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Form factors of the $D_s \to \phi \ell \nu_\ell$ semileptonic decay with (2+1)-flavor lattice QCD

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We present a systematic lattice calculation of the vector and axial vector form factors V and A_i $(i = 0, 1, 2)$ for the $D_s \to \phi \ell \nu_\ell$ semileptonic decay using (2+1)-flavor Wilson-clover fermion configurations generated by the CLQCD collaboration. Seven gauge ensembles with different lattice spacings, from 0.052 fm to 0.105 fm, and different pion masses, from about 210 MeV to 320 MeV are utilized, enabling us to take both the continuum limit and physical pion mass extrapolation. The form factor ratios are obtained to be $r_V = 1.614(19)$ and $r_2 = 0.741(31)$. Our results of form factors reach the precision of $1\% - 4\%$, which greatly improves the previous lattice QCD results and obtains the most precise determination to date.

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1. Introduction

Semileptonic decays of D_s mesons provide valuable information to study the weak and strong interactions of charmed hadrons. The partial decay rate is related to the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{cs}|$, which parametrizes the mixing of different quark flavors, and the form factors describing the non-perturbative strong interactions. Precise calculations of form factors can help to rigorously test the Standard Model and probe potential new physics. Theoretically, the process with a vector final particle is much less studied and poses further challenges due to the decay of the unstable vector particle.

The Euclidean transition matrix element is traditionally parametrized as the following [1]

$$\begin{aligned}\left\langle \phi\left(\vec{p}\right)\left|J_\mu^W\left(0\right)\right|D_s\left(p'\right)\right\rangle = {} & \varepsilon_\nu^* \epsilon_{\mu\nu\alpha\beta} p'_\alpha p_\beta \frac{2V(q^2)}{m+M} + (M+m)\,\varepsilon_\mu^* A_1(q^2) \\ & + \frac{\varepsilon^* \cdot q}{M+m}\left(p+p'\right)_\mu A_2(q^2) - 2m\frac{\varepsilon^* \cdot q}{q^2} q_\mu \left[A_0(q^2) - A_3(q^2)\right], \end{aligned} \tag{1}$$

where M is the mass of the D_s meson; m, $p = (iE, \vec{p})$, and ε_μ are the mass, momentum, and polarization vector of the ϕ meson; and $q^2 = (M-E)^2 - |\vec{p}|^2$ is the transfer momentum square as D_s is at rest. The weak current has the form $J_\mu^W = \bar{s}\gamma_\mu\left(1-\gamma_5\right)c$. Four form factors V, A_0, A_1, A_2 are introduced here and are extracted using the scalar function method, which possesses exact rotational invariance and has been applied to various physical processes [2–6]. The scalar functions are constructed by contracting the Lorentzian tensor structure in the transition matrix element. The form factors then can be accessed via solving the linear equations. Then, the key quantities $r_V \equiv V\left(0\right)/A_1\left(0\right)$, $r_2 \equiv A_2\left(0\right)/A_1\left(0\right)$, and $r_0 \equiv A_0\left(0\right)/A_1\left(0\right)$ can be obtained. The formalism details can be found in Ref. [7].

2. Lattice setup and simulation results

We employ seven $(2+1)$-flavor Wilson-clover gauge ensembles generated by the CLQCD collaboration [8, 9]. The dynamical ensembles use tadpole-improved tree-level Symanzik gauge action and tadpole-improved tree-level clover fermions. The valence strange and charm quark masses are tuned using the "fictitious" meson η_s and the D_s meson masses. Parameters of gauge ensembles used in this work can be found in Ref. [7].

