Karlsruhe, July 2007

Progress on supersymmetric effects in rare K decays

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- Outline

A- Motivation and generalities

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

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

D- Conclusion

Motivation and generalities

- 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*

    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.

SM

- The $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ decays

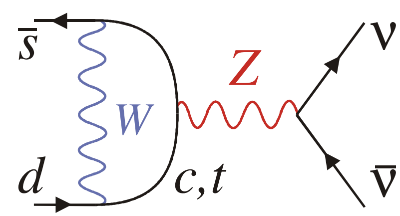
$$B(K_L \to \pi^0 \nu\bar{\nu}) \approx \kappa^0 \left(|\mathrm{Im}\,\lambda_t X(x_t)|^2 \right)$$

$$B(K^+ \to \pi^+ \nu\bar{\nu}) \approx \kappa^+ \left(|\mathrm{Im}\,\lambda_t X(x_t)|^2 + \underbrace{|\mathrm{Re}\,\lambda_t X(x_t) + \mathrm{Re}\,\lambda_c (P_c + \delta P_{u,c})|^2}_{\sim Br(K_S \to \pi^0 \nu\bar{\nu})} \right)$$

1- Dimension-six: $(\bar{s}d)_V (\bar{\nu}\nu)_{V-A}$

t-quark: $X(x_t) \overset{NLO}{=} 1.464(41)$

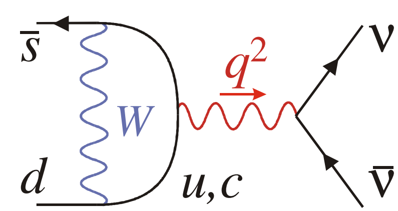
c-quark: $P_c \overset{NNLO}{=} 0.37(4)\lambda^4$



Buchalla,Buras ('93)

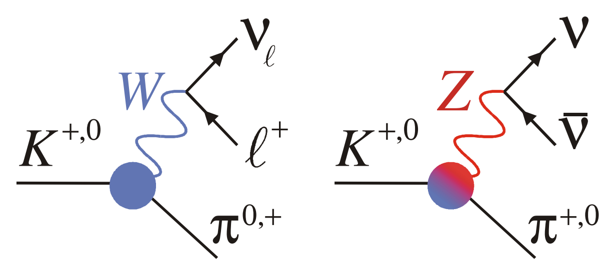
Buras,Gorbahn, Haisch,Nierste ('05)

2- Higher dim.: Dim-8 *c-quark*, LD *u-quark* } $\delta P_{u,c} = 0.04(2)\lambda^4$



Isidori,Mescia, CS ('05)

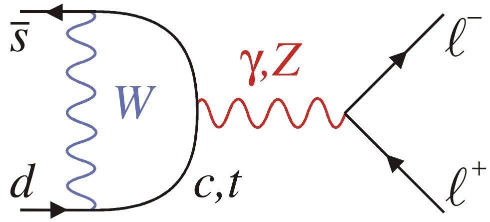
3- Matrix elements: $\begin{cases} \kappa^+ = 0.5173(25)\cdot 10^{-10} \\ \kappa^0 = 2.231(13)\cdot 10^{-10} \end{cases}$



Mescia, CS ('07)

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

1. Direct CPV: Short-distance, from top & charm integrations (known at NLO):

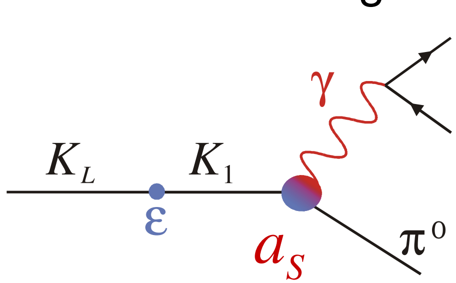


$y_{7A}\ (\bar{s}d)_{V-A}(\bar{\ell}\ell)_A \quad (1^{++}, 0^{-+})$

$y_{7V}\ (\bar{s}d)_{V-A}(\bar{\ell}\ell)_V \quad (1^{--})$

Buras,Lautenbacher Misiak,Münz ('94)

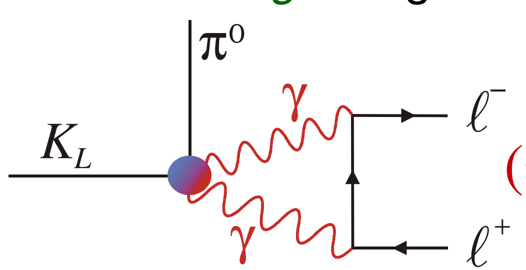
2. Indirect CPV: Long-distance γ penguin (→ ChPT) *D'Ambrosio,Ecker,Isidori,Portolés ('98)*

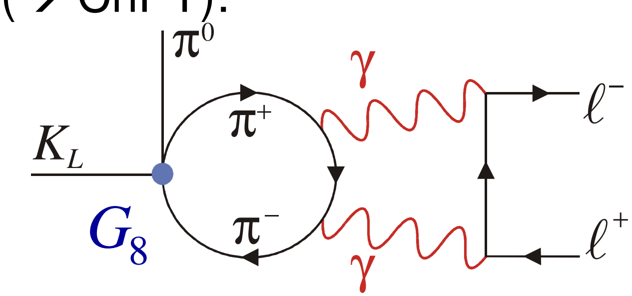


- Dominated by a counterterm, fixed using $B(K_S \to \pi^0 \ell^+ \ell^-)$ as $|a_S| = 1.2 \pm 0.2$.
- Indications for constructive interference.

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

3. CP-conserving: Long-distance γγ penguin (→ ChPT):





Higher order corrections estimated from $K_L \to \pi^0 \gamma\gamma$ rate and spectrum.

