Charmonium spectroscopy at BES-III

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(IHEP, Beijing)

QWG 2013

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Charmonium physics at BESIII

-- ideal place to test pQCD, study non-perturbative effects

- Spectroscopy

  η_c , J/ψ, h_c , χ_{cJ} , η (2S), ψ(2S)

- Charmonium Transitions
  - $\psi' \rightarrow \gamma\eta_c/\eta_c'$, $\psi' \rightarrow \gamma\chi_{cJ}$, $\chi_{cJ} \rightarrow \gamma J/\psi$ …
  - $\psi' \rightarrow \eta J/\psi$, $\pi^0 J/\psi$
  - $\chi_c \rightarrow \eta_c \pi^+\pi^-$
  - $\psi' \rightarrow \gamma\gamma J/\psi$

- Decays ➔ *Aiqiang's talk on 04/25*
  - EM decays $\chi_{c0/2} \rightarrow \gamma\gamma$; $J/\psi \rightarrow \gamma\gamma$; $\eta_c \rightarrow \gamma\gamma$
  - light hadron decays
  - baryonic decays
  - Rare and forbidden decays

- Hunt for XYZ states ➔ *Zhiqing's talk on 04/22*

Experimental data samples

$\psi(2S)$

106 M in 2009 ➔ *reults shown in this talk*

500 M in 2012 (analysis in progress)

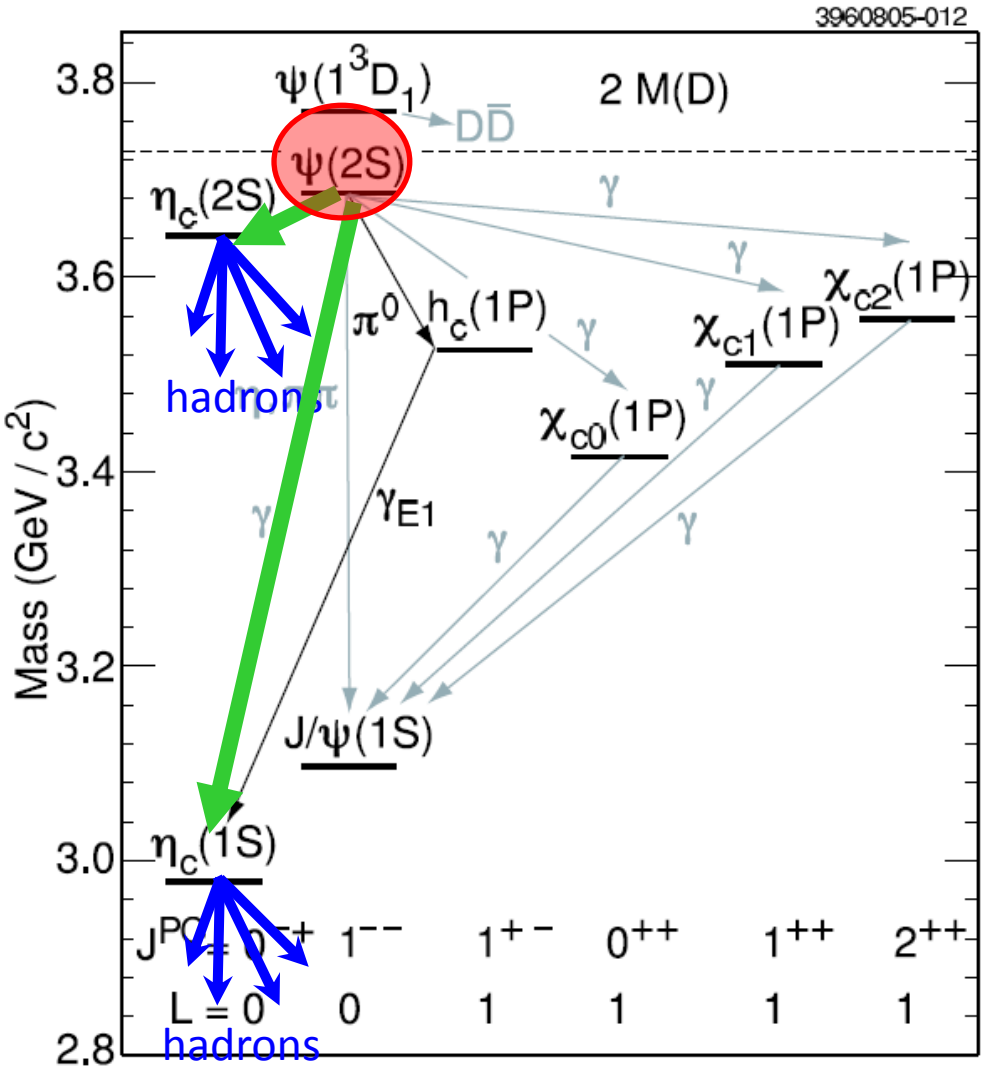
At higher energies, above 4 GeV

4009 GeV (2011)

4260 GeV (2013)

…. ➔ *for XYZ study*

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



$\eta_c(1S)$

- The S-wave spin-singlet charmonium ground state, found in 1980
- The mass & width

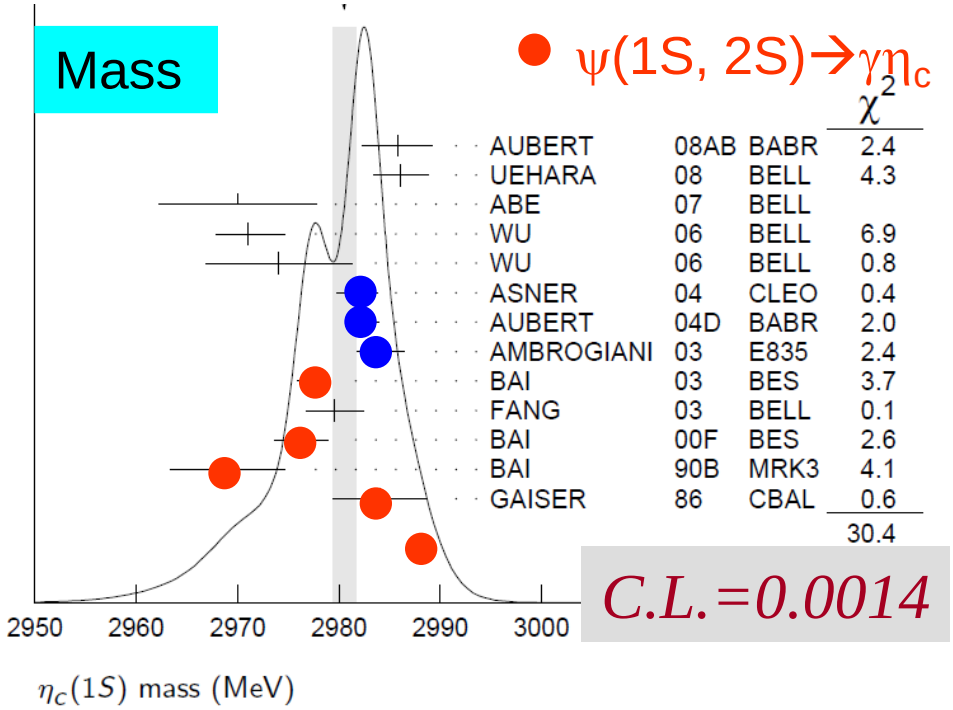
  J/ψ radiative transition: M ~ 2978.0MeV/c^2, Γ ~ 10MeV

