Discerning new physics in charm meson (semi)leptonic decays

Based on 1502.07488, with Svjetlana Fajfer and Urša Rojec

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Outline

- Motivation
- Pseudoscalar operators $D_s \to l\upsilon$ $D \to K^* l\upsilon$
- Scalar operators $D \to K l\upsilon$

Motivation

Motivation

Goal: Search for the effects of a physics BSM by comparing the SM predictions and the measurements

Hadronic matrix elements of the weak Hamiltonian (sources of the uncertainties)

Study the processes induced by $c \to s \ell \nu$ transitions, hadronic uncertainties under the control (in lattice QCD)

New lattice calculations (Fermilab Lattice, MILC, Lattice HPQCD), precision about 0.5% in f_{Ds}, calculations of shapes of functions $f_+(q2)$, $f_0(q2)$.

Awaiting the new measurements (Belle II, BES III, LHCb)

Effective Lagrangian:

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cs}^* \sum_{\ell=e,\mu,\tau} \sum_i c_i^{(\ell)} \mathcal{O}_i^{(\ell)} + \text{H.c.}.$$

$$\mathcal{O}_{L(R)}^{(\ell)} = \left(\bar{s} P_{L(R)} c\right) \left(\bar{\nu}_\ell P_R \ell\right)$$

Wilson coefficients - flavor dependent and complex, in general

Pseudoscalar coefficients $c_P^{(\ell)}=c_R^{(\ell)}-c_L^{(\ell)}$ affect $D_s \to \ell \nu$, $D \to K^* \ell \nu$

Scalar coefficients $c_S^{(\ell)}=c_R^{(\ell)}+c_L^{(\ell)}$ affect $D \to K \ell \nu$

Wilson coefficients of pseudoscalar operators (in $D_s \to \ell\nu$ and $D_{(s)} \to K^*(\varphi)\ell\nu$)

Ds→ℓν

Definition of f_{Ds}:

$$\langle 0|\bar{s}\gamma_\mu\gamma_5|D_s(k)\rangle = f_{D_s} k_\mu$$

Pseudoscalar density matrix element:

$$\langle 0|\bar{s}\gamma_5 c|D_s(k)\rangle = \frac{f_{D_s} m_{D_s}^2}{m_c + m_s}$$

Branching fraction modified:

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

with:

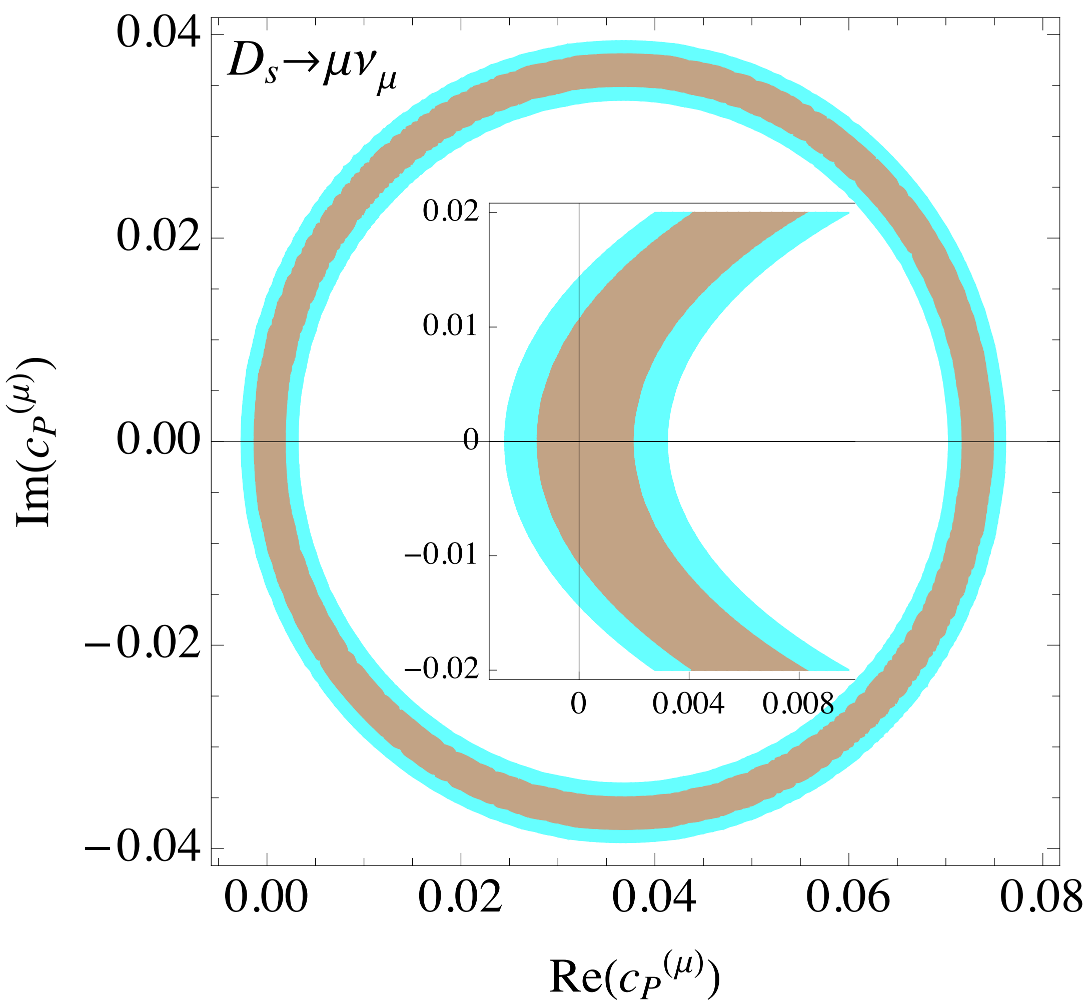
$$f_{D_s} = 249.0(0.3)(^{+1.1}_{-1.5})\,\mathrm{MeV}$$

