Rome, September 2008

Searching for new physics with rare kaon decays

Christopher Smith

b
UNIVERSITÄT
BERN

- Outline

I- New Physics in flavor transitions

II- Pattern of deviations in rare K decays

Conclusion

New Physics in flavor transitions

A. The New Physics flavor puzzle

- Most New Physics (NP) models have either *new flavored particles*, or *new flavor-breaking interactions* between quarks and leptons.

- At the same time, there is *no signal of NP in flavor experiments.*

→ Experiments ~ SM predictions

→ $\begin{cases} b \to s: \\ |V_{tb}^* V_{ts}| \sim \lambda^2 \end{cases}$ $\begin{cases} b \to d: \\ |V_{tb}^* V_{td}| \sim \lambda^3 \end{cases}$ $\begin{cases} s \to d: \\ |V_{ts}^* V_{td}| \sim \lambda^5 \end{cases}$

Most constraining!

- New Physics cannot be *both light and generic*:

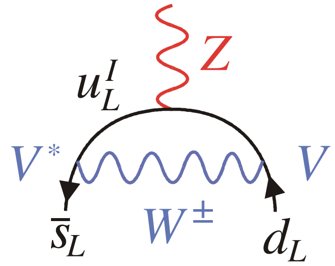
$$\mathcal{L}_{eff} = \frac{c_{bs}}{\Lambda^2}(\bar{b}\Gamma s)(\bar{\nu}\Gamma\nu) + \frac{c_{bd}}{\Lambda^2}(\bar{b}\Gamma d)(\bar{\nu}\Gamma\nu) + \frac{c_{sd}}{\Lambda^2}(\bar{s}\Gamma d)(\bar{\nu}\Gamma\nu) + \ldots$$

$c_{sd} \approx 1, \quad \Lambda \gtrsim 75\,\mathrm{TeV}$: NP very massive, beyond the reach of LHC,

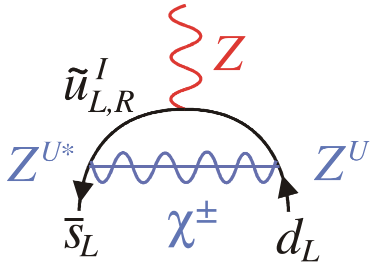
$\Lambda \approx 1\,\mathrm{TeV}, \quad c_{sd} \lesssim V_{ts}^* V_{td}$: NP flavor structures highly non-generic.

B. Application to the MSSM

Squarks are new flavored particles, not aligned with quarks:



$\overset{?}{\ll}$



CKM = small mistmatch between quark mass and gauge eigenstates.

Large mass and gauge eigenstate mismatch for squarks?

Squarks must be quasi parallel to quarks (e.g., $Z^U \approx V_{CKM}$).

Minimal Flavor Violation: $c_{qq'} \sim V_{tq}^* V_{tq'}$

Systematic symmetry principle allowing to parametrize all NP flavor-breaking in terms of the SM Yukawa couplings.

Hall,Randall '90/D'Ambrosio et al. '02

C. SUSY implementations of Minimal Flavor Violation

Hall,Randall '90
D'Ambrosio et al. '02
Colangelo,Nikolidakis,CS '08

1- Electroweak-scale MFV

- Squark soft SUSY-breaking terms fixed in terms of the Yukawa couplings.
- Allows for several new CP-violating phases, beside the CKM one.

$$\mathrm{Im}(\delta_{LL}^{23,13}) \neq 0\ !$$

$$\mathbf{m}_Q^2 = m_0^2 (a_1 \mathbf{1} + b_1 \mathbf{Y}_u^\dagger \mathbf{Y}_u + b_2 \mathbf{Y}_d^\dagger \mathbf{Y}_d + c_1 \mathbf{Y}_u^\dagger \mathbf{Y}_u \mathbf{Y}_d^\dagger \mathbf{Y}_d + c_1^* \mathbf{Y}_d^\dagger \mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u)$$

$$\mathbf{A}_u = A_0 \mathbf{Y}_u (a_2 \mathbf{1} + b_3 \mathbf{Y}_u^\dagger \mathbf{Y}_u + b_4 \mathbf{Y}_d^\dagger \mathbf{Y}_d + c_2 \mathbf{Y}_u^\dagger \mathbf{Y}_u \mathbf{Y}_d^\dagger \mathbf{Y}_d + c_3 \mathbf{Y}_d^\dagger \mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u)$$

$$\mathrm{Im}(\delta_{RL}) \neq 0\ !$$

For K physics:

- Small impact on ε_K since δ_{LL}^{12} does not feel the new phase (note $\delta_{LL}^{23} \sim \delta_{LL}^{13}$).
- Double LR mass-insertion, relevant for rare K, stays essentially real:

$$(\delta_{RL}^U)_{32}^* (\delta_{RL}^U)_{31} \sim m_t^2 V_{ts}^* V_{td} \left| A_0 a_2^* - \cot\beta\mu \right|^2 .$$

