

# Charmonium spectroscopy from BESIII

Chi Zhang (张 弛)

(representing BESIII Collaboration)



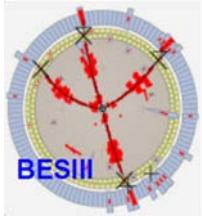
Nanjing University, China



November 4<sup>th</sup>-8<sup>th</sup>, 2013

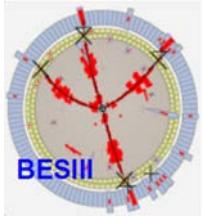


# Outline



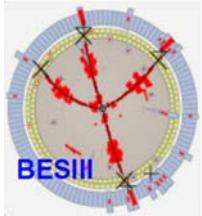
- Introduction to charmonium physics at BESIII
- BESIII data sets for charmonium study
- Selected results in this talk
  - ✓ Charmonium spectroscopy:  
 $\eta_c, h_c, \eta_c(2S)$
  - ✓ Charmonium transitions:  
 $X_{cJ} \rightarrow \pi^+ \pi^- \eta_c,$   
 $\psi(2S) \rightarrow n J/\psi, \pi^0 J/\psi, \psi(4040) \rightarrow n J/\psi, \pi^0 J/\psi,$   
 $\psi(3770) \rightarrow \gamma \eta_c, \gamma \eta_c(2S)$
- Summary

# Outline



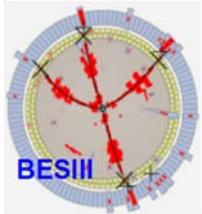
- Introduction to charmonium physics at BESIII
- BESIII data sets for charmonium study
- Selected results in this talk
  - ✓ Charmonium spectroscopy:  
 $\eta_c, h_c, \eta_c(2S)$
  - ✓ Charmonium transitions:  
 $X_{cJ} \rightarrow \pi^+ \pi^- \eta_c,$   
 $\psi(2S) \rightarrow \eta J/\psi, \pi^0 J/\psi, \psi(4040) \rightarrow \eta J/\psi, \pi^0 J/\psi,$   
 $\psi(3770) \rightarrow \gamma \eta_c, \gamma \eta_c(2S)$
- Summary

# Charmonium



- Charmed-quark ( $c$ ) anticharmed-quark ( $\bar{c}$ ) bound states.
- Has been a powerful tool for the understanding of the strong interaction
  - ✓ QCD is well tested at high energies
  - ✓ In low-energy regime, many aspects are not understood
  - ✓ Charmonium sector is in an important position to test QCD and improve our limited understanding of QCD

# Charmonium physics at BESIII



- Charmonium spectroscopy

$\eta_c$ ,  $J/\psi$ ,  $h_c$ ,  $\chi_{cJ}$ ,  $\eta_c(2S)$ ,  $\psi(2S)$ ,  
 $\psi(3770)$  ...

- Charmonium transitions

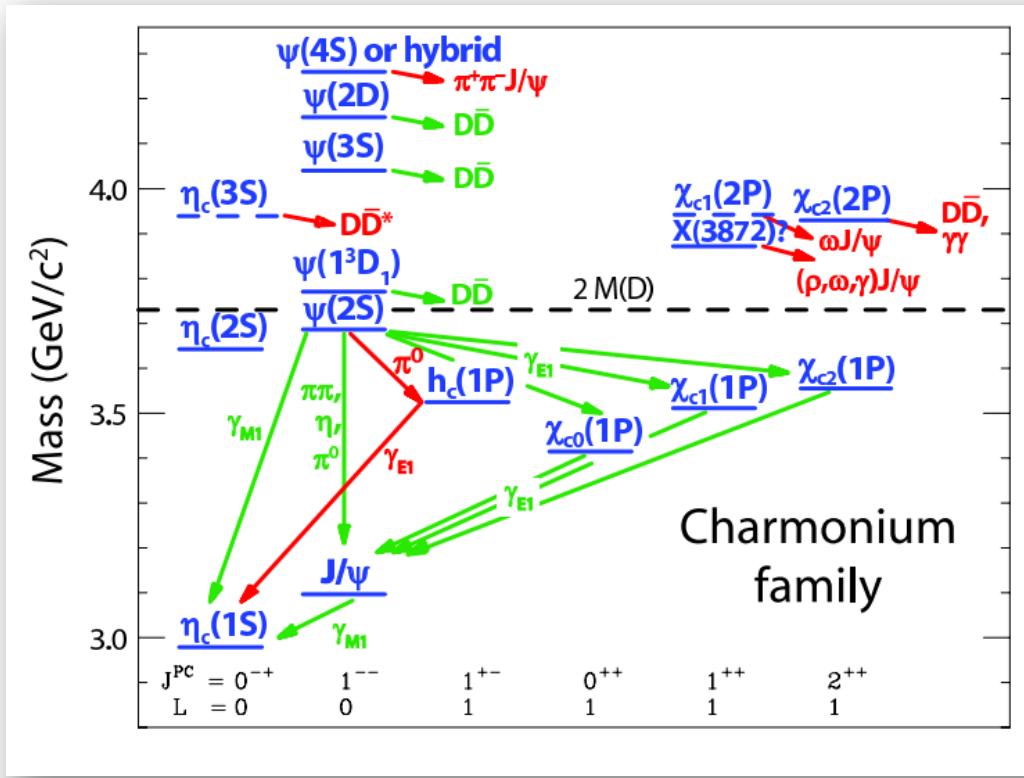
$\chi_{cJ} \rightarrow \pi^+ \pi^- \eta_c$ ,  
 $\psi(2S) \rightarrow \eta J/\psi$ ,  $\pi^0 J/\psi$ ,  
 $\psi(4040) \rightarrow \eta J/\psi$ ,  $\pi^0 J/\psi$ ,  
 $\psi(3770) \rightarrow \gamma \eta_c$ ,  $\gamma \eta_c(2S)$

...

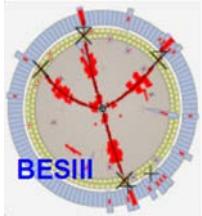
- Charmonium decays

- ✓  $X_{c0,2} \rightarrow \gamma\gamma$ ,  $J/\psi \rightarrow \gamma\gamma$ ,  $\eta_c \rightarrow \gamma\gamma$
- ✓ Light hadron decays
- ✓ Baryonic decays

- Hunt for XYZ or exotic charmonium-like states

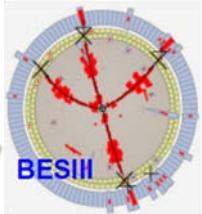


# Outline



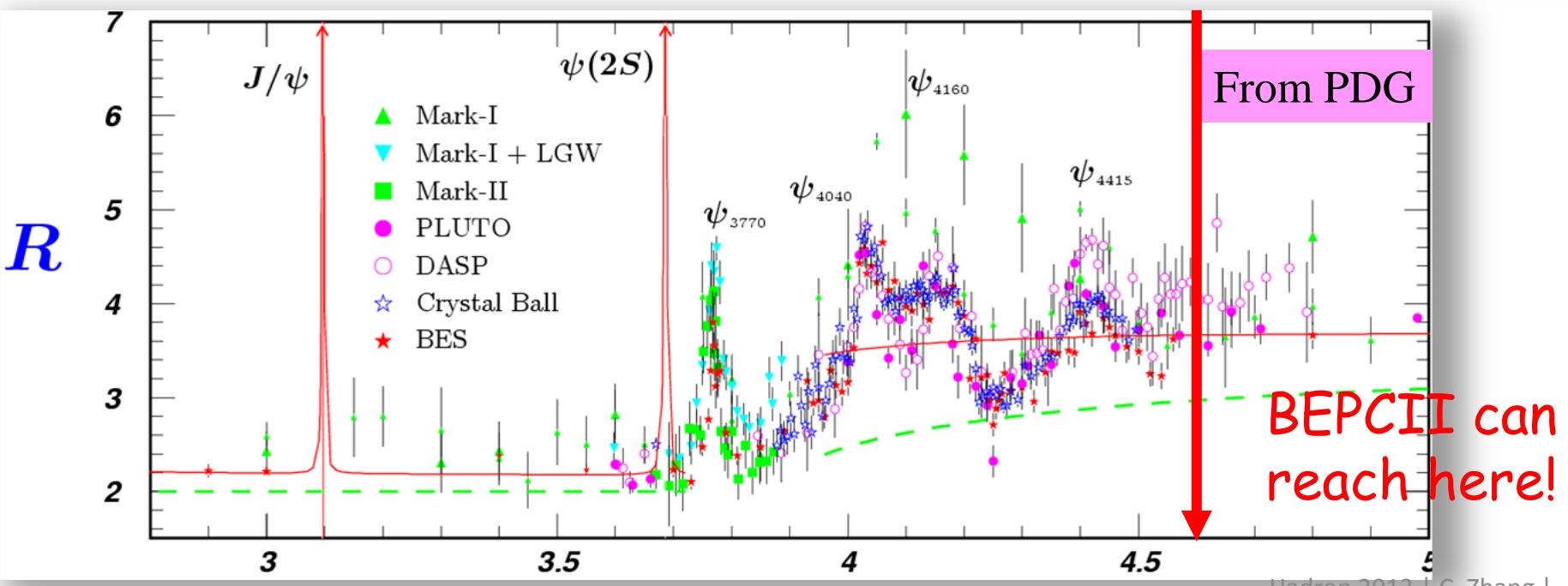
- Introduction to charmonium physics at BESIII
- BESIII data sets for charmonium study
- Selected results in this talk
  - ✓ Charmonium spectroscopy:  
 $\eta_c, h_c, \eta_c(2S)$
  - ✓ Charmonium transitions:  
 $\psi(2S) \rightarrow \gamma\gamma J/\psi, X_{cJ} \rightarrow \pi^+\pi^-\eta_c,$   
 $\psi(2S) \rightarrow \eta J/\psi, \pi^0 J/\psi, \psi(4040) \rightarrow \eta J/\psi, \pi^0 J/\psi,$   
 $\psi(3770) \rightarrow \gamma\eta_c, \gamma\eta_c(2S)$
- Summary

# BESIII data sets for charmonium study

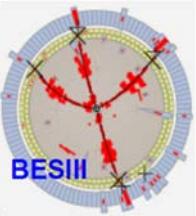


	Previous data	BELII present	Goal
J/ $\psi$	BESII: 58 M	1.2 B 20×BESII	10 B
$\psi(2S)$	CLEO: 28 M	0.5 B 20×CLEO-c	3 B
$\psi(3770)$	CLEO: 0.8 /fb	2.9 /fb 3.5×CLEO-c	20 /fb
4040/4160/4260/ 4360 MeV	CLEO: 0.6/fb @ $\psi(4160)$	2011: 0.5 /fb @ $\psi(4040)$ 2013: 2 /fb @4260 MeV 0.5 /fb @4360 MeV Data for lineshape	5-10 /fb

Vector  $\psi/Y$  states can be produced directly.  
C-even states can be produced from radiative transitions.