  γγ process: M = 2983.1 ± 1.0 MeV/c^2, Γ = 31.3 ± 1.9 MeV

Mass

● γγ, $p\bar{p}$

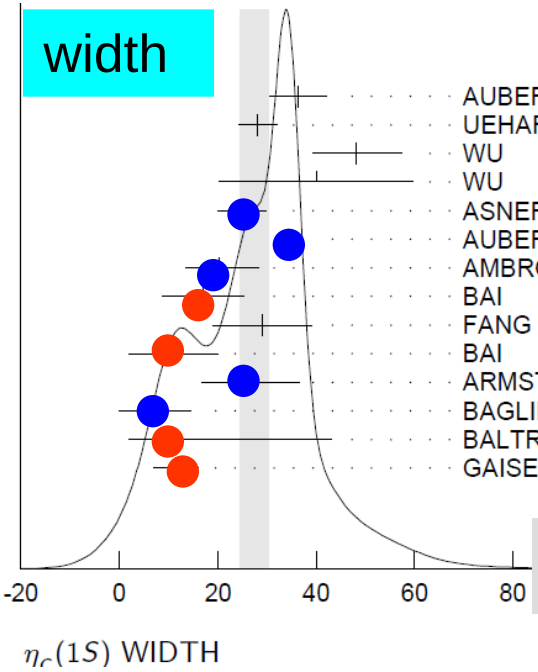
● $\psi(1S, 2S) \rightarrow \gamma\eta_c$



			χ^2
AUBERT	08AB	BABR	2.4
UEHARA	08	BELL	4.3
ABE	07	BELL	
WU	06	BELL	6.9
WU	06	BELL	0.8
ASNER	04	CLEO	0.4
AUBERT	04D	BABR	2.0
AMBROGIANI	03	E835	2.4
BAI	03	BES	3.7
FANG	03	BELL	0.1
BAI	00F	BES	2.6
BAI	90B	MRK3	4.1
GAISER	86	CBAL	0.6
			30.4

C.L.=0.0014

width

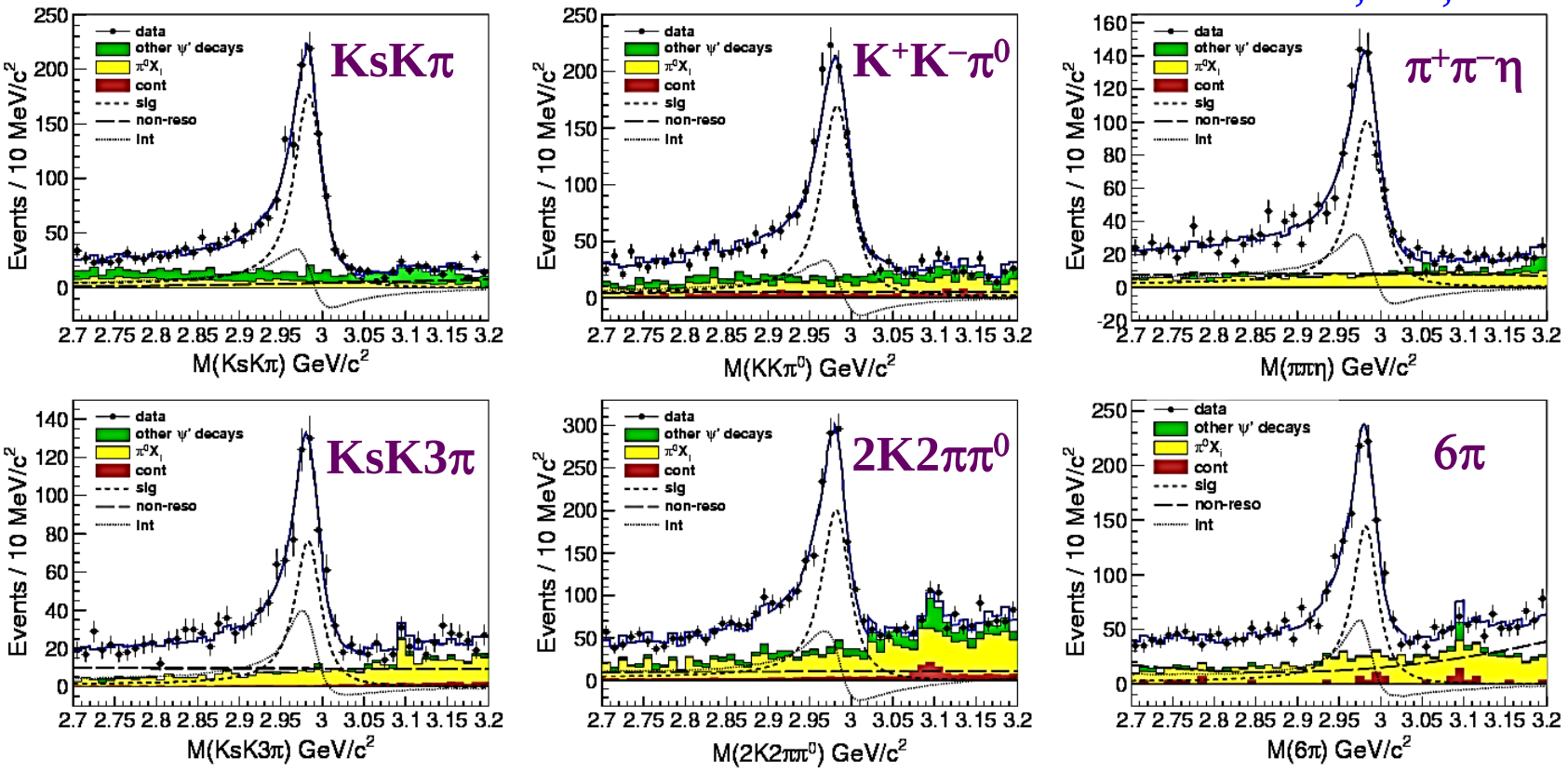


			χ^2
AUBERT	08AB	BABR	2.5
UEHARA	08	BELL	0.0
WU	06	BELL	5.7
WU	06	BELL	
ASNER	04	CLEO	0.3
AUBERT	04D	BABR	7.8
AMBROGIANI	03	E835	0.8
BAI	03	BES	1.6
FANG	03	BELL	0.0
BAI	00F	BES	3.3
ARMSTRONG	95F	E760	0.1
BAGLIN	87B	SPEC	7.4
BALTRUSAIT...	86	MRK3	
GAISER	86	CBAL	12.5
			42.0

C.L.<0.0001

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

PRL,108,22202



The interference between η_c and non-resonant is significant.

