# PROJECT X AND THE LHC

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*PROJECT X PHYSICS WORKSHOP, FERMILAB, 16-17 NOVEMBER 2007*

# SCENARIOS FOR PRECISION PHYSICS WITH PROJECT X IN THE “LHC ERA”

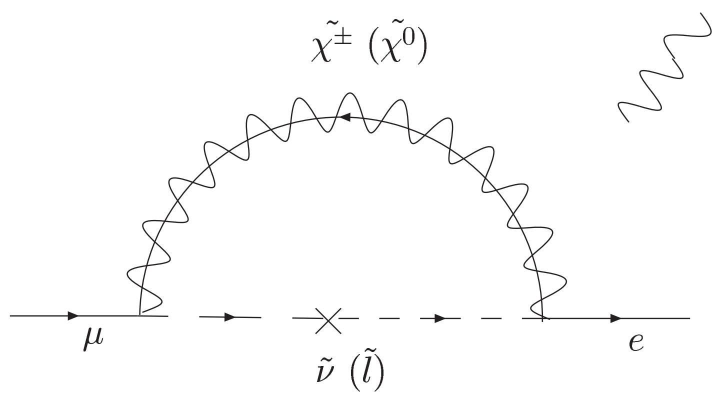
- SCENARIOS WITH SUPERSYMMETRY AND CHARGED LEPTON FLAVOR VIOLATION
- KAON PHYSICS AND MINIMAL FLAVOR VIOLATION
- ADD YOUR OWN EXAMPLES HERE!

# SCENARIOS WITH SUPERSYMMETRY AND CHARGED LEPTON FLAVOR VIOLATION

- A neutrino see-saw implies larger, perhaps order 1, neutrino Yukawa couplings up at some high energy scale

- If there is also supersymmetry, this implies that the slepton soft mass matrix will acquire CLFV entries from the renormalization group running down from the high scale

- These in turn will induce CLFV decays at low energies via loop effects



# SCENARIOS WITH SUPERSYMMETRY AND CHARGED LEPTON FLAVOR VIOLATION

- ➡ If supersymmetry is discovered by CMS and ATLAS, one of the most compelling challenges will be to connect this discovery to neutrino physics via charged lepton flavor violation

- ➡ This will (most probably) be our best chance to explore unification scale physics in the next decade (i.e. in the pre- “ILC Era”)

