Exploring beyond-the-SM phenomena with K physics

Gino Isidori [*INFN-Frascati*]

Plan :

- General considerations about flavour physics in the LHC era
- The four golden modes of Kaon physics
- Rare K decays beyond the SM
- Anatomy of $K \to \pi \nu \nu$ within SUSY models
- Not only rare K decays...
- Conclusions

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Special thanks to:

- Federico Mescia
- Paride Paradisi
- Christopher Smith
- Stephanie Trine

General considerations about flavour physics in the LHC era

Given the great phenomenological success of the SM up to LEP energies and the limitations / unsatisfactory-aspects of the model above the e.w. scale [$v = \langle \phi \rangle \approx$ 250 GeV] $\Rightarrow$ 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 :

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi_i, A_i, \psi_i ; Y, v) + \ldots.$$

The stability of the Higgs sector

naturally points toward $\Lambda \sim$ TeV

⇒ High-energy experiments are the key tool to determine the energy scale of the new d.o.f. (or the value of Λ) via their direct production

⇒ Low-energy experiments are a fundamental ingredient to determine the symmetry properties of the new d.o.f. via indirect effects in precision observables

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm gauge}(A_i, \psi_i) + \mathcal{L}_{\rm Higgs}(\phi_i, A_i, \psi_i ; Y, v) + \sum_{d \geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\,d}(\phi_i, A_i, \psi_i)$$

$\mathcal{L}_{SM}$ = renormalizable part of $\mathcal{L}_{eff}$
[= all possible operators with $d \leq 4$
compatible with the gauge symmetry]

most general parameterization
of the new (heavy) d.o.f.
as long as we perform
low-energy experiments

Precision measurements in the flavour sector allows us to study the *flavour symmetries* of physics beyond the SM

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi_i, A_i, \psi_i\, ; Y, v) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}}\, O_n^{\,d}(\phi_i, A_i, \psi_i)$$

3 identical replica of the basic fermion family

$\Rightarrow$ huge flavour-degeneracy [$U(3)^5$ group]

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3 identical replica of the basic fermion family
$\Rightarrow$ huge flavour-degeneracy [$U(3)^5$ group]

Within the SM the flavour-degeneracy is broken only by the Yukawa interaction:

$$\bar{Q}_L^{\,i}\, Y_D^{\,ik}\, d_R^{\,k}\, \Phi \;\rightarrow\; \bar{Q}_L^{\,i}\, M_D^{\,ik}\, d_R^{\,k}$$

$$\bar{Q}_L^{\,i}\, Y_U^{\,ik}\, u_R^{\,k}\, \Phi_c \;\rightarrow\; \bar{Q}_L^{\,i}\, M_U^{\,ik}\, u_R^{\,k}$$

Nowadays we have an *excellent knowledge* of all the physical couplings appearing in the quark- Yukawa sector...

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

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

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi_i, A_i, \psi_i ; Y, v) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\ d}(\phi_i, A_i, \psi_i)$$

...but we have only started to investigate the flavour structure of the new degrees of freedom (which hopefully will show up around the TeV scale):

- Several new sources of flavour symmetry breaking are possible

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_{\rm i}, \psi_{\rm i}) + \mathscr{L}_{\rm Higgs}(\phi_{\rm i}, A_{\rm i}, \psi_{\rm i}; Y, v) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\,d}(\phi_{\rm i}, A_{\rm i}, \psi_{\rm i})$$

...but we have only started to investigate the flavour structure of the new degrees of freedom (which hopefully will show up around the TeV scale):

- Several new sources of flavour symmetry breaking are possible
- Rare FCNC decays [$q_i \to q_j + \gamma,\ l^+l^-, \nu\nu$], K-Kbar & B-Bbar mixing [$\Delta F=2$] are the observables more sensitive to these new flavour-breaking couplings:

$$A(\, s \to d\,)_{\rm FCNC} \sim c_{\rm SM} \frac{y_t^2\, V_{ts}^{*} V_{td}}{16\, \pi^2 M_W^2} + c_{\rm new} \frac{\Delta_{sd}}{\Lambda^2}$$

- No SM tree-level contributions
- Strong SM suppression due to CKM hierarchy
- Predicted with high precision when <u>dominated by short-distance (e.w.) dynamics</u>

key point !

FLAVOUR COUPLING:

ELECTROWEAK STRUCTURE

	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
ΔF=2 box	$(b_L \Gamma s_L)^2$	$(b_L \Gamma d_L)^2$	$(s_L \Gamma d_L)^2$
ΔF=1 4-quark box	⋮		
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

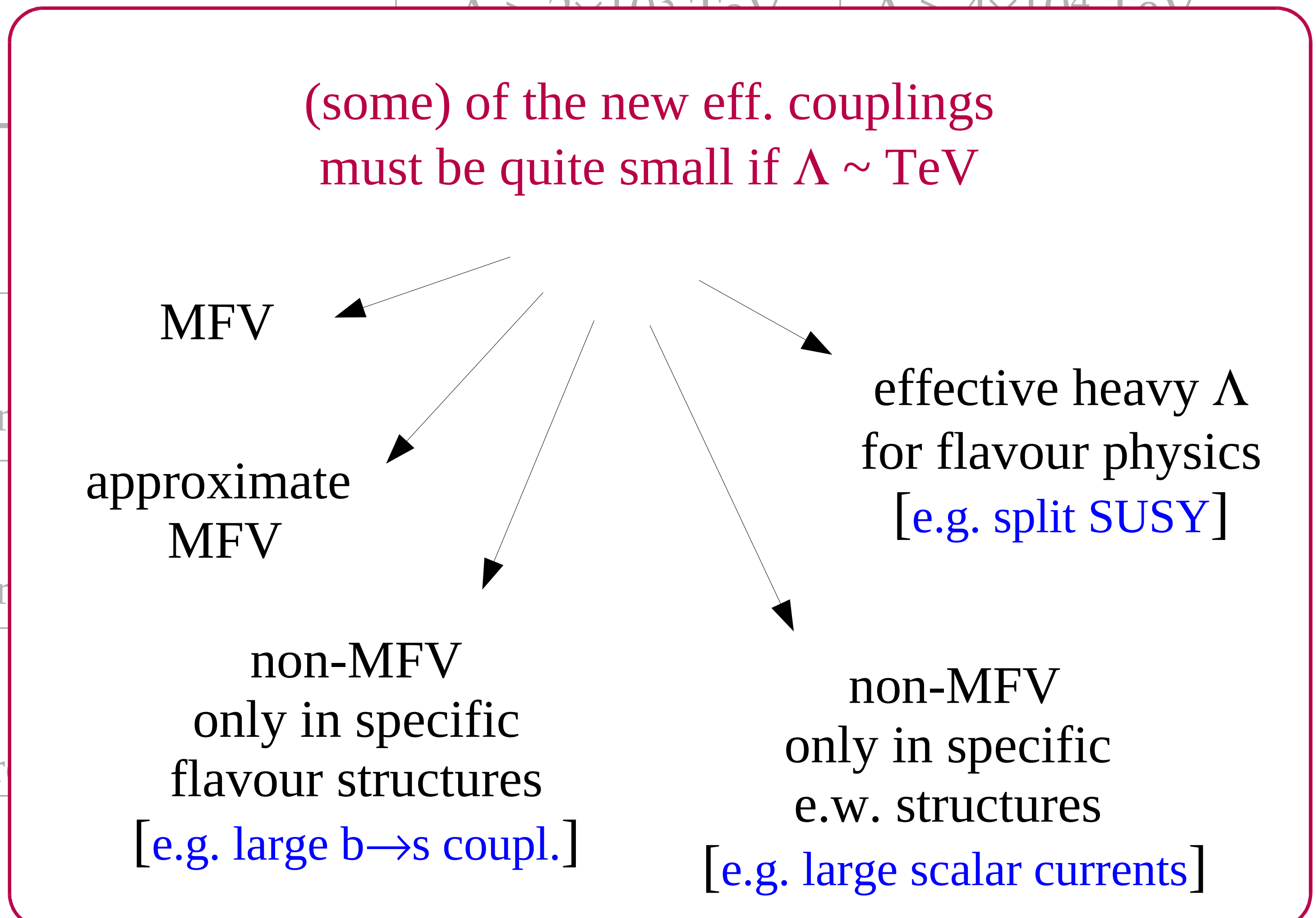
Some of the most significant bounds on the scale of new physics, assuming O(1) couplings for the new operators:

	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
$\Delta F=2$ box		$\Lambda \gtrsim 2\times10^3$ TeV from $A_{CP}(B_d \to \psi K)$	$\Lambda \gtrsim 4\times10^4$ TeV from ε_K
$\Delta F=1$ 4-quark box			
gluon penguin	$\Lambda \gtrsim 20$ TeV from $B(B \to X_s\gamma)$		
γ penguin	$\Lambda \gtrsim 40$ TeV from $B(B \to X_s\gamma)$		
Z^0 penguin	$\Lambda \gtrsim 20$ TeV from $B(B \to X_s l^+ l^-)$		
H^0 penguin			

→ (some) of the new eff. couplings must be quite small if $\Lambda \sim$ TeV

Our present knowledge is too limited to draw definite conclusions: only with the help of both high- and low-energy experiments we can hope to solve the puzzle...

