Kaons
CP violation & rare decays

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Strangeness

$$K^+ \sim u\bar{s} \qquad K^- \sim \bar{u}s$$

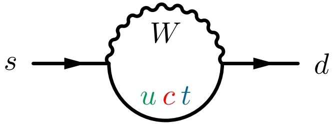
$$K^0 \sim d\bar{s} \qquad \overline{K}^0 \sim \bar{d}s$$

Differences to B physics

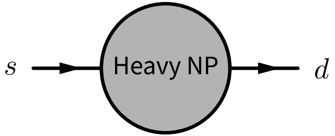
- Less phase-space ➜ less decays ✘
- Stronger CKM suppression of top contribution
  ➜ less SM background ✓
  Kaons: $\lambda^5 \sim 0.0005$ B mesons: $\lambda^3 \sim 0.01$
- Charm can *potentially* contribute ➜ care is needed!

Kaons: SM vs NP

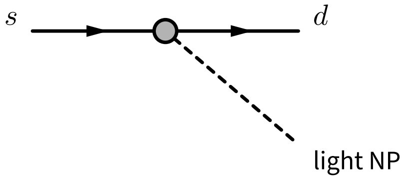
SM
loop induced, precision



Heavy NP
virtual, indirect probe
SUSY, Composite Higgs, Extra Dimensions, …



Light NP
decays to “invisible”
Axions, Dark Photons, …



K- vs B/D-physics probes of NP

- **Complementarity**
  comparison only possible within specific models/setup
  ➜ search in all sectors

- **Acquired theoretical control** in Kaon modes
  ➜ Large sensitivity to high-scale dynamics

- **Non-MFV models** / no-alignment of NP FV with SM FV
  ➜ typically Kaon constraints supersede B/D probes

  Even in models **with** alignment Kaons important

  ϵ_K "excludes" composite-Higgs models partial compositeness and anarchic Yukawas

Kaons in the era of the LHC

- **If** the LHC continues to reduce the parameter-space for TeV-scale NP
- the phenomenological **need** for flavour alignment is lifted
  (MFV, flavour symmetries, partial compositeness,…)

➜ "importance" of Kaon observables as probes of NP increases

There is a strong, ongoing and planned experimental program in place to take advantage of Kaon modes

[recent review of Kaon community: Goudzovski et al., 2201.07805]

- situation similar for probes of light NPs (e.g., the QCD axion)

Kaons and light-NP – example QCD Axion

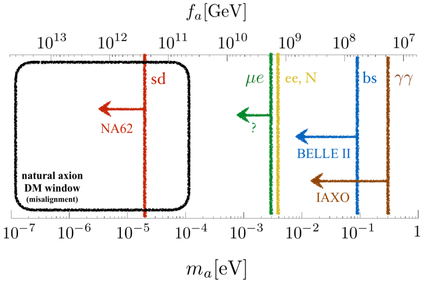
$$\Gamma_K^{\text{tot}} \sim M_K^5/M_W^4 \qquad\qquad \Gamma_B^{\text{tot}} \sim M_B^5/M_W^4$$

- Dimension-5 QCD axion couplings: $\frac{\partial^\mu a}{f_a}\,\bar{q}_i\gamma_\mu(\gamma_5)q_j$

$$\text{BR}(K \to \pi a) \propto \frac{M_W^4}{\boldsymbol{M_K^2} f_a^2}$$

$$\text{BR}(B \to \pi a) \propto \frac{M_W^4}{\boldsymbol{M_B^2} f_a^2}$$

➜ High sensitivity to light NP



(for $C_i = 1$)

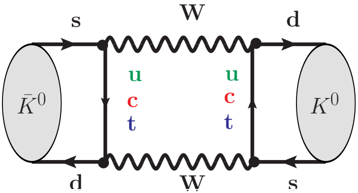
[from R. Ziegler @ La Thuille]

Observables

- **CP violation in $K - \overline{K}$ mixing**
  - ϵ_K: indirect CP violation
  - ϵ'/ϵ: direct CP violation (hadronic uncertainties ➜ lattice, not today)

