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)

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第七届全国重味物理与量子色动力学研讨会

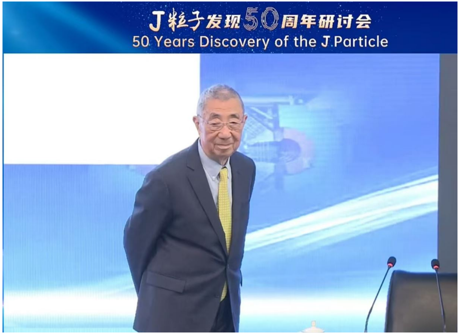
2025年4月18-22日，江苏·南京

Outline

- Introduction
- A puzzle in charmonium decays
  - $\eta_c \to 2\gamma$
  - $J/\psi \to \gamma\eta_c$
- Charmed radiative decay
  - $D_s^* \to D_s\gamma$
- Charmed semileptonic decay
  - $J/\psi \to D_s/Dl\nu_l$
  - $D \to K^* l\nu_l$
- Conclusion and outlook

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

- "November Revolution"— The discovery of J/ψ particle in 1974, greatly facilitated the establishment of the Standard Model.

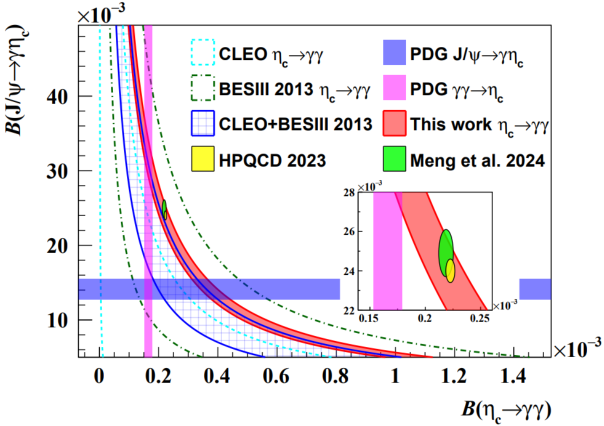


A puzzle in charmonium decay

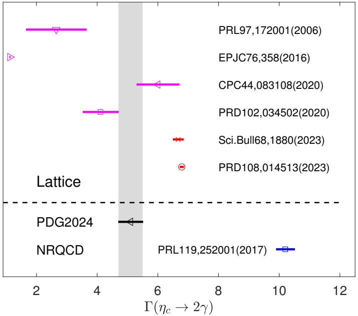
- Individual channel: Lattice vs PDG

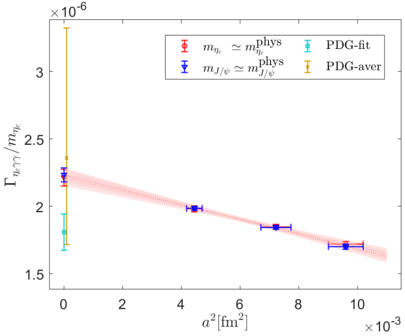
$\eta_c \to 2\gamma$: 3.6 σ tension
$J/\psi \to \gamma\eta_c$: 5.9 σ tension

- Latest BESIII measurement: 2411.12998,PRL accepted



$\eta_c \to 2\gamma$



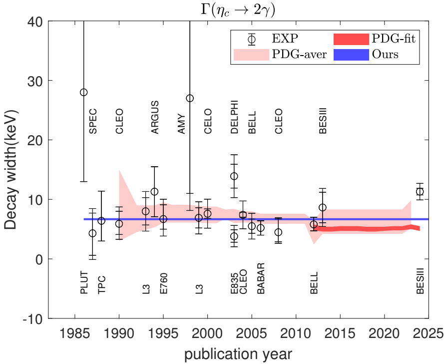


$$\Gamma(\eta_c \to 2\gamma) = \begin{cases} 6.67(16)(6)\,\mathrm{keV} \\ 5.1(4)\,\mathrm{keV} \quad \text{PDG-fit(2024)} \\ 7.04^{+2.9}_{-1.9}\,\mathrm{keV} \quad \text{PDG-aver(2023)} \end{cases}$$

