Perturbative Aspects or rare K and B decays

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Based on work with
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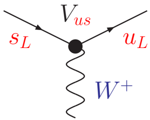
Content

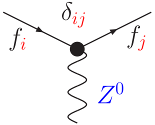
- Introduction
  - CKM Input, $K_{\ell\ 2,3}$, EFTs & Lattice
- $B_s \to \mu\mu$ and $B \to X_s \ell^+ \ell^-$
- $K \to \pi\bar{\nu}\nu$
- $K \to \mu\mu$
- ϵ_K & B_K
- Parametric uncertainties

Neutral & Charged Current Interactions

Mass $\neq$ flavour eigenstates



SM: Only charged currents change the flavour ($\propto V_{us}$)



SM: Neutral currents do not change the flavour (i=j) at tree-level

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho+i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- SM: Yukawas only source of flavour & CP violation
- CKM parametrises CP & flavour violation
- First row from tree-level semi-leptonic decays

Charged Current decays

- $\mathrm{K}_{\ell 2}$ and $\mathrm{K}_{\ell 3}$ extraction of $\lambda = |V_{us}|$

$$\Gamma(K^0 \to \pi^- \ell^+ \nu_\ell(\gamma)) = \frac{G_F^2 m_K^5}{128\pi^3} |V_{us}|^2 \; S_{EW} \; |f_+^{K^0\pi^-}(0)|^2 \; I_{K^0\ell}^{(0)} \left(1 + \delta_{EM}^{K^0\ell} + \delta_{SU(2)}^{K^0\pi^-}\right).$$

- QED: χPT [Seng et.al.'2019,Cirigliano et.al.'23] and Lattice [Carrasco et.al.'15,DiCarlo et.al.'19]

- EW corrections in W-Mass scheme [Marciano, Sirlin]

- EFT Approach [Gorbahn et.al.'22,Cirigliano et.al.'23]

- $|V_{ud}|$, extracted from nuclear β decays [Hardy,Towner'20],

- $\Delta_{CKM} \equiv 1 - |V_{ud}|^2 - |V_{us}|^2 - \mathcal{O}(|V_{ub}|^2) = 0.$

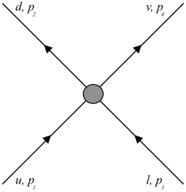
Effective Theory Calculation

- Decoupling Theorem (Renormalization [Collins]):

$$\langle \ell_3|T|K\rangle = 4G_F/\sqrt{2}C(\mu_W)\langle \ell_3|O|K\rangle(\mu_W) + \mathcal{O}(p_\ell^2/M_W^2)$$

- Determine $C(\mu_W)$ in perturbation theory
- Use RGE to run $\langle \ell_3|T|K\rangle =$ $4G_F/\sqrt{2}C(\mu_W)U(\mu_W,\mu_{Lat})\langle \ell_3|O|K\rangle(\mu_{Lat}) + \mathcal{O}(p_\ell^2/M_W^2)$
- Determine $\langle\ \ell_3 \mid \mathrm{O} \mid \mathrm{K}\ \rangle$ using symmetries and data or Lattice calculation
- Lattice: have to convert Lattice to continuum scheme
- Residual μ_W and μ_{Lat} dependence reduces at N^n LO

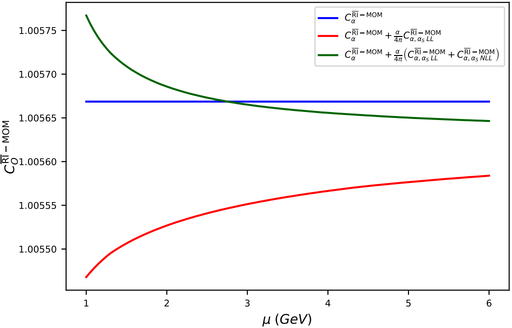
Lattice Renormalisation



- off-shell renormalisation conditions
  - $\mathrm{RI}^{(\prime)} - \mathrm{MOM}$: $p_1 = p_2 = p_3 = p_4 = p, \quad p^2 = -\mu^2$
  - $\mathrm{RI} - \mathrm{SMOM}$:
    $p_1 = p_3, \quad p_2 = p_4, \quad p_1^2 = p_2^2 = -\mu^2, \quad p_1 \cdot p_2 = -\frac{1}{2}\mu^2$
  - Choose projectors so that $Z_O = 0 + \mathcal{O}(\alpha)$ [2209.05289]

