Measurement of Charmonium Decays from BESIII

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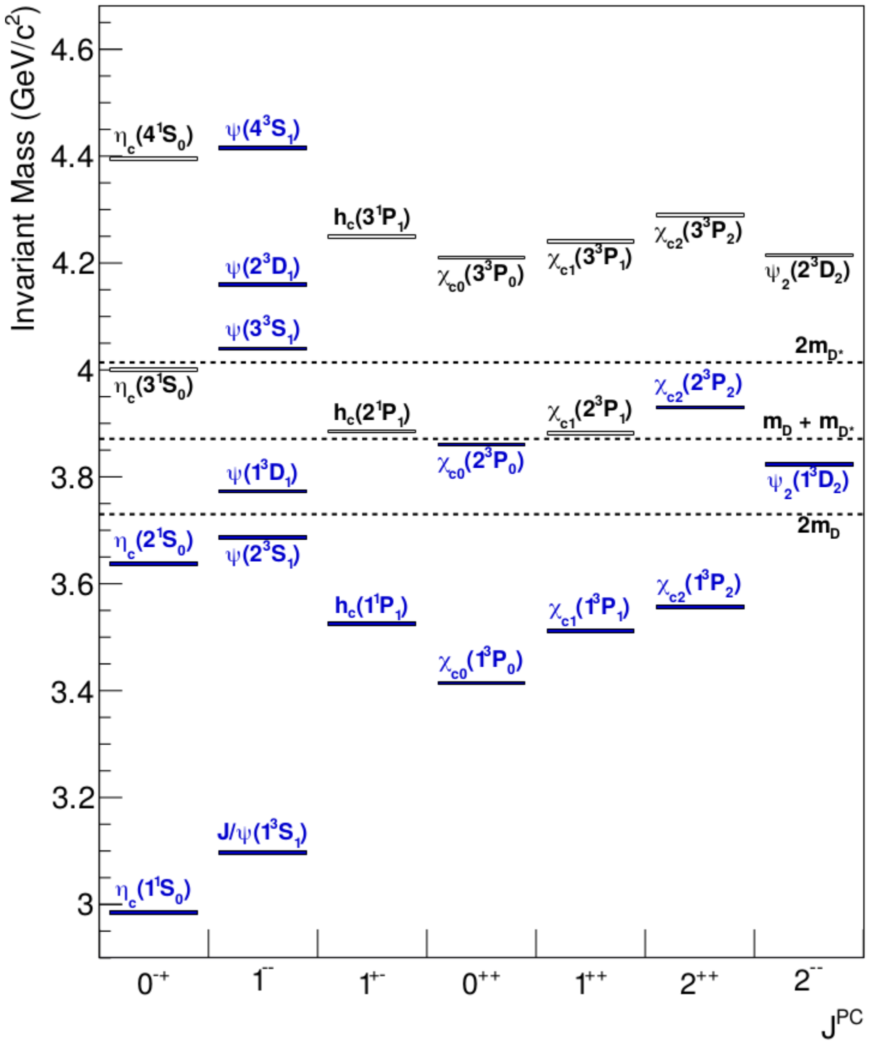
On behalf of the BESIII Collaboration

HADRON 2023 – Genova – 2023/06/06



Charmonium Spectrum

Discovered in 1974, opened a new window in understanding the nature of the hadrons

Potential models describe well the spectrum below open charm threshold

Crucial to keep exploring the charmonium decays with high precision:

- Non-vector states are still less known

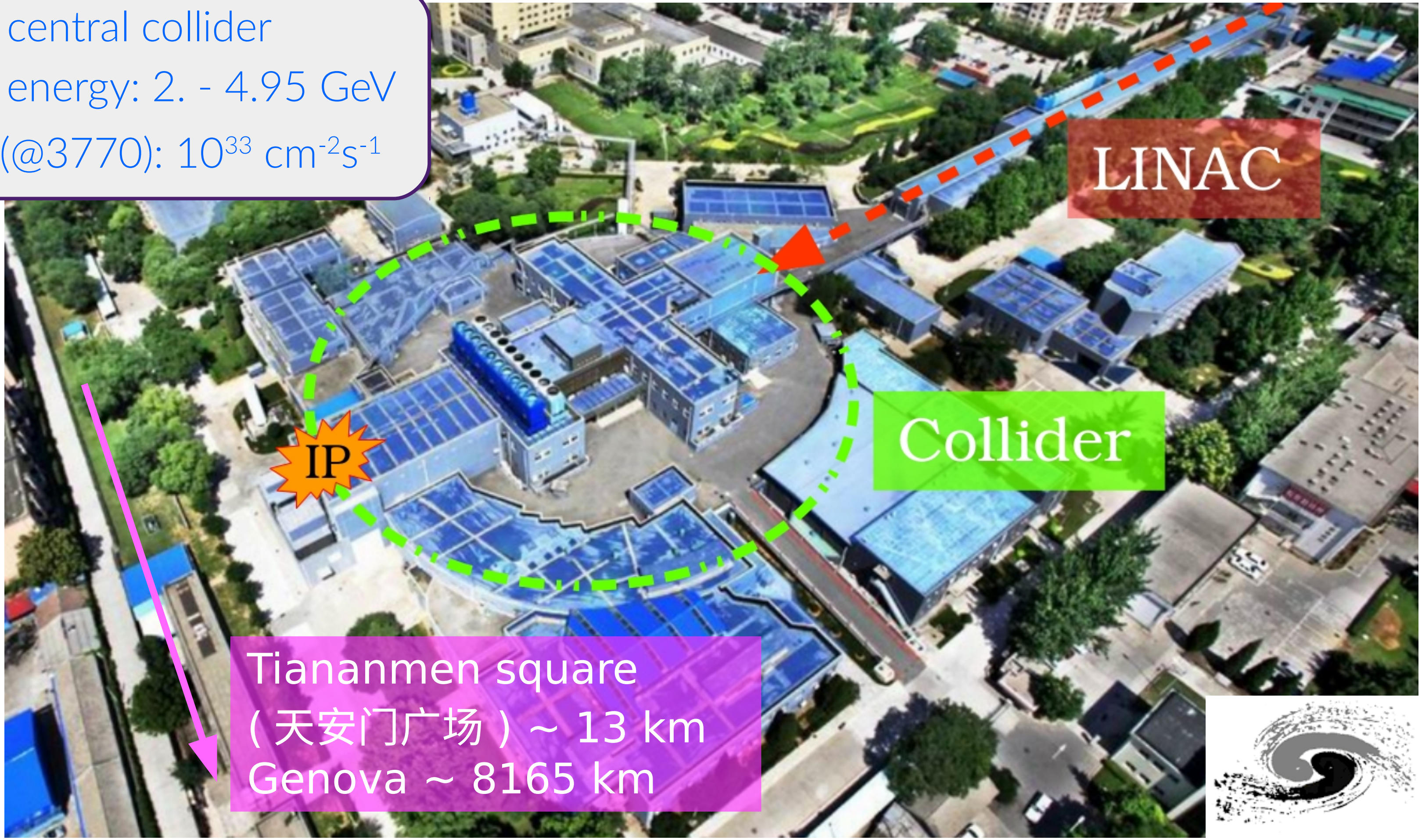
- Above the DD* threshold, new states have been observed that were not predicted