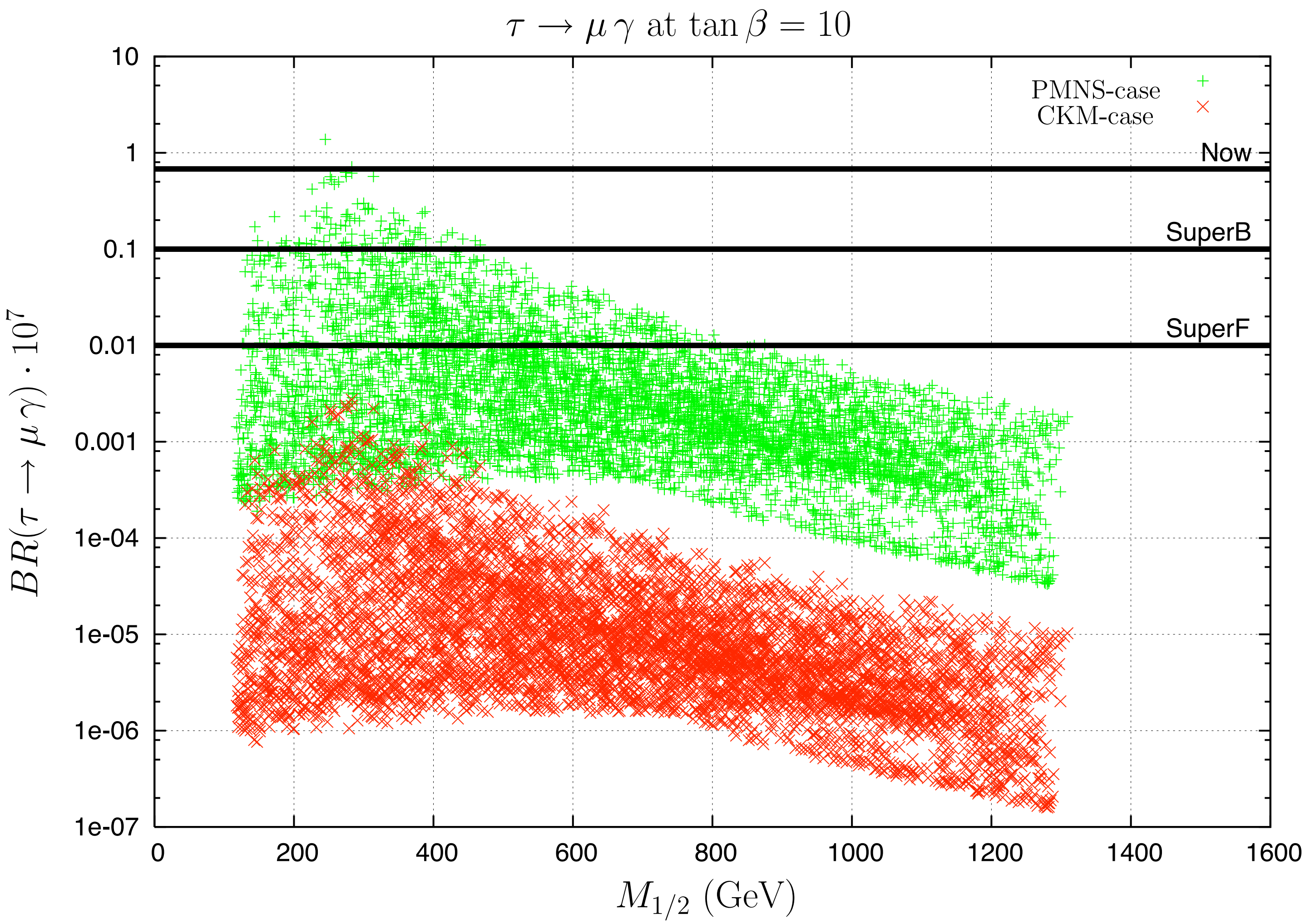
# SCENARIOS WITH SUPERSYMMETRY AND CHARGED LEPTON FLAVOR VIOLATION

- One immediate difficulty is that we don't know the neutrino Yukawas matrices at the high scale
- One can look at two extremes: where the mixing seen by the sleptons is small, CKM-like
- Or the mixing is large, PMNS-like
- Then one can scan over SUSY models, computing the rates for $\mu \to \mathbf{e}\,\gamma$

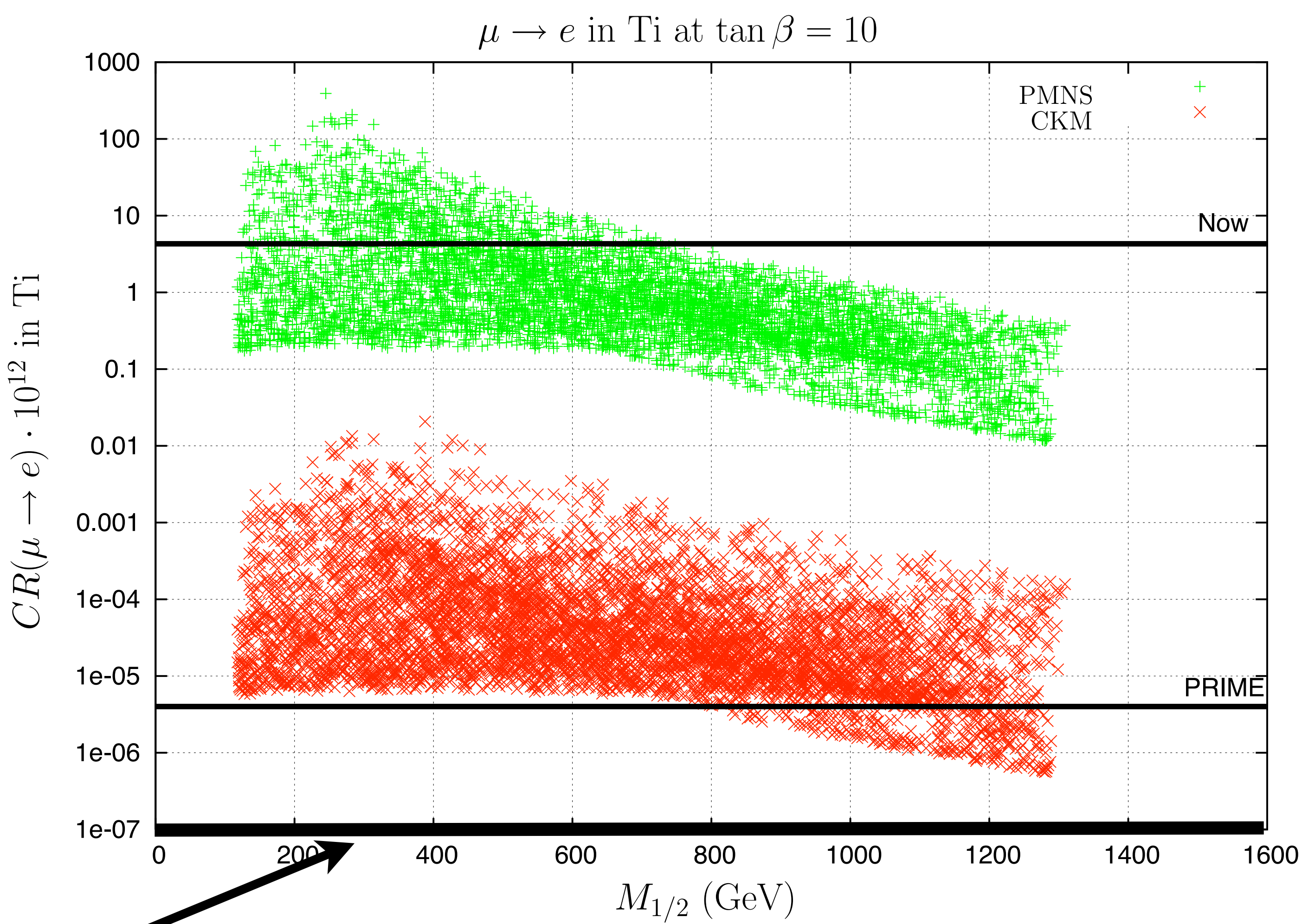
  $\tau \to \mu\,\gamma$

  $\mu \to \mathbf{e}$

# Super B reach is interesting but not comprehensive




L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139




**Project X reach**

L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

# CONNECTING CLFV TO SUSY

- ➡ Suppose that you observe CLFV in the MEG experiment, in  a Project X experiment, and at a Super Flavor factory
- ➡ What can we learn about supersymmetry from these measurements?
- ➡ Can we make a direct connection between CLFV and its SUSY origins?

