

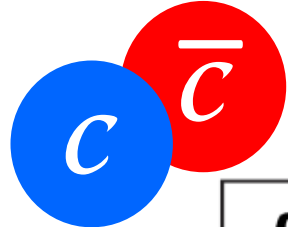
Spin-singlet charmonium states

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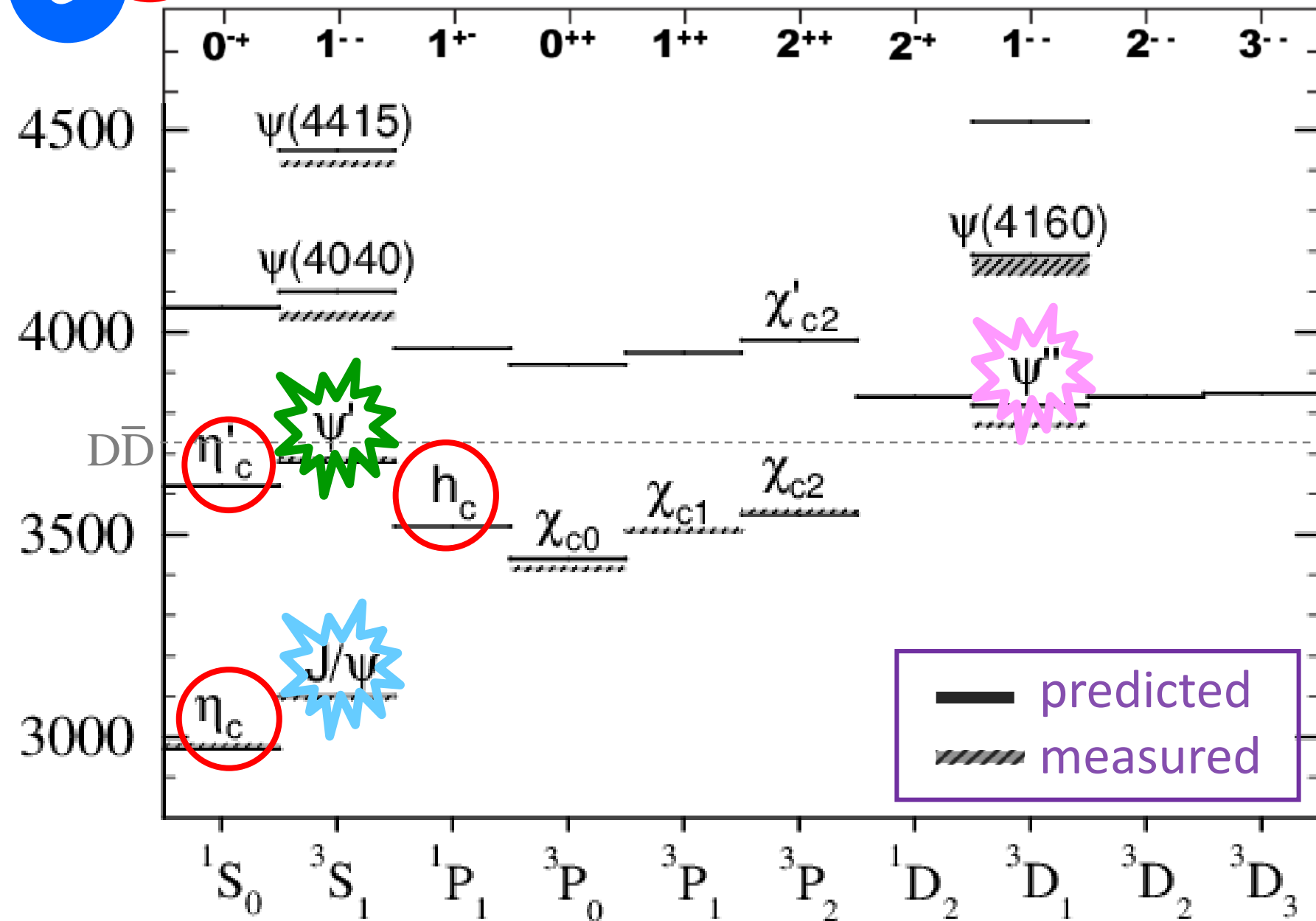


International Workshop on using Heavy Flavors to
Probe New Hadron Spectroscopies/Dynamics

November 18-21, 2012, Busan, South Korea



Charmonium mesons



BESIII data samples

- 2009: **106 million ψ'**
225 million J/ψ
- 2010: **$\sim 900 \text{ pb}^{-1} \psi(3770)$**
- 2011: **$\sim 1900 \text{ pb}^{-1} \psi(3770)$**
 $470 \text{ pb}^{-1} @ 4.01 \text{ GeV}$
- 2012: **~ 0.3 billion ψ'**
 ~ 0.7 billion J/ψ , started from 5th April