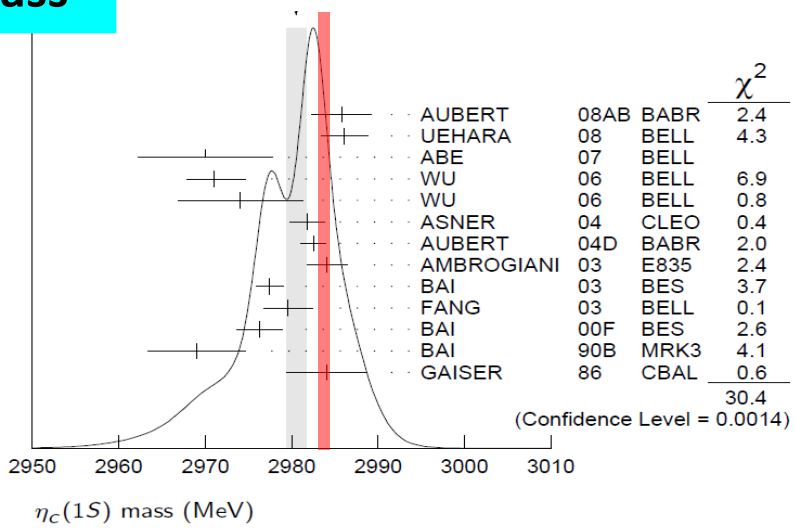
Simultaneous fit to 6 modes,

Mass = 2984.3 ± 0.6 ± 0.6 MeV/c²

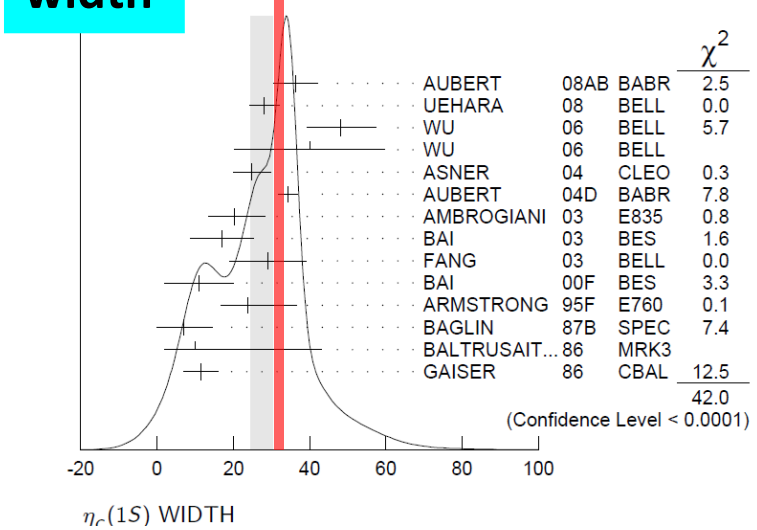
Width = 32.0 ± 1.2 ± 1.0 MeV

Comparison with previous η_c results

Mass



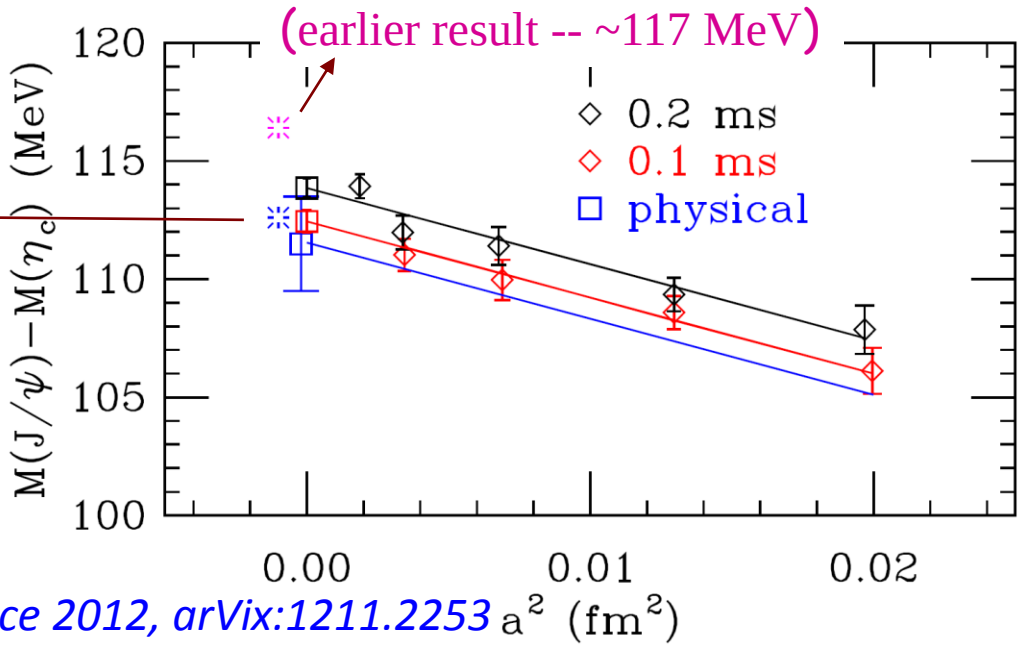
width



Hyperfine splitting (BESIII alone)

$\Delta M(1S) = \mathbf{112.5 \pm 0.8}$ MeV

Closer to prediction than earlier result



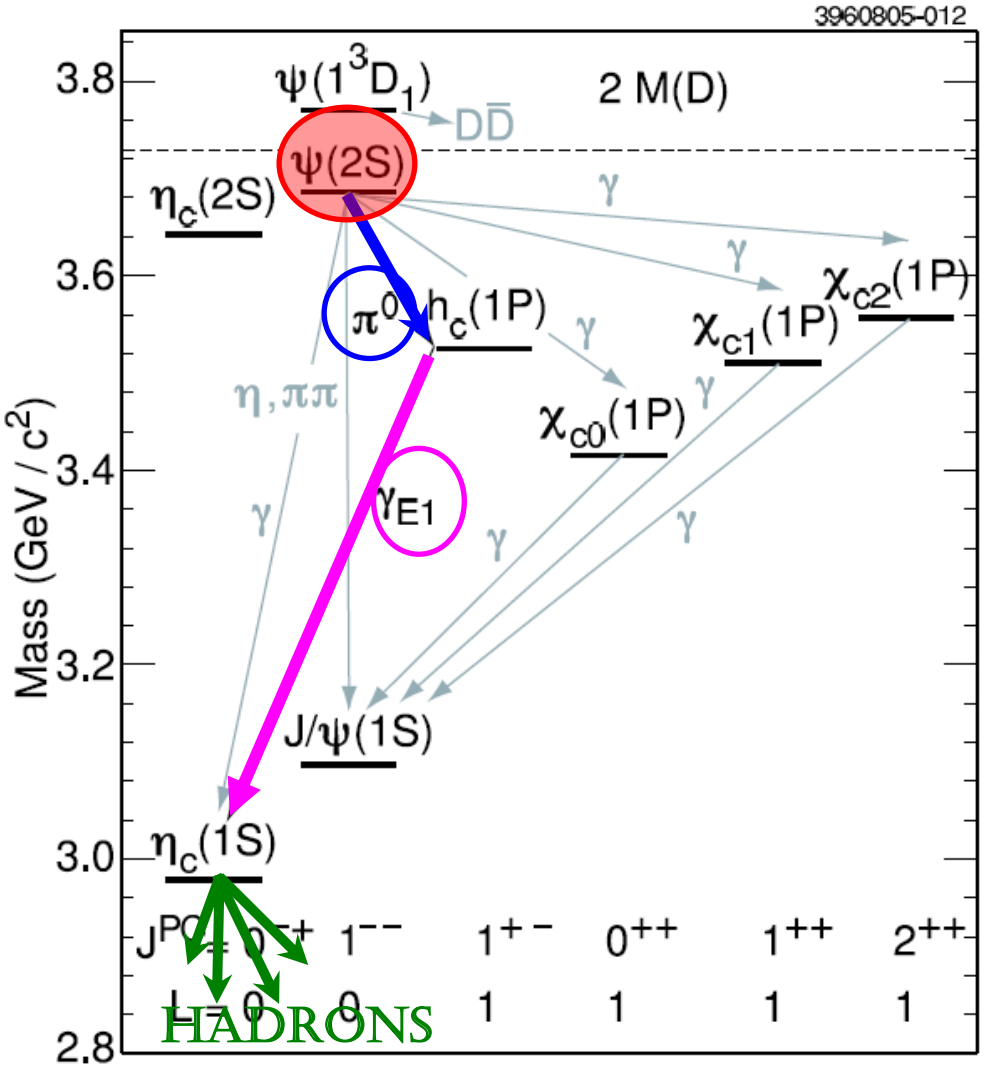
Lattice 2012, arVix:1211.2253

$h_c(^1P_1)$

- Spin singlet P wave (S=0, L=1)
- Potential model: if non-vanishing P-wave spin-spin interaction,
  $\Delta M_{hf}(1P)=M(h_c)-<M(1\ ^3P_J)> \neq 0$,
  where $<M(1\ ^3P_J)>=[M(\chi_{c0})+3M(\chi_{c1})+5M(\chi_{c2})]/9$
- Theoretical predictions:
  - $\mathcal{B}(\psi' \to \pi^0 h_c) = (0.4\text{-}1.3)\times 10^{-3}$, $\mathcal{B}(h_c \to \gamma\eta_c) = 41\%$ (NRQCD)
    $\mathcal{B}(h_c \to \gamma\eta_c) = 88\%$ (PQCD)

    Y. P. Kuang, PR D65, 094024 (2002)
  - $\mathcal{B}(h_c \to \gamma\eta_c) = 38\%$ *Godfrey and Rosner, PR D66, 014012 (2002)*

h_c analysis



"inclusive" (published in 2011)

only detect the π^0

(compute $M(h_c)$ from kinematic)

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

"*E1* tagged" (published in 2011)

detect the π^0 & γ

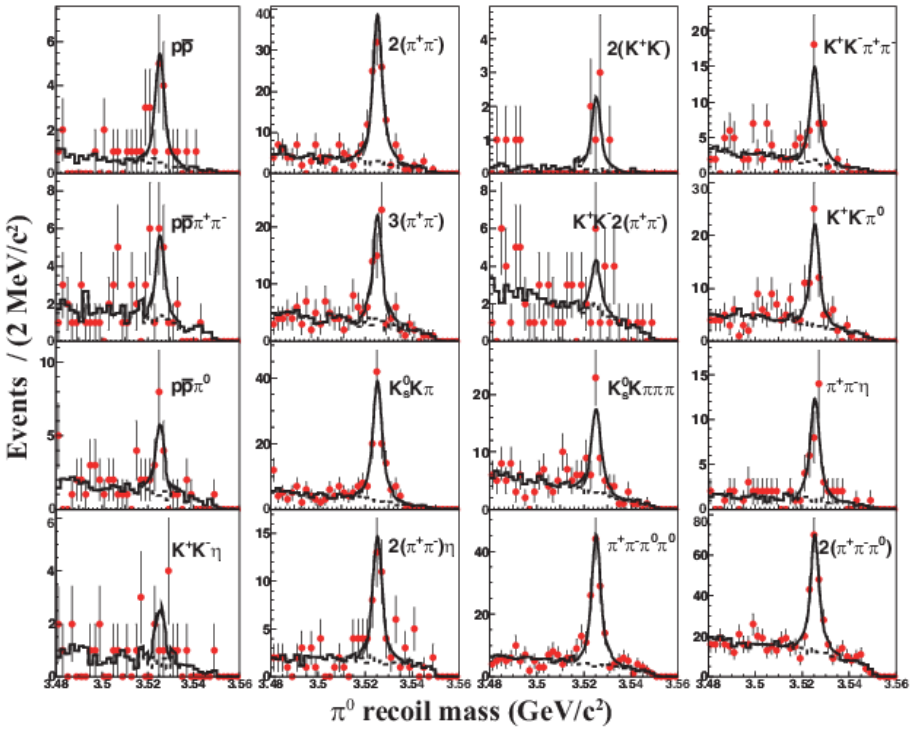
Rate $\propto \mathcal{B}(\psi' \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma \eta_c)$

"exclusive" (2012)

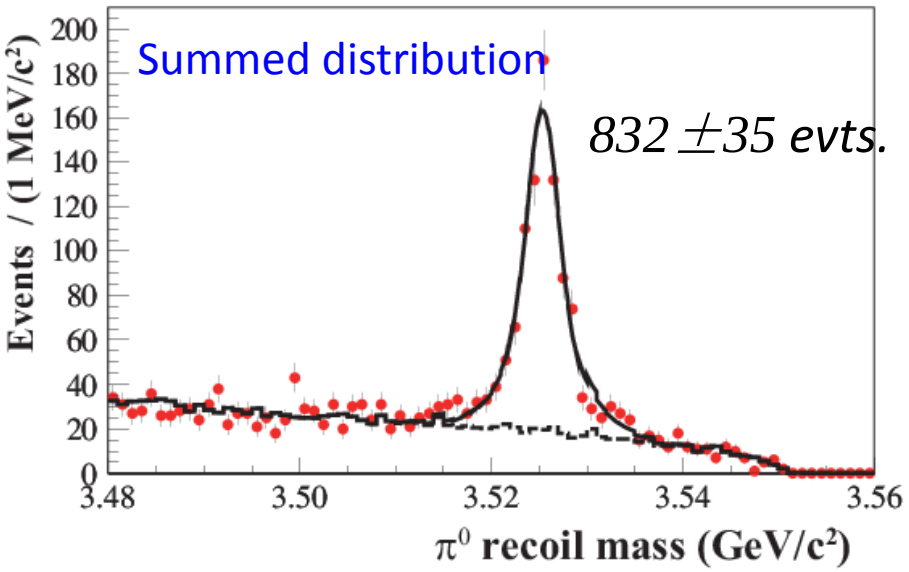
detect the π^0, γ & $\eta_c \to X_i$ decay products

Rate $\propto \mathcal{B}(\psi' \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma \eta_c) \times \mathcal{B}(\eta_c \to Xi)$

16 hadronic decays (~40% η_c decays)



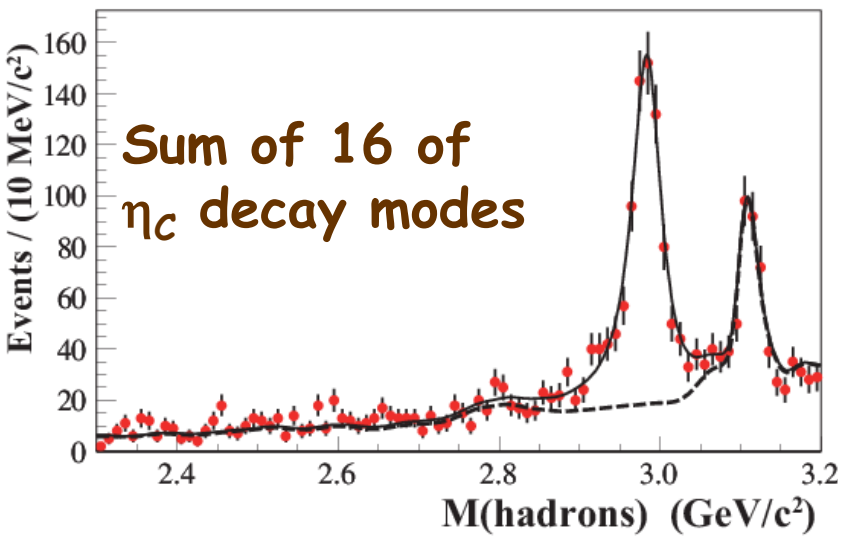
Phys. Rev. D 86, 092009 (2012)

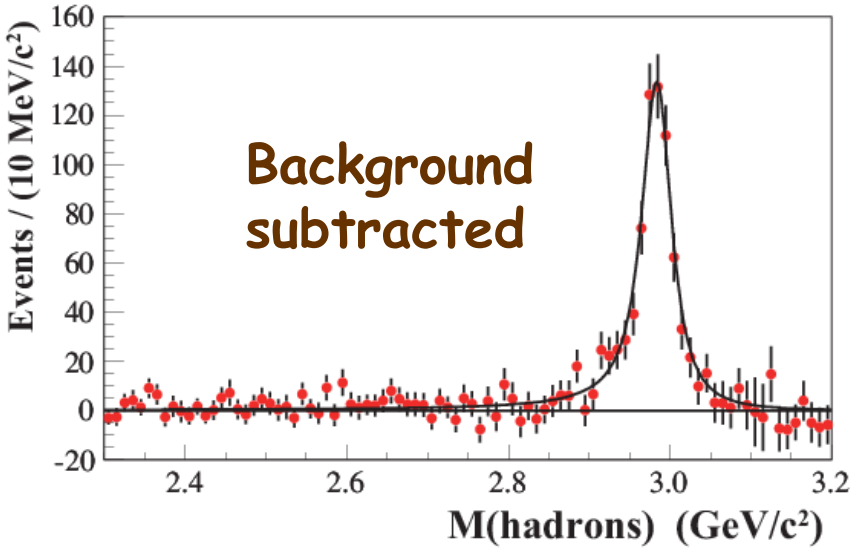


(MeV)	BESIII Exclusive	BESIII Inclusive	CLEO
mass	*3525.31 ±0.11 ±0.14*	*3525.40 ±0.13 ±0.18*	*3525.21 ±0.27 ±0.14*
width	*0.70 ±0.28 ±0.22*	*0.73 ±0.45 ±0.28*	--
$\Delta M_{hf}(1P)$	*-0.01±0.11± 0.15*	*0.10 ±0.13 ±0.18*	*0.08± 0.18± 0.12*

