Possible New Physics on $D_s^+ \to \eta^{(\prime)} l^+ \nu_l$ Decays in Scalar Leptoquark Model

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Motivation

B Anomalies for the $b \to cl\nu_l$ decays

Observable	Exp. Result	SM Prediction	Deviation
R_D	$0.339 \pm 0.026 \pm 0.014$ HFLAG [1]	0.299 ± 0.003 [1]	1.4σ
R_{D^*}	$0.295 \pm 0.010 \pm 0.010$ HFLAG [1]	0.254 ± 0.005 [1]	2.8σ
$R_{J/\psi}$	$0.71 \pm 0.17 \pm 0.18$ [2]	0.283 ± 0.048 [3]	2σ
$P_{\tau D^*}$	$-0.38 \pm 0.51^{+0.21}_{-0.16}$ [7, 8]	-0.497 ± 0.013 [4]	–
$F_{L D^*}$	$0.60 \pm 0.08 \pm 0.035$ [9]	0.46 ± 0.04 [5]	1.7σ
R_{X_c}	0.223 ± 0.030 [6]	0.216 ± 0.003 [6]	–

Is there any possibility to find such anomalous results in charm decays?

Therefore, there are some possibilities to exist some NP. Several theoretical efforts [10, 13, 14] have been done recently to find the NP contribution in D meson decays.

Decay	SM result [10]	Experiment [11]	$Pull_{SM}$
$\mathcal{B}(D_s^+ \to \eta\mu^+\nu_\mu) \times 10^{-2}$	1.52 ± 0.31	2.4 ± 0.5	1.5σ
		$2.215 \pm 0.051 \pm 0.052$ [12]	2.2σ
$\mathcal{B}(D_s^+ \to \eta'\mu^+\nu_\mu) \times 10^{-3}$	5.64 ± 1.10	11.0 ± 5.0	1.05σ
		$8.01 \pm 0.55 \pm 0.31$ [12]	1.9σ
$\mathcal{B}(D_s^+ \to \eta e^+\nu_e) \times 10^{-2}$	1.55 ± 0.33	2.29 ± 0.19	2σ
$\mathcal{B}(D_s^+ \to \eta' e^+\nu_e) \times 10^{-3}$	5.91 ± 1.26	7.4 ± 1.4	0.8σ

[11] R. L. Workman et al. (Particle Data Group), *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).
[12] M. Ablikim *et. al.,* (BESIII Collaboration), [arXiv:2307.12852 [hep-ex]] (2023).

Theoretical Framework

Considering all possible Lorentz structures and assuming only left-handed neutrinos, the general effective Lagrangian for the $c \to q\bar{l}\nu_l$ transitions can be written as [10, 13]

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cq}^{*}\left[\left(1 + C_{V_L}^{l}\right)O_{V_L}^{l} + C_{V_R}^{l}O_{V_R}^{l} + C_{S_L}^{l}O_{S_L}^{l} + C_{S_R}^{l}O_{S_R}^{l} + C_{T}^{l}O_{T}^{l}\right] + h.c, \quad (1)$$

The two-fold differential angular decay distribution of $D \to Pl^{+}\nu_l$ $(P = \eta, \eta')$ decay can be expressed as

$$\frac{d^2\Gamma(D\to Pl^{+}\nu_l)}{dq^2 d\cos\theta_l} = \frac{G_F^2|V_{cq}|^2\sqrt{Q_+Q_-}}{256\pi^3 m_D^3}\left(1 - \frac{m_l^2}{q^2}\right)^2\left[q^2 A_1^P + \sqrt{q^2}m_l A_2^P + m_l^2 A_3^P\right], \quad (2)$$

with

$$A_1^P = \left|C_{S_L} + C_{S_R}\right|^2 |H^{PS}|^2 + Re\left[\left(C_{S_L} + C_{S_R}\right)C_T^{*}\right]H^{PS}\left(H_{0,t}^{PT} + H_{0,-1}^{PT}\right)\cos\theta_l + 4|C_T|^2\left|H_{0,t}^{PT} + H_{1,-1}^{PT}\right|^2 \cos^2\theta_l + \left|1 + C_{V_L} + C_{V_R}\right|^2\left|H_0^{PV}\right|^2 \sin^2\theta_l, \quad (3)$$

