Exploring New Physics in $D_{(s)}^+ \to \eta^{(\prime)} \bar{\ell} \nu_\ell$ decays

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Outline

- Introduction
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- Constraints on New Couplings
- Sensitivity to NP
- Conclusion

Introduction

Motivation

- Flavor anomalies in b-hadron decays - Indications of Beyond SM (BSM) Physics
- Discrepancies seen in decays: $b \to s\ell^+\ell^-$, $b \to c\tau^-\bar{\nu}_\tau$
- Lepton flavor universality (LFU) violation

  Tensions at the $(2-3)\sigma$ level between measured and SM predictions for the ratios

$$R_{D^{(*)}} = \frac{(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{(\bar{B} \to D^{(*)}l^-\bar{\nu}_\ell)}, \quad R_{K^{(*)}} = \frac{(\bar{B} \to K^{(*)}\mu^+\mu^-)}{(\bar{B} \to K^{(*)}e^+e^-)}$$

- Probe similar phenomena and possible new physics (NP) sensitivity in the charm sector. We focus on $c \to (s,d)\bar{\ell}\nu_\ell$ charge-current transitions here, in particular $D^+_{(s)} \to \eta^{(')}\bar{\ell}\nu_\ell$ decays.

Theoretical Framework

- The effective Lagrangian for $c \to (s, d)\bar{\ell}\nu_\ell$ transitions including NP contributions is [1]

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cq} \left[(1 + C^\ell_{V_L}) O^\ell_{V_L} + C^\ell_{V_R} O^\ell_{V_R} + C^\ell_{S_L} O^\ell_{S_L} + C^\ell_{S_R} O^\ell_{S_R} + C^\ell_T O^\ell_T\right] + h.c.$$

with fermionic operators defined as

$$O^\ell_{V_L} = (\bar{q}\gamma^\mu P_L c)(\bar{\nu}_\ell \gamma_\mu P_L \ell) \quad , \quad O^\ell_{V_R} = (\bar{q}\gamma^\mu P_R c)(\bar{\nu}_\ell \gamma_\mu P_L \ell),$$
$$O^\ell_{S_L} = (\bar{q} P_L c)(\bar{\nu}_\ell P_R \ell) \quad , \quad O^\ell_{S_R} = (\bar{q} P_R c)(\bar{\nu}_\ell P_R \ell),$$
$$O^\ell_T = (\bar{q}\sigma^{\mu\nu} P_L c)(\bar{\nu}\ell \sigma_{\mu\nu} P_R \ell)$$

and $C^\ell_i (i = V_L, V_R, S_L, S_R, T)$ are corresponding Wilson coefficients.

[1] X. Leng et al., Chin. Phys. C 45 (2021) 063107

$D \to P\bar{\ell}\nu_\ell$:

Hadronic matrix elements :

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

- $$\langle P(p_2)|\bar{q}c|D(p_1)\rangle = \frac{q^\mu}{m_c - m_q}\langle P(p_2)|\bar{q}\gamma^\mu c|D(p_1)\rangle = \frac{m_D^2 - m_P^2}{m_c - m_q}f_0(q^2)$$

Form factors:

- We use form factors obtained from LCSR [2]. Parametrisation is given by

$$F^i(q^2) = \frac{F^i(0)}{1 - a\frac{q^2}{M_D^2} + b\left(\frac{q^2}{M_D^2}\right)^2}$$

Decay	F(0)		a	b
$D \to \eta$	f_+	$0.556^{+0.056}_{-0.053}$	$1.25^{-0.04}_{+0.05}$	$0.42^{-0.06}_{+0.05}$
	f_0	$0.556^{+0.056}_{-0.053}$	$0.65^{-0.01}_{+0.02}$	$-0.22^{-0.03}_{+0.02}$
$D_s \to \eta$	f_+	$0.611^{+0.062}_{-0.054}$	$1.20^{-0.02}_{+0.03}$	$0.38^{-0.01}_{+0.01}$
	f_0	$0.611^{+0.062}_{-0.054}$	$0.64^{-0.01}_{+0.02}$	$-0.18^{+0.04}_{-0.03}$

[2] Y-L. Wu, M. Zhong, Y-B. Zuo, Int. J. Mod. Phys. A 21 (2006) 6125

Helicity Amplitudes :

