CONSTRAINING NEW PHYSICS WITH *D* MESON DECAYS

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ABSTRACT

On one hand, we investigated the decay rates of meson decays from the basic computations of the Feynman diagrams. Under this approach, we derived analytically expressions for the square amplitudes of leptonic and semileptonic decays and finally used them to determine the analytical and numerical results for the decay rates. With decay rates results at our disposal, we determined the branching ratios of leptonic and semileptonic decays separately within the standard model (SM) compared our results to the latest theoretical and experimental results. On the other hand, we focused on the effective Lagrangian (EL) under weak interaction from a general approach and used it in our calculation of differential decay rates of mesons. Thereafter, we calculated the total decay rates via integration with respect to. In addition, using the total decay rates results, the branching ratios and the contributions from the new physics (NP) operators were investigated resulting in some phenomenologies of physics beyond the SM.

Keywords : Dmeson; Leptonic decay; Semileptonic decay; New physics

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INTRODUCTION

The process of D meson's semileptonic decay has been extensively investigated in the field of particle physics. This process entails the decay of a D meson into a comparatively lighter meson, along with the discharge of a lepton and a neutrino. This phenomenon has garnered significant attention owing to its capacity to offer valuable understanding regarding the characteristics of the weak force and the composition of the D meson. This is a powerful tool for studying the weak interaction, which is one of the four fundamental forces of nature. The Standard Model (SM) is a theoretical construct that elucidates the dynamics of three fundamental forces of nature, specifically the electromagnetic, weak, and strong forces. Furthermore, it presents a thorough and inclusive depiction of the entirety of elementary particles that are presently recognized. The Standard Model postulates that the weak interaction is facilitated by the W and Z bosons. The decay of D mesons is attributed to the interaction between charm quarks in the D mesons and bosons. The strength of the weak interaction can be measured by utilizing the decay rate of semileptonic D meson decay. The investigation of the quarks and leptons characteristics implicated in the decay process can be facilitated by analyzing the angular distribution of semileptonic D meson decay. The investigation of potential indications of ne physics beyond the Standard Model can also be conducted through the analysis of semileptonic decay of D mesons. The investigation of these decay presents an opportunity to explore the possibility of detecting indications of novel physical phenomena that extend beyond the Standard Model (SM), such as the presence of additional quarks or bosons. The phenomenon of semileptonic decay of D mesons is a complex process that remains incompletely comprehended. The process under consideration holds significant importance in the domain of particle physics, and it is highly probable that the continuous research endeavors in this area will culminate in an enhanced comprehension of the weak interaction and the constituent particles that constitute matter.

From theory and experiments, there are several arguments to believe that the SM is just the low energy limit of a more fundamental theory. This is not necessarily true because the SM has been successfully tested at an impressive level of accuracy and provides at present our best fundamental understanding of the phenomenology of particle physics. During the 20th century, physicists made tremendous progress in observing smaller and smaller objects and today's accelerators allow us to study matter on length scales as short as 10 m to 18 m [1].

The basic questions of particle physics are:

1. What is the world made of?
2. What is the smallest indivisible building block of matter?
3. Is there such a thing?

A major goal of physics is to find a common ground that would give an integrated approach and understanding on how to solve these questions surrounding nature [2].

Despite the high level of consistence and accuracy within the SM, it does leave some phenomena unexplained and it falls short of being a complete theory of fundamental interactions [3]. Therefore, the answer to these challenges lie in probing more of physics beyond the SM [4].

Semileptonic D Meson Decay

Semileptonic D meson decay refers to the decay of D mesons, which are particles composed of a charm quark and an up or down antiquark. In this type of decay, the D meson undergoes a weak interaction, which transforms the charm quark into a strange quark, and emits a W boson. The W boson can then decay into a lepton (either an electron or a muon) and a neutrino. Since the weak interaction only affects one of the quarks in the D meson, the other quark remains unchanged, and a new meson is formed. This new meson could be either a D meson with a strange quark, or a D meson with an up or down antiquark. The semileptonic decay of D mesons is interesting because it allows us to study the weak interaction, which is responsible for processes like beta decay in atomic nuclei.

By measuring the properties of the leptons and mesons produced in these decays, scientists can learn more about the fundamental forces that govern the behavior of particles in the universe. Moreover, semileptonic D meson decay is important in the study of CP violation, which is the phenomenon of the violation of the combined symmetry of charge conjugation (C) and parity (P). The measurement of CP violation in D meson decay can help to understand why there is more matter than antimatter in the universe, a puzzle that has puzzled scientists for decades .

