Physics beyond the SM in Kaon decays --Theory--

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Kaon as a basis of the SM

- Kaon played a very important role to find out flavor structure of particle physics

Suppression of Flavor Changing Neutral Current Processes

=> GIM mechanism

=> Charm quark

CP violation in K decays

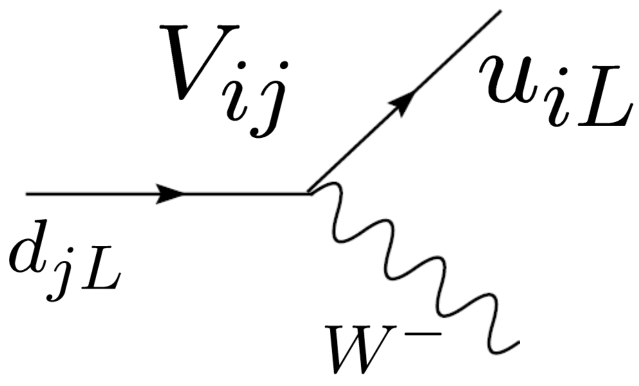
=> Kobayashi-Maskawa theory

=> Three generation structure

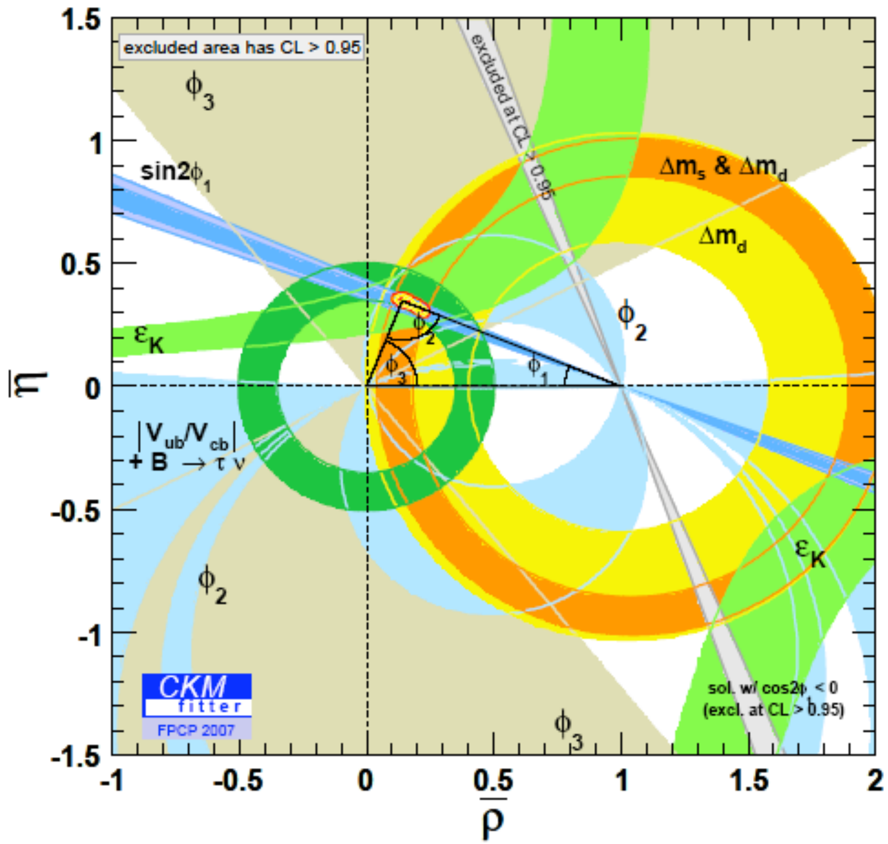
These are basis of the Standard Model

Status of quark flavor physics

- The Cabibbo-Kobayashi-Maskawa matrix works perfectly.



$$\sim \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



K vs. B in the SM

- Flavor signals and CP violation are quite different.

Kaon	B meson
$\epsilon \sim 2.3 \times 10^{-3}$	$S_{CP}(B \to J/\psi K_S) \sim 0.7$
$\epsilon'/\epsilon \sim 1.7 \times 10^{-3}$	$A_{CP}(B \to K^+\pi^-) \sim -0.1$
$B(K_L \to \pi^0 \nu\bar{\nu}) \sim 3 \times 10^{-11}$ $B(K^+ \to \pi^+ \nu\bar{\nu}) \sim 8 \times 10^{-11}$ (predictions from the present CKM parameter fit)	$B(b \to sll) \sim 5 \times 10^{-6}$

This is in accordance with the pattern predicted in the Standard Model.

Flavor in the era of LHC

- The LHC experiment will provide the first direct look at physics at Terascale.
- Terascale is the scale of electroweak symmetry breaking, where we expect a new force/new symmetry.
- Flavor should be closely related to the Higgs sector, so that new physics may have a new flavor structure.
- Considering current experimental constraints, it is likely that new physics effects are less than O(1) of the SM contribution in quark flavor observables.
- Correlations among B,D,K, τ and μ flavor signals are important to understand flavor structure of new physics.

