New Physics Signatures in Kaon Decays

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A very brief history of K physics

Kaon physics – a long and successful story. . .

- charm quark prediction from $K_L \to \mu^+\mu^-$

  Glashow, Iliopoulos, Maiani (1970)
- third generation from CP violation in $K - \bar{K}$ mixing

  Kobayashi, Maskawa (1973)

. . . and the show will go on: What discovery is next?

K versus $B_{d,s}$ and D physics

Grand picture in the Standard Model (SM)

- flavor and CP violation governed by CKM matrix

$$V_{\text{CKM}} \propto \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

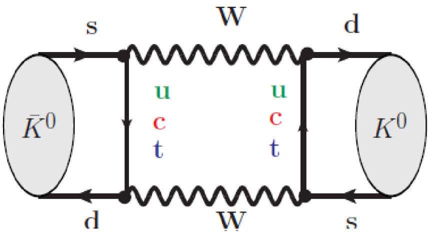
- hierarchical structure predicts specific pattern of effects

$$\underbrace{V_{ts}^* V_{td}}_{K \text{ system}} \sim 5 \cdot 10^{-4} \ll \underbrace{V_{tb}^* V_{td}}_{B_d \text{ system}} \sim 10^{-2} < \underbrace{V_{tb}^* V_{ts}}_{B_s \text{ system}} \sim 4 \cdot 10^{-2}$$

- D system long-distance (LD) dominated and hence hard to predict

➢ **in general K decays exhibit highest new physics sensitivity**

$K - \bar{K}$ mixing in the SM

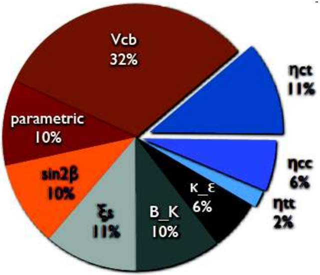


- governed by one single operator $(\bar{s}d)_{V-A}(\bar{s}d)_{V-A}$
- CP-conserving quantities (e. g. ΔM_K) affected by long distance contributions
- CP-violation (ε_K) governed by short-distance physics
  ➢ theoretically much cleaner

ε_K in the SM – status

$$\varepsilon_K = \frac{\langle(\pi\pi)_{I=0}|K_L\rangle}{\langle(\pi\pi)_{I=0}|K_S\rangle} = \kappa_\varepsilon e^{i\phi_\varepsilon}\frac{\mathrm{Im}M_{12}^K}{\Delta M_K}$$

- tremendous progress in lattice calculations
- theory error now dominated by parametric uncertainties, in particular $|V_{cb}|$



SM prediction: Brod, Gorbahn (2011)

$$|\varepsilon_K| = 1.81(28)\cdot 10^{-3}$$

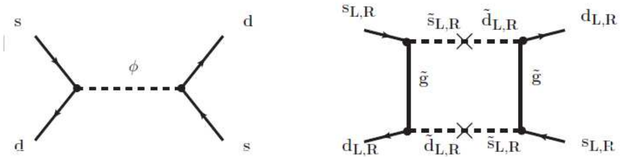
data: PDG (2010)

$$|\varepsilon_K| = 2.228(11)\cdot 10^{-3}$$

➢ **a hint for new physics?**

ε_K in the presence of new physics

- small NP contribution welcome – but many models yield **huge** effects (e. g. SUSY, RS, TC, LHT, LR, ...)



- chiral enhancement of non-SM operators and absence of NP flavor protection leads to strong generic constraint UTFIT (2007)

$$\Lambda_{\text{NP}} \gtrsim 10^5 \text{ TeV} \sim 10^5 \times \text{scales probed by LHC!}$$

➢ **TeV-scale NP must have a very non-generic flavor structure**

Why rare kaon decays?

Rare kaon decays are. . .

1. theoretically very clean
2. highly suppressed in the SM
3. very sensitive to new physics
4. governed by different NP structures than $K - \bar{K}$ mixing
5. able to distinguish between various NP scenarios
6. experimentally challenging but very worth the effort

. . . unique tests of physics beyond the SM!

