Probing New Physics in Charm Couplings

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Outline of talk

* **Introduction**
* **Tree-level processes**
* **Loop-induced processes**
* **Conclusions**

Introduction

* Existing data on various decays of hadrons and mixing of neutral mesons are consistent with the loop-induced nature of flavor-changing neutral currents (FCNC's) in the standard model (SM)
* They are also consistent with the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix with three generations.
* Our understanding of the dynamics of flavor is nevertheless not yet complete.
* The continuing study of low-energy flavor-changing processes with increased precision will play a crucial role in the search for new physics.

Anomalous couplings of quarks

* In many types of new physics, the new particles are heavier than their SM counterparts.
  - Their effects can be described by an effective low-energy theory.
* It is possible that the effect of new physics is mainly to modify the SM couplings between gauge bosons and certain fermions.
* Anomalous top-quark couplings have been much studied in the literature.
  - They are most tightly constrained by the $b \to s\gamma$ decay.
  - This mode does not place severe constraints on the corresponding charm-quark couplings due to the relative smallness of the charm mass.
* It is thus interesting to explore anomalous charm-quark couplings subject to existing and future data.

Effective interactions

* We focus on new physics affecting primarily the charged weak currents involving the charm quark.

* The effective Lagrangian for a general parametrization of the W boson interacting with an up-type quark U_k and a down-type quark D_l can be written as

$$\mathcal{L}_{UDW} = -\frac{g}{\sqrt{2}} V_{kl} \bar{U}_k \gamma^\mu \left[\left(1+\kappa_{kl}^{\rm L}\right) P_{\rm L} + \kappa_{kl}^{\rm R} P_{\rm R} \right] D_l W_\mu^+ + \text{H.c.}$$

g is the weak coupling constant, the anomalous couplings $\kappa_{kl}^{\rm L,R}$ are normalized relative to the CKM-matrix elements V_{kl}, and $P_{\rm L,R} = \frac{1}{2}(1 \mp \gamma_5)$.

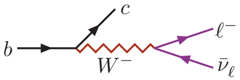
* In general, $\kappa_{kl}^{\rm L,R}$ are complex and therefore provide new sources of CP violation.

Tree-level processes

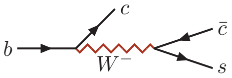
* Anomalous charm-W couplings affect various flavor-changing transitions at tree level.

* CP-conserving processes
  - $\bar{c}\,(d,s) \to \ell^-\bar{\nu}_\ell$

  - $b \to c e^- \bar{\nu}_e$



* CP-violating processes
  - $b \to c\bar{c}s$



$D \to \ell\nu$ & $D_s \to \ell\nu$

* In the presence of anomalous charm couplings

$$\Gamma(D \to \ell\nu) \; = \; \frac{G_F^2\, f_D^2\, m_\ell^2\, m_D}{8\pi} \left(1 - \frac{m_\ell^2}{m_D^2}\right)^2 \left|V_{cd}\left(1 + \kappa_{cd}^{\rm L} - \kappa_{cd}^{\rm R}\right)\right|^2$$

the decay constant f_D defined by $\langle 0|\bar{d}\gamma^\mu c|D(p)\rangle = i f_D p^\mu$.

* Similarly for $\Gamma(D_s \to \ell\nu)$.

* Recent measurements yield PDG, CLEO

$$f_D^{\rm exp} \; = \; (205.8 \pm 8.9)\,{\rm MeV} \;, \qquad f_{D_s}^{\rm exp} \; = \; (261.2 \pm 6.9)\,{\rm MeV}$$

* SM calculations give Dobrescu & Kronfeld, Narison

$$f_D^{\rm th} \; = \; (202 \pm 8)\,{\rm MeV} \;, \qquad f_{D_s}^{\rm th} \; = \; (240 \pm 7)\,{\rm MeV}$$

$D, D_s \to \ell\nu$

* The data for $D \to \ell\nu$ agree with theoretical predictions well, but for $D_s \to \ell\nu$ there is deviation at the 2-sigma level.
* It has been argued that this deviation may be due to physics beyond the SM, but it is too early to conclude that new physics is needed.
* Nevertheless, one can turn the argument around to constrain the new physics parameterized by the anomalous couplings.
* Using the experimental and theoretical numbers above, one can then extract

$$\left|\mathrm{Re}\left(\kappa_{cd}^{\mathrm{L}} - \kappa_{cd}^{\mathrm{R}}\right)\right| \le 0.04 \,, \qquad 0 \le \mathrm{Re}\left(\kappa_{cs}^{\mathrm{L}} - \kappa_{cs}^{\mathrm{R}}\right) \le 0.1$$

