Rare decays and flavour physics: a theoretical overview

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- Introduction
  - The flavour sector of the SM & the flavour problem
- Rare FCNC Kaon decays within the SM
  - Generalities
  - The mangificent four:
    $K^+ \to \pi^+ \nu\nu$, $K_L \to \pi^0 \nu\nu$, $K_L \to \pi^0 e^+ e^-$ & $K_L \to \pi^0 \mu^+ \mu^-$
- Rare FCNC decays beyond the SM
  - Minimal Flavour Violation
  - Beyond the MFV ansatz
- A few comments on rare B, D decays [B, D$\to \mu^+ \mu^-$]
- Conclusions

Introduction

According to:

- solid cosmological evidences [cosmological constant, dark matter, matter-anti-matter asymmetry, inflation, ...]
- convincing theoretical arguments [inclusion of gravity, instability of the Higgs potential, neutrino masses, origin of flavour, ...]

(+ some *religious beliefs* [string theory...])

there is no doubt that the Standard Model

$$\mathscr{L}_{\mathrm{SM}} = \mathscr{L}_{\mathrm{gauge}}(A_i, \psi_i) + \mathscr{L}_{\mathrm{Higgs}}(A_i, \psi_i, \phi)$$

cannot be the end of the story...

...but (unfortunately?) we must admit that the SM works pretty well up to the e.w. scale

Natural to consider the SM as an effective theory, or the low-energy limit of a more fundamental theory, with new degrees of freedom appearing above some energy threshold Λ_{NP}

Given the great success of the SM up to LEP energies:

- $\Lambda_{NP} \geq \langle\phi\rangle \sim 250$ GeV
- the new d.o.f. must respect the $SU(3)\times SU(2)\times U(1)$ gauge symmetry

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{gauge}}(A_i, \psi_i) + \mathscr{L}_{\text{Higgs}}(A_i, \psi_i, \phi) + \Sigma_i \frac{c_i}{\Lambda_{NP}} O_i^{(d\geq 5)} + \ldots$$

general parameterization of the possible new heavy d.o.f.
valid as long as we perform low-energy experiments

Key questions:

- How large can Λ_{NP} be?
- Which is the nature (⇔ symmetries) of the new degrees of freedom?

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Key questions:

- How large can Λ_{NP} be?
- Which is the nature ($\Leftrightarrow$ symmetries) of the new degrees of freedom?

Flavour physics – and particularly precision studies of rare decays – provides a key ingredient to answer these questions

The flavour sector of the SM:

$$\mathscr{L}_{\mathrm{SM}} = \mathscr{L}_{\mathrm{gauge}}(A_{\mathrm{i}}, \psi_{\mathrm{i}}) + \mathscr{L}_{\mathrm{Higgs}}(A_{\mathrm{i}}, \psi_{\mathrm{i}}, \phi)$$

3 identical replica of the basic fermion family

flavour degeneracy broken by the Yukawa interaction

$$Q_i \, Y_d^{ij} \, d_j \, \phi \;\rightarrow\; Q_i \, M_d^{ij} \, d_j$$

$$Q_i \, Y_u^{ij} \, u_j \, \phi_c \;\rightarrow\; Q_i \, M_u^{ij} \, d_j$$

$$M_d = \mathrm{diag}(\mathrm{m_d}, \mathrm{m_s}, \mathrm{m_b})$$

$$M_u^{+} = \mathrm{diag}(\mathrm{m_u}, \mathrm{m_c}, \mathrm{m_t}) \times \mathrm{V_{CKM}}$$

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Nowadays we have a good knowledge of all the 10 observables entries [6 masses + 4 CKM angles] of the quark mass matrices:

- strong hierarchical structure
- no clear symmetric pattern

$$M_d = \mathrm{diag}(m_d, m_s, m_b)$$

$$M_u^+ = \mathrm{diag}(m_u, m_c, m_t) \times V_{\mathrm{CKM}}$$

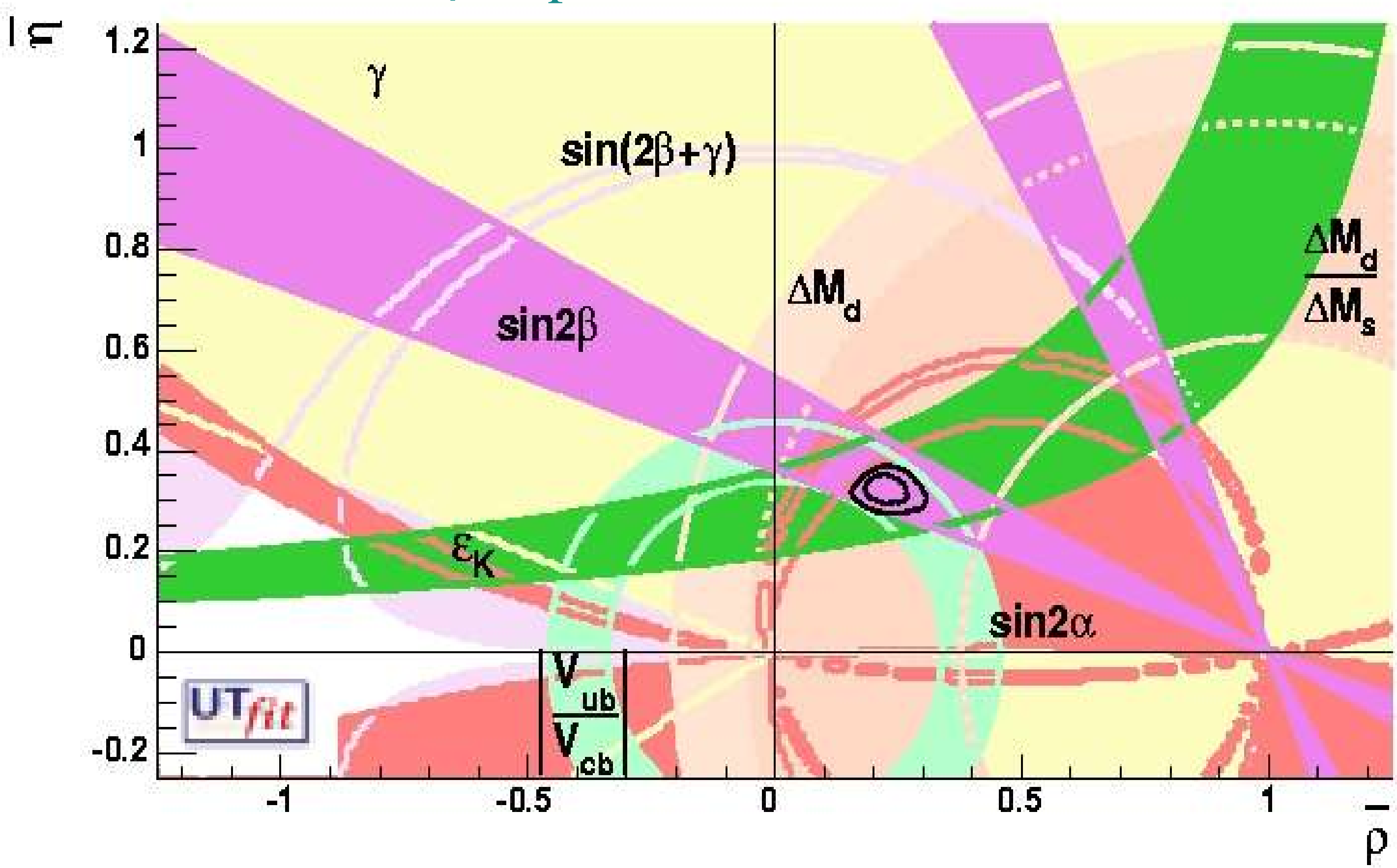
$$V_{CKM} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4) \qquad \lambda = \sin\theta_c \approx 0.22$$

$A\lambda^3(\rho - i\eta) \longrightarrow V_{ub}$

$V_{td} \longleftarrow A\lambda^3(1-\rho-i\eta)$

Wolfenstein, ' 83

ρ-η plane: ICHEP '04 status



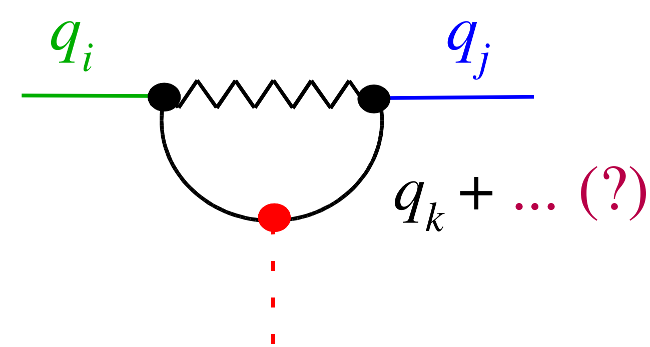
courtesy of UT_{fit}
M. Bona *et al.*

➡ Precision studies of rare decays can (slightly) improve our knowledge of the CKM matrix but their main interest is in probing the flavour structure of new physics:

⬇

Rare processes mediated by
Flavor Changing Neutral Currents
are the ideal candidates

$$q_i \rightarrow q_j + \gamma,\ l^+l^-,\ \nu\bar{\nu}$$

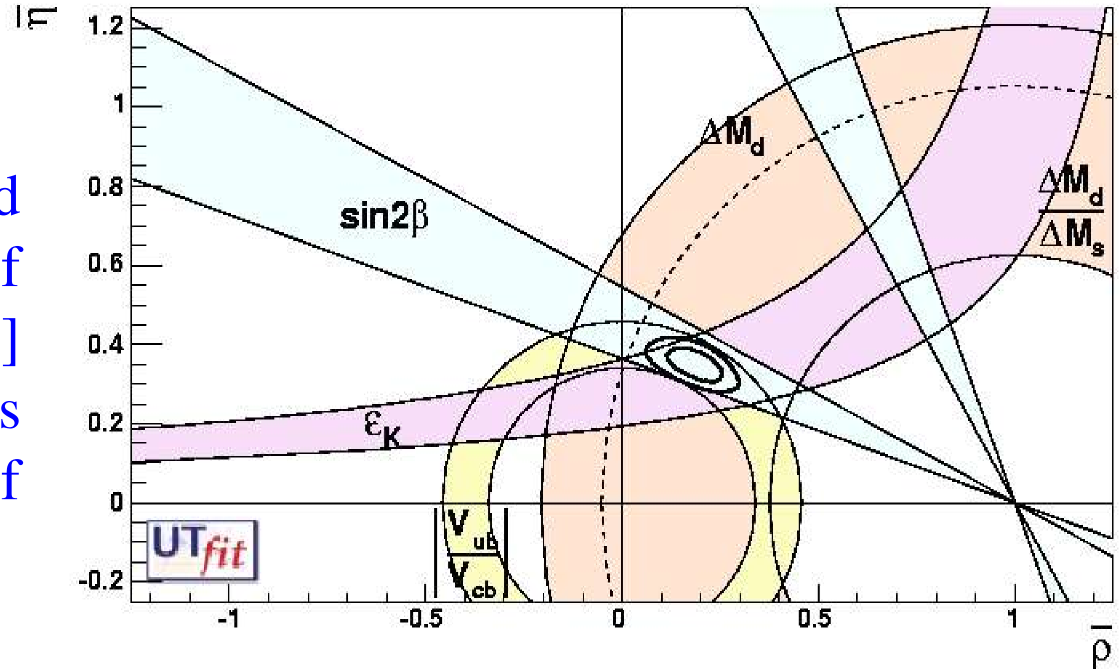


- no SM tree-level contribution
- strong suppression – within the SM – by CKM hierarchy
- calculable with high precision within the SM if dominated by short-distance dynamics [*key point*]

precise determination of flavor mixing within the SM

enhanced sensitivity to
[*the flavour structure of*]
physics beyond the SM

The flavour problem:



Precise data on loop-induced flavour-changing processes of ΔF=2 type [*K-K & B-B mixing*] already provide stringent bounds on possible new degrees of freedom beyond the SM

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Higgs}(A_i, \psi_i, \phi) + \Sigma_i \boxed{\frac{c_i}{\Lambda_{\rm NP}} O_i^{(d \geq 5)}} + \ldots$$

E.g.: K^0-$\bar{K}^0$ mixing $\Rightarrow$ $\Lambda_{\rm NP} > 10^3$ TeV for $O^{(6)} \sim (\bar{s}d)^2$

...while a natural stabilization of the Higgs sector $\Rightarrow$ $\Lambda_{\rm NP} \sim 1$ TeV

Two possible solutions:

- *pessimistic* [very unnatural]: $\Lambda > 100$ TeV
  $\Rightarrow$ almost nothing to learn from rare decays
  (but also very difficult to find evidences of NP at LHC...)

- *natural*: $\Lambda \sim 1$ TeV + flavor-mixing protected by additional symmetries
  $\Rightarrow$ still a lot to learn from rare decays:

  - present fits of the CKM unitarity triangle involve only $\Delta F=2$ loops + tree-level amplitudes $\Rightarrow$ we known very little yet about rare $\Delta F=1$ FCNC transitions

  - CKM fits provide mainly a consistency check of the SM hypothesis but do not provide a bound on the NP parameter space $\Rightarrow$ only with the help of rare decays we can study the underlying flavor symmetry in a model-independent way

Towards a model independent approach to the flavour problem:

FLAVOUR STRUCTURE

ELECTROWEAK STRUCUTRE

	b→s	b→d	s→d
ΔF=2 box	$\bar{Q}_b \gamma^\mu Q_s \bar{Q}_b \gamma_\mu Q_s$	$\cdots$	
ΔF=1 4-quark box	$\vdots$		
gluon penguin			
γ penguin			
Z^0 penguin			
H^0 penguin			

The FCNC matrix:

each box correspond to an indep. combination of dim.-6 SU(3)× SU(2)×U(1)-invariant operators

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ELECTROWEAK STRUCUTRE

	$b\to s$	$b\to d$	$s\to d$
$\Delta F=2$ box	ΔM_d $A_{CP}(B_s\to\psi K)$	ΔM_s $A_{CP}(B_s\to\psi\phi)$	ΔM_K ε_K
$\Delta F=1$ 4-quark box	$B_d\to\pi K$, $B_d\to\eta K$, $A_{CP}(B_d\to\phi K)$, ...	$B_d\to\pi\pi$, $B_d\to\rho\pi$, $A_{CP}(B_d\to\pi\pi)$, ...	ε'/ε, $A_{CP}(K\to 3\pi)$, ...
gluon penguin	$B_d\to X_s\gamma$, $B_d\to\pi K$, $A_{CP}(B_d\to\phi K)$, ...	$B_d\to X_d\gamma$, $B_d\to\pi\pi$, $A_{CP}(B_d\to\pi\pi)$, ...	$K_L\to\pi^0 l^+ l^-$, ε'/ε, ...
γ penguin	$B_d\to X_s l^+ l^-$, $B_d\to X_s\gamma$ $B_d\to\pi K$, $B_s\to KK$, ...	$B_d\to X_d l^+ l^-$, $B_d\to X_d\gamma$ $B_d\to\pi\pi$, $B_s\to\pi K$, ...	$K_L\to\pi^0 l^+ l^-$, ε'/ε, ...
Z^0 penguin	$B_d\to X_s l^+ l^-$, $B_s\to\mu^+\mu^-$ $B_d\to\pi K$, $B_s\to KK$, ...	$B_d\to X_d l^+ l^-$, $B_d\to\mu^+\mu^-$ $B_d\to\pi K$, $B_s\to KK$, ...	$K_L\to\pi^0 l^+ l^-$, $K_L\to\pi^0\nu\nu$, $K^+\to\pi^+\nu\nu$, ε'/ε, ...
H^0 penguin	$B_s\to\mu^+\mu^-$	$B_d\to\mu^+\mu^-$	$K_{L,S}\to\mu^+\mu^-$

Towards a model independent approach to the flavour problem:

Th. error $\lesssim 10\%$

decreasing SM contrib. →

		$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
	$\Delta F=2$ box	ΔM_d $A_{CP}(B_s \to \psi K)$	ΔM_s $A_{CP}(B_s \to \psi\phi)$	ΔM_K ε_K
decrea-sing SM contrib. ↓	$\Delta F=1$ 4-quark box	$B_d \to \pi K$, $B_d \to \eta K$, $A_{CP}(B_d \to \phi K)$, ...	$B_d \to \pi\pi$, $B_d \to \rho\pi$, $A_{CP}(B_d \to \pi\pi)$, ...	ε'/ε, $A_{CP}(K \to 3\pi)$, ...
	gluon penguin	$B_d \to X_s\gamma$, $B_d \to \pi K$, $A_{CP}(B_d \to \phi K)$, ...	$B_d \to X_d\gamma$, $B_d \to \pi\pi$, $A_{CP}(B_d \to \pi\pi)$, ...	$K_L \to \pi^0 l^+ l^-$, ε'/ε, ...
	γ penguin	$B_d \to X_s l^+ l^-$, $B_d \to X_s\gamma$ $B_d \to \pi K$, $B_s \to KK$, ...	$B_d \to X_d l^+ l^-$, $B_d \to X_d\gamma$ $B_d \to \pi\pi$, $B_s \to \pi K$, ...	$K_L \to \pi^0 l^+ l^-$, ε'/ε, ...
	Z^0 penguin	$B_d \to X_s l^+ l^-$, $B_s \to \mu^+\mu^-$ $B_d \to \pi K$, $B_s \to KK$, ...	$B_d \to X_d l^+ l^-$, $B_d \to \mu^+\mu^-$ $B_d \to \pi K$, $B_s \to KK$, ...	$K_L \to \pi^0 l^+ l^-$, $K_L \to \pi^0 \nu\nu$ $K^+ \to \pi^+ \nu\nu$, ε'/ε, ...
	H^0 penguin	$B_s \to \mu^+\mu^-$	$B_d \to \mu^+\mu^-$	$K_{L,S} \to \mu^+\mu^-$

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decrea-sing SM contrib.

