Investigation of Effects of New Physics in $c \to s l^+ \nu$ Transitions

Ying Li

Yantai University

Chin.Phys.C 45 (2021) 6, 063107

Outline

- Motivation
- Framework
  - The Effective Hamiltonian
  - Form Factors
  - Leptonic Decays
  - Semi-leptonic Decays
- Predictions
- Summary

Gauge couplings of the quarks

$$\mathcal{L}_{\text{fermion}} = \sum_{j=1}^{3} \bar{Q}_j i \not{D}_Q Q_j + \bar{U}_j i \not{D}_U U_j + \bar{D}_J i \not{D}_D D_j$$

with the covariant derivatives ($Y_Q = 1/6$, $Y_U = 2/3$, $Y_D = -1/3$)

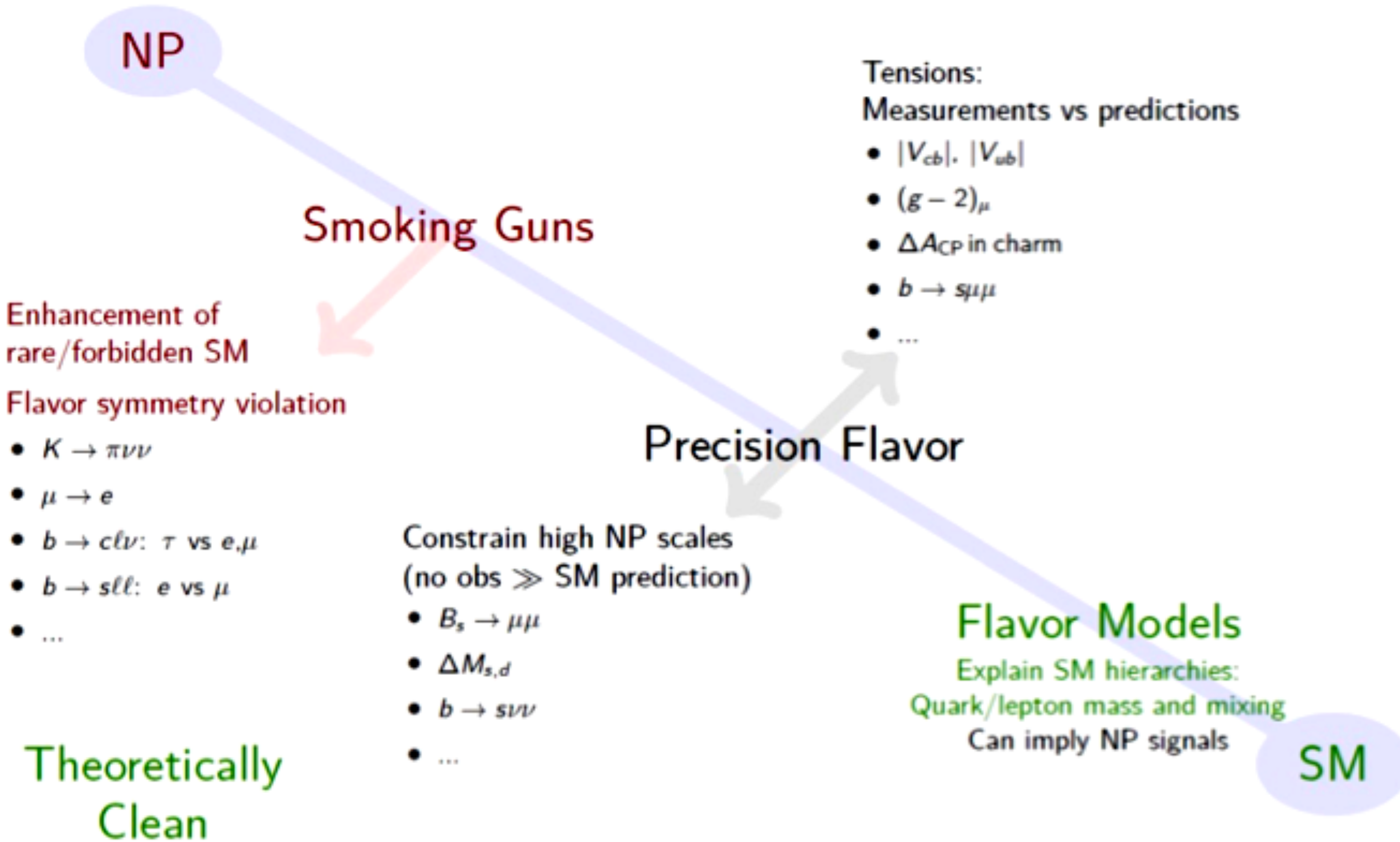
$$\begin{aligned} D_{Q,\mu} &= \partial_\mu + i g_s T^a G^a_\mu + i g \tau^a W^a_\mu + i Y_Q g' B_\mu \\ D_{U,\mu} &= \partial_\mu + i g_s T^a G^a_\mu + i Y_U g' B_\mu \\ D_{D,\mu} &= \partial_\mu + i g_s T^a G^a_\mu + i Y_D g' B_\mu \end{aligned}$$

$$\mathcal{L}_{\text{Yuk}} = \sum_{i,j=1}^{3} (-Y_{U,ij} \bar{Q}_{Li} \tilde{H} U_{Rj} - Y_{D,ij} \bar{Q}_{Li} H D_{Rj} + h.c.)$$

Flavour universality: gauge couplings are equal for all three generations

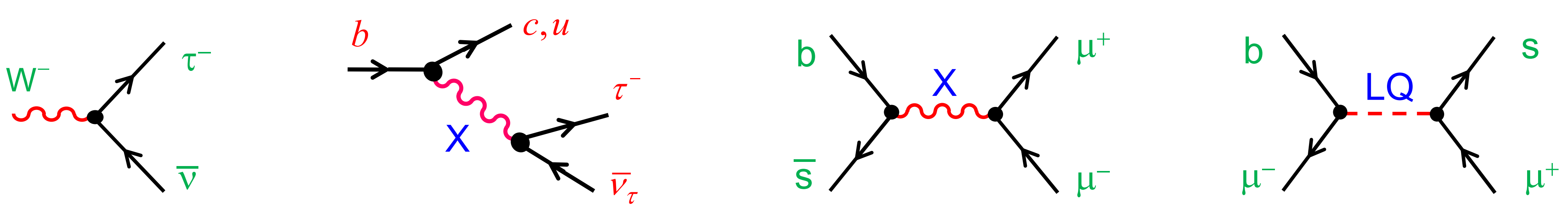
Flavour non-universality introduced by Yukawa couplings between the Higgs field and the quarks

Perspectives on Flavour NP



Many Interesting Flavour Anomalies

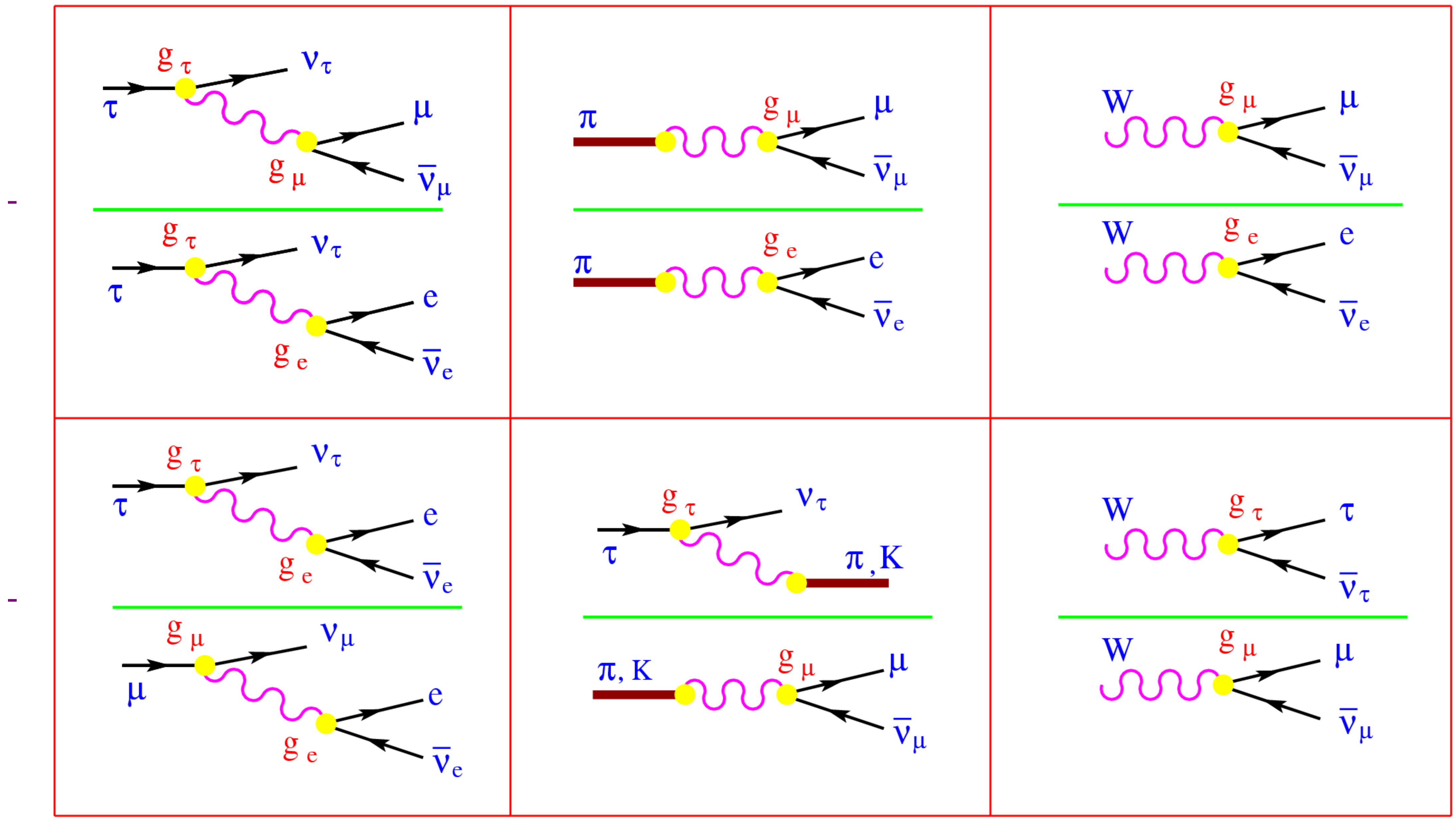
$$W \to \tau\nu, b \to c\tau\nu, b \to s\mu\mu, , (g-2)_\mu, V_{cb}, V_{ub}, \ldots .$$



- Statistical fluctuation
- Underestimated systematics
- Incorrect SM prediction or measurement
- Effects of New Physics beyond SM

- Not easy common explanation (within appealing BSM models)
- Separate analyses are (perhaps) more enlightening

Lepton flavour universality



Lepton flavour universality

A. Pich, arXiv:1310.7922

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0018 ± 0.0014
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0003 ± 0.0012
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0020
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	0.996 ± 0.010

PIENU 1506.05845

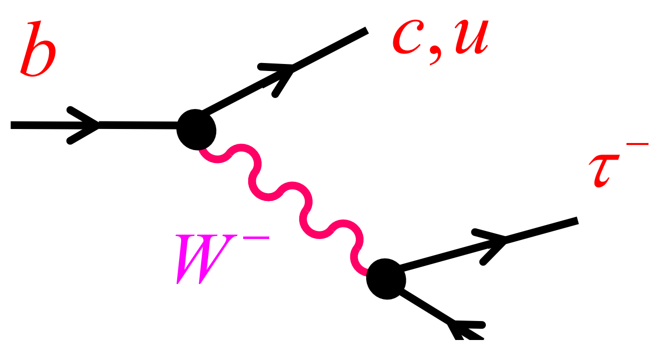
$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0011 ± 0.0015
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9962 ± 0.0027
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.9858 ± 0.0070
$B_{W\to\tau}/B_{W\to\mu}$	1.034 ± 0.013

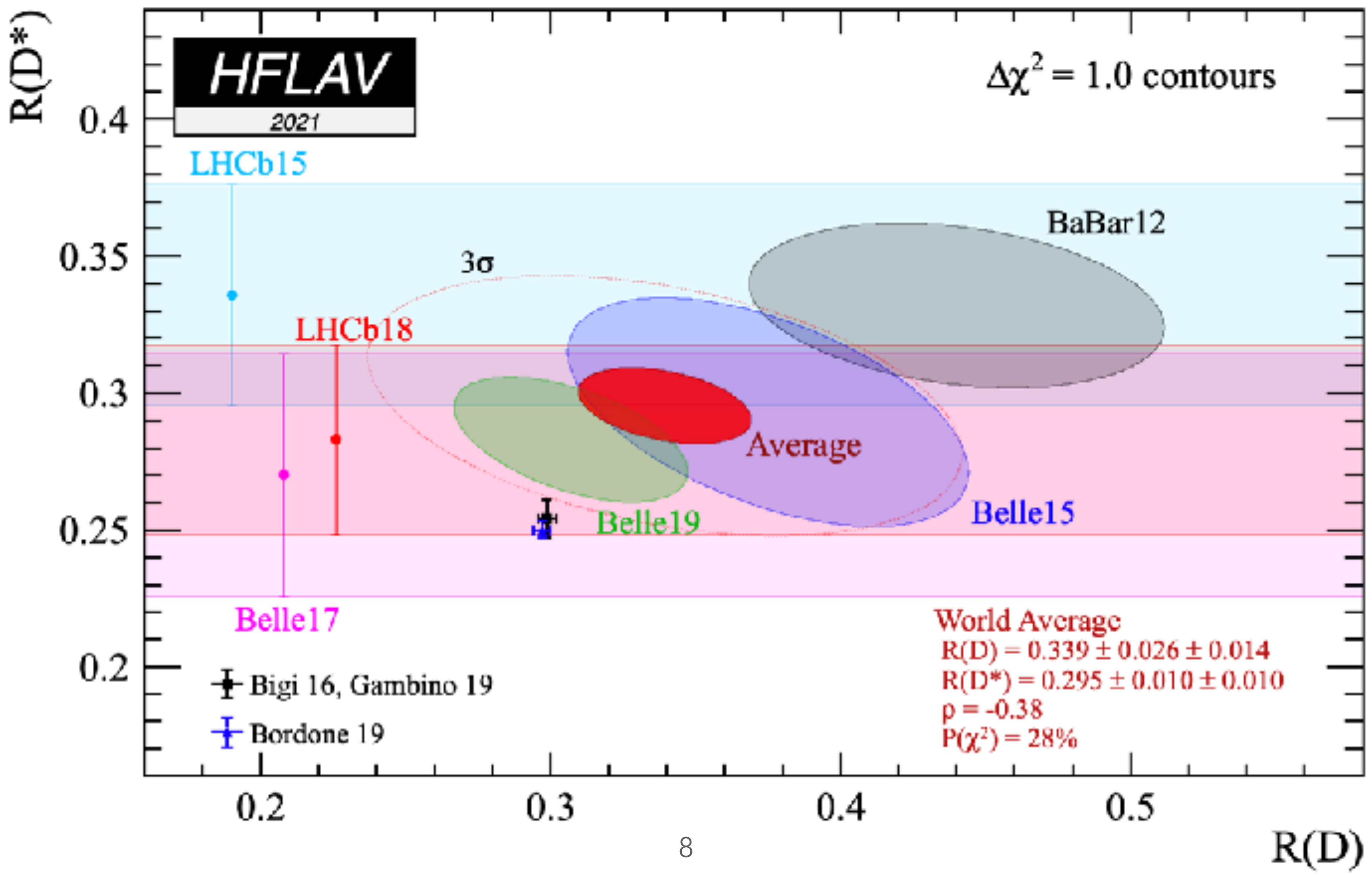
$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0030 ± 0.0015
$B_{W\to\tau}/B_{W\to e}$	1.031 ± 0.013