Exclusive & inclusive $b \to c\ell^-\bar{\nu}_\ell$ decays

- $b \to c\ell^-\bar{\nu}_\ell$ decays provide avenues to measure V_{cb}.
- The presence of anomalous cbW couplings affects V_{cb} extraction.
- They scale the hadronic vector and axial-vector currents by the factors $1+\kappa_{cb}^{\rm L} \pm \kappa_{bc}^{\rm R}$, respectively.
- $\bar{B} \to D\ell^-\bar{\nu}_\ell$ is sensitive only to the vector form-factor.
  - Its decay rate gets multiplied by $\left|1+\kappa_{cb}^{\rm L}+\kappa_{bc}^{\rm R}\right|^2$.
  - To $\mathcal{O}(\kappa)$, what is measured is then PDG

$$V_{cb}^{\rm eff} = V_{cb}\left(1+{\rm Re}\,\kappa_{cb}^{\rm L}+{\rm Re}\,\kappa_{cb}^{\rm R}\right) = (39.4 \pm 4.4)\times 10^{-3}$$

- $\bar{B} \to D^*\ell^-\bar{\nu}_\ell$ is sensitive to both the vector and axial-vector currents.
  - The axial-vector current dominates the decay rate.
  - Using constant form-factors yields to $\mathcal{O}(\kappa)$ PDG

$$V_{cb}^{\rm eff} = V_{cb}\left(1+{\rm Re}\,\kappa_{cb}^{\rm L}-0.93{\rm Re}\,\kappa_{cb}^{\rm R}\right) = (38.6 \pm 1.4)\times 10^{-3}$$

$b \to c\ell^-\bar{\nu}_\ell$

* The inclusive decay rate in the presence of the κ_{cb}'s

$$\Gamma\big(b \to c\ell^-\bar{\nu}_\ell\big) = \frac{G_{\rm F}^2\, m_b^5}{192\pi^3}|V_{cb}|^2\Big\{F(r)\Big(\big|1+\kappa_{cb}^{\rm L}\big|^2 + \big|\kappa_{cb}^{\rm R}\big|^2\Big) + 2G(r)\,{\rm Re}\big[\big(1+\kappa_{cb}^{\rm L}\big)\kappa_{cb}^{\rm R*}\big]\Big\}$$

where $r = m_c/m_b \simeq 0.3$, $F(r) = 1 - 8r^2 + 8r^6 - r^8 - 24r^4\,\ln r$,
$G(r) = -8r\left[1 + 9r^2 - 9r^4 - r^6 + 12r^2\left(1+r^2\right)\,\ln r\right]$.

PDG

* To $\mathcal{O}(\kappa)$, $V_{cb}^{\rm eff} = V_{cb}\left(1 + {\rm Re}\,\kappa_{cb}^{\rm L} - 1.5\,{\rm Re}\,\kappa_{cb}^{\rm R}\right) = (41.6 \pm 0.6) \times 10^{-3}$
* It is not possible to extract a bound on $\kappa_{cb}^{\rm L}$ (as long as quadratic effects are ignored), but one can extract bounds on $\kappa_{cb}^{\rm R}$.
* A two-parameter fit results in a χ^2 minimum for

$$V_{cb}\left(1 + {\rm Re}\,\kappa_{cb}^{\rm L}\right) = 0.038\,, \qquad {\rm Re}\,\kappa_{cb}^{\rm R} = -0.057$$

with a corresponding 1-σ range

$$-0.13 \le {\rm Re}\,\kappa_{cb}^{\rm R} \le 0$$

Loop-induced processes

* The anomalous quark-W couplings also generate flavor-changing neutral-current interactions via
  - γ- and Z-penguin diagrams

  - box diagrams

(a) (b)

* They therefore affect loop-induced processes, such as $K \to \pi\nu\bar{\nu}$, $K_L \to \ell^+\ell^-$, and neutral-meson mixing.

Loop contributions

* The effective theory with anomalous couplings is not renormalizable
  - This results in divergent contributions to some of the processes we consider.
* These divergences are understood in the context of effective field theories as contributions to the coefficients of higher-dimension operators.
* For our numerical analysis, we will limit ourselves to the anomalous couplings ignoring the higher-dimension operators.
* In so doing, we trade the possibility of obtaining precise predictions in specific models for order-of-magnitude estimates of the effects of new physics parameterized in a model-independent way.

Loop evaluations

* Not having the knowledge about the new degrees of freedom, we adopt the unitary gauge, implying that the loops contain only fermions and W-bosons.
* We follow the common procedure of using dimensional regularization, dropping the resulting pole in 4 dimensions, and identifying the renormalization scale μ with the scale of the new physics underlying the effective theory.
* Our results thus contain a logarithmic term of the form $\ln(\mu/m_W)$ in which we set $\mu = \Lambda = 1$ TeV for definiteness.
* We also keep in our estimates those finite terms that correspond to contributions from SM quarks in the loops.
* In the SM limit $(\kappa^{\mathrm{L,R}} = 0)$, after CKM unitarity is imposed, our results are finite and reproduce those obtained in the literature in R_ξ gauges.