Theoretical Framework

$$A_2^P = 2\{Re[(C_{S_L} + C_{S_R})(1 + C_{V_L} + C_{V_R})^*]H^{PS}H_t^{PV} - 2Re[C_T(1 + C_{V_L} + C_{V_R})^*]H_0^{PV}(H_{0,t}^{PT} + H_{1,-1}^{PT})\} - 2\{Re[(C_{S_L} + C_{S_R})(1 + C_{V_L} + C_{V_R})^*]H^{PS}H_0^{PV} - 2Re[C_T(1 + C_{V_L} + C_{V_R})^*]H_t^{PV}(H_{0,t}^{PT} + H_{1,-1}^{PT})\}cos\theta_l, \quad (4)$$

$$A_3^P = 4|C_T|^2\left|H_{0,t}^{PT} + H_{1,-1}^{PT}\right|^2 \sin^2\theta_l + \left|1 + C_{V_L} + C_{V_R}\right|^2(\left|H_0^{PV}\right|^2\cos^2\theta_l - 2H_0^{PV}H_T^{PV}cos\theta_l + \left|H_t^{PV}\right|^2), \quad (5)$$

where θ_l is the angle between the charged lepton and opposite direction of the motion of the final meson in the virtual W^{*+} rest frame and $M_\pm = m_D \pm m_P$ and $Q_\pm = M_\pm^2 - q^2$.

Theoretical Framework

The $D \to Pl^+\nu_l$ decays have contributions through only five helicity amplitudes, which are given by

$$H_0^{PV} = \frac{f_+\sqrt{Q_+Q_-}}{\sqrt{q^2}}, \quad H_t^{PV} = \frac{f_0 M_+ M_-}{\sqrt{q^2}}, \quad H^{PS} = \frac{f_0 M_+ M_-}{m_c - m_q},$$
$$H_{0,t}^{PT} = -\frac{f_T\sqrt{Q_+Q_-}}{M_+}, \quad H_{1,-1}^{PT} = -\frac{f_T\sqrt{Q_+Q_-}}{M_+}. \tag{6}$$

In this work, we have used the form factors obtained from light cone sum rules (LCSR) [15], which are parameterized as

$$F^i(q^2) = \frac{F^i(0)}{1 - a\frac{q^2}{m_D^2} + b\left(\frac{q^2}{m_D^2}\right)^2} \quad . \tag{7}$$

Table: Form factors for $D \to \eta_q$ and $D_s \to \eta_s$ [15].

Decay	$D \to \eta_q$		$D_s \to \eta_s$	
Form factors	f_+	f_0	f_+	f_0
$F(0)$	$0.56^{+0.06}_{-0.05}$	$0.56^{+0.06}_{-0.05}$	$0.61^{+0.06}_{-0.05}$	$0.61^{+0.06}_{-0.05}$
a	$1.25^{-0.04}_{+0.05}$	$0.65^{-0.01}_{+0.02}$	$1.20^{-0.02}_{+0.03}$	$0.64^{-0.01}_{+0.02}$
b	$0.42^{-0.06}_{+0.05}$	$-0.22^{-0.03}_{+0.02}$	$0.38^{-0.01}_{+0.01}$	$-0.18^{+0.04}_{-0.03}$

Theoretical Framework

Scalar Leptoquark Model

To describe the $c \to q\bar{l}\nu_l$ transitions through LQ as mediator, the Lagrangian can be defined as [16]

$$\mathcal{L}_{int}^{\phi} \supset \bar{Q}_L^c \lambda^L i\tau_2 L\phi^* + \bar{u}_R^c \lambda^R l_R \phi^* + h.c.. \quad (8)$$

In terms of Yukawa coupling the NP Wilson coefficients are defined as

$$C_{V_L}(M_\phi) = \frac{\lambda^L_{c\nu_l}\lambda^{L*}_{ql}}{4\sqrt{2}G_F V_{cq} M_\phi^2},$$

$$C_{S_L}(M_\phi) = -\frac{\lambda^L_{c\nu_l}\lambda^{R*}_{ql}}{4\sqrt{2}G_F V_{cq} M_\phi^2},$$

$$C_T(M_\phi) = -\frac{1}{4} S_L(M_\phi). \quad (9)$$

CMS Collaboration [17] has predicted the mass of Leptoquark to be in the range of $0.98 - 1.73$ TeV.

