Theory Review on Rare Kaon Decays: SM and Beyond

Wolfgang Altmannshofer

Fermilab

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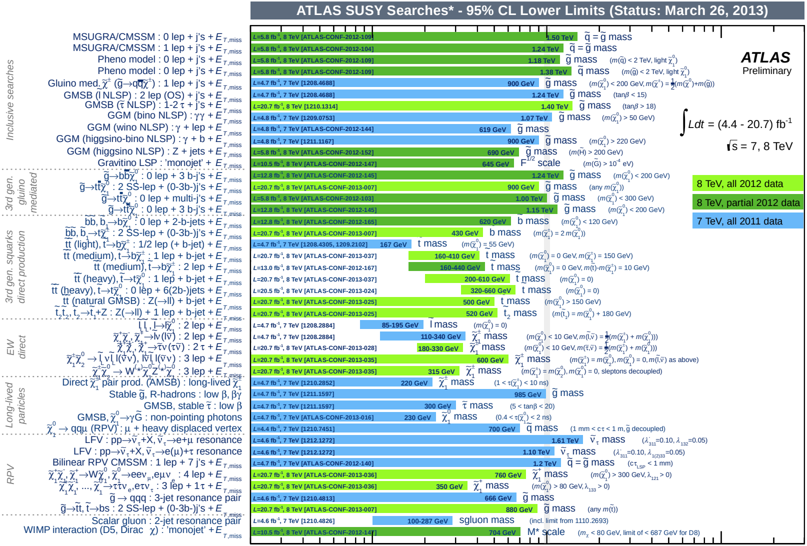
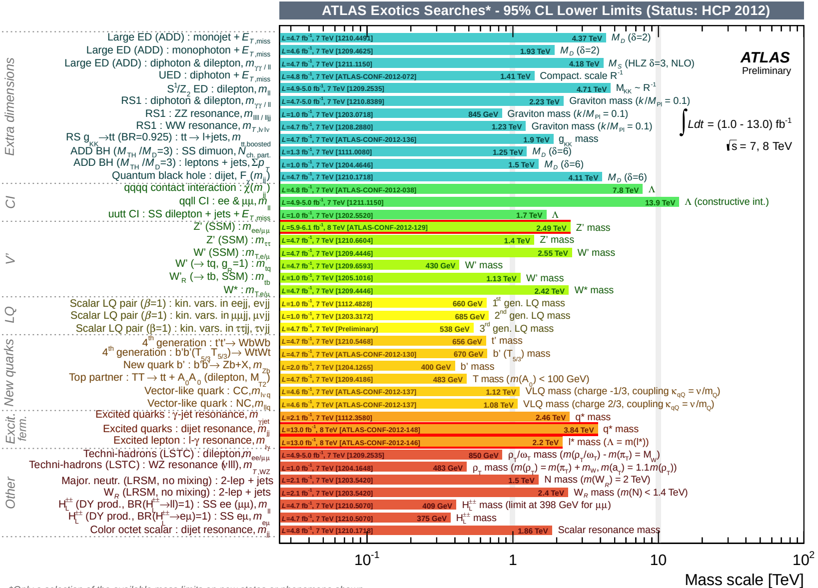
Oh New Physics, Where Art Thou?



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

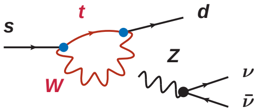
Oh New Physics, Where Art Thou?

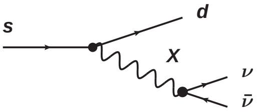


*Only a selection of the available mass limits on new states or phenomena shown

The Rarer the Better

	Standard Model	generic New Physics
$s \to d$	$\sim \frac{g_2^4}{16\pi^2} \frac{1}{M_W^2} V_{ts} V_{td}^* \simeq \frac{1}{(130\text{ TeV})^2}$	$\sim \frac{1}{M_X^2}$
$b \to d$	$\sim \frac{g_2^4}{16\pi^2} \frac{1}{M_W^2} V_{tb} V_{td}^* \simeq \frac{1}{(26\text{ TeV})^2}$	$\sim \frac{1}{M_X^2}$
$b \to s$	$\sim \frac{g_2^4}{16\pi^2} \frac{1}{M_W^2} V_{tb} V_{ts}^* \simeq \frac{1}{(12\text{ TeV})^2}$	$\sim \frac{1}{M_X^2}$