First e^+e^- collision event on 19th July, 2008

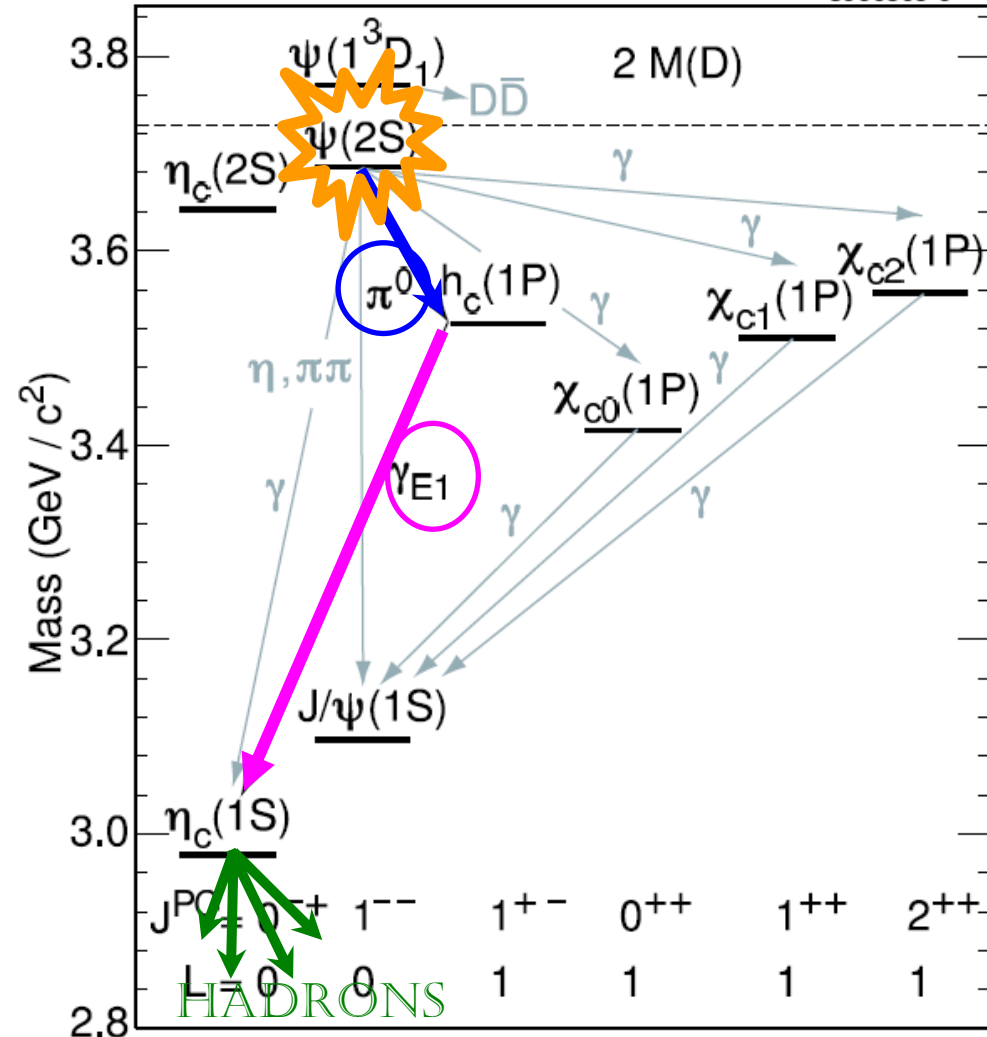
Peak luminosity have reached $0.65 \times 10^{33} @ 3.770 \text{ GeV}$

$h_c(^1P_1)$

- Spin singlet P wave (S=0, L=1)
- Potential model: if non-vanishing P-wave spin-spin interaction,
 $\Delta M_{\text{hf}}(1P) = M(h_c) - \langle M(1^3P_J) \rangle \neq 0$,
where $\langle M(1^3P_J) \rangle = [M(\chi_{c0}) + 3M(\chi_{c1}) + 5M(\chi_{c2})] / 9$
- CLEO-c observed h_c in $e^+e^- \rightarrow \psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$
 $\Delta M_{\text{hf}}(1P) = 0.08 \pm 0.18 \pm 0.12 \text{ MeV}/c^2$
(consistent with 1P hyperfine splitting = 0)
- Theoretical predictions:
 - $B(\psi' \rightarrow \pi^0 h_c) = (0.4-1.3) \times 10^{-3}$, $B(h_c \rightarrow \gamma \eta_c) = 48\%$ (NPQCD)
 $B(h_c \rightarrow \gamma \eta_c) = 88\%$ (PQCD)
 - $B(h_c \rightarrow \gamma \eta_c) = 38\%$ *Y. P. Kuang, PRD65, 094024 (2002)*
Godfrey and Rosner, PRD66, 014012 (2002)

h_c analysis

3960805-012



“inclusive”

only detect the π^0

(compute $M(h_c)$ from kinematic)

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

“E1 tagged”

detect the π^0 & γ

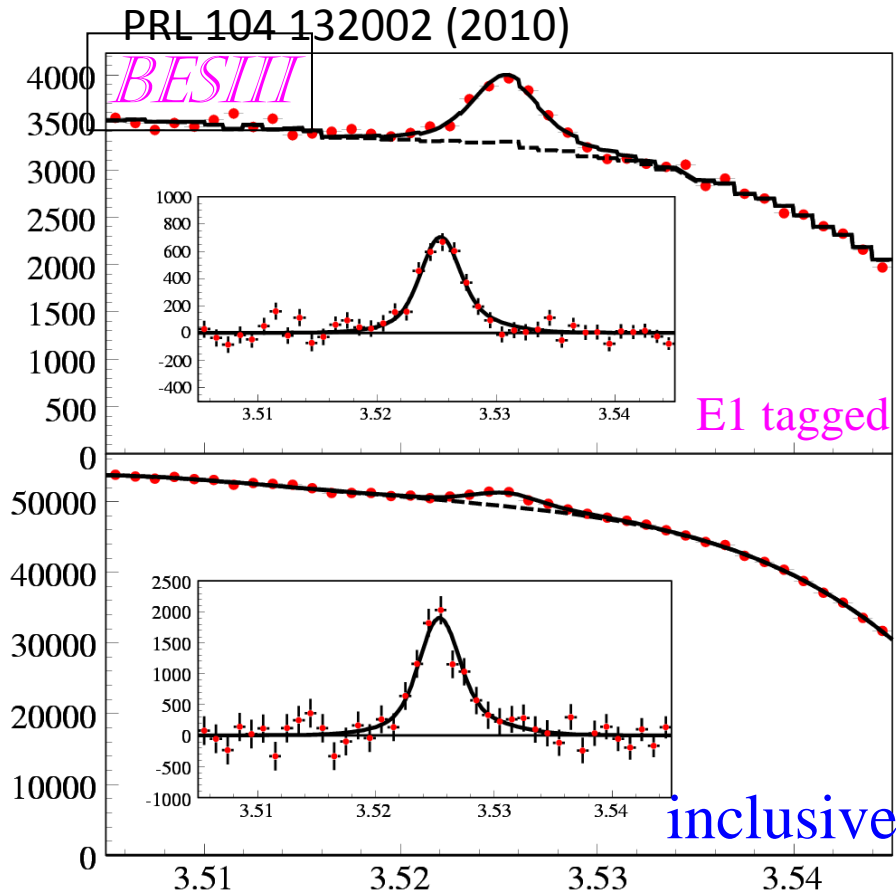
Rate $\propto \text{BF}(\psi' \rightarrow \pi^0 h_c) \times \text{BF}(h_c \rightarrow \gamma \eta_c)$

