Decay $D_s^+ \to \phi \ell^+ \nu_\ell$ in covariant quark model

Nakul Soni* and J. N. Pandya

Applied Physics Department, Faculty of Technology & Engineering,
The Maharaja Sayajirao University of Baroda,
Vadodara 390 001, Gujarat, *INDIA*
* *nrsoni-apphy@msubaroda.ac.in*

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Content

Experimental data

- For channel $\mathcal{B}(D_s^+ \to \phi e^+ \nu_e)$

Data in %	Reference	Year
$2.26 \pm 0.45 \pm 0.09$	BESIII	2018
$2.14 \pm 0.17 \pm 0.08$	CLEO-c	2015
$2.61 \pm 0.03 \pm 0.17$	*BABAR*	2008
2.39 ± 0.23	PDG Average	

- For channel $\mathcal{B}(D_s^+ \to \phi \mu^+ \nu_\mu)$

Data in %	Reference	Year
$1.94 \pm 0.53 \pm 0.09$	BESIII	2018

Covariant 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).

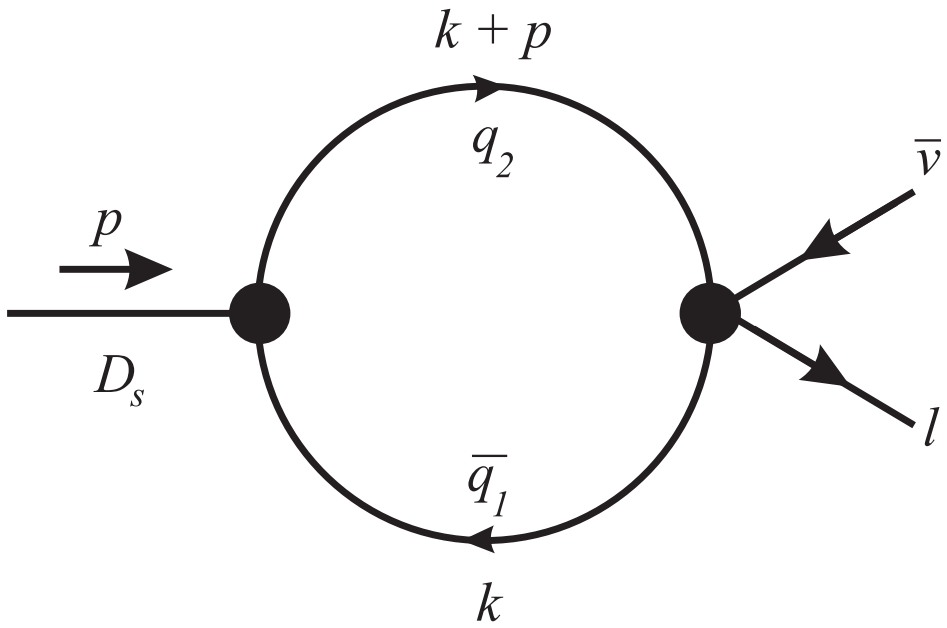
Model parameters

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

m_s	m_c	λ
0.428	1.67	0.181

Λ_{D_s}	Λ_ϕ
1.74	0.88

Leptonic D_s-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_s-Meson Decays

