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Exploring the flavor structure of the MSSM with rare K decays

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- Outline

A- General framework: Rare K decays & MSSM

B- Minimal Flavor Violation in the MSSM

C- MSSM with large trilinear couplings in the up sector

D- General New Physics impact on $K_L \to \pi^0 \ell^+ \ell^-$

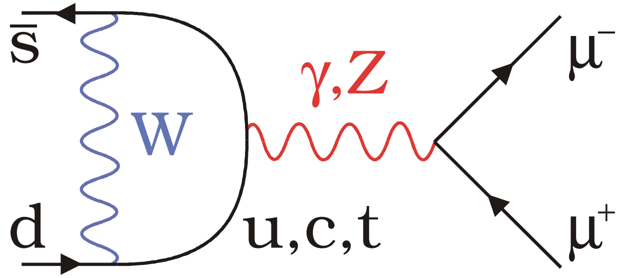
E- Conclusion

General framework:

Rare K decays and MSSM

- Rare K_L decays

Direct CPV

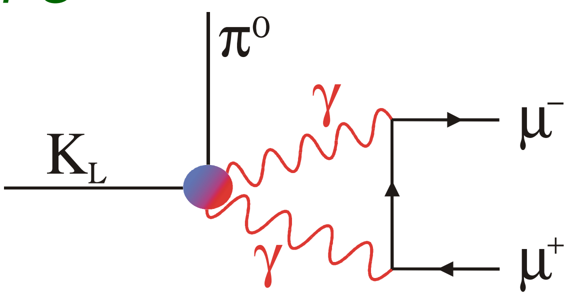


Axial-vector current $(1^{++}, 0^{-+})$

Vector current (1^{--})

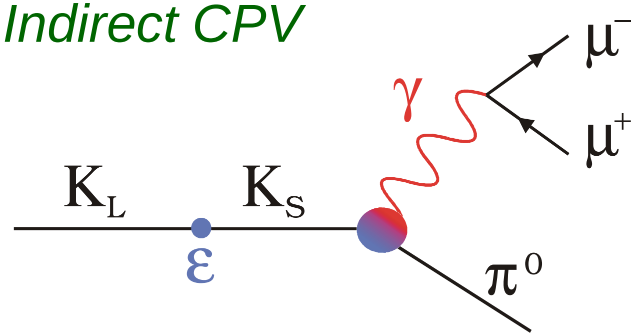
Constructive*

CPC



$(0^{++}, 2^{++})$

Indirect CPV



(1^{--})

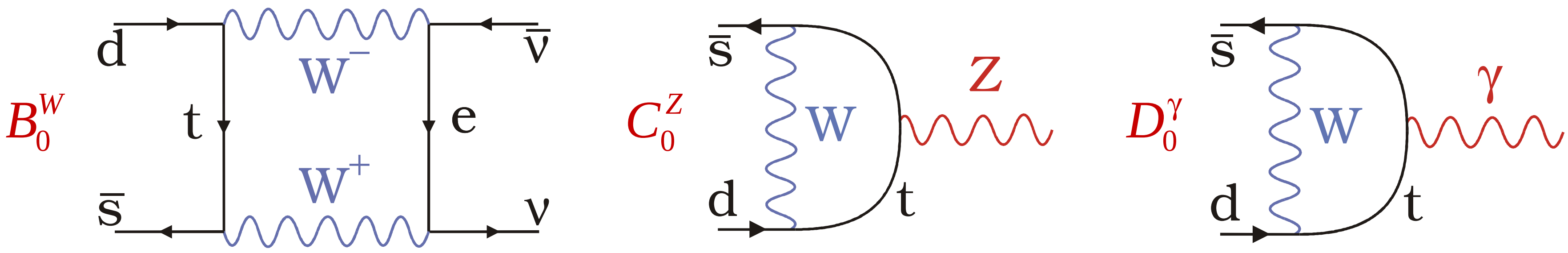
	DCPV	*ICPV*	*CPC-2⁺⁺*	*CPC-0⁺⁺*
$K_L \to \pi^0 \nu\bar{\nu}$	100%	(≈ 1%)	–	–
$K_L \to \pi^0 e^+ e^-$	40%	60%	(< 3%)	–
$K_L \to \pi^0 \mu^+ \mu^-$	30%	35%	–	35%

– ⇔ < 0.1%

*Buchalla,D'Ambrosio,Isidori ('03)/de Rafael,Friot,Greynat ('04)

1- Direct CPV:

FCNC are generated at one-loop (penguin and box diagrams):



and encoded into effective operators and Wilson coefficients:

$$H_{eff}(\bar{s}d \to \bar{\nu}\nu) = \frac{G_F}{\sqrt{2}}\left(y_\nu\, (\bar{s}d)_{V-A}(\bar{\nu}\nu)_{V-A} + y_\nu^*\, (\bar{d}s)_{V-A}(\bar{\nu}\nu)_{V-A}\right)$$

$$H_{eff}(\bar{s}d \to \ell^+\ell^-) = \frac{G_F}{\sqrt{2}}\left(y_{7V}\, (\bar{s}d)_{V-A}(\bar{\ell}\ell)_V + y_{7A}\, (\bar{s}d)_{V-A}(\bar{\ell}\ell)_A\right) + h.c.$$

$$C_0^Z, B_0^W, D_0^\gamma \to y_{7V} \qquad\qquad C_0^Z, B_0^W \to y_\nu, y_{7A}$$

The matrix elements are extracted from the well-measured decay $K^+ \to \pi^0\ell^+\nu_\ell$ ($K_{\ell 3}$) using isospin symmetry $\langle\pi^0|(\bar{s}d)_V|K^0\rangle = \langle\pi^0|(\bar{s}u)_V|K^+\rangle$ (small hadronic uncert.)

2- Indirect CPV: $A(K_L \to \pi^0 \ell^+ \ell^-)_{ICPV} = \varepsilon A(K_S \to \pi^0 \ell^+ \ell^-),\ \varepsilon \approx 10^{-3}$

Long-distance dominated: $\mathrm{Re}\, y_{7V} \approx \mathrm{Re}\, \lambda_u D_0^\gamma(x_u) \gg y_{7A}$

→ To be estimated using *Chiral Perturbation Theory*:

- Loops are small; the decay is dominated by a single counterterm a_S,
- From NA48 measurements of $B(K_S \to \pi^0 \ell^+ \ell^-)$: $|a_S| = 1.2 \pm 0.2$.

D'Ambrosio,Ecker,Isidori,Portolés ('98)

3- CP-conserving:

Measurements (KTeV & NA48) of the rate and spectrum of $K_L \to \pi^0 \gamma\gamma$ permits the estimation of both scalar and tensor CPC contributions:

- The ratio $R_{\gamma\gamma}^{\ell} = \dfrac{\Gamma(K_L \to \pi^0 \ell^+ \ell^-)_{J=0^{++}}}{\Gamma(K_L \to \pi^0 \gamma\gamma)}$ can be estimated theoretically within 30%.

Isidori,Unterdorfer,C.S. ('04)

- Production of $(\gamma\gamma)_{J=2}$ is constrained by the low-energy end of the $\gamma\gamma$ spectrum, and is found negligible.