- The helicity amplitudes are

$$H^P_{V,\lambda_W}(q^2) = \epsilon^*_\mu(\lambda_W)\langle P(p_2)|\bar{q}\gamma^\mu c|D(p_1)\rangle$$

$$H^P_{V,0} = \sqrt{\frac{\lambda_P(q^2)}{q^2}}\, f_+(q^2)$$

$$H^P_{V,t} = \frac{M_D^2 - M_P^2}{\sqrt{q^2}}\, f_0(q^2)$$

- The scalar helicity amplitudes are

$$H^P_S = \frac{M_D^2 - M_P^2}{m_c - m_q}\, f_0(q^2),$$

where

$$\lambda_P(q^2) = [(M_D - M_P)^2 - q^2][(M_D + M_P)^2 - q^2]$$

Angular Decay distribution

- The two-fold differential angular decay distribution is given by

$$\frac{d^2\Gamma(D \to P\ell^+\nu_\ell)}{dq^2 d\cos\theta_\ell} = \frac{G_F^2|V_{cq}|^2\sqrt{Q_+Q_-}}{256\pi^3 M_D^3}\left(1-\frac{m_\ell^2}{q^2}\right)^2\left[q^2 A_1^P + \sqrt{q^2}m_\ell A_2^P + m_\ell^2 A_3^P\right]$$

where

$$Q_\pm = (M_D \pm M_P)^2 - q^2$$

and

$$A_1^P = |C_{S_L} + C_{S_R}|^2|H_S^P|^2 + |1 + C_{V_L} + C_{V_R}|^2|H_{V,0}^P|^2\sin^2\theta_\ell$$

$$\begin{aligned} A_2^P =& 2\left\{Re[(C_{S_L} + C_{S_R})(1 + C_{V_L} + C_{V_R})^*]H_S^P H_{V,t}^P\right\} \\ &- 2\left\{Re[(C_{S_L} + C_{S_R})(1 + C_{V_L} + C_{V_R})^*]H_S^P H_{V,0}^P\right\}\cos\theta_\ell \end{aligned}$$

$$A_3^P = |1 + C_{V_L} + C_{V_R}|^2(|H_{V,0}^P|^2\cos^2\theta_\ell - 2H_{V,0}^P H_{V,t}^P\cos\theta_\ell + |H_{V,t}^P|^2)$$

Differential branching fraction :

Integrating out $\cos\theta_\ell$ terms, we get the differential decay rate ($\frac{d\Gamma}{dq^2}$). The differential branching fraction is

$$
\begin{aligned}
\frac{d\mathcal{B}}{dq^2} =& \frac{G_F^2|V_{cq}|^2\tau_D\sqrt{Q_+Q_-}}{256\pi^3 M_D^3}\left(1-\frac{m_\ell^2}{q^2}\right) \\
& \Bigg\{\frac{2}{3}\left[|1+C_{V_L}+C_{V_R}|^2(|H^P_{V,0}|^2+3|H^P_{V,t}|^2)\right]m_\ell^2 \\
& +4\Bigg[(C_{S_L}+C_{S_R})(1+C_{V_L}+C_{V_R}) \\
& H^P_S H^P_{V,t}\Bigg]m_\ell\sqrt{q^2}+\Bigg[2(C_{S_L}+C_{S_R})^2|H^P_S|^2 \\
& +\frac{4}{3}|1+C_{V_L}+C_{V_R}|^2|H^P_{V,0}|^2\Bigg]q^2\Bigg\}
\end{aligned}
$$

q^2-dependent Observables :

- Forward-backward asymmetry in the lepton-side :

$$A_{FB}^{\ell}(q^2) = \frac{\int_0^1 d\cos\theta_\ell \frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} - \int_{-1}^0 d\cos\theta_\ell \frac{d^2\Gamma}{dq^2 d\cos\theta_\ell}}{\int_0^1 d\cos\theta_\ell \frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} + \int_{-1}^0 d\cos\theta_\ell \frac{d^2\Gamma}{dq^2 d\cos\theta_\ell}}$$

- Lepton polarization asymmetry

$$P_F^{\ell}(q^2) = \frac{\frac{d\Gamma(\lambda_\ell=1/2)}{dq^2} - \frac{d\Gamma(\lambda_\ell=-1/2)}{dq^2}}{\frac{d\Gamma(\lambda_\ell=1/2)}{dq^2} + \frac{d\Gamma(\lambda_\ell=-1/2)}{dq^2}}$$

- Tilted parabola

$$\tilde{W}(\theta_\ell) = \frac{a + b\cos\theta_\ell + c\cos^2\theta_\ell}{2(a + c/3)}$$

where a, b, c are q^2-dependent coefficients. Convexity parameter is

$$C_F^{\ell}(q^2) = \frac{d^2\tilde{W}(\theta_\ell)}{d(\cos\theta_\ell)^2} = \frac{c}{a + c/3}$$