$K \to \pi\nu\bar{\nu}$ – a unique opportunity

$K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$ decays

- governed by single effective operator $(\bar{s}d)_V(\bar{\nu}\nu)_{V-A}$ both in and beyond the SM
- hadronic matrix element measured in $K^+ \to \pi^0 e^+\nu$ (+IB corrections), charm-quark contributions (K^+ mode) well known

➢ **theoretically extremely clean – main uncertainty from $|V_{cb}|$**

SM prediction and experimental status

$$Br(K^+)_{\text{SM}} = (8.5 \pm 0.7) \cdot 10^{-11} \qquad Br(K_L)_{\text{SM}} = (2.6 \pm 0.4) \cdot 10^{-11}$$
$$Br(K^+)_{\text{exp}} = 17.3^{+11.5}_{-10.5} \cdot 10^{-11} \qquad Br(K_L)_{\text{exp}} < 2.6 \cdot 10^{-8}$$

NLO: Buchalla, Buras (1994); Misiak, Urban (1999)
NNLO: Buras, Gorbahn, Haisch, Nierste (2006);Brod, Gorbahn, Stamou (2010)
exp: E949 (2008), E301a (2009)

$K \to \pi\nu\bar{\nu}$ and new physics

effective Hamiltonian for $K \to \pi\nu\bar{\nu}$

$$\mathcal{H}_{\text{eff}} \propto \Big[\underbrace{V_{cs}^* V_{cd} X_{\text{NNL}}(x_c)}_{\text{charm contribution}} + \underbrace{V_{ts}^* V_{td} |X| e^{i\theta_X}}_{\text{SD contribution}} \Big] (\bar{s}d)_V (\bar{\nu}\nu)_{V-A}$$

new physics!

➢ short-distance physics described model-independently by complex function

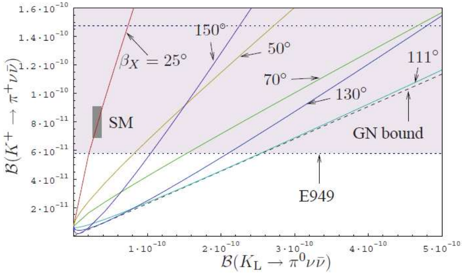
$$X = |X| e^{i\theta_X} \qquad \text{where } |X|^{\text{SM}} = X(x_t)\,,\, \theta_X^{\text{SM}} = 0$$

$K^+ \to \pi^+\nu\bar{\nu}$ mode sensitive to $|X|$ (CP-conserving), while $K_L \to \pi^0\nu\bar{\nu}$ mode measures $\text{Im}X$ (CP-violating)

$K \to \pi\nu\bar{\nu}$ – model-independent considerations

$\beta_X = \beta - \theta_X$

figure taken from Buras, Schwab, Uhlig (2004)



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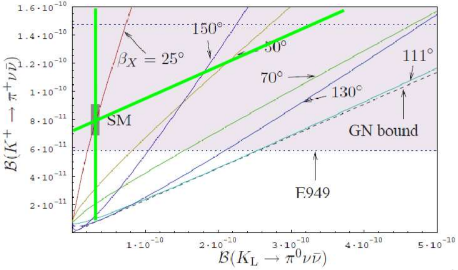


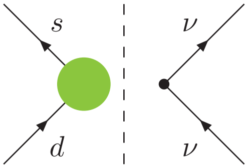
➢ **test of operator structure in ε_K**

Blanke (2009)

pure V-A structure:

- ε_K **constrains phase** of $s \to d$ transition
- **same phase** enters $K \to \pi\nu\bar{\nu}$

➢ only two branches are allowed



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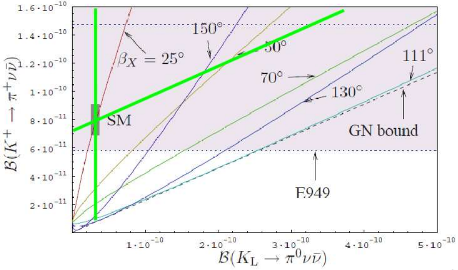

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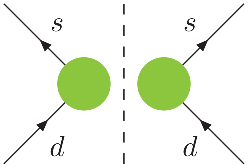

