LFV, R-parity, and invisible particles in rare decays with missing energy

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Introduction

The goal of this talk:

Characterization of some NP effects in the very rare decays

$$K \to \pi + \text{missing energy}$$

$$B \to (\pi, K, K^*) + \text{missing energy}$$

The outline of this talk:

I. Observables & kinematics

II. Lepton flavor violating effects

III. Signals of R-parity violation

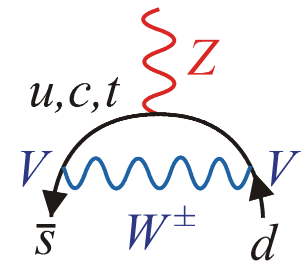
IV. Very light invisible particles

Conclusion

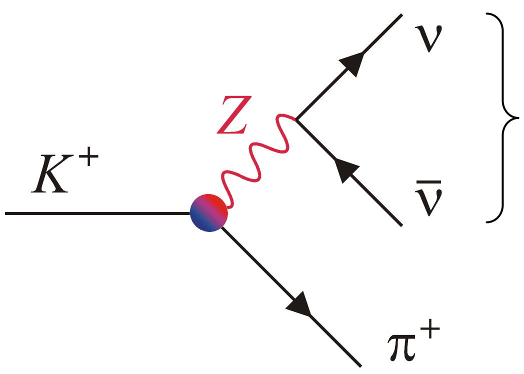
I. Observables & Kinematics

A. The $K \to \pi\nu\bar{\nu}$ decays

	SM $(\times 10^{-11})$	Experiment
$K_L \to \pi^0\nu\bar{\nu}$	$2.57^{+0.37}_{-0.37}$	$< 6.7 \cdot 10^{-8}$ E391a
$K^+ \to \pi^+\nu\bar{\nu}(\gamma)$	$8.22^{+0.75}_{-0.75}$	$17.3^{+11.5}_{-10.5} \cdot 10^{-11}$ E787 E949



Only the pion is seen, whose energy is not fixed (three-body decay).



Missing "energy": $z = (p_\nu + p_{\bar{\nu}})^2 / m_K^2$

Pion momentum: $|\mathbf{p}_\pi| = \frac{m_K}{2} \lambda(1, z, r_\pi^2)$

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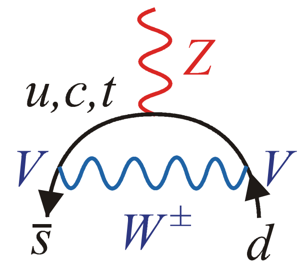
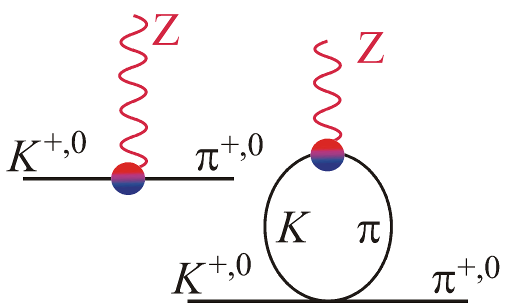


Z penguin & W boxes lead to the interaction $\bar{s}\gamma^{\mu}(1-\gamma_5)d \otimes \bar{\nu}\gamma_{\mu}(1-\gamma_5)\nu$.

Hadronic matrix element: $\langle \pi | \bar{s}\gamma^{\mu} d | K \rangle \approx f(z)(p_K + p_\pi)^{\mu}, \quad f(z) \approx \dfrac{1}{1 - z / m_{K^*}^2}$,



- $f(0) \approx 1$ (Ademollo-Gatto Theorem),
- Vector meson dominance away from zero.

Chiral & isospin corrections (partial NNLO) are estimated using $K_{\ell 3}$ *decays*.

Mescia,CS '06

A. The $K \to \pi\nu\bar{\nu}$ decays

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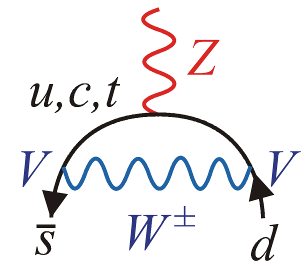
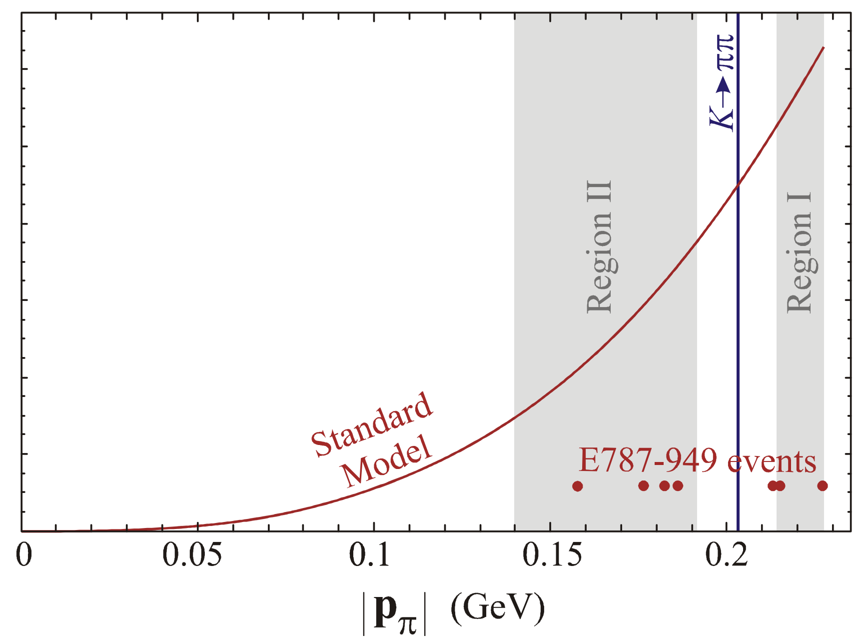


The observable differential rate is

$$\frac{\partial \ln \Gamma}{dz} \sim \frac{|\mathbf{p}_\pi|^3}{m_K^3} \, | f(z) |^2$$

Essential for the necessarily aggressive background rejection.