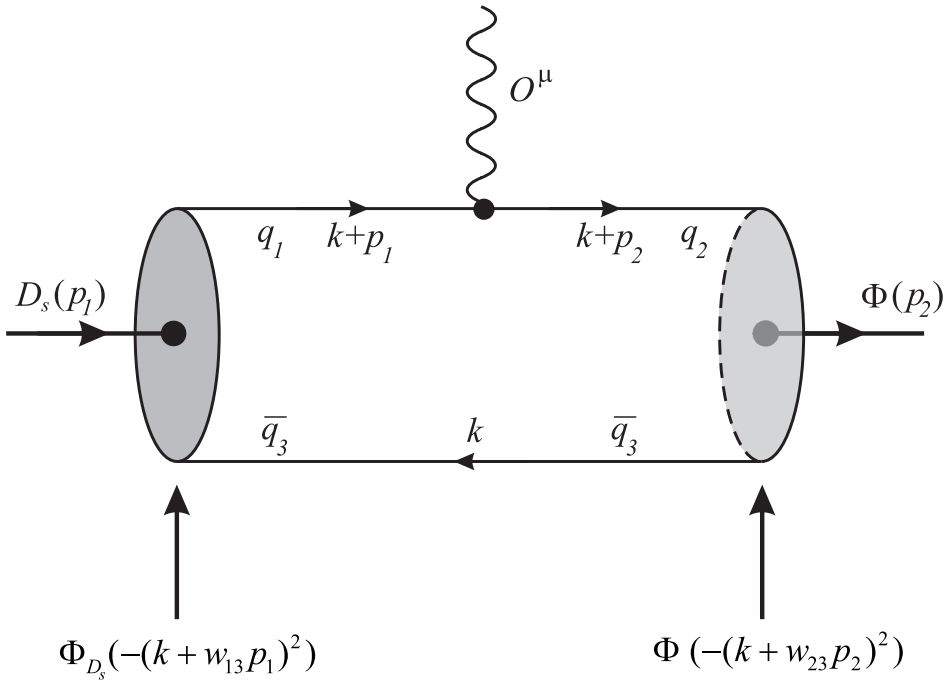
- The Leptonic D_s-Meson Decays given by

$$\mathcal{B}(D_s^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} m_{D_s} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{D_s}}\right)^2 f_{D_s}^2 |V_{cs}|^2 \tau_{D_s}$$

Table: Leptonic D_s^+-decay branching fraction ($\tau_{D_s^+} = 5 \times 10^{-13}$ s)

Channel	Present	PDG 2016
$D_s^+ \to e^+ \nu_e$	1.33×10^{-7}	$< 8.3 \times 10^{-5}$
$D_s^+ \to \mu^+ \nu_\mu$	5.64×10^{-3}	$(5.50 \pm 0.23) \times 10^{-3}$
$D_s^+ \to \tau^+ \nu_\tau$	5.49%	(5.48 ± 0.23)%

Semileptonic D_s^+-Meson Decays



- The invariant matrix element of semi leptonic decays of $D_s^+ \to \phi\ell^+\nu_\ell$

$$M(D_s^+ \to \phi\ell^+\nu_\ell) = \frac{G_F}{\sqrt{2}} V \langle\phi|\bar{s}O^\mu c|D_s\rangle \ell^+ O^\mu \nu_\ell$$

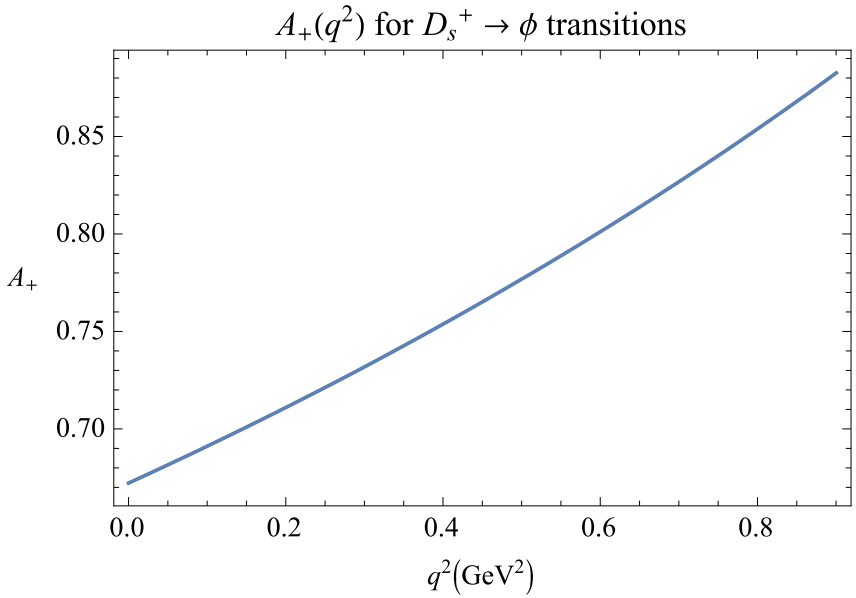
Form Factors of Semi Leptonic D_s-Meson Decays