Effective Hamiltonians for $d\bar{d}' \to \nu\bar{\nu}, \ell\bar{\ell}$ induced by κ's

* The effective Hamiltonians generated at one loop by the anomalous charm couplings, at the m_W scale,

$$\mathcal{H}^{\kappa}_{d\bar{d}'\to\nu\bar{\nu}} = \frac{\alpha\, G_{\rm F}\, \lambda_c \left(\kappa^{\rm L}_{cd} + \kappa^{\rm L*}_{cd'}\right)}{\sqrt{8}\,\pi\, \sin^2\theta_{\rm W}} \left(-3\, \ln\frac{\Lambda}{m_W} + 4X_0(x_c)\right) \bar{d}'\gamma^\sigma P_{\rm L} d\, \bar{\nu}\gamma_\sigma P_{\rm L}\nu$$
$$+ \frac{\alpha\, G_{\rm F}\, \lambda_c\, \kappa^{\rm R}_{cd}\kappa^{\rm R*}_{cd'}}{\sqrt{8}\,\pi\, \sin^2\theta_{\rm W}} \left[(4x_c - 3)\, \ln\frac{\Lambda}{m_W} + \tilde{X}(x_c)\right] \bar{d}'\gamma^\sigma P_{\rm R} d\, \bar{\nu}\gamma_\sigma P_{\rm L}\nu\ ,$$

$$\mathcal{H}^{\kappa}_{d\bar{d}'\to\ell^+\ell^-} = \frac{\alpha\, G_{\rm F}\, \lambda_c \left(\kappa^{\rm L}_{cd} + \kappa^{\rm L*}_{cd'}\right)}{\sqrt{8}\,\pi} \Bigg[\left(3\, \ln\frac{\Lambda}{m_W} - 4Y_0(x_c)\right) \frac{\bar{d}'\gamma^\sigma P_{\rm L} d\, \bar{\ell}\gamma_\sigma P_{\rm L}\ell}{\sin^2\theta_{\rm W}}$$
$$+ \left(-\frac{16}{3}\, \ln\frac{\Lambda}{m_W} + 8Z_0(x_c)\right) \bar{d}'\gamma^\sigma P_{\rm L} d\, \bar{\ell}\gamma_\sigma \ell\Bigg]$$
$$+ \frac{\alpha\, G_{\rm F}\, \lambda_c\, \kappa^{\rm R}_{cd}\kappa^{\rm R*}_{cd'}}{\sqrt{8}\,\pi} \Bigg\{\left[(3 - 4x_c)\, \ln\frac{\Lambda}{m_W} + \tilde{Y}(x_c)\right] \frac{\bar{d}'\gamma^\sigma P_{\rm R} d\, \bar{\ell}\gamma_\sigma P_{\rm L}\ell}{\sin^2\theta_{\rm W}}$$
$$+ \left[\left(8x_c - \frac{16}{3}\right)\, \ln\frac{\Lambda}{m_W} + \tilde{Z}(x_c)\right] \bar{d}'\gamma^\sigma P_{\rm R} d\, \bar{\ell}\gamma_\sigma \ell\Bigg\}$$

Effective Hamiltonians induced by κ's

* From the box diagrams

$$
\begin{aligned}
\mathcal{H}^{\kappa}_{d\bar{d}'\to\bar{d}d'} =& \\
&\frac{G_F^2\, m_W^2}{8\pi^2}\,\lambda_c\big(\kappa^{\rm L}_{cd}+\kappa^{\rm L*}_{cd'}\big)\left(-\lambda_t\,x_t\,\ln\frac{\mu^2}{m_W^2}-\sum_q\lambda_q\,\mathcal{B}_1(x_q,x_c)\right)\bar{d}'\gamma^\alpha P_{\rm L}d\,\bar{d}'\gamma_\alpha P_{\rm L}d \\
&-\frac{G_F^2\, m_W^2}{4\pi^2}\,\lambda_c\kappa^{\rm R}_{cd}\kappa^{\rm R*}_{cd'}\left(\lambda_t\,x_t\,\ln\frac{\mu^2}{m_W^2}+\sum_q\lambda_q\,\mathcal{B}_2(x_q,x_c)\right)\bar{d}'\gamma^\alpha P_{\rm L}d\,\bar{d}'\gamma_\alpha P_{\rm R}d \\
&-\frac{G_F^2\, m_W^2}{4\pi^2}\,\lambda_c^2 x_c\left(\ln\frac{\mu^2}{m_W^2}+\mathcal{B}_3(x_c,x_c)\right)\Big[\big(\kappa^{\rm R}_{cd}\big)^2\,\bar{d}'P_{\rm R}d\,\bar{d}'P_{\rm R}d+\big(\kappa^{\rm R*}_{cd'}\big)^2\,\bar{d}'P_{\rm L}d\,\bar{d}'P_{\rm L}d\Big]
\end{aligned}
$$