D Meson Decays

D mesons contain quarks and are one of the lightest particles in this family [5].

Leptonic Decays $D \to l^{+} v_{l}$

The purely leptonic charged D meson decays are the easiest to analyze among its decays. The factorization of its hadronic dynamics is given by

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$$\langle 0|\bar{d}\gamma^{\mu}(1-\gamma_5)c|D^+(p)\rangle = -if_{D^+}p^{\mu}_{D^+} \ . \qquad (1)$$

Figure 1 shows the process of a D$^+$ meson decaying into a lepton and a neutron pair. Starting with the computation of the amplitude from the Feynman diagram, we arrive at the structure of the decay width to lowest order as

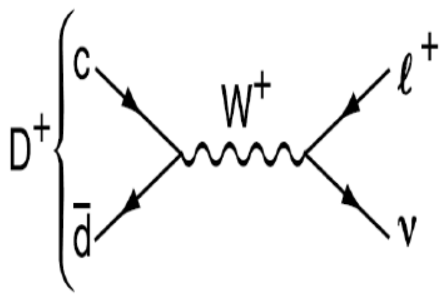

FIG. 1. **The Feynman diagram for purely leptonic D^+ decays in the Standard Model.**

$$\Gamma\left(D^+ \to l^+ \nu_l\right) = \frac{G_F^2 m_{D^+} m_l^2 f_{D^+}^2}{8\pi}|V_{cd}|^2\left(1-\frac{m_l^2}{m_{D^+}^2}\right)^2 \qquad (2)$$

From equation (2) the Fermi constant is given by G$_F$, the D$^+$ From equation (2) the Fermi constant is given by G$_F$, the D$^+$ meson mass by m_{D^+}, and the lepton mass by m_l . V_{cd} is the CKM matrix element and f_{D^+} is the decay constant. 4222

Analyzing equation (1), it is evident that there are no leftover variables in our decay rate calculation under the leptonic decay in question. Thus, the branching ratio is determined straight forwardly without any integration by multiplying the decay rate to the mean life, τ_{D^+}

Semileptonic Decays

Due to the fact that leptons do not involve strong interaction, the lepton pair is free from the strong binding effects in the semileptonic decays. Consequently, we can factor them out and arrive at

$$A = \frac{G_F}{\sqrt{2}}V^*_{cq}\bar{v}\gamma_{\mu}(1-\gamma_5)l\langle X|\bar{q}\gamma^{\mu}(1-\gamma_5)c|D\rangle \qquad (3)$$

In the above expression, $\langle X|\bar{q}\gamma^{\mu}(1-\gamma_5)c|D\rangle$ include all strong interactions. Leptonic and semileptonic D meson decays are ideal laboratories to study non-perturbative QCD, and to determine important quark mixing parameters. In addition, they may provide additional constraints on physics beyond the SM.

$D \to P l^+ v_l$ **Decay:** Within the Standard Model, the D meson semileptonic decay amplitude is given by [6]

$$M\left(D \to P l^+ v_l\right) = -i\frac{G_F}{\sqrt{2}} V_{cq}^* L^{\mu\dagger} H_\mu \quad (4)$$

with L^μ being the leptonic current and H_μ the hadronic current describing weak and strong dynamics of the interaction, respectively. Here the leptonic current is defined as

$$L^\mu = \overline{u_l}\gamma^\mu\left(1-\gamma_5\right)v_\nu \quad (5)$$

Where u_1 and v_ν are the lepton and neutrino Dirac spinors, respectively. On the other hand, the hadronic current can be written as

$$H_\mu = \left\langle P\right|\bar{q}\gamma_\mu\left(1-\gamma_5\right)c\left|D\right\rangle \quad (6)$$

It is vivid that D semileptonic decays involve the non-perturbative effects of quantum chromodynamics (QCD). As a result, this matrix element cannot be solved analytically. However, it can be parameterized by expanding the current in terms of all possible independent 4-vectors that can describe the decay, with each of these multiplied by a Lorentz-invariant form factor. 4223

In our case, there are only two independent 4 -vectors, which can be taken to be $p_1 + p_2$ and $p_1 - p_2$. Moreover, there is only one Lorentz invariant quantity, which is traditionally taken to be the invariant mass squared of the virtual W boson,

$$q^2 = \left(p_1 - p_2\right)^2$$

Thus, H_μ can take a decomposed in the form

$$\left\langle P\right|\bar{q}\gamma^\mu\left(1-\gamma_5\right)c\left|D\right\rangle = \left(p_1 + p_2\right)^\mu f_+\left(q^2\right) + \left(p_1 - p_2\right)^\mu f_-\left(q^2\right) \quad (7)$$

with p_1 and p_2 being the initial D momenta and and pseudoscalar meson in the final state, respectively.