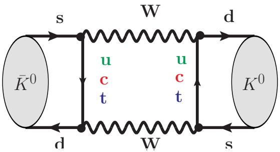
- **Rare FCNC decays**
  - $K \to \pi\nu\nu$ (the Kaon "golden" modes)
  - $K_S \to \mu^+\mu^-$ (NP sensitivity from time-dependent rates)
  - $K_L \to \pi^0\ell^+\ell^-$ (sensitivity to tensors [Mescia, Smith, Trine 06], not today)
  - non-FCNC decays, …

$K - \overline{K}$ mixing



Progress and future directions for ϵ_K

ϵ_K – disentagling long-distance charm contributions

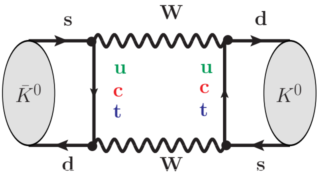


- among the most stringent constraints of BSM with new FV
  (feeds back into predictions of clean BSM-sensitive rare decays)
  ($K_L \to \pi\nu\nu$ [Buchalla, Buras 96;] $K_S \to \mu\mu$ [Brod, ES 23])

- **but** prediction had reached an **impasse**

  ϵ_K seemed to be plagued by non-perturbative uncertainties associated to charm impeding further progress

➜ **solution "simple"** (ct vs ut unitarity)
modifying CKM-unitarity relation used decouples charm in ϵ_K
➜ opens path to permille-level accuracy [Brod, Gorbahn, ES 19)]



$\lambda_i \equiv V_{id}V_{is}^*$ and $\lambda \sim 0.23$

Choice: Eliminate either λ_u or λ_c via different unitarity relations

		Im[...]	**Re[...]**	**order**
	$\boldsymbol{\lambda_t^2}$	λ^{10}	λ^{10}	m_t^2/M_W^2
"ct"	$\boldsymbol{\lambda_c\lambda_t}$	λ^6	λ^6	$m_c^2/M_W^2 \log(m_c/m_t)$
	$\boldsymbol{\lambda_c^2}$	λ^6	λ^2	m_c^2/M_W^2
"ut"	$\boldsymbol{\lambda_u\lambda_t}$	λ^6	λ^6	$m_c^2/M_W^2 \log(m_c/m_t)$
	$\boldsymbol{\lambda_u^2}$	$\mathbf{0}$	λ^2	m_c^2/M_W^2

$\lambda_u = -\lambda_t - \lambda_c$ ct-unitarity (old computation, 3 imaginary parts)

$\lambda_c = -\lambda_t - \lambda_u$ ut-unitarity (new computation, 2 imaginary parts)

“ct” VS **“ut”**

- **Beyond LO** different conditions correspond to a rearrangement/reshuffling of the perturbative expansion
(A priori it is **not clear** that results can be trivially translated into one another)

- It is always possible (phase-convention independent) to transparetly separate the long-distance charm contributions entering ΔM_K from ϵ_K

[Brod, Gorbahn, ES 19]

Phase-(in)dependent Hamiltonian

- Make convention-independence of ϵ_K explicit (**Trick:** factor out $1/(\lambda_u^*)^2$)

$$\boldsymbol{\mathcal{H}^{\Delta S=2} = \frac{G_F^2 M_W^2}{4\pi^2} \frac{1}{(\lambda_u^*)^2} Q_{S2} \Big\{ f_1\, \mathcal{C}_1 + iJ\, [f_2\, \mathcal{C}_2 + f_3\, \mathcal{C}_3] \Big\}} + \text{h.c.} + \ldots$$

[Brod, Gorbahn, ES 19]

- $\mathcal{C}_1, \mathcal{C}_2, \mathcal{C}_3$: real Wilson coefficients
- J, f_1, f_2, f_3 real, phase-convention invariant CKM structures
- Real part of $f_1 = |\lambda_u|^4$ is unique, splitting of f_2 and f_3 is not

➜ **One contribition to real part** $\propto \mathcal{C}_1$ (relevant for ΔM_K)

➜ **Only two independent imaginary pieces** $\propto J f_1$ **and** $J f_2$

(relevant for ϵ_K)