$d'\neq d$, terms linear in $\kappa^{\rm L}$ and quadratic in $\kappa^{\rm R}$ are kept, $\lambda_q=V^*_{qd'}V_{qd}$, $\theta_{\rm W}$ is the Weinberg angle, X_0, Y_0, Z_0, $\tilde{X}$, $\tilde{Y}$, $\tilde{Z}$, and $\mathcal{B}_{1,2,3}$ are loop functions.

$K^+ \to \pi^+ \nu\bar{\nu}$

* The dominant contribution in the SM comes from the top loop

$$\mathcal{M}_{\rm SM}\big(K^+ \to \pi^+\nu\bar{\nu}\big) \;=\; \frac{G_{\rm F}}{\sqrt{2}}\,\frac{\alpha\, V_{td} V_{ts}^*\, X_0\big(x_t\big)}{2\pi\, \sin^2\theta_{\rm W}}\, \langle\pi^+|\bar{s}\gamma_\mu d|K^+\rangle\, \bar{\nu}\gamma^\mu(1-\gamma_5)\nu$$

* The combined SM and anomalous-charm contribution

$$\mathcal{M}(K^+ \to \pi^+\nu\bar{\nu}) \;=\; (1+\delta)\,\mathcal{M}_{\rm SM}\big(K^+ \to \pi^+\nu\bar{\nu}\big)\;,$$

$$\delta \;=\; \frac{V_{cd}V_{cs}^*}{V_{td}V_{ts}^*}\,\frac{\big(\kappa_{cd}^{\rm L}+\kappa_{cs}^{\rm L*}\big)\big[-3\,\ln\big(\Lambda/m_W\big)+4X_0\big(x_c\big)\big]}{4X\big(x_t\big)} \;+\; \mathcal{O}\big(\kappa^2\big)$$

* The SM branching ratio $\mathcal{B}_{\rm SM}(K^+ \to \pi^+\nu\bar{\nu}) = (8.5 \pm 0.7)\times 10^{-11}$ to be compared with its experimental value $\mathcal{B}_{\rm exp} = \big(1.73^{+1.15}_{-1.05}\big)\times 10^{-10}$.
* We then require $-0.2 \le {\rm Re}\,\delta \le 1$, which translates into

$$-2.5\times 10^{-4} \;\le\; -{\rm Re}\big(\kappa_{cd}^{\rm L}+\kappa_{cs}^{\rm L}\big) \;+\; 0.42\,{\rm Im}\big(\kappa_{cd}^{\rm L}-\kappa_{cs}^{\rm L}\big) \;\le\; 1.3\times 10^{-3}$$

$K_L \to \mu^+\mu^-$

- The dominant short-distance SM contribution is also due to the top loop

$$\mathcal{M}_{\rm SM}^{\rm SD}\big(K^0 \to \mu^+\mu^-\big) \;=\; -\frac{G_{\rm F}}{\sqrt{2}}\, \frac{\alpha\, V_{td} V_{ts}^*\, Y_0\big(x_t\big)}{2\pi\, \sin^2\theta_{\rm W}} \langle 0|\bar{s}\gamma^\sigma\gamma_5 d|K^0\rangle\, \bar{\mu}\gamma_\sigma\gamma_5\mu$$

- The total SD amplitude

$$\mathcal{M}_{\rm SD}\big(K_L \to \mu^+\mu^-\big) \;=\; (1+\delta')\, \mathcal{M}_{\rm SM}^{\rm SD}\big(K_L \to \mu^+\mu^-\big)\ ,$$

$$\delta' \;=\; \frac{{\rm Re}\big[V_{cd}^* V_{cs}\,\big(\kappa_{cs}^{\rm L} + \kappa_{cd}^{\rm L*}\big)\big]\big[-3\,\ln\big(\Lambda/m_W\big) + 4Y_0\big(x_c\big)\big]}{4\,{\rm Re}\big(V_{td}^* V_{ts}\big)\, Y\big(x_t\big)} \;+\; \mathcal{O}\big(\kappa^2\big)$$

