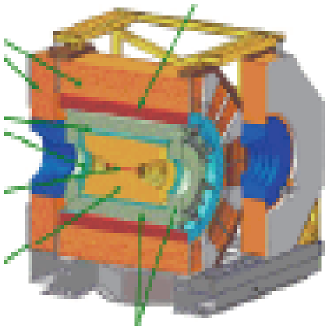


Recent Charmonium results at BESIII

Ji Chang-sheng

(On behalf of BESIII Collaboration)

University of Science and Technology of China

Rencontres de Moriond
QCD and High Energy Interactions
La Thuile, March 9-16, 2013

Outline

- ***Charmonium physics at BESIII***

- ***Selected topics in this talk***

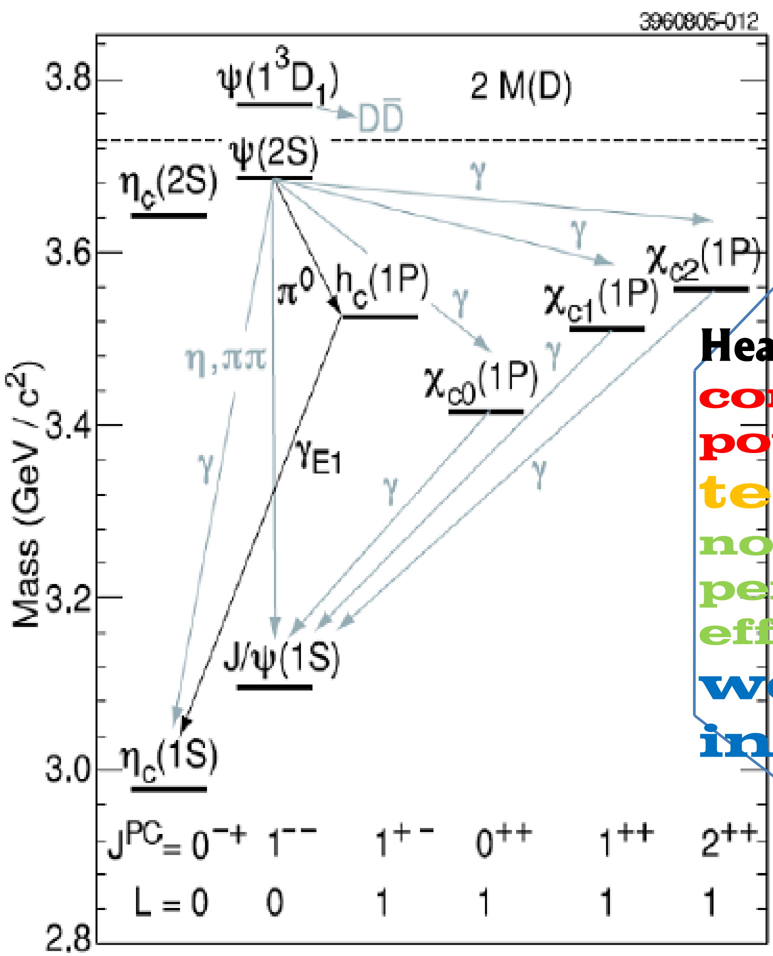
  $\mathbf{h_c}$

  η_c

  $\eta_c(2S)$

- ***Summary***

Charmonium physics @ BESIII



Heavy quarkonia:
confinement potential
test pQCD
non-perturbative effects
weak interaction

- **Charmonium spectroscopy**

  η_c, J/Ψ, h_c, $\eta_c(2S)$, χ_{cJ}, $\Psi(2S)$…

- **Charmonium transitions**

  $\psi(2S) \to \gamma\gamma J/\psi$,
  $\psi(2S) \to \eta J/\psi$, $\pi^0 J/\psi$
  $\chi_{cJ} \to \eta_c \pi^+\pi^-$
  …..

- **Charmonium decays**

  $\psi(2S) \to K^+K^-\pi^0$, $K^+K^-\eta$
  $\chi_{cJ} \to \gamma\gamma$
  $\chi_{cJ} \to B\bar{B}$
  $\chi_{cJ} \to \Lambda\bar{\Lambda}\pi^+\pi^-$
  $\chi_{cJ} \to p\bar{n}\pi^-$, $p\bar{n}\pi^-\pi^0$
  …..

- **Rare and forbidden charmonium decays**

  $J/\Psi \to e\mu$
  Invisible/Weak decays of η/η`
  ….

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- ***Charmonium physics at BESIII***
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$h_c(^1P_1)$

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

  $\Delta M_{hf}(1P) = M(h_c) - \langle m(1\,^3P_J)\rangle \neq 0$

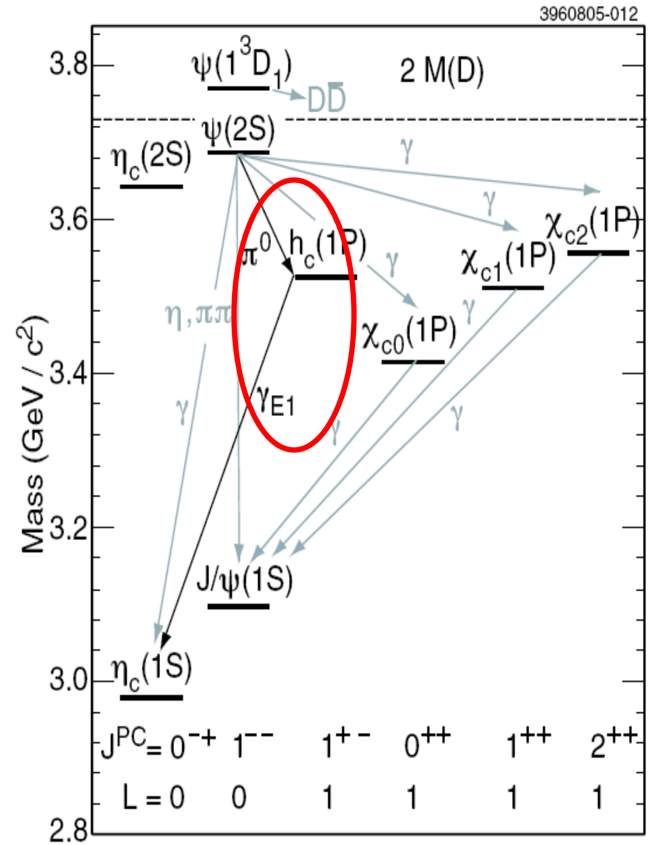
  where $\langle m(1\,^3P_J)\rangle = [(M(c_{c0})+3M(c_{c1})+5M(c_{c2})]/9$,
- E835 found evidence for h_c in $p\bar{p} \to h_c \to \gamma\eta_c$
- CLEOc observed h_c in *cascade process*

  $\Psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$

  $\Delta M_{hf}(1P)=0.08\pm0.18\pm0.12$ MeV/c^2

  Consistent to 1P hyperfine splitting of 0.
- . Recently, CLEOc reported evidence for the decay

  $h_c \to \pi^+\pi^-\pi^+\pi^-\pi^0$



<u>*Theoretical prediction:*</u>

$BF(\Psi(2S)\to\pi^0 h_c) = (0.4\text{-}1.3)\times10^{-3}$

$BF(h_c\to\gamma\eta_c) = 88\%$ (PQCD)

$\Gamma(h_c)=(0.51 \pm 0.01)$MeV(PQCD)

