Recent Results of Charmonium Decays and Transitions at BESIII

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For BESIII collaboration

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QCD and High Energy Interactions

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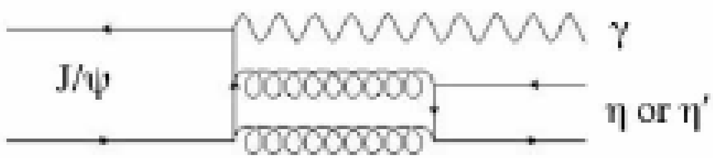
Outline

- **Charmonium Decays**
  - $\psi' \to \gamma\pi^0, \gamma\eta, \gamma\eta'$ ***(PRL 105, 261801 (2010))***
  - **First evidence of** $\psi' \to \gamma\gamma J/\psi$
  - $\chi_{cJ} \to \gamma\rho, \gamma\omega, \gamma\phi$ ***(PRD 83, 112005 (2011))***
  - $\chi_{cJ} \to ppK^+K^-$ **(PRD 83, 112009(2011))**
  - $\chi_{cJ} \to VV$ ***(PRL 107, 091803(2011))***
  - ***Search for*** $\eta_c(2S) \to VV$ ***(PRD 84,091102(2011))***
- **Charmonium Transitions**
  - **Properties of the** h_c ***(PRL 104, 132002 (2010))***
  - **Mass and width of the** η_c ***(arXiv:1111.0398)***
  - **Observation of** $\psi' \to \gamma\eta_c(2S)$
  - **Multipoles in** $\psi' \to \gamma\chi_2$ ***(PRD 84,092006(2011))***

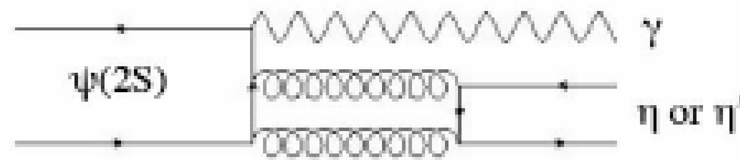
$\psi' \to \gamma P(\pi^0, \eta, \eta')$, arise surprises

$V \to \gamma P$ are important tests for various mechanisms:

Vector meson Dominance Model (VDM); **Couplings & form factor;** Mixing of η-η'(-η_c); **FSR by light quarks;** 12% rule and "$\rho\ \pi$ puzzle".



VS



theory	experiment
$$R_{(c\bar{c})} = \frac{Br((c\bar{c})\to\gamma\eta)}{Br((c\bar{c})\to\gamma\eta')}$$ **LO-pQCD** $\Downarrow$ $R_{\psi'} \simeq R_{J/\psi}$ PRP 112,173 (1984)	CLEO-c: $J/\psi, \psi', \psi'' \to \gamma P$ $R_{J/\psi} = (21.1 \pm 0.9)\%$ No Evidence for $\psi' \to \gamma\pi^0$ or $\gamma\eta$ $Br(\psi' \to \gamma\eta') = (1.19 \pm 0.09)\%$ $R_{\psi'} < 1.8\%$ at 90% CL $\Downarrow$ $R_{\psi'} \ll R_{J/\psi}$ PRD 79, 111101 (2009)

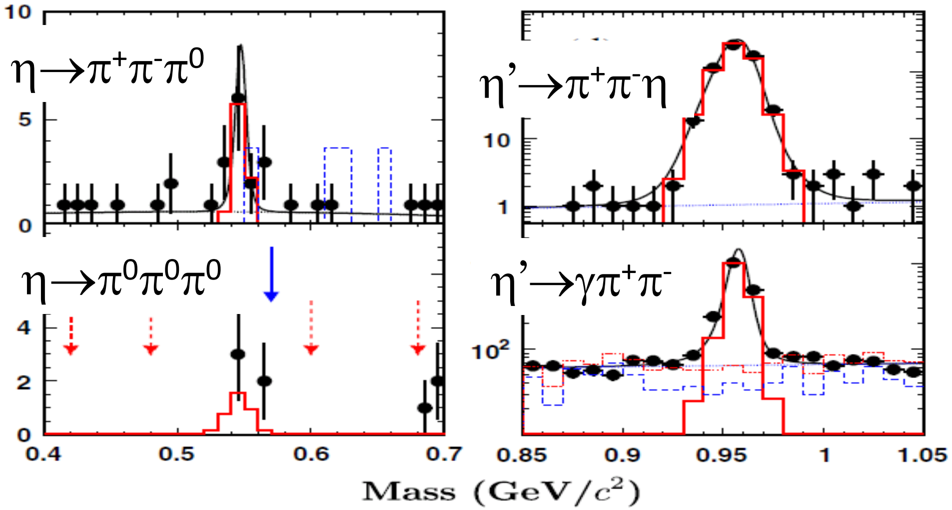
$\psi' \to \gamma$ P at BESIII

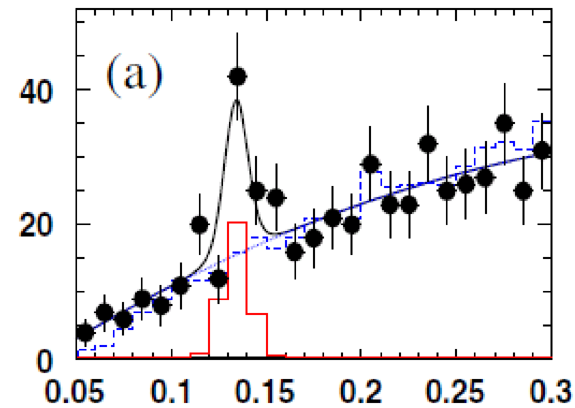
PRL 105, 261801 (2010)

$\psi' \to \gamma\eta$ (First observation)

$\psi' \to \gamma\eta'$

$\psi' \to \gamma\pi^0$ (First observation)





$R_{\psi'} = 1.10 \pm 0.38 \pm 0.07\%$ << $R_{J/\psi}$

Mode	B(ψ') [x10^{-6}]	B(J/ψ) [x10^{-4}]	Q (%)
$\gamma\pi^0$	1.58±0.42	0.35±0.03	4.5 ± 1.3
$\gamma\eta$	1.38±0.49	11.04±0.34	0.13 ± 0.04
$\gamma\eta'$	126±9	52.8±1.5	2.4 ± 0.2

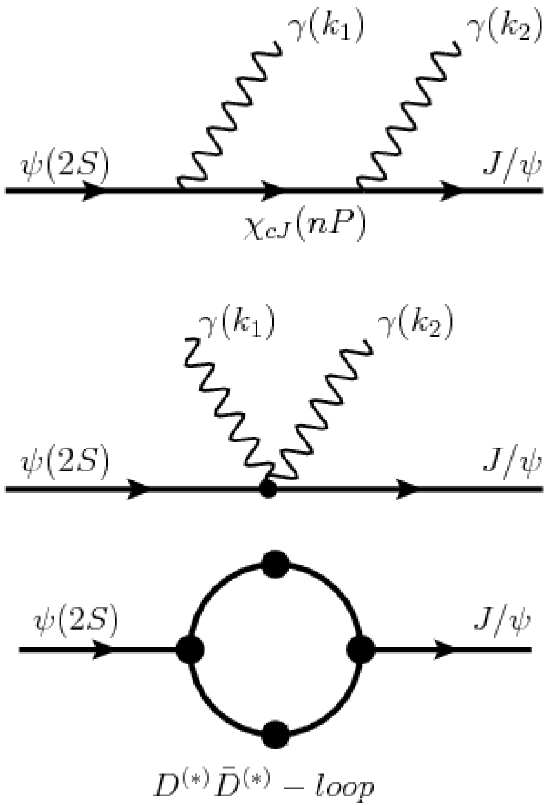
Possible interpretation: Q. Zhao, Phys. Lett. B697, 52 (2011)

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

- 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.
- Observation helpful to understand heavy quarkonium spectrum and the strong interaction

Theoretically:

- possibility of testing the hadron-loop effect
- potential models give discrete spectra ($\psi(2S) \to \gamma\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi$)
- coupled channel: **the hadron-loop effect also may play a important role in the continuous spectra**