= exp. error $\lesssim 10\%$ = exp. error $\sim$ 30-50%

Rare FCNC Kaon decays within the SM

General decomposition

of the decay amplitude for $K \to \pi + l^+l^- / \nu\nu$ modes:

I. Clean electroweak short-distance component

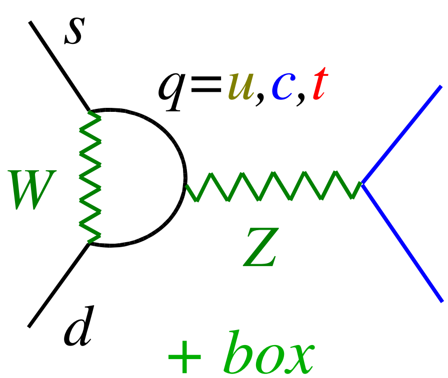
- similar -within the SM- for all the channels
- modified by NP in (very) different ways in the various channels

II. Long-distance component of e.m. origin

- relevant to $K \to \pi + l^+l^-$ modes only
- insensitive to NP

I. The clean electroweak short-distance amplitude

Z-penguin + W-box diagrams $\Rightarrow$ scale-independent amplitude dominated by *short-distance* [top-quark] thanks to the *"har d"* GIM mechanism:



$$\Rightarrow \quad A^{q}_{\text{loop}} \sim m_q^2 V^*_{qs} V_{qd} \sim \begin{cases} \Lambda^2_{QCD}\,\lambda & \textbf{(u)} \\ m_c^2\,\lambda + i\, m_c^2\,\lambda^5 & \textbf{(c)} \\ m_t^2\,\lambda^5 + i\, m_t^2\,\lambda^5 & \textbf{(t)} \end{cases}$$

- Genuine $O(G_F^2)$ effect
- QCD corrections small and known beyond LO
- large CPV-phase contributing to $\boxed{K_L \to \pi^0 + \nu\nu, l^+l^-}$

$$\mathcal{H}_{\text{eff}} = \sum_i C_i(M_W)\, Q_i$$

$$\begin{cases} Q_\nu = (\bar{s}\,d)_{V-A}(\bar{\nu}\,\nu)_{V-A} \\ Q_{9V} = (\bar{s}\,d)_{V-A}(\bar{l}\,l)_{V} \\ Q_{10A} = (\bar{s}\,d)_{V-A}(\bar{l}\,l)_{A} \end{cases}$$

Neutrino modes:

- Hadronic matrix element of the leading operator directly extracted from K_{l3}
- No sizable long distance corrections [only Z-penguin & W-box $\Rightarrow$ hard GIM suppression effective also for the leading l.d. terms]
- Dominant uncertainty from the perturbative charm contribution [NNLO corr.] + subleading long distance terms [power-suppressed higher-dim. operators]

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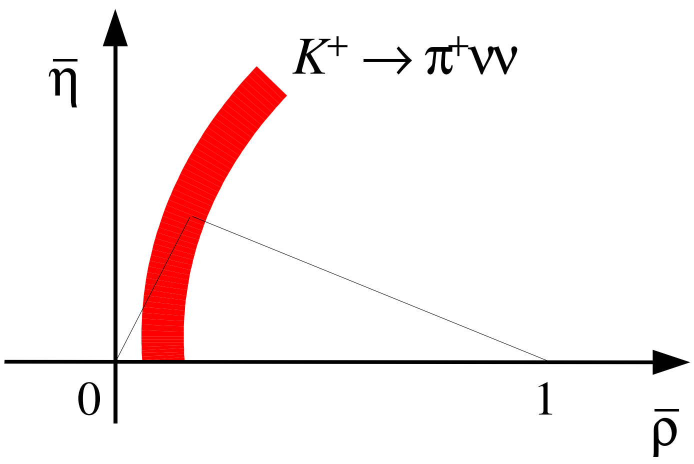
$\boxed{K^+ \to \pi^+ \nu\nu}$

Buchalla & Buras '97
Lu & Wise ' 94 Falk *et al.* ' 00

large fraction of the present error still due to parametric CKM uncertainties

$$\mathrm{BR}(K^+)^{[\mathrm{SM}]} = C\,|V_{cb}|^4\,[(\bar\rho - \rho_c)^2 + (\sigma\bar\eta)^2] = (8.0 \pm 1.0)\cdot 10^{-11}$$

$$\rho_c = 1.40 \pm 0.06 \quad \Rightarrow \quad \delta\,\mathrm{BR_{th}} \approx 8\%$$



On-going theoretical activity to reduce $\delta\,\mathrm{BR_{th}}$ below the 5% level: Munich, Frascati

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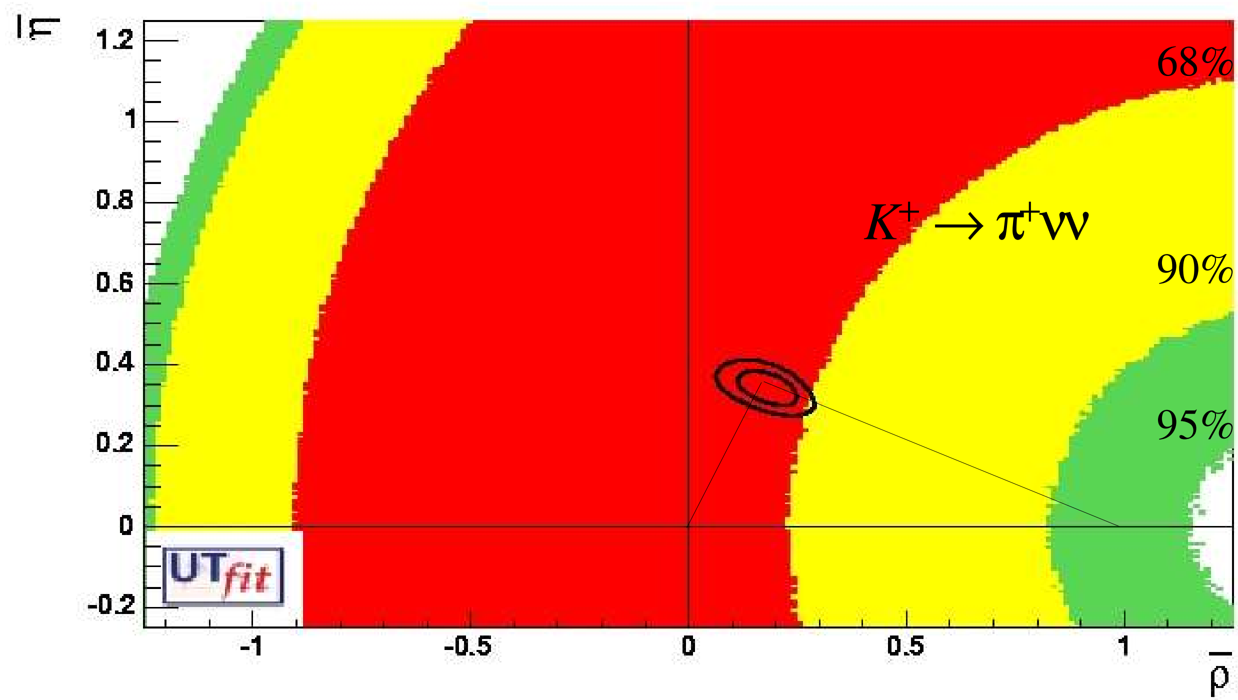
$$\mathrm{BR}(K^+)^{\mathrm{exp}} = (1.47^{+1.9}_{-0.9}) \cdot 10^{-10}$$

