Rare Kaon Decays in Supersymmetric Models

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Fermilab

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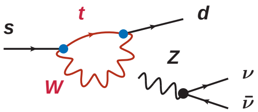
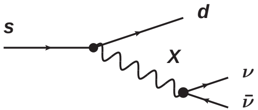
Sensitivity to Very Short Distances



$$\sim \frac{g^4}{16\pi^2} \frac{1}{M_W^2} V_{ts}^* V_{td}$$

SM amplitude is
loop suppressed and
CKM suppressed



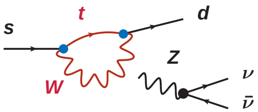
$$\sim \frac{1}{M_X^2}$$

Generic NP
not necessarily suppressed

- rare K decays probe very high scales

$$M_X \sim \frac{M_W}{g^2} \sqrt{\frac{16\pi^2}{|V_{ts}^* V_{td}|}} \sim 130 \text{ TeV}$$

Sensitivity to Very Short Distances



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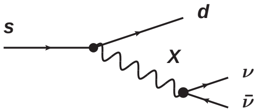

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- rare K decays probe very high scales

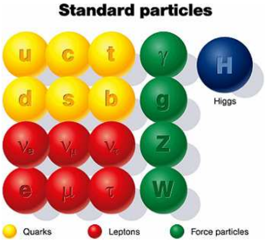
$$M_X \sim \frac{M_W}{g^2}\sqrt{\frac{16\pi^2}{|V_{ts}^* V_{td}|}} \sim 130 \text{ TeV}$$

- compare to rare B decays:

$$b \to d: \quad M_X \sim \frac{M_W}{g^2}\sqrt{\frac{16\pi^2}{|V_{td}^* V_{tb}|}} \sim 25 \text{ TeV}; \quad b \to s: \quad M_X \sim \frac{M_W}{g^2}\sqrt{\frac{16\pi^2}{|V_{ts}^* V_{tb}|}} \sim 12 \text{ TeV}$$

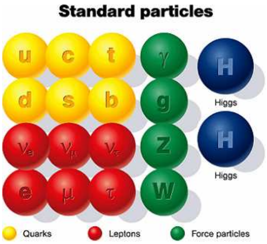
The MSSM and its Flavor Structure

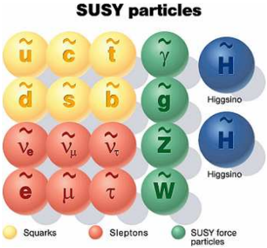
- In the SM, the only sources of flavor violation are the Yukawa couplings Y_u and Y_d



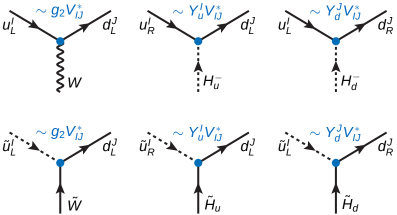
The MSSM and its Flavor Structure

- In the SM, the only sources of flavor violation are the Yukawa couplings Y_u and Y_d
- In supersymmetric models every fermionic degree of freedom has a bosonic partner and vice versa
- In the MSSM, some partners (Higgsinos, stops) should be below the TeV scale to have a natural solution to the hierarchy problem
- squark soft masses, m_Q^2, and trilinear couplings of squarks with the Higgs, A_q, can introduce new sources of flavor violation





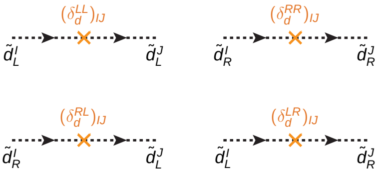
The MSSM and its Flavor Structure II



misalignment between up quarks and down quarks in flavor space

- ▶ CKM matrix

→ FCNCs naturally suppressed
hierarchical CKM + GIM mechanism



misalignment between quarks and squarks in flavor space

- ▶ Mass Insertions

$$M^2_{\tilde{q}} = \tilde{M}^2(\mathbb{1} + \delta_q)$$

→ Flavor and CP violating neutral gaugino-quark-squark interactions

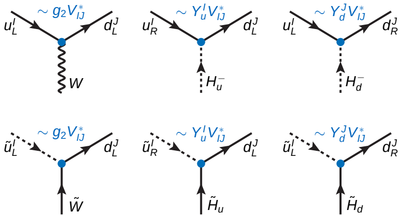
- ▶ SUSY Flavor Problem

Outline

1. $K \to \pi\nu\bar{\nu}$ in the MSSM with Minimal Flavor Violation
2. $K \to \pi\nu\bar{\nu}$ in the MSSM beyond Minimal Flavor Violation
3. $K \to \pi\nu\bar{\nu}$ and Very Light Neutralinos
4. Summary