BEPCII @ IHEP (Beijing)

e^+e^- central collider

CM energy: 2. - 4.95 GeV

L_{peak}(@3770): 10^{33} $cm^{-2}s^{-1}$



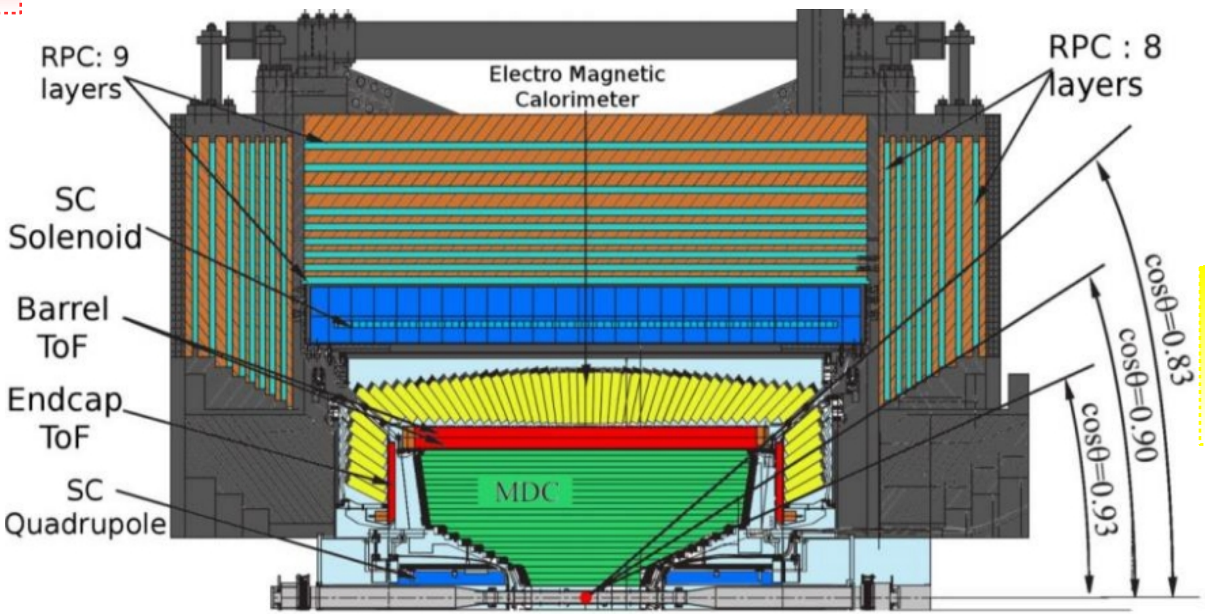
Tiananmen square
(天安门广场) ~ 13 km
Genova ~ 8165 km

BESIII @ BEPCII

Time Of Flight:
σ_t (barrel) = 68 ps
σ_t (endcap) = 60 ps

1 Tesla Magnetic field

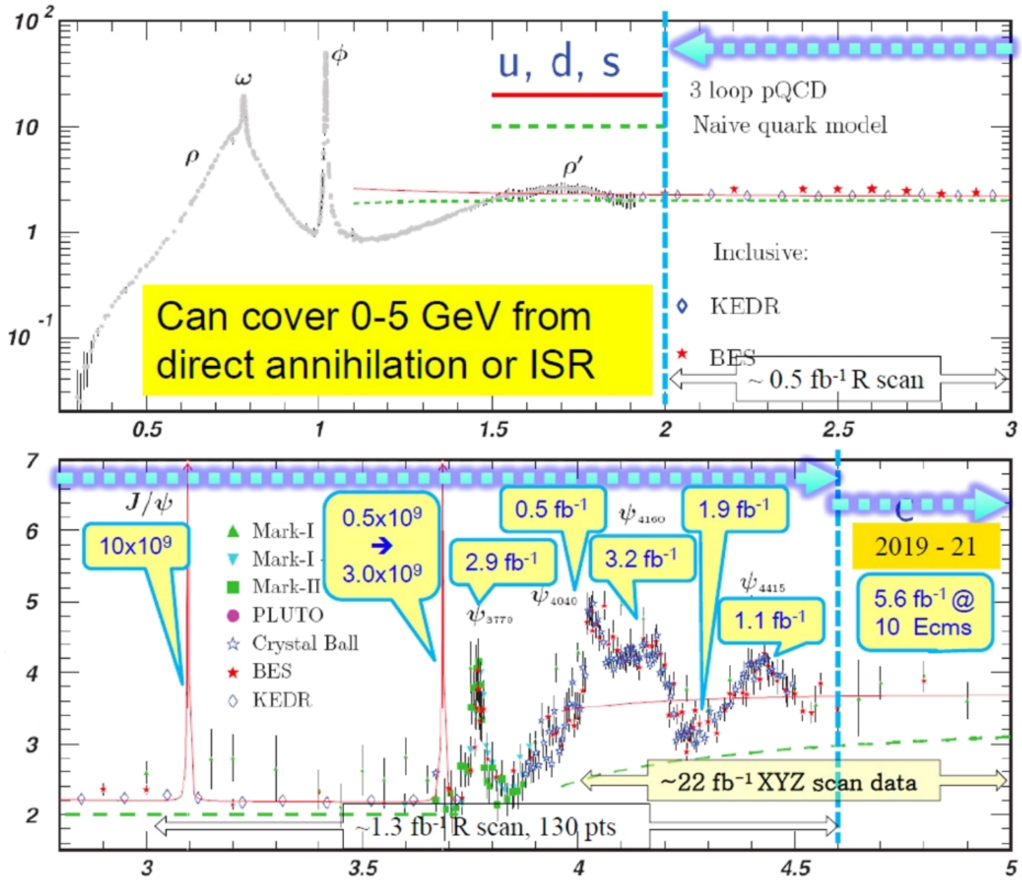
Muon counters:
$\delta_{r\varphi}$ = 1.4 cmv – 1.7 cm