Y.M et al, Sci Bull 68,1880(2023)

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

Lattice & Experiments



PDG(2023)

$\Gamma(\eta_c(1S) \to \gamma\gamma)$

VALUE (keV)		*EVTS*
$\mathbf{5.4 \pm 0.4}$	OUR FIT	

PDG(2024)

Γ_{59} $\eta_c(1S) \to \gamma\gamma$ $(1.66 \pm 0.13) \times 10^{-4}$

Category: Radiative decays

The following data is related to the above value:

$\Gamma(\eta_c(1S) \to \gamma\gamma)$

VALUE (keV)	*EVTS*	*DOCUMENT ID*
$\mathbf{5.1 \pm 0.4}$	OUR FIT Error includes scale factor of 1.2.	

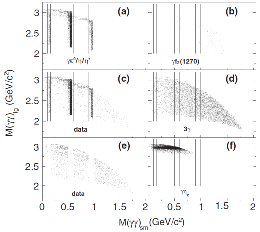
- The PDG-aver and PDG-fit are wrong before 2023 since the CLEO(08) experimental value is misused.
- PDG-fit(2024) is lower since the $\Gamma^{total}_{\eta_c}$ is changed: $32.0(7) \to 30.5(5)$ MeV.
- PDG-aver is removed from the PDG listing since 2024.

Discussion

- 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, $\mathrm{Br}(\eta_c \to 2\gamma)$



VALUE (10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{1.68 \pm 0.12}$ OUR FIT						
$\mathbf{2.2^{+0.9}_{-0.6}}$ OUR AVERAGE						
$2.7 \pm 0.8 \pm 0.6$			[1] ABLIKIM	2013I	BES3	
$0.7\ ^{+1.6}_{-0.7} \pm 0.2$		$1.2\ ^{+2.8}_{-1.1}$	[2] ADAMS	2008	CLEO	$\psi(2S) \to \pi^+\pi^- J/\psi$
• • We do not use the following data for averages, fits, limits, etc. • •						
$2.0\ ^{+0.9}_{-0.7} \pm 0.2$		13	[3] WICHT	2008	BELL	$B^\pm \to K^\pm\gamma\gamma$
$2.80\ ^{+0.67}_{-0.58} \pm 1.0$			[4] ARMSTRONG	1995F	E760	$\bar{p}\,p \to \gamma\gamma$
< 9	90		[5] BISELLO	1991	DM2	$J/\psi \to \gamma\gamma\gamma$
$6\ ^{+4}_{-3} \pm 4$			[4] BAGLIN	1987B	SPEC	$\bar{p}\,p \to \gamma\gamma$
< 18	90		[6] BLOOM	1983	CBAL	$J/\psi \to \eta_c\gamma$

[1] ABLIKIM 2013I reports $[\Gamma(\eta_c(1S) \to \gamma\gamma)/\Gamma_{\rm total}] \times [B(J/\psi(1S) \to \gamma\eta_c(1S))] = (4.5 \pm 1.2 \pm 0.6) \times 10^{-6}$ which we divide by our best value $B(J/\psi(1S) \to \gamma\eta_c(1S)) = 0.017 \pm 0.004$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

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

$\eta_c \to 2\gamma$:PDG24-update

VALUE (10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{1.66 \pm 0.13}$	**OUR FIT** Error includes scale factor of 1.2.					
• • We do not use the following data for averages, fits, limits, etc. • •						
$3.2 \pm 1.0 \pm 0.3$			[1] ABLIKIM	2013I	BES3	
$0.9\,^{+1.9}_{-.8} \pm 0.1$		$1.2\,^{+2.8}_{-1.1}$	[2] ADAMS	2008	CLEO	$\psi(2S) \to \pi^+\pi^- J/\psi$
$2.0\,^{+0.9}_{-0.7} \pm 0.1$		13	[3] WICHT	2008	BELL	$B^\pm \to K^\pm \gamma\gamma$
$2.80\,^{+0.67}_{-0.58} \pm 1.0$			[4] ARMSTRONG	1995F	E760	$\overline{p}\,p \to \gamma\gamma$
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< 18	90		[6] BLOOM	1983	CBAL	$J/\psi \to \eta_c \gamma$