Buchalla,D'Ambrosio,Isidori ('03)

4- Complete prediction

$$Br(K_L \to \pi^0 \ell^+ \ell^-) = \left(C_{\text{dir}}^{\ell} \kappa^2 \pm C_{\text{int}}^{\ell} |a_S| \kappa + C_{\text{mix}}^{\ell} |a_S|^2 + C_{\gamma\gamma}^{\ell} \right) \cdot 10^{-12}$$

$$\kappa = \text{Im}\,\lambda_t 10^{-4}$$

$$C_{\text{dir}}^{e} \approx 2.3 \left(y_{7V}^2 + y_{7A}^2 \right)$$

$$C_{\text{int}}^{e} \approx 8.1 y_{7V}$$

$$C_{\text{mix}}^{e} \approx 14.5, C_{\gamma\gamma}^{e} \approx 0$$

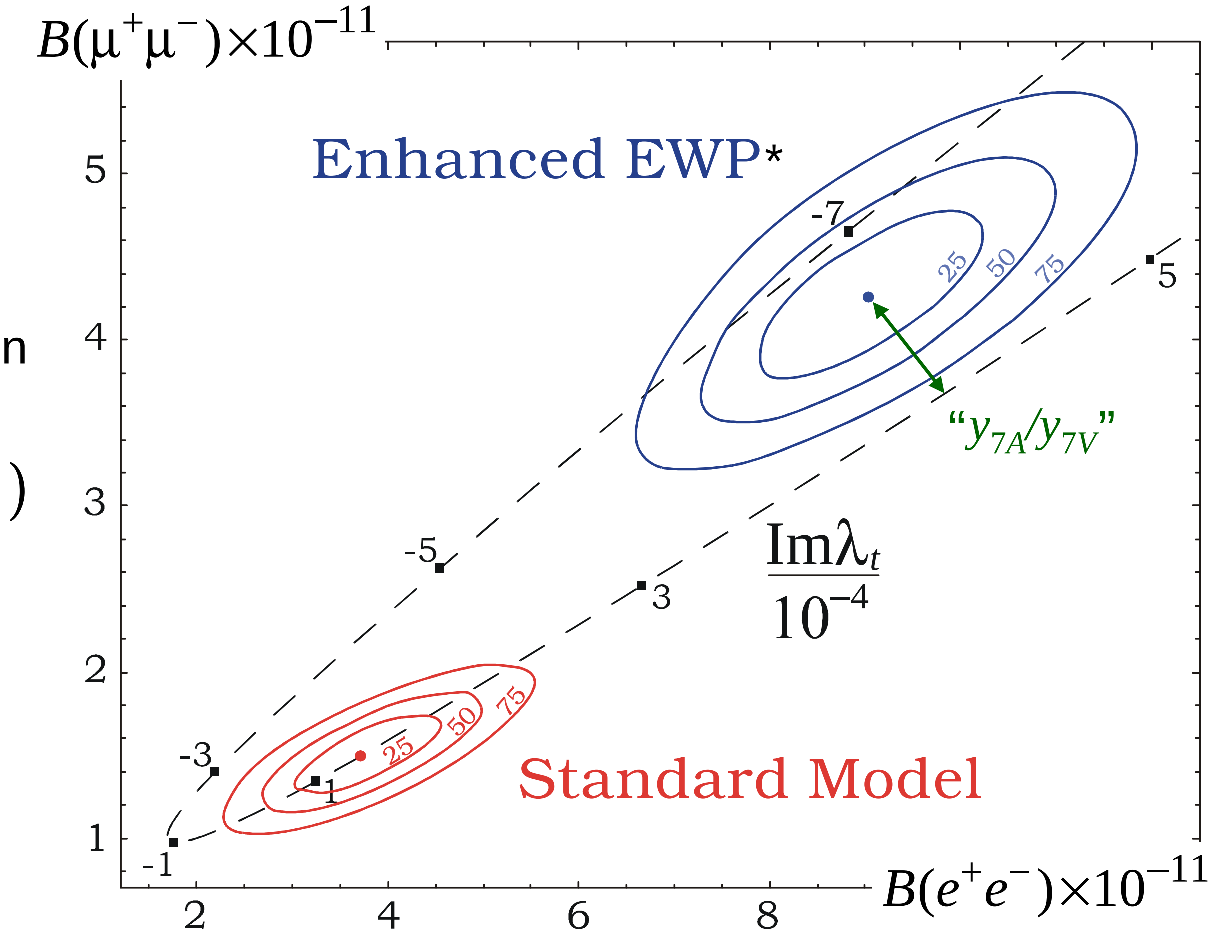
¼ phase-space suppression

$$C_{\text{dir}}^{\mu} \approx 0.55 \left(y_{7V}^2 + 2.33 y_{7A}^2 \right)$$

$$C_{\text{int}}^{\mu} \approx 1.9 y_{7V}$$

$$C_{\text{mix}}^{\mu} \approx 3.4, C_{\gamma\gamma}^{\mu} \approx 5.2$$

Helicity-suppressed terms



* Buras, Fleischer, Recksiegel, Schwab ('04)

- Rare K^+ decay

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) \approx \kappa^+ \left(\,|\mathrm{Im}\,\lambda_t X(x_t)|^2 + |\underbrace{\mathrm{Re}\,\lambda_t}_{O(\lambda^5)}\, \underbrace{X(x_t)}_{O(1)} + \underbrace{\mathrm{Re}\,\lambda_c}_{O(\lambda)}\, \underbrace{X(x_c)}_{O(10^{-4})}|^2 \,\right)$$

$$\kappa^+ = \frac{3\alpha^2 Br(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \lambda^2 \sin^4 \theta_W}$$

$|\mathrm{Im}\,\lambda_t X(x_t)|^2$: $K_L \to \pi^0 \nu\bar{\nu}$

$O(\lambda^5)\,O(1)$: 68%

$O(\lambda)\,O(10^{-4})$: 32%

Precision Physics:

The *t-quark effects*: $X(x_t) \overset{NLO}{=} 1.464 \pm 0.041$ $\quad$ *known to* $\sim 3\%$

The *c-quark effects*: $X(x_c) \overset{NNLO}{=} \lambda^4 (0.38 \pm 0.04)$ $\quad$ *known to* $\sim 10\%$

Buras,Gorbahn,Haisch,Nierste ('05)

Subleading *c-quark effects* from dimension-eight operators
Residual *u-quark effects*, pure long-distance

$$\delta X_c = \lambda^4 (0.04 \pm 0.02)$$

Isidori,Mescia,C.S. ('05)

- MSSM flavor-symmetry breaking

The MSSM has a rich flavor-symmetry breaking sector encoded in its *soft-breaking terms*:

$$Sfermion\ Masses = -\mathbf{m}_Q^2 \tilde{Q}^* \tilde{Q} - \mathbf{m}_U^2 \tilde{U}^* \tilde{U} - \mathbf{m}_U^2 \tilde{D}^* \tilde{D} - \mathbf{m}_L^2 \tilde{L}^* \tilde{L} - \mathbf{m}_R^2 \tilde{R}^* \tilde{R}$$

$$Trilinear\ Terms = -\tilde{U}\mathbf{A}_u \tilde{Q} \cdot H_u + \tilde{D}\mathbf{A}_d \tilde{Q} \cdot H_d + \tilde{R}\mathbf{A}_\ell \tilde{L} \cdot H_d + h.c.$$

The down-squark trilinear couplings are already phenomenologically well-constrained. Our work concerns the *up-quark trilinear* terms.