	$b \to s$ ($\sim\lambda^2$)	$b \to d$ ($\sim\lambda^3$)	$s \to d$ ($\sim\lambda^5$)
$\Delta F=2$ box		$\Lambda > 2\times10^3$ TeV	$\Lambda > 4\times10^4$ TeV
$\Delta F=1$ 4-quark box			
gluon penguin			
γ penguin			
Z^0 penguin			
H^0 penguin			



...and there is also still hope to obsereve sizable deviations from the SM:

	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
$\Delta F=2$ box	$B_s - \bar{B}_s$	$\Lambda \gtrsim 2\times10^3$ TeV from $A_{CP}(B_d \to \psi K)$	$\Lambda \gtrsim 4\times10^4$ TeV from ε_K
$\Delta F=1$ 4-quark box			
gluon penguin	$\Lambda \gtrsim 20$ TeV from $B(B \to X_s \gamma)$		
γ penguin	$\Lambda \gtrsim 40$ TeV from $B(B \to X_s \gamma)$		
Z^0 penguin	$\Lambda \gtrsim 20$ TeV from $B(B \to X_s l^+ l^-)$		$K \to \pi \nu\nu$ $K_L \to \pi^0 l^+ l^-$
H^0 penguin	$B_s \to \mu\mu$	$B_d \to \mu\mu$	

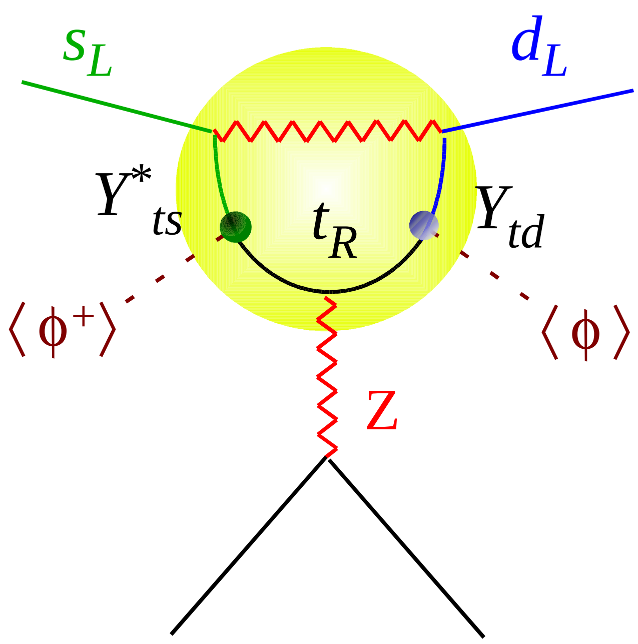
Three very interesting corners which, for different & well-motivated reasons, could hide sizable effects

The four golden modes of Kaon physics

Channels where short-distance dynamics (*W* - top quark loops) constitutes the dominant contribution (or a large fraction) of the decay amplitude:

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

common leading short-distance amplitude within the SM :



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I. Clean electroweak short-distance amplitude

- similar -within the SM- for all the channels
  potentially different beyond the SM

Here is where NP can show up
Natural normalization for non-SM effects

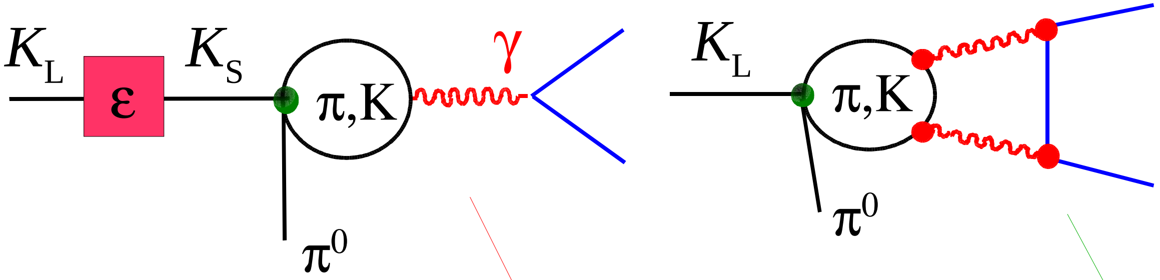
II. Long-distance contributions due to charm & light quarks

- potentially large effects of e.m. origin in $K \to \pi\, ll$
  [but under good th. control in the $K_L \to \pi^0$ case]
- small effects in $K \to \pi\, \nu\nu$ modes
  [totally negligible in the $K_L \to \pi^0$ case]

These are the contributions which can *obscure* possible NP effects

In the last few years there has been a substantial progress in the control of the theory error associated to charm & light-quark loops:

- $K_L \to \pi^0 l^+ l^-$ Complete analysis of the long-distance effects of e.m. origin:



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

G.I., Smith, Unterdorfer '04

[key inputs by NA48 & NA48/1]

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

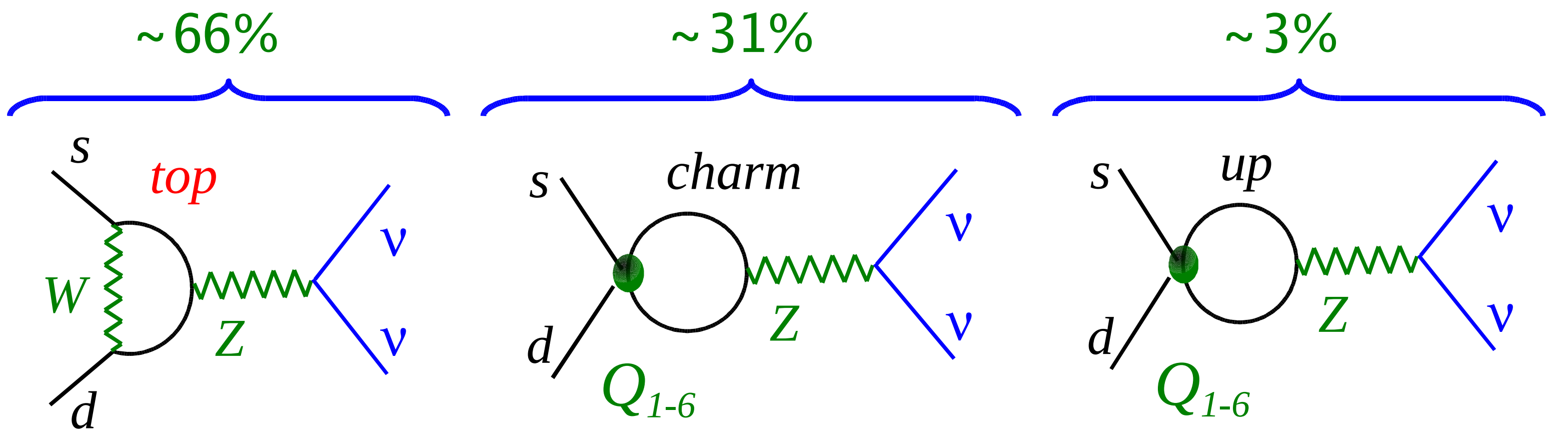
$$[\, e^+ e^- \,] \approx 23 + (10 + 4) + 0 \Rightarrow (3.7 \pm 1.0) \times 10^{-11}$$

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

In the last few years there has been a substantial progress in the control of the theory error associated to charm & light-quark loops:

- $K_L \to \pi^0 l^+ l^-$ Complete analysis of the long-distance effects of e.m. origin
- $K^+ \to \pi^+ \nu\nu$ NNLO analysis of the leading (dim.-6) charm contribution:

amplitude decomposition:

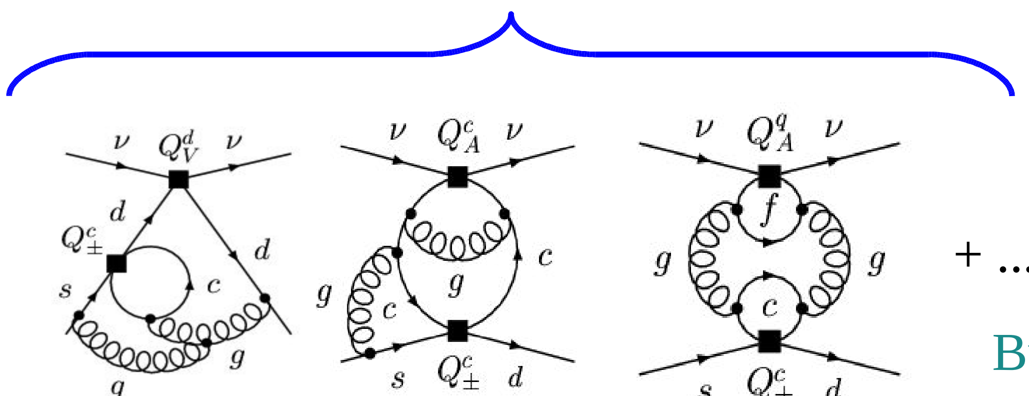


$\Delta(\mathrm{BR})_{\mathrm{NLO}} = \pm\, 10\ \%$

↓

$\Delta(\mathrm{BR})_{\mathrm{NNLO}} = \pm\, 6\ \%$

totally dominated by the param. uncertainty of mc



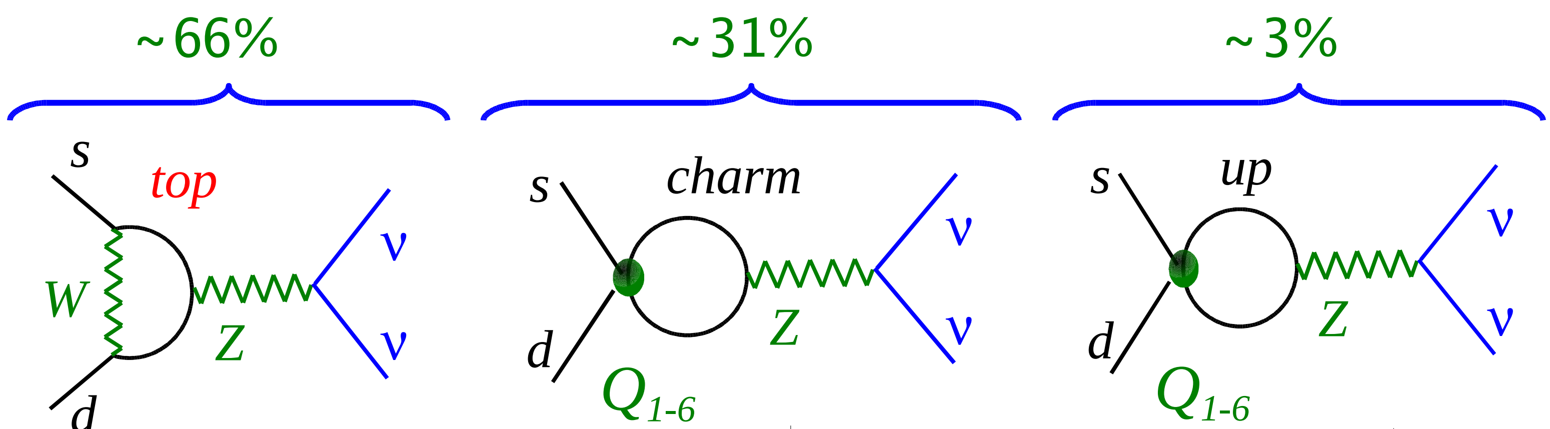
Ulrich Haisch, Kaon '05

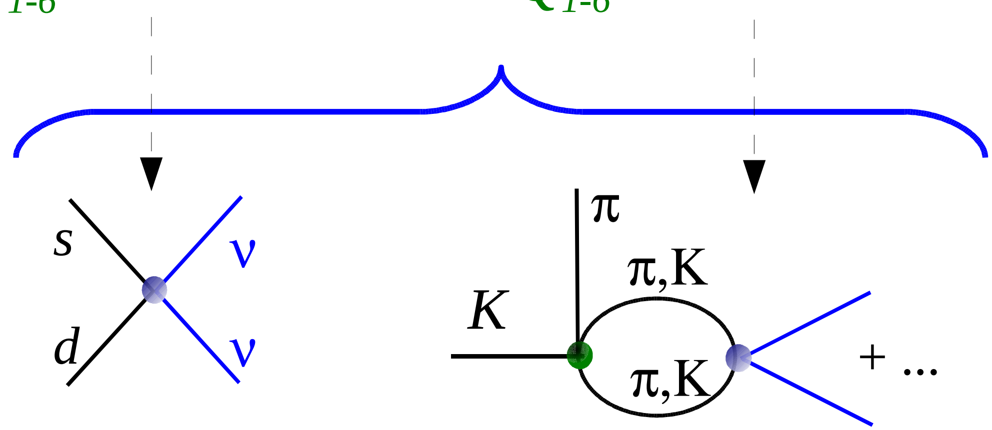
Buras, Gorbahn, Haisch, Nierste '05

In the last few years there has been a substantial progress in the control of the theory error associated to charm & light-quark loops:

- $K_L \to \pi^0 l^+ l^-$ Complete analysis of the long-distance effects of e.m. origin
- $K^+ \to \pi^+ \nu\nu$ NNLO analysis of the leading (dim.-6) charm contribution & first consistent analysis of the $O(m_K^2/m_c^2)$ corrections:

amplitude decomposition:





$$Q_\nu^{(8)} \sim (s\partial d)(\nu\partial\nu)$$

$\Delta(BR)_{long} = \pm 3\%$

G.I., Mescia, Smith '05

Summary of the *irreducible theoretical uncertainties* :

	short-distance (e.w.) contrib. to the total rate $(\Gamma - \Gamma_{\text{no s.d.}}) / \Gamma$	present irreducible th. error on the s.d. amplitude extracted from BR only	total BR withinSM (central value)
$K_L \to \pi^0 \nu\nu$	$> 99\%$	1%	3×10^{-11}
$K^+ \to \pi^+ \nu\nu$	88%	3%	8×10^{-11}
$K_L \to \pi^0 e^+e^-$	38%	15% —Dalitz→ ~ 10%	3.5×10^{-11}
$K_L \to \pi^0 \mu^+\mu^-$	28%	30% —Dalitz→ ~ 15%	1.5×10^{-11}

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→ Very few observables, also in the B system, have a similar degree of short-distance sensitivity & theoretical cleanliness

▶ *Rare Kaon decays beyond the SM* [general properties]

Two basic scenarios:

Minimal Flavour Violation

flavour symmetry broken only by the (SM) Yukawa couplings

⬇

- Small deviations (10-20%) from SM
- Stringent correlations with other rare decays in B physics [$B_d \to X_{s,d} \nu\nu$, $B_d \to X_{s,d}\, l^+ l^-$, $B_{s,d} \to l^+ l^-$]

New sources of Flavour Symmetry breaking around the TeV scale

⬇

- Potentially large effects, especially in the three CPV K_L decays (no λ^5 suppression)
- Correlations with observables in B physics not obvious