BESIII: PRL 104 132002 (2010)
CLEOc: PRL 101 182003 (2008)

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





The η_c lineshape in $h_c \rightarrow \gamma \eta_c$ is not as distorted as in $\psi' \rightarrow \gamma \eta_c$ decays;
$\rightarrow$the non-resonant interfering bkg is smaller than $\psi' \rightarrow \gamma \eta_c$.
$\rightarrow$this channel will be best suited to determine η_c resonance parameters, $\mathcal{B}(\psi' \rightarrow \gamma \eta_c)$

η_c resonance parameters from $h_c \rightarrow \gamma\eta_c$

η_c Mass = 2984.49 ± 1.16 ± 0.52 MeV/c^2
η_c Width = 36.4 ± 3.2 ± 1.7 MeV

Compared with the reults from $\psi' \rightarrow \gamma\eta_c$

Mass = 2984.3 ± 0.6 ± 0.6 MeV/c^2

Width = 32.0 ± 1.2 ± 1.0 MeV

1. *Statistic errors are dominated, need more statistics.*
2. *Reults are consistent with those from $\psi' \rightarrow \gamma\eta_c$ decays within errors.*

η_c'

Observed in different production mechanisms

1. $B \to K \eta_c'$
2. $\gamma\gamma \to \eta_c' \to KK\pi$
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 $\psi' \to \gamma\eta_c'$

1. Disagreement of transition rate between exp. and theory

   $\mathcal{B}(\psi' \to \gamma\eta_c)$: *theory: (1.6/3.4)%* *Exp. : 0.34%*

   $\mathcal{B}(\psi' \to \gamma\eta_c')$: *theory: (5.9/7.3)* $\times 10^{-4}$ *Exp.: ???* *PR D72 054026*

   $(0.1\text{-}6.2)\times 10^{-4}$ *PRL 89,162002*

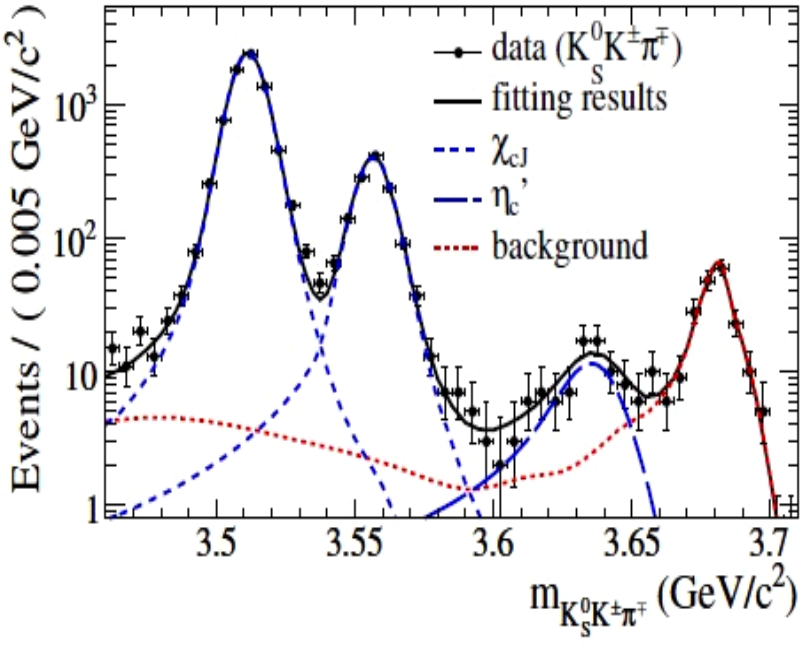
2. CLEO found no signal in 25M ψ'

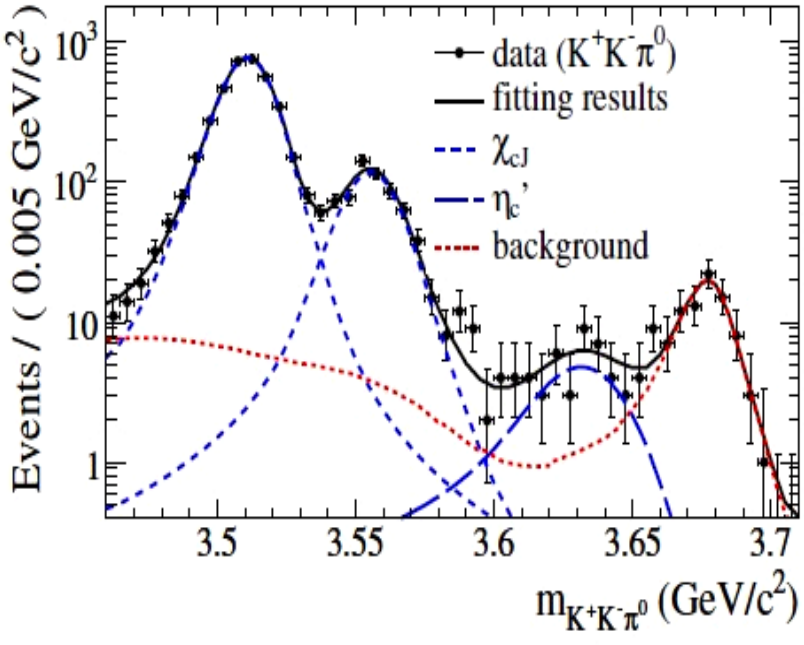
   $\mathcal{B}(\psi' \to \gamma\eta_c') < 7.6 \times 10^{-4}$ *PRD 81 052002 (2010)*

3. BESIII made the first observation $\eta_c' \to KK\pi$;
   find evidence in $\eta_c' \to KsK3\pi$; no hint for $\eta_c' \to VV$