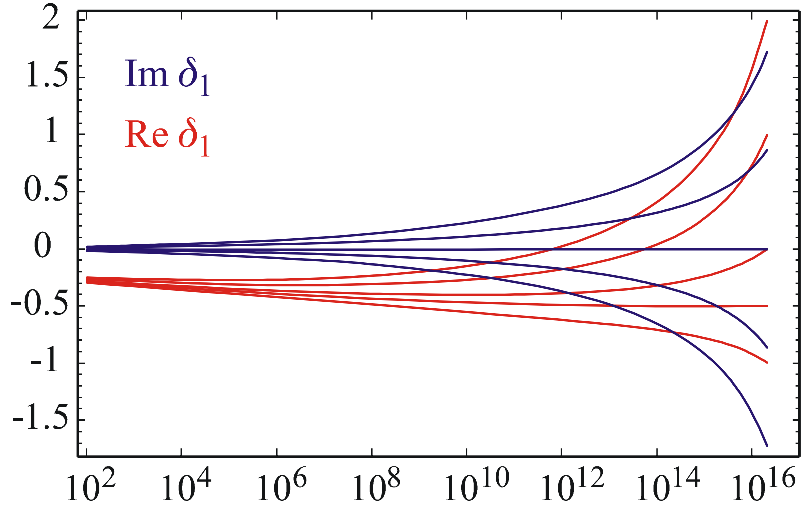
2- Running down GUT-scale MFV

Paradisi,Ratz,Schieren,Simonetto '08
Colangelo,Nikolidakis,C.S. '08

- "Running *infrared fixed points*" ↔ predictions for all *mass-insertions.*

  (essentially: the mSUGRA-like a_i, running as the gluino mass, dominates)

- All seven new *CP-violating phases* run towards zero (in the squark sector).



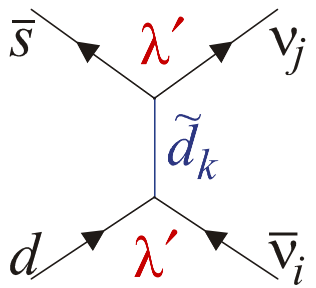
$$\delta_1 \equiv \frac{(\delta^U_{RL})^{32}}{V_{ts}} = \frac{(\delta^U_{RL})^{31}}{V_{td}}$$

(similar for other mass-insertions)

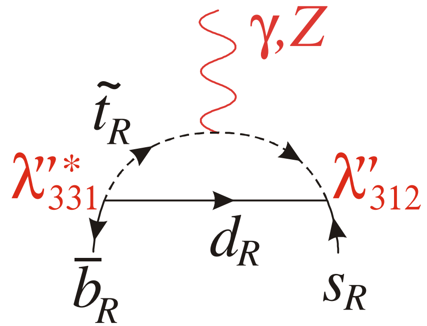
- *Running up* from MFV at the electroweak scale, starting away from the fixed points does not lead to MFV at the GUT scale.

Nikolidakis,C.S. '07

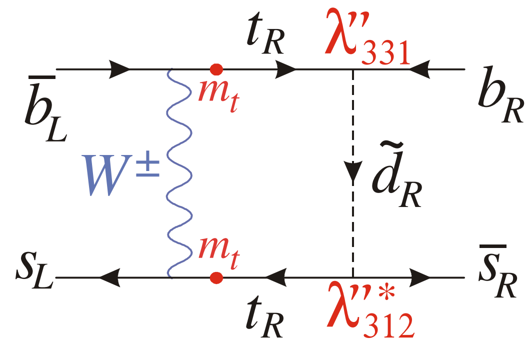
3- Electroweak-scale MFV without R-parity



Grossman,Isidori,Murayama '03, Deandrea,Welzel,Oertel '04,...



Chakraverty,Choudhury '01,...



Barbieri,Masiero '86, Slavich '00,...

- Surprisingly, *MFV alone is sufficient to pass all proton decay bounds.*
- All *lepton-violating couplings are tiny*, proportional to neutrino masses.
- Strong *hierarchy of baryon-violating couplings* suppresses their contributions