Rare Kaon decays

- Rare dacays

  K_{L}-> $\pi\nu\nu$

  K^{+}-> $\pi\nu\nu$
- “Null” test

  T violation in K->$\pi\mu\nu$
- Lepton universality test

  B(K->$\mu\nu$)/B(K->eν)
- LFV

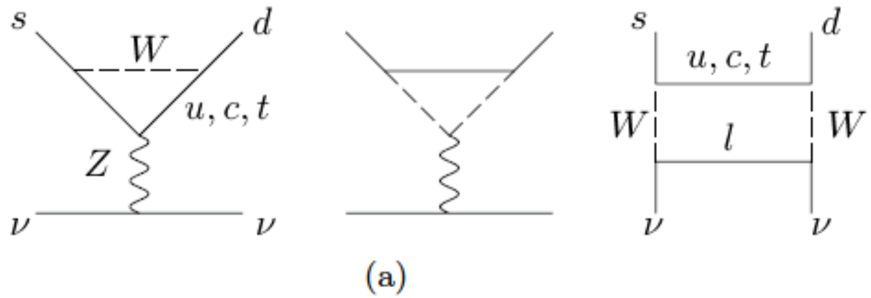
  K->μe, $\pi\mu$e

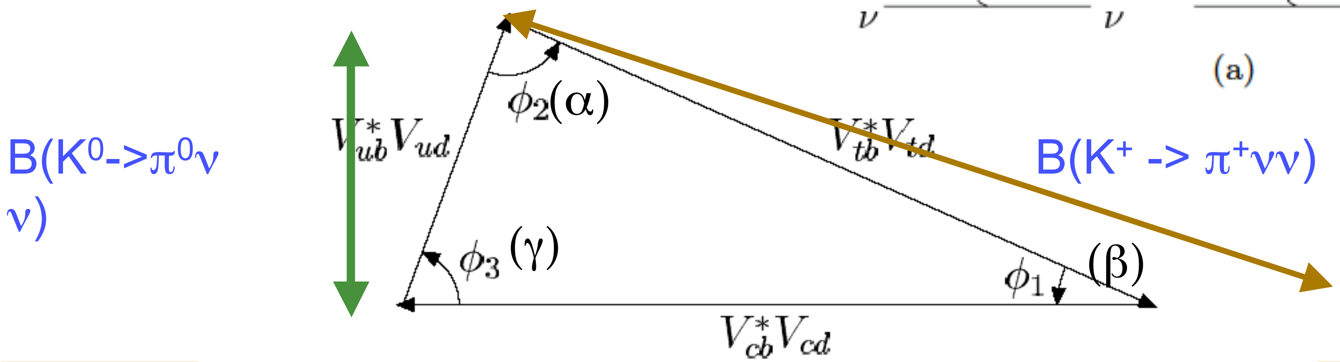
K_L->πνν, K^+->πνν

- Theoretically clean processes

$$H = C(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$$

The relevant form factor is obtained by K->π eν.
Completely short distance dominated.
Top loop dominated (+ charm loop for K+ decay)
A few % theoretical uncertainty.





K-> πνν in the SM

- Both K_L->πνν and K^+->πνν are theoretically under control.

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = (2.29 \pm 0.03) \left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X \right)^2 \times 10^{-10}$$

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (5.26 \pm 0.06) \left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X \right)^2 + \left(\frac{\mathrm{Re}\lambda_t}{\lambda^5} X + \frac{\mathrm{Re}\lambda_c}{\lambda} (P_c + \delta P_c) \right)^2 \right] \times 10^{-11}$$

Top contribution $X = 1.464 \pm 0.041$

Charm contribution $P_c = \begin{cases} 0.369 \pm 0.036_{\mathrm{theory}} \pm 0.033_{m_c} \pm 0.009_{\alpha_s}\,, & \mathrm{NLO}\,, \\ 0.375 \pm 0.009_{\mathrm{theory}} \pm 0.031_{m_c} \pm 0.009_{\alpha_s}\,, & \mathrm{NNLO} \end{cases}$

Sub-leading contribution $\delta P_c = 0.04 \pm 0.02$

$$\lambda_q = V_{qs}^* V_{qd}$$

From Ulich Haisch hep-ph/060517

A few % theoretical errors for both processes.

Grossman-Nir bound (1997)

- Since the two processes are determined by the imaginary part and the absolute value of the same coupling, a simple model-independent bound is obtained.

$$B(K_L \to \pi^0 \nu\bar{\nu}) < 4.4 B(K^+ \to \pi^+ \nu\bar{\nu})$$

Present experimental bounds

$B(K^+ \to \pi^+ \nu\bar{\nu})$	$B(K_L \to \pi^0 \nu\bar{\nu})$
$(1.47^{+1.30}_{-0.89}) \cdot 10^{-10}$	$< 2.1 \cdot 10^{-7}$
BNL E949	KEK E391a

The GN bound can be violated if lepton flavor violation exists.