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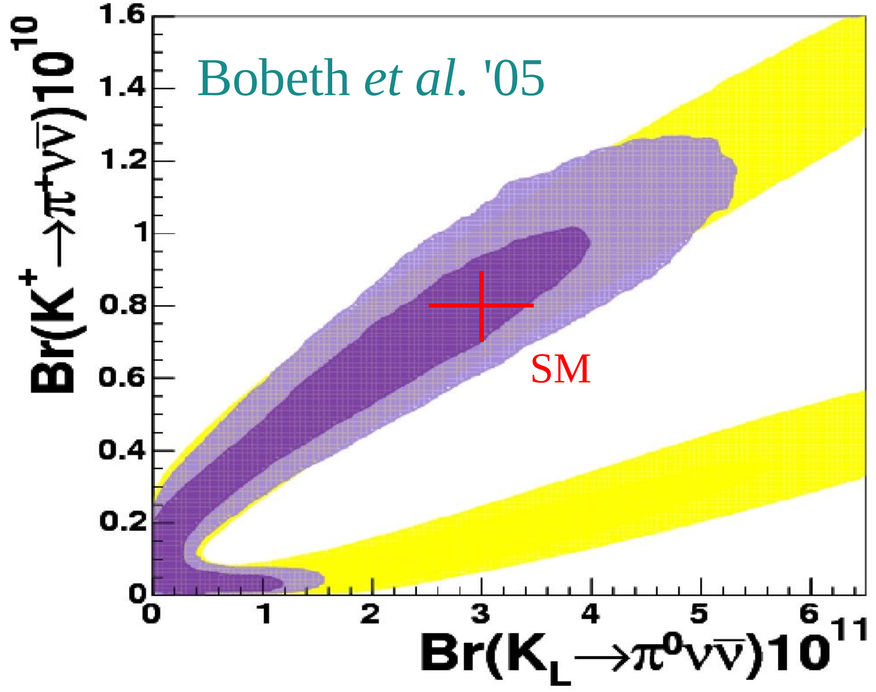
Recent (almost) model-indep. analysis :



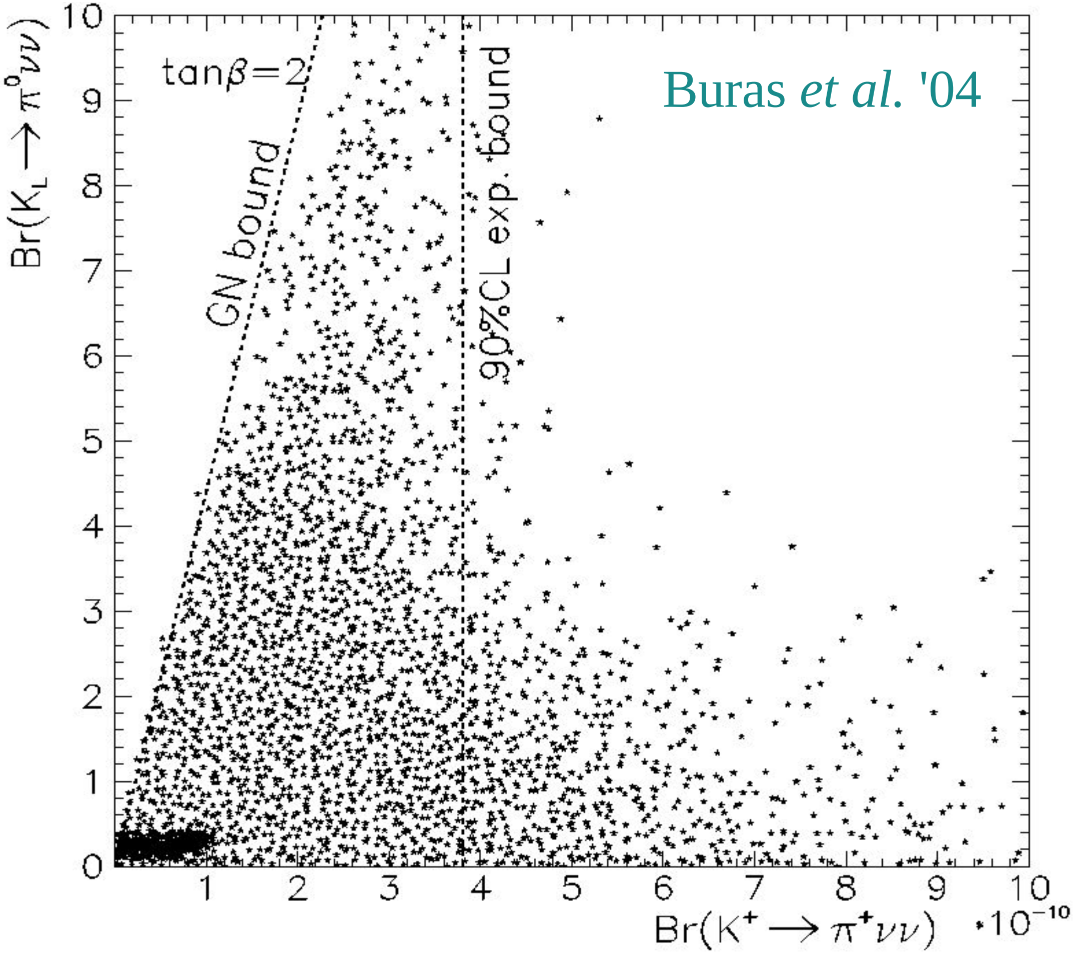
Consistent with results of specific models:

- Constrained MSSM [Buras *et al.* '01]
- One universal extra dim. [Buras *et al.* '03]
- Littlest-Higgs [Buras *et al.* '05]

Rare Kaon decays beyond the SM [general properties]

Two basic scenarios:

E.g.: II. Generic MSSM



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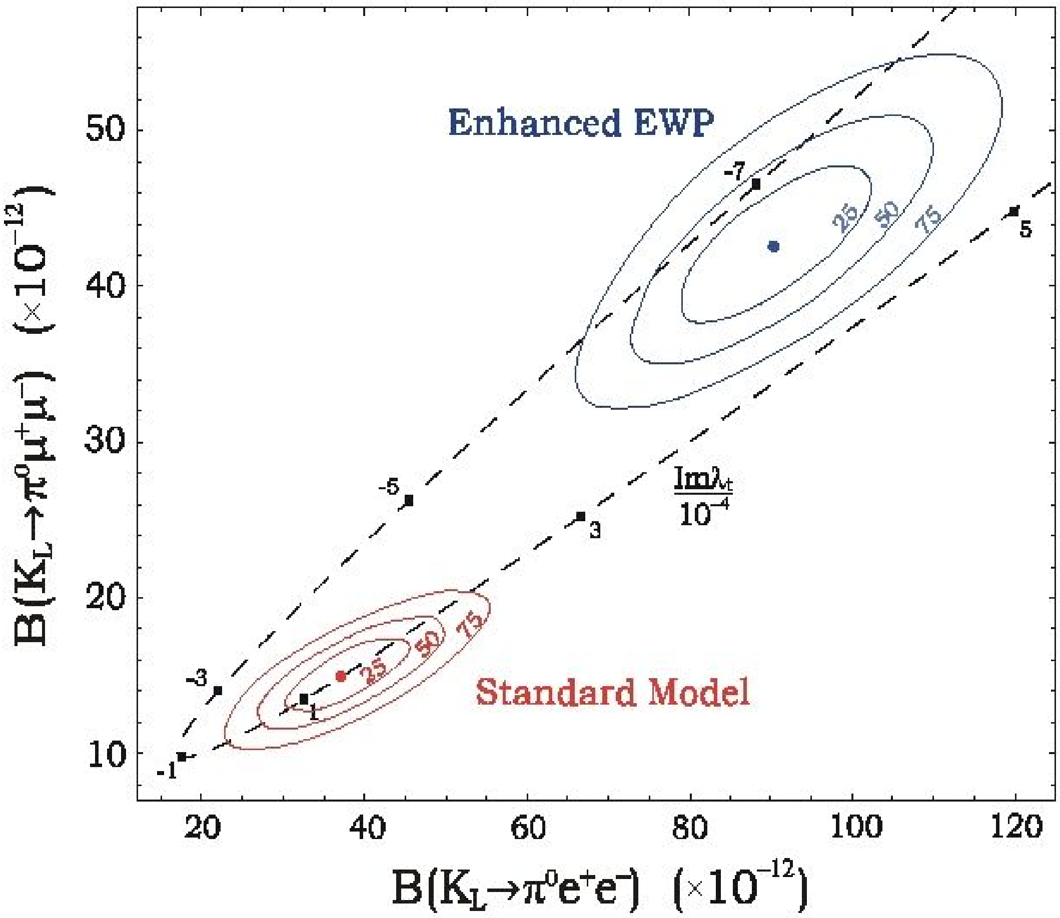
Grossman-Nir bound:

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

Rare Kaon decays beyond the SM [general properties]

Two basic scenarios:

E.g.: II. Enhanced e.w. penguins



G.I., Smith, Unterdorfer '04

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- Stringent correlations with other rare decays in B physics [$B_d \to X_{s,d} \nu\nu$, $B_d \to X_{s,d}\, l^+l^-$, $B_{s,d} \to l^+l^-$]

A precise exp. info from one of the two $K \to \pi \nu\nu$ modes is a key ingredient to verify or disproof the MFV hypothesis

New sources of Flavour Symmetry breaking around the TeV scale

↓

- Potentially large effects, especially in the three CPV K_L decays (no λ^5 suppression)
- Correlations with observables in B physics not obvious

In presence of sizable non-MFV couplings mandatory to explore also the $K_L \to \pi\, ll$ modes

Anatomy of $K \to \pi\nu\nu$ within low-energy SUSY models

...or better within supersymmetric extensions of the SM with

- minimal particle content
- R-parity conservation
- soft-breaking terms in the TeV range:

$$\mathscr{L}_{soft} = (M_f)_{ij}\, \chi_i\, \chi_j + (M_s^{\,2})_{ij}\, \phi_i\, \phi_j + A_{ijk}\, \phi_i \phi_i \phi_k$$

gaugino/higgsino masses — squark/slepton masses — trilinear scalar couplings

$$M^2_{squarks} = \begin{bmatrix} (M^2_Q)_{LL} & (M^2_{U,D})_{LR} \\ (M^2_{U,D})^+_{LR} & (M^2_{U,D})_{RR} \end{bmatrix}$$

Five very different structures

- which naturally contain new sources of flavor-symmetry breaking
- which contribute in different ways to different FCNC processes

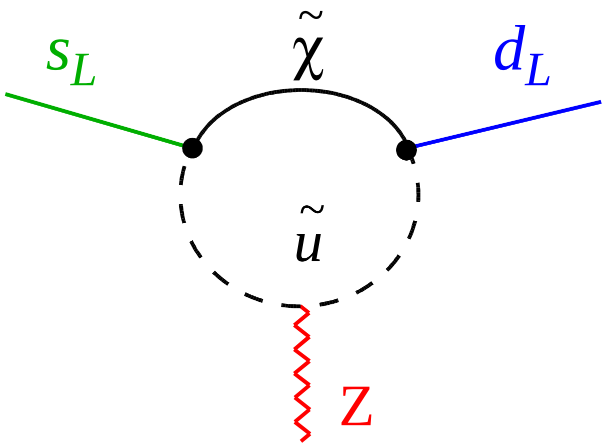
Anatomy of $K \to \pi\nu\nu$ within low-energy SUSY models

Main distinctive features $K \to \pi\nu\nu$ amplitudes [wide literature] :

- Gluino-type amplitudes essentially negligible, even in presence of new sources of flavour mixing [contrary to ε_K, $b \to s\gamma$, ΔM_{Bd}, CPV in B decays]

  $\Rightarrow$ reduced sensitivity to LL, RR and LR-down type mixings

- Appreciable deviations from SM induced only by chargino -- up-squark diagrams $\Rightarrow$ minor effects within pure MFV [except for very light sparticles]



+ *box*

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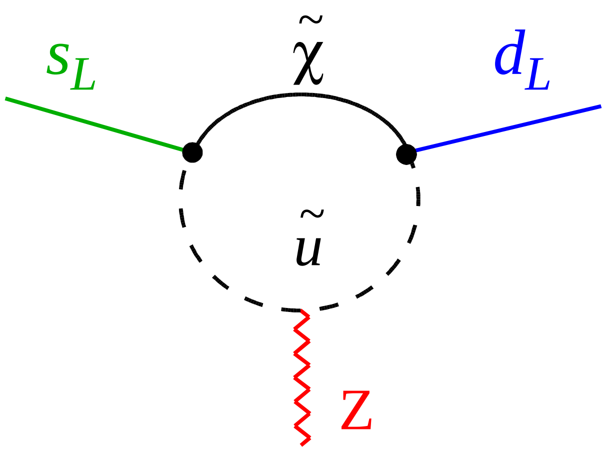
$K \to \pi\nu\nu$ decays are the *best probe* of the flavour structure of the up-type trilinear terms which are still largely unknown:

$$\mathscr{L}_{soft} \subset (A^U Y^U)_{ij}\, Q_L^{\,i}\, U_R^{\,j}\, \phi$$



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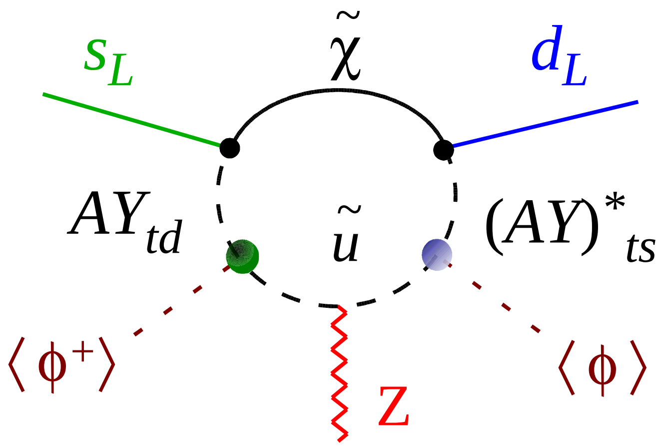
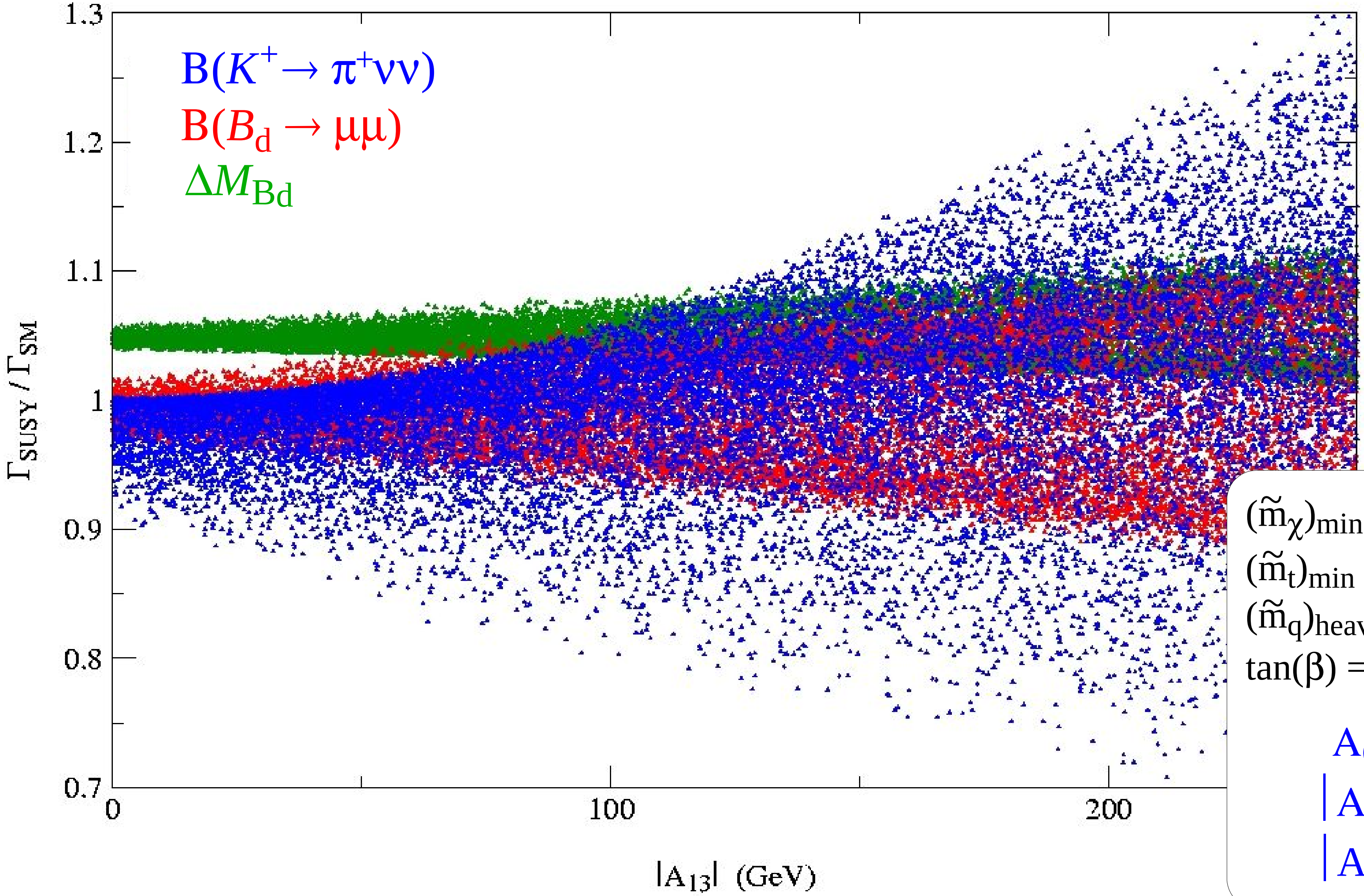