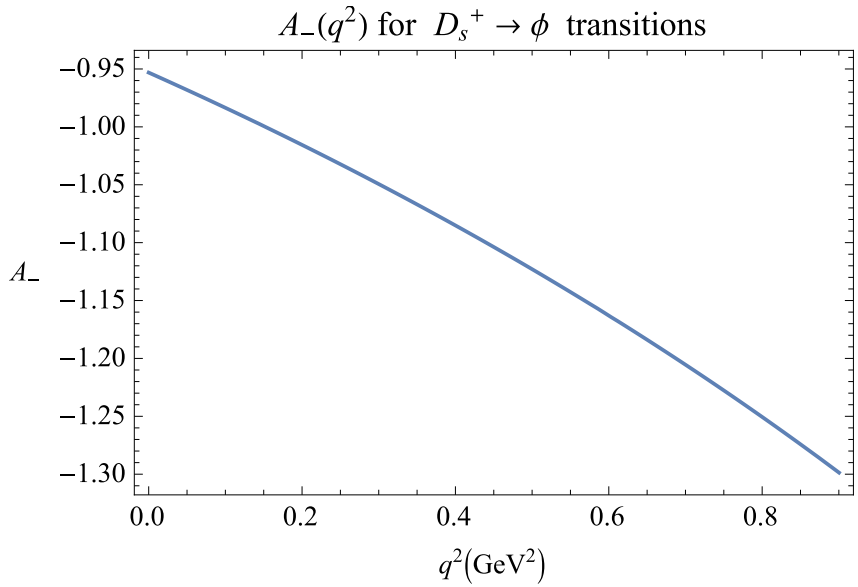
The matrix element of semileptonic $D_s \to \phi$ transitions

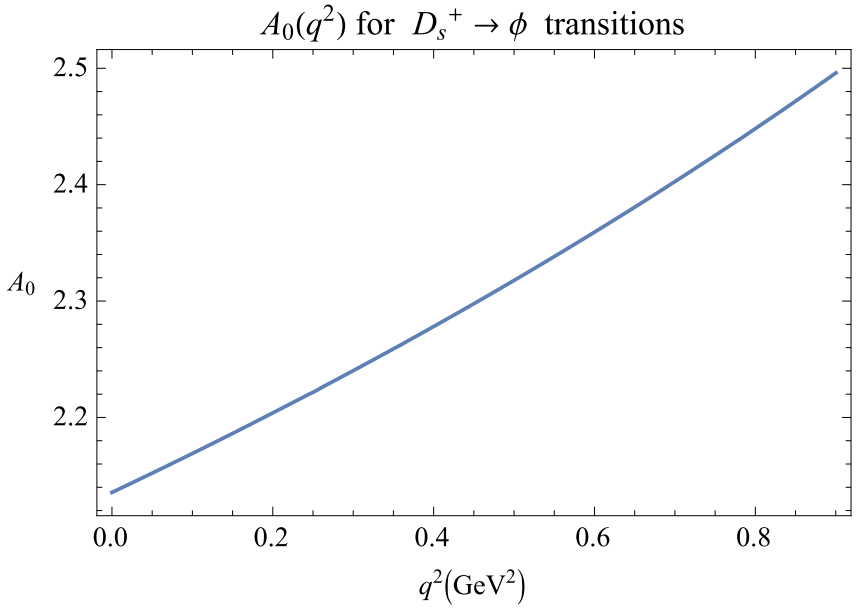
$$\begin{aligned}\epsilon^{\dagger}_{\nu\alpha} T^{\mu\alpha} &= N_c g_{D_s} g_{\phi} \int \frac{d^4k}{(2\pi)^4 i} \phi_{D_s}(-(k + w_{13} p_1)^2) \phi_{\phi}(-(k + w_{23} p_2)^2) \\ & \quad tr[O^{\mu} S_1(k + p_1) \gamma^5 S_3(k) \not{\epsilon}^{\dagger}_{\nu} S_2(k + p_2)]\end{aligned}$$