Buchalla,D'Ambrosio,Isidori ('03)/ Isidori,Unterdorfer,CS ('04)

4. Complete predictions

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

SM: $\kappa = {\rm Im}\,\lambda_t \times 10^4 \approx 1.41,\ \ y_{7A} \approx -0.68,\ \ y_{7V} \approx 0.73$

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

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

$C_{\rm ind}^{e} \approx 14.5, C_{\gamma\gamma}^{e} \approx 0$

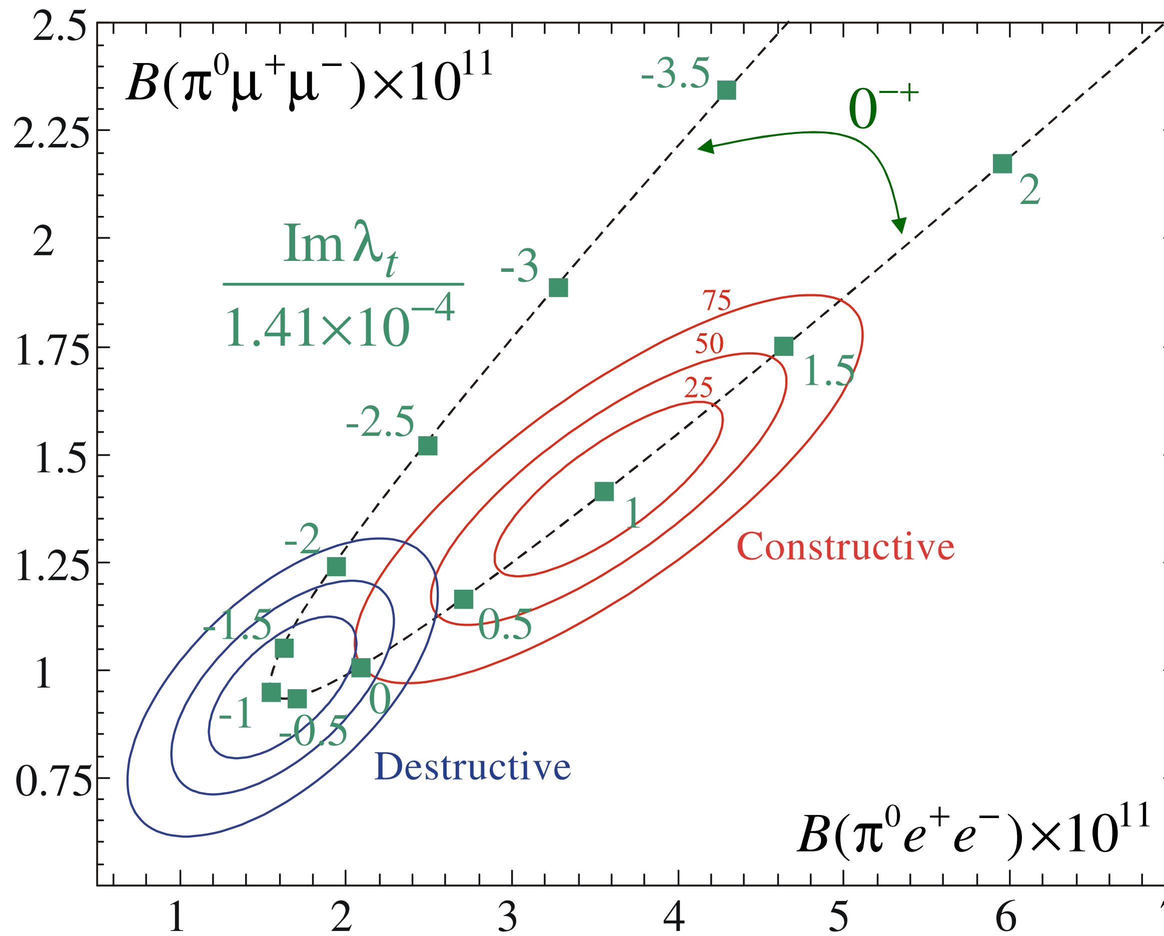
¼ phase-space suppression

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

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

$C_{\rm ind}^{\mu} \approx 3.4, C_{\gamma\gamma}^{\mu} \approx 5.2$

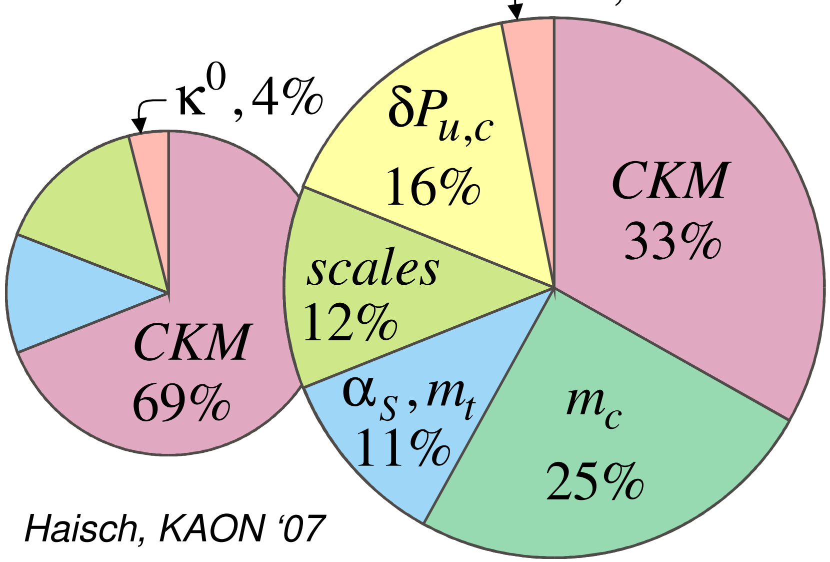
Additional helicity-suppressed terms



- Summary of current status in the SM:

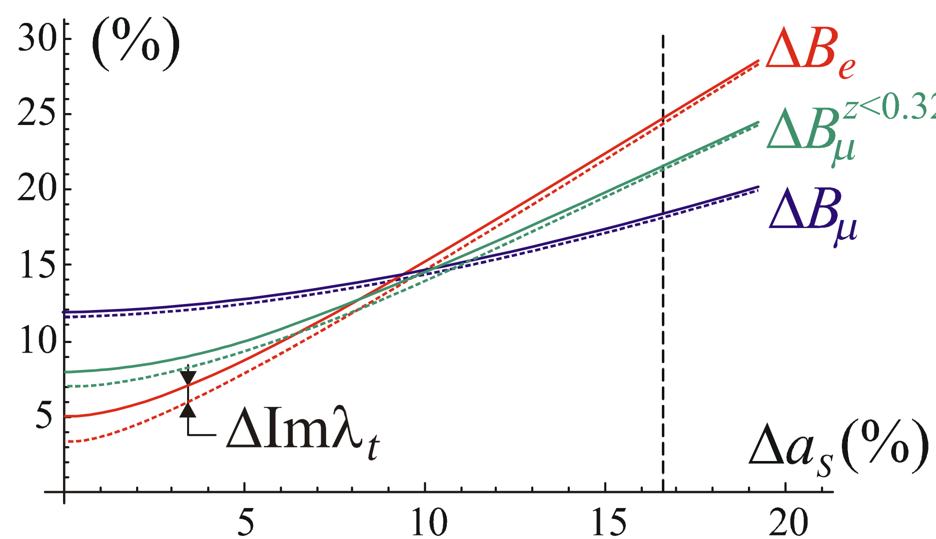
	V, A	K^0-$\bar{K}^0$	2^{++}	0^{++}	SM $(\times 10^{-11})$	Experiment
$K_L \to \pi^0 \nu\bar{\nu}$	**100%**	(≈ 1%)	–	–	$2.54^{+0.35}_{-0.35}$	$< 2.1 \cdot 10^{-7}$ E391a
$K_L \to \pi^0 e^+ e^-$	**40%**	60%	(<3%)	–	$3.54^{+0.98}_{-0.85}$	$< 2.8 \cdot 10^{-10}$ KTeV
$K_L \to \pi^0 \mu^+ \mu^-$	**30%**	35%	–	35%	$1.41^{+0.28}_{-0.26}$	$< 3.8 \cdot 10^{-10}$ KTeV
$K^+ \to \pi^+ \nu\bar{\nu}$	**100%**	–	–	–	$8.0^{+0.9}_{-0.9}$	$14.7^{+13.0}_{-8.9} \cdot 10^{-11}$ E787 E949

Theory errors for $K \to \pi\nu\bar{\nu}$:



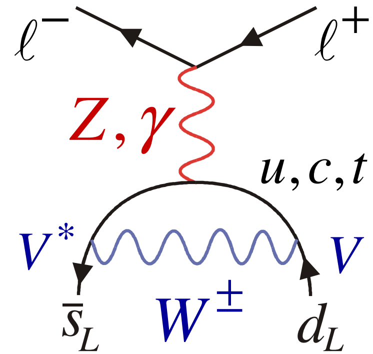
Haisch, KAON '07

Theory errors for $K_L \to \pi^0 \ell^+ \ell^-$:



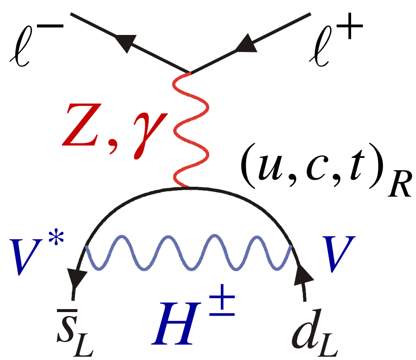
- Windows into the MSSM flavor structures:

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

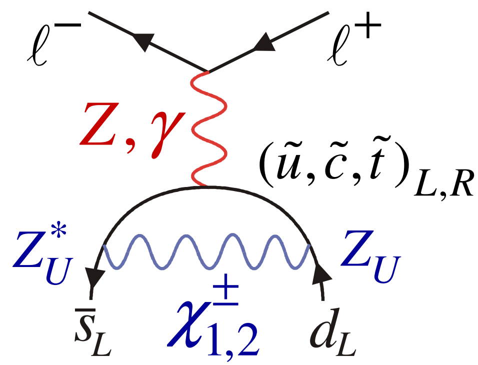


(+ boxes)

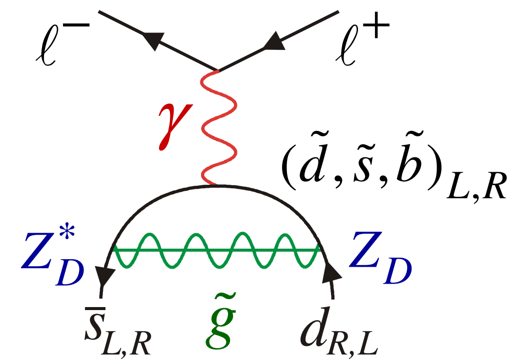
Charged Higgs:



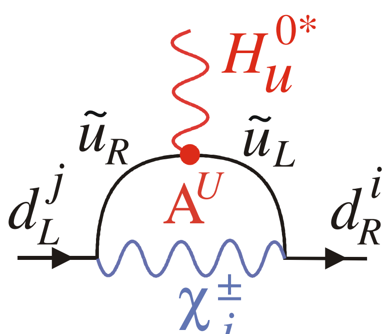
Charginos- up-squarks:



Gluinos- down-squarks:



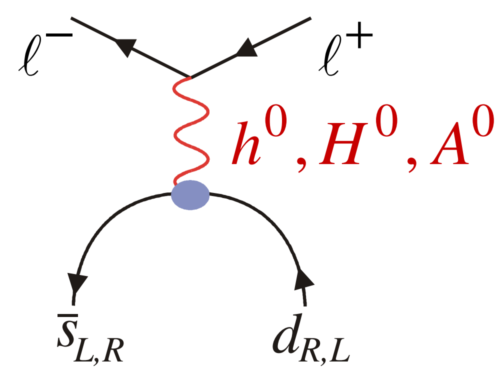
Neutral Higgses at large $\tan\beta = v_u / v_d \approx m_t / m_b \approx 50$:



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

($H_d^0 \to v_d$, $H_u^{0*} \to v_u$)

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



- 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.

Here: *MFV from a symmetry principle:*

SM Yukawas are the only source of flavor-breaking.

Hall,Randall ('90) / D'Ambrosio,Giudice,Isidori,Strumia ('02)

- 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:

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

- Introduces "minimal" departures with respect to *mSUGRA* ($\tilde{a}_i = 1, \tilde{b}_i = 0$)
- Approximate CCB/UFB: $|a_{4(5)}|^2 \lesssim 3(a_1^2 + a_{2(3)}^2)$ $\quad (a_i \equiv m_0^2\tilde{a}_i / a_0\tilde{a}_i,\ b_i \equiv m_0^2\tilde{b}_i / a_0\tilde{b}_i)$

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

1- *SUSY effects in the SM operator*

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

$$\to (y_L^{\nu} + y_R^{\nu})\,(\bar{s}d)_V\,(\bar{\nu}\nu)_{V-A}$$

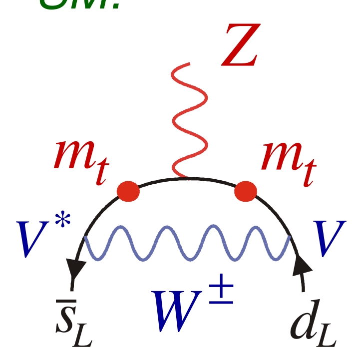
General analysis in terms of a single complex quantity. *Buras,Romanino,Silvestrini ('98)*