New physics examples

Supersymmetry

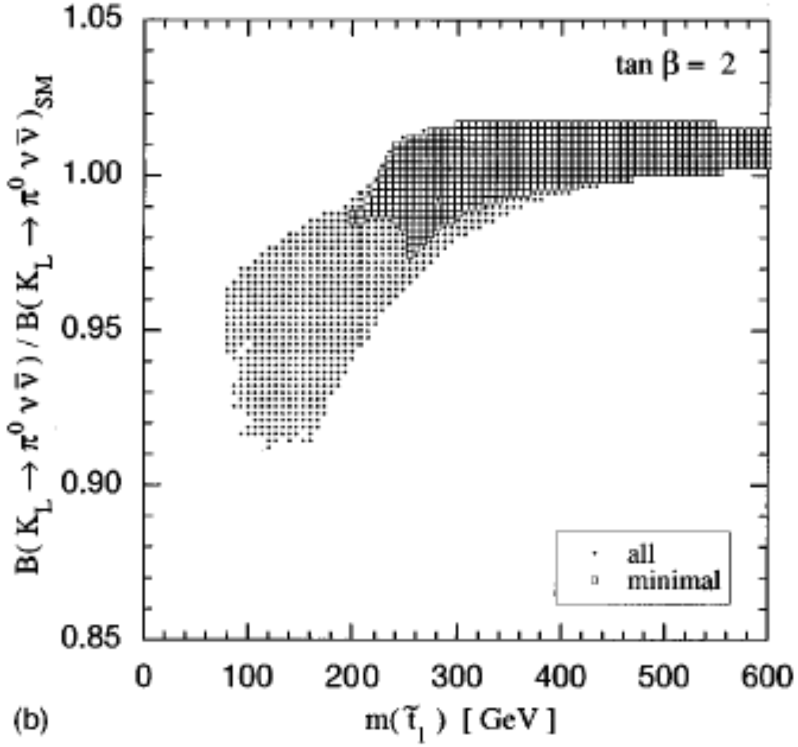
- SUSY models introduce SUSY partners.
- Squark/slepton mass matrixes are new sources of flavor mixing and CP violation.
- Squarks up to ~3 TeV will be searched for at LHC.
- Flavor signals depends on how the off-diagonal terms are generated.

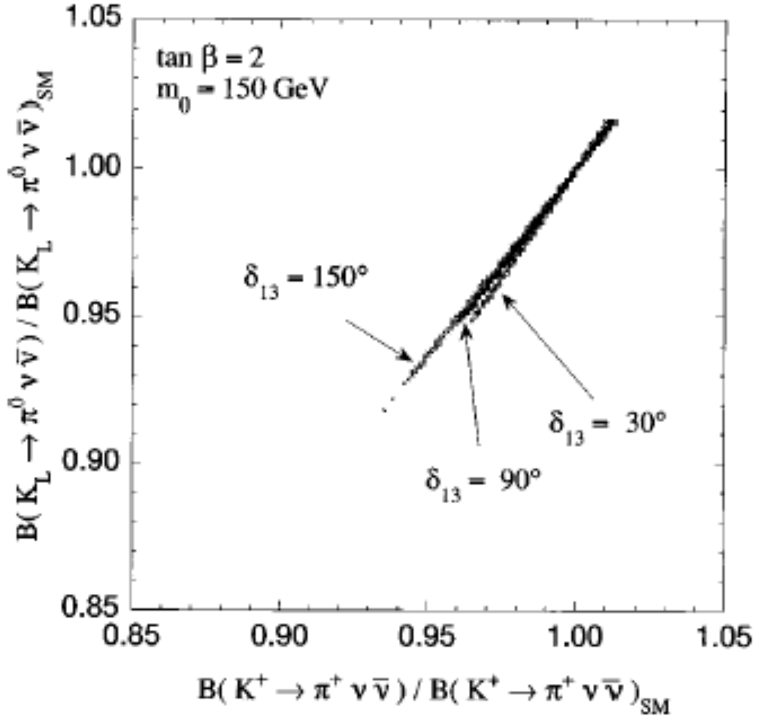
The K-K mixing is still one of the most strong phenomenological constraints for the SUSY model building.

$$(m_{\tilde{q}}^2)_{ij} = \begin{pmatrix} m_{11}^2 & m_{12}^2 & m_{13}^2 \\ m_{21}^2 & m_{22}^2 & m_{23}^2 \\ m_{31}^2 & m_{32}^2 & m_{33}^2 \end{pmatrix}$$

- In SUSY models, SUSY particle and charged Higgs loops contribute to B(K->πνν)
- The size of the SUSY contributions depends on a SUSY breaking scenario.