+ *box*

N.B.: The LR mixing in the up sector contains at least one large source of flavour symmetry breaking (y_t)

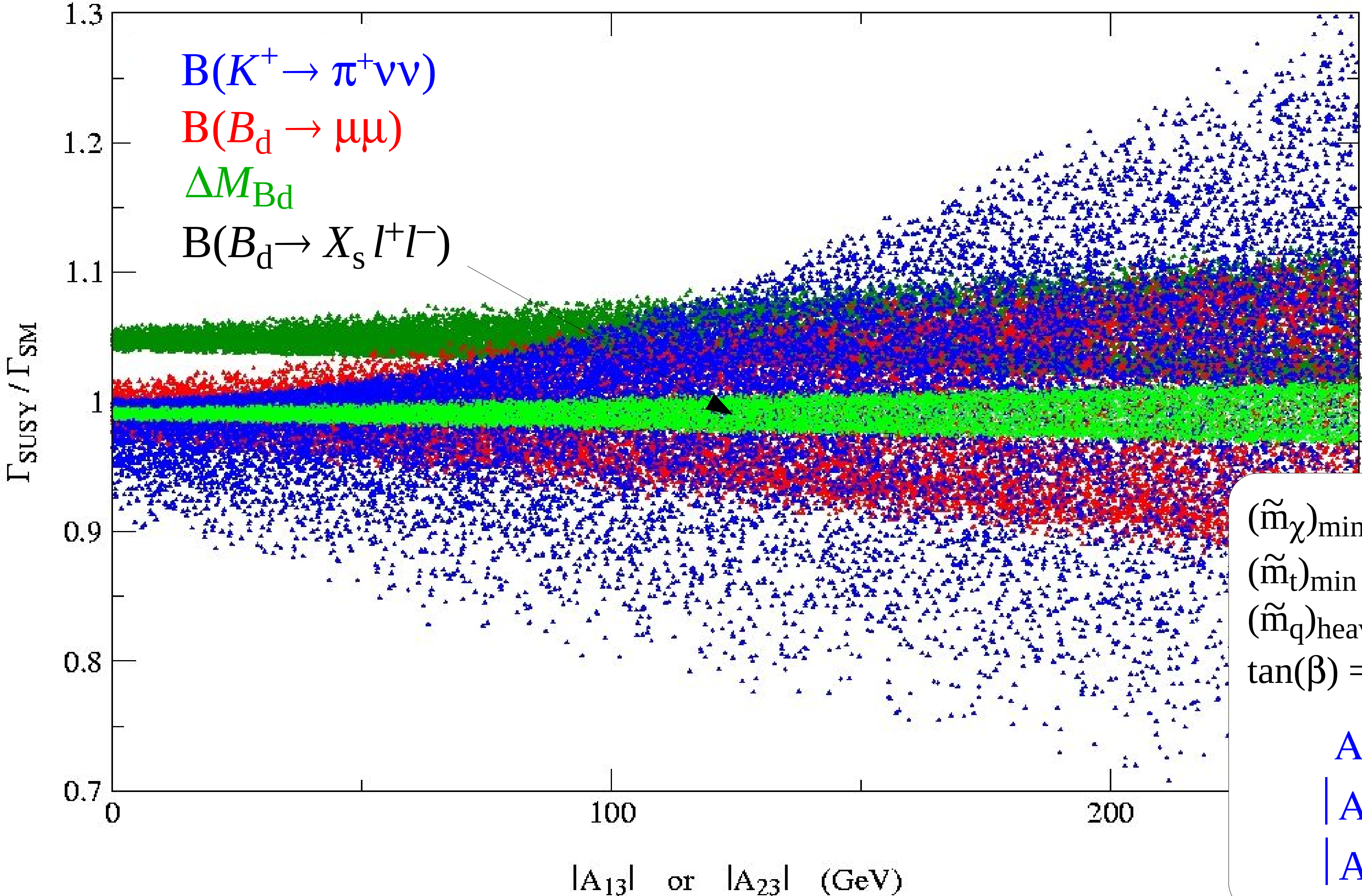
Systematic investigation of the correlations of SUSY effects in $K \to \pi \nu\nu$, other FCNCs, e.w. & future high-energy observables [G.I., F.Mescia, P.Paradisi, C.Smith, S.Trine]:



$(\tilde{m}_\chi)_{min}$ = 250±10 GeV
$(\tilde{m}_t)_{min}$ = 500±10 GeV
$(\tilde{m}_q)_{heavy}$ = 1000 GeV
$\tan(\beta) = 2$