$K \to \pi\nu\bar{\nu}$ and Minimal Flavor Violation

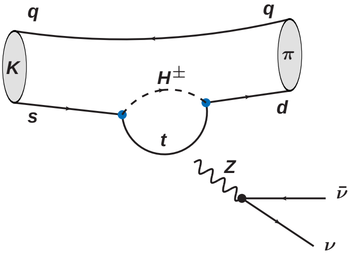
The MSSM with Minimal Flavor Violation



- Yukawa couplings $\leftrightarrow$ CKM matrix is the only source of flavor violation
- (note that mass insertions are not necessarily 0 but strongly suppressed by CKM elements, e.g. $\delta_{sd}^{LL} \sim V_{ts}^* V_{td}$ ...)

- FCNCs suppressed by the same CKM elements as in the SM
- strong constraints from meson mixing naturally avoided
- nonetheless large effects in rare B decays are possible (e.g. $B_s \to \mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$) due to additional enhancement factors (large tan β)
- what about $K \to \pi\nu\bar{\nu}$?

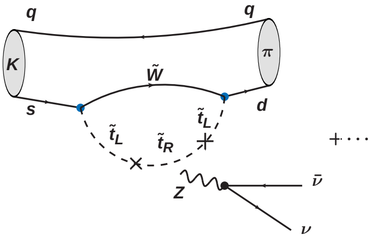
Charged Higgs Contributions



$$\sim \frac{g^4}{16\pi^2}\frac{1}{M_{H^\pm}^2}\left(\frac{m_t^2}{M_W^2}\cot^2\beta - \frac{m_s m_d}{M_W^2}\tan^2\beta\right) V_{ts}^* V_{td}$$

- suppressed by either small quark masses or $\cot^2\beta$
- *in the MSSM* a light Higgs mass of $M_h \simeq 125$GeV implies $\tan\beta \gtrsim 5$ (unless stops are super heavy $\gg$ 10 TeV)
- only few % effects in from charged Higgs loops possible
- however: light Higgs mass is sensitive to physics beyond the MSSM (BMSSM, NMSSM, ...)
- $\tan\beta$ can be O(1) in these models
- always constructive interference with the SM
- how large can the effects in $K \to \pi\nu\bar{\nu}$ be?

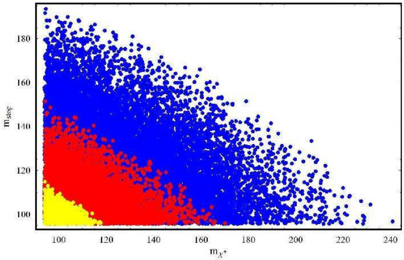
Chargino Contributions



$$\sim \frac{g^4}{16\pi^2} \frac{1}{M_{\tilde{t}}^2} \frac{m_t^2}{M_W^2} V_{ts}^* V_{td}$$

- no sensitivity to flavor blind phases
- only phase comes from $V_{ts}^* V_{td}$
- constructive and destructive interference with the SM possible
- contributions from chargino loops only visible if stops and charginos are very light (100 - 200) GeV

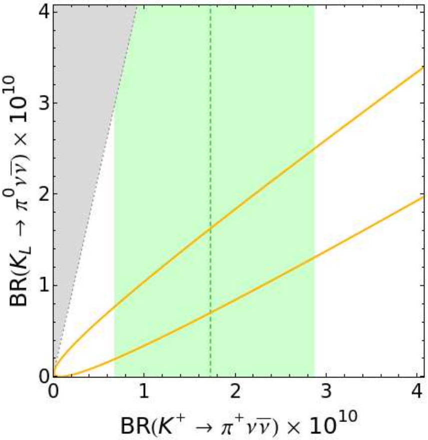
$$\Delta BR(K_L \to \pi^0 \nu\bar{\nu}) > 15\%$$
$$\Delta BR(K_L \to \pi^0 \nu\bar{\nu}) > 12.5\%$$
$$\Delta BR(K_L \to \pi^0 \nu\bar{\nu}) > 10\%$$



Isidori, Mescia, Paradisi, Smith, Trine, JHEP 0608 (2006)

- Minimal Flavor Violation predicts a strong correlation between $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ (only phase comes from $V_{ts}^* V_{td}$)
- what are the possible ranges for the branching ratios?

model independent MFV framework



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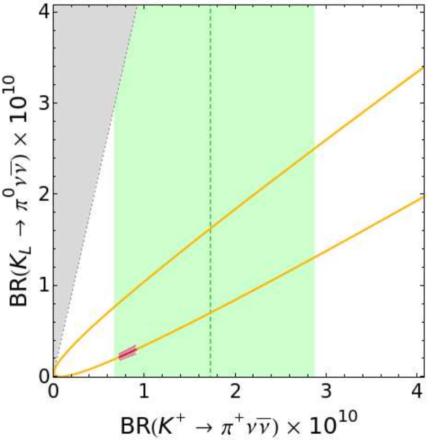
model independent MFV framework

MSSM with MFV



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

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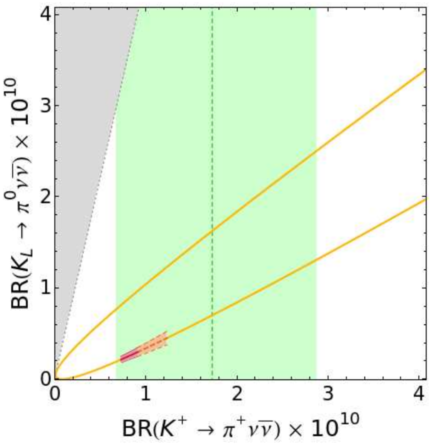
model independent MFV framework

MSSM with MFV

MSSM with MFV
+ extended Higgs sector



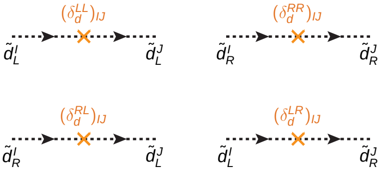
$K \to \pi\nu\bar{\nu}$
Beyond MFV

The MSSM with Generic Flavor Structure

- squark soft masses and trilinear couplings are in general 3×3 matrices in flavor space and not necessarily aligned with the quark masses

$$M^2_{\tilde{d}} = \begin{pmatrix} m_Q^2 & m_d (A_d - \mu \tan\beta) \\ m_d (A_d^\dagger - \mu^* \tan\beta) & m_D^2 \end{pmatrix} + O(v^2)$$

$$M^2_{\tilde{u}} = \begin{pmatrix} V_{CKM}\, m_Q^2\, V_{CKM}^\dagger & m_u (A_u - \mu \cot\beta) \\ m_u (A_u^\dagger - \mu^* \cot\beta) & m_U^2 \end{pmatrix} + O(v^2)$$



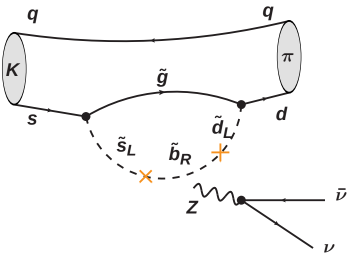
misalignment between quarks and squarks in flavor space

- Mass Insertions

$$M^2_{\tilde{q}} = \tilde{M}^2 (\mathbb{1} + \delta_q)$$

$\rightarrow$ Flavor and CP violating neutral gaugino-quark-squark interactions

Large Gluino Contributions?

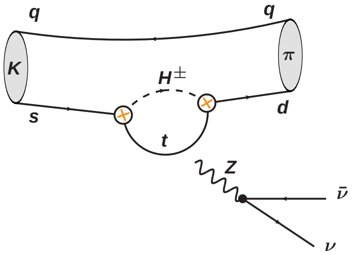


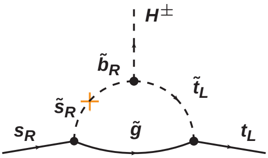
$+ \cdots$

$$\sim \frac{g_s^4}{16\pi^2} \frac{1}{M_{\tilde{g}}^2} \frac{m_b^2}{M_W^2} \frac{A_{sb} A_{bd}}{M_{\tilde{b}}^2}$$

- gluino contributions are always tiny! Nir, Worah, Phys. Lett. B423 (1998)
- unique feature of rare decays that are dominated by Z penguins

Isidori, Paradisi, Phys. Rev. D73 (2006)



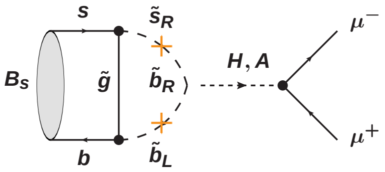


- in presence of flavor changing RH currents in the down sector, charged Higgs couplings are strongly modified by tan β enhanced loop corrections

$$\frac{m_s m_d}{M_W^2} V_{ts}^* V_{td} \tan^2\beta \quad \rightarrow \quad \frac{\alpha^2}{(4\pi)^2} \frac{m_b^2}{M_W^2} (\delta_d^{RR})_{32}^* (\delta_d^{RR})_{31} \tan^4\beta$$

- effectively a 3 loop contribution, but can be very relevant!