Uncertainty estimates – ϵ_K without ΔM_K pollution

“Old” / ct-unitarity

$$|\epsilon_K| \propto |V_{cb}|^2(1-\bar{\rho})\widehat{C}^{tt}_{\mathrm{S2}} + \widehat{C}^{ct}_{\mathrm{S2}} - \widehat{C}^{cc}_{\mathrm{S2}}$$

- Do we vary scales indepedently? ➜ large uncertainties

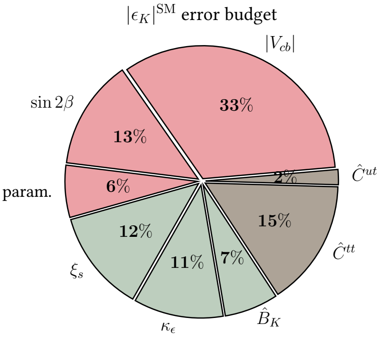
“New” / ut-unitarity

$$|\epsilon_K| \propto |V_{cb}|^2(1-\bar{\rho})\widehat{\mathscr{C}}^{tt}_{\mathrm{S2}} + \widehat{\mathscr{C}}^{ut}_{\mathrm{S2}}$$

- No ambiguity any more ➜ clean/clear uncertainty estimation

SM prediction of ϵ_K

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

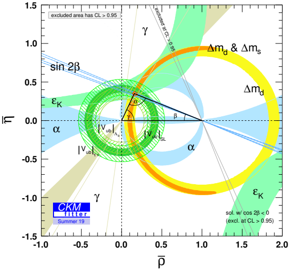


- $\hat{B}_K = 0.7625(97)$
  [FLAG19, 1902.08191]
- $\boldsymbol{\eta_{ut} = 0.402(5)}$
  [Brod, Gorbahn, ES 19]
- $|\epsilon_K|^{\mathsf{SM}} = 2.16(18) \times 10^{-3}$
- $|\epsilon_K|^{\mathsf{exp}} = 2.228(11) \times 10^{-3}$

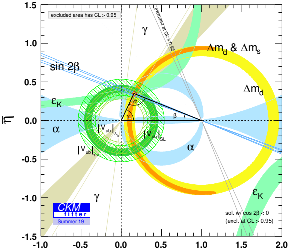
ϵ_K – disentagling charm contributions

– reshuffling the perturbative expansion ➜ϵ_K without ΔM_K pollution
– opens path to permille level precision

before



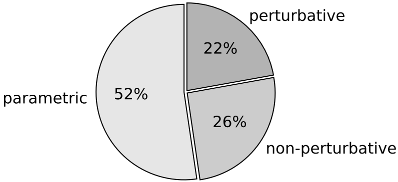
after



$$|\epsilon_K|^{\text{exp}} = 2.228(11)\times 10^{-3}$$
$$|\epsilon_K|^{\text{SM}} = 2.16(18)\times 10^{-3}$$

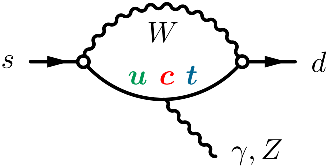
[Brod, Gorbahn, ES 19]

[top@NNLO-QCD in progress with Gorbahn, Yu also for B-$\bar{B}$ mixing]



Rare K decays

Rare K decays: CKM structure in SM



$$\mathrm{Re}(\boldsymbol{\lambda_u}) \sim \lambda \qquad \mathrm{Im}(\boldsymbol{\lambda_u}) = 0$$

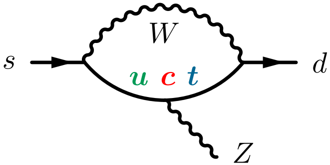
$$\mathrm{Re}(\boldsymbol{\lambda_c}) \sim \lambda \qquad \mathrm{Im}(\boldsymbol{\lambda_c}) \sim \lambda^5$$

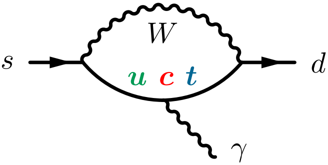
$$\mathrm{Re}(\boldsymbol{\lambda_t}) \sim \lambda^5 \qquad \mathrm{Im}(\boldsymbol{\lambda_t}) \sim \lambda^5$$

