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Progress on supersymmetric effects in rare K decays

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- Outline

A- Motivation and generalities

B- SUSY effects in $K \rightarrow \pi\nu\bar{\nu}$

C- SUSY effects in $K_L \rightarrow \pi^0 \ell^+ \ell^-$

D- Conclusion

Motivation and generalities

Why?

- Why rare K decays are so interesting?

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

- "*Would-be forbidden*" modes in the SM → *New Physics can be dominant*
  - Helicity-suppression: $Br(K_L \to e^+ e^-)^{\exp} = 9^{+6}_{-4} \times 10^{-12}$
  - Lepton Flavor Violation: $Br(K_L \to \mu^\pm e^\mp)^{\exp} < 4.7 \times 10^{-12}$
  - Flavor Changing Neutral Currents

    ↪ *GIM mechanism*: probe the SM at the quantum level (loop).

- *CP-violating FCNC*: Additional suppression in the SM $\left(\mathrm{Im}\,\lambda_t = \mathrm{Im}(V_{td} V_{ts}^*) \sim 10^{-4}\right)$

  Heaviest SM particle (top quark) gives the largest contribution

  → Well-controlled perturbative regime.

- *Semi-leptonic decays*: QCD effects under excellent control (compare with ε'/ε)

  (FCNC and CC matrix-elements are related).

- *The only theoretically clean window on the $\Delta S = 1$ sector*

  → Essential input for the "inverse problem" in the LHC era.

A few generalities about the MSSM

Supersymmetry: Unify matter (fermions) and interactions (bosons).

By-products:
- LSP and dark-matter,
- Gauge-coupling unification,
- Powerful shield for the EW-scale physics

MSSM: the simplest (phenomenologically viable) realization of supersymmetry

Characteristics:
- Doubling of matter & gauge degrees of freedom,
- Very specific Higgs sector (2HDM - type II),
- Few free parameters in its supersymmetric sector.

Problems:
- Supersymmetry must be broken, but how?
  - → *Effective description* (many free parameters).
- Origin of masses and mixings not explained.

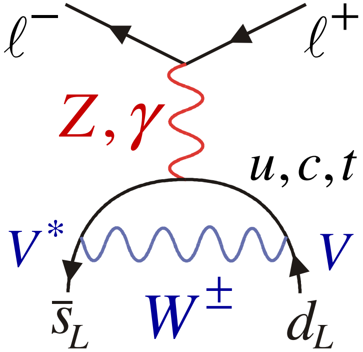
Soft-supersymmetry breaking: Introduces a very rich flavor-breaking sector

$$\mathcal{L}_{soft-breaking} = -\mathbf{m}_Q^2 \tilde{Q}^* \tilde{Q} - \mathbf{m}_U^2 \tilde{U}^* \tilde{U} - \mathbf{m}_D^2 \tilde{D}^* \tilde{D} - \tilde{U} \mathbf{A}^U \tilde{Q} \cdot H_u + \tilde{D} \mathbf{A}^D \tilde{Q} \cdot H_d + \ldots$$

MSSM

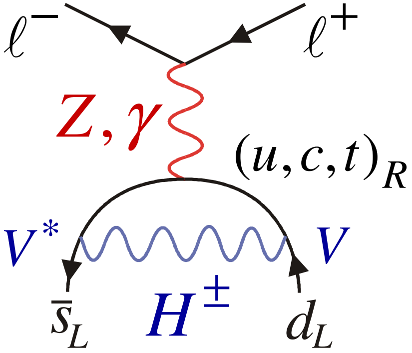
Impact on the FCNC's:

Standard Model:
FCNC arise at one-loop,
(V = CKM)

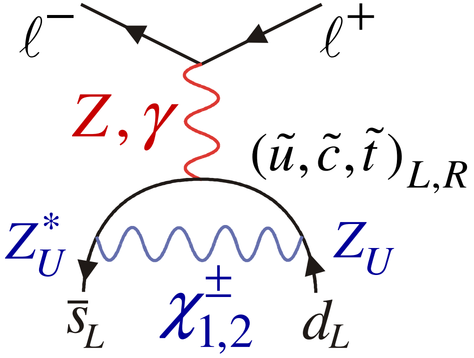


(+ boxes)

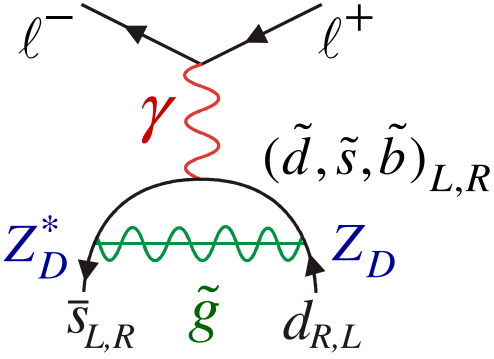
Charged Higgs:



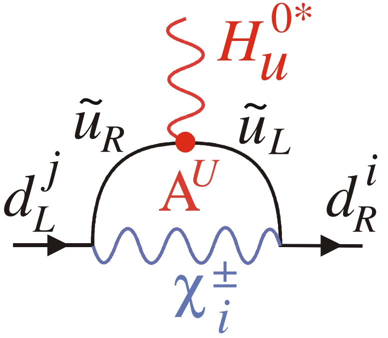
Charginos- up-squarks:



Gluinos- down-squarks:

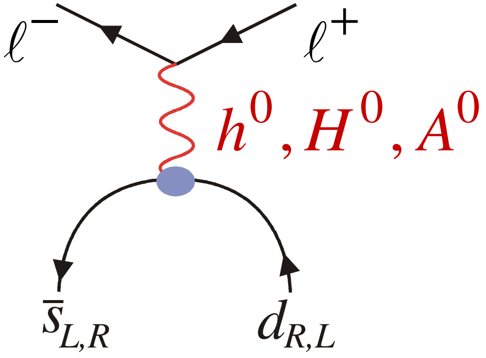


Neutral Higgses at large $\tan\beta = v_u / v_d \approx m_t / m_b \approx 50$:



$$\mathcal{L}_{eff} = \bar{d}_R^i Y_d^{ik} \left(\underset{\searrow\, v_d}{H_d^0} + \varepsilon Y_u^\dagger Y_u \underset{\searrow\, v_u}{H_u^{0*}} \right)^{kj} d_L^j$$

Mismatch between mass-matrices
and Higgs couplings at one-loop.



- What rare K decays can tell us?