Constraints on New Couplings

- The parameter space of new couplings is obtained using available experimental measurements of semileptonic D meson decays, $\mathcal{B}(D \to \eta^{(\prime)} \ell^+ \nu_\ell)$.
- Semileptonic decay : branching ratios are [3]

Decay	Experiment
$\mathcal{B}(D^+ \to \eta \mu^+ \nu_\mu)$	$(1.04 \pm 0.11) \times 10^{-3}$
$\mathcal{B}(D_s^+ \to \eta \mu^+ \nu_\mu)$	$(2.4 \pm 0.5) \times 10^{-2}$
$\mathcal{B}(D_s^+ \to \eta' \mu^+ \nu_\mu)$	$(11.0 \pm 5.0) \times 10^{-3}$

- We consider complex couplings in our work.
- For $c \to s$ transitions, the parameter space for the scalar coupling $C_S = C_{S_L} + C_{S_R}$ is obtained from the observable $\mathcal{R}$ defined below

$$\mathcal{R} \equiv \frac{\mathcal{B}(D \to \eta \ell^+ \nu_\ell)}{\mathcal{B}(D \to \eta' \ell^+ \nu_\ell)}$$

[3] P. Zyla et. al. PTEP 2020(8),083C01(2020)

- For $c \to d$ transitions, the parameter space for the scalar coupling $C_S = C_{S_L} + C_{S_R}$ is obtained using $\mathcal{B}(D^+ \to \eta \bar{\ell} \nu_\ell)$.
- For the vector coupling $C_V = C_{V_L} + C_{V_R}$, the parameter space is obtained using $\mathcal{B}(D^+ \to \eta \bar{\ell} \nu_\ell)$.

$c \to s$ transition

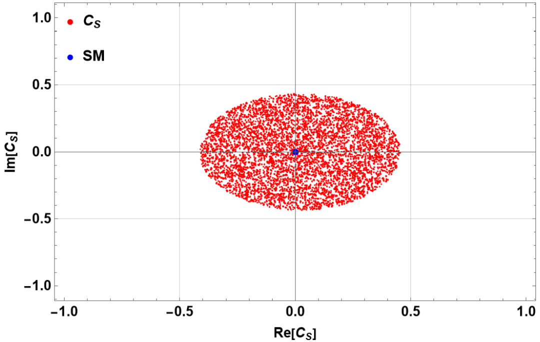

Figure 1: The allowed parameter space of the scalar coupling $C_S = C_{S_L} + C_{S_R}$ using $\mathcal{R}$.

$c \to s$ transition

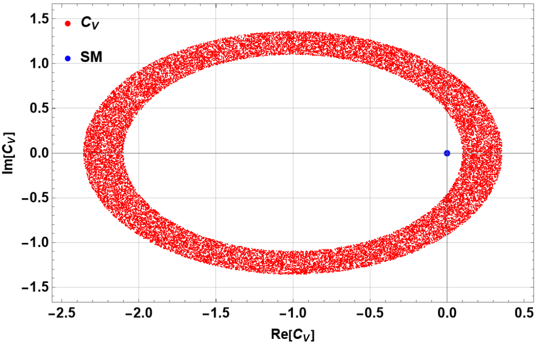

Figure 2: The allowed parameter space of the vector coupling $C_V = C_{V_L} + C_{V_R}$ using $\mathcal{B}(D_s^+ \to \eta \bar{\ell} \nu_\ell)$.

$c \to d$ transition

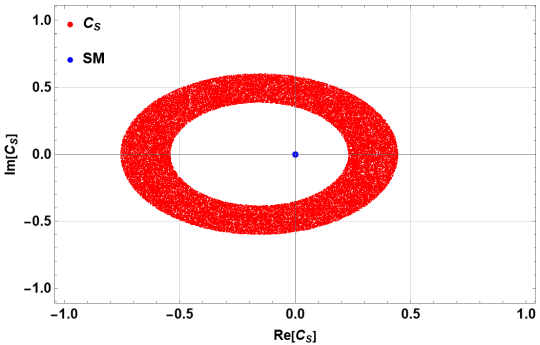

Figure 3: The allowed parameter space of the scalar coupling $C_S = C_{S_L} + C_{S_R}$ using $\mathcal{B}(D^+ \to \eta \bar{\ell} \nu_\ell)$.