MSSM at moderate $tan\beta$:

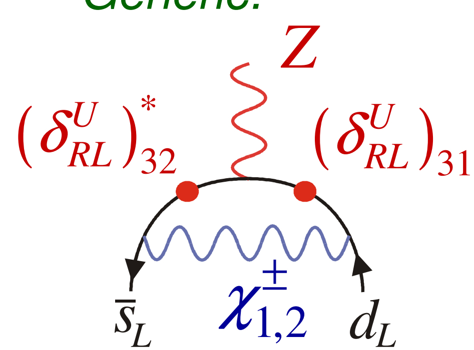
Dominant effect from *chargino penguins*, boxes smaller and constrained by $\Delta S = 2$.
Nir,Worah ('98)/Buras,Romanino,Silvestrini ('98)

LR-induced breaking of $SU(2)_L \sim (\delta_{RL}^U)_{32}^*\,(\delta_{RL}^U)_{31}$, hence very sensitive to A^U terms.
Colangelo,Isidori ('98)

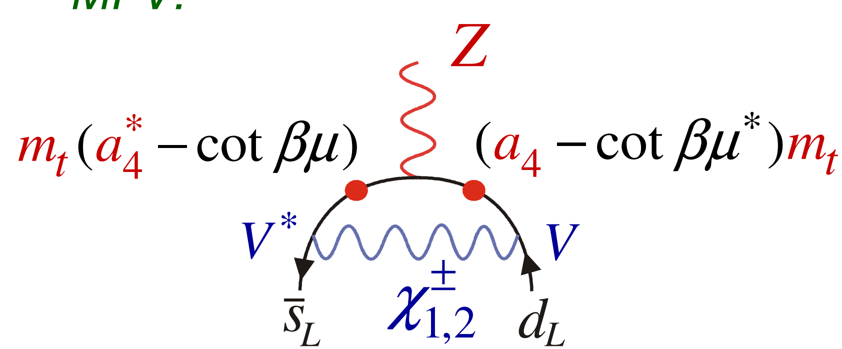
SM:



Generic:



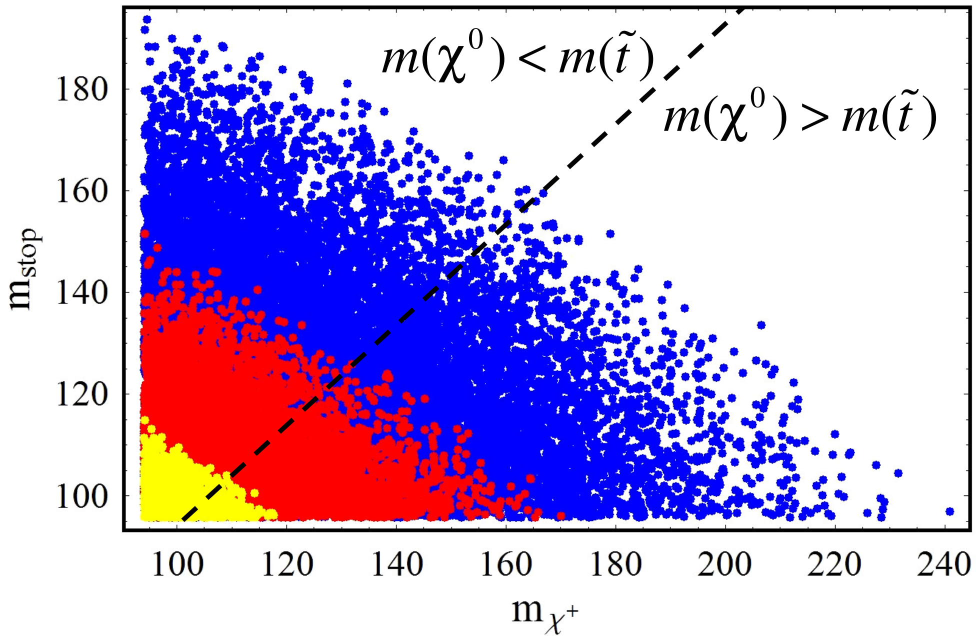
MFV:



Maximal effect under the MFV hypothesis? *Isidori,Mescia,Paradisi,Trine,CS ('06)*

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

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



- Enhanced only for *very light stop and chargino* (~ higgsino).
- 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)

$H^\pm$ contributions further enhance $K \to \pi\nu\bar{\nu}$ by ~10% if $\tan\beta = 2$, $m_{H+} \approx 300$ GeV (effect gets smaller for larger $\tan\beta$ and/or m_{H+}).