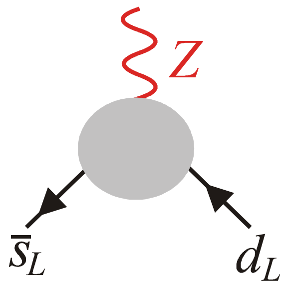
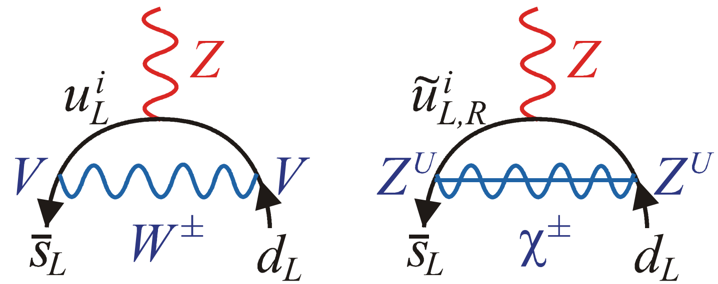
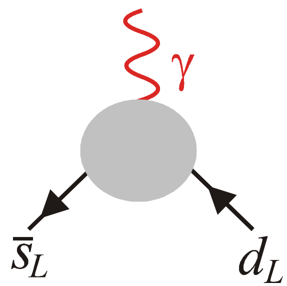
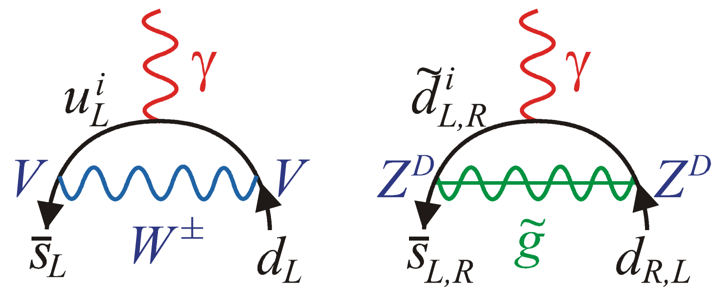
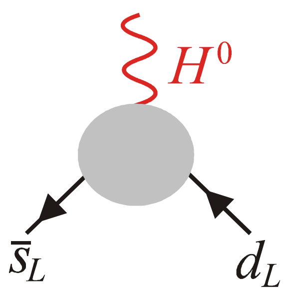
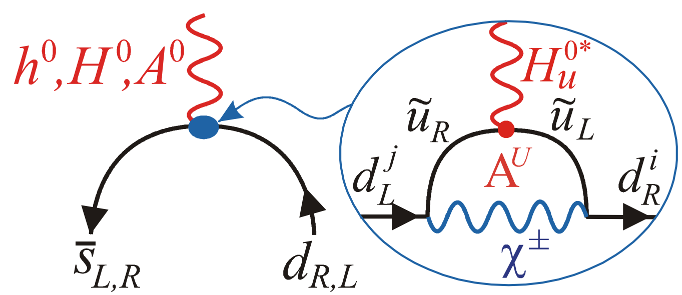
$$b \to s : \left|\lambda''_{312}\lambda''^*_{331}\right| < 10^{-3}, \quad b \to d : \left|\lambda''_{312}\lambda''^*_{323}\right| < 10^{-5}, \quad s \to d : \left|\lambda''_{313}\lambda''^*_{323}\right| < 10^{-8}$$

$$b \to s : \left|V^*_{tb}V_{ts}\right| \sim 10^{-2}, \quad b \to d : \left|V^*_{tb}V_{td}\right| \sim 10^{-3}, \quad s \to d : \left|V^*_{ts}V_{td}\right| \sim 10^{-4}$$

$\Rightarrow$ at most a few % of the SM contributions.