$\overline{RI}$ and $\overline{MS}$ Wilson coefficients

Including 2-loop EW matching and 3-loop RGE [MG, SJ, Moretti, EM]



For V_{ud} we have $C_O(m_c) = 1.00754$ [Cirigliano et.al.'23] $\longrightarrow$ $C_O(m_c) = 1.00794$

Rare b → s decays

- Up quark contribution CKM suppressed
- $V_{cb}^* V_{cs} \to -V_{tb}^* V_{ts} - \mathcal{O}(\lambda^4)$
- Only $V_{tb}^* V_{ts}$
- Operators:
  - $O_L = (\bar{s}\gamma_\nu b_L)(\bar{\mu}\gamma^\nu P_L \mu)$ generated at M_W
  - $O_V = (\bar{s}\gamma_\nu b_L)(\bar{\mu}\gamma^\nu \mu)$ generated at $\mathcal{O}(\alpha)$
- Pseudoscalar decay $B_s \to \mu^+\mu^-$ has $\langle O_V \rangle = \mathcal{O}(\alpha)$

$B_s \to \mu^+\mu^-$

- In the SM for $\alpha_{\text{QED}} = 0$ only one operator:
  - $\mathcal{L}_{\text{eff}} = V_{tb}V_{ts}^* G_F^2 M_W^2 \pi^{-2} \tilde{c}_{10} (\bar{s}\gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha\gamma_5\mu)$
  - ME: $\langle 0|\bar{s}\gamma_\alpha\gamma_5 b)|\bar{B}_s\rangle = if_{B_s} p_\alpha$
  - Scalar contribution suppressed; $\langle O_9\rangle = \mathcal{O}(\alpha/4\pi)$
- NNLO QCD and two-loop EW corrections @ M_W plus $\mathcal{O}(\alpha)\ln m_b/M_W$ [1311.0903,1311.1347,1311.1348]
  - Reduce perturbative uncertainties from 7% to 1%
  - Power enhanced non-local QED corrections [1708.09152] gives $+1 \times (1 - 0.2)$% (resum [1908.07011])
  - Factorisation theorem: RGI improved O_7 contribution [2211.04209]

Time integrated branching branching ratio

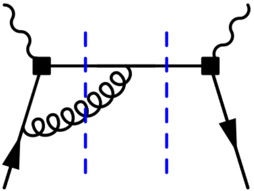
- Measured branching ratio in terms of time = 0 [1204.1737]: $\overline{\mathcal{B}}_{s\mu} = (1 - y_s)^{-1} \mathcal{B}_{s\mu}^{[t=0]]}$

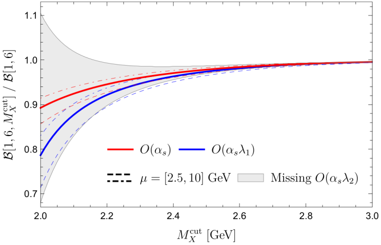
- $\overline{\mathcal{B}}_{s\mu} = (3.65 \pm 0.06) \times (1.008) \times \; R_{t\alpha} \, R_s \times 10^{-9}$ [1311.0903] including QED 0.8% effect [1908.07011]

- Input f_{B_s} (Lattice), CKM, $m_t^{\overline{MS}}$ and α_s:
  $$R_s = \left(\frac{f_{B_s}[\mathrm{MeV}]}{227.7} \right)^2 \left(\frac{|V_{cb}|}{0.0424} \right)^2 \left(\frac{|V_{tb}^{\star} V_{ts} / V_{cb}|}{0.980} \right)^2 \frac{\tau_H^s \, [\mathrm{ps}]}{1.615}$$
  $$R_{t\alpha} = (m_t / (163.5 \, \mathrm{GeV}))^{3.02} \; (\alpha_s(M_Z)/0.1184) \, \alpha^{0.032}$$