Too many free parameters? Bottom-up approach:

Observed FCNC & CP-violation: *small departures* with respect to the SM.

a. Assume LHC fixes (at least part of) the mass spectrum.

b. Start from minimal (universal) soft-breakings (and no RPV):

mSUGRA (mostly for LHC),

Alignment of squarks with quarks (super-CKM basis),

Minimal flavor violation (most natural for the flavor sector).

c. Probe possible signatures of departures from minimal soft-breakings.

Constrain SUSY-breaking models, as they imply specific soft-breaking structures.

Information from the *three sectors* $K(s \to d), B_d(b \to d), B_s(b \to s)$ *crucial*.

• The “leading order basis” : Minimal Flavor Violation

Generically, *MFV designed to suppress FCNC*, but this leaves some freedom in how it is to be defined or implemented:

- *Phenomenological or “constrained MFV”*:

No new operators, no new phase, CKM rules all the FCNC (unique CPV phase).

*Buras,Gambino,Gorbahn,Jager,Silvestrini (‘00)/Bobeth,Bona,Buras,Ewerth,Pierini,Silvestrini,Weiler (‘05)/**...***

- *From a symmetry principle*: (adopted here)

SM Yukawas remain the only source of flavor-breaking:

- SM has a global $G = SU(3)^3$ flavor symmetry, broken only by Y_u, Y_d .
- In the MSSM, this symmetry also broken by the *soft-breaking terms*, therefore:

$$\begin{cases} \mathbf{m}_Q^2 = m_0^2\left(\tilde{a}_1\mathbf{1}+\tilde{b}_1\mathbf{Y}_u^\dagger\mathbf{Y}_u+\tilde{b}_2\mathbf{Y}_d^\dagger\mathbf{Y}_d+\tilde{b}_3(\mathbf{Y}_d^\dagger\mathbf{Y}_d\mathbf{Y}_u^\dagger\mathbf{Y}_u+\mathbf{Y}_u^\dagger\mathbf{Y}_u\mathbf{Y}_d^\dagger\mathbf{Y}_d)\right), \\ \mathbf{m}_U^2 = m_0^2\left(\tilde{a}_2\mathbf{1}+\tilde{b}_4\mathbf{Y}_u\mathbf{Y}_u^\dagger\right), \mathbf{m}_D^2 = m_0^2\left(\tilde{a}_3\mathbf{1}+\tilde{b}_5\mathbf{Y}_d\mathbf{Y}_d^\dagger\right), \\ \mathbf{A}^U = a_0\mathbf{Y}_u\left(\tilde{a}_4\mathbf{1}+\tilde{b}_6\mathbf{Y}_d^\dagger\mathbf{Y}_d\right), \mathbf{A}^D = a_0\mathbf{Y}_d\left(\tilde{a}_5\mathbf{1}+\tilde{b}_7\mathbf{Y}_u^\dagger\mathbf{Y}_u\right) \end{cases} \qquad \tilde{a}_i,\tilde{b}_i \sim \mathcal{O}(1)$$

D’Ambrosio,Giudice,Isidori,Strumia (’02)

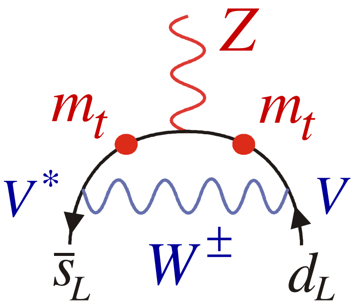
MSSM

- The CKM matrix is the only source of flavor-breakings, since (neglecting *b*'s):

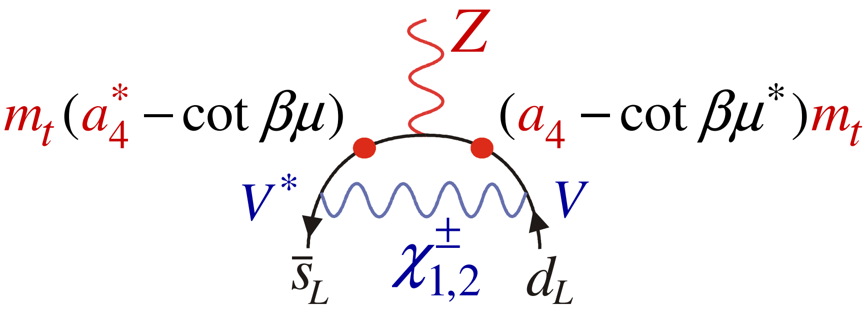
$$M_{\tilde{u}}^2 \approx \left(\begin{array}{ccc|ccc} a_1^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_1^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & a_1^2+m_t^2 & 0 & 0 & (a_4^*-\cot\beta\mu)m_t \\ \hline 0 & 0 & 0 & a_2^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & a_2^2 & 0 \\ 0 & 0 & (a_4-\cot\beta\mu^*)m_t & 0 & 0 & a_2^2+m_t^2 \end{array}\right) \quad \text{for} \quad \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \hline \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix} \quad \text{(super-CKM)}$$

e.g., LR-mixing in the chargino Z penguin $\sim m_t^2 V_{ts}^* V_{td} \left|a_4^* - \cot\beta\mu\right|^2$:

SM:



MFV:



Remarks:

- Introduces "minimal" departures with respect to *mSUGRA*: $\begin{cases} \mathbf{m}_Q^2 = \mathbf{m}_U^2 = \mathbf{m}_D^2 = m_0^2 \mathbf{1} \\ \mathbf{A}^U = a_0 \mathbf{Y}_u, \mathbf{A}^D = a_0 \mathbf{Y}_d \end{cases}$
- Approximate CCB/UFB: $\left|a_{4(5)}\right|^2 \lesssim 3\left(a_1^2 + a_{2(3)}^2\right)$
- $a_{1,2,3} \equiv m_0^2 \tilde{a}_{1,2,3},\ b_{1,\ldots,5} \equiv m_0^2 \tilde{b}_{1,\ldots,5},\ a_{4.5} \equiv a_0 \tilde{a}_{4.5},\ b_{6,7} \equiv a_0 \tilde{b}_{6,7}.$