$c \to d$ transition

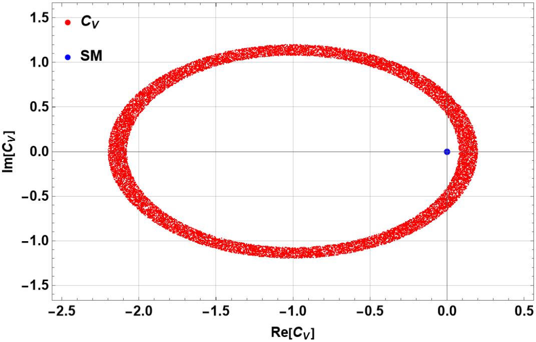

Figure 4: The allowed parameter space of the vector coupling $C_V = C_{V_L} + C_{V_R}$ using $\mathcal{B}(D^+ \to \eta \bar{\ell} \nu_\ell)$.

NP Sensitivity for $D_s^+ \to \eta \mu^+ \nu_\mu$

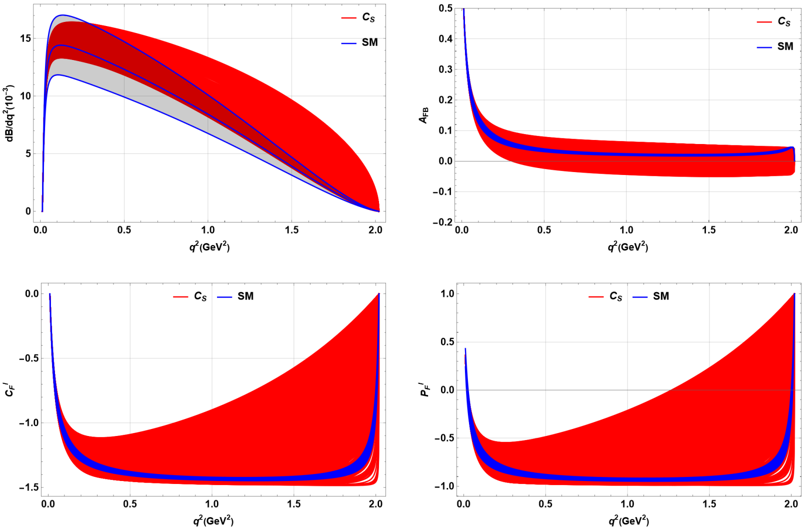

Figure 5: q^2-dependence of various observables for $D_s^+ \to \eta \mu^+ \nu_\mu$ in presence of C_S

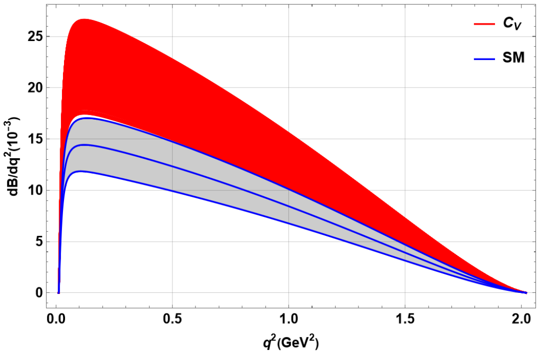

Figure 6: q^2-dependence of differential branching fraction for $D_s^+ \to \eta\mu^+\nu_\mu$ in presence of C_V.

NP Sensitivity for $D_s^+ \to \eta' \mu^+ \nu_\mu$

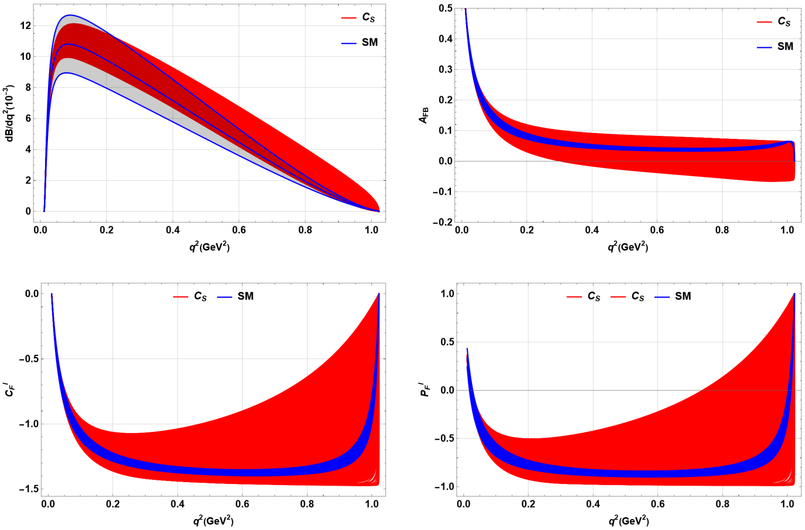

Figure 7: q^2-dependence of various observables for $D_s^+ \to \eta' \mu^+ \nu_\mu$ in presence of C_S