E787+E949 [BNL] ' 40



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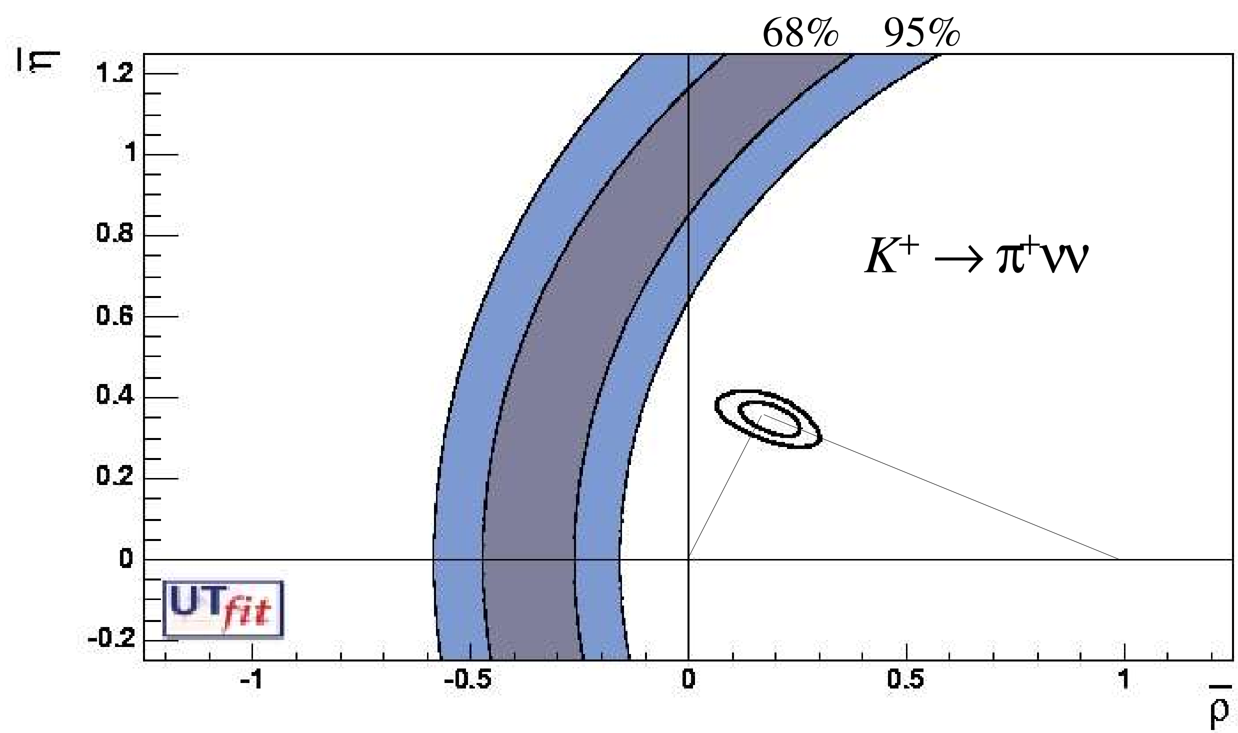
if we could decrease the error at the 10% level...

$$\mathrm{BR}(K^+)^{\mathrm{exp}} = (1.47\,\cancel{{}^{+1.9}_{-0.9}}) \cdot 10^{-10}$$

$\pm 10\%$ $\longrightarrow$

The situation could become quite interesting...



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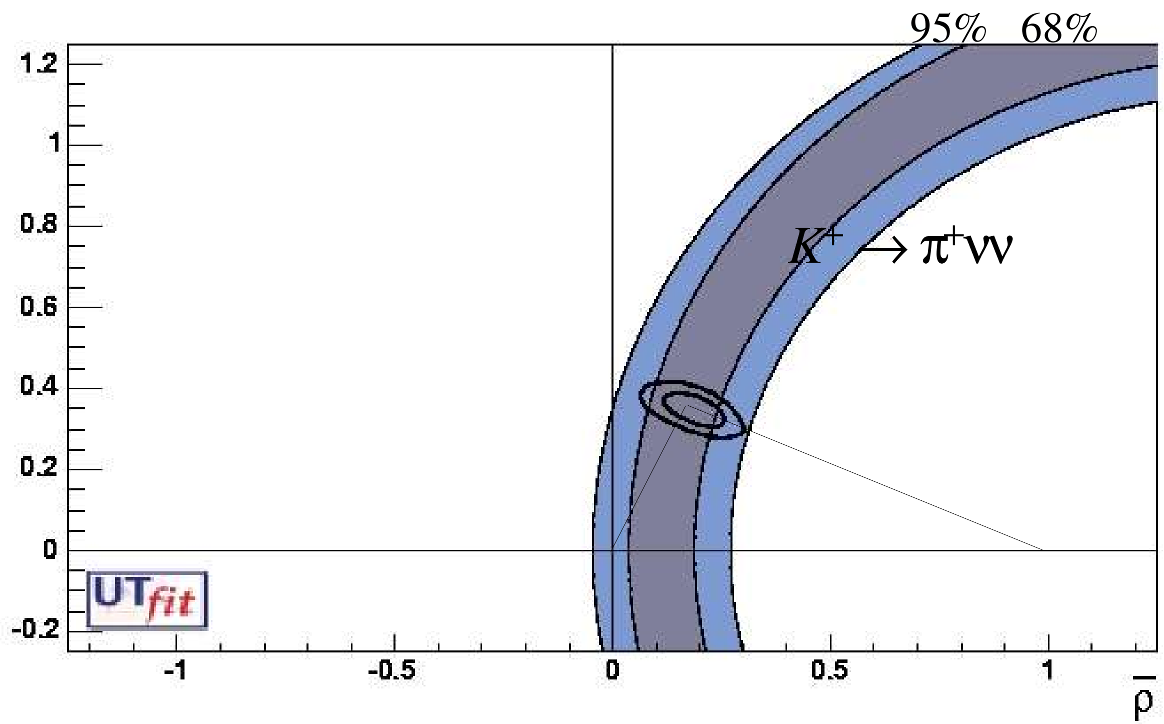
N.B.: plotting the $\mathrm{BR}(K^+)^{\mathrm{exp}}$ contour in the ρ–η plane is only a fast way to compare it with the SM prediction:

the main interest of such measurement is not a more precise determination of V_{td} but the extraction of a key information about NP



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$K_L \to \pi^0 \nu\nu$ $\Rightarrow$ peculiar CP structure $\Rightarrow$ charm & l.d. effects further suppressed (~ negligible)

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

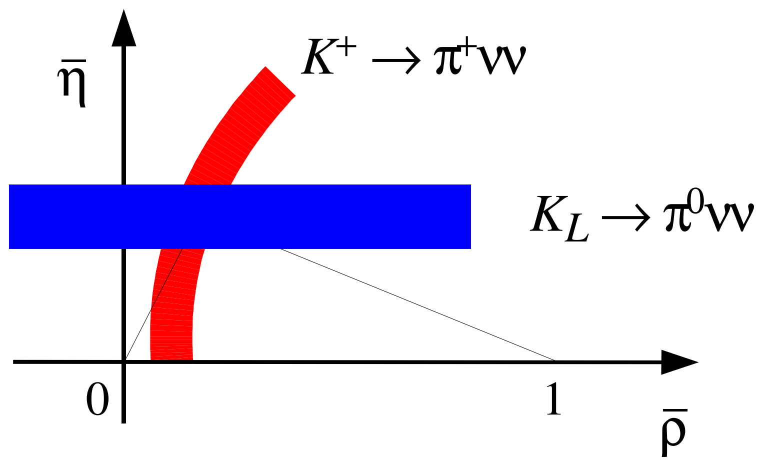
Littenberg, '89
Buchalla & Buras '97
Buchalla & G.I. ' 98

$$\mathrm{BR}(K_L)^{[\mathrm{SM}]} = 1.48 \cdot 10^{-11} \left[\frac{m_t(m_t)}{166\ \mathrm{GeV}}\right]^{2.3} \left[\frac{\mathrm{Im}(V_{ts}{}^{*} V_{td})}{10^{-4}}\right]^{2}$$

$$= (3.0 \pm 0.6) \cdot 10^{-11}$$

th. error ~ 2% !

control the amount of CPV within the SM



$\boxed{K_L \to \pi^0 \, l^+ l^-}$

The 3 components of the $K_L \to \pi^0 \, l^+ l^-$ amplitude:

A. direct CPV amplitude

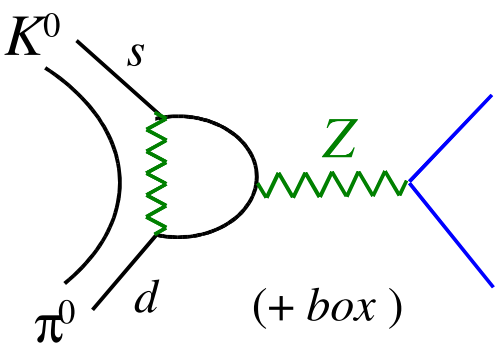
- short-distance dominated
- very similar to $K_L \to \pi^0 \nu\nu$