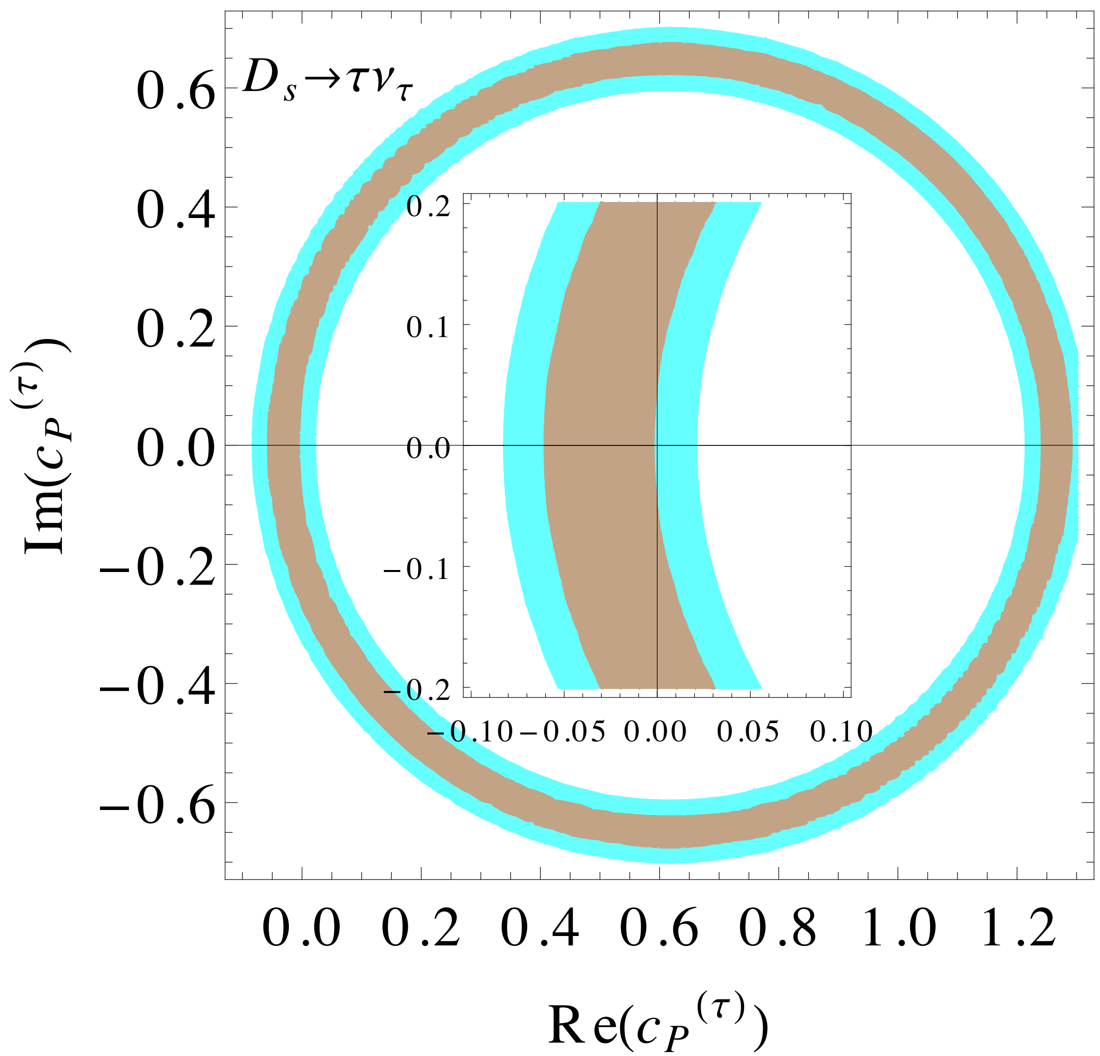
Fermilab Lattice and MILC, 1407.3772

Measurement: Belle, 1307.6240

$$\mathcal{B}(D_s \to \ell\nu_\ell) = \begin{cases} (5.7 \pm 0.21^{+0.31}_{-0.3})\%, & D_s \to \tau\nu_\tau, \\ (0.531 \pm 0.028 \pm 0.020)\%, & D_s \to \mu\nu_\mu, \\ < 1.0 \cdot 10^{-4}\,,\ 95\%\,\mathrm{C.L.}, & D_s \to e\nu_e. \end{cases}$$