Important messages: V-A current assumed & kinematical range limited.

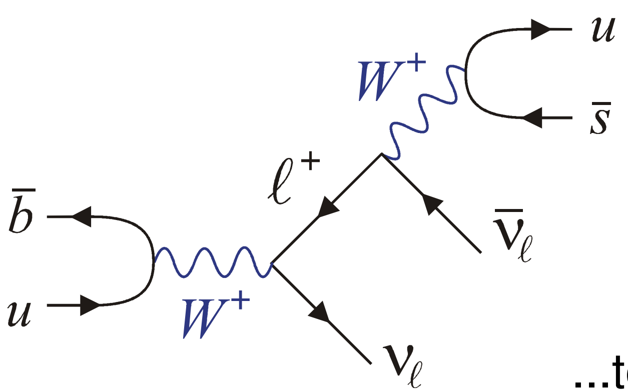
B. The $B^+ \to (\pi^+, K^{(*)+})\nu\bar{\nu}$ *decays*

Kamenik,CS '09

Charged decays are intimately connected to $B \to \bar{\nu}_\tau \tau\, [\to (\pi, K, K^*)\nu_\tau]$.

See talk by J. Kamenik.

Tree-level dim-8 contributions to all charged $\nu\bar{\nu}$ rare decays:



$$\sim G_F^2 V_{ub} V_{us}^* \times \frac{p_\ell^2}{p_\ell^2 - m_\ell^2 + i m_\ell \Gamma_\ell} \times \bar{u}_\nu \not{p}_\ell (1-\gamma_5) v_{\bar{\nu}}$$

...to be compared to the dim-6 penguin $\sim G_F \alpha V_{tb} V_{ts}^*$.

Hence, sizeable only for $\ell = \tau$ which is kinematically allowed to be on-shell:

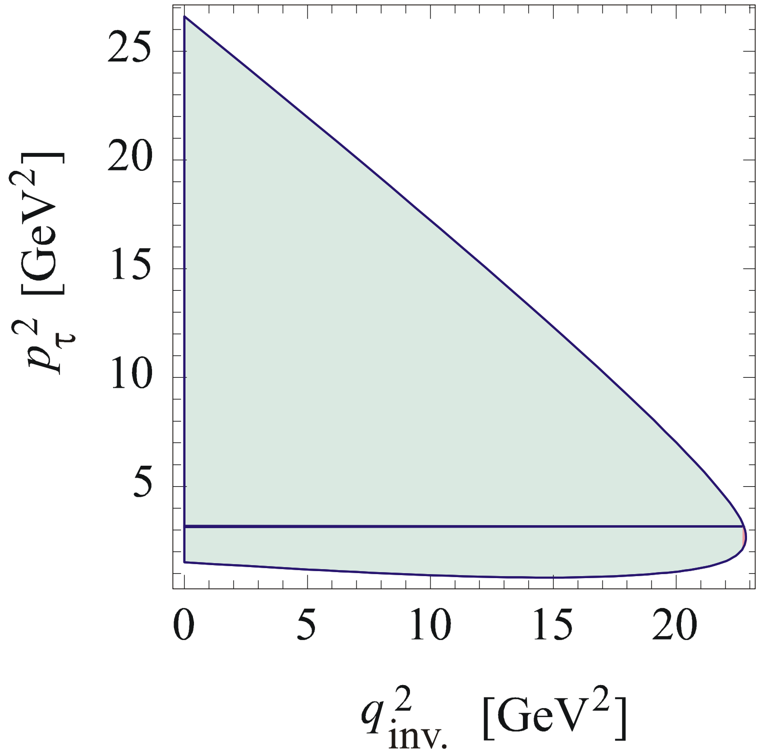
- *K decays*: Helicity suppression inactive → negligible dim-10 effect.
- *B decays*: The τ pole in $\Gamma_\tau^{-1} \sim G_F^{-2}$ makes it potentially dominant.

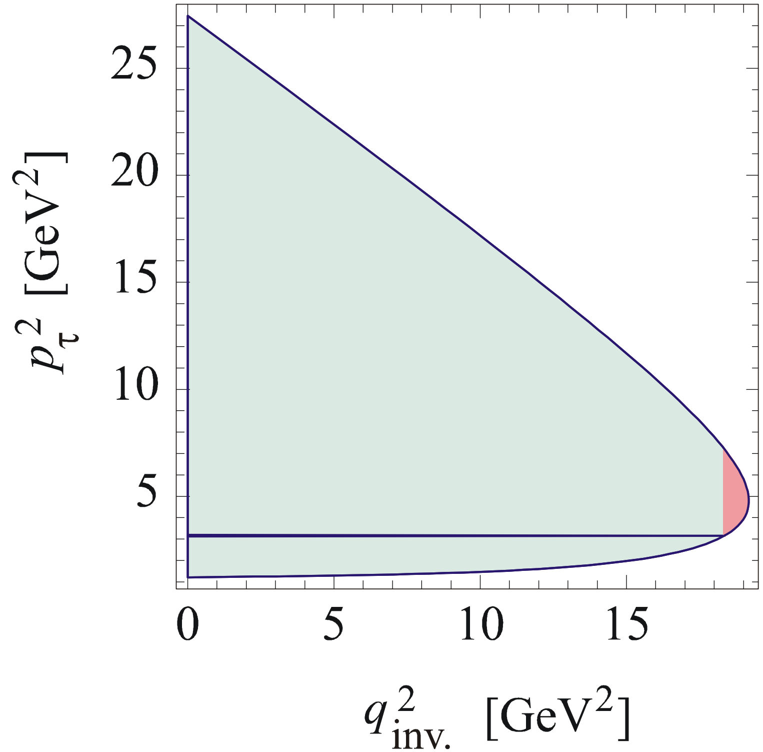
(note the inverted CKM scaling of the pole and penguin)

B. The $B^+ \to (\pi^+, K^{(*)+})\nu\bar{\nu}$ *decays*

Kamenik,CS '09

Entanglement: the τ pole runs over the whole missing energy range.