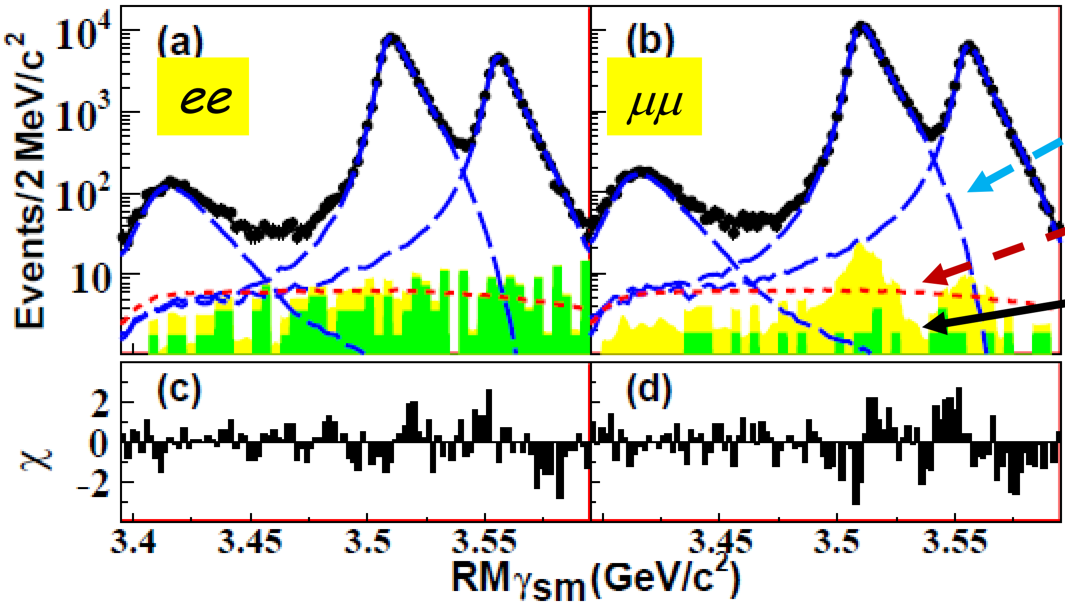


Theoretical study is on going. (Z.G. He et al)

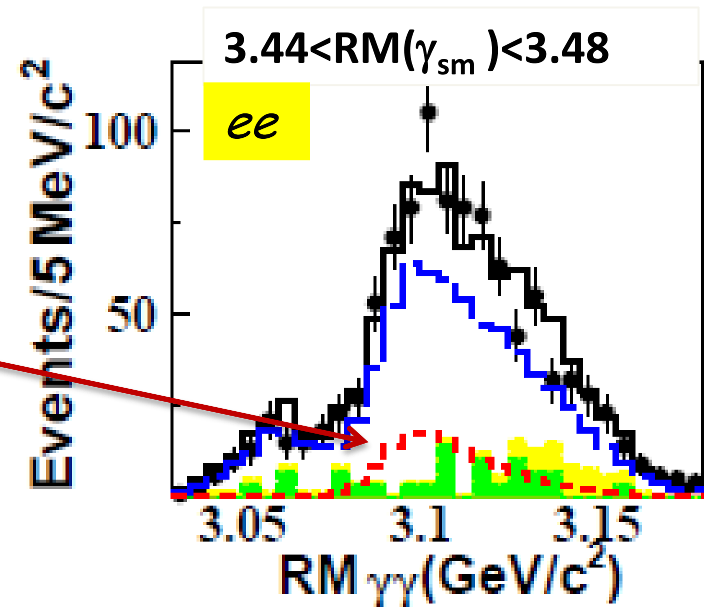
First evidence of $\psi' \to \gamma\gamma J/\psi$

- select $\psi(2S) \to \gamma\gamma J/\psi$, $J/\psi \to l^+l^-$ events

γ_{sm} - low energy gamma



- the χ_{cJ} components: double E1 scaling
- yields of the two-photon events
- continuum(green)+ ψ'-decay BG(yellow)

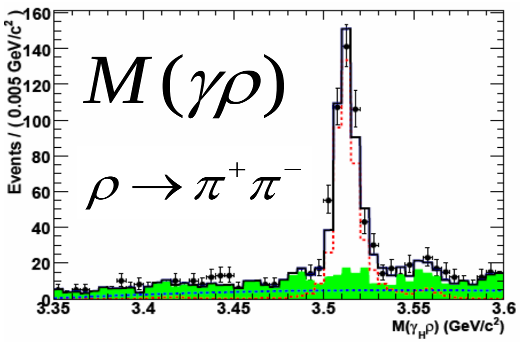


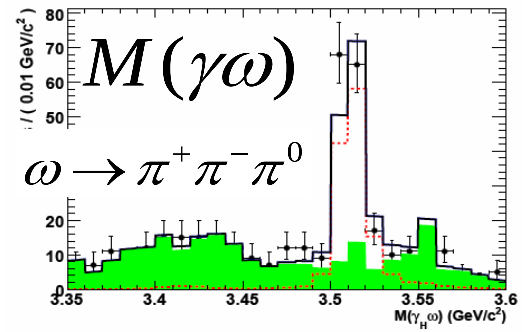
- global fit of the two-photon process and cascade χ_{cJ} processes
- see **clear excess** over BG + continuum

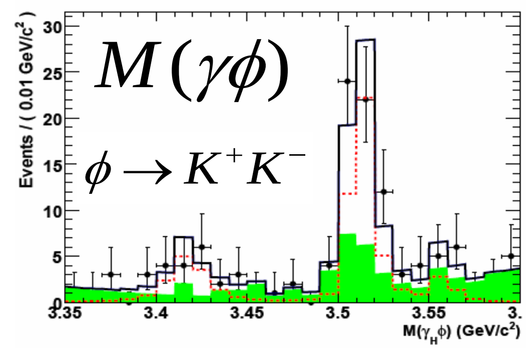
- $B(\psi' \to \gamma\gamma J/\psi)$ [both *ee* and $\mu\mu$]
  $= (3.3 \pm 0.6\ ^{+0.8}_{-1.1}) \times 10^{-4}$
- significance : 3.8σ including systematics
- $B(\psi' \to \gamma\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi)$ are also measured

$\chi_{cJ} \to \gamma V(\rho,\omega,\phi)$

prediction by pQCD much lower than experiment







Mode	CLEO[1]	pQCD[2]	QCD[3]	QCD+QED[3]	BESIII
$\chi_{c0} \to \gamma\rho^0$	< 9.6	1.2	3.2	2.0	**<10.5**
$\chi_{c1} \to \gamma\rho^0$	$243 \pm 19 \pm 22$	14	41	42	**228±13±22**
$\chi_{c2} \to \gamma\rho^0$	< 50	4.4	13	38	**<20.8**
$\chi_{c0} \to \gamma\omega$	< 8.8	0.13	0.35	0.22	**<12.9**
$\chi_{c1} \to \gamma\omega$	$83 \pm 15 \pm 12$	1.6	4.6	4.7	**69.7±7.2±6.6**
$\chi_{c2} \to \gamma\omega$	< 7.0	0.5	1.5	4.2	**<6.1**
$\chi_{c0} \to \gamma\phi$	< 6.4	0.46	1.3	0.03	**<16.2**
$\chi_{c1} \to \gamma\phi$	< 26	3.6	11	11	**25.8±5.2±2.3**
$\chi_{c2} \to \gamma\phi$	< 13	1.1	3.3	6.5	**<8.1**

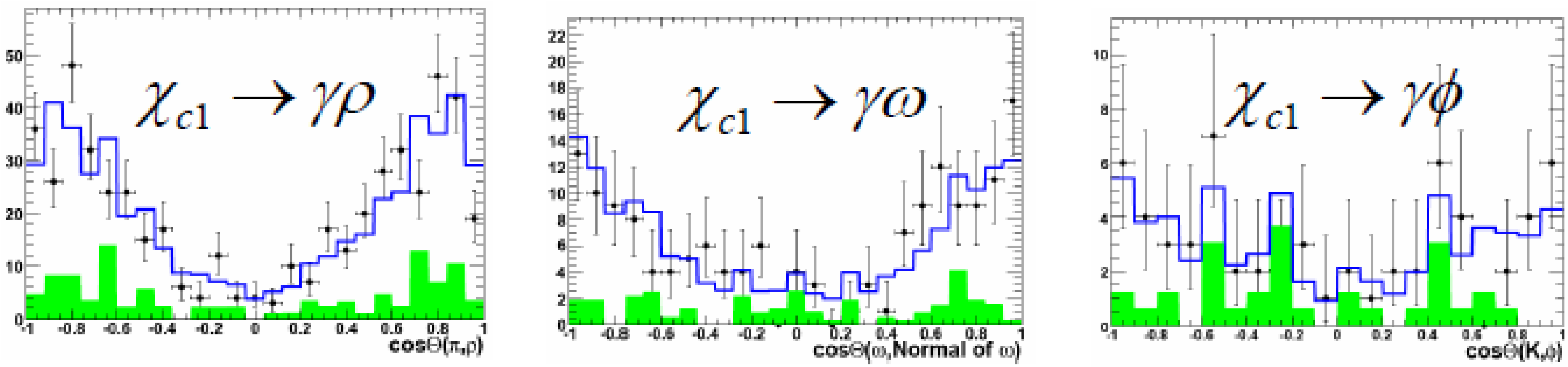
First observation

Polarization of $\chi_{c1} \to \gamma V(\rho, \omega, \phi)$

Longitudinal polarization (f_L);