$A_0 = 1$ TeV
$|A_{13}| \leq \lambda A_0$
$|A_{23}| \leq \lambda A_0$

- 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



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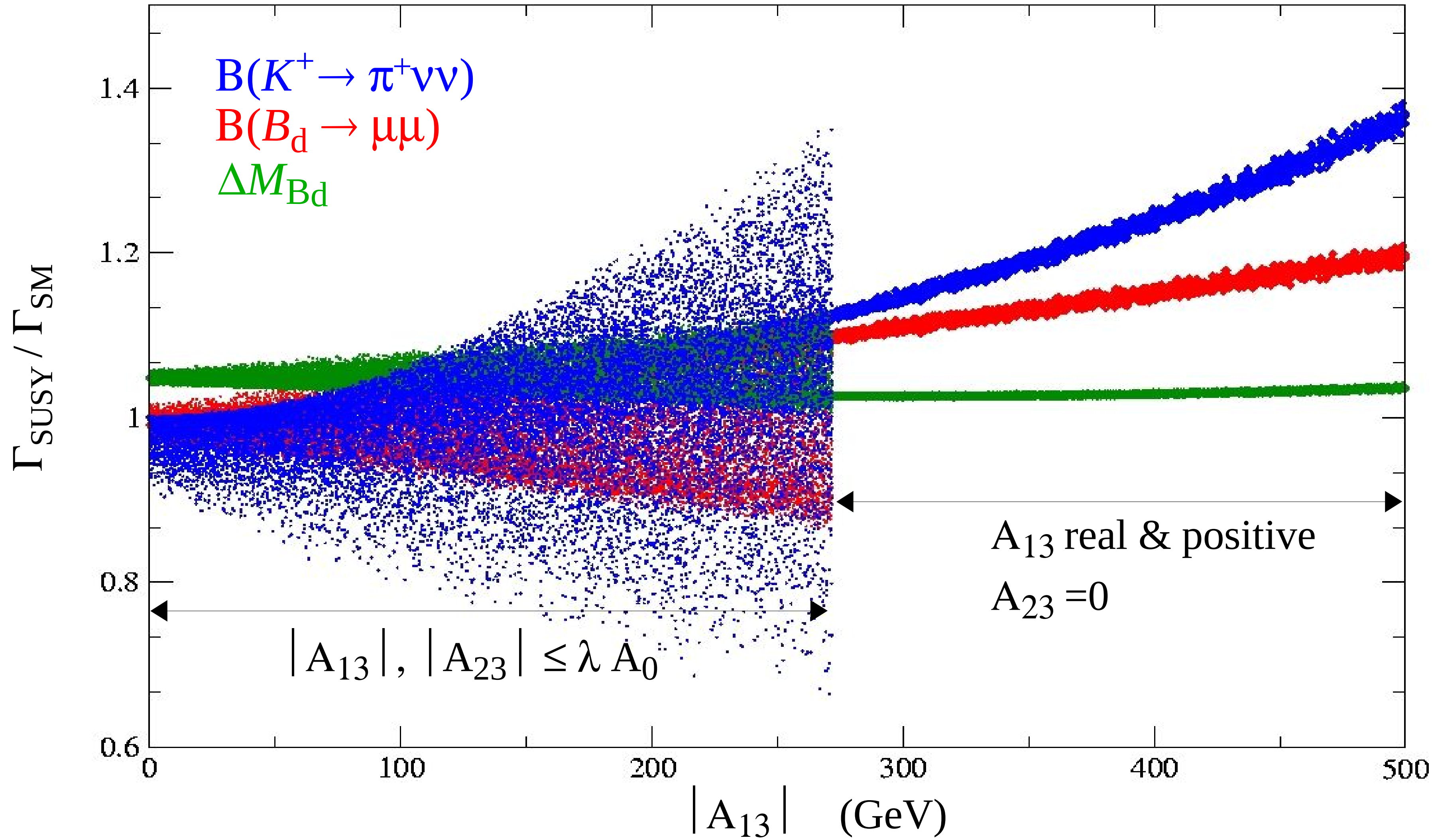
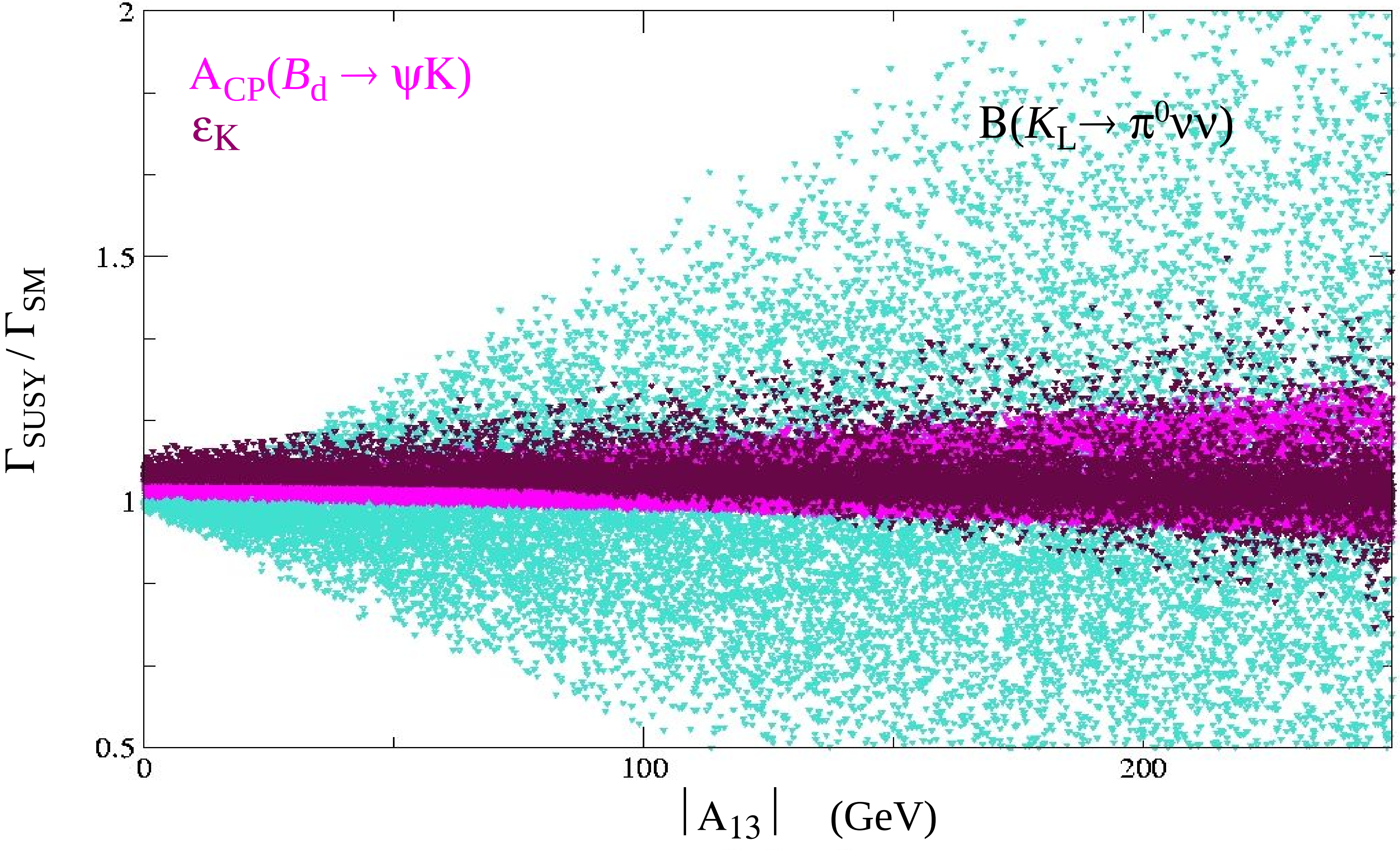
$|A_{13}| \leq \lambda A_0$
$|A_{23}| \leq \lambda A_0$

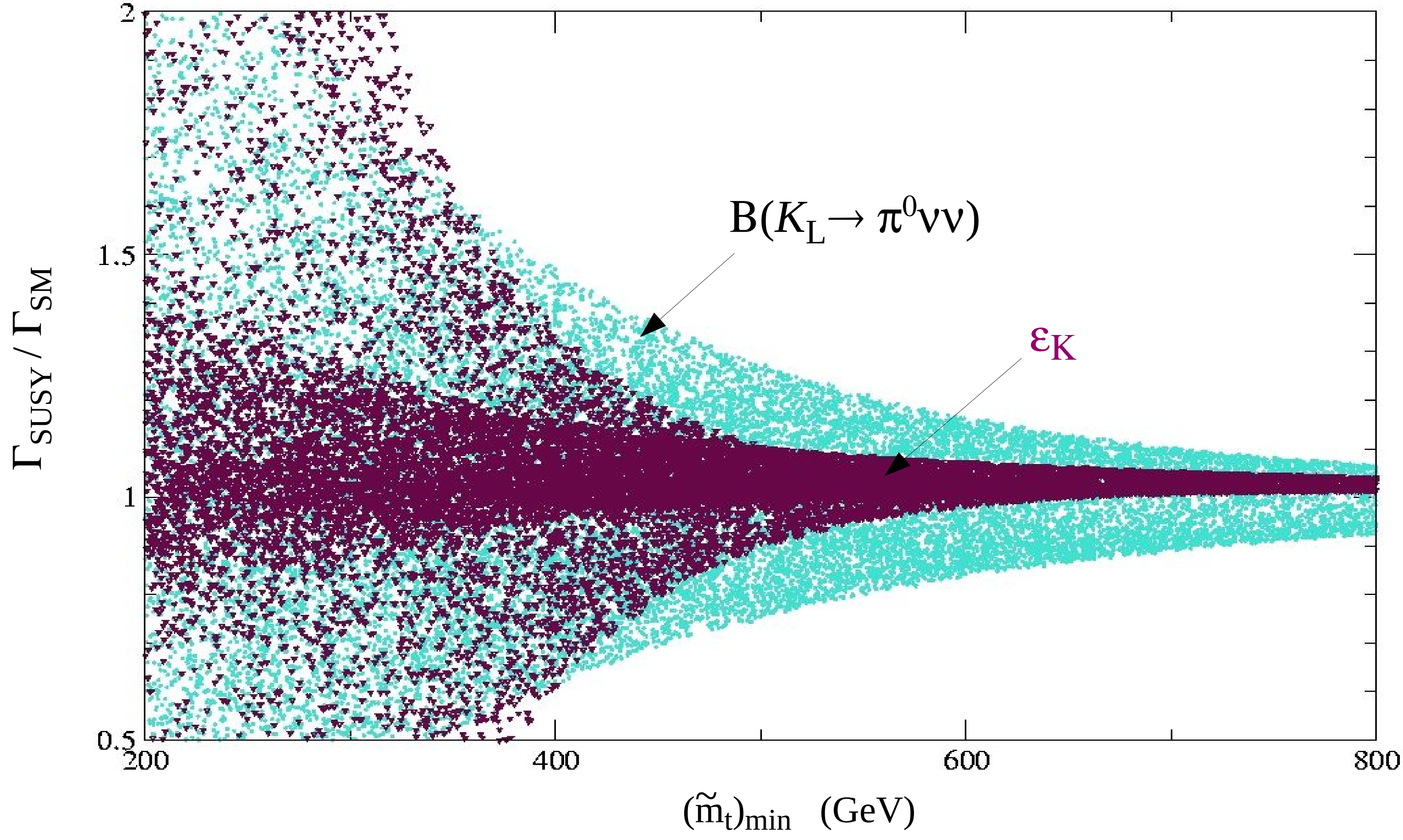
- Even if the mass spectrum is fully determined by LHC, large uncertainties in FCNCs due to several FV couplings ⇒ important to combine different observables
- The single MIA (mass insert. approx.) is bad approximation for $K\to\pi\nu\nu$, even in presence of a single flavour-violating coupling ⇒ dominance of the double-MIA [Colangelo & G.I. '98]