Note: the differential rates for the pole and loop have similar dependences on q^2.

B. The $B^+ \to (\pi^+, K^{(*)+})\nu\bar{\nu}$ decays

Kamenik,CS '09

$\times 10^{-6}$	τ pole	Direct SD	Ratio
$B^+ \to \pi^+\nu\bar{\nu}$	$9.4(2.1)$	$0.16(4)$	$SD/\tau = 2\%$
$B^+ \to K^+\nu\bar{\nu}$	$0.61(13)$	$4.5(7)$	$\tau/SD = 14\%$
$B^+ \to K^{*+}\nu\bar{\nu}$	$1.2(3)$	$7.2(1.1)$	$\tau/SD = 17\%$

$B^+ \to \nu_\tau \tau^+ [\to e\nu_e, \mu\nu_\mu]$: Safe, no pollution from $b \to (s,d)\nu\bar{\nu}$.

$B^+ \to \nu_\tau \tau^+ [\to \pi^+ \bar{\nu}_\tau]$: 2% pollution by the direct $b \to d\nu\bar{\nu}$ transition.
Any NP in $b \to d\nu\bar{\nu}$ is essentially inaccessible.

$B^+ \to \nu_\tau \tau^+ [\to K^{(*)+} \bar{\nu}_\tau]$: 600-700% apparent enhancement due to $b \to s\nu\bar{\nu}$.
Sensitive to NP through both $B \to \nu_\tau \tau$ and $b \to s\nu\bar{\nu}$.

Alternatively: $B^0 \to X^0_{s,d}\nu\bar{\nu}$ or $B_c^+ \to D_s^+\nu\bar{\nu}$ induced purely by $b \to (s,d)\nu\bar{\nu}$.

Lepton flavor violating effects

A. Effective operators for $P \to P'\nu^I\bar{\nu}^J$ *and* $P \to P'\ell^I\bar{\ell}^J$

Assume the matter content is that of the SM:

$$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad U = u_R^\dagger, \quad D = d_R^\dagger, \quad L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}, \quad E = \ell_R^\dagger$$

Five dimension-six gauge-invariant structures can be constructed:

$$\bar{Q}\Gamma_i Q \otimes \bar{L}\Gamma^i L \qquad \bar{Q}\Gamma_i Q \otimes E\Gamma^i \bar{E} \qquad \bar{Q}\Gamma_i \bar{D} \otimes E\Gamma^i L$$

$$D\Gamma_i \bar{D} \otimes \bar{L}\Gamma^i L \qquad D\Gamma_i \bar{D} \otimes E\Gamma^i \bar{E}$$

Contributes to $P \to P'\nu^I\bar{\nu}^J$ and $P \to P'\ell^I\bar{\ell}^J$.

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Five dimension-six gauge-invariant structures can be constructed:

$$\mathcal{H}_{eff} = \frac{C^{IJKL}}{\Lambda_{NP}^2}\left(\begin{array}{ccc} \bar{Q}^I\Gamma_i Q^J \otimes \bar{L}^K\Gamma^i L^L & \bar{Q}^I\Gamma_i Q^J \otimes E^K\Gamma^i\bar{E}^L & \bar{Q}^J\Gamma_i\bar{D}^I \otimes E^K\Gamma^i L^L \\ D^I\Gamma_i\bar{D}^J \otimes \bar{L}^K\Gamma^i L^L & D^I\Gamma_i\bar{D}^J \otimes E^K\Gamma^i\bar{E}^L & \end{array} \right)$$

Contributes to $P \to P'\nu^I\bar{\nu}^J$ and $P \to P'\ell^I\bar{\ell}^J$.

New Physics flavor puzzle: If all the $C^{IJKL} \sim 1$, then $\Lambda_{NP} \gg$ 1 TeV.

B. What Minimal Flavor Violation can say

- The gauge interactions exhibit the $U(3)^5$ *flavor symmetry*:

$$G_f = U(3)^5 = U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$$

Chivukula, Georgi '87

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- The only sources of breaking are the fermionic Yukawa and mass terms:

$$\mathcal{L}_{matter} = U\mathbf{Y}_u(QH) + D\mathbf{Y}_d(QH^*) + E\mathbf{Y}_e(LH^*) + N\mathbf{M}N + N\mathbf{Y}_\nu(LH)$$

$$\to U\mathbf{Y}_u(QH) + D\mathbf{Y}_d(QH^*) + E\mathbf{Y}_e(LH^*) + (LH)^T\,\mathbf{Y}_\nu^T\mathbf{M}^{-1}\mathbf{Y}_\nu(LH)$$

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- *Artificially invariance under* G_f created when the breaking terms are spurions.

With them, all the *effective operators are made invariant under* G_f .

Hall,Randall '90
D'Ambrosio,Giudice, Isidori,Strumia '02

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- The *spurions are frozen back to their physical values:*

Hall, Randall '90
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Dirac masses: $v\mathrm{Y}_u = m_u V_{CKM}\,,\quad v\mathrm{Y}_d = m_d\,,\quad v\mathrm{Y}_e = m_e\,,$

Majorana masses: $v^2\mathrm{Y}_\nu^T\mathrm{M}^{-1}\mathrm{Y}_\nu = U^*_{PMNS}\,\mathrm{m}_\nu\,U^\dagger_{PMNS}\,,$

Cirigliano, Grinstein Isidori, Wise '05

Note: $\mathrm{m}_\nu \sim 1\,\mathrm{eV}$ with $\mathrm{Y}_\nu \sim \mathcal{O}(1)$ when $\mathrm{M} \sim 10^{13}\,\mathrm{GeV}$.

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Casas,Ibarra '01, Pascoli,Petcov, Yaguna '03,...

Majorana masses: $v^2\mathrm{Y}_\nu^T\mathrm{M}^{-1}\mathrm{Y}_\nu = U^*_{PMNS}\mathrm{m}_\nu U^\dagger_{PMNS}\,,$

LFV spurion: $v^2\mathrm{Y}_\nu^\dagger\mathrm{Y}_\nu = M_R\,U_{PMNS}\,\mathrm{m}_\nu^{1/2}e^{2i\Phi}\,\mathrm{m}_\nu^{1/2}U^\dagger_{PMNS}\,,\quad \Phi^{IJ} = \varepsilon^{IJK}\phi_K\,.$

B. What Minimal Flavor Violation can say

Chiral suppressions:

Quark transitions: $\bar{Q}Q \to \bar{Q}^I (Y_u^\dagger Y_u)^{IJ} Q^J$ ~ 1

$D\bar{D} \to D^I Y_d^{II} (Y_u^\dagger Y_u)^{IJ} Y_d^{\dagger JJ} \bar{D}^J$ $\sim m_{d^I} m_{d^J} / v^2$

$DQ \to D^I Y_d^{II} (Y_u^\dagger Y_u)^{IJ} Q^J$ $\sim m_{d^I} / v$

Lepton transitions: $\bar{L}L \to \bar{L}^I (Y_\nu^\dagger Y_\nu)^{IJ} L^J$ ~ 1

$E\bar{E} \to E^I Y_e^{II} (Y_\nu^\dagger Y_\nu)^{IJ} Y_e^{\dagger JJ} \bar{E}^J$ $\sim m_{\ell^I} m_{\ell^J} / v^2$

$EL \to E^I Y_e^{II} (Y_\nu^\dagger Y_\nu)^{IJ} L^J$ $\sim m_{\ell^I} / v$

So, the dominant operator is $\bar{Q}^I (Y_u^\dagger Y_u)^{IJ} Q^J \otimes \bar{L}^I (Y_\nu^\dagger Y_\nu)^{IJ} L^J$.

C. Numerics (rough preliminary outline)

$$\frac{1}{\Lambda^2}\bar{Q}^I\left(Y_u^\dagger Y_u\right)^{IJ}Q^J\otimes\bar{L}^I\left(a_0 1+a_1 Y_\nu^\dagger Y_\nu\right)^{IJ}L^J$$

Lepton-flavor conserving:

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

So, for $\Lambda \lesssim$ 1 TeV, $\frac{\Gamma_{NP}^{LFC}}{\Gamma_{SM}}\left(P\to P'\nu^I\bar{\nu}^I, P'\ell^I\bar{\ell}^I\right)\lesssim 1$.

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So, for $\Lambda \lesssim$ 1 TeV, $\frac{\Gamma_{NP}^{LFC}}{\Gamma_{SM}}(P \to P'\nu^I \bar{\nu}^I, P'\ell^I \bar{\ell}^I) \lesssim 1$.

Lepton-flavor violating:

Since $\mathrm{m}_\nu \sim \mathrm{Y}_\nu^2 / \mathrm{M}$, take M sufficiently large so that $\mathrm{Y}_\nu \sim \mathcal{O}(1)$.

But, Y_ν is bounded by $\mathcal{H}_{eff}(\ell \to \ell'\gamma) = \frac{e}{\Lambda^2} E^I \mathrm{Y}_e^{II} (\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu)^{IJ} \sigma^{\mu\nu} L^J H^\dagger F_{\mu\nu}$.

So, conservatively, $(\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu)^{I \neq J} < 1\%$ for $\Lambda \lesssim$ 1 TeV, and $\frac{\Gamma_{NP}^{LFV}}{\Gamma_{NP}^{LFC}} \lesssim 10^{-4}$.

C. Numerics (rough preliminary outline)

$$\frac{1}{\Lambda^2}\bar{Q}^I (Y_u^\dagger Y_u)^{IJ} Q^J \otimes \bar{L}^I (a_0 1 + a_1 Y_\nu^\dagger Y_\nu)^{IJ} L^J$$

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So, for $\Lambda \lesssim$ 1 TeV, $\frac{\Gamma_{NP}^{LFC}}{\Gamma_{SM}}(P \to P'\nu^I\bar{\nu}^I, P'\ell^I\bar{\ell}^I) \lesssim 1$.

Lepton-flavor violating:

So, conservatively, $(Y_\nu^\dagger Y_\nu)^{I\neq J} < 1\%$ for $\Lambda \lesssim$ 1 TeV, and $\frac{\Gamma_{NP}^{LFV}}{\Gamma_{NP}^{LFC}} \lesssim 10^{-4}$.

In other words, when $I \neq J$, MFV says:

$$Br_{NP}^{LFV}(K \to \pi\nu^I\bar{\nu}^J, \pi\ell^I\bar{\ell}^J) < 10^{-15}$$

$$Br_{NP}^{LFV}(B \to (\pi, K)\nu^I\bar{\nu}^J, (\pi, K)\ell^I\bar{\ell}^J) < 10^{-10}$$

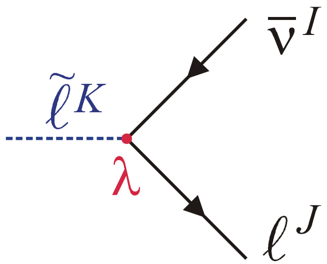
R-parity violation

A. The MSSM without R-parity

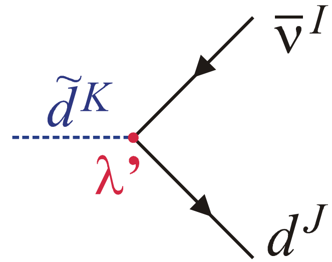
With scalar squarks & sleptons, renormalizable couplings can violate $\mathcal{B}$ or $\mathcal{L}$:

$$\mathcal{W}_{RPV} = \underbrace{\mu'^{I} L^{I} H_{d} + \lambda^{IJK} L^{I} L^{J} E^{K} + \lambda'^{IJK} L^{I} Q^{J} D^{K}}_{\Delta\mathcal{L}=1} + \underbrace{\lambda''^{IJK} U^{I} D^{J} D^{K}}_{\Delta\mathcal{B}=1}$$

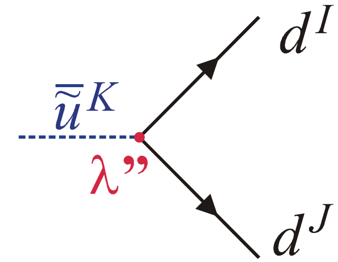
Dilepton currents:



Leptoquark currents:



Diquark currents:



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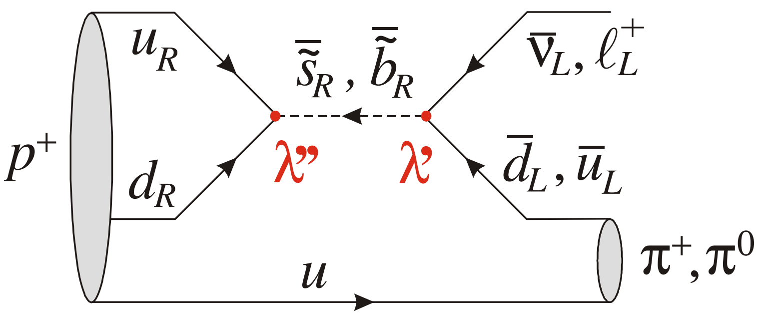
$$\mathcal{W}_{RPV} = \underbrace{\mu'^{I} L^I H_d + \lambda^{IJK} L^I L^J E^K + \lambda'^{IJK} L^I Q^J D^K}_{\Delta\mathcal{L}=1} + \underbrace{\lambda''^{IJK} U^I D^J D^K}_{\Delta\mathcal{B}=1}$$

With both $\Delta\mathcal{L}$ and $\Delta\mathcal{B}$, *proton decay* (and associated) occurs at tree-level:

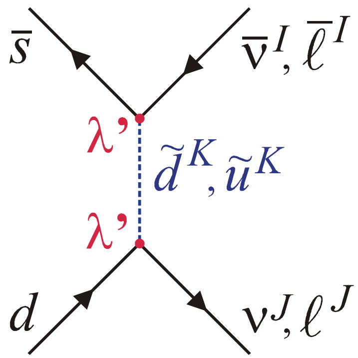


$$p \to \pi^+ \bar{\nu}_\ell,\ K^+ \bar{\nu}_\ell,\ \pi^0 \ell^+, \ldots$$
$$n \to \pi^0 \bar{\nu}_\ell,\ K^0 \bar{\nu}_\ell,\ \pi^- \ell^+, \ldots$$

But experimentally, $\tau_{p^+} > 10^{30}\ years$: $\Gamma_{p^+} \sim \frac{m_p^5}{M_{\tilde{d}}^4} |\lambda'' \lambda'|^2 \quad \Rightarrow |\lambda' \lambda''| \leq 10^{-27}$?

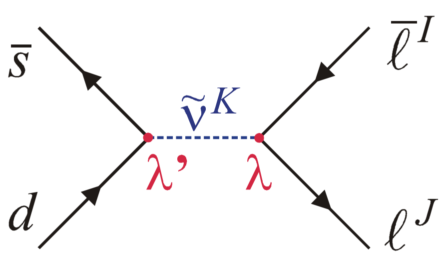
B. Possible effects in rare decays

Rare decays conserve both $\mathcal{B}$ and $\mathcal{L}$ → Quadratic in the R-parity couplings.



Fermi-like $V \pm A \otimes V - A$ effective couplings:

$$\bar{s}\gamma^\mu(1 \pm \gamma_5)d \otimes \begin{cases} \bar{\nu}\gamma_\mu(1-\gamma_5)\nu \\ \bar{\ell}\gamma_\mu(1-\gamma_5)\ell \end{cases}$$



Scalar-pseudoscalar effective couplings:

$$\bar{s}(1 \pm \gamma_5)d \otimes \bar{\ell}(1 \mp \gamma_5)\ell$$

The RPV couplings can induce quark & lepton flavor transitions,

hence could contribute to all $P \to P'\nu^I\bar{\nu}^J$ and $P \to P'\ell^I\bar{\ell}^J$ decays.

Choudhury,Roy'96,Grossman,Isidori,Murayama'03,Deandrea,Welzel,Oertel'04,Deshpande,Ghosh,He'04,…

Nikolidakis,C.S. '07

C. What Minimal Flavor Violation can say

- The $\mathcal{B}$ *violating couplings can be constructed* using $\Delta\mathcal{B}=0$ quark Yukawas:

$$\lambda''^{IJK} = \varepsilon^{LJK}(\mathrm{Y}_u \mathrm{Y}_d^\dagger)^{IL} \quad \Rightarrow \lambda''^{IJK} U^I D^J D^K \to \det(g_D^\dagger)\lambda''^{IJK} U^I D^J D^K$$

$$\lambda''^{IJK} = \varepsilon^{LMN}\mathrm{Y}_u^{IL}\mathrm{Y}_d^{JM}\mathrm{Y}_d^{KN} \quad \Rightarrow \lambda''^{IJK} U^I D^J D^K \to \det(g_Q^\dagger)\lambda''^{IJK} U^I D^J D^K$$

$$\dots$$

- But $\mathcal{L}$ *violating couplings are strictly forbidden* as long as $m_\nu = 0$*:*

The SU(3) combinatorics demands a spurion transforming like a *six*.

The only spurion available is the suppressed $\Delta\mathcal{L}=2$ Majorana mass term:

$$\Upsilon_\nu \equiv v_u \mathrm{Y}_\nu^T \mathrm{M}^{-1} \mathrm{Y}_\nu \to g_L^* \Upsilon_\nu g_L^\dagger \qquad \sim 6_{SU(3)_L} \otimes 1_{SU(3)_E}$$

All $\Delta\mathcal{L}=1$ *couplings are suppressed by neutrino masses.*

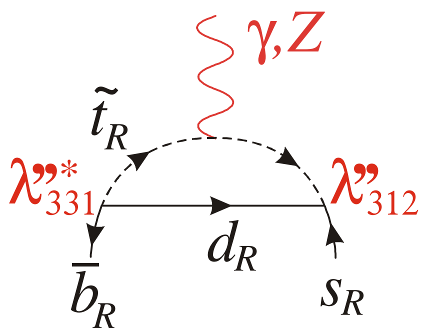
- These *suppressions are sufficient to pass all the bounds from proton decay.*

C. What Minimal Flavor Violation can say

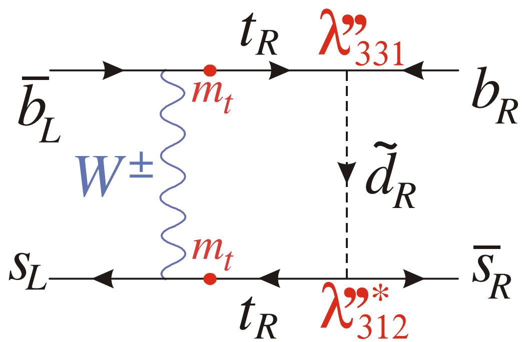
Nikolidakis,C.S. '07

- Since $\Delta\mathcal{L}$ couplings are negligible, we turn to $\Delta\mathcal{B}$ and *diquark currents*.

- Induce *new FCNC* at the loop level (nothing at tree level)



Chakraverty,Choudhury '01,...



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

...

- *With MFV,* these are *typically small* compared to the SM contributions:

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

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

Very light invisible particles

A. Flavor-based classification

Kamenik,CS, in prep.

New very light and neutral particles X coupled to the SM particles

Flavor-breaking: $\{\bar{q}^I \Gamma q^J\} X$

Flavor-blind: $\{\bar{q}^I \Gamma q^I\} X$

Able to induce the $\Delta F = 1$ quark transition.

Needs W *bosons* for the weak transitions

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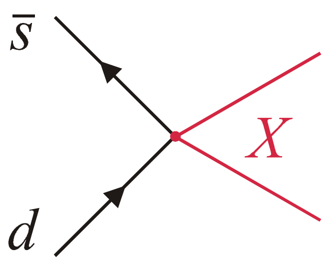
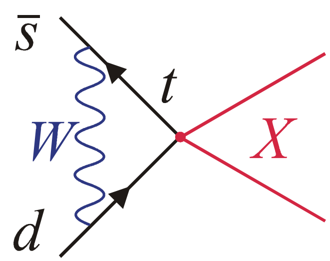
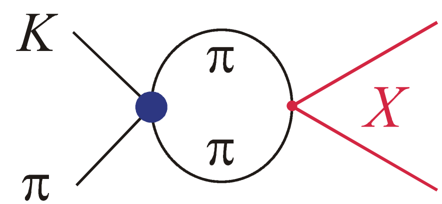
Heavy quarks: New FCNC

Light quarks: Long-distance effects







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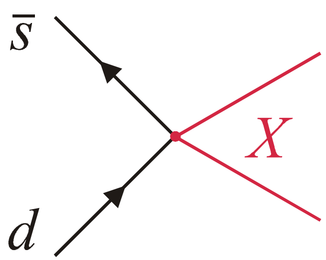
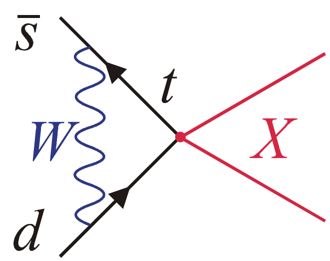
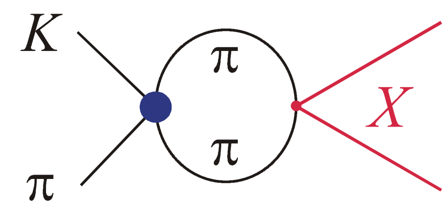






$P \to P'X$ may be large, competitive with $P \to P'\nu\bar{\nu}$.

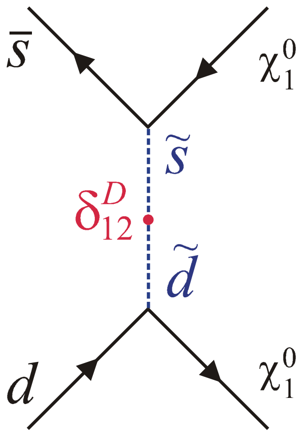
Flavor-blind searches with EWPO, quarkonium decay,... may be more sensitive.

In all cases: The X mass range probed is limited by experimental requirements.

B. Flavor-breaking scenario: Very light neutralinos

Dreiner et al ‘09

Beyond MFV, the flavor-breaking comes from squark mixings.



Effective couplings:

$\bar{s}\gamma^\mu(1\pm\gamma_5)d \otimes \bar{\chi}\gamma_\mu\gamma_5\chi$, tuned by δ_{LL},δ_{RR} .

$\bar{s}(1\pm\gamma_5)d \otimes \bar{\chi}(1\pm\gamma_5)\chi$, tuned by δ_{LR} .

(Illustrated for $K\to\pi\chi_1^0\chi_1^0$, but similar for $B\to(\pi,K^{(*)})\chi_1^0\chi_1^0$)

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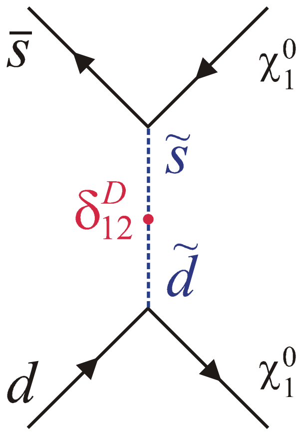

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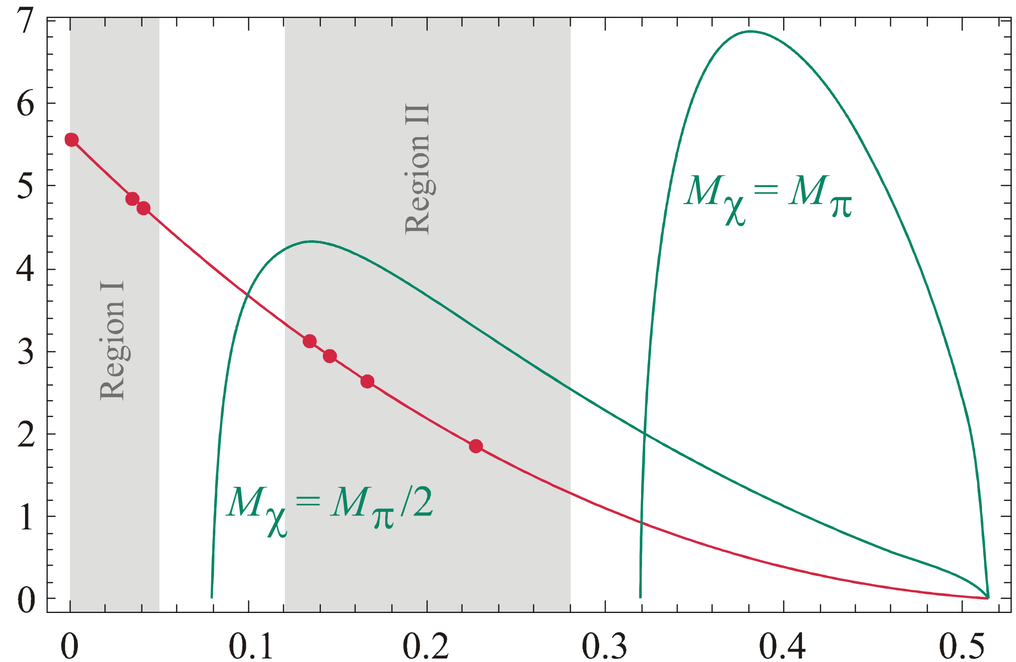

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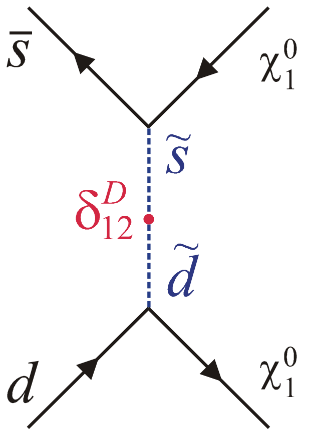

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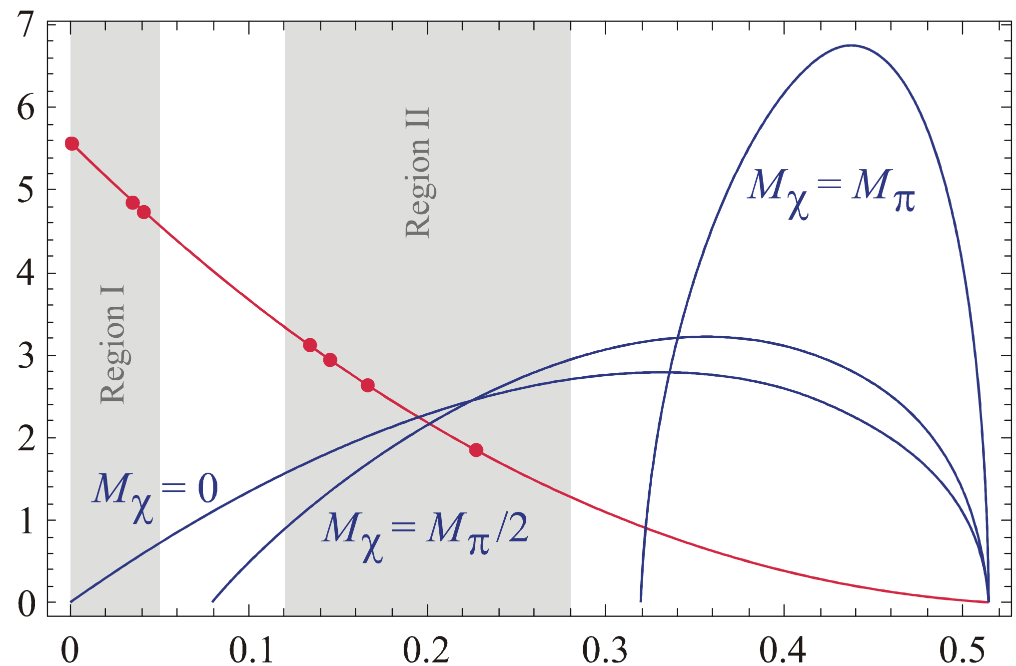
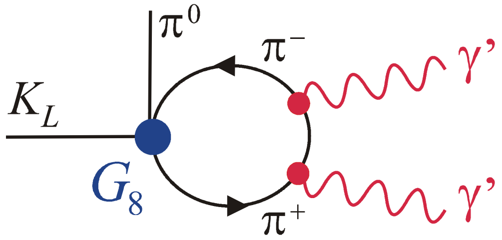


C. Flavor-blind scenario: Weakly-coupled new photon

$$\mathcal{L}_{int} = e' A'_\mu \left(\frac{2}{3} \bar{u} \gamma^\mu u - \frac{1}{3} \bar{d} \gamma^\mu d - \frac{1}{3} \bar{s} \gamma^\mu s \right)$$



Problem 1: The EW transition strongly suppresses the rate.