From above, the form factors are given by $q = p_1 - p_2$, and $f_+\left(q^2\right)$ and $f_-\left(q^2\right)$. We can also express the decomposition in the form

$$\left\langle P\right|\bar{q}\gamma^\mu\left(1-\gamma_5\right)c\left|D\right\rangle = \left(p_1^\mu + p_2^\mu - \frac{m_D^2 - m_P^2}{q^2} q^\mu\right) f_+\left(q^2\right) + \frac{m_D^2 - m_P^2}{q^2} q^\mu f_0\left(q^2\right) \quad (8)$$

with $f_0\left(q^2\right)$ being the scalar and $f_+\left(q^2\right)$ the vector form factors, respectively.

Here we note that p_1^2 and p_2^2 are not variables since the initial and final particles are on-the-mass-shell; $p_1^2 = m_D^2$, $p_2^2 = m_P^2$. The form factors depend only on $p_1 \cdot p_2$, and hence for we can write an equivalently relation as

$$q^2 = p_1^2 - 2p_1.p_2 + p_2^2 \cdot \quad (9)$$

With an electron in the final state, its mass is much less with respect to parent D, therefore, only $f_+(q^2)$ contributes. As a result, taking the limit $m_l \to 0$ is an excellent approximation, and the current is further simplified to

$$H_\mu = (p_1 + p_2)_\mu f_+(q^2) \quad (10)$$

Using these expressions for the hadronic and leptonic currents, we arrive at the partial decay width:

$$\frac{d\Gamma(D \to Pev_e)}{dq^2} = X\frac{G_F^2|V_{cq}|^2}{24\pi^3} p^3 |f_+(q^2)|^2 \quad (11)$$

with p and X being the hadronic momentum and multiplicative factor, respectively. By neglecting lepton masses and plugging in all the necessary parameters we arrive at

$$\frac{d\Gamma}{dq^2}(D \to Pl^+ v_l) = \frac{G_F^2}{192\pi^3 m_D^3}|V_{cq}|^2 \left[(m_D^2 + m_P^2 - q^2) - 4m_D^2 m_P^2\right]^{3/2} |f_+(q^2)|^2 \quad (12)$$

with only $f_+(q^2)$ contributing. $f_-(q^2)$ contributions are neglected due to its proportionality relation with m_l^2. Here $0 \le q^2 \le (m_D - m_P)^2$ gives the q^2 distribution range.

Experimental studies measure $d\Gamma/dq^2$ integrated over several q^2 bins in each semileptonic mode. In order to compare these with theoretical predictions, which provide estimates of $f_+(q^2)$ at one or several points in q^2 , it is convenient to fit the results using parameterizations of $f_+(q^2)$. Theoretically, a number of parameterizations of $f_+(q^2)$ have been suggested. The most theoretically motivated one is known as the "series" parameterization [7] and follows from a dispersion relation:

$$f_+(q^2) = f_+(0)\frac{1-\alpha}{1-\frac{q^2}{m_{D^+}^2}} + \frac{1}{\pi}\int_{(m_D+m_P)^2}^{\infty} dt \frac{\operatorname{Im} f_+(t)}{t - q^2 - i\varepsilon} \quad (13)$$

with m_D and m_P being the parent and daughter masses, respectively, and α is related to the relative meson contribution to $f_+(0)$.

Here we are not going to dwell much on this one but on another parameterization called 'simple pole' model which suggests that the dispersion relation given in Eq. (13) is described by

$$f_{\pm}(q^2) = \frac{f_{\pm}(0)}{1 - \frac{q^2}{m_{pole}^2}}. \quad (14)$$

While this model can provide reasonable fits when both m_{pole} and $f_+(q^2)$ are allowed to float, experimental fits of m_{pole} are far away from the expected value of $M_{D^*_{(s)}}$, indicating the higher-order poles are not negligible [8].

The semileptonic decay branching ratio is determined by integration with respect to q^2 as

$$Br(D \to Pl^+\nu_l) = \tau_D \int_0^{(m_D - m_P)^2} dq^2 \frac{d\Gamma(D \to Pe^+\nu_e)}{dq^2} \quad (15)$$

with τ_D being the mean life of the D meson.