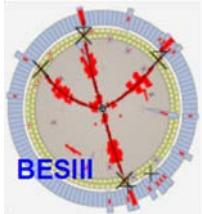


# Outline

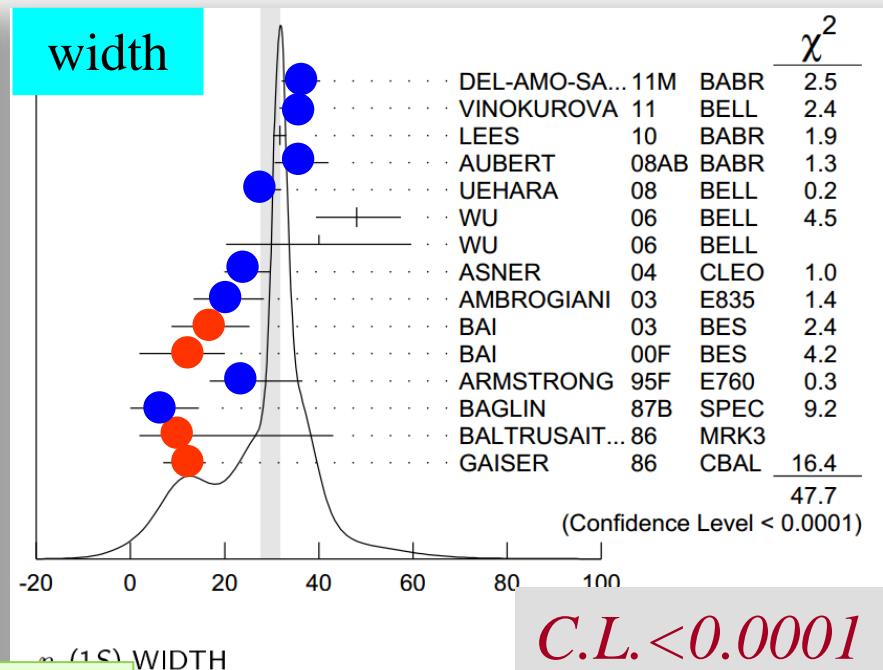
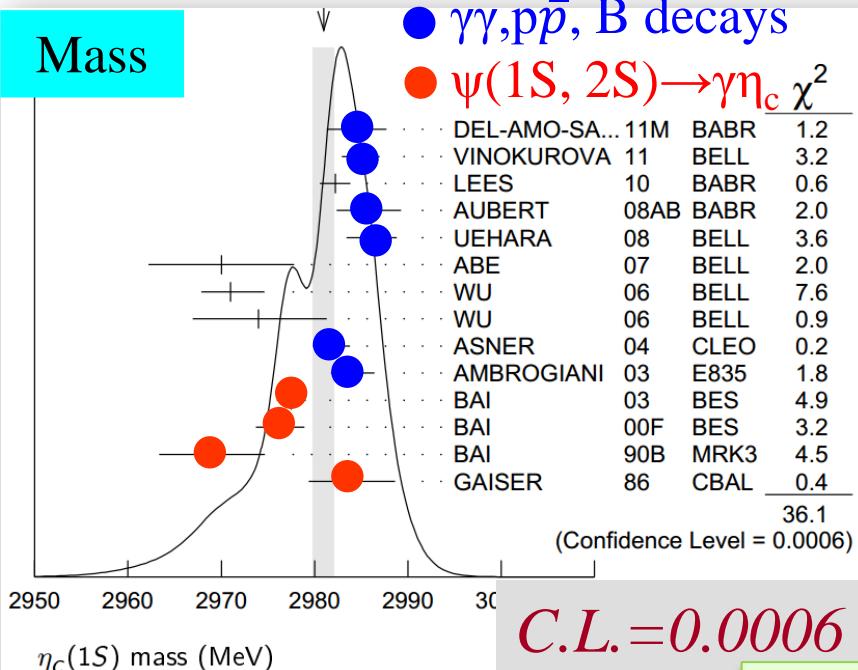


- Introduction to charmonium physics at BESIII
- BESIII data sets for charmonium study
- Selected results in this talk
  - ✓ Charmonium spectroscopy:  
 $\eta_c, h_c, \eta_c(2S)$
  - ✓ Charmonium transitions:  
 $X_{cJ} \rightarrow \pi^+ \pi^- \eta_c,$   
 $\psi(2S) \rightarrow \eta J/\psi, \pi^0 J/\psi, \psi(4040) \rightarrow \eta J/\psi, \pi^0 J/\psi,$   
 $\psi(3770) \rightarrow \gamma \eta_c, \gamma \eta_c(2S)$
- Summary

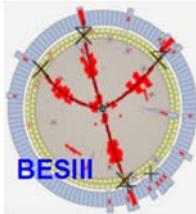
# $\eta_c(1S)$



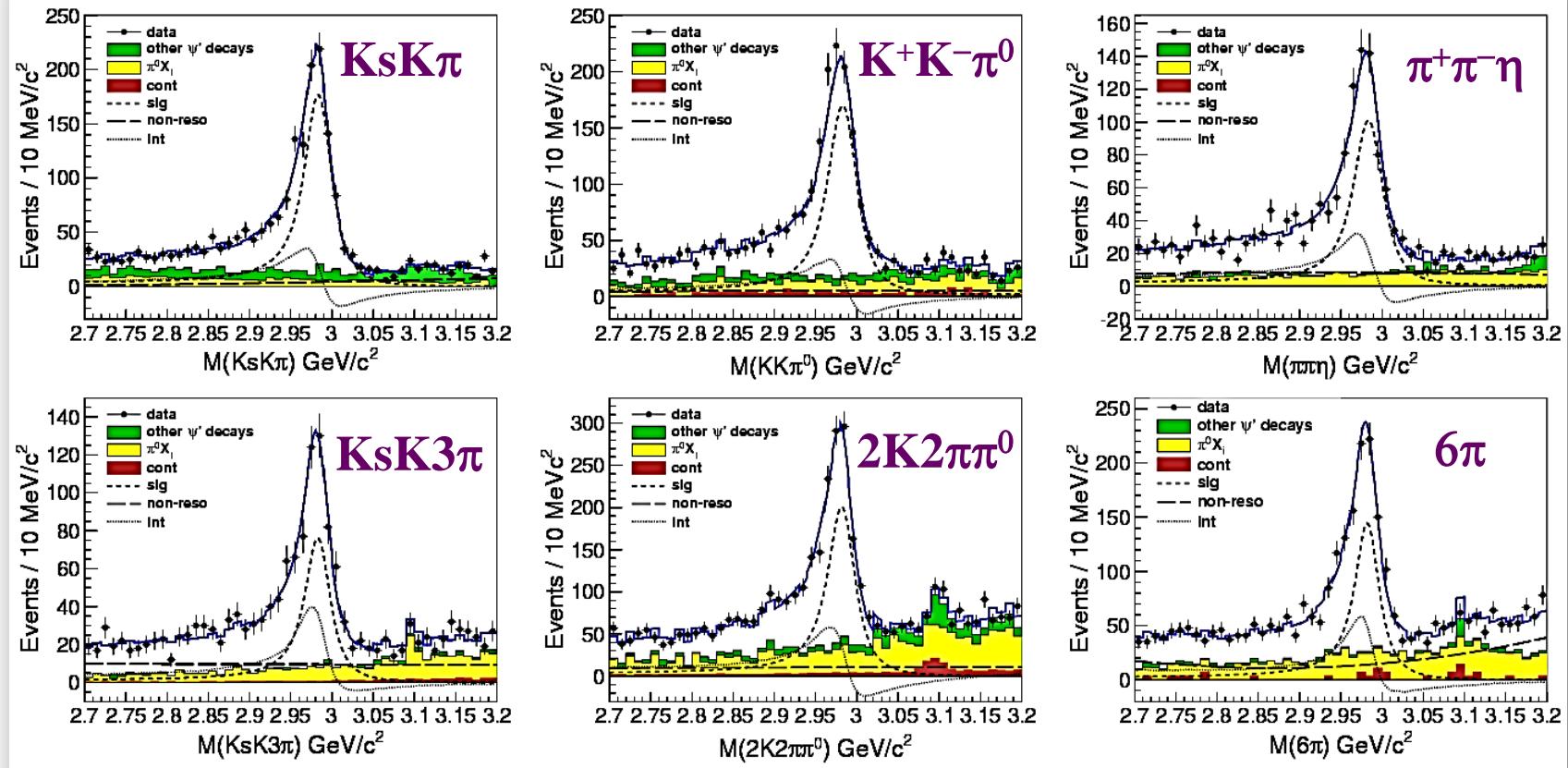
- Ground state of S-wave spin singlet charmonium, discovered in 1980 by Mark II. Properties not well known.
- The obvious discrepancy between different experiment:  
 $J/\psi$  radiative transitions:  $M \sim 2978.0 \text{ MeV}/c^2$ ,  $\Gamma \sim 10 \text{ MeV}$   
 $\gamma\gamma$  process:  $M = 2983.1 \pm 1.0 \text{ MeV}/c^2$ ,  $\Gamma = 31.3 \pm 1.9 \text{ MeV}$
- $c\bar{c}$  hyperfine splitting  $M(J/\psi) - M(\eta_c(1S))$  is an important parameter for understanding confinement potential and as a test of LQCD.



