Overview of Kaon Physics

Martin Gorbahn
(University of Liverpool)
Input from work with J. Brod, F. Bishara, E. Stamou
U. Moldanazarova 1911.06822, 2104.10930,
2105.02868

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Topics in Kaon Physics: A Personal Selection

- ▶ (Semi-)leptonic decays

- ▶ ϵ_K
- ▶ $K \to \pi \bar{\nu} \nu$
    - ▶ New Physics contributions
- ▶ Missing:
    - ▶ $\epsilon'/\epsilon \to$ Peter Boyle
    - ▶ Other rare decays ($K_{S/L} \to (\pi)\ell^+\ell^-$)
    - ▶ New physics invisible final states,
    - ▶ ΔM_K
    - ▶ . . .

(Semi-)leptonic Decays

- $K_{\ell 3}$ Observables: $K \to \pi \ell \bar{\nu}_\ell$
  - Input: $S_{ew} = 1.0232(3)$, $I_{K\ell}$ (Phase space), C_K (C.G.)

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3} C_K S_{ew} |V_{us}|^2 f_+^K(0)^2 I_{K\ell} (1 + \delta_{EM+SU(2)}^{K\ell})$$

- $K(\pi)_{\ell 2}$ Observables: $K(\pi) \to \ell \bar{\nu}_\ell$

$$\frac{\Gamma(K_{\ell 2(\gamma)}^{\pm})}{\Gamma(\pi_{\ell 2(\gamma)}^{\pm})} = \left| \frac{V_{us}}{V_{ud}} \right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi} \left(\frac{1 - m_\ell^2/m_K^2}{1 - m_\ell^2/m_\pi^2} \right)^2 (1 + \delta R_{K\pi})$$

Constraints

- FLAG webupdate 2020:

$\Gamma(K_{\ell 3}) \to |V_{us}| f_+(0) = 0.2165(4)$

$\dfrac{\Gamma(K_{\ell 2})}{\Gamma(\pi_{\ell 2})} \to \left| \dfrac{V_{us}}{V_{ud}} \right| \dfrac{f_{K^\pm}}{f_{\pi^\pm}} = 0.2760(4)$

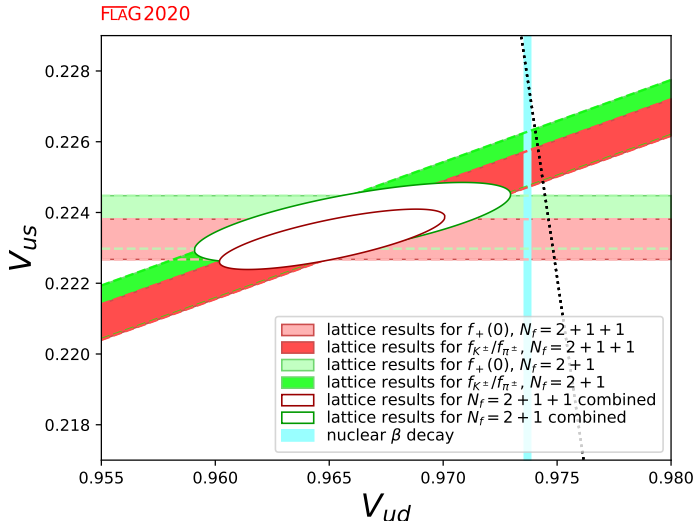 - First principle calculation $\delta R_{K\pi}$ = -0.0126(14) [1904.08731] in the isoQCD limit gives
  $\left| \dfrac{V_{us}}{V_{ud}} \right| \dfrac{f_K}{f_\pi} = 0.27683(35)$
    - They also include the QCD × QED running [hep-ph/0805.4119]

- In addition, we also have:
  - nuclear β decay: $|V_{ud}| = 0.97373(11)_{exp} (9)_{RC} (27)_{NS}$ (Hardy and Towner)
  - CKM unitarity $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

FLAG2020

V_{us} & V_{ud} using $\left|\dfrac{V_{us}}{V_{ud}}\right|\dfrac{f_{K^{\pm}}}{f_{\pi^{\pm}}} = 0.2760(4)$