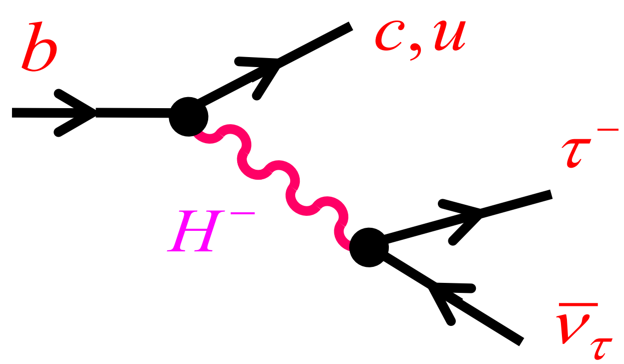
Many Interesting Flavour Anomalies

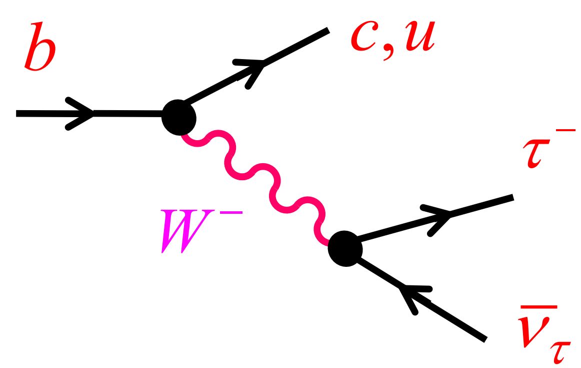


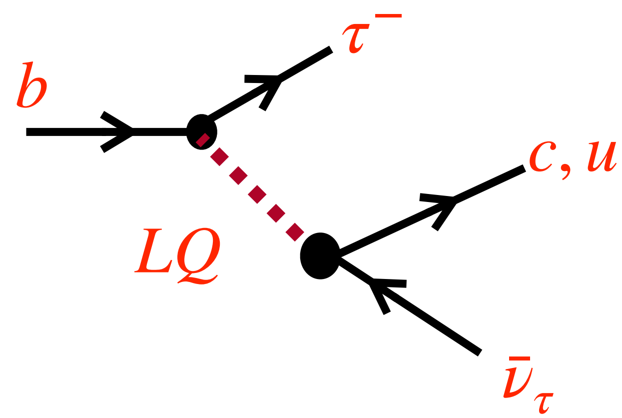
$$R(D^{(*)}) \equiv \frac{\mathrm{Br}(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{\mathrm{Br}(\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell)}$$



Many Interesting Flavour Anomalies

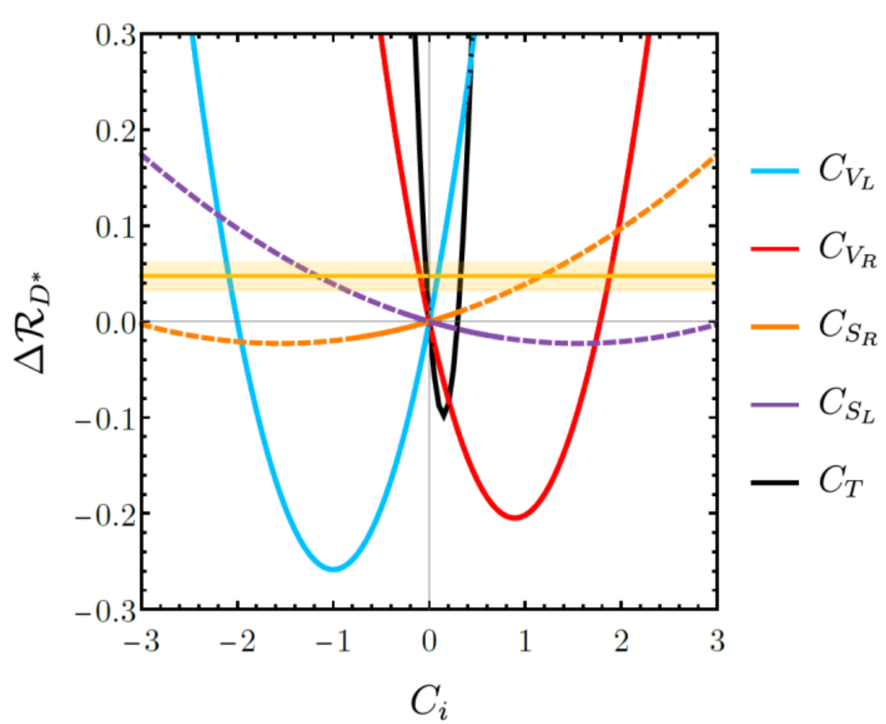


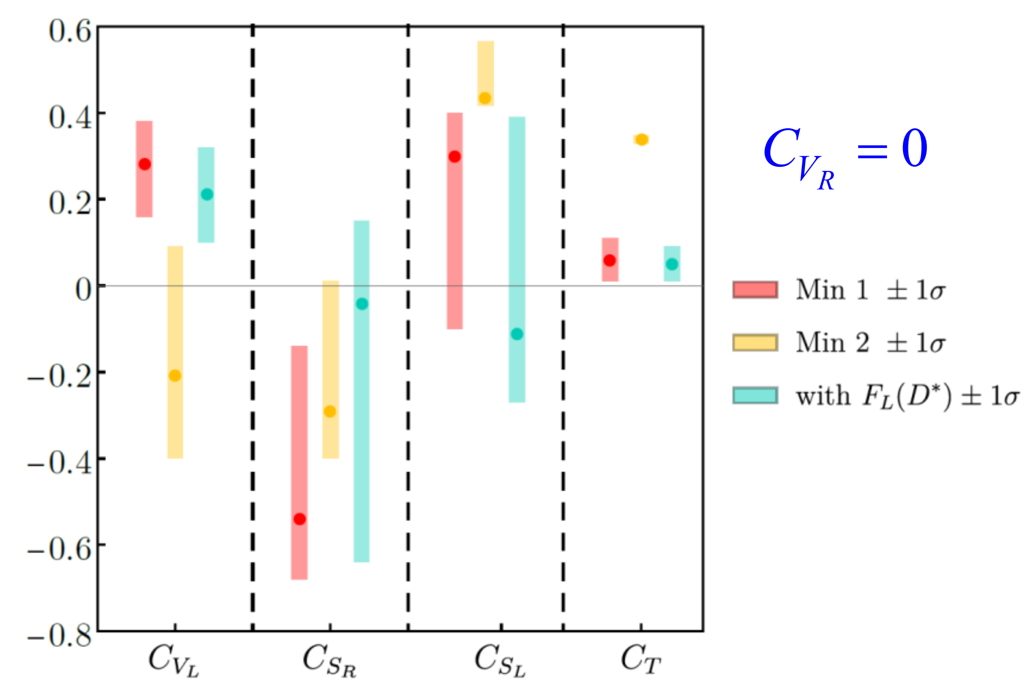




$$H_{\rm eff}^{b\to c\tau\nu} = \frac{4G_F}{\sqrt{2}} V_{cb} \left\{ (1+C_{V_L})\, O_{V_L} + C_{V_R}\, O_{V_R} + C_{S_R}\, O_{S_R} + C_{S_L}\, O_{S_L} + C_T\, O_T \right\} + \text{h.c.}$$

$O_{V_L} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$, $O_{V_R} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L)$, $O_{S_R} = (\bar{c}_L b_R)(\bar{\tau}_R \nu_L)$, $O_{S_L} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_L)$, $O_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_L)$





The Effective Hamiltonian

- The most general effective Hamiltonian containing all possible local operators of the lowest dimension transitions can therefore be written as

$$H_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cq}^{*} \Big[(1 + C_{VL}^{\ell})\mathcal{O}_{VL}^{\ell} + C_{VR}^{\ell}\mathcal{O}_{VR}^{\ell} + C_{SL}^{\ell}\mathcal{O}_{SL}^{\ell} + C_{SR}^{\ell}\mathcal{O}_{SR}^{\ell} + C_{T}^{\ell}\mathcal{O}_{T}^{\ell}\Big],$$

$$O_{VL}^{\ell} = (\bar{q}\gamma^{\mu}P_L c)(\bar{\nu}_{\ell}\gamma_{\mu}P_L\ell),\ O_{VR}^{\ell} = (\bar{q}\gamma^{\mu}P_R c)(\bar{\nu}_{\ell}\gamma_{\mu}P_L\ell),$$
$$O_{SL}^{\ell} = (\bar{q}P_L c)(\bar{\nu}_{\ell}P_R\ell),\ O_{SR}^{\ell} = (\bar{q}P_R c)(\bar{\nu}_{\ell}P_R\ell),$$
$$O_{T}^{\ell} = (\bar{q}\sigma^{\mu\nu}P_L c)(\bar{\nu}_{\ell}\sigma_{\mu\nu}P_R\ell),$$

- In our analysis, we shall assume real Wilson coefficients for simplicity, i.e. that the NP effects do not involve new sources of CP violation.

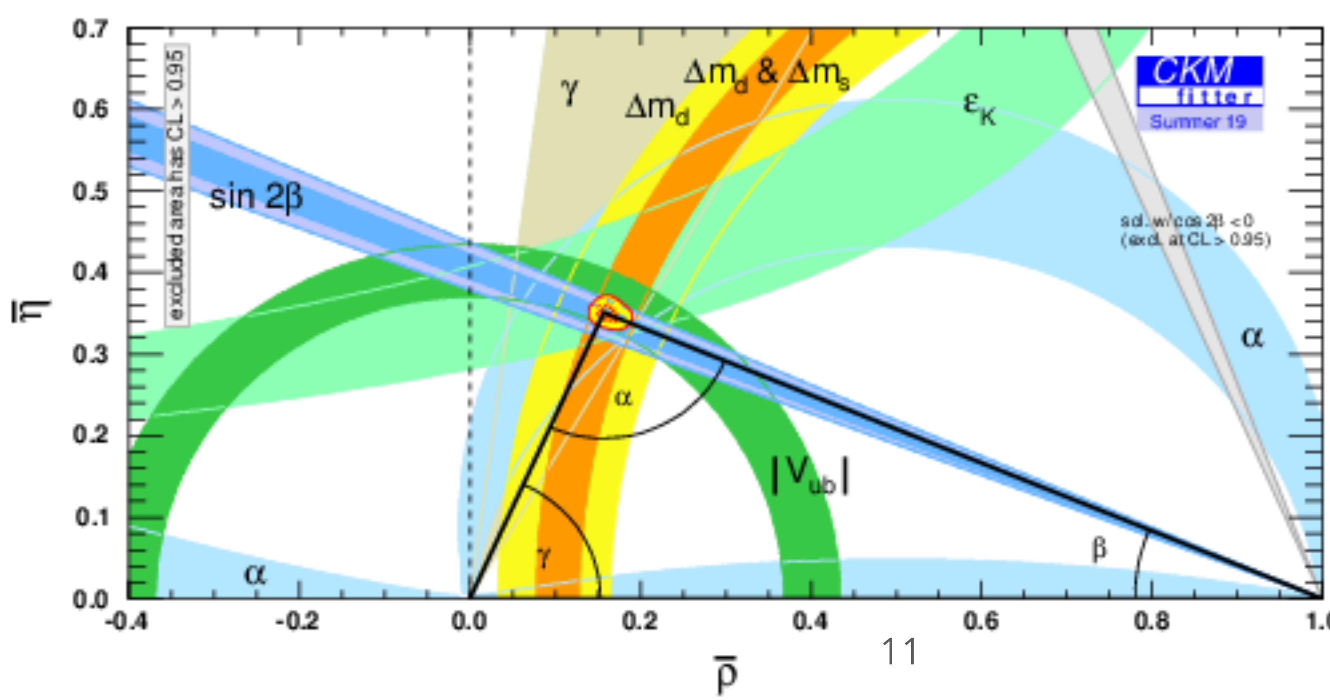
  - $\mathcal{O}_{VL(R)}^{\ell}$: W' Model, W_R Model, Leptoquark Model, SUSY,...
  - $\mathcal{O}_{SL(R)}^{\ell}$: 2HDM, Leptoquark Model, SUSY,...

V_{cs} And V_{cd}

- The CKM matrix elements are usually determined directly from leptonic and semi-leptonic decays and assuming the SM.
- Here, we are investigating these decays in the presence of NP contributions, hence we need an independent determination of them.
- So, we adopt the Wolfenstein parametrization of the CKM matrix, exploiting its unitarity.

$$V_{cd} = -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] + \mathcal{O}(\lambda^7),$$

$$V_{cs} = 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) + \mathcal{O}(\lambda^6)\,.$$



$$|V_{cd}| = 0.2242 \pm 0.0005,$$

$$|V_{cs}| = 0.9736 \pm 0.0001.$$

Leptonic D Decays

- The branching fraction for leptonic D decays is given as

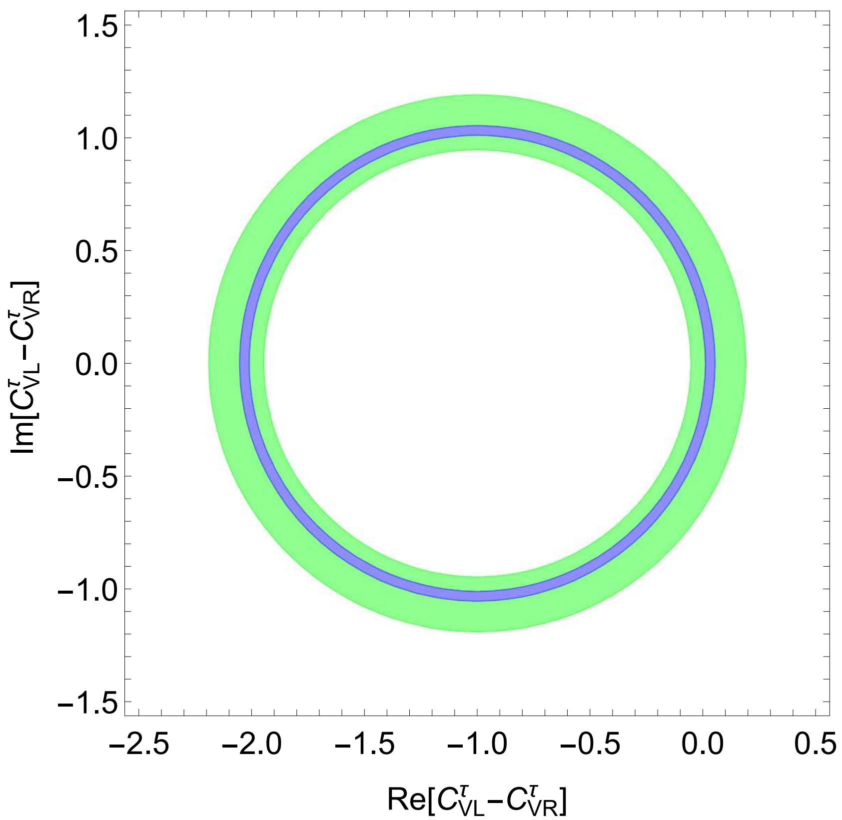
$$\mathcal{B}(D^+ \to \ell^+ \nu_\ell) = \tau_D \frac{G_F^2}{8\pi} |V_{cq}|^2 f_D^2 m_D m_\ell^2 \left(1 - \frac{m_\ell^2}{m_D^2}\right)^2 \times \left|1 + C_{VL}^\ell - C_{VR}^\ell + \frac{m_D^2}{m_\ell(m_c + m_q)}(C_{SR}^\ell - C_{SL}^\ell)\right|^2 (1 + \delta_{em}^\ell) \,.$$

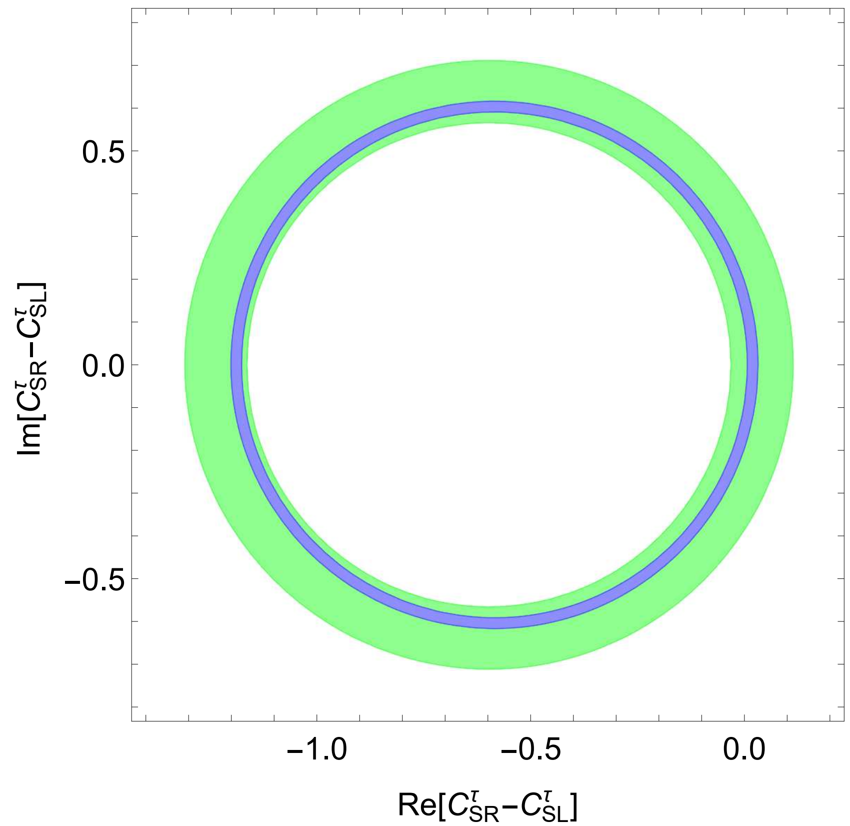
  - In SM, the branching fraction is suppressed by m_ℓ^2, due to the helicity suppression.
  - The most theoretical uncertainty is from the decay constant.
  - $\delta_{em}^\ell \sim (0-3)\,\%$ is from the electromagnetic corrections.

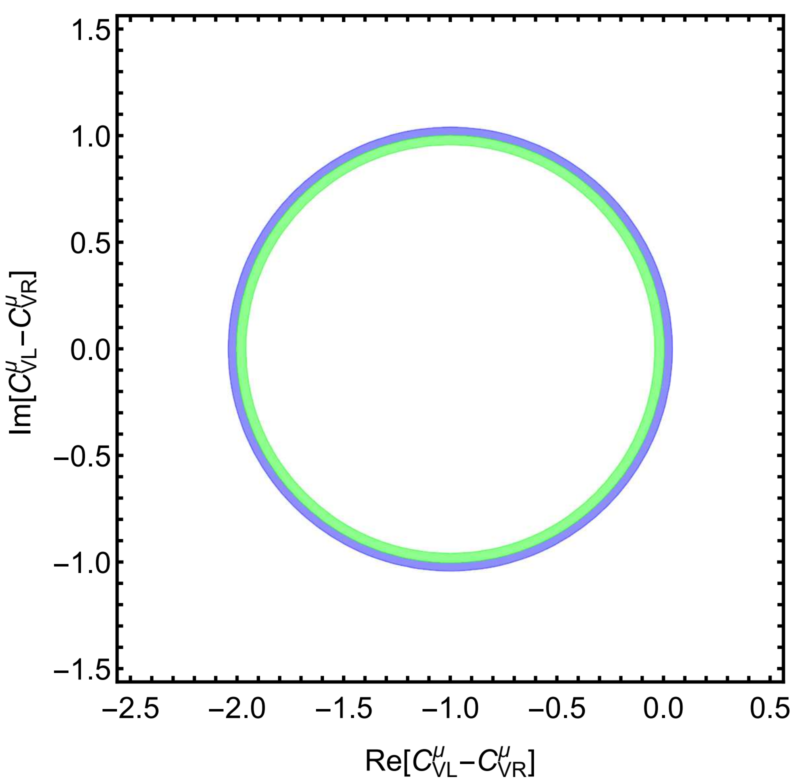
Decay	SM	Experiment
$\mathcal{B}(D^+ \to e^+ \nu_e)$	$(9.17 \pm 0.22) \times 10^{-9}$	$< 8.8 \times 10^{-6}$
$\mathcal{B}(D^+ \to \mu^+ \nu_\mu)$	$(3.89 \pm 0.09) \times 10^{-4}$	$(3.74 \pm 0.17) \times 10^{-4}$
$\mathcal{B}(D^+ \to \tau^+ \nu_\tau)$	$(1.04 \pm 0.03) \times 10^{-3}$	$(1.20 \pm 0.27) \times 10^{-3}$
$\mathcal{B}(D_s^+ \to e^+ \nu_e)$	$(1.24 \pm 0.02) \times 10^{-7}$	$< 8.3 \times 10^{-5}$
$\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu)$	$(5.28 \pm 0.08) \times 10^{-3}$	$(5.50 \pm 0.23) \times 10^{-3}$
$\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau)$	$(5.14 \pm 0.08) \times 10^{-2}$	$(5.48 \pm 0.23) \times 10^{-2}$

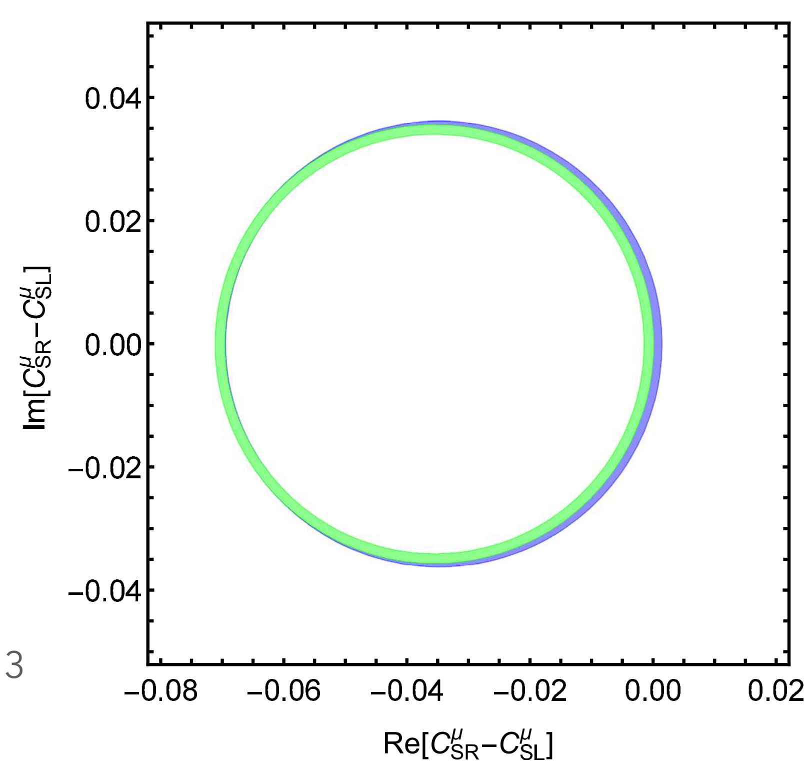
$(5.27 \pm 0.10 \pm 0.12) \times 10^{-2}$ PRL 127, 171801 (2021)