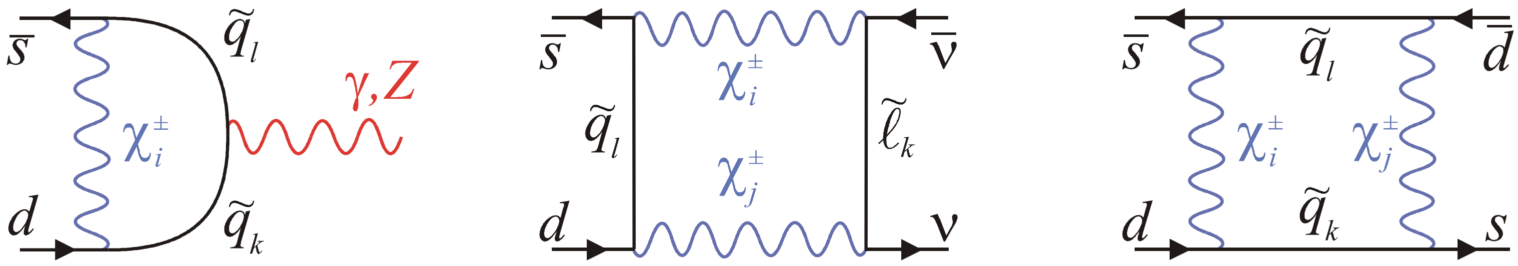
If the SM is of any guide, it is natural to investigate the situation in which the *largest flavor-symmetry breaking* occurs in the up-sector.

Our goal is to analyze the information rare K decays could give on these terms, assuming the chargino sector has been fixed by LHC (μ, β, M_2).

G.Isidori, F.Mescia, P.Paradisi, S.Trine, C.S., hep-ph/0604074

• Chargino-squark contributions to FCNC

The chargino – up-squark penguins and boxes we probe are:



with the amplitudes functions of the mass matrices, i.e.

$$\delta C^Z, \delta B^W \approx f(M_{\tilde{q}}^2, M_{\chi}^2, M_{\tilde{\ell}}^2, V, U, H)$$

Strategy: - Fix SUSY parameters,

- Diagonalize the mass matrices (no Mass Insertion Approximation),

Colangelo,Isidori ('98)

- Compute corrections to FCNC basic functions,
- Compute corrections to observables:

In *K physics*: $K \to \pi\nu\bar{\nu},\ K_L \to \pi^0 \ell^+\ell^-,\ K_L \to \mu^+\mu^-,\ \varepsilon_K,\ \Delta M_K$

In *B physics*: $B \to X_{s,d}\nu\bar{\nu},\ B_{s,d} \to \mu^+\mu^-,\ B \to X_{s,d}\ell^+\ell^-,\ b \to s\gamma,\ \Delta M_{Bs,d}$

Minimal Flavor Violation in the MSSM and rare K decays

• The MFV hypothesis in the MSSM

MFV assumes that the SM Yukawa matrices are the only source of flavor-symmetry breaking in the MSSM. This implies the expansion for the soft-breaking terms: *D'Ambrosio,Giudice,Isidori,Strumia ('02)*

$$\begin{cases} \mathbf{m}_Q^2 = \tilde{m}\left(\tilde{a}_1\mathbf{1} + \tilde{b}_1\mathbf{Y}_u^\dagger\mathbf{Y}_u + \tilde{b}_2\mathbf{Y}_d^\dagger\mathbf{Y}_d + \tilde{b}_3(\mathbf{Y}_d^\dagger\mathbf{Y}_d\mathbf{Y}_u^\dagger\mathbf{Y}_u + \mathbf{Y}_u^\dagger\mathbf{Y}_u\mathbf{Y}_d^\dagger\mathbf{Y}_d)\right), \mathbf{m}_U^2 = \tilde{m}\left(\tilde{a}_2\mathbf{1} + \tilde{b}_4\mathbf{Y}_u\mathbf{Y}_u^\dagger\right), \\ \mathbf{m}_D^2 = \tilde{m}\left(\tilde{a}_3\mathbf{1} + \tilde{b}_5\mathbf{Y}_d\mathbf{Y}_d^\dagger\right), \mathbf{A}_u = a_0\mathbf{Y}_u\left(\tilde{a}_4\mathbf{1} + \tilde{b}_6\mathbf{Y}_d^\dagger\mathbf{Y}_d\right), \mathbf{A}_d = a_0\mathbf{Y}_d\left(\tilde{a}_5\mathbf{1} + \tilde{b}_7\mathbf{Y}_u^\dagger\mathbf{Y}_u\right) \end{cases}$$

Slightly less constraining than mSUGRA, $\tilde{a}_i = 1, \tilde{b}_i = 0$.

$$M_{\tilde{u}} = \begin{pmatrix} (\mathbf{m}_U)_{LL} & (\mathbf{m}_U)_{RL}^\dagger \\ (\mathbf{m}_U)_{RL} & (\mathbf{m}_U)_{RR} \end{pmatrix} \quad \text{with}$$

$$K = V_{CKM}$$

$$(\mathbf{m}_U)_{RL} = a_4\mathbf{M}_u + \frac{b_6}{v_d^2}\mathbf{M}_u K \mathbf{M}_d K^\dagger - \cot\beta\mu^*\mathbf{M}_u,$$

$$(\mathbf{m}_U)_{RR} = a_2^2\mathbf{1} + b_4^2\frac{\mathbf{M}_u^2}{v_u^2} + \mathbf{M}_u^2 + \mathbf{1}\frac{2M_Z^2}{3}\cos 2\beta\sin^2\theta_W,$$

$$(\mathbf{m}_U)_{LL} = a_1^2\mathbf{1} + b_1^2\frac{\mathbf{M}_u^2}{v_u^2} + b_2^2\frac{K\mathbf{M}_d^2K^\dagger}{v_d^2} + b_3^2(\ldots) + \mathbf{M}_u^2 + \mathbf{1}\frac{4M_W^2 - M_Z^2}{6}\cos 2\beta,$$

Along an $s - \tilde{t} - d$ line: $(\delta_{RL}^U)_{32}^*(\delta_{RL}^U)_{31} \sim m_t^2 V_{ts}^* V_{td}\left|a_4^* - \cot\beta\mu\right|^2$ (BRS basis).

- Scanning of the squark-chargino contributions

Experimental Constraints : $M(\chi_i^\pm) > 94\,GeV,\ M(\chi_1^0) > 46\,GeV,\ M(\chi_2^0) > 63\,GeV$

$M(\tilde{t}) > 96\,GeV,\ M(\tilde{b}) > 89\,GeV,\ M(\tilde{u},\tilde{c},\tilde{d},\tilde{s}) > 250\,GeV$

Stability Bounds : $|a_4|^2 \le 3\left(a_1^2 + a_2^2\right),\ |a_5|^2 \le 3\left(a_1^2 + a_3^2\right)$

Conditions on the scalar potential so that no unphysical SSB occurs.

Parameter ranges :

$$a_{1,2,3} : 0 \to 1000,\ \tan\beta = 2,$$
$$|a_4| : 0 \to 3000,\ \Phi_{a_4} : -\pi \to \pi \qquad \text{(GeV)}$$
$$\mu : -500 \to 500,\ M_2 : 0 \to 3000$$

– The role of M_2 and a_3 is essentially to keep masses above experimental bounds.

