# 含粲强子衰变高精度格点QCD研究

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### Based on Sci.Bull 68,1880(2023), PRD109,074511(2024) PRD110,074510(2024), PRD111,014508(2025)

#### 第四届强子与重味物理理论与实验联合研讨会

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# Outline

#### Introduction

- A puzzle in charmonium decays
  - $\eta_c \to 2\gamma$
  - $J/\psi \to \gamma \eta_c$
- Radiative decay
  - $D_s^* \to D_s \gamma$
- Weak decay
  - $J/\psi \to D_s/Dl\nu_l$
- Conclusion and outlook

### Motivation

Charmed hadron: a meson containing at least one charm or anti-charm quark

• "November Revolution"— The discovery of  $J/\psi$  particle in 1974, greatly facilitated the establishment of the Standard Model.





#### Why charmed hadron decays ?

- Precise test for the standard model
  - The world's largest  $\tau\text{-charm}$  factory—BESIIII
- Test various perturbative and non-perturbative approaches — intermediate energy scale
- More possibilities for the search of new physics
   rare decays

$$\eta_c \to 2\gamma$$



- H-P.Wang and C-Z.Yuan, New puzzle in charmonium decays, CPC46,071001(2022)
- Ours is verified by HPQCD,  $\Gamma_{\eta_c \gamma \gamma} = 6.788(45)_{fit}(41)_{syst}$  keV, PRD108,014513(2023)

# Lattice & Experiments



#### PDG(2023)

|                                 | $\Gamma(~\eta_s(1S) 	o \gamma\gamma$ | )                             |                            |
|---------------------------------|--------------------------------------|-------------------------------|----------------------------|
|                                 | VALUE (keV)                          |                               | EVTS                       |
|                                 | $\textbf{5.4} \pm \textbf{0.4}$      | OUR FIT                       |                            |
|                                 |                                      |                               |                            |
| DG(20                           | 24)                                  |                               |                            |
| $\Gamma_{59} \eta_c(1S) -$      | + γγ                                 |                               | $(1.66\pm 0.13)	imes 10^-$ |
| Category: Radiative d           | ecays                                |                               |                            |
| The following dat               | a is related to th                   | e above value:                |                            |
| $\Gamma( \eta_c(1S)  ightarrow$ | <i>าา</i> )                          |                               |                            |
|                                 |                                      |                               |                            |
| VALUE (keV)                     |                                      | EVTS                          | DOCUMENTID                 |
| $\textbf{5.1} \pm \textbf{0.4}$ | OUR FIT Error                        | includes scale factor of 1.2. |                            |

- The PDG-aver and PDG-fit are wrong before 2023 since the CLEO(08) experimental value is misused.
- PDG-fit(2024) is lower since the  $\Gamma_{n_c}^{\text{total}}$  is changed:  $32.0(7) \rightarrow 30.5(5)$  MeV.
- PDG-aver is removed from the PDG listing since 2024.

• CLEO(08) and BESIII(13) extract the branching fraction of  $\eta_c \to 2\gamma$  by