With respect to CKM:

- **CP conserving modes**: potential top/charm competition ✘
- **CP violating modes**: free from long-distance up-quark (Λ_{QCD}) contributions, suppressed, and dominated by short-distance dynamics ✓

Rare K decays: GIM structure





$$x \equiv m_{u,c,t}^2 / M_W^2$$

$$X_0(x) \xrightarrow{x\to\infty} x \qquad D_0(x) \xrightarrow{x\to\infty} \log x$$

$$X_0(x) \xrightarrow{x\to 0} x \log x \qquad D_0(x) \xrightarrow{x\to 0} \log x$$

➜ If photonic penguins contribute, long-distance “pollution”

➜ Z penguins quadratically sensitive to x – **hard quadratic GIM**

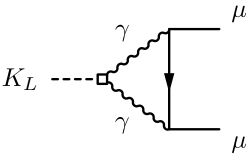
A tricky opportunity

$$K_S \to (\mu^+\mu^-)_{\ell=0}$$

$K_S \to (\mu^+\mu^-)_{\ell=0}$

CP structure depends on dimuon angular momentum, ℓ

	$\to (\mu\mu)_{\ell=0}$	$\to (\mu\mu)_{\ell=1}$
K_L	CP conserving	**CP violating ✗**
K_S	**CP violating ✓**	CP conserving



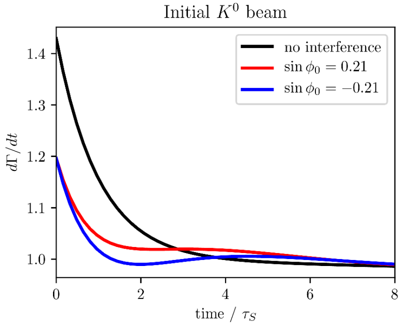
- $\boldsymbol{K_L}$: long-distance dominated due to two-photon penguin
  BR$(K_L \to \mu\mu) = 6.84(11) \times 10^{-9}$
- $\boldsymbol{K_S}$: $\ell = 0$ component, CP violating and top-quark dominated
  BR$(K_S \to \mu\mu) < 2.1 \times 10^{-10}$

Challenges: tag K_S (small lifetime) and access the $(\mu\mu)_{\ell=0}$ state

BR$(K_S \to \mu\mu)_{\ell=0}$ from time-dependent rate

Leverage intereference in **time-dependent** rate to access the short-distance dominated $(\mu\mu)_{\ell=0}$ state [D'Ambrosio, Kitahara 17]

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



[plot from J. Brod @ LPCP]

$$\frac{\mathrm{BR}[K_S \to (\mu\mu)_{\ell=0}]}{\mathrm{BR}[K_L \to \mu\mu]} = \frac{\tau_S}{\tau_L}\left(\frac{C_{\mathrm{int}}}{C_L}\right)^2$$

[Dery et al 21]

BR$(K_S \to \mu\mu)_{\ell=0}$ SM prediction and NP sensitivity

- Top-quark dominated and $\cancel{CP}$ ➜ $\sim 1\%$ theory uncertainty
- Sizable 3% component from CP-conserving amplitude $\times \epsilon_K$

➜ only rough estimate possible for relative strong phase

[estimation from $K_L \to \mu\mu$ $K_L \to \gamma\gamma$ data]

$$\textbf{BR}(K_S \to \mu\mu)_{\ell=0} = \mathbf{1.70(2)(1)(19) \times 10^{-13}}$$

[Brod, ES 22]

- Presently no heavy-NP bounds; not clear whether exp. feasible

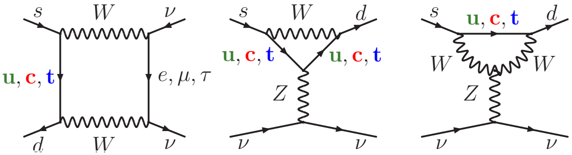
$$\mathcal{L}_{\text{NP}} = \frac{C_{\text{NP}}}{\Lambda^2}(\bar{s}_L \gamma^\nu d_L)(\bar{\mu}_L \gamma_\nu \mu_L) + \text{hc}$$