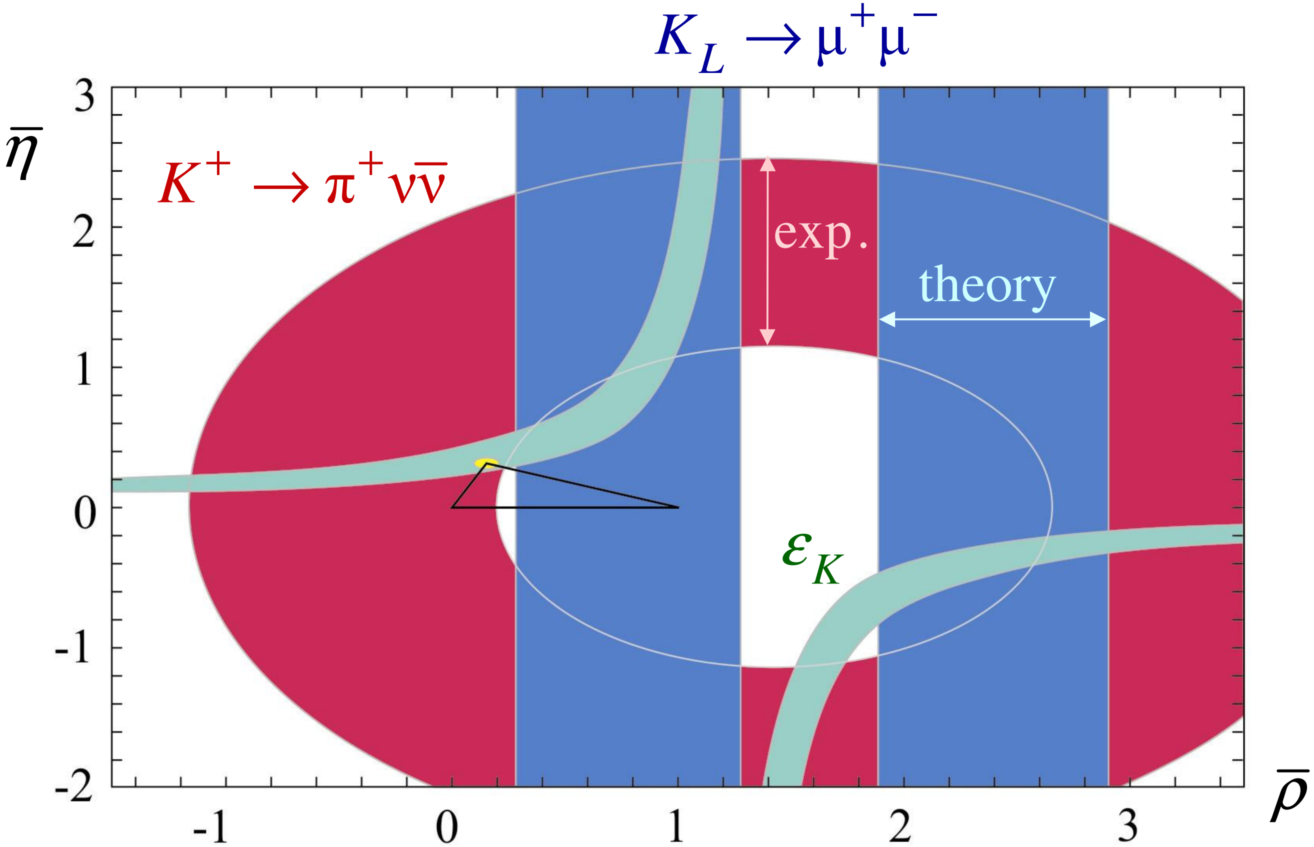
Patterns of deviations

A. Probing EW structures with rare K decays

EW Penguin	SM and/or example of SUSY diagram	Contributes to
		$K \to \pi\nu\bar{\nu}$ $K_L \to \pi^0\ell^+\ell^-$ $K_L \to \ell^+\ell^-$
		$K_L \to \pi^0\ell^+\ell^-$
		$K_L \to \pi^0\mu^+\mu^-$ $K_L \to \mu^+\mu^-$ (helicity-suppressed)

New Physics to be identified by looking at patterns of deviations!

B. Where do we stand?



$K_L \to \pi^0 \nu\bar{\nu}$:
$\bar{\eta} < 17$

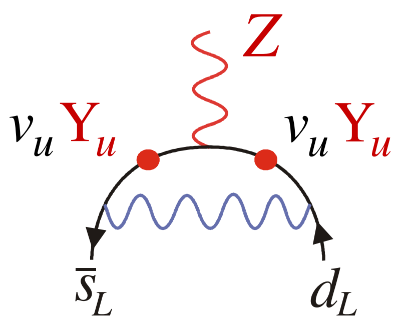
$K_L \to \pi^0 e^+ e^-$:
$\bar{\eta} < 3.3$

$K_L \to \pi^0 \mu^+\mu^-$:
$\bar{\eta} < 5.4$

- For $K_L \to \mu^+\mu^-$: large error due to $K_L \to \gamma\gamma \to \mu^+\mu^-$, only upper bound for the contribution corresponding to the range 1 - 3 GeV. *Isidori,Unterdorfer '04*

- Interference SD-LD fixed from the Q_1 operator evolution, to be confirmed experimentally with $K^+ \to \pi^+\gamma\gamma$ and/or $K_S \to \pi^0\gamma\gamma$. *Gerard,Trine,C.S '05*

C. The Z penguin (and its associated W box)



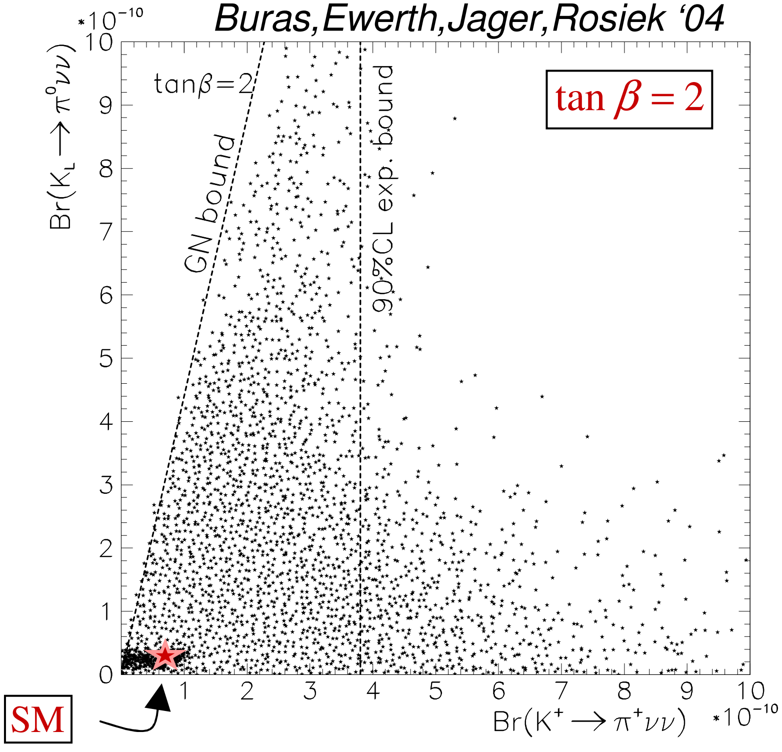
- $SU(2)_L$ breaking: $SM: v_u^2 Y_u^{*32} Y_u^{31} \sim m_t^2 V_{ts}^* V_{td}$