Ds→ℓν





and $|c_P^{(e)}| < 0.005$

$D_{(s)} \to K^*(\phi)\ell\nu$

$D \to K^*(\varphi)\ell\nu$

The parametrization of the P→V matrix element of the V-A current:

$$\langle V(k',\epsilon)|\bar{s}\gamma_\mu(1-\gamma_5)c|P(k)\rangle = \epsilon_{\mu\nu\alpha\beta}\frac{2i\,V(q^2)}{m_P+m_V}\epsilon^{*\nu}k^\alpha k'^\beta - (m_P+m_V)\left(\epsilon_\mu - \frac{\epsilon\cdot q q^\mu}{q^2}\right)A_1(q^2) +$$
$$+\epsilon\cdot q\left(\frac{(k+k')_\mu}{m_P+m_V} - \frac{m_P-m_V}{q^2}q_\mu\right)A_2(q^2) - 2\,m_V\frac{\epsilon\cdot q q^\mu}{q^2}A_0(q^2),$$

$$A_3(q^2) \equiv \frac{m_P+m_V}{2m_V}A_1(q^2) - \frac{m_P-m_V}{2m_V}A_2(q^2), \qquad A_3(0) = A_0(0)$$

Pseudoscalar density: $$\langle V|\bar{s}\gamma_5 c|P\rangle = \frac{2m_V\epsilon^*\cdot q}{m_c+m_s}A_0(q^2)$$

Amplitudes: $$\mathcal{M}_{\lambda_\ell,\lambda_W} = \frac{G_F}{\sqrt{2}}V_{cs}^*\sum_{\lambda_W}\eta_{\lambda_W}L_{\lambda_\ell,\lambda_W}H_{\lambda_M,\lambda_W}$$

with hadronic and leptonic *helicity amplitudes:*

$$H_{\lambda_M,\lambda_W} = \tilde{\epsilon}_\mu(\lambda_W)\langle M_f(p_{M_f},\lambda_{M_f})|J^\mu_{cs}|P_i(p_{M_i}\rangle$$

$$L_{\lambda_\ell,\lambda_W} = \tilde{\epsilon}_\mu(\lambda_W)\langle \ell(p_\ell,\lambda_{M_\ell})|J^\mu_{\ell\nu}|0\rangle$$

$D \to K^*(\varphi)\ell\nu$

Modification in the presence of the pseudoscalar coupling

$$H_t \to \left(1 - c_P^{(\ell)} \frac{q^2}{m_\ell(m_c + m_s)}\right) H_t$$

Longitudinally and transversally polarized K*:

$$\frac{d\Gamma_L}{dq^2} = \mathcal{N}(q^2)\left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[\left(1 + \frac{m_\ell^2}{2q^2}\right)|H_0|^2 + \frac{3m_\ell^2}{2q^2}|H_t|^2\right]$$

$$\frac{d\Gamma_T}{dq^2} = \mathcal{N}(q^2)\left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[\left(1 + \frac{m_\ell^2}{2q^2}\right)\left(|H_+|^2 + |H_-|^2\right)\right]$$

$$R_{L/T} = \frac{\Gamma_L}{\Gamma_T}$$

Current PDG average for $D \to K^* \mu \nu$: $R_{L/T} = 1.13 \pm 0.08$

Form factor ratios extracted by BaBar (2013)

