Recent progresses on the radiative and weak decays of charmed hadron

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

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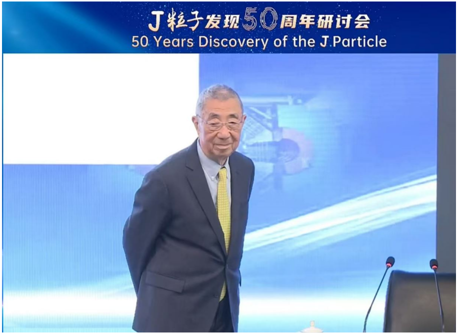
Outline

- Introduction
- Radiative decay
  - $D_s^* \to D_s\gamma$
  - $\eta_c \to 2\gamma$
  - $J/\psi \to \gamma\eta_c$
- Weak decay
  - $J/\psi \to D_s/Dl\nu_l$
- Summary and outlook

Motivation

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.



Motivation

Why charmed hadron decays ?

- Precise test for the standard model
  — The world's largest τ-charm factory—BESIII
- Test various perturbative and non-perturbative approaches
  — intermediate energy scale
- More possibilities for the search of new physics
  — rare decays

D_s^* radiative decay from the lattice QCD

Y.M.,Jin-Long Dang,Chuan Liu,Zhaofeng Liu,Tinghong Shen, Haobo Yan, and Ke-Long Zhang, PRD109,074511(2024)

D_s^* decay mode

$D_s^{*\pm}$ $\quad I(J^P) = 0(?^?)$

J^P is natural, width and decay modes consistent with 1^-.

$D_s^{*\pm}$ 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	$D_s^+ \gamma$	$(93.5 \pm 0.7)\%$		139
Γ_2	$D_s^+ \pi^0$	$(5.8 \pm 0.7)\%$		48
Γ_3	$D_s^+ e^+ e^-$	$(6.7 \pm 1.6) \times 10^{-3}$		139

- No absolute measurements, above branching fraction are determined by two relative measurements

$$R_{ee} = \Gamma(D_s^* \to D_s e^+ e^-)/\Gamma(D_s^* \to D_s \gamma)$$
$$R_{D_s \pi^0} = \Gamma(D_s^* \to D_s \pi^0)/\Gamma(D_s^* \to D_s \gamma)$$

assuming no other decay mode exists.

- Total decay width of D_s^* is experimentally unknown.

D_s^* leptonic decay

- Decay width of $D_s^* \to l\nu_l$ is

$$\Gamma(D_s^* \to l\nu_l) = \frac{G_F^2}{12\pi}|V_{cs}|^2 f_{D_s^*}^2 m_{D_s^*}^3 \left(1 - \frac{m_l^2}{m_{D_s^*}^2}\right)^2 \left(1 + \frac{m_l^2}{2m_{D_s^*}^2}\right)^2$$

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

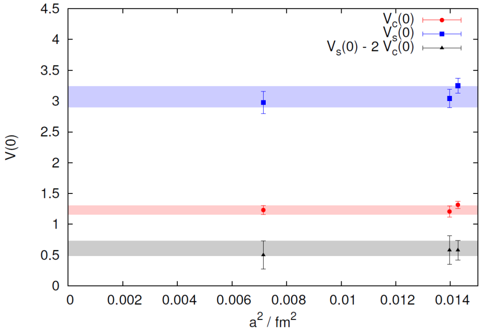
$$\mathrm{Br}(D_s^{*,+} \to e^+\nu_e) = (2.1^{+1.2}_{-0.9}{}_{\mathrm{stat.}} \pm 0.2_{\mathrm{syst.}}) \times 10^{-5}$$

- Total decay width of D_s^* is essential to extract $f_{D_s^*}|V_{cs}|$, playing a important role to test the standard model.
- Radiative decay $D_s^* \to D_s\gamma$ can be used to estimate the D_s^* total decay width.