Electromagnetic Calorimeter:
dE/√E (1 GeV) = 2.5 %

Main Drift Chamber:
σ_x (1 GeV/c) ~ 130 μm
dp/p (1 GeV/c) = 0.5 %

Datasets



BESIII datasets guarantee rich physics program

Today we focus on these datasets:

- 2.7B ψ(2S)
- 2.9/fb ψ(3770)

Simple and clear transitions to access non-vector charmonia from ψ(2S):

- $\psi(2S) \to \gamma\, \chi_{cJ}$
- $\psi(2S) \to \gamma\, \eta_c(2S)$
- $\psi(2S) \to \pi^0\, h_c$

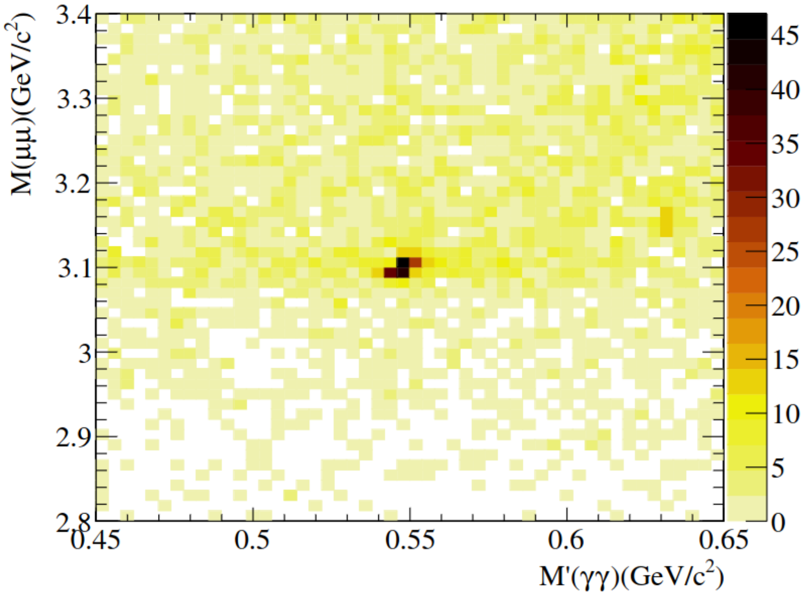
Today's results

- Observation of $\psi(3770) \to \eta J/\psi$ – PRD 107, L091101 (2023)
- Evidence of $\eta_c(2S) \to \pi^+\pi^-\eta$ - PRD107, 052007 (2023)
- Observation of $\chi_{cJ} \to \Omega^- \bar{\Omega}^+$ - PRD 107, 092004 (2023)
- Helicity amplitude of $\chi_{cJ} \to \Phi\Phi$ - arXiv: 2301.12922

$\psi(3770) \rightarrow \eta J/\psi$

$\psi(3770)$ is usually considered 1^3D_1 state of charmonium spectrum. However, few pieces of experimental evidence has led theoritical models to hypothesize a possible tetraquark contribution.

BESIII has also found connections between Y states and $\psi(3770)$, that may strengthen tetraquark hypothesis

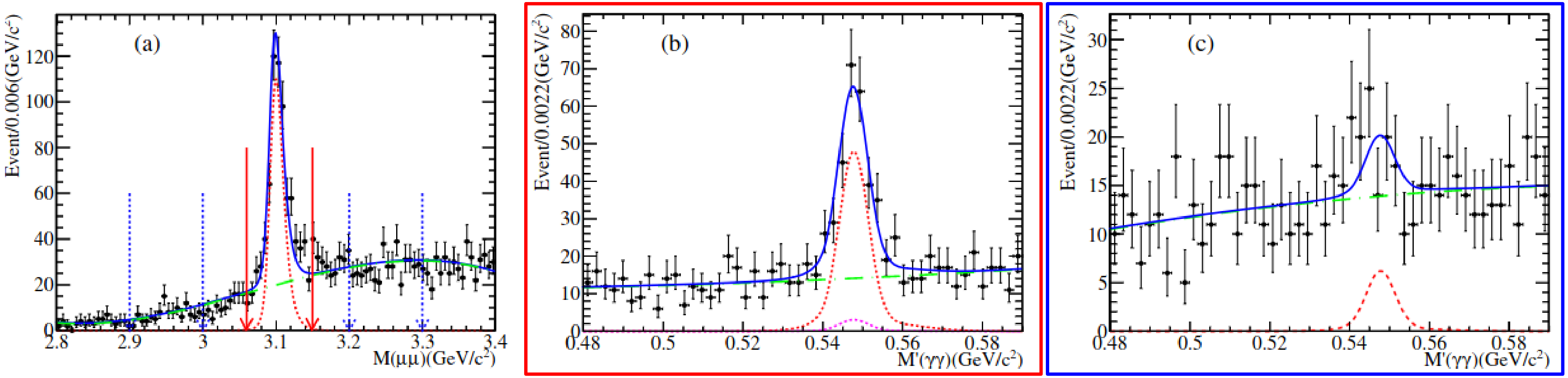


- If sizeable tetraquark, BR($\psi(3770) \rightarrow \eta J/\psi$) expected to be enhanced to 15 x 10^{-4} level
- One single measurement made by CLEO found evidence of the process with a BR ~ 8.7×10^{-4}, but neglects any possible interference with continuum
- BR($\psi(3770) \rightarrow \eta J/\psi$) is frequently used in hadronic transition calculation, so a better measurement is needed
- BESIII can use $\psi(3770)$ dataset and recent measurement in the Y states region to observe this process and study the possible interference contribution