Some recent work

- ▶ Using $\left|\dfrac{V_{us}}{V_{ud}}\right| \dfrac{f_{K^{\pm}}}{f_{\pi^{\pm}}} = 0.27683(35)$ and isoQCD parameters [2104.06747]:
  - ▶ $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99861(48)$, i.e. a $\simeq 3\,\sigma$ deviation from CKM unitarity
  - ▶ Lattice QED × QCD predictions result in several discrepancies in data 2012.02120.
- ▶ Determine χPT counterterms for $K_{\ell 3}$ from γ-W boxes on Lattice [2102.12048]
- ▶ Used in updated $|V_{ud}|$ and $|V_{us}/V_{ud}|$ determination [2107.14708]
  - ▶ results in an even larger deviation

$$\epsilon_K$$

CP violation in $K \to \pi\pi$

- Experimental definition using $\eta_{ij} = \dfrac{\langle \pi^i \pi^j | K_L \rangle}{\langle \pi^i \pi^j | K_S \rangle}$

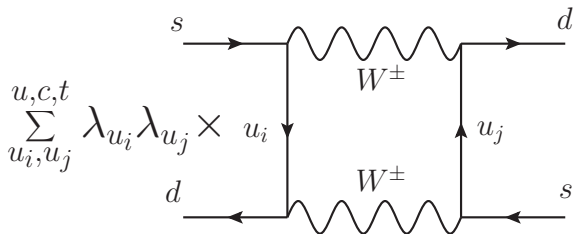$$\epsilon_K = (2\eta_{+-} + \eta_{00})/3 , \qquad \epsilon' = (\eta_{+-} - \eta_{00})/3$$

- ϵ_K theory expression $\epsilon_K \simeq \dfrac{\langle (\pi\pi)_{I=0} | K_L \rangle}{\langle (\pi\pi)_{I=0} | K_S \rangle} =$

$$e^{i\phi_\epsilon} \sin\phi_\epsilon \frac{1}{2} \arg\left(\frac{-M_{12}}{\Gamma_{12}}\right) = e^{i\phi_\epsilon} \sin\phi_\epsilon\left(\frac{\text{Im}(M_{12})^{Dis}}{\Delta M_K} + \xi\right)$$

$\langle K^0 | H^{|\Delta S|=2} | \bar{K}^0 \rangle \to \text{Im}(M_{12})^{Dis}$, $\frac{\text{Im}\langle(\pi\pi)_{I=0}|K^0\rangle}{\text{Re}\langle(\pi\pi)_{I=0}|K^0\rangle} \to \xi$ $\phi_\epsilon \equiv \arctan\frac{\Delta M_K}{\Delta\Gamma_K/2}$

- $\dfrac{2}{3} f_K^2 M_K^2 \hat{B}_K = \langle \bar{K}^0 | Q^{|\Delta S=2|} | K^0 \rangle u^{-1}(\mu_{\text{had}})$

- $Q_{S2} = (\bar{s}_L \gamma_\mu d_L) \otimes (\bar{s}_L \gamma^\mu d_L)$

Kaon Mixing: CKM Structure

$$\sum_{u_i,u_j}^{u,c,t} \lambda_{u_i}\lambda_{u_j} \times$$

	Im	Re	O
λ_t^2	$\sim \lambda^{10}$	$\sim \lambda^{10}$	m_t^2/M_W^2
$\lambda_c\,\lambda_t$	$\sim \lambda^6$	$\sim \lambda^6$	$m_c^2/M_W^2\,\ln(m_t/m_c)$
λ_c^2	$\sim \lambda^6$	$\sim \lambda^2$	m_c^2/M_W^2
$\lambda_u\,\lambda_t$	$\sim \lambda^6$	$\sim \lambda^6$	$m_c^2/M_W^2\,\ln(m_t/m_c)$
λ_u^2	0	$\sim \lambda^2$	m_c^2/M_W^2

Where $\lambda_i = V_{id}V_{is}^*$, $\lambda \equiv |V_{us}| \sim 0.2$ and we eliminated either: $\lambda_u = -\lambda_c - \lambda_t$ or $\lambda_c = -\lambda_u - \lambda_t$.