SUSY effects in $K \to \pi\nu\bar{\nu}$

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

1- *SUSY effects in the SM operator*

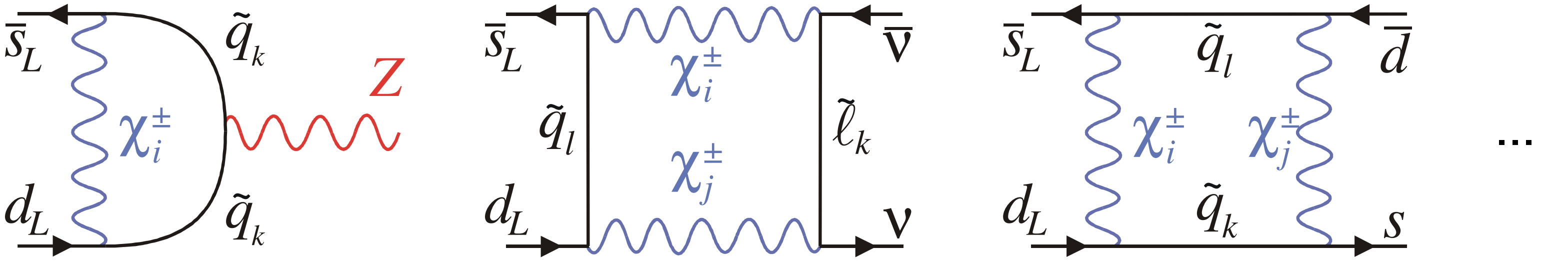
$$H_{eff}(K \to \pi\nu\bar{\nu}) \sim y_L^\nu\,(\bar{s}d)_{V-A}(\bar{\nu}\nu)_{V-A} + y_R^\nu\,(\bar{s}d)_{V+A}(\bar{\nu}\nu)_{V-A}$$
$$\sim \underbrace{(y_L^\nu + y_R^\nu)}_{X}\,(\bar{s}d)_V\,(\bar{\nu}\nu)_{V-A}$$

General analysis in terms of a single complex quantity. *Buras,Romanino,Silvestrini('98)*

MSSM at moderate $tan\beta$:

Dominant effect from *chargino penguins*, boxes smaller and constrained by $\Delta S = 2$:

Nir,Worah ('98)/Buras,Romanino,Silvestrini ('98)



Breaking of $SU(2)_L$ $\sim (\delta_{RL}^U)_{32}^*\,(\delta_{RL}^U)_{31}$, hence very sensitive to A^U terms.

Colangelo,Isidori ('98)

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

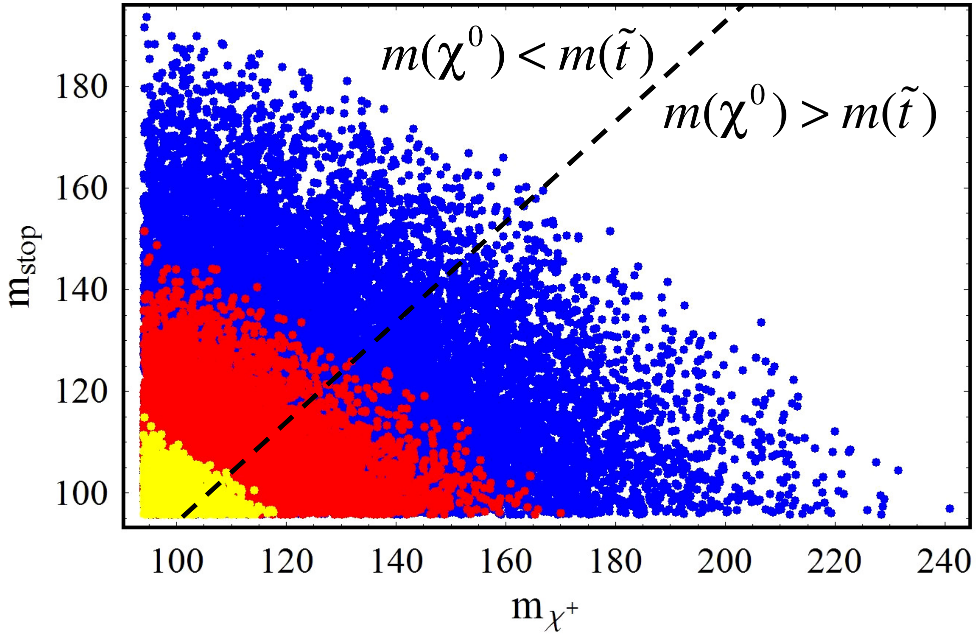
Maximal effect under the MFV hypothesis?

Isidori,Mescia,Paradisi,Trine,C.S. ('06)

With MFV, largest effects expected from terms enhanced by the *top* Yukawa.

$K \to \pi\nu\bar{\nu}$ ideal given its sensitivity to $\sim (\delta^U_{RL})^*_{32} (\delta^U_{RL})_{31} \sim m_t^2 V_{ts}^* V_{td} \left| a_4^* - \cot\beta\mu \right|^2$.

Colors $\Leftrightarrow$ enhancements of $K_L \to \pi^0\nu\bar{\nu}$ by **10%,12%,15%.**



- Determining factors: lightest squark and chargino (~ higgsino) masses.
- Small correlation with $\Delta F = 2$
- Large correlation with $B_{s,d} \to \mu^+\mu^-$
- Large correlation with $\Delta\rho$

Buras,Gambino,Gorbahn,Jager,Silvestrini ('00)

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

SUSY masses > 200GeV & $tan\beta > 5$: MFV falsified with enhancement $\gtrsim$ 5%.

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

Sensitivity to A^U, compared to other K & B observables?

The $K \rightarrow \pi\nu\bar{\nu}$ modes are the best probe of the $\mathbf{A}^U$ terms (quadratic dependence).

Isidori,Mescia,Paradisi,Trine,C.S. ('06)

Scanning over trilinear terms:

$|\mathbf{A}_{13}^U|,|\mathbf{A}_{23}^U| \leq A_0\lambda,$

$A_0 = 1$ TeV

Phases left free.

Fixed sparticle masses:

$\tan\beta = 2-4$

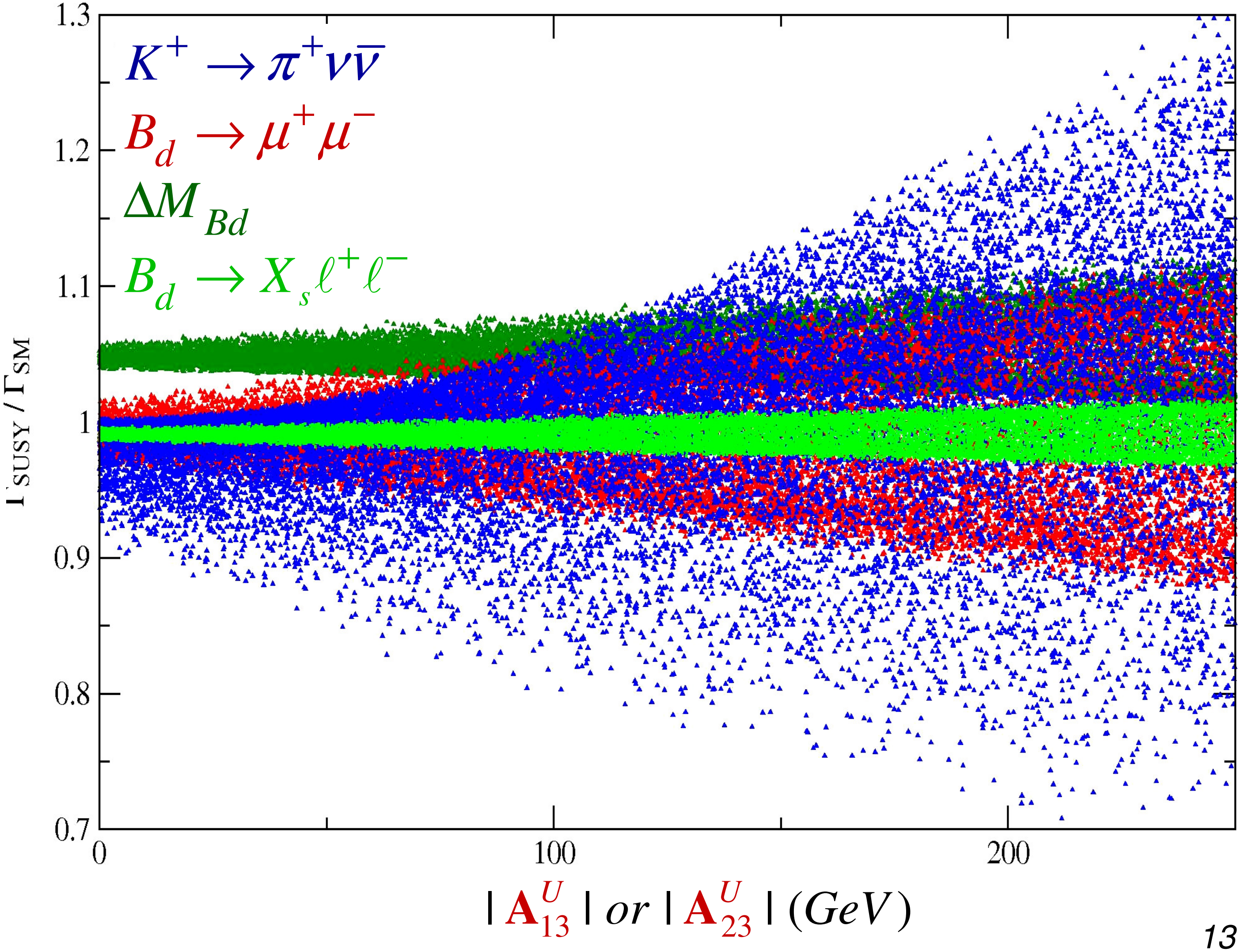
$\mu = 500 \pm 10$ GeV

$M_2 = 300 \pm 10$ GeV

$m_{u_R} = 600 \pm 20$ GeV

$m_{q_L} = 800 \pm 20$ GeV

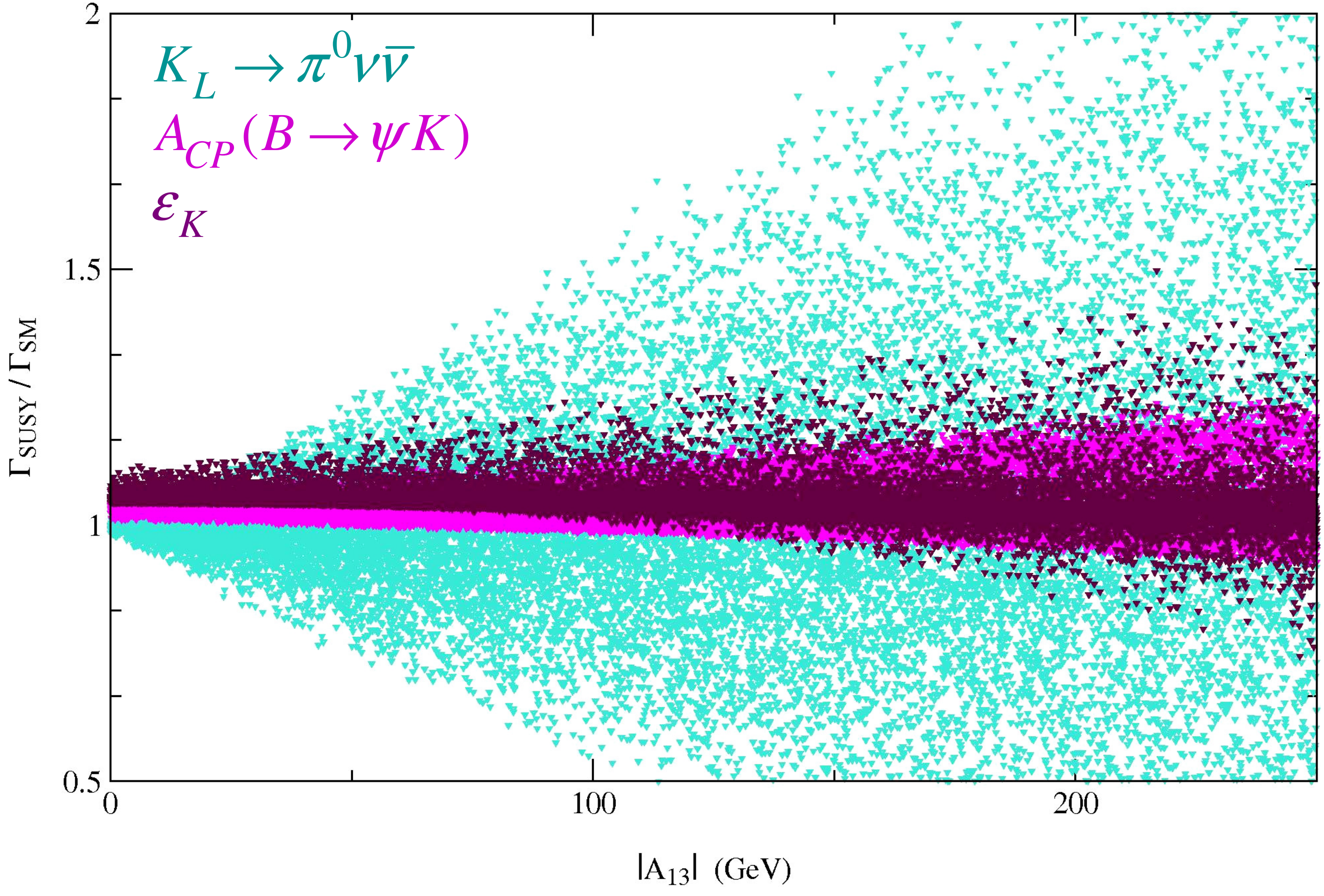
$others: 2$ TeV



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

Same within *CP-violating* K & B *observables*:

(*Further*: decoupling slower for penguins than for boxes as $m_{\tilde{t}} \rightarrow \infty$)



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

Is it possible to saturate the GN bound with these effects?