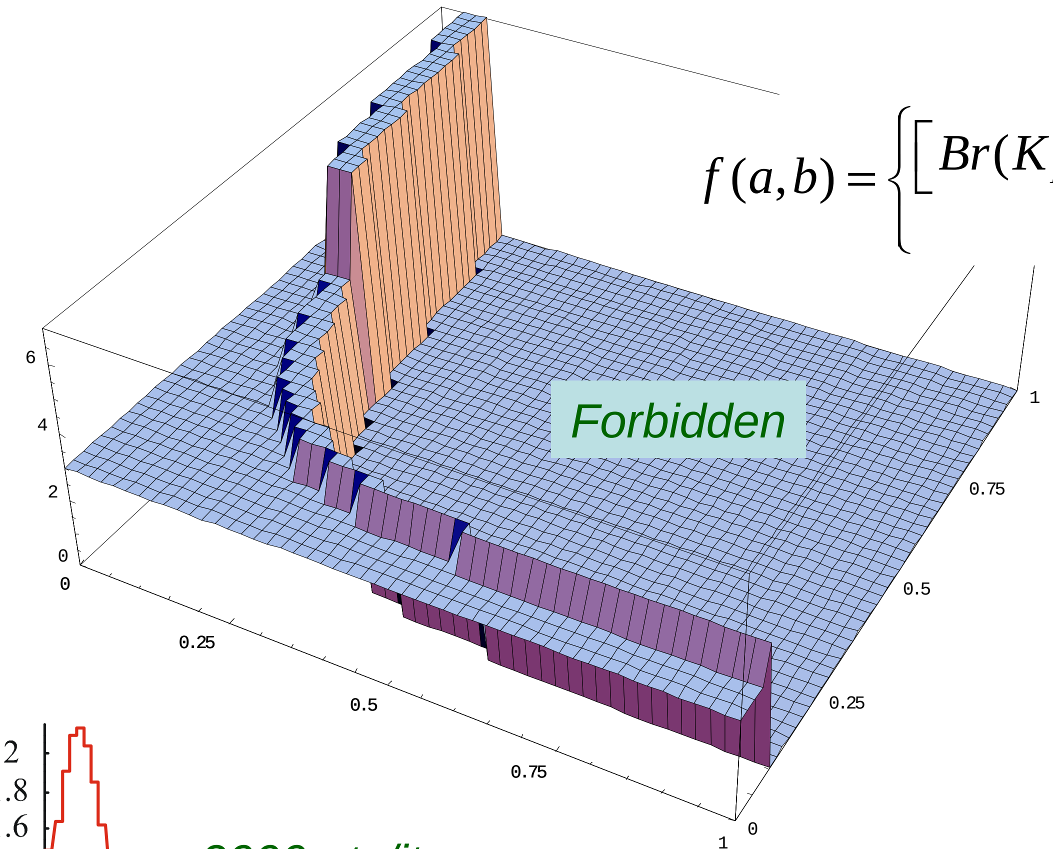
– Negligible impact on rare K decays for most of the parameter space.

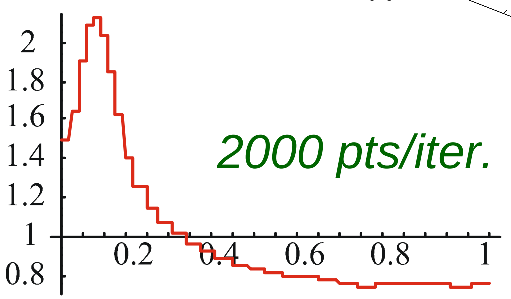
– The scans are optimized combining various numerical techniques (*simple random, VEGAS*, range/parameter redefinitions*).

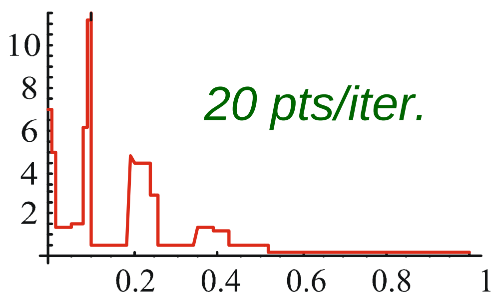
**Brein ('04)*

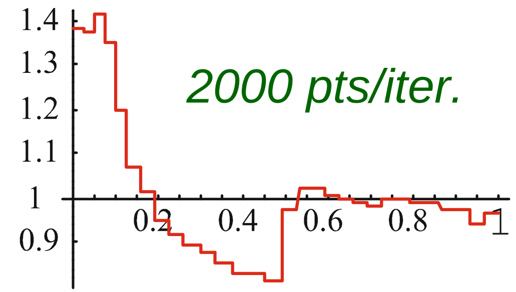
MFV

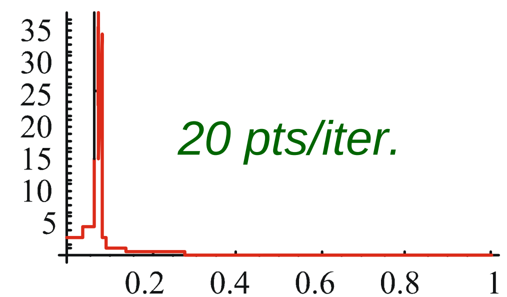
$$f(a,b)=\begin{cases}\left[Br(K_L\rightarrow\pi^0\nu\bar{\nu})\right]^n & if\ \ a,b\Rightarrow bounds\,ok\\ 0 & otherwise\end{cases}$$











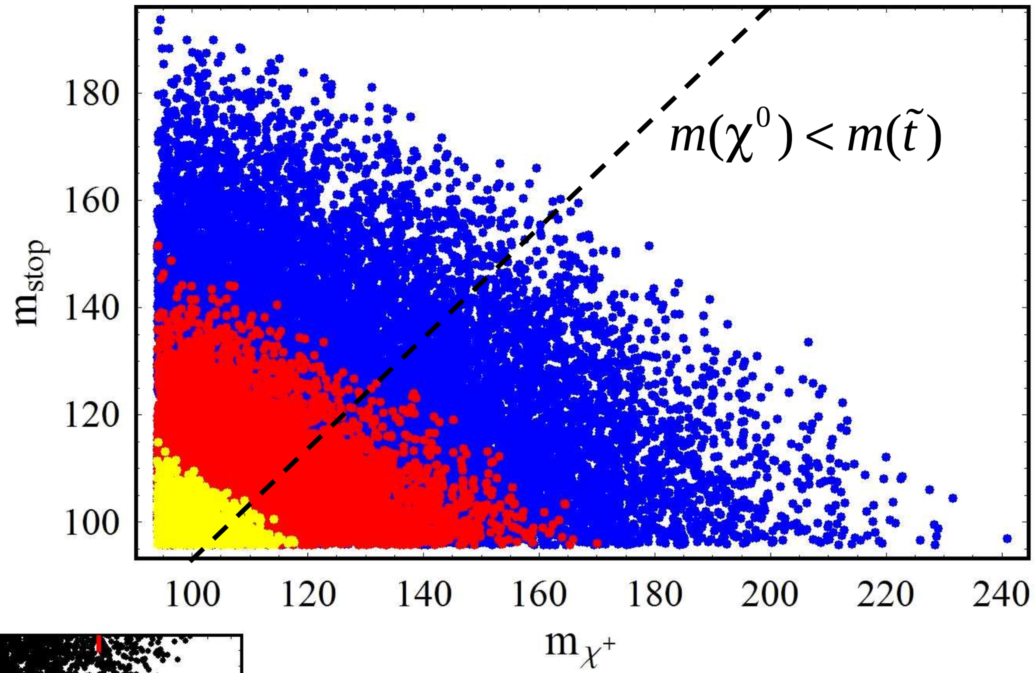
Given the type of dependence on parameters, adaptative scans are dangerous in high dimensions.

