A precise determination of D_s^* radiative decay width from lattice QCD

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2401.13475(PRD in press)

第六届重味物理与量子色动力学研讨会，青岛，4.19-4.22, 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)

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

- 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.

Phenomenological studies

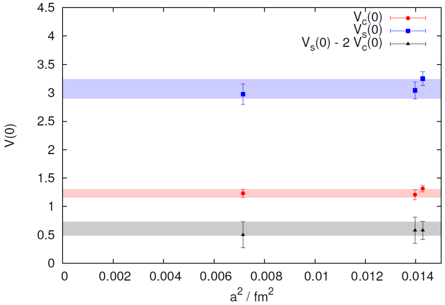
- $D_s^* \to D_s\gamma$

Method	$\Gamma_{D_s\gamma}$(keV)	Refs
χPT	4.5	H-Y.Cheng et al, PRD49,5857(1994)
χPT	0.32 ± 0.3	B.Wang et al, PRD100,016019(2019)
LFQM	0.18 ± 0.01	H.M.Choi,J.Korean Phys.Soc.53,1295(2008)
RQM	$0.321^{+0.009}_{-0.008}$	J.L. Goity et al,PRD64,094007(2001)
QCDSR	0.25 ± 0.08	T.M. Aliev,PLB334,169(2004)
QCDSR	0.51 ± 0.15	G.L.Yu et al,EPJC75,243(2015)
NJLM	0.09	H.B.Deng et al, CPC38,013103(2014)
NRQM	0.21	A.N.Kamal et al, PLB284,421(1992)
NRQM	0.4	A.Fayyazuddin, PRD48,1220(1993)

Lattice result

- 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 determinted 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

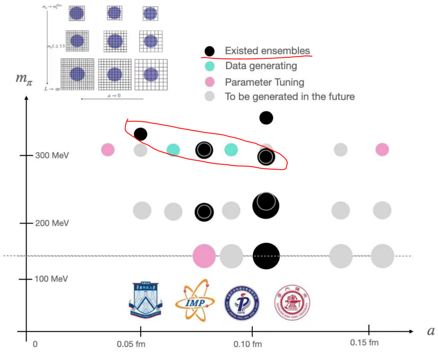
$$f_{D_s^*}|V_{cs}| = (207.9^{+59.4}_{-44.6\,\mathrm{stat.}} \pm 42.7_{\mathrm{syst.}})\mathrm{MeV}$$

with

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

Our target

- CLQCD gauge ensembles



CLQCD Collaboration, PRD109,054507(2024), much effort from Ming Gong,Liuming Liu,Peng Sun,Wei Wang,Yi-Bo Yang et al.

- Statistical error $\leq 10\% \Leftarrow 40\%(\text{HPQCD})$

Computational Resources

"SongShan" supercomputer at Zhengzhou University

- The queue vip1 is only used for lattice study

- A small step now, a promising future(total 3800 nodes and 100PB storage at Zhengzhou University)

Lattice setup

Ensemble	C24P29	F32P30	H48P32
a(fm)	0.10530(18)	0.07746(18)	0.05187(26)
$a\mu_s$	-0.2400	-0.2050	-0.1700
$a\mu_c$	0.4479	0.2079	0.0581
$L^3 \times T$	$24^3 \times 72$	$32^3 \times 96$	$48^3 \times 144$
$N_{\rm cfg} \times N_{\rm src}$	450×72	377×96	306×72
m_π(MeV)	292.7(1.2)	303.2(1.3)	317.2(0.9)
$m_{J/\psi}$(MeV)	3098.6(0.3)	3094.9(0.4)	3096.5(0.3)
t	3-18	2-22	8-30
Z_V	0.79814(23)	0.83548(12)	0.86855(04)

- (2+1)-flavor Wilson-clover gauge ensembles
- Similar pion mass ~ 300 MeV, volume ~ 2.5 fm, more fine lattice spacing $\Rightarrow$ continuum limit
- Each ensemble with the statistics 3-4 times larger than HPQCD.

Methodology

- The effective form factor

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

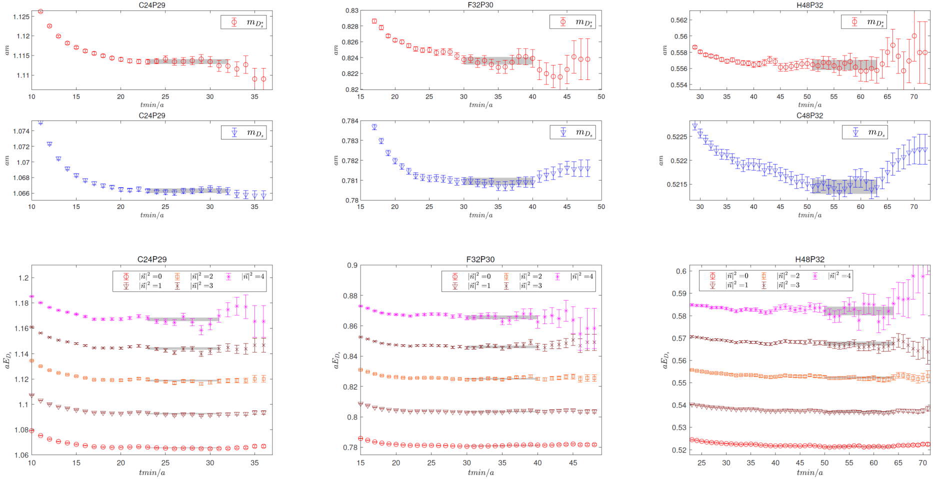
- Scalar function method   YM,Xu Feng,Chuan Liu,et al,Sci.Bull 68,1880(2023)

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

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

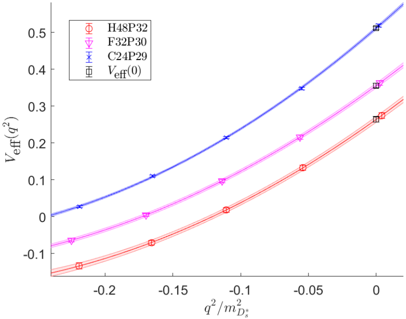
  - Zero transfer momentum $\vec{p}=(0,0,0)$ is projected directly, which is missed in the traditional way.
  - Finite-volume effect is exponentially suppressed and also easily examined with an integral truncation $|\vec{x}|=R$.