$$MSSM: v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 \times O(1)\,?$$

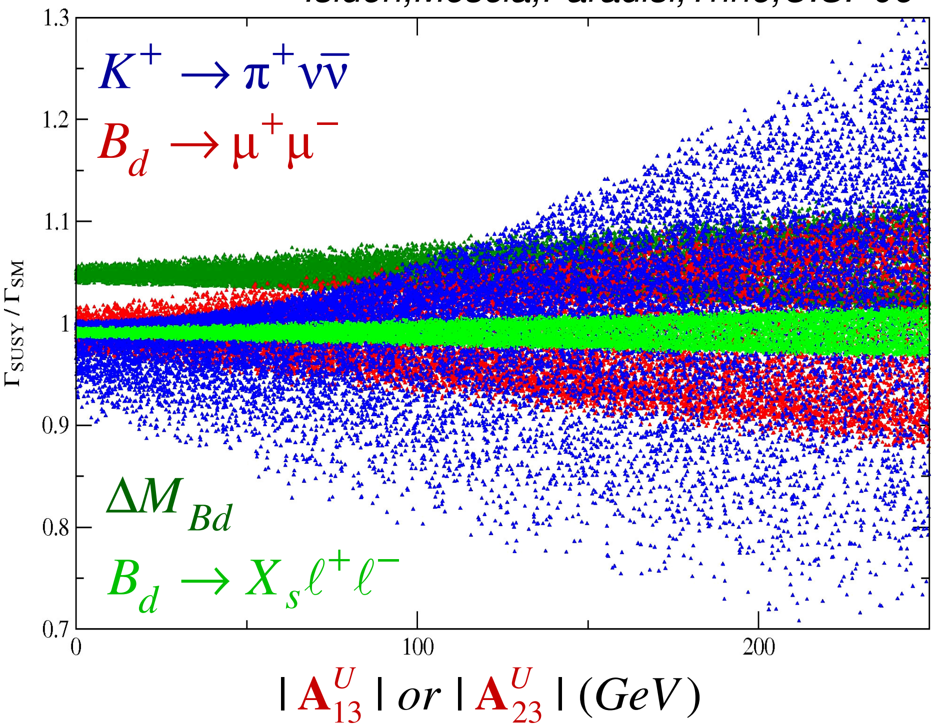
$$MFV: v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 V_{ts}^* V_{td} \left|A_0 a_2^* - \cot\beta\mu\right|^2.$$

- Relatively slow decoupling (w.r.t. boxes or tree).

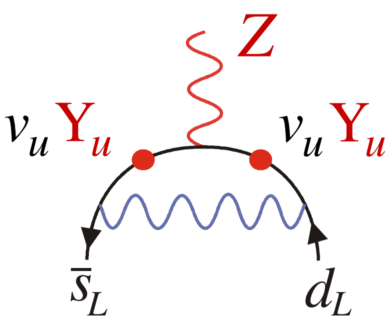
Buras,Ewerth,Jager,Rosiek '04



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



C. The Z penguin (and its associated W box)



- $SU(2)_L$ breaking: $SM: v_u^2 Y_u^{*32} Y_u^{31} \sim m_t^2 V_{ts}^* V_{td}$

$$MSSM: v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 \times O(1)\,?$$

$$MFV: v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 V_{ts}^* V_{td} \left| A_0 a_2^* - \cot\beta\mu \right|^2 .$$

- Relatively slow decoupling (w.r.t. boxes or tree).

Most *NP models effects of this type,* or give essentially the same eff. operator:

MSSM moderate $\tan\beta$ (chargino), — *Nir,Worah '98, Buras,Romanino,Silvestrini '98, Colangelo,Isidori '98*

MSSM large $\tan\beta$ (charged Higgs), — *Isidori,Paradisi '06*

R-parity violation (non MFV), — *Grossman,Isidori,Murayama '03, Deshpande,Ghosh,He '04,Deandrea,Welzel,Oertel '04*

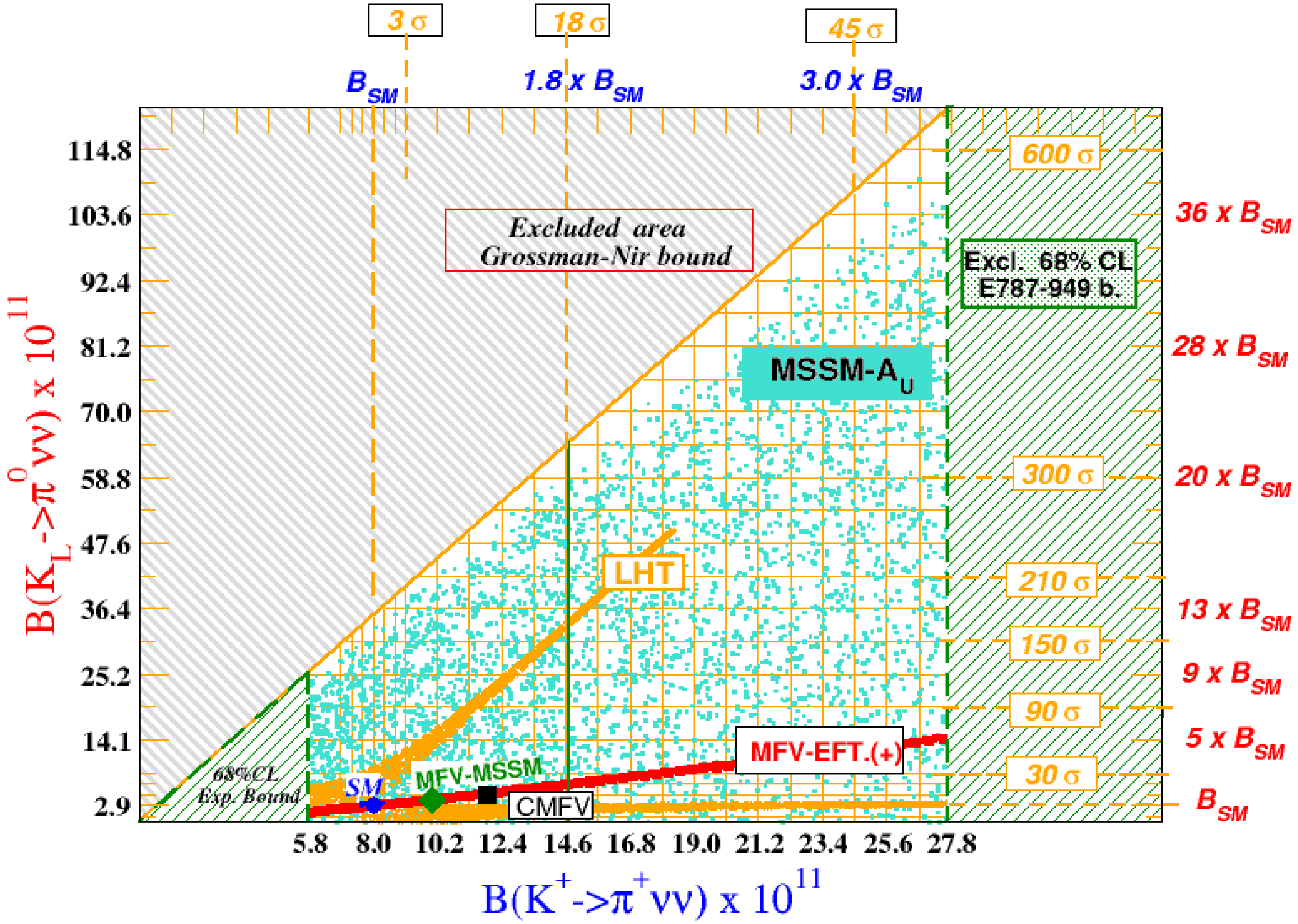
EEWP, — *Buras,Fleischer,Recksiegel,Schwab '04*