Leptonic D Decays

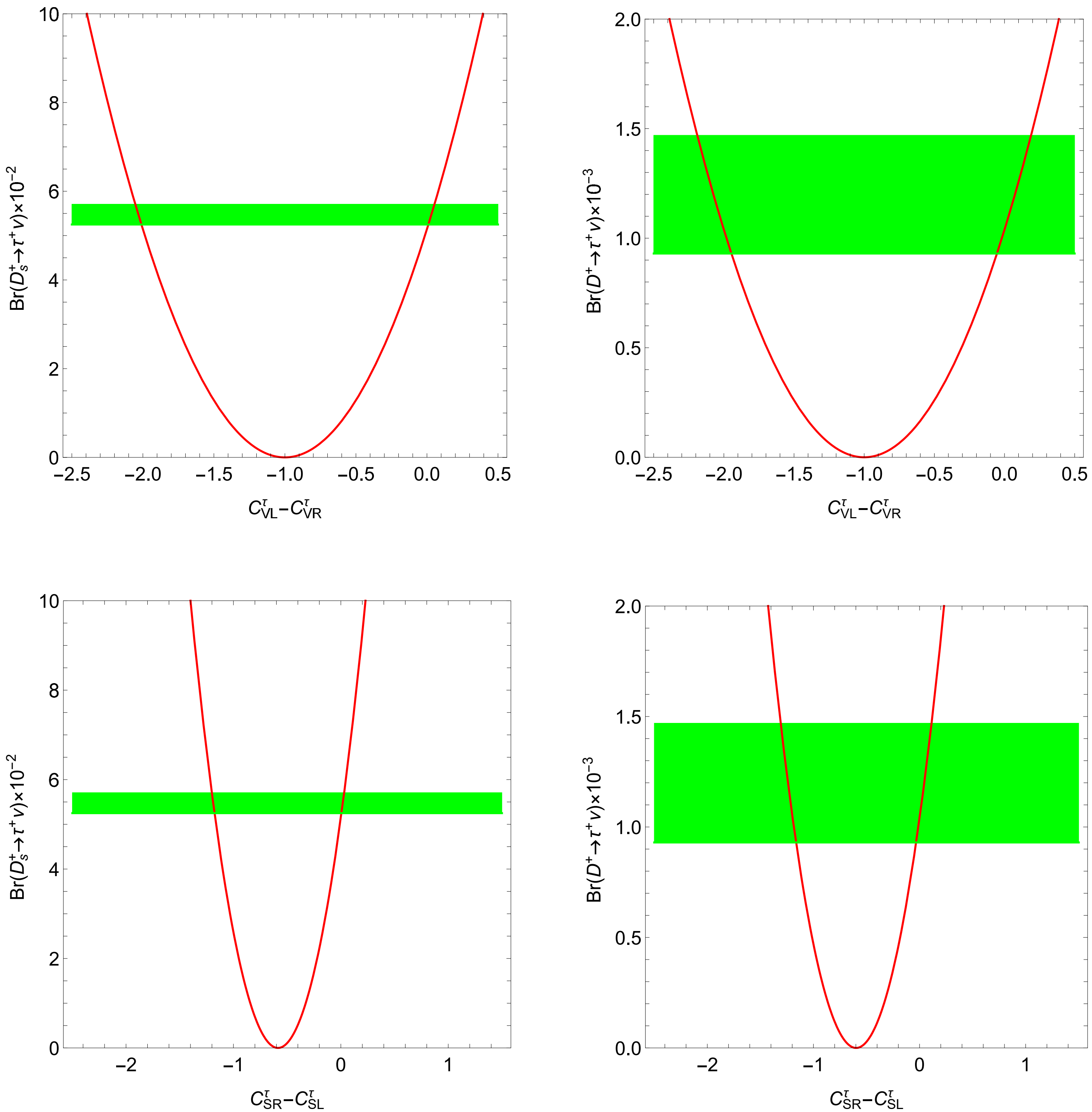








Leptonic D Decays



Leptonic D Decays

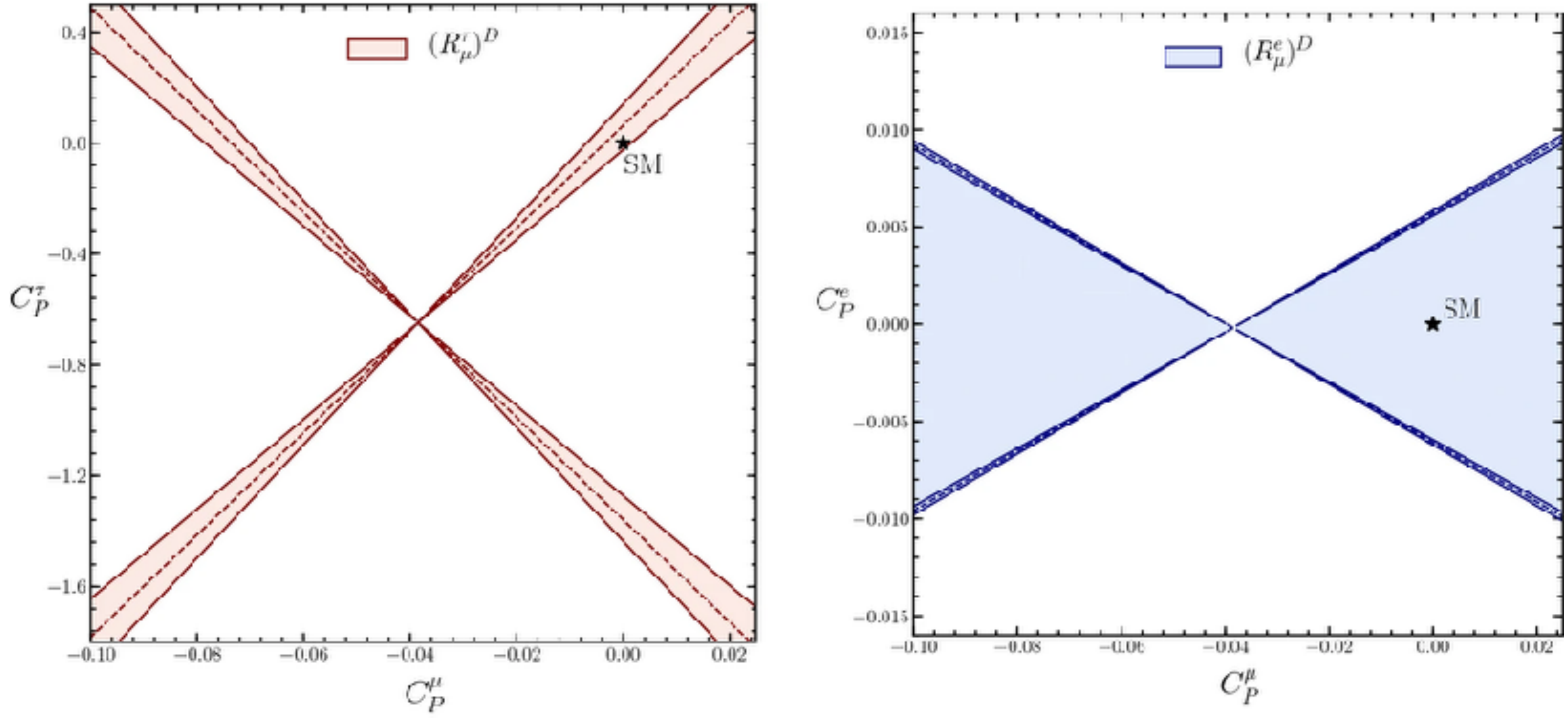
- In order to test the lepton flavor universality, we can define

$$R^{\ell_1}_{\ell_2} \equiv \frac{B(D^+_{(s)} \to \ell_1^+ \nu_{\ell_1})}{B(D^+_{(s)} \to \ell_2^+ \nu_{\ell_2})} = \frac{\alpha^{\ell_1} \left| 1 + C^{\ell_1}_{VL} - C^{\ell_1}_{VR} + \beta^{\ell_1}(C^{\ell_1}_{SR} - C^{\ell_1}_{SL}) \right|^2}{\alpha^{\ell_2} \left| 1 + C^{\ell_2}_{VL} - C^{\ell_1}_{VR} + \beta^{\ell_2}(C^{\ell_2}_{SR} - C^{\ell_2}_{SL}) \right|^2}$$

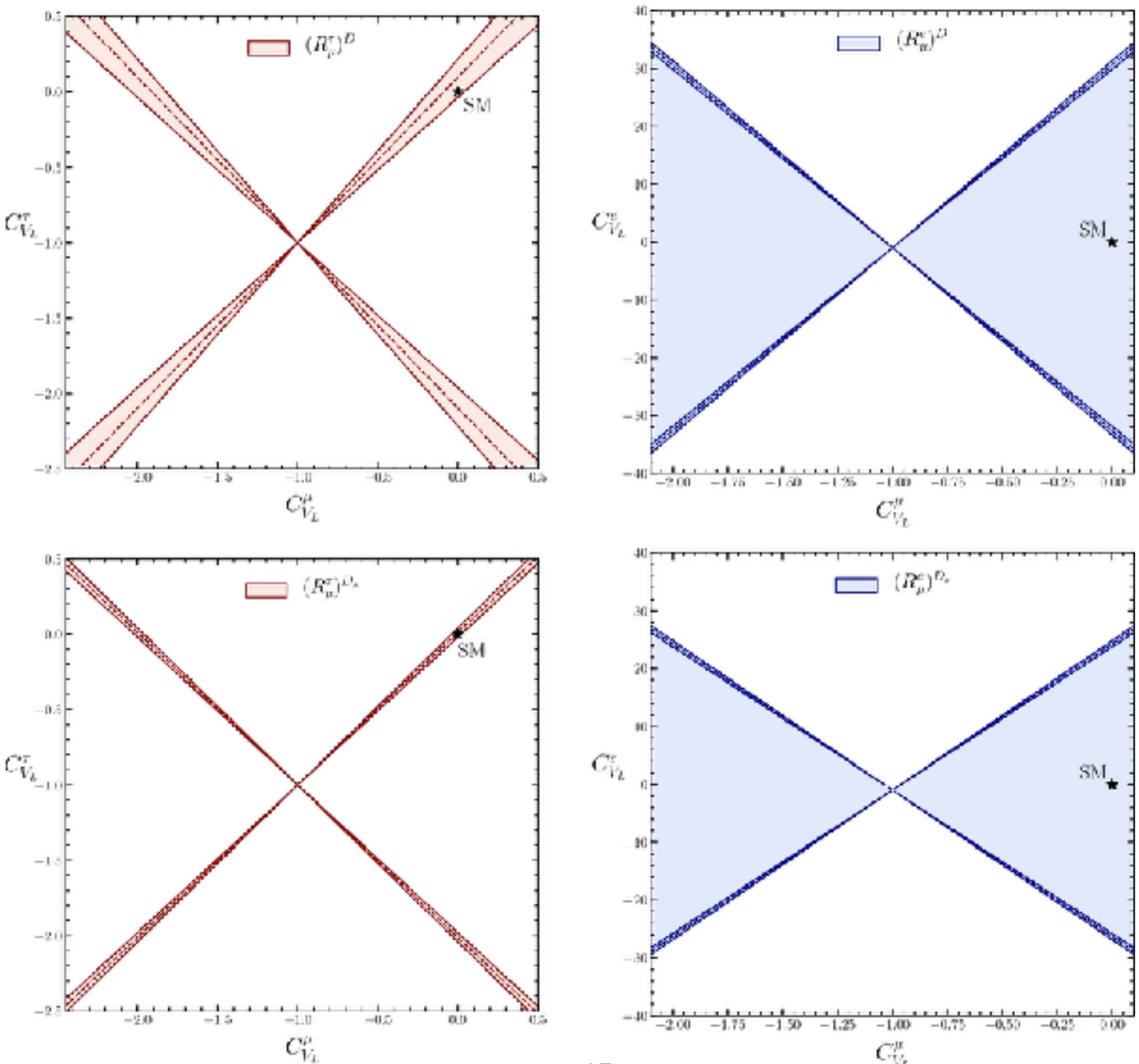
$$\alpha^{\ell_{1(2)}} = m^2_{\ell_{1(2)}} \left(1 - \frac{m^2_{\ell_{1(2)}}}{M^2_{D^+_{(s)}}}\right)^2 \qquad \beta^{\ell_{1(2)}} = \frac{M^2_{D^+_{(s)}}}{[m_{\ell_{1(2)}}(m_c + m_q)]}$$

- $(R^\tau_\mu)^D = 3.21 \pm 0.73$ BESIII PRL,123,211802
- $(R^e_\mu)^D < (2.35 \pm 0.11) \times 10^{-2}$
- $(R^\tau_\mu)^{D_s} = 9.96 \pm 0.59$
- $(R^\tau_\mu)^{D_s} = 9.72 \pm 0.37$ PRL 127, 171801 (2021)
- $(R^e_\mu)^{D_s} < (1.51 \pm 0.06) \times 10^{-2}$

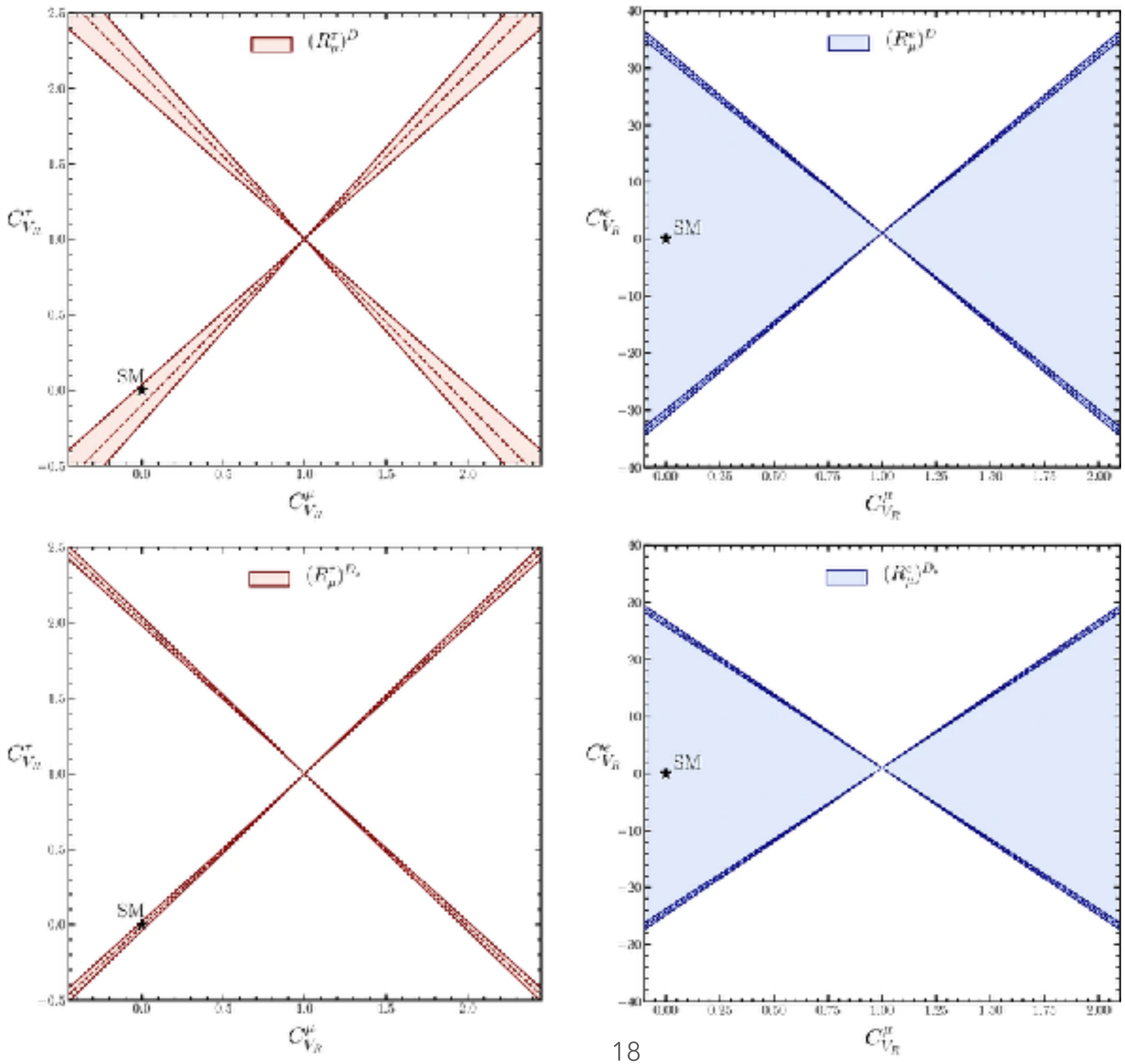
Leptonic D Decays



Leptonic D Decays



Leptonic D Decays



Semi-Leptonic D Decays

- In calculations, the hadronic transitions are parameterized by the heavy-to-light form factors, which are nonperturbative and universal.