“exclusive”

detect the π^0 , γ & $\eta_c \rightarrow X_i$ decay products

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

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



Mass = $3525.40 \pm 0.13 \pm 0.18 \text{ MeV}/c^2$

Width = $0.73 \pm 0.45 \pm 0.28 \text{ MeV}$

$< 1.44 \text{ MeV @90\%}$

CLEOc: PRL 101 182003 (2008)

Mass = $3525.28 \pm 0.19 \pm 0.12 \text{ MeV}$

Width: fixed at 0.9 MeV

Hyperfine mass splitting

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

BESIII: $0.10 \pm 0.13 \pm 0.18 \text{ MeV}/c^2$

CLEOc: $0.02 \pm 0.19 \pm 0.13 \text{ MeV}/c^2$

By combining inclusive results with *E1- γ* tagged results

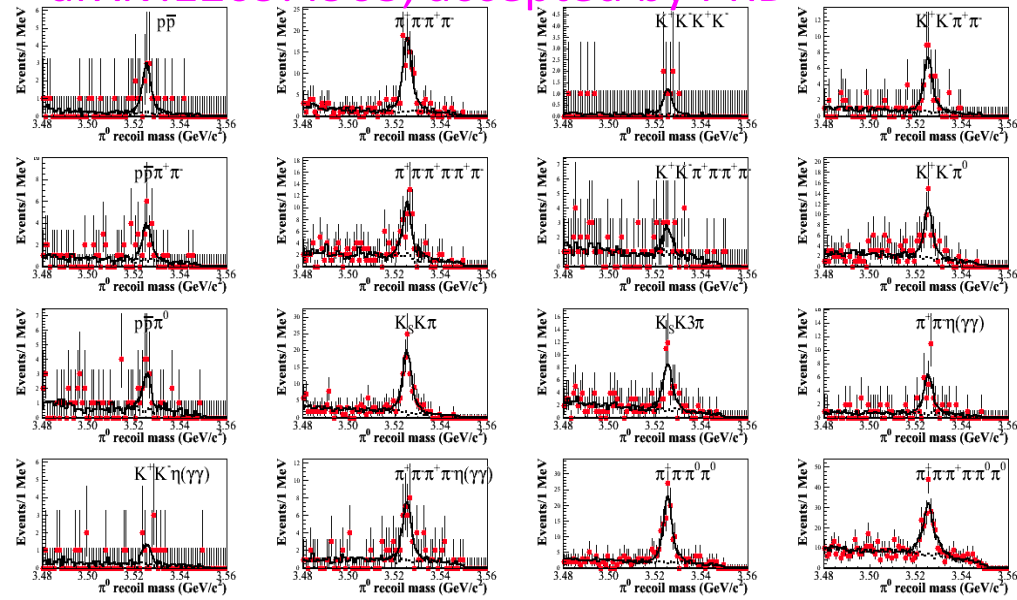
$$BF(\psi' \rightarrow \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$$

$$BF(h_c \rightarrow \gamma \eta_c) = (54.3 \pm 6.7 \pm 5.2)\%$$

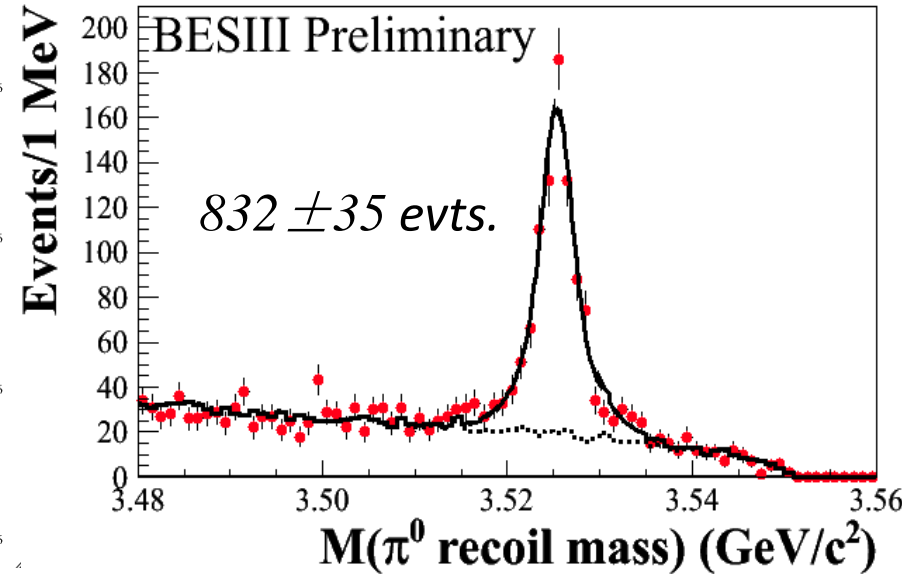
Agree with prediction from Kuang, Godfrey, Dude et al.