Little Higgs, — *Rai Choudhury,Gaur,Joshi,McKellar '04, Blanke et al '06,'07*

Extra Dimensions, — *Buras,Spranger,Weiler '02*

...

- $K \to \pi\nu\bar{\nu}$: best probe, and their correlation tests various possible models



Mescia '06

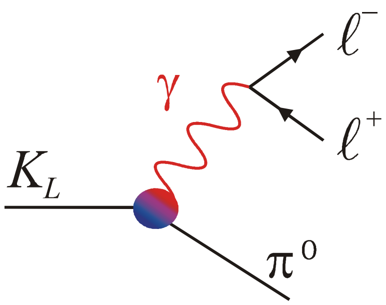
- $K_L \to \pi^0 \ell^+ \ell^-$: does not bring in any new information here

- $K_L \to \mu^+ \mu^-$: effect directly correlated to that in $K \to \pi\nu\bar{\nu}$, but CP-conserving.

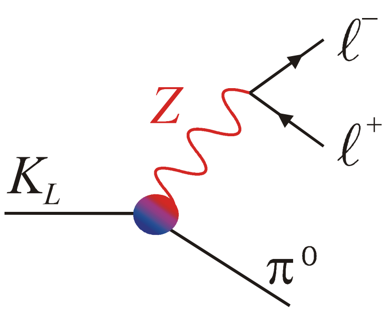
With MFV: in general both are simultaneously larger or smaller!

D. Helicity-suppressed New Physics effects

The $K_L \to \pi^0 \ell^+ \ell^-$ modes permit to isolate the *γ penguin*:



1^{--}



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

0^{-+}

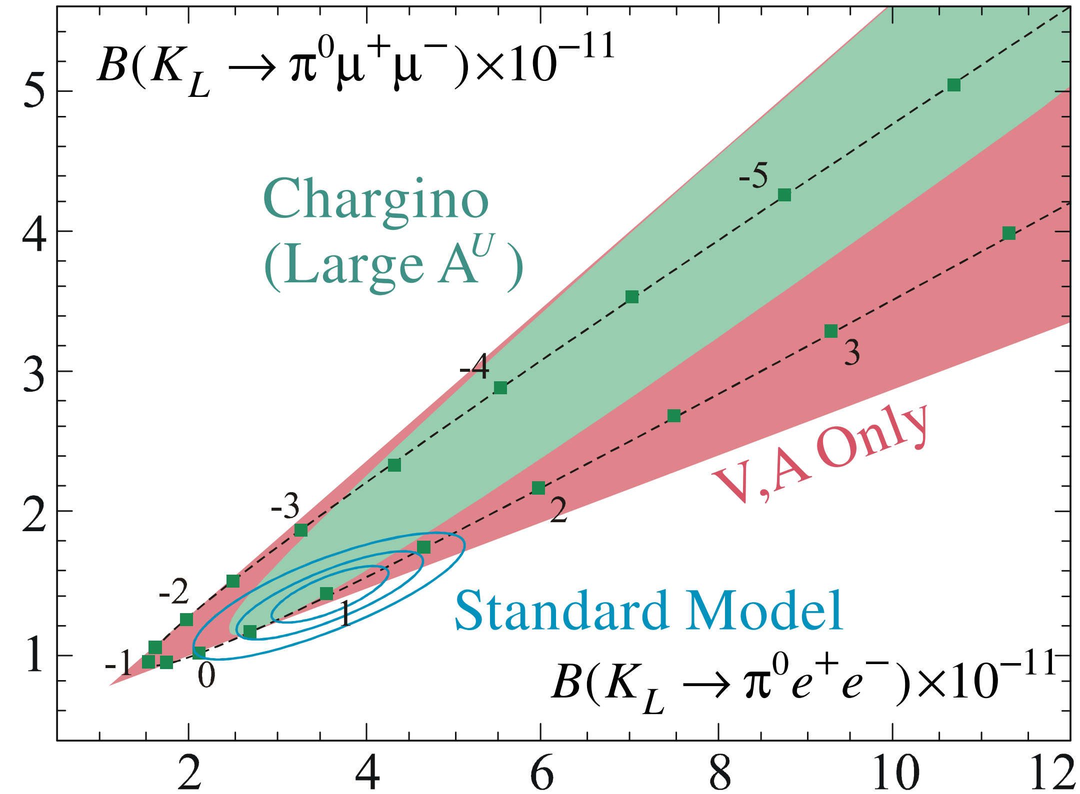
$\uparrow$

$\sim m_\ell$

$\Rightarrow$ Only for muons!

Specific regions in the plane for specific correlations between *γ and Z penguins*.

Isidori,Unterdorfer,C.S. '04

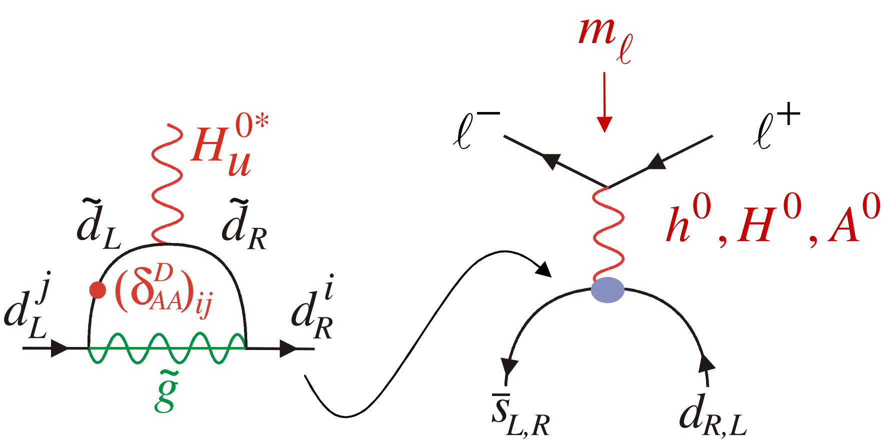


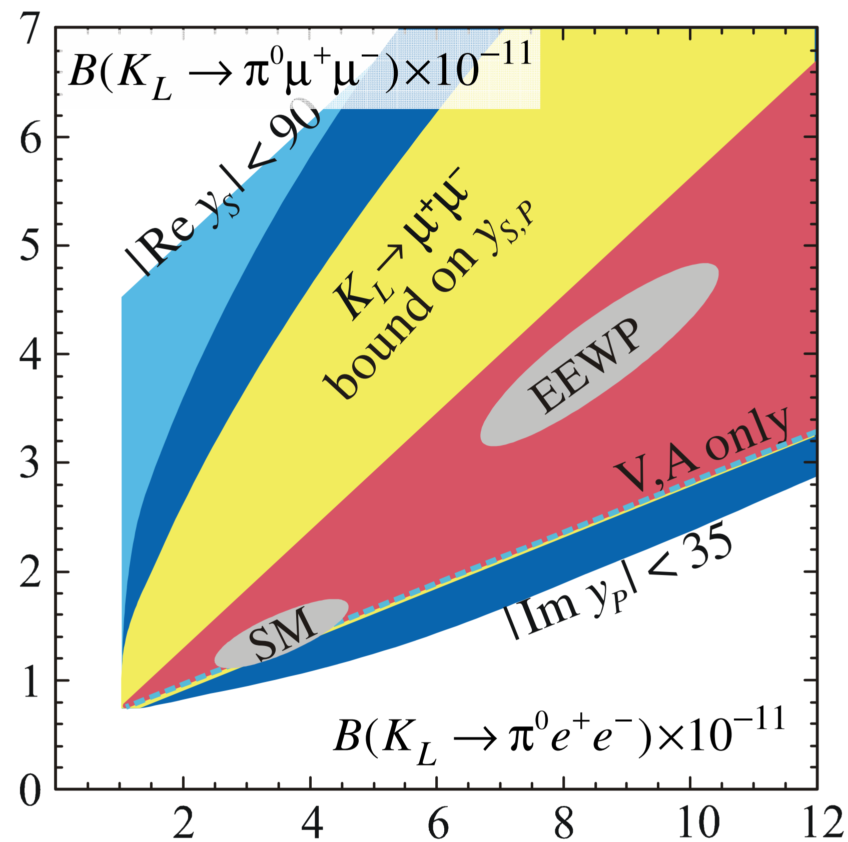
$\Leftrightarrow\ 0.1 + 0.24 B_e \leq B_\mu \leq 0.6 + 0.58 B_e$

with $B_\ell \equiv B(K_L \to \pi^0 \ell^+ \ell^-) \cdot 10^{11}$

They also probe a broad class of helicity-suppressed NP effects, as those generated by *neutral Higgs penguins*.

Isidori, Retico '01, '02
Mescia, Trine, CS '06





$$H_{eff} \sim y_S\, (\bar{s}d)(\bar{\ell}\ell) + y_P\, (\bar{s}d)(\bar{\ell}\gamma_5\ell)$$

Even if directly correlated with $K_L \to \mu^+\mu^-$, *large effects still possible*.

