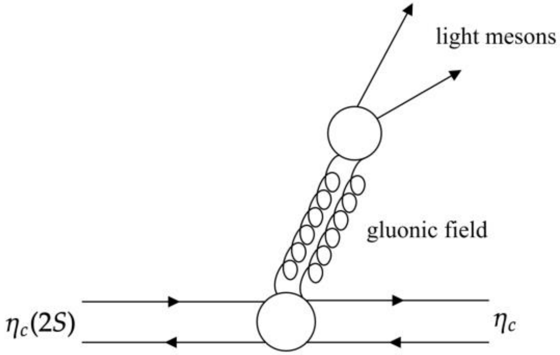
- No obvious intermediate state is found. The branching fraction is measured for the first time.

$$\mathcal{B}_{\psi(3686)\to3\phi} = \frac{N_{(3686)\to3\phi} - f_c \times N_{(3773)\to3\phi}}{N_{\psi(3686)}\mathcal{B}^3_{\phi\to K^+K^-}\epsilon_{\psi(3686)\to3\phi}} = (1.46 \pm 0.05 \pm 0.17) \times 10^{-5}.$$

Search for $\eta_c(2S) \to \pi^+\pi^-\eta_c, \eta_c \to K_S^0 K^\pm \pi^\mp$ decay

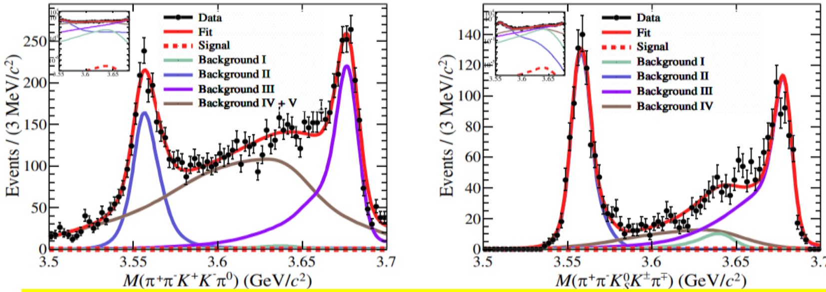
PRD109, 072017(2024)

- The branching fraction of $\eta_c(2S) \to \pi^+\pi^-\eta_c$ is estimated to be **~5%** with the single-channel approach, but it may be suppressed due to the chromo-magnetic interaction.



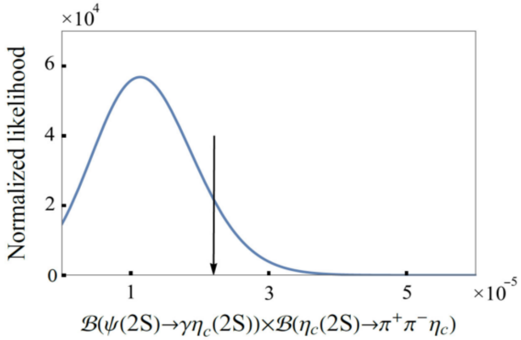
- No clear signal is observed in previous BABAR experiment.

- η_c are tagged by its golden decay channel, $KK\pi$, with two modes, $K^+K^-\pi^0, K_S^0K^\pm\pi^\mp$. But no obvious signals are found



After requiring $M(KK\pi)$ in η_c mass window

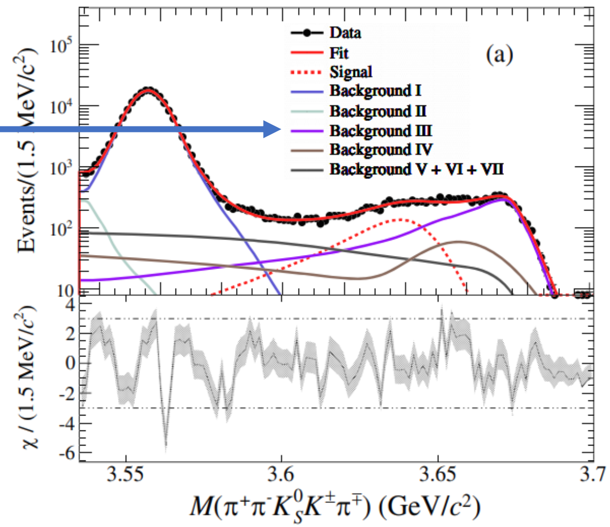
- The upper limit for product branching fraction $\mathcal{B}(\psi(2S) \to \gamma\eta_c(2S)) \cdot \mathcal{B}(\eta_c(2S) \to \pi^+\pi^-\eta_c)$ is set to be 2.21×10^{-5} using Bayesian method **@90%** C.L.

