Charmonium Decays at

BESIII

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(on behalf of the BESIII collaboration)

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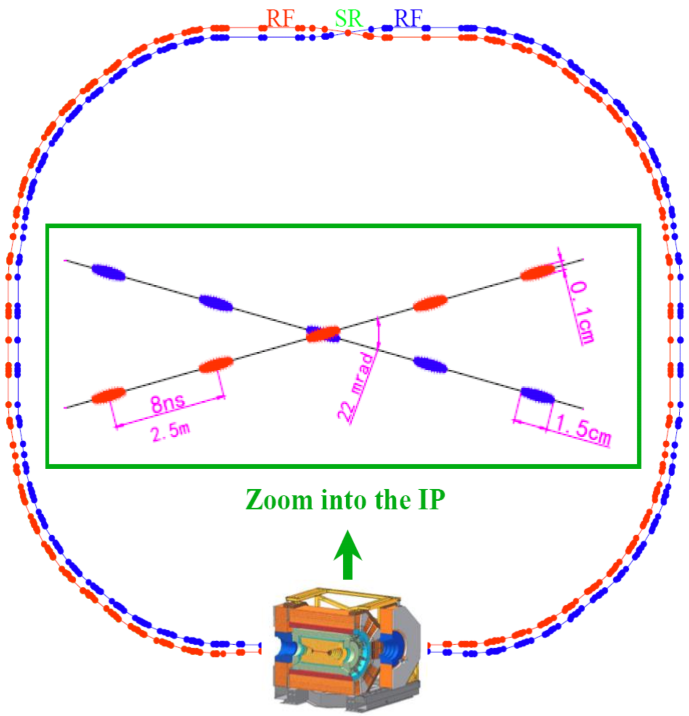
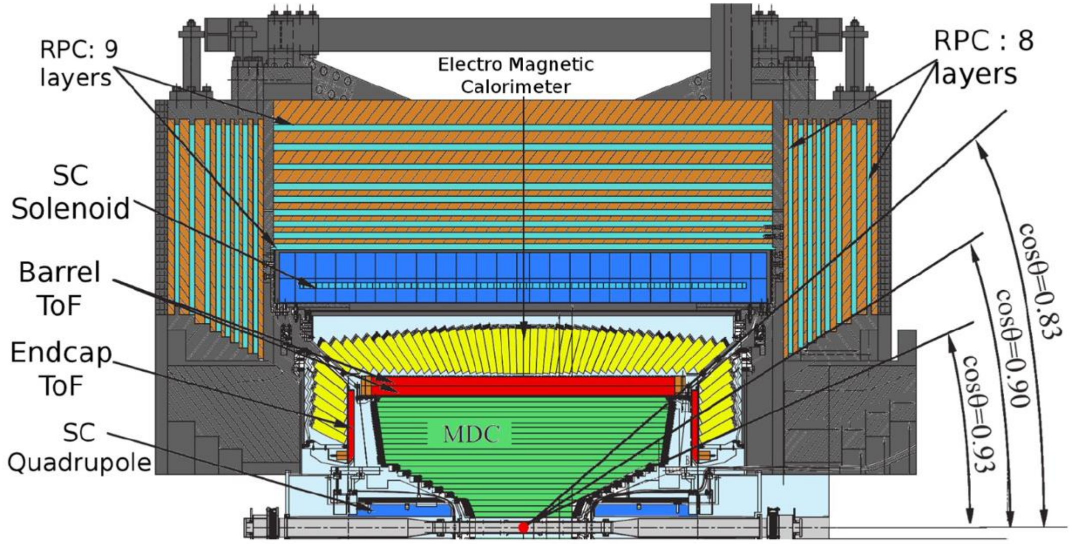
The BESIII detector at BEPCII collider





MDC
$\frac{\delta p}{p} < 0.5\%$ @1 GeV
$\frac{\delta(dE/dx)}{dE/dx} < 6\%$

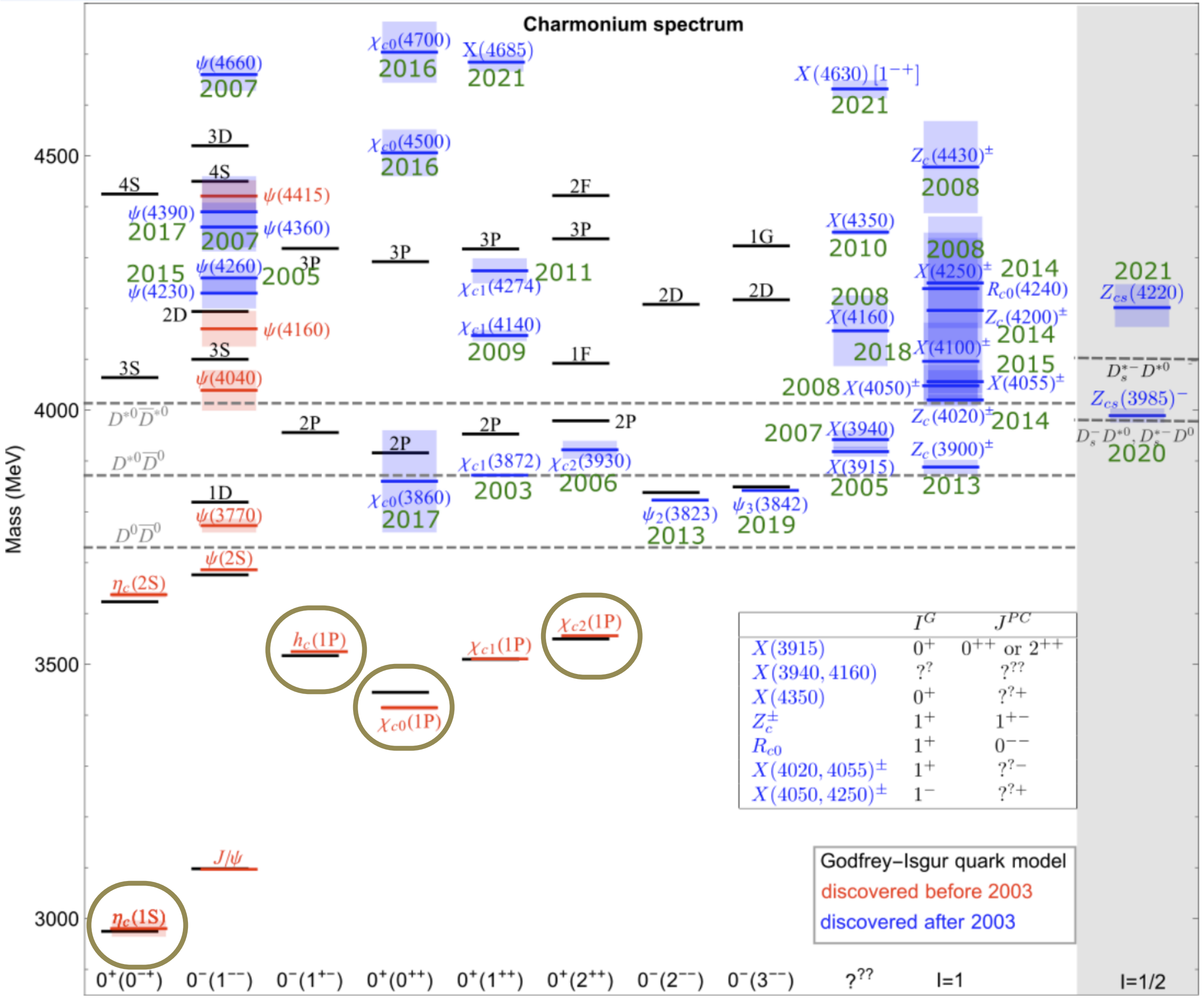
TOF
δt 80 ps Barrel
δt 110(60)ps Endcap

EMC
$\frac{\delta E}{E} < 2.5\%$ @1 GeV
$\delta z = 0.6/\sqrt{E}$

MUC
$\delta(xy)$ <2 cm

- Double-ring multi-bunch e^+e^- collider (2×93)
- Luminosity reached $1.1\text{x}10^{33}\text{cm}^{-2}\text{s}^{-1}$ (10% higher than the design value) in 2022
- Beam energy: $1.0 - 2.5$ GeV
- Circumference: 237m

Charmonium Spectroscopy



	I^G	J^{PC}
$X(3915)$	0^+	0^{++} or 2^{++}
$X(3940, 4160)$	$?^?$	$?^{??}$
$X(4350)$	0^+	$?^{?+}$
$Z_c^{\pm}$	1^+	1^{+-}
R_{c0}	1^+	0^{--}
$X(4020, 4055)^{\pm}$	1^+	$?^{?-}$
$X(4050, 4250)^{\pm}$	1^-	$?^{?+}$

Godfrey–Isgur quark model
discovered before 2003
discovered after 2003

From F. K. Guo

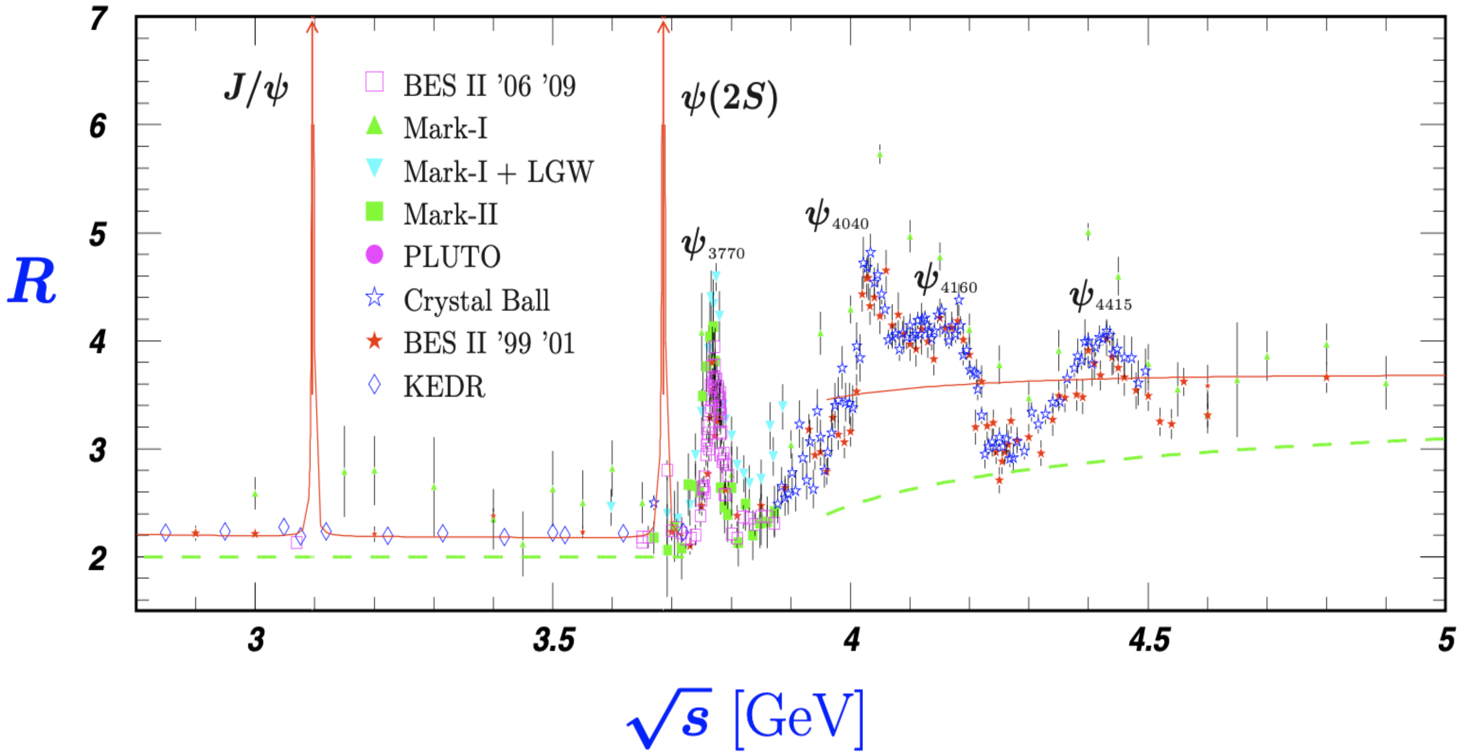
Charmonium resonances are located in the transition region of perturbative and non-perturbative QCD.

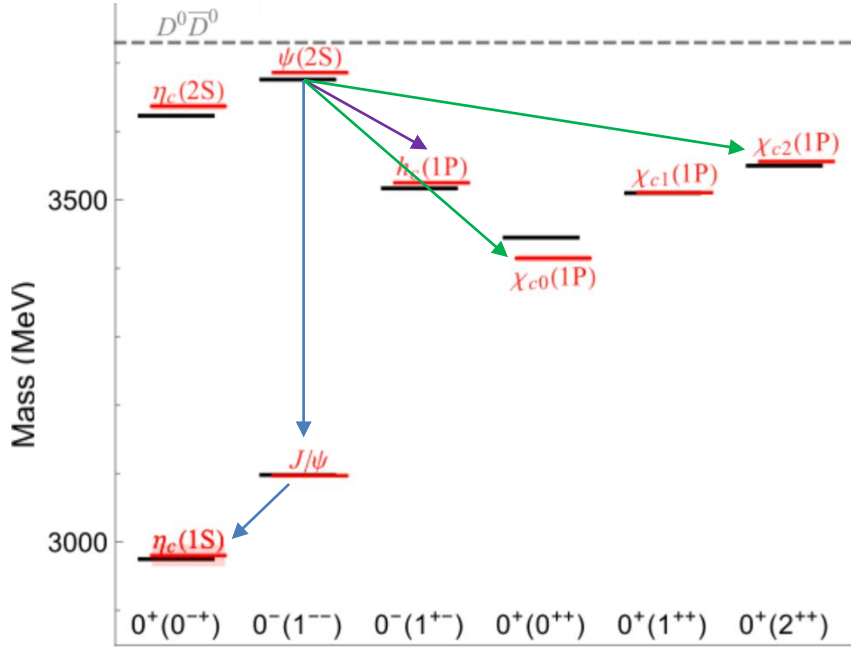
Testing theoretical predictions with experimental observations in the low energy regime of QCD

Charmonium decays highlighted in this talk

- $h_c \to \gamma X, X = \pi^+\pi^-, \pi^+\pi^-\eta, 2(\pi^+\pi^-), p\bar{p}$
- $\chi_{c0,c2} \to \pi^+\pi^-/K^+K^-$
- $\eta_c \to \gamma\gamma$

$\psi(2S)$ samples at BESIII





- $\psi(2S) \to \pi^0 \boldsymbol{h_c}$
- $\psi(2S) \to \gamma \boldsymbol{\chi_{c0,c2}}$
- $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma \boldsymbol{\eta_c}$

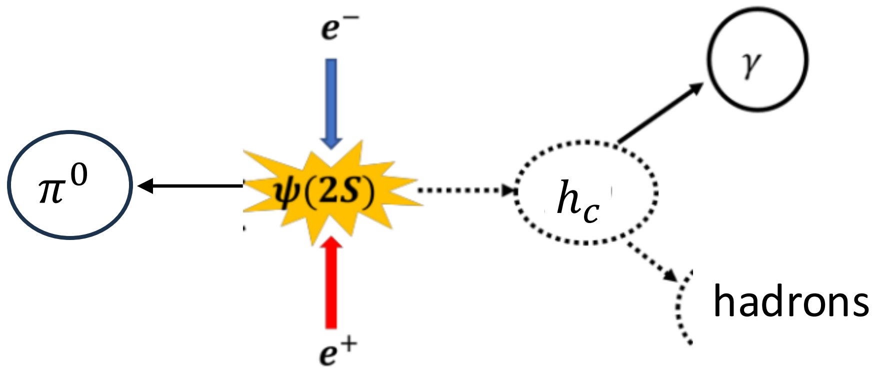
- World largest $\psi(2S)$ sample: $(27.12 \pm 0.14) \times 10^8$ $\psi(2S)$ events

h_c Radiative Decays

BESIII Phys. Rev. Lett. 134, 241902 (2025)

$h_c \to \gamma X$: h_c candidates from the $\psi(2S)$ decays

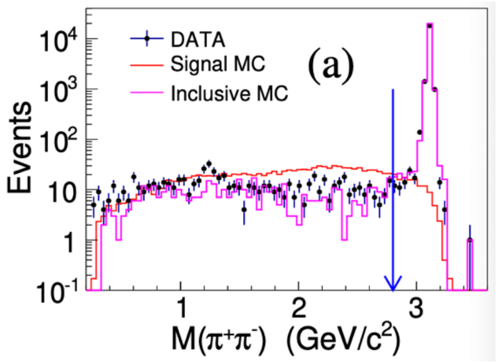
- h_c has the same C-parity as J/ψ but different orbital angular momentum → improving our understanding of charmonium radiative decays and searching for exotic states
- QCD predicts $\mathcal{B}(h_c \to \gamma + 2g)\sim 5.5\%$, while experiments measure $\mathcal{B}(h_c \to \gamma + \eta/\eta')\sim 0.2\%$
- h_c mesons produced by the isospin-violating decay $\boldsymbol{\psi(2S) \to \pi^0 h_c}$



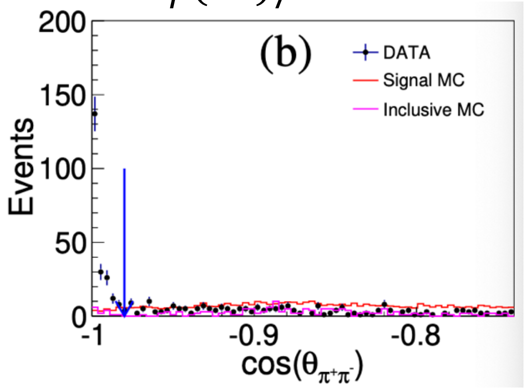
- 5C kinematic fit by constraining the four-momentum of final states of $\psi(2S)$ and π^0 mass → combination with minimum χ^2_{5C} selected
- To suppress background events with wrong number of photons: $\chi^2_{4C,n\gamma} < \chi^2_{4C,(n-1)\gamma}$ and $\chi^2_{4C,n\gamma} < \chi^2_{4C,(n+1)\gamma}$

$h_c \to \gamma X$: Non-peaking Background

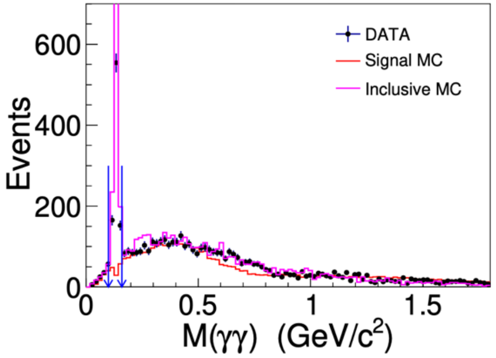
- Mode I: $\psi(2S) \to \pi^0 h_c$ *and* $\pi^0 \to \gamma_H \gamma_L$, $h_c \to \gamma\pi^+\pi^-$
  - $\omega/\phi \longrightarrow \pi^+\pi^-\pi^0$, $\omega \longrightarrow \pi^0\gamma$, $\pi^0 \to \gamma_H \gamma$
  - $\psi(2S) \to \pi^0\,\pi^0\, J/\psi$, $J/\psi \to l^+l^-$



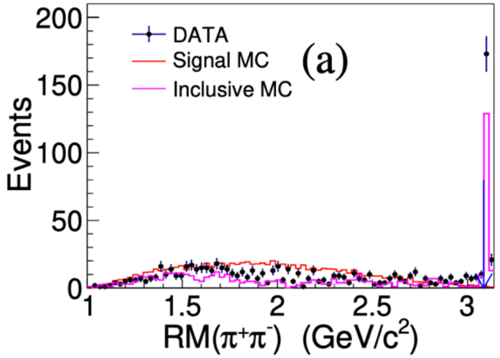
  - $\psi(2S)/ee \to l^+l^-$



- Mode II: $h_c \to \gamma\pi^+\pi^-\eta$, $\eta \to \gamma\gamma$
  - photon combination



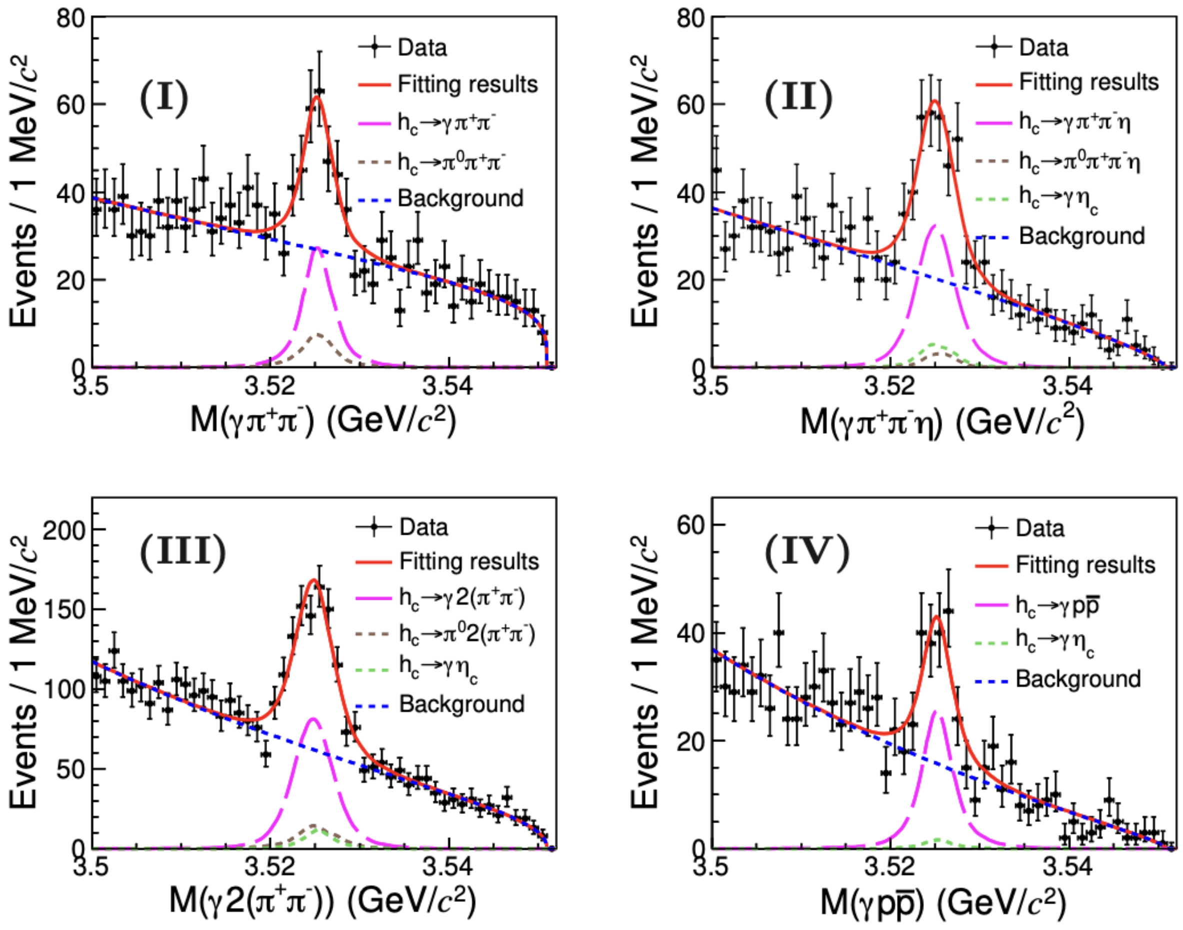
  - $\psi(2S) \to \pi^+\,\pi^-\, J/\psi$



- Mode III: $h_c \to \gamma 2(\pi^+\pi^-)$
  - $\omega/\eta \longrightarrow \pi^+\pi^-\pi^0$
  - $\psi(2S) \to \pi^+\,\pi^-\, J/\psi$
- Mode IV: $h_c \to \gamma p\bar{p}$

$h_c \to \gamma X$: Signal Extraction

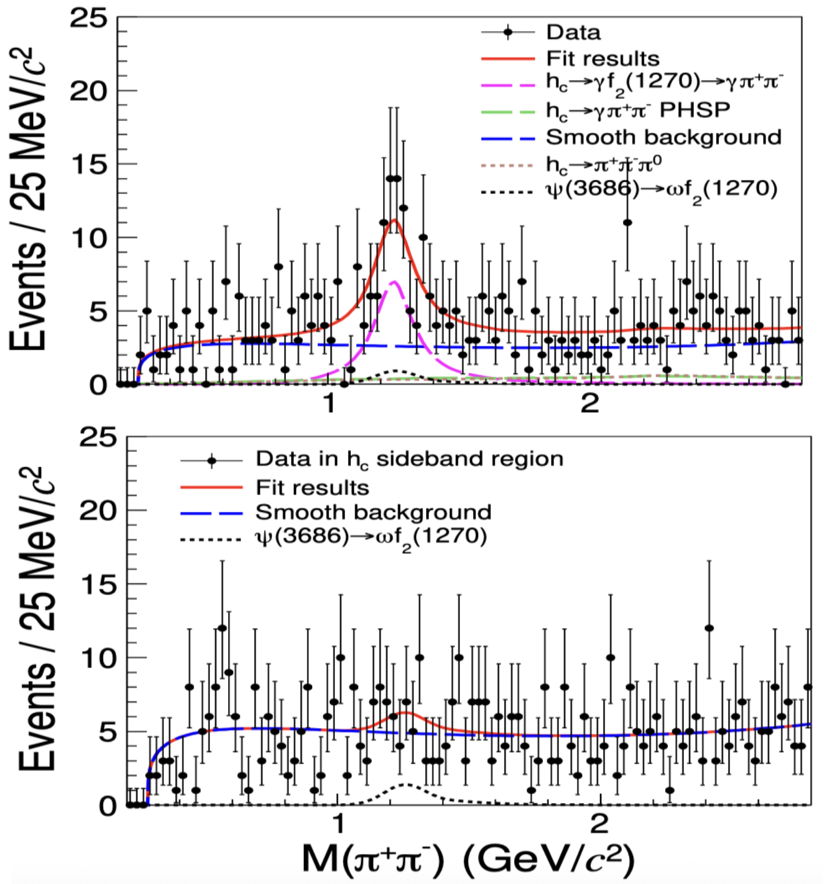
- Two types of **peaking background**
  - $h_c \to \gamma\eta_c$, with $\eta_c \to X$ ($X = \pi^+\pi^-\eta, 2(\pi^+\pi^-), p\bar{p}$)and $\boldsymbol{M(X) < 2.8\mathrm{GeV}/c^2}$, contribution obtained by fitting $M(X)$
  - $h_c \to \pi^0 X$ with a γ missing from π^0 , contribution simulated according to measured BFs
- Smooth background described with ARGUS function
- Singal shape derived from simulation



$\mathcal{B}(h_c \to \gamma + 2g)$

Decay model	Branching fraction	Signal yield	Efficiency (%)	Significance (σ)
$h_c \to \gamma\pi^+\pi^-$	$(3.06 \pm 0.54 \pm 0.37 \pm 0.21) \times 10^{-4}$	127.0 ± 22.2	20.9	5.4
$h_c \to \gamma f_2(1270) \to \gamma\pi^+\pi^-$	$(1.81 \pm 0.35 \pm 0.19 \pm 0.12) \times 10^{-4}$	71.8 ± 13.8	20.0	5.1
$h_c \to \gamma\pi^+\pi^-\eta$	$(3.52 \pm 0.50 \pm 0.30 \pm 0.24) \times 10^{-3}$	191.6 ± 27.1	7.0	7.5
$h_c \to \gamma 2(\pi^+\pi^-)$	$(2.19 \pm 0.20 \pm 0.16 \pm 0.15) \times 10^{-3}$	494.9 ± 44.5	11.4	11.8
$h_c \to \gamma p\bar{p}$	$(3.34 \pm 0.53 \pm 0.33 \pm 0.23) \times 10^{-4}$	127.4 ± 20.1	19.3	6.4

- Total BF of the h_c radiative decay is $\sim 0.6\%$ in this analysis, significantly lower than the predicted 5.5% of $\mathcal{B}(h_c \to \gamma + 2g)$
- Need for further exploration of h_c radiative decays
- The first observation of h_c radiative decay to a tensor state
  - Simultaneous fit to $M(\pi^+\pi^-)$ in h_c signal and sideband regions: share the smooth background $F_{BG}(m)$
  - BF of $\boldsymbol{h_c \to \gamma f_2(1270) \to \gamma\pi^+\pi^-}$ an order of magnitude smaller than that in J/ψ decay

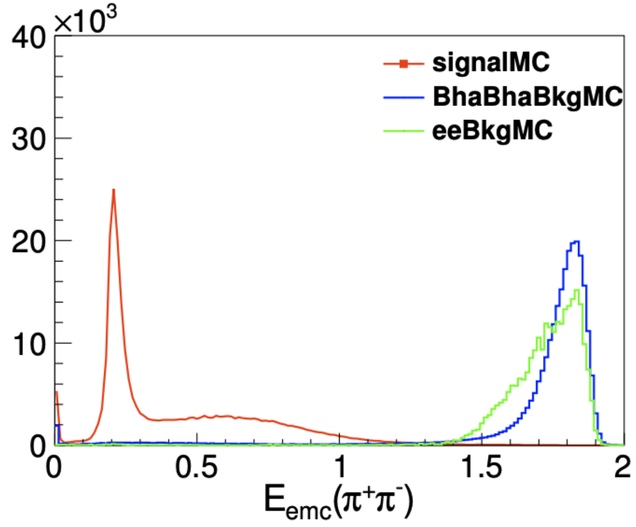


Precise measurement of $\chi_{c0,c2} \to \pi^+\pi^-/K^+K^-$

BESIII arXiv:2502.08929

$\chi_{c0,c2} \to \pi^+\pi^-/K^+K^-$: Signal Selection and Background Study

- The decay of χ_{c0} to light hadrons proceeds predominately via two-gluon exchanges.
- SU(3) flavor symmetry→$\Gamma(0^{++} \to \pi^+\pi^-) \sim \Gamma(0^{++} \to K^+K^-)$
- $\psi(2S) \to \gamma\chi_{c0,c2}$, $\chi_{c0,c2} \to \pi^+\pi^-/K^+K^-$
  - Constrain the four-momentum of two charged tracks and a photon to the four-momentum of $\psi(2S)$
  - Radiative photon with minimum χ^2_{4C} kept. No PID , events are classified as $\pi^+\pi^-$or K^+K^- according to χ^2_{4C}
- **Backgrounds**
  - $(\gamma)e^+e^-$ and $\pi^0\pi^0e^+e^-$: vetoed using deposited energy of electrons in EMC
  - $(\gamma)\mu^+\mu^-$: serious due to π and μ mis-identification, non-peaking background well simulated and fixed
  - Cross-contamination between $\gamma\pi^+\pi^-$ and γK^+K^- : $< 1\%$, fixed via simulation



$\chi_{c0,c2} \to \pi^+\pi^-/K^+K^-$: Signal Extraction

- $[\mathrm{BW}^2(\sqrt{s}) \times \mathcal{PS}_1^2(\sqrt{s}) \times \mathcal{D}^2(\sqrt{s}) \times \mathcal{PS}_2^2(\chi_{c0,c2} \to \pi^+\pi^-/K^+K^-) \times \epsilon(\sqrt{s})] \otimes \mathrm{Resolution}$

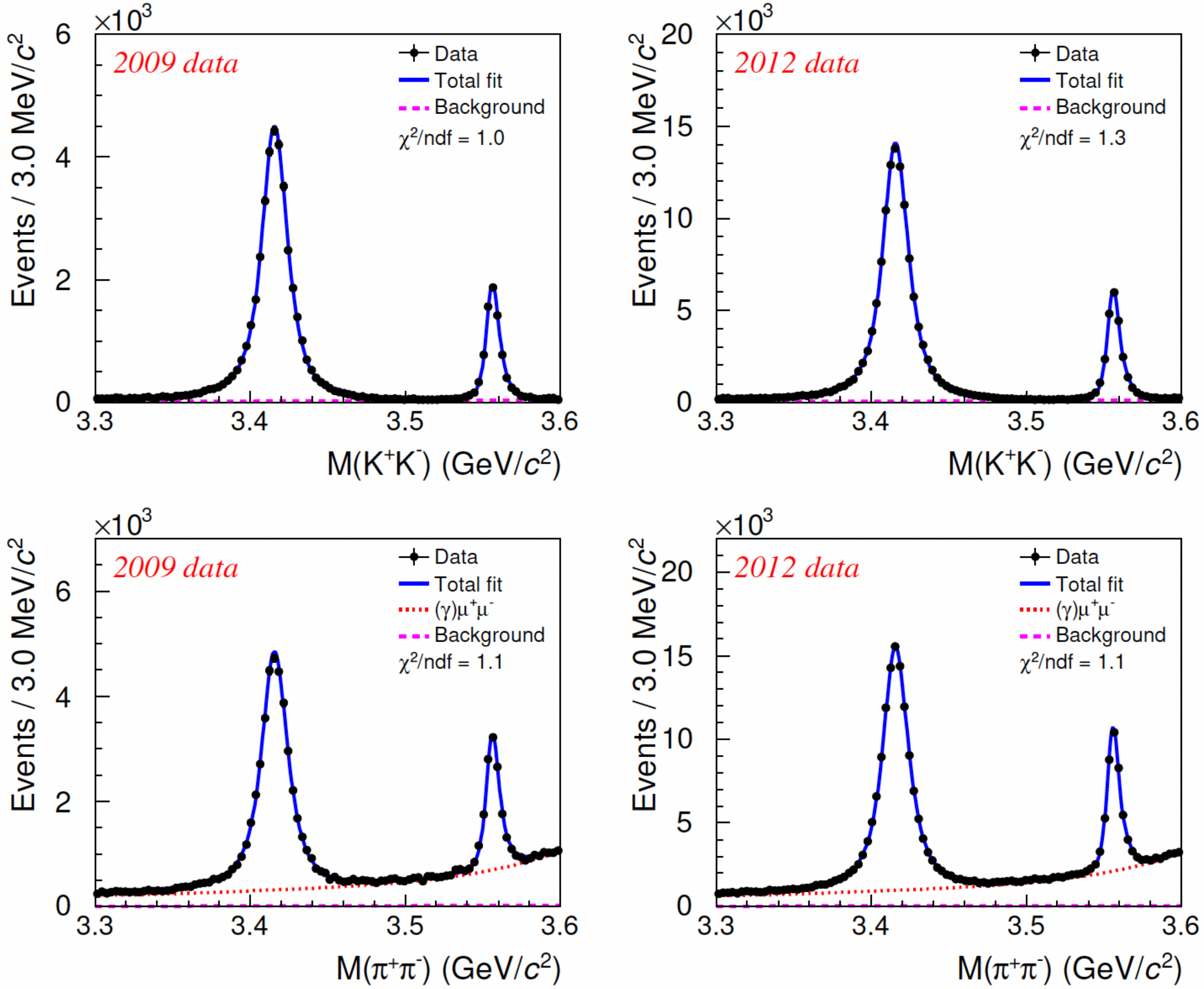
  - $\mathrm{BW}(\sqrt{s}) = \frac{1}{s - M^2 + iM\Gamma \frac{p}{p'} \frac{M}{\sqrt{s}}}$

  - $\mathcal{PS}_1(\sqrt{s}) = (\frac{E_\gamma}{E_\gamma^0})^{3/2}$

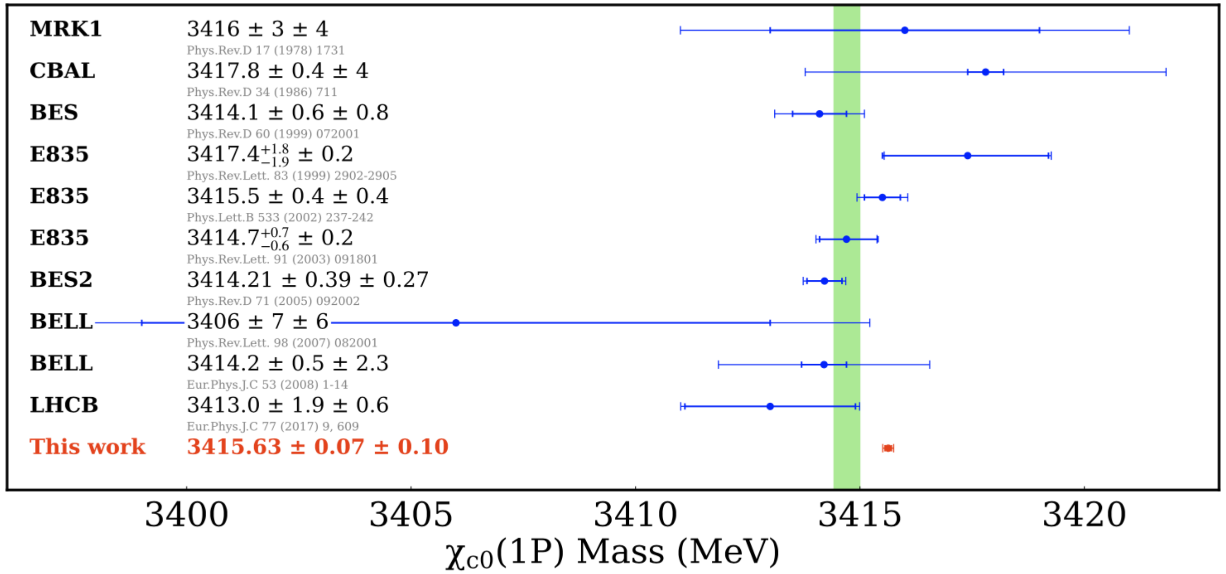
    Phase space factor in E1 radiative transition $\psi(2S) \to \gamma\chi_{c0,c2}$

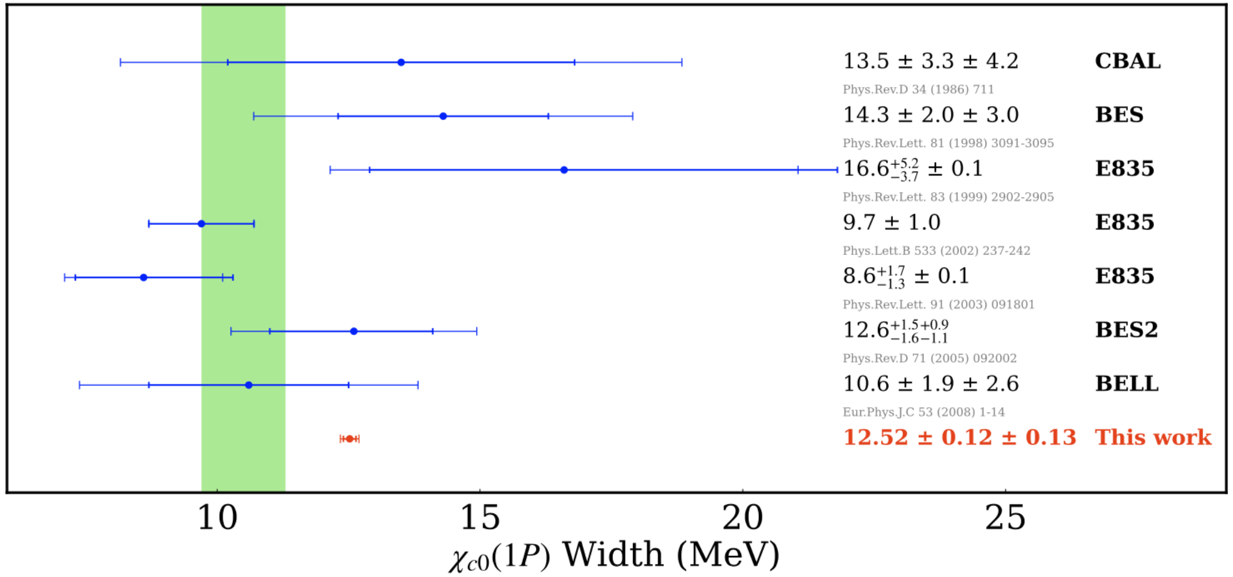
  - $\mathcal{D}(\sqrt{s}) = (\frac{(E_\gamma^0)^2}{E_\gamma^0 E_\gamma + (E_\gamma^0 - E_\gamma)^2})^{1/2}$

    Damping factor to suppress the higher energy tail



$\chi_{c0} \to \pi^+\pi^-/K^+K^-$





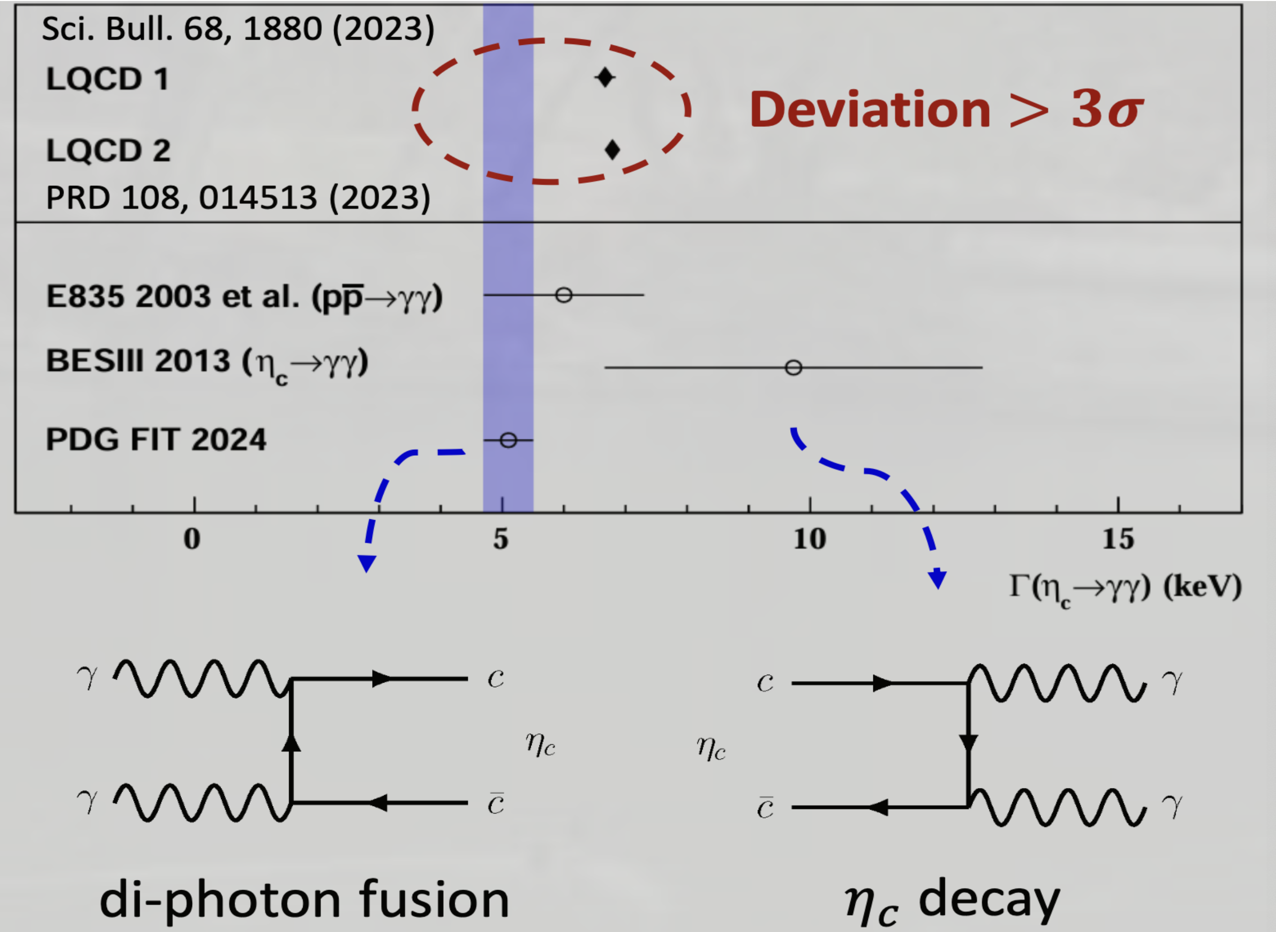
- The mass split between χ_{c2} and χ_{c0} is measured.
- Taking the world average mass of χ_{c2} as input →the most precise χ_{c0} mass/width measurement to date
- $$\mathcal{B}(\chi_{c0} \to K^+K^-) = (6.36 \pm 0.02 \pm 0.08 \pm 0.13) \times 10^{-3}$$
  $$\mathcal{B}(\chi_{c0} \to \pi^+\pi^-) = (6.06 \pm 0.02 \pm 0.07 \pm 0.13) \times 10^{-3}$$
  $$\mathcal{B}(\chi_{c2} \to K^+K^-) = (1.22 \pm 0.01 \pm 0.02 \pm 0.03) \times 10^{-3}$$
  $$\mathcal{B}(\chi_{c2} \to \pi^+\pi^-) = (1.61 \pm 0.01 \pm 0.02 \pm 0.04) \times 10^{-3}$$

$$\mathcal{R} = \frac{\mathcal{B}(\chi_{c0}\to\pi^+\pi^-)}{\mathcal{B}(\chi_{c0}\to K^+K^-)} = (0.95 \pm 0.01 \pm 0.01)$$

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

BESIII PRL 134 (2025) 181901

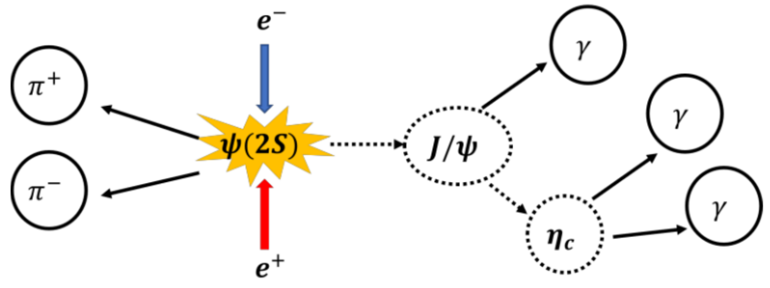
$\Gamma(\eta_c \to \gamma\gamma)$

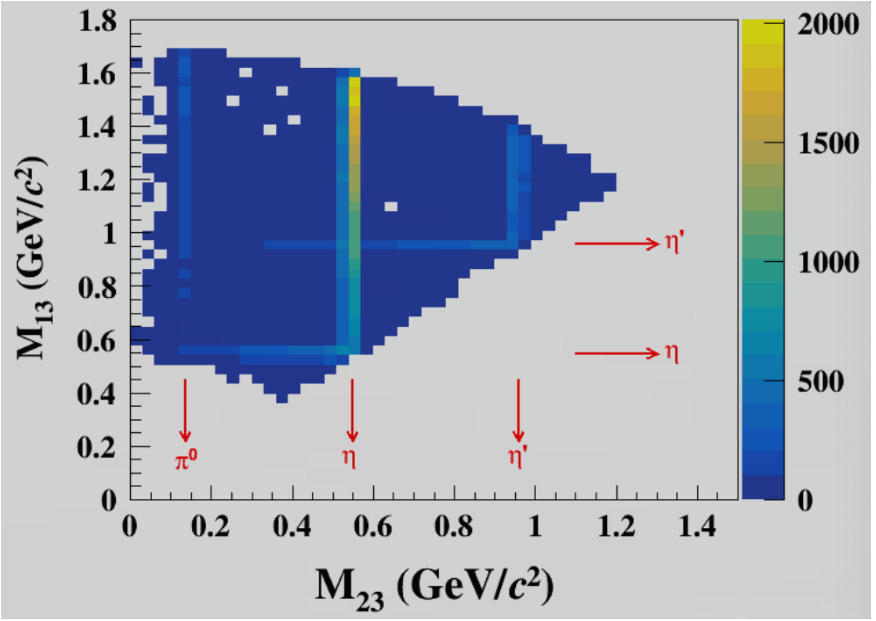


- Measurements with the time-inversion process are more precise
- Large discrepancies between different measurements of $\boldsymbol{\gamma\,\gamma \to \eta_c}$
- Theoretical predictions for $\Gamma(\eta_c \to \gamma\,\gamma)$ not agree with each other or the measured world-average value

$\eta_c \to \gamma\gamma$: Signal Selection and Background Study

- $\boldsymbol{\psi(2S) \to \pi^+\pi^- J/\psi}$, $\boldsymbol{J/\psi \to \gamma\eta_c}$, $\boldsymbol{\eta_c \to \gamma\gamma}$
  - Why not using $\psi(2S) \to \gamma\eta_c$? Huge background from $e^+e^- \to \gamma\gamma\gamma$
- A four-constraint kinematic fit carried out constraining the total four-momentum of the final states to the initial state
- The $\pi^+\pi^-\gamma\gamma\gamma$ combination with minimum χ^2_{4C} is selected.
- $E_{\gamma1} > E_{\gamma2} > E_{\gamma3}$
- $\boldsymbol{\eta_c}$ peak in $M(\gamma_1\gamma_2)$
- Dominant backgrounds peak in $M(\gamma_1\gamma_3)$ and $M(\gamma_2\gamma_3)$, rejected with the study of $M(\gamma\gamma)$





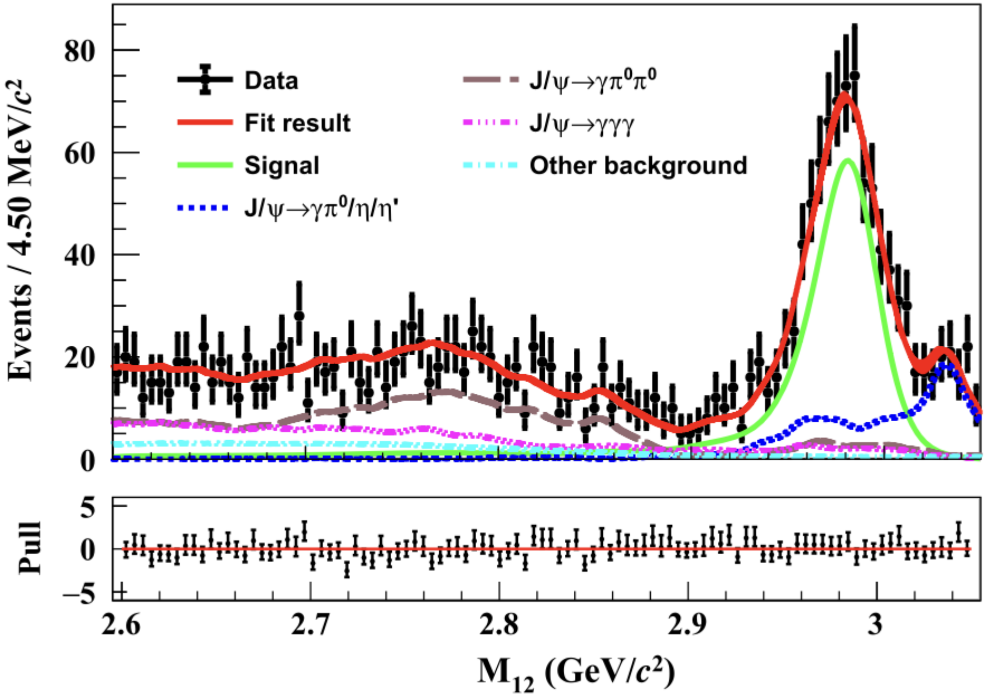
$\eta_c \to \gamma\gamma$: Signal Extraction

- unbinned extended maximum likelihood fit on $M(\gamma_1\gamma_2)$ to extract the signal yield
- Line shape of $\boldsymbol{\eta_c}$ described as

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

Mass-dependent efficiency | M1 transition from factor | Damping factor | Breit Wigner function | Detector resolution

- $$E_\gamma(m) = \frac{M_{J/\psi}^2 - m^2}{2 \times M_{J/\psi}}$$
- $$f_{\rm damp}(m) = \frac{E_0^2}{E_0 \times E_\gamma(m) + [E_0 - E_\gamma(m)]^2}$$
- $$BW(m) = \frac{M_{\eta_c}\Gamma_{\eta_c}}{m^2 - M_{\eta_c}^2 + iM_{\eta_c}\Gamma_{\eta_c}}$$

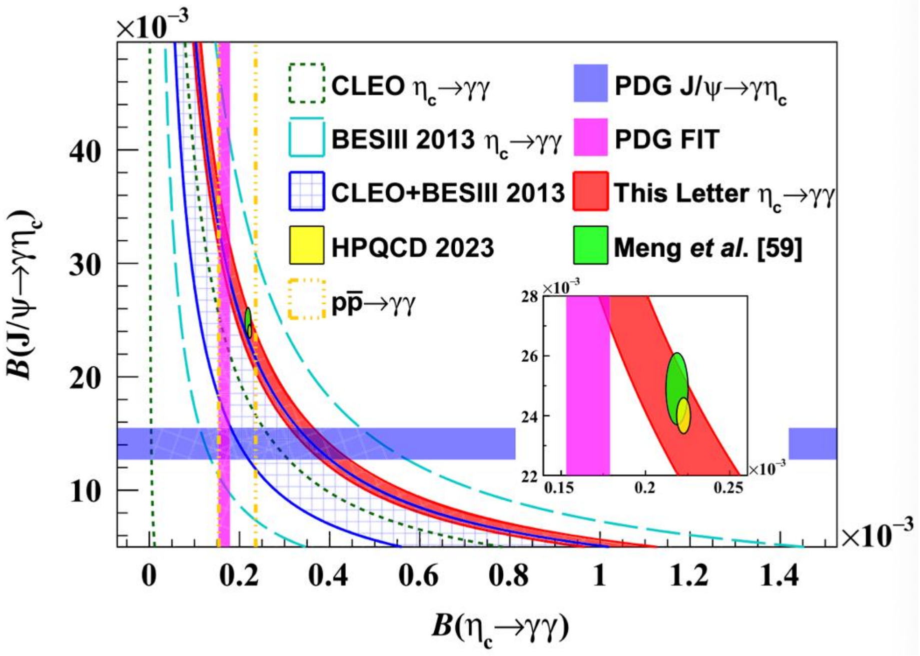


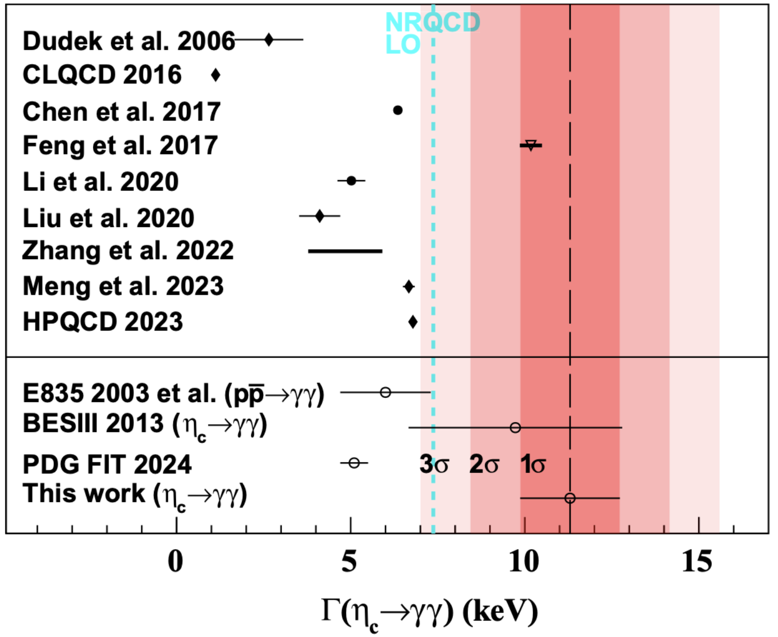
- Background shapes from simulation and contributios constrained according to the luminosity and BFs

$\mathcal{B}(\eta_c \to \gamma\gamma)$ and $\Gamma(\eta_c \to \gamma\gamma)$

$$\mathcal{B}(J/\psi \to \gamma\eta_c) \times \mathcal{B}(\eta_c \to \gamma\gamma) = \frac{N_{\rm sig}}{N_{\psi(3686)} \times \epsilon_{\rm sig} \times \mathcal{B}[\psi(3686) \to \pi^+\pi^- J/\psi]}$$

$$\Gamma(\eta_c \to \gamma\gamma) = \frac{\mathcal{B}(J/\psi \to \gamma\eta_c) \times \mathcal{B}(\eta_c \to \gamma\gamma)}{\mathcal{B}^{\rm PDG}(J/\psi \to \gamma\eta_c)} \times \Gamma^{\rm PDG}_{\eta_c}$$





- The measurement is consistent with the lattice QCD calculation from HPQCD in 2023.
- By using the world-average values of $\mathcal{B}(J/\psi \to \gamma\eta_c)$ and the total decay width of η_c, $\Gamma(\eta_c \to \gamma\gamma)$ is determined, deviating from the world-average value by 3.4σ

Summary

- Thanks to the largest $\psi(2S)$ data samples collected at BESIII, charmonium (h_c , χ_{c0}, η_c) decays have been studied in a clean environment.
  - $\psi(2S) \to \pi^0 \boldsymbol{h_c}$, $h_c \to \gamma + \pi^+\pi^-$ / $\pi^+\pi^-\eta$ / $2(\pi^+\pi^-)$ / $p\bar{p}$
  - $\psi(2S) \to \gamma \boldsymbol{\chi_{c0}}$, $\chi_{c0} \to \pi^+\pi^-/K^+K^-$
  - $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma \boldsymbol{\eta_c}$, $\eta_c \to \gamma\gamma$
- More measurements expected to further advance our understanding of QCD