$BF(h_c\to\gamma\eta_c) = 41\%$ (NRQCD)

$\Gamma(h_c)=(1.1 \pm 0.09)$MeV(PQCD)

Kuang, PR D65 094024 (2002)

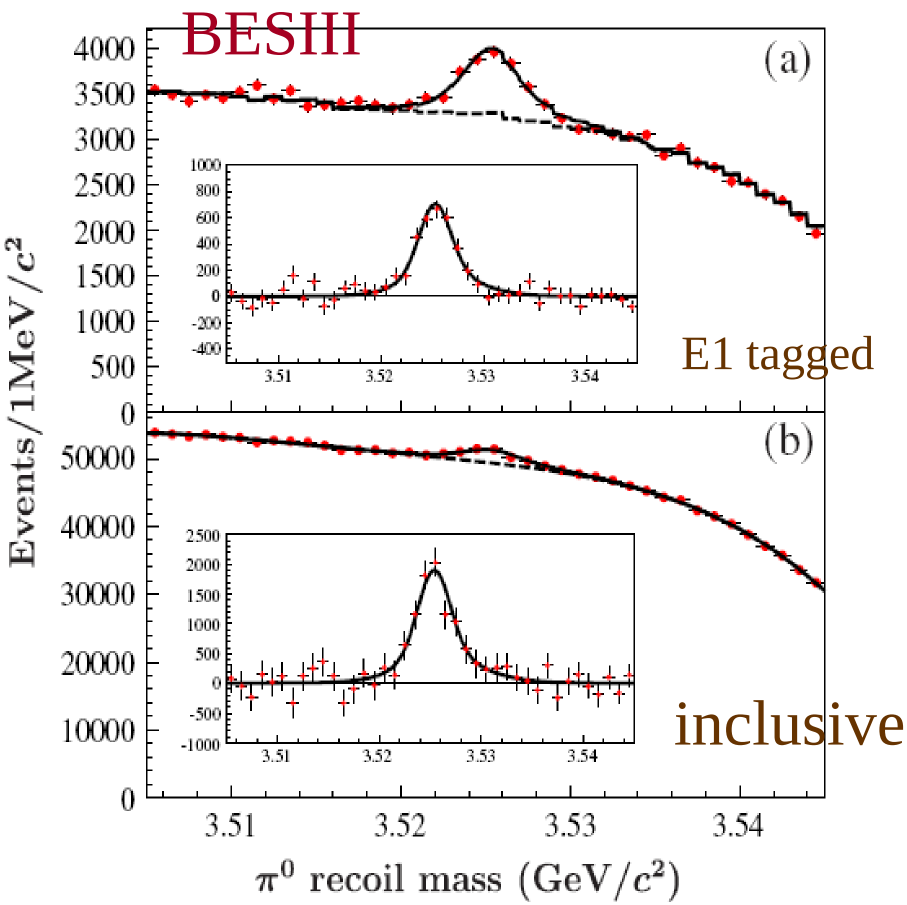
$BF(h_c\to\gamma\eta_c) = 38\%$

Godfrey and Rosner, PR D66 014012(2002)

$\Gamma(h_c)=(0.601 \pm 0.055)$MeV(unquenched lattice QCD)

J.J.Dudek, PR D73, 074507 (2006)

$\Psi(2S) \to \pi^0 h_c$, $h_c \to \gamma \eta_c$



BESIII: PRL 104 132002 (2010) (E1-tagged)

Mass = **3525.40±0.13±0.18** MeV/c^2

Width = **0.73±0.45±0.28** MeV

<1.44 MeV @90%

CLEOc inclusive results: PRL 101 182003 (2008)

Mass = **3525.35±0.23±0.15** MeV

Width: fixed at 0.9 MeV

Hyperfine mass splitting

$\Delta M_{hf}(1P) = M(h_c) - \langle m(1\ ^3P_J)\rangle$

BESIII: ***0.10 ±0.13 ±0.18*** MeV/c^2

CLEOc: ***0.02 ±0.19 ±0.13* MeV/c^2**

Consistent with no strong spin-spin interaction

By combining inclusive results with E1-photon tagged results

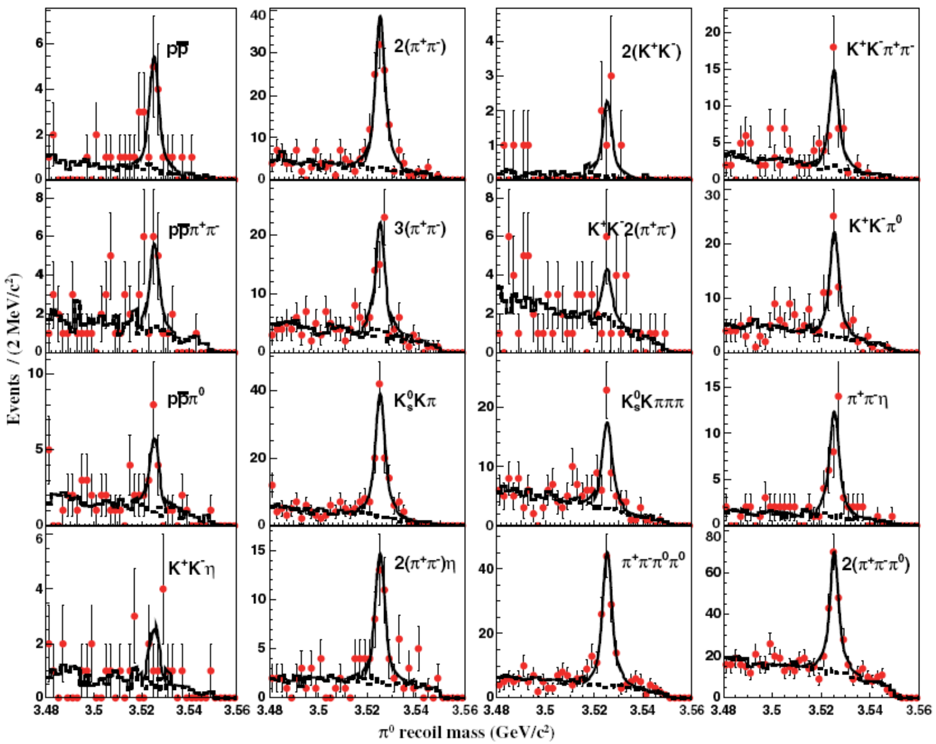
$BF(\psi' \to \pi^0 h_c) =$ **(8.4±1.3±1.0) ×10^{-4}**

$BF(h_c \to \gamma \eta_c) =$ **(54.3±6.7±5.2)%**

Agree with prediction from Kuang, Godgrey, Dude et al.