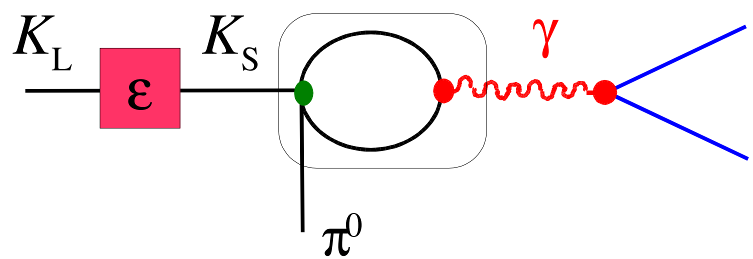
interference

B. indirect CPV

- determined by $\boxed{K_S \to \pi^0 \, l^+ l^-}$

need exp. input



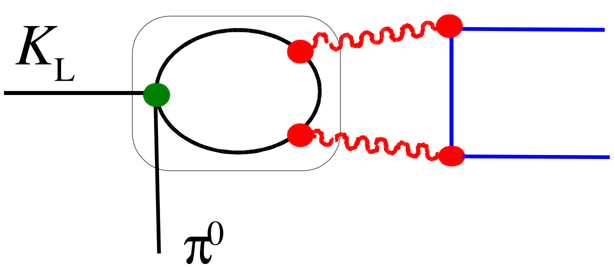


C. CPC amplitude

- no interference & different Dalitz plot
- predicted by theory with good accuracy

in terms of rate & spectrum of $\boxed{K_L \to \pi^0 \gamma\gamma}$

need exp. input



$\boxed{K_L \to \pi^0 l^+ l^-}$

Thanks to some recent results by NA48-NA48/1:

$$B(K_S \to \pi^0 e^+ e^-)_{m_{ee} > 165\ \mathrm{MeV}} = (3.0^{+1.5}_{-1.2} \pm 0.2) \cdot 10^{-9}$$

$$B(K_S \to \pi^0 \mu^+ \mu^-) = (2.9^{+1.4}_{-1.2} \pm 0.2) \cdot 10^{-9}$$

$$B(K_L \to \pi^0 \gamma\gamma)_{m_{\gamma\gamma} < 110\ \mathrm{MeV}} < 0.9 \cdot 10^{-8}$$

+

Some related th. works:

Buchalla, D' Ambrosio, G.I. ' 03
G.I., Smith, Unterdorfer '04
Friot, Grenat, de Rafael ' 04

We finally have a clear picture of the various terms:

$$B(K_L \to \pi^0 l^+ l^-)^{[SM]} = [\, C_{mix} + C_{int}\, y_t + C_{dir}\, y_t^2 + C_{CPC} \,] \cdot 10^{-12} \qquad y_t = \frac{\mathrm{Im}(V_{ts}^* V_{td})}{10^{-4}}$$

$$(e^+ e^-) \quad \approx \quad 23 \quad + \quad (10 \quad + \quad 4) \quad + \quad 0 \quad \Rightarrow \quad (3.7 \pm 1.0) \cdot 10^{-11}$$

$$(\mu^+ \mu^-) \quad \approx \quad 5.4 \quad + \quad (2.5 \quad + \quad 1.8) \quad + \quad 5.2 \quad \Rightarrow \quad (1.5 \pm 0.3) \cdot 10^{-11}$$

$B(K_L \to \pi^0 e^+ e^-)^{[SM]} = (3.7 \pm 1.0) \cdot 10^{-11}$ [≈ 50% due to short dist.]

$B(K_L \to \pi^0 \mu^+ \mu^-)^{[SM]} = (1.5 \pm 0.3) \cdot 10^{-11}$ [≈ 30% due to short dist.]

Errors on SM predictions dominated by the large (exp.) uncertainty on $B(K_S \to \pi^0 l^+ l^-)$, but <u>irreducible theoretical error below 10%</u>

$\Updownarrow$

$B(K_L \to \pi^0 e^+ e^-)^{exp} < 2.8 \cdot 10^{-10}$ [90% CL] KTeV '03

$B(K_L \to \pi^0 \mu^+ \mu^-)^{exp} < 3.8 \cdot 10^{-10}$ [90% CL] KTeV '00

not too far...

$\Downarrow$

<u>Very interesting candidates for future dedicated experiments</u>

- More observables to be studied [Dalitz plot, time-dependent distrib.]
- Different sensitivity to NP with respect to $K_L \to \pi^0 \nu\nu$

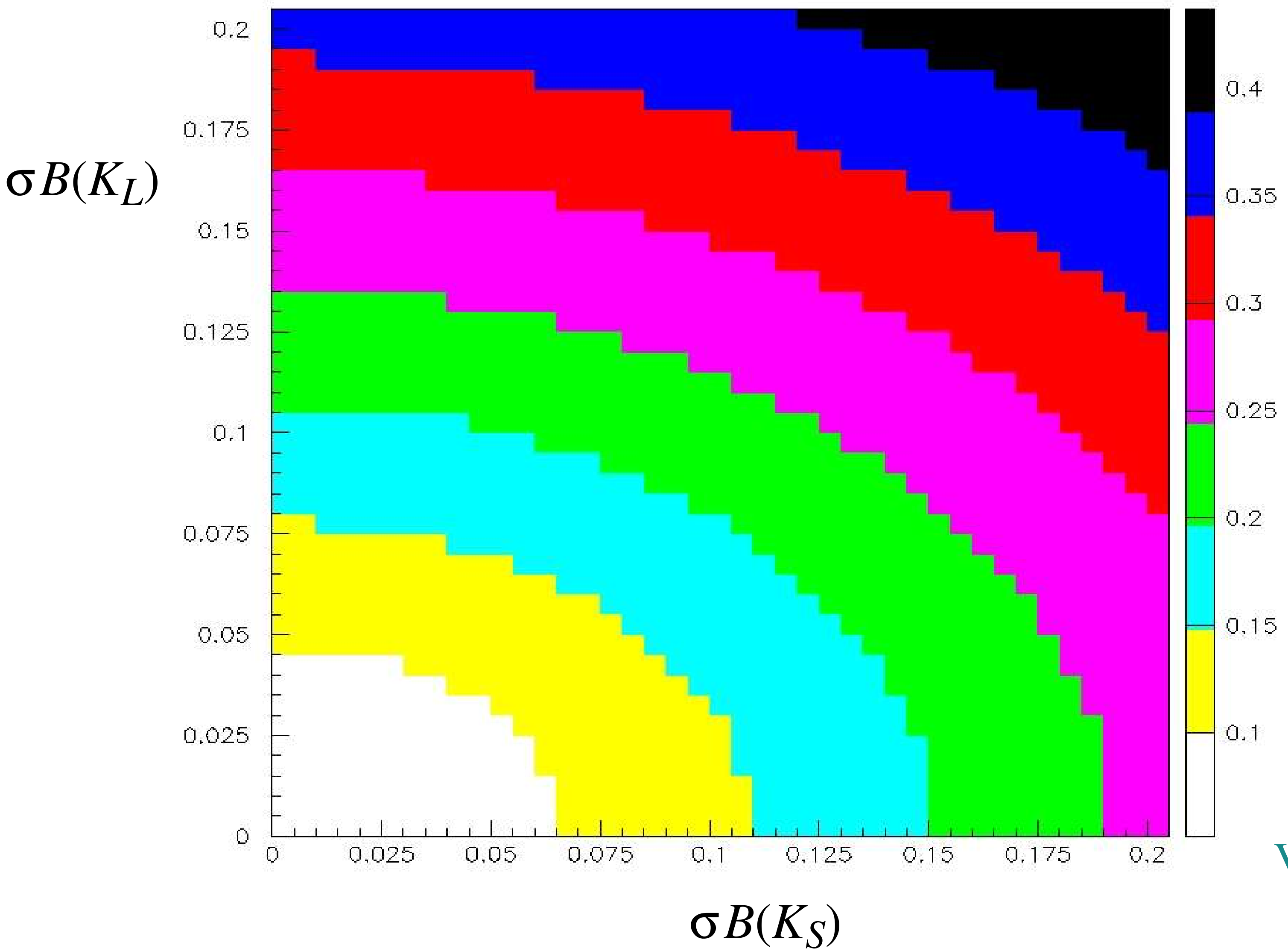
the 3 decay modes $K_L \to \pi^0 +$ e^+e^-, $\mu^+\mu^-$, $\nu\,\nu$
are sensitive to different short-distance structures
$\Rightarrow$ 3 independent info on NP

$$Q_\nu = (\bar{s}\,d)_{V-A}(\bar{\nu}\,\nu)_{V-A}$$
$$Q_{9V} = (\bar{s}\,d)_{V-A}(\bar{l}\,l)_{V}$$
$$Q_{10A} = (\bar{s}\,d)_{V-A}(\bar{l}\,l)_{A}$$

Relative error on $\mathrm{Im}(V_{ts}^{*}V_{td})$

vs.

relative exp. errors on $B(K_S \to \pi^0 e^+ e^-)$ & $B(K_L \to \pi^0 e^+ e^-)$



courtesy of
V. Patera [KLOE]