Rare Kaon Decays Discussed in this Talk

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

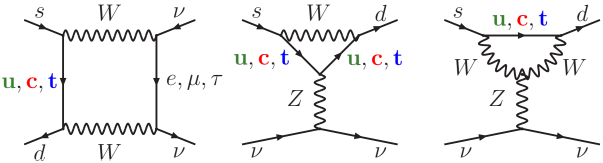
$$K_L \to \pi^0 \nu \bar{\nu}$$

$$K_L \to \pi^0 e^+ e^-$$

$$K_L \to \pi^0 \mu^+ \mu^-$$

Rare Kaon Decays in the Standard Model

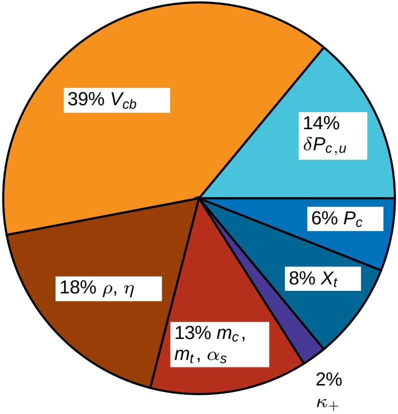
(many thanks to Joachim Brod for providing many slides)



$$\text{BR}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \kappa_+ (1 + \Delta_{\text{EM}}) \times \left| \frac{1}{\lambda^5} \lambda_t X_t(m_t^2) + \frac{1}{\lambda} \left(\lambda_c P_c(m_c^2) + \lambda_c \delta P_{c,u} \right) \right|^2$$

- hadronic matrix element κ_+ from well measured $K \to \pi \ell \nu$ decay, corrected for isospin breaking and QED effects (Mescia, Smith '07)
- top contrib. $\propto \lambda^5 \frac{m_t^2}{m_W^2}$ NLO QCD and NLO EW (Misiak, Urban '99; Brod et al. '11)
- charm contrib. $\propto \lambda \frac{m_c^2}{m_W^2} \log \frac{m_c^2}{m_W^2}$ NNLO QCD and NLO EW (Buras et al. '06; Brod et al. '11)
- long distance $\propto \lambda \frac{\Lambda_{\text{QCD}}^2}{m_W^2}$ estimated in χPT (Isidori et al. '05)

$K^+ \to \pi^+ \nu\bar{\nu}$: Error Budget



- main parametric error from V_{cb}
- improve on $\delta P_{c,u}$ by lattice calculations

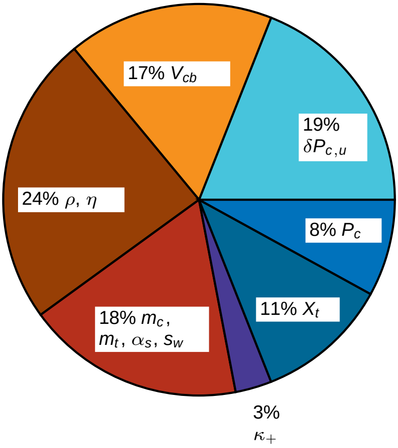
$$\mathrm{Br}^{\mathrm{th}}(K^+) = 7.81(75)(29) \times 10^{-11}$$

Brod, Gorbahn, Stamou ’11

$$\mathrm{Br}^{\mathrm{exp}}(K^+) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

E787, E949 ’08

$K^+ \to \pi^+ \nu \bar{\nu}$: Future Error Budget



- assume reduced uncertainty on V_{cb}

$$\delta V_{cb}/V_{cb} = 1\%$$

$$\text{Br}^{\text{th}}(K^+) = 7.81(37)(29) \times 10^{-11}$$

talk by Brod, Project X Physics Study '12

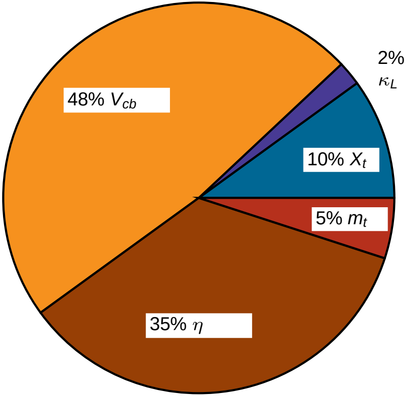
$$\text{Br}^{\text{exp}}(K^+) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