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

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

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

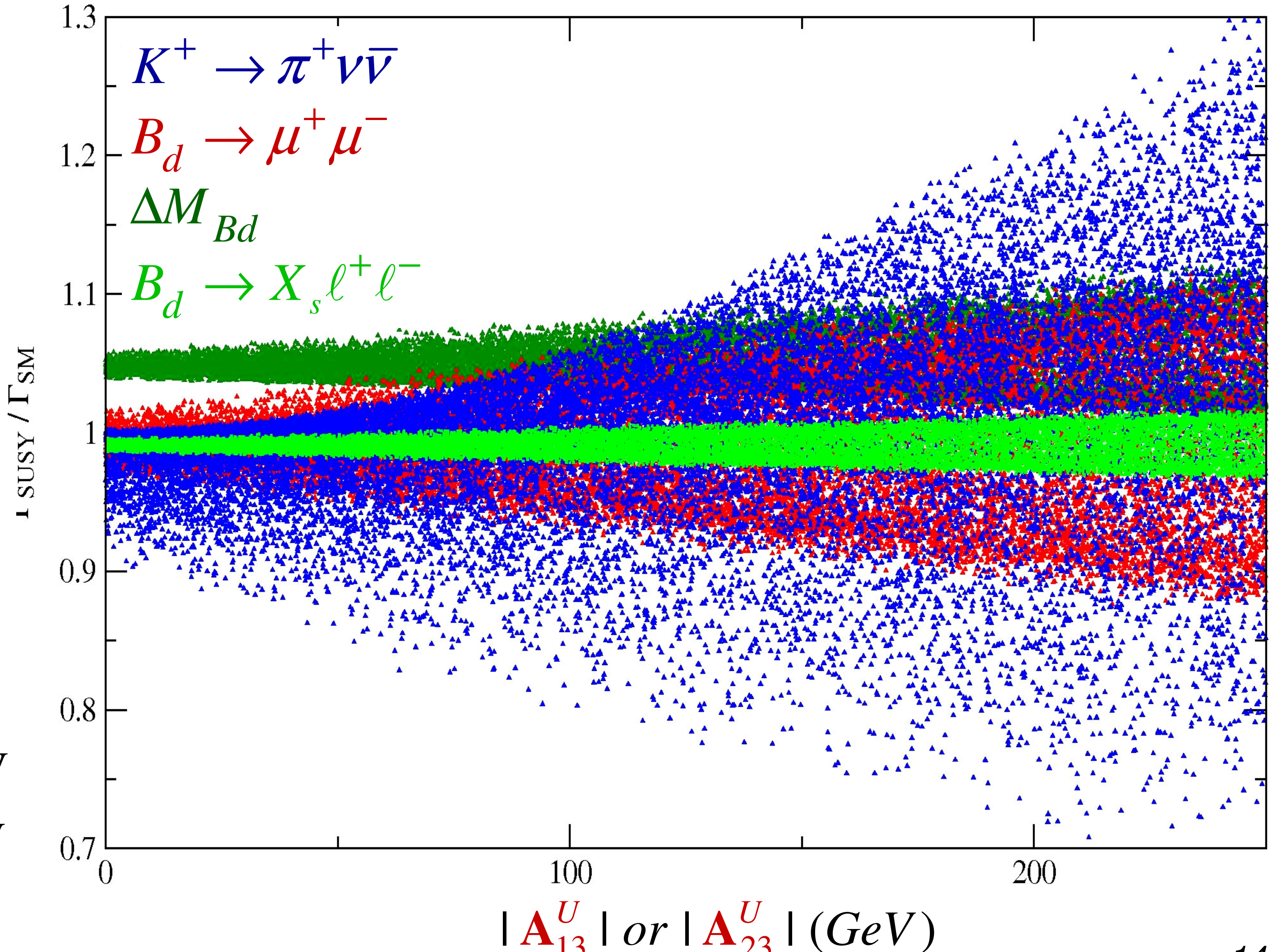
Isidori,Mescia,Paradisi,Trine,CS ('06)

Scanning over trilinear terms:

$|\mathbf{A}_{13}^U|, |\mathbf{A}_{23}^U| \leq A_0\lambda$,
$A_0 = 1$ TeV
Phases left free.

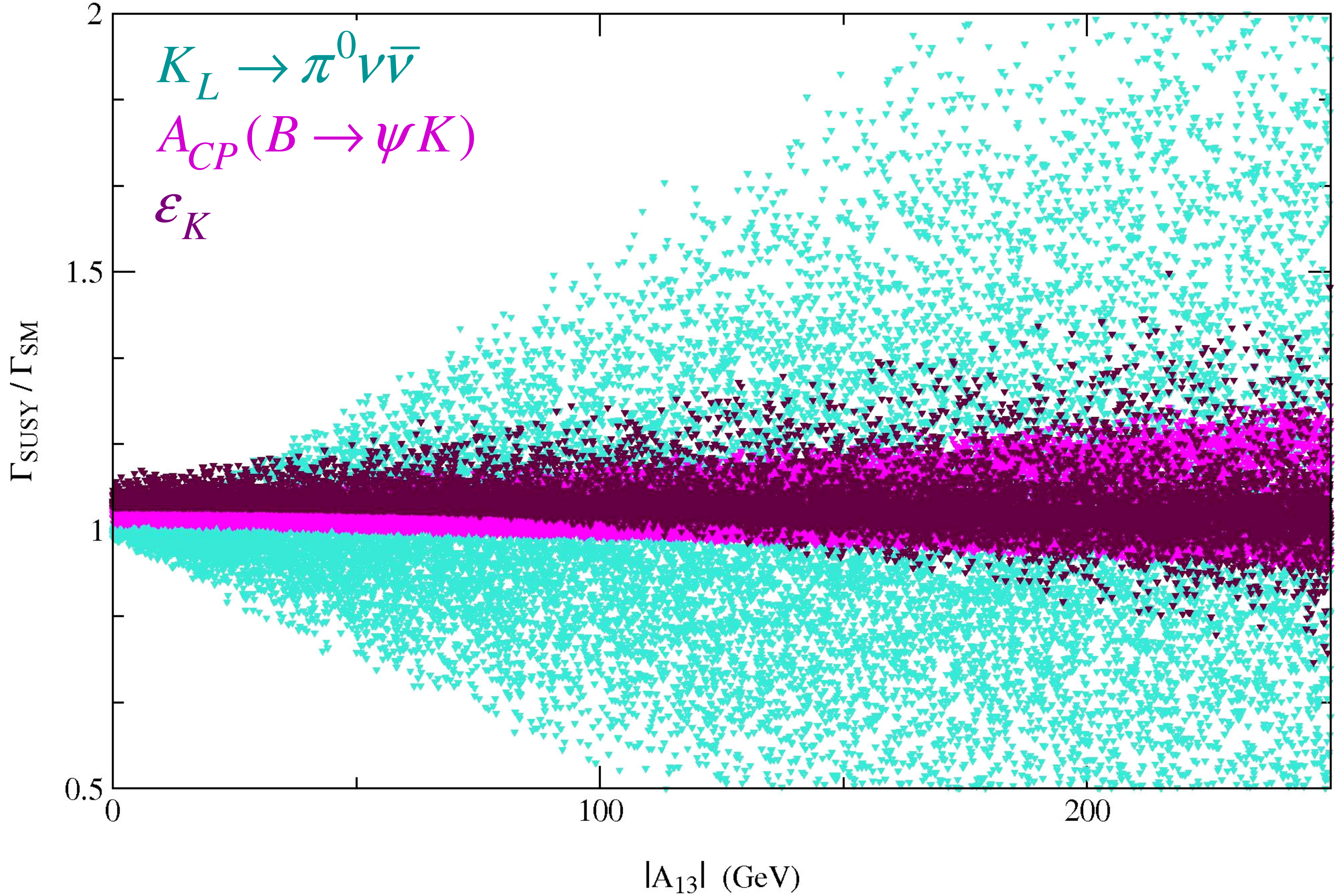
Fixed sparticle masses:

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



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

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



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

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

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

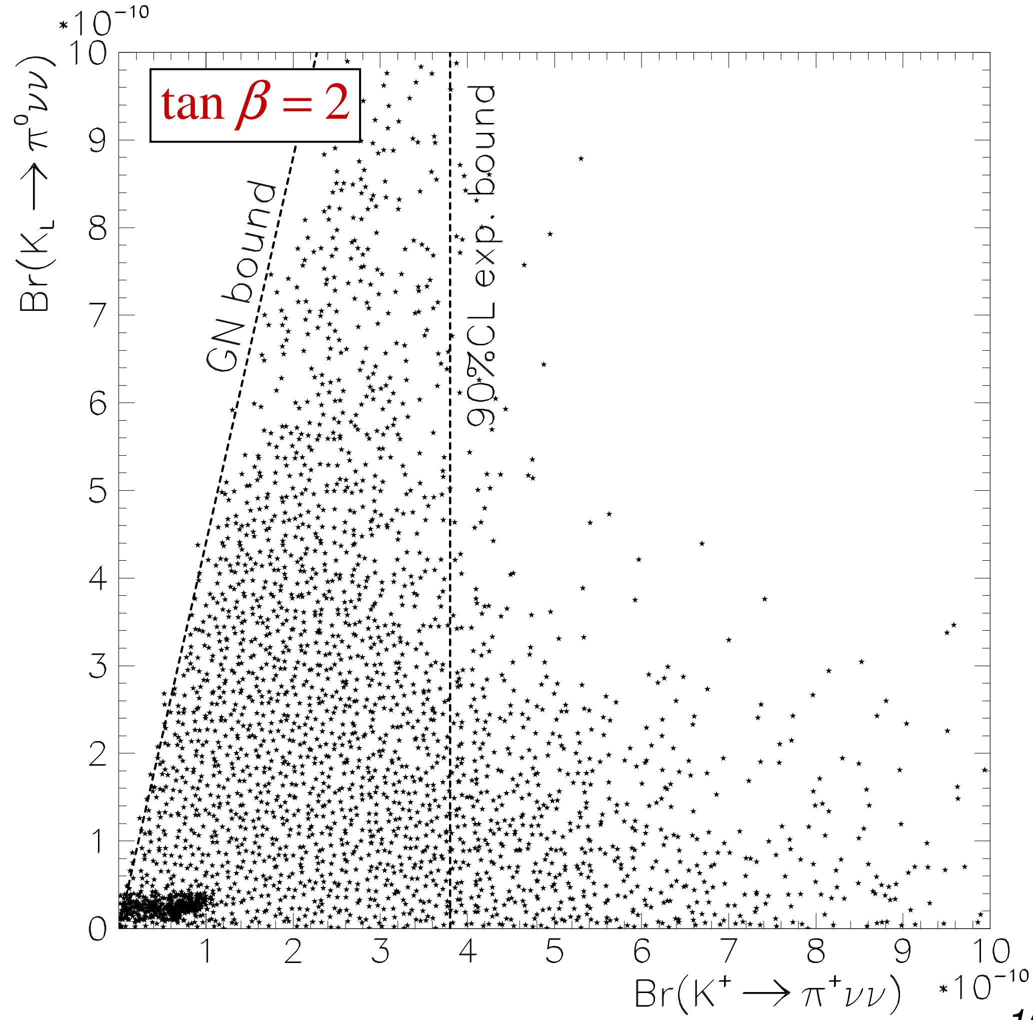
Grossman,Nir ('97)

Full scan over MSSM parameters.

Buras,Ewerth,Jager,Rosiek ('04)

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

Brein ('04)



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

And at large $\tan\beta$?

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

- Effects from *charginos*:

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

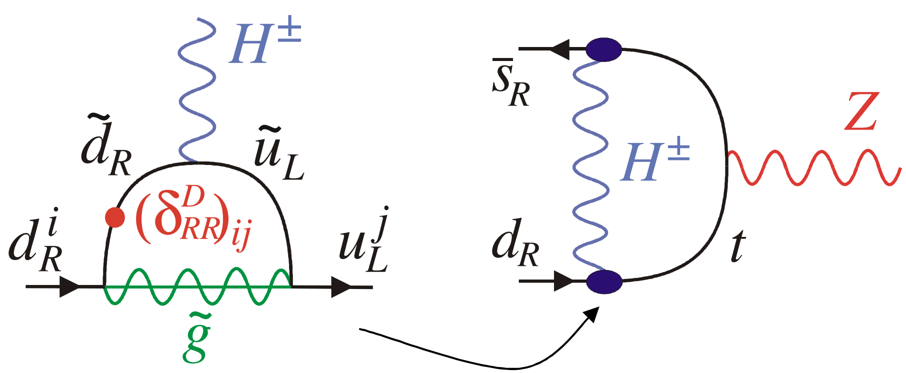
Isidori,Mescia,Paradisi,Trine,CS ('06)

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

Beyond MFV: a priori similar as for moderate $\tan\beta$. *Buras,Ewerth,Jager,Rosiek ('04)*

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

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*.

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

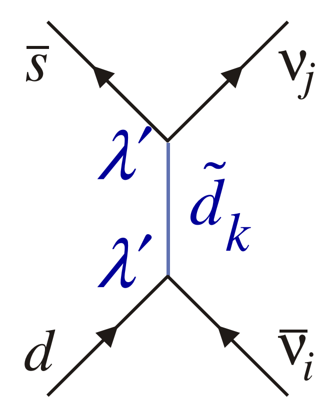
Grossman,Isidori,Murayama ('03)/
Deandrea,Welzel,Oertel ('04)/
Deshpande,Ghosh,He ('04)

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

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 exchanges:
(→ 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 $m_e \neq m_\mu$

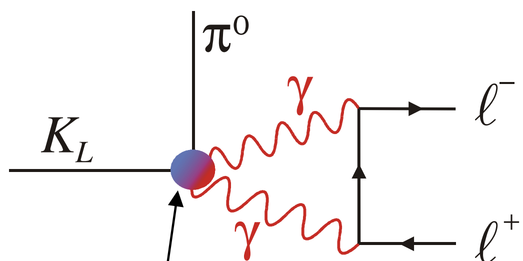
→ Sensitivity to a larger class of operators (*helicity-suppressed effects)*.