$$V(0)/A_1(0) = 1.463 \pm 0.035$$

$$A_2(0)/A_1(0) = 0.801 \pm 0.03$$

$$A_1(0) = 0.6200 \pm 0.0057$$

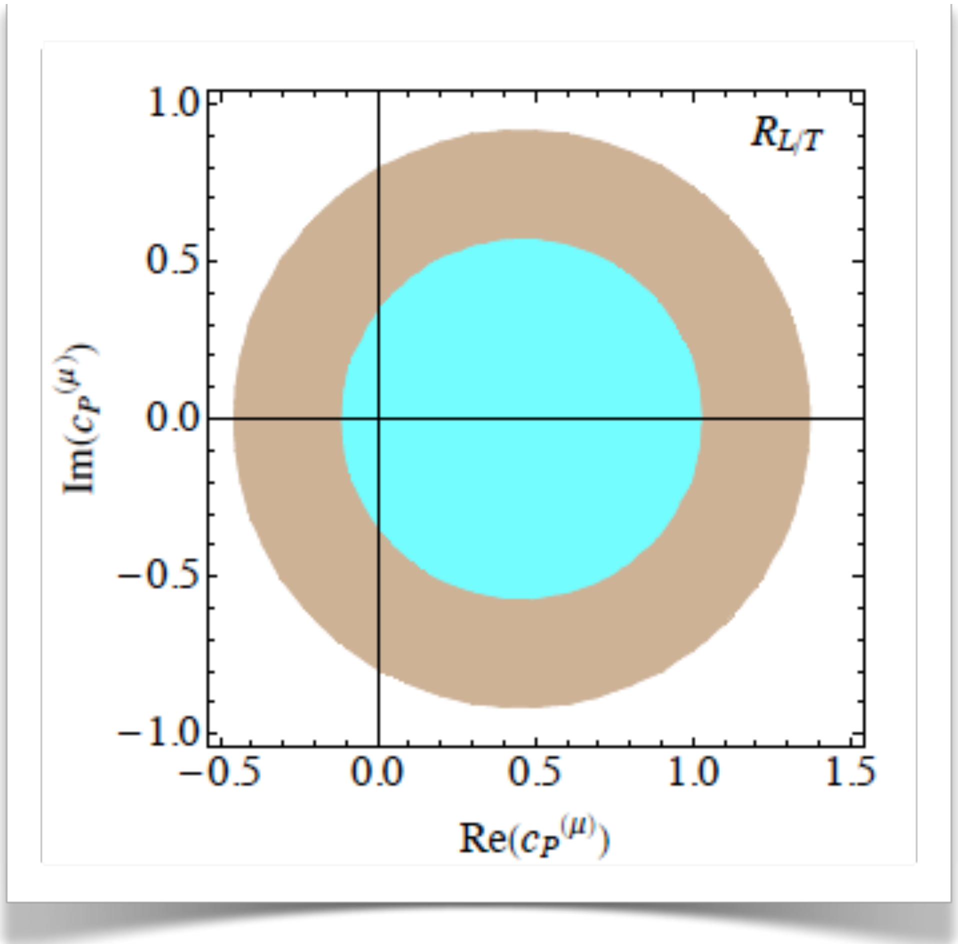
BaBar, 1307.6240

$D_{(s)} \to K^*(\varphi)\ell\nu$

To estimate the allowed contributions, use

$$A_3(0) = A_0(0)$$

and assume single pole parametrization of $A_0(q^2)$.



Current constraint is weak.

Precise knowledge of FFs, including $A_0(q^2)$ needed.

$D_{(s)} \to \varphi\ell\nu$ easier on lattice HPQCD, 1311.669

Wilson coefficients of scalar operator (from $D \to K \ell \nu$)

D→Kℓ ν

The matrix element

$$\langle K(k')|\bar{s}\gamma_\mu c|D(k)\rangle = f_+(q^2)\left((k+k')_\mu - \frac{m_D^2-m_K^2}{q^2}q_\mu\right) + f_0(q^2)\frac{m_D^2-m_K^2}{q^2}q_\mu$$

Scalar matrix element

$$\langle K|\bar{s}c|D\rangle = \frac{m_D^2-m_K^2}{m_s-m_c}f_0(q^2)$$

Helicity amplitudes D→Kℓν:

$$h_0(q^2) = \frac{\sqrt{\lambda(m_D^2,m_K^2,q^2)}}{\sqrt{q^2}}f_+(q^2), \quad h_t(q^2) = \left(1+g_S^{(\ell)}\frac{q^2}{m_\ell(m_s-m_c)}\right)\frac{m_D^2-m_K^2}{\sqrt{q^2}}f_0(q^2)$$

The decay rate:

$$\frac{d\Gamma^{(\ell)}}{dq^2} = \frac{G_F^2|V_{cs}|^2|\mathbf{q}|q^2}{96\pi^3m_D^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2\left[|h_0(q^2)|^2\left(1+\frac{m_\ell^2}{2q^2}\right)+\frac{3m_\ell^2}{2q^2}|h_t(q^2)|^2\right]$$

Measurements (PDG averages):

$$\mathcal{B}(D\to K\ell\nu_\ell) = \begin{cases}(8.83\pm0.22)\%, & D^+\to\bar{K}^0e^+\nu_e,\\ (9.2\pm0.6)\%, & D^+\to\bar{K}^0\mu^+\nu_\mu,\\ (3.55\pm0.04)\%, & D^0\to K^-e^+\nu_e,\\ (3.30\pm0.13)\%, & D^0\to K^-\mu^+\nu_\mu.\end{cases}$$