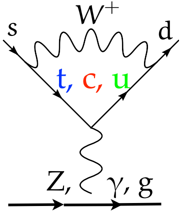
$b \to s\ell^+\ell^-$

- $\mathcal{L}_{eff} = 2\sqrt{2} G_F V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i Q_i$ for $\bar{B} \to K^{(*)}\mu^+\mu^-$ pheno
- Alternative test $\bar{B} \to X_s\mu^+\mu^-$
  - SD Lagrangian known at NNLO + (EW)
  - Updated SM predictions [2007.04191]
    $\mathcal{B}[1,6]^{SM}_{\mu\mu} = (1.73 \pm 0.13) \times 10^{-6}$
  - High q^2 analysis using C_L & C_V [2305.03076]
  - Dependence on M_X cut@NLO [2306.03134]

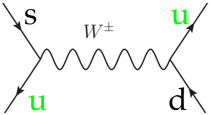




Rare Decays: CKM Structure (Kaons)



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



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.): $A_c - A_u \propto O(\mathrm{Log}(m_c^2/m_u^2))$

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

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

- $K \rightarrow \pi\bar{\nu}\nu$ (from Z & Boxes): Clean and suppressed
- $K \rightarrow \mu\mu$ pollution from two photon contribution

$$K \to \mu^+ \mu^-$$

$K \to \mu^+\mu^-$

SD: $Y_t + Y_{NNLO}$ from SM $\mathcal{L}_{eff}^{d=6}$ gives $\ell = 0$. $[\mathcal{O}(\lambda_t, \frac{m_c^2}{M_W^2}\lambda_c)]$

LD: from γ-γ loop is CP conserving: $\mathcal{O}(\frac{\alpha_{QED}}{4\pi})$

Setting ϵ_K to zero, K_L and K_S are CP eigenstates:

K_i^{CP}	BR_{exp}	$(\mu^+\mu^-)^-_{\ell=0}$	$(\mu^+\mu^-)^+_{\ell=1}$
$K_L^{(-)}$	$6.84(11) \times 10^{-9}$	$\lambda_t, \frac{m_c^2}{M_W^2}\lambda_c, \gamma$-$\gamma$	(~~CP~~) $\simeq 0$
$K_S^{(+)}$	$< 2.1 \times 10^{-10}$	~~CP~~: Im λ_t	γ-γ

ℓ is not experimentally accessible, but interference term in time dependent decay sensitive to *SD* [D'Ambrosio, Kitahara '17]

$K(t) \to \mu^+\mu^-$

$$\frac{d\Gamma}{dt} \propto C_L e^{-\Gamma_L} + C_S e^{-\Gamma_S} + 2[C_{sin}\sin(\Delta M t) + C_{cos}\cos(\Delta M t)]e^{-\Gamma t}$$

$$C_{sin/cos} = Im/Re\left\{(A_0^S)^* A_0^L + (A_1^S)^* A_1^L\right\}$$

$$\frac{BR(K_S \to \mu^+\mu^-)^{(pert)}_{\ell=0}}{BR(K_L \to \mu^+\mu^-)} = \frac{\tau_S}{\tau_L}\frac{|A_0^S A_0^L|^2}{|A_0^L|^4} = \frac{\tau_S}{\tau_L}\frac{C_{int}^2}{C_L^2}$$

where we assumed $A_1^L = 0$, $\epsilon_K = 0$

- Measurement of $BR(K_S \to \mu^+\mu^-)_{\ell=0}$ [Dery et.al.'21]

NNLO, EW and $\epsilon_K = 0$

Higher order corrections from $b \to s\ell^+\ell^-$ for 5 flavour

{NNLO QCD [Hermann et.al.'13]; 2-loop EW [Bobeth et.al.'13] RGE [Bobeth et.al.'03]}

$$BR(K_S \to \mu^+\mu^-)^{(pert)}_{\ell=0} = 1.70(02)_{QCD/EW}(01)_{f_K}(19)_{param.}\times 10^{-13}$$

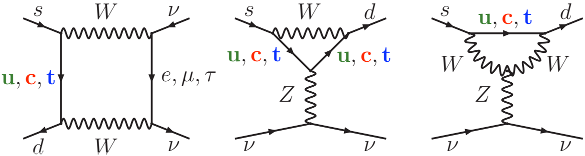
indirect CP violation mixes γ-γ: $A_0^S \to A_0^S + \epsilon_K A_0^L$

$$\frac{BR(K_S \to \mu^+\mu^-)_{\ell=0}}{BR(K_S \to \mu^+\mu^-)^{(pert)}_{\ell=0}} = 1 + \sqrt{2}|\epsilon_K \frac{|A_0^L|}{|A_0^S|}(\cos\phi_0 - \sin\phi_0)$$

[Brod, Stamou'22] and can shift by $\mathcal{O}(3\%)$, while ϕ_0 can be obtained from $K_L \to \mu^+\mu^-$ and $K_L \to \gamma\gamma$ [Dery et al.'22]

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

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



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

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

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

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 $\Rightarrow$

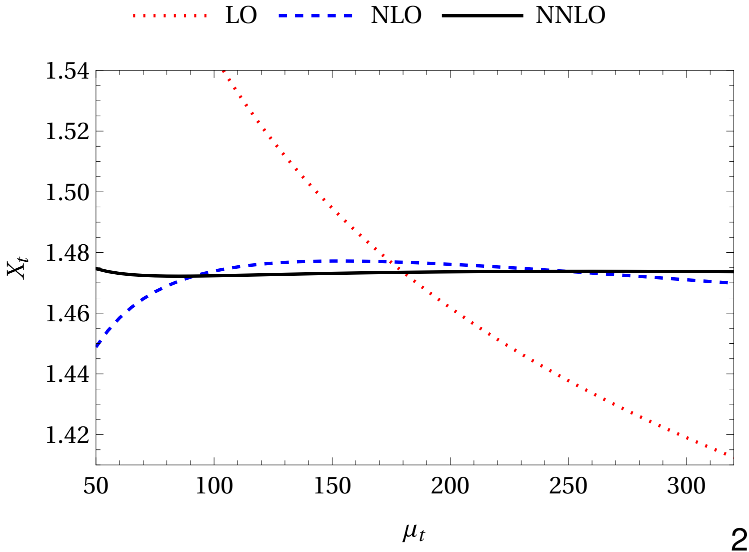
$$\mathcal{H}_{\text{eff}} = \frac{\sqrt{2}\alpha G_F}{\pi \sin^2\theta_w} \sum_{\ell=e,\mu,\tau} (\lambda_c X^\ell + \lambda_t X_t)(\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{\ell L}\gamma^\mu \nu_{\ell L}) + \text{h.c.}$$

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 [Buchalla,Buras;Misiak,Urban'99] and two-loop EW [Brod et.al.'10]:
  $X_t = 1.462 \pm 0.017_{\text{QCD}} \pm 0.002_{\text{EW}}$
- $P_c = (0.2255/\lambda)^4 \times (0.3604 \pm 0.0087)$ at NNLO QCD [Buras et.al.'05] + NLO EW [Brod et.al.'08]
  - χ PT matching logs: $\delta P_{c,u} = 0.04 \pm 0.02$ [Isidori et.al.'05]
  - Future Lattice: [Bai et.al.'18]

Scale Dependence @ NNLO

- Residual μ_t dependence estimates uncertainty
- Reduces from ±1% @NLO → ± 0.1% @NNLO



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

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

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

- indirect CP violation contribution given by r_{ϵ_K}

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

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

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

- 2105.02868 Standard Model Prediction
  $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = 7.73(16)_{SD}(25)_{LD}(54)_{para.} \times 10^{-11}$,
  $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = 2.59(6)_{SD}(2)_{LD}(28)_{para.} \times 10^{-11}$.
- Using 2022 PDG CKM fitter values
  $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = 8.25(11)_{SD}(25)_{LD}(57)_{para.} \times 10^{-11}$,
  $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = 2.83(1)_{SD}(2)_{LD}(30)_{para.} \times 10^{-11}$.
- V_{cb} dominates uncertainty: ϵ_K has similar $\mathrm{V_{cb}}$ dependence
- 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 $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) \le 2.0 \times 10^{-9}$

$$\epsilon_K$$

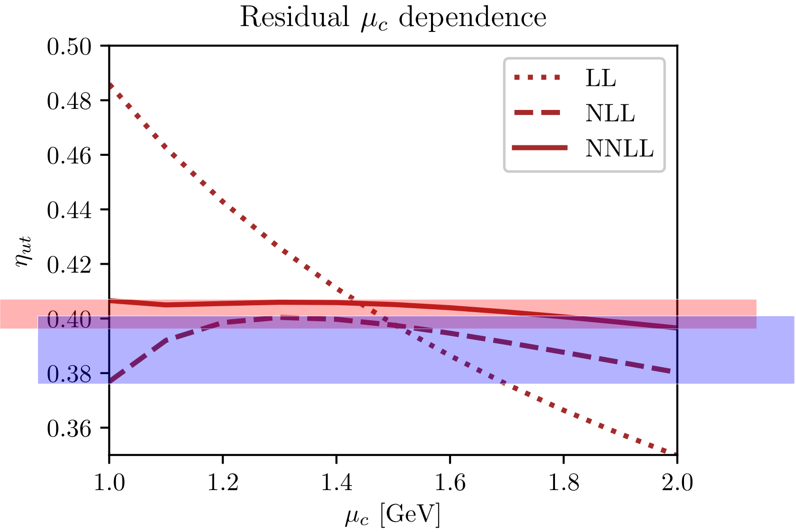
$\Delta S = 2$ Hamiltonian - Phase (In)Dependence

- Rephaseing invariant: $\lambda_i \lambda_j^* = V_{id} V_{is}^* V_{jd}^* V_{js}$
- One Operator: $Q_{S2} = (\bar{s}_L \gamma_\mu d_L) \otimes (\bar{s}_L \gamma^\mu d_L)$

$$\mathrm{H}_{f=3}^{\Delta S=2} = \frac{G_F^2 M_W^2}{4\pi^2 (\lambda_u^*)^2} Q_{S2} \Big\{ f_1 C_{S2}^{uu}(\mu) + iJ \Big[f_2 C_{S2}^{tt}(\mu) + f_3 C_{S2}^{ut}(\mu) \Big] \Big\} + \mathrm{h.c.}$$

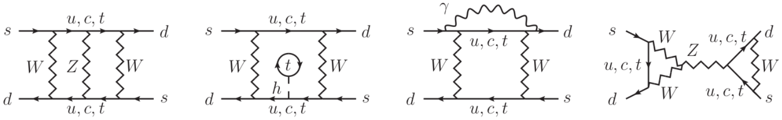
- $f_1 = |\lambda_u|^4$, $f_2 = 2\mathrm{Re}(\lambda_t \lambda_u^*)$ and $f_3 = |\lambda_u|^2$
- NNLO QCD corrections [Brod et.al.'10,Brod et.al.'11] to C_{S2}^{ut} absorbed into η_{ut} [Brod et.al.'19]
- C_{S2}^{uu} is purely SD, while C_{S2}^{uu} does not contribute

Residual scale dependence



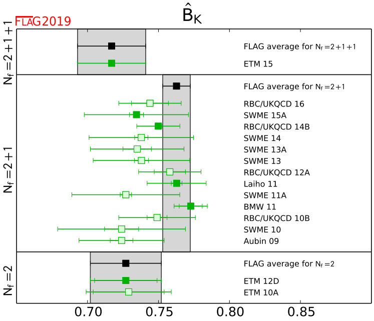
Further Improvements

- EW corrections to η_{tt} and η_{ut} [2207.07669,2108.00017]