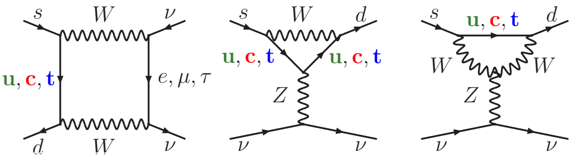
➜ Measurement at 10% would probe $\mathbf{\Lambda \sim 600}$ **TeV** for Im$[C_{\text{NP}}]$

The golden modes

$$K_L \to \pi^0 \nu\bar{\nu}$$

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



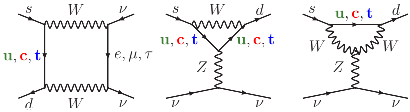


$$\sum_i \lambda_i F(x_i) = \lambda_t \left(\boldsymbol{F}(\boldsymbol{x_t}) - \boldsymbol{F}(\boldsymbol{x_u})\right) + \lambda_c \left(\boldsymbol{F}(\boldsymbol{x_c}) - \boldsymbol{F}(\boldsymbol{x_u})\right)$$

- Top: $\lambda_t \boldsymbol{F}(\boldsymbol{x_t}) \propto \lambda^5 m_t^2/M_W^2$
  matching NLO@QCD [Misiak, Urban 99; Buchalla, Buras 99], NLO@EW [Brod, Gorbahn, ES 10], matching NNLO@QCD [in progress with Gorbahn, Yu]

- Charm: $\lambda_c \boldsymbol{F}(\boldsymbol{x_c}) \propto \lambda m_c^2/M_W^2 \log(m_c/M_W)$ obtained via operator mixing in EFT
  running NNLO@QCD [Buras et al 06] NLO@EW [Brod, Gorbahn 08]

- Up: $\lambda_c \boldsymbol{F}(\boldsymbol{x_u}) \propto \lambda \Lambda_{\text{QCD}}^2/M_W^2$ from χPT and lattice
  small, 10% of total charm contribution



$K_L \to \pi^0 \nu\bar{\nu}$ CP violating mode (1% from CP-conserving amplitude $\times \epsilon_K$)

➜ only top-quark contribution: short-dist. uncertainty of $\mathcal{O}(2\%)$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})^{\mathrm{SM}} = \kappa_L r_{\epsilon_K} \left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X_t \right)^2$$

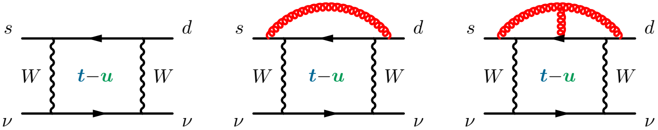
$K^+ \to \pi^+ \nu\bar{\nu}$ CP conserving mode

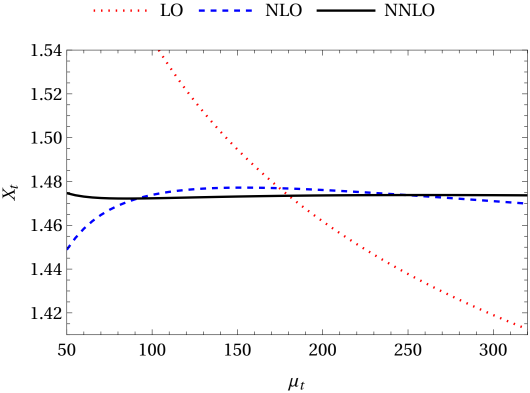
➜ charm contributes: $\mathcal{O}(3\%)$ long-distance theory uncertainties

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})^{\mathrm{SM}} = \kappa_+ (1 + \Delta_{\mathrm{EM}}) \left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X_t \right)^2 + \left(\frac{\mathrm{Re}\lambda_c}{\lambda} (P_c + \delta P_{cu}) + \left(\frac{\mathrm{Re}\lambda_t}{\lambda^5} X_t \right) \right)^2 \right]$$

[details in Brod, Gorbahn, ES from BEAUTY2020]