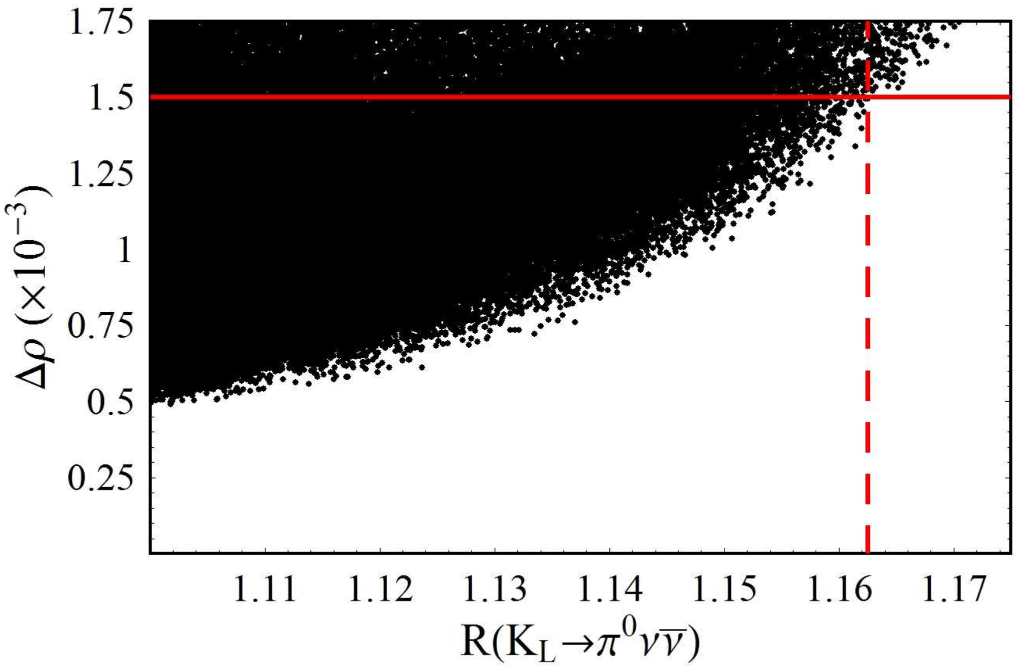
- **Results**

- Colors $\Leftrightarrow$ enhancements of the $K_L \to \pi^0 \nu \bar{\nu}$ mode by

  10%, 12%, 15%.

- The determining factors are the masses of the lightest squark and chargino (~ higgsino).





- Large a_4 preferred, while impact of the b's small, only felt through the mass spectrum.

- Strongest constraint from $\Delta\rho$ (*), sensitive to the mass-splitting among up and down squarks.

*Buras,Gambino,Gorbahn,Jaeger,Silvestrini ('00)

- # Results

– Adding the charged Higgs contribution, enhancements of $\sim 20\%$ for K^{+}, $\sim 25\%$ for K_L are possible with $\tan\beta = 2$, $m_{H+} > 300\ \mathrm{GeV}$ (gets larger for smaller β).

– Among the rare K decay modes, $K \to \pi\nu\bar{\nu}$ are the *only ones significantly affected* (compared to hadronic uncertainties) by chargino contributions in MFV.

– The enhancements for other decay modes, driven by chargino penguins, are correlated with $K \to \pi\nu\bar{\nu}$, while that of chargino boxes are not ($\varepsilon_K, \Delta M_s, \Delta M_d$).

Comparing to the literature:

Buras,Gambino,Gorbahn,Jaeger,Silvestrini ('00)
Bobeth,Bona,Buras,Ewerth,Pierini,Silvestrini,Weiler ('05)

– Slightly less constraining framework,

– CKM parameters taken as given from unitary triangle analyses (Universal UT),

– MFV cannot be excluded as long as $R < 25\%$, except if SUSY masses are found sufficiently heavy.

MSSM with large trilinear couplings in the up sector

- The Non-alignment of $\boldsymbol{A}_u$ hypothesis

The scenario: $(\mathbf{m}_U)_{RL} = \left[\mathbf{A} - \cot\beta\mu^*\right]\mathbf{M}_u$, with $\mathbf{A}$ non-diagonal, $(\mathbf{A})_{33} = A_0$, $|\mathbf{A}|_{i\neq j} \leq \lambda A_0$.

The goal

- To illustrate the potential of rare K decays in constraining these $\mathbf{A}_u$ terms, still largely unknown, and compare their sensitivity with the other K, B modes.

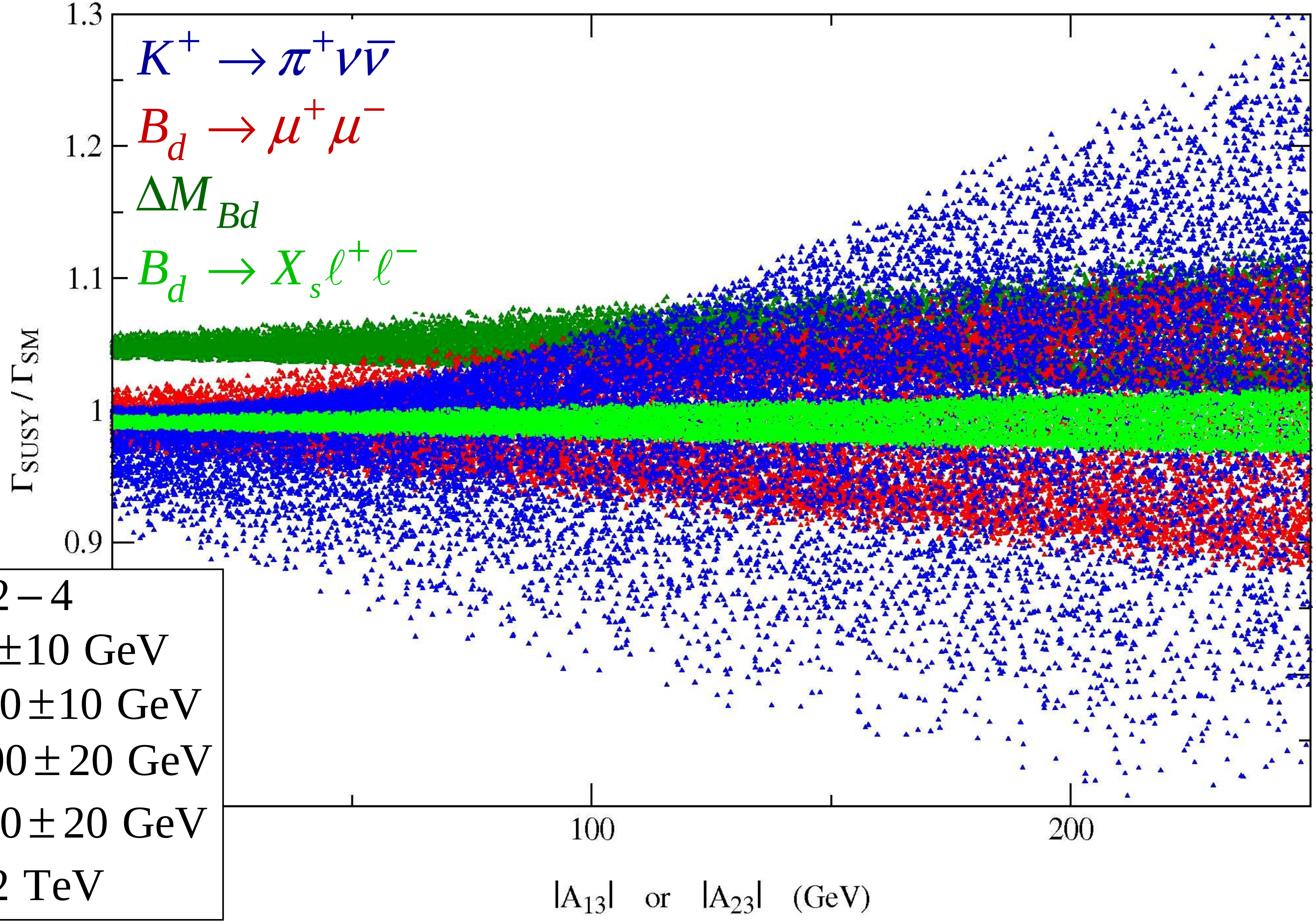
The strategy

- Extensive (but standard) scans for constrained SUSY masses over $\mathbf{A}_{13}$, $\mathbf{A}_{23}$. Large effects are not searched for*, but arise naturally as the $\mathbf{A}_u$ increases.