- $D \to P$

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

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

$$\langle P(p_2)|\bar{q}\sigma^{\mu\nu}c|D(p_1)\rangle = -i(p_1^\mu p_2^\nu - p_1^\nu p_2^\mu)\frac{2f_T(q^2)}{m_D + m_P},$$

  - ✦ Regarding the various form factors in the D → K, pi transitions, we adopt the latest results from the LQCD.
  - ✦ However, for the form factors of Ds → K, D → η, and Ds → η, LQCD results are still unavailable till now, and we have to employ the results obtained from other approaches. In this work, we adopted the results based on the light-cone sum rules.
  - ✦ For $\eta - \eta'$ mixing, we adopt $\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \sin\theta_p & \cos\theta_p \\ -\cos\theta_p & \sin\theta_p \end{pmatrix}\begin{pmatrix} q\bar{q} \\ s\bar{s} \end{pmatrix}$, $q\bar{q} = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$. $\theta = 39.3^\circ$

Semi-Leptonic D Decays

- $D \to V$

$$\langle V(p_2,\varepsilon^*)|\bar{q}\gamma^\mu c|D(p_1)\rangle = \frac{-2iV(q^2)}{m_D+m_V}\epsilon_{\mu\nu\alpha\beta}\varepsilon^{*\nu}p_1^\alpha p_2^\beta,$$

$$\langle V(p_2,\varepsilon^*)|\bar{q}\gamma^\mu\gamma_5 c|D(p_1)\rangle = -(m_D+m_V)\varepsilon^{*\mu}A_1(q^2) + \frac{\varepsilon^*\cdot q}{m_D+m_V}(p_1+p_2)^\mu A_2(q^2) + 2m_V\frac{\varepsilon^*\cdot q}{q^2}q^\mu\left(A_3(q^2)-A_0(q^2)\right),$$

$$\langle V(p_2,\varepsilon^*)|\bar{q}\sigma^{\mu\nu}c|D(p_1)\rangle = \epsilon^{\mu\nu\rho\sigma}\Big[\varepsilon^*_\rho(p_1+p_2)_\sigma T_1(q^2) + \varepsilon^*_\rho q_\sigma\frac{m_D^2-m_V^2}{q^2}(T_2(q^2)-T_1(q^2)) + 2\frac{\varepsilon^*\cdot q}{q^2}p_{1\rho}p_{2\sigma}(T_2(q^2)-T_1(q^2)+\frac{q^2}{m_D^2-m_V^2}T_3(q^2))\Big],$$

- For the form factors of D $\to$ V , there are several studies in literature based on different approaches, such as QCD sum rules, light-cone sum rules (LCSR), quark models, covariant light-front quark models, and LQCD.

- The results of D $\to$ K*,ρ from LQCD had been released in as early as 1995; however, the predicted branching fraction of $D \to K^*\mu\nu_\mu$ is significantly larger than the upper limits of experimental result. The recent undated results from LQCD remain absent to date.

- Although most results of the covariant light-front quark model agree well with the experimental data with certain uncertainties, the predicted branching fraction of $D \to K^*\mu\nu_\mu$ is also significantly larger than the experimental data, which reduces its prediction power.

Semi-Leptonic D Decays

- For consistency, we adopted the results with The LCSR calculation, which is based on the framework of the heavy quark effective field theory.

  Y.-L. Wu, M. Zhong, and Y.-B. Zuo, Int. J. Mod. Phys. A **21**, 6125-6172 (2006), arXiv:hep-ph/0604007

  H.-B. Fu, L. Zeng, R. L, W. Cheng, and X.-G. Wu, Eur. Phys. J. C **80**(3), 194 (2020), arXiv:1808.06412

  H.-B. Fu, W. Cheng, L. Zeng, and D.-D. Hu, Phys.Rev.Res. 2 (2020) 4, 043129, arXiv: 2003.07626

- In the heavy quark effective theory, the tensor form factors of $D \to V$ are related to the vector and scalar form factors A_1, A_2, A_3 and V , and the relations are given as

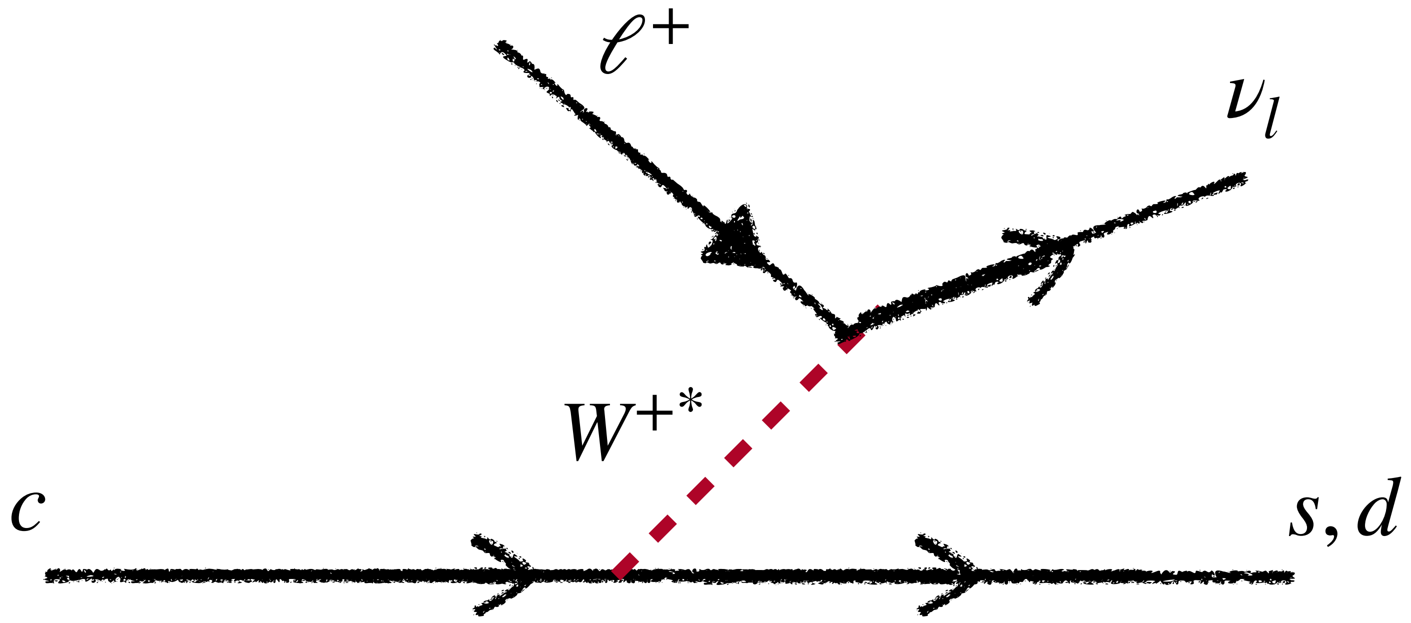
$$T_1(q^2) = \frac{m_D^2 - m_V^2 + q^2}{2m_D}\frac{V(q^2)}{m_D + m_V} + \frac{m_D + m_V}{2m_D}A_1(q^2),$$

$$T_2(q^2) = \frac{2}{m_D^2 - m_V^2}\left[\frac{(m_D - y)(m_D + m_V)}{2}A_1(q^2) + \frac{m_D(y^2 - m_V^2)}{m_D + m_V}V(q^2)\right],$$

$$T_3(q^2) = -\frac{m_D + m_V}{2m_D}A_1(q^2) + \frac{m_D - m_V}{2m_D}\left[A_2(q^2) - A_3(q^2)\right] + \frac{m_D^2 + 3m_V^2 - q^2}{2m_D(m_D + m_V)}V(q^2),$$

- As significant improvements have recently been made in lattice QCD, a calculation of the $D \to V$ form factors exploiting the current state-of-the-art methods would be very desirable for testing LFU in the charm sector.

Semi-Leptonic D Decays



The off-shell W^{*+} has four helicities, namely $\lambda_W = \pm1, 0$ (J = 1) and $\lambda_W = 0$ (J = 0), and only the W^{*+} boson has a time-like polarization, In the D meson rest frame, we set the z-axis to be along the moving direction of W^{*+}, and write the polarization vectors of the W^{*+} as

$$\epsilon^\mu(\pm) = \frac{1}{2}(0, 1, \mp i, 0), \quad \epsilon^\mu(0) = -\frac{1}{\sqrt{q^2}}(q_3, 0, 0, q_0), \quad \epsilon^\mu(t) = -\frac{q^\mu}{\sqrt{q^2}},$$

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

$$H^{PS}(q^2) = \langle P(p_2)|\bar{q}c|D(p_1)\rangle,$$

$$H^{PT}_{\lambda_W,\lambda'_W}(q^2) = \epsilon^*_\mu(\lambda_W)\epsilon^*_\nu(\lambda'_W)\langle P(p_2)|\bar{q}\sigma^{\mu\nu}c|D(p_1)\rangle.$$

$$H^{VAL(VAR)}_{\lambda_W,\varepsilon_V}(q^2) = \epsilon^*_\mu(\lambda_W)\langle V(p_2,\varepsilon^*)|\bar{q}\gamma^\mu(1\pm\gamma^5)c|D_{(s)}(p_1)\rangle$$

$$H^{SPL(SPR)}_{\varepsilon_V}(q^2) = \langle V(p_2,\varepsilon^*)|\bar{q}\gamma^\mu(1\pm\gamma^5)c|D_{(s)}(p_1)\rangle,$$

$$H^{T}_{\lambda_W,\lambda'_W,\varepsilon_V}(q^2) = \epsilon^*_\mu(\lambda_W)\epsilon^*_\nu(\lambda'_W)\langle V(p_2,\varepsilon^*)|\bar{q}\sigma^{\mu\nu}(1-\gamma^5)c|D_{(s)}(p_1$$

Semi-Leptonic D Decays

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

with

$$A_1^P = |C_{SL}+C_{SR}|^2|H^{PS}|^2 + \mathrm{Re}\left[(C_{SL}+C_{SR})C_T^*\right]H^{PS}(H_{0,t}^{PT}+H_{0,-1}^{PT})\cos\theta_\ell + 4|C_T|^2|H_{0,t}^{PT}+H_{1,-1}^{PT}|^2\cos^2\theta_\ell$$
$$+|1+C_{VL}+C_{VR}|^2|H_0^{PV}|^2\sin^2\theta_\ell,$$

$$A_2^P = 2\left\{\mathrm{Re}\left[(C_{SL}+C_{SR})(1+C_{VL}+C_{VR})^*\right]H^{PS}H_t^{PV} - 2\mathrm{Re}\left[C_T(1+C_{VL}+C_{VR})^*\right]H_0^{PV}(H_{0,t}^{PT}+H_{1,-1}^{PT})\right\}$$
$$-2\left\{\mathrm{Re}\left[(C_{SL}+C_{SR})(1+C_{VL}+C_{VR})^*\right]H^{PS}H_0^{PV} - 2\mathrm{Re}\left[C_T(1+C_{VL}+C_{VR})^*\right]H_t^{PV}(H_{0,t}^{PT}+H_{1,-1}^{PT})\right\}\cos\theta_\ell,$$

$$A_3^P = 4|C_T|^2|H_{0,t}^{PT}+H_{1,-1}^{PT}|^2\sin^2\theta_\ell + |1+C_{VL}+C_{VR}|^2(|H_0^{PV}|^2\cos^2\theta_\ell - 2H_0^{PV}H_T^{PV}\cos\theta_\ell + |H_t^{PV}|^2),$$

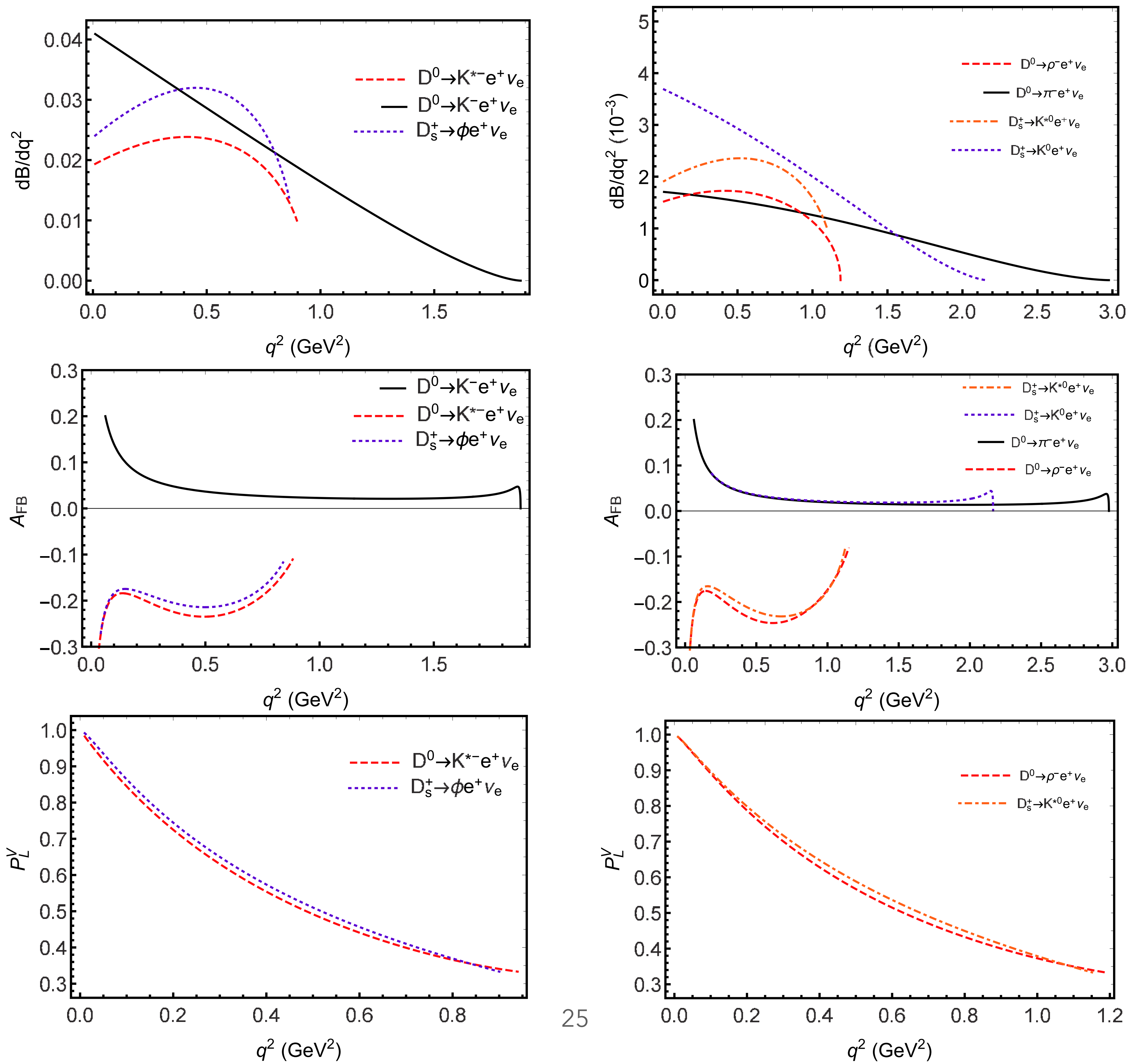
$$\mathcal{B}(D\to F\ell^+\nu_\ell) = \tau_D\int_{m_l^2}^{M_-^2} dq^2\,\frac{d\Gamma(D\to F\ell^+\nu_\ell)}{dq^2},$$