[16] X.-L. Mu, Y. Li, Z.-T. Zou and B. Zhu, *Phys. Rev. D* **100**, 113004 (2019) [arXiv:1909.10769 [hep-ph]].
[17] A. M Sirunyan *et at*. (CMS Collaboration), *Phys. Lett. B* 819, 136446 (2021) [arXiv:2012.04178 [hep-ex]].

Results

Table: the SM and experimental results of branching fraction of semileptonic and leptonic D meson decays.

$c \to s\mu^+\nu_\mu$		
Decay	SM Result [10]	Exp. Result [11]
$D^0 \to K^-\mu^+\nu_\mu$	$(3.40 \pm 0.22) \times 10^{-2}$	$(3.41 \pm 0.04) \times 10^{-2}$
$D^+ \to \bar{K}^0\mu^+\nu_\mu$	$(8.69 \pm 0.57) \times 10^{-2}$	$(8.76 \pm 0.19) \times 10^{-2}$
$D^0 \to K^{*-}\mu^+\nu_\mu$	$(1.81 \pm 0.16) \times 10^{-2}$	$(1.89 \pm 0.24) \times 10^{-2}$
$D^+ \to \bar{K}^{*0}\mu^+\nu_\mu$	$(4.71 \pm 0.42) \times 10^{-2}$	$(5.27 \pm 0.15) \times 10^{-2}$
$D_s^+ \to \phi\mu^+\nu_\mu$	$(2.33 \pm 0.40) \times 10^{-2}$	$(1.90 \pm 0.50) \times 10^{-2}$
$D_s^+ \to \eta\mu^+\nu_\mu$	$(1.52 \pm 0.31) \times 10^{-2}$	$(2.4 \pm 0.5) \times 10^{-2}$
$D_s^+ \to \eta'\mu^+\nu_\mu$	$(5.64 \pm 1.10) \times 10^{-3}$	$(11.0 \pm 5.0) \times 10^{-3}$
$\boldsymbol{D_s^+ \to \mu^+\nu_\mu}$	$(5.28 \pm 0.08) \times 10^{-3}$	$(5.43 \pm 0.15) \times 10^{-3}$

$c \to se^+\nu_e$		
Decay	SM Result [10]	Exp. Result [11]
$D^0 \to K^-e^+\nu_e$	$(3.49 \pm 0.23) \times 10^{-2}$	$(3.542 \pm 0.0035) \times 10^{-2}$
$D^+ \to \bar{K}^0e^+\nu_e$	$(8.92 \pm 0.59) \times 10^{-2}$	$(8.73 \pm 0.10) \times 10^{-2}$
$D^0 \to K^{*-}e^+\nu_e$	$(1.92 \pm 0.17) \times 10^{-2}$	$(2.15 \pm 0.16) \times 10^{-2}$
$D^+ \to \bar{K}^{*0}e^+\nu_e$	$(4.98 \pm 0.45) \times 10^{-2}$	$(5.40 \pm 0.10) \times 10^{-2}$
$D_s^+ \to \phi e^+\nu_e$	$(2.46 \pm 0.42) \times 10^{-2}$	$(2.39 \pm 0.16) \times 10^{-2}$
$D_s^+ \to \eta e^+\nu_e$	$(1.55 \pm 0.33) \times 10^{-2}$	$(2.29 \pm 0.19) \times 10^{-2}$
$D_s^+ \to \eta' e^+\nu_e$	$(5.91 \pm 1.26) \times 10^{-3}$	$(7.4 \pm 1.4) \times 10^{-3}$
$D_s^+ \to e^+\nu_e$	$(1.24 \pm 0.02) \times 10^{-7}$	$< 8.3 \times 10^{-5}$