Constraints from $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$



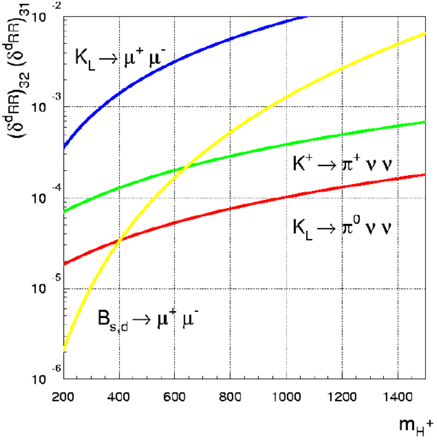
$$\sim \frac{g_s^2 g^2}{16\pi^2} \frac{1}{M_H^2} \frac{m_\mu m_b}{M_W^2} (\delta_d^{RR})_{32} \tan^3\beta$$

- the same flavor structures entering the charged Higgs loops to $K \to \pi\nu\bar{\nu}$ also induce strongly tan β enhanced contributions to $B_q \to \mu^+\mu^-$
- different decoupling properties for heavy Higgs masses

$$K \to \pi\nu\bar{\nu} \to \frac{\log(M_H^2/m_t^2)}{M_H^2} \quad , \quad B_q \to \mu^+\mu^- \to \frac{1}{M_H^2}$$

Sensitivity to $(\delta_d^{RR})_{32}$ and $(\delta_d^{RR})_{31}$

(in the plot: tan $\beta = 50$, $M_{\tilde{q}} = M_{\tilde{g}} = -\mu$)

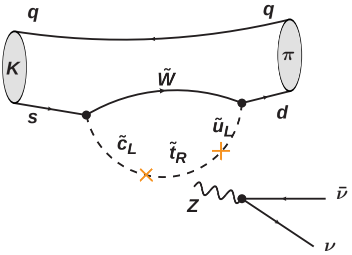


- the $K \to \pi\nu\bar{\nu}$ decays are the most sensitive probes of $(\delta_d^{RR})_{32}$ and $(\delta_d^{RR})_{31}$ for large Higgs masses
- but note:
  the bounds on $B_q \to \mu^+\mu^-$ improved by more than one order of magnitude since this plot was done, and they will continue to improve

Isidori, Paradisi, Phys. Rev. D73 (2006)

Wino Contributions

Colangelo, Isidori, JHEP 9809 (1998)

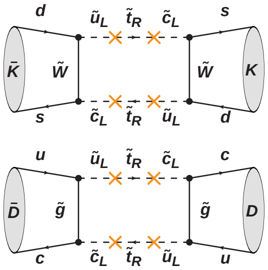


$$\sim \frac{g^4}{16\pi^2}\frac{1}{M_Z^2}\,(\delta_u^{LR})_{23}(\delta_u^{LR})^*_{13}$$

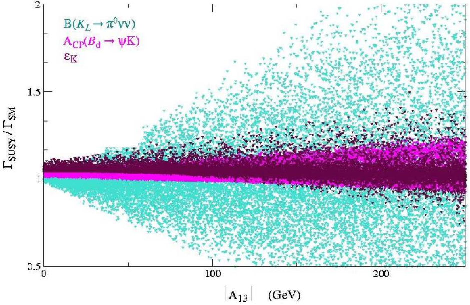
- effective $(2 \to 1)$ transition through the third generation $(2 \to 3) \times (3 \to 1)$
- decoupling with the SUSY scale "hidden" in the left-right couplings $(\delta_u^{LR})_{23}$ and $(\delta_u^{LR})^*_{13}$
- the Wino loop can give the by far largest contribution to Z penguin mediated decays like $K \to \pi\nu\bar{\nu}$ in the MSSM
- $K \to \pi\nu\bar{\nu}$ decays probe flavor violation in the up-squark sector!