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

Semi-Leptonic D Decays

Current	Mode	SM	Experiment
$c \to s e^+ \nu_e$	$D^0 \to K^- e^+ \nu_e$	$(3.49 \pm 0.23) \times 10^{-2}$	$(3.542 \pm 0.0035) \times 10^{-2}$
	$D^+ \to \overline{K}^0 e^+ \nu_e$	$(8.92 \pm 0.59) \times 10^{-2}$	$(8.73 \pm 0.10) \times 10^{-2}$
	$D^0 \to K^{*-} e^+ \nu_e$	$(1.92 \pm 0.17) \times 10^{-2}$	$(2.15 \pm 0.16) \times 10^{-2}$
	$D^+ \to \overline{K}^{*0} e^+ \nu_e$	$(4.98 \pm 0.45) \times 10^{-2}$	$(5.40 \pm 0.10) \times 10^{-2}$
	$D_s^+ \to \phi e^+ \nu_e$	$(2.46 \pm 0.42) \times 10^{-2}$	$(2.39 \pm 0.16) \times 10^{-2}$
	$D_s^+ \to \eta e^+ \nu_e$	$(1.55 \pm 0.33) \times 10^{-2}$	$(2.29 \pm 0.19) \times 10^{-2}$
	$D_s^+ \to \eta' e^+ \nu_e$	$(5.91 \pm 1.26) \times 10^{-3}$	$(7.4 \pm 1.4) \times 10^{-3}$
$c \to s \mu^+ \nu_\mu$	$D^0 \to K^- \mu^+ \nu_\mu$	$(3.40 \pm 0.22) \times 10^{-2}$	$(3.41 \pm 0.04) \times 10^{-2}$
	$D^+ \to \overline{K}^0 \mu^+ \nu_\mu$	$(8.69 \pm 0.57) \times 10^{-2}$	$(8.76 \pm 0.19) \times 10^{-2}$
	$D^0 \to K^{*-} \mu^+ \nu_\mu$	$(1.81 \pm 0.16) \times 10^{-2}$	$(1.89 \pm 0.24) \times 10^{-2}$
	$D^+ \to \overline{K}^{*0} \mu^+ \nu_\mu$	$(4.71 \pm 0.42) \times 10^{-2}$	$(5.27 \pm 0.15) \times 10^{-2}$
	$D_s^+ \to \phi \mu^+ \nu_\mu$	$(2.33 \pm 0.40) \times 10^{-2}$	$(1.90 \pm 0.50) \times 10^{-2}$
	$D_s^+ \to \eta \mu^+ \nu_\mu$	$(1.52 \pm 0.31) \times 10^{-2}$	$(2.4 \pm 0.5) \times 10^{-2}$
	$D_s^+ \to \eta' \mu^+ \nu_\mu$	$(5.64 \pm 1.10) \times 10^{-3}$	$(11.0 \pm 5.0) \times 10^{-3}$
$c \to d e^+ \nu_e$	$D^0 \to \pi^- e^+ \nu_e$	$(2.63 \pm 0.32) \times 10^{-3}$	$(2.91 \pm 0.04) \times 10^{-3}$
	$D^+ \to \pi^0 e^+ \nu_e$	$(3.41 \pm 0.41) \times 10^{-3}$	$(3.72 \pm 0.17) \times 10^{-3}$
	$D^0 \to \rho^- e^+ \nu_e$	$(1.74 \pm 0.25) \times 10^{-3}$	$(1.77 \pm 0.16) \times 10^{-3}$
	$D^+ \to \rho^0 e^+ \nu_e$	$(2.25 \pm 0.32) \times 10^{-3}$	$(2.18^{+0.17}_{-0.25}) \times 10^{-3}$
	$D^+ \to \omega^0 e^+ \nu_e$	$(1.91 \pm 0.27) \times 10^{-3}$	$(1.69 \pm 0.11) \times 10^{-3}$
	$D^+ \to \eta e^+ \nu_e$	$(0.76 \pm 0.16) \times 10^{-3}$	$(1.11 \pm 0.07) \times 10^{-3}$
	$D^+ \to \eta' e^+ \nu_e$	$(1.12 \pm 0.24) \times 10^{-4}$	$(2.0 \pm 0.4) \times 10^{-4}$
	$D_s^+ \to K^0 e^+ \nu_e$	$(3.93 \pm 0.82) \times 10^{-3}$	$(3.9 \pm 0.9) \times 10^{-3}$
	$D_s^+ \to K^{*0} e^+ \nu_e$	$(2.33 \pm 0.34) \times 10^{-3}$	$(1.8 \pm 0.4) \times 10^{-3}$
$c \to d \mu^+ \nu_\mu$	$D^0 \to \pi^- \mu^+ \nu_\mu$	$(2.60 \pm 0.31) \times 10^{-3}$	$(2.67 \pm 0.12) \times 10^{-3}$
	$D^+ \to \pi^0 \mu^+ \nu_\mu$	$(3.37 \pm 0.40) \times 10^{-3}$	$(3.50 \pm 0.15) \times 10^{-3}$
	$D^0 \to \rho^- \mu^+ \nu_\mu$	$(1.65 \pm 0.23) \times 10^{-3}$	$--$
	$D^+ \to \rho^0 \mu^+ \nu_\mu$	$(2.14 \pm 0.30) \times 10^{-3}$	$(2.4 \pm 0.4) \times 10^{-3}$
	$D^+ \to \omega^0 \mu^+ \nu_\mu$	$(1.82 \pm 0.26) \times 10^{-3}$	$--$
	$D^+ \to \eta \mu^+ \nu_\mu$	$(0.75 \pm 0.15) \times 10^{-3}$	$--$
	$D^+ \to \eta' \mu^+ \nu_\mu$	$(1.06 \pm 0.20) \times 10^{-4}$	$--$
	$D_s^+ \to K^0 \mu^+ \nu_\mu$	$(3.85 \pm 0.76) \times 10^{-3}$	$--$
	$D_s^+ \to K^{*0} \mu^+ \nu_\mu$	$(2.23 \pm 0.32) \times 10^{-3}$	$--$

Semi-Leptonic D Decays



Semi-Leptonic D Decays

Case	Wilson Coefficient	Fitted Results	$\chi^2_{1\sigma}$
Case-I	C^{ℓ}_{VL}	$(4.3 \pm 9.6) \times 10^{-3}$	10.1
	C^{ℓ}_{VR}	$(2.7 \pm 9.8) \times 10^{-3}$	10.2
	C^{ℓ}_{SL}	$(0.3 \pm 0.6) \times 10^{-3}$	10.0
	C^{ℓ}_{SR}	$(-0.3 \pm 0.6) \times 10^{-3}$	10.0
	C^{ℓ}_{T}	$(1.1 \pm 2.9) \times 10^{-3}$	7.2
Case-II	C^{e}_{VL}	$(9.9 \pm 16.2) \times 10^{-3}$	4.4
	C^{e}_{VR}	$(2.6 \pm 16.9) \times 10^{-3}$	4.8
	C^{e}_{SL}	$(0.4 \pm 0.6) \times 10^{-3}$	4.8
	C^{e}_{SR}	$-(0.4 \pm 0.6) \times 10^{-3}$	4.8
	C^{e}_{T}	$(1.3 \pm 3.5) \times 10^{-3}$	4.6
	C^{μ}_{VL}	$(1.4 \pm 11.9) \times 10^{-3}$	5.5
	C^{μ}_{VR}	$(2.7 \pm 12.0) \times 10^{-3}$	5.4
	C^{μ}_{SL}	$(70.2 \pm 0.6) \times 10^{-3}$	3.3
	C^{μ}_{SR}	$-(70.2 \pm 0.6) \times 10^{-3}$	3.3
	C^{μ}_{T}	$(0.6 \pm 4.9) \times 10^{-3}$	2.5

Semi-Leptonic D Decays

- If we only consider the LH or RH vector NP interactions

$$\frac{d\mathscr{B}(D \to P\bar{\ell}\nu_\ell)}{dq^2} = \frac{d\mathscr{B}(D \to P\bar{\ell}\nu_\ell)}{dq^2}\Bigg|_{\text{SM}} \left|1 + C^{\ell}_{VL(R)}\right|^2 .$$

- We can define

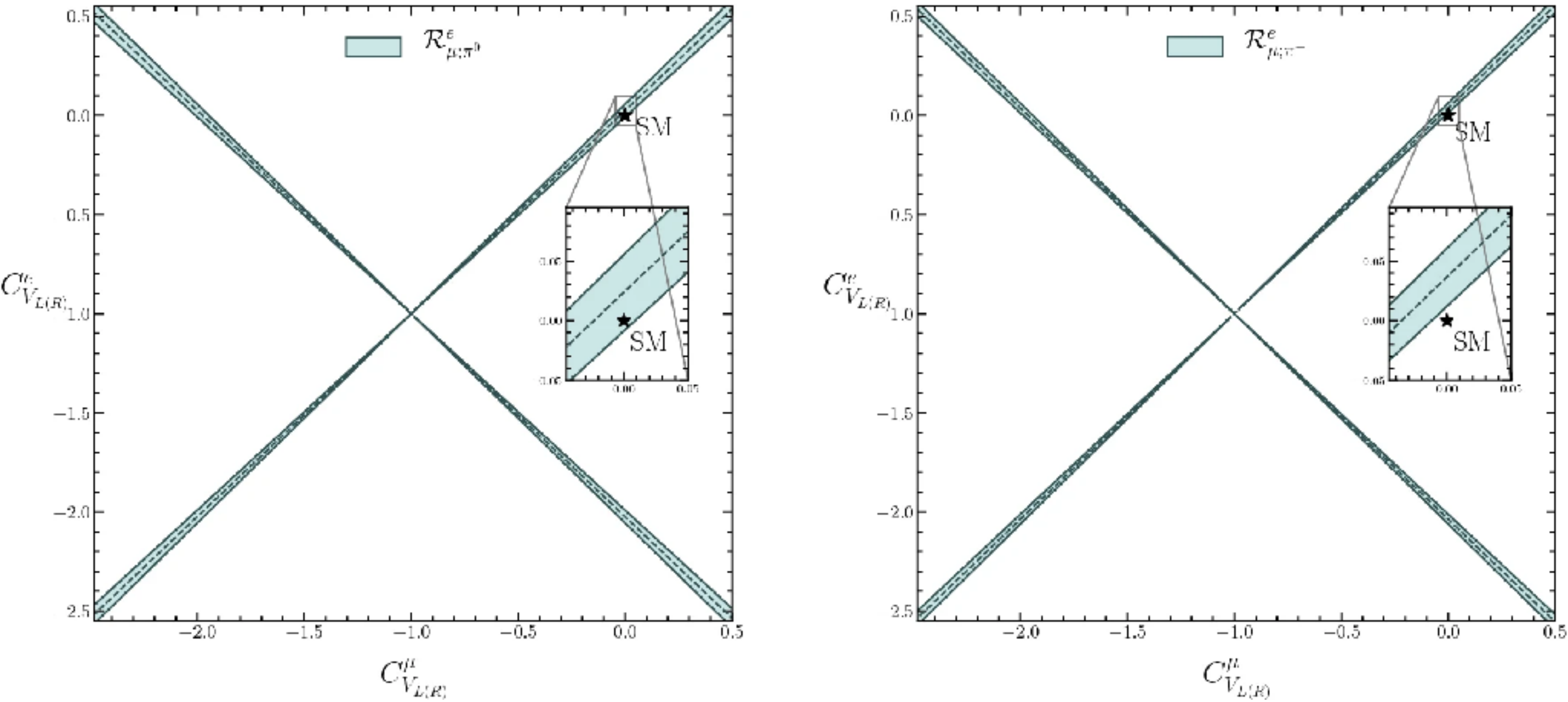
$$R^e_{\mu;\pi^0} \equiv \frac{\mathscr{B}(D^+ \to \pi^0 e^+ \nu_e)}{\mathscr{B}(D^+ \to \pi^0 \mu^+ \nu_\mu)}, R^e_{\mu;\pi^-} \equiv \frac{\mathscr{B}(D^0 \to \pi^- e^+ \nu_e)}{\mathscr{B}(D^0 \to \pi^- \mu^+ \nu_\mu)},$$

$$R^e_{\mu;\overline{K}^0} \equiv \frac{\mathscr{B}(D^+ \to \overline{K}^0 e^+ \nu_e)}{\mathscr{B}(D^+ \to \overline{K}^0 \mu^+ \nu_\mu)}, R^e_{\mu;K^-} \equiv \frac{\mathscr{B}(D^0 \to K^- e^+ \nu_e)}{\mathscr{B}(D^0 \to K^- \mu^+ \nu_\mu)} .$$

- These observables are independent of CKM matrix elements and sensitive to the coefficients. Hence, they provide interesting opportunities to test lepton flavour universality in D decays.