E787, E949 '08

$K_L \to \pi^0 \nu\bar\nu$ is almost purely *CP*-violating

$$\text{BR}\left(K_L \to \pi^0 \nu\bar\nu\right) = \kappa_L \times \left[\frac{1}{\lambda^5} \text{Im}\left(\lambda_t X_t(m_t^2) \right)\right]^2$$

- completely top-quark dominated
- essentially free of long distance “pollution”



- dominant uncertainty from V_{cb}
  sizable uncertainty also from η

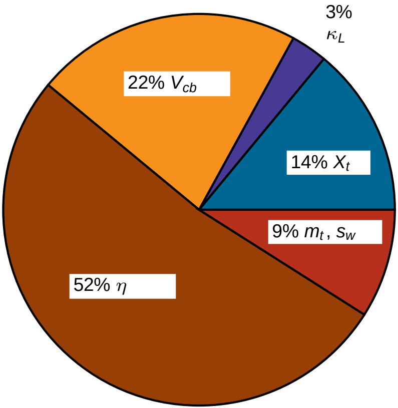
$$\text{Br}^{\text{th}}(K_L) = 2.43(39)(6) \times 10^{-11}$$

Brod, Gorbahn, Stamou ’11

$$\text{Br}^{\text{exp}}(K_L) < 2.6 \times 10^{-8}$$

E391a ’08

$K_L \to \pi^0 \nu\bar{\nu}$: Future Error Budget



- assume reduced uncertainty on V_{cb}

$$\delta V_{cb}/V_{cb} = 1\%$$

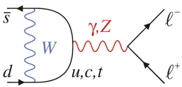
$$\text{Br}^{\text{th}}(K_L) = 2.43(25)(6) \times 10^{-11}$$

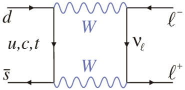
talk by Brod, Project X Physics Study '12

$$\text{Br}^{\text{exp}}(K_L) < 2.6 \times 10^{-8}$$

E391a '08

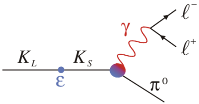
- short distance Direct CP Violating





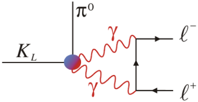
- described by local 4 fermion operators
- known at NLO in QCD (Buchalla et al. '95)

- long distance Indirect CP Violating



- estimate from ϵ_K and $K_S \to \pi \ell^+ \ell^-$ (D'Ambrosio et al. '98; Mescia et al. '06)
- sign of interference with DCPV?

- long distance CP Conserving



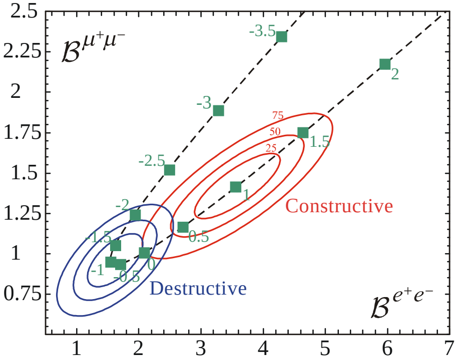
- estimate from $K_L \to \pi^0 \gamma\gamma$ (Isidori et al. '04)

SM Predictions for the Branching Ratios

$$B^{\rm SM}(K_L \to \pi^0 e^+ e^-)$$
$$= 3.23\,^{+0.91}_{-0.79}\;[1.37\,^{+0.55}_{-0.43}]\;\times 10^{-11}$$

$$B^{\rm SM}(K_L \to \pi^0 \mu^+ \mu^-)$$
$$= 1.29\,^{+0.24}_{-0.23}\;[0.86\,^{+0.18}_{-0.17}]\;\times 10^{-11}$$

Mertens, Smith '11



Mescia, Smith, Trine '06

$$B^{\rm exp}(K_L \to \pi^0 e^+ e^-) < 28 \times 10^{-11}$$

$$B^{\rm exp}(K_L \to \pi^0 \mu^+ \mu^-) < 38 \times 10^{-11}$$

KTEV '00; '03

Uncertainty in SM prediction dominated by $K_S \to \pi^0 \ell^+ \ell^-$ measurements!

Rare Kaon Decays as Probes of New Physics

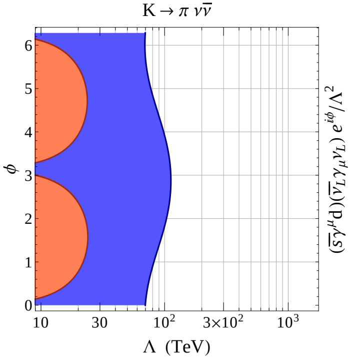
Model Independent Approach

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} + \sum_i \mathcal{O}_i \times (c_i/\Lambda_{\rm NP}^2)$$

	Operator	$K^+ \to \pi^+ \nu\bar\nu$	$K_L \to \pi^0 \nu\bar\nu$	$K_L \to \pi^0 l^+ l^-$	$K_L \to l^+ l^-$	$K^+ \to l^+ \nu$	$P_T(K^+ \to \pi^0 \mu^+ \nu)$	$\Delta_{\rm CKM}$	ϵ'/ϵ	ϵ_K	in MSSM?
$Q_{lq}^{(1)}$	$(\bar D_L \gamma_\mu S_L)(\bar L_L \gamma^\mu L_L)$	✓	✓	✓	hs	—	—	—	—	—	✓
$Q_{lq}^{(3)}$	$(\bar D_L \gamma_\mu \sigma^i S_L)(\bar L_L \gamma^\mu \sigma^i L_L)$	✓	✓	✓	hs	hs	✓	✓	—	—	✓
Q_{qe}	$(\bar D_L \gamma_\mu S_L)(\bar l_R \gamma^\mu l_R)$	—	—	✓	hs	hs	✓	✓	—	—	small
Q_{ld}	$(\bar d_R \gamma_\mu s_R)(\bar L_L \gamma^\mu L_L)$	✓	✓	✓	hs	—	—	—	—	—	small
Q_{ed}	$(\bar d_R \gamma_\mu s_R)(\bar l_R \gamma^\mu l_R)$	—	—	✓	hs	—	—	—	—	—	small
$Q_{lq}^\dagger$	$(\bar u_R S_L)(\bar l_R L_L)$	—	—	—	—	✓	✓	✓	—	—	tiny
$(Q_{lq}^t)^\dagger$	$(\bar u_R \sigma_{\mu\nu} S_L)(\bar l_R \sigma^{\mu\nu} L_L)$	—	—	—	—	—	?	?	—	—	tiny
Q_{qde}	$(\bar d_R S_L)(\bar L_L l_R)$	—	—	✓	✓	—	—	—	—	—	tiny
$Q_{qde}^\dagger$	$(\bar D_L s_R)(\bar l_R L_L)$	—	—	✓	✓	✓	✓	✓	—	—	large $\tan\beta$
$Q_{\phi q}^{(1)}$	$(\bar D_L \gamma_\mu S_L)(\phi^\dagger D^\mu \phi)$	✓	✓	✓	hs	—	—	—	✓	(✓)	✓
$Q_{\phi q}^{(3)}$	$(\bar D_L \gamma_\mu \sigma^i S_L)(\phi^\dagger D^\mu \sigma^i \phi)$	✓	✓	✓	hs	hs	✓	✓	✓	(✓)	✓
$Q_{\phi d}$	$(\bar d_R \gamma_\mu s_R)(\phi^\dagger D^\mu \phi)$	✓	✓	✓	hs	—	—	—	✓	(✓)	large $\tan\beta$ (non-MFV)