# CONNECTING CLFV TO SUSY

- $\mu \to e\gamma$ and $\tau \to \mu\gamma$ come from independent parts of the slepton mass matrix

$$(m_L^2)_{21} \text{ for } \mu \to e\gamma \text{ and } (m_L^2)_{32} \text{ for } \tau \to \mu\gamma.$$

- $\mu \to e\gamma$ and $\mu \to e$ are related in the underlying SUSY model

$$T = e\epsilon^{\alpha *}\bar{u}_i(p-q)\left[q^2\gamma_\alpha(A_1^L P_L + A_1^R P_R) + m_j i\sigma_{\alpha\beta}q^\beta(A_2^L P_L + A_2^R P_R)\right]u_j(p)$$

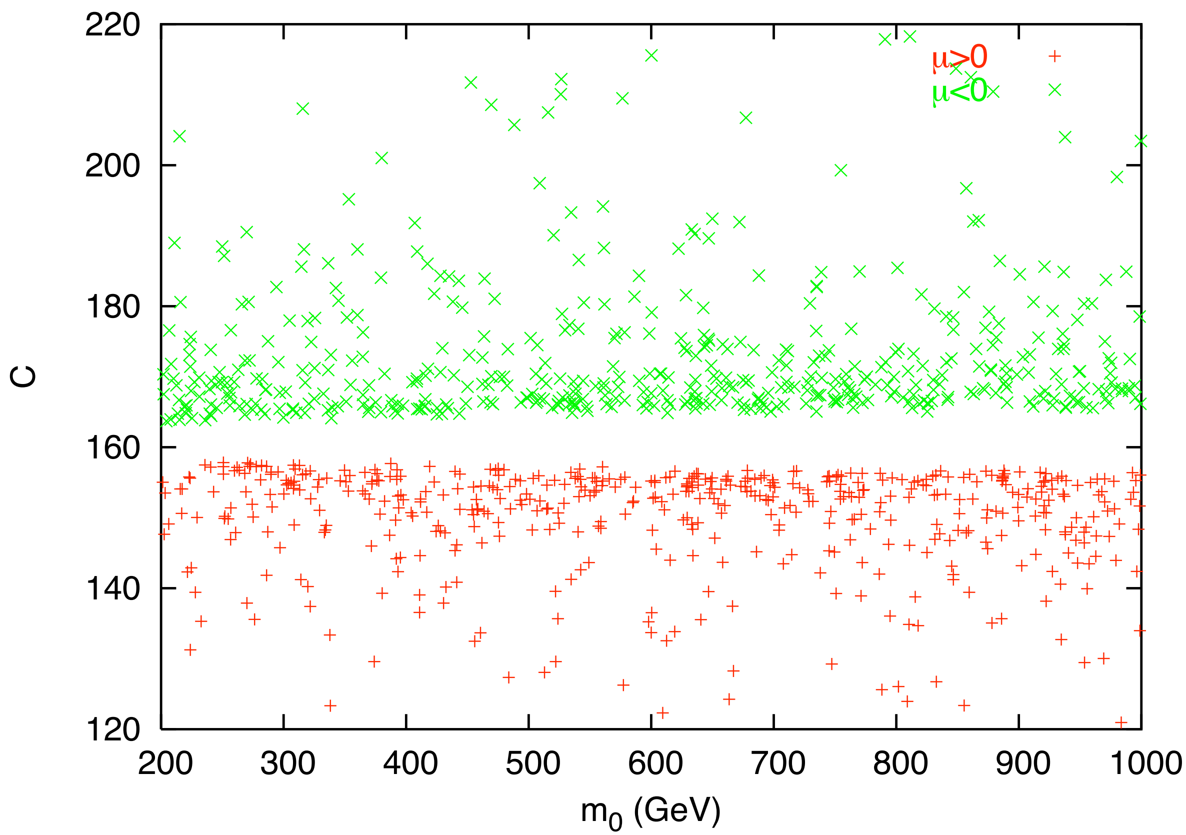
- Thus measuring both probes/constrains the SUSY model

$$BR(\mu \to e\gamma) = \frac{48\pi^3\alpha}{G_F^2}\left(\left|A_2^L\right|^2 + \left|A_2^R\right|^2\right)$$

$$\begin{aligned} R(\mu \to e) &= \frac{\Gamma(\mu \to e)}{\Gamma_{capt}} \\ &\simeq \frac{4\alpha^5 Z_{eff}^4 Z|F(q)|^2 m_\mu^5}{\Gamma_{capt}}\left[|A_1^L - A_2^R|^2 + |A_1^R - A_2^L|^2\right] \end{aligned}$$

