Observation of $\eta_c \to \gamma\gamma$ in $J/\psi \to \gamma\eta_c$

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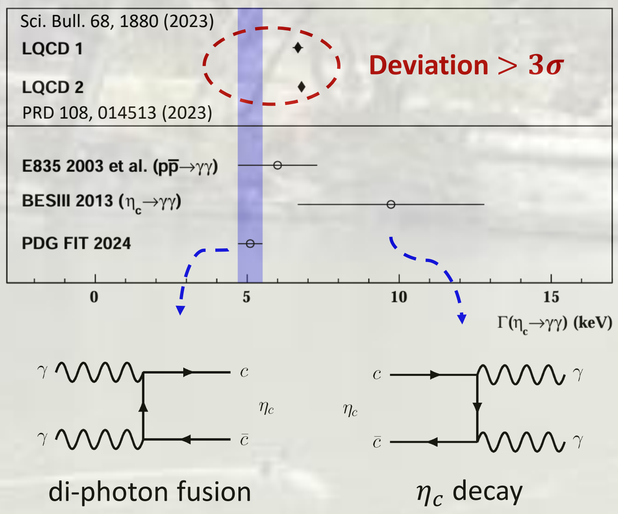
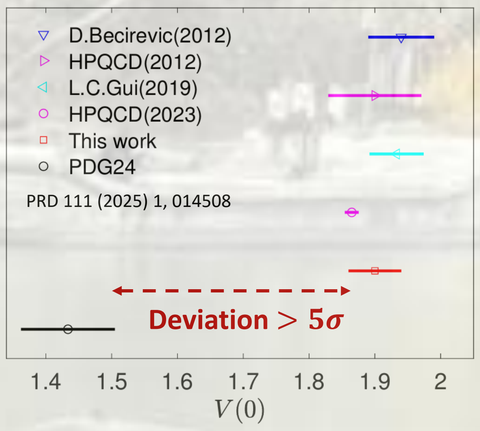
1. INTRODUCTION

- **QCD puzzles in charmonium decay** $\eta_c \to \gamma\gamma$ and $J/\psi \to \gamma\eta_c$





$$|V(0)|^2 \propto \Gamma(J/\psi \to \gamma\eta_c)$$

The decay width $\eta_c \to \gamma\gamma$ is determined by both strong and electromagnetic interaction:

$$\Gamma(\eta_c \to \gamma\gamma) = \pi\alpha^2 Q_c^4 M_{\eta_c} F^2$$

EM interaction

Strong interaction of charm quarks

Experimentally, $\Gamma(\eta_c \to \gamma\gamma)$ is dominated by di-photon fusion indirect measurement, while the direct measurements have a large uncertainty.

- This work: Measure $\eta_c \to \gamma\gamma$ in $J/\psi \to \gamma\eta_c$ with the new 2.7×10^9 $\psi(2S)$ data at BESIII

2. BEPCII AND BESIII EXPERIMENT

Beijing Spectrometer III (BESIII) is a general-purpose spectrometer working at the Beijing Electron Positron Collider II (BEPCII) and has collected large data in $\tau - c$ energy region.

Main drift chamber (MDC)
- $\Delta P/P = 0.5\%, dE/dx \sim 6\%$

Time-of-Flight system (TOF)
- $\sigma_T = 60 \sim 68$ ps

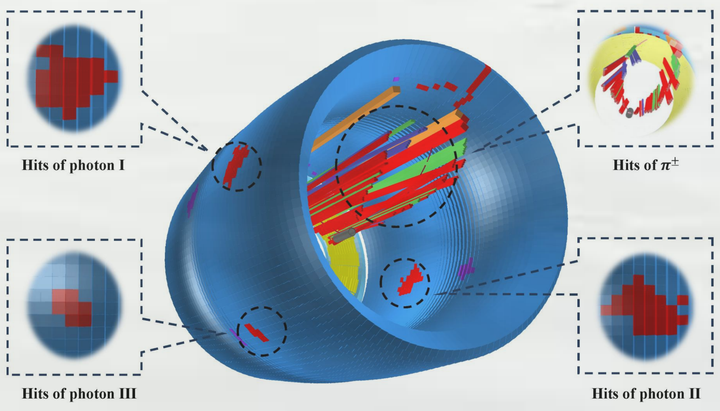
Electromagnetic Calorimeter (EMC)
- $\Delta E/E = 2.5\% \sim 5.0\%$

Muon chamber system (MUC)
- $\sigma_{z,\phi} = 2$ cm

Fig.1 (left) Beijing Electron Positron Collider II (BEPCII). (right) Beijing Spectrometer III (BESIII).