D→Kℓ ν

The matrix element

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Scalar matrix element

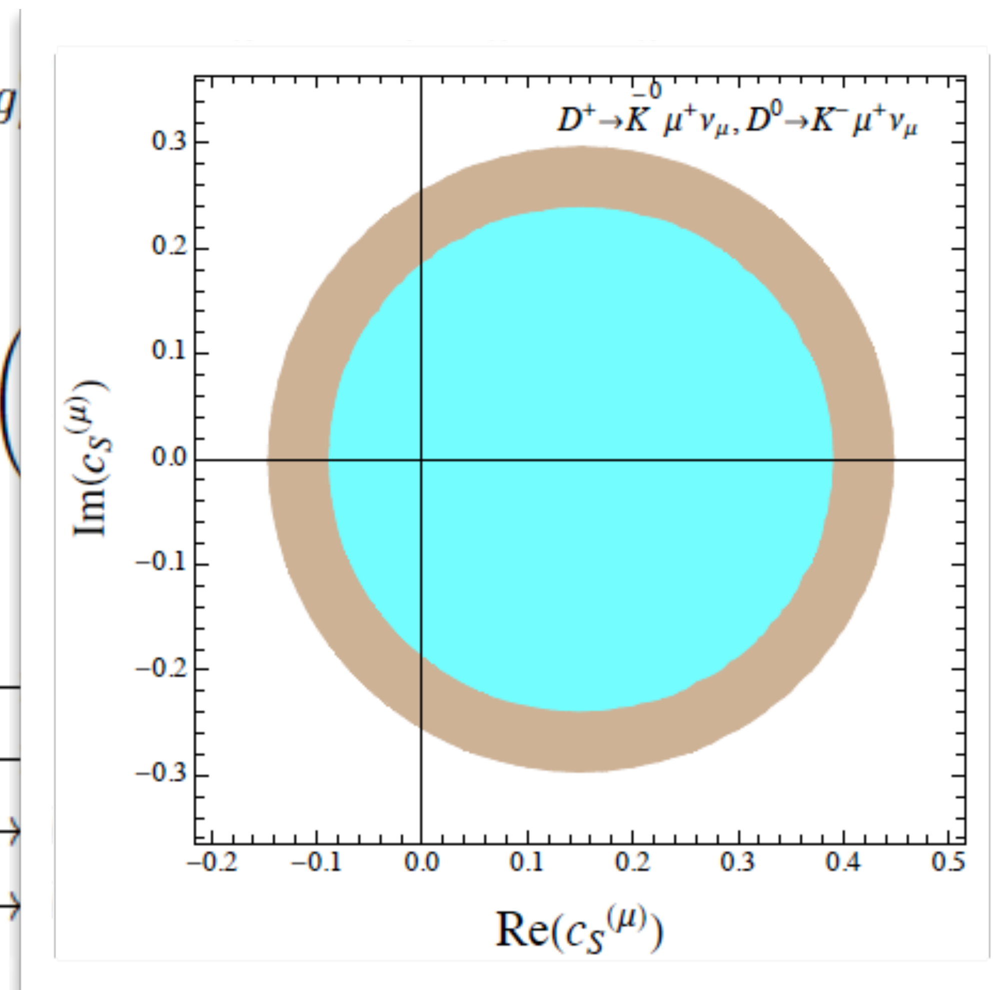
$$\langle K|\bar{s}c|D\rangle = \frac{m_D^2 - m_K^2}{m_s - m_c} f_0(q^2)$$

Helicity amplitudes D→Kℓν:

$$h_0(q^2) = \frac{\sqrt{\lambda(m_D^2, m_K^2, q^2)}}{\sqrt{q^2}} f_+(q^2), \quad h_t(q^2) = \Big(1 + g$$

Decay rate:

$$\frac{d\Gamma^{(\ell)}}{dq^2} = \frac{G_F^2|V_{cs}|^2|\mathbf{q}|q^2}{96\pi^3 m_D^2}\left(1 - \frac{m_\ell^2}{q^2}\right)^2 \Big[|h_0(q^2)|^2 \Big($$



Measurements (PDG averages):