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

arXiv:1209.4963, accepted by PRD



Summed distribution



Simultaneous fit to π^0 recoiling mass

$\chi^2/\text{d.o.f.} = 1.6$

Mass = $3525.31 \pm 0.11 \pm 0.14 \text{ MeV}/c^2$

Width = $0.70 \pm 0.28 \pm 0.22 \text{ MeV}$

Consistent with BESIII inclusive results

Mass = $3525.40 \pm 0.13 \pm 0.18 \text{ MeV}/c^2$

Width = $0.73 \pm 0.45 \pm 0.28 \text{ MeV}$

CLEOc exclusive results

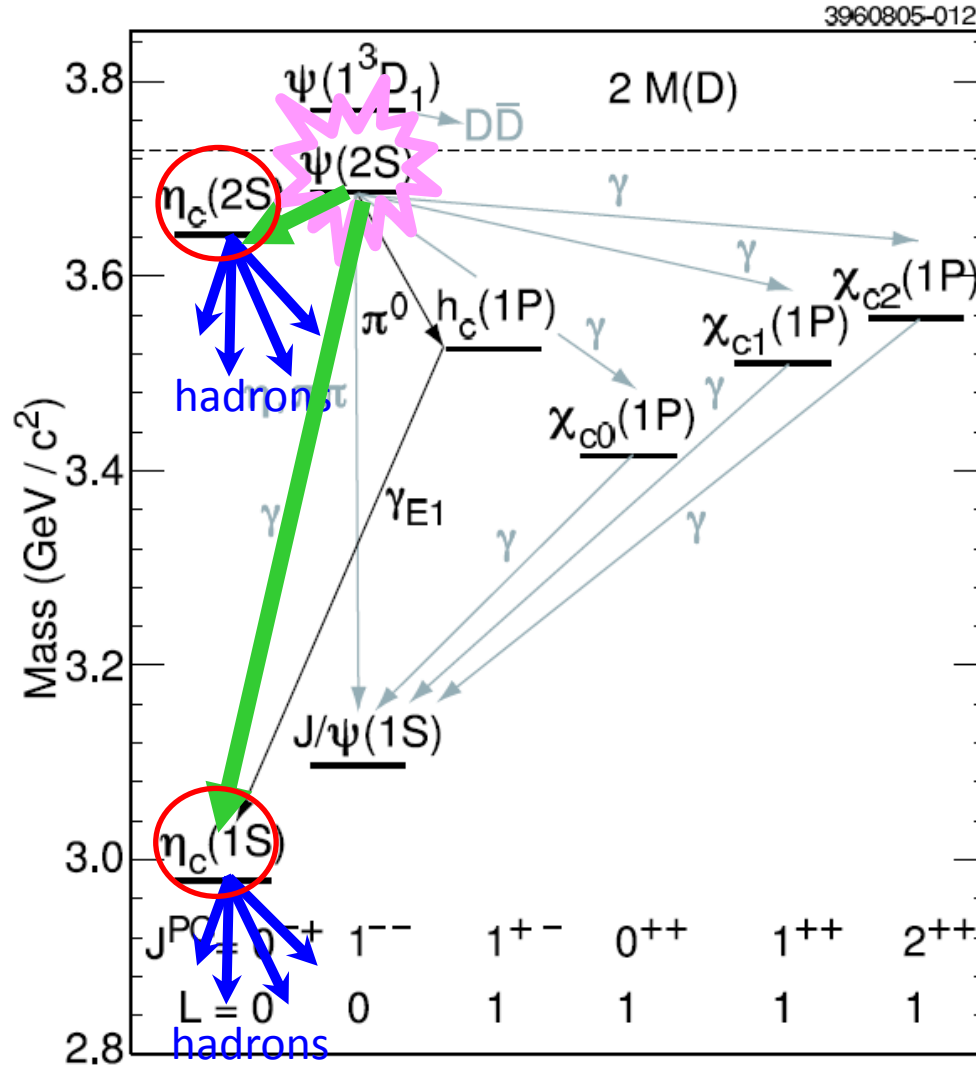
Mass = $3525.21 \pm 0.27 \pm 0.14 \text{ MeV}/c^2$

evts. = 136 ± 14

BESIII: PRL 104 132002 (2010)

CLEOc: PRL 101 182003 (2008)

