Charmonium Radiative Transitions

Jielei Zhang
Institute of High Energy of Physics
(for the BESIII collaboration)

- What to measure

- What have done with old datasets

  $1.06 \times 10^8\ \psi(3686)$ 2009

- What will do with new datasets

  $\sim 3.5 \times 10^8\ \psi(3686)$ 2012

  $\sim 1 \times 10^9\ J/\psi$ data

  ~ 5 fb^{-1} data above 4.0 GeV

What to measure

$\Gamma(J/\psi \to \gamma\eta_c)$

PDG2014: 1.58 ± 0.37 keV
Error is large

Lattice QCD 2.49 ± 0.19 keV
PRD 86,094501

η_c lineshape

large difference among the measurements

Interference common phase in $\psi(3686) \to \gamma\eta_c$?

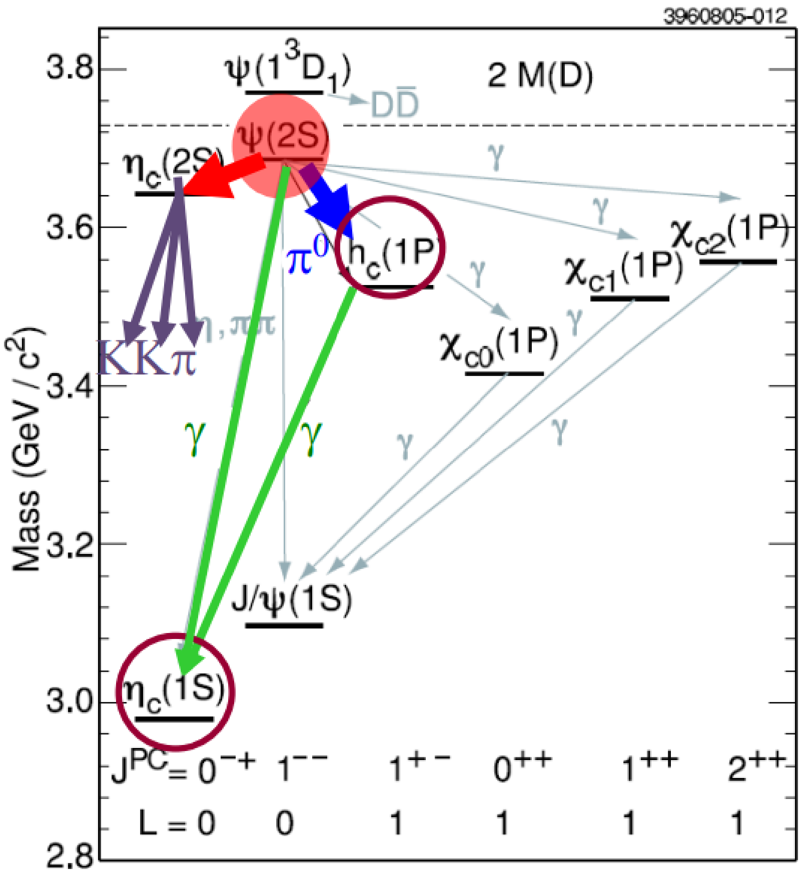
$\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S))$

$(7 \pm 2 \pm 4) \times 10^{-4}$ (PDG2014),
The systematic error dominated by $\mathcal{B}(\eta_c(2S) \to KK\pi)$

$\mathcal{B}(\psi(3686) \to \gamma\eta_c)$

$(0.34 \pm 0.05) \times 10^{-2}$ (PDG2014)