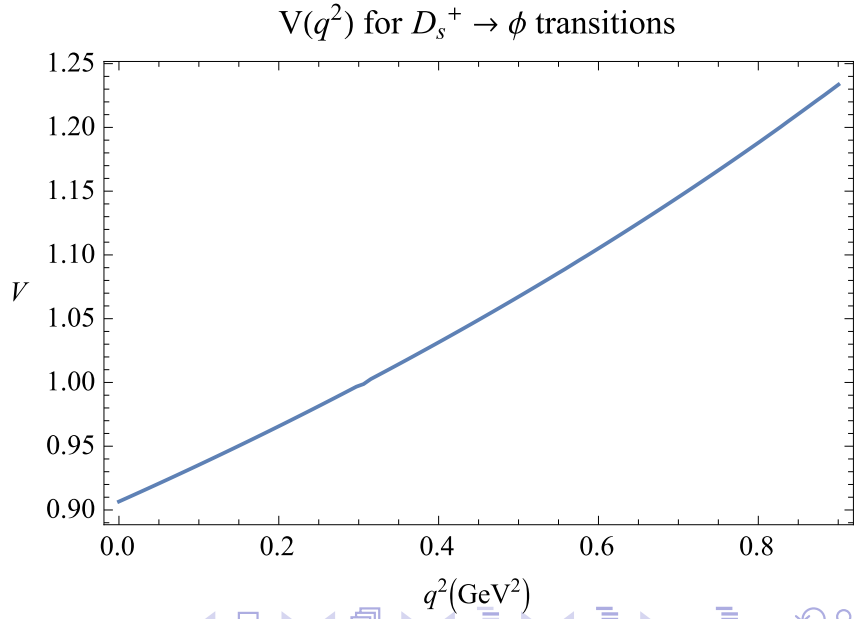
$$\begin{aligned}\langle \phi(p_2, \epsilon_2) | \bar{q}_2 O^{\mu} q_1 | D_s(p_1) \rangle &= \frac{\epsilon^{\dagger}_{\nu}}{m_1 + m_2} \Big[-g^{\mu\nu} P \cdot q A_0(q^2) \\ & \quad + P^{\mu} P^{\nu} A_+(q^2) \\ & \quad + q^{\mu} P^{\nu} A_-(q^2) \\ & \quad + i\varepsilon^{\mu\nu\alpha\beta} P_{\alpha} q_{\beta} V(q^2) \Big]\end{aligned}$$

Form factors for $q^2 \geq 0$









Form factors

Dipole interpolation

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

The paramaters of dipole interpolation:

	A_0	A_+	A_-	V
$F(0)$	2.13	0.67	-0.95	0.91
a	0.59	1.06	1.21	1.20
b	-0.12	0.17	0.26	0.24

Table: $D_s^+ \to \phi \ell^+ \nu_\ell$ form factors

Form factor	Present	PDG 2016
$r_2 = A_2(0)/A_1(0)$	0.99	0.84 ± 0.11
$r_v = V(0)/A_1(0)$	1.33	1.80 ± 0.08