# $n_c$ resonance parameters from $\psi(2S) \rightarrow \gamma n_c$



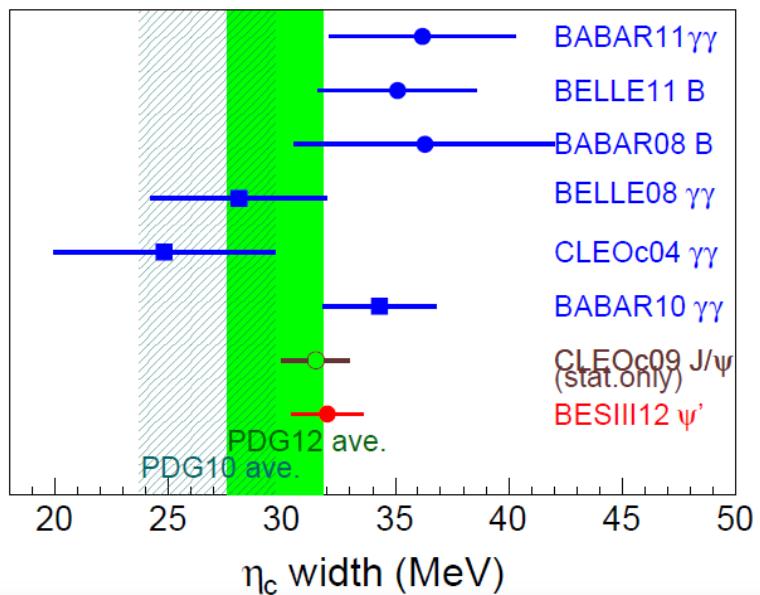
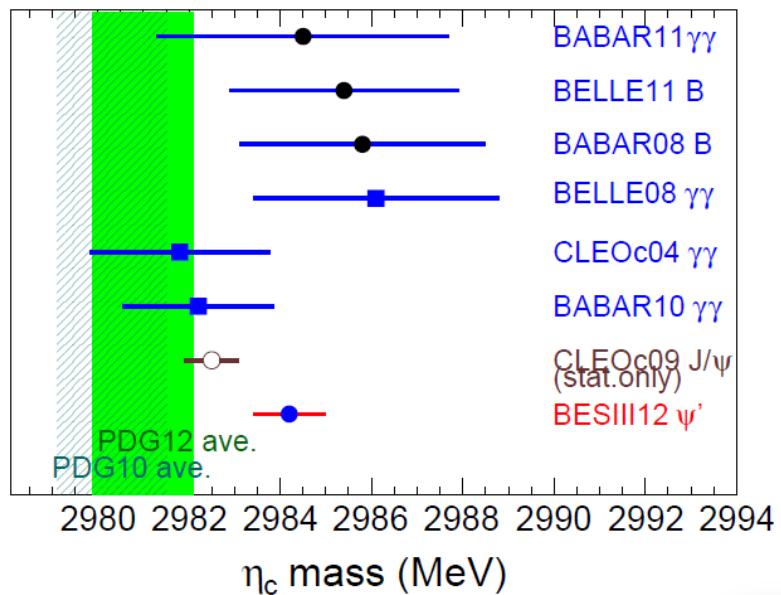
PRL 108, 222002 (2012)



- The interference between  $\eta_c$  and non-resonant is significant. Simultaneous fit to 6 modes.
- Modified Breit-Wigner (hindered M1)

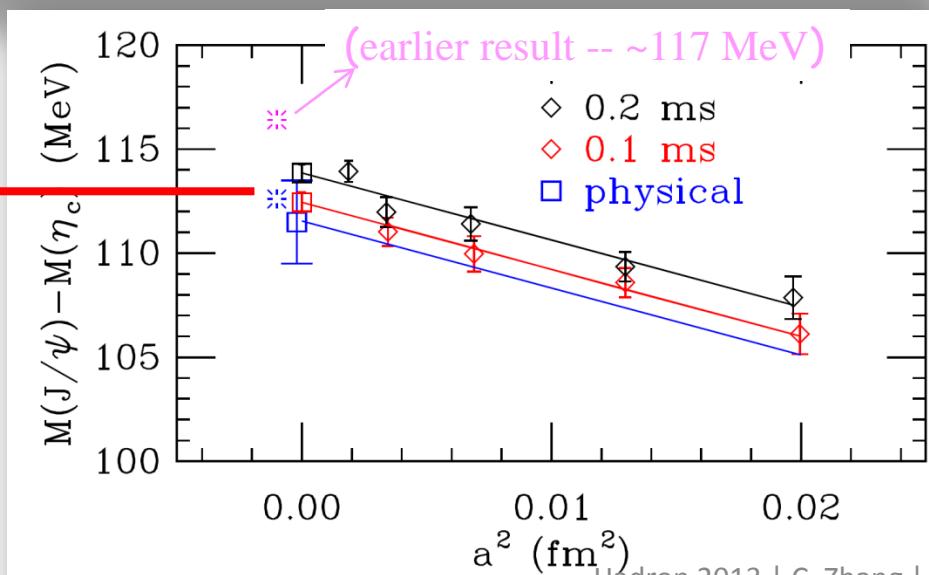
Mass =  **$2984.3 \pm 0.6 \pm 0.6$  MeV/c<sup>2</sup>**  
 Width =  **$32.0 \pm 1.2 \pm 1.0$  MeV**

# Comparison with previous $\eta_c$ results

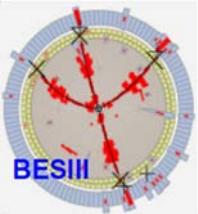


Hyperfine splitting (BESIII alone):  
 $\Delta M(1S) = 112.5 \pm 0.8 \text{ MeV}/c^2$

- ✓ The most precise measurement
- ✓ Better agreement with LQCD calculation.



# $h_c(1^1P_1)$



- Spin singlet P wave ( $S = 0, L = 1$ )
- Potential model: if non-vanishing P-wave spin-spin interaction,

$$\Delta m_{hf}(1P) = m(1^1P_1) - \langle m(1^3P_J) \rangle \neq 0$$

with  $\langle m(1^3P_J) \rangle = \frac{1}{9} (m(\chi_{c0}) + 3m(\chi_{c1}) + 5m(\chi_{c2}))$

Hyperfine splitting

- First observation by CLEO-c in cascade process

$$e^+e^- \rightarrow \psi(3686) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c$$

$$\Delta M_{hf}(1P) = \mathbf{0.08 \pm 0.18 \pm 0.12 \text{ MeV}/c^2}$$

- Theoretical predictions:

$$BF(\psi(2S) \rightarrow \pi^0 h_c) = (0.4-1.3) \times 10^{-3},$$

$$BF(h_c \rightarrow \gamma \eta_c) = 41\% \text{ (NRQCD)}$$

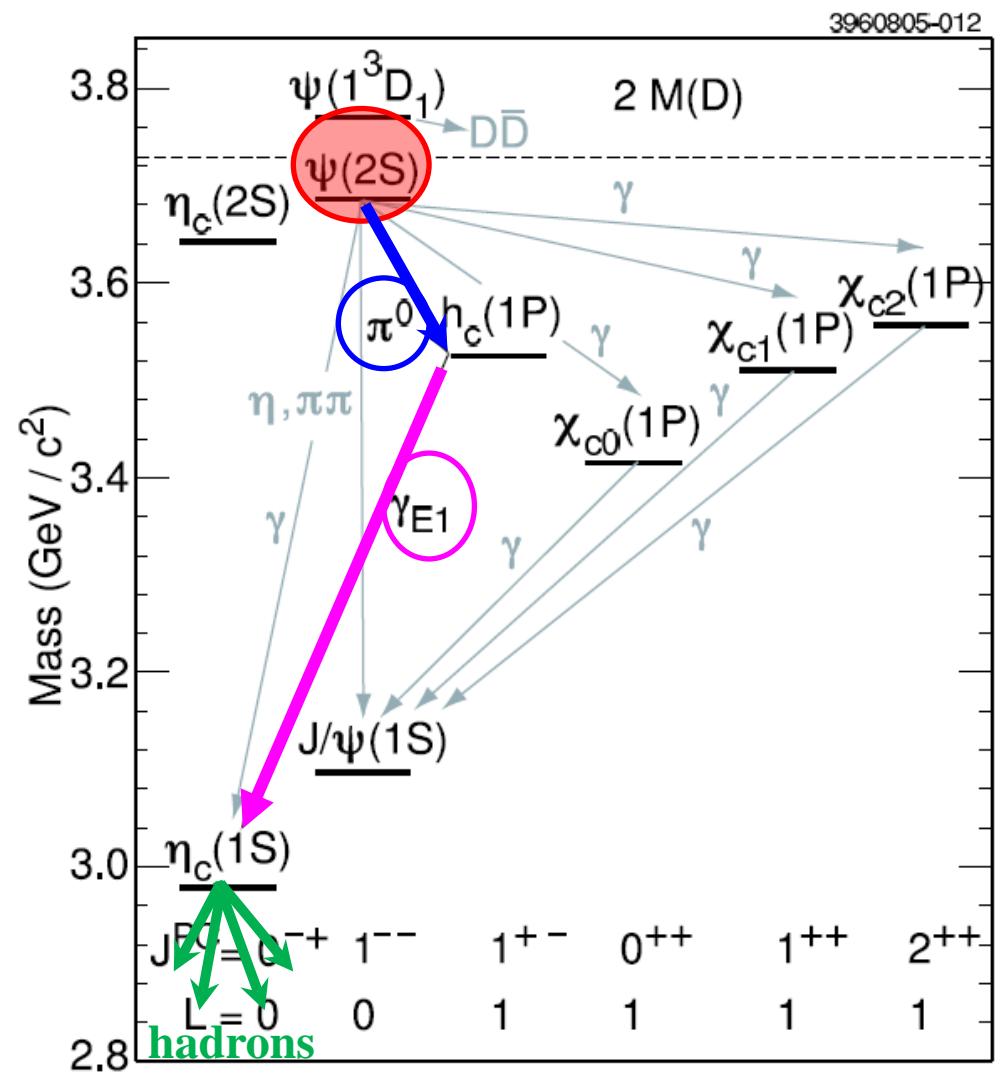
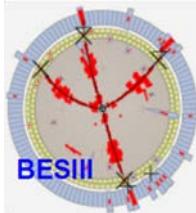
$$BF(h_c \rightarrow \gamma \eta_c) = 88\% \text{ (PQCD)}$$