Transverse polarization (f_T); $\boldsymbol{\theta}$: Helicity angle

$$\frac{d\Gamma}{\Gamma d\cos\theta} \propto (1 - f_T)\cos^2\theta + \frac{1}{2} f_T \sin^2\theta \qquad f_T = \frac{|A_T|^2}{|A_T|^2 + |A_L|^2}$$



$f_T = 0.158 \pm 0.034^{+0.015}_{-0.014}$ $\qquad$ $f_T = 0.247^{+0.090+0.044}_{-0.087-0.026}$ $\qquad$ $f_T = 0.29^{+0.13+0.10}_{-0.12-0.09}$

Longitudinal polarization dominates, consistent with theoretical prediction

Z. Phys. C 66, **71** (1995)
Phys. Rev. **77**, 242 (1950)

$\chi_{cJ} \to p\bar{p}K^+K^-$ (first measurement)

- Test Color Octet Mechinasim (COM) theory
- Search for new χ_{cJ} decay mode

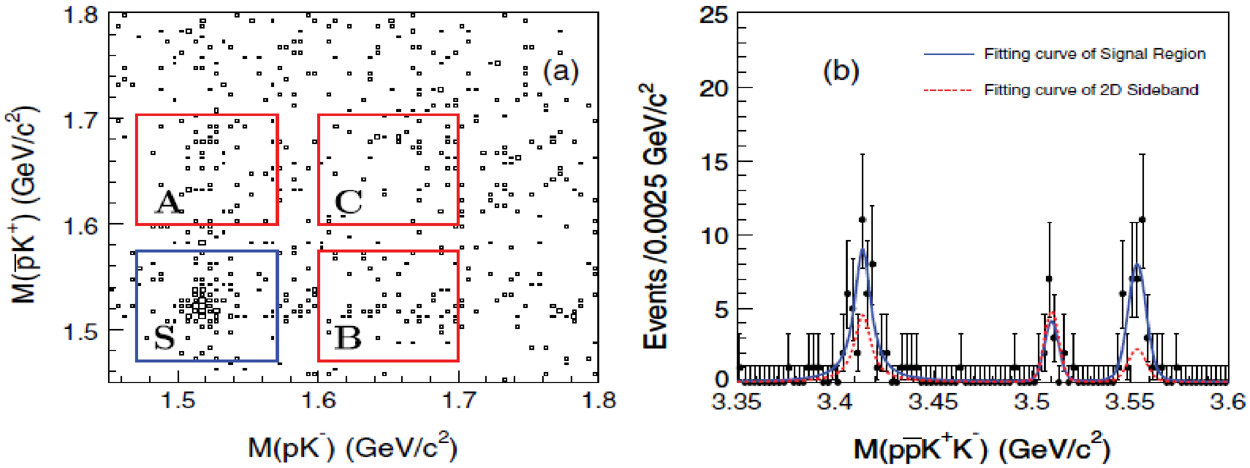


TABLE VII. Summary of branching fractions for 12 χ_{cJ} decay modes to $p\bar{p}K^+K^-$. The first errors are statistical, and the second ones are systematic. The upper limits are at the 90% C.L. including the systematic errors.

	χ_{c0}	χ_{c1}	χ_{c2}
$\mathcal{B}(\chi_{cJ} \to p\bar{p}K^+K^-)$ (10^{-4})	$1.24 \pm 0.20 \pm 0.18$	$1.35 \pm 0.15 \pm 0.19$	$2.08 \pm 0.19 \pm 0.30$
$\mathcal{B}(\chi_{cJ} \to \bar{p}K^+\Lambda(1520) + \text{c.c.})$ (10^{-4})	$3.00 \pm 0.58 \pm 0.50$	$1.81 \pm 0.38 \pm 0.28$	$3.06 \pm 0.50 \pm 0.54$
$\mathcal{B}(\chi_{cJ} \to \Lambda(1520)\bar{\Lambda}(1520))$ (10^{-4})	$3.18 \pm 1.11 \pm 0.53$	<1.00	$5.05 \pm 1.29 \pm 0.93$
$\mathcal{B}(\chi_{cJ} \to p\bar{p}\phi)$ (10^{-5})	$6.12 \pm 1.18 \pm 0.86$	<1.82	$3.04 \pm 0.85 \pm 0.43$

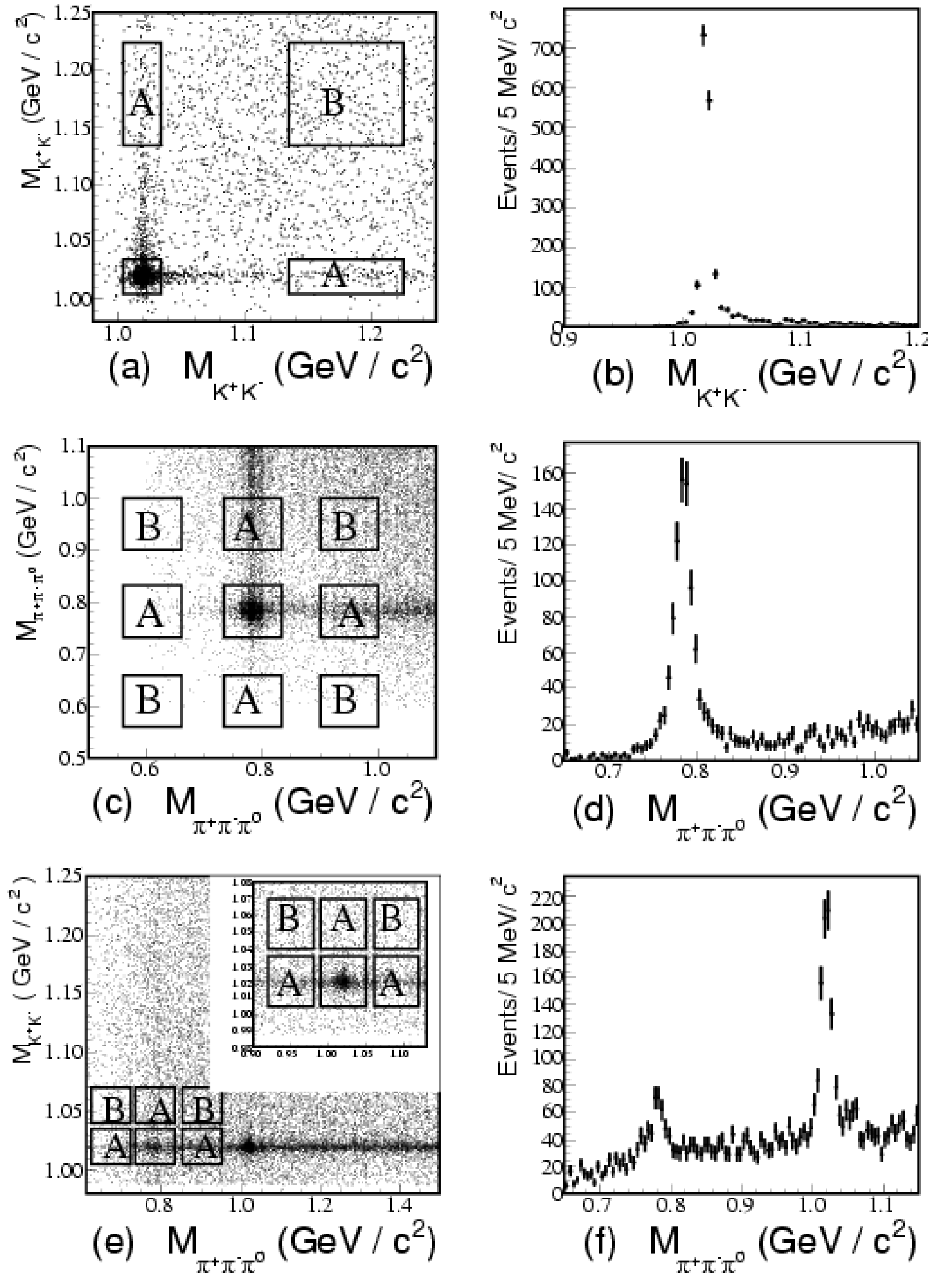
$\chi_{cJ} \rightarrow VV (V: \omega, \phi)$