$\psi(3770) \to \eta J/\psi$

Unbinned maximum likelihood fit to $M'(\gamma\gamma)$ distribution in both J/ψ signal and sideband region

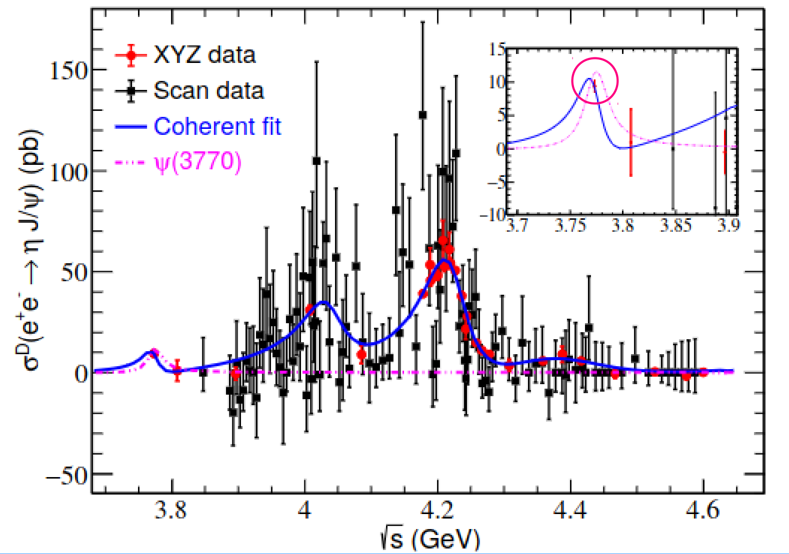
$$M'(\gamma\gamma) \equiv M(\gamma\gamma) + M(\mu\mu) - m_{J/\psi}$$

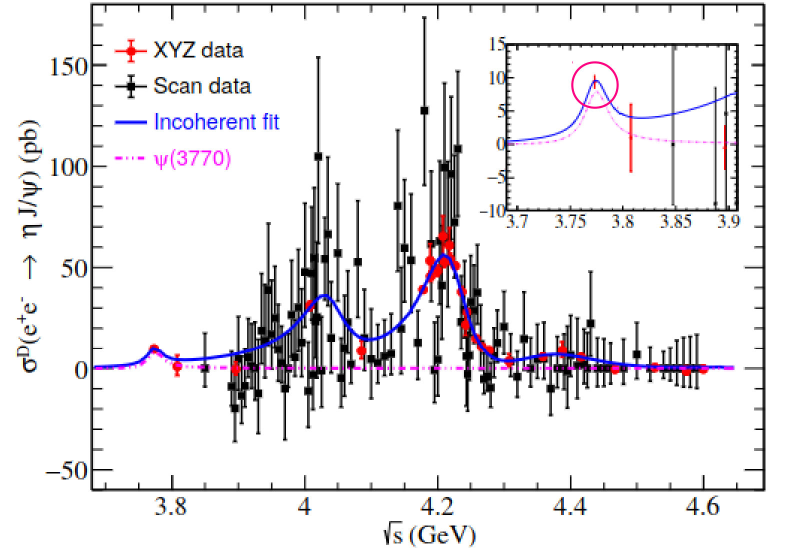


Dressed cross-section

$$\sigma^B(e^+e^- \to \eta J/\psi) = \frac{N^{\rm obs}}{\mathcal{L}\cdot(1+\delta^{\rm ISR})\cdot(1+\delta^{\rm VP})\cdot\varepsilon\cdot\mathcal{B}r}$$

$\mathcal{L}$ (pb^{-1})	ε(%)	$(1+\delta^{\rm ISR})\cdot(1+\delta^{VP})$	$\mathcal{B}(J/\psi\to\mu^+\mu^-)$(%)	$\mathcal{B}(\eta\to\gamma\gamma)$(%)	$N^{\rm obs}$	σ^B(pb)
2931 ± 15	45.4 ± 0.1	0.80	5.96 ± 0.03	39.4 ± 0.2	222 ± 22	8.89 ± 0.88





$\psi(3770) \to \eta J/\psi$

To extract BR fit to the full lineshape using previous BESIII measurements

Two hypotheses:

- Coherent fit

$$\sigma_{\text{co.}} = |C \cdot \sqrt{\Phi(s)} + e^{i\phi_1}\mathrm{BW}_{\psi(3770)} + e^{i\phi_2}\mathrm{BW}_{\psi(4040)} + e^{i\phi_3}\mathrm{BW}_{Y(4230)} + e^{i\phi_4}\mathrm{BW}_{Y(4390)}|^2,$$

- Incoherent fit

$$\sigma_{\text{inco.}} = |\mathrm{BW}_{\psi(3770)}|^2 + |C \cdot \sqrt{\Phi(s)} + e^{i\phi_2}\mathrm{BW}_{\psi(4040)} + e^{i\phi_3}\mathrm{BW}_{Y(4230)} + e^{i\phi_4}\mathrm{BW}_{Y(4390)}|^2.$$

First observation at 7.6σ level of this decay

Fit scenario		$\mathcal{B}(\psi(3770) \to \eta J/\psi)$ $(\times 10^{-4})$	ϕ_1(rad)
Coherent fit	Solution1	$11.6 \pm 6.1 \pm 1.0$	4.0±0.5
	Solution2	$12.0 \pm 6.3 \pm 1.1$	4.3±0.5
	Solution3	$11.6 \pm 6.1 \pm 1.0$	3.8±0.5
	Solution4	$11.9 \pm 6.3 \pm 1.1$	4.1±0.5
Incoherent fit		$7.9 \pm 1.0 \pm 0.7$	-

Close to tetraquark model prediction

Fine scan needed

Compatible with CLEO, better precision

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

Observed by BELLE in B decays, $\eta_c(2S)$ is the first radial excitation of the S-wave spin singlet.