*Y. P. Kuang, PRD 65, 094024 (2002)*

$$BF(h_c \rightarrow \gamma \eta_c) = 38\%$$

*Godfrey and Rosner, PRD 66, 014012 (2002)*

# $h_c(1^1P_1)$ analysis



**“inclusive”** (published in 2011)

only detect the  $\pi^0$

(compute  $M(h_c)$  from kinematic)

Rate  $\propto \mathcal{B}(\psi' \rightarrow \pi^0 h_c)$

**“*E1* tagged”** (published in 2011)

detect the  $\pi^0$  &  $\gamma$

(compute  $M(h_c)$  from kinematic)

Rate  $\propto \text{BF}(\psi' \rightarrow \pi^0 h_c) \times \text{BF}(h_c \rightarrow \gamma \eta_c)$

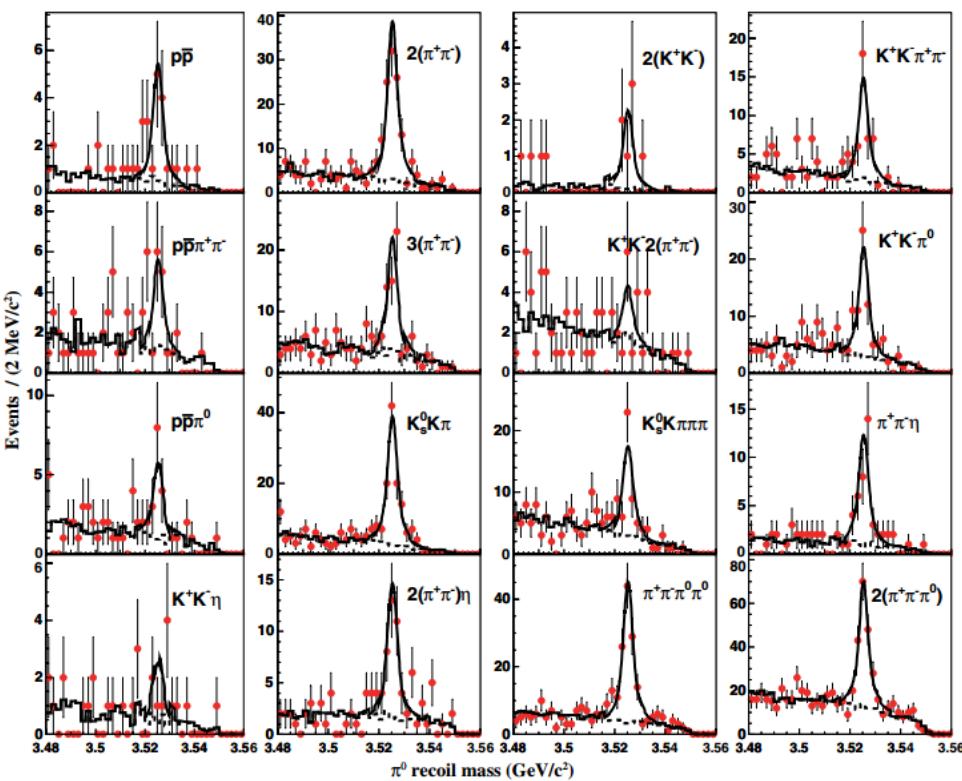
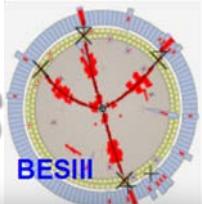
**“exclusive”** (published in 2012)

detect the  $\pi^0$ ,  $\gamma$  &  $\eta_c \rightarrow X_i$  decay products

( $M(h_c)$  from 4C kinematic fit)

Rate  $\propto \text{BF}(\psi' \rightarrow \pi^0 h_c) \times \text{BF}(h_c \rightarrow \gamma \eta_c) \times \text{BF}(\eta_c \rightarrow X_i)$

# $\psi(2S) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma n_c, n_c$ exclusive decays



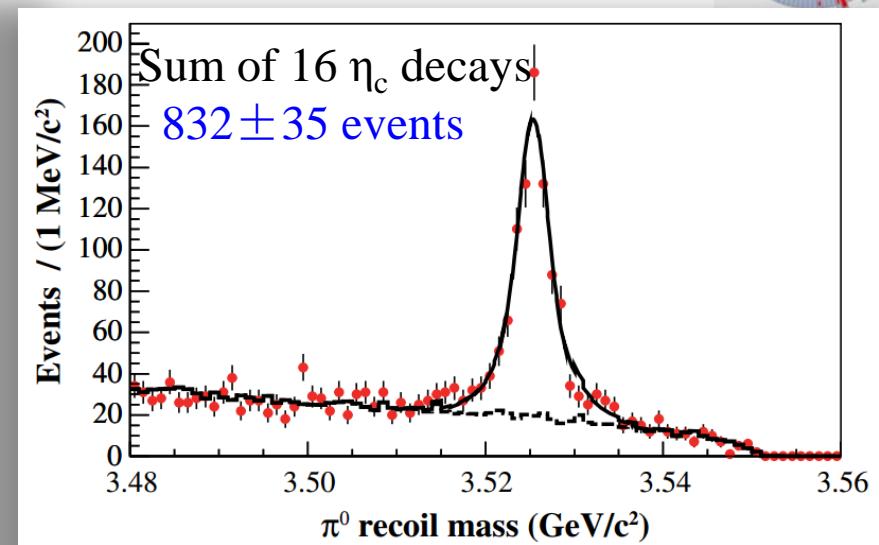
Simultaneous fit to  $\pi^0$  recoiling mass:

Mass =  $3525.31 \pm 0.11 \pm 0.14$  MeV/c<sup>2</sup>

Width =  $0.70 \pm 0.28 \pm 0.22$  MeV

$\Delta M_{hf}(1P)$  =  $-0.01 \pm 0.11 \pm 0.15$  MeV/c<sup>2</sup>

BESIII: PRD 86, 092009 (2012)



Consistent with BESIII inclusive results:

Mass =  $3525.40 \pm 0.13 \pm 0.18$  MeV/c<sup>2</sup>

Width =  $0.73 \pm 0.45 \pm 0.28$  MeV

$\Delta M_{hf}(1P)$  =  $-0.10 \pm 0.13 \pm 0.18$  MeV/c<sup>2</sup>

BESIII: PRL 104, 132002 (2010)

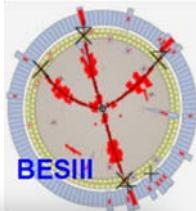
CLEO-c exclusive results:

Mass =  $3525.21 \pm 0.27 \pm 0.14$  MeV/c<sup>2</sup>

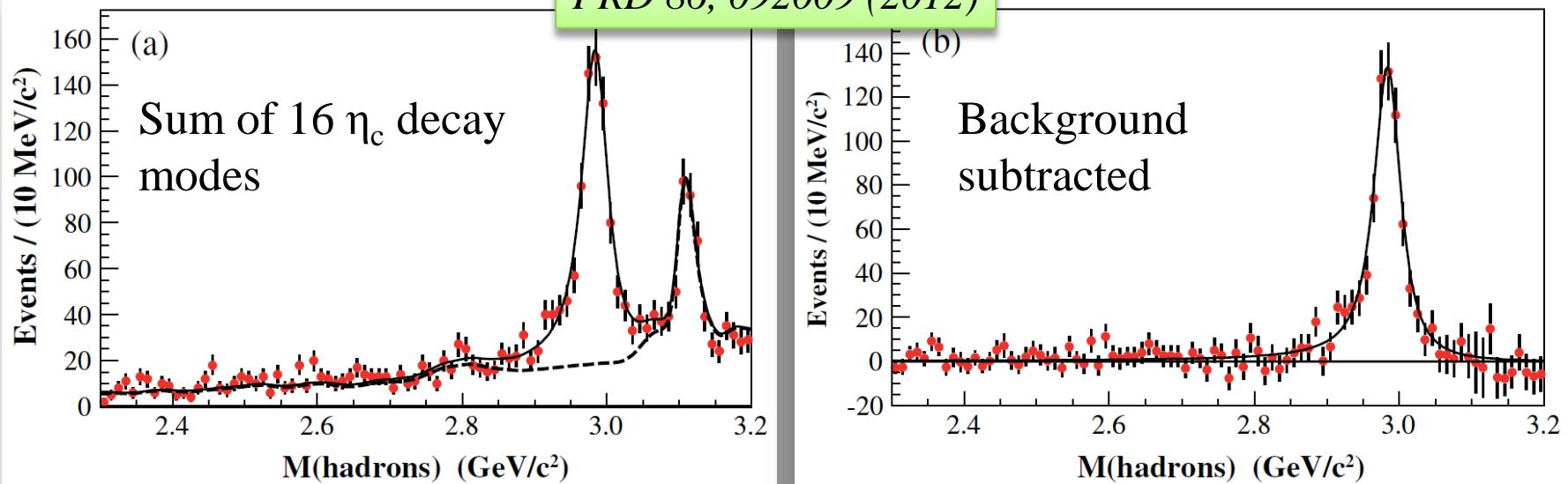
$\Delta M_{hf}(1P)$  =  $0.08 \pm 0.18 \pm 0.12$  MeV/c<sup>2</sup>

CLEO-c: PRL 101, 182003 (2008)

# $\eta_c$ lineshape from $\psi(2S) \rightarrow \pi^0 h_c$ , $h_c \rightarrow \gamma \eta_c$



PRD 86, 092009 (2012)



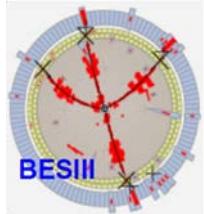
- The  $\eta_c$  lineshape in  $h_c \rightarrow \gamma \eta_c$  is not as distorted as in  $\psi(2S) \rightarrow \gamma \eta_c$  decays.
- ✓ The non-resonant interfering background is smaller than  $\psi(2S) \rightarrow \gamma \eta_c$ .
- ✓ This channel will be best suited to determine  $\eta_c$  resonance parameters.