Observation of $\psi' \to \gamma\eta_c'$, $\eta_c' \to KK\pi$

PRL,109, 042003





M = ***3637.6 ±2.9 ±1.6*** MeV/c^2; Γ= ***16.9±6.4±4.8*** MeV

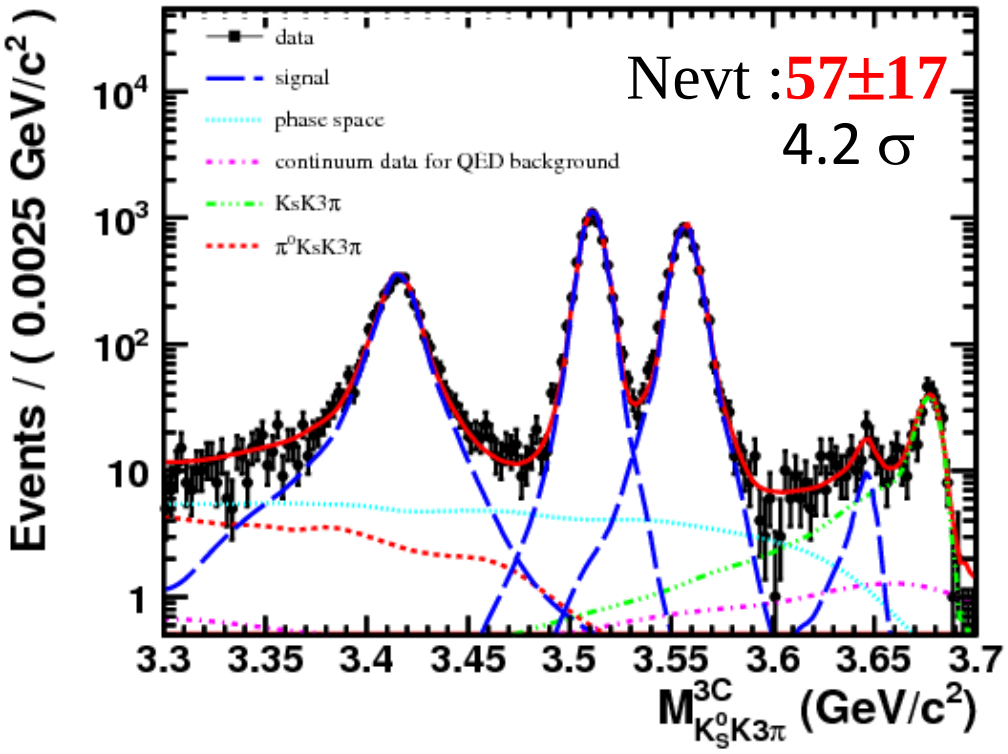
$\mathcal{B}(\psi' \to \gamma\eta_c' \to \gamma KK\pi)$ =***(1.30 ±0.20 ±0.30) ×10^{-5}***

$\mathcal{B}(\psi' \to \gamma\eta_c') = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$

Potential model: (0.1-6.2)×10^{-4}
PRL89,162002(2002)

PRD 87 052005

$\psi' \rightarrow \gamma\eta_c'$, $\eta_c' \rightarrow$ KsK3π



Mass = $3646.9 \pm 1.6 \pm 3.6$ MeV/c^2;

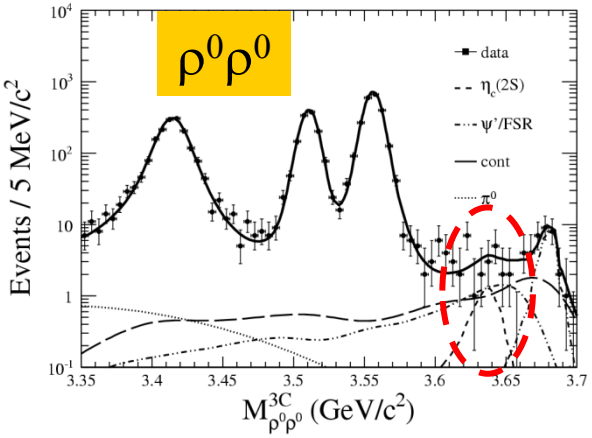
Γ = $9.2 \pm 4.8 \pm 2.9$ MeV;

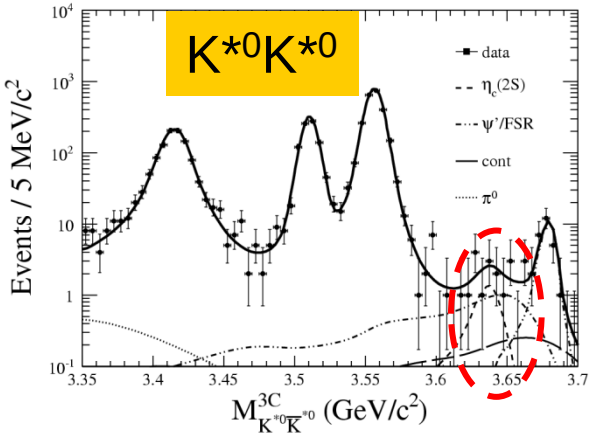
$\mathcal{B}(\psi' \rightarrow \gamma\eta_c' \rightarrow \gamma\text{KsK3}\pi) = (7.03 \pm 2.10 \pm 0.70) \times 10^{-6}$

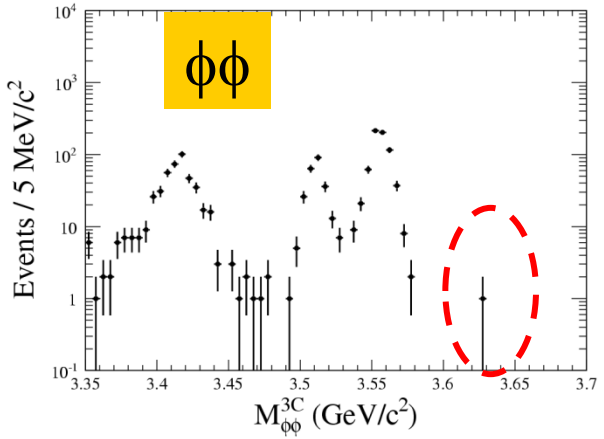
Search for $\eta_c(2S) \rightarrow VV$ @BESIII

"Intermediate charmed meson loops" can evade helicity seletion rule

PRD84, 091102







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

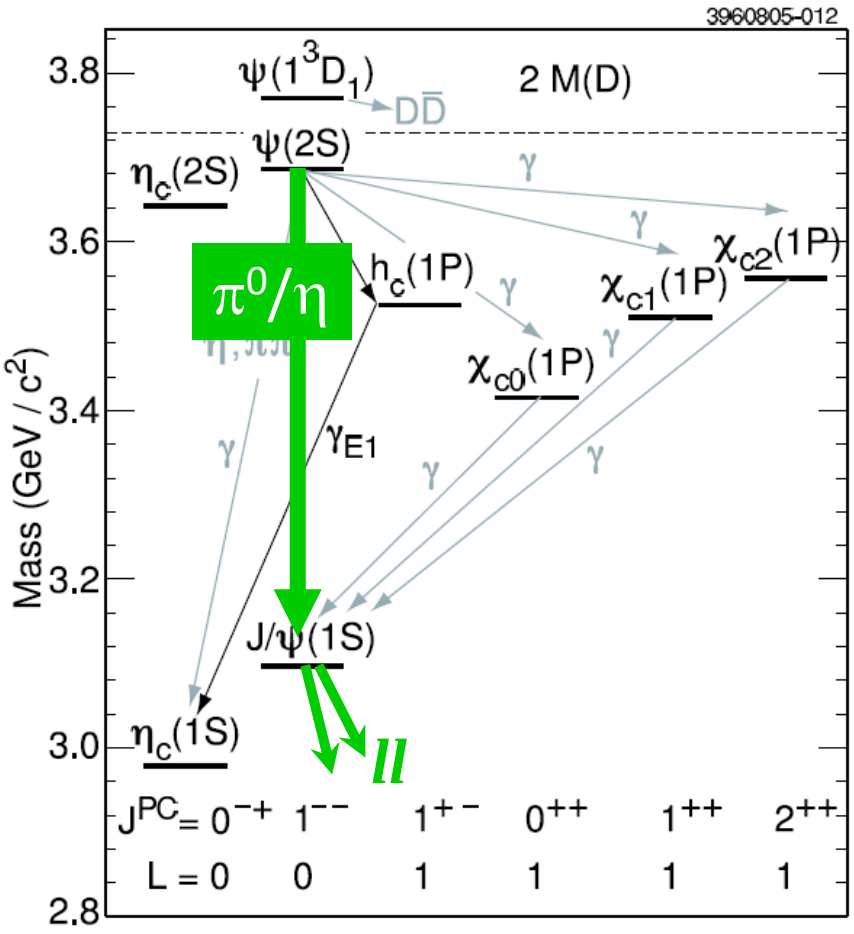
	B($\eta_c' \rightarrow$ VV) (10^{-3})	B($\eta_c' \rightarrow$ VV) (10^{-3})
$\rho^0\rho^0$	<3.1	6.4 ~ 28.9
$K^{*0}K^{*0}$	<5.3	7.9 ~ 35.8
$\phi\phi$	<2.0	2.1 ~ 9.8

arXiv: 1010.1343

Hadronic transition & 2-γ transition

PRD 86, 092008(2012)

$\psi' \to \eta J/\psi, \pi^0 J/\psi$



- $\psi' \to \pi^0 J/\psi$ isospin violation
- $R = \frac{\mathcal{B}(\psi' \to \pi^0 J/\psi)}{\mathcal{B}(\psi' \to \eta J/\psi)}$ can be used to measure m_u/m_d
- multipole-expansion + axial anomaly predicts

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

  significant smaller than exp.