Spectrum of D_s^* and D_s



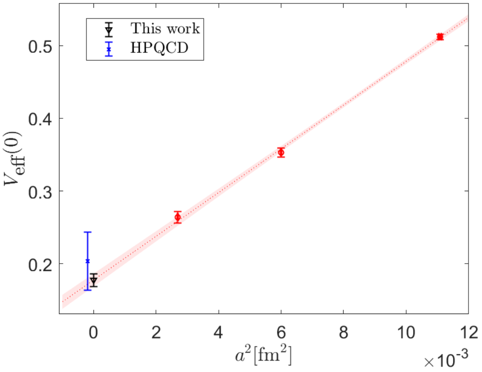
- Extracted by correlated fit within the range $t \in [2.3, 3.4]$ fm

Form factor



- The far right points are missed in traditional extrapolation. $V_{\text{eff}}(0)$ is strictly constrained by $V_{\text{eff}}(\delta^2 m)$.
  - Note $q^2 = (m_{D_s^*} - E_{D_s})^2 - |\vec{p}|^2 \to \delta^2 m$ as $|\vec{p}| = 0$
- New method has a unique advantage in precision calculation.

Continuum limit



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

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

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 [2401.13475]

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

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

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

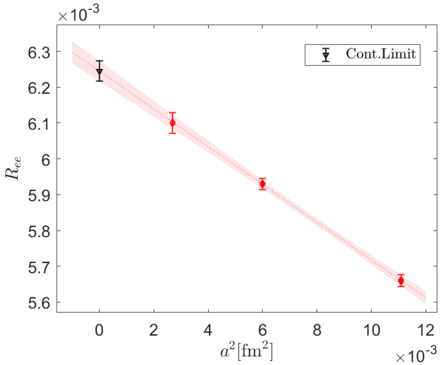
- The third decay mode observed by CLEO, giving the branching fraction

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

PRD 86,072005(2014)

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

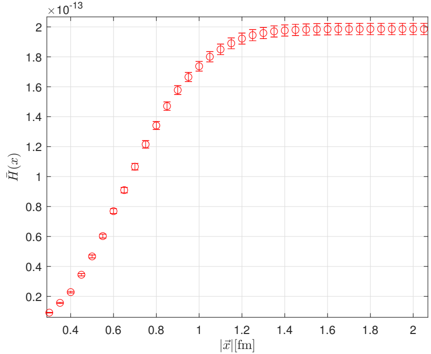
L.Landsberg,Phys.Rept 128,301(1995)



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

Finite-volume effect

- R-dependence of the quantity $\bar{H}(\vec{x},t) = \epsilon_{\mu\nu\alpha 0} x_\alpha \langle 0|\mathcal{O}_{D_s}(\vec{x},t) J_\nu^{\text{em}}(0)|D^*_{s,\mu}(p')\rangle$
- Three volumes are 2.53fm, 2.48fm, and 2.49fm for L=24,32 and 48. Take L=32 with $t = 1.24$ fm as an example



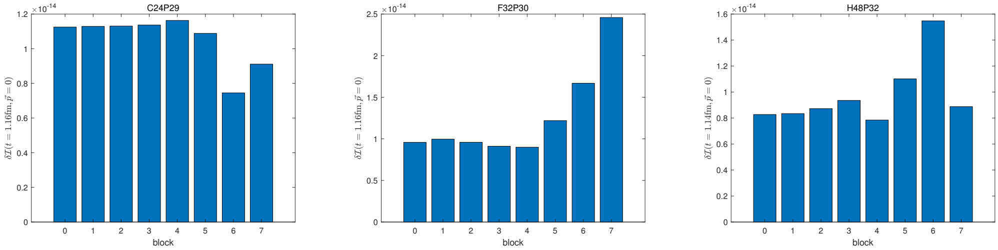
- $R > 1.4$ fm, the hadronic function has a negligible contribution.

Conclusion and outlook

- Conclusion
  - We present a lattice calculation of D_s^* radiative decay using Wilson-clover gauge ensembles by CLQCD.
  - After a continuum limit, we obtain $\Gamma(D_s^* \to D_s\gamma) = 0.0549(54)$ keV with much reduced statisticl error than before.
  - Dalitz decay $D_s^* \to D_s e^+ e^-$ is studied for the first time and the ratio is obtained as $R_{ee} = 0.624(3)\%$.
  - We determine $f_{D_s^*}|V_{cs}| = (190.5^{+55.1}_{-41.7}{}_{\text{stat.}} \pm 12.6_{\text{syst.}})$ MeV with the experimental input of $\mathrm{Br}(D_s^{+,*} \to e^+\nu_e)$.
- Outlook
  - The effects from the neglected disconnected diagrams, the quenching of the charm quark, and nonphysical light quark masses are considered in the future.

Thank you for attention!

Autocorrelation



Blocking $\mathcal{I}(t, |\vec{p}|)$ to check the potential autocorrelation effects.