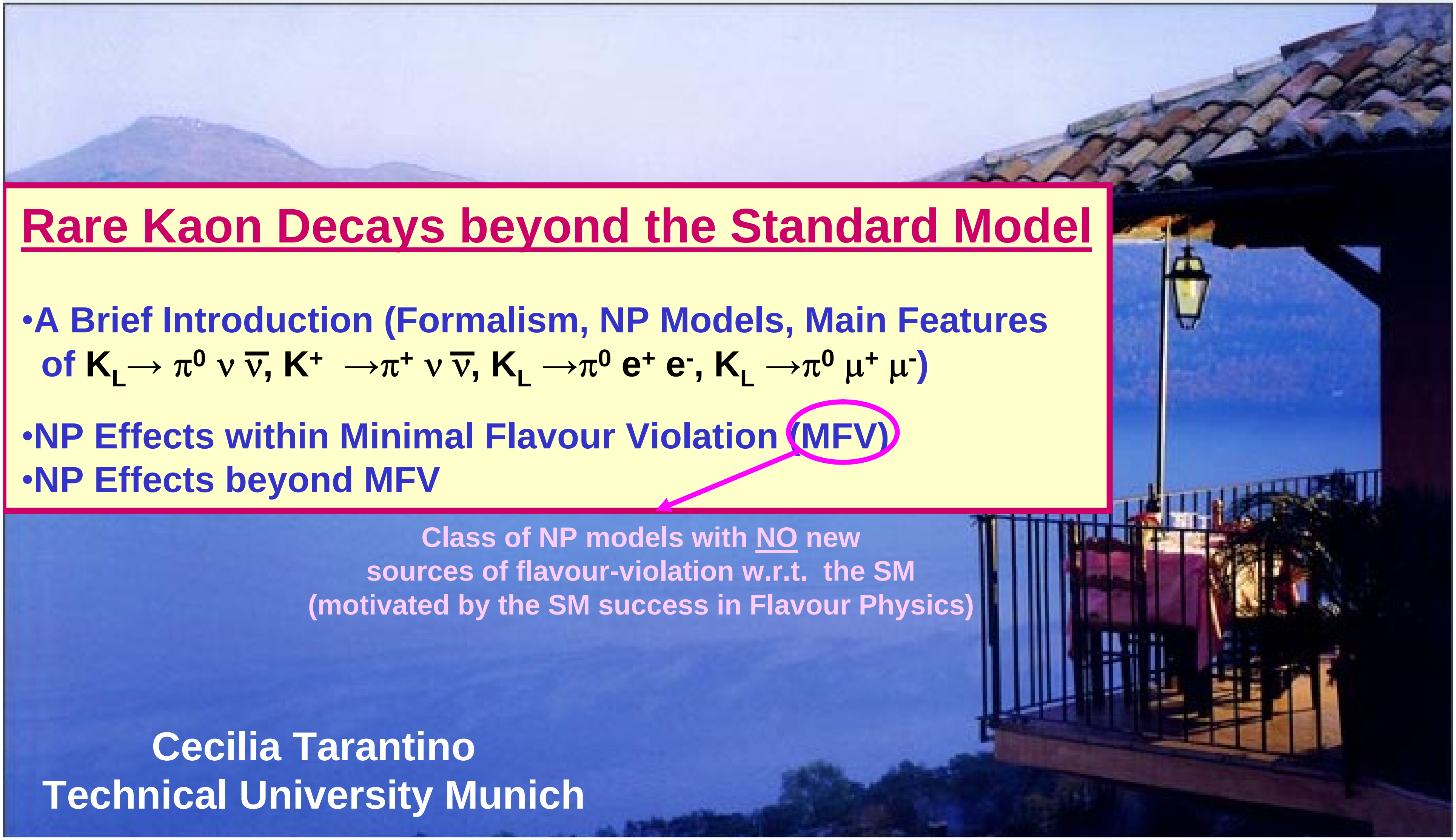
KAON´07
Laboratori Nazionali di Frascati dell´INFN
May 21-25, 2007



Rare Kaon Decays beyond the Standard Model

- A Brief Introduction (Formalism, NP Models, Main Features of $K_L \to \pi^0 \nu \bar{\nu}$, $K^+ \to \pi^+ \nu \bar{\nu}$, $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+ \mu^-$)
- NP Effects within Minimal Flavour Violation (MFV)
- NP Effects beyond MFV

Class of NP models with NO new sources of flavour-violation w.r.t. the SM (motivated by the SM success in Flavour Physics)

Cecilia Tarantino
Technical University Munich

Master Formula for Weak Decays

A.J. Buras, hep-ph/0101336
hep-ph/0109197

(General) Minimal Flavour Violation
(MFV) G.D´Ambrosio et al., hep-ph/0207036

Constrained Minimal Flavour Violation
(CMFV) A.J.Buras et al., hep-ph/0007085

$$A(\mathrm{Decay}) = V^i_{CKM}\left\{B_i \eta^i_{QCD}\left[F^i_{SM} + F^i_{CMFV}\right] + B_i^{MFV}\left(\eta^i_{QCD}\right)^{MFV} F^i_{MFV}\right\} + V^i_{NEW} B_i^{NEW}\left(\eta^i_{QCD}\right)^{NEW} F^i_{NEW}$$

Most General NP (beyond MFV)

F^i´s: short-distance Loop Functions (Penguins, Boxes) [from perturbation theory]
(η^i_{QCD})´s: QCD corrections [from RG improved perturbation theory]
B_i´s: long-distance Parameters [the most uncertain: from experiments, Lattice, …]

CMFV: (pragmatic approach) a CMFV Model has to satisfy two constraints: the only source of flavour-violation is the CKM, the only operators are the SM ones [A.J. Buras et al., hep-ph/0007085]

MFV: (top-down approach) in building a MFV Model the SM Yukawa couplings are the only *building-blocks* of flavour violation [G.D´Ambrosio et al., hep-ph/0207036]

General NP beyond MFV: new sources of flavour violation (V^i_{NEW}) can appear

The Most Appealing Models

CMFV

Littlest Higgs (LH) [N.Arkani-Hamed, A.G.Cohen, E.Katz, A.E.Nelson, hep-ph/0206021]
(Higgs= Goldstone boson of a global symmetry $SU(5) \xrightarrow{f} SO(5)$,
``little hierarchy problem´´ cured by heavy partners with the same spin-statistics
(W_H, Z_H, A_H, T, Φ)
f is constrained to be large (>2-3 TeV) by electroweak (ew) precision tests)

Appelquist-Cheng-Dobrescu (ACD) [T.Appelquist, H.C.Cheng, B.A.Dobrescu, hep-ph/0012100]
(1 universal extra-dimension → SM particles propagate in 5 dimensions,
in 4 dimensions Kaluza-Klein modes appear , KK—Parity conservation,
only one additional free parameter: 1/R > 200-300 GeV from ew precision tests)