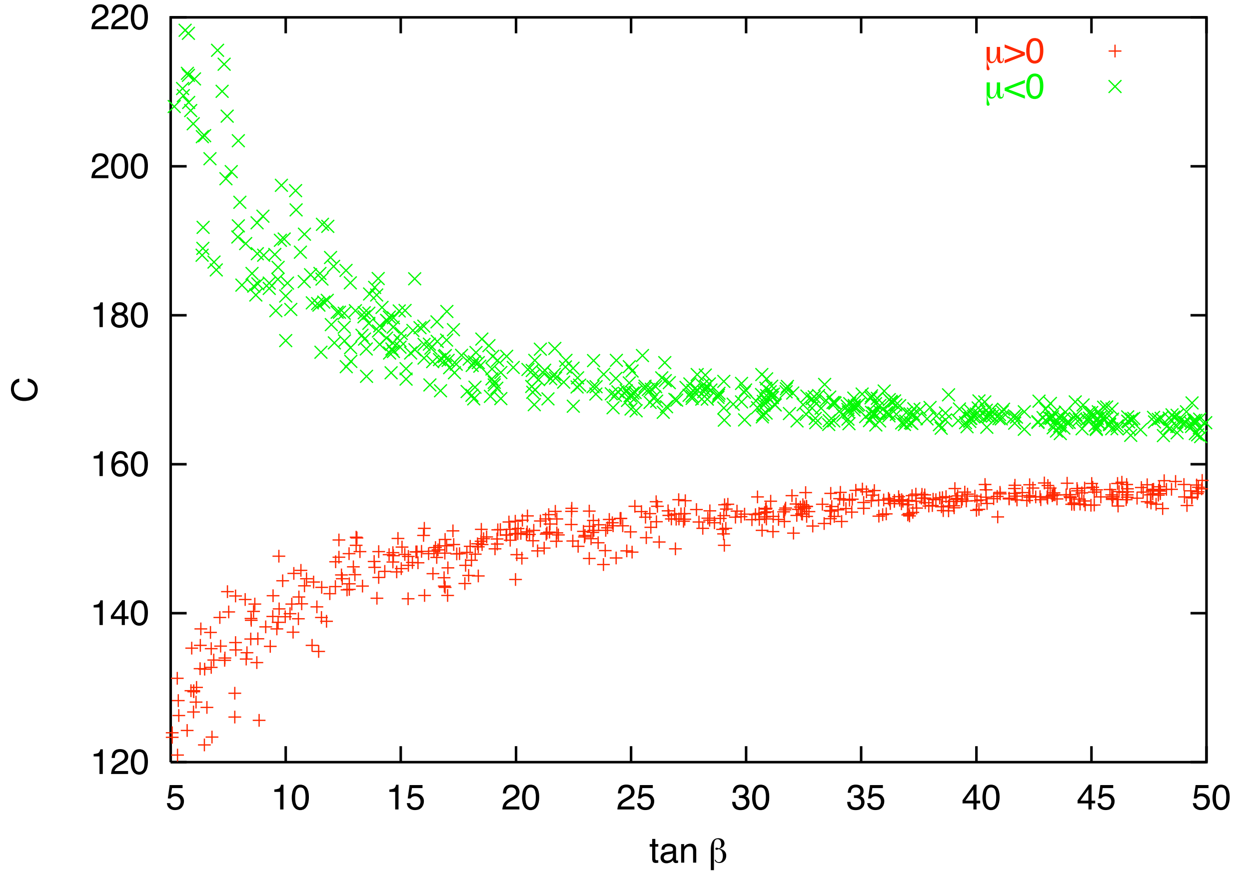
➡ Thus suppose we can measure (with pretty good precision) the ratio