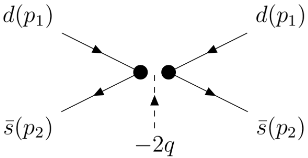


- LD effects can be calculated on the Lattice, but not at physical masses yet [2309.01193]
- $\hat{B}_K = \dfrac{3}{2f_K^2 M_K^2} \langle \bar{K}^0 | Q^{|\Delta S=2|} | K^0 \rangle u^{-1}(\mu_{\mathrm{had}})$ from Lattice

$\hat{B}_K$

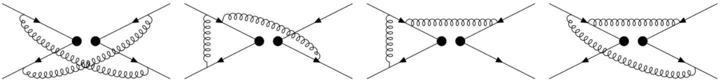


E.g. RBC UKQCD uses SMOM kinematics



- Define momentum-space subtraction schemes
- Projected renormalised Green's function $P_{(\gamma_\mu)}(\Lambda_R) \to$
- $Z_{Q_{S2}}^{(\gamma_\mu,\gamma_\mu)} = \left(Z_q^{(\gamma_\mu)}\right)^2 \dfrac{1}{P_{(\gamma_\mu)}(\Lambda_B)}$
- $Z_{Q_{S2}}^{(\gamma_\mu,\gamma_\mu)} / Z_{Q_{S2}}^{\overline{\mathrm{MS}}}$ converts between Lattice and continuum

SMOM $\hat{B}_K$ @ NNLO

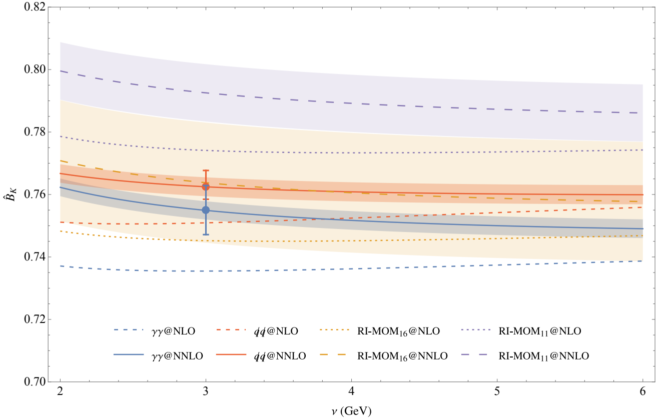


- Use projectors to find $\Lambda^{ijkl}_{\alpha\beta\gamma\delta}$ at 2-loops
- Integrals reduce to scalar off-shell 4-point functions
- The result should be independent of the matching scale

$$B_K^{(X,Y)}(|p|)C_{B_K}^{(X,Y)}(|p|,\mu)u^{-1}(\mu)u(\mu_0)$$

- study scale variation setting $\mu_0 = |p|$
- Compute $\hat{B}_K$ for f=3,4 for SMOM, RIMOM, RI'MOM

$\hat{B}_K$ at NNLO



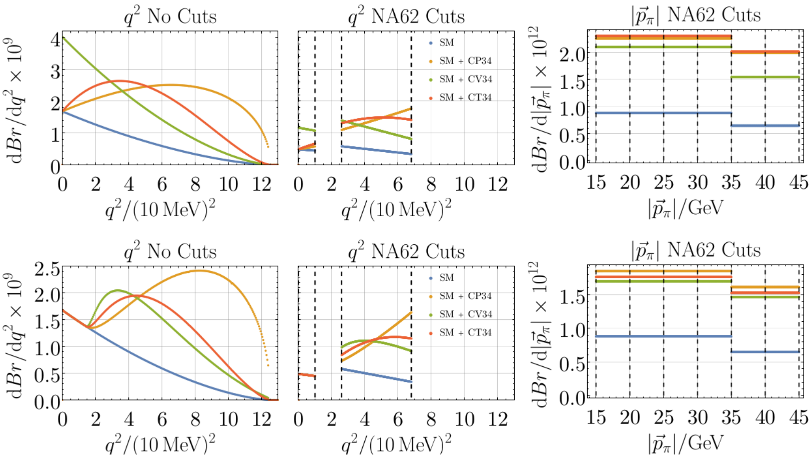
Numerics of NNLO result by [MG, Kvedaraitė, Jäger]