Previous lattice study

- HPQCD, HISQ fermion with pion mass ~ 300 MeV, $a \sim 0.12$ and 0.09 fm, each ensemble with statistic $\sim 2000 \times 4$

$$\langle D_s(p)|J_\nu^{\rm em}(0)|D^*_{s,\mu}(p')\rangle = \frac{2V(q^2)}{3(m_{D_s}+m_{D_s^*})}\epsilon_{\mu\nu\alpha\beta}p_\alpha p'_\beta$$



- $\Gamma_{D_s\gamma} = 0.066(26)$ keV, PRL112,212002(2014)

$f_{D_s^*}|V_{cs}|$

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

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

- HPQCD, PRL112,212002(2014)

$$\Gamma_{D_s\gamma} = 0.066(26)\mathrm{keV}$$

- Combining the above results, it arrives at

$$f_{D_s^*}|V_{cs}| = (207.9^{+59.4}_{-44.6}{}_{\mathrm{stat.}} \pm 42.7_{\mathrm{syst.}})\mathrm{MeV}$$

with

$$\boxed{42.7_{\mathrm{syst.}} \to 9.9_{\mathrm{syst.exp}} 41.5_{\mathrm{syst.latt}}}$$

$D_s^* \to D_s\gamma$ with new method

- The effective form factor

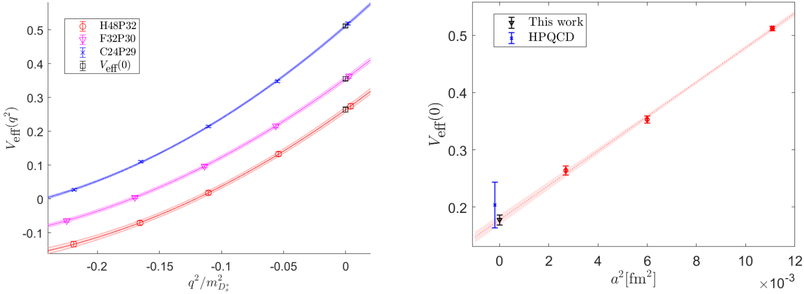
$$\langle D_s(p)|J_\nu^{\text{em}}(0)|D_{s,\mu}^*(p')\rangle = \frac{2V_{\text{eff}}(q^2)}{m_{D_s}+m_{D_s^*}}\epsilon_{\mu\nu\alpha\beta}p_\alpha p'_\beta$$

- Scalar function method

$$\begin{aligned} V_{\text{eff}}(q^2) &= \frac{-(m_{D_s}+m_{D_s^*})E_{D_s}}{2Z_{D_s}m_{D_s^*}}e^{E_{D_s}t} \\ &\times \int^R d^3\vec{x}\frac{j_1(|\vec{p}||\vec{x}|)}{|\vec{p}||\vec{x}|}\epsilon_{\mu\nu\alpha 0}x_\alpha\langle 0|\mathcal{O}_{D_s}(\vec{x},t)J_\nu^{\text{em}}(0)|D_{s,\mu}^*(p')\rangle \end{aligned}$$

with $q^2 = (m_{D_s^*} - E_{D_s})^2 - |\vec{p}|^2$.

- Zero transfer momentum $\vec{p} = (0,0,0)$ is projected directly, which is missed in the traditional way.
- Finite-volume effect is exponentially suppressed and also easily examined with an integral truncation $|\vec{x}| = R$.



- We obtain $V_{\rm eff}(0) = 0.178(9)$ and the decay width

$$\Gamma(D_s^* \to \gamma D_s) = 0.0549(54)\ \mathrm{keV}$$

with a much reduced stastistical error compared with previous $0.066(26)$ keV.

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

- BESIII+ HPQCD [PRL112,212002(2014)]

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

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

- BESIII+ this work Y.M et al,PRD109,074511(2024)

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

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

Dalitz decay $D_s^* \to D_s e^+ e^-$

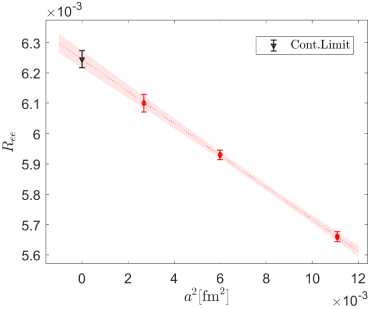
- The third decay mode observed by CLEO, giving the branching fraction

$$R_{ee} = [0.72^{+0.15}_{-0.13} \pm 0.10]\%$$

PRD 86,072005(2014)

$$R_{ee} = \frac{\Gamma(D_s^* \to D_s e^+ e^-)}{\Gamma(D_s^* \to D_s \gamma)}$$
$$= \frac{\alpha}{3\pi} \int \frac{dq^2}{q^2} \left| \frac{V_{\text{eff}}(q^2)}{V_{\text{eff}}(0)} \right|^2 \left(1 - \frac{4m_e^2}{q^2}\right)^{\frac{1}{2}} \left(1 + \frac{2m_e^2}{q^2}\right)$$
$$\times \left[\left(1 + \frac{q^2}{m_{D_s^*}^2 - m_{D_s}^2}\right)^2 - \frac{4m_{D_s^*}^2 q^2}{(m_{D_s^*}^2 - m_{D_s}^2)^2} \right]^{\frac{3}{2}}$$