- The measured $\mathcal{B}\big(K_L \to \mu^+\mu^-\big) = (6.84 \pm 0.11) \times 10^{-9}$ is almost saturated by the absorptive part of the long-distance contribution, $\mathcal{B}_{\rm abs} = (6.64 \pm 0.07) \times 10^{-9}$.
- This suggests the allowed room for new physics, $\mathcal{B}_{\rm NP} \lesssim 3.8 \times 10^{-10}$, the upper bound about $\frac{1}{2}$ the SD SM contribution, $\mathcal{B}_{\rm SM}^{\rm SD} = (7.9 \pm 1.2) \times 10^{-10}$.
- Consequently, we demand $|\delta'| \le 0.2$, implying

$$\Big|{\rm Re}\big(\kappa_{cs}^{\rm L} + \kappa_{cd}^{\rm L}\big) \;+\; 6 \times 10^{-4}\, {\rm Im}\big(\kappa_{cs}^{\rm L} - \kappa_{cd}^{\rm L}\big)\Big| \;\le\; 1.5 \times 10^{-4}$$

K-$\bar{K}$ mixing

* The matrix element for K^0-$\bar{K}^0$ mixing $M_{12}^K = \langle K^0 | \mathcal{H}_{d\bar{s}\to\bar{d}s} | \bar{K}^0 \rangle / (2m_K)$ consists of SM and new-physics terms.
* The anomalous charm contribution

$$M_{12}^{K,\kappa} = \frac{G_F^2 m_W^2}{24\pi^2} f_K^2 m_K \lambda_c^{ds} \Bigg[\bar{\eta}^3 B_K \big(\kappa_{cd}^{L*} + \kappa_{cs}^{L}\big) \Bigg(-\lambda_t^{ds} x_t \ln \frac{\mu^2}{m_W^2} - \sum_q \lambda_q^{ds} \mathcal{B}_1(x_q, x_c) \Bigg) + \frac{\bar{\eta}^{3/2} B_K m_K^2}{(m_d + m_s)^2} \kappa_{cd}^{R*} \kappa_{cs}^{R} \Bigg(\lambda_t^{ds} x_t \ln \frac{\mu^2}{m_W^2} + \sum_q \lambda_q^{ds} \mathcal{B}_2(x_q, x_c) \Bigg) \Bigg]$$

$\lambda_q^{ds} = V_{qd}^* V_{qs}$

* The K_L-K_S mass difference $\Delta M_K = 2\,\mathrm{Re}\, M_{12}^K + \Delta M_K^{\rm LD}$ contains a sizable long-distance term, $\Delta M_K^{\rm LD}$.
* Since the LD part has significant uncertainties, we constrain the κ's by requiring that their contribution to ΔM_K be less than the largest SM contribution, arising from the charm loop,

$$M_{12}^{K,\rm SM} \simeq \frac{G_F^2\, m_W^2}{12\pi^2} f_K^2 m_K B_K\, \eta_{cc} \big(\lambda_c^{ds}\big)^2 S_0(x_c)$$

K-$\bar{K}$ mixing

* As a result

$$\left|0.043\mathrm{Re}\left(\kappa_{cd}^{\mathrm{L}}+\kappa_{cs}^{\mathrm{L}}\right)+0.015\mathrm{Im}\left(\kappa_{cd}^{\mathrm{L}}-\kappa_{cs}^{\mathrm{L}}\right)-\mathrm{Re}\left(\kappa_{cd}^{\mathrm{R}*}\kappa_{cs}^{\mathrm{R}}\right)+0.28\mathrm{Im}\left(\kappa_{cd}^{\mathrm{R}*}\kappa_{cs}^{\mathrm{R}}\right)\right| \le 8.5\times10^{-4}$$

* A complementary constraint on the couplings can be obtained from the CP-violation parameter ϵ.
* Its magnitude is related to M_{12}^K by

$$|\epsilon| \simeq \frac{\left|\mathrm{Im}\, M_{12}^K\right|}{\sqrt{2}\,\Delta M_K^{\mathrm{exp}}}\,, \qquad \Delta M_K^{\mathrm{exp}} = (3.483\pm0.006)\times10^{-15}\,\mathrm{GeV}$$

* Since $|\epsilon|_{\mathrm{exp}} = (2.229\pm0.012)\times10^{-3}$ and $|\epsilon|_{\mathrm{SM}} = \left(2.06^{+0.47}_{-0.53}\right)\times10^{-3}$, we demand $|\epsilon|_\kappa < 0.7\times10^{-3}$, leading to

$$\left|0.015\mathrm{Re}\left(\kappa_{cs}^{\mathrm{L}}+\kappa_{cd}^{\mathrm{L}}\right)+0.043\mathrm{Im}\left(\kappa_{cs}^{\mathrm{L}}-\kappa_{cd}^{\mathrm{L}}\right)-0.28\mathrm{Re}\left(\kappa_{cd}^{\mathrm{R}*}\kappa_{cs}^{\mathrm{R}}\right)-\mathrm{Im}\left(\kappa_{cd}^{\mathrm{R}*}\kappa_{cs}^{\mathrm{R}}\right)\right| \le 2.5\times10^{-6}$$

B_d-$\bar{B}_d$ mixing

* The SM mixing matrix element M_{12}^d is dominated by the top loop

$$M_{12}^{d,\mathrm{SM}} \simeq \frac{G_{\mathrm{F}}^2\, m_W^2}{12\pi^2}\, f_{B_d}^2 m_{B_d}\, \eta_B B_{B_d}\, \left(V_{tb}V_{td}^*\right)^2 S_0\left(x_t\right)$$

* In contrast, the anomalous couplings of charm and top may produce similar effects on M_{12}^d.
* The anomalous top contributions having been studied before, we switch them off and get to $\mathcal{O}(\kappa)$

$$M_{12}^{d,\kappa} = \frac{G_{\mathrm{F}}^2 m_W^2}{24\pi^2}\, f_{B_d}^2 m_{B_d} \eta_B B_{B_d} \lambda_c^{db}\left(\kappa_{cb}^{\mathrm{L}} + \kappa_{cd}^{\mathrm{L}*}\right)\left(-\lambda_t^{db}\, x_t\, \ln\frac{\Lambda^2}{m_W^2} - \sum_q \lambda_q^{db}\, \mathcal{B}_1\left(x_q, x_c\right)\right)$$

$\lambda_q^{db} = V_{qd}^* V_{qb}$

* The heavy-light mass difference $\Delta M_d = M_H - M_L = 2\left|M_{12}^d\right|$, $M_{12}^d = M_{12}^{d,\mathrm{SM}} + M_{12}^{d,\kappa}$
* The measured value $\Delta M_d^{\mathrm{exp}} = (0.507 \pm 0.005)\,\mathrm{ps}^{-1}$ agrees with the SM prediction $\Delta M_d^{\mathrm{SM}} = \left(0.563_{-0.076}^{+0.068}\right)\mathrm{ps}^{-1}$

B_d-$\bar{B}_d$ mixing

* In the presence of the anomalous couplings

$$\Delta M_d^{\rm exp} = \Delta M_d^{\rm SM} \left|1+\delta_d\right| , \qquad \delta_d = \frac{M_{12}^{d,\kappa}}{M_{12}^{d,\rm SM}}$$

* We can then impose $-0.2 \le {\rm Re}\,\delta_d \le +0.02,$ leading to

$$-0.031 \le {\rm Re}\big(\kappa_{cb}^{\rm L}+\kappa_{cd}^{\rm L}\big) + 0.4\,{\rm Im}\big(\kappa_{cb}^{\rm L}-\kappa_{cd}^{\rm L}\big) \le 0.003$$

* An additional constraint can be extracted from the β measurement in $B \to J/\psi K$.
* The anomalous couplings enter $\beta^{\rm eff}$ via both the mixing and decay amplitudes.

$$\frac{q_{B_d}}{p_{B_d}} \simeq \sqrt{\frac{M_{12}^{d,{\rm SM}*}\big(1+\delta_d^*\big)}{M_{12}^{d,\rm SM}\big(1+\delta_d\big)}} \simeq \frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}}\, e^{-i\,{\rm Im}\,\delta_d}$$

* From the decay amplitude

$$\frac{\mathcal{M}\big(\bar{B}^0\to\psi K_S\big)}{\mathcal{M}\big(B^0\to\psi K_S\big)} = -\frac{V_{cd}^*V_{cb}\big(1+\kappa_{cs}^{\rm L*}+\kappa_{cb}^{\rm L}\big)}{V_{cd}V_{cb}^*\big(1+\kappa_{cs}^{\rm L}+\kappa_{cb}^{\rm L*}\big)} \simeq -\frac{V_{cd}^*V_{cb}}{V_{cd}V_{cb}^*}\big[1+2i\,{\rm Im}\big(\kappa_{cb}^{\rm L}-\kappa_{cs}^{\rm L}\big)\big]$$

B_d-$\bar{B}_d$ mixing

* It follows that

$$e^{-2i\beta_{\psi K}^{\rm eff}} = \frac{q_{B_d}}{p_{B_d}} \frac{\mathcal{M}\big(\bar{B}^0 \to \psi K_S\big)}{\mathcal{M}\big(B^0 \to \psi K_S\big)} \simeq e^{-2i\beta^{\rm SM}}\, e^{2i\,{\rm Im}(\kappa_{cb}^{\rm L}-\kappa_{cs}^{\rm L})-i\,{\rm Im}\,\delta_d}$$