mSUGRA-type model



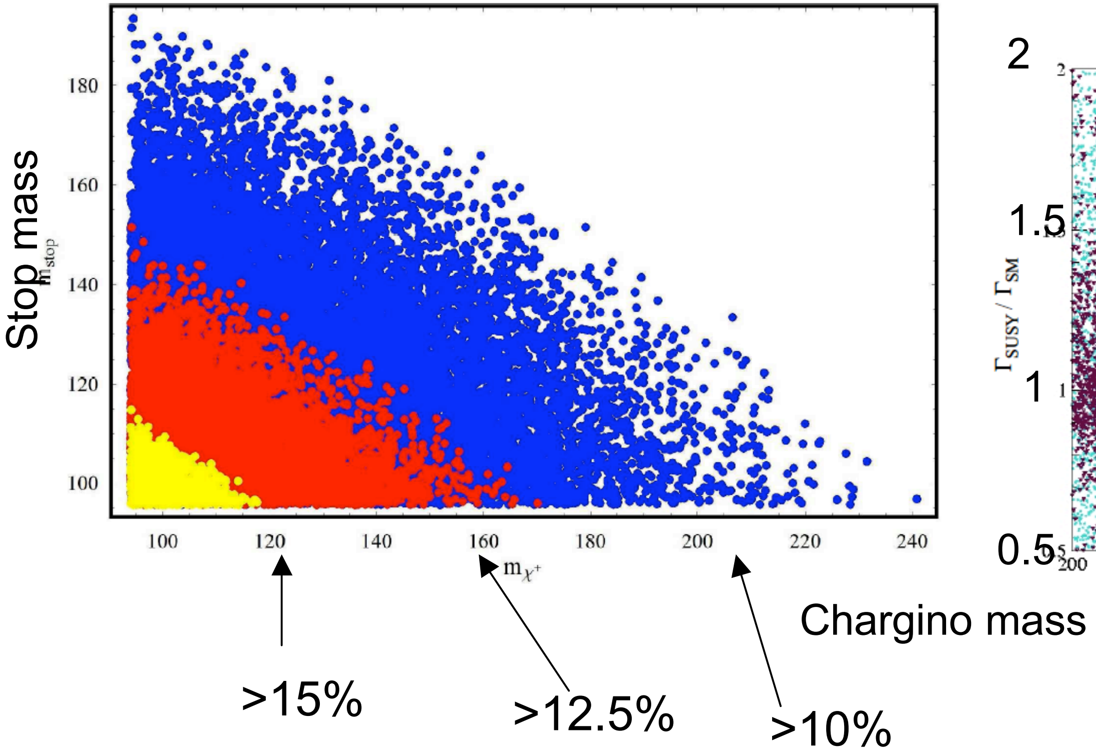


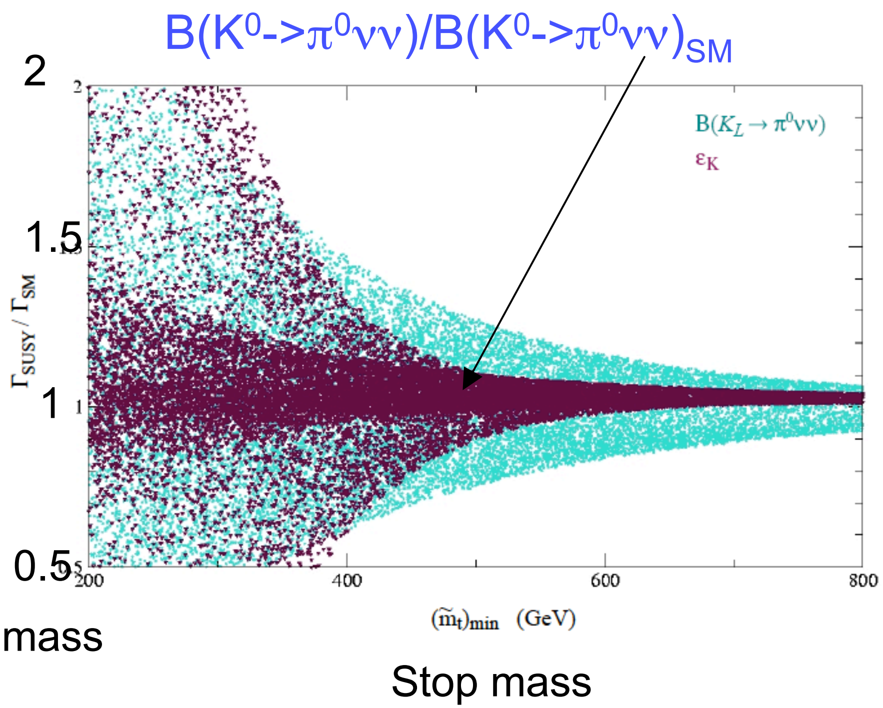
T.Goto.Y.O.Y.Shimizu, 1997

Need to update => a few%?

Minimal Flavor Violation (MFV)scenario in minimal SUSY SM (MSSM)

Generic MSSM





G.Isidori, et al. 2006

Little Higgs model with T parity

- Little Higgs model : a model with a composite Higgs boson.

  N.Arkani-Hamed,A.G.Cohen, E.Katz,and A.E.Nelson,2002

- New particles (heavy gauge bosons, a heavy top partner) are introduced to cancel the quadratic divergence of the Higgs mass at one loop level.

- The mass of these particles are around 1 TeV if the model is extended with “T parity”.

  C.H.Cheng and I.Low,2003

Particle content of the littlest Higgs model with T parity.