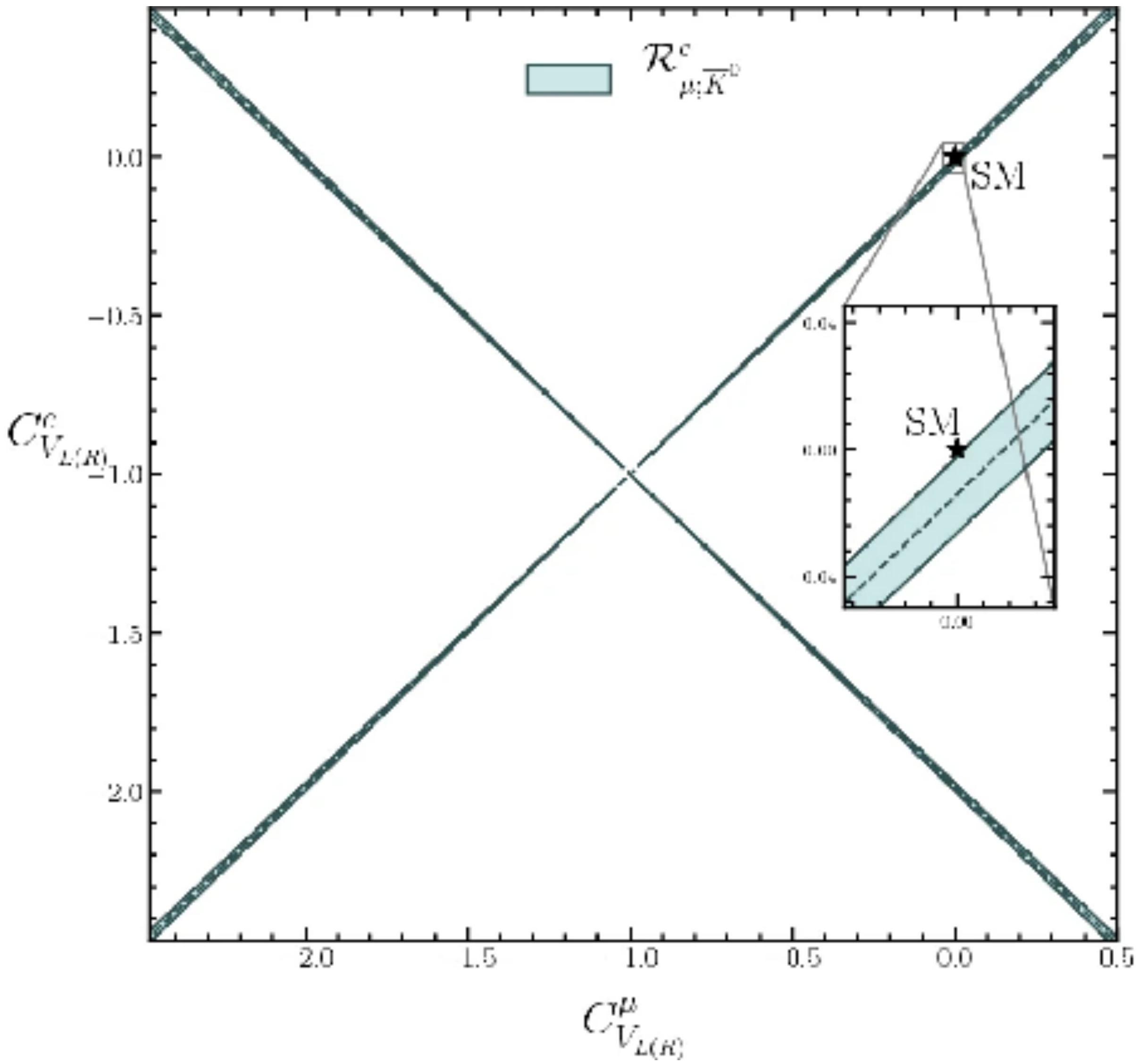
Semi-Leptonic D Decays

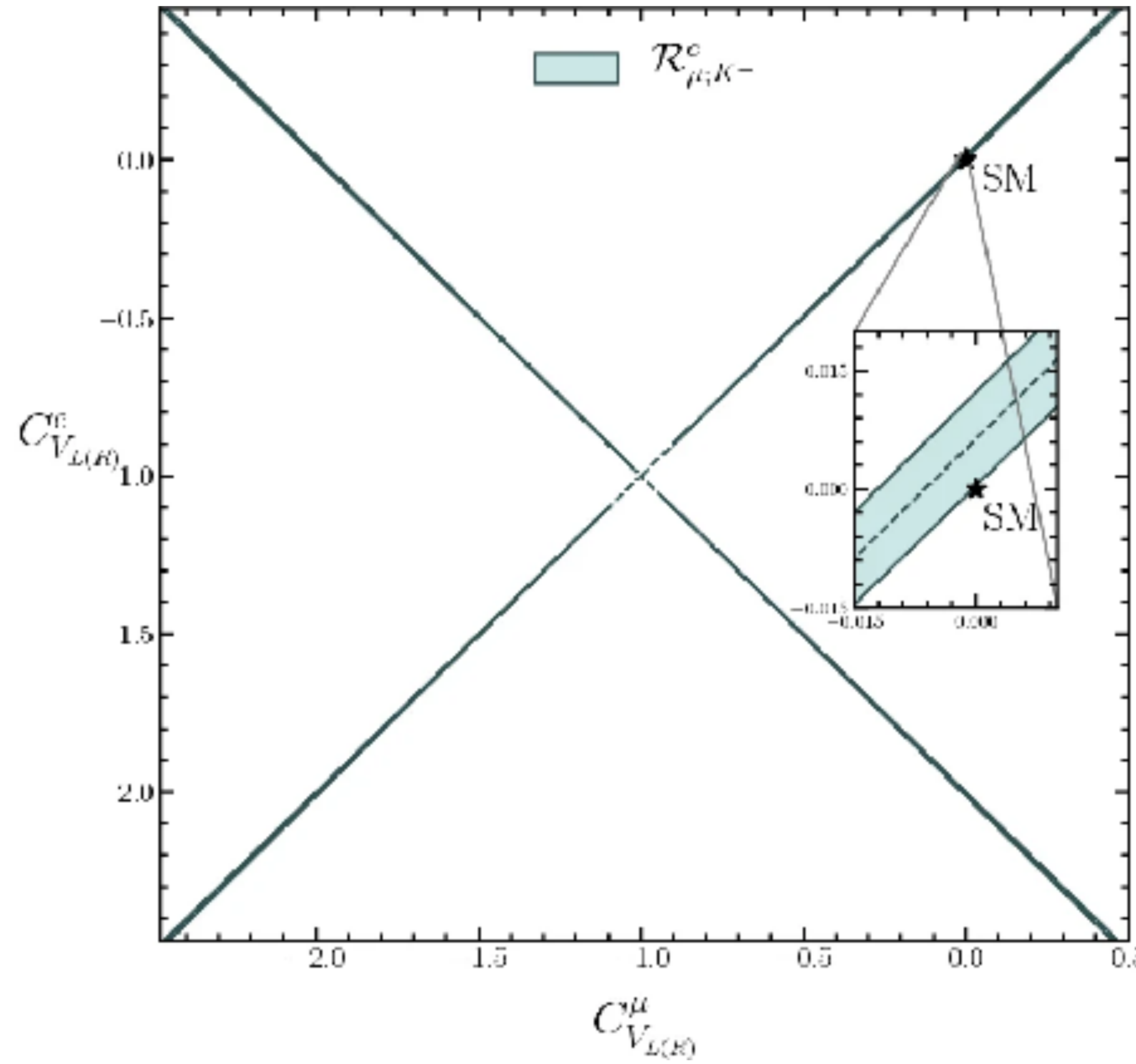
$$R^{e}_{\mu;\pi^0} = 1.06 \pm 0.07,\ \ R^{e}_{\mu;\pi^-} = 1.09 \pm 0.05,$$



Semi-Leptonic D Decays

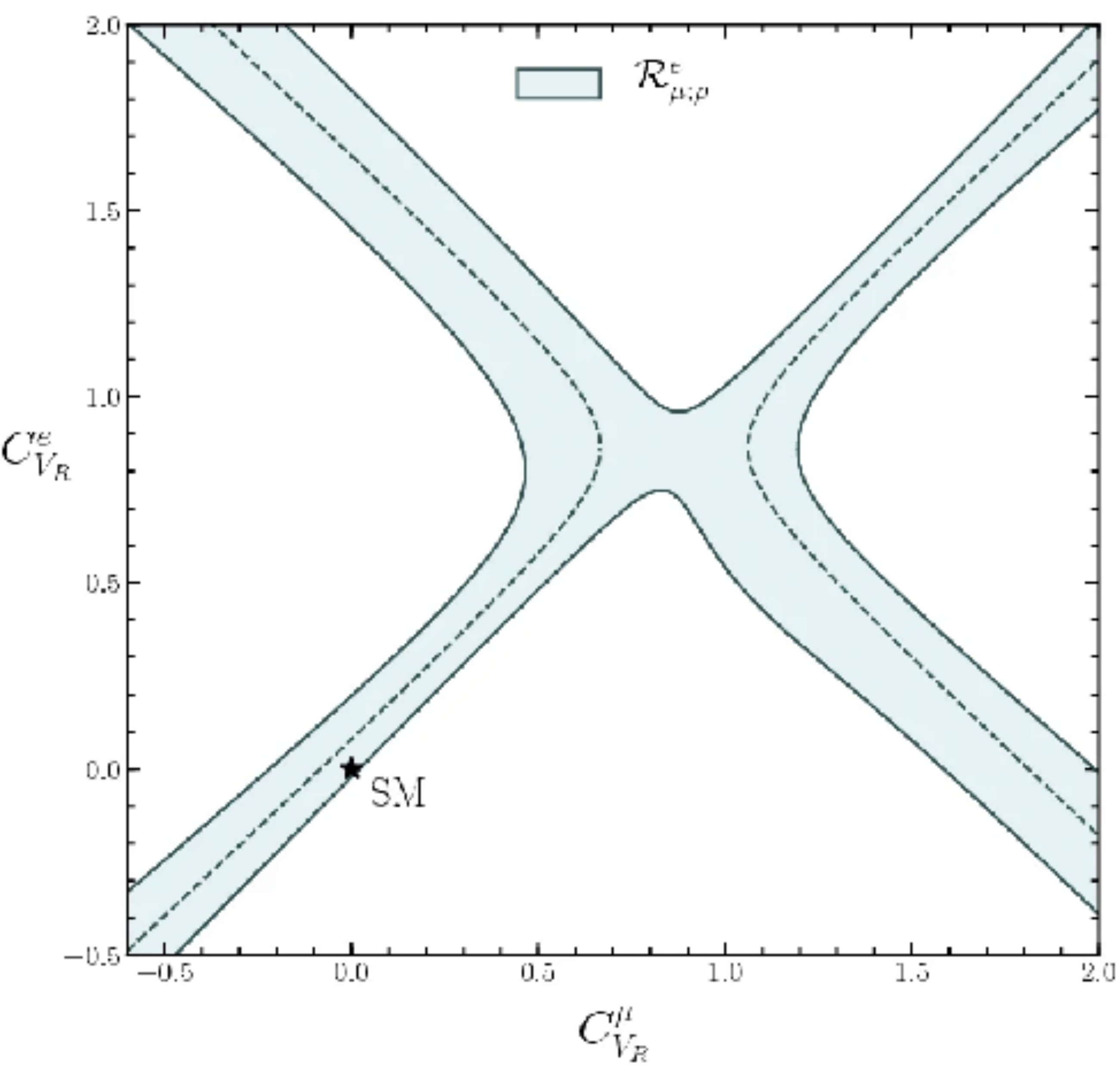
$$R^{e}_{\mu;\overline{K}^0} = (9.97 \pm 0.24) \times 10^{-1}, \quad R^{e}_{\mu;K^-} = 1.04 \pm 0.01.$$



