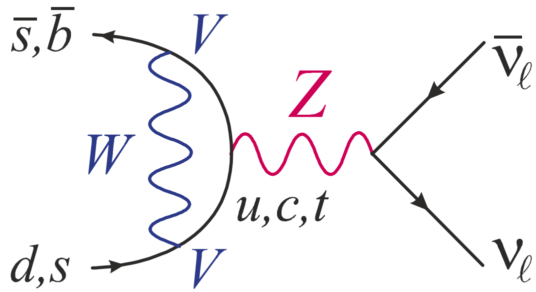
Rare K and B decays with non-standard missing energy

Christopher Smith

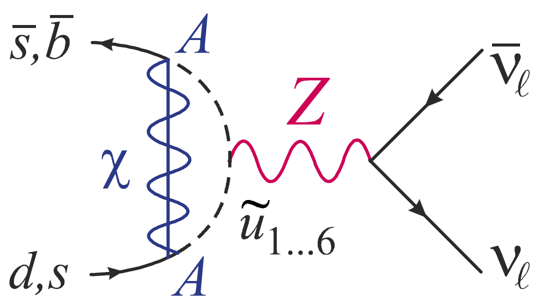
Introduction

The rare $P \to P'\nu\bar{\nu}$ decays are induced by *suppressed* FCNC processes

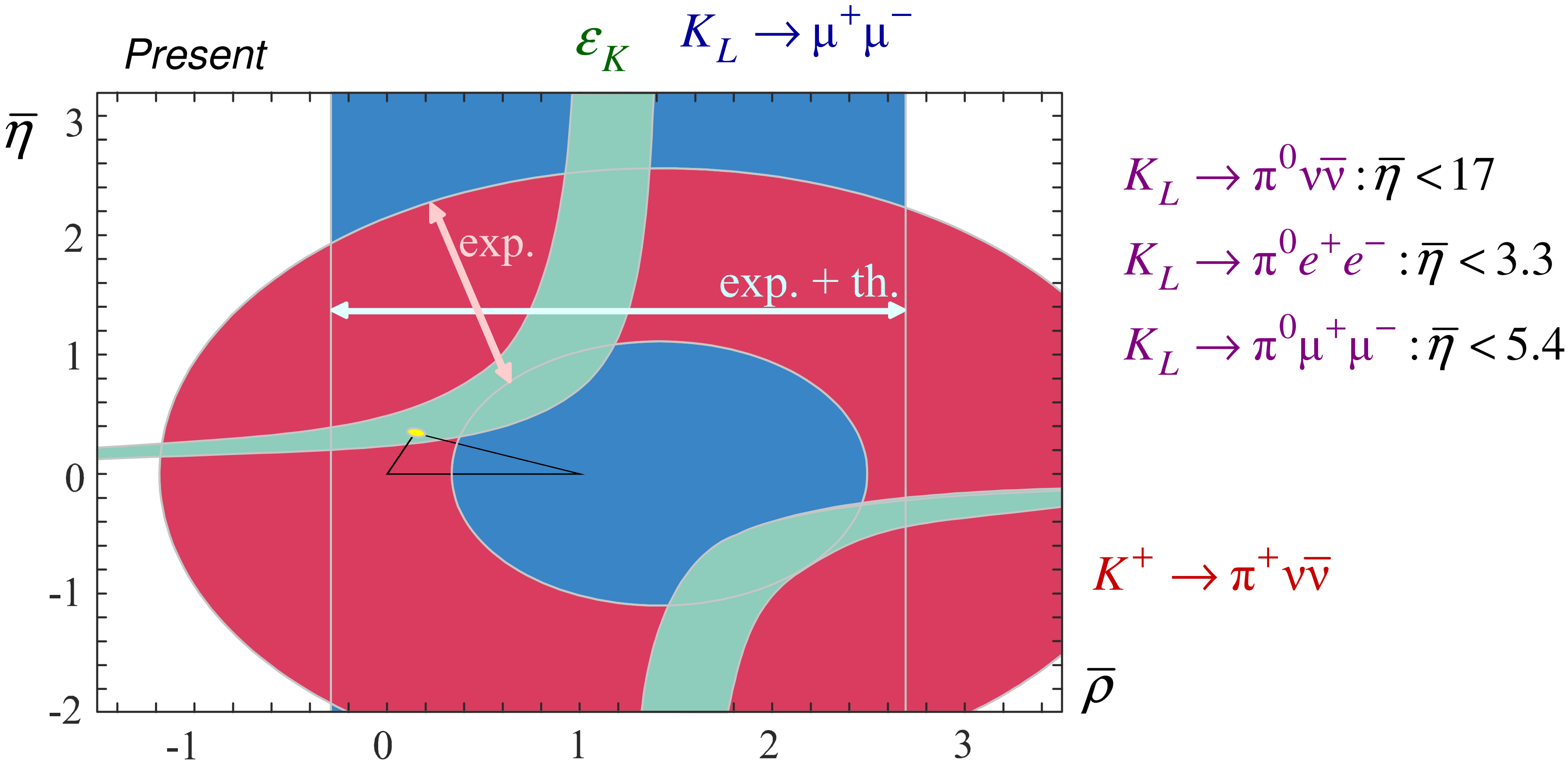


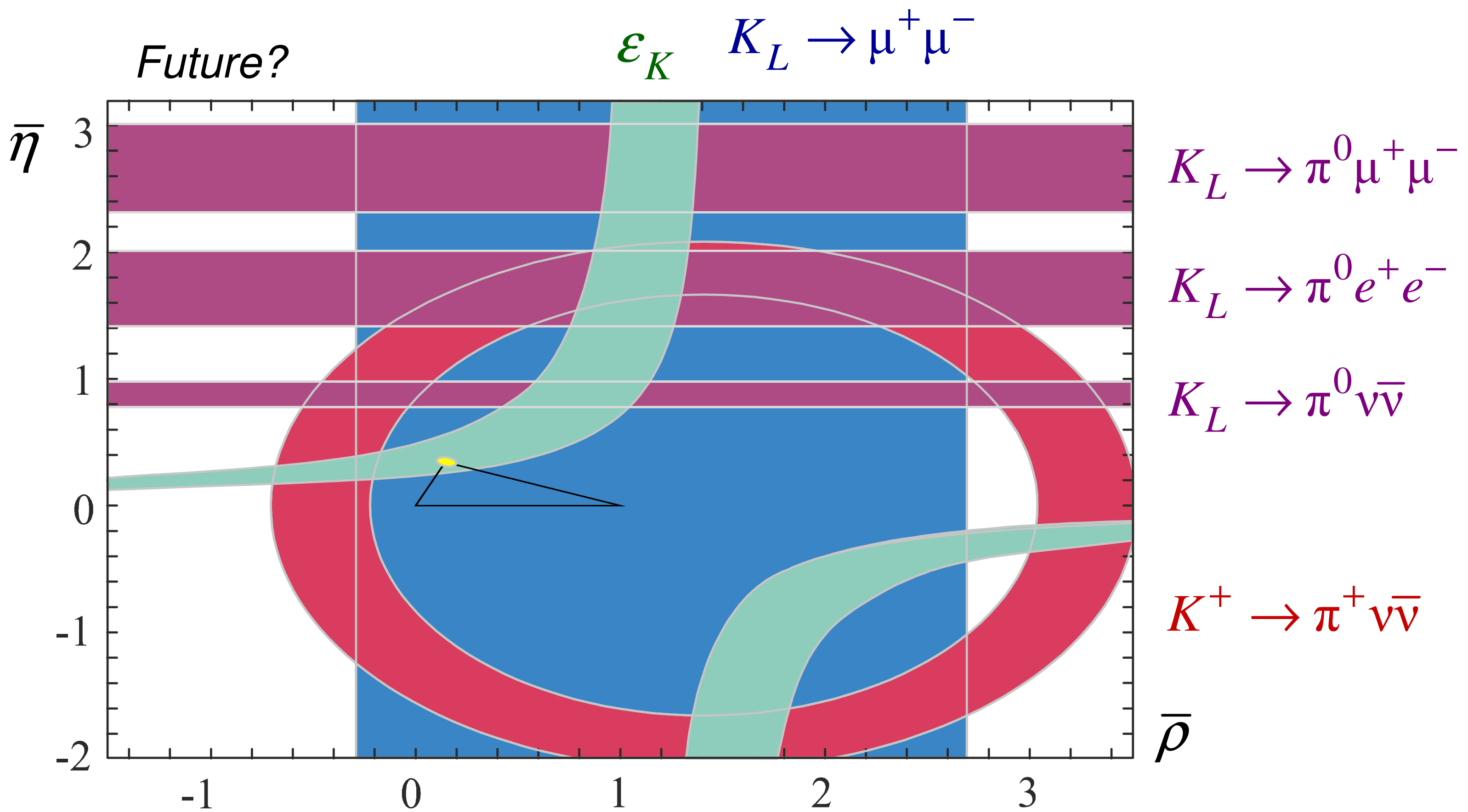
K decays are particularly small, tuned by $\left|V_{ts}^* V_{td}\right| \sim 10^{-4}$.