Branching fraction for $D_s^+ \to \phi \ell^+ \nu_\ell$

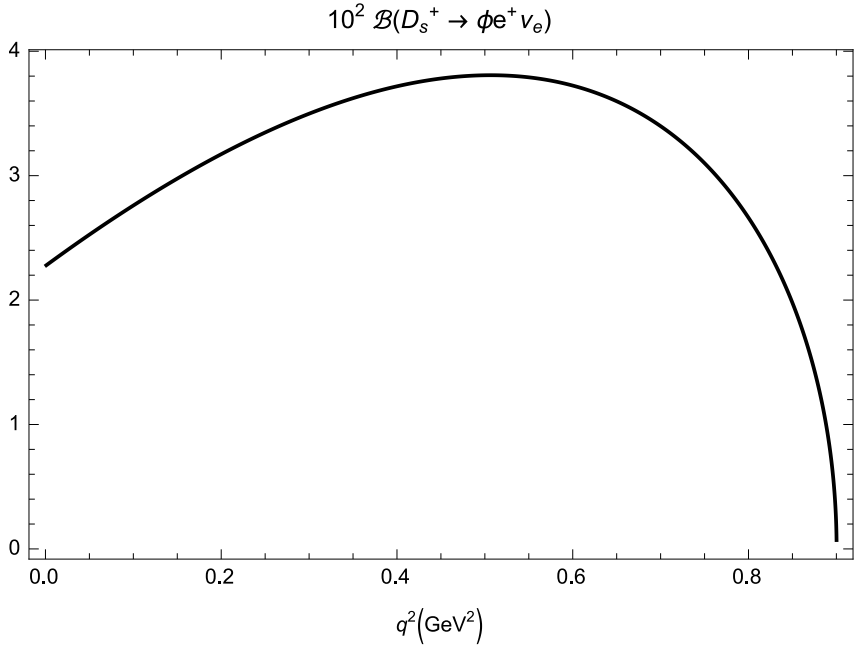
$$\frac{d\Gamma(D_s^+ \to \phi \ell^+ \nu_\ell)}{dq^2} = \frac{G_F^2 |V_{cs}|^2 |p_2| q^2 v^2}{12(2\pi^3) m_{D_s}^2} H_{tot}$$

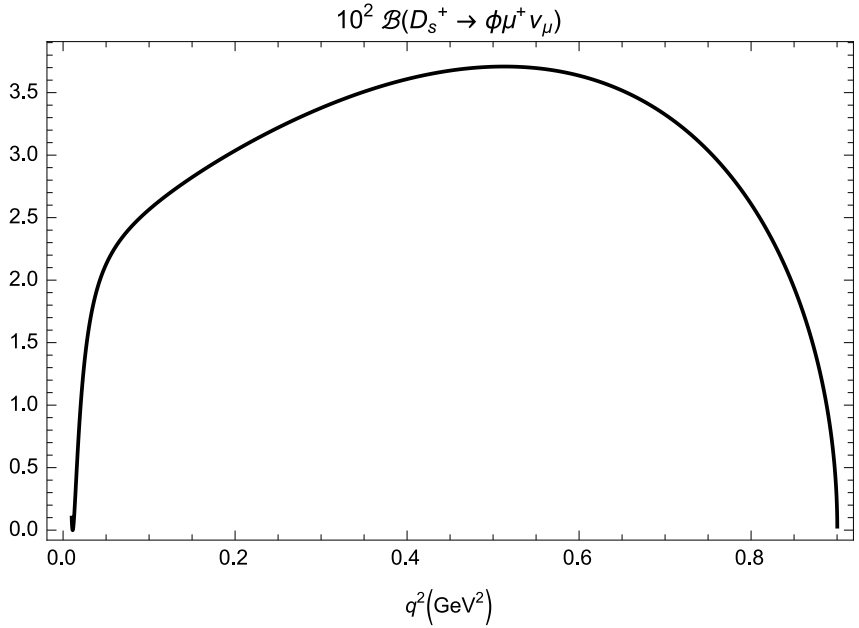
where $H_{tot} = H_U + H_L + \delta_\ell (H_U + H_L + 3H_s)$. Here $H's$ are the helicity structure functions which depends on form factors.

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

Branching fraction for $D_s^+ \to \phi \ell^+ \nu_\ell$

Figure: Differential braching fraction for the decays $D_s^+ \to \phi \ell^+ \nu_\ell$





Branching fraction for $D_s^+ \to \phi \ell^+ \nu_\ell$

Table: Semileptonic branching fraction for D_s meson. $\mathcal{B}(D_s^+ \to \phi \ell^+ \nu_\ell)$ (in %)