(General) MFV

MSSM [P.Fayet (1976,1977,1979), G.R.Farrar, P.Fayet(1978),…] **with MFV**
(boson-fermion symmetry,minimal spectrum (sparticles,2 Higgs doublets,$\tan\beta=v_u/v_d$),
R-parity)
•low $\tan\beta$ →CMFV(true only if μ is small) [W.Altmannshofer, A.J.Buras, D.Guadagnoli, hep-ph/0703200]
•large $\tan\beta$ →new operators are generated by Higgs contributions

Beyond MFV

MSSM [P.Fayet (1976,1977,1979), G.R.Farrar, P.Fayet(1978),…] with a general Flavour Structure
(boson-fermion symmetry, minimal spectrum (sparticles, 2 Higgs doublets),
R-parity,
27 new Flavour Changing couplings along the squark lines)

Littlest Higgs with T-Parity (LHT) [H.C.Cheng, I.Low, hep-ph/0308199, hep-ph/0405243]
(LH + a discrete symmetry (T-Parity)
→heavy particles cannnot appear at tree-level
→ew precision tests are less constraining (f>500GeV),
in addition to W_H, Z_H, A_H, T, Φ,
new mirror fermions with new flavour interactions)

Minimal 3-3-1 Model [P.H.Frampton(1992), F.Pisano, V.Pleitez(1992), R.Foot et al.(1993)]
(extended gauge group $SU(3)_c \times SU(3)_L \times U(1)_X$, 3 generations required for anomaly cancellation and QCD asymptotic freedom, new heavy quarks and gauge bosons,
FCNC´s can be trasmitted at tree-level by the new neutral gauge boson Z´ and involve a new mixing matrix)

Main Features of Rare Kaon Decays

See talk by Uli for details and complete bibliography

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

Golden modes [intrinsic theoretical uncertainty <5%]

- Short-distance dominated
- Operator matrix elements extracted from K/3 → Beyond LO in ChPT

F.Mescia and C.Smith, hep-ph/0705.2025 (last week!)

Strongly suppressed within the SM

K_L

$$K_L \cong \frac{1}{\sqrt{2}}\left(K^0 + \overline{K}^0\right)$$

$$\left\langle \pi^0 \middle| \left(\bar{d}s\right)_{V-A} \middle| \overline{K}^0 \right\rangle = -\left\langle \pi^0 \middle| \left(\bar{d}s\right)_{V-A} \middle| K^0 \right\rangle$$

$$A(K_L \to \pi^0 \nu\bar{\nu}) \propto (\lambda_t - \lambda_t^*)X(x_t) + (\lambda_c - \lambda_c^*)X(x_c)$$

$$\cong \mathrm{Im}(\lambda_t)X(x_t) \to O\left(\lambda^5\right)$$

$X(x) \approx x$

$\mathrm{Im}(\lambda_t) \approx \mathrm{Im}(\lambda_c) \approx \lambda^5$

K^+

$$A(K^+ \to \pi^+ \nu\bar{\nu}) : \mathrm{Im}(\lambda_t)X(x_t), \mathrm{Re}(\lambda_t)X(x_t) \to O\left(\lambda^5\right)$$

and $\mathrm{Re}(\lambda_c)X(x_c)$ suppressed as well by x_c → At NNLO

$\approx \lambda$

A.J.Buras et al., hep-ph/0508165

+ long-distance and dimension-8 operator effects

G.Isidori, F.Mescia, C.Smith, hep-ph/0503107

highly sensitive to NP, where theoretical cleanness is not spoiled!

$K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$

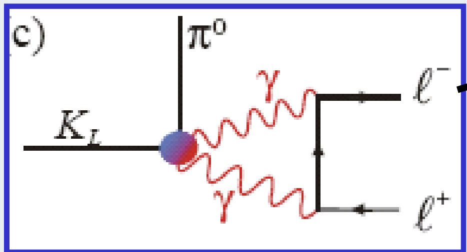
Promising modes

Three contributions of comparable size:

a) direct CP-violating (short-distance→clean),

b) indirect CP-violating (↔exp. observation of $K_S \to \pi^0 l^+ l^-$),

c) long-distance CP-conserving (↔exp. studies of $K_L \to \pi^0 \gamma \gamma$)



Recently, theoretically under control

G.Buchalla et al., hep-ph/0308008,
G.Isidori et al., hep-ph/0404127

The two-photon CP-conserving contribution $K_L \to \pi^0 (\gamma\gamma)_{J=0,2} \to \pi^0 (l^+ l^-)_{J=0,2}$ represents the main difference between muon and electron channels: $J^{CP}=0^{++}$ is helicity suppressed and can be neglected in the electron mode

Different NP effects can be disentangled by measuring both rates

F.Mescia, C.Smith, S.Trine, hep-ph/0606081

See talk by Christopher

SM Predictions and Experimental Measurements

Golden Modes	SM	Experiment
$K^+ \to \pi^+ \nu \bar{\nu}$	$(7.8 \pm 0.8) \cdot 10^{-11}$ F.Mescia and C.Smith, hep-ph/0705.2025	$\left(14.7^{+13}_{-8.9}\right) \cdot 10^{-11}$ E787 E949
$K_L \to \pi^0 \nu \bar{\nu}$	$(2.5 \pm 0.4) \cdot 10^{-11}$ F.Mescia and C.Smith, hep-ph/0705.2025	$< 2.1 \cdot 10^{-7}$ E391a
$K_L \to \pi^0 e^+ e^-$	$\left(3.5^{+1.0}_{-0.9}\right) \cdot 10^{-11}$ F.Mescia et al. hep-ph/0606081	$< 2.8 \cdot 10^{-10}$ KTeV
$K_L \to \pi^0 \mu^+ \mu^-$	$(1.4 \pm 0.3) \cdot 10^{-11}$ F.Mescia et al. hep-ph/0606081	$< 3.8 \cdot 10^{-10}$ KTeV

Very clean

Still a lot of room for NP

Rare Kaon Decays within Constrained- and General-MFV

CMFV analysis of C.Bobeth at al., hep-ph/0505110:

Imposing available information from the **Universal Unitary Triangle Analysis** and from the measurements of **Br($B \to X_s \gamma$), Br($B \to X_s l^+ l^-$)** and **Br($K^+ \to \pi^+ \nu \bar{\nu}$)**

→Determination of the allowed range for the short-distance function **C(Z-penguin)**

→Evaluation of the upper bounds for Rare Decays

Branching Ratios	CMFV (95%)	SM (95%)	SM (68%)	Exp
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \cdot 10^{11}$	<11.9	<10.9	8.3±1.2	$14.7^{+13.0}_{-8.9}$
$Br(K_L \to \pi^0 \nu\bar{\nu}) \cdot 10^{11}$	<4.6	<4.2	3.1±0.6	$<5.9 \cdot 10^4$