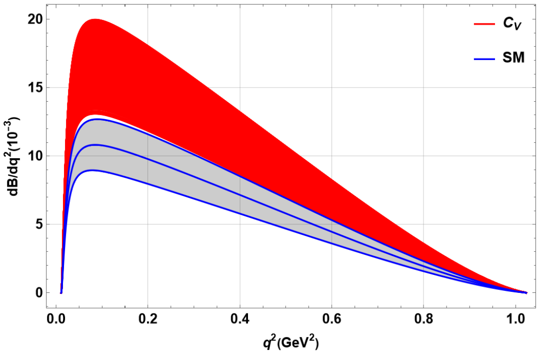

Figure 8: q^2-dependence of differential branching fraction for $D_s^+ \to \eta' \mu^+ \nu_\mu$ in presence of C_V.

NP Sensitivity for $D^+ \to \eta\mu^+\nu_\mu$

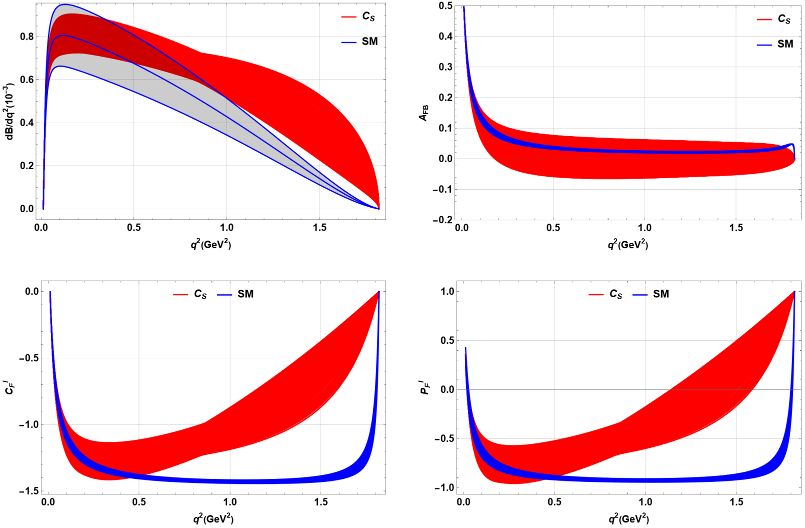

Figure 9: q^2-dependence of various observables for $D^+ \to \eta \mu^+ \nu_\mu$ in presence of C_S

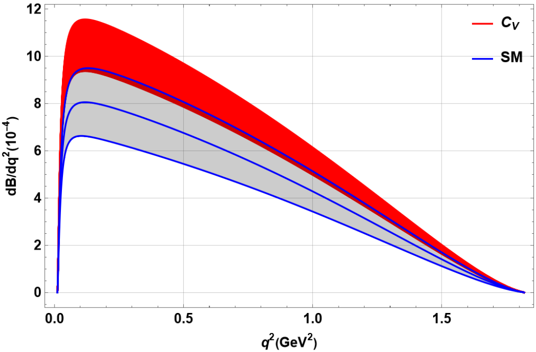

Figure 10: q^2-dependence of differential branching fraction for $D^+ \to \eta\mu^+\nu_\mu$ in presence of C_V.

Conclusion

- The decay modes $D^+_{(s)} \to \eta^{(\prime)}\bar{\ell}\nu_\ell$ are analyzed within the SM and beyond using an effective Lagrangian approach.
- The parameter space for NP couplings are obtained using available experimental measurements of semileptonic D meson decays.
- NP sensitivity of various q^2-dependent observables such as $\frac{d\mathcal{B}}{dq^2}(q^2)$, $A^\ell_{FB}(q^2)$, $C^\ell_F(q^2)$ and $P^\ell_F(q^2)$ are probed.
- Deviations from SM predictions are observed in the presence of the new couplings. For the scalar couplings, the sensitivity is more pronounced in $C^\ell_F(q^2)$ and $P^\ell_F(q^2)$. For the vector coupling, except for the differential branching fraction, the dependence cancels out in the other q^2-dependent observables.
- Studies of charm meson decays as those in this work provide a unique environment to probe flavor physics beyond SM in the up-sector.
- Precision future measurements will help in obtaining stronger constraints on possible NP contributions.

Thank You