**Buras,Ewerth,Jaeger,Roziek ('05)*

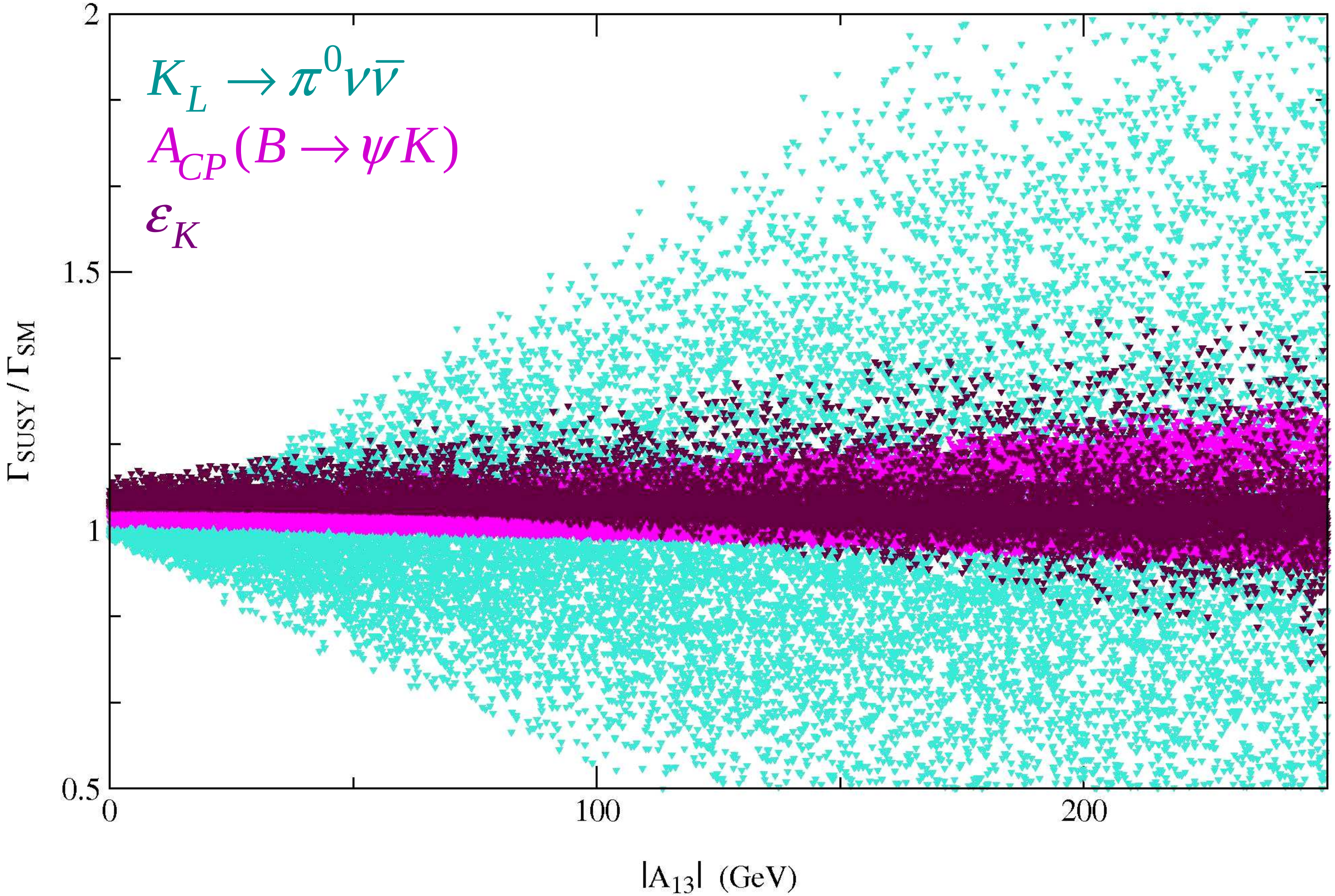
- MFV structure kept for LL, RR and also for the full down-sector.
- Chargino penguins/boxes play the major role. Gluino and neutralino subleading.

- Sensitivity $|\mathbf{A}_{13}|, |\mathbf{A}_{23}| \le A_0 \lambda, \quad A_0 = 1\ \mathrm{TeV}$, and phases left free.



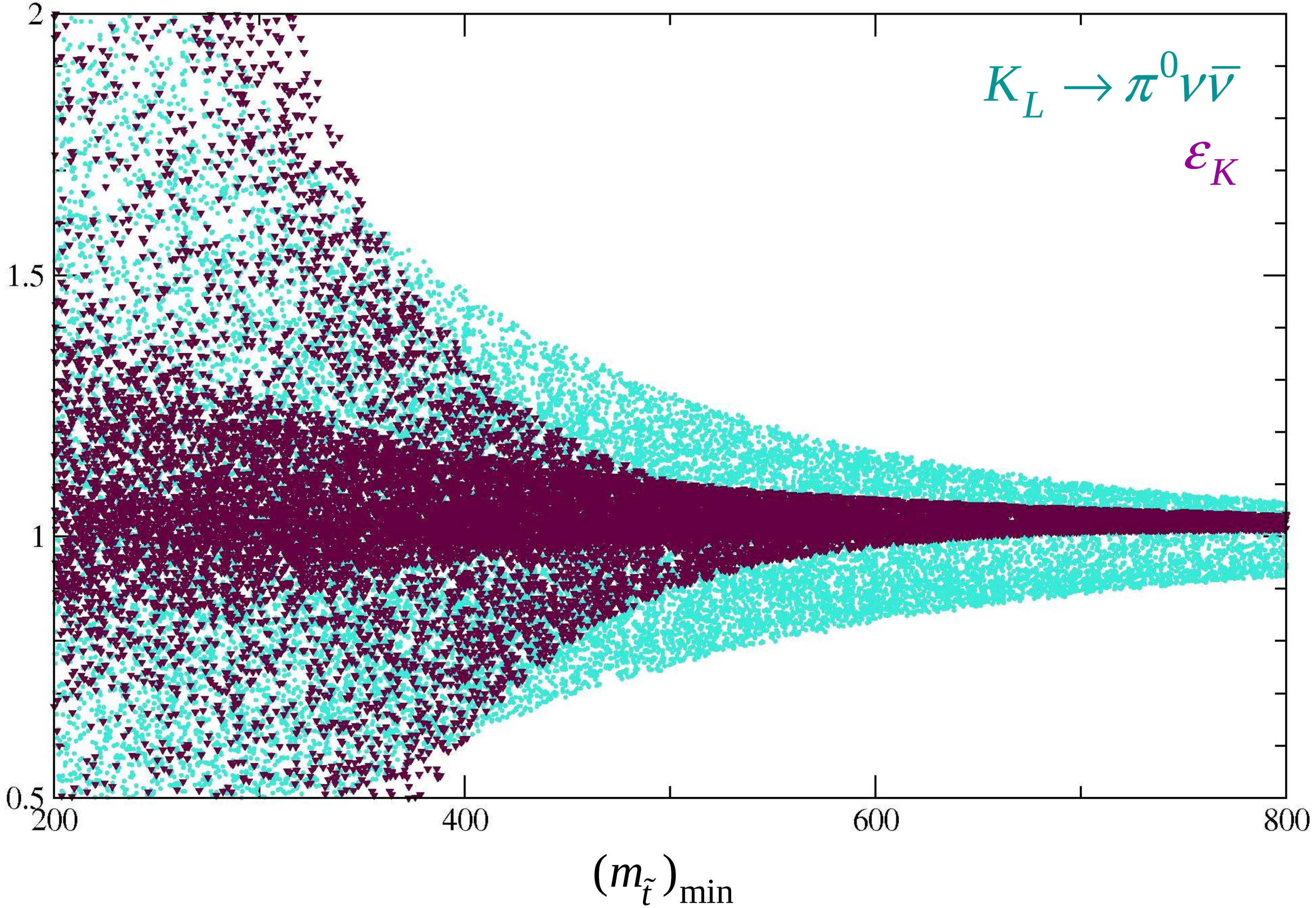
$\tan\beta = 2 - 4$
$\mu = 500 \pm 10$ GeV
$M_2 = 300 \pm 10$ GeV
$m_{u_R} = 600 \pm 20$ GeV
$m_{q_L} = 800 \pm 20$ GeV
others : 2 TeV

- Sensitivity $|\mathbf{A}_{13}|,|\mathbf{A}_{23}| \leq A_0\lambda, \quad A_0 = 1\ \text{TeV}$, and phases left free.