L.Landsberg,Phys.Rept 128,301(1995)



- First lattice result $R_{ee} = 0.624(3)\%$, much precise than $0.67(16)\%$ PDG

$\eta_c \to 2\gamma$ decay width from lattice QCD

Y.M.,Xu Feng,Chuan Liu,Teng Wang,and Zuoheng Zou,Sci.Bull68,1880(2023)

$\eta_c \to 2\gamma$

- Experiments

	$\mathrm{Br} \times 10^5$	Note
CLEO	$0.7^{+1.6}_{-0.7} \pm 0.2$	PRL 101,101801(2008)
BESIII	$2.7 \pm 0.8 \pm 0.6$	PRD 87,032003(2013)
World average	$2.2^{+0.9}_{-0.6}$	PDG-aver
Global fit	1.68 ± 0.12	PDG-fit

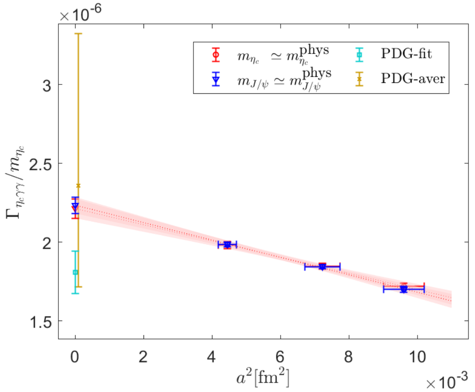
- Theories: perturbative+nonperturbative

	$\Gamma(\mathrm{keV})$	Note
NRQCD	$9.9 \sim 10.6$	PRL**119**,252001(2017)
DSE	$6.32 \sim 6.39$	PRD**95**,016010(2017)
Lattice	$6.04(68)$	CLQCD(2020)
PDG-fit	$5.4(4)$	PDG-fit

- High precision lattice simulation is essential

Results: $\eta_c \to 2\gamma$

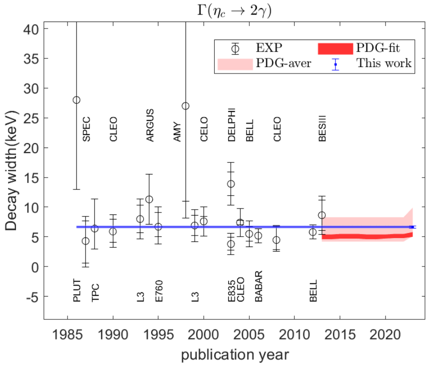
- NRQCD(NLO) ~ 6.2
  K.-T.Chao et al, PRD**56**,368(1997)
- NRQCD(NNLO) ~ 10
  F.Feng et al, PRL**119**,252001(2017)
- Lattice QCD $\sim 6.0(7)$
  CLQCD(2020)
- DSE ~ 6.4
  J.Chen et al, PRD**95**,016010(2017)



$$\Gamma(\eta_c \to 2\gamma) = \begin{cases} 6.67(16)(6)\,\text{keV} \\ 5.4(4)\,\text{keV} \quad \text{PDG-fit} \\ 7.04^{+2.9}_{-1.9}\,\text{keV} \quad \text{PDG-aver} \end{cases}$$

YM et al, Sci Bull 68,1880(2023)

Lattice & Experiments



PDG(2023)

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

VALUE (keV)		*EVTS*
5.4 ± 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*
5.1 ± 0.4	OUR FIT Error includes scale factor of 1.2.	

