Semileptonic Decays of Charmed Mesons

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Motivation

- Good platform for weak and strong interaction
- CKM matrix determination V_{cs} and V_{cd}
- To provide insights into the origin of flavor and CP-violation.
- To look for new physics beyond the standard model.
- Test for lepton flavor universality
- BESIII, *BABAR* and other collaborations have reported precise and improved measurement on semileptonic decays

Covariant Confined Quark Model of Hadrons

- Interaction Lagrangian

$$L_{int} = g_M M(x) \int dx_1 \int dx_2 F_M(x; x_1, x_2) \cdot \bar{q}^a_{f_1}(x_1) \Gamma_M q^a_{f_2}(x_2) + H.c.$$

- Vertex function

$$F_M(x, x_1, x_2) = \delta^{(4)} \left(x - \sum_{i=1}^{2} w_i x_i \right) \Phi_M \left((x_1 - x_2)^2 \right)$$

$$\tilde{\Phi}_M(-K^2) = exp\left(k^2 / \Lambda_M^2 \right)$$

- IR confinement [1]

$$\Pi^c = \int_0^{1/\lambda^2} dt t^{n-1} \int_0^1 \delta \left(1 - \sum_{i=1}^{n} \alpha_i \right) F(t\alpha_1, ..., t\alpha_n)$$

[1] T. Branz, A. Faessler, T. Gutsche, M. A. Ivanov, J. G. Korner and V. E. Lyubovitskij, Phys. Rev. D **81**, 034010 (2010).

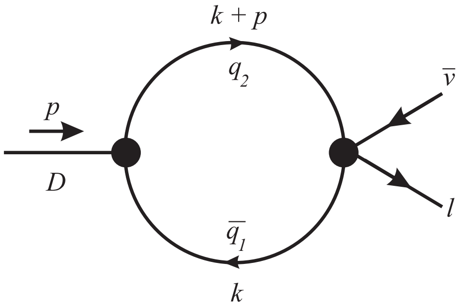
Model parameters

Quark masses m_{qi}, the infrared cutoff parameter λ and the size parameters Λ_{H_i} (all in GeV)

$m_{u/d}$	m_s	m_c	λ
0.241	0.428	1.67	0.181

Λ_D	Λ_K	Λ_{K^*}	Λ_π
1.600	1.014	0.805	0.870

Leptonic D-Meson Decays



Matrix elements of leptonic decays

$$N_c g_P \int \frac{d^4k}{(2\pi)^4 i} \tilde{\phi}_P(-k^2) tr[O^\mu S_1(k + w_1 p)\gamma^5 S_2(k - w_2 p)] = f_p p^\mu$$

$$N_c g_V \int \frac{d^4k}{(2\pi)^4 i} \tilde{\phi}_V(-k^2) tr[O^\mu S_1(k + w_1 p) \not\epsilon_V S_2(k - w_2 p)] = m_V f_V \epsilon_V^\mu$$

Leptonic D-Meson Decays

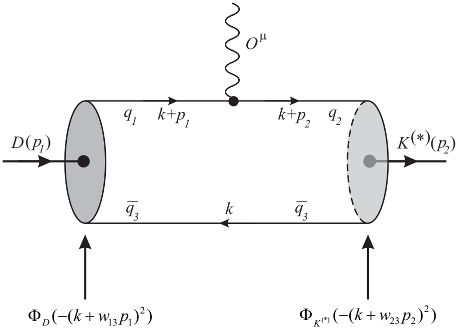
- The Leptonic D-Meson Decays given by

$$\mathcal{B}(D^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} m_D m_\ell^2 \left(1 - \frac{m_\ell^2}{m_D}\right)^2 f_D^2 |V_{cd}|^2 \tau_{D^+}$$

Table: Leptonic D^+-decay branching fraction

Channel	Present	PDG 2018
$D^+ \to e^+ \nu_e$	8.42×10^{-9}	$< 8.8 \times 10^{-6}$
$D^+ \to \mu^+ \nu_\mu$	3.57×10^{-4}	$(3.74 \pm 0.17) \times 10^{-4}$
$D^+ \to \tau^+ \nu_\tau$	0.95×10^{-3}	$< 1.2 \times 10^{-3}$

Semileptonic D-Meson Decays



- The invariant matrix element of semileptonic decays of $D \to K^{(*)}\ell^+\nu_\ell$

$$M(D \to K^{(*)}\ell^+\nu_\ell) = \frac{G_F}{\sqrt{2}} V_{cs} \langle K^{(*)}|\bar{s}O^\mu c|D\rangle \ell^+ O^\mu \nu_\ell$$