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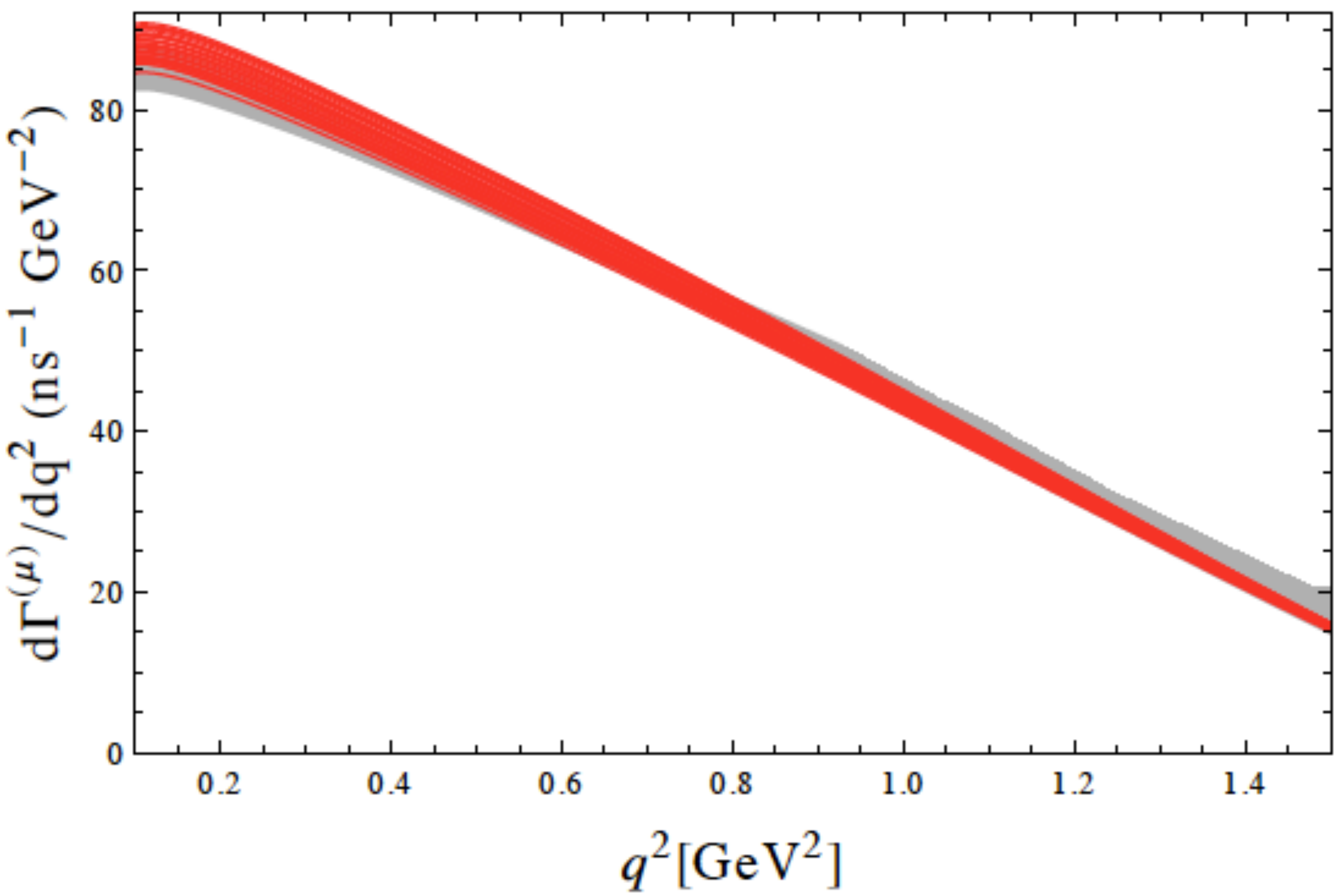
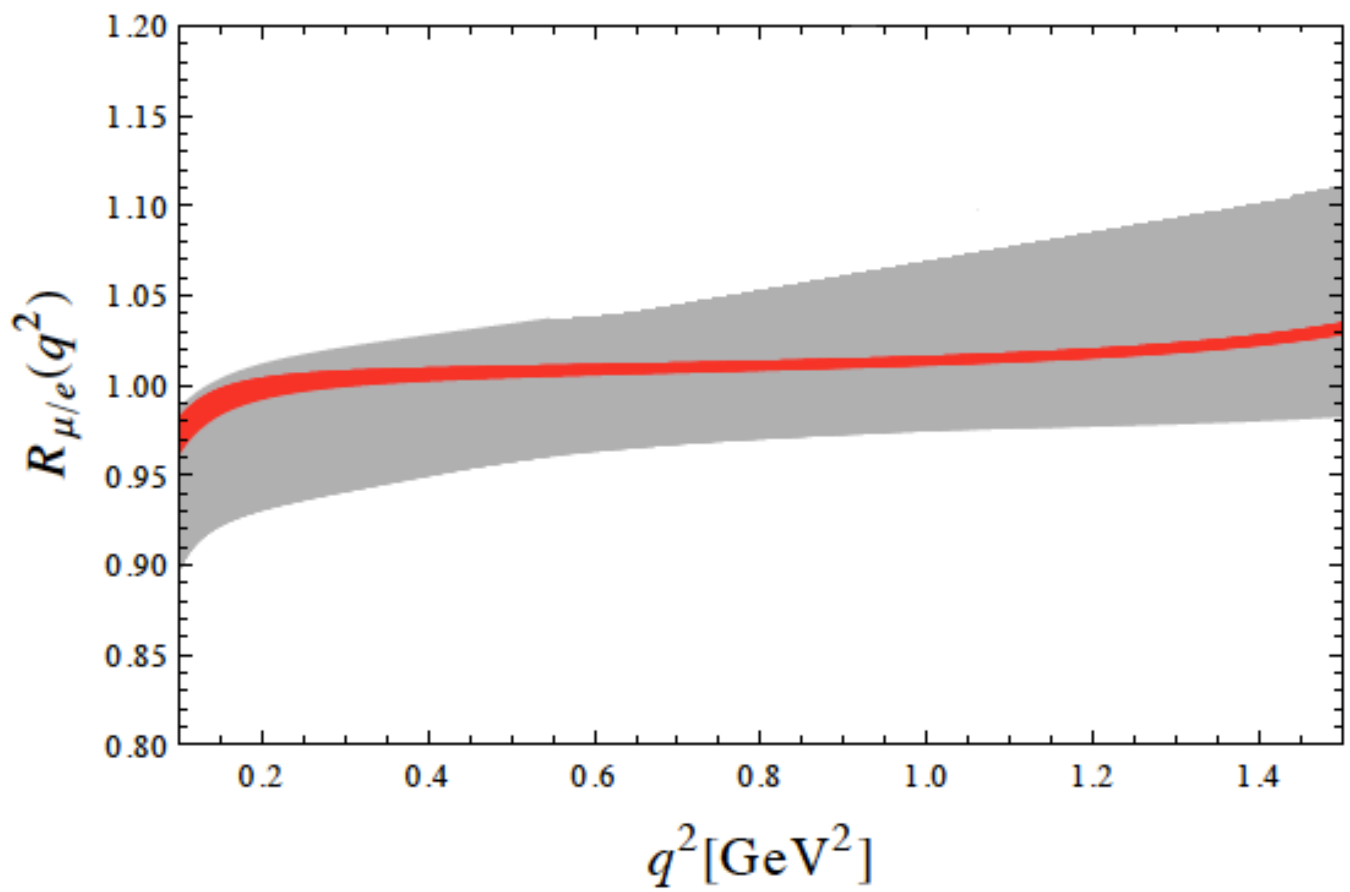
Testing the Lepton Flavour Universality (LFU) of charged currents