Only 5% of its decays are measured, and the BR of the radiative $\psi(2S) \to \gamma\eta_c(2S)$ is still poorly known.

Charmonium decays into light hadron can be described by the $c\bar{c}$ annihilation into two or three gluons. Theoretical models predict a fixed ratio for these process for S-wave ground states and radial excitations:

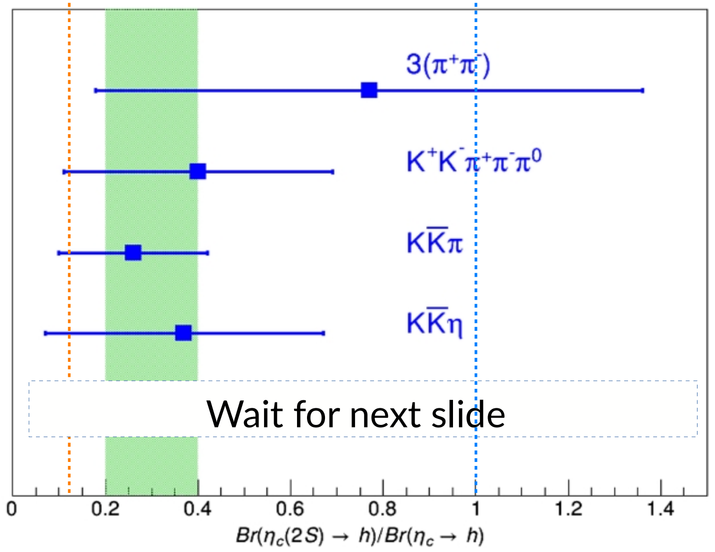
- For the spin triplet, the ratio follow the 12% rules.
- For the spin singlet, different hypothesis on the expected ratio

Phys. Rev. D 44, 1597 (1991)

$$\boxed{\frac{\mathrm{Br}(\eta_c(2S) \to h)}{\mathrm{Br}(\eta_c \to h)} \approx \frac{\mathrm{Br}(\psi(3686) \to h)}{\mathrm{Br}(J/\psi \to h)} = 0.128,}$$

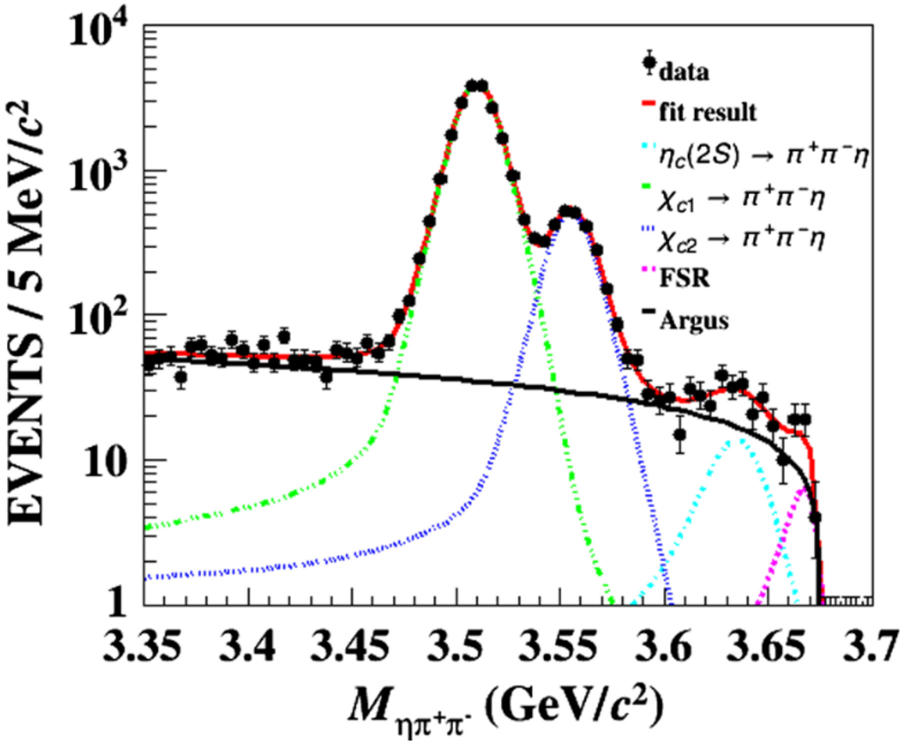
Commun. Theor. Phys. 25, 471 (1996)

$$\boxed{\frac{\mathrm{Br}(\eta_c(2S) \to h)}{\mathrm{Br}(\eta_c \to h)} \approx 1}$$



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

Use 448M psi(2S) dataset to search for the radiative transition and study this final state



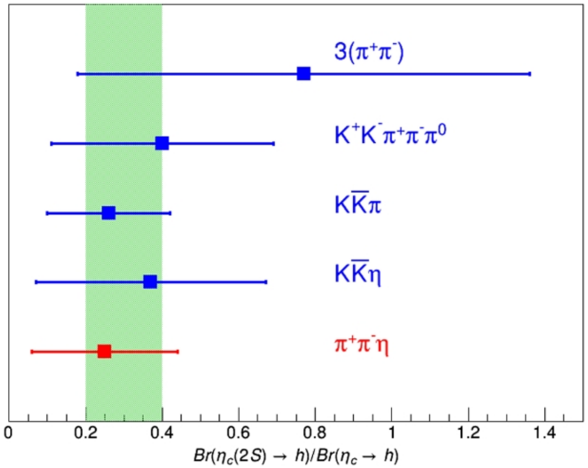
$\eta_c(2S)$ is described by

$$[E_\gamma^3 \times BW_0(m) \times f_d(E_\gamma)] \otimes DGaus(\delta m, \sigma)$$

Dumping factor

$$f_d(E_\gamma) = \frac{E_0^2}{E_\gamma E_0 + (E_\gamma - E_0)^2} \qquad E_0 = \frac{m^2_{\psi(3686)} - m^2_{\eta_c(2S)}}{2m_{\psi(3686)}}$$