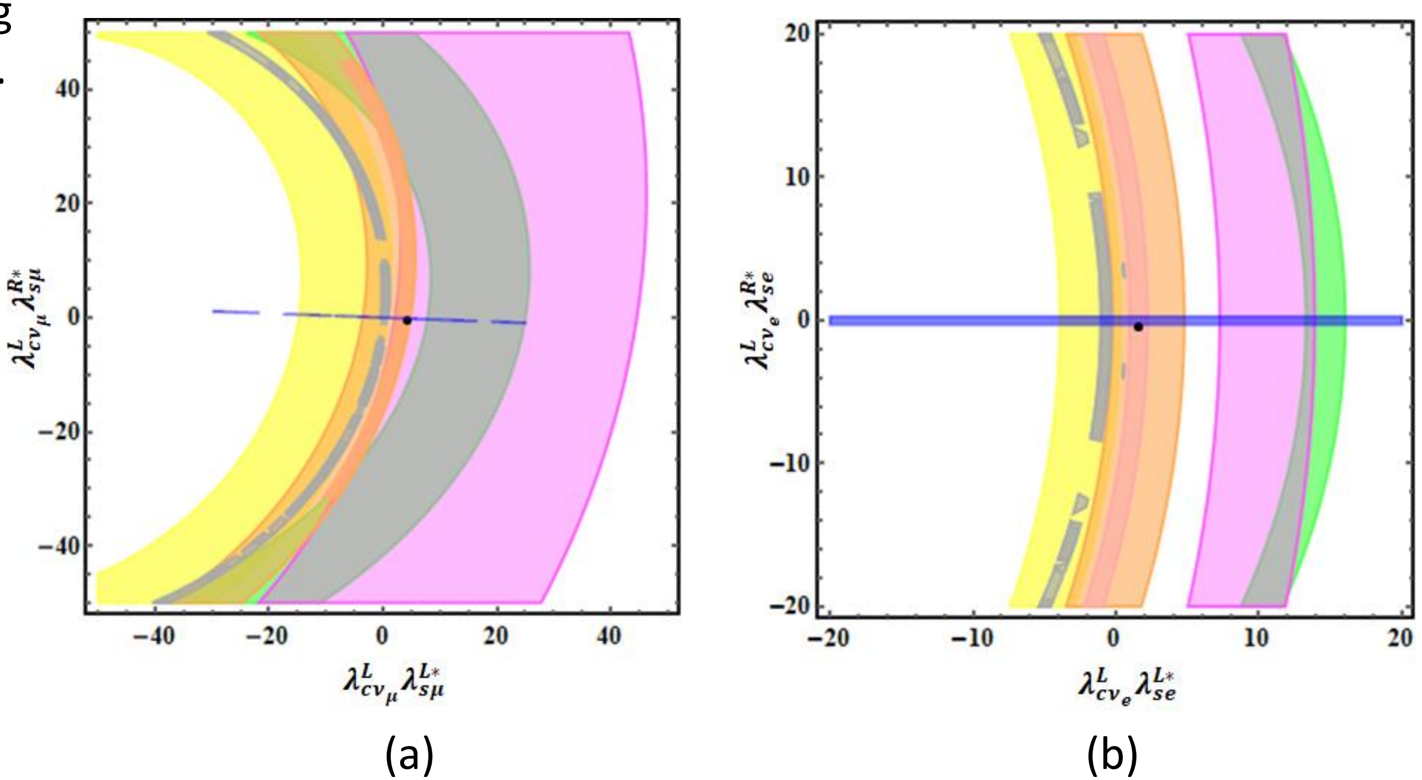


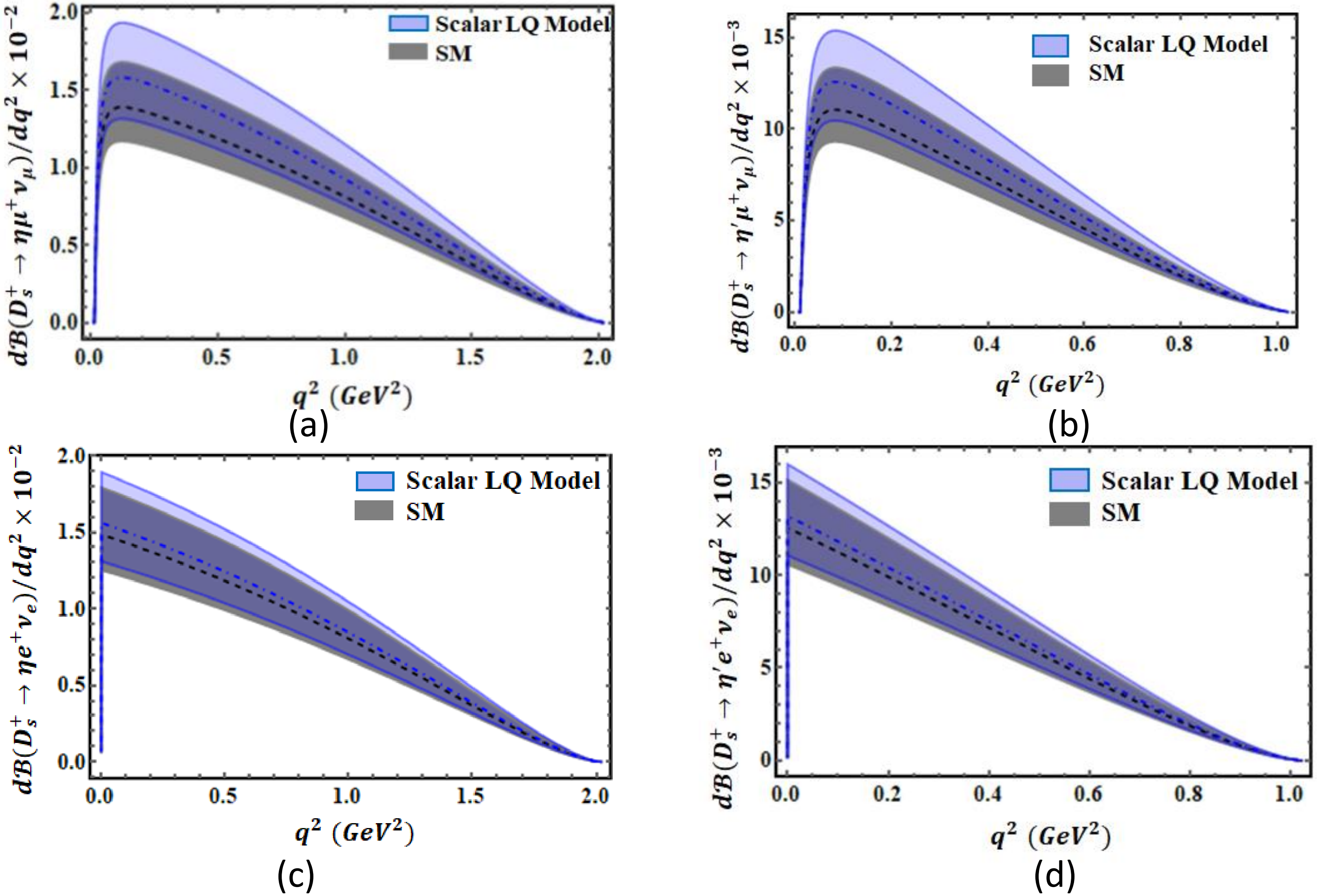
Fig: Allowed parameter space in the $(\lambda^L_{c\nu_l}\lambda^{L*}_{sl}, \lambda^L_{c\nu_l}\lambda^{R*}_{sl})$ plane for (a) $c \to s\mu^+\nu_\mu$ and (b) $c \to se^+\nu_e$ transitions. Here, colour notations are: Green ($D_s^+ \to \eta$), Magenta ($D_s^+ \to \eta'$), Yellow ($D_s^+ \to \phi$), Pink ($D^+ \to \bar{K}^{*0}$), Orange ($D^0 \to K^{*-}$), Grey ($D^0 \to K^-$ and $D^+ \to \bar{K}^0$) and Blue ($D_s^+ \to l^+\nu_l$). Black dot represents the fitted point of coupling parameters.

Results

Table: Values of the scalar LQ coupling parameters.