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

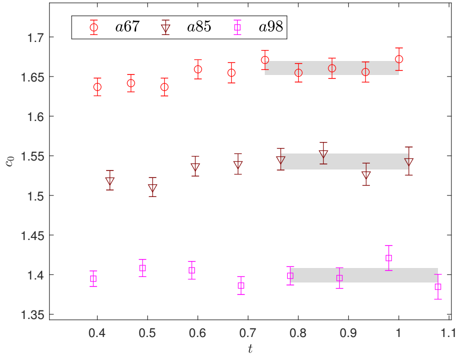
[2] ADAMS 2008 reports $[\Gamma(\eta_c(1S) \to \gamma\gamma)/\Gamma_{\text{total}}] \times [B(J/\psi(1S) \to \gamma\eta_c(1S))] = (1.2\,^{+2.7}_{-1.1} \pm 0.3) \times 10^{-6}$ which we divide by our best value $B(J/\psi(1S) \to \gamma\eta_c(1S)) = (1.41 \pm 0.14) \times 10^{-2}$. Our first error is their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

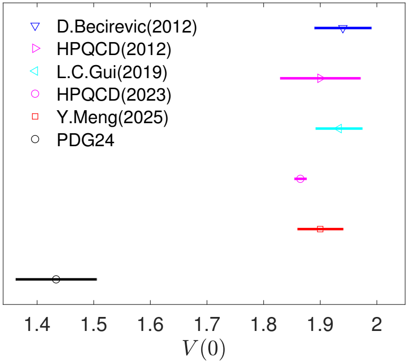
$$\mathrm{Br}(J/\psi \to \gamma\eta_c) : 1.7(4)\% \to 1.41(14)\%$$

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

- New method for $J/\psi \to \gamma\eta_c$ without momentum extrapolation

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

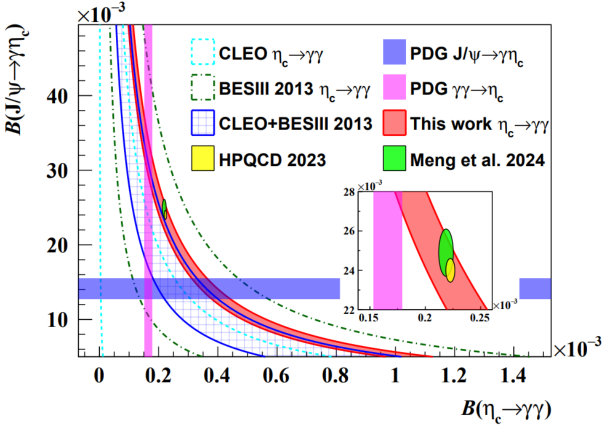




Y.M et al, PRD111,014508(2025)

A breakthrough in charmonium decay

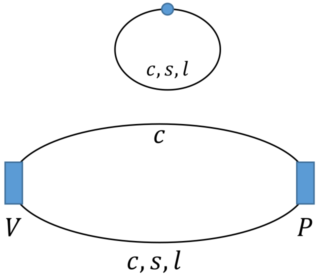
- $\mathrm{Br}(J/\psi \to \gamma\eta_c) \times \mathrm{Br}(\eta_c \to 2\gamma)$
  - Ours: $5.43(42) \times 10^{-6}$ BESIII: $5.23(40) \times 10^{-6}$



Disconnected contribution in charmed radiative decay

- Target: $J/\psi \to \gamma\eta_c$, $D_s^* \to \gamma D_s$, $D^* \to \gamma D$

Ensemble	C24P29
$a(\mathrm{fm})$	0.10524(05)(62)
$m_\pi(\mathrm{MeV})$	292.3(1.0)
$L^3 \times T$	$24^3 \times 72$
N_{con}	450×72
N_{dis}	$450 \times 72 \times 256$
Z_V	1.57353(18)



- Preliminary: $\left|\frac{V^D_{J/\psi\to\gamma\eta_c}(0)}{V^C_{J/\psi\to\gamma\eta_c}(0)}\right| = 0.05(3)\%$, $V(0) = 1.8640(57)_{\mathrm{stat}}(9)_{\mathrm{dis}}$

  Y.M et al, in preparation

D_s^* decay mode

$D_s^{*\pm}$ $I(J^P) = 0(1^-)$

$J^P = 1^-$ established by ABLIKIM 2023AZ.