$$R_{\mu/e}(q^2) \equiv \frac{d\Gamma^{(\mu)}}{dq^2} / \frac{d\Gamma^{(e)}}{dq^2}$$



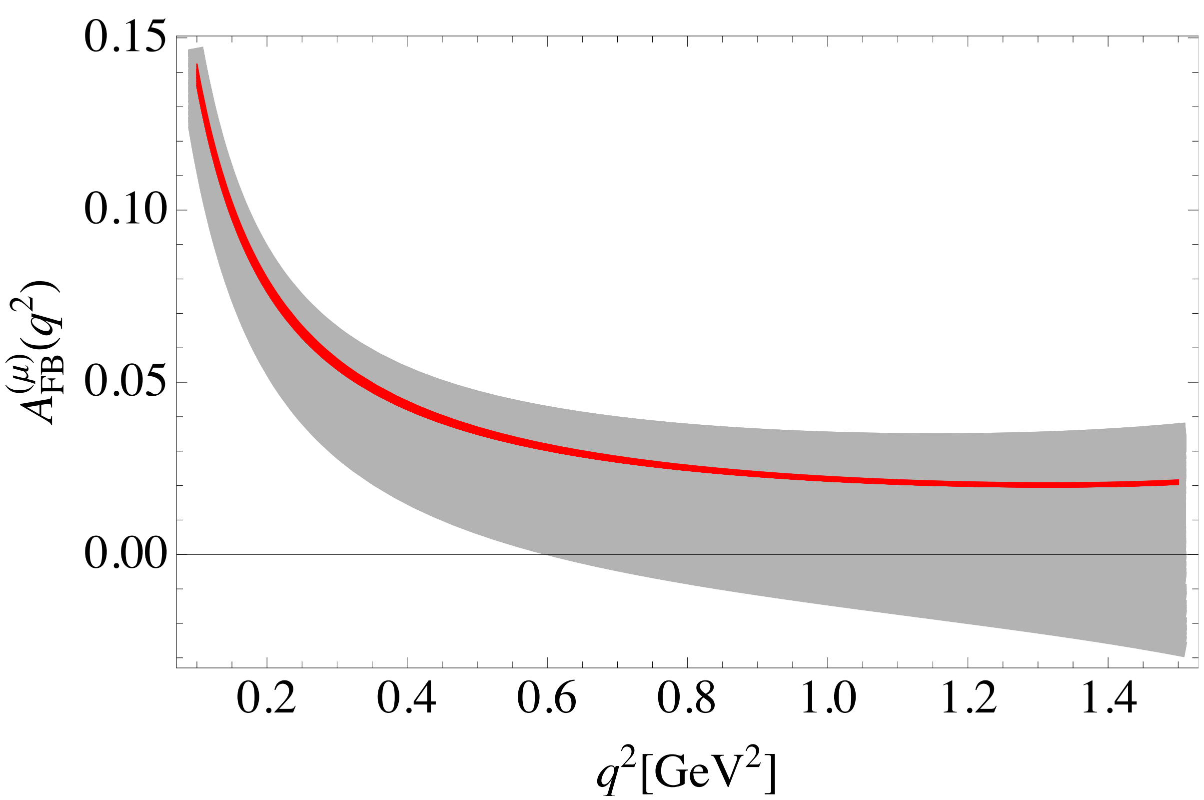


Forward-backward asymmetry in angle θℓ

$$\frac{d^2\Gamma^{(\ell)}}{dq^2 d\cos\theta_\ell} = a_\ell(q^2) + b_\ell(q^2)\cos\theta_\ell + c_\ell(q^2)\cos^2\theta_\ell$$