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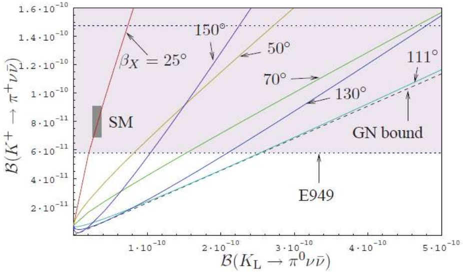
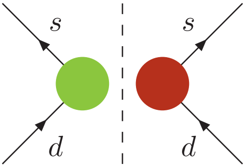


➢ **test of operator structure in ε_K** BLANKE (2009)



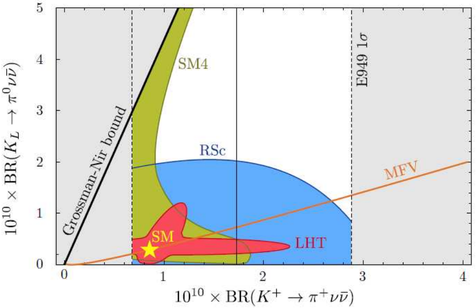
both V-A and V+A:

- $\mathcal{Q}_{LR}$ **dominates** in ε_K
- **connection** between $\Delta S = 2$ and $\Delta S = 1$ is **spoiled**

➢ full $K \to \pi\nu\bar{\nu}$ plane possible

$K \to \pi\nu\bar{\nu}$ in specific NP models

Blanke et al. (2006,2008), Buras et al. (2010)
figure taken from Straub (2010)



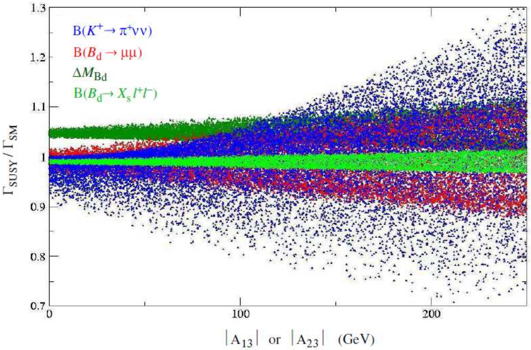
- custodial Randall Sundrum model (RSc) and Littlest Higgs with T-parity (LHT) *predicted* rather small effects in B physics
  ➢ **large enhancements of $K \to \pi\nu\bar{\nu}$ still allowed**
- 4th generation (SM4) in serious trouble with LHC data

$K \to \pi\nu\bar{\nu}$ in the MSSM

MSSM: main contribution from chargino loops

➢ unique sensitivity to up-type trilinear couplings
& slower decoupling than in $\Delta F = 2$ processes

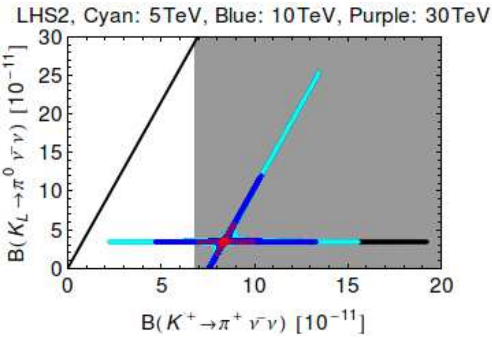
➢ **large effects in $K \to \pi\nu\bar{\nu}$ not excluded by LHC(b) results**



Isidori et al. (2006)

$K \to \pi\nu\bar{\nu}$ and a flavor changing Z'

Buras, De Fazio, Girrbach (2012)



➢ **observable effects even for $M_{Z'} \simeq 20 - 30$ TeV**
well beyond the reach of the LHC and B physics experiments

A word on ε'/ε

ε'/ε measures $\frac{\text{direct}}{\text{indirect}}$ CP violation in $K_L \to \pi\pi$ decays

- measured at the 10% level
- (potentially) strong constraint on NP models
  partly complementary to rare K decays
- however large hadronic uncertainties in relevant matrix elements
  (from QCD and electroweak penguin operators)

➢ **progress on the lattice required – and on the way**

see e. g. Blum et al. (2011), RBC-UKQCD (2012)

$K \to \ell\nu$ and lepton universality

K decays also offer a sensitive probe of lepton flavor physics!

$$R_K = \frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)}$$

- very clean SM prediction (hadronic uncertainties cancel to a large extent)

$$R_K^{\mathrm{SM}} = 2.472(1) \cdot 10^{-5}$$

- recent NA48/2 data in good agreement with SM value, but still with an order of magnitude larger uncertainty