  Charmed-meson loops:

  $R = 0.11 \pm 0.06$ PRL 103, 082003

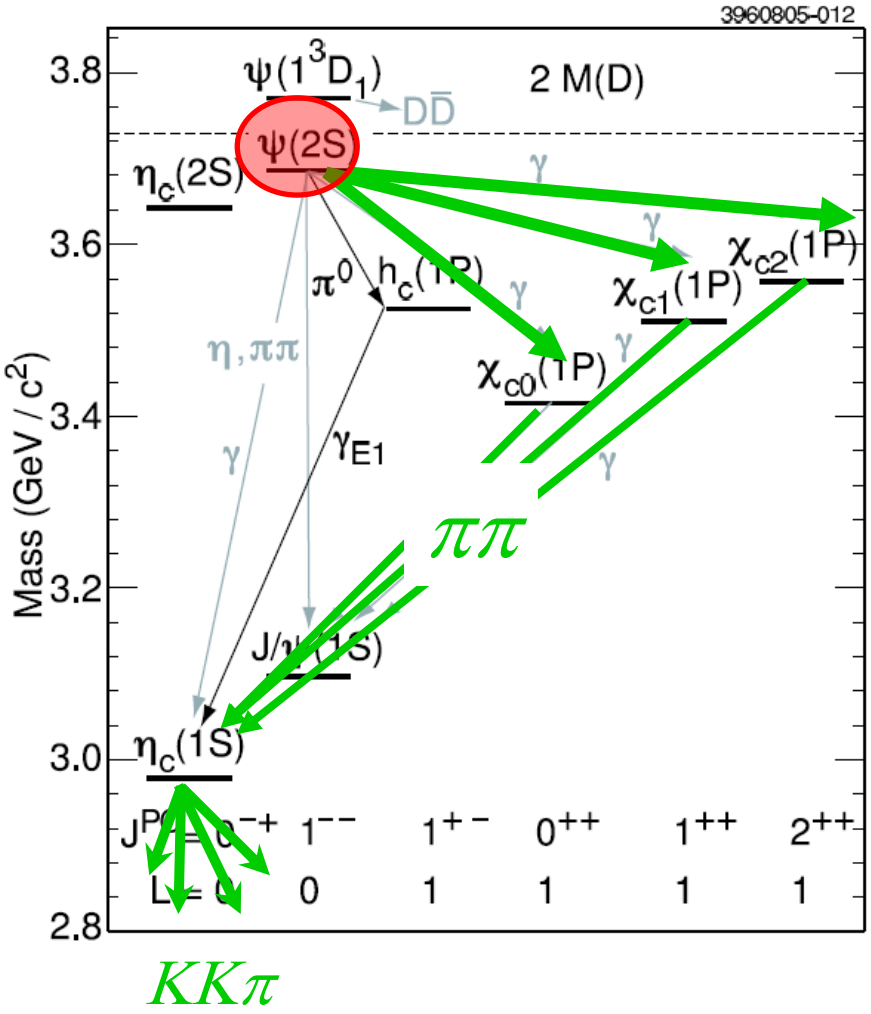
Our results:

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

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

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

Search for $\chi_c \rightarrow \eta_c \pi^+ \pi^-$



Hadronic transition of P-wave charmonium further test the multipole-expansion

Our results PRD 87 012002

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

$\mathcal{B}(\chi_{c1}(1P) \rightarrow \pi^+\pi^-\eta_c(1S)) < 0.32\%$

theory: 1.81 ± 0.26%

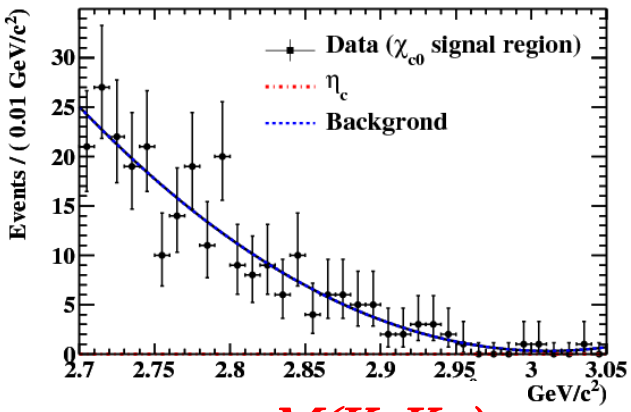
by a E1-M1 soft gluon emission model

PRD 75, 054019

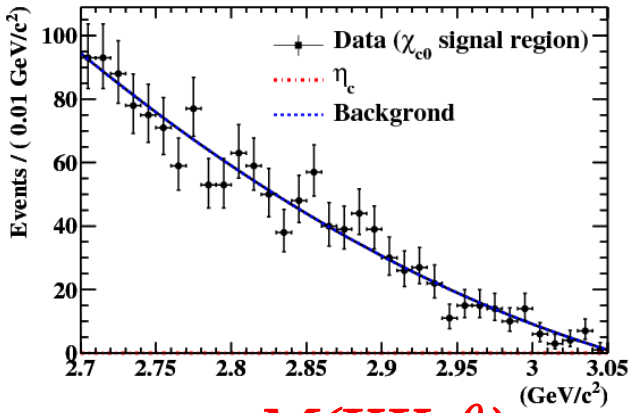
$\mathcal{B}(\chi_{c2}(1P) \rightarrow \pi^+\pi^-\eta_c(1S)) < 0.54\%$