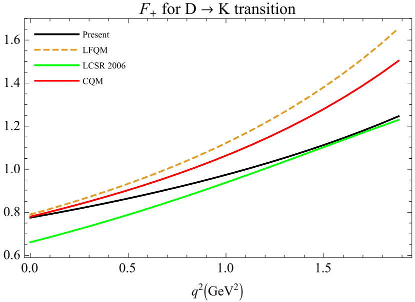
Form Factors of Semi Leptonic D-Meson Decays

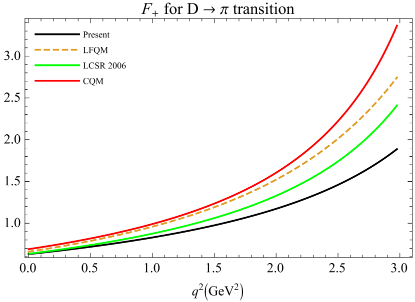
The matrix element of semileptonic $D \to K^{(*)}$ transitions

$$\langle K(p_2)|\bar{q}_2 O^{\mu} q_1|D(p_1)\rangle = F_+(q^2)P^{\mu} + F_-(q^2)q^{\mu}$$

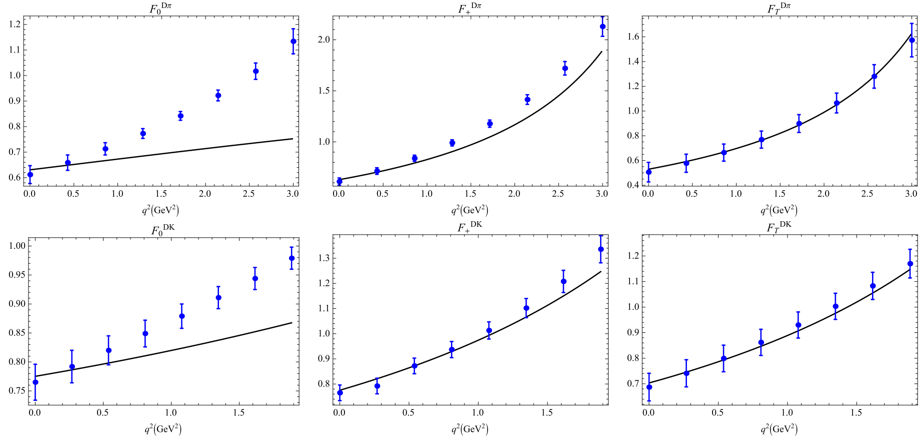
$$\begin{aligned}\langle K^{(*)}(p_2,\epsilon_2)|\bar{q}_2 O^{\mu} q_1|D(p_1)\rangle = \frac{\epsilon_\nu^\dagger}{m_1+m_2}\Big[&-g^{\mu\nu}P\cdot qA_0(q^2)\\ &+P^{\mu}P^{\nu}A_+(q^2)\\ &+q^{\mu}P^{\nu}A_-(q^2)\\ &+i\varepsilon^{\mu\nu\alpha\beta}P_\alpha q_\beta V(q^2)\Big]\end{aligned}$$

Form Factors Comparison



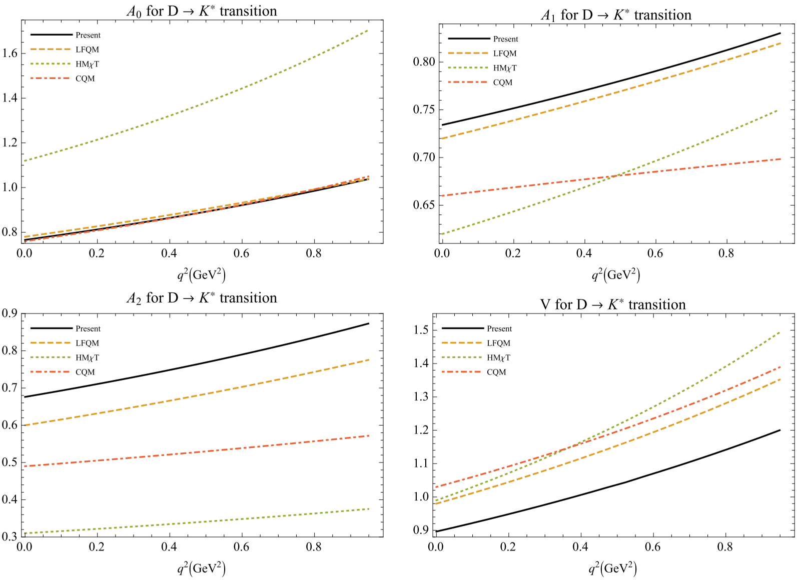


Form Factors Comparison with LQCD data by ETM [2]



[2] V. Lubicz *et al.* (ETM Collaboration), PRD **96**, 054514 (2017); PRD **98**, 014516 (2018).

