Charmonium radiative transitions

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(for the BESIII collaboration)

- What we want to measure
- What we have done
- What we will do

What we want to measure

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

PDG2014: 1.58 ± 0.37 keV   Lattice QCD 2.49 ± 0.19 keV

Error is large   PRD 86,094501

η_c lineshape

Big difference between different measurements

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

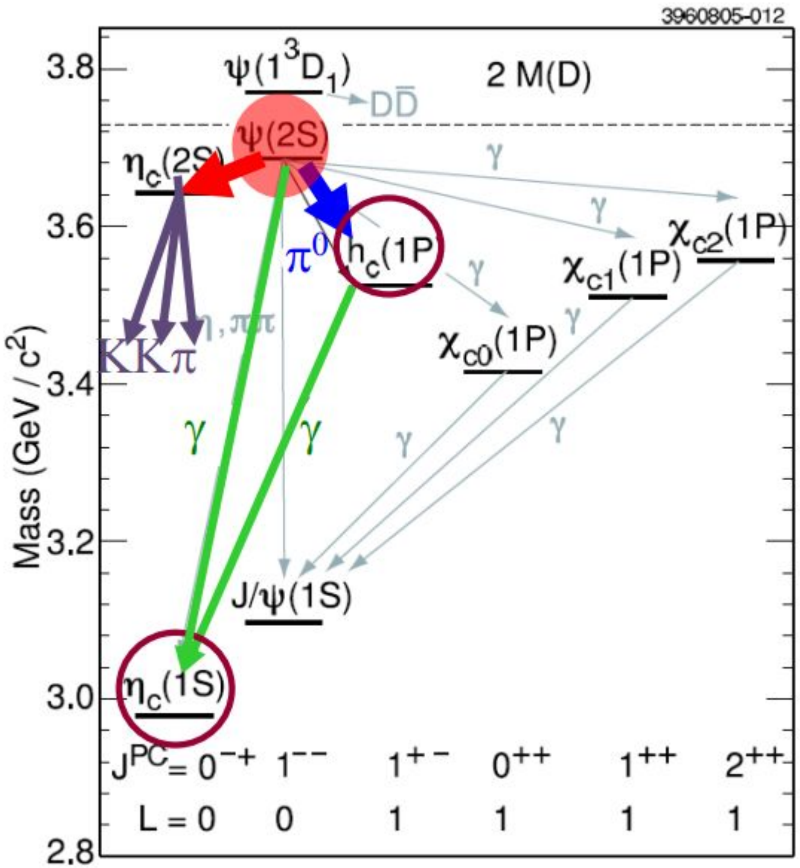
$\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S))$

$(7 \pm 2 \pm 4) \times 10^{-4}$ (PDG2014),
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),

What we have done



- η_c line-shape
  - $\psi(3686)$ M1 transition
  - h_c E1 transition
- M1 transition $\psi(3686) \to \gamma\eta_c(2S)$ first observation
- $\psi(3770) \to \gamma\eta_c/\eta_c(2S)$

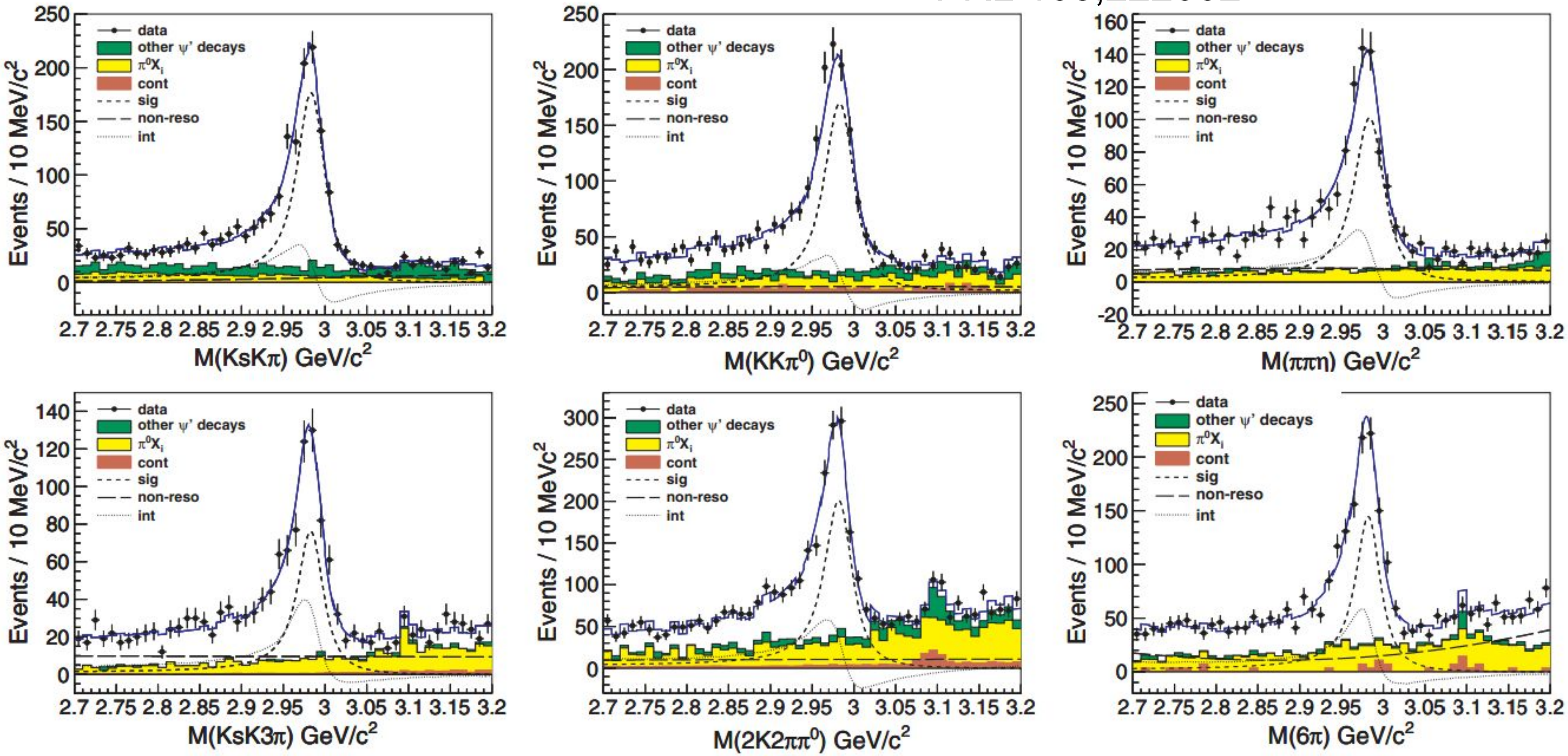
What we used

106 M $\psi(3686)$ data

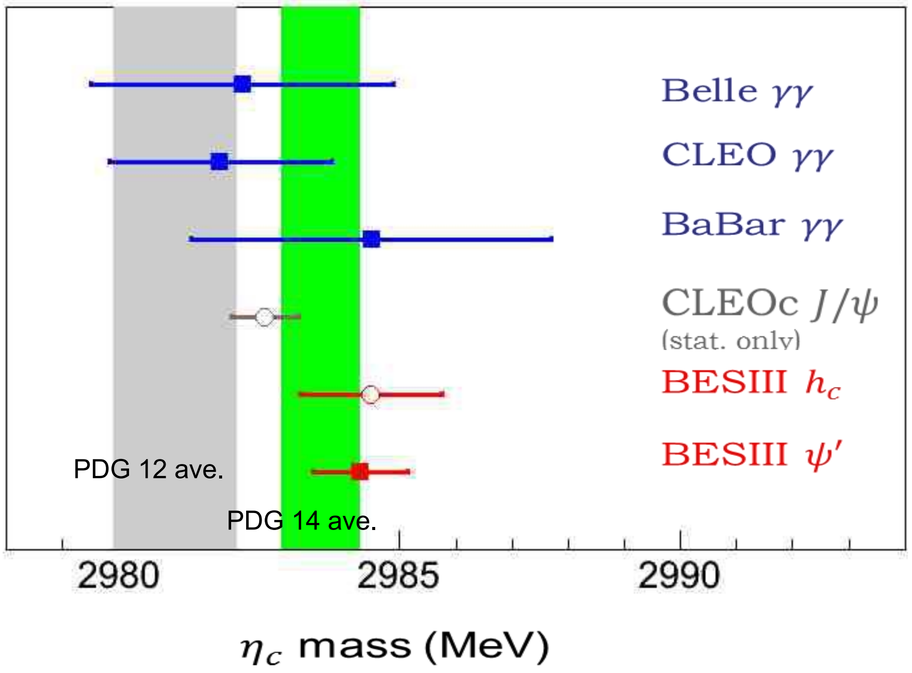
2.92 fb^{-1} $\psi(3770)$ data.

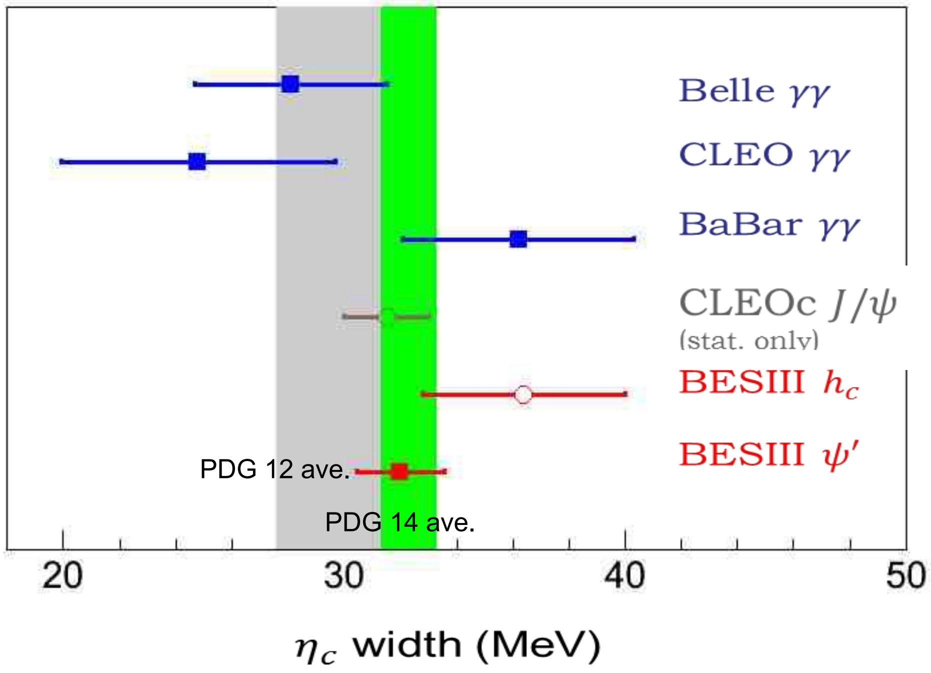
$\psi(3686) \to \gamma\eta_c$

PRL 108,222002



Simultaneous fit with modified Breit-Wigner (hindered M1).
Significance of interference is of order 15σ.
(may partly clarify the discrepancy puzzle)





mass = $2984.3 \pm 0.6 \pm 0.6$ MeV/c^2
width = $32.0 \pm 1.2 \pm 1.0$ MeV
Relative phases are consist with each other within 3σ.

$2983.9 \pm 0.6 \pm 0.6$ MeV/c^2
$31.3 \pm 1.2 \pm 0.9$ MeV
$\phi = 2.40 \pm 0.07 \pm 0.47$ rad
The phases are constrained to be same

Suggest a common phase in all the modes.

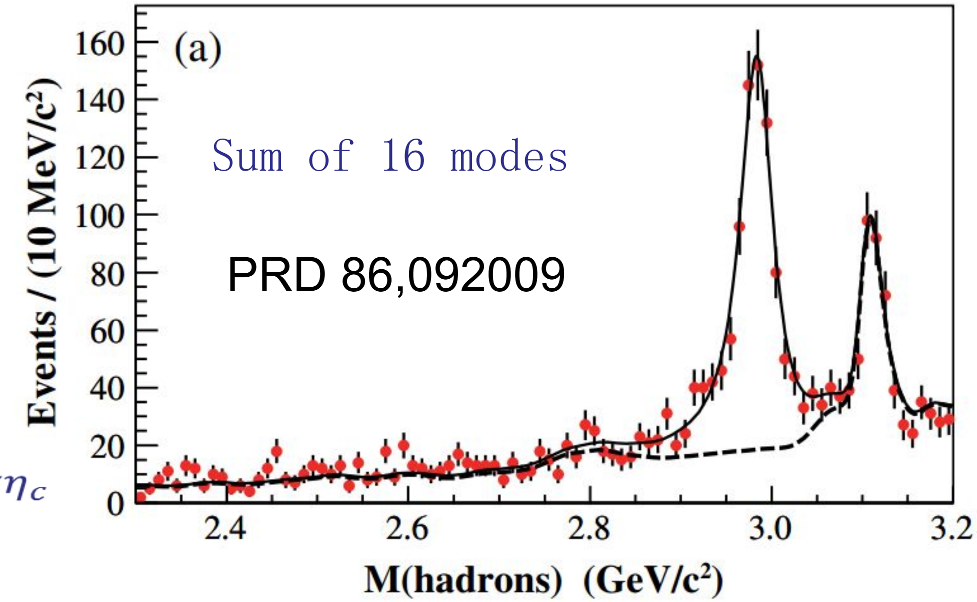
h_c E1 transition to η_c

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

Energy of photon in rest frame of h_c

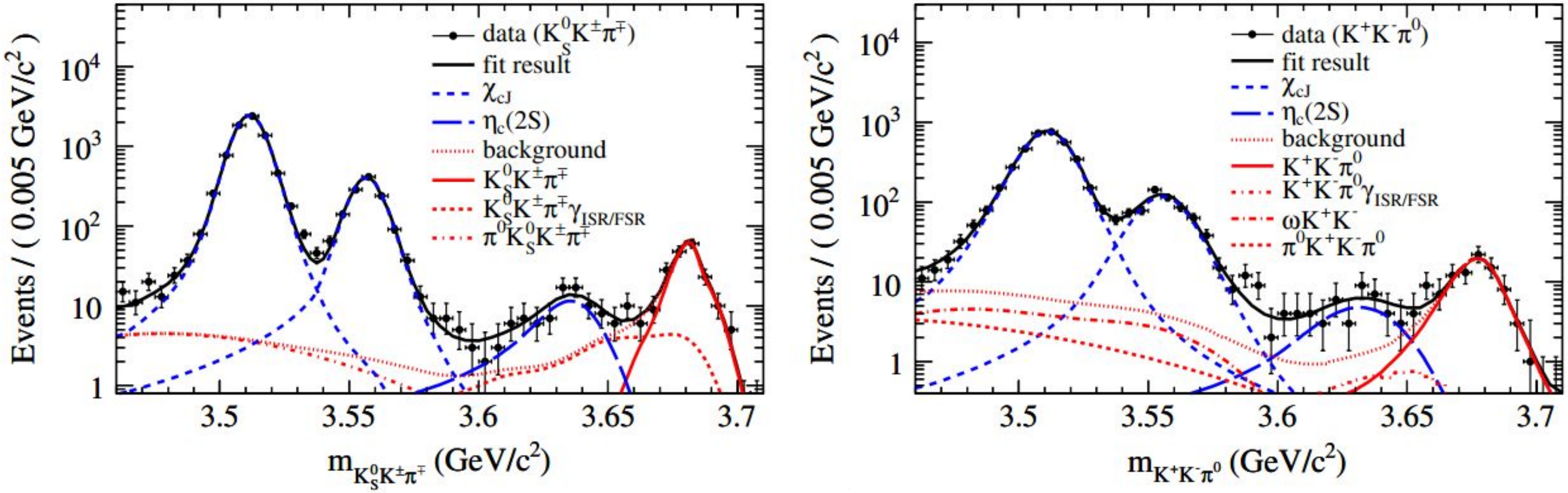
For convergence

Resolution for ith mode

$$M(\eta_c) = 2984.40 \pm 1.16 \pm 0.52 \ \mathrm{MeV}/c^2$$
$$\Gamma(\eta_c) = 36.4 \pm 3.2 \pm 1.7 \ \mathrm{MeV}/c^2$$

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

PRL 109,042003



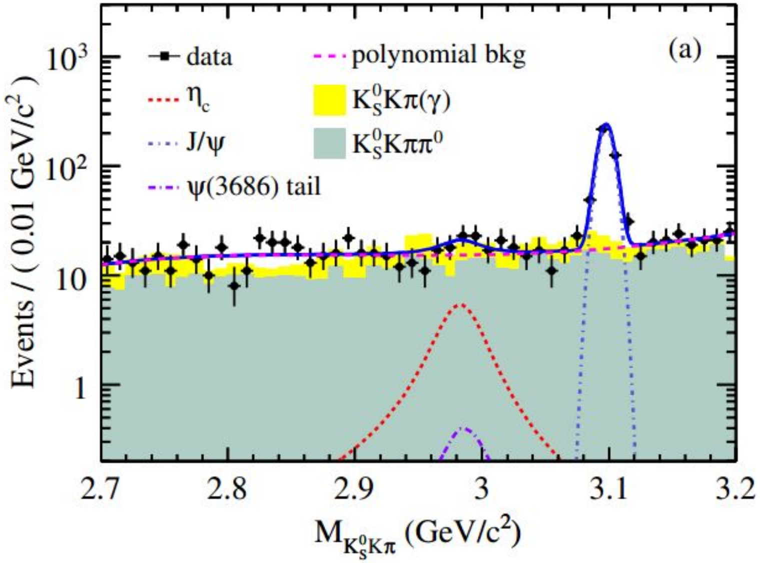
Significance larger than 10σ

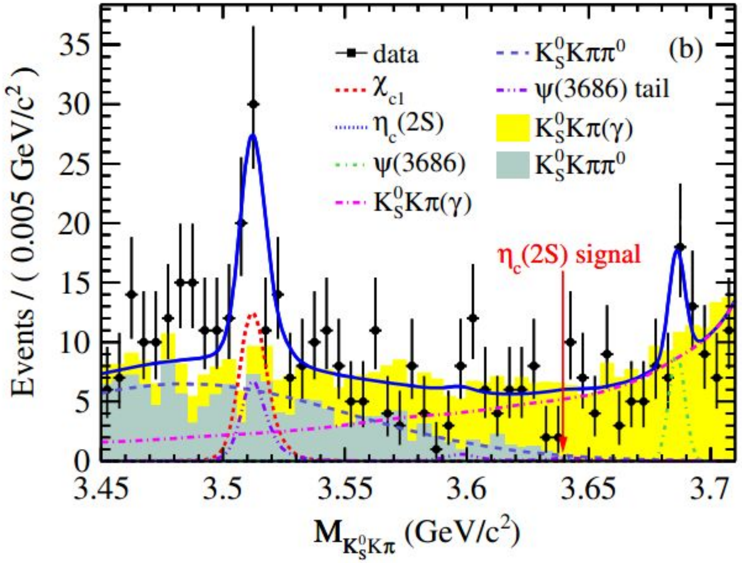
$$M_{\eta_c(2S)} = 3637.6 \pm 2.9 \pm 1.6\ \text{MeV}/c^2$$
$$\Gamma_{\eta_c(2S)} = 16.9 \pm 6.4 \pm 4.8\ \text{MeV}$$

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

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

Search for radiative transitions $\psi(3770) \to \gamma\eta_c$ and $\psi(3770) \to \gamma\eta_c(2S)$





This work PRD 89,112005

$\mathcal{B}(\psi(3770) \to \gamma\eta_c) < 6.8 \times 10^{-4}$ $\mathcal{B}(\psi(3770) \to \gamma\eta_c(2S)) < 2.0 \times 10^{-3}$

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

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

What we will do

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

$\sim 3.5 \times 10^8\ \psi(3686)$ 2012,
(under data quality check, will be available soon))

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

$\sim 5\ \mathrm{fb}^{-1}$ 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

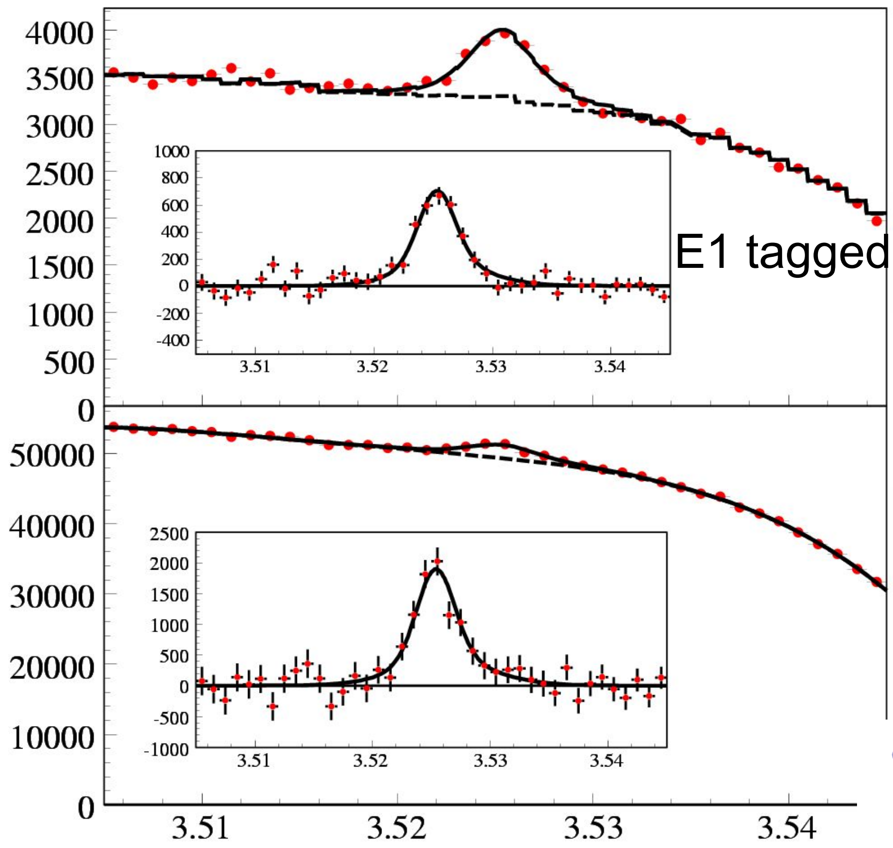
How?

Use $h_c \to \gamma\eta_c$ Seems no interference

inclusive and exclusive

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

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



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.

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 yield .

- 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(ψ(3686)):	4%	1%
Tracking:	8%	4%
Photon:	3%	1%
Bkg shape:	4.7%	More reliable
Kinematic fit:	6.8%	MC

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

Understand the difference.

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

$\eta_c(2S)$ lineshape

Inclusive

Seems impossible at BESIII, $\sim$ 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.

Transition from $\eta_c(2S)$ Theoretical predictions

$$\mathcal{B}(\eta_c(2S) \to \pi^+\pi^-\eta_c) = (5 - 10)\%$$

$$\mathcal{B}(\eta_c(2S) \to \gamma J/\psi) = 7 \times 10^{-4}$$

$$\mathcal{B}(\eta_c(2S) \to \gamma h_c) = 4 \times 10^{-3}$$

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 $\psi(3686) \to \gamma\eta_c(2S)$
- The upper limit on branching ratio of $\psi(3770) \to \gamma\eta_c(\eta_c(2S))$.

We can measure $\Gamma(J/\psi/\psi(3686) \to \gamma\eta_c)$ more precise.

More result will come out.

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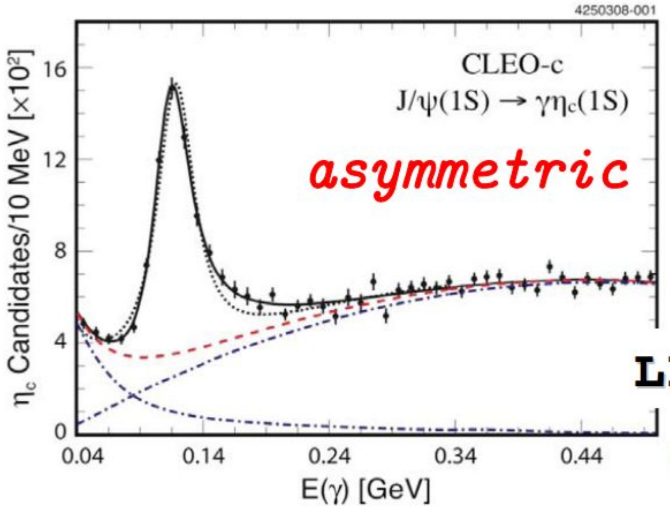
Back-up

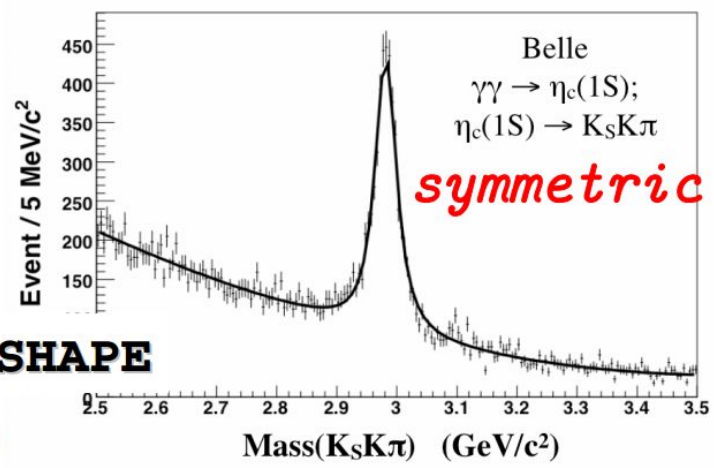
η_c, lightest charmonium state

- 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:
  $K_S K^+ \pi^-$, $K^+ K^- \pi^0$, $\eta\pi^+\pi^-$,
  $K_S K^+ \pi^+ \pi^- \pi^-$, $K^+ K^- \pi^+ \pi^- \pi^0$, $3(\pi^+\pi^-)$.

$$F(m) = \sigma \otimes \left[\epsilon(m) \left| e^{i\phi} \underbrace{E_\gamma^{7/2} S(m)}_{\text{Hindered M1 transition}} + \underbrace{\alpha N(m)}_{\text{Non-resonant component}} \right|^2 \right] + B(m)$$

resolution

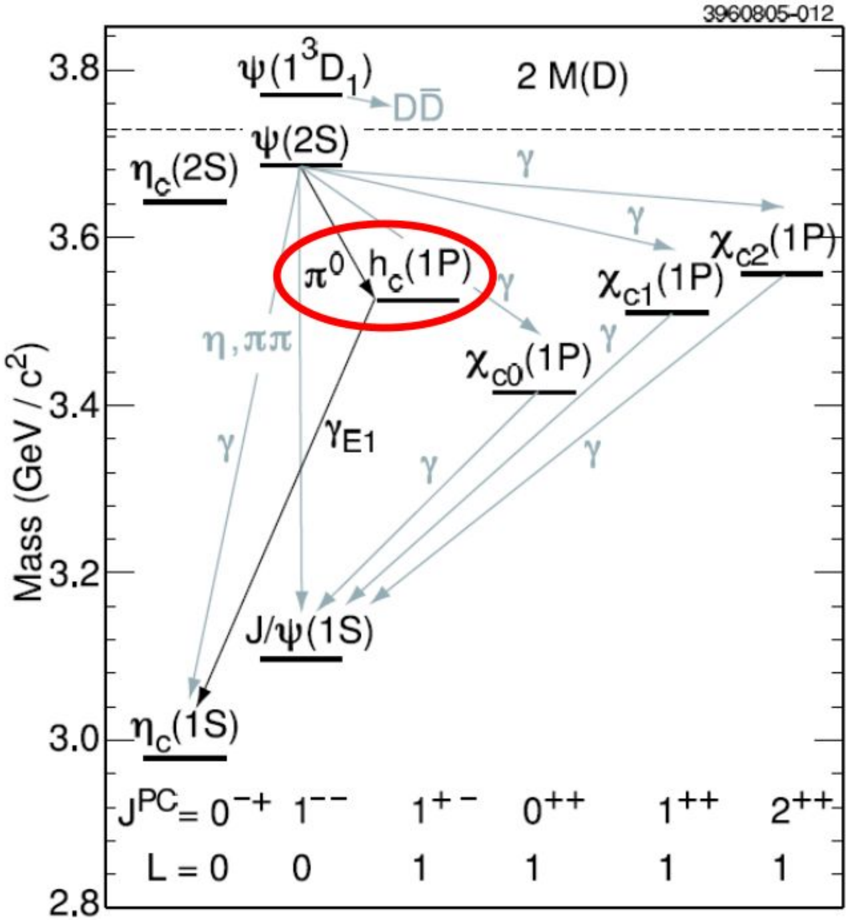
Interference phase

Non-resonant component

Mass-dependent efficiency

Hindered M1 transition

h_c E1 transition to η_c



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

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

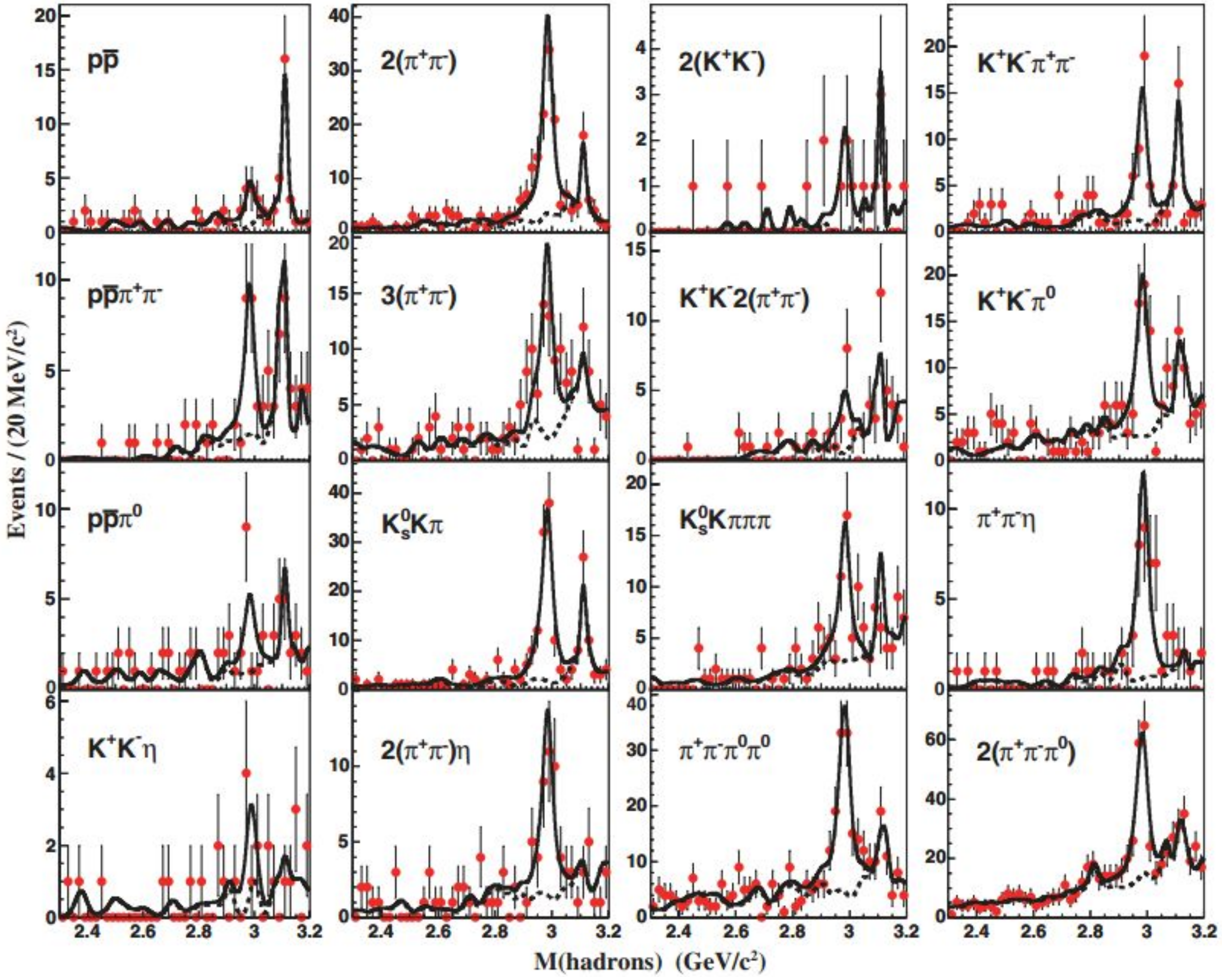
Interference term in $h_c \to \gamma\eta_c$ is much Smaller than that in $\psi(3686) \to \gamma\eta_c$

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

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

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

PRD 86,092009



Simultaneous fit to combine 16 η_c decay modes.

$\eta_c(2S)$ signal:

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

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

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