Top-contribution X_t at NNLO in QCD





Reduces uncertainty from $\pm 1\%$ (@NLO) down to $\pm 0.1\%$ (@NNLO)

[in progress with Gorbahn, Yu]

SM prediction using PDG input

Preliminary numerics including X_t@NNLO

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})^{\mathrm{SM}} = 8.25(11)_{\mathrm{SD}}(25)_{\mathrm{LD}}(57)_{\mathrm{para}} \times 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})^{\mathrm{SM}} = 2.83(1)_{\mathrm{SD}}(2)_{\mathrm{LD}}(30)_{\mathrm{para}} \times 10^{-11}$$

NA62 and KOTO measuments

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

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})^{\mathrm{KOTO}} < 3.0 \times 10^{-9} \qquad \text{@90\% CL}$$

Ratios of rates as clean SM tests [Buras, Venturini 21]

$$R_S = \frac{\mathrm{BR}(K_S \to \mu\mu)_{\ell=0}}{\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})} \sim 1.55 \times 10^{-2} \frac{Y(x_t)}{X(x_t)}$$

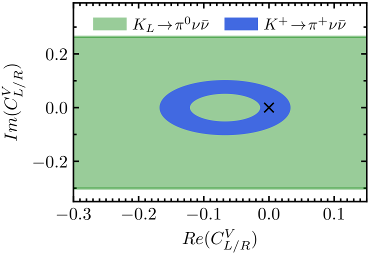
Essentially CKM-parameter free (up to $\mathcal{O}(3\%)$ correction)

Heavy NP in $K \to \pi\nu\nu$

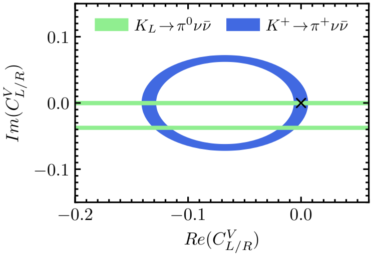
- powerful probes of NP (for Vector "SM-like" NP)

$$\mathscr{L}_{\text{NP}} = \frac{C^V_{L/R}}{\Lambda^2}(\bar{s}\gamma^\mu P_{L/R} d)(\bar{\nu}_L \gamma_\mu \nu_L) + hc$$

present $\Lambda = 10$TeV



projection $\Lambda = 10$TeV



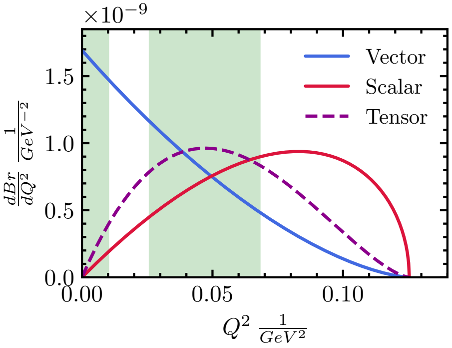
forecast K_+:5-10%@NA62, K_L:20% @KLEVER(?)

Lepton-Number-Violation in $K \to \pi\nu\nu$ distributions

- Lepton-number-violating (LNV) NP in $s \to d\nu\nu$

$$\mathscr{L}_{\text{LNV}} = \frac{C^S_{L/R}}{\Lambda^2} \underbrace{(\bar{s}P_{L/R}d)(\nu_L^T \mathcal{C}\nu_L)}_{\text{scalar}} + \frac{C^T}{\Lambda^2} \underbrace{(\bar{s}_R\sigma_{\mu\nu}d_L)(\nu_L^T\mathcal{C}\sigma^{\mu\nu}\nu_L)}_{\text{tensor/only LFV}} + hc$$

- Modified $\nu\nu$ distributions ➜ probing LNV at NA62

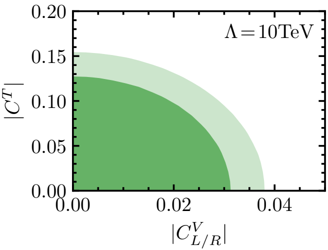


[in progress with Sieja, Tabet; SMEFT/scalar-case Deppisch et al 20]