* The experimental value $2\beta^{\rm eff} = 2\beta_{\psi K}^{\rm eff} = 0.717 \pm 0.033$ agrees with the SM prediction $2\beta^{\rm SM} = 0.753^{+0.032}_{-0.028}$.
* We then require $-0.01 \le 2\,{\rm Im}(\kappa_{cb}^{\rm L} - \kappa_{cs}^{\rm L}) - {\rm Im}\,\delta_d \le 0.08$, implying

$$-1.5\times 10^{-3} \le 0.4\,{\rm Re}\big(\kappa_{cb}^{\rm L} + \kappa_{cd}^{\rm L}\big) - 0.69\,{\rm Im}\,\kappa_{cb}^{\rm L} + {\rm Im}\,\kappa_{cd}^{\rm L} - 0.31\,{\rm Im}\,\kappa_{cs}^{\rm L} \le 0.012\ .$$

B_s-$\bar{B}_s$ mixing

* Constraint from ΔM_s

$$-0.014 \le \mathrm{Re}\big(\kappa^{\rm L}_{cs} + \kappa^{\rm L}_{cb}\big) + 0.018\,\mathrm{Im}\big(\kappa^{\rm L}_{cs} - \kappa^{\rm L}_{cb}\big) \le 0.015$$

* Additional constraint from β_s in $B_s \to J\psi\phi$ decay

$$-0.09 \le 0.026\,\mathrm{Re}\big(\kappa^{\rm L}_{cb} + \kappa^{\rm L}_{cs}\big) + \mathrm{Im}\big(\kappa^{\rm L}_{cb} - \kappa^{\rm L}_{cs}\big) \le 7 \times 10^{-4}$$

Constraints from dipole penguin operators

* Electromagnetic and chromomagnetic dipole operators describing $d \to d'\gamma$ and $d \to d'g$ are generated at one loop with W and up-type quark in the loop.
  - New-physics effects are known to give rise to potentially large corrections to SM contribution.

* Constraints on the κ's can be obtained from
  - $b \to s\gamma$
  - $s \to d\gamma$
  - $s \to dg$ contribution to CP-violation parameters ϵ and ϵ' in the kaon sector and $A_{\Lambda\Xi}$ in hyperon nonleptonic decays

* The corresponding flavor-conserving contributions to the electric dipole moment of the neutron also provide constraints on some of the κ's.

Summary of constraints

Process	Constraint
$D \to \ell\nu$	$\left\|\mathrm{Re}(\kappa^{\mathrm{L}}_{cd} - \kappa^{\mathrm{R}}_{cd})\right\| \leq 0.04$
$D_s \to \ell\nu$	$0 \leq \mathrm{Re}(\kappa^{\mathrm{L}}_{cs} - \kappa^{\mathrm{R}}_{cs}) \leq 0.1$
$b \to c\ell\bar{\nu}$	$-0.13 \leq \mathrm{Re}\,\kappa^{\mathrm{R}}_{cb} \leq 0$
$B \to \psi K, \eta_c K$	$-5 \times 10^{-4} \leq \mathrm{Im}(\kappa^{\mathrm{R}}_{cb} + \kappa^{\mathrm{R}}_{cs}) \leq 0.04$
$K^+ \to \pi^+\nu\bar{\nu}$	$-2.5 \times 10^{-4} \leq -\mathrm{Re}(\kappa^{\mathrm{L}}_{cd} + \kappa^{\mathrm{L}}_{cs}) + 0.42\,\mathrm{Im}(\kappa^{\mathrm{L}}_{cd} - \kappa^{\mathrm{L}}_{cs}) \leq 1.3 \times 10^{-3}$
$K_L \to \mu^+\mu^-$	$\left\|\mathrm{Re}(\kappa^{\mathrm{L}}_{cs} + \kappa^{\mathrm{L}}_{cd}) + 6 \times 10^{-4}\,\mathrm{Im}(\kappa^{\mathrm{L}}_{cs} - \kappa^{\mathrm{L}}_{cd})\right\| \leq 1.5 \times 10^{-4}$
ΔM_K	$\left\|0.043\mathrm{Re}(\kappa^{\mathrm{L}}_{cd} + \kappa^{\mathrm{L}}_{cs}) + 0.015\mathrm{Im}(\kappa^{\mathrm{L}}_{cd} - \kappa^{\mathrm{L}}_{cs}) - \mathrm{Re}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs}) + 0.28\mathrm{Im}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs})\right\| \leq 8.5 \times 10^{-4}$
ϵ (mixing)	$\left\|0.015\mathrm{Re}(\kappa^{\mathrm{L}}_{cs} + \kappa^{\mathrm{L}}_{cd}) + 0.043\mathrm{Im}(\kappa^{\mathrm{L}}_{cs} - \kappa^{\mathrm{L}}_{cd}) - 0.28\mathrm{Re}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs}) - \mathrm{Im}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs})\right\| \leq 2.5 \times 10^{-6}$
ΔM_d	$-0.031 \leq \mathrm{Re}(\kappa^{\mathrm{L}}_{cb} + \kappa^{\mathrm{L}}_{cd}) + 0.4\,\mathrm{Im}(\kappa^{\mathrm{L}}_{cb} - \kappa^{\mathrm{L}}_{cd}) \leq 0.003$
$\sin(2\beta)$	$-1.5 \times 10^{-3} \leq 0.4\,\mathrm{Re}(\kappa^{\mathrm{L}}_{cb} + \kappa^{\mathrm{L}}_{cd}) - 0.69\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cb} + \mathrm{Im}\,\kappa^{\mathrm{L}}_{cd} - 0.31\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs} \leq 0.012$
ΔM_s	$-0.014 \leq \mathrm{Re}(\kappa^{\mathrm{L}}_{cs} + \kappa^{\mathrm{L}}_{cb}) + 0.018\,\mathrm{Im}(\kappa^{\mathrm{L}}_{cs} - \kappa^{\mathrm{L}}_{cb}) \leq 0.015$
$\sin(2\beta_s)$	$-0.09 \leq 0.026\,\mathrm{Re}(\kappa^{\mathrm{L}}_{cb} + \kappa^{\mathrm{L}}_{cs}) + \mathrm{Im}(\kappa^{\mathrm{L}}_{cb} - \kappa^{\mathrm{L}}_{cs}) \leq 7 \times 10^{-4}$