BESIII What have done with old data

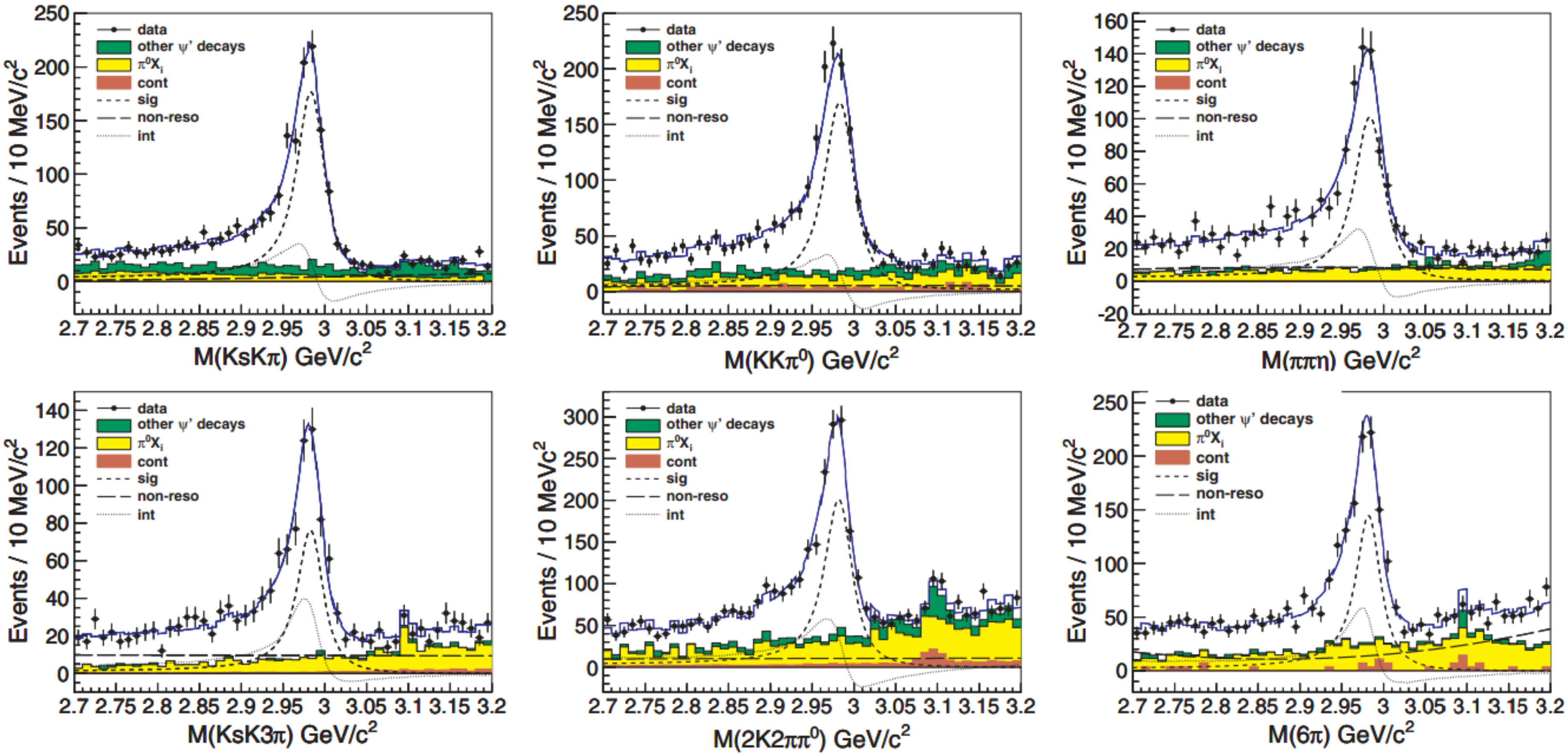


- η_c line-shape
  - $\psi(3686)$ M1 transition
  - h_c E1 transition
- M1 transition $\psi(3686) \rightarrow \gamma\eta_c(2S)$ first observation
- $\psi(3686) \rightarrow \gamma\gamma J/\psi$

106 M $\psi(3686)$ events

BESIII

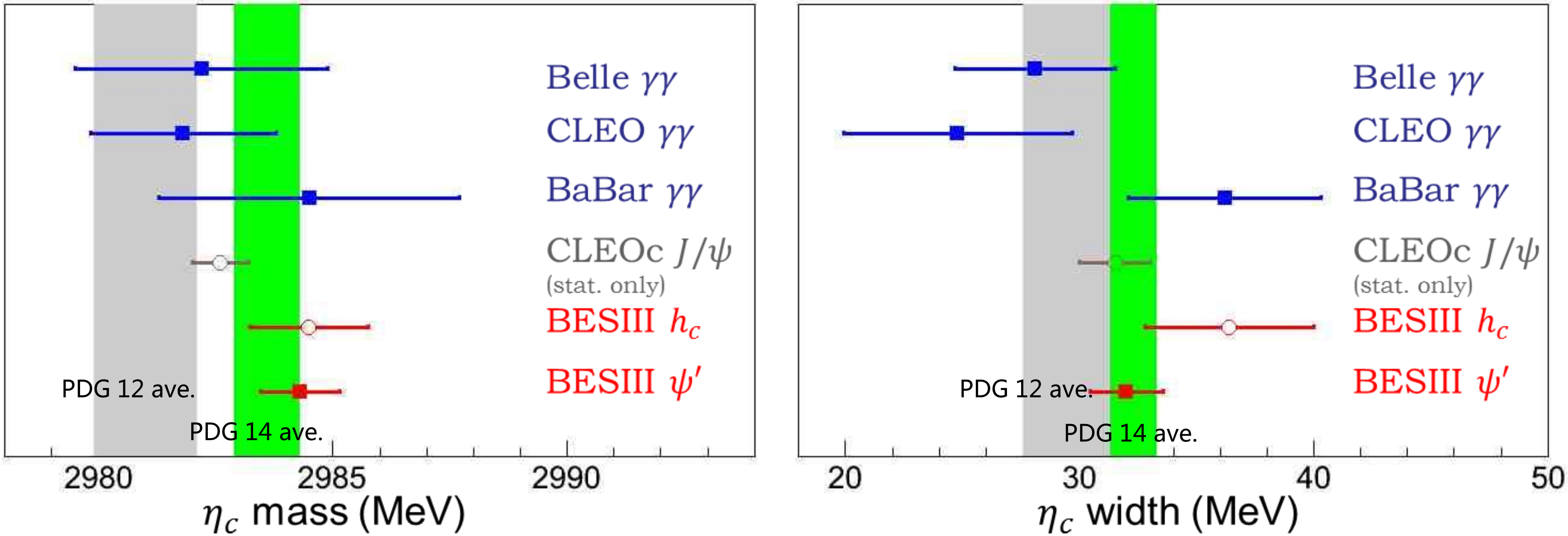
PRL 108,222002



Simultaneous fit with modified Breit-Wigner (hindered M1)

Significance of interference is 15σ

(may partly explain the discrepancy among measurements)



mass = $2984.3 \pm 0.6 \pm 0.6$ MeV/c^2 $2983.9 \pm 0.6 \pm 0.6$ MeV/c^2

width = $32.0 \pm 1.2 \pm 1.0$ MeV $31.3 \pm 1.2 \pm 0.9$ MeV

Relative phases are consist with each other within 3σ.

$\phi = 2.40 \pm 0.07 \pm 0.47$ rad

The phases are constrained to be same

Suggest a common phase in all the modes.

$$\Delta M_{hf}(1S) \equiv M(J/\psi) - M(\eta_c) = 112.6 \pm 0.8\,\mathrm{MeV}/c^2$$

agree well with quark-model and lattice computation

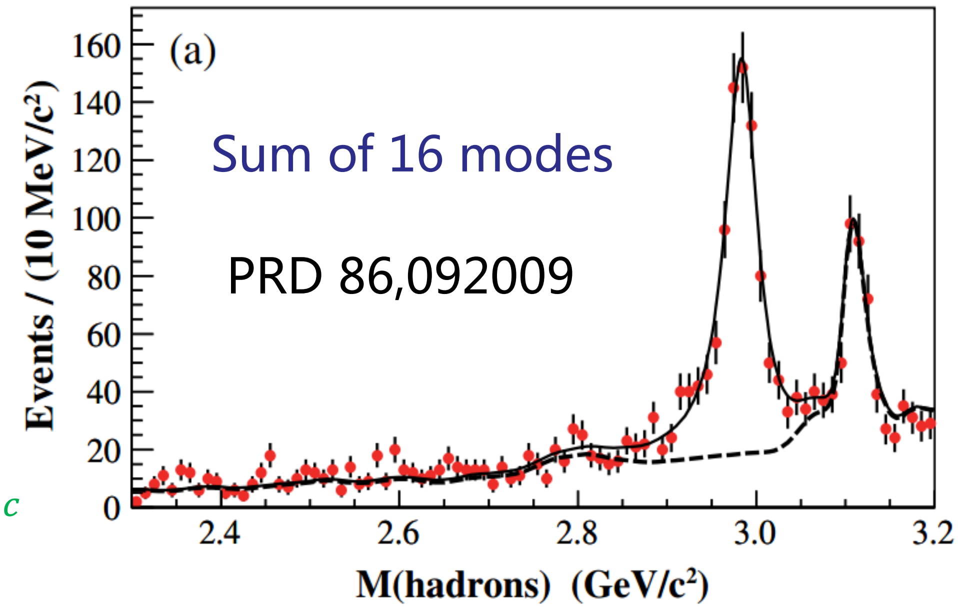
h_c E1 transition to η_c

Huge interference in $\psi(3686) \to \gamma\eta_c$

The η_c amplitude in h_c decays is larger than in $\psi(3686)$ decays

Weaker interference in $h_c \to \gamma\eta_c$

Easier and better than $\psi(3686) \to \gamma\eta_c$



Signal: $\left[E_\gamma^3 \times BW(m) \times f_d\left(E_\gamma\right)\right] \otimes R_i(m)$

Energy of photon in rest frame of h_c

For convergence

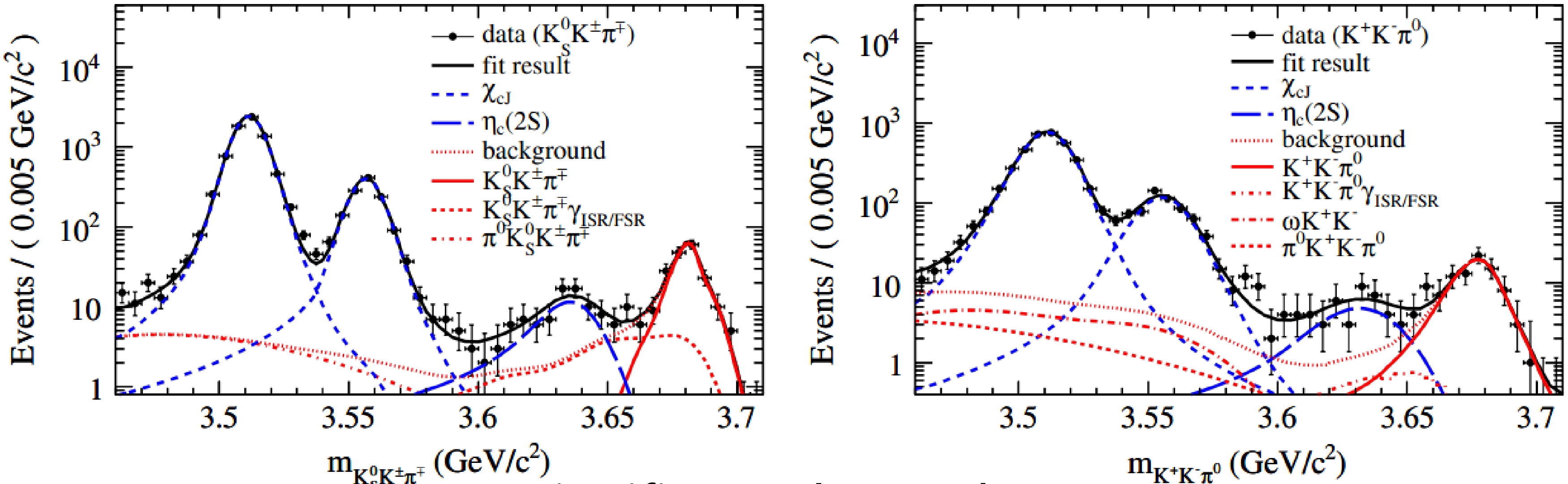
Resolution for ith mode

$M(\eta_c) = 2984.40 \pm 1.16 \pm 0.52$ MeV/c^2

$\Gamma(\eta_c) = 36.4 \pm 3.2 \pm 1.7$ MeV

The first observation of the M1 transition $\psi(3686) \to \gamma\eta_c(2S)$

PRL 109,042003



Significance larger than 10σ

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

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

$$\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S)) = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$$

Systematic error is dominated by $\mathcal{B}(\eta_c(2S) \to KK\pi)$

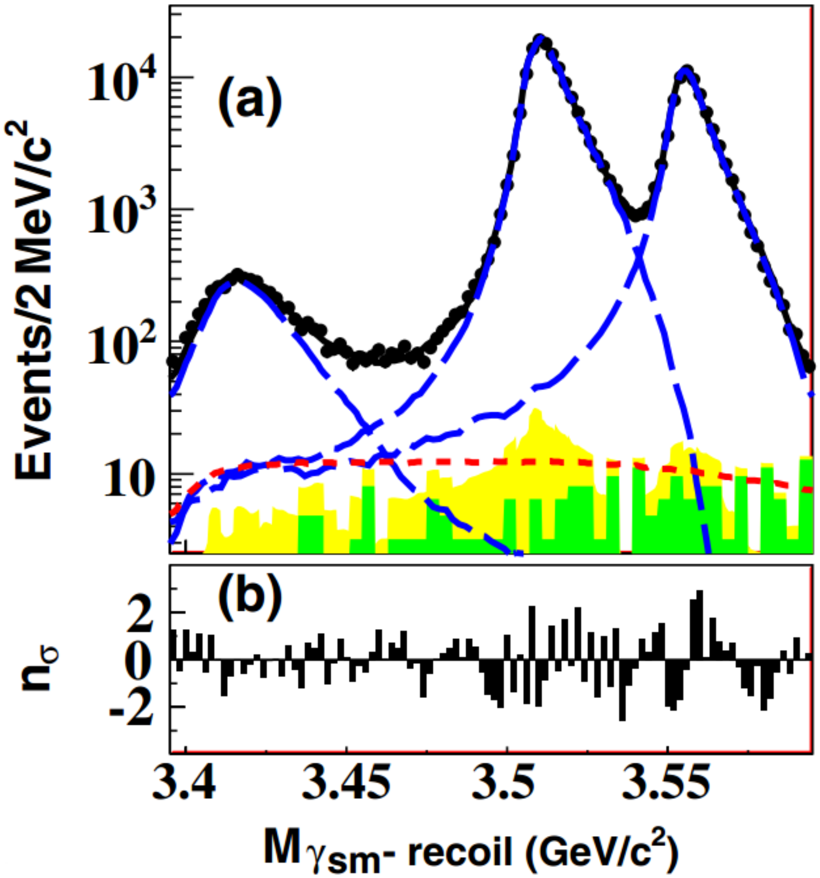
BESIII Direct two-photon transition $\psi(3686) \to \gamma\gamma J/\psi$

- Sensitive to the coupling between $c\bar{c}$ and $D\bar{D}$ meson pairs

- E1 transition $\psi(3686) \to \gamma\chi_{cJ} \to \gamma\gamma J/\psi$

	$\mathcal{B}(\times 10^{-4})$	
$\gamma\gamma J/\psi$	$3.1 \pm 0.6^{+0.8}_{-1.0}$	6.6σ
$\gamma(\gamma J/\psi)_{\chi_{c0}}$	$15.1 \pm 0.3 \pm 1.0$	
$\gamma(\gamma J/\psi)_{\chi_{c1}}$	$337.7 \pm 0.9 \pm 18.3$	
$\gamma(\gamma J/\psi)_{\chi_{c2}}$	$187.4 \pm 0.7 \pm 10.2$	

PRL 109,172002



What we do with the new data

$1.06 \times 10^{8}\ \psi(3686)$ 2009

$\sim 3.5 \times 10^{8}\ \psi(3686)$ 2012

$\sim 1 \times 10^{9}\ J/\psi$ data

~ 5 fb^{-1} data above 4.0 GeV

$\Gamma(J/\psi/\psi(3686) \to \gamma\eta_c)$ η_c lineshape

Inclusive

Difficult to deal with the interference

Exclusive

Seems simpler than inclusive method

Need to know a branching ratio in high precision

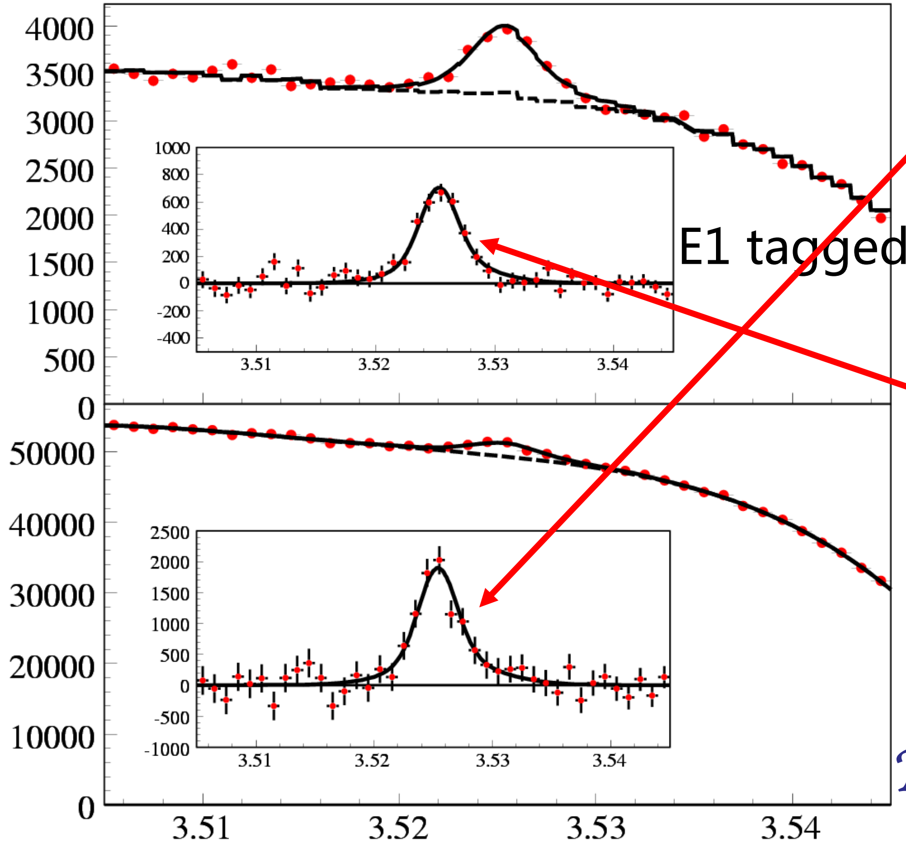
How?

Use $h_c \to \gamma\eta_c$ Seems small interference

inclusive and exclusive

$\psi(3686) \to \pi^0 h_c,\, h_c \to \gamma\eta_c$

PRL 104,132002 $1.06 \times 10^8\ \psi(3686)$ events



Select inclusive π^0 in $\psi(3686)$ decays

Select E1 photon in $h_c \to \gamma\eta_c$ (E1 tagged)

Absolute branching fraction

$$\mathcal{B}(h_c \to \gamma\eta_c) = (54.3 \pm 6.7 \pm 5.2)\%$$

dominated by BKG shape

Will be improved

Now $\psi(3686) \sim 4.5$ times of old datasets.
And ~ 5 fb^{-1} data above 4.0 GeV $\pi\pi h_c$ ~2 times with part of data $\pi^+\pi^- h_c$

PRL 111,242001

Together we have ~9 times h_c signals.

- Measure $\mathcal{B}(h_c \to \gamma\eta_c)$ using inclusive method.
- $\mathcal{B}(\eta_c \to X)$ for 16 exclusive modes. More precise η_c lineshape.

$\mathcal{B}(\eta_c \to K_S^0 K^\pm \pi^\mp) = (2.60 \pm 0.29(stat) \pm 0.34 \pm 0.25(syst))\%$ PRD 86,092009

reduce to one-third

Due to $\mathcal{B}(\psi(3686) \to \pi^0 h_c) \cdot \mathcal{B}(h_c \to \gamma\eta_c)$,
Will be improved

dominant systematic errors

N($\psi(3686)$):	4%	1%
Tracking:	8%	4%
Photon:	3%	
Bkg shape:	4.7%	
Kinematic fit:	6.8%	

More reliable MC

- $\mathcal{B}(J/\psi/\psi(3686) \to \gamma\eta_c)$ using exclusive method. PWA?

Understand the difference.

BESIII

$\Gamma(\psi(3686) \to \gamma\eta_c(2S))$ $\eta_c(2S)$ lineshape

Inclusive

Seems difficult at BESIII, ~ 50 MeV photon

Exclusive

$\mathcal{B}(\eta_c(2S) \to X)$, error > 60% PDG 2014

Difficult to measure $\mathcal{B}(\eta_c(2S) \to X)$ at BESIII

Hope this work will be done at Belle or Babar.

Try to search other transitions of the $\eta_c(2S)$

$\eta_c(2S) \to \pi^+\pi^-\eta_c$

$\eta_c(2S) \to \gamma J/\psi$

$\eta_c(2S) \to \gamma h_c$

Summary

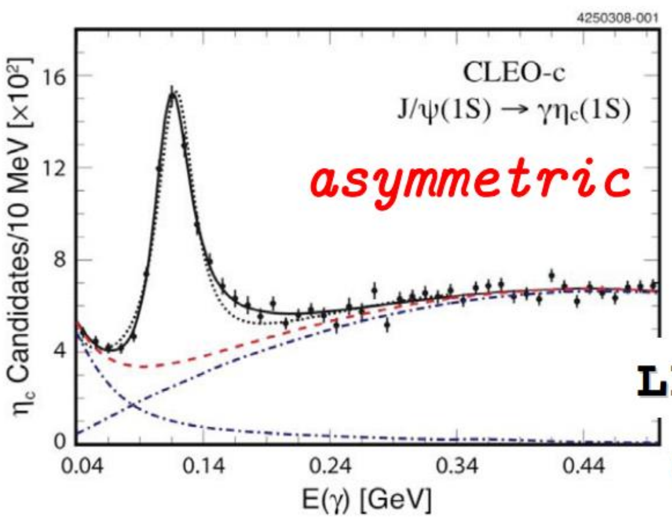
- The η_c parameters are measured through M1 transition of $\psi(3686)$ and E1 transition of h_c. The most accurate measurement.
- First observation of M1 transition $\psi(3686) \to \gamma\eta_c(2S)$.
- First observation of two-photon transition $\psi(3686) \to \gamma\gamma J/\psi$.
- We can measure $\Gamma(J/\psi/\psi(3686) \to \gamma\eta_c)$ more precisely with new data.

More results will come out.

Back-up

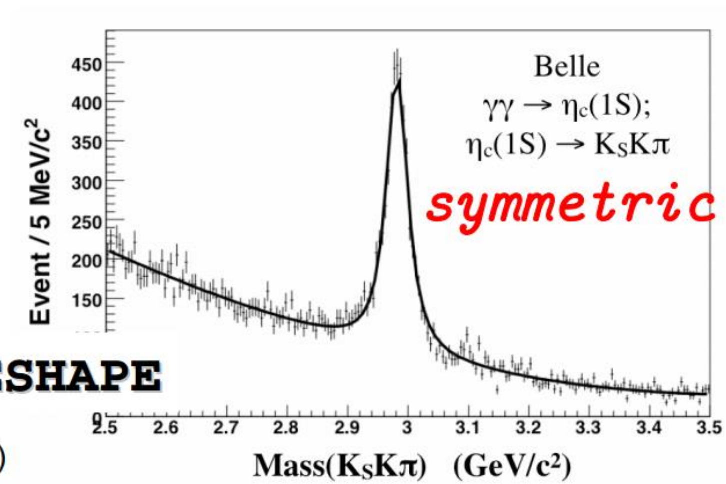
η_c, lightest charmonium state

- Large uncertainties compared to other charmonium states.
- Big difference between different measurements ($\gamma\gamma$ fusion, B decays $\cdots$)
- Distortion of η_c line-shape in $\psi(3686) \to \gamma\eta_c$ compared with $J/\psi \to \gamma\eta_c$
- 1S Hyperfine splitting.



LINESHAPE

(IHEP)



- Use 1.06×10^8 $\psi(3686)$ events.
- Full interference between $\gamma\eta_c$ and non-resonant $\psi(3686)$ radiative decay.
- Six modes to reconstruct the η_c:
  $K_S K^+\pi^-$, $K^+K^-\pi^0$, $\eta\pi^+\pi^-$,
  $K_S K^+\pi^+\pi^-\pi^-$, $K^+K^-\pi^+\pi^-\pi^0$, $3(\pi^+\pi^-)$.

$$F(m) = \sigma \otimes \left[\epsilon(m)\left|e^{i\phi}\underline{E_\gamma^{7/2}S(m)} + \underline{\alpha N(m)}\right|^2\right] + B(m)$$

resolution

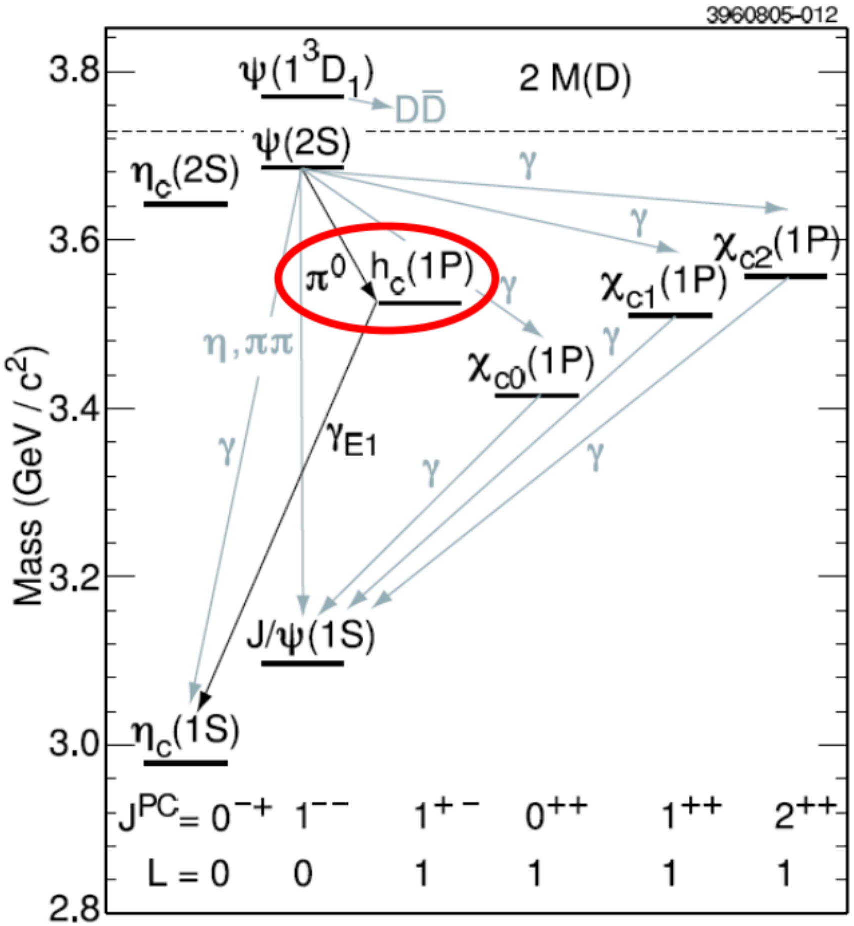
Interference phase

Non-resonant component

Mass-dependent efficiency

Hindered M1 transition

h_c E1 transition to η_c



Huge interference in $\psi(3686) \rightarrow \gamma\eta_c$

The η_c amplitude in h_c decays is much larger than in $\psi(3686)$ decay.

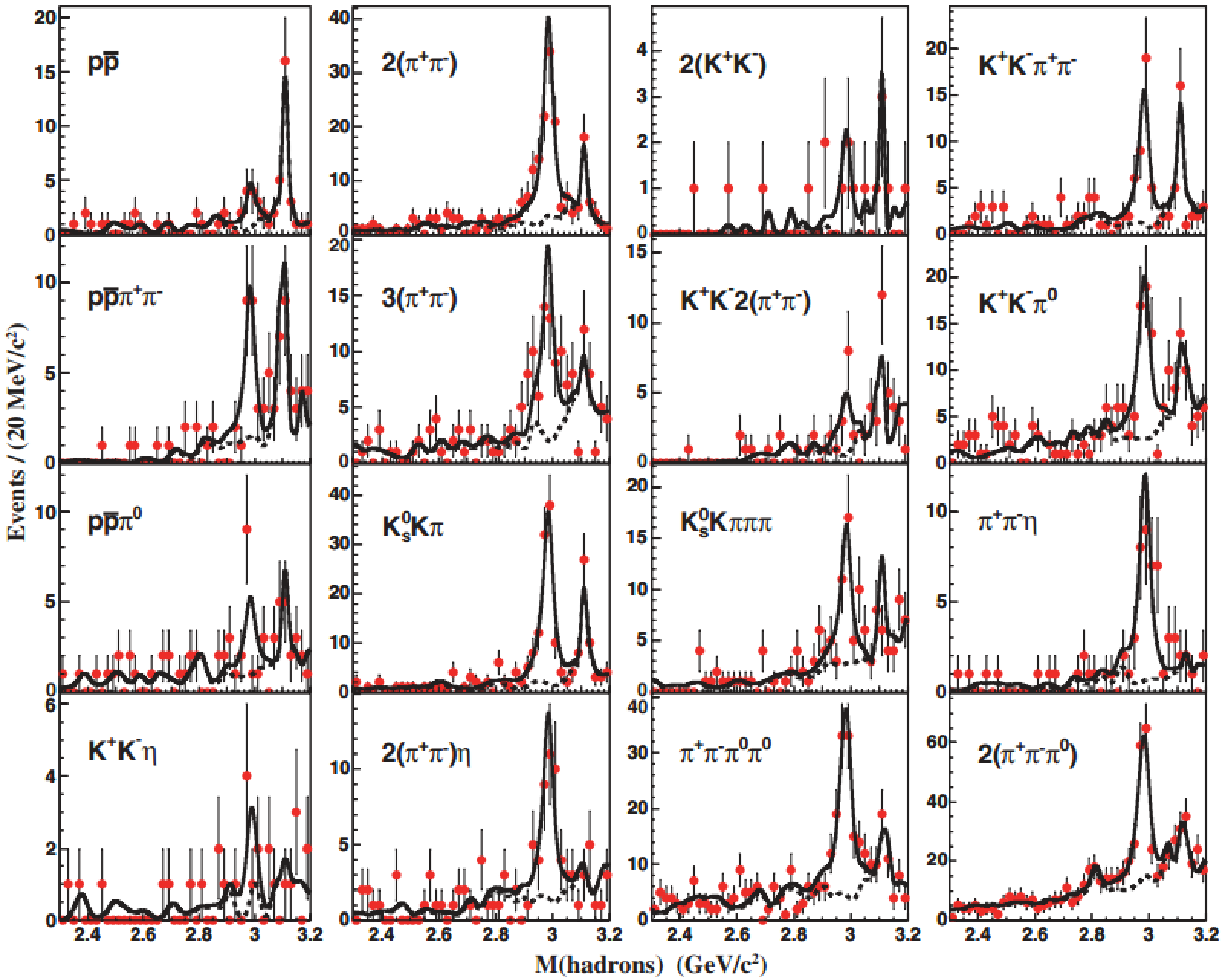
Interference term in $h_c \rightarrow \gamma\eta_c$ is much Smaller than that in $\psi(3686) \rightarrow \gamma\eta_c$

Means η_c line-shape from h_c E1 transition can be measured easier and better than $\psi(3686)$?

Branching ratio of $h_c \rightarrow \gamma\eta_c$

$\psi(3686) \to \pi^0 h_c, h_c \to \gamma\eta_c$, 16 η_c exclusive decays

PRD 86,092009



Simultaneous fit to combine 16 η_c decay modes.

$\eta_c(2S)$ signal:

$$\left[E_\gamma^3 \times BW(m) \times f_d\left(E_\gamma\right) \times \epsilon(m)\right] \otimes G(\delta m, \sigma)$$

M1 transition

For convergence

Mass shift and detector resolution, fixed to linear extrapolation from $\gamma\chi_{cJ}$

χ_{cJ}: MC shape $\otimes$ Gaussian, fixed

Background:

$e^+e^- \to KK\pi(\gamma_{ISR/FSR})$, MC shape, normalized to the measurements with data

$e^+e^- \to \pi^0 KK\pi$, Novosibirsk function, measured with data and fixed

ωK^+K^- for $K^+K^-\pi^0$ mode, double Gaussian, measured with data and fixed.

The first observation of the M1 transition $\psi(3686) \to \gamma\eta_c(2S)$

- First observed by Belle in the process $B^+ \to K^\pm \eta_c(2S)$, $\eta_c(2S) \to K_S^0 K^\pm \pi^\mp$, confirmed in two-photon production and double-charmonium production.
- Experimental challenge: search for real photon **~50MeV**.
- The branching ratio $\mathcal{B}\big(\psi(3686) \to \gamma\eta_c(2S)\big)$ is predicted to be in $(0.1 - 6.2) \times 10^{-4}$
- Chance with 1.06×10^8 $\psi(3686)$ data at BESIII.
- Two modes: $\eta_c(2S) \to K_S^0 K^\pm \pi^\mp$, $K^+ K^- \pi^0$

- Lightest charmonium state above open charm threshold, assigned to be a dominant 1^3D_1 with a small 2^3S_1 admixture.

- Non-$D\bar{D}$ branching fraction,
  $(14.7 \pm 3.2)\%$ by BESIII, $(-3.3 \pm 1.4^{+6.6}_{-4.8})\%$ by CLEO

- Exclusive modes:
  Hadronic transition: $\pi\pi J/\psi$, $\eta J/\psi$, E1 radiative transition $\gamma\chi_{cJ}(J=0,1)$

What about $\gamma\eta_c/\eta_c(2S)$?

$\mathcal{B}(\psi(3770) \to \gamma\eta_c) = (6.3^{+8.4}_{-4.4}) \times 10^{-4}$, $\mathcal{B}\big(\psi(3770) \to \gamma\eta_c(2S)\big) = (6.7^{+7.2}_{-4.4}) \times 10^{-5}$

Consider the intermediate meson loop (IML). (PRD 84,074005)

Background:

- $e^+e^- \to \pi^0 K_S^0 K^\pm \pi^\mp$, measured with data and fixed
- $e^+e^- \to (\gamma_{ISR}/\gamma_{FSR}) K_S^0 K^\pm \pi^\mp$, fixed,
  using Born cross section of $e^+e^- \to K_S^0 K^\pm \pi^\mp$ by BABAR.
- Tail of the $\psi(3686)$, including $\gamma_{ISR}\psi(3686), \psi(3686) \to \gamma X$

$$N^b_{\psi(3686)} = \sigma(s) \times \mathcal{L} \times \epsilon \times \mathcal{B}$$

$$\sigma(s) = \int_0^{x_{cut}} W(s,x) \cdot BW\big(s'(x)\big) \cdot F_x\big(s'(x)\big) dx$$

ISR γ-emission probability

Relativistic

Phase space factor