Lepton-Number-Violation in $K \to \pi\nu\nu$ distributions

$$\mathscr{L}_{\text{LNV}} = \frac{C^S_{L/R}}{\Lambda^2}(\bar{s}P_{L/R}d)(\nu_L^T \mathcal{C}\nu_L) + \frac{C^T}{\Lambda^2}(\bar{s}_R\sigma_{\mu\nu}d_L)(\nu_L^T\mathcal{C}\sigma^{\mu\nu}\nu_L) + hc$$

- correlations/preliminary recast of NA62



- washout process, constrain Leptogenesis[Deppisch et al 15,18;Chun et al 17]
- **Further options:** sterile-ν signatures ($K \to \pi\nu_l\nu_h, \pi\nu_h\nu_h$), SU$(2)$ invariant models and LNV pheno, KOTO data, projections

[in progress with Gorbahn and Moldanazarova]

Summary and conclusions

- Kaons remain at the frontier of searches for **heavy NP** and **light NP**

- **Precision predictions** necessary to disentagle NP effects

➜ Recent and expected improvements targeting 0.1%-level accuracy (ϵ_K, $K \to \pi\nu\bar{\nu}$)

- **New ideas** to maximize impact of data

➜ e.g., time-dependendet rate in $K \to \mu\mu$ or $K \to \pi\nu\bar{\nu}$ distributions

backup

ϵ_K: indirect CP violation

- If CP is conserved $K_L \not\to \pi\pi$, but mixing allows it:

$$\boldsymbol{\epsilon_K \equiv \frac{\langle(\pi\pi)_{I=0}|K_L\rangle}{\langle(\pi\pi)_{I=0}|K_S\rangle}} = \frac{1-\lambda_0}{1+\lambda_0}$$

- With $\lambda_0 = \frac{q}{p}\frac{\langle(\pi\pi)_{I=0}|\overline{K}^0\rangle}{\langle(\pi\pi)_{I=0}|K^0\rangle} = 1 - i\phi \underbrace{\frac{\Delta M_K}{\Delta M_K + i\Delta\Gamma_K/2}}_{\text{Take from experiment}}$

- With the weak phase $\phi = \underbrace{arg(-M_{12}/\Gamma_{12})}_{\text{Compute}}$

[Nierste in Anikeev et al; hep-ph/0201071]

ϵ_K: indirect CP violation

In **PDG-phase convention** M_{12} and Γ_{12} nearly real

$$\boldsymbol{\epsilon_K = e^{i\phi_\epsilon} \sin\phi_\epsilon \left(\frac{Im(M_{12})}{\Delta M_K} + \xi \right)}$$

- $\phi_\epsilon \equiv arctan \frac{\Delta M_K}{\Delta\Gamma_K/2}$ and $\boldsymbol{\xi = -\frac{Im(\Gamma_{12})}{2Re(\Gamma_{12})}}$ (non-perturbative / long-distance)

(Estimates from: ϵ'/ϵ [Nierste 02, Buras et al 08], ChPT [Buras et al 10], lattice [Blum et al 15, Bai et al 15])

- $\boldsymbol{Im(M_{12})}$: scale separation (EFT) **factorizes** computation

$$\langle \mathcal{H}_{\text{eff}} \rangle = \underbrace{\langle Q^{\Delta S=2} \rangle(\mu_{\text{had}}) U(\mu_{\text{had}},}_{\text{hadronic matrix element}, \hat{B}_K} \underbrace{\mu_c) U(\mu_c, \mu_W) \boldsymbol{C}(\mu_W)}_{\text{pertubative evolution of } C}$$

Traditional: ct-unitarity

$$\mathcal{H}^{\Delta S=2} = \frac{G_F^2 M_W^2}{4\pi^2} Q_{S2} \Big\{ \lambda_t^2 C^{tt} + \lambda_c^2 C^{cc} + \lambda_c \lambda_t C^{ct} \Big\} + \text{h.c.} + \dots$$

Match to phase-convention “independent” Hamiltonian

- $C^{cc} = \boldsymbol{\mathcal{C}_1} \quad C^{ct} = 2\boldsymbol{\mathcal{C}_1} + \mathcal{C}_3 \quad C^{tt} = 2\boldsymbol{\mathcal{C}_1} + \mathcal{C}_2 + \mathcal{C}_3$
- $\mathcal{C}_1$, controlling ΔM_K, enters all pieces

➜ **<u>Bad</u> news**

- ΔM_K is long-distance dominated [Brod, Gorbahn 11]

➜ We artificially included $\mathcal{C}_1$ into the prediction of ϵ_K!