$\Delta S = 2$ Hamiltonian - Phase (In)Dependence

- ▶ Recall $\epsilon_K \propto \arg(-M_{12}/\Gamma_{12})$
- ▶ Trick: pull out λ_u^* and $(\lambda_u^*)^2$ from $H^{\Delta S=1}$ and $H^{\Delta S=2}$:
- ▶ Rephaseing invariant: $\lambda_i \lambda_j^* = V_{id} V_{is}^* V_{jd}^* V_{js}$
- ▶ $\Gamma_{12} \simeq A_0^* \bar{A}_0$ where $A_0 = \langle (\pi\pi)_{I=0} | K^0 \rangle$

$$\mathcal{H}_{f=3}^{\Delta S=2} = \frac{G_F^2 M_W^2}{4\pi^2 (\lambda_u^*)^2} Q_{S2} \left\{ f_1 C_1(\mu) + iJ \left[f_2 C_2(\mu) + f_3 C_3(\mu) \right] \right\} + \text{h.c.}$$

- ▶ $J = \mathrm{Im}(V_{us} V_{cb} V_{ub}^* V_{cs}^*)$, f_1, f_2 and f_3 are rephasing invariant
- ▶ Real part $f_1 = |\lambda_u|^4$ is unique
- ▶ Splitting of $f_2 = 2\mathrm{Re}(\lambda_t \lambda_u^*)$ and $f_3 = |\lambda_u|^2$ not, but expect good convergence for C_2 and C_3.

Traditional Form
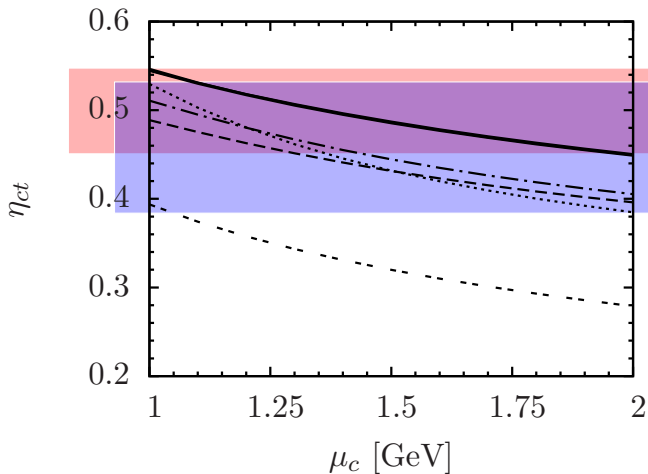
Traditionally the effective Hamiltonian is written as:

$$\mathcal{H}_{f=3}^{\Delta=2} = \frac{G_F^2 M_W^2}{4\pi^2}\Big[\lambda_c^2 C_{S2}^{cc}(\mu) + \lambda_t^2 C_{S2}^{tt}(\mu) + \lambda_c\lambda_t C_{S2}^{ct}(\mu)\Big]Q_{S2} + \text{h.c.}$$

where $f_2 = 2\text{Re}(\lambda_t\lambda_u^*)$, $f_3 = |\lambda_u|^2$ and, using PDG convention and CKM unitarity,

$$C_{S2}^{cc} \equiv C_1, \quad C_{S2}^{ct} \equiv 2C_1 - C_3, \quad C_{S2}^{tt} \equiv C_1 + C_2 - C_3$$

- A_{cu} denotes amplitude with internal charm and up
- $C_1 \leftarrow A_{uu} - 2A_{cu} + A_{cc}$ bad short distance behaviour
- C_1 determines ΔM_K via $\text{Re}M_{12}$
- But C_1 contributes to $\text{Im}M_{12}$ and hence ϵ_K

Residual scale dependence

- QCD corrections to $C_{S2}^{ct} \to \eta_{ct} = 0.497(47)$
- QCD corrections to $C_{S2}^{cc} \to \eta_{cc} = 1.87(76)$

ImM_{12} without ΔM_K pollution

▶ Using CKM unitarity and the PDG convention we can also write (as used in Lattice [Christ et.al.]):