- Verified by HPQCD, $\Gamma_{\eta_c\gamma\gamma} = 6.788(45)_{\rm fit}(41)_{\rm syst}$ keV, PRD108,014513(2023)

PDG global fit

An overall fit to total width,10 combinations of particle width obtained from integrated cross section,21 branching ratios uses 97 measurements and one constraint to determine 15 parameters. The overall fit has a $\chi^2 = 120.8$ for 83 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i = \Gamma_i / \Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_1	x_5	x_8	x_{15}	x_{17}	x_{34}	x_{35}	x_{38}	x_{42}	x_{45}	x_{48}	x_{50}	x_{56}	Γ	x_{999}
x_1	100														
x_5	13	100													
x_8	25	14	100												
x_{15}	10	5	10	100											
x_{17}	5	3	6	2	100										
x_{34}	30	17	35	13	7	100									
x_{35}	15	8	17	6	3	48	100								
x_{38}	16	9	17	7	3	21	10	100							
x_{42}	12	7	13	5	3	21	10	8	100						
x_{45}	18	10	20	8	4	24	12	13	10	100					
x_{48}	17	10	19	7	4	26	13	12	9	14	100				
x_{50}	4	2	5	2	1	6	3	3	2	3	24	100			
x_{56}	-45	-25	-50	-19	-10	-60	-29	-31	-24	-36	-36	-9	100		
Γ	-2	-1	-2	-1	0	-3	-1	-2	-1	-2	6	1	-28	100	
x_{999}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100

	Mode	Rate (MeV)	Scale factor
Γ_1	$\eta_c(1S) \to \eta'(958)\pi\pi$	0.60 ± 0.08	
Γ_5	$\eta_c(1S) \to K^*(892)\overline{K}^*(892)$	0.20 ± 0.04	
Γ_8	$\eta_c(1S) \to \phi\phi$	0.051 ± 0.006	
Γ_{15}	$\eta_c(1S) \to \omega\omega$	0.066 ± 0.015	
Γ_{17}	$\eta_c(1S) \to f_2(1270) f_2(1270)$	0.31 ± 0.08	
Γ_{34}	$\eta_c(1S) \to K\overline{K}\pi$	2.25 ± 0.14	
Γ_{35}	$\eta_c(1S) \to K\overline{K}\eta$	0.42 ± 0.05	
Γ_{38}	$\eta_c(1S) \to K^+K^-\pi^+\pi^-$	0.206 ± 0.032	
Γ_{42}	$\eta_c(1S) \to 2(K^+K^-)$	0.044 ± 0.009	
Γ_{45}	$\eta_c(1S) \to 2(\pi^+\pi^-)$	0.277 ± 0.035	
Γ_{48}	$\eta_c(1S) \to p\overline{p}$	0.043 ± 0.004	
Γ_{50}	$\eta_c(1S) \to \Lambda\overline{\Lambda}$	0.033 ± 0.007	
Γ_{56}	$\eta_c(1S) \to \gamma\gamma$	0.0054 ± 0.0004	

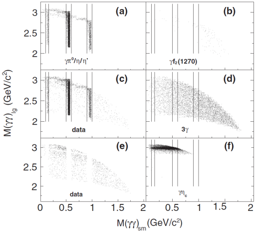
- The smaller errros of fitting may due to: (i)large uncertainties of $\eta_c \to 2\gamma$; (ii)Highly correlated with other decay channels ;

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
1.66 ± 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	$\bar{p}\, p \to \gamma\gamma$
< 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	$J/\psi \to \eta_c \gamma$

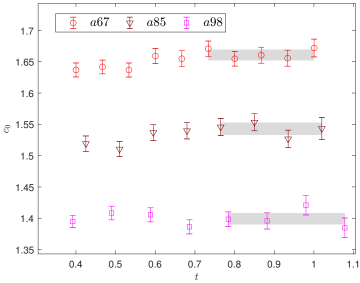
[1] ABLIKIM 2013I reports $[\Gamma(\eta_c(1S) \to \gamma\gamma)/\Gamma_{\text{total}}] \times$ [B($J/\psi(1S) \to \gamma\eta_c(1S)$)] = $(4.5 \pm 1.2 \pm 0.6) \times 10^{-6}$ which we divide by our best value B($J/\psi(1S) \to \gamma\eta_c(1S)$) = $(1.41 \pm 0.14) \times 10^{-2}$. Our first error is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