We can do better.

New: ut-unitarity

First proposed for a lattice computation [Christ et al 12, see also Barbieri 07]

$$\mathcal{H}^{\Delta S=2} = \frac{G_F^2 M_W^2}{4\pi^2} Q_{S2} \left\{ \lambda_t^2 C^{tt} + \lambda_u^2 C^{uu} + \lambda_u \lambda_t C^{ut} \right\} + \text{h.c.} + \ldots$$

Match to phase-convention “independent” Hamiltonian

- $C^{uu} = \boldsymbol{\mathcal{C}_1} \quad C^{tt} = \mathcal{C}_2 \quad C^{ut} = \mathcal{C}_3$
- Disentangled $Re(M_{12})$ and $Im(M_{12})$

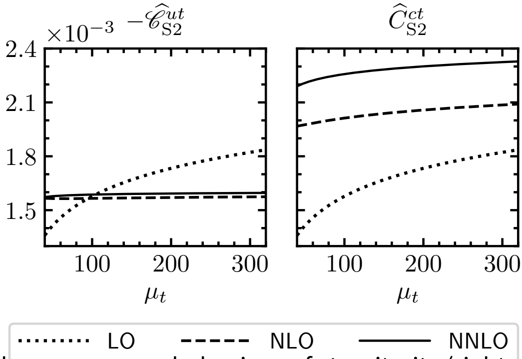
➜ **Good news!**, $\boldsymbol{Im(M_{12})}$ **without** $\boldsymbol{\Delta M_K}$ **pollution**

✚ It can be shown that Wilson coefficients and ADMs can be extracted from the “traditional” results

[Brod, Gorbahn, ES 19]

Comparison: ut VS ct

- Residual theory uncertainties from scale variation (μ_t, μ_c)



- Miserable convergence behaviour of ct-unitarity (right panel)
- Excellent convergence behaviour of ut-unitarity (left panel)

$\boldsymbol{\eta_{ut} = 0.402 \pm 0.005}$ **@ NNLO**[Brod, Gorbahn, ES 19]

$\boldsymbol{\eta_{tt} = 0.55 \pm 0.02}$ **@ NLO** [Buras et al 90 with our variation]

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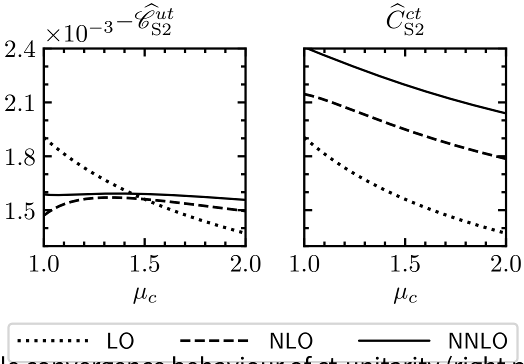

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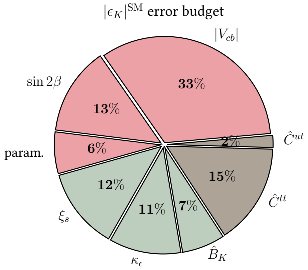
Towards permille-level accuracy in ϵ_K



- Charm no longer leading uncertainty

→ **Reassessment of uncertainties**

- Reduce top uncertainty by NNLO QCD matching
  [in progress with Brod, Gorbahn, and Hang]

- Residual EW/QED uncertainties 2%? [path analogous to Brod, Gorbahn, ES 10; Brod, Gorbahn 08, Bobeth, Gorbahn, ES 14; Gambino, Kwiatkowski, Pott 98]

- Lattice target: ME with dynamical charm. Will allow to fully compute ϵ_K

- Reassess contributions from lon-local insertions