Mescia,Trine,CS ('06)

1- *SUSY effects in QCD operators*

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

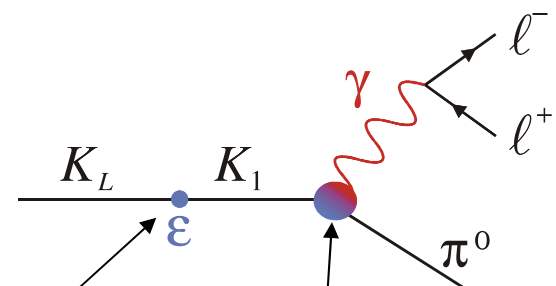
No direct impact: LD background fixed entirely from experimental data.



$(K_L \to \pi\pi\pi, \pi\gamma\gamma)_{exp}$

CP-conserving $\gamma\gamma$ contribution,

Buchalla,D'Ambrosio,Isidori ('03)
Isidori,Unterdorfer,CS ('04)



$(\varepsilon_K)_{exp}$ $(K_S \to \pi^0 \ell^+ \ell^-)_{exp}$

Indirect CP-violating contribution.

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

At the low scale $\mu \sim 1$ GeV, SUSY effects are in *semi-leptonic FCNC operators.*

2- SUSY effects in the SM electroweak operators

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

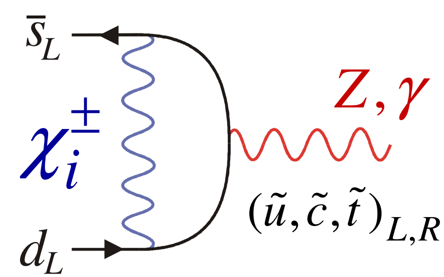
$1^{--}, CPV$ $\qquad$ $1^{++}\ \&\ 0^{-+}, CPV$

- *Chargino penguins*: smaller but correlated with $K \to \pi\nu\bar{\nu}$:

  Isidori,Mescia,Paradisi,Trine,CS ('06)

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

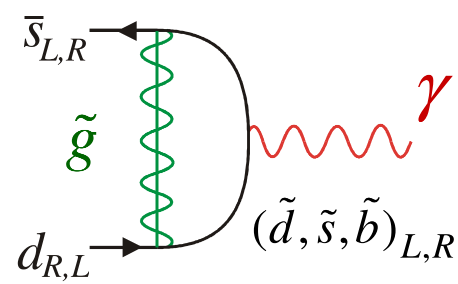
(MFV enhancement: ~7% max.)



- *Gluino EMO* operator, strongly correlated with ε'/ε:

  Buras,Colangelo,Isidori,Romanino,Silvestrini ('00)

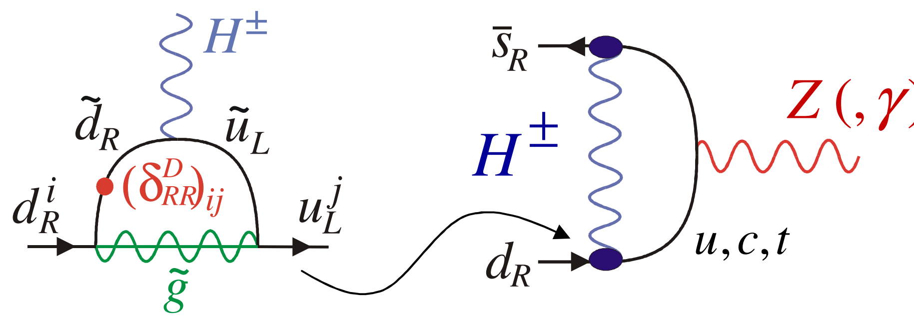
$$(\bar{s}\sigma_{\mu\nu}d)F^{\mu\nu} \to y_{7V} \sim (\delta^D_{RL})_{12(21)}$$



- *Charged Higgs at large* $tan\beta$:

  Isidori,Paradisi ('06)

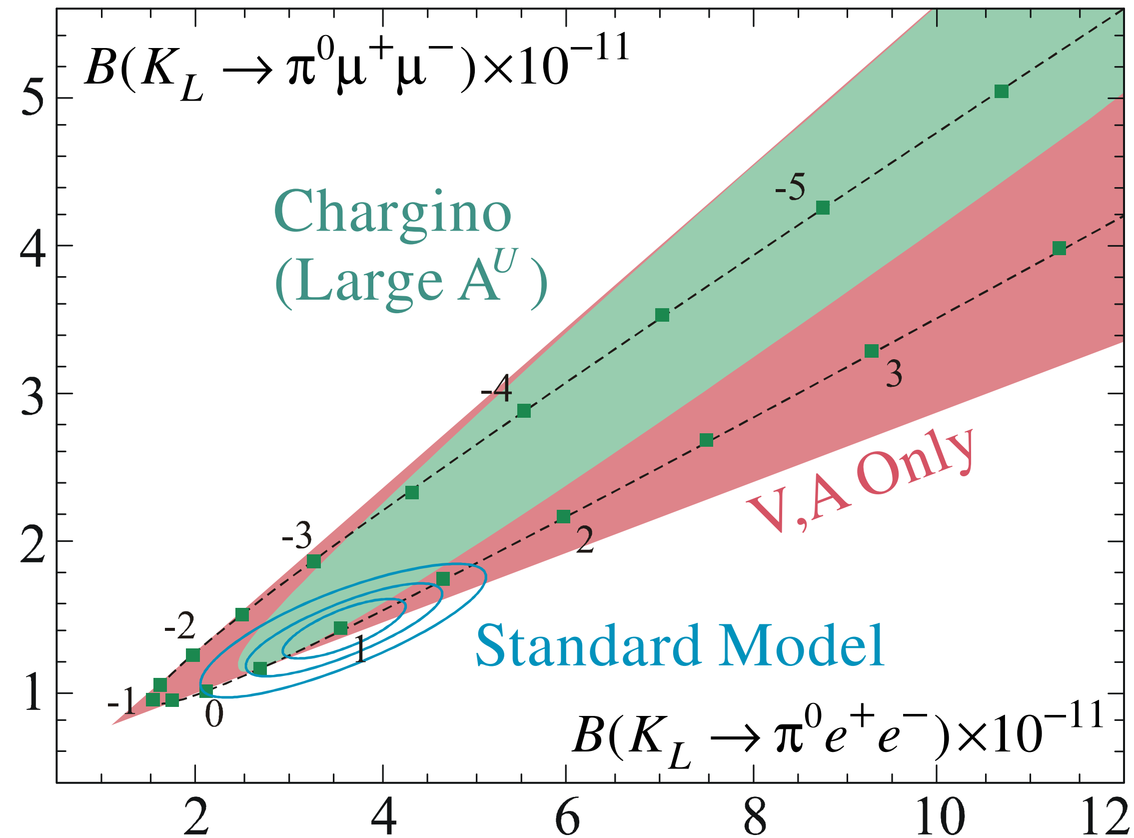
$$y_{7V}, y_{7A} \sim (\delta^D_{RR})_{12}$$



How to disentangle V & A operators:

Specific regions in the plane signal specific correlations between y_{7A} and y_{7V}.