~10 TeV,
new strong dynamics

~ 1TeV
W_H, Z_H, ϕ_{ij}, T+,T- u_H,d_H

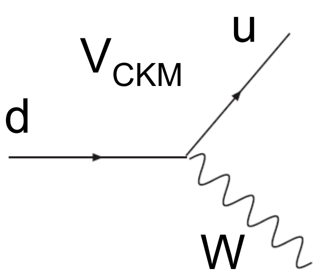
~200 GeV A_H

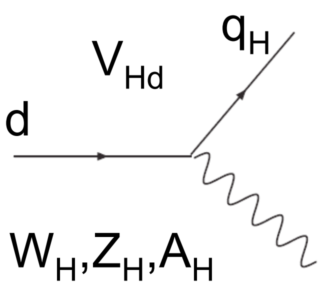
A Higgs boson and SM particles

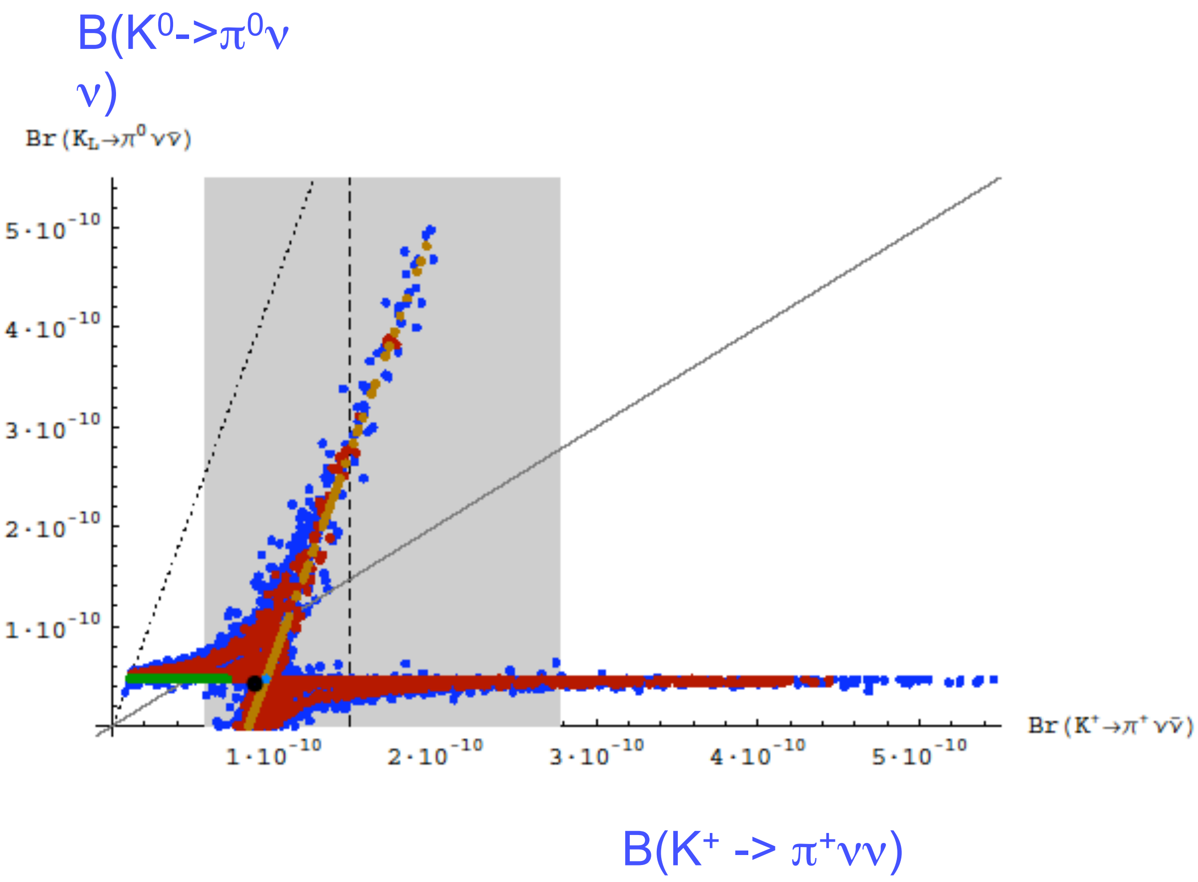
T-odd SU(2) doublet mirror fermions
=> A new flavor mixing matrix

M.Blanke et.al, 2007

$$\begin{pmatrix} u_H^1 \\ d_H^1 \end{pmatrix} \quad \begin{pmatrix} u_H^2 \\ d_H^2 \end{pmatrix} \quad \begin{pmatrix} u_H^3 \\ d_H^3 \end{pmatrix}$$



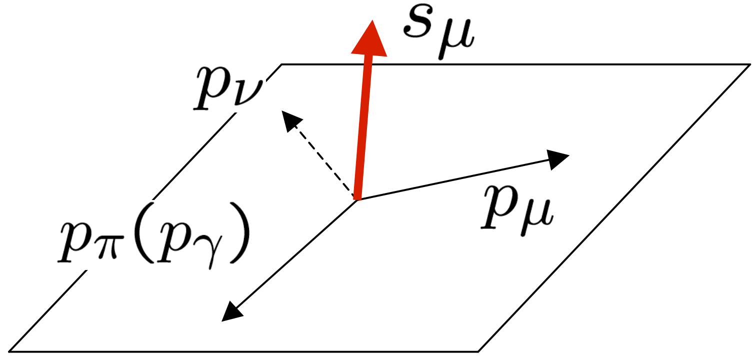




Large effects on $K \to \pi\nu\nu$ are possible.

T violation in K decays

$$K^+ \to \pi^0 \mu^+ \nu_\mu$$
$$K^+ \to \gamma \mu^+ \nu_\mu$$



T-odd triple vector product

$$P_\perp = \frac{s_\mu \cdot (p_{\pi(\gamma)} \times p_\mu)}{|p_{\pi(\gamma)} \times p_\mu|}$$

A window to new physics.

Small contribution from the KM phase

$0(10^{-7})$ for $K^+ \to \pi^0 \mu \nu$

Small and calculable effects of QED final state interaction

$0(10^{-6})$ for $K^+ \to \pi^0 \mu^+ \nu$

$0(10^{-4})$ for $K^+ \to \gamma \mu^+ \nu$

Effective four fermion interaction

$$\mathcal{L} = -\frac{G_F}{\sqrt{2}} \sin\theta_C \overline{s}\gamma_\alpha(1-\gamma_5)u\overline{\nu}\gamma^\alpha(1-\gamma_5)\mu$$

$$+ G_S \overline{s}u\overline{\nu}(1+\gamma_5)\mu + G_P \overline{s}\gamma_5 u\overline{\nu}(1+\gamma_5)\mu$$

$$+ G_V \overline{s}\gamma_\alpha u\overline{\nu}\gamma^\alpha(1-\gamma_5)\mu + G_A \overline{s}\gamma_\alpha\gamma_5 u\overline{\nu}\gamma^\alpha(1-\gamma_5)\mu$$

$$+ \text{H.c.},$$

The transverse polarization needs interference between the SM four fermion term and new contributions and a relative phase between them.

$P_\perp(K^+ \to \pi^0\mu^+\nu_\mu)$: G_S

$P_\perp(K^+ \to \gamma\mu^+\nu_\mu)$: G_P, $G_R = (G_V + G_A)/2$

$G_L = (G_V - G_A)/2$ does not contribute to $P_\perp$ at the first order.

New physics examples

- The multi-Higgs model is a simplest model with a possible transverse muon polarization by the charged Higgs boson exchange.
- If the tree-level neutral Higgs boson FCNC is forbidden by a discrete symmetry, more than three Higgs doublets are necessary to induce the transverse polarization.
- SUSY with a large squark flavor mixing or SUSY without R-parity could induce the transverse polarization of $O(10^{-3})$.
- This process is particularly important if we find a charged Higgs at LHC, but not find SUSY.

Three Higgs doublet model

Yukawa couplings

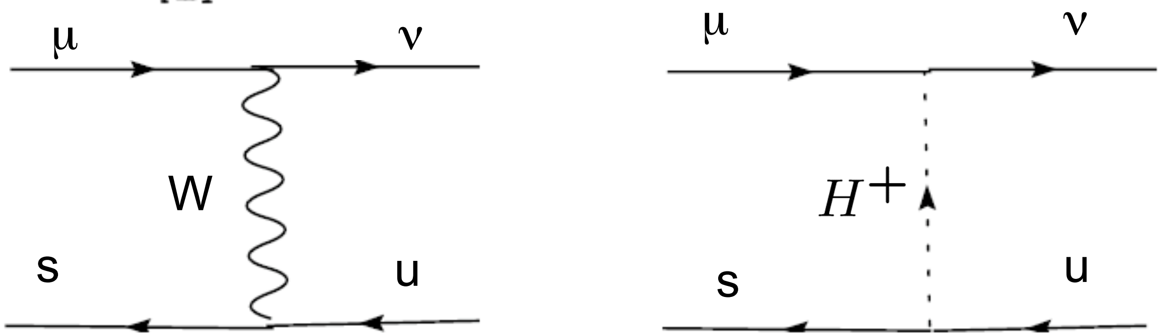
$$\mathcal{L} = \bar{q}_L y_d d_R H_d + \bar{q}_L y_u u_R \tilde{H}_u + \bar{l} y_e e_R H_l + \text{h.c.}$$

Charged Higgs boson mixing

$$\begin{pmatrix} \frac{H_d^+}{v_1} \\ \frac{H_u^+}{v_2} \\ \frac{H_e^+}{v_3} \end{pmatrix} = \frac{1}{v} \begin{pmatrix} 1 & \alpha_1 & \alpha_2 \\ 1 & -\beta_1 & -\beta_2 \\ 1 & \gamma_1 & \gamma_2 \end{pmatrix} \begin{pmatrix} G^+ \\ H_1^+ \\ H_2^+ \end{pmatrix},$$

Charged Higgs boson coupling

$$\mathcal{L} = (2\sqrt{2}G_F)^{1/2} \sum_{i=1}^{2} \{\alpha_i \bar{u}_L K M_D d_R H_i^+ + \beta_i \bar{u}_R M_U K d_L H_i^+ + \gamma_i \bar{\nu}_L M_E e_R H_i^+\} + \text{h.c.}$$