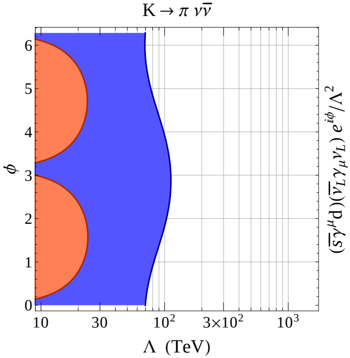
[see S. Jäger, talk at NA62 Physics Handbook Workshop]

current situation

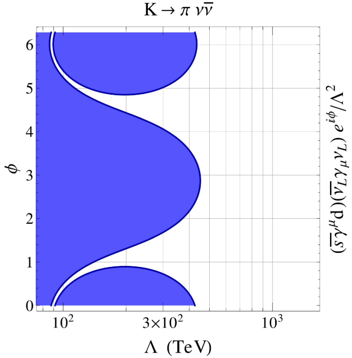


- $K^+ \to \pi^+\nu\bar{\nu}$ already constrains scales of $\sim$ 100 TeV
- $K_L \to \pi^0\nu\bar{\nu}$ bound still above the Grossman-Nir bound $\to$ no additional constraint

current situation



assuming 5% measurements of both modes



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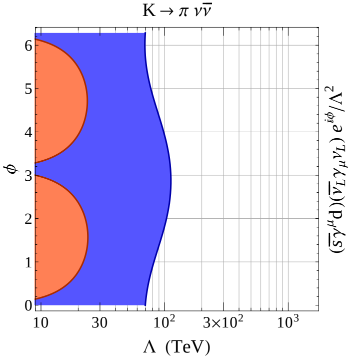

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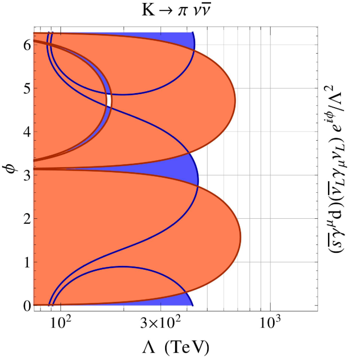


- $K^+ \to \pi^+\nu\bar{\nu}$ already constrains scales of $\sim$ 100 TeV
- $K_L \to \pi^0\nu\bar{\nu}$ bound still above the Grossman-Nir bound $\to$ no additional constraint

- $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ give complementary information
- scales of order 700 TeV are probed

Modified Z Penguins

- in many NP models, largest effects in the Kaon decays come from Z penguins
- model independent parametrization of modified Z couplings

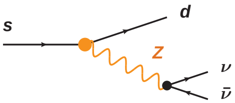
$$(V_{ts}V_{td}^* C_{\rm SM} + C_{\rm NP})(\bar{d}_L \gamma_\mu s_L) Z^\mu \quad + \quad \tilde{C}_{\rm NP}(\bar{d}_R \gamma_\mu s_R) Z^\mu$$

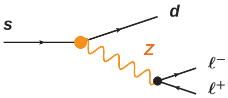
- correlated effects in various processes

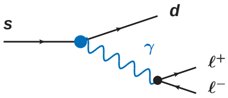
$K \to \pi \nu \bar{\nu}$

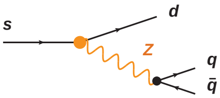
$K_L \to \pi^0 \ell^+ \ell^-$

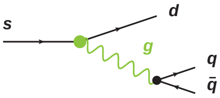
$\epsilon'/\epsilon \quad (K \to \pi\pi)$







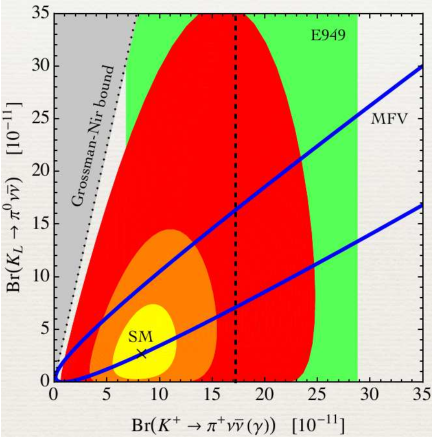




Z Penguins in $K \to \pi\nu\bar{\nu}$

- $|C_{\text{NP}}| \leq 0.5|V_{ts}V_{td}^* C_{\text{SM}}|$
- $|C_{\text{NP}}| \leq |V_{ts}V_{td}^* C_{\text{SM}}|$
- $|C_{\text{NP}}| \leq 2|V_{ts}V_{td}^* C_{\text{SM}}|$

- The assumption of Minimal ~~Flavor~~ CP Violation leads to a strict correlation between the two neutrino modes



talk by Haisch, Project X Physics Study '12

Z Penguins in $K \to \pi\nu\bar{\nu}$

- $|C_{\rm NP}| \leq 0.5 |V_{ts} V_{td}^* C_{\rm SM}|$
- $|C_{\rm NP}| \leq |V_{ts} V_{td}^* C_{\rm SM}|$
- $|C_{\rm NP}| \leq 2 |V_{ts} V_{td}^* C_{\rm SM}|$

- The assumption of Minimal ~~Flavor~~ CP Violation leads to a strict correlation between the two neutrino modes

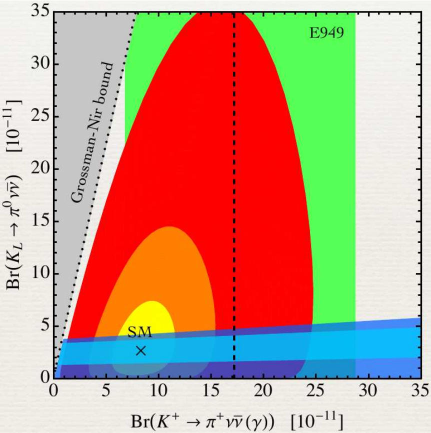
- constraint from ϵ'/ϵ

$$0.2(\epsilon'/\epsilon)_{\rm SM} < \epsilon'/\epsilon < 5(\epsilon'/\epsilon)_{\rm SM}$$

$$0.5(\epsilon'/\epsilon)_{\rm SM} < \epsilon'/\epsilon < 2(\epsilon'/\epsilon)_{\rm SM}$$

excludes huge enhancements of $K_L \to \pi^0\nu\bar{\nu}$

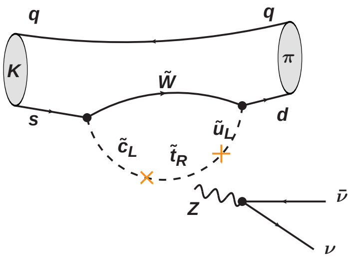
(barring cancellations with contrib. other than Z penguins)



talk by Haisch, Project X Physics Study '12

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

Colangelo, Isidori '98



$$\sim \frac{g^4}{16\pi^2}\frac{1}{M_Z^2}\,(\delta_u^{LR})_{23}(\delta_u^{LR})^*_{13}$$

- dominant contribution comes from a Wino-loop induced Z penguin
- effective $(2 \to 1)$ transition through the third generation $(2 \to 3) \times (3 \to 1)$
- $K \to \pi\nu\bar{\nu}$ decays probe flavor violation in the up-squark sector!
- several motivated frameworks exist that lead to O(1) effects in the BRs

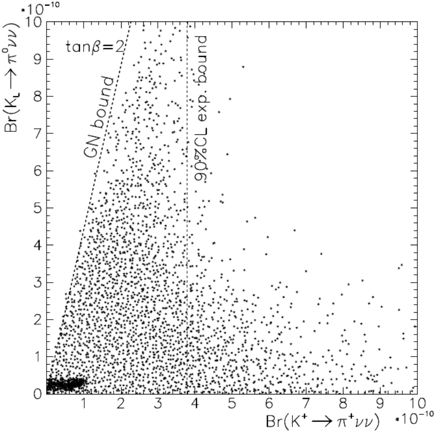
  models with "Radiative Flavor Violation" Crivellin, Hofer, Nierste, Scherer '11
  "Disoriented A terms" Giudice, Isidori, Paradisi '12

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

- large effects in $K \to \pi\nu\bar{\nu}$ cannot be excluded by Kaon and charm mixing constraints
  (mainly sensitive to other, independent sources of flavor violation)

- result of a general scan of the MSSM parameter space, taking into account all relevant constraints (apart from ϵ'/ϵ !):

  both branching ratios can in principle be enhanced by more than an order of magnitude
  (ϵ'/ϵ constraint has to be "fine-tuned away")



Buras, Ewerth, Jager, Rosiek '05

- mixing of elementary SM quarks with heavy composite fermions leads to flavor changing Z couplings already at tree level
- various representations of the heavy fermions, and various flavor structures are possible

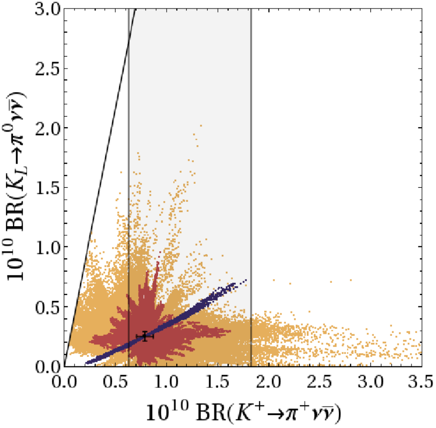
  anarchic triplets

  anarchic bidoublets

  bidoublets with $U(2)^3$ LH compositeness

- strong constraints from ϵ_K do not exclude large effects in the rare decays

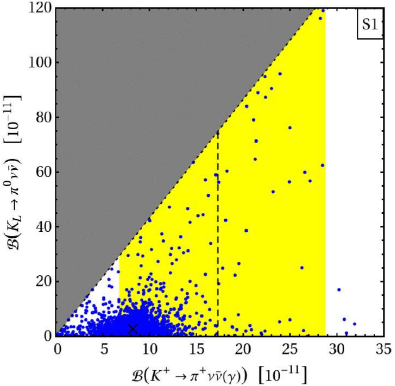
  what about ϵ'/ϵ ?



Straub '13

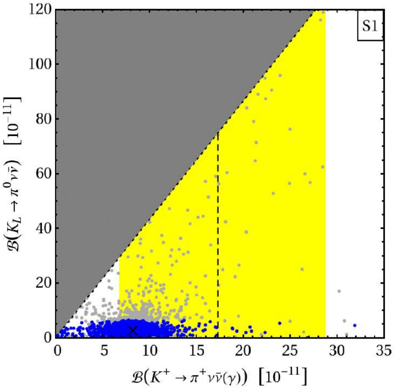
$K \to \pi\nu\bar{\nu}$ in Warped Extra Dimensions

- dual description of the partial composite models:
  composite fermions
  $\leftrightarrow$ KK modes of SM fermions
- model has tree level flavor changing Z couplings
- assuming anarchic flavor structure: no correlation between the charged and neutral mode



Bauer, Casagrande, Haisch, Neubert ’09
(see also Blanke, Buras, Duling, Gemmler, Gori ’08)

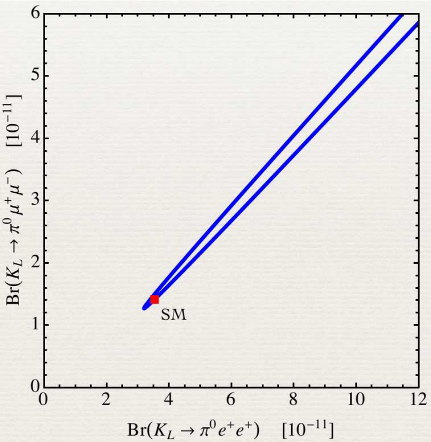
- dual description of the partial composite models:
  composite fermions
  $\leftrightarrow$ KK modes of SM fermions
- model has tree level flavor changing Z couplings
- assuming anarchic flavor structure: no correlation between the charged and neutral mode
- ϵ'/ϵ disfavors very large enhancements of $K_L \to \pi^0\nu\bar{\nu}$
- $K^+ \to \pi^+\nu\bar{\nu}$ not constrained by ϵ'/ϵ



Bauer, Casagrande, Haisch, Neubert '09
(see also Blanke, Buras, Duling, Gemmler, Gori '08)

- leptonic modes receive contributions from Vector, Axialvector, Scalar, and Pseudoscalar operators

  Z penguins



talk by Haisch, Project X Physics Study '12
see also Mescia, Smith, Trine '06

$K \to \pi\ell^+\ell^-$: Z Penguins and Beyond

- leptonic modes receive contributions from Vector, Axialvector, Scalar, and Pseudoscalar operators