(illustrated for chargino penguins, taking irrealistically large $\mathbf{A}^U$ for clarity)



General bound if only vector/axial-vector FCNC operators are present:

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

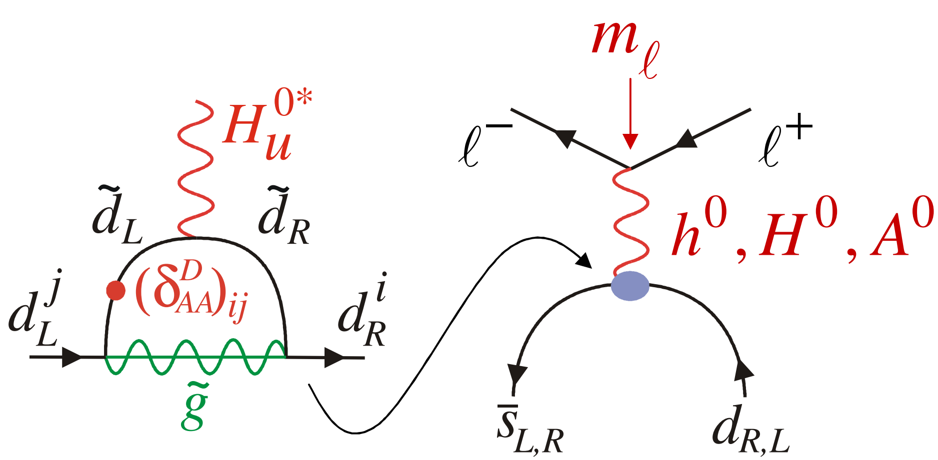
3- SUSY effects in the scalar/pseudoscalar operators

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

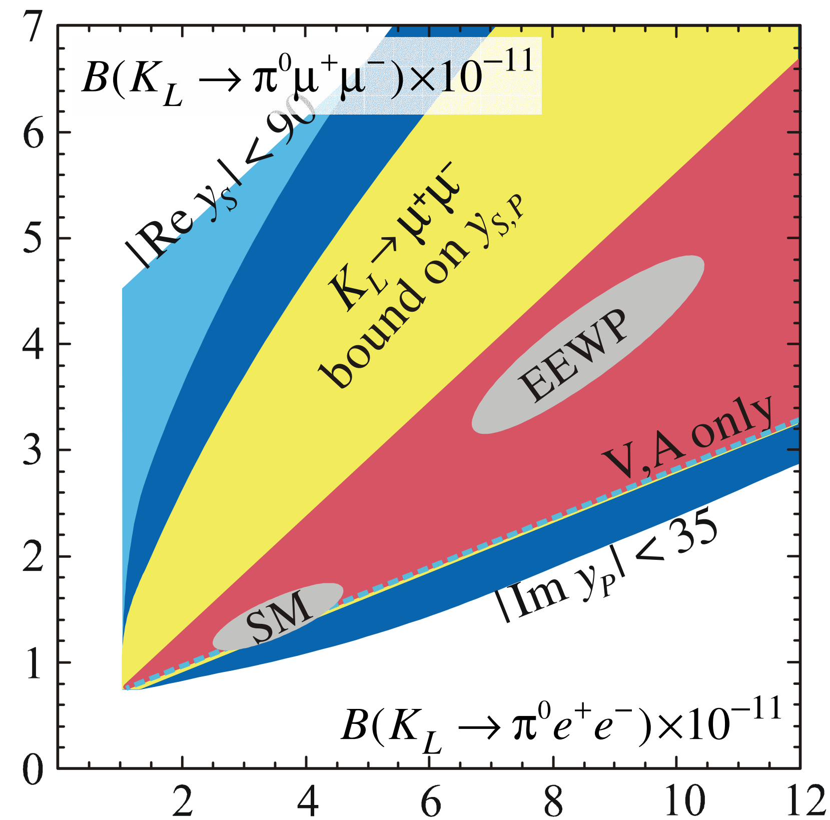
$0^{++}, CPC$ $\qquad$ $0^{-+}, CPV$

A- Helicity-suppressed from neutral Higgs at large $\tan\beta$ (only effective *beyond MFV*):

Isidori,Retico ('01,'02) / Mescia,Trine,CS ('06)



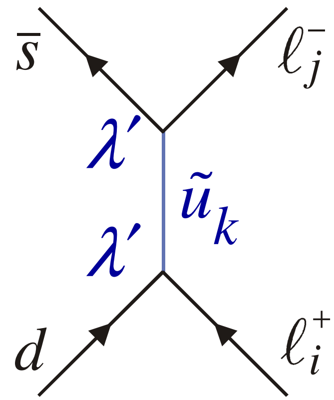
$$y_{S,P} \sim (\delta^D_{RR,LL})_{12},\ (\delta^D_{RR,LL})_{23}(\delta^D_{LL,RR})_{31}$$



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

$(y_{S,P} = y'_{P,S})$ $\qquad$ $0^{++}, CPV$ $\qquad$ $0^{-+}, CPC$

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 $K_L \to e^\pm \mu^\mp, \ldots$

→ *No visible impact.*

4- SUSY effects in the tensor/pseudotensor operators

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

$1^{--}, CPV$ $1^{+-}, CPC$

Bobeth, Buras, Kruger, Urban ('02)

- Necessarily *helicity- and loop-suppressed* in the MSSM,
- In addition, their contributions are *phase-space suppressed*,
- *Cannot arise from R-parity violating* couplings, → *No visible impact.*
- *But*: do not contribute to $K_L \to \ell^+ \ell^-$.

Conclusion

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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*.

Scenario	$K \to \pi\nu\bar{\nu}$	$K_L \to \pi^0 \ell^+ \ell^-$
MFV $\tan\beta \approx 2$	Best sensitivity, but maximum enhancement < 20-25%	Less sensitive, but precisely correlated 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 as $M_H \to \infty$)	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.