$D_s^{*\pm}$ MASS	2112.2 ± 0.4 MeV	
$m_{D_s^{*\pm}} - m_{D_s^\pm}$	143.8 ± 0.4 MeV	
$D_s^{*\pm}$ WIDTH	< 1.9 MeV CL=90.0%	

D_s^{*+} DECAY MODES

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

	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D_s^+ \gamma$	$(93.6 \pm 0.4)\%$		139
Γ_2	$D_s^+ \pi^0$	$(5.77 \pm 0.35)\%$		48
Γ_3	$D_s^+ e^+ e^-$	$(6.7 \pm 1.6) \times 10^{-3}$		139
Γ_4	$e^+ \nu_e$	$(2.1^{+1.2}_{-0.9}) \times 10^{-5}$		1056

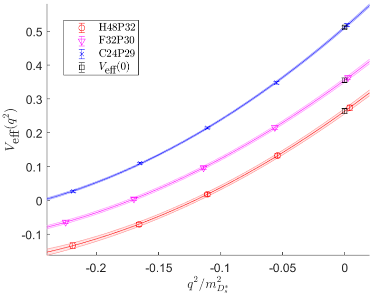
- Branching fraction first determined by BESIII PRL131,141802(2023)

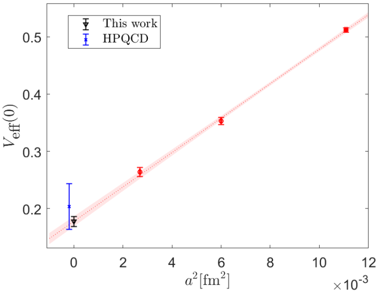
$$\mathrm{Br}(D_s^{*,+} \to e^+ \nu_e) = (2.1^{+1.2}_{-0.9}{}_{\mathrm{stat.}} \pm 0.2_{\mathrm{syst.}}) \times 10^{-5}$$

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

$D_s^* \to \gamma D_s$ from lattice QCD

$$\langle D_s(p)|J_\nu^{\rm em}(0)|D^*_{s,\mu}(p')\rangle = \frac{2V_{\rm eff}(q^2)}{m_{D_s}+m_{D_s^*}}\epsilon_{\mu\nu\alpha\beta}p_\alpha p'_\beta$$





- 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)

New constraint on $f_{D_s^*}|V_{cs}|$

- BESIII+ HPQCD

$$f_{D_s^*}|V_{cs}| = (207.9^{+59.4}_{-44.6}{}_{\rm stat.} \pm 9.9_{\rm syst.exp} \pm 41.5_{\rm syst.latt})\rm MeV$$

where $\Gamma^{\rm total}_{D_s^*} = 0.0700(280)$ keV.

- BESIII+ Ours

$$f_{D_s^*}|V_{cs}| = (190.5^{+55.1}_{-41.7}{}_{\rm stat.} \pm 9.1_{\rm syst.exp} \pm 8.7_{\rm syst.latt})\rm MeV$$

where $\Gamma^{\rm total}_{D_s^*} = 0.0589(54)$ keV.