Mass =  **$2984.49 \pm 1.16 \pm 0.52$  MeV/c<sup>2</sup>**

Width =  **$36.4 \pm 3.2 \pm 1.7$  MeV**

- ✓ These results are consistent with those from  $\psi(2S) \rightarrow \gamma \eta_c$  decays within errors.

# Search for $\psi(2S) \rightarrow \pi^0 h_c$ , $h_c \rightarrow p\bar{p}$



- No clear signal for  $\psi(2S) \rightarrow \pi^0 h_c$ ,  $h_c \rightarrow p\bar{p}$  is observed. UL on BF is set at 90% C.L.

*arXiv:1310.6099  
submitted to PRD*

## Branching fraction

$$BF(\psi(2S) \rightarrow \pi^0 h_c \rightarrow \pi^0 p\bar{p}) < 1.3 \times 10^{-7}$$

Using BESIII measurement:

$$BF(\psi(2S) \rightarrow \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0)\%$$

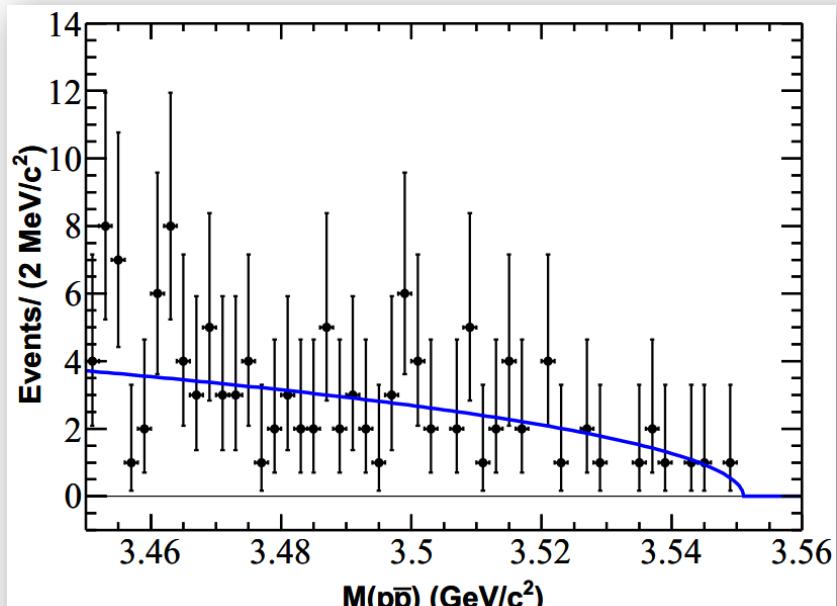
PRD 78, 012006 (2008)

$$BF(h_c \rightarrow p\bar{p}) < 1.7 \times 10^{-4}$$

## Theoretical predictions

$$BF(h_c \rightarrow p\bar{p}) = (1.52 - 1.93) \times 10^{-3}$$

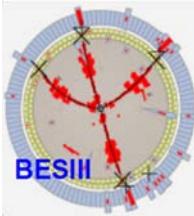
$$BF(h_c \rightarrow p\bar{p}) = (3.2 \pm 0.5) \times 10^{-3}$$



X.H. Liu and Q. Zhao, J. Phys. G 38, 035007 (2011)

S. Barsuk, J. He, E. Kou and B. Viaud, PRD 86, 034011 (2012)

# $\eta_c(2S)$



- First seen by Crystal Ball at SLAC from recoil mass spectrum of  $\psi(2S) \rightarrow \gamma X$ , using 1.8M  $\psi(2S)$ , with  $m = 3495 \pm 5 \text{ MeV}/c^2$
- Observed by Belle in  $B^\pm \rightarrow K^\pm \eta_c(2S)$ ,  $\eta_c(2S) \rightarrow K_S^0 K^\pm \pi^\mp$ , also seen by BABAR and CLEO in  $\gamma\gamma$  production

Experiment	Process	$m[\text{MeV}/c^2]$	$\Gamma[\text{MeV}]$
Belle	$B^\pm \rightarrow K^\pm \eta_c(2S) \rightarrow K^\pm K_S^0 K^\pm \pi^\mp$	$3654 \pm 6 \pm 8$	—
CLEO	$\gamma\gamma \rightarrow \eta_c(2S) \rightarrow K_S^0 K^\pm \pi^\mp$	$3642.9 \pm 3.1 \pm 1.5$	$6.3 \pm 12.4 \pm 4.0$
BABAR	$\gamma\gamma \rightarrow \eta_c(2S) \rightarrow K_S^0 K^\pm \pi^\mp$	$3630.8 \pm 3.4 \pm 1.0$	$17.0 \pm 8.3 \pm 2.5$
BABAR	$e^+ e^- \rightarrow J/\psi c\bar{c}$	$3645.0 \pm 5.5^{+4.9}_{-7.8}$	—
PDG '12		$3638.9 \pm 1.3$	$10 \pm 4$

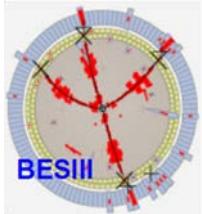
- M1 transition  $\psi(2S) \rightarrow \gamma \eta_c(2S)$  with exclusive reconstruction of  $\eta_c(2S)$  not yet observed. CLEO found no signals in 25M  $\psi(2S)$ :

$$BF(\psi(2S) \rightarrow \gamma \eta_c(2S)) < 7.6 \times 10^{-4}$$

- Better chance with 106M  $\psi(2S)$  data at BESIII
- Decay mode explored by BESIII:  $\psi(2S) \rightarrow \gamma \eta_c(2S) \rightarrow \gamma K_S^0 K \pi / K^+ K^- \pi^0$ ,  
 $\psi(2S) \rightarrow \gamma \eta_c(2S) \rightarrow \gamma K_S^0 K 3\pi$  and  $\psi(2S) \rightarrow \gamma \eta_c(2S) \rightarrow \gamma pp\bar{p}$

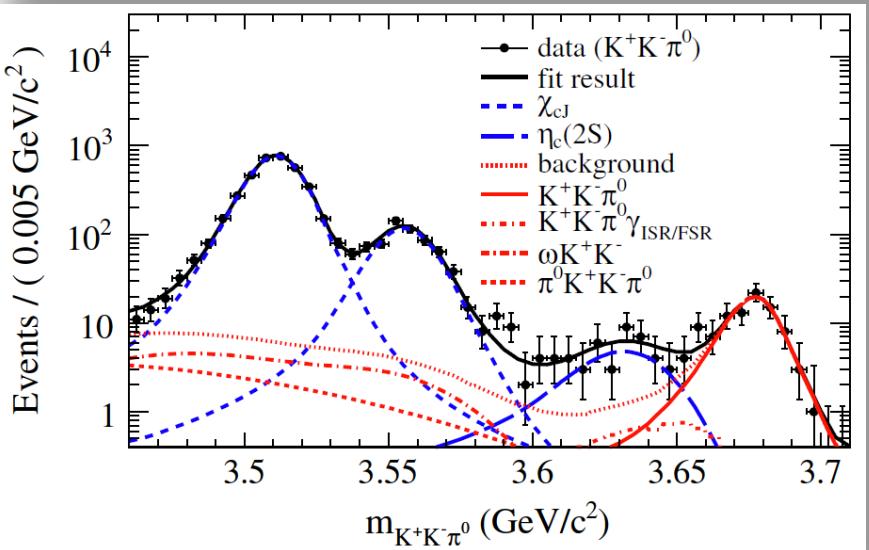
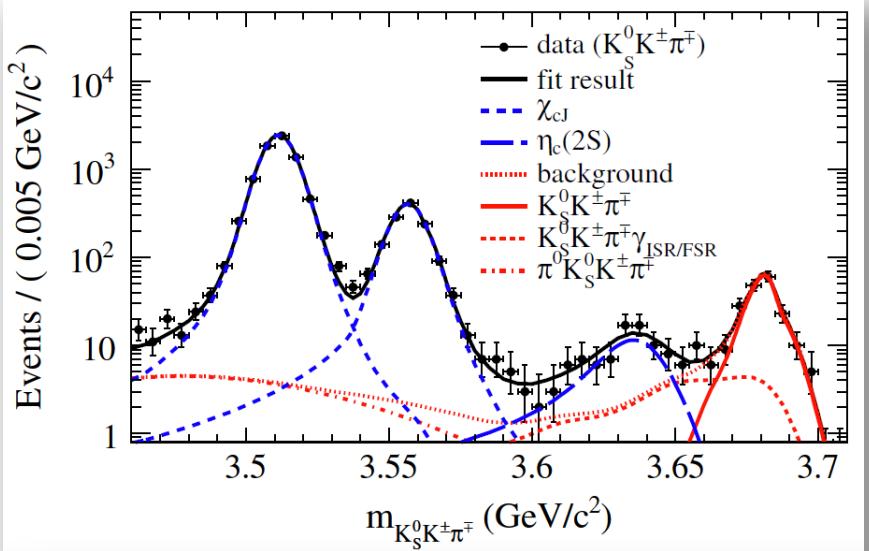
Experimental challenge:  $E_\gamma \sim 50 \text{ MeV}$