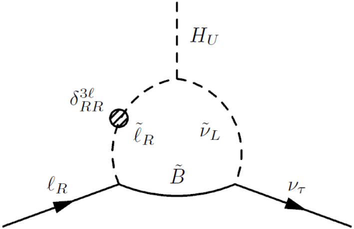
$$R_K^{\mathrm{exp}} = 2.488(10) \cdot 10^{-5}$$

- deviation from SM value would signal lepton non-universality

➢ **improved measurement will yield significant constraint on NP**

Lepton non-universality beyond the SM

MSSM: dominant contribution through LFV interactions



Masiero, Paradisi, Petronzio (2005) and others

- no interference with SM ➢ enhancement of R_K
- complementary to LFV μ and τ decays

Neutrinos: breaking of lepton universality also from sterile neutrinos

Shrock (1980) and others

Summary

1. K decays offer unique sensitivity to flavor violation beyond the SM

2. $K \to \pi\nu\bar{\nu}$ are theoretically cleanest and can differ vastly from their SM predictions

3. different modes yield complementary constraints

   correlated study of ε_K, ε'/ε and rare K decays* provides excellent tool to **distinguish between different NP scenarios** – in conjunction with constraints from B and D physics and direct searches

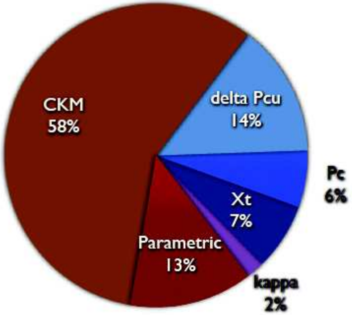
   * $K_L \to \pi^0\nu\bar{\nu}$, $K^+ \to \pi^+\nu\bar{\nu}$, but also $K_L \to \pi^0\mu^+\mu^-$, $K_L \to \pi^0 e^+e^-$

4. $K \to \ell\nu$ decays serve as very good probe of lepton universality

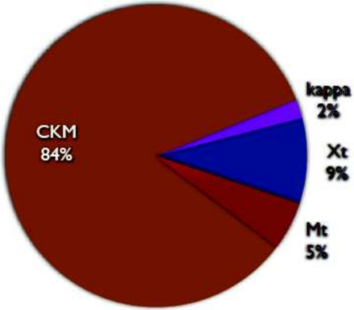
Back-up slides

$K \to \pi\nu\bar{\nu}$ – SM error budgets

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



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



uncertainties dominated by CKM input, in particular $|V_{cb}|$ and γ

➢ **better measurements + theoretical understanding needed**

The $K_L \to \pi^0 \ell^+ \ell^-$ system

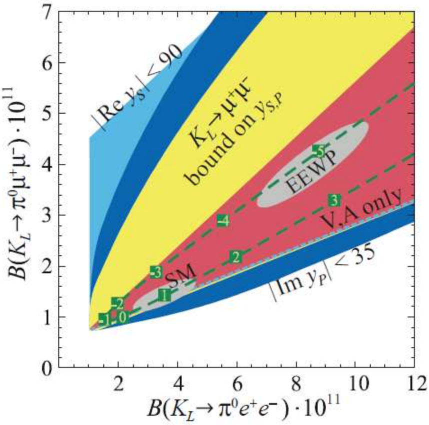
- not as theoretically clean as $K \to \pi\nu\bar{\nu}$, but sensitive to different SD operators ➢ complementary information
- theory error dominated by interference between directly and indirectly CP-violating contributions
  ➢ **improve through better measurement of $K_S \to \pi^0 \ell^+ \ell^-$**
- SM predictions

$$Br(K_L \to \pi^0 \mu^+ \mu^-)_{\text{SM}} = 3.54^{+0.98}_{-0.85} \cdot 10^{-11}$$
$$Br(K_L \to \pi^0 e^+ e^-)_{\text{SM}} = 1.41^{+0.28}_{-0.26} \cdot 10^{-11}$$

- muon mode sensitive to scalar contributions
  ➢ **correlation can distinguish various NP scenarios**

Mescia, Smith, Trine (2006)

Model discrimination through $K_L \to \pi^0 \ell^+ \ell^-$



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