- $\chi_{cJ} \rightarrow \phi\phi$ and $\chi_{cJ} \rightarrow \omega\omega$ are Singly OZI suppressed
- $\chi_{c1} \rightarrow \phi\phi$ and $\chi_{c1} \rightarrow \omega\omega$ is suppressed by helicity selection rule.
- $\chi_{cJ} \rightarrow \phi\omega$ is doubly OZI suppressed, not measured yet

Reconstruct

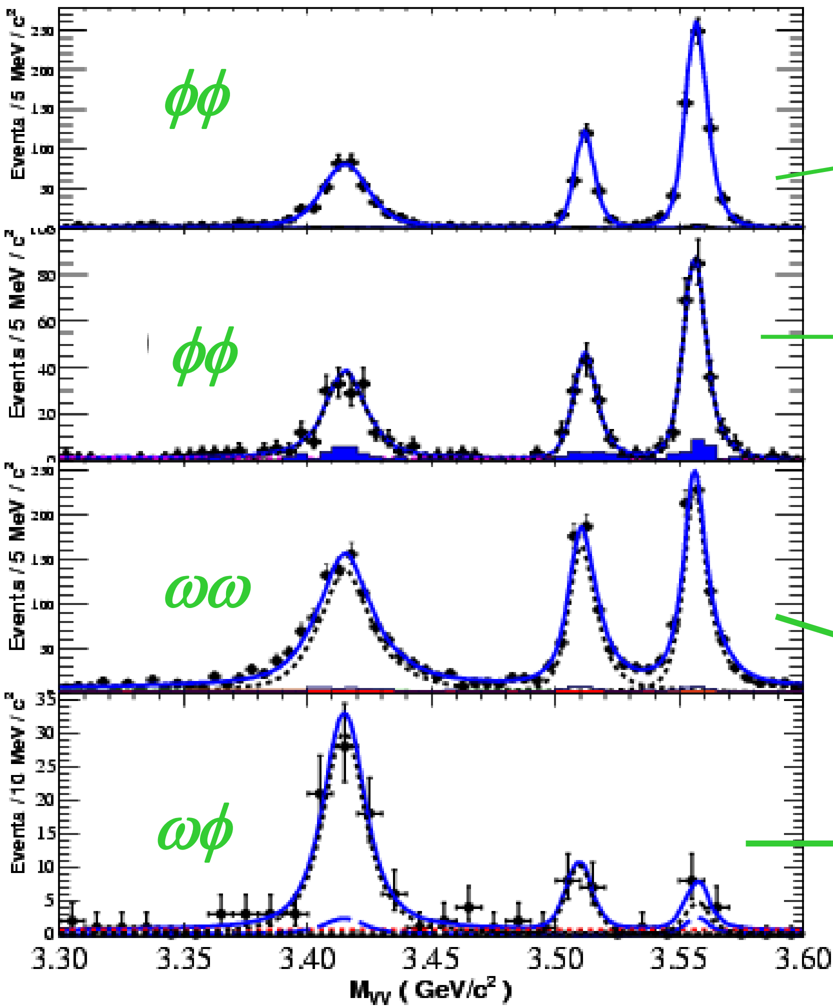
$\phi \rightarrow K^+K^-,\ \pi^+\pi^-\pi^0$

$\omega \rightarrow \pi^+\pi^-\pi^0$



BESIII PRL 107 091803(2011)

$\chi_{cJ} \to VV$ at BESIII



Mode	N_{net}	ϵ (%)	$\mathcal{B}(\times 10^{-4})$
$\chi_{c0} \to \phi\phi$	433 ± 23	22.4	$7.8 \pm 0.4 \pm 0.8$
$\chi_{c1} \to \phi\phi$	254 ± 17	26.4	$4.1 \pm 0.3 \pm 0.4$
$\chi_{c2} \to \phi\phi$	630 ± 26	26.1	$10.7 \pm 0.4 \pm 1.1$
$\to 2(K^+K^-)$			
$\chi_{c0} \to \phi\phi$	179 ± 16	1.9	$9.2 \pm 0.7 \pm 1.0$
$\chi_{c1} \to \phi\phi$	112 ± 12	2.3	$5.0 \pm 0.5 \pm 0.6$
$\chi_{c2} \to \phi\phi$	219 ± 16	2.2	$10.7 \pm 0.7 \pm 1.2$
$\to K^+K^-\pi^+\pi^-\pi^0$			
Combined:			
$\chi_{c0} \to \phi\phi$	—	—	$8.0 \pm 0.3 \pm 0.8$
$\chi_{c1} \to \phi\phi$	—	—	$4.4 \pm 0.3 \pm 0.5$
$\chi_{c2} \to \phi\phi$	—	—	$10.7 \pm 0.3 \pm 1.2$
$\chi_{c0} \to \omega\omega$	991 ± 38	13.1	$9.5 \pm 0.3 \pm 1.1$
$\chi_{c1} \to \omega\omega$	597 ± 29	13.2	$6.0 \pm 0.3 \pm 0.7$
$\chi_{c2} \to \omega\omega$	762 ± 31	11.9	$8.9 \pm 0.3 \pm 1.1$
$\to 2(\pi^+\pi^-\pi^0)$			
$\chi_{c0} \to \omega\phi$	76 ± 11	14.7	$1.2 \pm 0.1 \pm 0.2$
$\chi_{c1} \to \omega\phi$	15 ± 4	16.2	$0.22 \pm 0.06 \pm 0.02$
$\chi_{c2} \to \omega\phi$	< 13	15.7	< 0.2
$\to K^+K^-\pi^+\pi^-\pi^0$			

Evidence

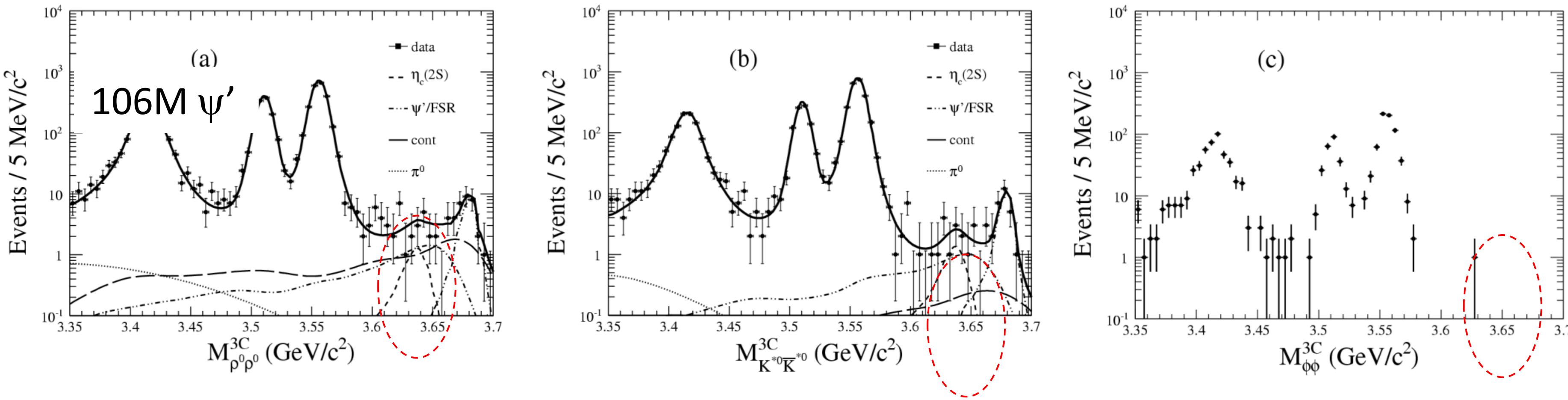
First observation

Long distance transitions could contribute via the intermediate meson loops.

PR D81 014017 (2010)
PR D81 074006 (2010)

Search for $\eta_c(2S) \rightarrow VV$

Test for the "Intermediate charmed meson loops"



	BF($\psi' \rightarrow \gamma\eta_c(2S) \rightarrow \gamma VV$) ($10^{-7}$)	BF($\eta_c' \rightarrow VV$) (10^{-3})	Theory BF($\eta_c' \rightarrow VV$) (10^{-3})
$\rho^0\rho^0$	<11.4	<3.1	6.4 ~ 28.9
$K^{*0}K^{*0}$	<19.4	<5.3	7.9 ~ 35.8
$\phi\phi$	<7.8	<2.0	2.1 ~ 9.8

No signals observed in $\eta_c \rightarrow \rho\rho$, $K^{*0}K^{*0}$, $\phi\phi$; more stringent UL's are set.