3. EVENT SELECTIONS

- Decay chain: $e^+e^- \to \psi(2S)$, $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma\eta_c, \eta_c \to \gamma\gamma$
- Select two charged Pions and three photons in the final states

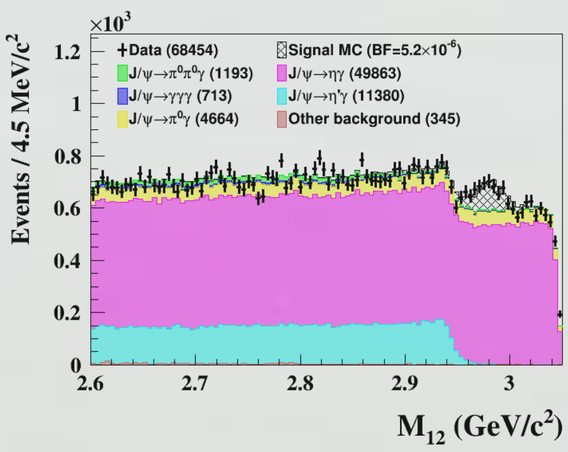


- Why using $\pi^+\pi^- J/\psi$?
- To avoid the huge background from $e^+e^- \to \gamma\gamma\gamma$

Fig.2 An event display of $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma\eta_c, \eta_c \to \gamma\gamma$ from MC simulation

4. BACKGROUND SUPPRESSION

- Main background: $J/\psi \to \gamma\pi^0/\eta/\eta', \pi^0/\eta/\eta' \to \gamma\gamma$
- Veto $\pi^0/\eta/\eta'$ backgrounds in the di-photon invariant mass for the two combinations



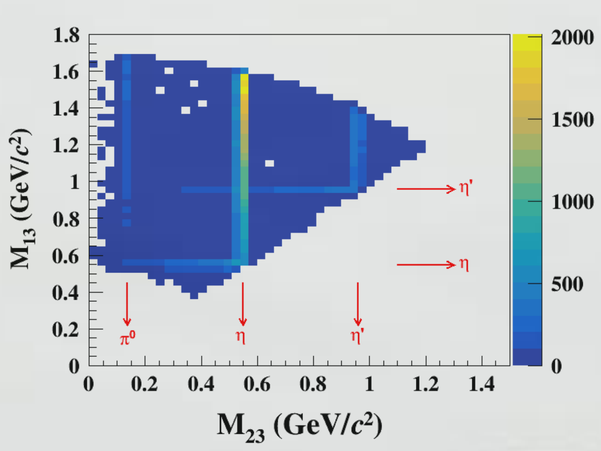


Fig.3 (left) The invariant mass distribution of the two high energy photons. (right) The invariant mass distribution of the other two photon combinations

5. SIGNAL EXTRACTION

The signal yield is extracted from an unbinned extended maximum likelihood fit on the $m_{\gamma\gamma}$ distribution. The signal shape is described with

$$\mathcal{F}(m) = \left[\epsilon(m) \times E_\gamma^3(m) \times f_{damp}(m) \times |BW(m)|^2\right] \otimes G(\mu, v)$$

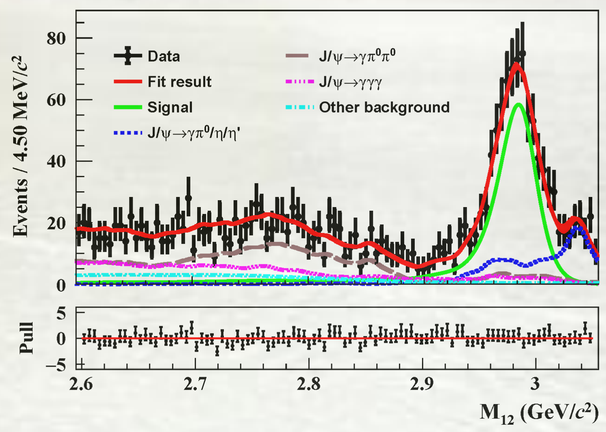
Mass-dependent efficiency

M1 transition form factor

Damping factor

Breit Wigner function

Detector resolution



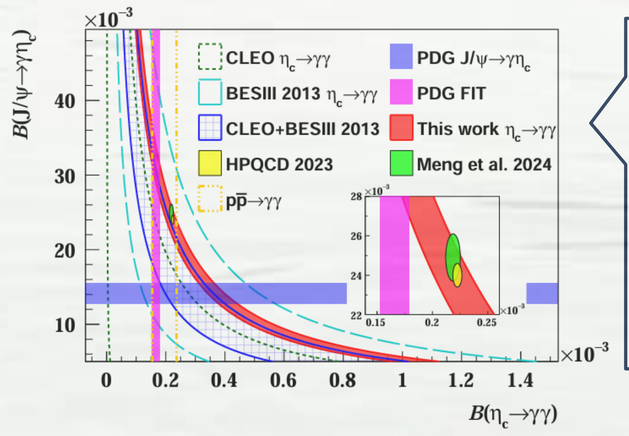
Source	Uncertainty (%)
Tracking	0.6
PID	0.5
Photon detection	1.5
$M^{\text{recoil}}_{\pi^+\pi^-}$ requirement	0.2
N_γ requirement	0.8
χ^2_{4C} requirement	2.9
Veto cuts	0.7
Lineshape of η_c	3.6
Background shape	0.2
Background yield	2.7
Total number of $\psi(3686)$ events	0.5
$\mathcal{B}(\psi(3686) \to \pi^+\pi^- J/\psi)$	1.0
Total	5.8