- At fixed magnitude of the A terms, there is a larger room for deviations from the SM in the CPV observables ⇒ great interest of $K_L \to \pi^0 \nu\nu$



- At fixed magnitude of the A terms, there is a larger room for deviations from the SM in the CPV observables ⇒ great interest of $K_L \to \pi^0 \nu\nu$
- Slower decoupling of penguins ($K \to \pi\nu\nu$) with respect to boxes ($\Delta F=2$)



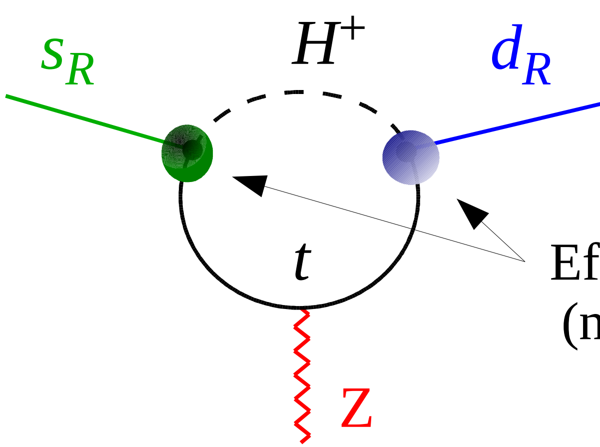
Complete analysis still in progress [more observables & more correlations under investigation] but general conclusions already clear:

- The flavour structure of the up-type trilinear terms is still largely unknown
- $K \to \pi \nu\nu$ decays are a *unique probe* of these soft-breaking terms, while they are marginally sensitive to flavour-blind strucutres compared to ε_K and $b \to s\gamma$
- The maximal sensitivity to the up-type trilinear terms is obtained for
  - Light stop & charginos [but non-negligible effects up to masses ~ 1 TeV]
  - Small tan β

Other interesting and peculiar aspects of rare K decays arise in more specific corners of the MSSM parameter-space

E.g.: RR Higgs-mediated Z penguins at large tanβ

Paradisi & G.I. '05 [to appear]



Effective one-loop couplings (non decoupling in the limit of large SUSY masses)

$\sim y_b\, (\delta_{RR})_{3i}\, \epsilon_{loop}\, (\tan\beta)^2$

$(\tan\beta)^4$ – contribution to the decay amplitude

If $\tan\beta \sim 50$ sizable corrections to the BR's even for $(\delta_{RR})_{31}(\delta_{RR})_{32} = O(\lambda^5)$

Not only $K \to \pi\nu\nu$ ...

The four golden FCNC modes provide a key information for any model with new d.o.f. at the TeV scale carrying quark-flavour quantum numbers,

but there are other observables in the kaon sector which provides useful infos about more specific BSM scenarios, which is still worth to search / measure with better precision in the future:

- Precision tests of Lepton-Flavour Universality in charged-current interactions [e.g.: $\Gamma(K^+ \to \mu^+\nu)/\Gamma(K^+ \to e^+\nu)$]
- Search for LFV decays [e.g.: $\Gamma(K_L \to \mu e)$, ...]
- T-violating observables [e.g.: $P_T^{\mu}(K^+ \to \pi^0\mu^+\nu)$, ...]
- Precision tests of CPT and QM by means of interference measurements

⋮

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observable effects within realistic SUSY models

The neutral kaon system is by far the best probe of these type of effects

Violations of Lepton-Flavour Universality in charged-current interactions

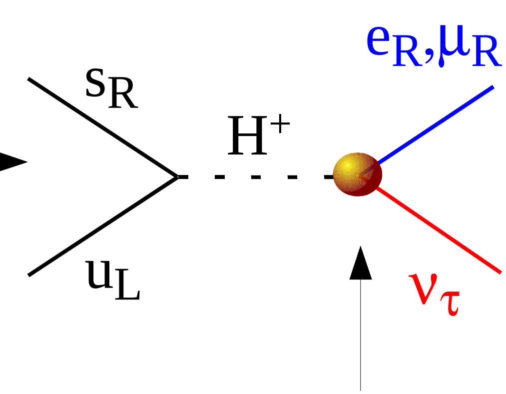
Interesting effect generated within the MSSM

Masiero, Paradisi, Petronzio, '05
[*to appear*]

Key ingredients:
- large $\tan\beta$
- sizable LFV terms [slepton sector]

$$\Gamma(K \to \mu\nu)^{exp} = \Gamma(K \to \mu\nu_\mu) + \Gamma(K \to \mu\nu_e) + \Gamma(K \to \mu\nu_\tau)$$

$\approx$ SM $\qquad \approx 0 \qquad$ scalar LFV amplitude



sizable one-loop eff. coupl. because of 3[rd] generation & large mixing in the lepton sector

The best probe of this effect is obtained by means of

$$R^K_{\mu e} = \frac{\Gamma(K^+ \to \mu^+\nu)}{\Gamma(K^+ \to e^+\nu)}$$

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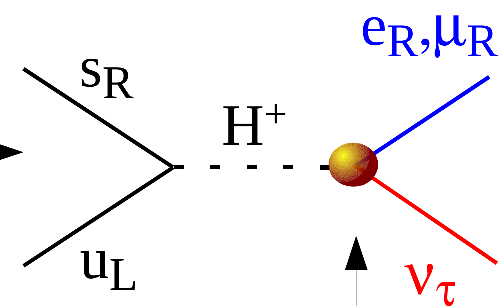

$$R^K_{\mu e} = \frac{\Gamma(K^+\to \mu^+\nu)}{\Gamma(K^+\to e^+\nu)}$$

$$R^K_{\mu e} \approx (R^K_{\mu e})^{SM}\left[1+0.013\left(\frac{\tan\beta}{40}\right)^6\left(\frac{500\ \text{GeV}}{M_H}\right)^4\left(\frac{\Delta_{13}}{5\times10^{-4}}\right)^2\right]$$

< 0.017 [NA48/2 @ ICHEP'05]

sizable one-loop eff. coupl. because of 3rd generation & large mixing in the lepton sector

N.B.: $\Delta_{13} \sim 5\times10^{-4}$ ⇔ LFV τ decays of $O(10^{-10})$ ⇒ $R^k_{\mu e}$ deep probe of LFV

CPT tests & neutral kaon interferometry

CPT symmetry is linked to the basic mathematical tools that we use in particle physics:

QFT + Lorentz invariance + Locality $\Rightarrow$ CPT

These tools have intrinsic limitations [we are not able to include gravity in consistent way] $\Rightarrow$ we should expect ~~CPT~~ at some level

But we do not have a consistent & predictive theory if we abandon these tools $\Rightarrow$ hard to define a reference scale/size for ~~CPT~~

$$|M_{\bar{K}} - M_K| < 10^{-18}\, M_K$$

Very suggestive...
(but should not be over-emphasized)

Main message:

- The neutral kaon system offer a unique framework to test CPT (& QM)
- The reference scale in this type of search is set by the most significant experimental bounds $\Rightarrow$ worth to improve

Conclusions

There is no doubt that Kaon physics will still be very interesting in the LHC era

The still-open question is if we will have dedicated experiments [hopefully more the one...] able to fully exploit its discovery potential