$\chi_c \to \eta_c \pi^+ \pi^-$, $\eta_c \to KK\pi$

χ_{c0} region

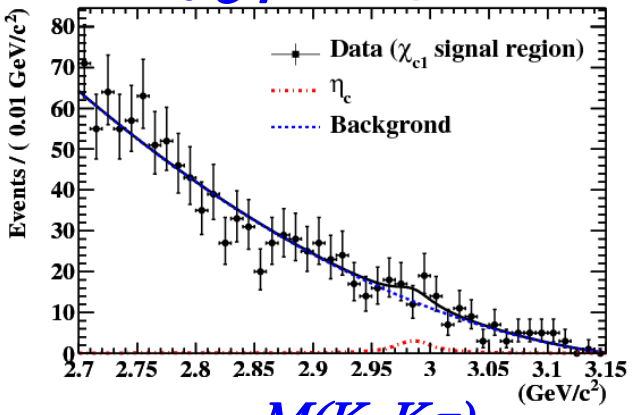


$M(K_S K\pi)$

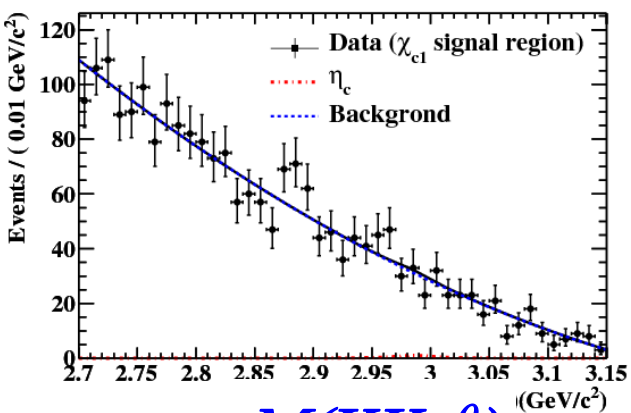


$M(KK\pi^0)$

χ_{c1} region

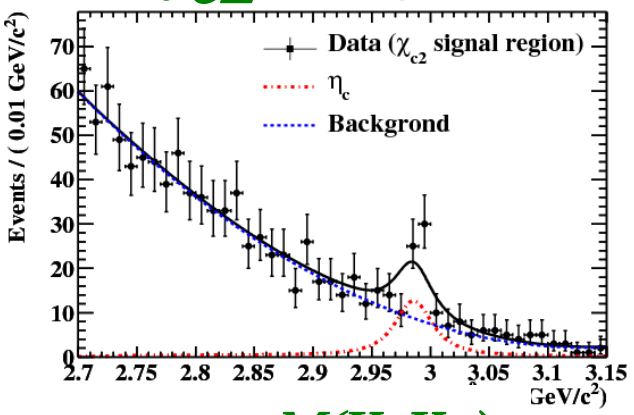


$M(K_S K\pi)$

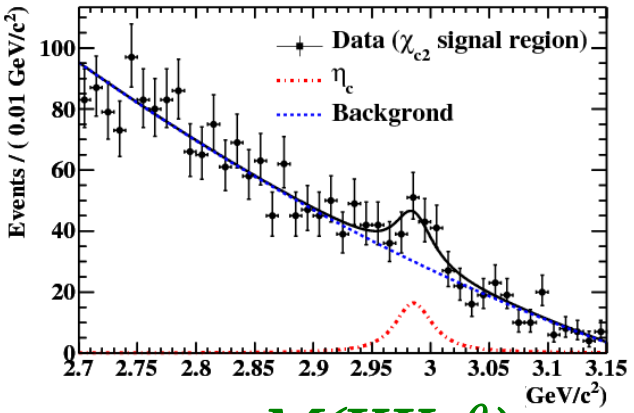


$M(KK\pi^0)$

χ_{c2} region



$M(K_S K\pi)$

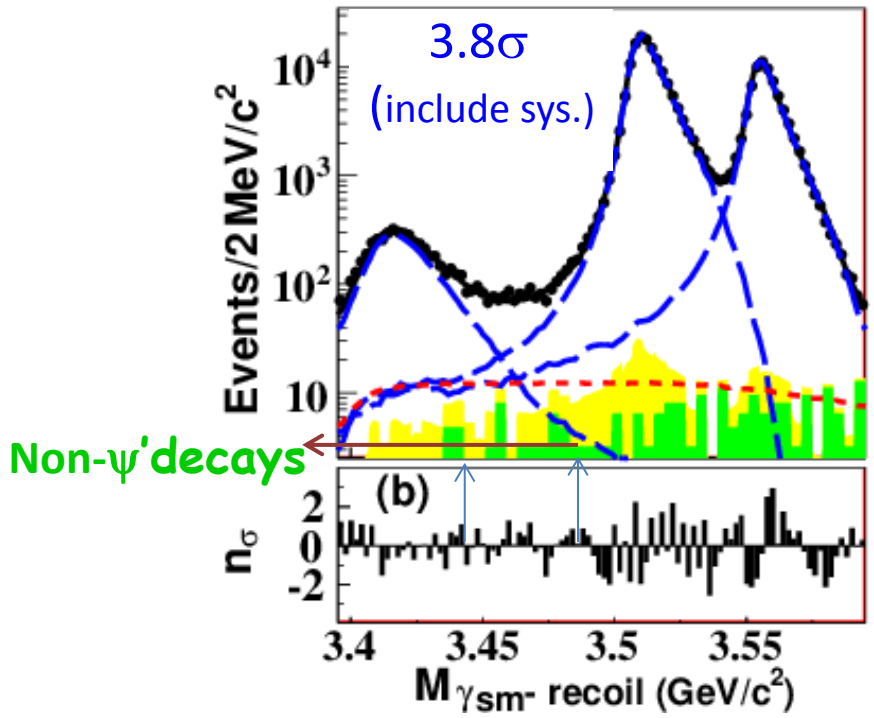


$M(KK\pi^0)$

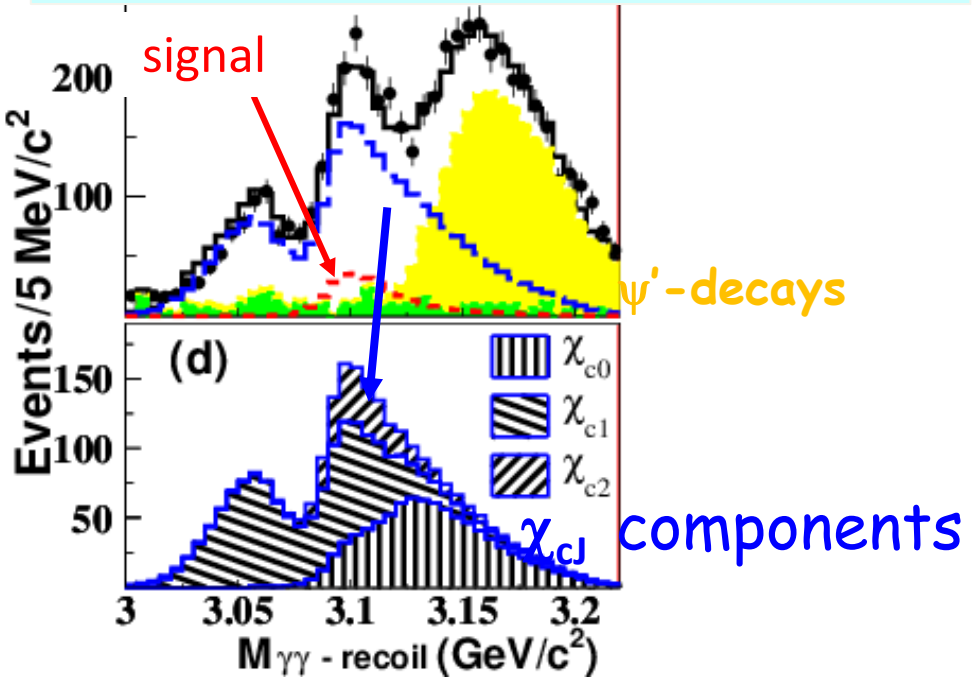
Set stringent upper limit on the $\chi_c \to \eta_c \pi^+ \pi^-$ *branching fraction*

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

Sensitive probe to hadronic loop effects



For events in $3.44 < M(\gamma_{sm\text{-}recoil}) < 3.48$GeV



$\mathcal{B}(\psi' \rightarrow \gamma\gamma J/\psi)$	$(3.1 \pm 0.6^{+0.8}_{-1.0}) \times 10^{-4}$
$\mathcal{B}(\psi' \rightarrow \gamma\chi_{c0}, \chi_{c0} \rightarrow \gamma J/\psi)$	$(15.1 \pm 0.3 \pm 1.0) \times 10^{-4}$
$\mathcal{B}(\psi' \rightarrow \gamma\chi_{c1}, \chi_{c1} \rightarrow \gamma J/\psi)$	$(337.7 \pm 0.9 \pm 18.3) \times 10^{-4}$
$\mathcal{B}(\psi' \rightarrow \gamma\chi_{c2}, \chi_{c2} \rightarrow \gamma J/\psi)$	$(187.4 \pm 0.7 \pm 10.2) \times 10^{-4}$

PRL109, 172002

Summary

With 106 M ψ' data sample collected by BESIII,

- η_c mass and width have been measured in high precision; interference between η_c and the non-resonant amplitude is considered.

- η_c' is observed in ψ' *M1* transition for the first time in $KK\pi$ decays; $KsK3\pi$ / *VV* decays are also studied.

- h_c is futher studied by exclusive analysis in addition to the inclusive method; precision has been improved.

- Studies of charmonium transition impose stringent constraints on theory.