$\eta_c(2S)$, χ_{c1}, χ_{c2} parameter fixed to PDG



First evidence of this decay

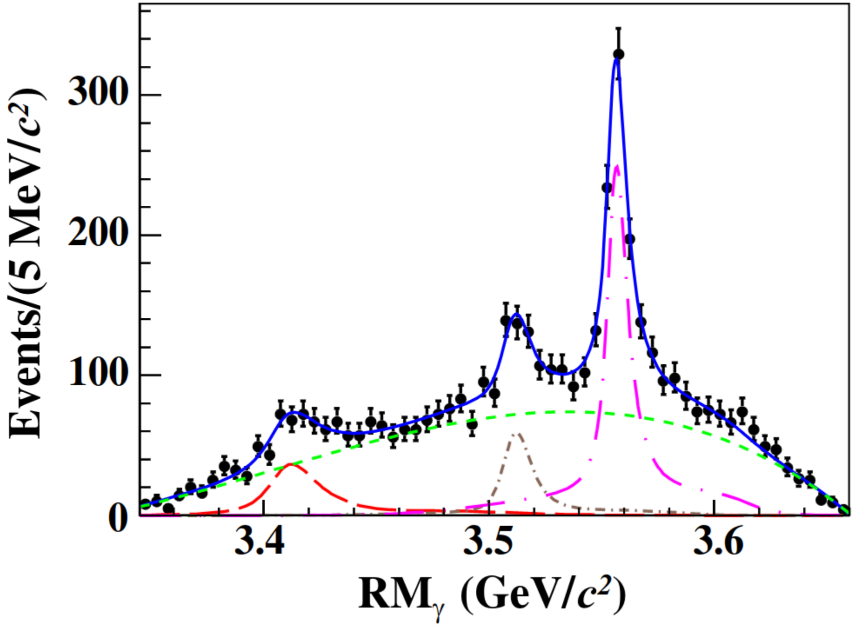
Largerly dominated by uncertainty on the $\psi(2S) \to \gamma\eta_c(2S)$ BR

$\chi_{cJ} \to \Omega^- \overline{\Omega}^+$

Decays of charmonia into baryon-antibaryon ($B\overline{B}$) are useful for many test of QCD.

χ_{cJ} decays into ½ $B\overline{B}$ are described by color octet model, with few important exception ($\chi_{cJ} \to \Lambda\overline{\Lambda}$ prediction are 1 order of magnitude lower than experimental measurement)

Never observed a χ_{cJ} decay into 3/2 $B\overline{B}$ final states.



Using partial reconstruction and full 3B ψ(2S) dataset, BESIII reports the first observation of $\chi_{cJ} \to \Omega^- \overline{\Omega}^+$ with large significance

$$\mathcal{B}(\chi_{c0} \to \Omega^- \bar{\Omega}^+) = (3.51 \pm 0.54 \pm 0.29) \times 10^{-5}$$
$$\mathcal{B}(\chi_{c1} \to \Omega^- \bar{\Omega}^+) = (1.49 \pm 0.23 \pm 0.10) \times 10^{-5}$$
$$\mathcal{B}(\chi_{c2} \to \Omega^- \bar{\Omega}^+) = (4.52 \pm 0.24 \pm 0.18) \times 10^{-5}$$

In future super tau-charm factories, useful also to probe spin polarization of Ω^- baryon

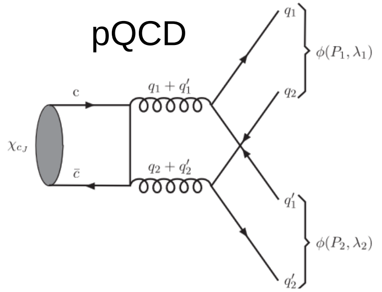
$\chi_{cJ} \to \Phi\Phi$

For a charmonia decaying into two hadron, pQCD predicts $\mathcal{B}[\psi(\lambda) \to h_1(\lambda_1)h_2(\lambda_2)] \sim \left(\frac{\Lambda^2_{QCD}}{m_c^2}\right)^{|\lambda_1+\lambda_2|+2}$

If light quark mass is neglected, $|\lambda1 + \lambda2| = 0$ due to quark helicity conservation in strong decay.
Any decay that do not respect this, should be suppressed

$\chi_{c1} \to \Phi\Phi$ shall be suppressed wrt to $\chi_{c0,2} \to \Phi\Phi$

pQCD

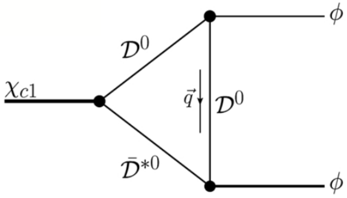


Experiments see close BR for three χ_{cJ}, so non-perturbative corrections are needed. Helicity amplitudes can help disentangle between models

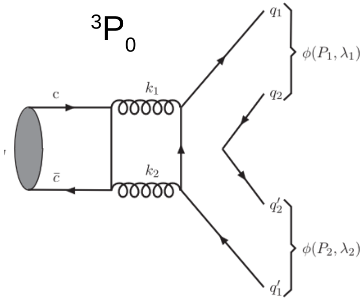
Decay channel	$\chi_{c0} \to \phi\phi$	$\chi_{c2} \to \phi\phi$		
Parameter	x	ω_1	ω_2	ω_4
pQCD	0.293 ± 0.030	0.812 ± 0.018	1.647 ± 0.067	0.344 ± 0.020
$^3P_0$	0.515 ± 0.029	1.399 ± 0.580	0.971 ± 0.275	0.406 ± 0.017
$D\bar{D}$ loop	0.359 ± 0.019	1.285 ± 0.017	5.110 ± 0.057	0.465 ± 0.002

$x = |F^0_{1,1}/F^0_{0,0}|$ $\omega_1 = |F^2_{0,1}/F^2_{0,0}|$ $\omega_2 = |F^2_{1,-1}/F^2_{0,0}|$ $\omega_4 = |F^2_{1,1}/F^2_{0,0}|$