$$\frac{BR(\mu \to e\gamma)}{R(\mu\,Ti \to e\,Ti)} \equiv C$$




C. Yaguna, hep-ph/0502014

**scan over mSUGRA models**
**note C is always between ~ 120 and 220**




C. Yaguna, hep-ph/0502014

**sensitivity to both $\tan\beta$ and the sign of $\mu$**

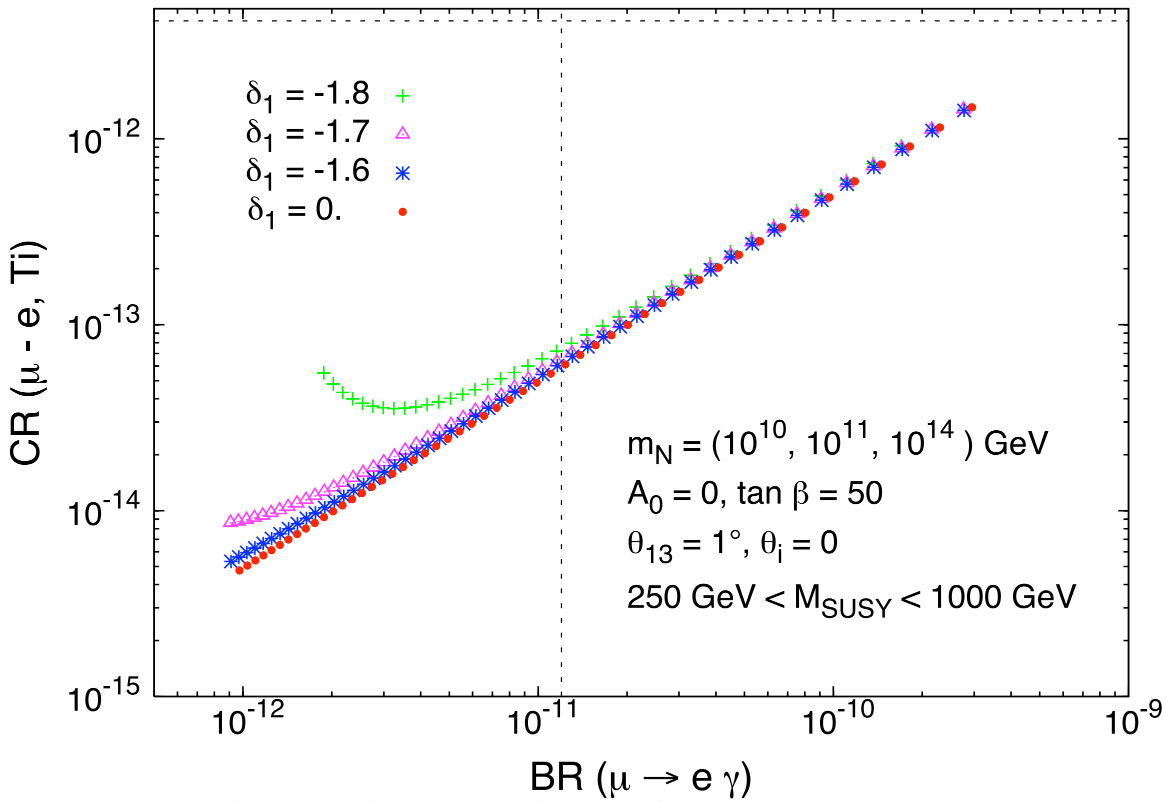
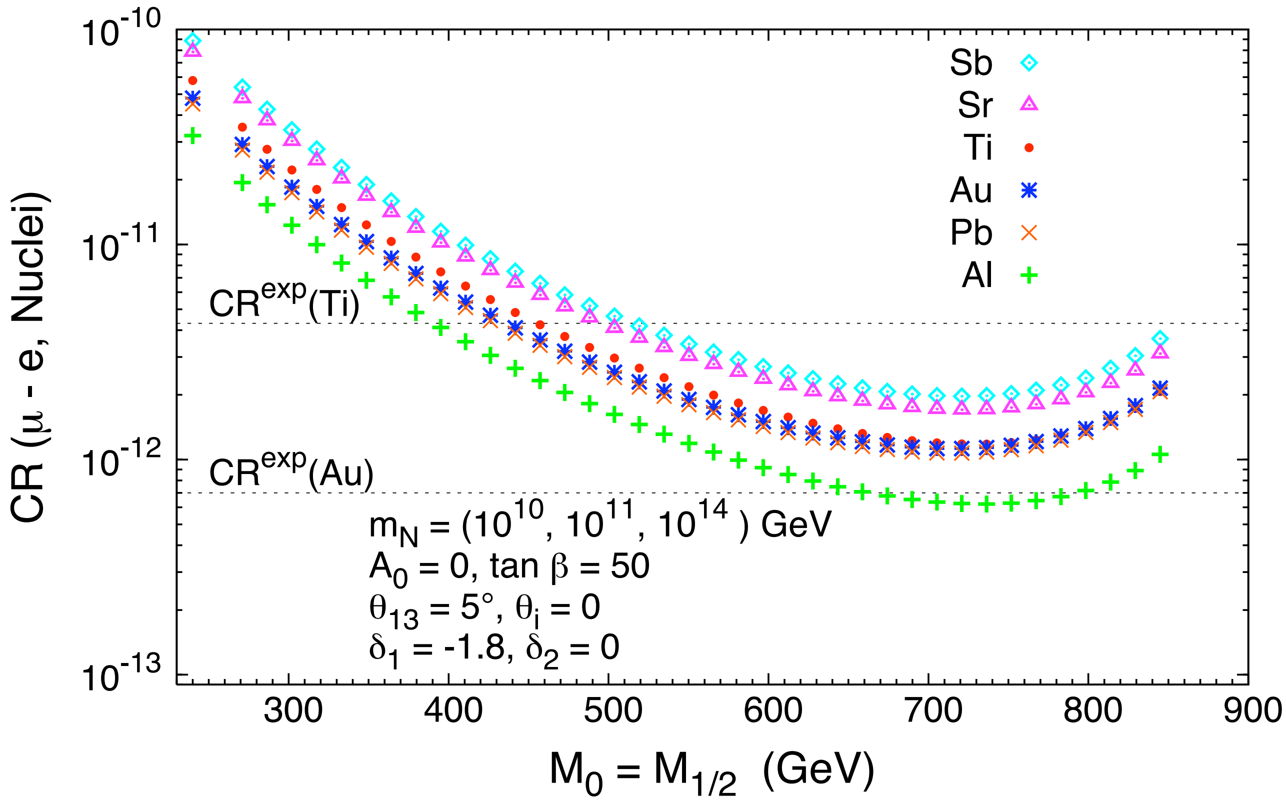



Figure 10: CR($\mu - e$, Ti) versus BR($\mu \to e\gamma$) for 250 GeV $\leq M_{\rm SUSY} \leq$ 1000 GeV, and $\delta_1 = -1.8, -1.7, -1.6, 0$ (crosses, triangles, asterisks, dots, respectively). We set $\delta_2 = 0$, and take $m_{N_i} = (10^{10}, 10^{11}, 10^{14})$ GeV, $A_0 = 0$, $\tan\beta = 50$ and $R = 1$ ($\theta_i = 0$). From left to right and top to bottom, the panels are associated with $\theta_{13} = 10°, 5°, 1°$ and $0.2°$. In each case, the horizontal and vertical dashed (dotted) lines denote the present experimental bounds (future sensitivities) for CR($\mu - e$, Ti) and BR($\mu \to e\gamma$), respectively.

E. Arganda, M-J Herrero, A. Teixeira, arXiv:0707.2955

**if basic SUSY parameters are already known from LHC, can constrain other high scale parameters**




E. Arganda, M-J Herrero, A. Teixeira, arXiv:0707.2955

**using other nuclei gives added handles**

(SLIDE FROM MY PREVIOUS TALK)

# IMPLICATIONS OF AN ALMOST-MFV WORLD

- ➡ Measuring small deviations from MFV will be of great importance, since these can tell us about things like (i) the SUSY breaking scale, (ii) flavor symmetries related to unification, (iii) compositeness, extra dimensions, etc.

- ➡ Such measurements will be directly complementary to the central physics program of the LHC

- ➡ Future quark flavor experiments had better focus on modes with small theoretical uncertainties, and had better achieve experimental precision comparable to those small theory errors

- ➡ More $ for lattice gauge theory!