Constraints from Meson Mixing

- couplings $(\delta_u^{LR})_{23}$ and $(\delta_u^{LR})_{13}^*$ also induce Kaon and D meson mixing



- Kaon and D meson mixing can receive large contributions also from other flavor violating sources ($\rightarrow$ partial cancellations are easily possible)
- $K \rightarrow \pi\nu\bar{\nu}$ is more sensitive to $(\delta_u^{LR})_{23}$ and $(\delta_u^{LR})_{13}^*$



Isidori, Mescia, Paradisi, Smith, Trine, JHEP 0608(2006)

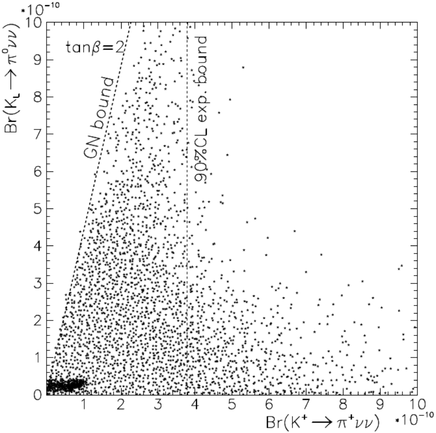
$\rightarrow$ constraints from ϵ_K and CPV in D^0 mixing cannot rule out large effects in $K \rightarrow \pi\nu\bar{\nu}$

General Parameter Scan

- Important constraints also come from ϵ'/ϵ and $K_L \to \mu^+\mu^-$
  Buras, Silvestrini, Nucl.Phys. B546 (1999)
  Buras, Colangelo, Isidori, Romanino, Silvestrini, Nucl. Phys. B566 (2000);
- result of a general scan of the MSSM parameter space, taking into account all relevant constraints (apart from ϵ'/ϵ !):

  both branching ratios can be enhanced by
  more than an order of magnitude
  (corresponding regions of parameter space are to a certain amount fine-tuned)

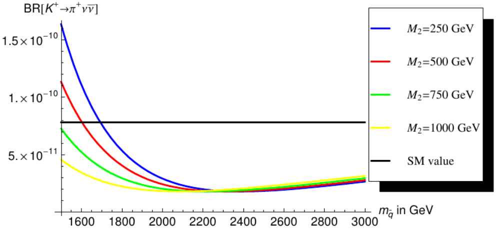
  exp. results already give non-trivial constraints on the MSSM parameter space

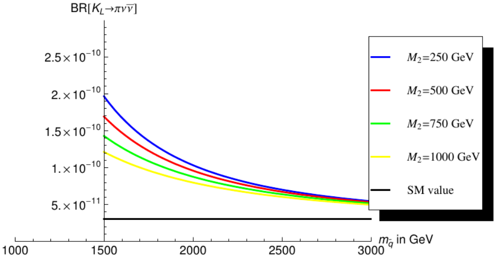


Buras, Ewerth, Jager, Rosiek, Nucl. Phys. B714 (2005)

A Model with "Radiative Flavor Violation"

- at tree level only bottom and top Yukawas are non-zero and CKM matrix is $\mathbb{1}$
- only source of flavor violation are the squark trilinear couplings
- small Yukawa couplings and CKM mixing angles are induced radiatively
- leads to observable effects in $K \to \pi\nu\bar{\nu}$





Crivellin, Hofer, Nierste, Scherer, Phys. Rev. D84 (2011)

“Disoriented A terms”

Giudice, Isidori, Paradisi, JHEP 1204 (2012)

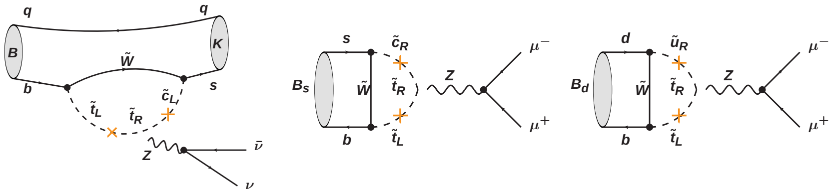
$$(\delta_q^{LR})_{ij} = \frac{m_{q_j} A}{M_{\tilde{q}}^2}\theta_{ij} \quad , \quad (\delta_q^{LL})_{ij},\ (\delta_q^{RR})_{ij} \simeq 0$$

($A \simeq M_{\tilde{q}}$, θ_{ij} are complex O(1) numbers)