NP effects in box and gluon-penguin diagrams are assumed negligible
$X^{NP} \approx C^{NP}$

2007 update by U.Haisch and A.Weiler, including constraints from R^0_b, A_b, $A^{0,b}_{FB}$:

•The negative (non-SM) sign of C is now excluded
•Br´s are also bounded from below

Branching Ratios	CMFV (95%)	SM (95%)	Exp.
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \cdot 10^{11}$	[4.3,10.7]	[5.4,9.1]	$14.7^{+13.0}_{-8.9}$
$Br(K_L \to \pi^0 \nu\bar{\nu}) \cdot 10^{11}$	[1.6,4.4]	[2.2,3.5]	<2.1• 10^4

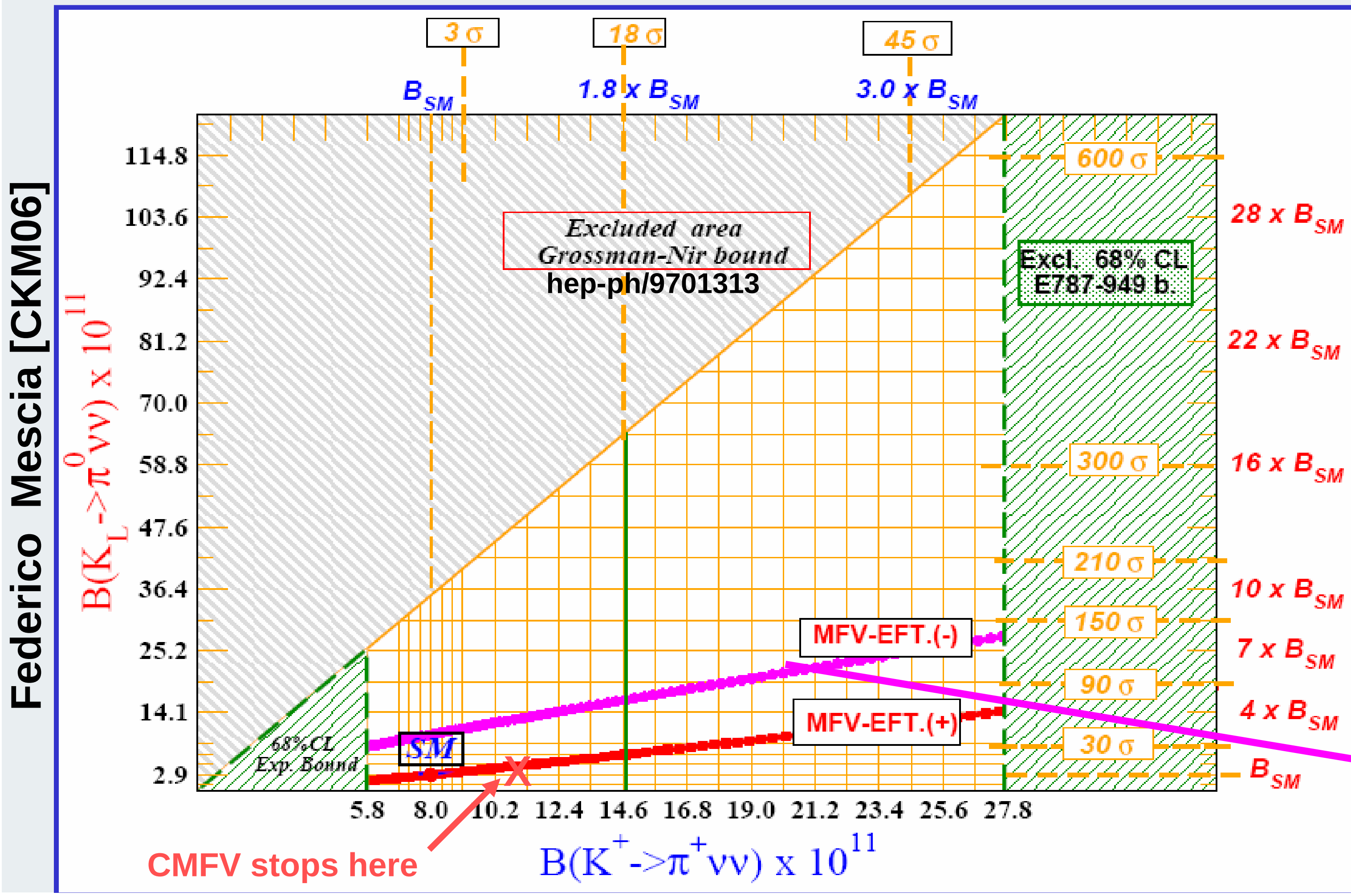
•Existing constraints forbid significant enhancements **(<30%)**
•Rare Kaon Decays are potentially the most constraining
[Next Decade Scenario with ~5% exp. uncertainty is looked forward]

C.Bobeth at al., hep-ph/0505110

$$\left.\frac{Br(K_L \to \pi^0 \nu\bar{\nu})}{Br(K^+ \to \pi^+ \nu\bar{\nu})}\right|_{CMFV} \approx \left.\frac{Br(K_L \to \pi^0 \nu\bar{\nu})}{Br(K^+ \to \pi^+ \nu\bar{\nu})}\right|_{SM}$$

In agreement with the MFV prediction:
G.D'Ambrosio et al., hep-ph/0207036
A.J.Buras, R.Fleischer, hep-ph/0104238

$$\left.\frac{Br(K_L \to \pi^0 \nu\bar{\nu})}{Br(K^+ \to \pi^+ \nu\bar{\nu})}\right|_{MFV} = \left.\frac{Br(K_L \to \pi^0 \nu\bar{\nu})}{Br(K^+ \to \pi^+ \nu\bar{\nu})}\right|_{SM} \times \left[1 + \varepsilon_c \mathrm{sign}(X)\right]$$



The ``minus´´ sign branch is now ruled out within CMFV
[2007 update by U.Haisch, A.Weiler]

In Specific CMFV Models:

Littlest Higgs (LH) [without T-parity]

Ew precision tests constrain the NP scale to be large: f > 2-3 TeV

$\longrightarrow$The enhancements of $Br(K \rightarrow \pi \nu \bar{\nu})$ amount to at most 15%

A.J.Buras et al., hep-ph/0607189

Appelquist-Cheng-Dobrescu [1 universal extra-dimension]

- For 1/R=200 GeV, Br´s are enhanced by 16% (K^+) and 17% (K_L)
- For 1/R=300 GeV (from ew tests if m_H<250GeV) the enhancements are twice smaller

A.J.Buras, M.Spranger, A.Weiler, hep-ph/0212143

- Even smaller enhancements would be found with the new NNLO SM prediction for $b \rightarrow s \gamma$ by M.Misiak et al., hep-ph/0609232

MSSM with MFV and moderate (<30) $\tan\beta$

Y.Nir, M.P.Worah, hep-ph/9711215
A.J.Buras, A.Romanino, L.Silvestrini, hep-ph/9712398
G.Colangelo, G.Isidori, hep-ph/9808487

The deviations from the SM in the two $Br(K \rightarrow \pi \nu \bar{\nu})$ are naturally small (~10%) but could saturate the model-independent bound [G.Isidori at al., hep-ph/0604074]

See talk by Christopher

- At large $\tan\beta$, charged-Higgs loops yield the new operator $(\bar{s}d)_{V+A}\,(\bar{\nu}\nu)_{V-A}$ not suppressed by $m_{d,s}$
- However, its impact on rare K decays is significant only beyond MFV [G.Isidori, P.Paradisi, hep-ph/0601094]

What about $K_L \to \pi^0 /^+ /^-$ within CMFV?

- **In general, models without new operators (like CMFV models) induce smaller effects (<10%) for $K_L \to \pi^0 /^+ /^-$ than for $K \to \pi \nu \bar{\nu}$**
- **Still, NP effects in vector (Q_{7V}) and axial-vector (Q_{7A}) can be disentangled by measuring both electron and muon modes**

Rare Kaon Decays
beyond MFV

MSSM with a general Flavour Structure

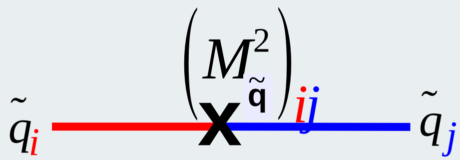
To obtain simple analytic formulae for s →d transitions,
it is useful to work in a basis where d^i_L-$\tilde{d}^j_L$-N_n and d^i_L-$\tilde{u}^j_L$-χ_n
are flavour diagonal and
to expand (non-diagonal) sfermion mass matrices

Mass Insertion Approximation

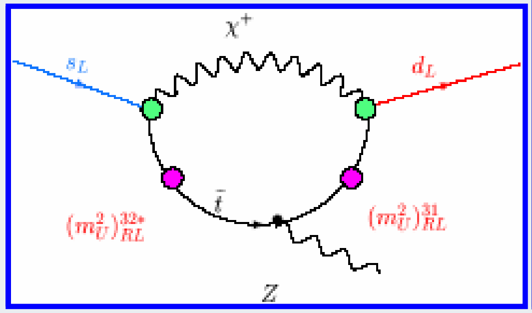
$$M^2_{\tilde{u}} = \begin{pmatrix} (m^2_U)_{LL} & (m^2_U)_{LR} \\ (m^2_U)^{\dagger}_{LR} & (m^2_U)_{RR} \end{pmatrix}$$

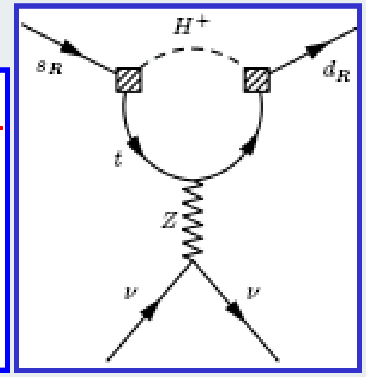
3x3 non-diagonal flavour matrices
expanded in small off-diagonal entries:
e.g., $(\delta^U_{LL})_{ij} \equiv (m^2_U)^{ij}_{LL} / \tilde{m}^2$

Flavour non-diagonality is brought
by squark propagators



Y.Nir, M.P.Worah, hep-ph/9711215
A.J.Buras, A.Romanino, L.Silvestrini, hep-ph/9712398
G.Colangelo, G.Isidori, hep-ph/9808487
A.J.Buras et al., hep-ph/9908371
A.J.Buras et al., hep-ph/0408142
G.Isidori, P.Paradisi, hep-ph/0601094





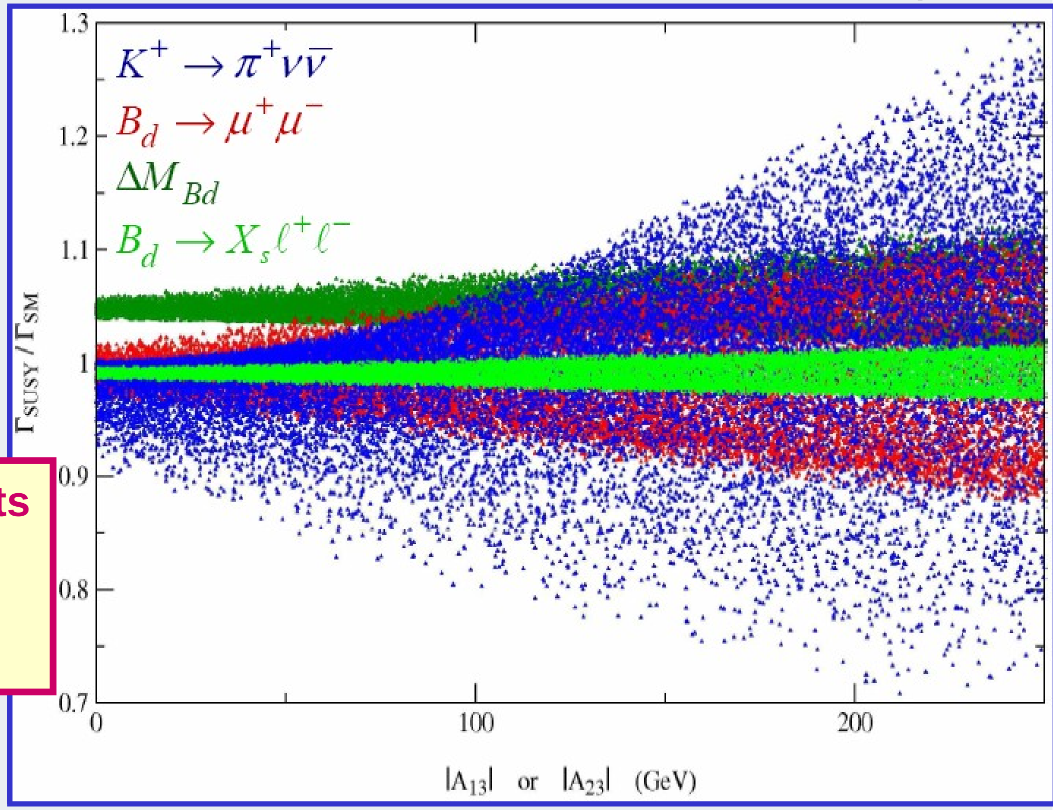
The dominant NP effects in rare kaon decays come from chargino up-squark loops
(non-MFV terms in the LR up sector, double ins. not suppressed by $O(M_W/M_{SUSY})$ nor CKM)
and charged-Higgs top-quark loops
(non-MFV terms in the RR down sector, not suppressed by $m_{d,s}$ and enhanced by $\tan^4\beta$)