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

- Current measurements

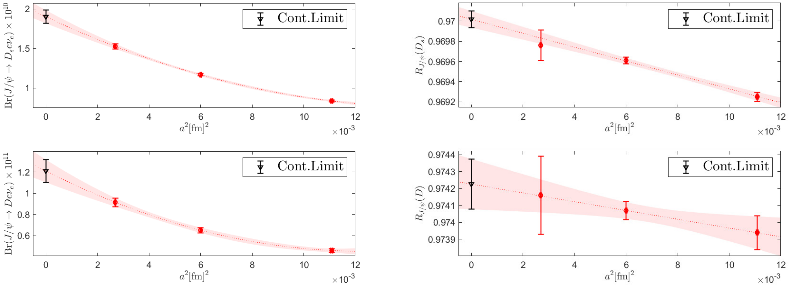
channels	Upper limit	J/ψ number	Refs
$J/\psi \to D_s e \nu_e$	4.9×10^{-5}	5.8×10^{7}	PLB639,418(2006)
$J/\psi \to D_s e \nu_e$	1.3×10^{-6}	2.3×10^{8}	PRD90,112014(2014)
$J/\psi \to D e \nu_e$	7.1×10^{-8}	1.01×10^{10}	JHEP06,157(2021)
$J/\psi \to D \mu \nu_\mu$	5.6×10^{-7}	1.01×10^{10}	JHEP01,126(2024)

BES & BESIII collaboration

- Future measurements ?

channels	Upper limit	J/ψ number	Refs
$J/\psi \to D_s e \nu_e$	—	1.01×10^{10}	BESIII
$J/\psi \to D_s \mu \nu_\mu$	—	1.01×10^{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

$J/\psi \to D/D_s l \nu_l$ decay width



- The branching fraction Y.M et al,PRD110,074510(2024)

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

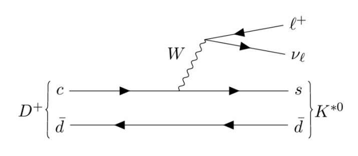
- The ratio between μ and e

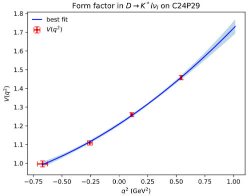
$$R_{J/\psi}(D_s) = 0.97002(8)_{\mathrm{stat}}$$
$$R_{J/\psi}(D) = 0.97423(15)_{\mathrm{stat}}$$

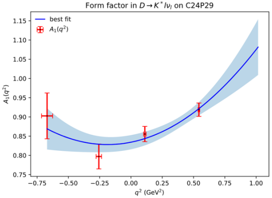
$D \to K^* l \nu_l$

$$\Gamma(D \to K^*\ell\nu) = \frac{G_F^2 |V_{cs}|^2}{192\pi^3 m_D^3} \int_0^{q^2_{\max}} dq^2 q^2 \lambda(q^2)^{1/2} \times \left(|H^+(q^2)|^2 + |H^-(q^2)|^2 + |H^0(q^2)|^2 \right)$$

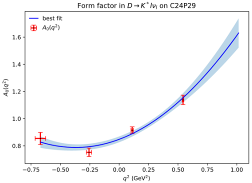
樊高峰，12:00-12:15（周一）

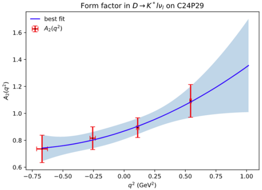






	This work	EPJC (2022)	BESIII (2025)
$r_V \equiv V(0)/A_1(0)$	1.445(36)	1.50	1.37(9)(3)
$r_2 \equiv A_2(0)/A_1(0)$	1.041(76)	0.68	0.76(6)(2)
$\mathcal{B}(D \to K^*\ell\nu) \times 10^{-2}$	4.63(44)	2.12(3)	2.073(39)(32)





$m_\pi = 292.3(1.0)\ MeV, a = 0.10524(05)(62)\ fm$

Conclusion and outlook

- Conclusion
  - A puzzle in $\eta_c \to 2\gamma$ and $J/\psi \to \gamma\eta_c$
  - The most precise $\Gamma(D_s^* \to D_s\gamma) = 0.0549(54)$ 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
  - √ Disconnected contribution in charmed radiative decays
    - $J/\psi \to \gamma\eta_c, D_s^* \to \gamma D_s, D^* \to \gamma D$
  - √ Charmed $P \to V$ semileptonic decay: $D \to K^*$ and $D_s \to \phi$
  - More systematic continuum limit $a \to 0$ and chiral limit $m_\pi \to m_\pi^{phys}$