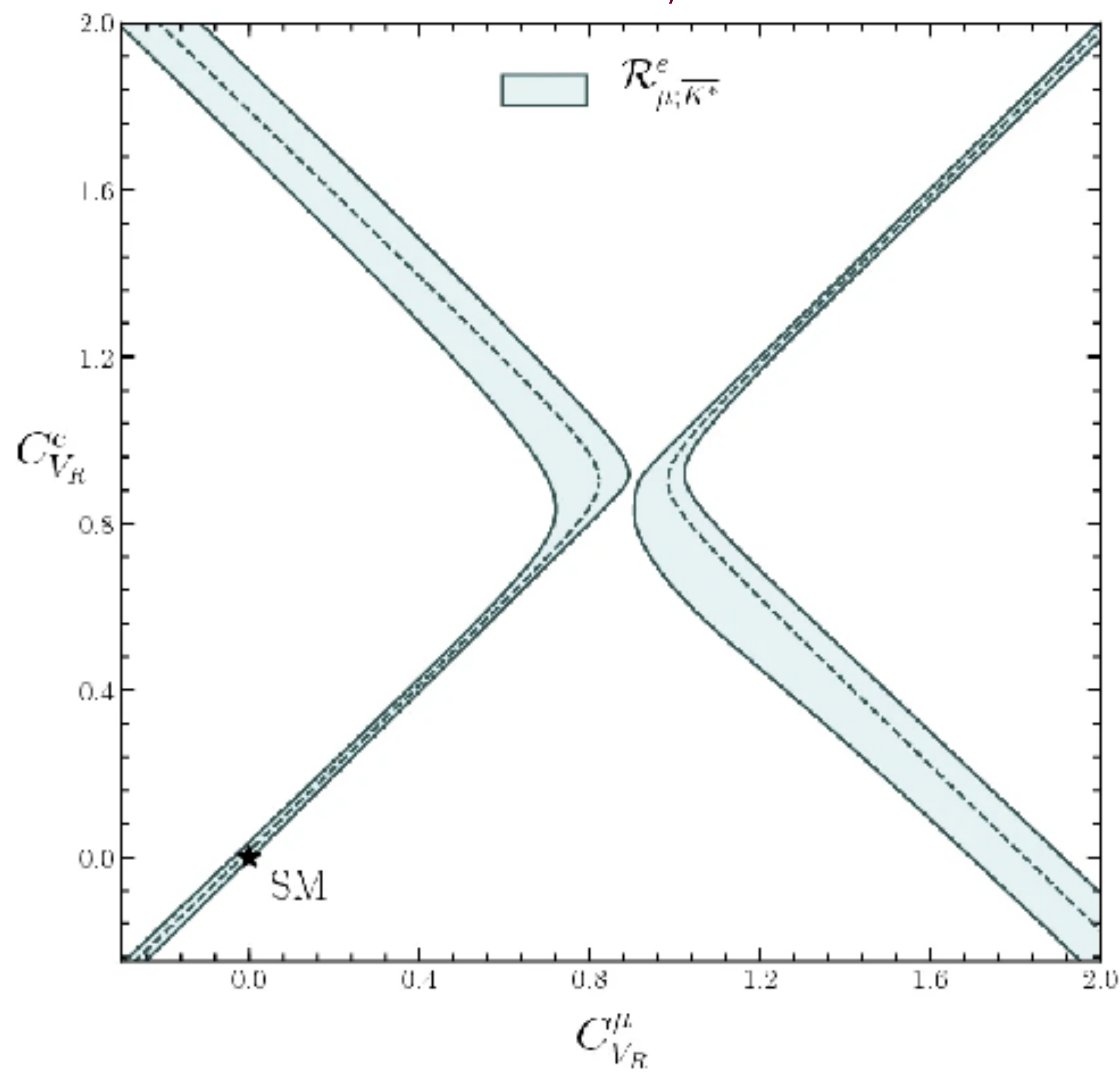


Semi-Leptonic D Decays

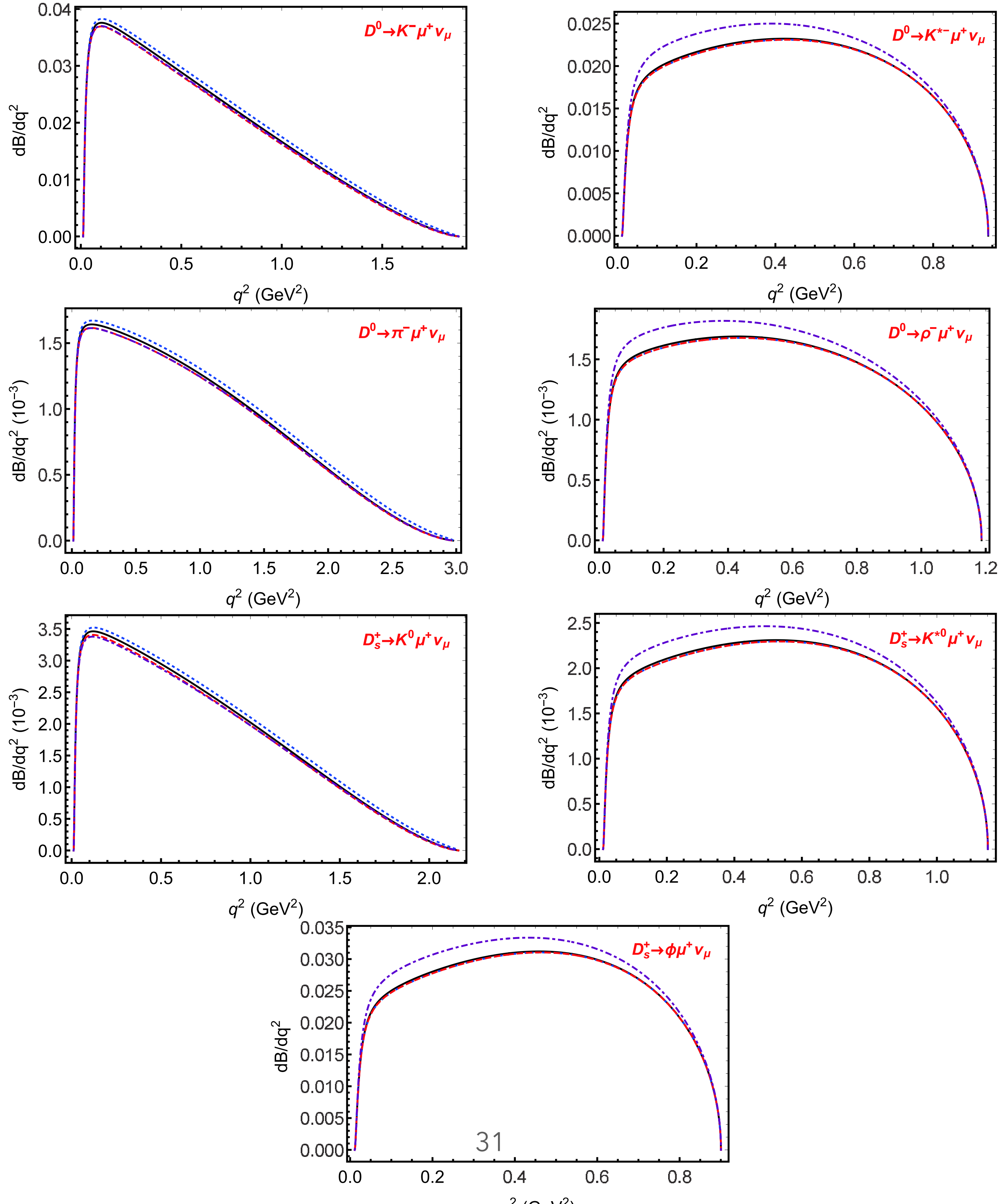
$$R^e_{\mu;\rho} \equiv \frac{\mathcal{B}(D^+ \to \rho^0 e^+ \nu_e)}{\mathcal{B}(D^+ \to \rho^0 \mu^+ \nu_\mu)} = 0.908 \pm 0.175$$



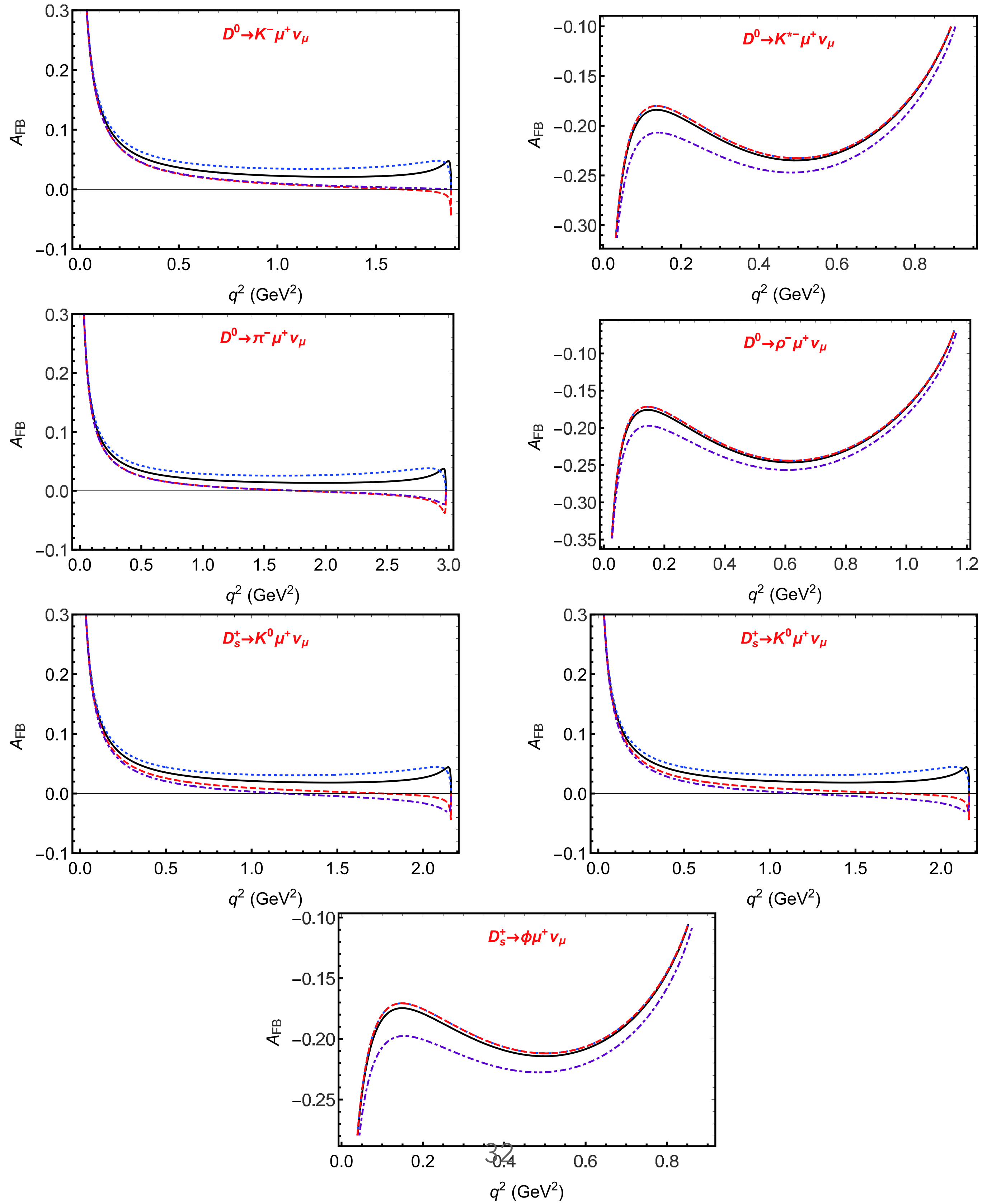
$$R^e_{\mu;\overline{K}^*} \equiv \frac{\mathcal{B}(D^+ \to \overline{K}^*(892)^0 e^+ \nu_e)}{\mathcal{B}(D^+ \to \overline{K}^*(892)^0 \mu^+ \nu_\mu)} = 1.02 \pm 0.03$$



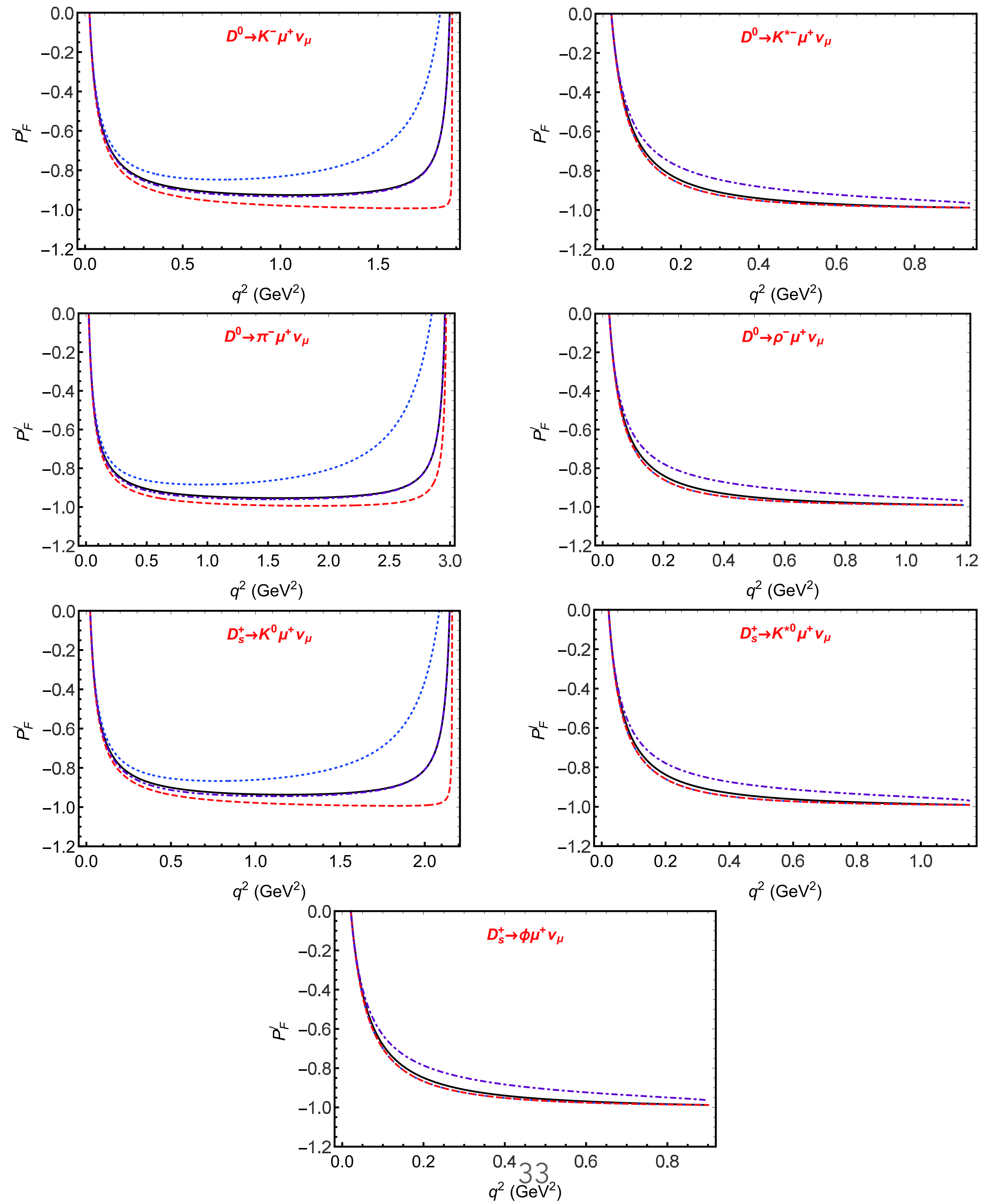
Predictions



Predictions



Predictions



Predictions

- The branching fractions of the pure leptonic D decays with the electron are very sensitive to the operators, because their contributions are related to 1/me. With the contribution of scalar operators, the branching fractions of these pure leptonic D decays are predicted to be

$$\mathcal{B}(D^+ \to e^+\nu_e) = (1.6^{+19.6}_{-0.7}) \times 10^{-8};$$
$$\mathcal{B}(D_s^+ \to e^+\nu_e) = (2.4^{+27.6}_{-1.2}) \times 10^{-7},$$

- And

$$(\mathcal{R}^e_\mu)^{D^+} = \frac{\mathcal{B}(D^+ \to e^+\nu_e)}{\mathcal{B}(D^+ \to \mu^+\nu_\mu)_{\rm Ex}} = (4.3^{+52.4}_{-2.0}) \times 10^{-5},$$
$$(\mathcal{R}^e_\mu)^{D_s^+} = \frac{\mathcal{B}(D_s^+ \to e^+\nu_e)}{\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)_{\rm Ex}} = (4.4^{+50.7}_{-2.1}) \times 10^{-5};$$

which are larger than predictions of SM

$$(\mathcal{R}^e_\mu)^{D^+} \simeq (\mathcal{R}^e_\mu)^{D_s^+} = 2.3 \times 10^{-5}.$$

However, the orders of this magnitude are too small to be measured now. We hope the future high intensity experiments can test above results.

Summary

- We have presented a comprehensive analysis of (semi)- leptonic D-meson decays to constrain possible effects of physics from beyond the SM arising from new (pseudo)- scalar, vector and tensor operators, allowing also for violations of LFU.
- We obtain a picture in agreement with the SM, including a few deviations at the 1 σ level. These results can be used to constrain the NP models.
- We extended the SM by assuming general effective Hamiltonians describing the $c \to s l^+ \nu$ transitions, which consists of the full set of the four-fermion operators. Within the latest experimental data, we performed a minimum χ2 fit of the Wilson coefficient corresponding to each operator in two different cases.
- The leptonic $D^+_{(s)} \to e^+ \nu_e$ decays are hugely helicity suppressed in the SM. However, this suppression may be lifted through new pseudoscalar interactions.
- For the semileptonic decays with electron, the effects of NP are negligible, and any deviations from SM predictions would be large challenges for SM and its extensions.
- We have identified various form factors with interesting potential for future improvement through lattice QCD calculations.