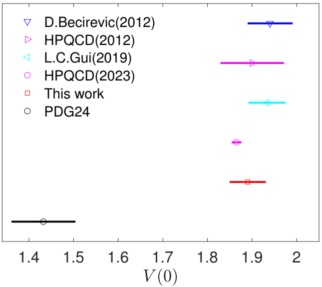
[2] ADAMS 2008 reports $[\Gamma(\eta_c(1S) \to \gamma\gamma)/\Gamma_{\text{total}}] \times$ [B($J/\psi(1S) \to \gamma\eta_c(1S)$)] = $(1.2\ ^{+2.7}_{-1.1} \pm 0.3) \times 10^{-6}$ which we divide by our best value B($J/\psi(1S) \to \gamma\eta_c(1S)$) = $(1.41 \pm 0.14) \times 10^{-2}$. Our first error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

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

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

- New method for $J/\psi \to \gamma\eta_c$ without momentum extrapolation
  $V(0) = 1.89(4)$ Y.M. et al, in preparation





- Lattice vs PDG: a puzzle !

3 σ tension for $\eta_c \to 2\gamma$ and 5 σ tension for $J/\psi \to \gamma\eta_c$

$J/\psi \to D/D_s l\nu_l$ semileptonic decay from lattice QCD

Y.M.,Jin-Long Dang,Chuan Liu,Xin-Yu Tuo,Haobo Yan,Yi-Bo Yang, and Ke-Long Zhang,PRD110,074510(2024)

J/ψ decay channels

- Decays involving hadronic resonances
- Decays into stable hadrons
- Radiative decays
- Dalitz decays
- Weak decays

Γ_{364}	$D^- e^+ \nu_e$ + c.c.	$< 7.1 \times 10^{-8}$	CL=90%	984	∨
Γ_{365}	$\overline{D}^0 e^+ e^-$ + c.c.	$< 8.5 \times 10^{-8}$	CL=90%	987	∨
Γ_{366}	$D_s^- e^+ \nu_e$ + c.c.	$< 1.3 \times 10^{-6}$	CL=90%	923	∨
Γ_{367}	$D_s^{*-} e^+ \nu_e$ + c.c.	$< 1.8 \times 10^{-6}$	CL=90%	828	∨
Γ_{368}	$D^- \pi^+$ + c.c.	$< 7.5 \times 10^{-5}$	CL=90%	977	∨
Γ_{369}	$\overline{D}^0 \overline{K}^0$ + c.c.	$< 1.7 \times 10^{-4}$	CL=90%	898	∨
Γ_{370}	$\overline{D}^0 \overline{K}^{*0}$ + c.c.	$< 2.5 \times 10^{-6}$	CL=90%	670	∨
Γ_{371}	$D_s^- \pi^+$ + c.c.	$< 1.3 \times 10^{-4}$	CL=90%	915	∨
Γ_{372}	$D_s^- \rho^+$ + c.c.	$< 1.3 \times 10^{-5}$	CL=90%	663	∨

- Semileptoinc decay: $J/\psi \to D/D_s l \nu_l$ this work
- Phenomenological aspect: plenties of studies on hadronic and radiative decay, less on semileptonic decay(Br $< 10^{-8}$) $\longleftarrow$ limited by the experimental detection

Experimental searches

- Completed 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

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

- 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)

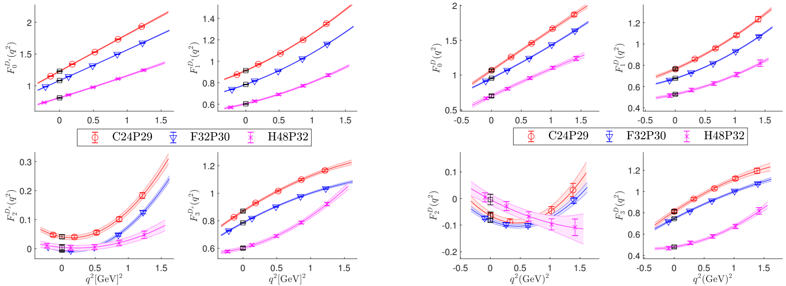
$$\begin{aligned} H_{\mu\alpha}(p,p') &\equiv \langle D/D_s(p)|J_\mu^W|J/\psi_\alpha(\epsilon,p')\rangle \\ &= F_1(q^2)g_{\mu\alpha} + \frac{F_2(q^2)}{Mm}p'_\mu p_\alpha + \frac{F_3(q^2)}{m^2}p_\mu p_\alpha - \frac{iF_0(q^2)}{Mm}\epsilon_{\mu\alpha\rho\sigma}p'_\rho p_\sigma \end{aligned}$$