The *GN model-independent bound* still leaves room for large effects:

$$B(K_L \to \pi^0\nu\bar{\nu}) \leq 4.4 \times B(K^+ \to \pi^+\nu\bar{\nu}) \approx 1.7 \cdot 10^{-9} \ (90\%\ C.L.)$$

Grossman,Nir ('97)

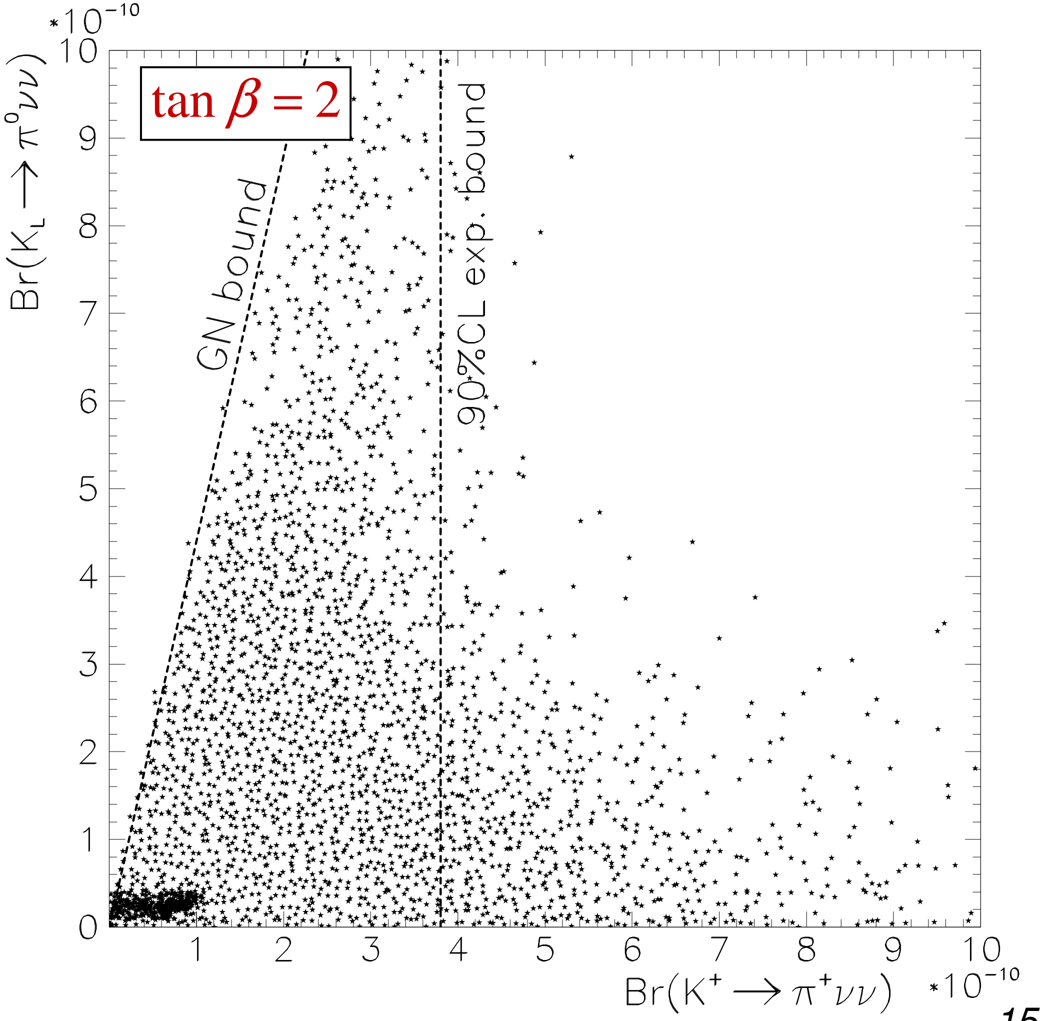
Full scan over MSSM parameters, checking compatibility with B, K and electroweak data, and CCB/UFB stability bounds.

Adaptive scanning (using VEGAS) to search for maximal effects.

Brein ('04)

Enhancement by a factor ~30 still allowed for the neutral mode.

Buras,Ewerth,Jager,Rosiek ('04)



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

And at large $tan\beta$ *?*

- No effects from *neutral Higgs FCNC* (~ neutrino masses).

- Negligible effects from *charginos*:

Isidori,Mescia,Paradisi,Trine,C.S. ('06)

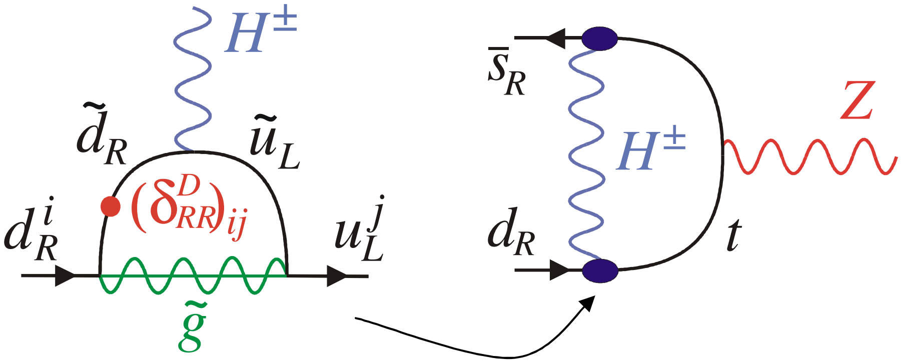
Within MFV: $tan\beta$ not sufficient to compensate for m_s, m_d factors:

$$m_t^2 V_{ts}^* V_{td} \left|a_4^* - \cot\beta\mu\right|^2 \to m_t^2 V_{ts}^* V_{td}\left(a_4^* - \cot\beta\mu + b_6^* \frac{m_s^2}{v_d^2}\right)\left(a_4 - \cot\beta\mu^* + b_6 \frac{m_d^2}{v_d^2}\right)$$

Beyond MFV: chargino contributions decrease with increasing $tan\beta$.