$D \to Vl^+\nu_l$ **Decay:** For the transitions to vector mesons, the structure of the hadronic matrix element of the process $D \to Vl^+\nu_l$ (**Figure 2**), according to its Lorentz structure, is given by 4225

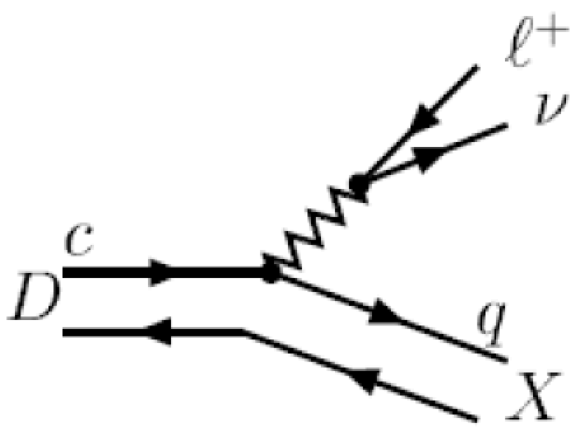

FIG. 2. **Feynman diagram of semileptonic D meson decay.**

On the other hand, the pole mass (m_bpole) of the b quark is a term that refers to the mass of the quark when it is viewed as an on-shell particle, which means when it is engaged in physical processes and can be detected as an independent particle. In other words, the pole mass of the b quark refers to the mass of the quark when it is considered to be an on-shell particle.

The running mass of the b quark is defined, according to the MS scheme, as the mass parameter that appears in the renormalized Lagrangian at a certain energy scale (). It is represented by the notation m_b(). This mass is selected in such a way that it eliminates any divergences that may have been produced as a result of the computation of loop diagrams involving the b quark.

Quantum chromodynamics, often known as QCD, is a theory that explains the powerful interactions that occur between quarks and gluons. The link between the running mass and the pole mass takes into account the effects of QCD. The relation may be stretched to the following form at the next-to-leading order level:

$$m_b^{pole} = m_b(\mu) * [1 + (4/3) * (\alpha_s(\mu)/\pi) + 16.3636 * (\alpha_s(\mu)/\pi)^2 + O(\alpha_s^3)]$$

In this context, the strong coupling constant is denoted by _s(), and it is evaluated at the energy scale denoted by. The magnitude of the effects of strong interactions may be measured using the symbol _s()/. The expansion takes into account terms all the way up to the second order in _s(), and the coefficients of these terms are determined by the particular renormalization method that is used

The probability for the muon hypothesis is calculated as an integration of the calibrating range of the muon between 0 and the observed mean squared distances relevance for the track (D20). The integral of the calibration range of the proton between 0 and D2 0 is used to calculate the non-muon assumption (pions, kaons, and protons). Due to decays in flight, the D2 for the two differently charged hadrons contains a component that is identical to a proton and another component that is comparable to a muon. The distinguishing variable muDLL is then determined by the difference in the logarithms of the likelihoods between the two hypotheses.

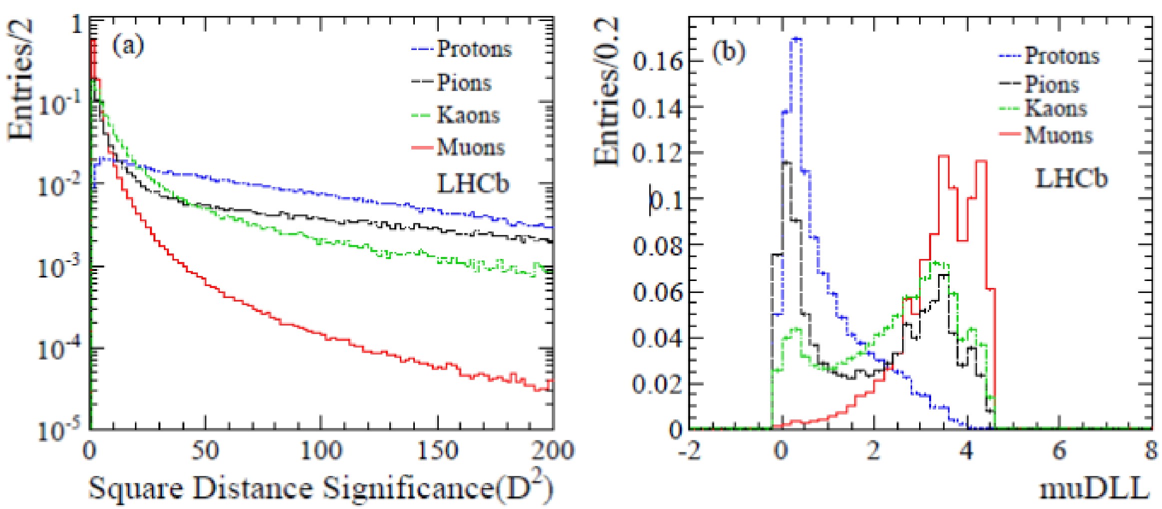

Figure 3 : Distributions and mu DLL Calculation: Average D2 Distribution and mu DLL Variable from Muon and Hadron Hypotheses

With only one lattice spacing, the systematic error from discretization effects can be estimated only by power counting. The leading discretization errors from the Asqtad action are O (αs(aΛQCD)2) ≈ 2% (after removal of taste-violating effects with SχPT), taking ΛQCD = 400 MeV and αs = 0.25.