$D\bar{D}$ loop

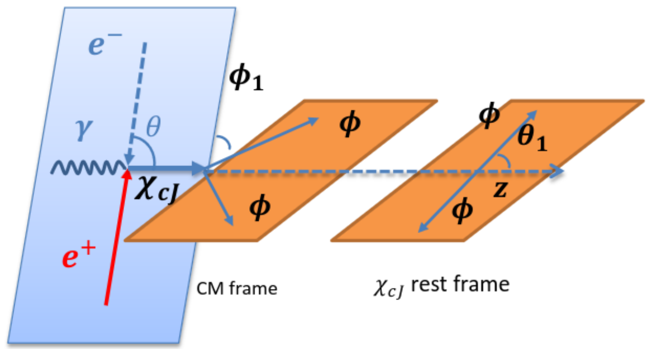


$^3P_0$

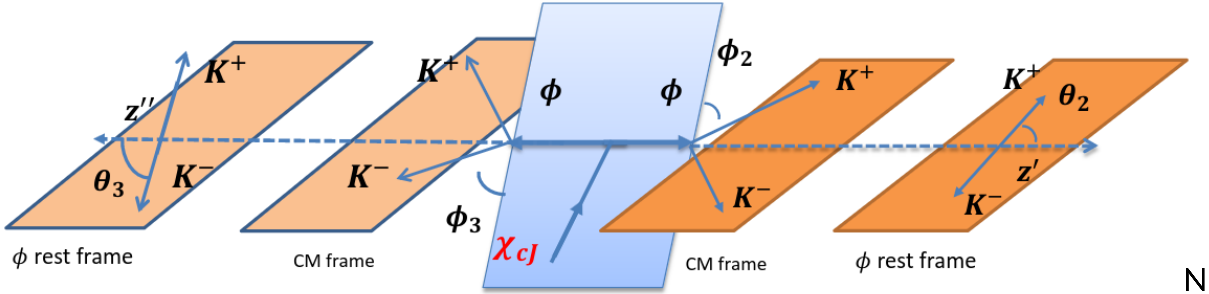


$\chi_{cJ} \to \Phi\Phi$

BESIII can use 448M psi(2S) to perform helicity amplitude measurement to provide insight on this decay dynamics and test the different models



(a)



Helicity amplitude of two body decay

$$A = \langle \vec{p}\lambda_1; -\vec{p}\lambda_2 \,|\mathcal{M}|\, JM \rangle$$
$$= 4\pi \left(\frac{\mu}{p}\right)^{\frac{1}{2}} \langle \phi\theta\lambda_1\lambda_2 | JM\lambda_1\lambda_2 \rangle \langle JM\lambda_1\lambda_2 \,|\mathcal{M}|\, JM \rangle$$
$$= N_J F^J_{\lambda_1,\lambda_2} D^{J*}_{M,\lambda}(\phi,\theta,0), \lambda = \lambda_1 - \lambda_2,$$

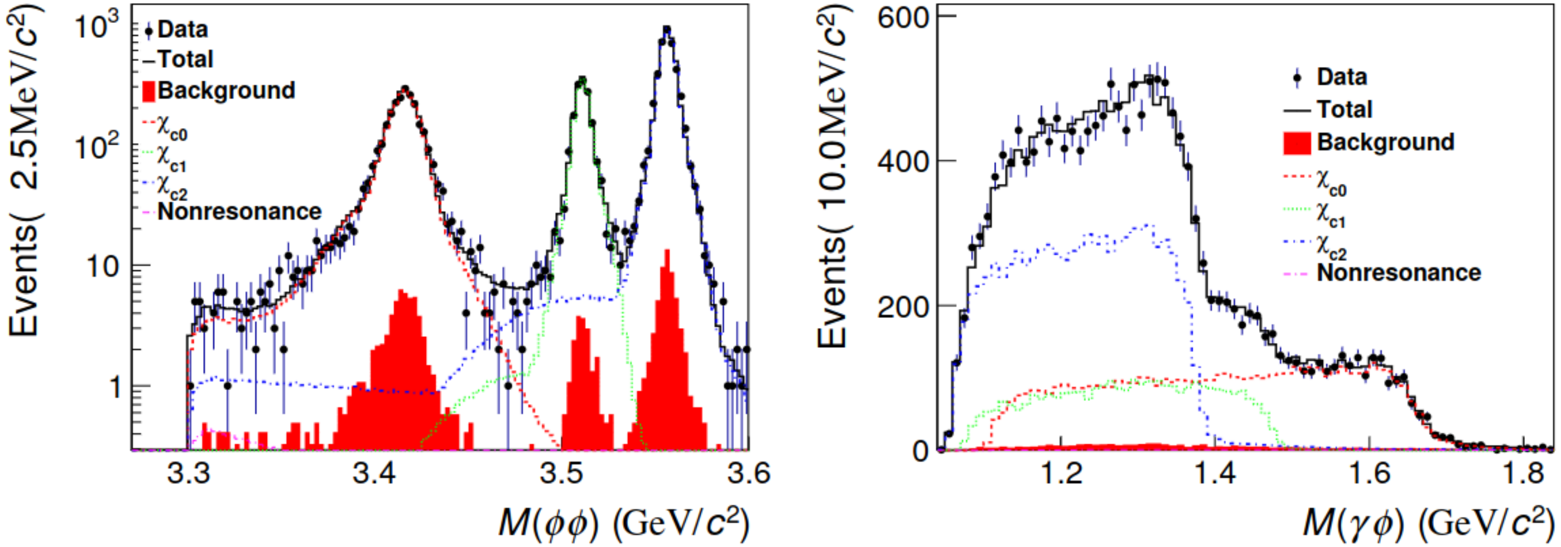
Partial wave included

Decay	Partial waves (LS)
$\psi(3686) \to \gamma\chi_{c0}$	(01) , (21)
$\psi(3686) \to \gamma\chi_{c1}$	(01) , (21) , (22)
$\psi(3686) \to \gamma\chi_{c2}$	(01) , (21) , (22) , (23) , (43)
χ_{c0} or NR$(0^+) \to \phi\phi$	(00) , (22)
χ_{c1} or NR$(1^+) \to \phi\phi$	(01) , (21) , (22)
χ_{c2} or NR$(2^+) \to \phi\phi$	(02) , (20) , (21) , (22) , (42)
NR$(0^-) \to \phi\phi$	(11)
$\phi \to K^+K^-$	(10)

NR components (0^+ and 0^-) treated separately to take into account possible interference