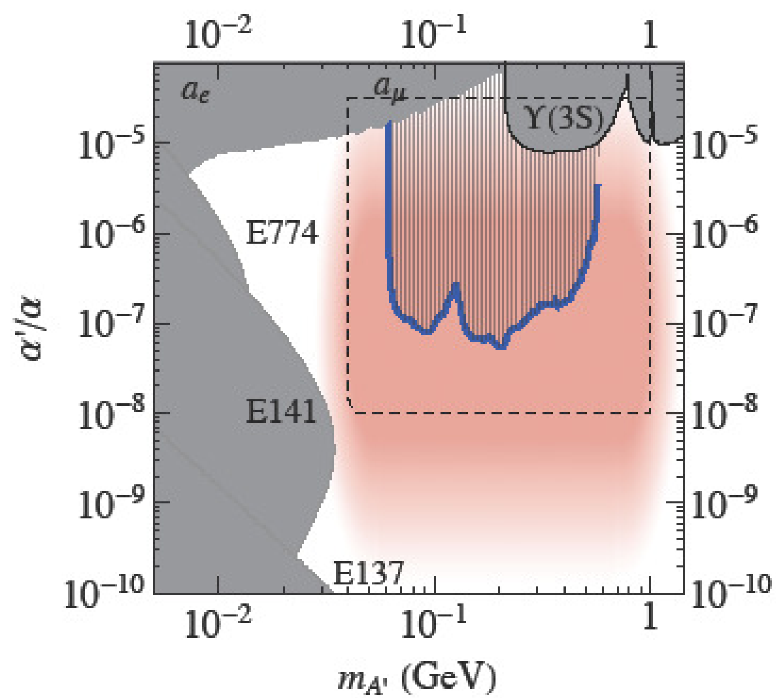
$$Br(K_L \to \pi^0 \gamma\gamma)^{exp} = 1.273(34) \times 10^{-6}$$

$$\to \; Br(K_L \to \pi^0 \gamma' \gamma') \approx \frac{\alpha'^2}{\alpha^2} \times 10^{-6}$$

A bound in the 10^{-12} range means

$$\alpha'/\alpha < 10^{-3} \; ,$$

which is already excluded...



From Essig et al, ArXiv:1001.2557

(Remember: $Br(K_L \to \pi^0 \nu \bar{\nu})^{SM} \sim 10^{-11}$)

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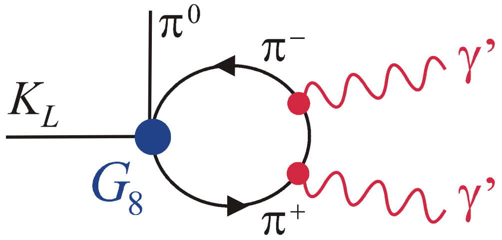
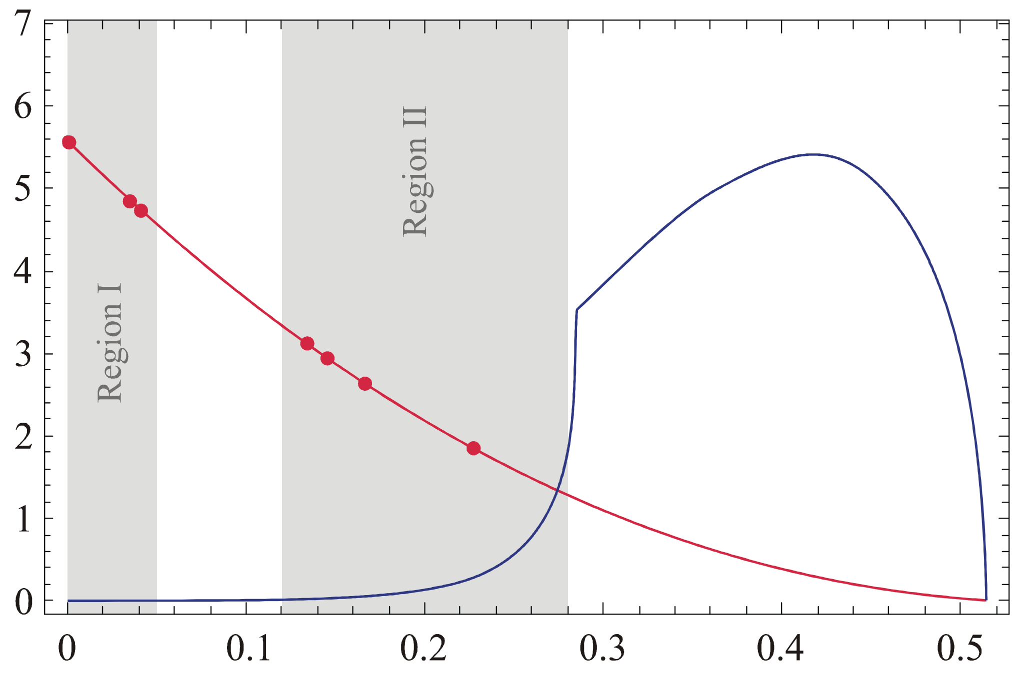


Problem 2: The LD dynamics strongly suppresses the rate below 2π.



So there is very little sensitivity, no matter the mass of γ'.

Conclusion

With the very rare $\nu\bar{\nu}$ modes one naturally probes several NP effects:

Lepton flavor violation: $P \to P'\nu^I\bar{\nu}^J$

Within MFV, $P \to P'\nu^I\bar{\nu}^J$ and $P \to P'\ell^I\bar{\ell}^J$ are both tightly constrained by $\ell^I \to \ell^J\gamma$, making them too suppressed to be seen.

R-parity violation: Tree-level effects possible from $\Delta\mathcal{L}=1$ couplings.

Within MFV, $\Delta\mathcal{L}$ couplings are negligible, and loop-level FCNC from $\Delta\mathcal{B}$ couplings are very suppressed (except maybe for $b \to s$).

New invisible states: $P \to P' + \text{missing energy}$

Competitive bounds if these states have flavor-breaking interactions, or if they couple to top quarks (?), but not if they couple to light quarks.

The main message: Let's keep an open mind and *look for the unexpected*!