$h_c(^1P_1)$

- 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 $\langle m(1\,^3P_J)\rangle = [(M(\chi_{c0})+3M(\chi_{c1})+5M(\chi_{c2})]/9$,

- E835 found evidence for h_c in $p\bar{p} \to h_c \to \gamma\eta_c$
- CLEOc observed h_c in $e^+e^- \to \psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ PRL 101 182003 (2008)

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

  Consistent to 1P hyperfine splitting of 0.

Theoretical prediction:

$BF(\psi(2S) \to \pi^0 h_c) = (0.4\text{-}1.3)\times10^{-4}$

$BF(h_c \to \gamma\eta_c) = 48\%$ (NRQCD)

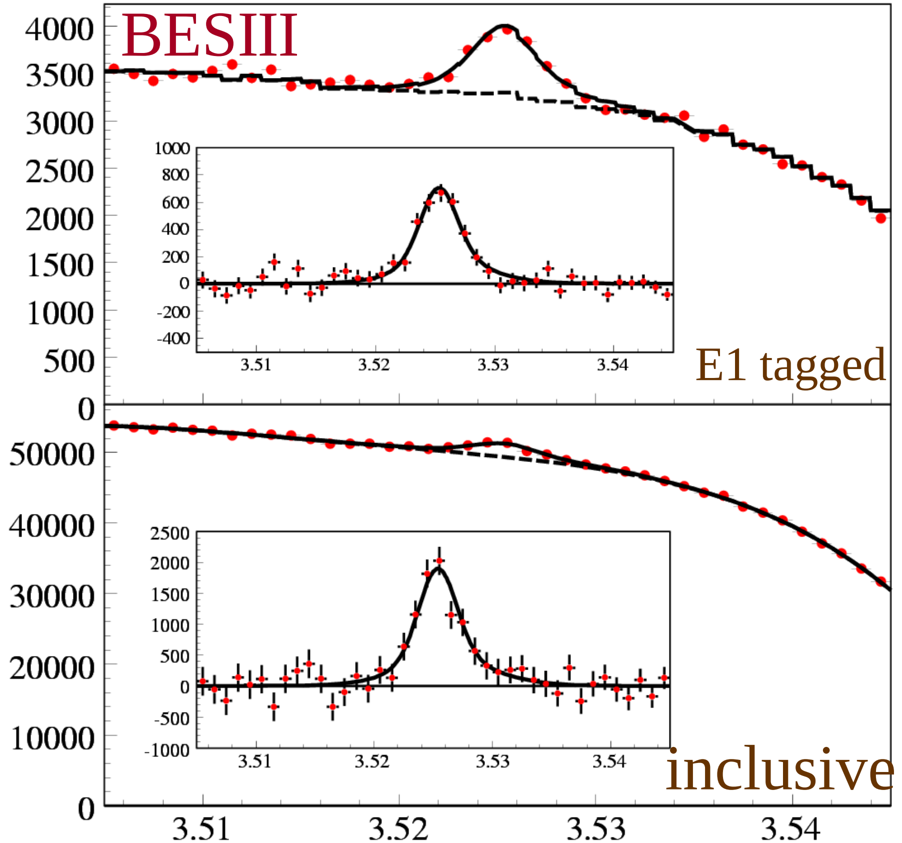
$BF(h_c \to \gamma\eta_c) = 88\%$ (PQCD)

Kuang, PR D65 094024 (2002)

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

Godfrey and Rosner, PR D66 014012(2002)

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



BESIII: PRL 104 132002 (2010)

Mass = **3525.40±0.13±0.18** MeV/c^2

Width = **0.73±0.45±0.28** MeV

<1.44 MeV @90%

CLEOc: PRL 101 182003 (2008)

Mass = **3525.28±0.19±0.12** 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**

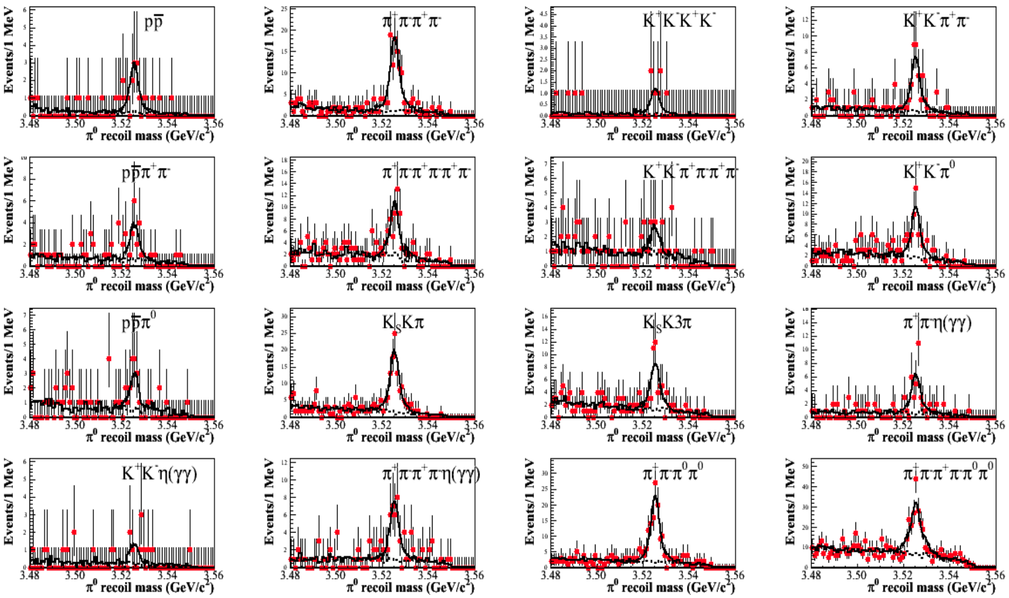
By combining inclusive results with E1-photon tagged results

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

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

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

$\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\eta_c$, η_c exclusive decays



BESIII Preliminary

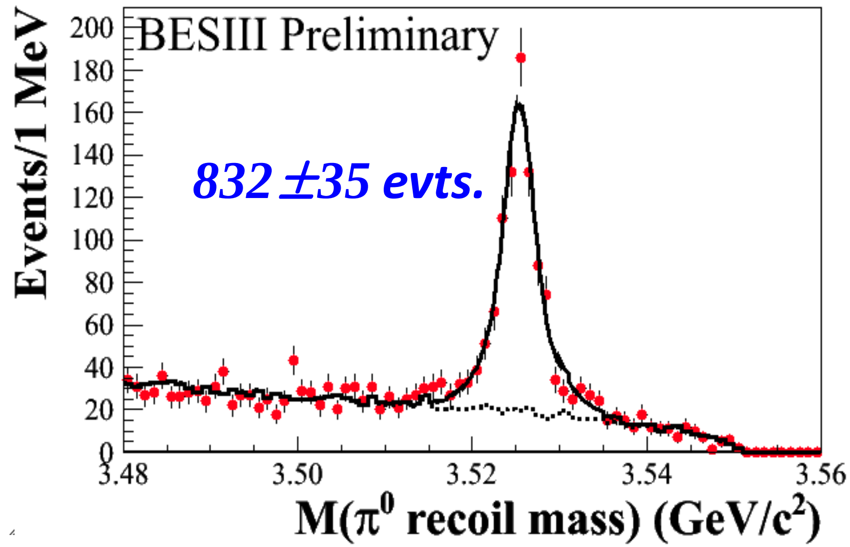
Simultaneous fit to π^0 recoiling mass

χ^2/d.o.f. = 32/46

Mass = **3525.31±0.11±0.15** MeV/c^2

Width = **0.70±0.28±0.25** MeV

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)

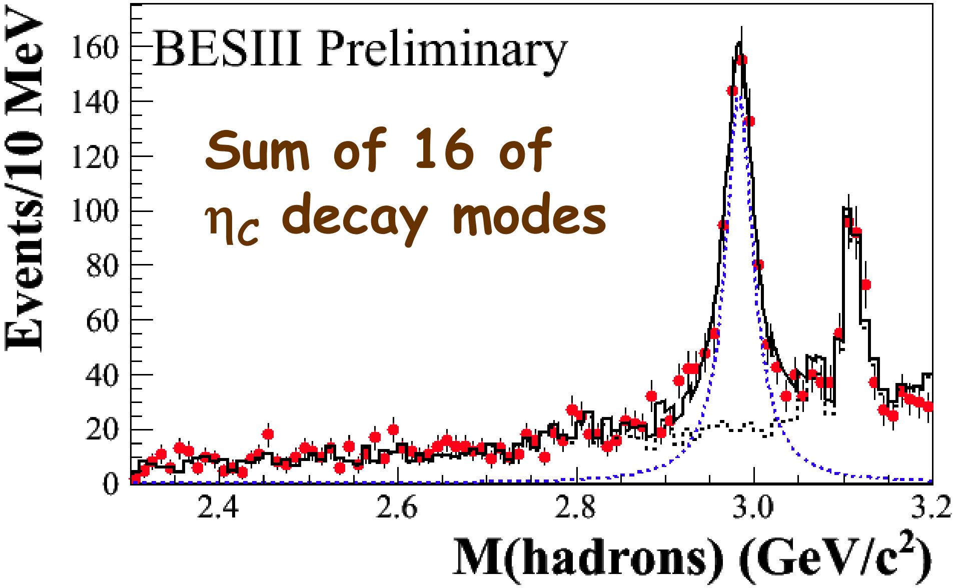
CLEOc exclusive results

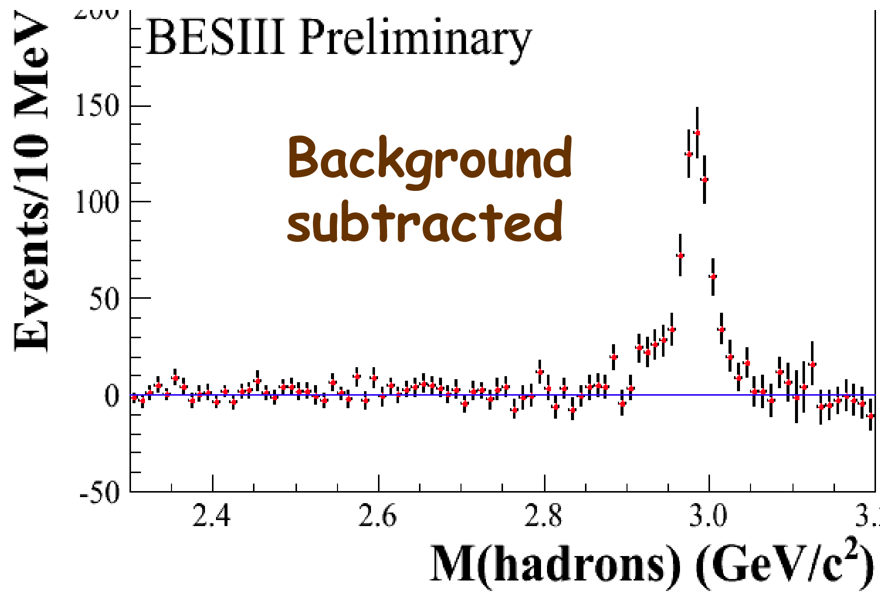
Mass =**3525.21±0.27±0.14** MeV/c^2

evts. =**136±14**

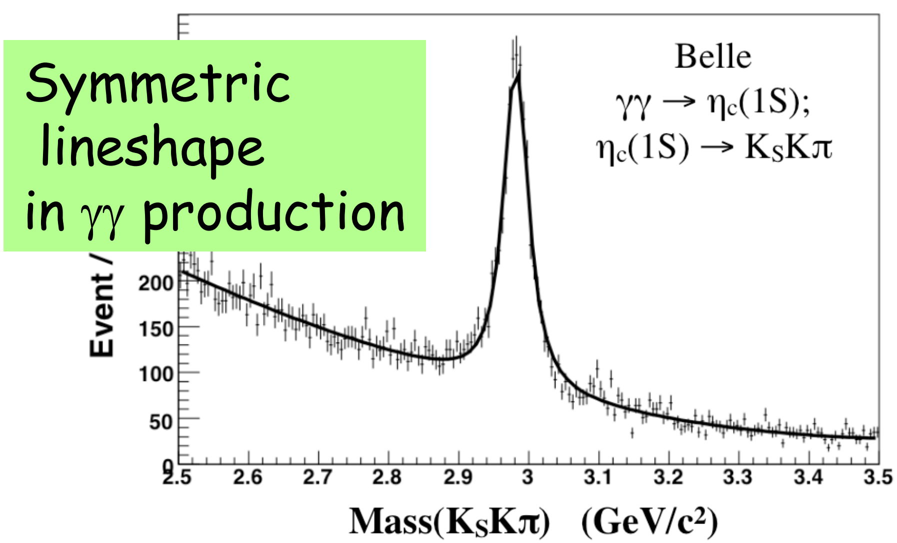
CLEOc: PRL 101 182003 (2008)

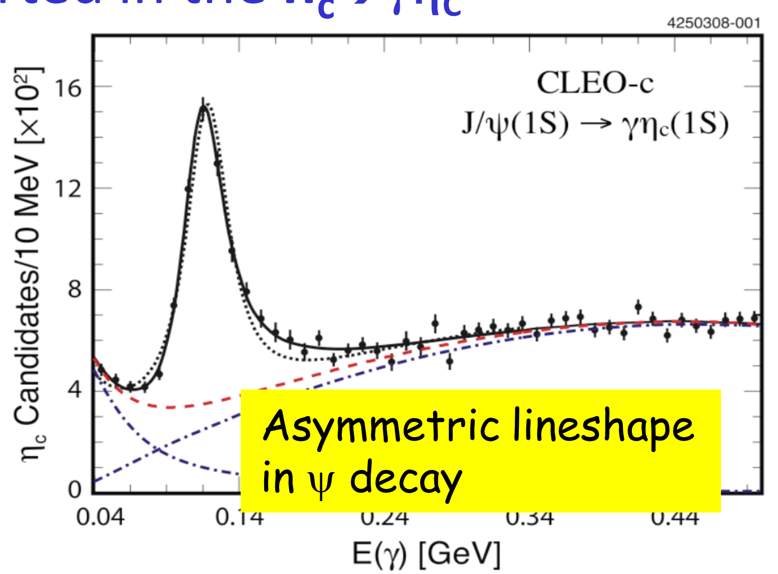
η_c lineshape from $\psi' \to \pi^0 h_c$, $h_c \to \gamma \eta_c$





The η_c lineshape is not distorted in the $\mathbf{h_c \to \gamma \eta_c}$



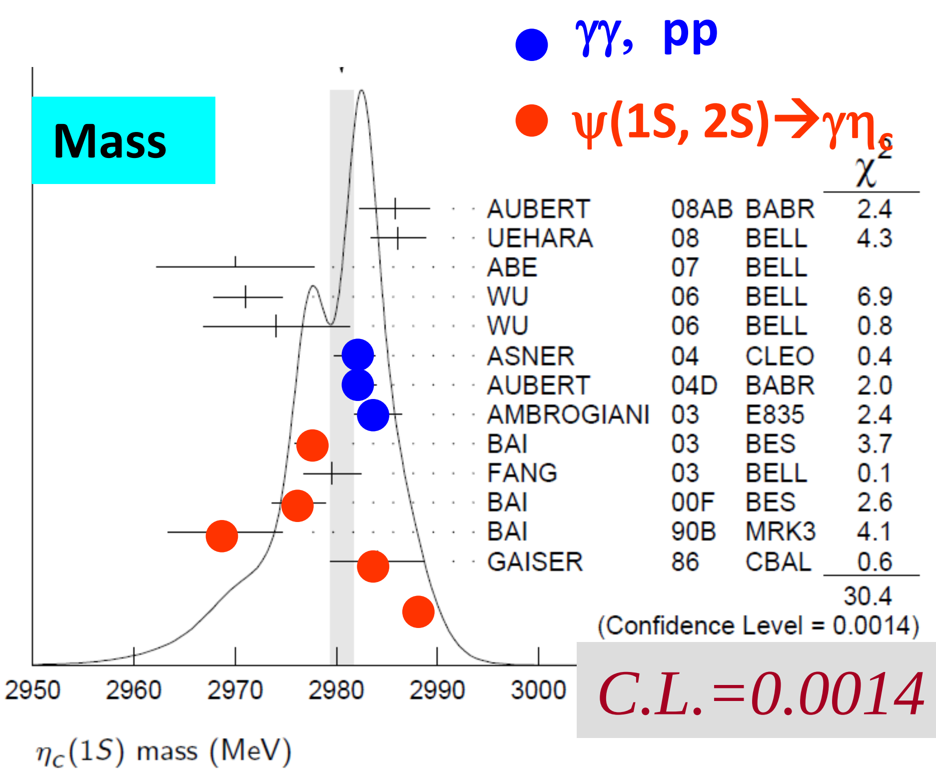


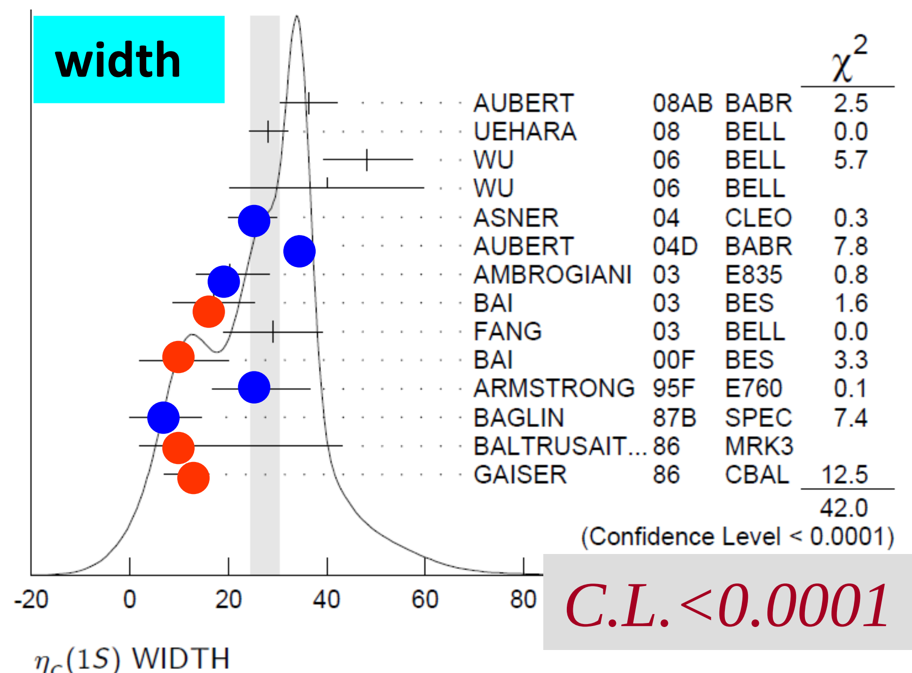
$\eta_c(1S)$

- The lowest lying S-wave spin singlet charmonium, discovered in 1980 by MarkII
- Parameters:

  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
- CLEOc found the distortion of the η_c line shape in ψ' decays.

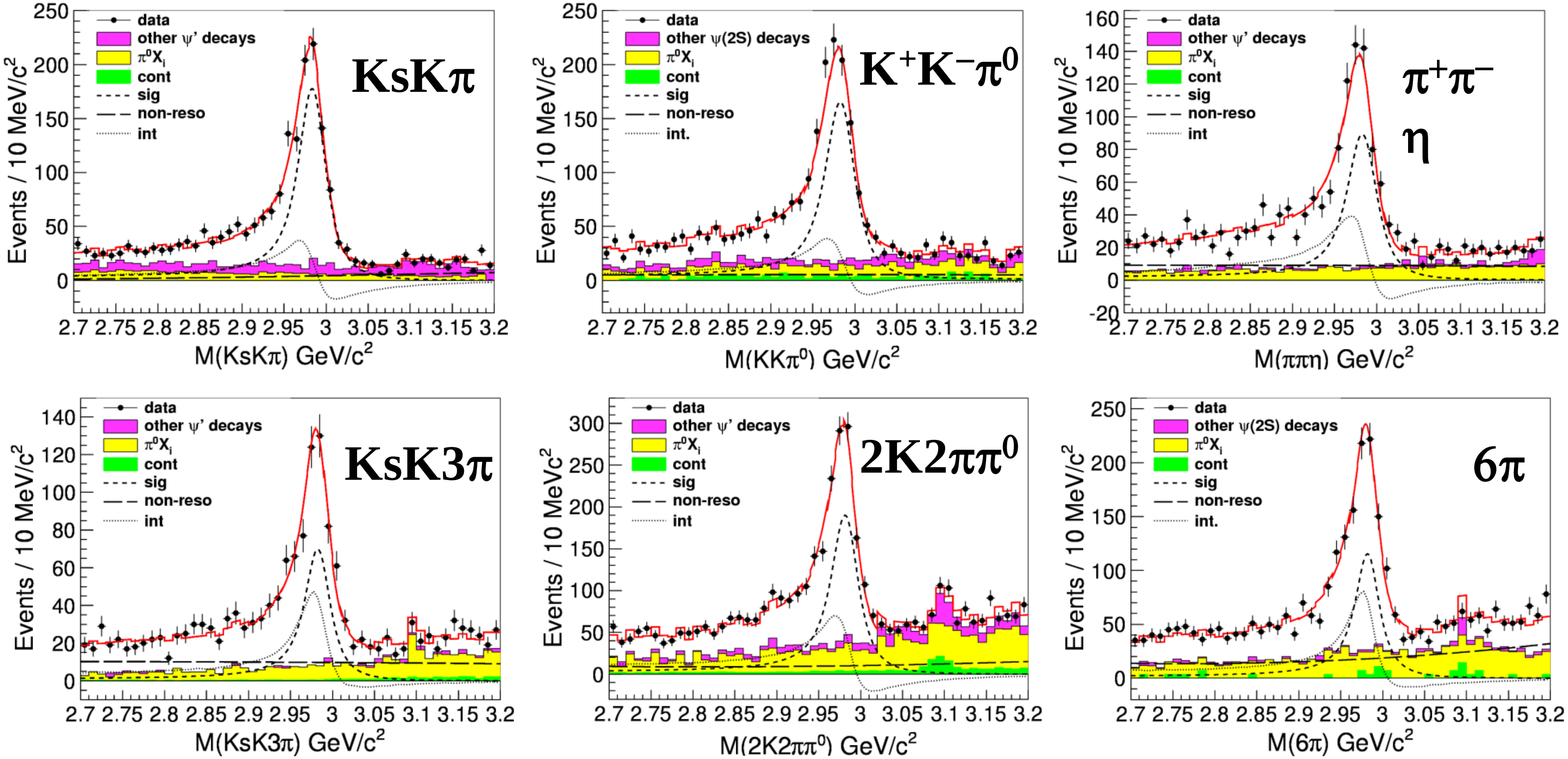




$\psi' \rightarrow \gamma\eta_c$, η_c *exclusive decays*

Possible interference has been take into account

arXiv:1111.0398



Relative phase ϕ values from each mode are consistent within 3σ,

➔ *use a common phase value in the simultaneous fit.*

M: **2984.4±0.6±0.6** MeV/c^2

width: **32.0±1.2±1.0** MeV

ϕ: **2.40±0.07±0.08** rad

4.19 ±0.03±0.09

$\eta_c(2S)$

Crystal Ball's "first observation" of $\psi' \to \gamma X$ never been confirmed
PRL 48 70 (1982)

Observed in different production mechanisms,

1. $B \to K \eta_c(2S)$
2. $\gamma\gamma \to \eta_c(2S) \to KK\pi$
3. double charmonium production

Belle: PRL 89 102001 (2002)
CLEOc: PRL 92 142001 (2004)
Belle: NPPS.184 220 (2008); PRL 98 082001(2007)
BaBar: PRL 92 142002 (2004); PR D72 031101(2005)
BaBar: PR D84 012004 (2011)

M1 transition $\psi' \to \gamma\eta_c(2S)$

CLEO found no signals in 25M ψ'.