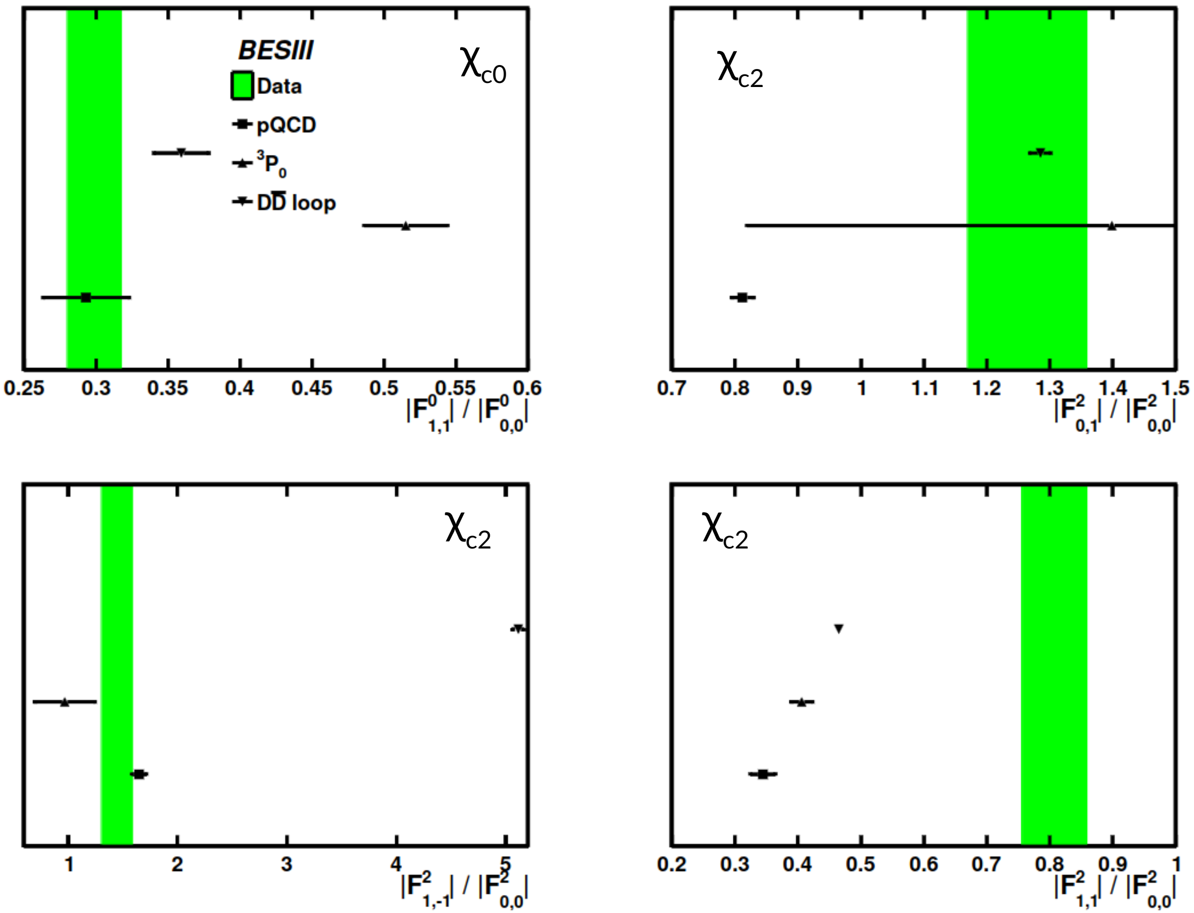
$\chi_{cJ} \rightarrow \Phi\Phi$

χ_{c0} mass and width floating in the fit, resolution function convoluted with χ_{c1} and χ_{c2} BW functions



Decay Mode	BF(2011 BESIII) [8]	BF(this work)	BF(PDG value) [22]
$\mathrm{Br}[\chi_{c0} \rightarrow \phi\phi](\times 10^{-4})$	7.8±0.4±0.8	$8.48 \pm 0.26 \pm 0.27$	7.7±0.7
$\mathrm{Br}[\chi_{c1} \rightarrow \phi\phi](\times 10^{-4})$	4.1±0.3±0.5	$4.36 \pm 0.13 \pm 0.18$	4.2±0.5
$\mathrm{Br}[\chi_{c1} \rightarrow \phi\phi](\times 10^{-4})$	10.7±0.4±1.2	$13.36 \pm 0.29 \pm 0.49$	11.2±1.0

$\chi_{cJ} \to \Phi\Phi$



Extract helicity amplitude ratio

χ_{c0}

$$\left|F^0_{1,1}\right| / \left|F^0_{0,0}\right| = 0.299 \pm 0.003 \pm 0.019$$

χ_{c2}

$$\left|F^2_{0,1}\right| / \left|F^2_{0,0}\right| = 1.265 \pm 0.054 \pm 0.079$$

$$\left|F^2_{1,-1}\right| / \left|F^2_{0,0}\right| = 1.450 \pm 0.097 \pm 0.104$$

$$\left|F^2_{1,1}\right| / \left|F^2_{0,0}\right| = 0.808 \pm 0.051 \pm 0.009$$

χ_{c0} results in good agreement with pQCD indicates that the decay follow helicity selection rule

χ_{c2} deviates more from all three proposed models

All will benefit from the newest BESIII 2.7B psi(2S) dataset!

Summary

- Charmonium decays provide insight to our understanding of QCD, expecially non-perturbative contribution
- BESIII profits from large data sample and clear transitions to produce non-vector charmonia

- First observation of $\psi(3770) \rightarrow \eta J/\psi$ will lead to new comprehension of $\psi(3770)$ nature?
  - BESIII is collecting more ~5 times more data with the possibility to access also $\psi(3770) \rightarrow \pi^0 J/\psi$

- $\eta_c(2S)$ exploration just started, many final states within reach with 2.7B $\psi(2S)$ dataset
  - Better constrain radiative transition are on-progress and deeply needed

- χ_{cJ} decay are a perfect benchmark to address non-perturbative models
  - Decays into hyperons allows also to extract spin polarization from non-vector states


谢谢
P. ALLORA
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