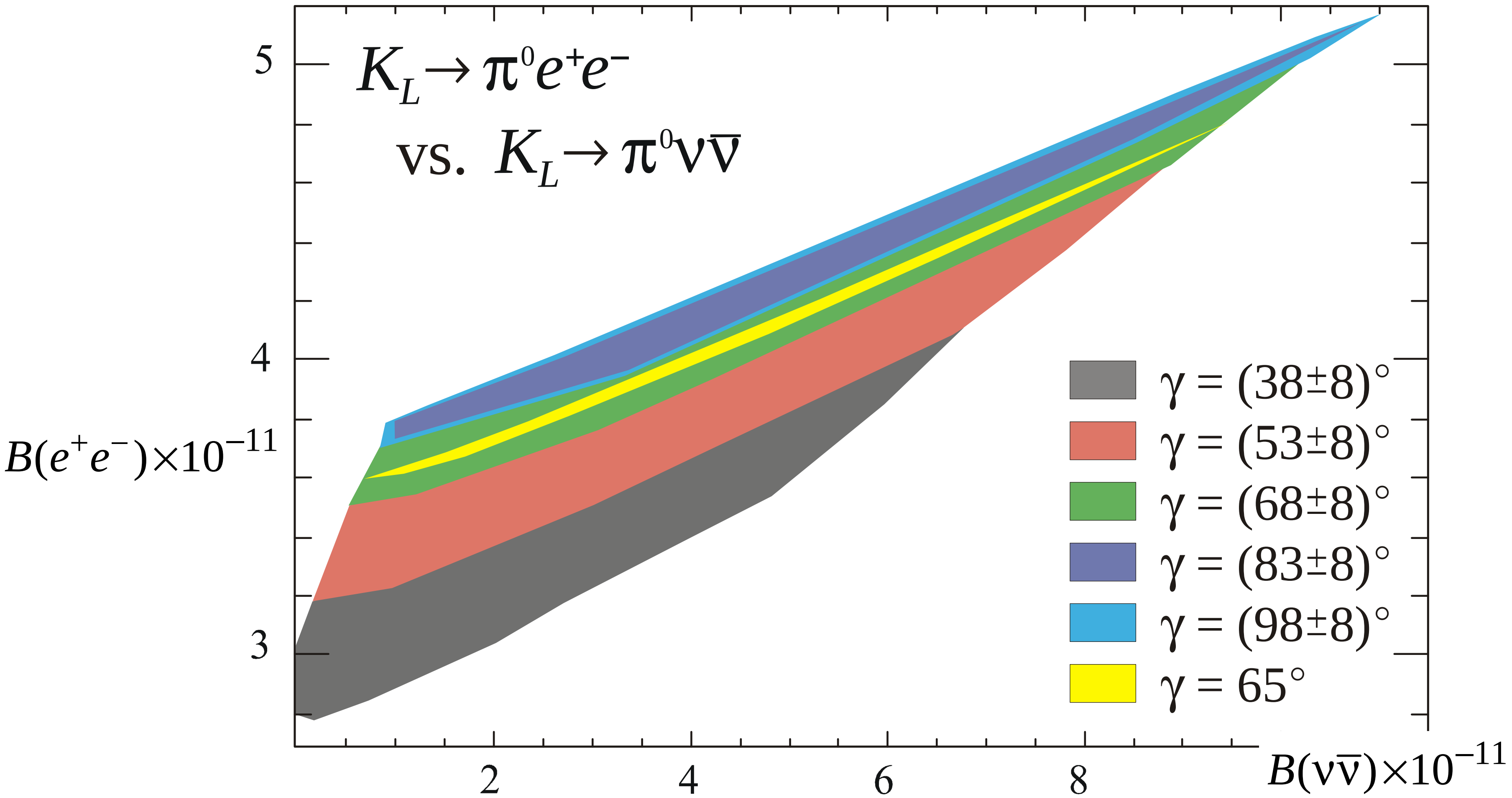
Large A_u

- **Decoupling:** Slower for penguins compared to boxes



- Correlation among rare K_L decays:

Impact of $\mathbf{A}_u$ on the K_L rare decays is correlated, hence a good signature of the model (similar for $K_L \to \pi^0\mu^+\mu^-$)



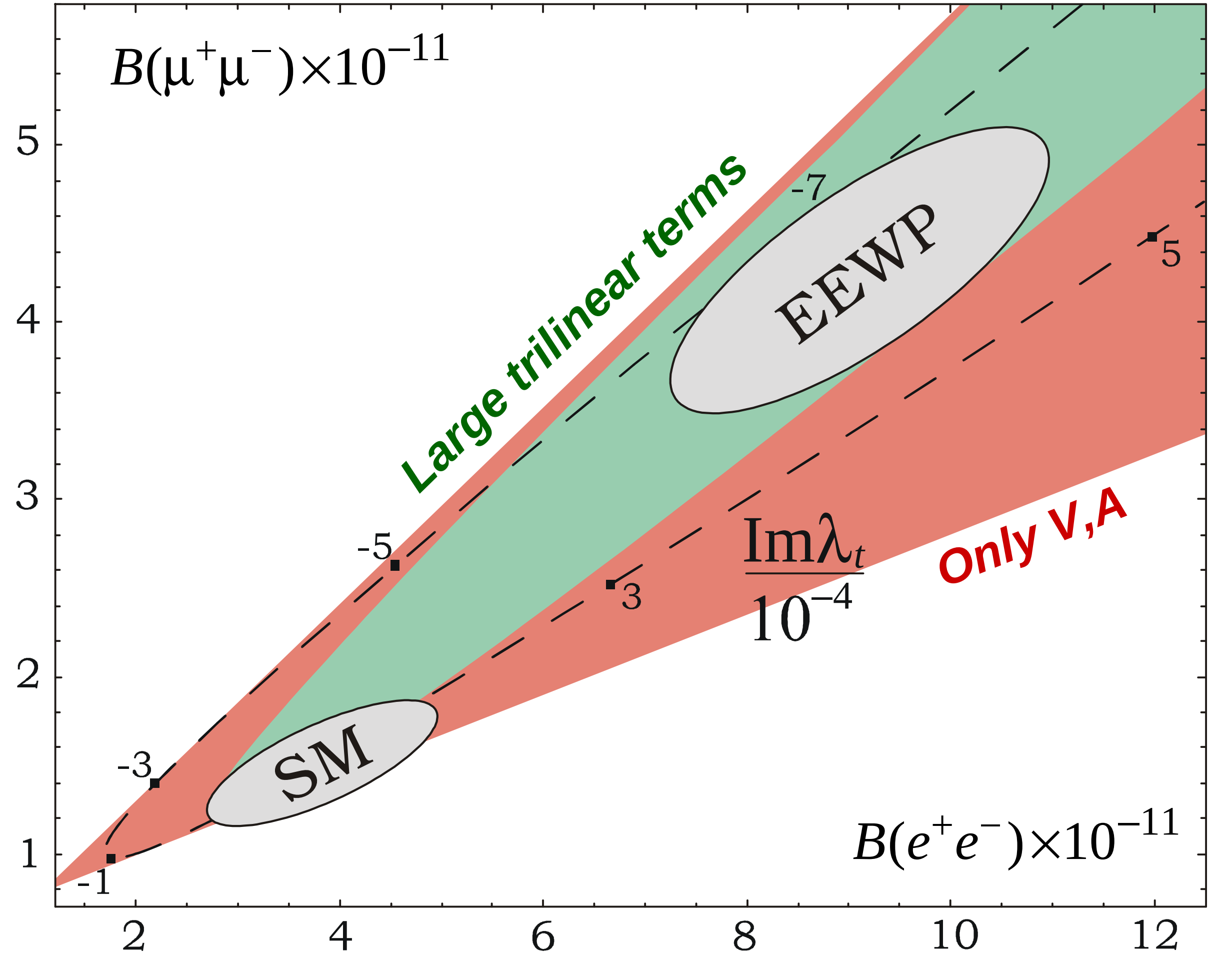
General New Physics impact on $K_L \to \pi^0 \ell^+ \ell^-$