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

$$b_\ell(q^2) = -\frac{G_F^2 |V_{cs}|^2 |\mathbf{q}| q^2}{128\pi^3 m_D^2}\left(1 - \frac{m_\ell^2}{q^2}\right)^2 \frac{m_\ell^2}{q^2} 2Re(h_0 h_t^*)$$



Transverse muon polarization in the process $D^+ \to K^0 \ell^+ \nu$ (probing imaginary part of the pseudoscalar coupling)

$$P_\perp^{(\mu)} = \frac{|\mathcal{A}(\vec{s})|^2 - |\mathcal{A}(-\vec{s})|^2}{|\mathcal{A}(\vec{s})|^2 + |\mathcal{A}(-\vec{s})|^2}$$

$$\vec{s} \equiv (\vec{p}_K \times \vec{p}_\ell)/|\vec{p}_K \times \vec{p}_\ell|$$

$$P_\perp \propto \epsilon_{\mu\nu\alpha\beta}\, s^\mu\, p_K^\nu\, p_\ell^\alpha\, p_\nu^\beta.$$

$$s^\mu \equiv (0, \vec{p}_K \times \vec{p}_\ell/|\vec{p}_K \times \vec{p}_\ell|),$$

$$|\mathcal{A}^\pm|^2 = |\mathcal{A}_{SM}^\pm|^2 + |\mathcal{A}_S^\pm|^2 + 2\Re(\mathcal{A}_{SM}^* \mathcal{A}_S)^\pm,$$

$$2\Re(\mathcal{A}_{SM}^* \mathcal{A}_S)^\pm \propto c_S^{(\ell)} \mathcal{T}^\pm,$$

$$\mathcal{T}^\pm = \left[\bar{\ell}(p_K + p_D)_\mu \gamma^\mu (1-\gamma^5)\nu\right] \times \left[\bar{\nu}(1+\gamma_5)\ell^\pm\right],$$

$$\begin{aligned} |\mathcal{A}^+|^2 - |\mathcal{A}^-|^2 &= 2\Re(\mathcal{A}_{SM}^* \mathcal{A}_S)^+ - 2\Re(\mathcal{A}_{SM}^* \mathcal{A}_S)^- \\ &\propto \epsilon_{\mu\nu\alpha\beta} s^\mu p_K^\nu p_\ell^\alpha p_\nu^\beta \Re(i c_s^{(\ell)}) \\ &= -\epsilon_{\mu\nu\alpha\beta} s^\mu p_K^\nu p_\ell^\alpha p_\nu^\beta \Im(c_s^{(\ell)}). \end{aligned}$$

In terms of helicity amplitudes

$$P_\perp^{(\mu)}(q^2, E_\mu) = \left(\frac{d\Gamma}{dq^2 dE_\mu}\right)^{-1} \kappa(q^2, E_\mu)\,\mathrm{Im}\left(h_0(q^2) h_t^*(q^2)\right)$$

Averaging:

$$\langle P_\perp^{(\mu)} \rangle = \frac{\int dq^2 dE_\mu\, P_\perp^{(\mu)}(q^2, E_\mu) \frac{d^2\Gamma}{dq^2 dE_\mu}}{\int dq^2 dE_\mu \frac{d^2\Gamma}{dq^2 dE_\mu}}$$

allowed: $c_S^{(\mu)} \simeq \pm 0.1\, i$ $\langle P_\perp^{(\mu)} \rangle \simeq \pm 0.2$

*) This observable was measured in $K^+ \to \pi^0 \mu^+ \nu$ by experiment KEK-PS-E246, Phys.Rev.D73 (2006) 072005

Conclusions

Several interesting observables could be probed experimentally to further constraint NP

Deviations are allowed and should be searched for

Needed: New precise measurements of the q^2 distributions, forward-backward asymmetry for muons, transverse muon polarization in $D \to K \ell \nu$ and the ratio of longitudinal and transverse polarizations of K^* (φ)

Precise calculations of $D_{(s)} \to K^*(\varphi) \ell \nu$ form factors required.

Appendix (hadronic helicity amplitudes)

$$H_\pm(q^2) = \mp \frac{\sqrt{\lambda(m_P^2, m_V^2, q^2)}}{m_P + m_V} V(q^2) + (m_P + m_V) A_1(q^2)$$

$$H_0(q^2) = \frac{1}{2m_V\sqrt{q^2}} \left[(m_P + m_V)(m_P^2 - m_V^2 - q^2) A_1(q^2) - \frac{\lambda(m_P^2, m_V^2, q^2)}{m_P + m_V} A_2(q^2) \right]$$

$$H_t(q^2) = \left[1 - c_P^{(\ell)} \frac{q^2}{m_\ell (m_q + m_{\bar{q}})} \right] \frac{\sqrt{\lambda(m_P^2, m_V^2, q^2)}}{\sqrt{q^2}} A_0(q^2).$$