

Lattice calculation of D_s^* radiative decay width lattice QCD

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

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

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

$$R_{D_s \pi^0} = \Gamma(D_s^* \rightarrow D_s \pi^0) / \Gamma(D_s^* \rightarrow D_s \gamma)$$

assuming no other decay mode exists.

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

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

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

- Branching fraction first determined by BESIII [PRL131,141802\(2023\)](#)

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

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

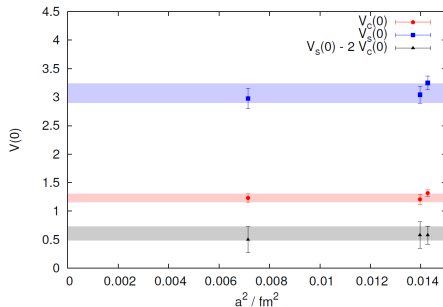
- $D_s^* \rightarrow D_s \gamma$

Method	$\Gamma_{D_s \gamma}(\text{keV})$	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 $\sim 2000 \times 4$

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



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

- Branching fraction first determined by BESIII [PRL131,141802\(2023\)](#)

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

- HPQCD, [PRL112,212002\(2014\)](#)

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

- Combining the above results, it arrives at

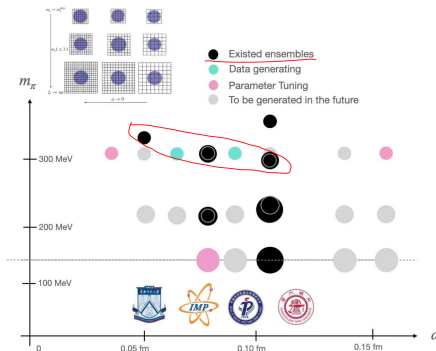
$$f_{D_s^*}|V_{cs}| = (207.9_{-44.6}^{+59.4}_{\text{stat.}} \pm 42.7_{\text{syst.}}) \text{MeV}$$

with

$$42.7_{\text{syst.}} \rightarrow 9.9_{\text{syst.exp}} 41.5_{\text{syst.latt}}$$

Our target

- CLQCD gauge ensembles



Quark masses and low energy constants in the continuum from the tadpole improved clover ensembles



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

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

"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)

Ensemble	C24P29	F32P30	H48P32
$a(\text{fm})$	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
$L^3 \times T$	$24^3 \times 72$	$32^3 \times 96$	$48^3 \times 144$
$N_{\text{cfg}} \times N_{\text{src}}$	450×72	377×96	306×72
$m_\pi(\text{MeV})$	292.7(1.2)	303.2(1.3)	317.2(0.9)
$m_{J/\psi}(\text{MeV})$	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.

- The effective form factor

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

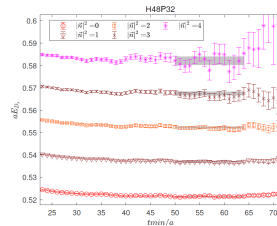
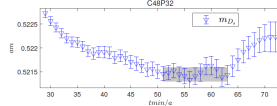
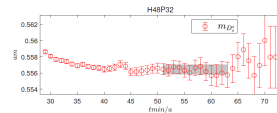
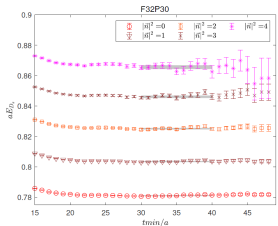
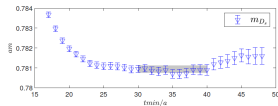
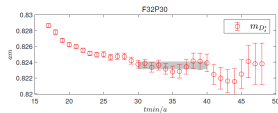
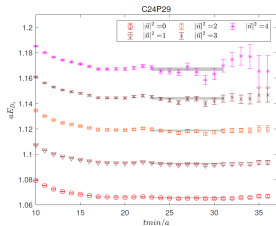
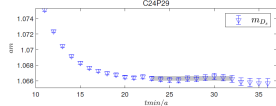
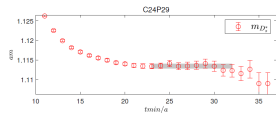
- Scalar function method YM,Xu Feng,Chuan Liu,et al,Sci.Bull 68,1880(2023)

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

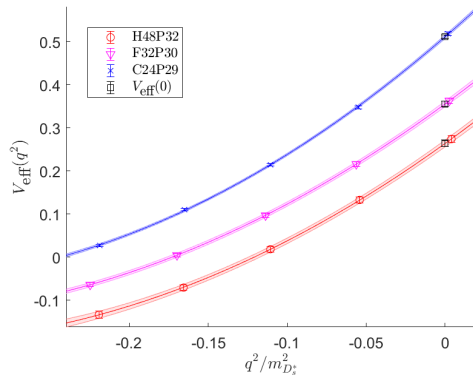
with $q^2 = (m_{D_s^*} - E_{D_s})^2 - |\vec{p}|^2$.