One of the most popular (and well motivated) scenarios about the flavor structure of physics beyond the SM is the so-called *Minimal Flavor Violation* (MFV) hypothesis [29, 30]. Within this framework (which can be regarded as the most *pessimistic* case for new-physics effects in rare decays), flavor- and CP-violating interactions are induced only by terms proportional to the SM Yukawa couplings. This implies that deviations from the SM in FCNC amplitudes rarely exceed the O(20%) level, or the level of irreducible theoretical errors in most of the presently available observables, although model independently effects of order 50% cannot be excluded at present [31]. Moreover, theoretically clean quantities such as $a_{\rm CP}(B \to J/\Psi K_S)$ and $\Delta M_{B_d}/\Delta M_{B_s}$, which measure only ratios of FCNC amplitudes, turn out to be insensitive to new-physics effects. Within this framework, the need for additional clean and precise information on FCNC transitions is therefore even more important. A precise measurement of $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ would offer a unique opportunity in this respect.

D. Bryman, A. Buras, G. Isidori, L. Littenberg, hep-ph/0505171

# KAON PHYSICS AND
# MINIMAL FLAVOR VIOLATION

- ➡ Look at the general MFV analysis of Buras et al
- ➡ Note that their definition of MFV is very strict, thus some effects called MFV SUSY by others are not MFV for them
- ➡ Thus their analysis is the most conservative scenario

As reviewed in [8], this class of models can be formulated to a very good approximation in terms of eleven parameters: four parameters of the CKM matrix and seven values of the universal master functions $F_i(v)$ that parametrize the short distance contributions to rare decays with $v$ denoting symbolically the parameters of a given MFV model. However, as argued in [8], the new physics contributions to the functions

$$S(v), \qquad C(v), \qquad D'(v), \tag{1.1}$$

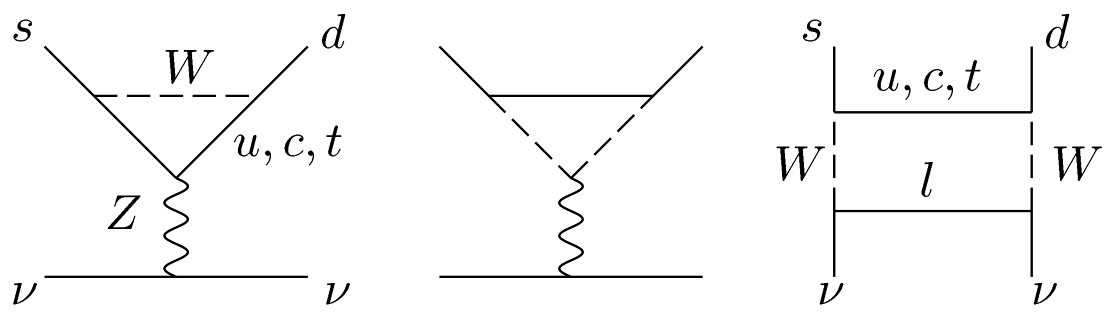
representing respectively $\Delta F = 2$ box diagrams, $Z^0$-penguin diagrams and the magnetic photon penguin diagrams, are the most relevant ones for phenomenology, with the remaining functions producing only minor deviations from the SM in low-energy processes. Several explicit calcu-

Eventually the decays $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_{\rm L} \to \pi^0 \nu\bar{\nu}$, being the theoretically cleanest ones [15, 16], will be used to determine $C(v)$. However, so far only three events of $K^+ \to \pi^+ \nu\bar{\nu}$ have been observed [17, 18, 19] and no event of $K_{\rm L} \to \pi^0 \nu\bar{\nu}$, with the same comment applying to $B_{s,d} \to \mu^+\mu^-$, $B \to X_{s,d}\nu\bar{\nu}$ and $K_L \to \pi^0 l^+ l^-$. On the other hand the branching ratio for $B \to X_s\gamma$ has been known for some time and the branching ratio for $B \to X_s l^+ l^-$ has been recently measured by Belle [20] and BaBar [21] collaborations. The latter, combined with $K^+ \to \pi^+ \nu\bar{\nu}$, provide presently the best estimate of the range for $C(v)$ within MFV models.

$$Br(K_L \to \pi^0 \nu\bar{\nu}) = 3.10 \cdot 10^{-11} (1 + 0.65(\Delta C + \Delta B^{\nu\bar{\nu}}))^2$$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = 8.30 \cdot 10^{-11} \left(1 + 0.20(\Delta C + \Delta B^{\nu\bar{\nu}})^2 + 0.89(\Delta C + \Delta B^{\nu\bar{\nu}})\right)$$

$$Br(B_s \to \mu^+\mu^-) = 3.76 \cdot 10^{-9} \left(1 + \Delta B^{l\bar{l}} + \Delta C\right)^2$$




Leading Feynman diagrams relevant to $K \to \pi\nu\bar{\nu}$ decays

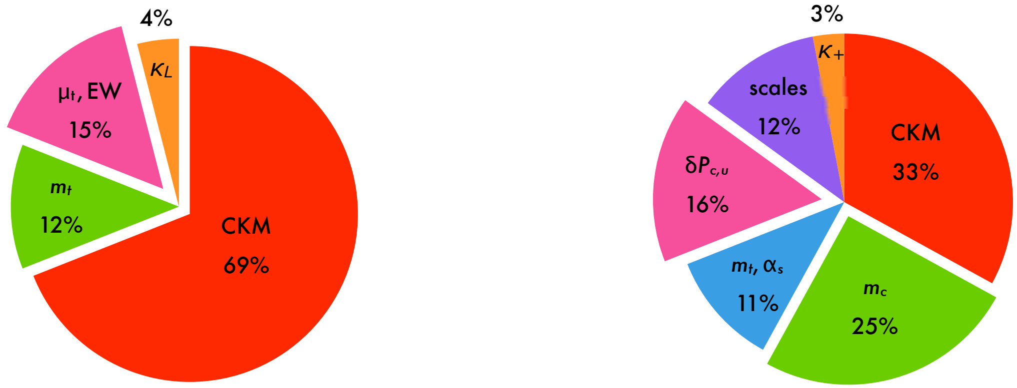
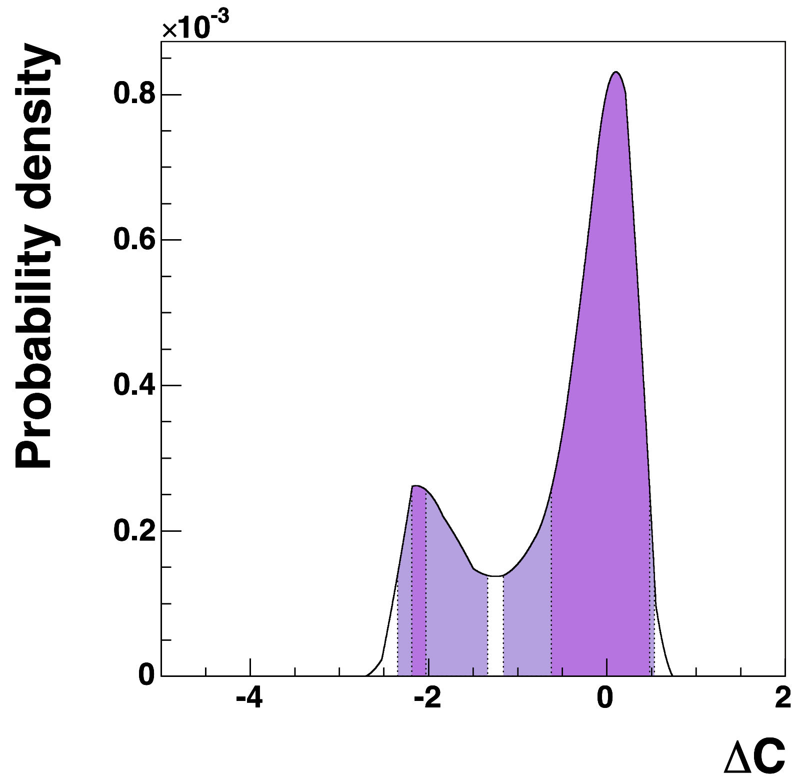



**Figure 3:** Error budget of the SM prediction of $\text{BR}(K_L \to \pi^0 \nu\bar{\nu})$ (left) and $\text{BR}(K^+ \to \pi^+ \nu\bar{\nu}(\gamma))$ (right). See text for details.

U. Haisch, arXiv:0707.3098

**lots of work to be done before we can fully exploit the precision of Project X kaon experiments**




C. Bobeth, M. Bona, A. Buras, T. Ewerth,
M. Pierini, L. Silvestrini, A. Weiler, hep-ph/0505110

**MFV new physics parameter $\Delta C$ not well-constrained**

## MFV SUSY effects on $\mathrm{K} \to \pi\nu\nu$

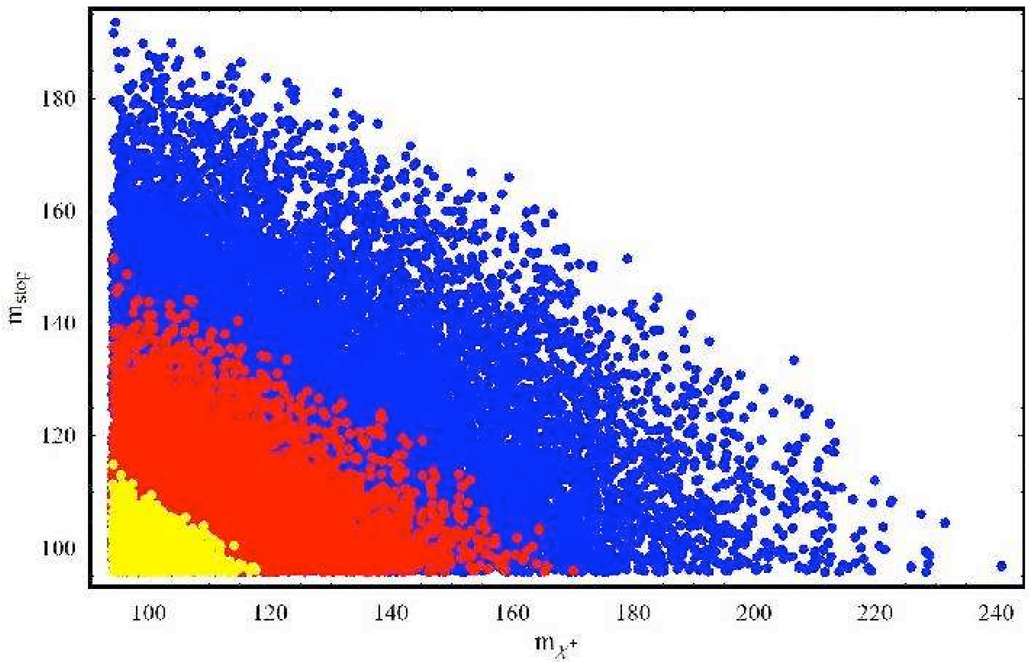
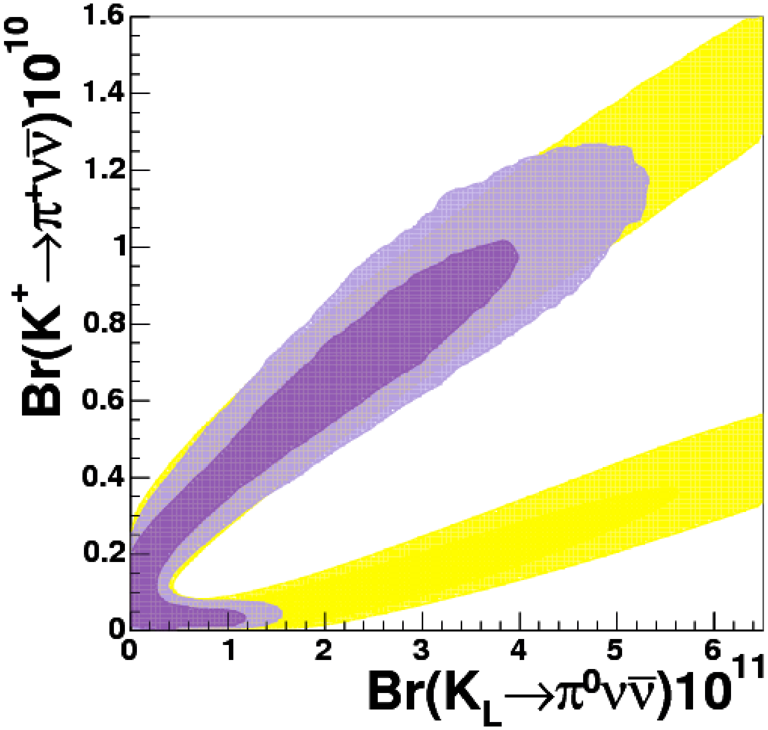