PRL 104, 132002 (2010)

$\Psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, η_c exclusive decays



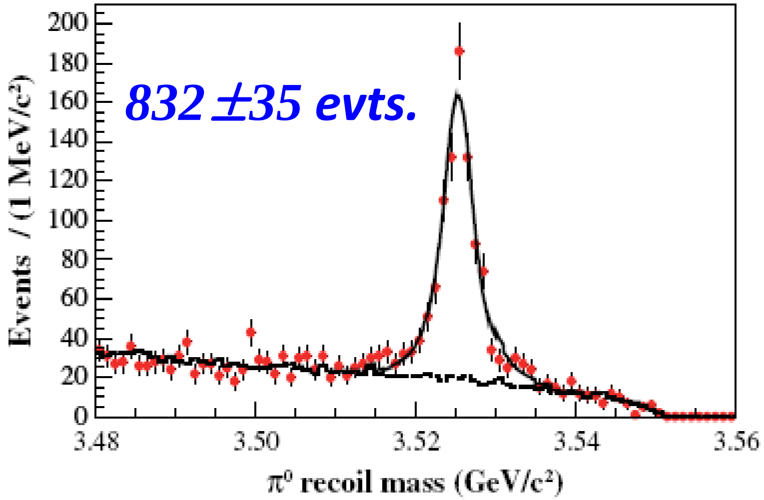
Simultaneous fit to π^0 recoiling mass:

Mass = **3525.31±0.11±0.14** MeV/c^2

Width = **0.70±0.28±0.22** MeV

PRD 86, 092009 (2012)

Summed distribution



Consistent with BESIII inclusive results

Mass = **3525.40±0.13±0.18** MeV/c^2

Width = **0.73±0.45±0.28** MeV

BESIII: PRL 104 132002 (2010)

CLEOc exclusive results

Mass =**3525.21±0.27±0.14** MeV/c^2

evts. =**136±14**

CLEOc: PRL 101 182003 (2008)

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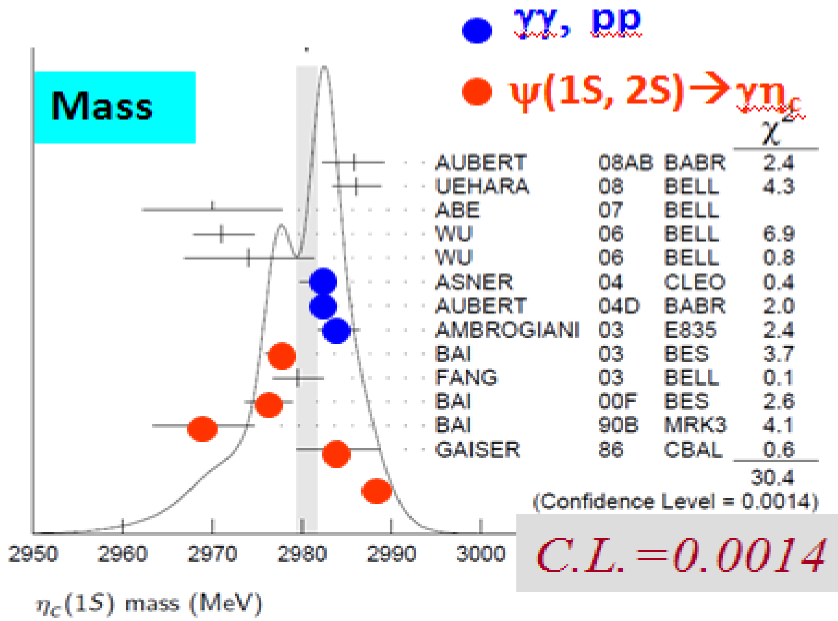
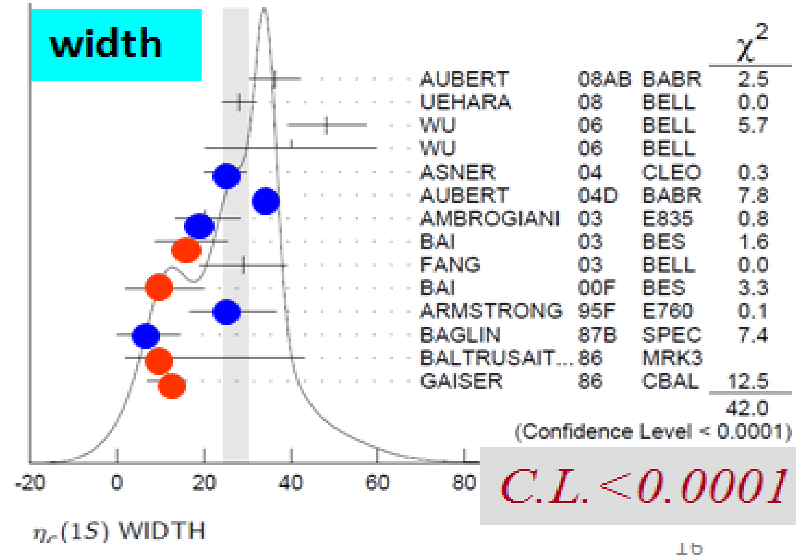
- *Summary*

η_c



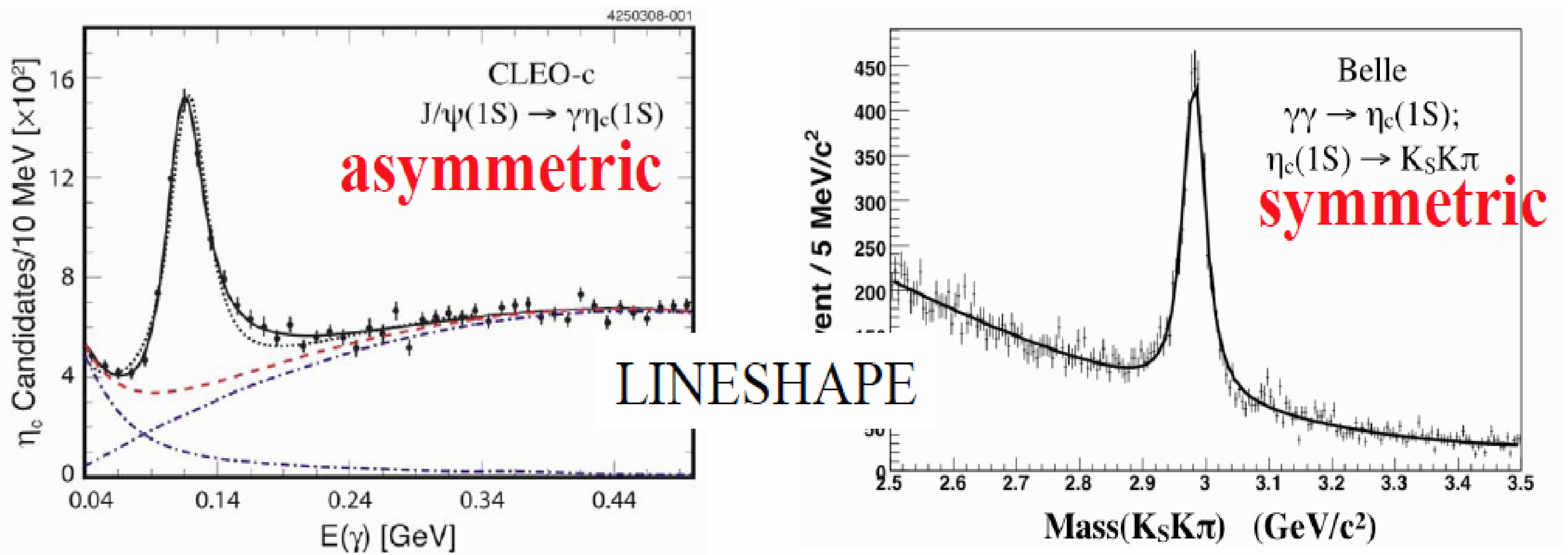


- Ground state of S-wave spin singlet charmonium, but its properties are not well known, discovered in 1980 by MarkII
- The obvious discrepancy between different experiments:

  J/Ψ radiative transition: M ~ 2978.0MeV/c^2, Γ ~ 10MeV

  γγ process: M = 2983.1±1.0 MeV/c^2, Γ= 31.3±1.9 MeV
- The cc hyperfine splitting: M(J/Ψ)-M(η_c) is an important parameter for understanding confinement potential and as a test of LQCD

η_c



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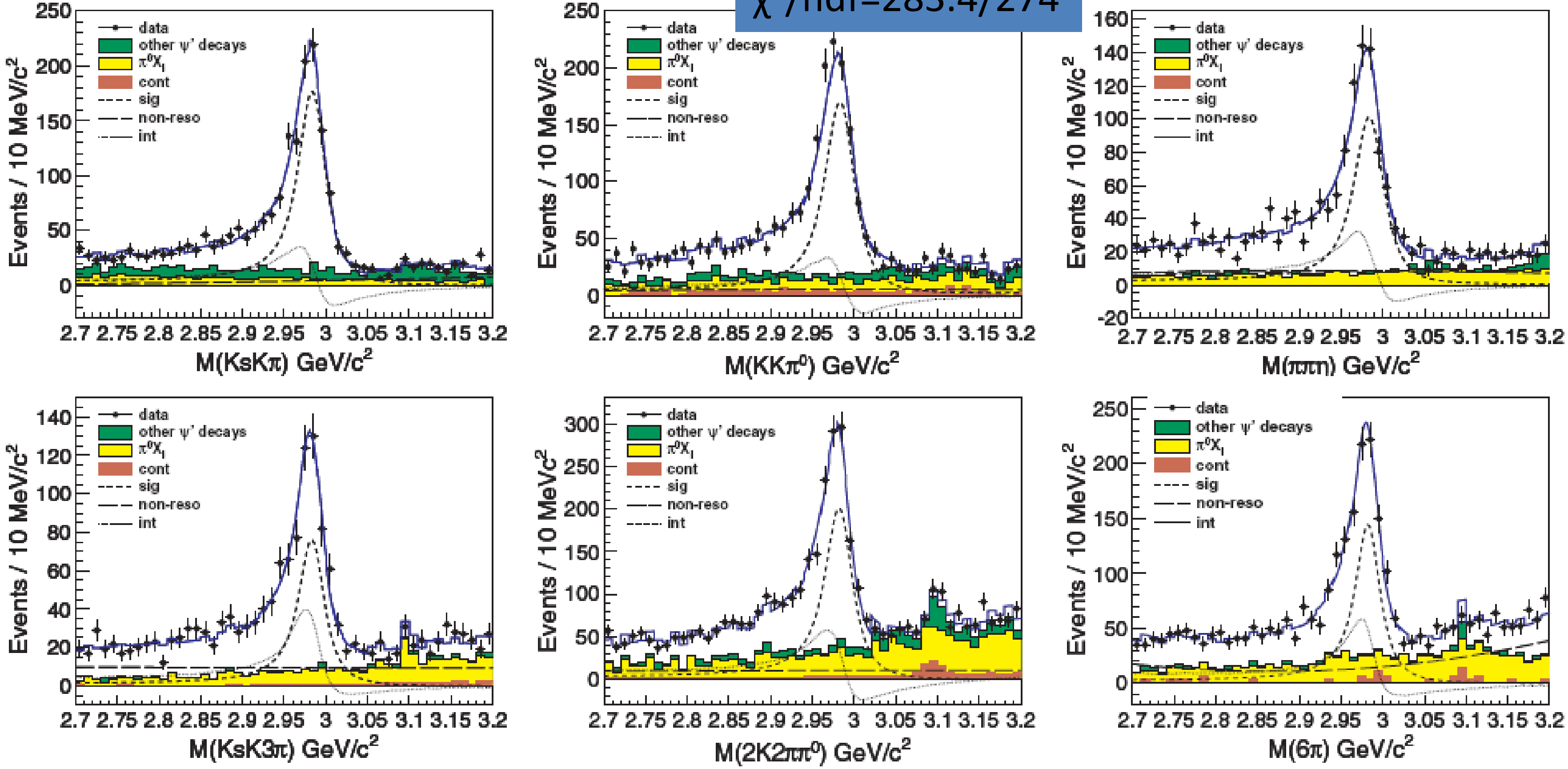
$\Psi(2S)\to\gamma\eta_c$, η_c exclusive decays

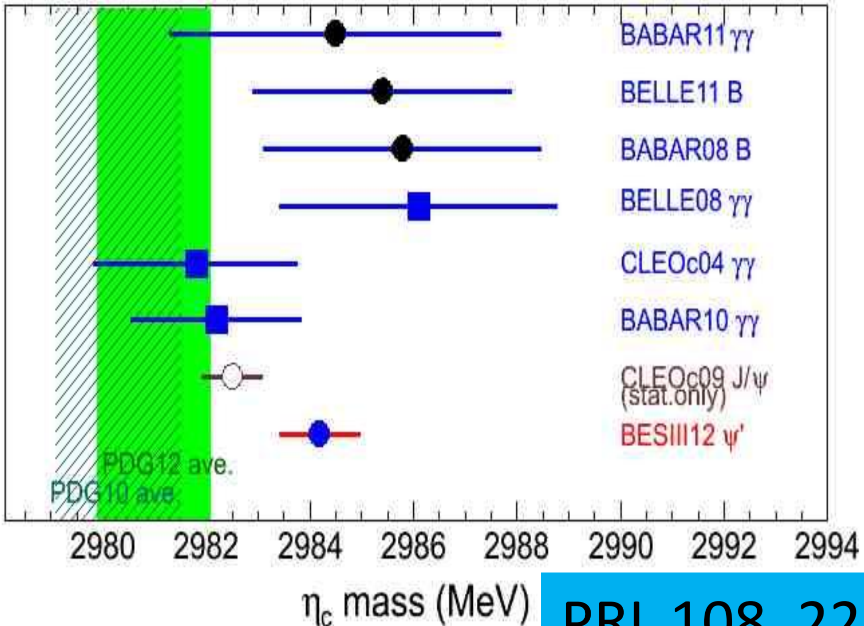
χ^2/ndf=283.4/274



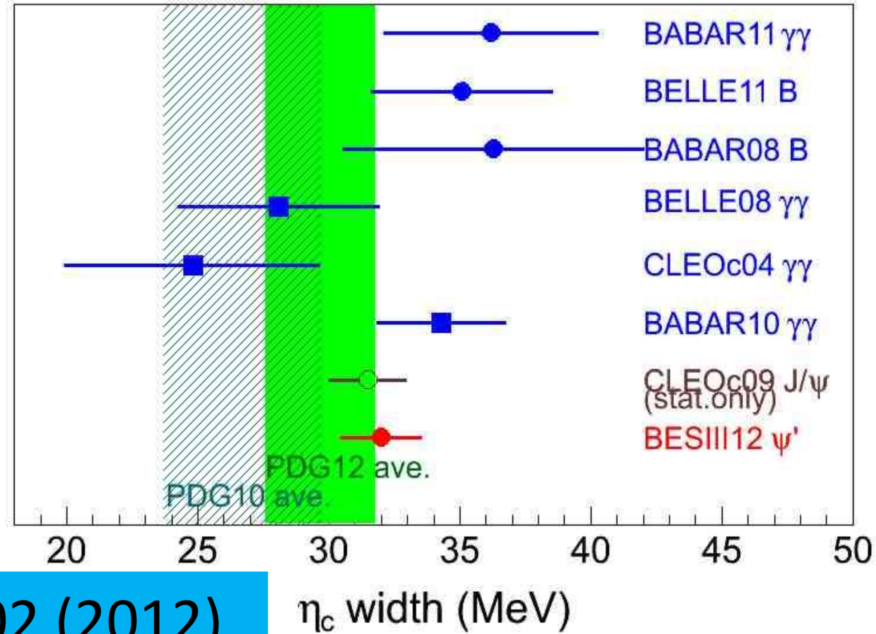
PRL 108, 222002 (2012)

- Modified Breit-Wigner (hindered M1)
- Simultaneously fit considering the interference between η_c and non-η_c backgrounds

η_c parameters @ BESIII



PRL 108, 222002 (2012)



η_c width (MeV)

$M(\eta_c)=$**2984.3±0.6±0.6** MeV/c^2

$\Gamma(\eta_c)$ =**32.0±1.2±1.0** MeV ➡ Consistent with gamma-gamma fusion from B factories.