- But sensitive to higher order effects in the $H^\pm$ *penguin*, though only *beyond MFV*:

Isidori & Paradisi ('06)



$$(\bar{s}_R \gamma_\mu d_R)(\bar{\nu}_L \gamma^\mu \nu_L)$$

$$\sim (\tan\beta)^4$$

Slow decoupling, $\sim x_{tH} \log(x_{tH})$,

compared to $B_{s,d} \to \mu^+\mu^-$, $\sim x_{tH}$.

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

2- *SUSY effects in new operators*

Kiyo et al('98)/Perez('99)

$$H_{eff}(K \to \pi\nu\bar{\nu}) \sim y_S^\nu\,(\bar{s}d)(\bar{\nu}\nu) + y_P^\nu\,(\bar{s}d)(\bar{\nu}\gamma_5\nu)$$
$$+ y_T^\nu\,(\bar{s}\sigma_{\mu\nu}d)(\bar{\nu}\sigma^{\mu\nu}\nu) + y_{\tilde{T}}^\nu\,(\bar{s}\sigma_{\mu\nu}d)(\bar{\nu}\sigma^{\mu\nu}\gamma_5\nu)$$

Not CP-violating, but requires *active right-handed neutrinos*.
(and operators with / without helicity-suppression)

3- *SUSY effects in new operators, different (but still invisible) final states*

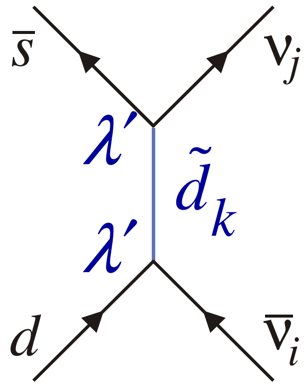
$$H_{eff}(K \to \pi\nu\bar{\nu}) \sim y_k\,(\bar{s}\Gamma_k d)(\bar{\nu}^i\Gamma_k\nu^j)$$

Grossman,Isidori,Murayama('03)/
Deandrea,Welzel,Oertel('04)/
Deshpande,Ghosh,He('04)

MSSM: Negligible effects from boxes with LFV effects.

Can be induced by *R-parity violating couplings*:

$$W_{\Delta L=1} = \lambda'^{IJK} L^I Q^J D^K + \ldots$$



Scalar leptoquark tree-level exchange:
(→ vector-current interactions)

SUSY effects in $K_L \to \pi^0 \ell^+ \ell^-$

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

$K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ have very similar dynamics, but for $m_e \neq m_\mu$

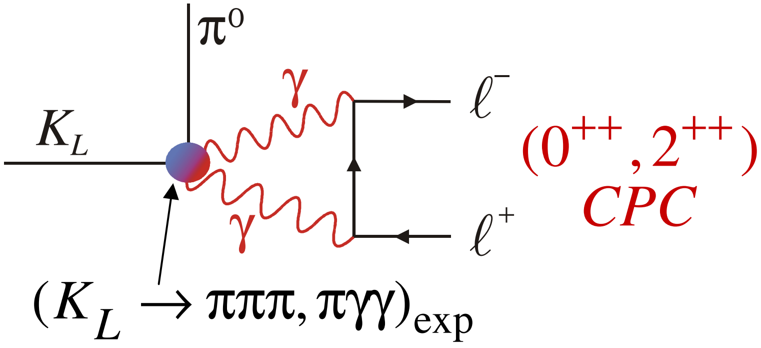
→ Possibility to probe *helicity-suppressed* effects.

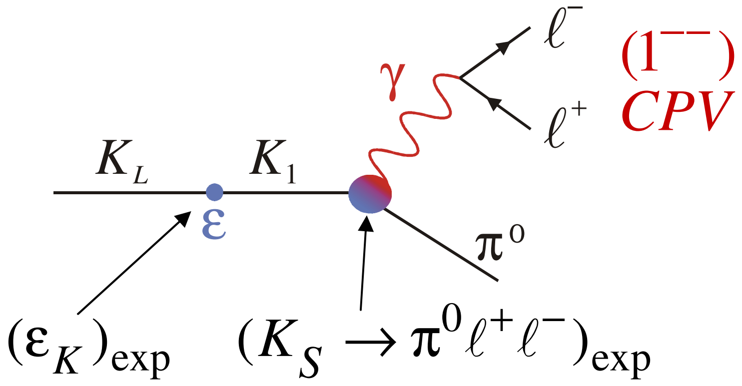
Mescia,Trine,C.S. ('06)

1- *SUSY effects in QCD operators*

$$(\bar{s}\sigma_{\mu\nu}d)G^{\mu\nu}, (\bar{q}\Gamma q)\times(\bar{q}\Gamma q)$$

No direct impact, LD background fixed entirely from experimental data:





Long-distance, CP-conserving *two-photon contribution*.

Buchalla,D'Ambrosio,Isidori ('03)
Isidori,Unterdorfer,C.S. ('04)

Indirect CP-violating contribution;
$K_S \to \pi^0 \ell^+ \ell^-$ long-distance dominated.

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

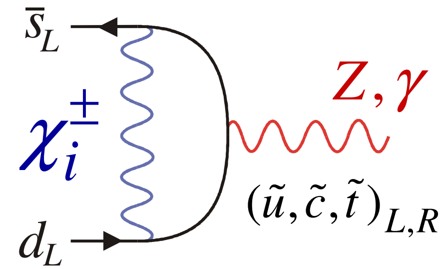
2- SUSY effects in the SM electroweak operators

$$H_{eff}(K_L \to \pi^0 \ell^+ \ell^-) \sim \underset{1^{--},\,CPV}{y_{7V}\,(\bar{s}d)_{V-A}(\bar{\ell}\ell)_V} + \underset{1^{++}\,\&\,0^{-+},\,CPV}{y_{7A}\,(\bar{s}d)_{V-A}(\bar{\ell}\ell)_A}$$

- Disentangle y_{7V}, y_{7A} thanks to helicity-suppressed effects.
  Isidori,Unterdorfer,C.S. ('04)