E. Looking for the unexpected?

1- $K_L \to \pi^0 \ell^+ \ell^-$ probe the (pseudo-)scalar and (pseudo-)tensor operators:

$$H_{eff} \sim y_S^{IJ} (\bar{s}d)(\bar{\ell}^I \ell^J) + y_P^{IJ} (\bar{s}d)(\bar{\ell}^I \gamma_5 \ell^J) + y_T (\bar{s}\sigma_{\mu\nu}d)(\bar{\ell}\sigma^{\mu\nu}\ell) + ...$$

Presummably killed by $K_L \to ee, e\mu$ ...but tensors still free.

2- Similar operators for $K \to \pi\nu\bar{\nu}$ require *active right-handed neutrinos*.

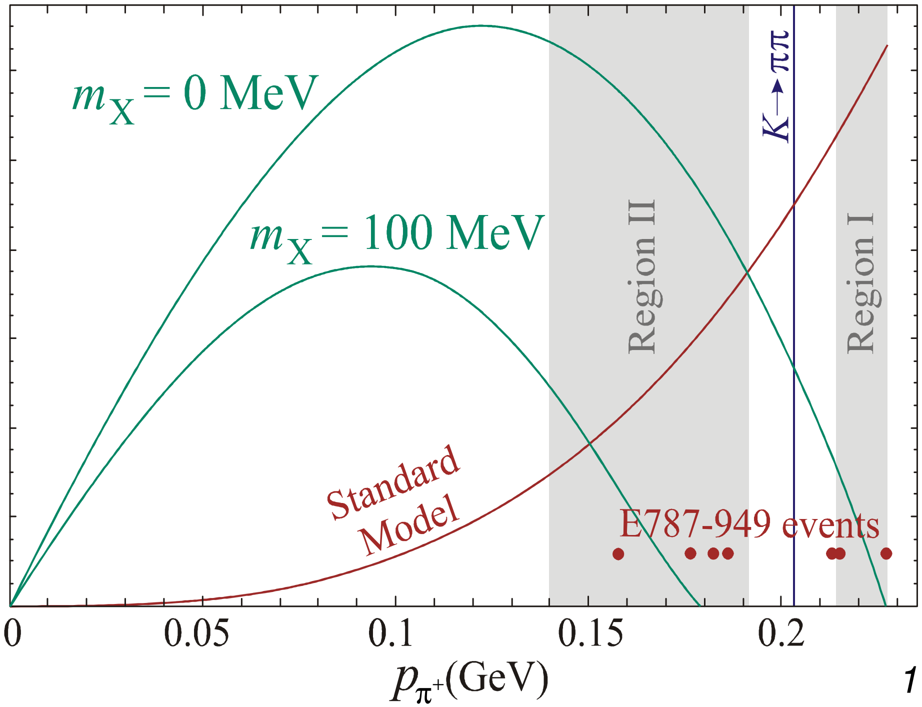
3- Decays into *other invisible state(s)*?

Beware of the kinematics!

- Two-body peak for $K \to \pi + X$
- Spectrum for $K \to \pi + X + X$

Depicted for scalar coupling,

$$H_{eff} \sim y_S (\bar{s}d)(\bar{X}X).$$



Conclusion

1- $K \to \pi\nu\bar{\nu}$ *and* $K_L \to \pi^0\ell^+\ell^-$ *decays are unique windows into the* $s \to d$ *sector.*

Essential to constrain (and discriminate among) New Physics models.

2- Still, *do not forget* $K_L \to \mu^+\mu^-$, the only mode measured with precision.

Further theoretical work would be much welcome on the two-photon contribution.

(or, alternatively, wait for $K_L \to \pi^0\mu^+\mu^-$, much cleaner and more sensitive)

3- *Message to experimentalists*: Go for the $K \to \pi\nu\bar{\nu}$ modes, they are the cleanest,

But do not disregard other modes:

$K_L \to \pi^0\ell^+\ell^-$: Sensitive to a larger class of NP effects

$K_S \to \pi^0\ell^+\ell^-, K_L \to \pi^0\gamma\gamma, K_{\ell 3}$: Theoretical control for rare K decays

$K_S \to \pi^0\gamma\gamma, K^+ \to \pi^+\gamma\gamma$: Theoretical control over $K_L \to \mu^+\mu^-$

$K \to (\pi)e\mu$: Probably too small, but one never knows...

...

Backup

Interference sign fixed from that of $A(K_L \to \gamma\gamma)$

Gerard, Trine, C.S ('05)

Driven by Q_1 → vanishes at LO in SU(3) ChPT.

$$A_{\gamma\gamma} \approx \overbrace{\left(G_8^s + \tfrac{2}{3}G_{27}\right)}^{\sim C_1(\mu_{hadr.})}\left(0.46_\pi - 1.83_\eta - 0.12_{\eta'}\right) \Leftrightarrow B(K_L \to \gamma\gamma)^{\exp} \Rightarrow G_8^s / G_8 \approx \pm\tfrac{1}{3}$$

Theoretically, G_8^s estimated from the smooth Q_1, Q_2 non-perturbative evolution

$$(C_1 + C_2)^2(C_2 - C_1) = 1.0 \pm 0.3 \Rightarrow G_8^s / G_8 = -0.38 \pm 0.12$$

Experimentally, G_8^s could be fixed from either: