Recent progress and future prospects in Kaon physics

Gino Isidori
[*INFN, Frascati & IAS-TUM, Munich*]

- Introduction: Kaon physics in the LHC era
  - Semileptonic K decays
  - Neutral Kaon mixing
  - Rare K decays
- Conclusions

Introduction: Kaon physics in the LHC era

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\cancel{\rm Higgs}}^{\;?}(\phi, A_a, \psi_i)$$

(Symmetry Breaking)

The key problem of particle physics we hope to address in the next decade, thanks to the high-p_T experiments at LHC, is the dynamical strucutre of the electroweak symmetry breaking mechanism [*Is there a Higgs boson? Is it fundamental or composite? ...*]

Introduction: Kaon physics in the LHC era

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\cancel{\text{Higgs}}}^{\;?}(\phi, A_a, \psi_i) + \text{“heavy d.o.f.”} \ldots.$$

(Symmetry Breaking)

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Given the instability of the “genuine” Higgs mechanism, we have strong theoretical projudices that the Higgs boson (if any) will not be alone: a “new sector” should show up around the TeV scale to stabilse the electroweak scale [$\langle \phi \rangle = 246$ GeV] $\Rightarrow$ *Key role of high-precision low-energy exps. (and especially Kaon physics) in investigating the symmetry properites of this sector*

Introduction: Kaon physics in the LHC era

Some of the main virtues of Kaon observables in investigating physics BSM:

- Weak decays (natural probes of the electroweak scale) with high teoretical cleanness (no comparison betweek K and B, D semileptonic decays)

- Short-distance FCNCs with the strongest SM suppression

- Accidental suppresson of K_L and K^+ leading modes, which enhance the BR of the most suppressed modes

- Limited number of decay modes which allow both unique consistency checkes (e.g.: Σ_i BR_i =1) as well as fundamental tests (CPT, etc....)

Semileptonic K decays

$$\underbrace{\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm gauge}(A_a, \psi_i) + \mathcal{L}_{\rm Higgs}(\phi, A_a, \psi_i)} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

$$\downarrow$$

$$\mathcal{L}_{\rm c.c.} = (g/\sqrt{2})\, W_\mu^+\ \bar{u}_L^{\,i}\, (V_{CKM})_{ij}\, \gamma^\mu d_L^{\,j} + {\rm h.c.}$$

The universality of g and the unitarity of V_{CKM} holds also beyond the SM, provided NP respects the gauge symmetry and $\Lambda > v$

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However, thanks to the s.s.b. of the SU(2)×U(1) group, what we measure at low energy is *not necessarily* only the gauge coupling of the W boson:

$$\mathscr{L}_{\rm c.c.\text{-}eff.} = G^{AB}_{ijkl}\ (u^i\, \Gamma_A\, d^j)\, (l^k\, \Gamma_B\, \nu^l) + \text{h.c.}$$

eff. <u>dimensional</u> coupling potentially sensitive to NP effects:

$$G^{AB}_{ijkl} \sim \frac{g^2 V_{ij}}{M_W^2} + \frac{c_n}{\Lambda^2}$$

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First key question: which is the natural size of the non-standard contributions?

No unambiguous answer [unfortunately the SM is renormalizable !]...

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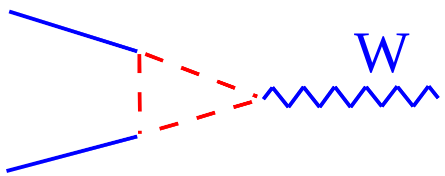
- Weakly coupled new particles appearing only at the loop level



e.g. SUSY at small $\tan\beta$

$$\frac{\Delta G^{\text{eff}}}{G_F} \sim \frac{M_W^2}{16\pi^2 M_{NP}^2} \lesssim 10^{-3}$$

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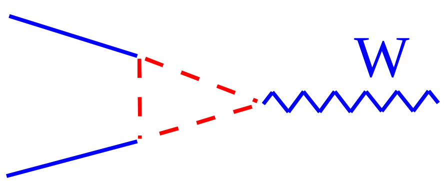

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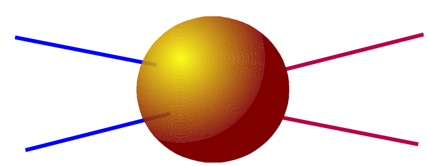
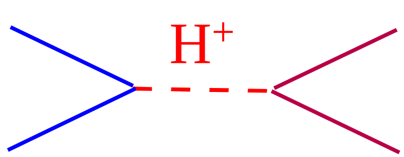


Higgsless
Tecnicolor
Extra dim.

$$\frac{\Delta G^{\text{eff}}}{G_F} \sim \frac{1}{16\pi^2} \lesssim 5\times10^{-3}$$

- New tree-level exchange



$$\frac{\Delta G^{\text{eff}}}{G_F} \sim \frac{g_H^2 M_W^2}{g^2 M_H^2} \lesssim 10^{-2}$$

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<u>First key question:</u> which is the natural size of the non-standard contributions?

In various consistent frameworks the effect is within the present exp. sensitivity in K_{l2} & K_{l3} decays

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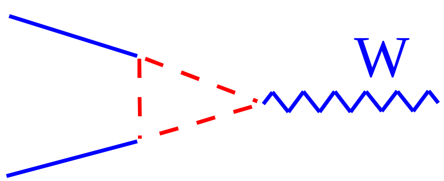

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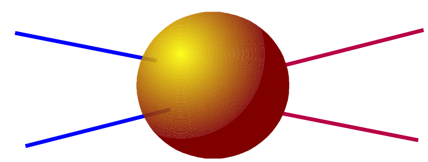

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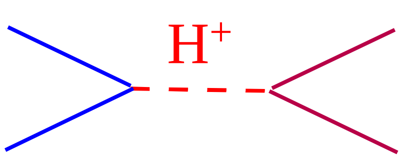

$$\frac{\Delta G^{\text{eff}}}{G_F} \sim \frac{g_H^{\,2} M_W^{\,2}}{g^2 M_H^{\,2}} \lesssim 10^{-2}$$

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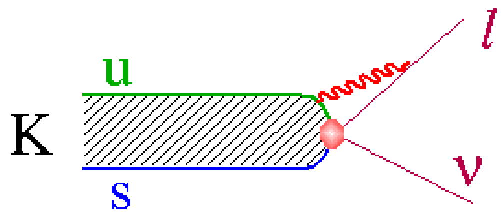
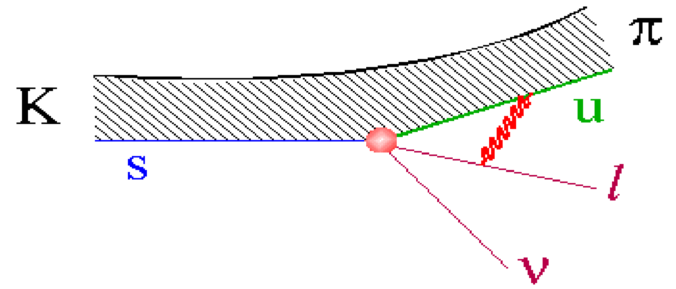
Second key question: can we control the SM predictions at this level of accuracy?





The K_{l2}-K_{l3} system offer several observables,
in some cases (lepton univ. ratios) the th. predicions are already below the 0.1% level, in others (V_{us}) the errors are larger but already below the 1% level (mainly thanks to Lattice progress)

$$\Gamma(K^i{}_{l3+n\gamma}) = C_i \times |V_{us}|^2 \times |f_+(0)|^2 \times I(\lambda'_+, \lambda''_+, \lambda'_0, \ldots) \times [\, 1 + \delta_{e.m.} + \delta_{SU(2)} \,]$$

$$\Gamma(K^+{}_{l2+n\gamma}) = C_0 \times |V_{us}|^2 \times F_K \times m_l^2 \,(1-m_l^2/M_K^2) \times [\, 1 + \delta_{e.m.} \,]$$

green = exp. inputs
red = th. inputs

Two universal hadronic f.f. presently known at the 0.5% level

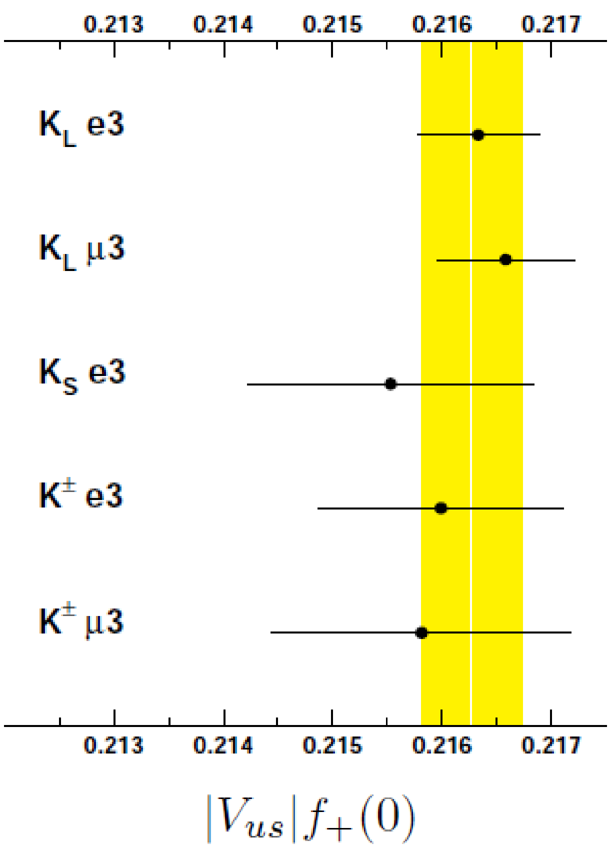
Electromagnetic and (m_u–m_d) effecs presently known at the 0.1% level

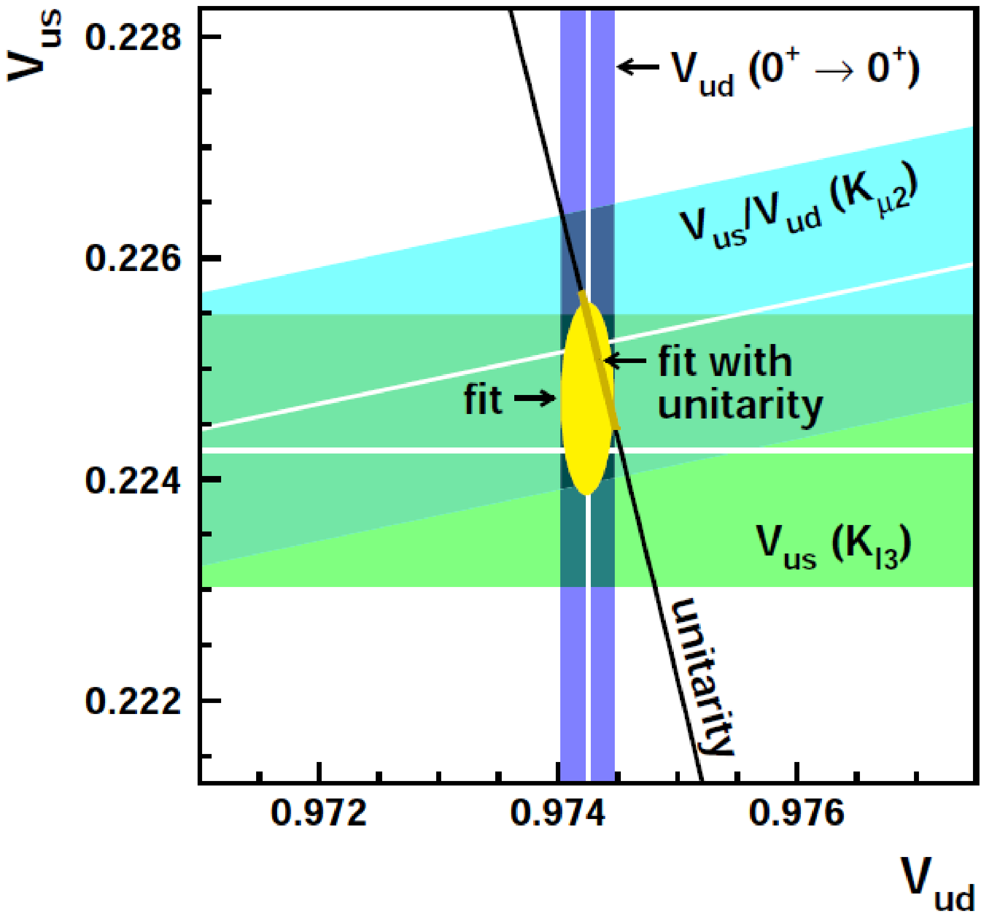
Recent global (th.+exp.) analysis [M. Antonelli *et al.* '10 - Flavianet Kaon WG]

I. *CKM Unitarity:*

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} - 1 = (-3 \pm 6) \times 10^{-4}$$

few 0.1% error





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I. CKM Unitarity:

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Very challenging for all extensions of the SM predicting some breaking of universality between quarks & leptons (*strong e.w. symm. breaking*, *extra dim*....)

$$G_F^{CKM} = G_F^{(\mu)} \left[|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \right]^{(1/2)} \quad \text{vs.} \quad G_F^{(\mu)}$$

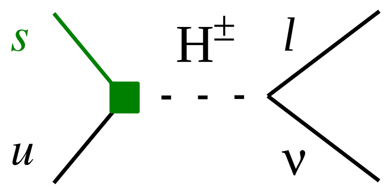
E.g.:

$$\mathscr{L}_{\rm eff.} = \frac{1}{\Lambda^2} (\bar{Q}_L \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L) \qquad \Lambda > 9.7 \text{ TeV [90\% C.L.]}$$

N.B.: bound stronger than from LEP [Cirigliano *et al.* '09]

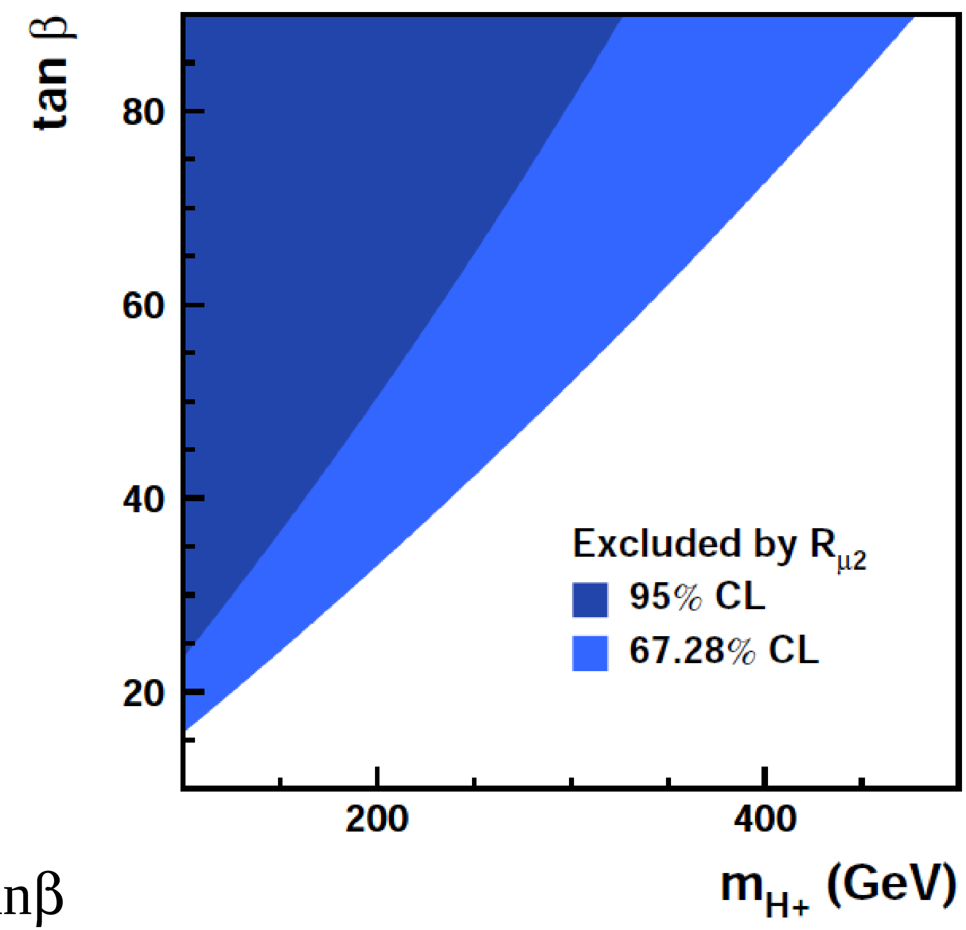
Recent global (th.+exp.) analysis [M. Antonelli *et al.* '10 - Flavianet Kaon WG]

II. K_{l2}-K_{l3} universality (or bounds on scalar currents):



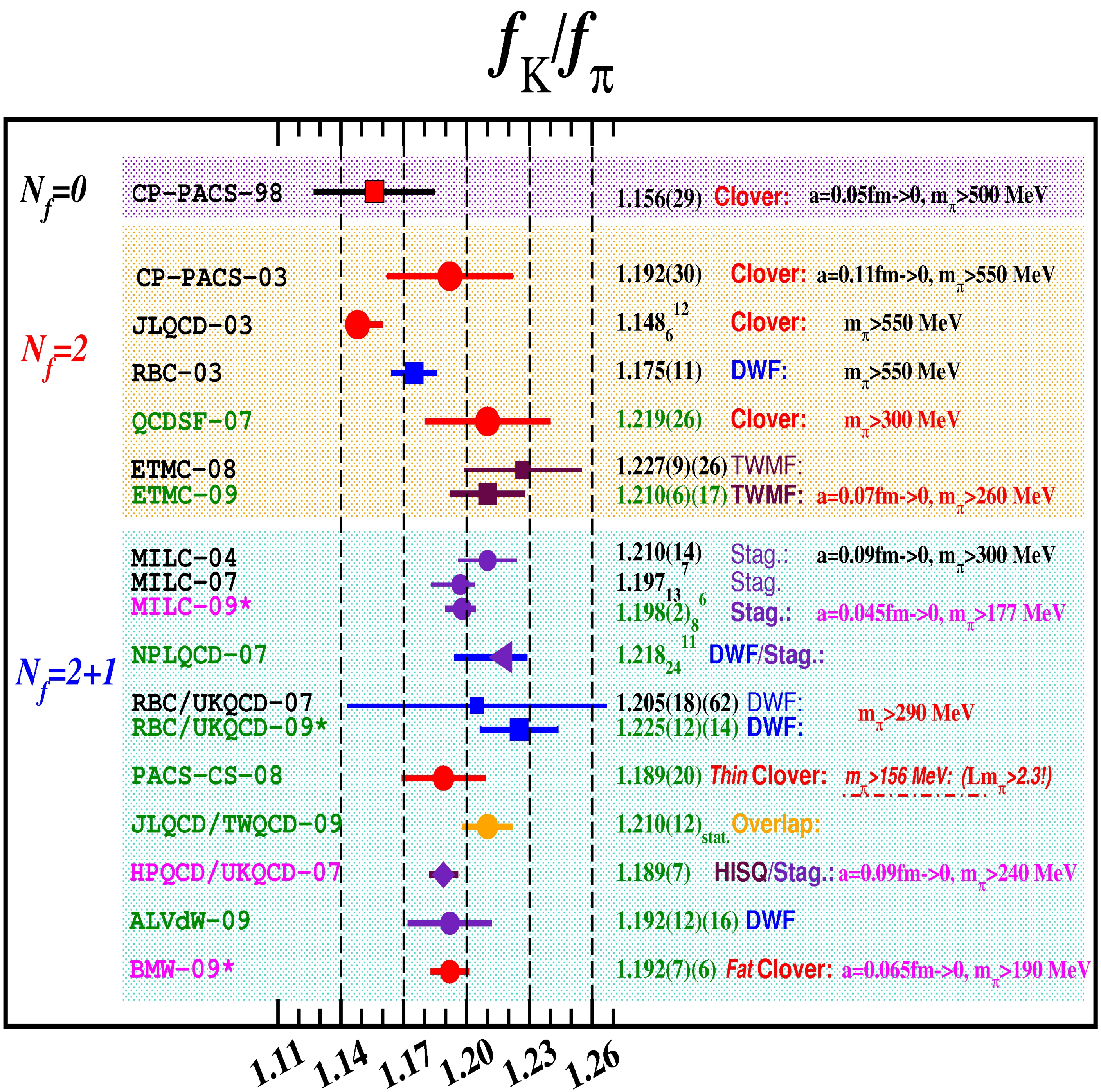
The effect of scalar currents is negligible in K_{l3}, while it could have a sizable impact in K_{l2}:

$$B(K\to l\,\nu) = B_{SM}\left(1 - \frac{m_K^2\ \tan\beta^2}{M_H^2\,(1+\epsilon_0\tan\beta)}\right)$$



Kaon data exclude the low-M_H & large-tanβ region "favoured" by $B\to\tau\nu$

N.B.: These highly non-trivial tests of the SM are possible mainly thanks to the great progress of Lattice QCD in kaon physics (*unquenched simul. with very light quark masses*)



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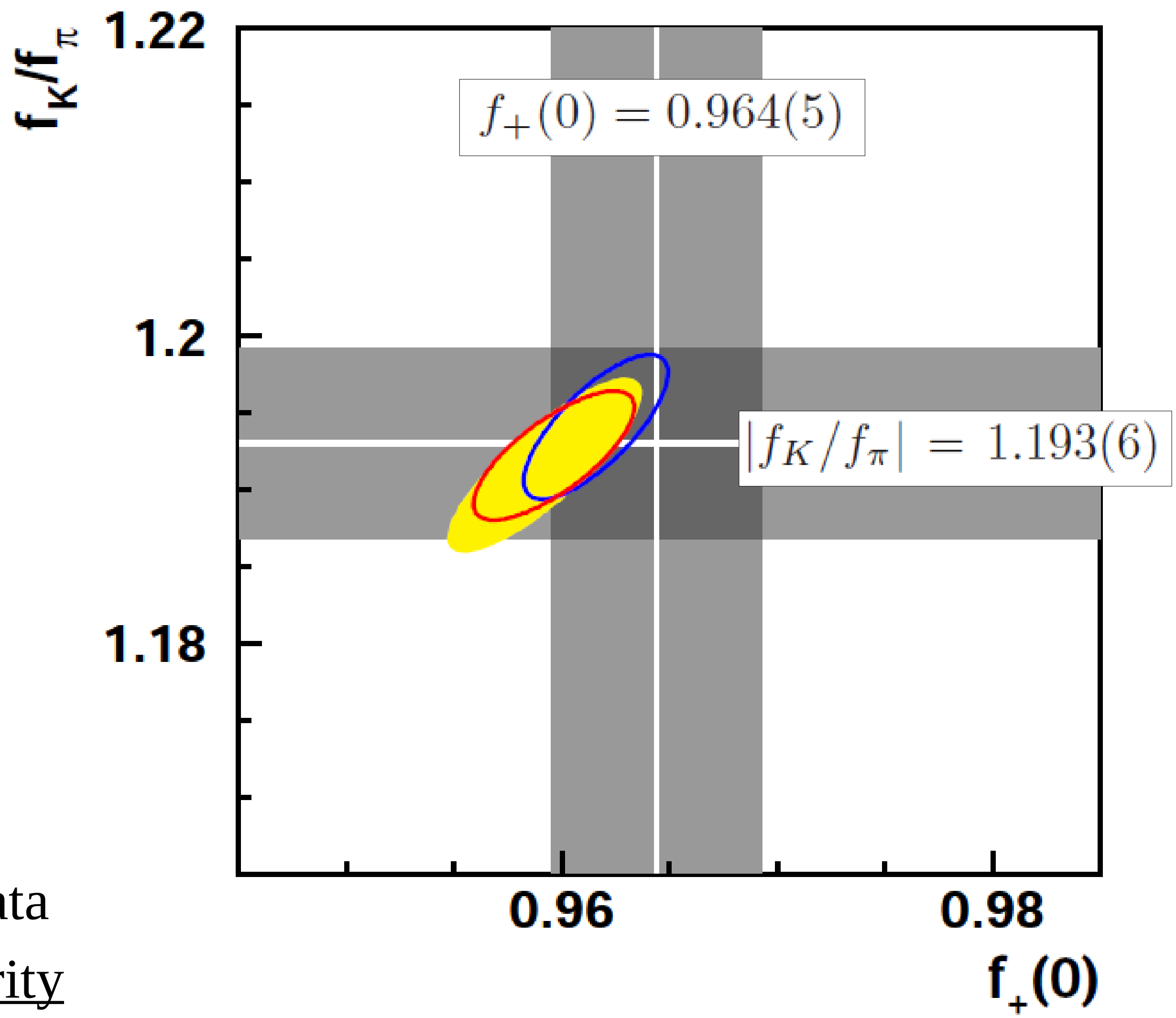


Yellow: f_K/f_π & $f_+(0)$ from data
imposing CKM unitarity

Antonelli *et al.* [Flavianet Kaon WG] '10

Neutral Kaon mixing

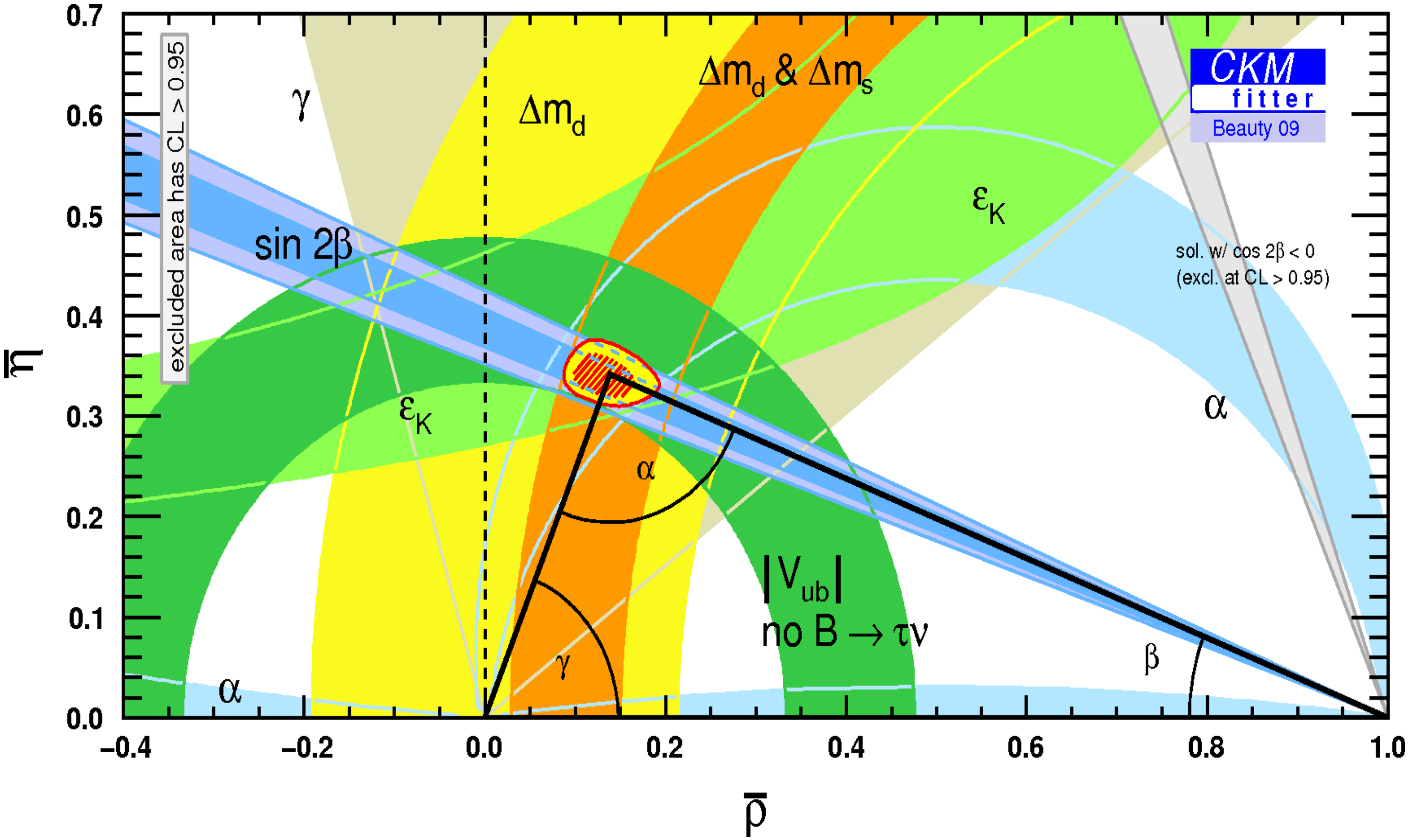
Neutral kaon mixing is one of the most "natural" systems to look for physics beyond the SM. Indeed ε_K leads to the most severe bound on barion- and lepton-number conserving dimension-six ops. in models with generic flavour structure (*one of the strongest motivations for MFV*):

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{M_iM_j}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{M_iM_j}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

G.I., Nir, Perez, '10

Neutral Kaon mixing

The UT plot by the CKMfitter collaboration shows an excellent consistency of ε_K with the other observables. However, an underlying "tension" is hidden by the rather conservative choice of the theory (Lattice) errors



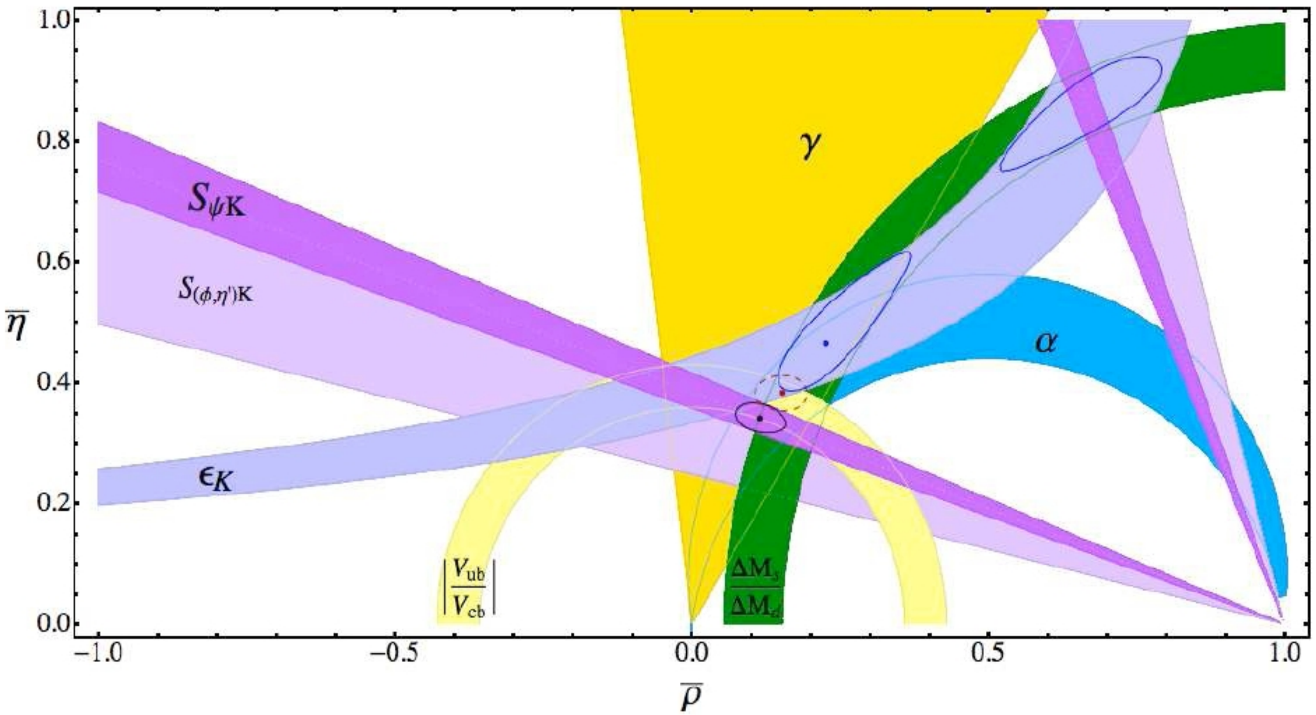
$$B_K = 0.79\ ^{+0.20}_{-0.12}$$

This tension is more evident (*although the overall statistical compatibilty is still not bad*) if we take into account only the recent unquenched determinations of B_K

Buras & Guadagnoli, '08
Soni & Lunghi, '08-'09

$B_K = 0.720 \pm 0.013 \pm 0.037$ D.J. Anotnio *et al*. [RBC Collab.] PRL '08

$B_K = 0.724 \pm 0.008 \pm 0.029$ Aubin, Laiho, Van de Water, PRD '10

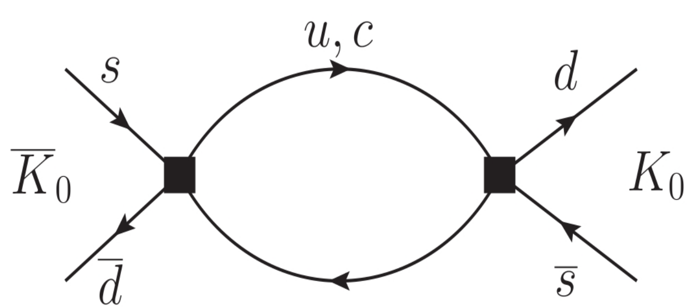


Given the pogress of the Lattice on B_K (few % error), worth to investigate if subleading terms in the OPE are under control.

At this level of accuracy long-distance effects due to higher-dimensional operators and genuine non-local constributions cannot be trivially neglected:

Buras, Guadagnoli, G.I. '10

(top-quark)



dim.-6

O[$G_F^2 m_t^2\, \mathrm{Im}((V_{ts}^* V_{td})^2)$, ...

$G_F^2 m_c^2\, \mathrm{Im}((V_{cs}^* V_{cd})^2)$]

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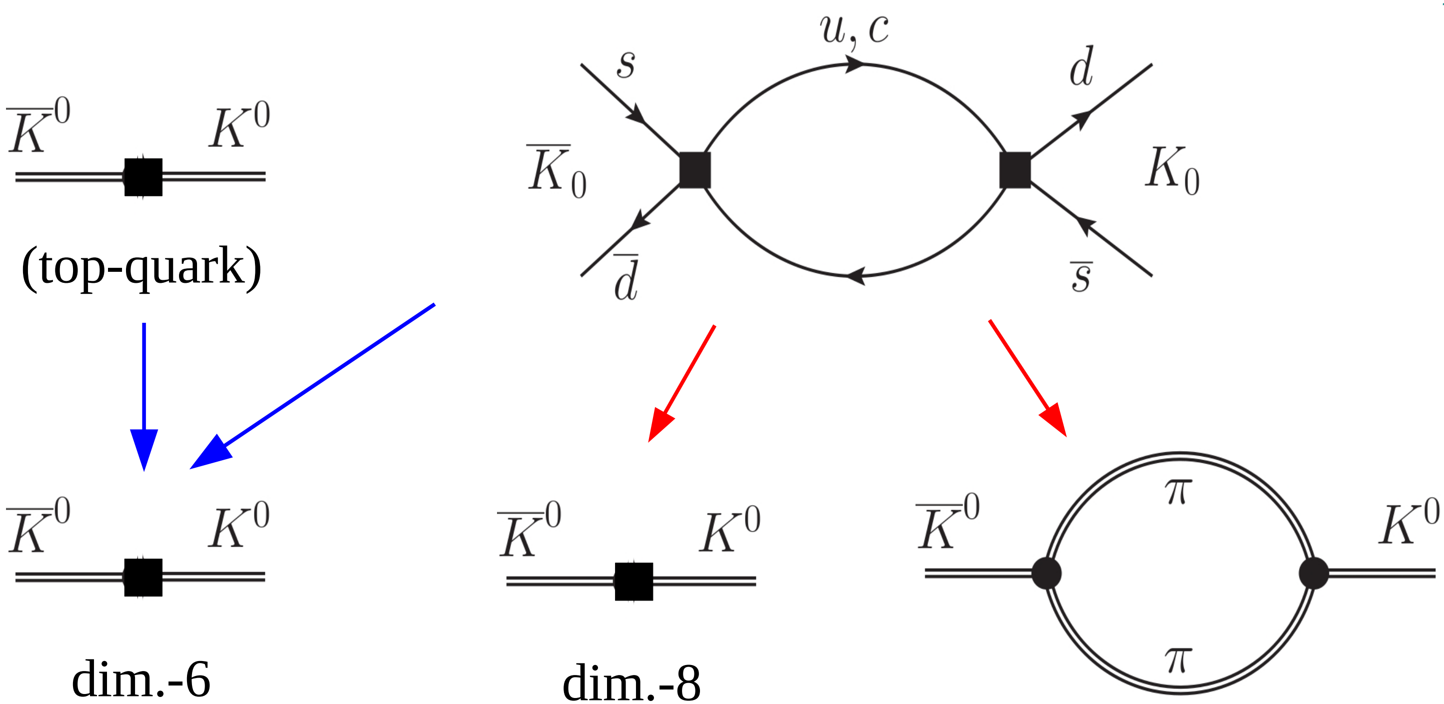

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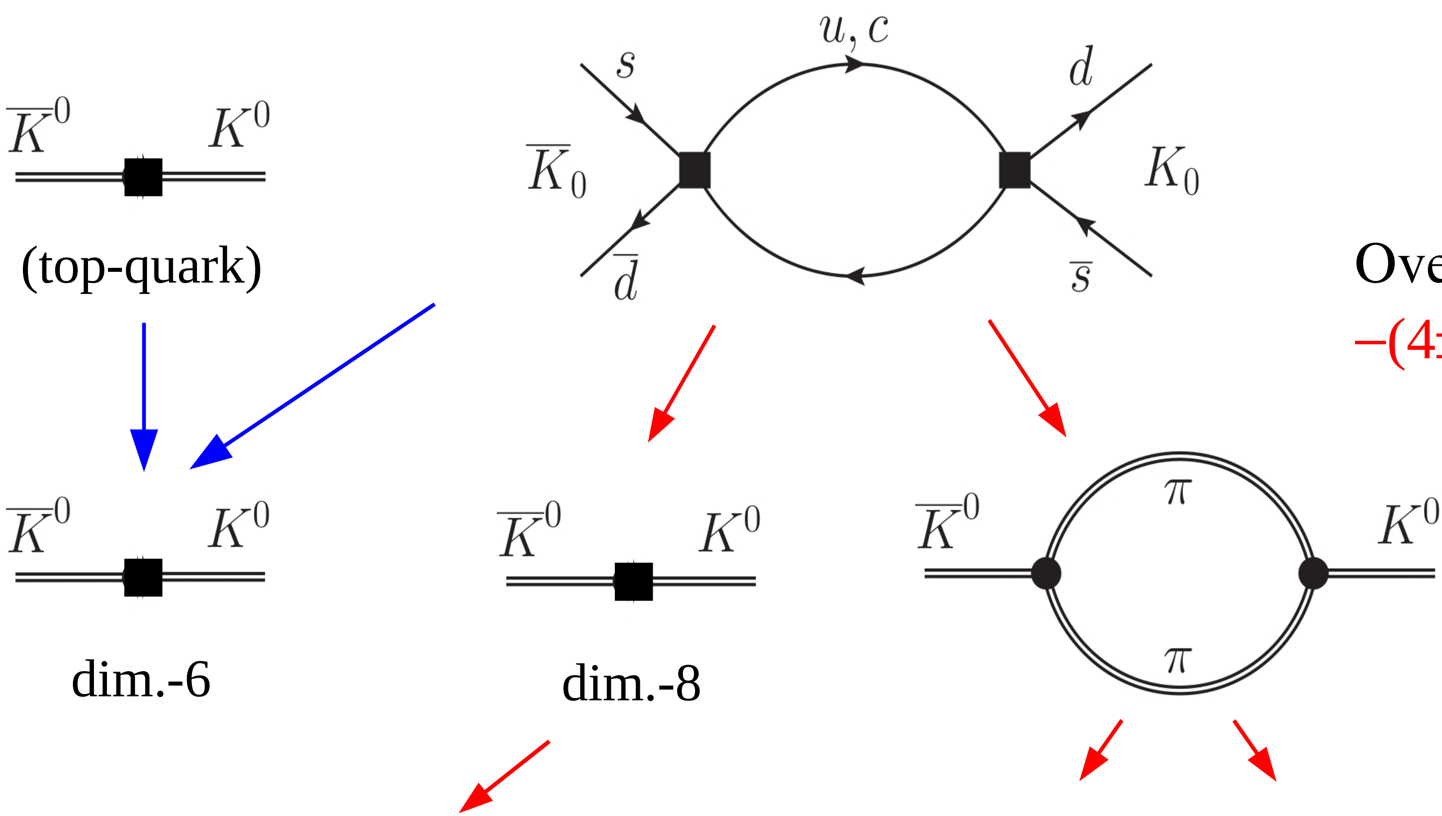

Overall effect:

$-(4\pm2)\%$ corr. to ε_K

below 1%

[Cata & Peris '03]

$$\mathrm{Re}(\varepsilon_K) \propto \left[\frac{\mathrm{Im}M_{12}}{2\mathrm{Re}M_{12}} - \frac{\mathrm{Im}\Gamma_{12}}{2\mathrm{Re}\Gamma_{12}}\right] \propto \left[\frac{\mathrm{Im}M_{12}}{\Delta m_K} + \xi\right]$$

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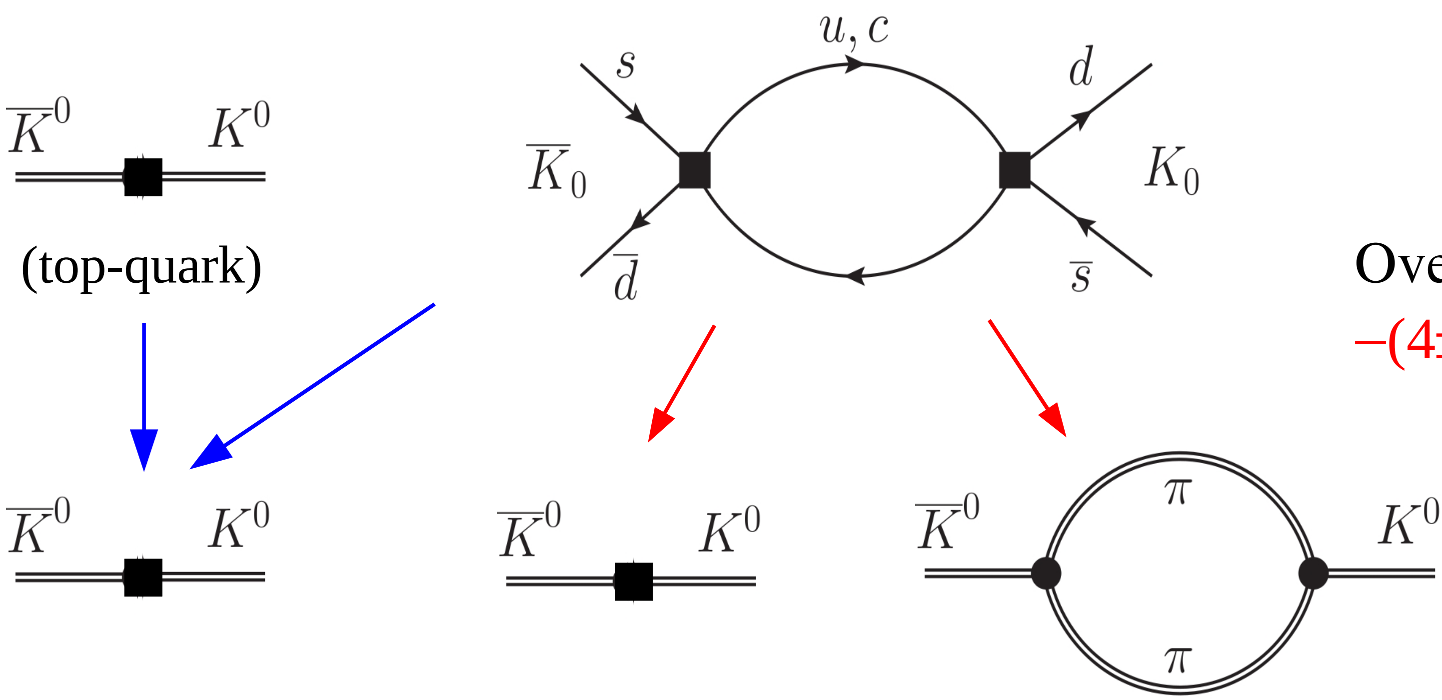

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The new LD effect we have evaluated slightly decrease the tension in the UT fit. Most important, it shows that ε_K is affected by an <u>irreducible th. error</u> (~2%), that is <u>very hard to be reduced</u> in the near future.