- originally discussed in the context of direct CP violation in charm decays ($D \to K^+K^-$ and $D \to \pi^+\pi^-$)
- setup can naturally explain the large values for $\Delta A_{\rm CP}$ observed by LHCb and CDF (the relevant coupling is $(\delta_u^{LR})_{12}$)
- the couplings $(\delta_u^{LR})_{13}$ and $(\delta_u^{LR})_{23}$ that enter $K \to \pi\nu\bar{\nu}$ are proportional to the large top mass
- “disoriented A terms” predict generically also O(1) effects in $K \to \pi\nu\bar{\nu}$

Possible Correlations with Rare B decays

- dominant contributions to $K \to \pi\nu\bar{\nu}$ is a Z penguin that involves $(2 \to 3)$ and $(3 \to 1)$ transitions
- also expect non standard effects in rare $b \to s$ and $b \to d$ decays



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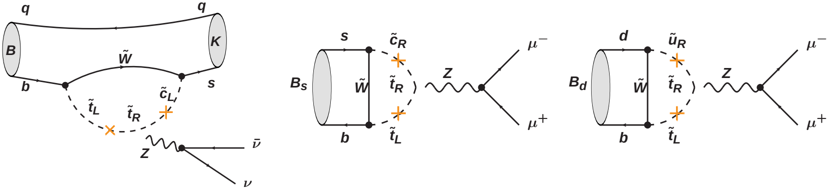


$$\Delta BR(K \to \pi\nu\bar{\nu}) \Big/ \Delta BR(B_d \to \mu^+\mu^-) \Big/ \Delta BR(B_s \to \mu^+\mu^-), \Delta BR(B \to K\nu\bar{\nu})$$

$$\sim \frac{|(\delta_u^{LR})_{23}(\delta_u^{LR})_{13}^*|}{\lambda^5} \Big/ \sim \frac{|(\delta_u^{LR})_{13}|}{\lambda^3} \Big/ \sim \frac{(\delta_u^{LR})_{23}}{\lambda^2}$$

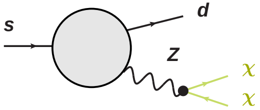
$$\sim 10 - 100 \Big/ \sim 5 \Big/ 1$$

- generic expectations, but no strict correlations

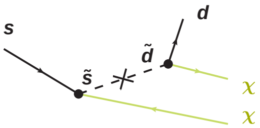
$K \to \pi\nu\bar{\nu}$ and Very Light Neutralinos

- the mass of the lightest neutralino is unconstrained by direct searches (note: the PDG says $M_\chi \gtrsim 46$ GeV this bound is obtained from direct searches of charginos and assumes gaugino mass unification at the GUT scale)
- very light (or even massless) neutralinos cannot be excluded
- if M_χ is sufficiently small the $K \to \pi\chi\chi$ decay is possible

loops



tree level

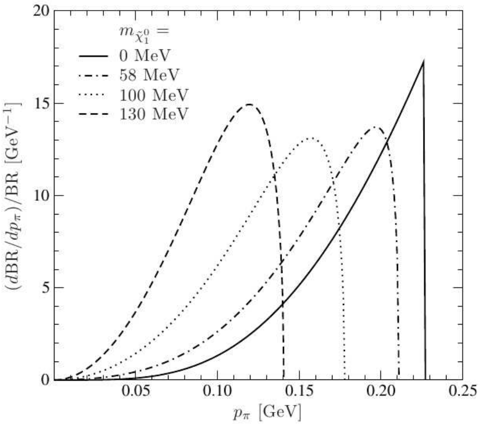


- neither ν's nor χ's are detected

$\rightarrow$ same experimental signature: "$K \to \pi + \not{E}$"

Dreiner et al. Eur. Phys. J. C62 (2009); Phys. Rev. D80 (2009)

Changes in the p_π Spectrum



Dreiner et al. Phys. Rev. D80 (2009)

- the p_π spectrum for $K \to \pi\chi\chi$ depends on the mass of the neutralinos
- more difficult to separate from backgrounds

see also talk by Philippe

Summary

- Rare Kaon decays are highly sensitive to New Physics at high scales
- In the MSSM with MFV,
  the $K \to \pi\nu\bar{\nu}$ decays remain to a large extent SM-like.
  Visible deviations might come from a extended Higgs sector and are highly correlated between $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$
- In the MSSM beyond MFV,
  $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ can be modified independently and are unique probes of flavor violation in the up-squark sector.
  Several motivated frameworks exist that lead to O(1) modifications of the branching ratios
- If neutralinos are very light, the $K \to \pi\chi\chi$ decay is possible and can lead to a non-standard p_π spectrum.