$$\mathcal{H}_{f=3}^{\Delta=2} = \frac{G_F^2 M_W^2}{4\pi^2}\Big[\lambda_u^2 C_{S2}^{uu}(\mu) + \lambda_t^2 C_{S2}^{tt}(\mu) + \lambda_u\lambda_t C_{S2}^{ut}(\mu)\Big]Q_{S2} + \text{h.c.}$$
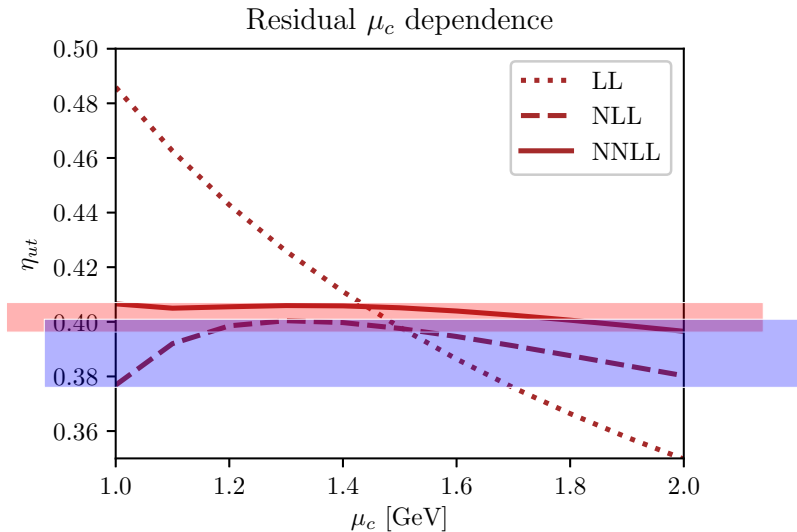
▶ Now real ReM_{12} and ImM_{12} are disentangled
$$C_{S2}^{uu} \equiv C_1, \quad C_{S2}^{tt} \equiv C_2, \quad C_{S2}^{ut} \equiv C_3$$

$$\begin{aligned}
C_3 &\leftarrow (A_{tu} - A_{tc} + A_{cc} - A_{cu}) \leftarrow \\
&\leftarrow (A_{uu} - 2A_{cu} + A_{cc}) - (A_{tc} - A_{tu} + A_{uu} - A_{cu})
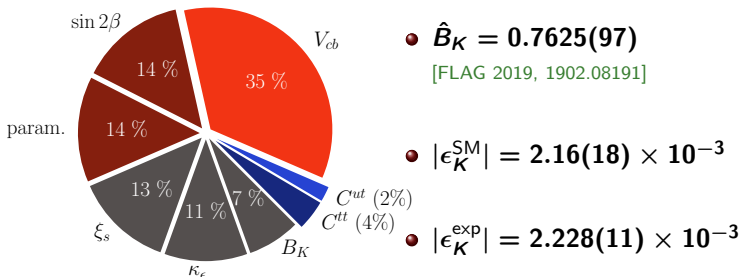\end{aligned}$$

▶ Extract anomalous dimensions and matching from old calculation and incorporate matching from η_{cc}

Residual scale dependence

Residual μ_c dependence

LL
NLL
NNLL

η_{ut}

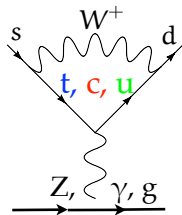μ_c [GeV]

SM prediction (1911.06822) using PDG input

$$|\epsilon_K| = \kappa_\epsilon C_\epsilon \widehat{B}_K |V_{cb}|^2 \lambda^2 \bar{\eta} \times \left[|V_{cb}|^2 (1 - \bar{\rho}) \eta_{tt}(x_t) - \eta_{ut}(x_c, x_t) \right]$$
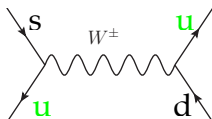

- $\widehat{B}_K = 0.7625(97)$
  [FLAG 2019, 1902.08191]

- $|\epsilon_K^{\mathsf{SM}}| = 2.16(18) \times 10^{-3}$

- $|\epsilon_K^{\mathsf{exp}}| = 2.228(11) \times 10^{-3}$

Pie chart labels: $\sin 2\beta$ 14 %, V_{cb} 35 %, param. 14 %, ξ_s 13 %, κ_ϵ 11 %, B_K 7 %, C^{ut} (2%), C^{tt} (4%)

▶ Improvements 2108.00017 2-loop EW, NNLO μ_t [Brod, Gorbahn, Stamou, Yu] and μ_{Lattice} [Gorbahn, Jager, Kvedaraitė] matching in progress. Lattice κ_ϵ

$$K \rightarrow \pi \, \bar{\nu} \, \nu$$

Rare Kaon Decays: CKM Structure

Using the GIM mechanism, we can eliminate either $V_{cs}^*V_{cd}$ or $V_{us}^*V_{ud} \to -V_{cs}^*V_{cd} - V_{ts}^*V_{td}$