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

δ^u_{LR} mass insertions are not strongly constrained by other B- and K-observables

$$\delta^u_{LR} \leftrightarrow \left(M_u^2\right)_{i_L 3_R} \approx m_t A_{i3}$$

tanβ < 30



- $K \to \pi \nu \bar{\nu}$ would be the best measurements to determine/constrain δ^u_{LR} ($\leftrightarrow A_{i3}$)
- Large (O(1)) departures from the SM are allowed in $K \to \pi \nu \bar{\nu}$

G.Isidori, P.Paradisi, hep-ph/0601094

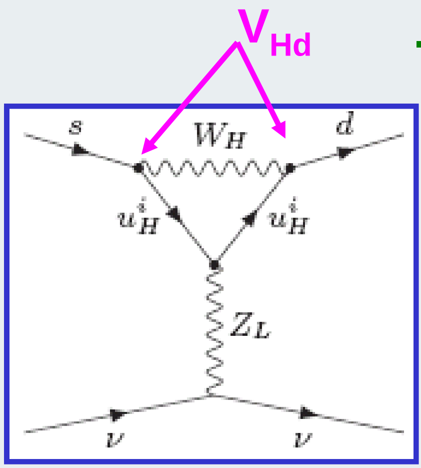
- Precise measurements of $K \to \pi \nu \bar{\nu}$ rates could provide the most stringent bounds on charged Higgs contributions (δ^d_{RR})

What about $K_L \to \pi^0 l^+ l^-$?

- At large tanβ (pseudo)-scalar operators $(\bar{s}d)(\bar{l}l)$ and $(\bar{s}d)(\bar{l}\gamma_5 l)$ are enhanced
- Being helicity suppressed, they affect only the muon mode and can lead to a clear signal

Littlest Higgs Model with T-Parity (LHT)

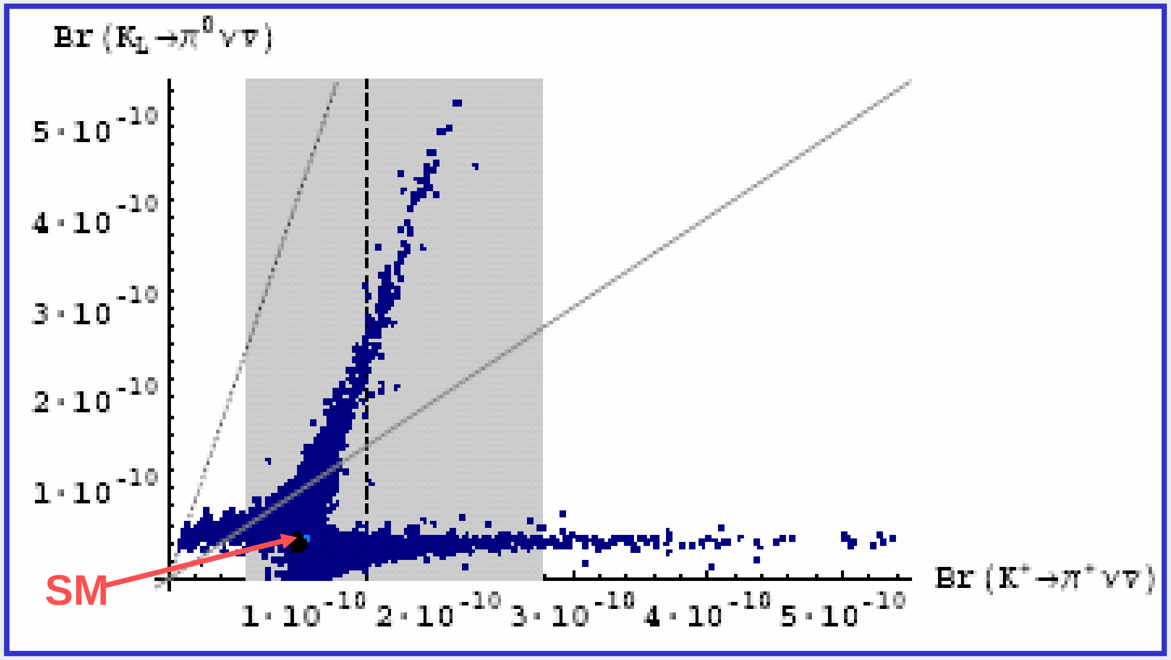
NP scale $f \approx 1$ Tev



- **Mirror fermions introduce new flavour interactions governed by the new mixing matrix V_{Hd}**
- **Large effects are expected, in particular in rare K decays where the CKM λ_t suppression has in general no analogy in V_{Hd}**

Blanke,Buras,Poschenrieder,Recksiegel,C.T.,Uhlig,Weiler, hep-ph/0610298

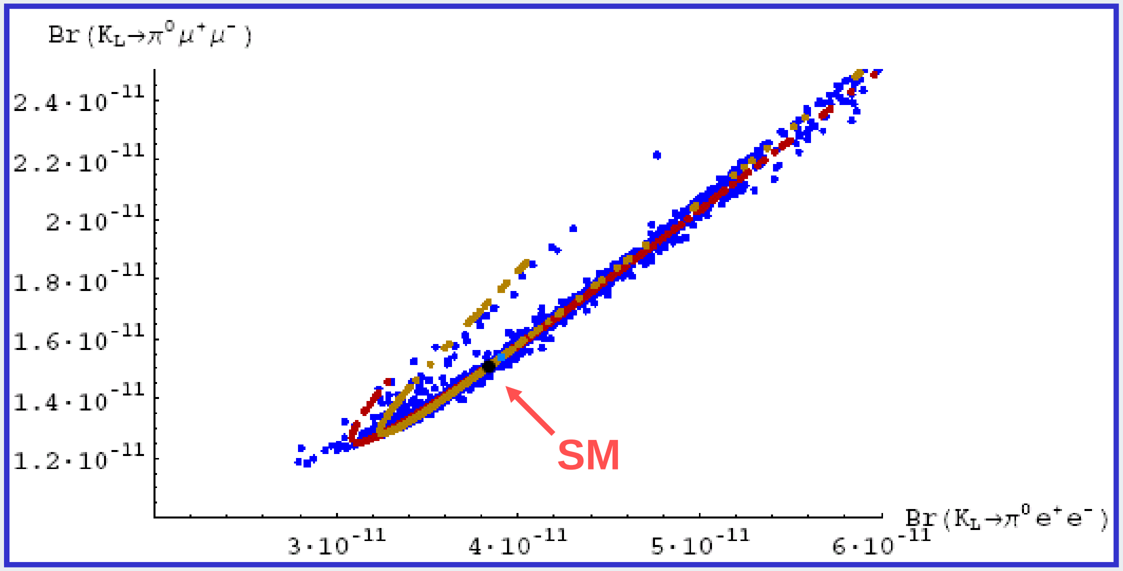
K_L vs. K^+



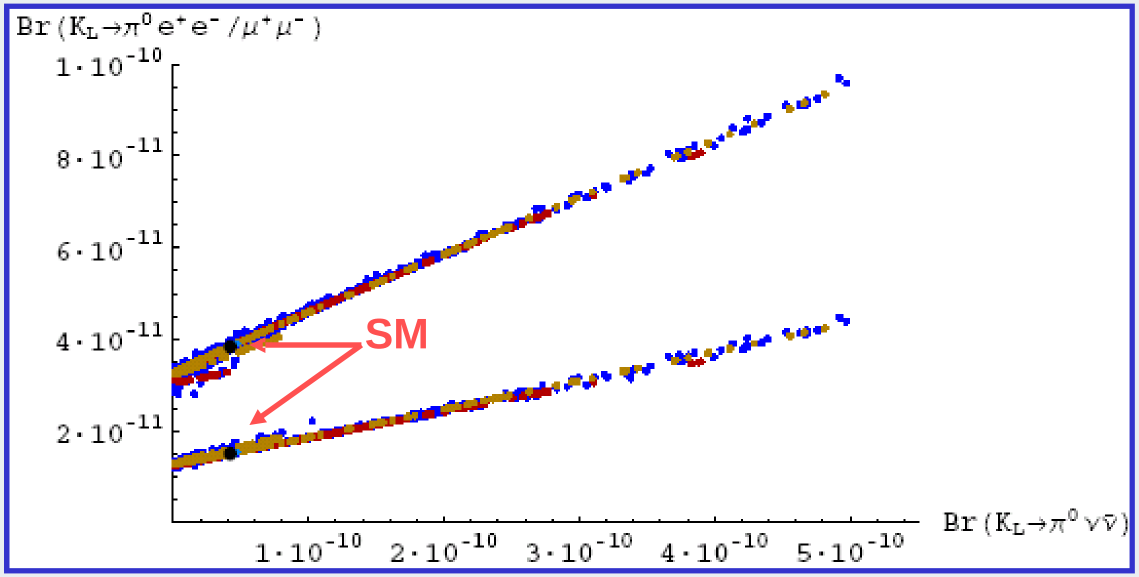
The strongest constraint comes from ε_K, which selects two branches:

- **$Br(K^+)$ can be enhanced by a factor 5 with $Br(K_L) \sim Br(K_L)_{SM}$**
- **$Br(K_L)$ can be enhanced by a factor 10 with $Br(K^+) < 2\text{-}3 \cdot Br(K^+)_{SM}$**

$K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$



Blanke,Buras,Poschenrieder,Recksiegel,C.T.,Uhlig,Weiler, hep-ph/0610298



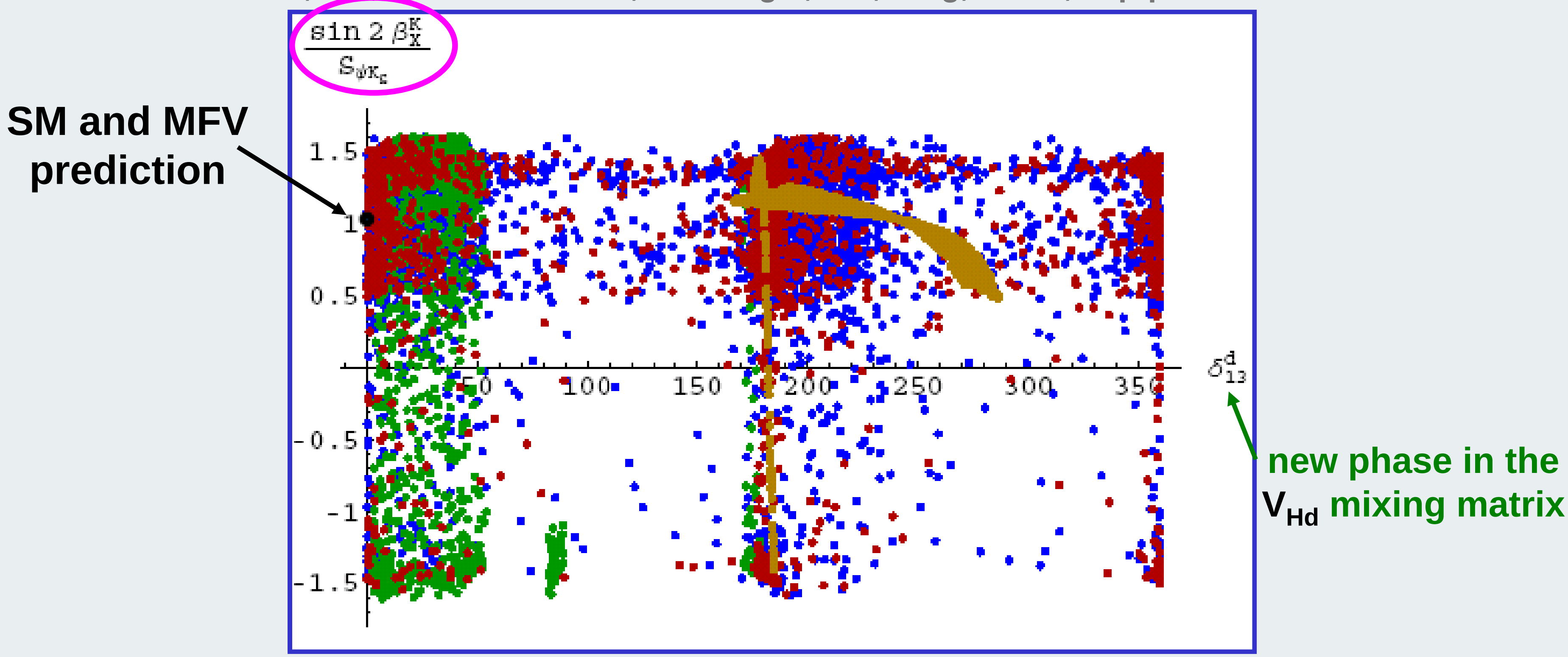
- Strong correlations between muon and electron modes and with $K_L \to \pi^0 \nu \bar{\nu}$

- Enhancements up to a factor 2 w.r.t. the SM

• Different values of β from $S_{\psi K_S}$ and $K_L \to \pi^0 \nu \bar{\nu}$ would be a clear signal of NP beyond MFV

•In LHT, the universality between B and K systems can be strongly violated

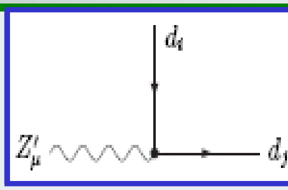
Blanke,Buras,Poschenrieder,Recksiegel,C.T.,Uhlig,Weiler, hep-ph/0610298



Minimal 3-3-1 Model

$M_{Z'} \approx$ 1-5 Tev

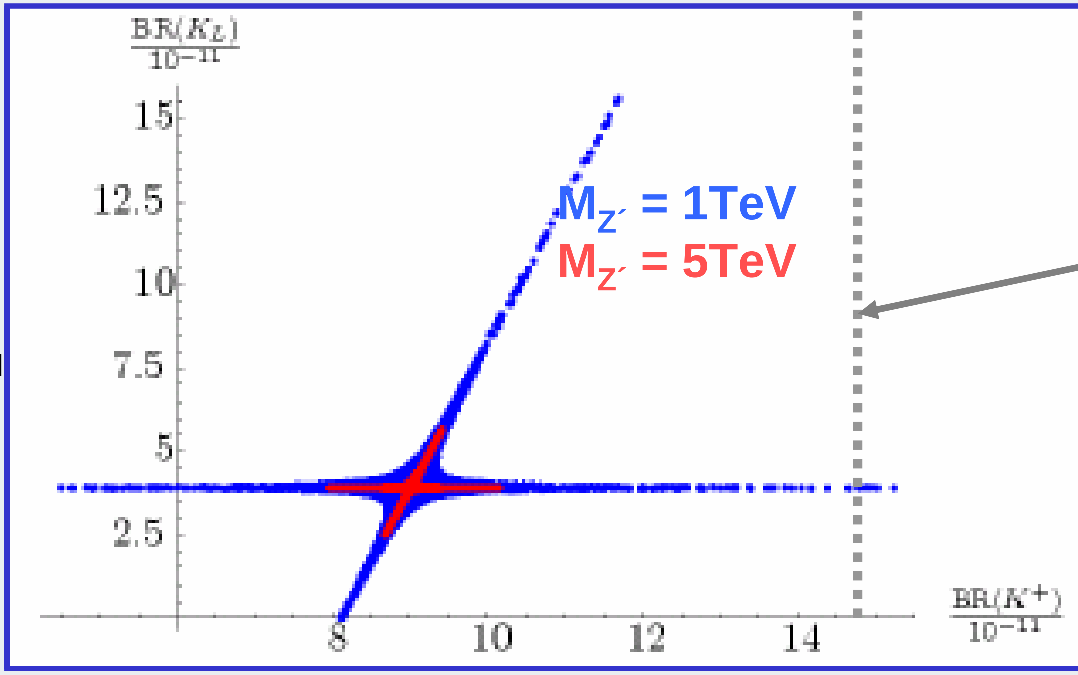
FCNC´s can be transmitted at tree-level by the new heavy gauge boson Z´ and involve a new mixing matrix



$$i\frac{g c_W}{\sqrt{3}\sqrt{1-4s_W^2}} \tilde V_{3d_i} \tilde V^*_{3d_j} \gamma_\mu P_L \qquad i,j = 1,2,3\,, i \neq j$$

C.Promberger, S.Schatt, F.Schwab, hep-ph/0702169

K_L vs. K^+



The present experimental central value for Br(K^+) can be reached only for a rather low $M_{Z'} \approx$1 TeV

- The 2-branch pattern is similar to LHT
- Due to the leptophobic nature of the $\bar{l}\, l\, Z'$ coupling (suppressed by $\sqrt{1-4s_W^2}$), smaller enhancements, w.r.t. LHT, are allowed: by a factor 2 (K^+) and 4 (K_L)

$K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$

- Strong correlations between muon and electron modes and with $K_L \to \pi^0 \nu \bar{\nu}$
- Enhancements up to a factor 3 w.r.t. the SM are allowed

Role of ε´/ε in constraining rare kaon decays

direct CP-violation in the K-system

$$\frac{\varepsilon'}{\varepsilon} = (16.7 \pm 1.6)\cdot 10^{-3}$$

NA48, KTeV

- ε´/ε and rare kaon decays are strongly correlated as both involve the short-distance functions X_K, Y_K, Z_K
- ε´/ε is unfortunately affected by a very large theoretical uncertainty (non-perturbative matrix element of the gluon-penguin operator ↔ R_6)

See talks by Chris Sachrajda and Bob Mawhinney

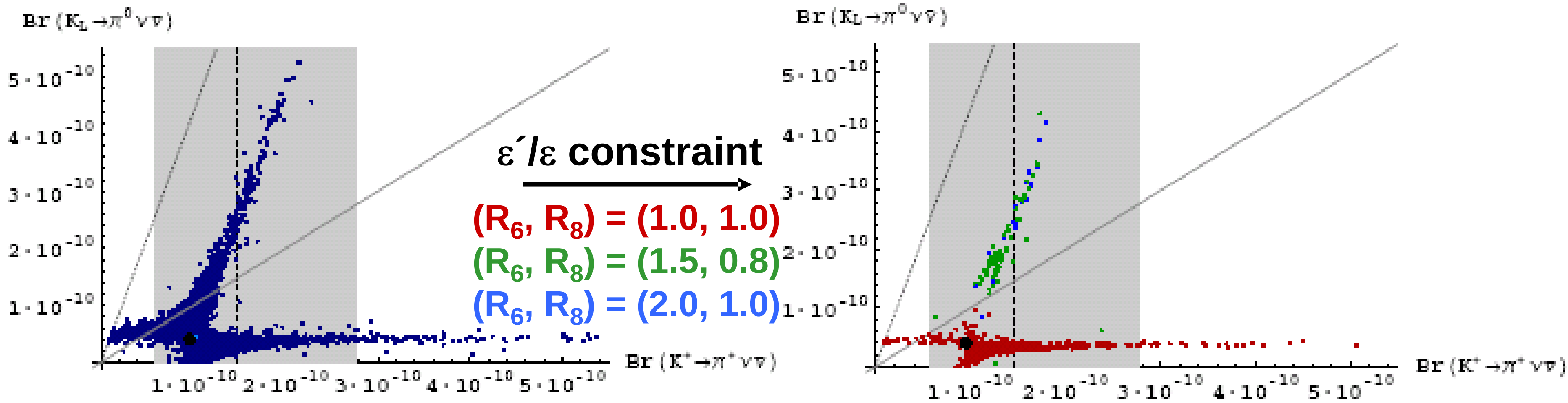
MSSM beyond MFV

A.J.Buras, L.Silvestrini, hep-ph/9811471; A.J.Buras et al., hep-ph/9908371

- Data on ε´/ε may constraint considerably the double LR insertions and the corresponding enhancement of rare kaon decays
- Significant enhancements are still possible

LHT

M.Blanke, A.J.Buras, S.Recksiegel, C.T., S.Uhlig, hep-ph/0704.3329

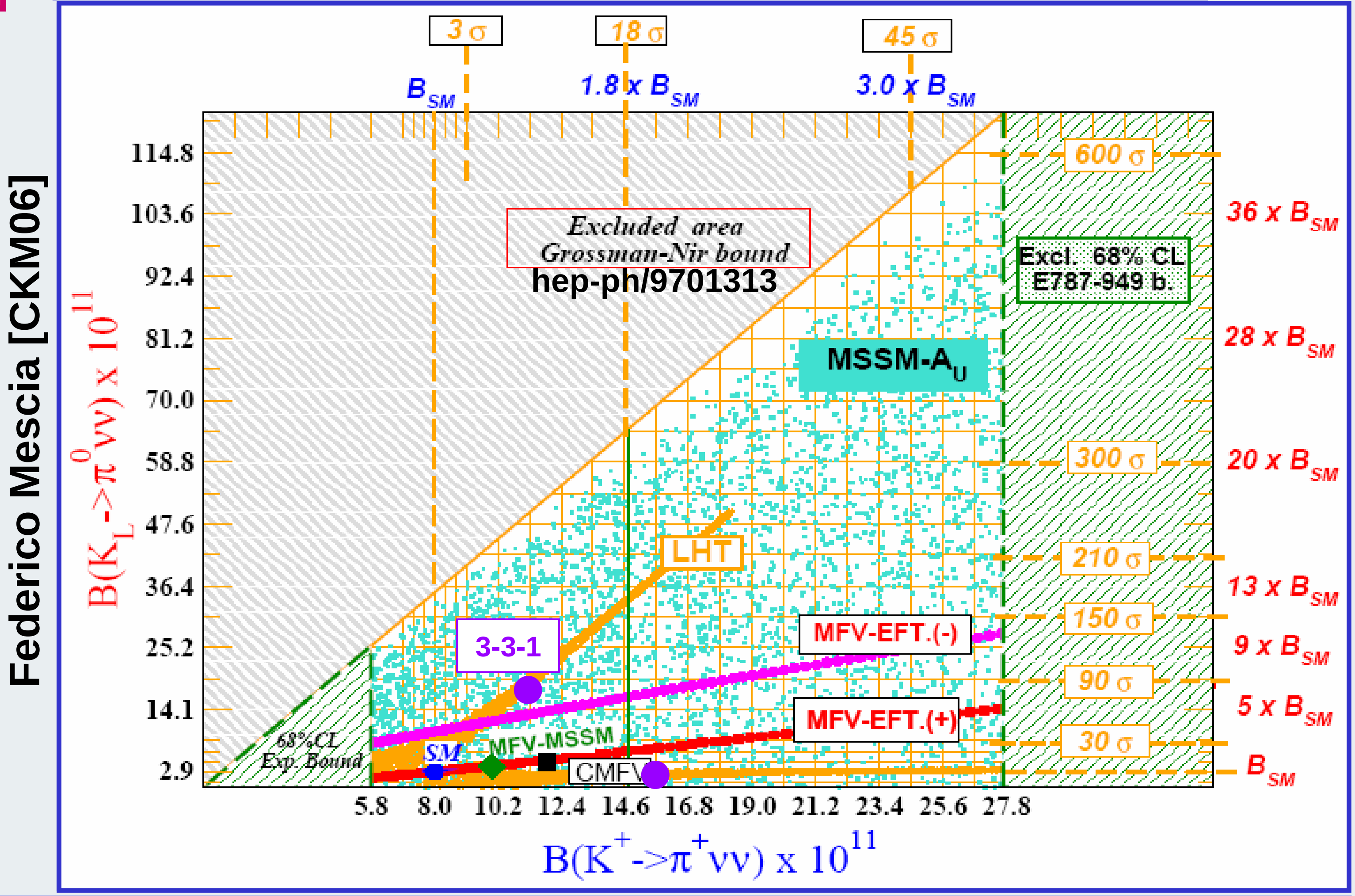


- With an improved theoretical accuracy, ε´/ε could strongly constrain rare K decays
- If the large-N values $(R_6.R_8)=(1.0,1.0)$ are confirmed, O(10)-enhancements of K_L are excluded

Conclusive Messages

$K_L \rightarrow \pi^0 \nu \bar{\nu}$
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Rare K decays are excellent probes of NP, for their theoretical cleanness and strong suppression within the SM



- Large NP signals could be seen in rare K decays (without large effects in B-systems)
- In particular, in MSSM or LHT, K_L can be enhanced by an order of magnitude
- Specific correlations could help in discriminating NP models

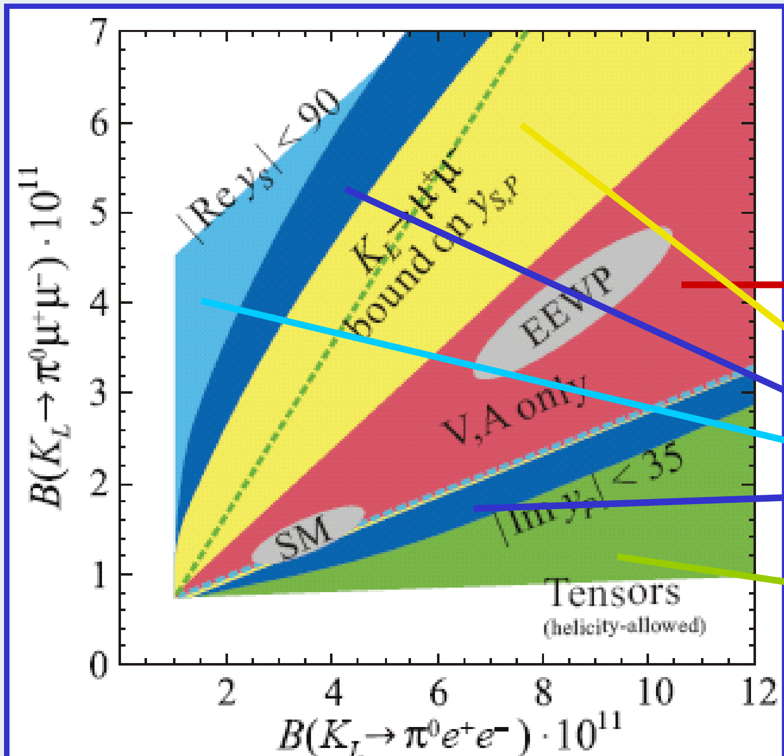
$K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$

- The recent theoretical control over the long-distance components makes $K_L \to \pi^0 l^+ l^-$ decays very clean and highly sensitve to NP
  [G.D´Ambrosio et al., hep-ph/9808289, G.Buchalla et al., hep-ph/0308008, G.Isidori et al., hep-ph/0404127]

- Different μ and **e** masses allow to probe helicity-suppressed effects

- NP enhancements by a factor 2-5 are possible (MSSM, LHT, 3-3-1)

F.Mescia, C.Smith, S.Trine, hep-ph/0606081



Model-independent analysis of the impact of ΔS=1 four-fermion operators $(\bar{s}\,\Gamma\, d)(\bar{l}\,\Gamma\, l)$

NP Models with no new operators
(MSSM at low tanβ [and small μ], LHT, 3-3-1)

NP Models with new (helicity-suppressed) operators (MSSM at large tanβ)

Other NP Models not discussed in this talk
(e.g. with tree-level leptoquark interactions)

See next talk, by Christopher…

Rare K Decays are unique probes of NP

Accurate experimental measurements are looked forward!