Current	Coupling Parameter	Mid-value
$c \to s\mu^+\nu_\mu$	$\lambda^L_{c\nu_\mu}\lambda^{L*}_{s\mu}$	4.30
	$\lambda^L_{c\nu_\mu}\lambda^{R*}_{s\mu}$	−0.47
$c \to se^+\nu_e$	$\lambda^L_{c\nu_e}\lambda^{L*}_{se}$	1.63
	$\lambda^L_{c\nu_e}\lambda^{R*}_{se}$	−0.44

Fig: Distribution of branching fraction.



Results

Table: Values of the branching fractions in scalar LQ model and their corresponding pull from the experimental results.

Decay	Scalar LQ Model	Experiment [11]	$pull_{SM}$	$Pull_{LQ}$
$\mathcal{B}(D_s^+ \to \eta\mu^+\nu_\mu) \times 10^{-2}$	1.73 ± 0.41	2.4 ± 0.5	1.5σ	1.0σ
		$2.215 \pm 0.051 \pm 0.052$ [12]	2.2σ	1.1σ
$\mathcal{B}(D_s^+ \to \eta'\mu^+\nu_\mu) \times 10^{-3}$	6.42 ± 1.47	11.0 ± 5.0	1.05σ	0.9σ
		$8.01 \pm 0.55 \pm 0.31$ [12]	1.9σ	0.8σ
$\mathcal{B}(D_s^+ \to \eta e^+\nu_e) \times 10^{-2}$	1.62 ± 0.38	2.29 ± 0.19	2σ	1.5σ
$\mathcal{B}(D_s^+ \to \eta' e^+\nu_e) \times 10^{-3}$	6.21 ± 1.36	7.4 ± 1.4	0.8σ	0.6σ

[11] R. L. Workman et al. (Particle Data Group), *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).
[12] M. Ablikim *et. al.,* (BESIII Collaboration), [arXiv:2307.12852 [hep-ex]] (2023).