# Observation of $\psi(2S) \rightarrow \gamma \eta_c(2S)$ , $\eta_c(2S) \rightarrow K\bar{K}\pi$



PRL 109, 042003 (2012)

Combined significance  $> 10 \sigma$



## Mass and width

Simultaneous fit to yields:

$$M(\eta_c(2S)) = 3637.6 \pm 2.9 \pm 1.6 \text{ MeV}/c^2$$

$$\Gamma(\eta_c(2S)) = 16.9 \pm 6.4 \pm 4.8 \text{ MeV}$$

## Branching fraction

Using BABAR's: PRD 78, 012006 (2008)

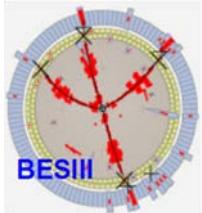
$$BF(\eta_c(2S) \rightarrow K\bar{K}\pi) = (1.9 \pm 0.4 \pm 1.1)\%$$

$$BF(\psi(2S) \rightarrow \gamma \eta_c(2S)) = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$$

Potential model:  $(0.1-6.2) \times 10^{-4}$

PPL 89, 162002 (2002)

# Evidence for $\eta_c(2S)$ in $\psi(2S) \rightarrow \gamma K_S K_3 \pi$



PRD 87, 052005 (2013)

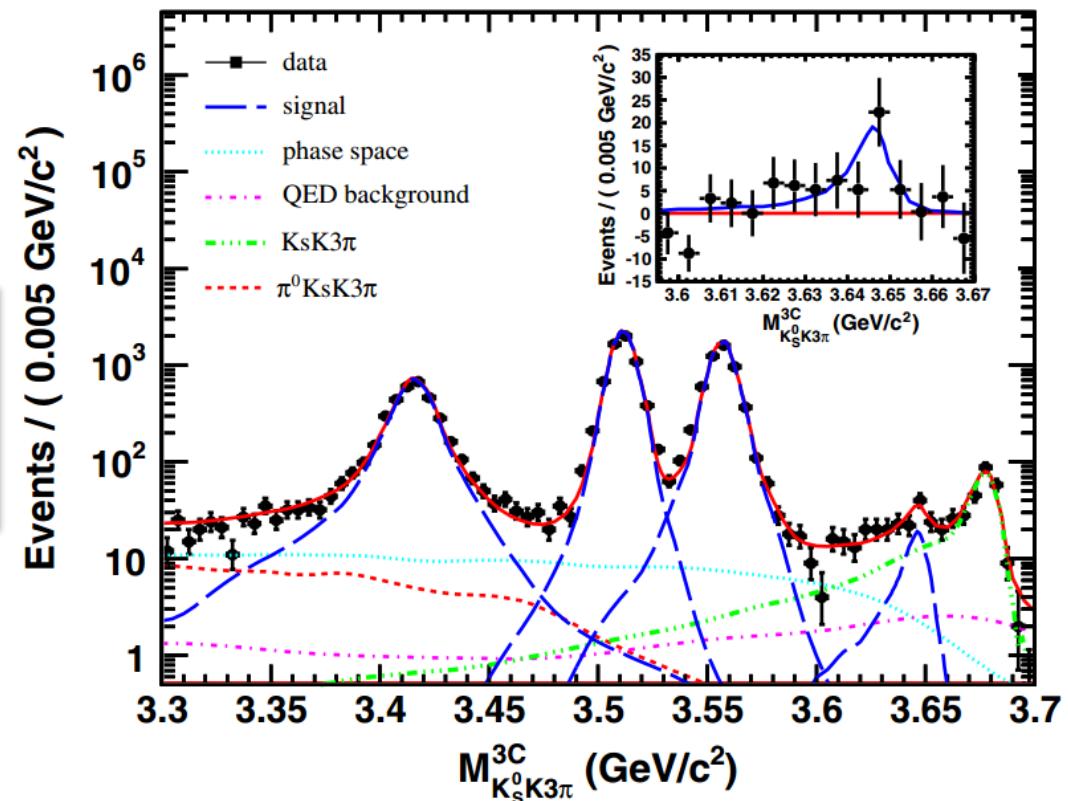
$N_{\text{evt}} = 57 \pm 17$   
Significance  $\sim 4.2 \sigma$

## Mass and width

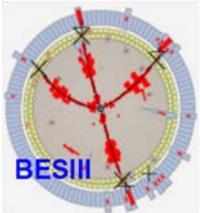
$$M(\eta_c(2S)) = 3646.9 \pm 1.6 \pm 3.6 \text{ MeV}/c^2$$
$$\Gamma(\eta_c(2S)) = 9.2 \pm 4.8 \pm 2.9 \text{ MeV}$$

## Branching fraction

$$\text{BF}(\psi(2S) \rightarrow \gamma \eta_c(2S) \rightarrow \gamma K_S K_3 \pi) = (7.03 \pm 2.10 \pm 0.70) \times 10^{-6}$$



# Search for $n_c(2S)$ in $\psi(2S) \rightarrow \gamma p\bar{p}$

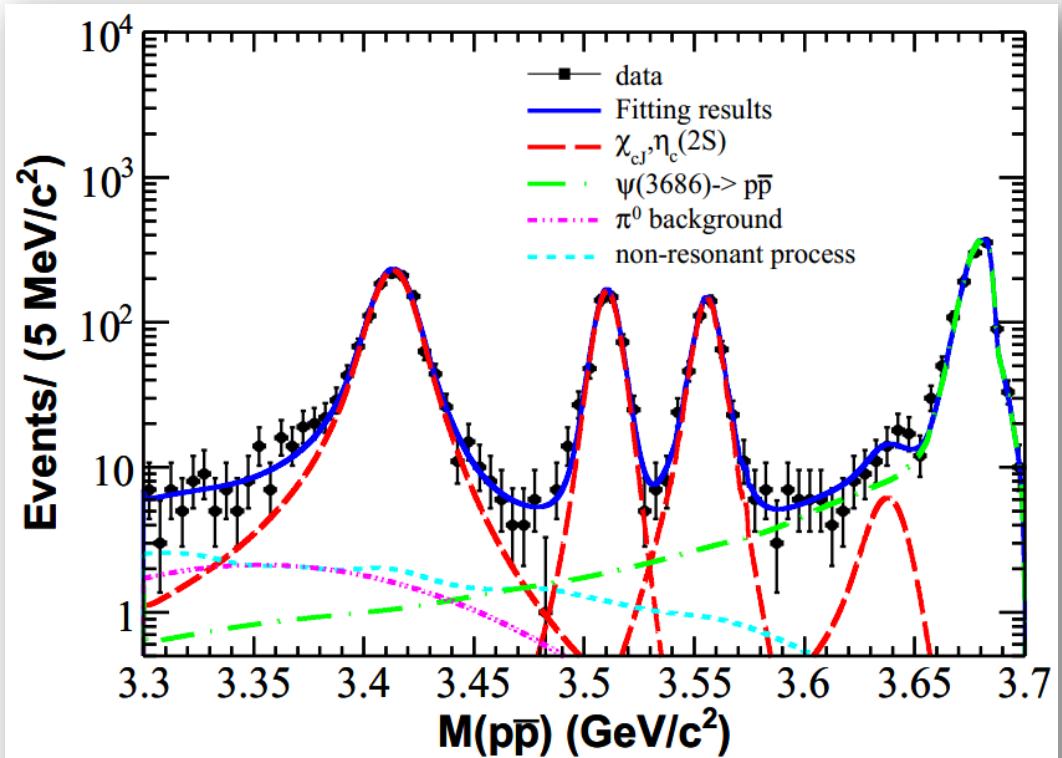


arXiv:1310.6099  
submitted to PRD

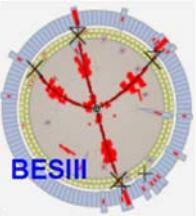
- No clear signal for  $\psi(2S) \rightarrow \gamma \eta_c(2S)$ ,  $\eta_c(2S) \rightarrow p\bar{p}$  is observed. UL on BF is set at 90% C.L.

## Branching fraction

$\text{BF}(\psi(2S) \rightarrow \gamma \eta_c(2S) \rightarrow \gamma p\bar{p}) < 1.6 \times 10^{-6}$