Φ=**2.40±0.07±0.08** rad

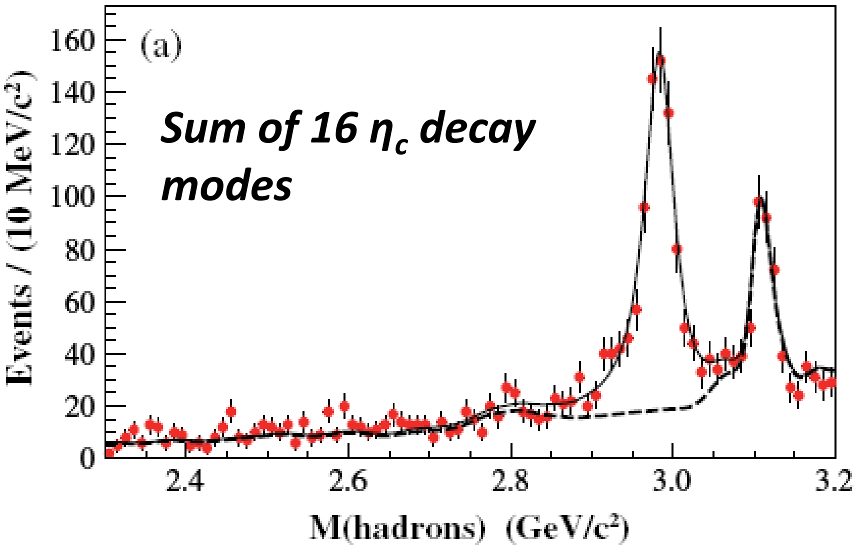
or **4.19 ± 0.03 ±0.09** rad

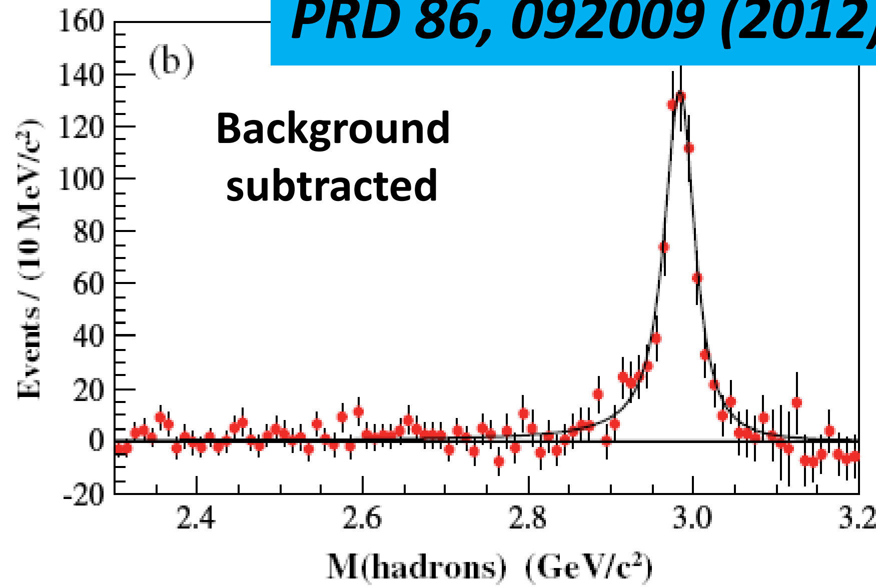
Hyperfine splitting:

$\Delta M(1S)$=**112.6±0.8** MeV/c^2 ➡ Agree with lattice QCD calculations and quark-model predictions of the charmonium hyperfine splitting

η_c lineshape from $h_c \rightarrow \gamma\eta_c$

PRD 86, 092009 (2012)





- The line shape in $h_c \rightarrow \gamma\eta_c$ is not as distorted as in $\Psi(2S) \rightarrow \gamma\eta_c$ decay, because the non-resonant interfering background is small. Ultimately, this channel will be best suited to determine η_c resonance parameters.

$$M(\eta_c) = 2984.49 \pm 1.16 \pm 0.52\ \mathrm{MeV}/c^2,$$

$$\Gamma(\eta_c) = 36.4 \pm 3.2 \pm 1.7\ \mathrm{MeV}.$$

These results are consistent with the recent BESIII *$\Psi(2S) \rightarrow \gamma$* η_c results and B-factory results from $\gamma\gamma \rightarrow \eta_c$ and B decays

Outline

- ***Charmonium physics at BESIII***

- ***Selected topics in this talk***

  h_c

  η_c

  $\eta_c(2S)$

- ***Summary***

$\eta_c(2S)$

- First "observed" by Crystal Ball in1982 from $\Psi(2S)\to\gamma X$,(much lower mass) never confirmed by other experiments. *PRL 48 70 (1982)*
- Observed in different process other than radiative transitions.