Form Factors Comparison



Form factors

Dipole interpolation

$$F(q^2) = \frac{F(0)}{1 - as + bs^2}, \quad s = \frac{q^2}{m_D^2}$$

The paramaters of dipole interpolation:

F	$F(0)$	a	b	F	$F(0)$	a	b
$A_+^{D\to K^*}$	0.68	0.86	0.09	$A_-^{D\to K^{*0}}$	-0.90	0.96	0.14
$A_0^{D\to K^*}$	2.08	0.40	-0.10	$V^{D\to K^{*0}}$	0.90	0.97	0.13
$F_+^{D\to K}$	0.77	0.73	0.05	$F_-^{D\to K}$	-0.39	0.78	0.07
$F_+^{D\to \pi}$	0.63	0.86	0.09	$F_-^{D\to \pi}$	-0.41	0.93	0.13

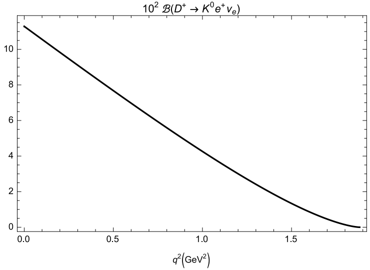
Branching fraction for $D^+ \to K^{(*)}\ell^+\nu_\ell$

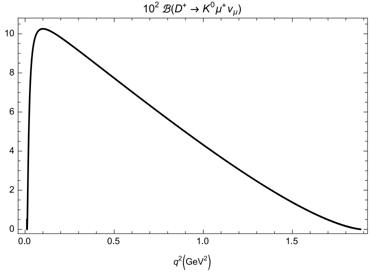
$$\frac{d\Gamma(D^+ \to K^{(*)}\ell^+\nu_\ell)}{dq^2} = \frac{G_F^2|V_{cs}|^2|p_2|q^2v^2}{12(2\pi^3)m_D^2}H_{tot}$$

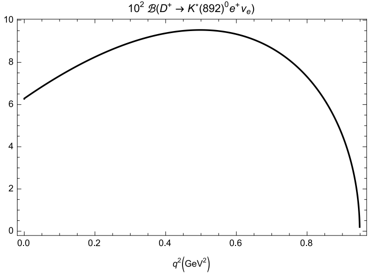
where $H_{tot} = H_U + H_L + \delta_\ell(H_U + H_L + 3H_s)$. Here $H's$ are the helicity structure functions which depends on form factors.

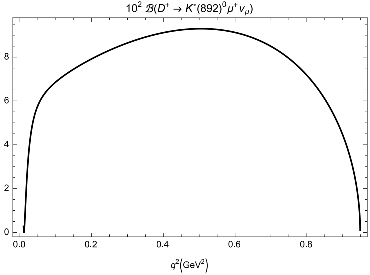
- $\delta_\ell = m_\ell^2/2q^2$
- $|p_2| = \lambda^{1/2}(m_D^2, m_{K^{(*)}}^2, q^2)/2m_D$
- $v = 1 - m_\ell^2/q^2$

Differential branching fraction for $D^+ \to K^{(*)}\ell^+\nu_\ell$









Semileptonic Branching fraction (in %)

Channel	Present	Data	Reference
$D^+ \to \bar{K}^0 e^+ \nu_e$	9.28	$8.60 \pm 0.06 \pm 0.15$	BESIII [3]
		$8.83 \pm 0.10 \pm 0.20$	CLEO [4]
$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	9.02	$8.72 \pm 0.07 \pm 0.18$	BESIII [5]
$D^+ \to \pi^0 e^+ \nu_e$	0.29	$0.350 \pm 0.011 \pm 0.010$	BESIII [6]
$D^+ \to \pi^0 \mu^+ \nu_\mu$	0.28		

[3] M. Ablikim *et al.* (BESIII Collaboration), PRD **96**, 012002 (2017).
[4] D. Besson *et al.* (CLEO Collaboration), PRD **80**, 032005 (2009).
[5] M. Ablikim *et al.* (BESIII Collaboration), EPJC **76**, 369 (2016).
[6] M. Ablikim *et al.* (BESIII Collaboratio), PRL **121**, 171803 (2018).