After obtaining the form factors on each ensemble, the z-expansion extrapolation to the continuum limit and physical pion mass point is performed. The fit function is

$$F\left(q^2, a, m_\pi\right) = \frac{1}{1 - q^2/m_{\text{pole}}^2} \sum_{i=0}^{2} \left(c_i + d_i a^2\right)\left[1 + f_i\left(m_\pi^2 - m_{\pi,\text{phys}}^2\right)\right] z^i, \tag{2}$$

with

$$z\left(q^2, t_0\right) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \tag{3}$$

where F denotes V and A_i $(i = 0, 1, 2)$; $t_+ = \left(m_{D_s} + m_\phi\right)^2$, $t_0 = 0$; c_i, d_i, and f_i are parameters to be determined by fitting. Here, m_{D_s}, m_ϕ, and pole masses $m_{D_s^*}$, $m_{D_{s1}}$ for V and A_i $(i = 0, 1, 2)$ are

fixed to their experimental values $m_{D_s} = 1968.4$ MeV, $m_\phi = 1019.5$ MeV, $m_{D_s^*} = 2112.2$ MeV and $m_{D_{s1}} = 2459.5$ MeV [10]. Our results are listed in Table 1. Detailed comparisons of $r_{V,2}$ between our results and previous lattice/phenomenological theory/experiment results are shown in Fig. 1.

Table 1: Numerical results of the form factors $V(0)$, $A_i(0)$ $(i = 0, 1, 2)$, and $r_{V,2,0}$.

	$V(0)$	$A_1(0)$	$A_2(0)$	$A_0(0)$	$A_3(0) - A_0(0)$	r_V	r_2	r_0
This work	1.002(9)	0.621(5)	0.460(19)	0.692(4)	0.004(12)	1.614(19)	0.741(31)	1.114(11)
HPQCD [11]	1.059(124)	0.615(24)	0.457(78)	0.706(37)	Enforced to 0	1.720(210)	0.740(120)	1.140(60)

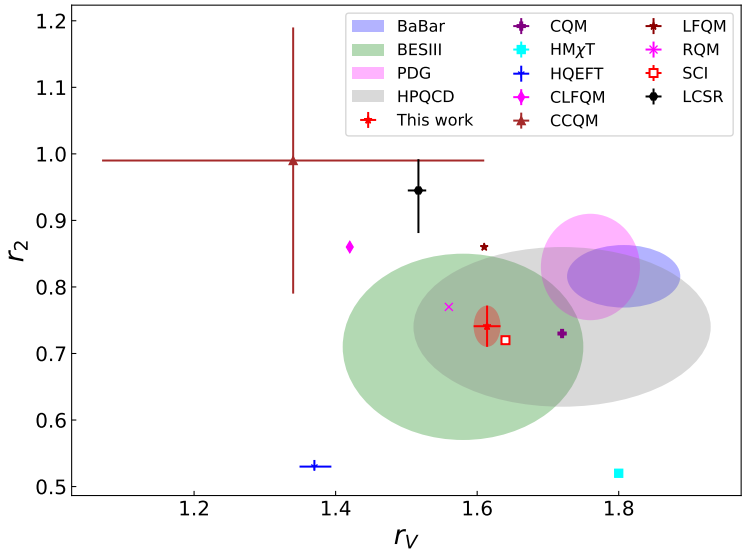

Figure 1: The comparisons of r_V and r_2 calculated in this work, and those given by different theoretical predictions [12–20] and experimental measurements [21, 22].

3. Summary

In this work, we present a systematic lattice calculation on the $D_s \to \phi \ell \nu_\ell$ semileptonic decay form factors. Seven (2+1)-flavor Wilson-clover gauge ensembles with different lattice spacings and pion masses are used. The calculations cover the full q^2 range, leading to a well-controlled accuracy. After the continuum limit and physical pion mass extrapolation, the form factor ratios are obtained to be $r_V = 1.614(19)$ and $r_2 = 0.741(31)$ with z-expansion. More results on the branching fractions, $|V_{cs}|$ and discussions on the finite-volume effects can be found in Ref. [7].

The scalar function scheme employed in this work can be widely applied to other pseudoscalar to vector semileptonic decays, for example, the $D \to K^*$ [23] channel.

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