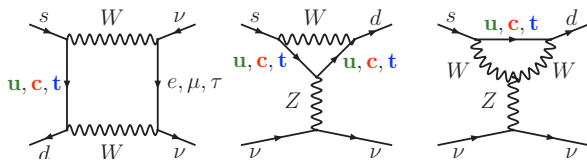Z-Penguin and Boxes (high virtuality): power expansion in: $A_c - A_u \propto 0 + O(m_c^2/M_W^2)$

γ/g-Penguin (expand in mom.): $A_c - A_u \propto O(\text{Log}(m_c^2/m_u^2))$

$$\text{Im}V_{ts}^*V_{td} = -\text{Im}V_{cs}^*V_{cd} = \mathcal{O}(\lambda^5) \qquad \text{Im}V_{us}^*V_{ud} = 0$$

$$\text{Re}V_{us}^*V_{ud} = -\text{Re}V_{cs}^*V_{cd} = \mathcal{O}(\lambda^1) \qquad \text{Re}V_{ts}^*V_{td} = \mathcal{O}(\lambda^5)$$

▶ $K \to \pi\bar{\nu}\nu$ (from Z & Boxes): Clean and suppressed

$K \to \pi \bar\nu \nu$ at M_W

$$\sum_i V_{is}^* V_{id} F(x_i) = V_{ts}^* V_{td}(F(x_t) - F(x_u)) + V_{cs}^* V_{cd}(F(x_c) - F(x_u))$$

$$x_i = \frac{m_i^2}{M_W^2}$$

Quadratic GIM: $\lambda^5 \dfrac{m_t^2}{M_W^2}$ $\lambda \dfrac{m_c^2}{M_W^2} \ln \dfrac{M_W}{m_c}$ $\lambda \dfrac{\Lambda_{QCD}^2}{M_W^2}$

Matching (NLO +EW):

Operator Mixing (RGE)   ChiPT & Lattice

$$Q_\nu = (\bar s_L \gamma_\mu d_L)(\bar\nu_L \gamma^\mu \nu_L)$$

- Below the charm: Only Q_ν, ME from K_{l3}
- semi-leptonic $(\bar s \gamma_\mu u_L)(\bar\nu \gamma^\mu \ell_L)$ operator: χ PT gives small contribution (10% of charm contribution)

Leading Effective Hamiltonian for $\mu < m_c$

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

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

generated by highly virtual particles + tiny light quark
contribution $\Rightarrow$ 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]

$K \to \pi\nu\bar{\nu}$ Branching Ratios

- ▶ Matrix elements from $K_{\ell 3}$ including strong and em iso-spin breaking [0705.2025] $\kappa_+, \kappa_L, \Delta_{EM}$

$\kappa_+ = \dfrac{s_w^{-2}\lambda^8\alpha(M_Z)^2}{7.5248 \cdot 10^{-9}} \times 0.5173(25) \times 10^{-10}$, $\Delta_{EM} = -0.003$

- ▶ indirect CP violation contribution given by r_{ϵ_K}

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

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

$K \to \pi \nu \bar{\nu}$ in the Standard Model

▶ 2105.02868 Standard Model Prediction

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

$$
\begin{aligned}
10^{11} \times \mathcal{B}_+ = 7.73 &\pm 0.12_{X_t^{QCD}} \pm 0.01_{X_t^{EW}} \pm 0.11_{P_c} \pm 0.24_{\delta P_{cu}} \pm 0.04_{\kappa_+} \\
&\pm 0.13_\lambda \pm 0.46_A \pm 0.18_{\bar{\rho}} \pm 0.03_{\bar{\eta}} \pm 0.05_{m_t} \pm 0.15_{m_c} \pm 0.05_{\alpha_s}\,.
\end{aligned}
$$

$$
\begin{aligned}
10^{11} \times \mathcal{B}_L = 2.59 &\pm 0.06_{X_t^{QCD}} \pm 0.01_{X_t^{EW}} \pm 0.02_{\kappa_L} \\
&\pm 0.16_{\bar{\eta}} \pm 0.22_A \pm 0.04_\lambda \pm 0.02_{m_t}
\end{aligned}
$$