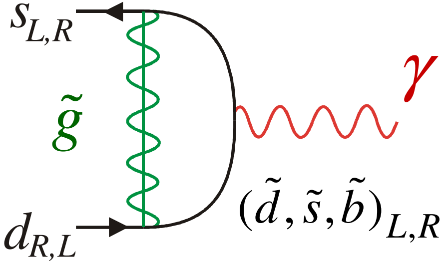
- *Chargino penguins* (smaller but correlated with $K \to \pi\nu\bar{\nu}$):
  Isidori,Mescia,Paradisi,Trine,C.S. ('06)

$$y_{7V}, y_{7A} \sim (\delta^U_{RL})^*_{32}(\delta^U_{RL})_{31}$$



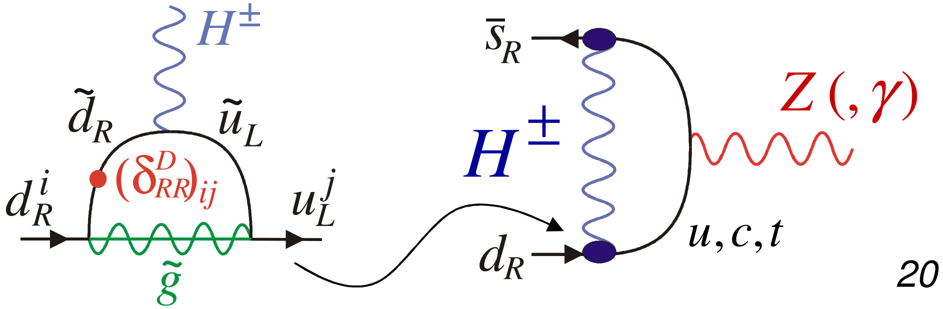
- *Gluino EMO* operator, strongly correlated with ε'/ε:
  Buras,Colangelo,Isidori,Romanino,Silvestrini ('00)

$$(\bar{s}\sigma_{\mu\nu}d)F^{\mu\nu} \to y_{7V} \sim (\delta^D_{RL})_{12(21)}$$



- *Charged Higgs at large $\tan\beta$*:
  Isidori,Paradisi ('06)

$$y_{7V}, y_{7A} \sim (\delta^D_{RR})_{12}$$



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

More details on how to disentangle V & A operators:

Bounds for general vector/axial vector FCNC operators (i.e. arbitrary y_{7A}, y_{7V}):

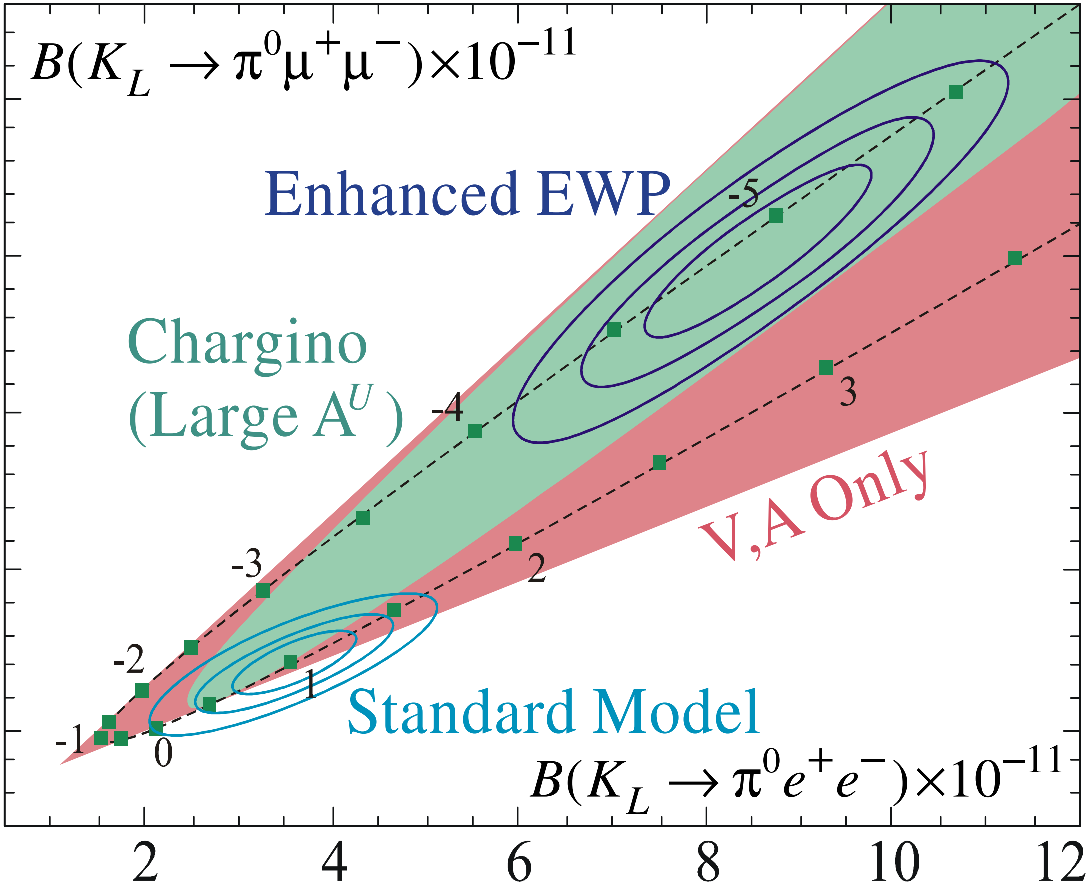
$$0.1+0.24B_{e^+e^-} \le B_{\mu^+\mu^-} \le 0.6+0.58B_{e^+e^-} \quad \text{with} \quad B_{\ell^+\ell^-} \equiv B(K_L \to \pi^0\ell^+\ell^-)\cdot 10^{11}$$

Mescia,Trine,C.S. ('06)

- *MFV enhancement: ~7% max.*, directly correlated to $K \to \pi\nu\bar{\nu}$.
  Isidori,Mescia,Paradisi,Trine,C.S. ('06)

- *Chargino contributions*: γ & Z penguins correlated
  → restricted region even for non-realistically large $\mathbf{A}^U$.

- For comparison:
  Enhanced EW penguins:
  $y_{7V}^{EEWP} \approx y_{7V}^{SM}$, $y_{7A}^{EEWP} \approx 5y_{7A}^{SM}$
  Buras,Fleischer,Recksiegel,Schwab ('04)