Channel	Present	Data	Reference
$\mathcal{B}(D_s^+ \to \phi e^+ \nu_e)$	2.85	$2.26 \pm 0.45 \pm 0.09$	BESIII [2]
		$2.61 \pm 0.03 \pm 0.08 \pm 0.15$	*BABAR* [3]
		$2.14 \pm 0.17 \pm 0.08$	CLEO-c [4]
		3.1 ± 0.3	LFQM [5]
$\mathcal{B}(D_s^+ \to \phi \mu^+ \nu_\mu)$	2.70	$1.94 \pm 0.53 \pm 0.09$	BESIII [2]
$\frac{\mathcal{B}(D_s^+ \to \phi \mu^+ \nu_\mu)}{\mathcal{B}(D_s^+ \to \phi e^+ \nu_e)}$	0.95	0.86 ± 0.29	BESIII [2]

[2] M Ablikim *et al*. Phys. Rev. D **97**, 012006 (2018).

[3] B Aubert *et al*. Phys Rev. D **78**, 051101 (2008).

[4] J. Hietala *et al*. Phys. Rev. D **92**, 012009 (2015).

[5] H. Y. Cheng and X. W. Kang, Eur. Phys. J. C **77**, 587 (2017).

Other Results on Charm Semileptonic decays

Ref: N. R. Soni and J. N. Pandya, Phys. Rev. D **96**, 016017 (2017).

Table: Semileptonic branching fraction in %

Channel	This Work	Data	Reference
$D^+ \to \overline{K}^0 e^+ \nu_e$	8.84	$8.60 \pm 0.06 \pm 0.15$	BESIII
		$8.83 \pm 0.10 \pm 0.20$	CLEO-c
$D^+ \to \overline{K}^0 \mu^+ \nu_\mu$	8.60	$8.72 \pm 0.07 \pm 0.18$	BESIII
$D^+ \to \pi^0 e^+ \nu_e$	0.619	$0.363 \pm 0.08 \pm 0.05$	BESIII
		$0.405 \pm 0.016 \pm 0.009$	CLEO-c
$D^+ \to \pi^0 \mu^+ \nu_\mu$	0.607	$0.342 \pm 0.011 \pm 0.010$	BESIII
$D^+ \to \overline{K}^*(892)^0 e^+ \nu_e$	8.35	–	–
$D^+ \to \overline{K}^*(892)^0 \mu^+ \nu_\mu$	7.94	–	–

Other Results on Charm Semileptonic decays

Ref: N. R. Soni and J. N. Pandya, Phys. Rev. D **96**, 016017 (2017).

Table: Semileptonic branching fraction in %

Channel	This Work	Data	Reference
$D^0 \to K^- e^+ \nu_e$	3.46	$3.505 \pm 0.014 \pm 0.033$	BESIII
		$3.50 \pm 0.03 \pm 0.04$	CLEO-c
		$3.45 \pm 0.07 \pm 0.20$	Belle
$D^0 \to K^- \mu^+ \nu_\mu$	3.36	$3.505 \pm 0.014 \pm 0.033$	BESIII
$D^0 \to \pi^- e^+ \nu_e$	0.239	$0.2770 \pm 0.0068 \pm 0.0092$	*BABAR*
		$0.295 \pm 0.004 \pm 0.003$	BESIII
		$0.288 \pm 0.008 \pm 0.003$	CLEO-c
		$0.255 \pm 0.019 \pm 0.016$	Belle
$D^0 \to \pi^- \mu^+ \nu_\mu$	0.235	$0.267 \pm 0.007 \pm 0.007$	BESIII
$D^0 \to K^*(892)^- e^+ \nu_e$	3.25	2.16 ± 0.16	PDG
$D^0 \to K^*(892)^- \mu^+ \nu_\mu$	3.09	1.92 ± 0.25	PDG

Conclusion

We have computed

- Pure leptonic decays of D_s-meson.
- $D_s \to \phi$ transition form factors in the entire range of momentum transfer
- Branching fractions for $D_s^+ \to \phi \ell^+ \nu_\ell$ within Covariant Quark Model
- $\mathcal{B}(D_s^+ \to \phi \mu^+ \nu_\mu)$ theoretically first time (To the best of our knowledge)

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