Heavy New Physics in Rare K Decays

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Based on 1903.05116, 2104.10930, 2105.02868 work with F. Bishara, J. Brod, E. Stamou & U. Moldanazarova

For Section 2.11 [Brod, MG, Grossman, Stamou]
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This talk

- What can we learn from $K \to \pi$invisible
- SM prediction for $K \to \pi\nu\bar{\nu}$
- Classifying New Physics
- General one-loop formula

$K \to \pi + \text{invisibles}$ in the Standard Model

SM: $\nu\bar{\nu}$ are only invisibles ⇒ no γ-Penguin ⇒

$$\mathcal{H}_{\text{eff}} = \frac{\sqrt{2}\alpha G_F}{\pi \sin^2\theta_w} \sum_{\ell=e,\mu,\tau} (\lambda_c X^\ell + \lambda_t X_t)(\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{\ell L}\gamma^\mu \nu_{\ell L}) + \text{h.c.}$$

generated by highly virtual particles + tiny light quark contribution ⇒ clean & CKM suppressed ($\lambda_i = V_{is}^* V_{id}$).

- X_t known at NLO QCD and two-loop EW:
  $X_t = 1.462 \pm 0.017_{\text{QCD}} \pm 0.002_{\text{EW}}$
- $P_c = \lambda^{-4}(\frac{2}{3}X^e + \frac{1}{3}X^\tau)$ at NNLO QCD + NLO EW is
  $$P_c = \left(\frac{0.2255}{\lambda}\right)^4 \times (0.3604 \pm 0.0087)$$

$\lambda \simeq V_{us}$ and updated values from [2105.02868]

Branching Ratios in the Standard Model

$$K_{l3} \to \kappa_+ = \frac{s_w^{-2}\lambda^8\alpha(M_Z)^2}{7.5248\cdot 10^{-9}} \times 0.5173(25) \times 10^{-10} \text{ [Mescia, Smith]}$$

$$\mathrm{Br}_{K^+} = \kappa_+(1+\Delta_{\mathrm{EM}})\left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5}X_t\right)^2 + \left(\frac{\mathrm{Re}\lambda_c}{\lambda}\left(P_c + \delta P_{c,u}\right) + \frac{\mathrm{Re}\lambda_t}{\lambda^5}X_t\right)^2\right].$$

$$\mathrm{Br}_{K_L} = \kappa_L r_{\epsilon_K}\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5}X_t\right)^2, \quad \kappa_L = \frac{s_w^{-2}\lambda^8\alpha(M_Z)^2}{7.5248\cdot 10^{-9}} \times 2.231(13) \times 10^{-10}$$

Using PDG input, $\Delta_{\mathrm{EM}} = -0.003$, ind. CP viol. ($r_{\epsilon_K}$):

$$\begin{aligned} \mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) &= 7.73(16)(25)(54) \times 10^{-11}, \\ \mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) &= 2.59(6)(2)(28) \times 10^{-11}. \end{aligned}$$

Heavy New Physics

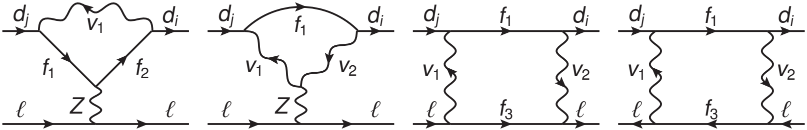
- Same light ($m \leq v_{ew}$) particle content (in draft)
  - Match onto $\Delta S = 1$ and $\Delta S = 2$ to find correlations in UV models
  - E.g. $K \to \pi\nu\bar{\nu}$, ΔM_K, ...
  - General one-loop result involves effects of symmetry breaking
  - In draft: Formulas for wide class of renormalisable models
- Extra light degrees of freedom also interesting (not in draft)

Theory Setup

Aim: 1-loop results for all renormalisable models:

$$\delta\mathcal{L}_{eff} \supset \frac{C^{sd\nu}_{\sigma\sigma'}}{16\pi^2}\left(\bar{s}\gamma^\mu P_\sigma d\right)\left(\bar{\nu}\gamma_\mu P_{\sigma'}\nu\right)+\frac{D^{sd}_{\sigma}}{16\pi^2}\left(\bar{s}\sigma^{\mu\nu}P_\sigma d\right)F_{\mu\nu}+\text{h.c.}\,.$$

and also $(\bar{s}\Gamma d)^2$



- How to calculate without specifying the theory
- Renorm. theory $\leftrightarrow$ Tree Unitarity [Cornwall et.al. 73/74]
- $0 = \sum_{v_5} g_{v_1 v_2 v_5} g_{v_3 v_4 \bar{v}_5} + g_{v_2 v_3 v_5} g_{v_1 v_4 \bar{v}_5} + g_{v_3 v_1 v_5} g_{v_2 v_4 \bar{v}_5}$
- Idea: Combine generic Lagrangian with sum rules
- [1903.05116] derives relevant sum rules