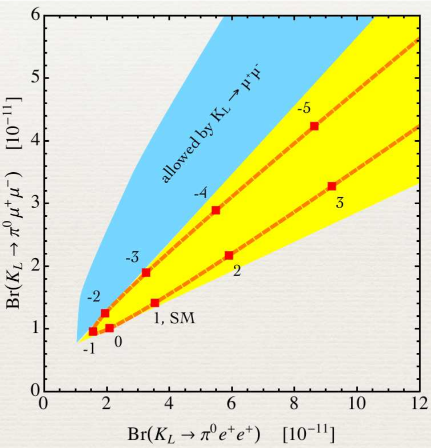
  Z penguins

  SM rescaled

  generic V and A
  ($\sim$ Z penguins + γ penguins)

  also S and P

- $K \to \pi\ell^+\ell^-$ decays allow to disentangle the various contributions



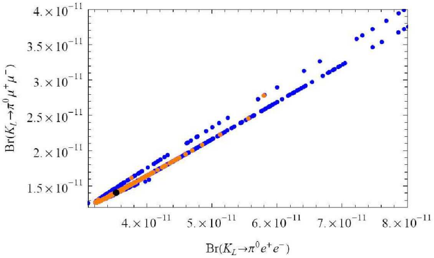
talk by Haisch, Project X Physics Study ’12
see also Mescia, Smith, Trine ’06

$K \to \pi \ell^+ \ell^-$ in Warped Extra Dimensions

- contributions to the decays dominated by Z boson exchange

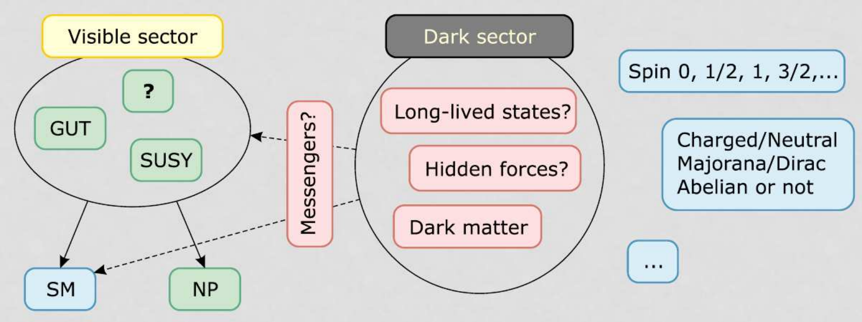
$\to$ clear correlation between the two $K_L \to \pi^0 \ell^+ \ell^-$ branching ratios

can be easily falsified



Blanke, Buras, Duling, Gemmler, Gori ’08
(see also Bauer, Casagrande, Haisch, Neubert ’09)

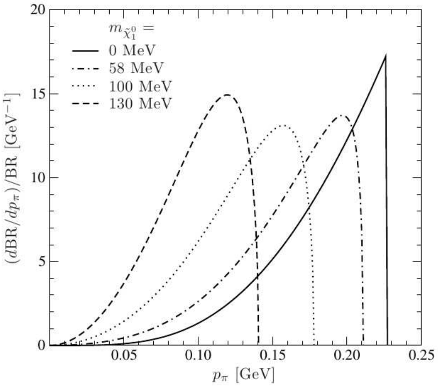
$K \to \pi + \not{E}$ as Portal to Hidden Sectors



talk by Philippe Mertens, Project X Physics Study '12; Kamenik, Smith '11

- there might be new, light, and very weakly coupled states (dark matter, axions, ...)
- rare Kaon decays can provide a portal to hidden sector experimental signature: $K \to \pi + \not{E}$
- model dependent distortion the pion momentum spectrum compared to $K \to \pi\nu\bar{\nu}$

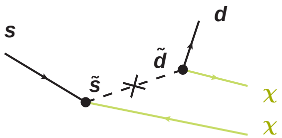
Concrete Example: Very Light Neutralinos



Dreiner et al. ’09

- the mass of the lightest neutralino is largely unconstrained by direct searches
- if M_χ is sufficiently small the $K \to \pi\chi\chi$ decay is possible

tree level



- the p_π spectrum for $K \to \pi\chi\chi$ depends on the mass of the neutralinos

Summary

- the $K_L \to \pi^0 \ell^+ \ell^-$ and in particular the $K \to \pi \nu \bar{\nu}$ decays are theoretically clean and highly sensitive to NP
- 5% measurements of the neutrino modes have discovery potential for New Physics up to scales of almost 1000 TeV
- model discriminating power once information from several decay modes is combined
- $K \to \pi \nu \bar{\nu}$ decays also probe dark sectors