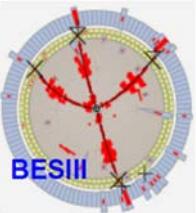


# Outline



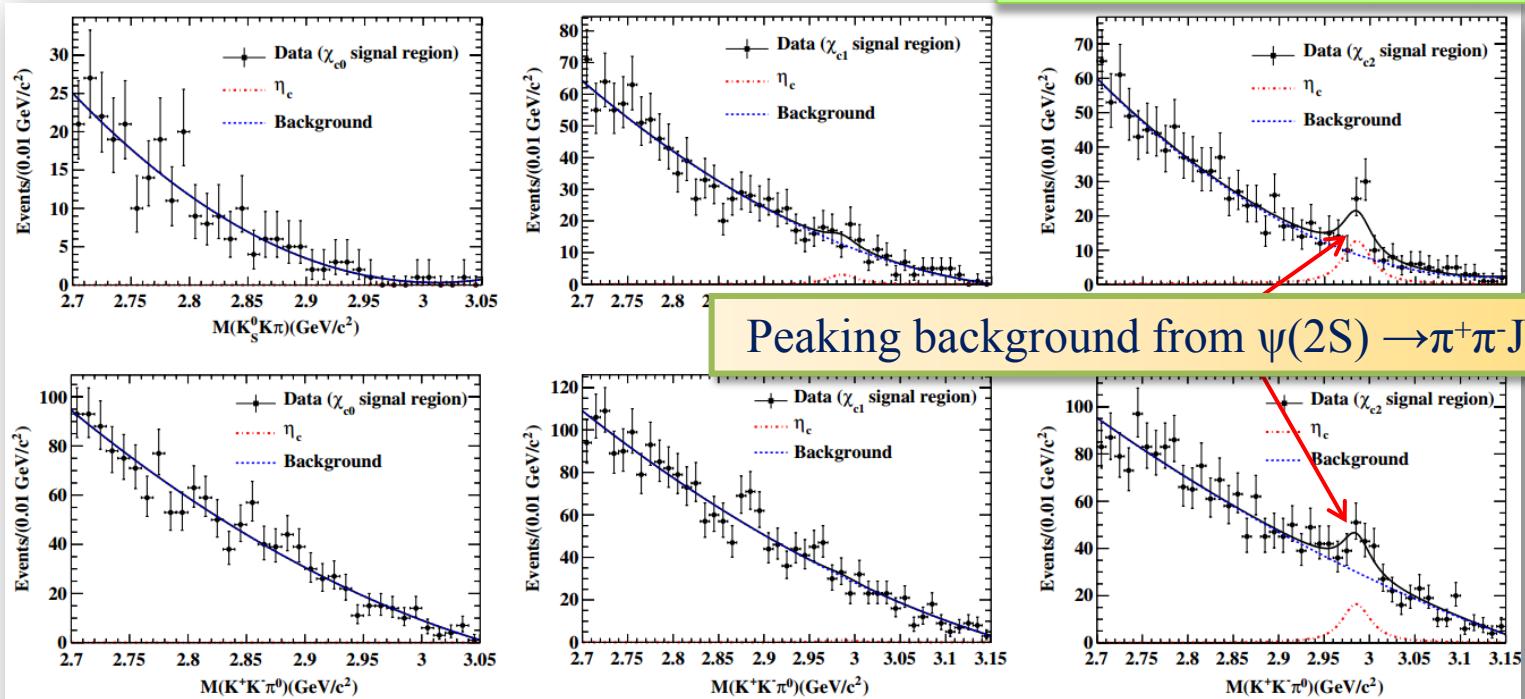
- Introduction to charmonium physics at BESIII
- BESIII data sets for charmonium study
- Selected results in this talk
  - ✓ Charmonium spectroscopy:  
 $\eta_c, h_c, \eta_c(2S)$
  - ✓ Charmonium transitions:  
 $X_{cJ} \rightarrow \pi^+ \pi^- \eta_c,$   
 $\psi(2S) \rightarrow n J/\psi, \pi^0 J/\psi, \psi(4040) \rightarrow n J/\psi, \pi^0 J/\psi,$   
 $\psi(3770) \rightarrow \gamma \eta_c, \gamma \eta_c(2S)$
- Summary

# Search for $\chi_{cJ} \rightarrow \eta_c \pi^+ \pi^-$



- Searching for the hadronic transitions of P-wave charmonium using 106 M  $\psi(2S)$  through process:  $\psi(2S) \rightarrow \gamma \chi_{cJ}$ ,  $\chi_{cJ} \rightarrow \eta_c \pi^+ \pi^-$ ,  $\eta_c \rightarrow K\bar{K}\pi$
- Further test the multipole-expansion

PRD 87, 012002 (2013)



$$BF(\chi_{c0}(1P) \rightarrow \pi^+ \pi^- \eta_c(1S)) < 0.07\%$$

$$BF(\chi_{c1}(1P) \rightarrow \pi^+ \pi^- \eta_c(1S)) < 0.32\% \text{ (theory: } 1.81 \pm 0.26\% \text{ by a E1-M1 soft gluon emission model)}$$

PRD 75, 054019 (2007)

$$BF(\chi_{c2}(1P) \rightarrow \pi^+ \pi^- \eta_c(1S)) < 0.54\%.$$

# $\psi(2S) \rightarrow \eta J/\psi, \pi^0 J/\psi$

PRD 86, 092008 (2012)

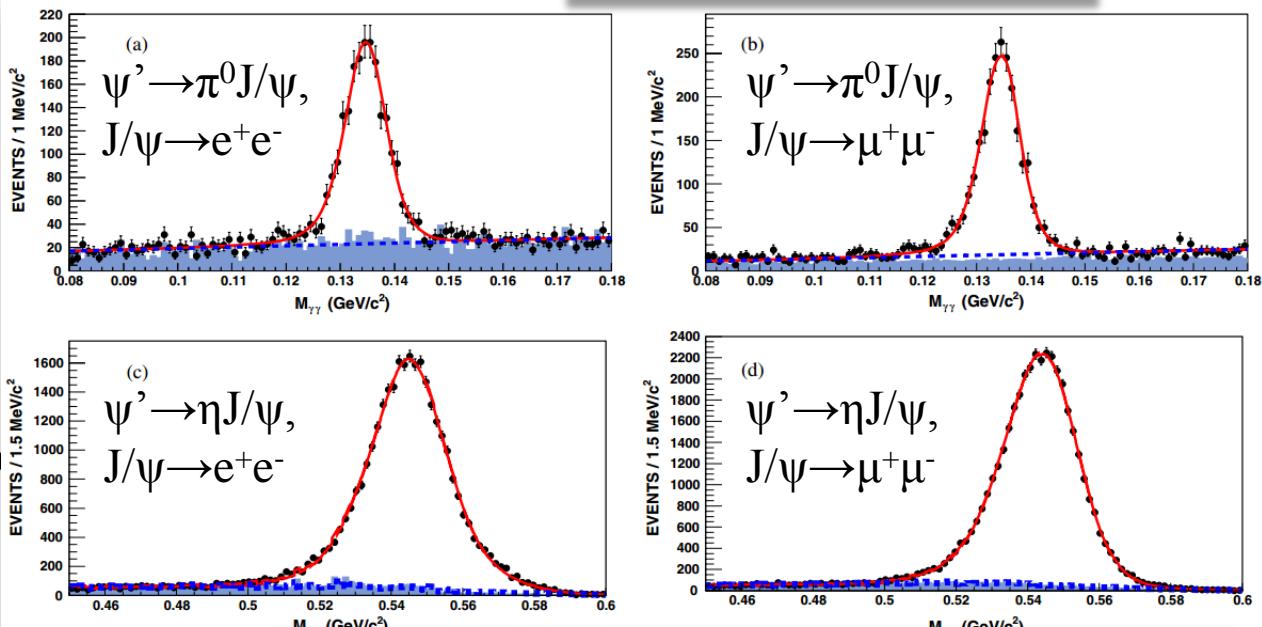


- Isospin violation transition:

$$\psi(2S) \rightarrow \pi^0 J/\psi$$

$$\text{➤ } R = \frac{\mathcal{B}(\psi' \rightarrow \pi^0 J/\psi)}{\mathcal{B}(\psi' \rightarrow \eta J/\psi)}$$

can be used to measure  
the light-quark mass ratio  
 $m_u/m_d$



## Theoretical predictions

✓  $R = 0.016$       *Phys. Rep. 194, 1 (1990)*

Based on QCD multipole-expansion  
and axial anomaly

✓  $R = 0.11 \pm 0.06$

Based on charmed-meson loop  
mechanism

*PRL 103, 082003 (2009)*

## Our results

$$\mathcal{B}(\psi(2S) \rightarrow \pi^0 J/\psi) = (1.62 \pm 0.02 \pm 0.03) \times 10^{-3}$$

$$\mathcal{B}(\psi(2S) \rightarrow \eta J/\psi) = (33.75 \pm 0.17 \pm 0.86) \times 10^{-3}$$

$$R = (3.74 \pm 0.06 \pm 0.04)\%$$

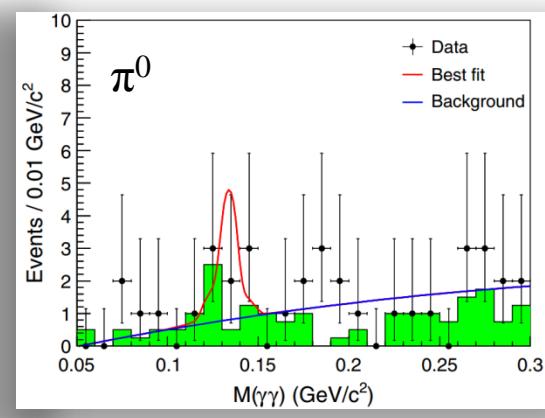
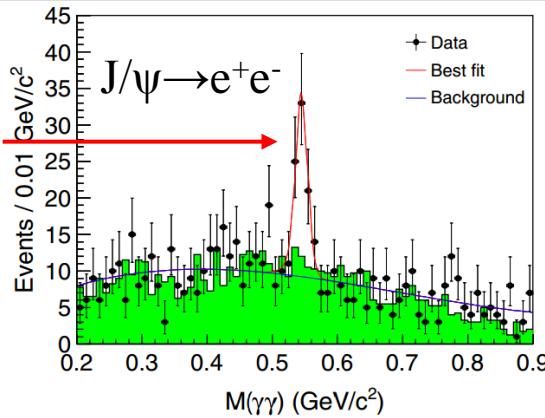
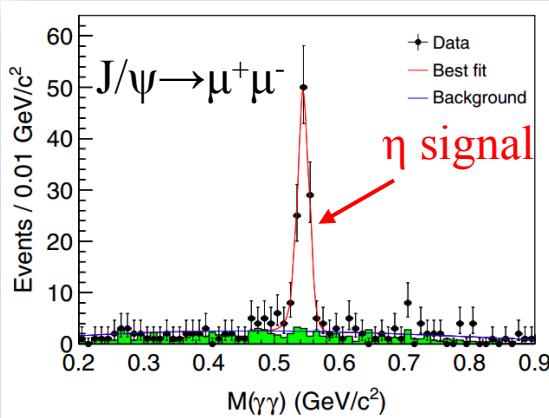
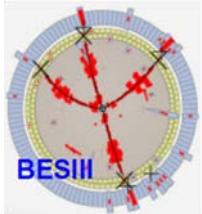
Precision improved!