$$\psi' \rightarrow \gamma \eta_c(2S), \gamma \eta_c$$



$\eta_c(1S)$

- The S-wave spin-singlet charmonium ground state

- The mass & width

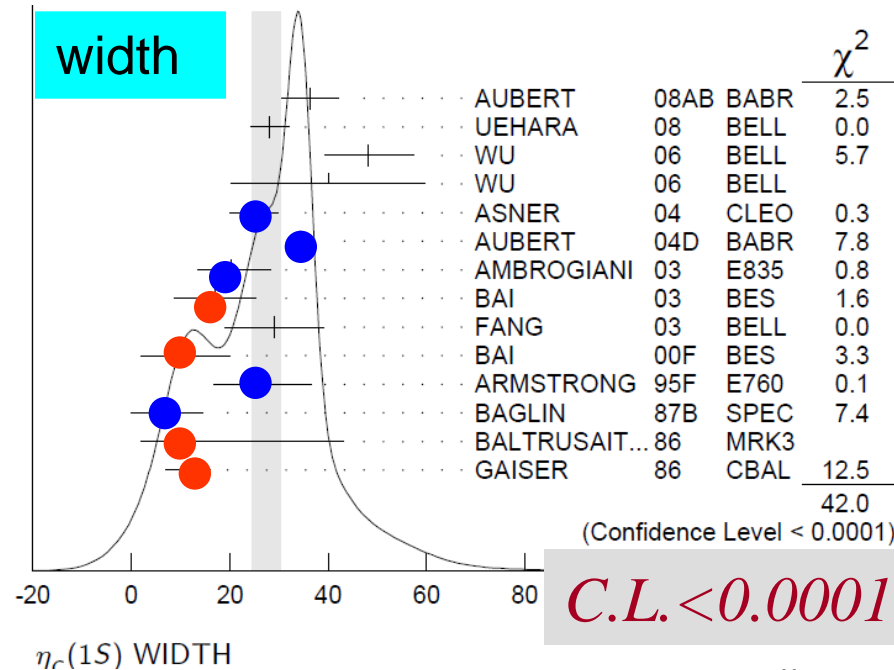
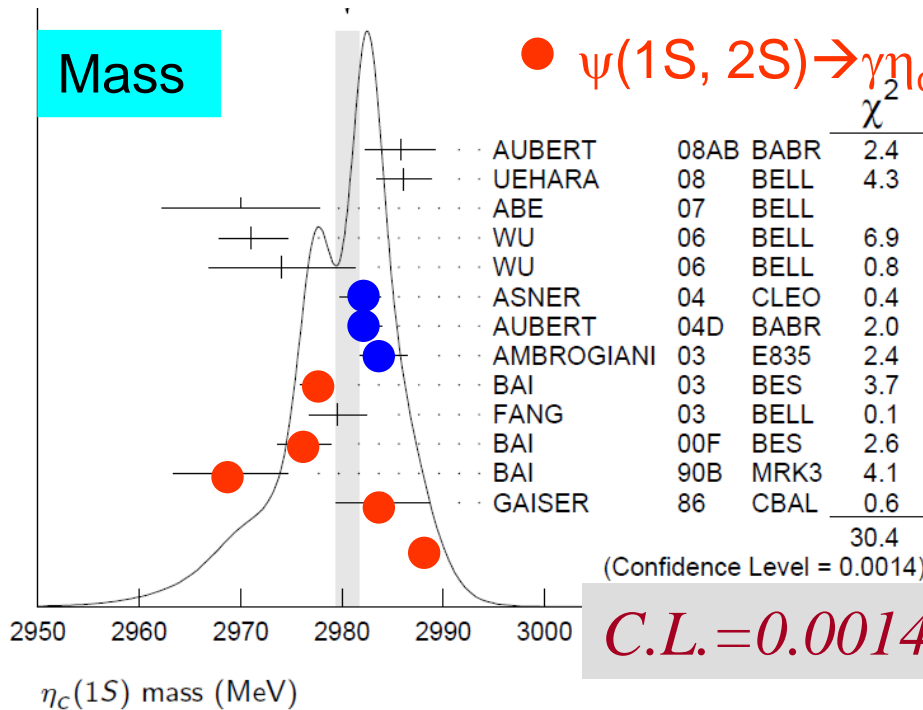
J/ ψ radiative transition: $M \sim 2978.0 \text{ MeV}/c^2$, $\Gamma \sim 10 \text{ MeV}$

$\gamma\gamma$ process: $M = 2983.1 \pm 1.0 \text{ MeV}/c^2$, $\Gamma = 31.3 \pm 1.9 \text{ MeV}$

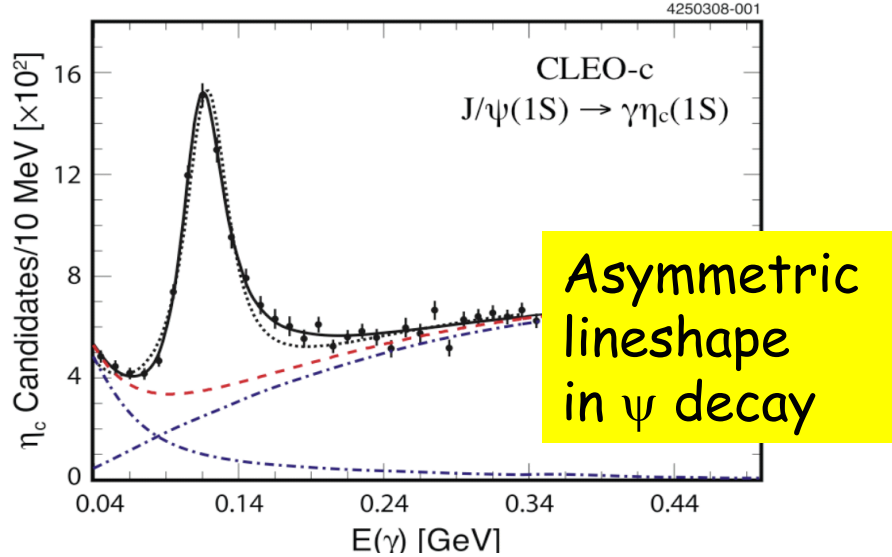
- CLEOc found the distortion of the η_c line shape in ψ' decays.