- 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 $|\vec{x}| = R$.

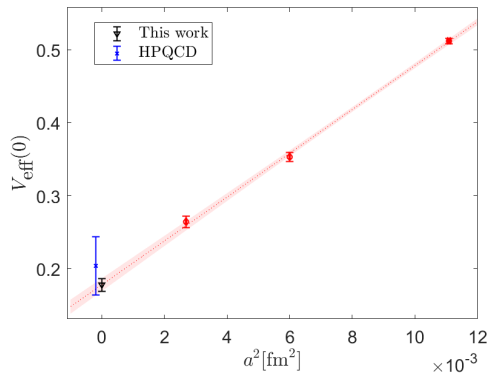
Spectrum of D_s^* and D_s



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



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



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

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

with a much reduced statistical error compared with previous $0.066(26) \text{ keV}$.

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

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

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

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

- BESIII+ this work [2401.13475]

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

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

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

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

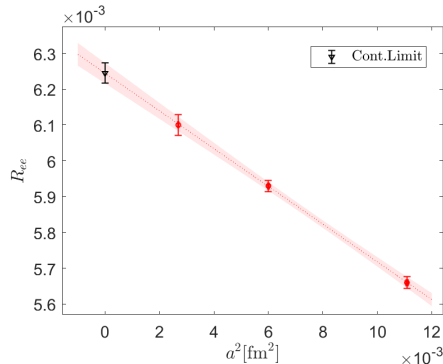
$$R_{ee} = [0.72^{+0.15}_{-0.13} \pm 0.10]\%$$

PRD 86,072005(2014)

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

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

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



• Conclusion

- We present a lattice calculation of D_s^* radiative decay using Wilson-clover gauge ensembles by CLQCD.
- After a continuum limit, we obtain $\Gamma(D_s^* \rightarrow D_s \gamma) = 0.0549(54) \text{ keV}$ with much reduced statistical error than before.
- Dalitz decay $D_s^* \rightarrow D_s e^+ e^-$ is studied for the first time and the ratio is obtained as $R_{ee} = 0.624(3)\%$.
- We determine $f_{D_s^*} |V_{cs}| = (190.5_{-41.7}^{+55.1} \text{stat.} \pm 12.6_{\text{syst.}}) \text{ MeV}$ with the experimental input of $\text{Br}(D_s^{+,*} \rightarrow e^+ \nu_e)$.

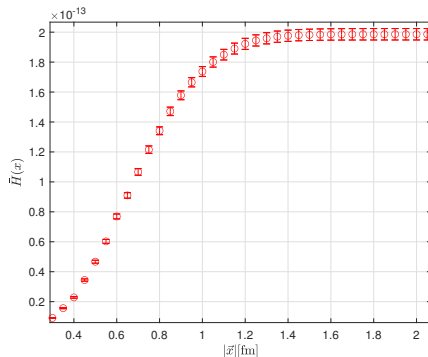
• Outlook

- 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!

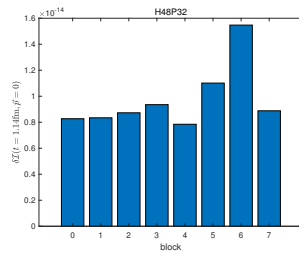
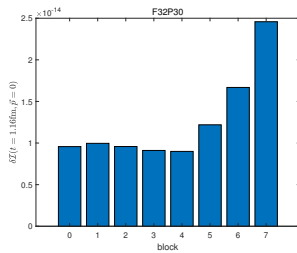
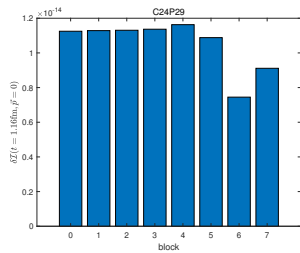
Finite-volume effect

- 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.

Autocorrelation



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