Rare K decays

The “ultimate goal” of kaon physics are precision measurements of the short-distance dominated FCNC rare modes ($K\to\pi\nu\nu$ & Co):

- Sizable deviations from SM even if NP appears only at the loop level
- Key source of info to shed more light on the (in)famous *flavour problem* because of their strong suppression $A_{SM} \sim \lambda^5$

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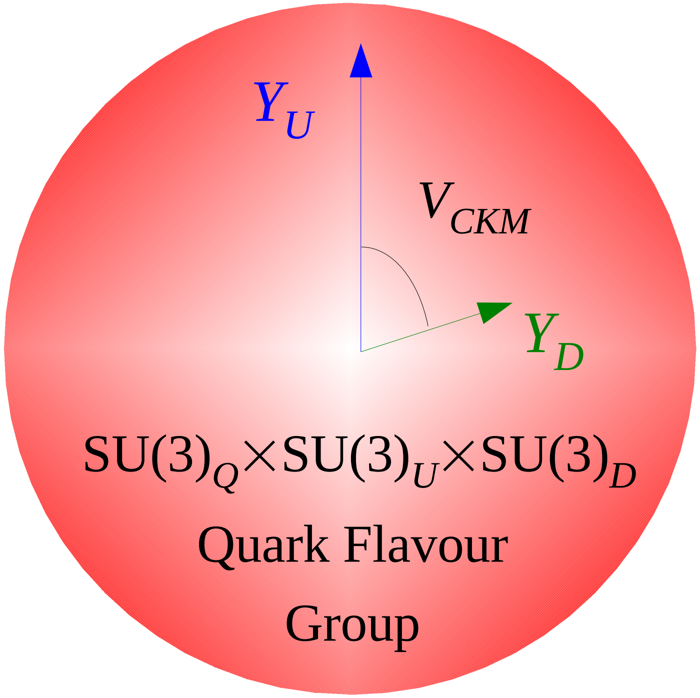
The flavour structure of the SM:

- large global symmetry in the gauge sector
  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$
- broken only by the Yukawa couplings
  $Y_D \sim \bar{3}_Q \times 3_D \quad Y_U \sim \bar{3}_Q \times 3_U$



If NP is in the TeV range,
something very similar must occur also beyond the SM...

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SM NP

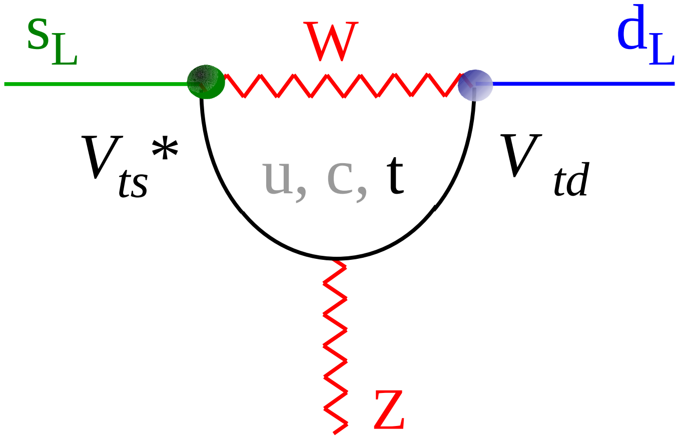
vs.

natural... *...artificial*

Rare decays mediated by Z-penguins are a unique probe of the interplay between the breaking of the electroweak symmetry and the breaking of the flavour symmetry

- No tree-level contribution
- One-loop contribution dominated by top-quark loops because A ~ m_{up}^2 ("hard" GIM mechanism or apparent non-decoupling behaviour)

$s \to d + Z\ (\to l^+l^-, \nu\nu)$



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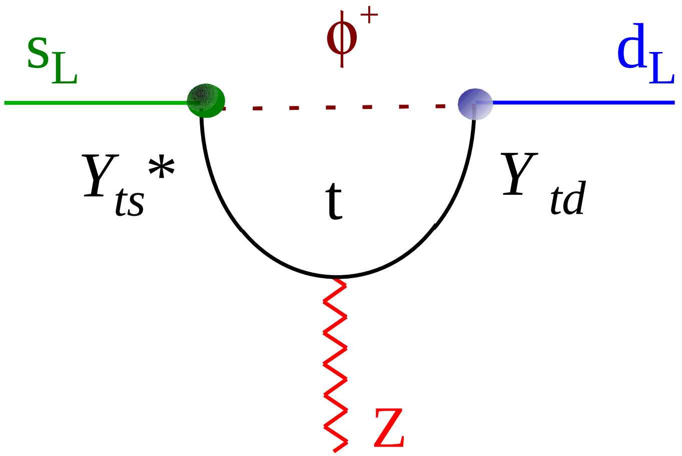

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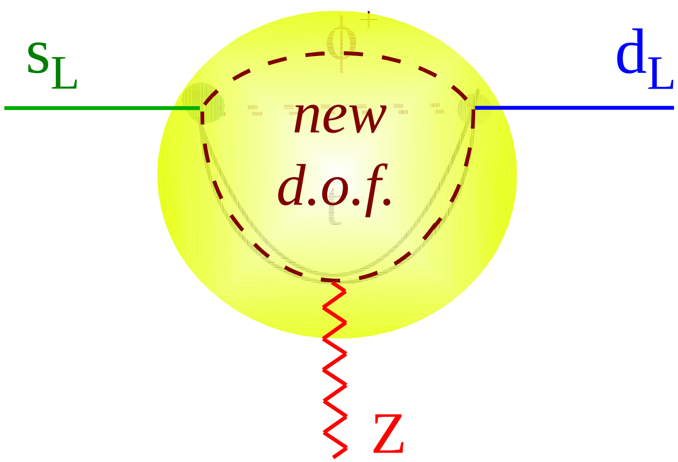
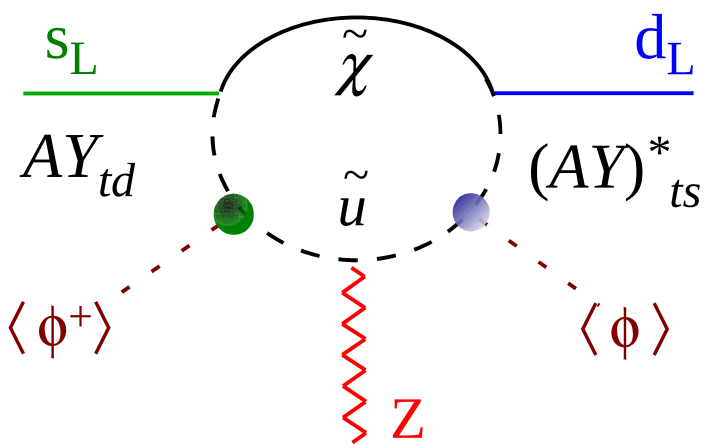


- <u>Unique sensitivity</u> to new sources of flavour symmetry breaking which break also the e.w. symmetry

Rare decays mediated by Z-penguins are a unique probe of the interplay between the breaking of the electroweak symmetry and the breaking of the flavour symmetry

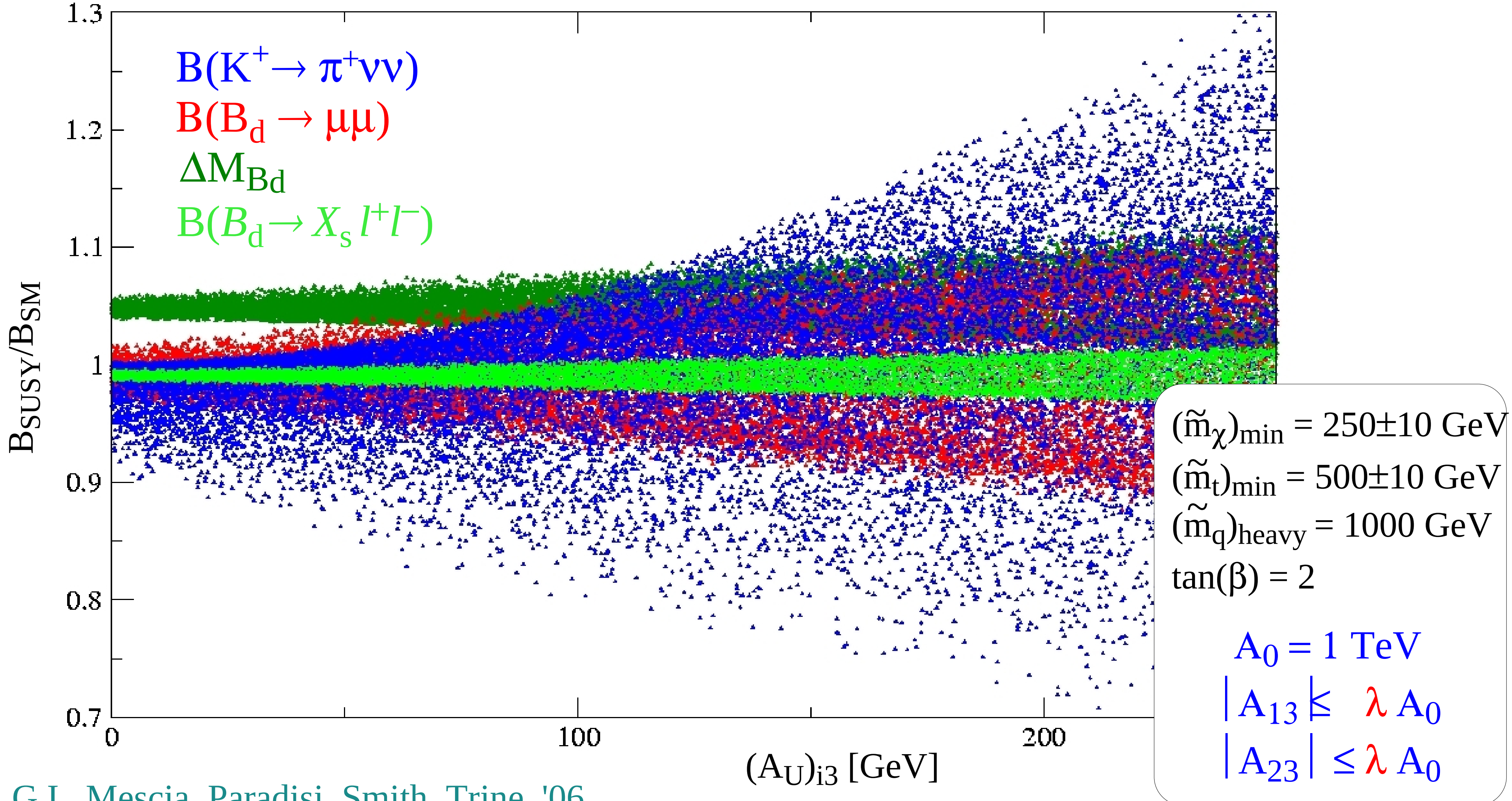
- No tree-level contribution
- One-loop contribution dominated by top-quark loops because $A \sim m_{up}^2$ ("hard" GIM mechanism or apparent non-decoupling behaviour)
- The origin of this behaviour is clear if we keep separated gauge and Yukawa interactions (the leading term surives even in the *gauge-less* limit of the SM)

$s \to d + Z\,(\to l^+l^-, \nu\nu)$



- Unique sensitivity to new sources of flavour symmetry breaking which break also the e.w. symmetry (e.g. SUSY A terms)

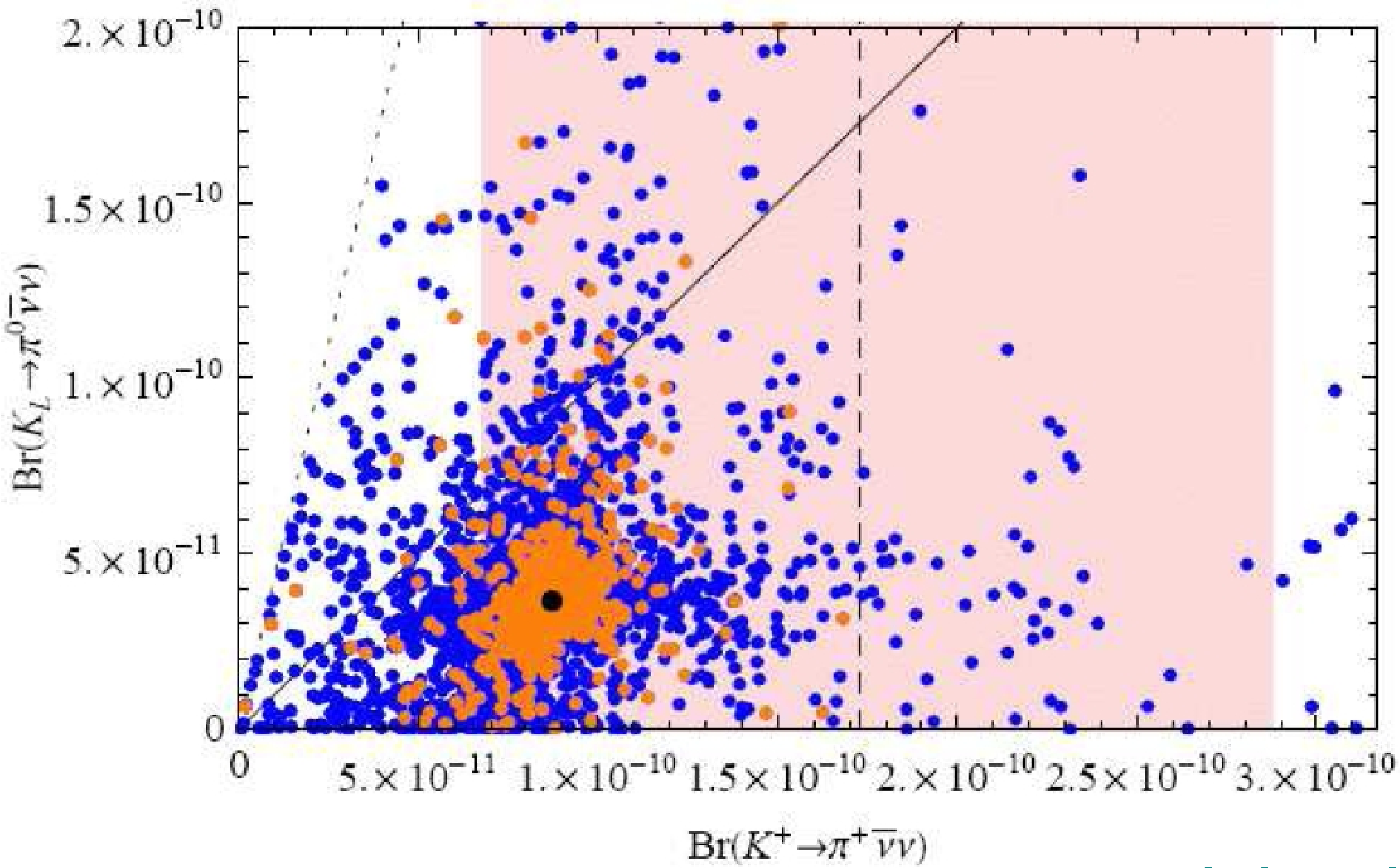
- Non-standard effects induced by chargino-squarks amplitudes largely dominant in $K \to \pi\nu\nu$ with respect to similar effects in B physics
- The A terms are still largely unconstrained
- Key example of <u>interplay</u> between high-pt physics and flavour physics



G.I., Mescia, Paradisi, Smith, Trine, '06

...and SUSY is only one of the examples where we can have sizable differences with respect to the SM...

E.g.: RS-type model (with cusotdial protection)



Blanke *et al*. '09

Conclusions

We learned a lot about flavour physics in the recent past...
...but a lot remains to be discovered !

We have understood that TeV-scale NP models must have a rather sophisticated flavour structure (not to be excluded by present data) but we have not clearly identified this structure yet

↓

- Several arguments suggest that Kaon physics will continue to play a key role, during the next decade, in investigating TeV-scale new physics
  The key observables to this purspose are the theoretically clean ones: rare FCNC decays, but also all the interesting observables of the clean leptonic and semileptonic modes

- And of course this is only one side of the interest in continuing high-precision Kaon physics. In addition we have all the issues related to a better understanding of QCD, chiral dynamics, ... where there is no doubt that we still have a lot to learn.