Constraint on each anomalous charm coupling

- * Constraints extracted by taking only one anomalous coupling at a time to be non-zero.

$-1.5\times10^{-4}\le \mathrm{Re}\,\kappa^{\rm L}_{cd} \le 1.5\times10^{-4}$	$-6\times10^{-5}\le \mathrm{Im}\,\kappa^{\rm L}_{cd} \le 6\times10^{-5}$
$-1.5\times10^{-4}\le \mathrm{Re}\,\kappa^{\rm L}_{cs} \le 1.5\times10^{-4}$	$-6\times10^{-5}\le \mathrm{Im}\,\kappa^{\rm L}_{cs} \le 6\times10^{-5}$
$-4\times10^{-3}\le \mathrm{Re}\,\kappa^{\rm L}_{cb} \le 3\times10^{-3}$	$-0.02\le \mathrm{Im}\,\kappa^{\rm L}_{cb} \le 7\times10^{-4}$
$-0.04\le \mathrm{Re}\,\kappa^{\rm R}_{cd} \le 0.04$	$-2\times10^{-3}\le \mathrm{Im}\,\kappa^{\rm R}_{cd} \le 2\times10^{-3}$
$-0.1\le \mathrm{Re}\,\kappa^{\rm R}_{cs} \le 0$	$-5\times10^{-4}\le \mathrm{Im}\,\kappa^{\rm R}_{cs} \le 2\times10^{-3}$
$-0.13\le \mathrm{Re}\,\kappa^{\rm R}_{cb} \le 0$	$-5\times10^{-4}\le \mathrm{Im}\,\kappa^{\rm R}_{cb} \le 0.04$

- * The left-handed couplings are much more constrained than the right-handed one.
- * The imaginary part of the couplings is more tightly constrained than the corresponding real part.
- * The largest deviations allowed by current data appear in the real part of the right-handed couplings, which can be as large as 10% of the corresponding SM couplings.

Guide for future measurements

* This study can serve as a guide as to which future measurements provide the most sensitive tests for new physics that can be parameterized with anomalous charm-W couplings.

* For the CP-violating, imaginary parts of the couplings, the electric dipole moment of the neutron and the hyperon asymmetry $A_{\Xi\Lambda}$ are the most promising channels to probe for right-handed couplings.

* To probe CP-violating left-handed couplings, more precise measurements of $\sin(2\beta)$ and $\sin(2\beta_s)$ are desirable.

* Constraints on the real parts of the right-handed couplings can be improved with better measurements of semileptonic B and D decays.

Conclusions

* We have explored the phenomenological consequences of anomalous W-boson couplings to the charm quark in a comprehensive way.

* The resulting constraints on the anomalous charm couplings are, perhaps surprisingly, comparable or tighter than existing constraints on anomalous W-boson couplings to the top quark.

* Our study also points out which future measurements can provide the most sensitive tests for new physics that can be parameterized with anomalous charm-W couplings.