Consistent with CLEO-c's

$$R = (3.88 \pm 0.23 \pm 0.05)\%$$

PRD 78, 011102 (2008)

# $e^+e^- \rightarrow \eta J/\psi, \pi^0 J/\psi$ @4.01 GeV

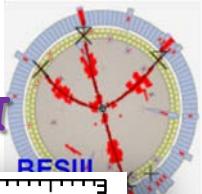


- Hadronic transition between charmonium states above open-charm threshold is not well understood.
- Data sample:  $478 \text{ pb}^{-1}$  @ 4.01 GeV
- First observation:  $e^+e^- \rightarrow \eta J/\psi$  (significance  $> 10 \sigma$ )
- Measured Born cross section:  
 $(32.1 \pm 2.8 \pm 1.3) \text{ pb}$
- Assume  $\eta J/\psi$  from  $\psi(4040)$   
 $\text{BF}(\psi(4040) \rightarrow \eta J/\psi) = (5.2 \pm 0.5 \pm 0.2 \pm 0.5) \times 10^{-3}$
- $\text{BF}(\psi(4040) \rightarrow \pi^0 J/\psi) < 2.8 \times 10^{-4}$  @ 90% C.L.
- Consistent with the theoretical calculation

*Q. Wang et al., arXiv:1206.4511*

*PRD 86, 071101(R) (2012)*

# Search for $\psi(3770) \rightarrow \gamma n_c(1S,2S)$ with $n_c(1S,2S) \rightarrow K_S K\pi$



- $\psi(3770)$  exclusive non-DD decays are not well understood
- M1 transition should be forbidden but higher multipoles may contribute

## Theoretical predictions

$$\Gamma(\psi(3770) \rightarrow \gamma n_c) = 17.14^{+22.93}_{-12.03} \text{ keV}$$

$$\Gamma(\psi(3770) \rightarrow \gamma n_c(2S)) = 1.82^{+1.95}_{-1.19} \text{ keV}$$

IML model PRD 84, 074005 (2011)

$$\Gamma(\psi(3770) \rightarrow \gamma n_c) = 10 \pm 11 \text{ keV LQCD PRD 79, 094504 (2009)}$$

- Data sample:  $2.9 \text{ fb}^{-1}$  @ 3.773 GeV
- No clear signals are observed. UL on BF is set at 90% C.L.

## Branching fraction

$$\text{BF}(\psi(3770) \rightarrow \gamma n_c \rightarrow \gamma K_S K\pi) < 1.6 \times 10^{-5}$$

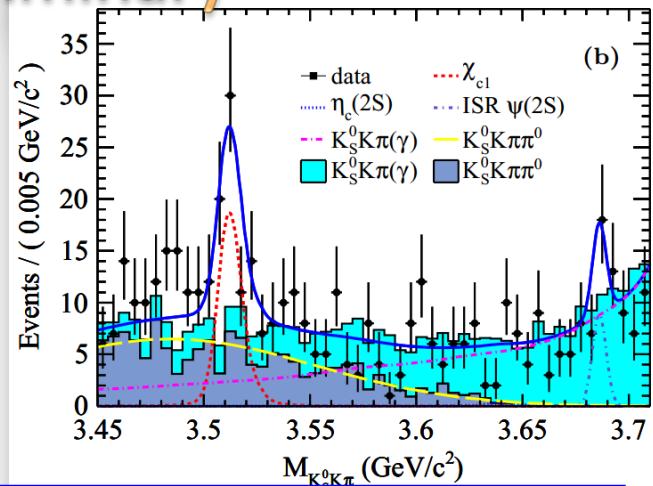
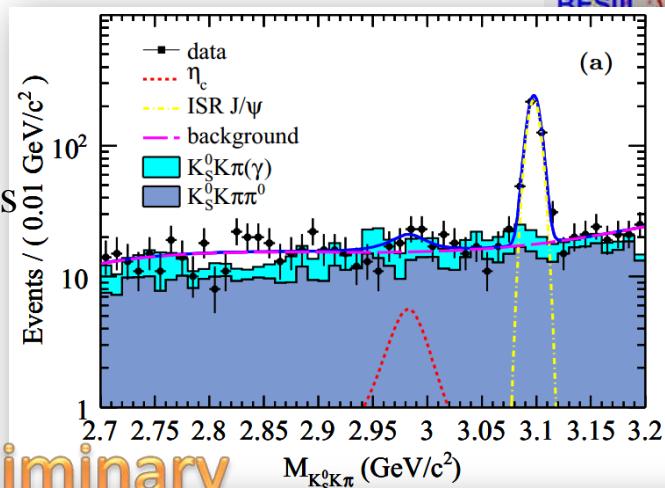
$$\text{BF}(\psi(3770) \rightarrow \gamma n_c(2S) \rightarrow \gamma K_S K\pi) < 5.8 \times 10^{-6}$$

Using PDG's BF( $n_c(1S,2S) \rightarrow K_S K\pi$ ):

$$\text{BF}(\psi(3770) \rightarrow \gamma n_c) < 6.7 \times 10^{-4}$$

$$\text{BF}(\psi(3770) \rightarrow \gamma n_c(2S)) < 2.1 \times 10^{-3}$$

## BESIII Preliminary



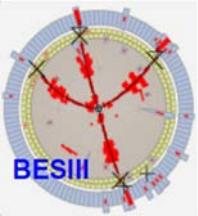
Also measured E1 transition:

$$\text{BF}(\psi(3770) \rightarrow \gamma \chi_{c1}) = (3.03 \pm 0.65 \pm 0.44) \times 10^{-3}$$

Consistent with PDG value:

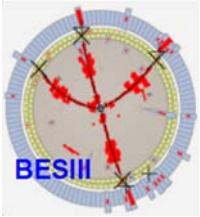
$$\text{BF}(\psi(3770) \rightarrow \gamma \chi_{c1}) = (2.9 \pm 0.6) \times 10^{-3}$$

# summary



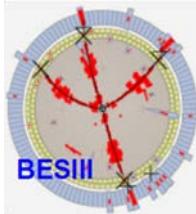
- Charmonium states provide a platform to study non-perturbative mechanism.
- $\eta_c$  mass and width have been measured in high precision; interference between  $\eta_c$  and the non-resonant amplitude is considered.
- $h_c$  is studied by exclusive analysis; precision has been improved.
- $\eta_c(2S)$  is observed in  $\psi(2S) M1$  transition for the first time with  $K\bar{K}\pi$  final states and evidence for the  $K_S K_3 \pi$
- Studies of charmonium transition impose stringent constraints on theory.

**Thank you for your attention!**

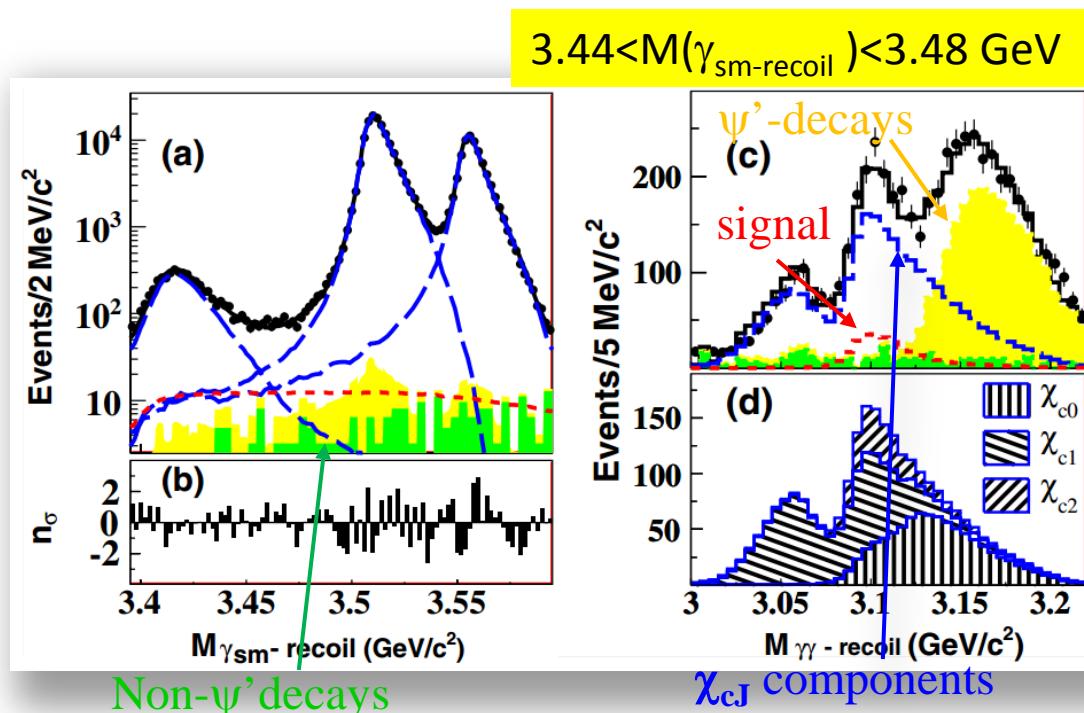


# BACK UP

# First evidence of $\psi(2S) \rightarrow \gamma\gamma J/\psi$



- Two photon transitions are well known in excitations of molecules, atomic hydrogen, and positronium. *A. Quattropani and F. Bassani, PRL 50, 1258 (1983)*
- Never been observed in the quarkonium system.  
CLEO-c: upper limit  $\text{BF}(\psi(2S) \rightarrow \gamma\gamma J/\psi) < 1 \times 10^{-3}$  *PRD 78, 011102 (2008)*
- Sensitive to hadron-loop effects and thus provides a unique opportunity to investigate these issues.



Significance  $\sim 3.8 \sigma$   
including systematics

$\text{BF}((\psi(2S) \rightarrow \gamma\gamma J/\psi) =$   
 $(3.1 \pm 0.6^{+0.8}_{-1.0}) \times 10^{-4}$   
( $J/\psi \rightarrow e^+e^-$  and  $\mu^+\mu^-$  mode combined)  
 $\text{BF}((\psi(2S) \rightarrow \gamma\chi_{cJ}, \chi_{cJ} \rightarrow \gamma J/\psi)$  are also measured.

*PRL 109, 172002 (2012)*