Fig.4 (left) The signal extraction in $m_{\gamma\gamma}$ distribution. (right) The systematic uncertainty in the BF measurement.

6. BRANCHING FRACTION

The signal yield is determined to be $N_{\text{sig}} = 677.7 \pm 33.5$. The product branching fraction of $J/\psi \to \gamma\eta_c$ and $\eta_c \to \gamma\gamma$ is calculated by

$$\mathcal{B}(J/\psi \to \gamma\eta_c) \times \mathcal{B}(\eta_c \to \gamma\gamma) = \frac{N_{\text{sig}}/\epsilon_{\text{sig}}}{N_{\psi(2S)} \times \mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi)}$$
$$= (5.23 \pm 0.26_{\text{stat.}} \pm 0.30_{\text{syst.}}) \times 10^{-6}$$



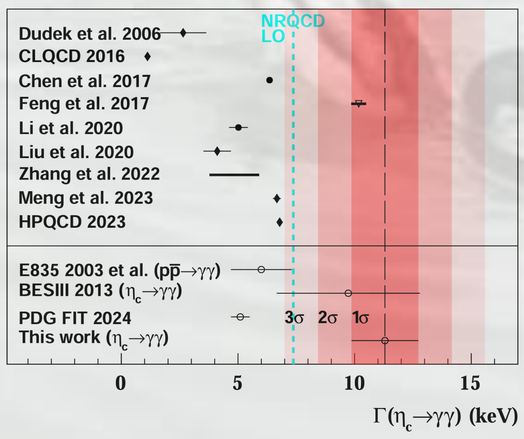
- Consistent with the previous evidences of $J/\psi \to \gamma\eta_c, \eta_c \to \gamma\gamma$
- Consistent with the two newest LQCD calculations
- Do not simultaneously align with the two PDG average values

Fig.5 The comparison of $\mathcal{B}(\eta_c \to \gamma\gamma)$ versus $\mathcal{B}(J/\psi \to \gamma\eta_c)$ within 1σ confidence level.

7. DECAY WIDTH

The decay width of $\eta_c \to \gamma\gamma$ is calculated by using $\mathcal{B}(J/\psi \to \gamma\eta_c) = (1.41 \pm 0.14)\%$ and $\Gamma_{\eta_c} = (30.5 \pm 0.5)$ MeV from PDG

$$\Gamma(\eta_c \to \gamma\gamma) = \frac{\mathcal{B}(J/\psi \to \gamma\eta_c) \times \mathcal{B}(\eta_c \to \gamma\gamma)}{\mathcal{B}^{\text{PDG}}(J/\psi \to \gamma\eta_c)} \times \Gamma_{\eta_c}^{\text{PDG}}$$
$$= \left(11.30 \pm 0.56_{\text{stat.}} \pm 0.66_{\text{syst.}} \pm 1.14_{\text{ref.}}\right) \text{keV}$$



- Consistent with the NNLO corrections of NRQCD
- Deviating from other calculations by more than 3σ
- Deviating from PDG average value by more than 3σ

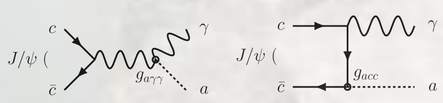
New Puzzle

Fig.6 The comparison of $\Gamma(\eta_c \to \gamma\gamma)$ between different measurements and different calculations.

➢ Why new puzzles?

- The current average values of either $\eta_c \to \gamma\gamma$ or $J/\psi \to \gamma\eta_c$ may not be fully reliable
- Something unknown beyond the SM

arXiv: 2506.04144 proposes an ALP weakly coupling to light quark but sizable coupling to heavy (charm) quark can explain the deviation between our value and PDG value



8. SUMMARY

- The new measurement of $\eta_c \to \gamma\gamma$ in $J/\psi \to \gamma\eta_c$ alleviates the previous QCD puzzles
- But also create a new puzzles of the deviation with PDG average value
- Need further individual measurements for $\eta_c \to \gamma\gamma$ and $J/\psi \to \gamma\eta_c$

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