Keeping only the lighter charged Higgs contribution,

$$< P_\perp(K^+ \to \pi^0 \mu^+ \nu_\mu) >\sim -0.3 m_K^2 \frac{Im\gamma_1 \alpha^*}{m_{H_1}^2}$$

$$< P_\perp(K^+ \to \gamma \mu^+ \nu_\mu) >\sim -0.1 m_K^2 \frac{Im\gamma_1 \alpha^*}{m_{H_1}^2}$$

Present constraint from B(B->τν) at B factory experiments

$$|P_{\perp:\pi^0}| < 0.005$$

In future, LHC direct charged Higgs search or B-> τν and B-> Dτν measurements at Super B can put a constraint like

$$|P_{\perp:\pi^0}| < 3 \times 10^{-4}$$

Present KEK-E246 limit.

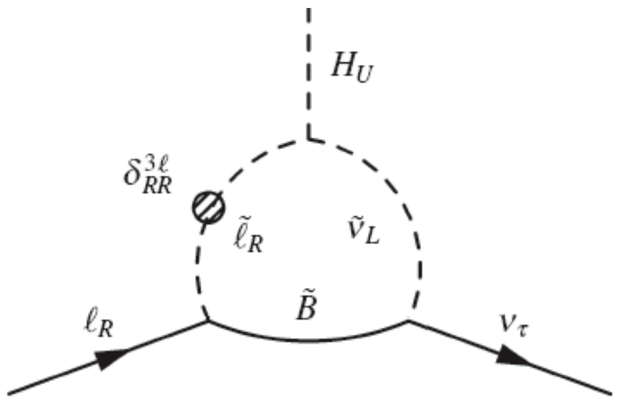
$$|P_{\perp:\pi^0}| < 0.0050 \text{ (90\%CL) E246 exp}$$

B(K->eν)/B(K->μν)

- This ratio can be different from the SM if there is a slepton flavor mixing in the SUSY model. This is due to flavor changing charged Higgs coupling .

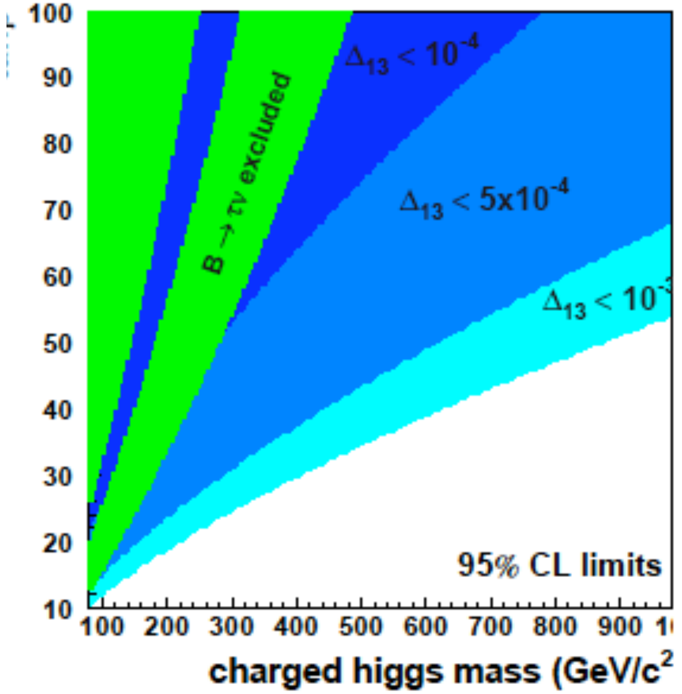
Present combined result

$$R_K^{e/\mu} = (2.457 \pm 0.032) \times 10^{-5} .$$



A.Masiero, P.Paradisi and R.Petronzio, 2006

From G.Isidori, KAON 2007 summary,



LFV K decays

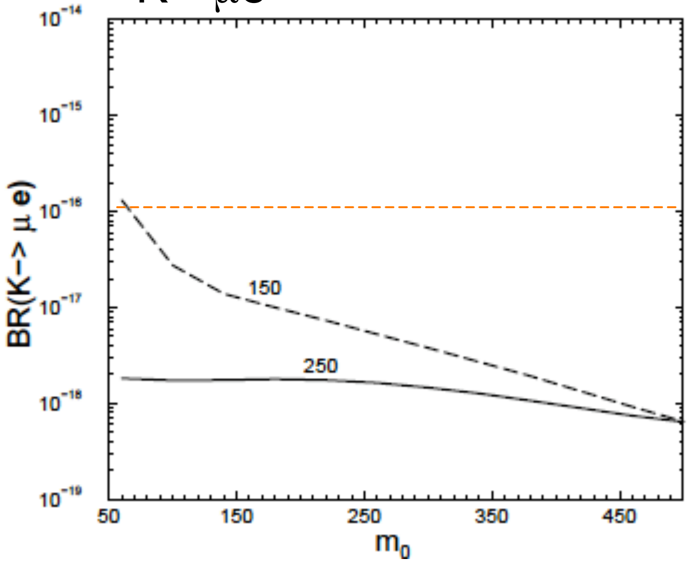
Current bounds

$BR(K_L^0 \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$	LFV
$BR(K^+ \to \pi^+ \mu^+ e^-) < 2.8 \times 10^{-11}$	LFV
$BR(K^+ \to \pi^+ \mu^- e^+) < 5.2 \times 10^{-10}$	LFV
$BR(K_L^0 \to \pi^0 \mu^\pm e^\mp) < 3.1 \times 10^{-9}$	LFV
$BR(K^+ \to \pi^- \mu^+ e^+) < 5.0 \times 10^{-10}$	LNV
$BR(K^+ \to \pi^- e^+ e^+) < 6.4 \times 10^{-10}$	LNV
$BR(K^+ \to \pi^- \mu^+ \mu^+) < 3.0 \times 10^{-9}$	LNV

