Probing New Physics in Charm Couplings with Kaon and Other Hadron Processes

Jusak Tandean

National Taiwan University

in collaboration with

XG He & G Valencia

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Outline of talk

* **Introduction**
* **Kaon processes**
* **Other hadron 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.
    - Physics beyond the SM is expected to be detected in the near future.
* 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

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

  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.

Loop-induced processes

* The anomalous quark-W couplings 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.
* Numerically, 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 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 $\ln(\mu/m_W)$.
    - We set $\mu = \Lambda = 1\,\text{TeV}$ for definiteness.
* We also keep in our estimates those finite terms corresponding 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 using 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,

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

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

Effective Hamiltonians induced by κ's

* From the box diagrams

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

$d' \neq d$, 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

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

* 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

Buras et al.
Mescia & Smith
Brod & Gorbahn

$$\mathcal{B}_{\rm SM}(K^+ \to \pi^+\nu\bar{\nu}) = (8.5 \pm 0.7)\times 10^{-11}$$

* Its experimental value $\mathcal{B}_{\rm exp} = \big(1.73^{+1.15}_{-1.05}\big)\times 10^{-10}$ Artamonov et al.

* 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

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

- The total SD amplitude

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

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

- The measured $\mathcal{B}\big(K_L \to \mu^+\mu^-\big) = (6.84 \pm 0.11)\times 10^{-9}$ PDG
is almost saturated by the absorptive part of the long-distance contribution,
$\mathcal{B}_{\rm abs} = (6.64 \pm 0.07)\times 10^{-9}$. Littenberg & Valencia
- The allowed room for new physics, $\mathcal{B}_{\rm NP} \lesssim 3.8\times 10^{-10}$, has an upper bound
$\sim \frac{1}{2}$ the SD SM contribution, $\mathcal{B}_{\rm SM}^{\rm SD} = (7.9 \pm 1.2)\times 10^{-10}$. Gorbahn & Haisch
- 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

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

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

* The K_L-K_S mass difference $\Delta M_K = 2\,\mathrm{Re}\, M_{12}^K + \Delta M_K^{\mathrm{LD}}$ contains a sizable long-distance term, ΔM_K^{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,

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

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

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

* Measurements yield $|\epsilon|_{\mathrm{exp}} = (2.229\pm0.012)\times10^{-3}$ PDG
* The SM predicts $|\epsilon|_{\mathrm{SM}} = \left(2.06^{+0.47}_{-0.53}\right)\times10^{-3}$ CKMfitter
* We thus demand $|\epsilon|_\kappa < 0.7\times10^{-3}$, leading to

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

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.

$B_{d,s}$ processes

* B_d-$\bar{B}_d$ mixing

* CP-violation parameter β in $B_d \to J/\psi K_S$
  - κ terms in both mixing & decay amplitudes.

* B_s-$\bar{B}_s$ mixing

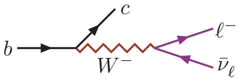
* CP-violation parameter β_s in $B_s \to J/\psi\phi$
  - κ terms in both mixing & decay amplitudes

Tree-level processes

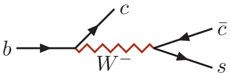
* Anomalous charm-W couplings affect some transitions at tree level.

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

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



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



* Decay constants f_D and f_{D_s} in $D \to \ell\nu$ & $D_s \to \ell\nu$.
* Exclusive & inclusive $b \to c\ell^- \bar{\nu}_\ell$ decays.
* Difference in $\sin\beta$ values from $B_d \to J/\psi K$ and $B_s \to \eta_c K$.

Summary of constraints

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

Constraint on each anomalous charm coupling

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

$0 \le \mathrm{Re}\,\kappa_{cd}^{\rm L} \le 1.5 \times 10^{-4}$	$(\mathrm{Im}\,\kappa_{cd}^{\rm L} = 0)$
$0 \le \mathrm{Re}\,\kappa_{cs}^{\rm L} \le 1.5 \times 10^{-4}$	$-6 \times 10^{-5} \le \mathrm{Im}\,\kappa_{cs}^{\rm L} \le 6 \times 10^{-5}$
$-4 \times 10^{-3} \le \mathrm{Re}\,\kappa_{cb}^{\rm L} \le 3 \times 10^{-3}$	$-0.02 \le \mathrm{Im}\,\kappa_{cb}^{\rm L} \le 7 \times 10^{-4}$
$-0.04 \le \mathrm{Re}\,\kappa_{cd}^{\rm R} \le 0.04$	$-2 \times 10^{-3} \le \mathrm{Im}\,\kappa_{cd}^{\rm R} \le 2 \times 10^{-3}$
$-0.1 \le \mathrm{Re}\,\kappa_{cs}^{\rm R} \le 0$	$-5 \times 10^{-4} \le \mathrm{Im}\,\kappa_{cs}^{\rm R} \le 2 \times 10^{-3}$
$-0.13 \le \mathrm{Re}\,\kappa_{cb}^{\rm R} \le 0$	$-5 \times 10^{-4} \le \mathrm{Im}\,\kappa_{cb}^{\rm R} \le 0.04$

Only 2 relative phases among the 3 left-handed charm-W couplings are physical and accordingly $\phi_{cd}^{\rm L}=0$ is chosen.

* 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.

Conclusions

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

* Kaon processes can be seen to have yielded some of the strongest bounds on the couplings.

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