Rare FCNC decays beyond the SM

Natural solution of the flavour (+hierarchy) problem:

$\Lambda \sim 1$ TeV + flavor-mixing protected by additional symmetries

As long as we are interested only in low-energy rare processes, the most important feature of the NP model is the nature of this symmetry

• Rare FCNC decays beyond the SM

Natural solution of the flavour (+hierarchy) problem:

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As long as we are interested only in low-energy rare processes, the most important feature of the NP model is the nature of this symmetry

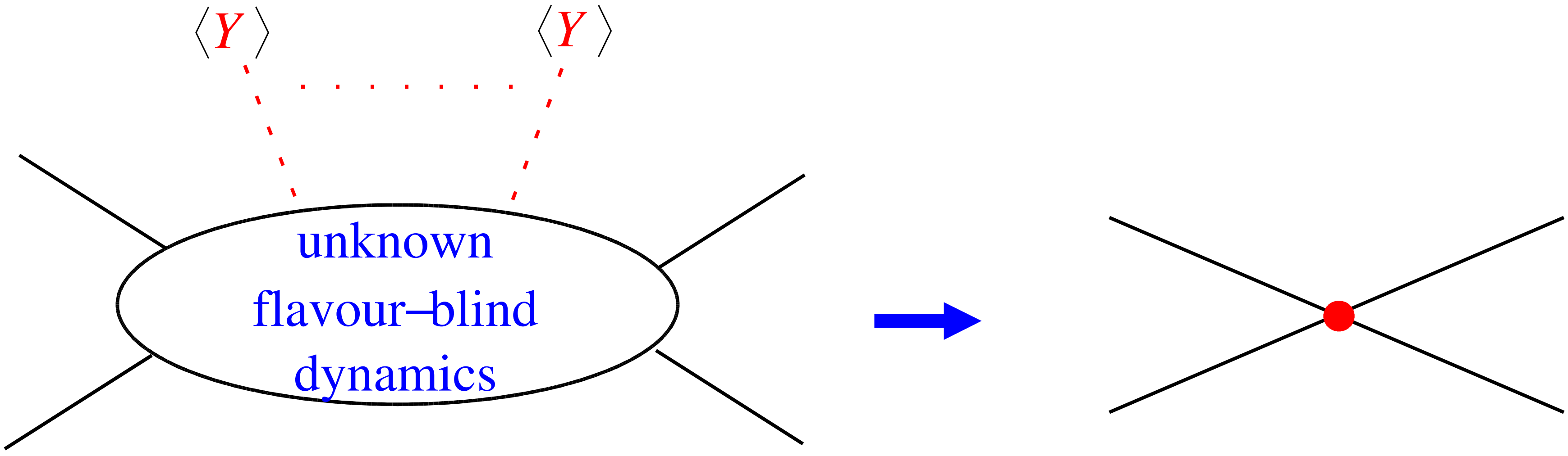
most restrictive possibility

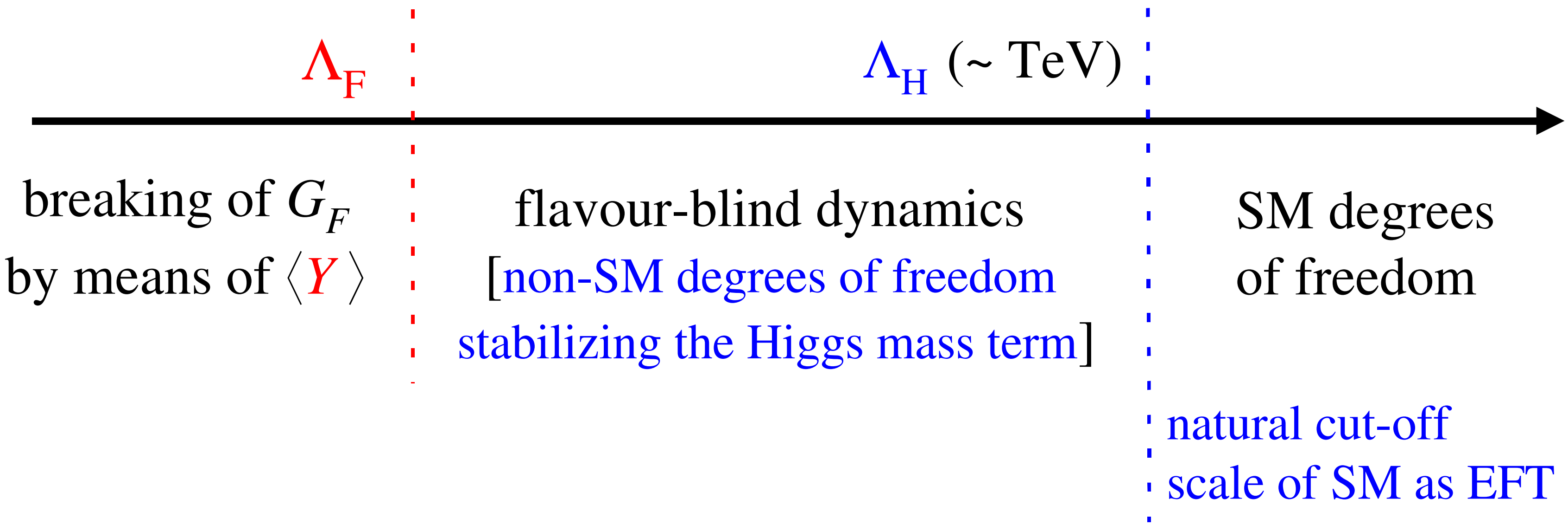
Minimal Flavour Violation (MFV) hypothesis:

The breaking of the flavour symmetry occurs at very high scales and is mediated at low energies only by terms prop. to SM Yukawa couplings

- natural implementation in many consistent scenarios
  [SUSY, technicolour, extra dimensions,...]

- possible to build a predictive low-energy EFT
  model-independent approach



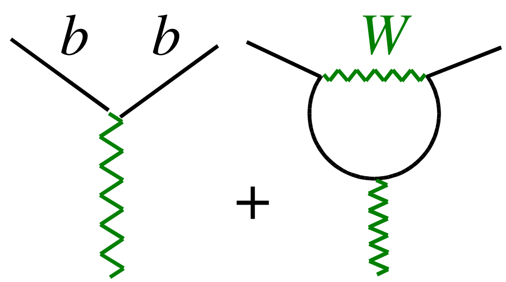


The MFV hypothesis can be considered as the <u>most pessimistic scenario</u>:

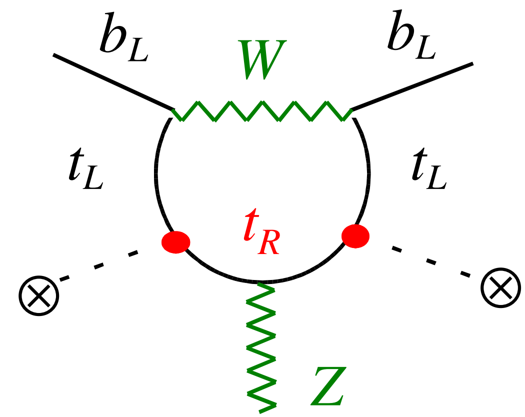
$\Rightarrow$ deviations from the SM in FCNCs bounded by flavour-conserving e.w. precision observables

E.g.: Z-penguins & R_b

$$R_b = \frac{\Gamma(Z\to bb)}{\Gamma(Z\to \text{had})}$$



breaking of universality $\longrightarrow$ driven by



$$R_b = R_d\,[\,1 - \boxed{G_F m_t^2/2\pi^2\sqrt{2}} + \ldots\,] \approx 0.2182 - 0.0024$$

$$R_b^{exp} = 0.2163 \pm 0.0007$$

tree +flavour univ. terms

$\downarrow$

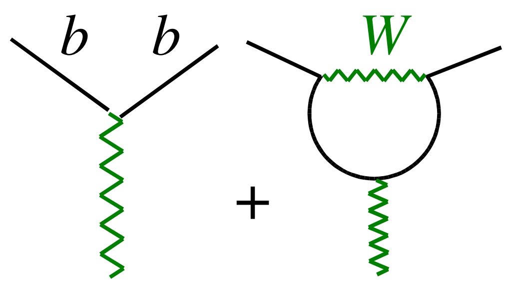
same e.w.-Yukawa structure of the leading $K \to \pi\nu\nu$ amplitude

The $O(10^{-3})$ accuracy on R_b of LEP let us to probe the genuine e.w.-Yukawa loop amplitude only at the 30% level

A 10% measurement of $B(K^+\to \pi^+\nu\nu)$ [or $B\to \pi\nu\nu$] would probe the same e.w.-Yukawa structure (assuming MFV) at the 6-8% level