● $\gamma\gamma, p\bar{p}$

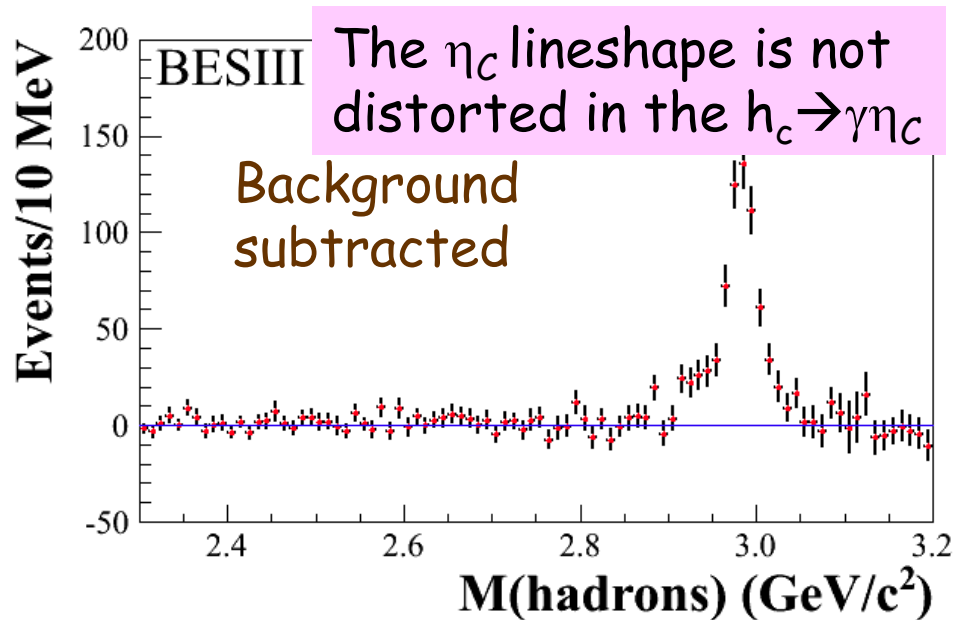
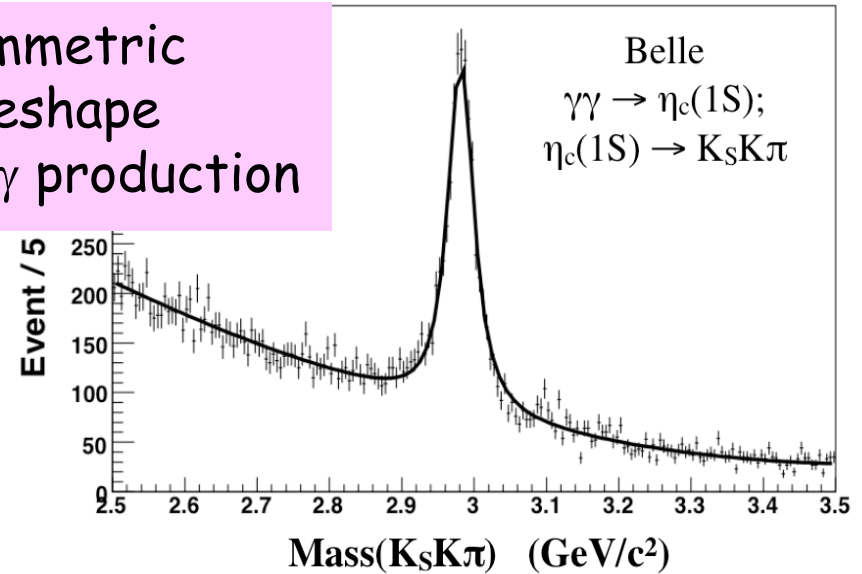
● $\psi(1S, 2S) \rightarrow \gamma\eta_c$



η_c lineshape



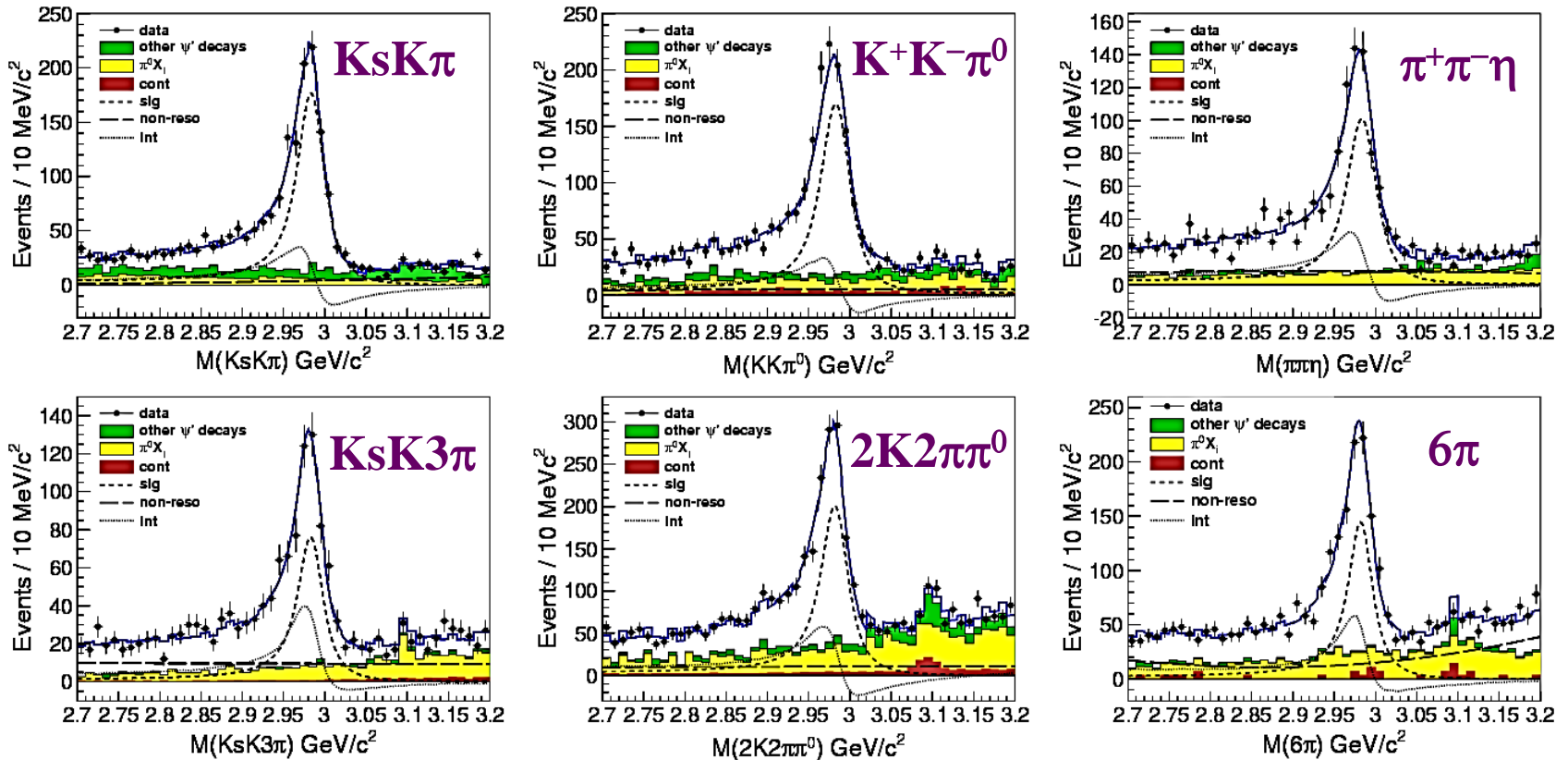
Symmetric lineshape in $\gamma\gamma$ production