▶ NA62 collaboration
  $\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+3.4}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$

▶ JPARC-KOTO has $\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) \leq 3.0 \times 10^{-9}$

New Physics

Heavy New Physics

$$\mathcal{H}_{\text{eff}} \supset \frac{C_{lq}^{(1),sd}}{(100\text{TeV})^2} \sum_{\ell=e,\mu,\tau} (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{\ell L} \gamma^\mu \nu_{\ell L}) + \text{h.c.}$$
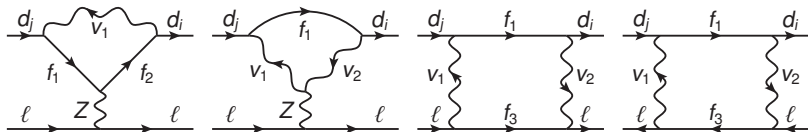
- ▶ Currently: $1/\sqrt{C_{lq}^{(1),sd}} \simeq 2$ in units of 100TeV @ 2σ

- ▶ 10% measurement: $1/\sqrt{C_{lq}^{(1),sd}} \simeq 4$ in units of 100TeV

- ▶ Same light ($m \leq v_{\text{ew}}$) particle content
    - ▶ 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

- ▶ Could be extended to extra light degrees of freedom

Theory Setup

Aim: 1-loop results for all renormalisable models:

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

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

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

Generic Vector Interactions

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

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

▶ $g_{W^+ \bar{u}_j d_k}^L = \dfrac{e}{s_w \sqrt{2}} V_{jk}$, $\quad y_{G^+ \bar{u}_j d_k}^L = \dfrac{m_{uj}}{M_W} \dfrac{e}{s_w \sqrt{2}} V_{jk}$

▶ $g_{Z\bar{f}_j f_k}^L = \dfrac{2e}{s_{2w}} \left(T_3^f - Q_f s_w^2 \right) \delta_{jk}$, $\quad g_{Z\bar{f}_j f_k}^R = -\dfrac{2e}{s_{2w}} Q_f s_w^2 \delta_{jk}$

▶ $g_{ZW^+ W^-} = \dfrac{e}{t_w}$, $g_{ZW^+ G^-} = -t_w^2 \dfrac{e}{t_w}$, $g_{ZG^+ G^-} = \left(1 - \dfrac{1}{2c_W^2} \right) \dfrac{e}{t_w}$

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

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

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

$$C_{L\sigma}^{sd\nu} = \sum_{v_1 v_2 f_1 f_3} \frac{g_{\bar{v}_2 \bar{s} f_1}^L g_{v_1 \bar{f}_1 d}^L}{M_{v_1}^2} g_{v_2 \bar{\nu} f_3}^\sigma g_{\bar{v}_1 \bar{f}_3 \nu}^\sigma F_V^{\sigma, B'Z}(x_{v_1}^{f_0}, x_{v_1}^{f_1}, x_{v_2}^{v_1}, x_{v_1}^{f_3})$$

$$+ \sum_{Z v_1 v_2 f_1 f_2} \frac{g_{Z\bar{\nu}\nu}^\sigma g_{v_1 \bar{f}_1 d}^L g_{\bar{v}_2 \bar{s} f_2}^L}{M_Z^2} \left\{ \delta_{f_1 f_2} g_{Z\bar{v}_1 v_2} F_{V''}^Z(x_{v_1}^{f_0}, x_{v_1}^{f_1}, x_{v_2}^{v_1}) \right.$$

$$\left. + \delta_{v_1 v_2} \left[g_{Z\bar{f}_2 f_1}^L F_V^Z(x_{v_1}^{f_1}, x_{v_1}^{f_2}) + g_{Z\bar{f}_2 f_1}^R F_{V'}^Z(x_{v_1}^{f_1}, x_{v_1}^{f_2}) \right] \right\},$$

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

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

Conclusions

- ▶ Tension in semi-leptonic data at the level of QED × QCD corrections.
- ▶ New formula for ϵ_K allows for better theory control.
- ▶ Measurement of $K \to \pi \bar{\nu} \nu$ can be compared with precise theory prediction.
- ▶ Suppression in the Standard Model gives high sensitivity to new physics.
- ▶ Generic one-loop results for realisable models of new physics available.