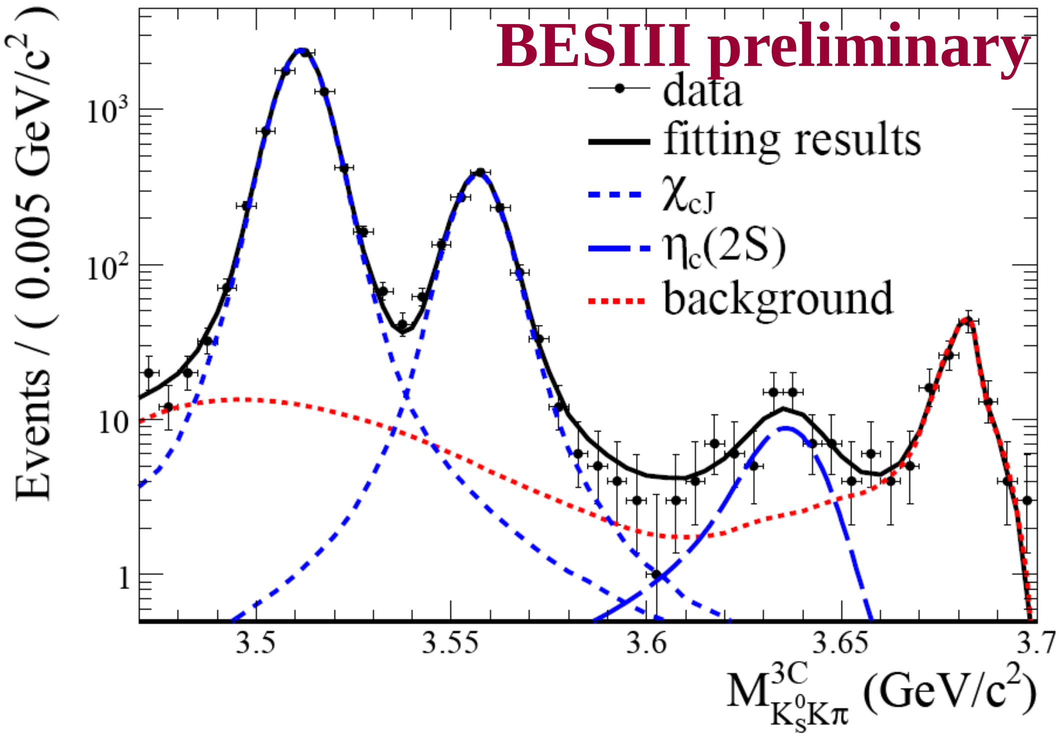
$BF(\psi' \to \gamma\eta_c(2S)) < 7.6 \times 10^{-4}$

CLEO: PRD 81 052002 (2010)

Experimental challenge : search for photons of 50 MeV

Observation of $\psi' \to \gamma\eta_c(2S) \to \gamma(K_sK\pi)$

106M ψ'



Width fixed to 12 MeV (world ave.)

Events: **50.6±9.7**; Significance >6.0σ!

Mass = **3638.5±2.3±1.0** MeV/c^2

BF($\psi' \to \gamma\eta_c(2S) \to \gamma K_sK\pi$)
=(2.98±0.57±0.48)×10^{-6}

BF($\eta_c(2S) \to K\bar{K}\pi$)=(**1.9**±**0.4**±**1.1**)%
BaBar: PR D78 012006 (2008)

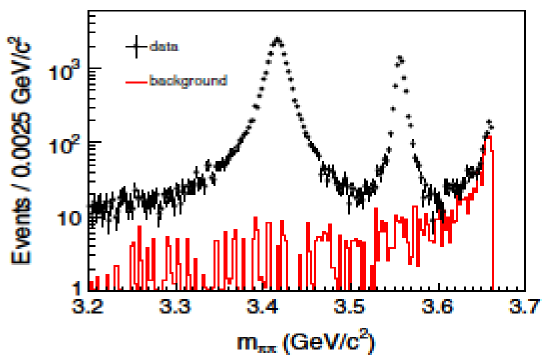
BF($\psi' \to \gamma\eta_c(2S)$)
= (4.7±0.9±3.0)×10^{-4}

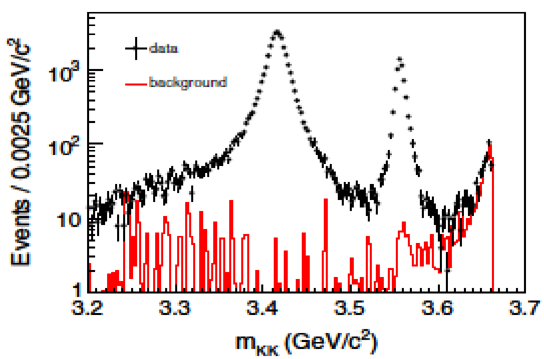
CLEOc: <**7.6×10^{-4}**
PR D81 052002 (2010)

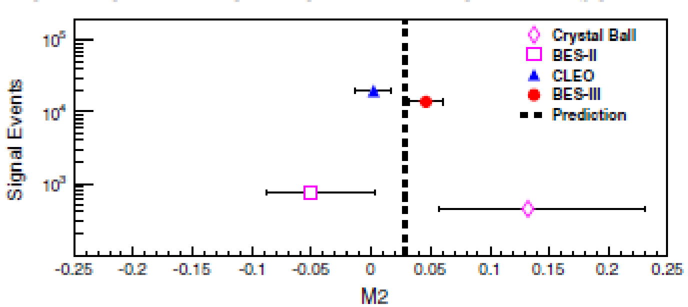
Potential model predicts
(0.1~ 6.2)×10^{-4}
PRL 89 162002 (2002)

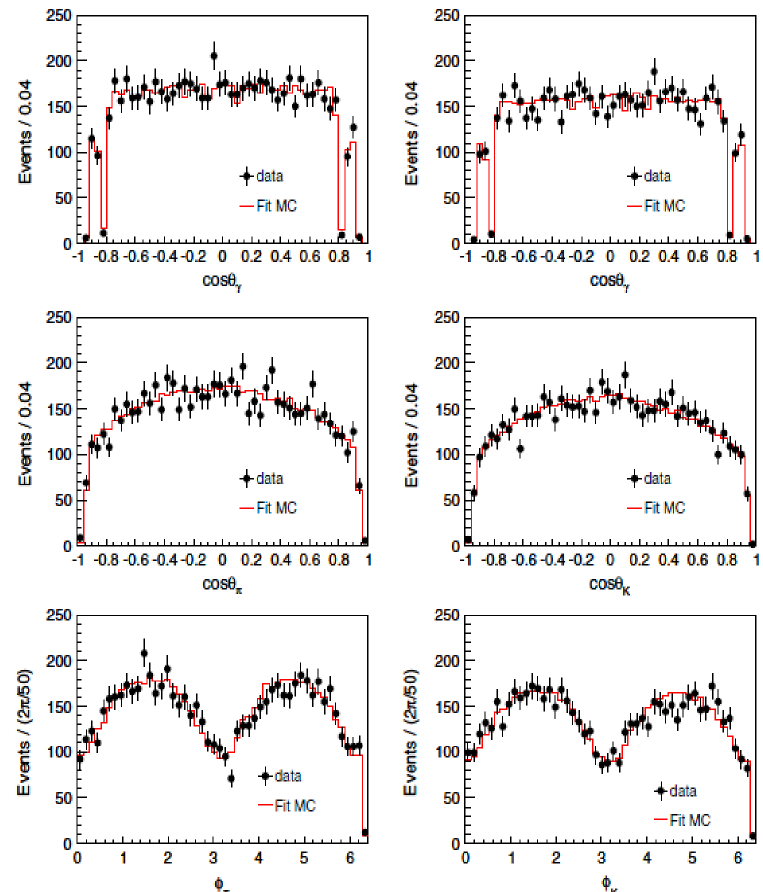
Multipoles transition of $\psi' \to \gamma\chi_{c2}, \chi_{c2} \to \pi^+\pi^-, K^+K^-$

- Investigate the contribution from high-order multi-pole amplitudes









$$M2 = 0.046 \pm 0.010 \pm 0.013,$$

$$E3 = 0.015 \pm 0.008 \pm 0.018,$$

4.4σ

Summary

- Many first observations or measurements on charmonium decay at BESIII. For example $\chi_{cJ}\rightarrow\gamma\phi$, $\chi_{c1}\rightarrow\phi\phi,\omega\omega$, and DOZI modes, $\chi_{cJ}\rightarrow\omega\phi$. $\chi_{cJ}\rightarrow ppK^+K^-$.
- **First evidence of $\psi'\rightarrow\gamma\gamma J/\psi$ is found.**
- No obvious signal is found in $\eta_c(2S)\rightarrow VV(V=\rho,K^{0*},\phi)$.
- Absolute $B(\psi'\rightarrow\pi^0 h_c)$, $B(h_c\rightarrow\gamma\eta_c)$, and $\Gamma(h_c)$ are measured for the first time.
- η_c resonant parameters are measured with higher precision.
- $\eta_c(2S)$ is observed in the charmonium decay for the first time.
- The transition amplitude of $\psi'\rightarrow\gamma\chi_{c2}$ maybe contain the contribution from high-order multipoles.

Thank you!