From A.Belyaev, et al, hep-ph/0008276

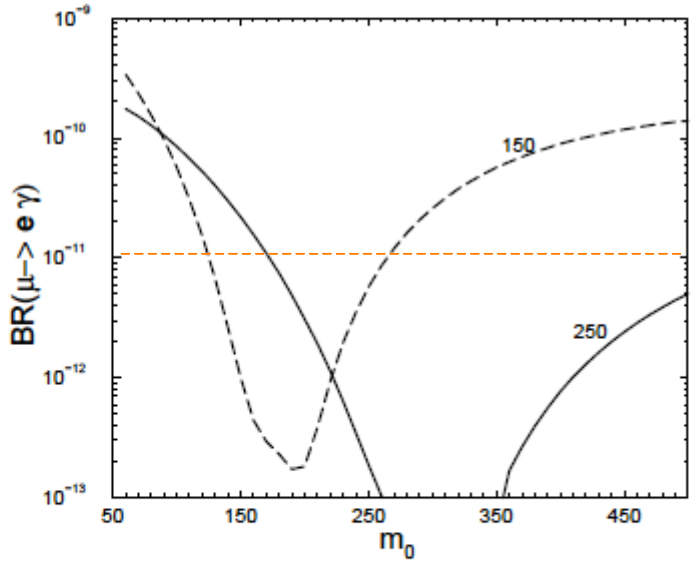
LFV K decays in the MSSM with a slepton mixing,

K->μe

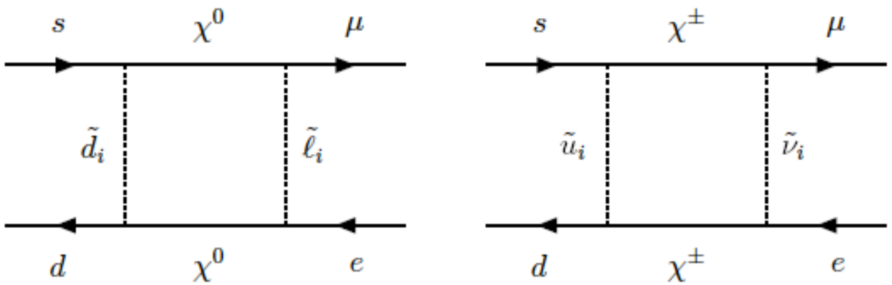


10^{-16}

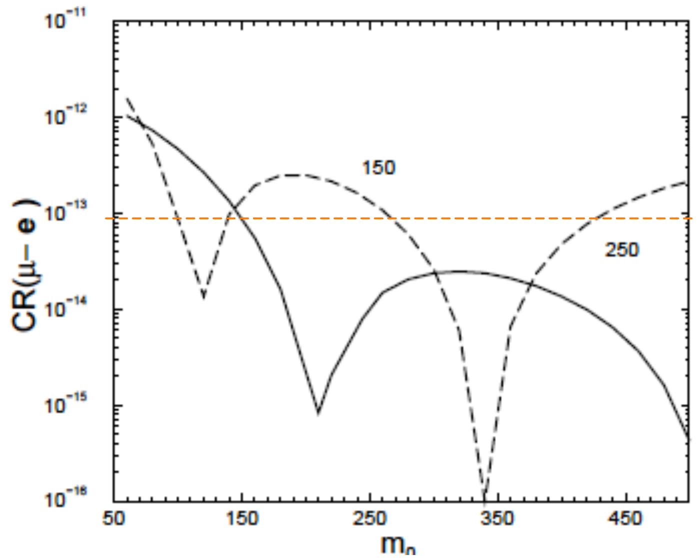
μ->eγ



10^{-11}



μ–e conversion



10^{-13}

Muon LFV are more promising.

If R-parity is broken, LFV K decays can be the limiting processes.

A.Belyaev, et al, hep-ph/0008276

Conclusions

- $K_L \to \pi\nu\nu$ and $K^+ \to \pi\nu\nu$ processes are unique among quark flavor signals in terms of theoretical cleanness. Goals of the branching ratio measurements should be less than 10 % of the SM prediction in order to match expected improvements in B physics in the coming years.
- T violation in $K^+ \to \pi^0\mu\nu$ and $K^+ \to \gamma\mu\nu$ is important processes to look for CP violation in the Higgs sector, especially when it turns out to be not of the SM type nor of the MSSM type.