- CLEO-c observe a distortion of η_c lineshape in charmonium radiative decay [*PRL102, 011801 (2009)*]
- The lineshape of η_c from BELLE is symmetric
- The abnormal line shape is also observed in BESIII exclusive channels in $\psi' \rightarrow \gamma\eta_c$ but not in $\psi' \rightarrow \pi^0 h_c; h_c \rightarrow \gamma\eta_c$

η_c resonance parameters from $\psi' \rightarrow \gamma \eta_c$

PRL,108,22202

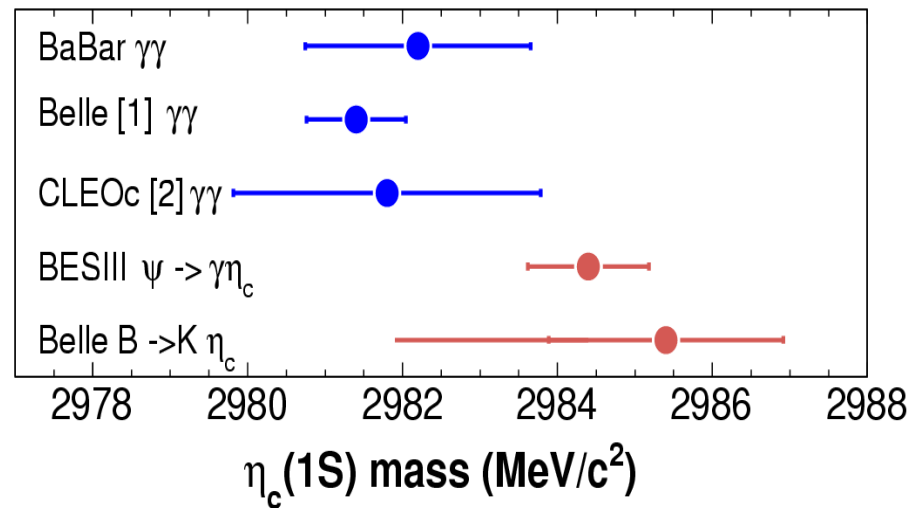


Simultaneous fit to 6 decay modes, the interference between η_c and non-resonant is significant

$$\text{Mass} = 2984.3 \pm 0.6 \pm 0.6 \text{ MeV}/c^2$$

$$\text{Width} = 32.0 \pm 1.2 \pm 1.0 \text{ MeV}$$

$$\phi = 2.40 \pm 0.07 \pm 0.08 \text{ rad, or } 4.19 \pm 0.03 \pm 0.09 \text{ rad}$$



Hyperfine splitting: $\Delta M(1S) = 112.5 \pm 0.8 \text{ MeV}$;

This value is closer to the LQCD prediction than earlier result

$\eta_c(2S)$

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

Observed in different production mechanisms,

1. $B \rightarrow K \eta_c(2S)$ *Belle: PRL 89 102001 (2002)*
2. $\gamma\gamma \rightarrow \eta_c(2S) \rightarrow KK\pi$ *CLEOc: PRL 92 142001 (2004)*
Belle: NPPS.184 220 (2008); PRL 98 082001(2007)
3. double charmonium production
BaBar: PRL 92 142002 (2004); PR D72 031101(2005)
BaBar: PR D84 012004 (2011)

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

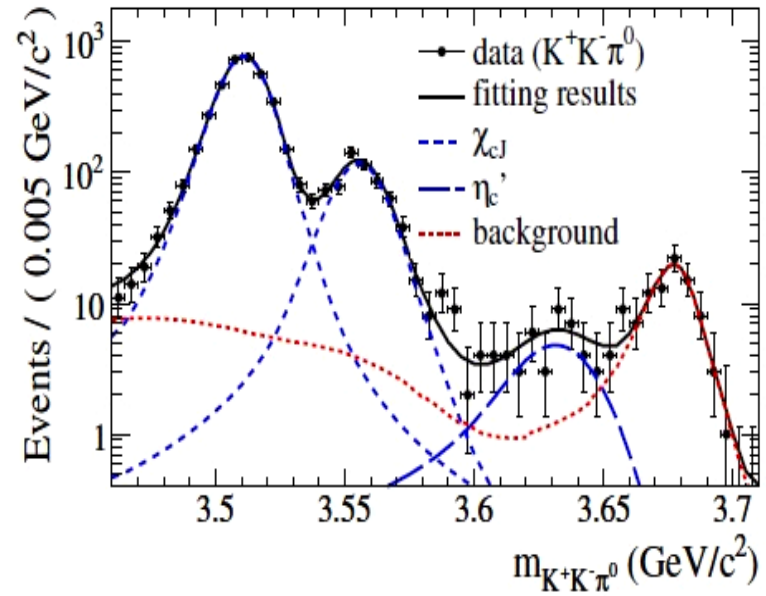
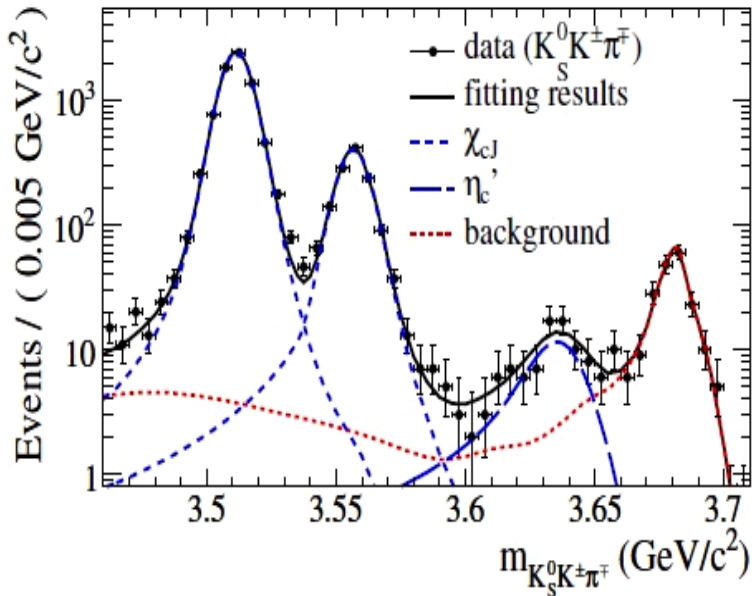
CLEO found no signals in 25M ψ' .