Semileptonic Branching fraction (in %)

Channel	Present	Data	Reference
$D^0 \to K^- e^+ \nu_e$	3.63	$3.505 \pm 0.014 \pm 0.033$	BESIII [7]
		$3.50 \pm 0.03 \pm 0.04$	CLEO [8]
		$3.45 \pm 0.07 \pm 0.20$	Belle [9]
$D^0 \to K^- \mu^+ \nu_\mu$	3.53	$3.413 \pm 0.019 \pm 0.035$	BESIII [10]
$D^0 \to \pi^- e^+ \nu_e$	0.22	$0.295 \pm 0.004 \pm 0.003$	BESIII [7]
		$0.2770 \pm 0.0068 \pm 0.0092$	BaBar [11]
		$0.288 \pm 0.008 \pm 0.003$	CLEO [8]
		$0.255 \pm 0.019 \pm 0.016$	Belle [9]
$D^0 \to \pi^- \mu^+ \nu_\mu$	0.22	$0.272 \pm 0.008 \pm 0.006$	BESIII [12]

[7] M. Ablikim *et al.* (BESIII Collaboration), PRD **92**, 071101 (2015).
[8] D. Besson *et al.* (CLEO Collaboration), PRD **80**, 032005 (2009).
[9] L. Widhalm *et al.* (Belle Collaboration), PRL **97**, 061804 (2006).
[10] M. Ablikim *et al.* (BESIII Collaboration), arXiv:1810.03127 [hep-ex]
[11] J. P. Lees *et al.* (BABAR Collaboration), PRD **91**, 052022 (2015).
[12] M. Ablikim *et al.* (BESIII Collaboratio), PRL **121**, 171803 (2018).

Semileptonic Branching fraction (in %)

Channel	Present	Data	Reference
$D^0 \to K^*(892)^- e^+ \nu_e$	2.96	$2.033 \pm 0.046 \pm 0.047$	BESIII [13]
		$2.16 \pm 0.15 \pm 0.08$	CLEO [14]
$D^0 \to K^*(892)^- \mu^+ \nu_\mu$	2.80		
$D^+ \to \bar{K}^*(892)^0 e^+ \nu_e$	7.61		
$D^+ \to \bar{K}^*(892)^0 \mu^+ \nu_\mu$	7.21		

[13] M. Ablikim *et al.* (BESIII Collaboration), arXiv:1811.11349 [hep-ex].

[14] E. Coan *et al.* (CLEO Collaboration), PRL **95**, 181802 (2005).

Ratios of the branching fractions

Ratio	SM	Value	Data	Reference
$\Gamma(D^0 \to K^- e^+ \nu_e)/\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)$	1.0	0.99	$1.08 \pm 0.22 \pm 0.07$	BESIII [15]
			$1.06 \pm 0.02 \pm 0.03$	CLEO [16]
$\Gamma(D^0 \to K^- \mu^+ \nu_\mu)/\Gamma(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)$	1.0	0.99		
$\Gamma(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)/\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)$	1.0	0.97		
$\Gamma(D^0 \to K^- \mu^+ \nu_\mu)/\Gamma(D^0 \to K^- e^+ \nu_e)$	1.0	0.97	$0.974 \pm 0.007 \pm 0.012$	BESIII [17]
$\mathcal{B}(D^0 \to \pi^- \mu^+ \nu_\mu)/\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$	1.0	0.98	$0.922 \pm 0.030 \pm 0.022$	BESIII [18]
$\mathcal{B}(D^+ \to \pi^0 \mu^+ \nu_\mu)/\mathcal{B}(D^+ \to \pi^0 e^+ \nu_e)$	1.0	0.98	$0.964 \pm 0.037 \pm 0.026$	BESIII [18]
$\Gamma(D^0 \to \pi^- e^+ \nu_e)/\Gamma(D^+ \to \pi^0 e^+ \nu_e)$	2.0	1.97	$2.03 \pm 0.14 \pm 0.08$	CLEO [16]

[15] M. Ablikim *et al.* (BES Collaboration), PLB **608**, 24 (2005).
[16] S. Dobbs *et al.* (CLEO Collaboration), PRD **77**, 112005 (2008).
[17] M. Ablikim *et al.* (BESIII Collaboration), arXiv:1810.03127 [hep-ex].
[18] M. Ablikim *et al.* (BESIII Collaboratio), PRL **121**, 171803 (2018).

Conclusion

- Our results are very well within the experimental uncertainty.
- Ratios of the branching fractions suggests no lepton flavor universality violation.
- Very recently, BESIII also approved our predictions [19] in their letter [20]
- We have computed the semileptonic decays of $D_{(s)}$ in our recent paper [21].
- This method is applicable for multiquark states also.

[19] N. R. Soni and J. N. Pandya, PRD **96**, 016017 (2017).

[20] M. Ablikim et al, (BESIII collaboration), arXiv:1810.03127.

[21] N. R. Soni, M. A. Ivanov, J.G. Körner , J.N. Pandya, P. Santorelli and C.T. Tran, arXiv:1810.11907 accepted for publication in PRD

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- M. A. Ivanov, J. G. Körner and P. Santorelli, Phys. Rev. D **63**, 074010 (2001).

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