Generic Vector Interactions

$$\mathcal{L}_3^V = g^{L/R}_{v_1 \bar{f}_1 f_2} V_{v_1,\mu} \bar{\psi}_{f_1} \gamma^\mu P_{L/R} \psi_{f_2} + \frac{i}{6} g^{abc}_{v_1 v_2 v_3} \Big(V_{v_1,\mu} V_{v_2,\nu} \partial^{[\mu} V^{\nu]}_{v_3} + \dots \Big).$$

In SM, for $K \to \pi\nu\bar{\nu}$ we would need the following:

- $g^L_{W^+\bar{u}_j d_k} = \frac{e}{s_w\sqrt{2}} V_{jk}, \quad y^L_{G^+\bar{u}_j d_k} = \frac{m_{uj}}{M_W} \frac{e}{s_w\sqrt{2}} V_{jk}$
- $g^L_{Z\bar{f}_j f_k} = \frac{2e}{s_{2w}} \left(T_3^f - Q_f s_w^2 \right) \delta_{jk}, \quad g^R_{Z\bar{f}_j f_k} = -\frac{2e}{s_{2w}} Q_f s_w^2 \delta_{jk}$
- $g_{ZW^+W^-} = \frac{e}{t_w}, \; g_{ZW^+G^-} = -t_w^2 \frac{e}{t_w}, g_{ZG^+G^-} = \left(1 - \frac{1}{2c_W^2}\right) \frac{e}{t_w}$

Eliminate (product of) couplings using $s\langle T\{\bar{u}_v(\dots)_{\text{ph}}\}\rangle = 0$.
E.g. we can combine Z/γ-Penguin and Boxes using:

$$\sum_Z g^\sigma_{Z\bar{\ell}\ell} g_{Z v_2 \bar{v}_1} = -\delta_{\bar{v}_1 v_2} g^\sigma_{\gamma\bar{\ell}\ell} g_{\gamma v_2 \bar{v}_1} - \sum_{f_3} \left(g^\sigma_{\bar{v}_1 \bar{\ell} f_3} g^\sigma_{v_2 \bar{f}_3 \ell} - g^\sigma_{v_2 \bar{\ell} f_3} g^\sigma_{\bar{v}_1 \bar{f}_3 \ell} \right)$$

Gauge independent result for $K \to \pi\nu\bar{\nu}$

$$
\begin{aligned}
C_{L\sigma}^{sd\nu} = \sum_{v_1 v_2 f_1 f_3} & \frac{g^L_{\bar{v}_2 \bar{s} f_1} g^L_{v_1 \bar{f}_1 d}}{M_{v_1}^2} g^\sigma_{v_2 \bar{\nu} f_3} g^\sigma_{\bar{v}_1 \bar{f}_3 \nu} F_V^{\sigma, B'Z}(x_{v_1}^{f_0}, x_{v_1}^{f_1}, x_{v_2}^{v_1}, x_{v_1}^{f_3}) \\
+ \sum_{Z v_1 v_2 f_1 f_2} & \frac{g^\sigma_{Z\bar{\nu}\nu} g^L_{v_1 \bar{f}_1 d} g^L_{\bar{v}_2 \bar{s} f_2}}{M_Z^2} \Bigg\{ \delta_{f_1 f_2} g_{Z \bar{v}_1 v_2} F^Z_{V''}(x_{v_1}^{f_0}, x_{v_1}^{f_1}, x_{v_2}^{v_1}) \\
& + \delta_{v_1 v_2} \left[g^L_{Z \bar{f}_2 f_1} F_V^Z(x_{v_1}^{f_1}, x_{v_1}^{f_2}) + g^R_{Z \bar{f}_2 f_1} F^Z_{V'}(x_{v_1}^{f_1}, x_{v_1}^{f_2}) \right] \Bigg\},
\end{aligned}
$$

Extends the Penguin Box Coefficients to generic theories ($X_t \leftrightarrow F_V^{\sigma,B'Z}(0, x_W^t, 1, 0)$ & $F^Z_{V^{(\prime)}}(x, x) = F^Z_{V''}(x, y, 1) = 0$)

- Full results includes also scalars and fermion flow in opposite direction in 2104.10930 and on `https://wellput.github.io/`.

Summary

- Standard Model update for $K \to \pi\nu\bar{\nu}$
- Generic one-loop results
- Q1) "What we would learn, if the experiments do not find anything?"
  - If we only see the SM in all measurement?
  - Rephrase: If we see NP somewhere what can we learn from SM Rare K decays?
- Q2) "What would be a good target branching ratio for each signatures (such that null result is still interesting)?"
  - Theory at 3% accuracy. ...