$$BF(\psi' \rightarrow \gamma \eta_c(2S)) < 7.6 \times 10^{-4} \quad \text{CLEO: PRD 81 052002 (2010)}$$

Experimental challenge : search for photons of 50 MeV

Observation of $\psi' \rightarrow \gamma \eta_c'$

PRL, 109, 042003



- Simultaneous fit with:

- η_c' signal: modified BW (*M1*) (Resolution extrapolated from χ_{cJ})
- χ_{cJ} signal: MC shape smeared with Gaussian
- BG from $e^+ e^- \rightarrow KK\pi$ (ISR), $\psi' \rightarrow KK\pi$ (FSR), $\psi' \rightarrow \pi^0 KK\pi$: are measured from data

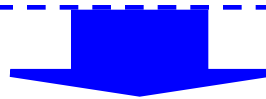
Statistical significance > 10 σ

Results on $\psi' \rightarrow \gamma \eta_c' \rightarrow \gamma \text{KK} \pi$

- $M(\eta_c') = 3637.6 \pm 2.9 \pm 1.6 \text{ MeV}/c^2$
- $\Gamma(\eta_c') = 16.9 \pm 6.4 \pm 4.8 \text{ MeV}$

- $\text{Br}(\psi' \rightarrow \gamma \eta_c' \rightarrow \gamma \text{KK} \pi) = (1.30 \pm 0.20 \pm 0.30) \times 10^{-5}$

$\text{Br}(\eta_c' \rightarrow \text{KK} \pi) = (1.9 \pm 0.4 \pm 1.1)\%$ from BaBar



$$\text{Br}(\psi' \rightarrow \gamma \eta_c') = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$$

CLEO-c: $< 7.6 \times 10^{-4}$

(PRD81,052002(2010))

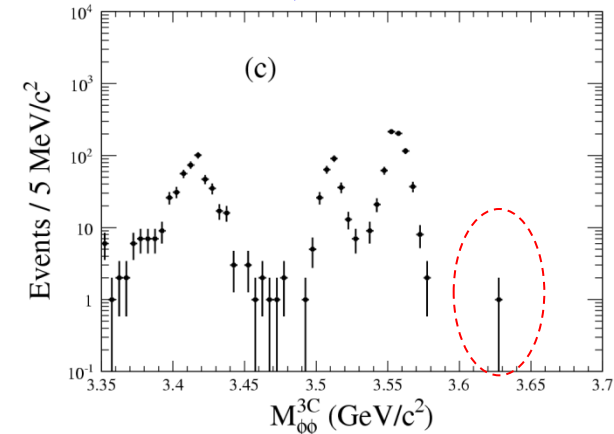
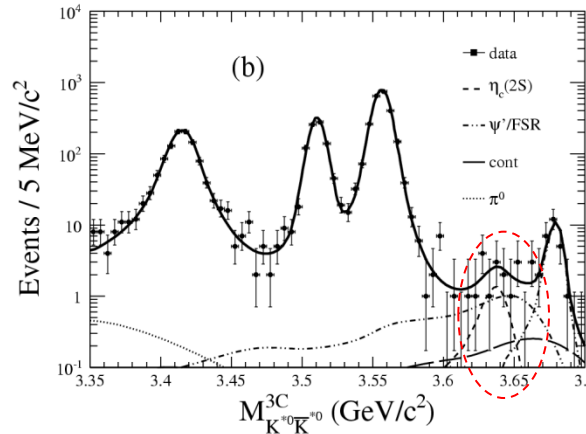
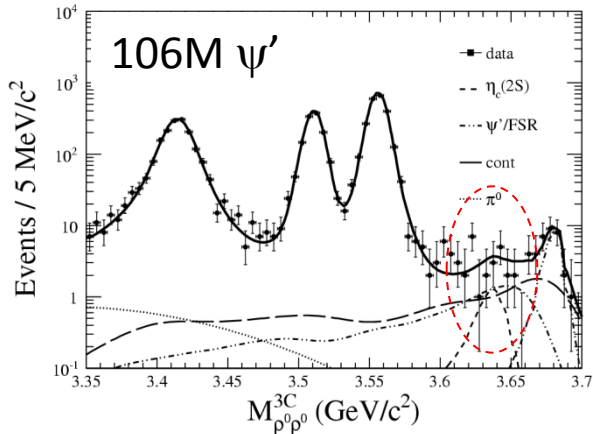
Potential model: $(0.1-6.2) \times 10^{-4}$

(PRL89,162002(2002))

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

Test for the “Intermediate charmed meson loops”

PRD84, 091102 (2011)



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

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

arXiv: 1010.1343

Summary

- The branching fractions of $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$ are determined, the absolute h_c cross sections become available; h_c is also seen in hadronic decays.
- The **resonance parameters of η_c** have been measured in high precision; **interference** between η_c and the non-resonant amplitude is considered.
- η_c' was observed in ψ' *M1* decays for the first time, and decay modes other than $KK\pi$ are studied.
- Hope to find the $h_c(2P)$ with the coming $Y(4360)$ data at BESIII.