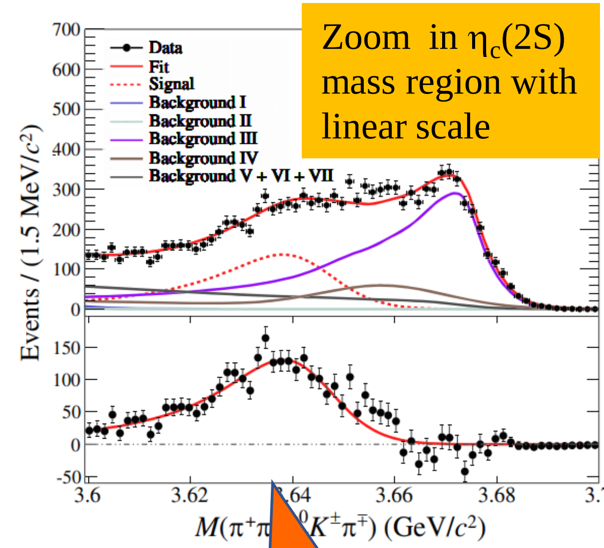


Search for $\eta_c(2S) \to \pi^+\pi^- K_S^0 K^\pm \pi^\mp$ decay

➢ **Removing the requirement of $M(KK\pi)$ in η_c mass window**

No.	Source
I	$\psi(2S) \to \gamma\chi_{c2}, \chi_{c2} \to \pi^+\pi^- K_S^0 K^\pm \pi^\mp$
II	$\psi(2S) \to \gamma\chi_{c1}, \chi_{c1} \to \pi^+\pi^- K_S^0 K^\pm \pi^\mp$
III	$\psi(2S) \to (\gamma_{\rm FSR})\pi^+\pi^- K_S^0 K^\pm \pi^\mp$
IV	Continuum production
V	$\psi(2S) \to \pi^0\pi^+\pi^- K_S^0 K^\pm \pi^\mp$
VI	$\psi(2S) \to \gamma\pi^+\pi^- K_S^0 K^\pm \pi^\mp$
VII	K/π misidentifications





Zoom in $\eta_c(2S)$ mass region with linear scale

After removing background contribution

TABLE V. Relative systematic uncertainties (%) in the measurement of the product branching fraction $\mathcal{B}(\psi(2S) \to \gamma\eta_c(2S)) \times \mathcal{B}(\eta_c(2S) \to \pi^+\pi^- K_S^0 K^\pm \pi^\mp)$.

Source	Uncertainty
$N_{\psi(2S)}$	0.5
Tracking	6.0
Photon reconstruction	1.0
K_S^0 reconstruction	1.0
Kinematic fit	2.0
J/ψ veto	3.8
Fit range	3.8
Signal shape	18.9
Background estimation	21.5
Total	29.8

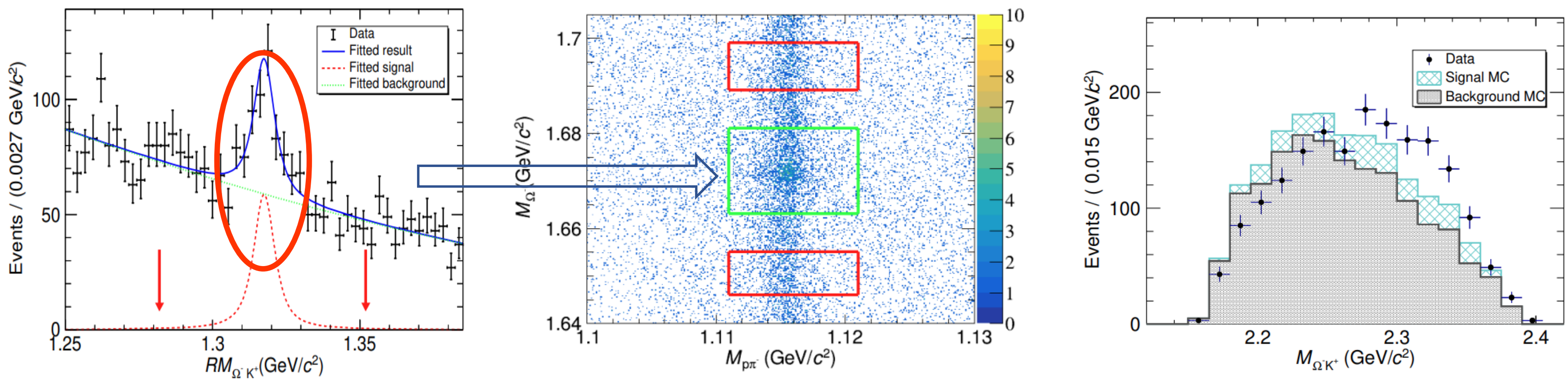
➢ The production branching fraction $\mathcal{B}(\psi(2S) \to \gamma\eta_c(2S)) \cdot \mathcal{B}(\eta_c(2S) \to \pi^+\pi^- K_S^0 K^\pm \pi^\mp)$ is measured to be $(9.31 \pm 0.72 \pm 2.77) \times 10^{-6}$, while $\mathcal{B}(\eta_c(2S) \to \pi^+\pi^- K_S^0 K^\pm \pi^\mp)$ is determined to be $(1.33 \pm 0.11 \pm 0.4 \pm 0.95) \times 10^{-2}$, the third uncertainty is from $\mathcal{B}(\psi(2S) \to \gamma\eta_c(2S))$ measurement.

➢ This measurement is consistent with our previous one, but with improved precision

Observation of $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0 + c.c.$

JHEP, 04 (2024) 013

- The study on 3-body decays of charmoniums are a bit poor for both theory and experiments relative to 2-body final states.
- Theoretical interest is stimulated by the discovery of $B\bar{B}$ mass threshold enhancements in some chomoium decays to 3-body decay final states.
- The study of baryon spectroscopy played an important role in the development of the quark model and QCD theory, but we haven't known well due to the small production rate. Only a few Ξ^* and Ω^* have been observed.
- In event selection, we just reconstruct $\Omega^- K^+$, $\bar{\Xi}^0$ is tagged by the recoil mass of $\Omega^- K^+$



$$\mathcal{B}_{\psi(3686)\to\Omega^- K^+ \bar{\Xi}^0 + \text{c.c.}} = \frac{N_{\text{obs.}} - N_{\text{QED}}}{N_{\psi(3686)} \cdot \mathcal{B}_{\Omega^- \to \Lambda K^-} \cdot \mathcal{B}_{\Lambda \to p^+ \pi^-} \cdot \epsilon} = (2.78 \pm 0.40 \pm 0.18) \times 10^{-6}$$

Observation of $\chi_{cJ} \to 3(K^+K^-)$

BESIII

- The sum of measured χ_{cJ} branching fractions are each still far less than **100%**. It indicates that there are a lot of unknown decay modes.

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- Intensive studies of χ_{cJ} multi-body decays are lacking relative to their few-body decays. The search for more new χ_{cJ} decay modes is useful in understanding their properties.
- We observe clear signal of $\chi_{cJ} \to 3(K^+K^-)$ for the first time , and the sub-resonant decays, $2\phi K^+K^-, \phi 2(K^+K^-)$, are also investigated by three-dimensional fit. The corresponding fractions are present.

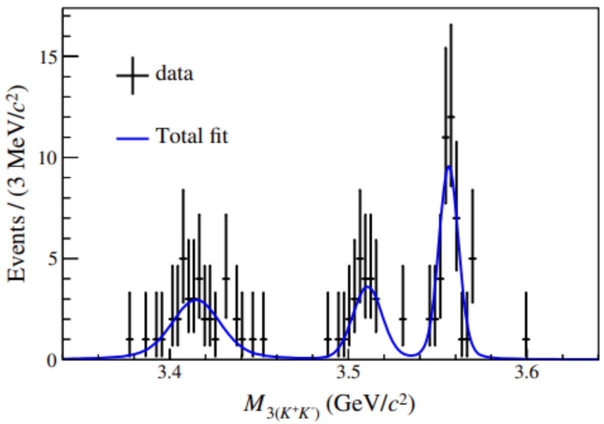

TABLE I. The fractions of the subresonant decays for the mixed signal MC events.

	$2\phi K^+K^-$	$\phi 2(K^+K^-)$	$3(K^+K^-)$
χ_{c0}	$0.480^{+0.167}_{-0.151}$	$0.038^{+0.306}_{-0.038}$	$0.481^{+0.139}_{-0.158}$
χ_{c1}	$1.000^{+0.131}_{-0.005}$	$0.000^{+0.125}_{-0.000}$	$0.000^{+0.041}_{-0.000}$
χ_{c2}	$0.783^{+0.243}_{-0.180}$	$0.217^{+0.179}_{-0.180}$	$0.000^{+0.222}_{-0.000}$

	χ_{c0}	χ_{c1}	χ_{c2}
$N_{\rm obs}$	37.7 ± 6.2	24.9 ± 5.1	46.4 ± 7.0
$\epsilon(\times 10^{-3})$	13.3 ± 0.1	22.3 ± 0.1	25.0 ± 0.2
$\mathcal{B}_{\psi(3686)\to\gamma\chi_{cJ}} \cdot \mathcal{B}_{\chi_{cJ}\to 3(K^+K^-)} (\times 10^{-7})$	10.5 ± 1.8	4.1 ± 0.9	6.8 ± 1.1
$\mathcal{B}_{\chi_{cJ}\to 3(K^+K^-)} (\times 10^{-6})$	10.7 ± 1.8	4.2 ± 0.9	7.2 ± 1.1

Summary

- The rare decay of $\psi(3686) \to \phi\phi\phi$ is observed for the first time, which provides a valuable insight into the dynamics of charmonium decay.
- The transition decay of $\eta_c(2S) \to \pi^+\pi^-\eta_c$ is searched, but no obvious signal is found. But clear signal for $\eta_c(2S) \to \pi^+\pi^-K_S^0K^\pm\pi^\mp$ is observed.
- The 3-body process of $\psi(3686) \to K^+\Omega^-\bar{\Xi}^0 + c.c.$ is observed for the first time. But no excited baryon candidates are found.
- The multi-body decay of $\chi_{cJ} \to 3(K^+K^-)$ is firstly observed. $\chi_{c0,1,2}$ show different patterns of the branching fractions with respect to the number of ϕ
- Much more results will be presented in the future.

Thank you!

Backup

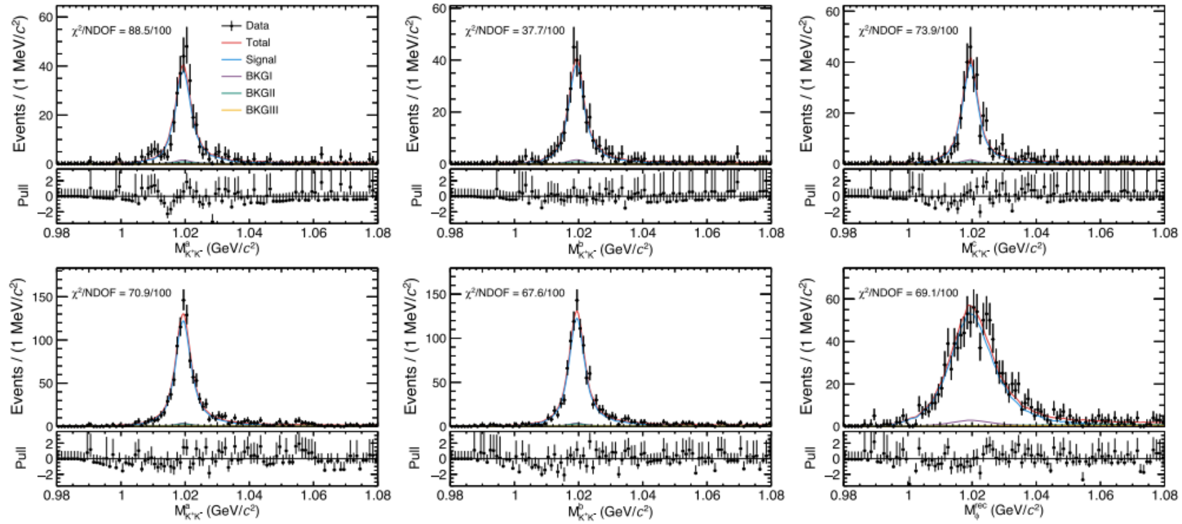

FIG. 5. One-dimensional projections of the simultaneous fit to the $M^a_{K^+K^-}$: $M^b_{K^+K^-}$: $M^c_{K^+K^-}$ ($M^{\rm rec}_\phi$) distribution of the (top row) full and (bottom row) partial reconstructed candidate events of $\psi(3686) \to 3\phi$ for $\psi(3686)$ data (shown as the dots with error bars). The red solid curves are the total fit results, while the blue curves are the signal contributions of the fit and other curves represent the different background contributions. For each projection, the χ^2/NDOF are provided, with χ^2 being calculated from the difference between the binned data points and the total fit projection, and the NDOF representing the number of bins.

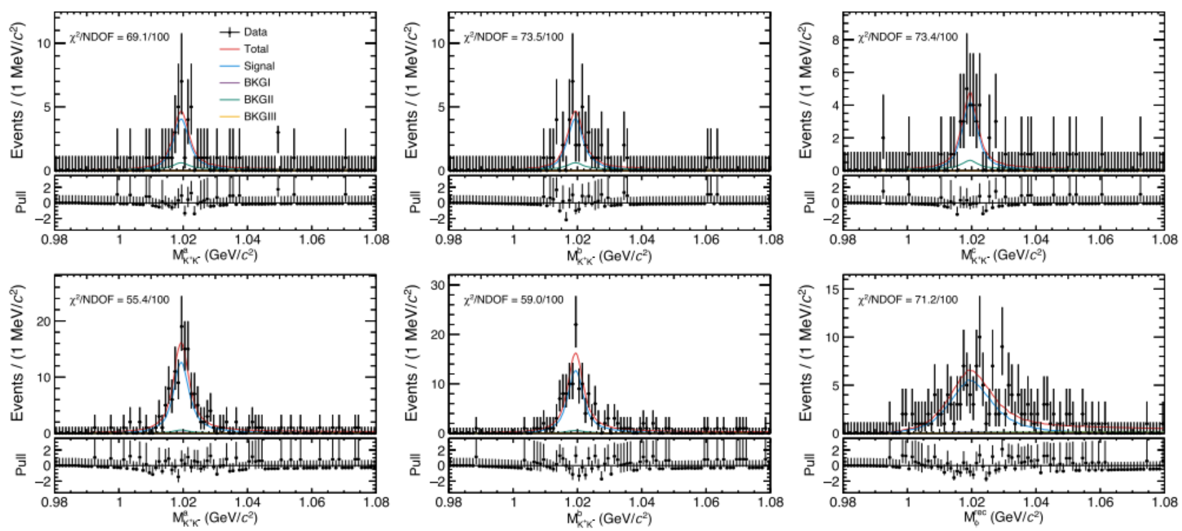

FIG. 6. One-dimensional projections of the simultaneous fit to the $M^a_{K^+K^-}$: $M^b_{K^+K^-}$: $M^c_{K^+K^-}$ ($M^{\rm rec}_\phi$) distribution of the (top row) full and (bottom row) partial reconstructed candidate events of $e^+e^- \to 3\phi$ for data taken at 3.773 GeV (shown as the dots with error bars). The red solid curves are the total fit results, while the blue curves are the signal contributions of the fit and other curves represent the different background contributions. For each projection, the χ^2/NDOF are given, with χ^2 being calculated from the difference between the binned data points and the total fit projection, and the NDOF representing the number of bins.