In addition, there is a momentum-dependent error from the final state. The BK parameters are determined by the lower momentum data; in particular, the fits are insensitive to the highest momentum 2π(1, 1, 1)/L. Therefore we estimate this effect to be O(αs(ap)2) ≈ 5%, taking the second-highest momentum p = 2π(1, 1, 0)/L. The HQET theory of cutoff ef- fects [18, 19] can be used to estimate the discretization error from the heavy charmed quark. In this way, we estimate the discretization error to be 4–7%, depending on the value chosen for ΛQCD (in the HQET context). This is consistent with the lattice spacing dependence seen in Ref. [8]. In future work

we expect to reduce and understand better this uncertainty, so we shall adopt the maximum, 7%, here. A summary of the systematic errors for the form factors f+,0 or the CKM matrix elements |Vcx| is as follows. The error from time fits is 3%; from chiral fits, 3% (2%) for D → π (K) decay; from BK parametrization, 2%. The 1-loop correction to ρVμ is only 1%, so 2-loop uncertainty is assumed to be negligible. The uncertainty for a−1 is about 1.2% [6]; this leads we obtain, for the total decay rates,

Γ(D0 → π−l+ν) = (7.7 ± 0.6 ± 1.5 ± 0.8) × 10−3ps−1,

Γ(D0 → K−l+ν) = (9.2 ± 0.7 ± 1.8 ± 0.2) × 10−2ps−1,

Γ(D0 → π−l+ν)

Γ(D0 → K−l+ν) = 0.084 ± 0.007 ± 0.017 ± 0.009, (8)

to a 1% error for |Vcx| (but not for the dimensionless form factors), from integrating over q2 to get Γ/|Vcx|2. Finally, we quote discretization uncertainties of 2%, 5%, and 7%, from light quarks, the final state energy, and the charmed quark, respectively. Adding all the systematic errors in quadrature, we find the total to be [3% + 3% (2%) + 2% + 1% + 2% + 5% + 7%] = 10%.

Incorporating the systematic uncertainties, we obtain

f D→π+ (0) = 0.64(3)(6), (6)

f D→K+ (0) = 0.73(3)(7), (7)

and the ratio f D→π+ (0)/f D→K+ (0) = 0.87(3)(9). Our re-

sults for the CKM matrix elements (Table I) are consistent with Particle Data Group averages |Vcd| = 0.224(12) and |Vcs| = 0.996(13) [1]; also with |Vcs| = 0.9745(8) from CKM unitarity. If we instead use these CKM values as inputs,

This Letter presents the first three-flavor lattice calculations for semileptonic D decays. With an improved staggered light quark, we have successfully reduced the two dominant uncertainties of previous works, i.e., the effect of the quenched approximation and the error from chiral extrapolation. Our results for the form factors, decay rates and CKM matrix, given in and Eq. (8) are in agreement with experimental results. The total size of systematic uncertainty is 10%, which is dominated by the discretization errors. To reduce this error, calculations at finer lattice spacings and with more highly-improved heavy-quark actions are necessary

Conclusion

The leptonic, pseudoscalar and vector decays have been studied under this work with the aid of the effective Lagrangian by including the allowed direct NP couplings. Charm decays has been and still is an exciting field for both theoretical and experimental investigations. Charm quark transition amplitudes, described in this work, represent a crucial tool to understand strong interaction dynamics in the non-perturbative regime. Complementary information that constrains model building and lattice gauge calculations is coming from the rich spectroscopy of charmed mesons and baryons, which is beyond the scope of this paper.

Coming to our results, we see from our results that more needs to be done in order to understand the real phenomenology of physics BSM. Parameterization of decay constants into physical numerical values still remain a challenge among theorists. Nevertheless, more progress has been made in recent years to try and fuse in the gaps that the SM has left scholars with more questions than answers.

From our results, we can see that a search for NP underD meson decay is equally important as well as that of theB meson. The results obtained under this work do not entail pure accuracy as earlier on mentioned as they are equally prone to errors just like those from experiments too.

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