- The decay width

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

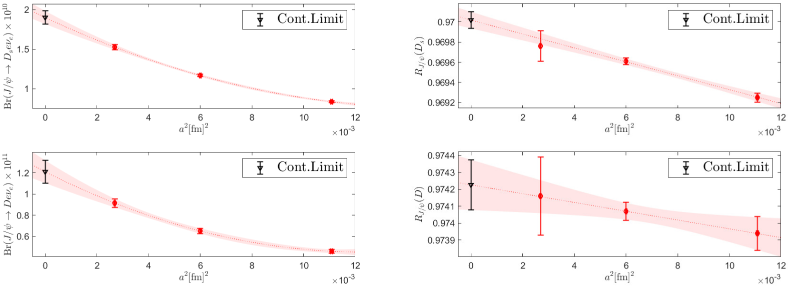
with $E_l^\pm = \frac{1}{2M}\left[q^2 + m_l^2 - \frac{1}{2q^2}\Big((q^2 - M^2 + m^2)(q^2 + m_l^2) \mp 2M|\vec{p}|(q^2 - m_l^2)\Big)\right]$

Form factors



- Correlated fit to a constant at suitable time region $\sim [0.8, 1.7]$ fm for all ensembles with $|\vec{p}| = 2\pi|\vec{n}|/L, |\vec{n}|^2 = 0, 1, 2, 3, 4.$
- A polynomial form $F_i(q^2) = d_i^{(0)} + d_i^{(1)} \cdot q^2 + d_i^{(2)} \cdot q^4$ describes lattice data well

Decay width



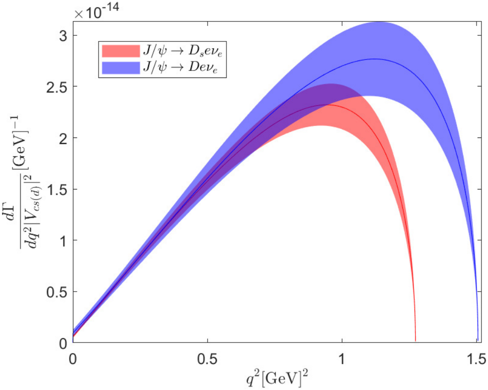
- The branching fraction Y.M et al,PRD110,074510(2024)

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

- The ratio between μ and e

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

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/ψ samples Front. Phys. (Beijing) 19, 14701(2024)

High precision flavor physics

- Light, strange and charm quark included (point+wall propagator)
  - Calculate arbitrary three-point function
  - Five lattice spacings for continuum limit
  - Physical pion mass extrapolation

Symbol	a(fm)	$L^3 \times T$	m_π(MeV)	$N_c \times N_t$	Disk(T)
C24P29	0.10521	$24^3 \times 72$	292.3(1.0)	200×72	90
E28P35	0.08970	$28^3 \times 64$	351.4(1.4)	150×64	85
F32P30	0.07751	$32^3 \times 96$	300.4(1.2)	150×96	285
G36P29	0.06884	$36^3 \times 108$	297.2(0.9)	150×54	256
H48P32	0.05198	$48^3 \times 144$	316.6(1.0)	80×72	576
C32P23	0.10521	$32^3 \times 64$	227.9(1.2)	150×64	130
C48P14	0.10521	$48^3 \times 96$	136.4(1.7)	80×96	512
F48P21	0.07751	$48^3 \times 96$	207.5(1.1)	80×96	512

- Total: 2.4P

Conclusion and outlook

- Conclusion
  - Lattice studies on $\eta_c \to 2\gamma, J/\psi \to \gamma\eta_c, D_s^* \to D_s\gamma$ and $J/\psi \to D/D_s l\nu_l$ with new lattice method
  - New puzzle in $\eta_c \to 2\gamma$, 2.9σ tension with the PDG value
  - 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 method can be generally applide to various $P \to V$ semileptonic decay.
- Outlook
  - Continuum limit and physical pion mass on the lattice, towards the world's highest precision lattice calculation on flavor physics.

CLQCD in china

CLQCD

China Lattice QCD
(CLQCD)
collaboration

北大，北航，北师大，
湖南师大，华南师大，
华中师大，江苏大学，
南开大学，上海交大，
四川大学，西安工大，
浙江大学，郑州大学，
中科院大学/高能所/
近物所/理论所…