$K \to \pi\nu\bar{\nu}$ & ϵ_K

- $|\epsilon_K| = (2.170 \pm 0.065_{pt} \pm 0.076_{np} \pm 0.153_{par}) \times 10^{-3} = \kappa_\epsilon C_\epsilon \widehat{B}_K |V_{cb}|^2 \lambda^2 \bar{\eta} \times \left(|V_{cb}|^2 (1-\bar{\rho}) \eta_{tttt}(x_t) - \eta_{utut}(x_c, x_t) \right)$
- CKM factors of ϵ_K and $K \to \pi\nu\bar{\nu}$ are quite similar
  - In fact $BR(K \to \pi\nu\bar{\nu})/|\epsilon_K|^{0.82}$ is effectively V_{cb} independent [Buras, Venturini '21] for current theory calculations
- This provides an excellent null test of the Standard Model
- Multiplying with $|\epsilon_K|^{0.82}$ results in a model prediction for $BR(K \to \pi\nu\bar{\nu})$ with 5% uncertainty (albeit ignoring other constraints)

$K \to \pi$ + invisibles

- Sensitive to QCD Axion, Dark Photon ... [2201.07805]
- Neutrino properties, such as Majorana vs. Dirac or sterile allows different NP effects [Gorbahn, Moldanarazova, Sieja, Stamou, Tabet, W.I.P.]



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

- $b \to s\ell\ell$ for generic theories [2104.10930] restricted to $K \to \pi\nu\bar{\nu}$ with only vectors and fermions:

$$C_{L\sigma}^{sd\nu} = \sum_{v_1 v_2 f_1 f_3} \frac{g^L_{\bar{v}_2 \bar{s} f_1} g^L_{v_1 \bar{f}_1 d}}{M^2_{v_1}} g^{\sigma}_{v_2 \bar{\nu} f_3} g^{\sigma}_{\bar{v}_1 \bar{f}_3 \nu} F_V^{\sigma, B'Z}(x^{f_0}_{v_1}, x^{f_1}_{v_1}, x^{v_1}_{v_2}, x^{f_3}_{v_1})$$
$$+ \sum_{Z v_1 v_2 f_1 f_2} \frac{g^{\sigma}_{Z\bar{\nu}\nu} g^L_{v_1 \bar{f}_1 d} g^L_{\bar{v}_2 \bar{s} f_2}}{M_Z^2} \Big\{ \delta_{f_1 f_2} g_{Z \bar{v}_1 v_2} F^Z_{V''}(x^{f_0}_{v_1}, x^{f_1}_{v_1}, x^{v_1}_{v_2})$$
$$+ \delta_{v_1 v_2} \left[g^L_{Z\bar{f}_2 f_1} F^Z_V(x^{f_1}_{v_1}, x^{f_2}_{v_1}) + g^R_{Z\bar{f}_2 f_1} F^Z_{V'}(x^{f_1}_{v_1}, x^{f_2}_{v_1}) \right] \Big\},$$

Extends the Penguin Box Coefficients to generic theories ($X_t \leftrightarrow F_V^{\sigma, B'Z}(0, x^t_W, 1, 0)$ & $F^Z_{V^{(\prime)}}(x, x) = F^Z_{V''}(x, y, 1) = 0$)

Conclusions

- Precise theory predictions for rare B and particular K decays.
- Can form null tests of the SM with ϵ_K.
- NNLO calculations for electroweak and lattice-continuum matching will increase precision.
- Measurement of $K \to \pi \bar{\nu} \nu$ can be compared with precise theory prediction.
- Precision test of the standard model (EFT)
  - but also of different light degrees of freedom