TABLE IV. Multiplicative systematic uncertainties (in %) in the measured branching fraction for $\eta_c(2S) \to \pi^+\pi^-\eta_c$.

Source	$\eta_c(2S)\to\pi^+\pi^-\eta_c$, $\eta_c\to K_S^0K^\pm\pi^\mp$	$\eta_c(2S)\to\pi^+\pi^-\eta_c$, $\eta_c\to K^+K^-\pi^0$	$\sigma^i_{\rm sum}$
$N_{\psi(2S)}$	0.5	0.5	0.5
Tracking	6.0	4.0	5.4
Photon reconstruction	1.0	3.0	1.6
K_S^0 reconstruction	1.0	...	0.7
π^0 reconstruction	...	1.0	0.3
Kinematic fit	2.0	2.5	2.1
J/ψ veto	4.4	4.0	3.3
η_c mass window	4.0	4.0	3.1
ω veto	...	0.1	0.03
η_c decay	11.2	13.6	8.9
Total	14.2	15.8	11.7
$\mathcal{B}(\psi(2S)\to\gamma\eta_c(2S))$	71.4		

that are correlated between these two decay modes, ρ_{12} is taken as 1. Finally, the total combined systematic uncertainty $\sigma_{\rm sum}$ is assigned as

$$\sigma_{\rm sum} = \sqrt{\Sigma(\sigma^i_{\rm sum})^2}, \quad (8)$$

$f_{\rm corr}$ by $\pm1\sigma$, changing the parametrization of continuum background, and changing the model of the cross-section dependence on the center-of-mass energy.

VI. SUMMARY

Based on $(27.12 \pm 0.14) \times 10^8$ $\psi(2S)$ events collected

TABLE IV. Multiplicative systematic uncertainties (in %) in the measured branching fraction for $\eta_c(2S) \to \pi^+\pi^-\eta_c$.

Source	$\eta_c(2S)\to\pi^+\pi^-\eta_c$, $\eta_c\to K_S^0K^\pm\pi^\mp$	$\eta_c(2S)\to\pi^+\pi^-\eta_c$, $\eta_c \to K^+K^-\pi^0$	$\sigma^i_{\rm sum}$
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VI. SUMMARY

Based on $(27.12 \pm 0.14) \times 10^8$ $\psi(2S)$ events collected

TABLE III. Relative systematic uncertainties in the branching fraction measurements (%). The last item is the systematic uncertainty of the introduced reference.

Source	χ_{c0}	χ_{c1}	χ_{c2}
$N_{\psi(3686)}$	0.5	0.5	0.5
$K^{\pm}$ tracking	6.0	6.0	6.0
$K^{\pm}$ PID	6.0	6.0	6.0
γ selection	1.0	1.0	1.0
Fractions of different subprocesses	3.3	0.8	2.4
$M_{3(K^+K^-)}$ fit	3.3	7.0	5.2
4C kinematic fit	3.0	3.0	3.0
Final state radiation	2.2	2.3	0.4
MC statistics	1.6	1.2	1.1
Sum	10.5	11.7	10.8
$\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ})$	2.0	2.4	2.0
Total	10.7	11.9	11.0

To estimate the systematic uncertainties of the MC model for the $\chi_{cJ} \to 3(K^+K^-)$ decays, we compare our nominal efficiencies with those determined from the signal MC events after varying ± 1 standard deviation of the relative fractions of the subresonant decays, including $\chi_{cJ} \to 2\phi K^+K^-$, $\chi_{cJ} \to \phi 2(K^+K^-)$, and $\chi_{cJ} \to 3(K^+K^-)$. The relative changes of efficiencies, which are 3.3%, 0.8%, and 2.4% for χ_{c0}, χ_{c1}, and χ_{c2} decays, respectively, are assigned as the corresponding systematic uncertainties.

The systematic uncertainty of the fit to the $M_{3(K^+K^-)}$ spectrum includes two parts:

(i) The first is from the signal shape, which is estimated by varying the width of the χ_{cJ} state by ± 1 standard