Results

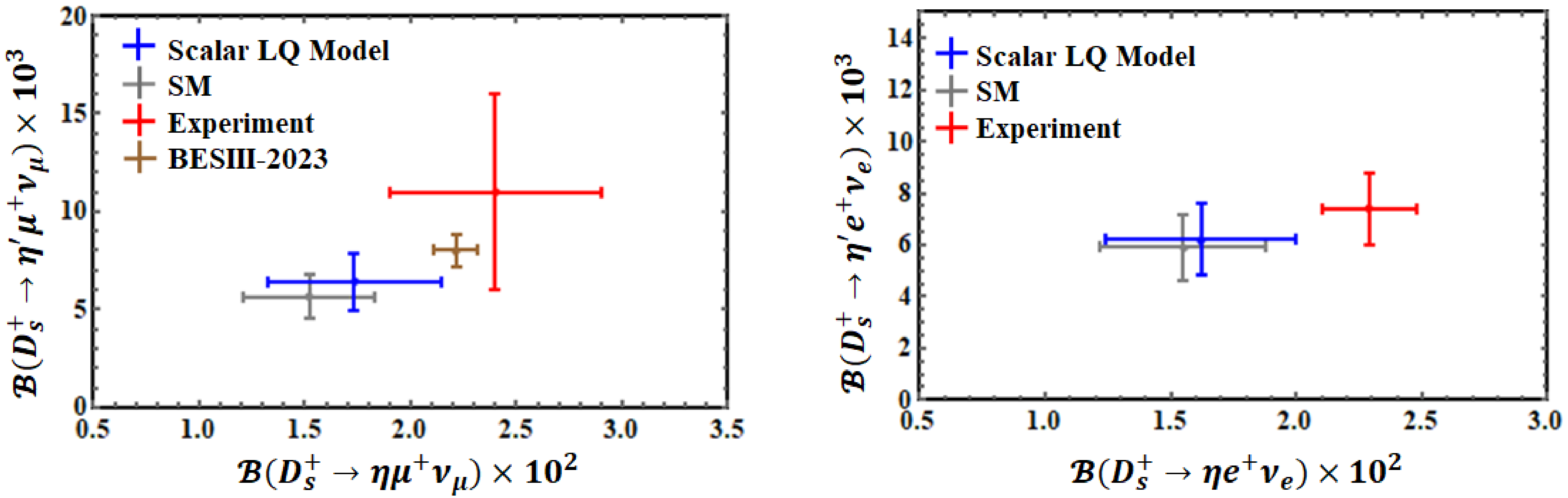


Fig: Comparison of the scalar LQ model results with the experiment and SM in 2D ($\mathcal{B}(D_s^+ \to \eta l^+ \nu_l)$,$\mathcal{B}(D_s^+ \to \eta' l^+ \nu_l)$) plane.

Conclusion

- Our predicted branching fraction results are found round 1σ range of the experimental results excluding $D_s^+ \to \eta e^+ \nu_e$ decay.

- We have also found good consistency with the BESIII 2023 results.

- The effectiveness of our models is clearly observed through the comparison of our predicted results with the experimental results and SM predictions in 2D branching fraction plane.

- The scalar LQ model is reliable to study $c \to s\bar{l}\nu_l$ transitions in the framework of NP.

- We will be able to better comprehend the existence of NP with the help of the impending measurement of D meson decays in the BESIII and Belle II experiments. We expect that our predicted values in scalar LQ model will be closer to the outcomes of upcoming experiments.

References

1. Y. Amhis et al. (Heavy Flavor Averaging Group), *Phys. Rev. D* **107**, 052088 (2023) [arXiv: 2206.07501 [hep-ex]].
2. R. Aaij et al. (LHCb Collaboration), *Phys. Rev. Lett.* **120**, 121801 (2018) [arXiv: 1711.05623 [hep-ex]].
3. R. Watanabe, *Phys. Lett. B* **776**, 5 (2018) [arXiv:1709.08644 [hep-ph]].
4. M. Tanaka and R. Watanabe, *Phys. Rev. D* **87**, 034028 (2013) [arXiv:1212.1878 [hep-ph]].
5. A. K. Alok, D. Kumar, S. Kumbhakar and S. U. Sankar, *Phys. Rev. D* **95**, 115038 (2017) [arXiv:1606.03164 [hep-ph]].
6. S. Kamali, *Int. J. Mod. Phys. A* **34**, 1950036 (2019) [arXiv:1811.07393 [hep-ph]].
7. S. Hirose et al. (Belle Collaboration), *Phys. Rev. D* **97**, 012004 (2018) [arXiv:1709.00129 [hep-ex]].
8. S. Hirose et al. (Belle Collaboration), *Phys. Rev. Lett*. **118**, 211801 (2017) [arXiv:1612.00529 [hep-ex]].
9. A. Abdesselam et al. (Belle Collaboration), [arXiv:1903.03102 [hep-ex]] (2019).
10. X. Leng, X. L. Mu, Z. T. Zou and Y. Li, *Chin. Phys. C* **45**, 063107 (2021) [arXiv:2011.01061 [hep-ph]].
11. R. L. Workman et al. (Particle Data Group), *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).
12. M. Ablikim *et. al.,* (BESIII Collaboration), [arXiv:2307.12852 [hep-ex]] (2023).
13. K. Jain and B. Mawlong, *20th Conference on Flavour Physics and CP Violation, Oxford, MS, 2022*, [arXiv:2207.04935v1 [hep-ph]].
14. J. Barranco, D. Delepine, V. Gonzalez Macias and L. Lopez-Lozano, *Phys. Lett. B* **731**, 36 (2014) [arXiv:1303.3896 [hep-ph]].
15. Y.-L. Wu, M. Zhong, and Y.-B. Zuo, *Int. J. Mod. Phys. A* **21**, 6125 (2006) [hep-ph/0604007].
16. X.-L. Mu, Y. Li, Z.-T. Zou and B. Zhu, *Phys. Rev. D* **100**, 113004 (2019) [arXiv:1909.10769 [hep-ph]].
17. A. M Sirunyan *et at*. (CMS Collaboration), *Phys. Lett. B* 819, 136446 (2021) [arXiv:2012.04178 [hep-ex]].

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Thank You