E.g.: Z-penguins & R_b

$$R_b = \frac{\Gamma(Z\to bb)}{\Gamma(Z\to had)}$$



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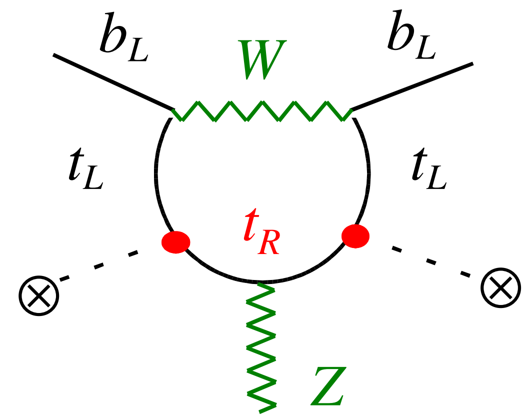

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tree +flavour univ. terms

same e.w.-Yukawa structure of the leading $K\to\pi\nu\nu$ amplitude

- Even within the most pessimistic NP scenario O(30-50%) deviations from SM possible in BR(rare short-distance dominated FCNC decays)
- O(10%) measurements of BR(rare) probe NP parameter space of NP not cover yet by LEP

Beyond Minimal Flavour Violation

[new sources of flavour symmetry breaking at the TeV scale]

- A priori the most natural possibility
  naturally appearing in several specific scenarios [e.g. SUSY: huge literature]

- challenged -at present- by the good agreement with SM in $\Delta F=2$ sector

Beyond Minimal Flavour Violation

[new sources of flavour symmetry breaking at the TeV scale]

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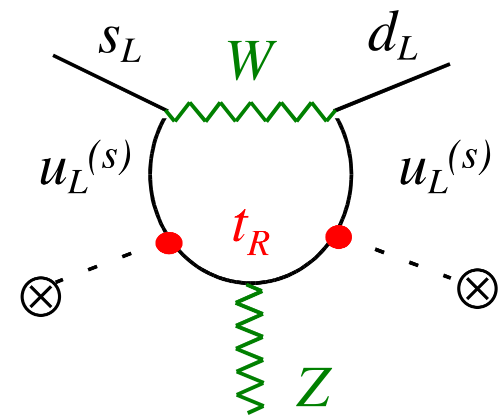
General features:



- Some decoupling between $\Delta F=2$ & $\Delta F=1$
  [i.e.: $\delta_{NP}(\Delta F=1)\sim 100\%$ vs. $\delta_{NP}(\Delta F=2)\sim 10\%$]
  possible thanks to the interplay between SU(2)· U(1) & flavour symm. breaking

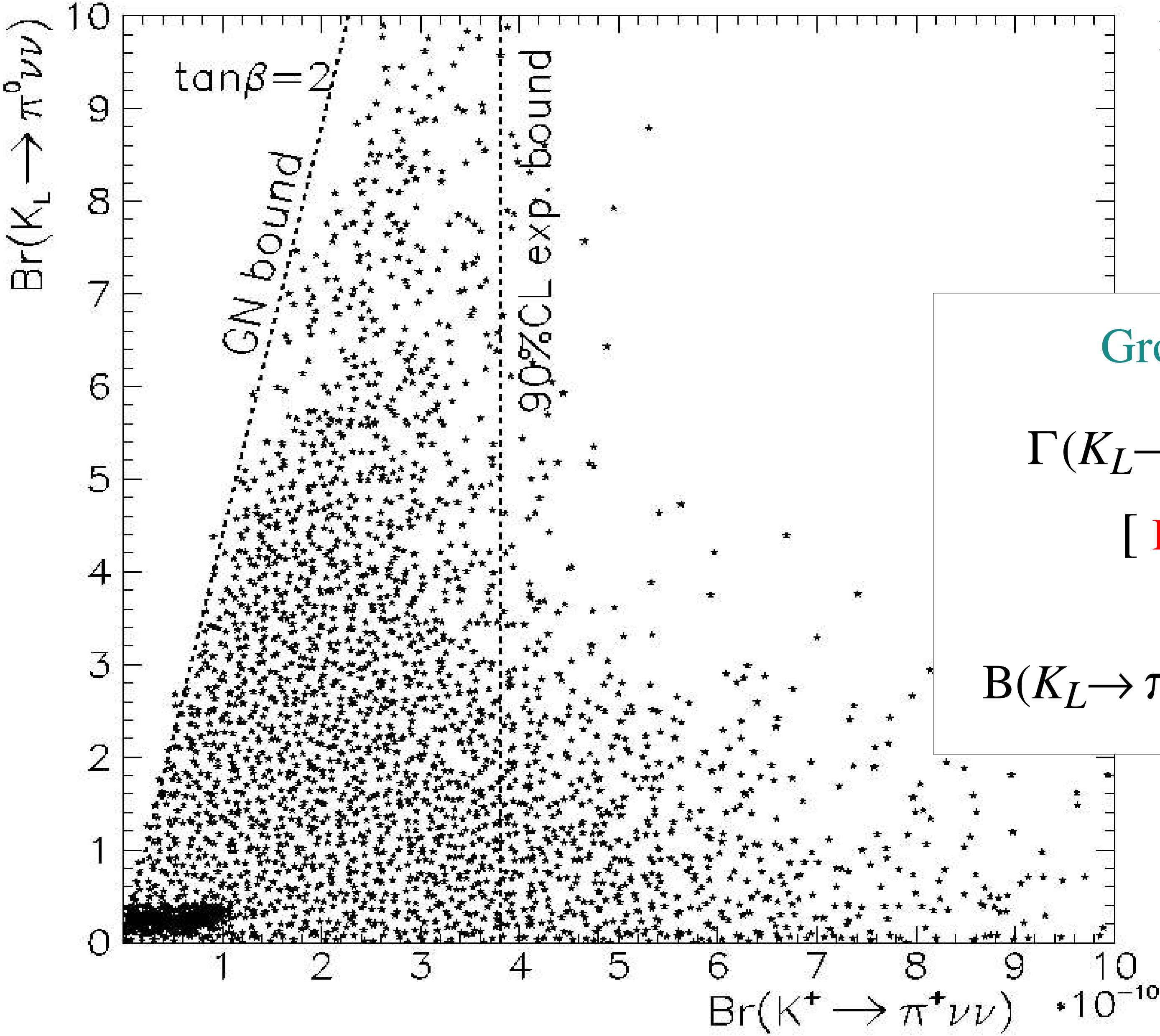
Colangelo & G.I. '98,
Nir & Worah ' 9;
Buras, Romanino & Silvestrini, ' 9

- Rare kaon decays are particularly sensitive to new sources of flavour symm. breaking because of the severe CKM suppression [$V_{ts}^{*}V_{td}\sim\lambda^{5}$]

E.g.: B($K \to \pi\nu\nu$) within generic MSSM

[including all the phenomenological constraints from ε_K, ΔM_K, $b \to s\gamma$, ...]

Buras *et al.* '04



Grossman-Nir bound:

$$\Gamma(K_L \to \pi^0\nu\nu) < \Gamma(K^+ \to \pi^+\nu\nu)$$

$$[\ \mathrm{Im}(A) < |A|\ ]$$

$$\Downarrow$$

$$B(K_L \to \pi^0\nu\nu) < 4.4\ B(K^+ \to \pi^+\nu\nu)$$

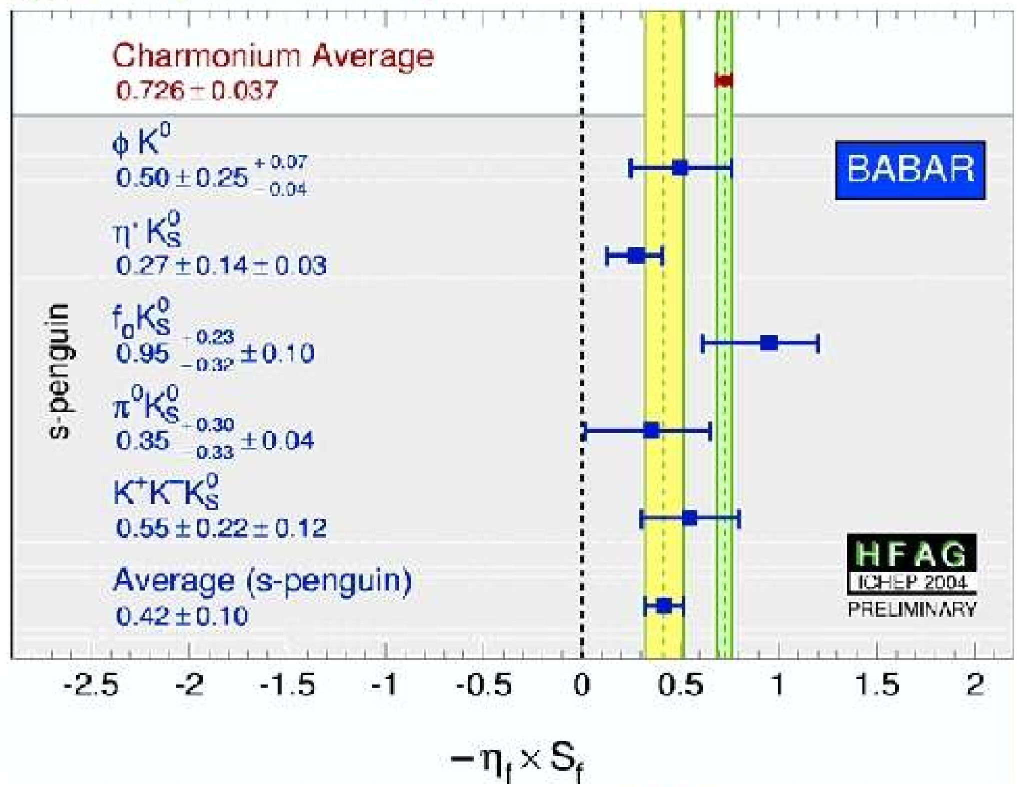
General features on non-MFV models:

- Possible some decoupling between $\Delta F=2$ & $\Delta F=1$ [i.e.: $\delta_{NP}(\Delta F=1)\sim 100\%$ vs. $\delta_{NP}(\Delta F=2)\sim 10\%$] $\Leftrightarrow$ interplay between SU(2)· U(1) & flavour symm. breaking

- Rare K decays are particularly sensitive to new sources of flavour-symmetry breaking

All new!

Giorgi, ICHEP '04



If a 10% deviation from SM is clearly estabilished in time-depedent CPV asymmetries in B decays →

2.7σ from s-penguin to sin2β ($c\bar{c}$)

↓

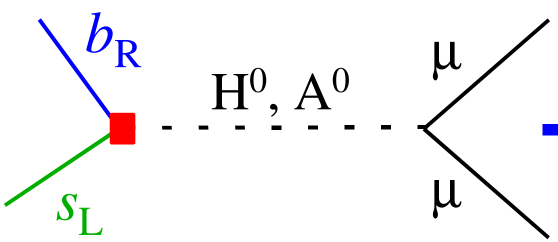
high chances to find O(1) non-standard effects in (at least some) rare K decays

A few comments on rare B, D decays

- The NP sensitivity of inclusive FCNC B decays [$B \to X_{s,d} + \nu\nu,\ l^+l^-$] is quite similar to the one of $K \to \pi + \nu\nu,\ l^+l^-$ [strict correlation in MFV models, different flavour structure in the general case]

- A <u>unique opportunity</u> in B decays is the possibility to probe non-standard scalar FCNCs via $B_{s,d} \to \mu^+\mu^-$ decays:

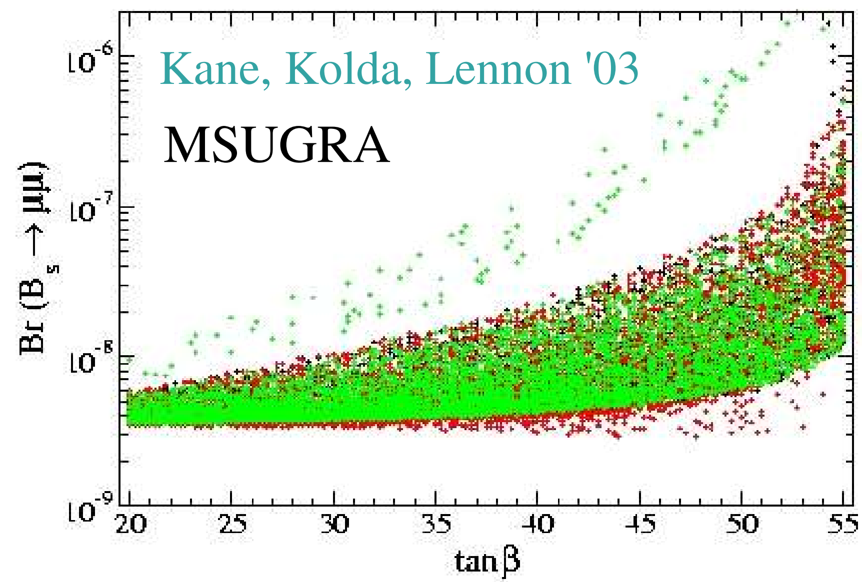
$$\mathrm{BR}(B_s)^{SM} \approx 3 \cdot 10^{-9}$$
$$\mathrm{BR}(B_d)^{SM} \approx 1 \cdot 10^{-10}$$



$$\Rightarrow \quad A_{scalar} \sim \frac{m_b m_\mu}{M_A^2}\ F$$

Scalar amplitude competitive with SM because of helicity suppression + large b-Yukawa coupling

sizable (& unique) NP effects in models with more than one Higgs doublet (even within MFV)



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- A <u>unique opportunity</u> in B decays is the possibility to probe non-standard scalar FCNCs via $B_{s,d} \to \mu^+\mu^-$ decays

- On general grounds, rare D decays are less interesting than B & K decays: dominated by long-distance dynamics which is difficult to control

Notable exceptions:

$D \to \mu^+\mu^-$ $\quad BR^{SM} < 10^{-12} \quad BR^{exp} < 3 \cdot 10^{-6}$

$D \to K,\pi + \nu\nu$ $\quad BR^{SM} < 10^{-15}$

+

LFV modes

Interesting windows for models <u>beyond MFV</u>

Conclusions

Which is the scale of flavour symmetry breaking?
Are there new sources of flavour-symm. breaking beyond the Yukawa?

Short-distance dominated rare decays are a key ingredient to answer these fundamental questions and, more in general, to explore the flavour structure of physics beyond the SM

LHC will *"ki ll the penguins"*
revealing the *"anat omy of the internal constituents"*
but this is not enough
we also need to carefully study *"pen guin ethology"*
via dedicated rare-decay experiments

Th. error $\lesssim$ 10%

decreasing SM contrib. →

decreasing SM contrib. ↓

	$b\to s$ $(\sim\lambda^2)$	$b\to d$ $(\sim\lambda^3)$	$s\to d$ $(\sim\lambda^5)$
$\Delta F=2$ box	ΔM_d $A_{CP}(B_s\to\psi K)$	ΔM_s $A_{CP}(B_s\to\psi\phi)$	ΔM_K ε_K
$\Delta F=1$ 4-quark box	$B_d\to\pi K$, $B_d\to\eta K$, $A_{CP}(B_d\to\phi K)$, ...	$B_d\to\pi\pi$, $B_d\to\rho\pi$, $A_{CP}(B_d\to\pi\pi)$, ...	ε'/ε, $A_{CP}(K\to 3\pi)$, ...
gluon penguin	$B_d\to X_s\gamma$, $B_d\to\pi K$, $A_{CP}(B_d\to\phi K)$, ...	$B_d\to X_d\gamma$, $B_d\to\pi\pi$, $A_{CP}(B_d\to\pi\pi)$, ...	$K_L\to\pi^0 l^+l^-$, ε'/ε, ...
γ penguin	$B_d\to X_s l^+l^-$, $B_d\to X_s\gamma$, $B_d\to\pi K$, $B_s\to KK$, ...	$B_d\to X_d l^+l^-$, $B_d\to X_d\gamma$, $B_d\to\pi\pi$, $B_s\to\pi K$, ...	$K_L\to\pi^0 l^+l^-$, ε'/ε, ...
Z^0 penguin	$B_d\to X_s l^+l^-$, $B_s\to\mu^+\mu^-$, $B_d\to\pi K$, $B_s\to KK$, ...	$B_d\to X_d l^+l^-$, $B_d\to\mu^+\mu^-$, $B_d\to\pi K$, $B_s\to KK$, ...	$K_L\to\pi^0 l^+l^-$, $K_L\to\pi^0\nu\nu$, $K^+\to\pi^+\nu\nu$, ε'/ε, ...
H^0 penguin	$B_s\to\mu^+\mu^-$	$B_d\to\mu^+\mu^-$	$K_{L,S}\to\mu^+\mu^-$

= exp. error $\lesssim$ 10% = exp. error ~ 30-50%

In the kaon sector we can identify 4 outstanding modes:

$$K^+ \to \pi^+ \nu\nu \quad K_L \to \pi^0 \nu\nu \quad K_L \to \pi^0 e^+ e^- \quad K_L \to \pi^0 \mu^+ \mu^-$$

- Measurements of these modes at 10% level (or below) is necessarily a major achievement: substantial improve in understanding flavour dynamics at the TeV scale
  (true for any realistic NP model)

- In planning new experiments, worth to think to the possibility of measuring more than one of these four channels in the same set-up (or with minor modifications)