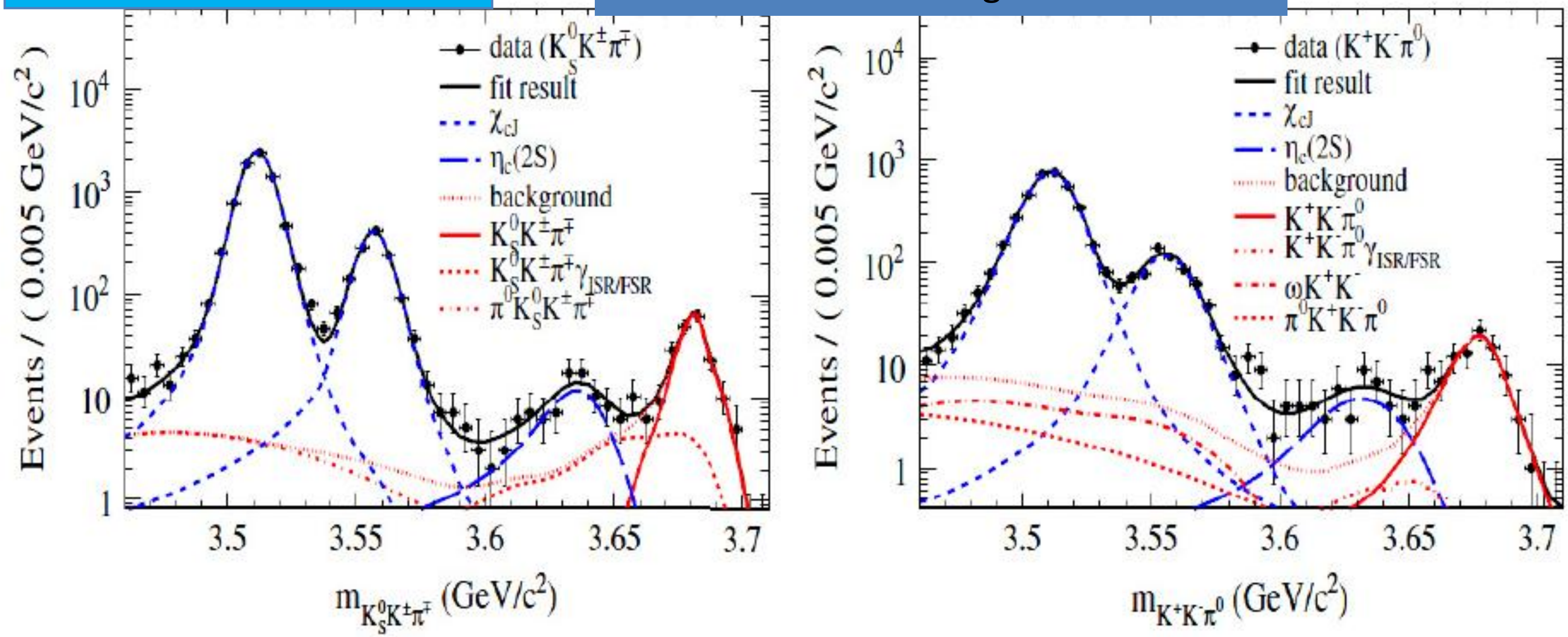
Experiment	M [MeV]	Γ [MeV]	Process
Belle [1]	$3654 \pm 6 \pm 8$	—	$B^\pm \to K^\pm \eta_c(2S), \eta_c(2S) \to K_S K^\pm \pi^\mp$
CLEO [2]	$3642.9 \pm 3.1 \pm 1.5$	$6.3 \pm 12.4 \pm 4.0$	$\gamma\gamma \to \eta_c(2S) \to K_S K^\pm \pi^\mp$
BaBar [3]	$3630.8 \pm 3.4 \pm 1.0$	$17.0 \pm 8.3 \pm 2.5$	$\gamma\gamma \to \eta_c(2S) \to K_S K^\pm \pi^\mp$
BaBar [4]	$3645.0 + 5.5^{+4.9}_{-7.8}$	—	$e^+e^- \to J/\psi c\bar{c}$
PDG [5]	3638 ± 4	14 ± 7	—

- The M1 transition $\Psi(2S) \to \gamma\eta_c(2S)$ has not been observed using CLEO 25M $\Psi(2S)$ events: *$BF(\Psi(2S) \to \gamma\eta_c(2S)) < 7.6 \times 10^{-4}$* CLEO: PRD 81 052002 (2010)
- Better chance to observe $\eta_c(2S)$ in Ψ' radiative transition with ~106M $\Psi(2S)$ data at BESIII
- Decay mode explored: $\Psi(2S) \to \gamma\eta_c(2S) \to \gamma K_s K^\pm \pi^\mp / K^+ K^- \pi^0$
  and $\Psi(2S) \to \gamma\eta_c(2S) \to \gamma K_S K^\pm \pi^\mp \pi^+ \pi^-$

First observation of $\psi(2S) \rightarrow \gamma\eta_c(2S)$

PRL 109, 042003 (2012)

Combined statistical significance: >10σ



Simultaneous fit with :

***η_c(2S)* signal**: modified BW (*M1*) *(Resolution extrapolated from χ_{cJ})*

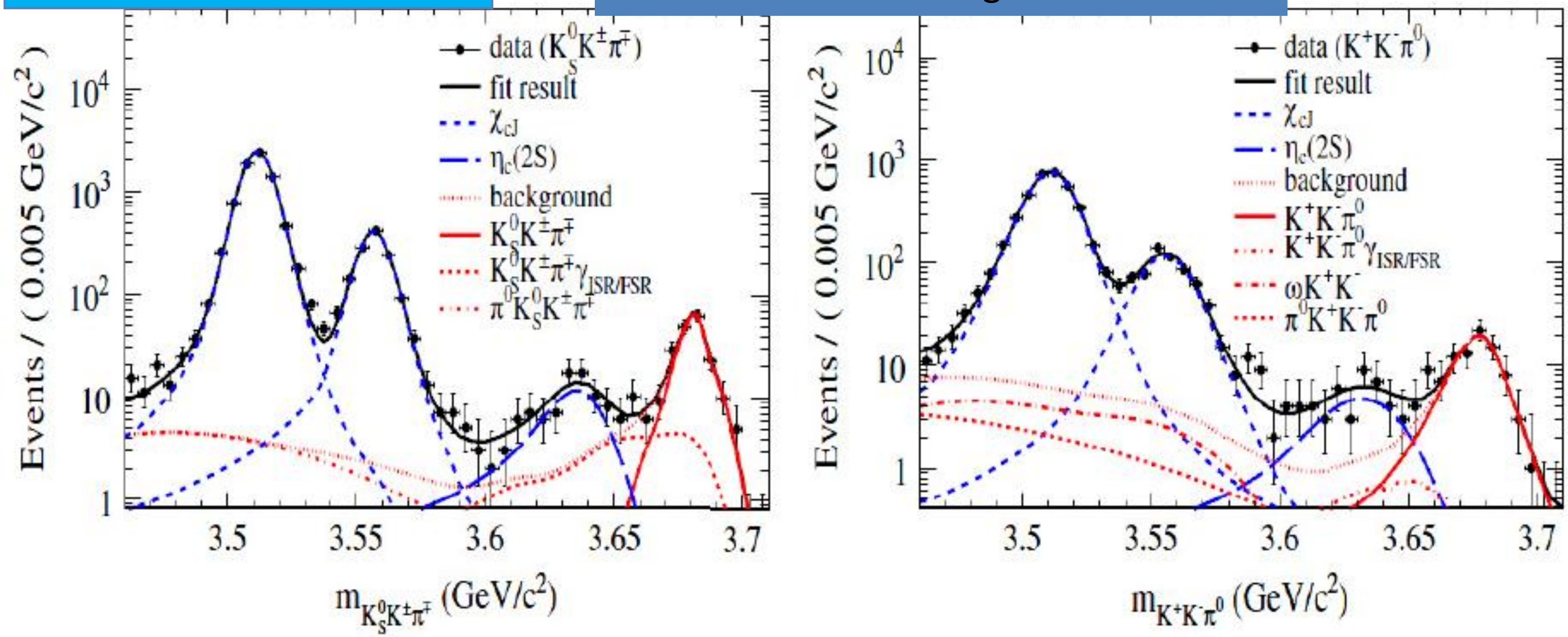
χ_{cJ} signal: MC shape smeared with Gaussian

BG from e+ e-→ $K\bar{K}\pi$ (ISR), $\psi(2S) \rightarrow K\bar{K}\pi$ (FSR), $\psi(2S) \rightarrow \pi^0 K\bar{K}\pi$: are measured from data

First observation of $\psi(2S) \to \gamma\eta_c(2S)$

PRL 109, 042003 (2012)

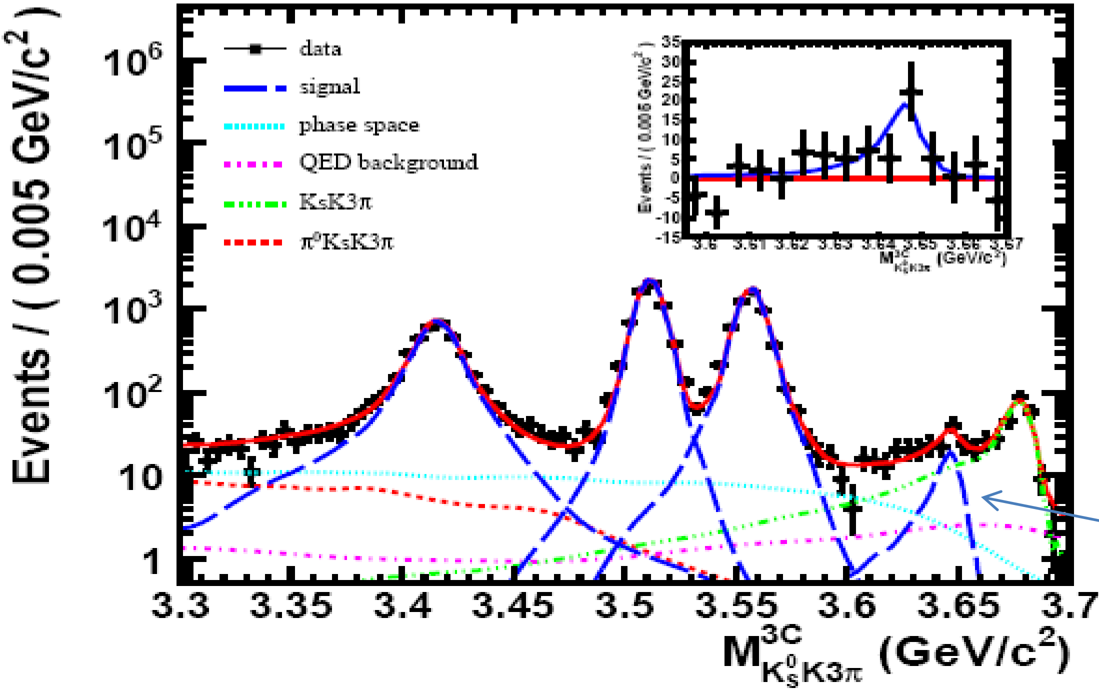
Combined statistical significance: >10σ



- **M(η_c (2S)) = (3637.6 ± 2.9 ± 1.6)MeV/c^2**
- **Γ(η_c(2S)) = (16.9 ± 6.4 ± 4.8) MeV**
- ***Br(Ψ(2S)→γη_c(2S) → $\gamma K \bar{K} \pi$)= (1.30 ±0.20 ±0.30) × 10^{-5}***

Using B(η_c (2S)→ $K \bar{K} \pi$) = (1.9 ± 0.4 ± 1.1)% (BABAR)
B(Ψ(2S)→γη_c(2S)) = (6.8 ± 1.1 ± 4.5) × 10^{-4}
CLEO-c: < 7.6 × 10^{-4} [PRD 81, 052002 (2010)]
Potential models: (0.1~6.2)× 10^{-4} [arXiv:0909.2812]

Evidence for $\eta_c(2S)$ in $\psi' \to \gamma K_S K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$



ignificance: ≈4.2σ

$$N_{\eta_c(2S)} \to K^0_S K^{\pm}\pi^{\mp}\pi^{+}\pi^{-} = 57 \pm 17;$$

$$\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S)) \times \mathcal{B}(\eta_c(2S) \to K^0_S K^{\pm}\pi^{\mp}\pi^{+}\pi^{-})$$

$$= (7.03 \pm 2.10 \pm 0.70) \times 10^{-6};$$

$$M_{\eta_c(2S)} = 3646.9 \pm 1.6 \pm 3.6\,\mathrm{MeV}/c^2;$$

$$\Gamma_{\eta_c(2S)} = 9.2 \pm 4.8 \pm 2.9\,\mathrm{MeV}/c^2;$$

PRD 87, 052005 (2013)

Summary

- **With 106 M *$\Psi(2S)$* data sample collected by BESIII detector at BEPCII, charmonium states h_c, η_c, $\eta_c(2S)$ have been well studied:**

✓ The absolute branching fractions of $\Psi(2S) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\eta_c$ as well as the width of h_c are measured for the first time

✓ Parameters of η_c are measured with high precision, interference between η_c and the non-resonant amplitudes around the η_c mass is considered for the first time.

✓ First observation of M1 transition $\Psi(2S) \rightarrow \gamma\eta_c(2S)$ with $K\bar{K}\pi$ final states and evidence for the $K_S K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$

Thank you!

Back up

$\psi' \to \gamma\gamma J/\psi$ transition

- Two photon transitions are well known in excitations of molecules, atomic hydrogen, and positronium.

  *[F. Bassani etal, PRL **39**, 1070 (1977);A. Quattropani etal, PRL **50**, 1258 (1983)]*

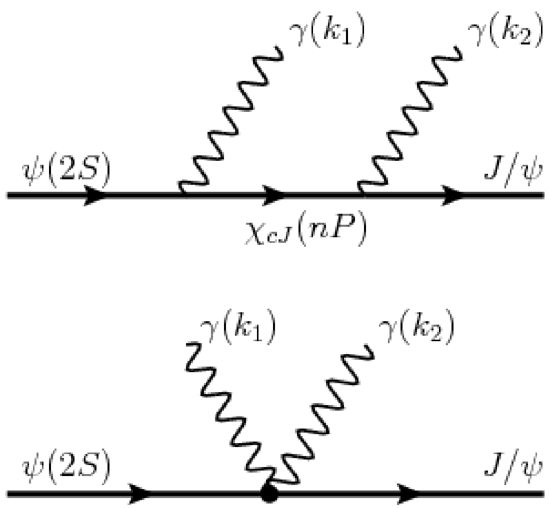
- Never been observed in the quarkonium system.

  CLEOc: upper limit of $Br(\psi' \to \gamma\gamma J/\psi)$ is 1×10^{-3} (PRD 78,011102(2008))

- Observation helpful to understand heavy quarkonium spectrum & strong interaction

Theoretically:

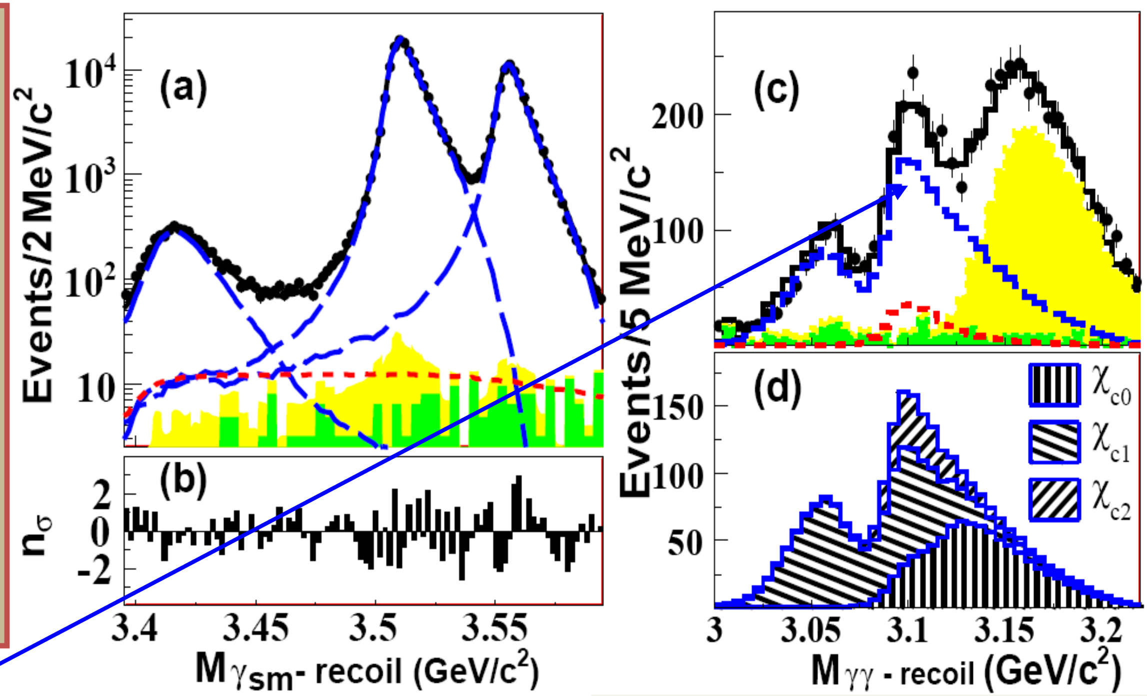
- **Potential models give discrete spectra ($\Psi(2S) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to \gamma J/\Psi$)**
- **Possibility of testing the hadron-loop effect**
- **Coupled channel: the hadron-loop effect also may play an important role in the continuous spectra**



Z. G. He *et al.*, Phys. Rev. D 83, 054028 (2011)

First evidence of $\psi' \to \gamma\gamma J/\psi$

Yellow: the background from ψ' decay.
Green: the continuum background
Blue: the $\psi' \to \gamma\chi_{cJ}$, $\chi_{cJ} \to \gamma J/\psi$ components
Global fit of the $\gamma\gamma$ process and cascade χ_{cJ} processes



γ_{sm} - low energy gamma

3.44<RM(γ_{sm})<3.48GeV

Clear excess over BG + continuum. Significance: 3.8σ including systematic s

- $Br(\psi' \to \gamma\gamma J/\psi) = (3.1 \pm 0.6^{+0.8}_{-1.0}) \times 10^{-4}$ ($J/\psi \to$ ee and $\mu\mu$ mode combined)
- $Br(\psi' \to \gamma\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi)$ are also measured.

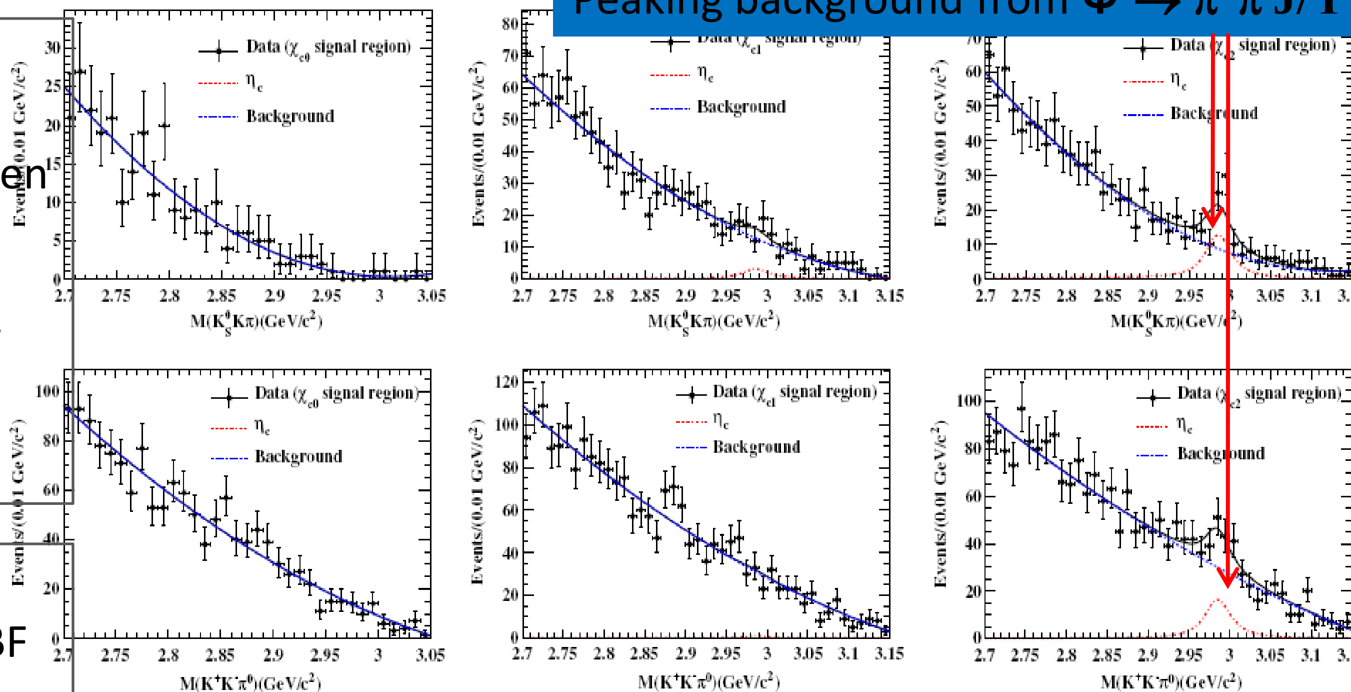
PRL 109, 172002 (2012)

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

Peaking background from $\Psi' \to \pi^+\pi^- J/\Psi$

Multipole expansion can make predictions for many hadronic transitions between the heavy quarkonia.

The hadronic transitions of ^3P_J states are seldom explored!



No clear signal for $\chi_{cJ} \to \eta_c \pi^+ \pi^-$ is observed. UL on BF is set at 90% C.L.

PRD 87, 012002 (2013)

Decay mode	N^{fit}	N^{signal}	$N^{up}_{observed}$	$N^{up}_{expected}$	ϵ (%)	$\mathcal{B}^{up}(\chi_{cJ} \to \eta_c \pi^+ \pi^-)$ (%)	$\mathcal{B}^{theory}(\chi_{cJ} \to \eta_c \pi^+ \pi^-)$ (%)
$\chi_{c0} \to (K^0_S K^\pm \pi^\mp)\pi^+\pi^-$	0.0 ± 4.6	0.0 ± 4.6	6.8	7.1	6.29	0.07	···
$\chi_{c0} \to (K^+ K^- \pi^0)\pi^+\pi^-$	0 ± 15	0 ± 15	34	27	6.82	0.41	···
$\chi_{c1} \to (K^0_S K^\pm \pi^\mp)\pi^+\pi^-$	18 ± 17	18 ± 17	49	44	9.45	0.32	1.81 ± 0.26
$\chi_{c1} \to (K^+ K^- \pi^0)\pi^+\pi^-$	6 ± 25	6 ± 25	50	47	9.82	0.44	
$\chi_{c2} \to (K^0_S K^\pm \pi^\mp)\pi^+\pi^-$	77 ± 19	31 ± 22	64	63	7.72	0.54	···
$\chi_{c2} \to (K^+ K^- \pi^0)\pi^+\pi^-$	89 ± 26	55 ± 27	105	94	7.83	1.2	···