- Vector/Axial vector currents:

Only a specific region can be attained for general vector and axial vector FCNC operators (i.e. y_{7A} , y_{7V}):

For example, if the NP comes from $\mathbf{A}_{13}$ & $\mathbf{A}_{23}$ through chargino contributions, the *effects on γ and Z penguins are correlated*.

→ restricted region is spanned, even for unrealistically large $\mathbf{A}_u$.



- Scalar/Pseudoscalar Currents: (*F.Mescia,S.Trine,C.S., to appear*)

To get away from the central region, FCNC scalar/pseudoscalar or tensor operators are needed:

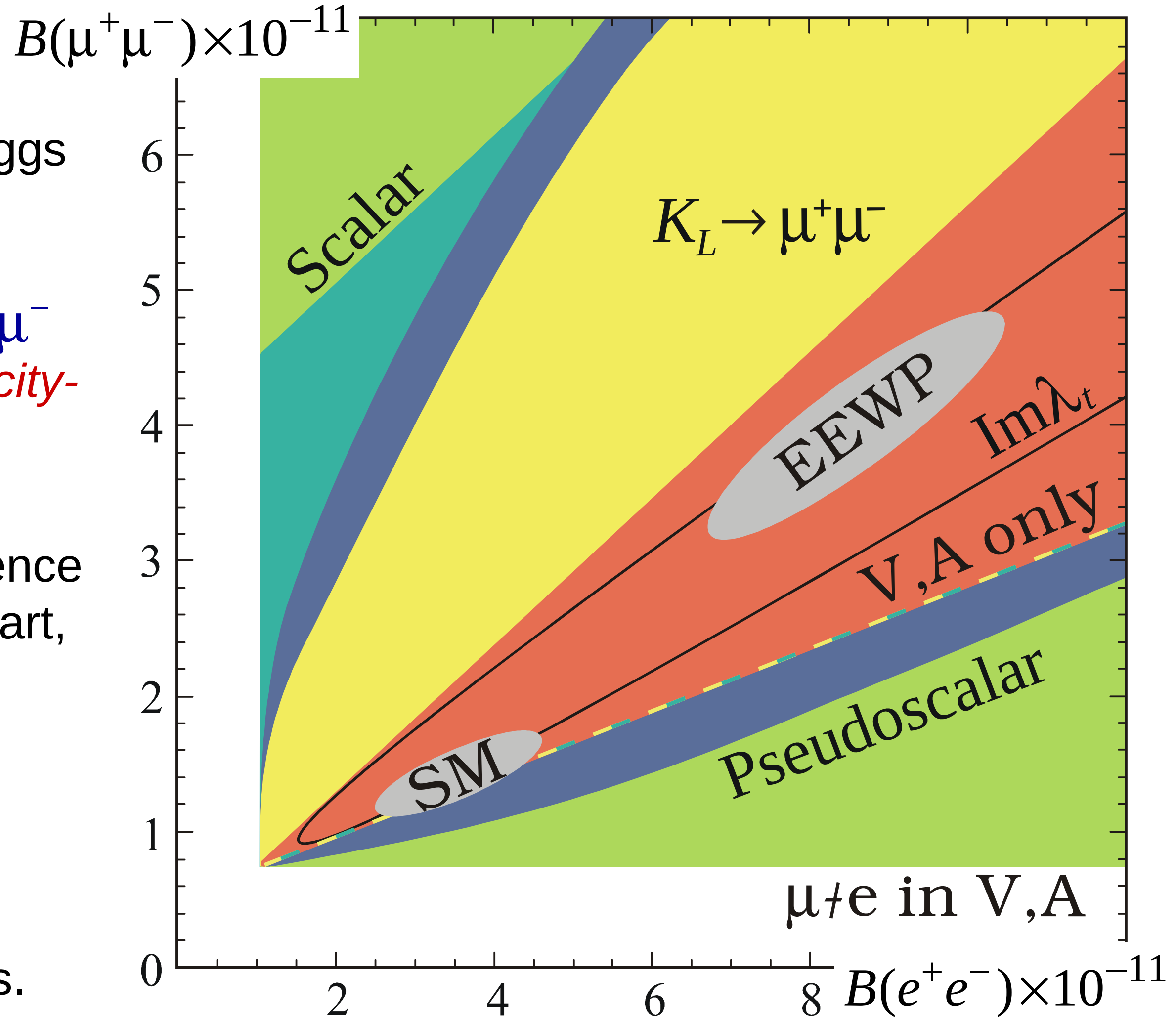
- Arise for example from the Higgs sector with *large* $\tan\beta$.

- $K_L \to \pi^0\mu^+\mu^-$ and $K_L \to \mu^+\mu^-$ *the only ones sensitive to helicity-suppressed operators!*

- Not trivial because of interference with scalar two-photon disp. part, $\rightarrow$ *ChPT inputs necessary*.

- $K_L \to \pi^0\mu^+\mu^-$ very promising compared to $K_L \to \mu^+\mu^-$.

- Corners require exotic physics.



Conclusion

Conclusion

The golden modes $K_L \to \pi^0 \nu\bar{\nu},\ K_L \to \pi^0 e^+ e^-,\ K_L \to \pi^0 \mu^+ \mu^-,\ K^+ \to \pi^+ \nu\bar{\nu}$

will remain an essential tool to investigate the flavor structure in the LHC era.

They are very *clean theoretically*, very sensitive to *New Physics signals* and able to constrain the *nature of New Physics*:

– *MFV:* effects of ~ 20%-25% for the $\nu\bar{\nu}$ modes are possible, but MFV does its job perfectly in killing any large deviation from the SM.

Very promising for reliably testing the MFV hypothesis.

– *Large Trilinear up-squark couplings:* rare K decays are the most sensitive probe of this sector of the MSSM parameter space.

Essential in the investigation of the nature of SUSY breaking mechanism.

– *General FCNC:* The muonic mode is the best probe of $\Delta S = 1$ helicity-suppressed FCNC operators.

If LHC finds New Physics, the four modes have to be measured!

A clear signal of NP would no longer be the main goal,
but the *pattern of deviations with respect to the SM would become crucial*.