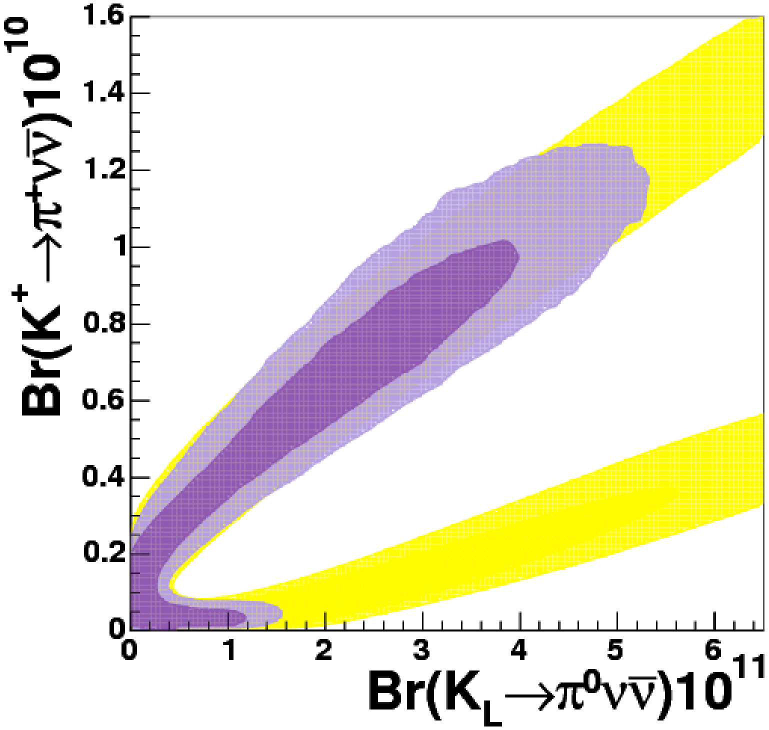

Figure 1: Regions in the $m_{\tilde{t}} - m_{\tilde{\chi}}$ plane (lightest stop and chargino masses) allowing enhancements of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ of more than 11% (yellow/light gray), 8.5% (red/medium gray) and 6% (blue/dark gray) in the MFV scenario, for $\tan\beta = 2$ and $M_{H^+} > 1$ TeV [the corresponding enhancements for $\mathcal{B}(K_{\rm L} \to \pi^0 \nu\bar{\nu})$ are 15%, 12.5% and 10%, respectively, see Eq. (21)].

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




C. Bobeth, M. Bona, A. Buras, T. Ewerth,
M. Pierini, L. Silvestrini, A. Weiler, hep-ph/0505110

One of such correlations predicts that the measurement of $\sin 2\beta$ and of $Br(K^+ \to \pi^+ \nu\bar{\nu})$ implies only two values of $Br(K_L \to \pi^0 \nu\bar{\nu})$ in the full class of MFV models that correspond to two signs of the function $X$ [42]. Figure 8 demonstrates that the solution with $X < 0$, corresponding to the values in the left lower corner, is practically ruled out so that a unique prediction for $Br(K_L \to \pi^0 \nu\bar{\nu})$ can in the future be obtained.




C. Bobeth, M. Bona, A. Buras, T. Ewerth,
M. Pierini, L. Silvestrini, A. Weiler, hep-ph/0505110

(see Figures 2, 5 and 6). In Figure 8 we see explicitly the correlation between the charged and neutral Kaon decay modes. We observe a very strong correlation, a peculiarity of models with MFV [42]. In particular, a large enhancement of $Br(K_{\rm L} \to \pi^0 \nu \bar{\nu})$ characteristic of models with new complex phases is not possible [43]. An observation of $Br(K_{\rm L} \to \pi^0 \nu \bar{\nu})$ larger than $6 \cdot 10^{-11}$ would be a clear signal of new complex phases or new flavour changing contributions that violate the correlations between $B$ and $K$ decays.

# KAON PHYSICS AND
# MINIMAL FLAVOR VIOLATION

➡ If supersymmetry is discovered at the LHC, it will be of great importance to understand to what extent it is minimally flavor violating

➡ Project X kaon experiments could play a decisive role here.