$$J/\psi \to \gamma \eta_c \to 3\gamma$$

• PDG23, 
$$Br(\eta_c \rightarrow 2\gamma)$$



| $VALUE(10^{-4})$                    |  | CL%                   | EVTS   | DOCUMENT IL                 | >           | TECN                  | COMMENT  |
|-------------------------------------|--|-----------------------|--|-----------------------------|-------------|-----------------------|--|
| $\bf 1.68 \pm 0.12$                 | OUR FIT  |                       |  |                             |             |                       |  |
| $2.2^{+0.9}_{-0.6}$ OUR             | AVERAGE  |                       |  |                             |             |                       |  |
| $2.7 \pm 0.8 \pm 0.6$               |  |                       |  | 1 ABLIKIM                   | 20131       | BES3                  |  |
| $0.7 \ ^{+1.6}_{-0.7} \ \pm 0.2$    |  |                       | $1.2 \ ^{+2.8}_{-1.1}$                                   | <sup>2</sup> ADAMS          | 2008        | CLEO                  | $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$   |
|                                     |  |                       | <ul> <li>We do not use the follow</li> </ul>             | ving data for ave           | rages, fits | , limits, etc. • •    |  |
| $2.0 \ ^{+0.9}_{-0.7} \ \pm 0.2$    |  |                       | 13   | <sup>3</sup> WICHT          | 2008        | BELL                  | $B^{\pm}  ightarrow K^{\pm} \gamma \gamma$   |
| $2.80 \ ^{+0.67}_{-0.58} \ \pm 1.0$ |  |                       |  | 4 ARMSTRONG                 | 1995F       | E760                  | $\overline{p} \ p \rightarrow \gamma \gamma$   |
| < 9                                 |  | 90                    |  | <sup>5</sup> BISELLO        | 1991        | DM2                   | $J/\psi \rightarrow \gamma\gamma\gamma$  |
| $6_{-3}^{+4}\pm 4$                  |  |                       |  | <sup>4</sup> BAGUN          | 1987B       | SPEC                  | $\bar{p} p \rightarrow \gamma \gamma$  |
| < 18                                |  | 90                    |  | 6 BLOOM                     | 1983        | CBAL                  | $J/\psi \rightarrow \eta_c \gamma$   |
| 1 ABLIKIM 2013                      | reports $[\Gamma(\eta_c(1S) \rightarrow \gamma \gamma) / \Gamma_{tc}]$ | tal] × [B( $J/\psi$ ( | $(1S) \rightarrow \gamma \eta_c(1S)$ ] = $(4.5 \pm 1.5)$ | $2\pm0.6 angle	imes10^{-6}$ | which we    | divide by our best ve | alue B( $J/\psi(1S)  ightarrow \gamma \eta_c(1S)$ ) = 0.017 $\pm 0.004.$ Our first error |
| is their experim                    | ent's error and our second error                                       | is the systemat       | ic error from using our best w                           | ue.                         |             |                       |  |

 $\frac{2}{2}$  ADAMS 2008 reports [ $\Gamma(\eta_c(1S) \rightarrow \gamma\gamma)/\Gamma_{total}$  × [B( $J/\psi(1S) \rightarrow \gamma\eta_c(1S)$ ]] = (1.2  $^{+2.7}_{-1.1} \pm 0.3$ ) × 10<sup>-6</sup> which we divide by our best value B( $J/\psi(1S) \rightarrow \gamma\eta_c(1S)$ ) = 0.017 ± 0.004. Our first error is their experiment's error and our second error is the systematic error from using our best value.

### $\eta_c \rightarrow 2\gamma$ :PDG24-update

| VALUE ( $10^{-4}$ )                 | CL%   | EVTS                 | DOCUMENT ID                           |                     | TECN     | COMMENT                              |  |
|-------------------------------------|---|----------------------|---------------------------------------|---------------------|----------|--------------------------------------|--|
| $\textbf{1.66} \pm \textbf{0.13}$   | OUR FIT Error includes scale factor of 1.2. |                      |                                       |                     |          |                                      |  |
|                                     |   | • • We de            | o not use the following data for aver | ages, fits, limits, | etc. • • |                                      |  |
| $3.2 \pm 1.0 \pm 0.3$               |   |                      | <sup>1</sup> ABLIKIM                  | 20131               | BES3     |                                      |  |
| $0.9 \ _{8}^{+1.9} \ {\pm} 0.1$     |   | $1.2~^{+2.8}_{-1.1}$ | <sup>2</sup> ADAMS                    | 2008                | CLEO     | $\psi(2S) 	o \pi^+\pi^- J/\psi$      |  |
| $2.0 \ _{-0.7}^{+0.9} \pm 0.1$      |   | 13                   | <sup>3</sup> WICHT                    | 2008                | BELL     | $B^\pm 	o K^\pm \gamma \gamma$       |  |
| $2.80 \ ^{+0.67}_{-0.58} \ \pm 1.0$ |   |                      | <sup>4</sup> ARMSTRONG                | 1995F               | E760     | $\overline{p} \; p 	o \gamma \gamma$ |  |
| < 9                                 | 90  |                      | <sup>5</sup> BISELLO                  | 1991                | DM2      | $J/\psi 	o \gamma\gamma\gamma$       |  |
| $6 {}^{+4}_{-3} \pm 4$              |   |                      | <sup>4</sup> BAGLIN                   | 1987B               | SPEC     | $\overline{p} \; p 	o \gamma \gamma$ |  |
| < 18                                | 90  |                      | <sup>6</sup> BLOOM                    | 1983                | CBAL     | $J/\psi 	o \eta_c \gamma$            |  |

<sup>1</sup> ABLIKIM 2013I reports [ $\Gamma(\eta_c(1S) \to \gamma \gamma)/\Gamma_{total}$ ] × [ $B(J/\psi(1S) \to \gamma \eta_c(1S)$ )] = (4.5 ±1.2 ±0.6) × 10<sup>-6</sup> which we divide by our best value  $B(J/\psi(1S) \to \gamma \eta_c(1S))$ ] = (1.41 ±0.14) × 10<sup>-2</sup>. Our first error is their experiment's error and our second error is the systematic error from using our best value.

<sup>2</sup> ADAMS 2008 reports  $[\Gamma(\eta_c(1S) \rightarrow \gamma\gamma)/\Gamma_{total}] \times [B(J/\psi(1S) \rightarrow \gamma\eta_c(1S))] = (1.2 + \frac{2.7}{-1.1} \pm 0.3) \times 10^{-6}$  which we divide by our best value B( $J/\psi(1S) \rightarrow \gamma\eta_c(1S)$ ) = (1.41 ± 0.14) × 10^{-2}. Our first error is their experiment's error and our second error is the systematic error from using our best value.

 $Br(J/\psi \to \gamma \eta_c) : 1.7(4)\% \to 1.41(14)\%$ 

# $J/\psi \to \gamma \eta_c$

 $\bullet~{\rm New}$  method for  $J/\psi\to\gamma\eta_c$  without momentum extrapolation

 $V(0) = 1.90(4), \ \operatorname{Br}(J/\psi \to \gamma \eta_c) = 2.49(11)_{\operatorname{lat}}(5)_{\operatorname{exp}}\%$ 



Y.M et al, PRD111,014508(2025)



### A puzzle in charmonium decay

• Individual channel: Ours vs PDG

 $\eta_c 
ightarrow 2\gamma$ : 3.6  $\sigma$  tension  $J/\psi 
ightarrow \gamma\eta_c$ : 5.9  $\sigma$  tension

• Combined channel:  $Br(J/\psi \to \gamma \eta_c) \times Br(\eta_c \to 2\gamma)$ 



• BESIII: 5.23(40) × 10<sup>-6</sup> 2412.12998



# $D^{\ast}_{s}$ decay mode

| $D_s^{*\pm}$ I(JPP) = 0(1-)              |                    |   |
|--|--------------------|---|
| $J^P=1^-$ established by ABLIKIM 2023AZ. |                    |   |
|  |                    |   |
| $D_s^{*\pm}$ MASS                        | $2112.2\pm0.4$ MeV | ~ |
| $m_{D_s^{\pm\pm}}$ - $m_{D_s^{\pm}}$     | $143.8\pm0.4$ MeV  | ~ |
| $D_s^{\star\pm}$ width                   | < 1.9 MeV CL=90.0% | ~ |
| $D_s^{st+}$ decay modes                  |                    |   |

 $D_s^{*-}$  modes are charge conjugates of the modes below.

| Mode       |               | Fraction ( $\Gamma_i$ / $\Gamma$ ) | Scale Factor/<br>Conf. Level | P(MeV/c) |   |
|------------|---------------|------------------------------------|------------------------------|----------|---|
| $\Gamma_1$ | $D_s^+\gamma$ | $(93.6\pm0.4)\%$                   |                              | 139      | ~ |
| $\Gamma_2$ | $D_s^+\pi^0$  | $(5.77\pm 0.35)\%$                 |                              | 48       | ~ |
| $\Gamma_3$ | $D_s^+e^+e^-$ | $(6.7 \pm 1.6) 	imes 10^{-3}$      |                              | 139      | ~ |
| $\Gamma_4$ | $e^+ u_e$     | $(2.1^{+1.2}_{-0.9})	imes 10^{-5}$ |                              | 1056     | ~ |

• Branching fraction first determined by BESIII PRL131,141802(2023)

$$Br(D_s^{*,+} \to e^+\nu_e) = (2.1^{+1.2}_{-0.9_{\text{stat.}}} \pm 0.2_{\text{syst.}}) \times 10^{-5}$$

• Radiative decay  $D_s^* \to D_s \gamma$  can be used to estimate the  $D_s^*$  total decay width.

# $D_s^* \rightarrow \gamma D_s$ from lattice QCD



- The right farmost points are included with the new method Y.M et al, PRD109,074511(2024)
- It gives  $\Gamma(D_s^* \to \gamma D_s) = 0.0549(54)$  keV, much precise than 0.066(26) keV by HPQCD PRL112,212002(2014)

### • BESIII+ HPQCD

 $f_{D_s^*}|V_{cs}| = (207.9^{+59.4}_{-44.6_{\text{stat.}}} \pm 9.9_{\text{syst.exp}} \pm 41.5_{\text{syst.latt}}) \text{MeV}$ where  $\Gamma_{D_s^*}^{\text{total}} = 0.0700(280)$  keV.

• BESIII+ Ours

 $f_{D_s^*}|V_{cs}| = (190.5^{+55.1}_{-41.7_{\text{stat.}}} \pm 9.1_{\text{syst.exp}} \pm 8.7_{\text{syst.latt}}) \text{MeV}$ where  $\Gamma_{D_s^*}^{\text{total}} = 0.0589(54)$  keV.

#### • Current measurements

| channels                          | Upper limit          | $J/\psi$ number       | Refs               |
|-----------------------------------|----------------------|-----------------------|--------------------|
| $J/\psi \to D_s e \nu_e$          | $4.9 \times 10^{-5}$ | $5.8 	imes 10^7$      | PLB639,418(2006)   |
| $J/\psi \to D_s e \nu_e$          | $1.3 \times 10^{-6}$ | $2.3 \times 10^8$     | PRD90,112014(2014) |
| $J/\psi \to De\nu_e$              | $7.1 \times 10^{-8}$ | $1.01 \times 10^{10}$ | JHEP06,157(2021)   |
| $J/\psi  ightarrow D\mu  u_{\mu}$ | $5.6 \times 10^{-7}$ | $1.01 \times 10^{10}$ | JHEP01,126(2024)   |

BES & BESIII collaboration

#### • Future measurements ?

| channels                     | Upper limit | $J/\psi$ number       | Refs   |
|------------------------------|-------------|-----------------------|--------|
| $J/\psi \to D_s e \nu_e$     | —           | $1.01 \times 10^{10}$ | BESIII |
| $J/\psi \to D_s \mu \nu_\mu$ | —           | $1.01 	imes 10^{10}$  | BESIII |
| $J/\psi \to D_s e \nu_e$     | —           | $\sim 10^{12}$        | STCF   |
| $J/\psi \to D_s \mu \nu_\mu$ |             | $\sim 10^{12}$        | STCF   |

# $J/\psi \to D/D_s l\nu_l$

• The amplitude

$$i\mathcal{M} = -i\frac{G_F}{\sqrt{2}}V_{cs(d)}\epsilon_{\alpha}(p')H_{\mu\alpha}(p,p')g_{\mu\nu}\bar{u}_l\gamma_{\nu}(1-\gamma_5)u_{\nu_l}$$

with the nonperturbative hadronic interaction ZPC46,93(1990)

$$\begin{aligned} H_{\mu\alpha}(p,p') &\equiv \langle D/D_s(p)|J^W_{\mu}|J/\psi_{\alpha}(\epsilon,p')\rangle \\ &= F_1(q^2)g_{\mu\alpha} + \frac{F_2(q^2)}{Mm}p'_{\mu}p_{\alpha} + \frac{F_3(q^2)}{m^2}p_{\mu}p_{\alpha} - \frac{iF_0(q^2)}{Mm}\epsilon_{\mu\alpha\rho\sigma}p'_{\rho}p_{\sigma} \end{aligned}$$