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

3- *SUSY effects in the scalar/pseudoscalar operators*

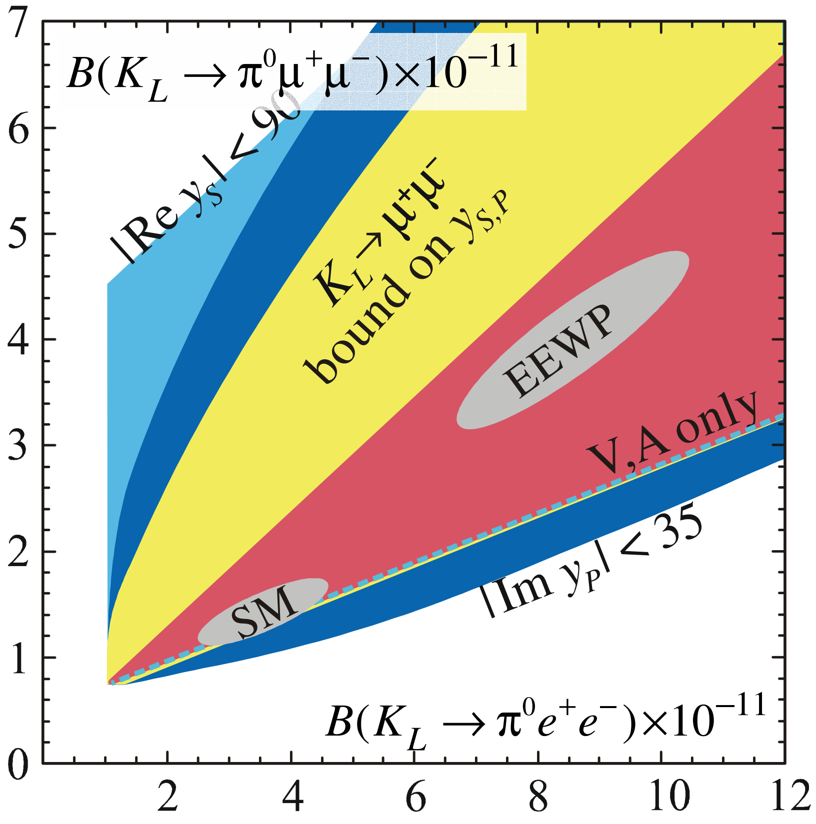
$$H_{eff}(K_L \to \pi^0 \ell^+ \ell^-) \sim y_S\ (\bar{s}d)(\bar{\ell}\ell) + y_P\ (\bar{s}d)(\bar{\ell}\gamma_5\ell)$$

$$0^{++}, CPC \qquad 0^{-+}, CPV$$

Can be correlated to similar operators for $K_L \to \ell^+ \ell^-$:

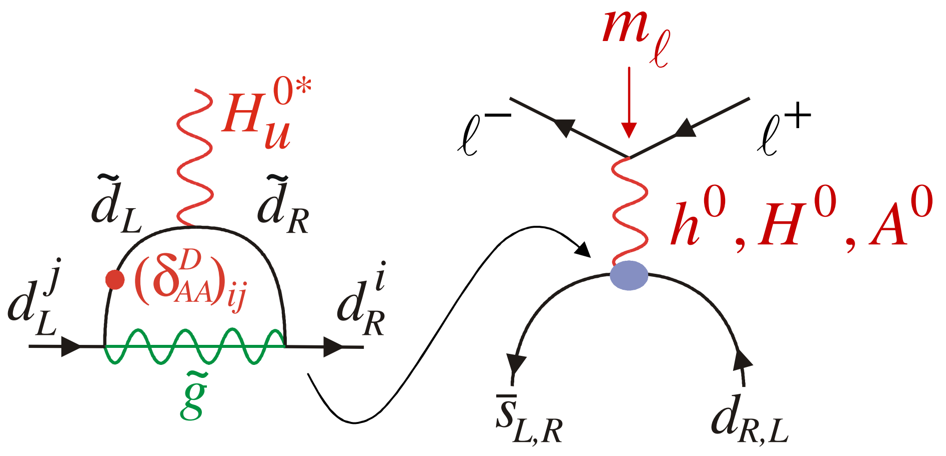
$$H_{eff}(K_L \to \ell^+ \ell^-) \sim y'_S\ (\bar{s}\gamma_5 d)(\bar{\ell}\ell) + y'_P\ (\bar{s}\gamma_5 d)(\bar{\ell}\gamma_5\ell)$$

$$0^{++}, CPV \qquad 0^{-+}, CPC$$



A- Helicity-suppressed from neutral Higgs at large tanβ (only effective *beyond MFV*):

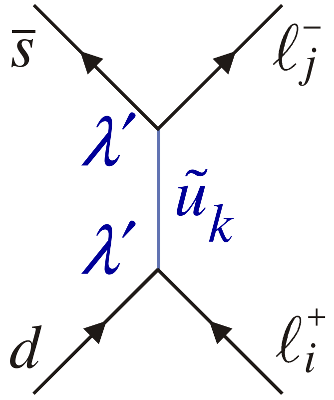
Isidori,Retico ('01,'02)/Mescia,Trine,C.S. ('06)



$$y_{S,P} = y'_{P,S} \sim (\delta^D_{RR,LL})_{12},\ (\delta^D_{RR,LL})_{23}(\delta^D_{LL,RR})_{31}$$

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

B- Helicity-allowed (pseudo-)scalar operators from *R-parity violating* couplings:



Baring (possible) fine-tunings, must be *very suppressed* given the measured:

$$B(K_L \to e^+ e^-) = 9^{+6}_{-4} \times 10^{-12}$$

As well as bounds on $K_L \to e^\pm \mu^\mp, \ldots$

4- SUSY effects in the tensor/pseudotensor operators

$$H_{eff}(K_L \to \pi^0 \ell^+ \ell^-) \sim \underset{1^{--}, CPV}{y_T\ (\bar{s}\sigma_{\mu\nu} d)(\bar{\ell}\sigma^{\mu\nu}\ell)} + \underset{1^{+-}, CPC}{y_{\tilde{T}}\ (\bar{s}\sigma_{\mu\nu} d)(\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell)}$$

- Necessarily *helicity-suppressed* in the MSSM,
- Smaller than (pseudo-)scalar operators, and *phase-space suppressed*,
- *Cannot arise from R-parity violating* couplings,
- *But*: do not contribute to $K_L \to \ell^+ \ell^-$.

Conclusion

Conclusion

Rare K decays are the *only theoretically clean window on the $\Delta S = 1$ sector*,
They are thus essential in the investigation of the *SUSY-breaking mechanism*.

	$K \to \pi\nu\bar{\nu}$	$K_L \to \pi^0 \ell^+ \ell^-$
MFV $\tan\beta \approx 2$	Best sensitivity, but maximum enhancement < 20-25%	Less sensitive, but testable correlation with $K \to \pi\nu\bar{\nu}$
MFV $\tan\beta \approx 50$	Negligible effects	
General $\tan\beta \approx 2$	Best probe of δ^U_{LR} (quadratic dependence)	δ^U_{LR} : correlated with $K \to \pi\nu\bar{\nu}$ δ^D_{LR} : correlated with ε'/ε (but much cleaner)
General $\tan\beta \approx 50$	Good probe of δ^D_{RR} (slow decoupling)	Good probe of $\delta^D_{RR,LL}$ Correlated with $K_L \to \ell^+\ell^-$ (but, again, much cleaner)

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

The pattern of deviations with respect to the SM would become crucial.