• The decay width

$$\begin{split} \Gamma &= \quad \frac{G_F^2 V_{cs(d)}^2}{12M^2} \frac{1}{32\pi^3} \int_{m_l^2}^{(M-m)^2} dq^2 \times \left[ c_0 (E_l^+ - E_l^-) \right] \\ &+ \quad \frac{c_1}{2} ((E_l^+)^2 - (E_l^-)^2) + \frac{c_2}{3} ((E_l^+)^3 - (E_l^-)^3) \right] \end{split}$$

with  $E_l^{\pm}=\frac{1}{2M}\Big[q^2+m_l^2-\frac{1}{2q^2}\Big((q^2-M^2+m^2)(q^2+m_l^2)\mp 2M|\vec{p}|(q^2-m_l^2)\Big)\Big]$ 

## $J/\psi \rightarrow D/D_s l\nu_l$ decay width



• The branching fraction

Y.M et al, PRD110,074510(2024)

$$\begin{array}{lll} {\rm Br}(J/\psi \to D_s e\nu_e) & = & 1.90(6)_{\rm stat}(5)_{V_{cs}} \times 10^{-10} \\ {\rm Br}(J/\psi \to D e\nu_e) & = & 1.21(6)_{\rm stat}(9)_{V_{cd}} \times 10^{-11} \end{array}$$

 $\bullet~$  The ratio between  $\mu~{\rm and}~e$ 

# Differential decay width



- The experimental inputs  $m_{J/\psi} = 3.09690(1)$  GeV,  $m_{D_s} = 1.96834(7)$  GeV, and  $m_D = 1.86966(5)$  GeV
- A potential test by future Super Tau Charm Facility with expected  $10^{12} J/\psi$  samples Front. Phys. (Beijing) 19, 14701(2024)

# CLQCD gauge ensembles



- High precision lattice calculation
  - Five lattice spacings for continuum limit  $a \to 0$
  - Three pion masses for chiral limit  $m_\pi o m_\pi^{phys}$

## Conclusion and outlook

#### Conclusion

- A puzzle in  $\eta_c \rightarrow 2\gamma$  and  $J/\psi \rightarrow \gamma \eta_c$
- The most precise  $\Gamma(D_s^*\to D_s\gamma)=0.0549(54)~{\rm keV}$  and  $R_{ee}=0.624(3)\%$  for the Dalitz decay  $D_s^*\to D_s e^+e^-$
- The methodology of  $J/\psi \to D/D_s l \nu_l$  can be applied to various  $P \to V$  semileptonic decay

#### • Outlook

- $\checkmark$  Disconnected contribution in charmed radiative decays
  - $J/\psi \to \gamma \eta_c, D_s^* \to \gamma D_s, D^* \to \gamma D$
- $\checkmark~$  Charmed  $P \rightarrow V$  semileptonic decay:  $D \rightarrow K^*$  and  $D_s \rightarrow \phi$
- More systematic continuum limit  $a \to 0$  and chiral limit  $m_\pi \to m_\pi^{phys}$





□2025年轻强子专题研讨会

- •河南安阳, 2025年5月8日-12日
- https://indico.ihep.ac.cn/event/24241/

□2025年强子物理和有效场论"前沿讲习班

- •河南郑州, 2025年8月17日-31日
- https://indico.ihep.ac.cn/event/24901/



- □所长:马伯强教授
- □研究方向: 粒子物理、强子物理、核子结构、高能物理实验 (BESIII, JUNO, ATLAS, JUNO, LHAASO)
- □招聘引进
- •学科骨干: 50-70, 1000
- •拔尖人才:40+,100
- •初聘教授/副教授/助理教授, 35/25/18, 30/20/12
- •博士后:专业九级+20/10/6
- •详细信息:https://www5.zzu.edu.cn/rsc/info/1050/6296.htm