New Physics easily competitive, leading to large signals, e.g. in the MSSM:



Dedicated $K \to \pi\nu\bar{\nu}$ experiments under construction at CERN & J-Parc.


Present
ε_K
K_L → μ⁺μ⁻
K_L → π⁰νν̄ : η̄ < 17
K_L → π⁰e⁺e⁻ : η̄ < 3.3
K_L → π⁰μ⁺μ⁻ : η̄ < 5.4
K⁺ → π⁺νν̄
exp.
exp. + th.
η̄
ρ̄
3
2
1
0
-1
-2
-1
0
1
2
3



All TH errors &
15% EXP errors

In this talk:

Most NP analyses concentrate on the quark transition.

What could happen on the lepton side?

Outline:

I. Observables & kinematics

II. Lepton flavor violation

III. R-parity violation

IV. New invisible particles

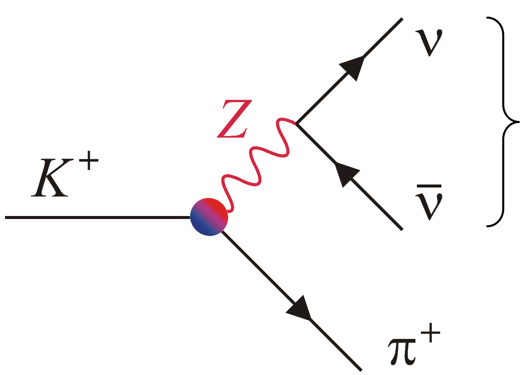
Conclusion

I. Observables & Kinematics

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

	SM $(\times 10^{-11})$	Experiment	Future (2015?)
$K_L \to \pi^0\nu\bar{\nu}$	$2.57^{+0.37}_{-0.37}$	$< 6.7 \cdot 10^{-8}$ E391a	$\mathrm{K^0TO} \sim 100\,evts$
$K^+ \to \pi^+\nu\bar{\nu}(\gamma)$	$8.22^{+0.75}_{-0.75}$	$17.3^{+11.5}_{-10.5} \cdot 10^{-11}$ E787 E949	$\mathrm{NA62} \sim 100\,evts$

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

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

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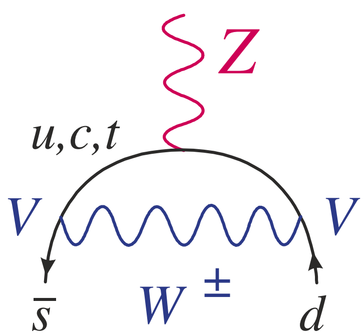
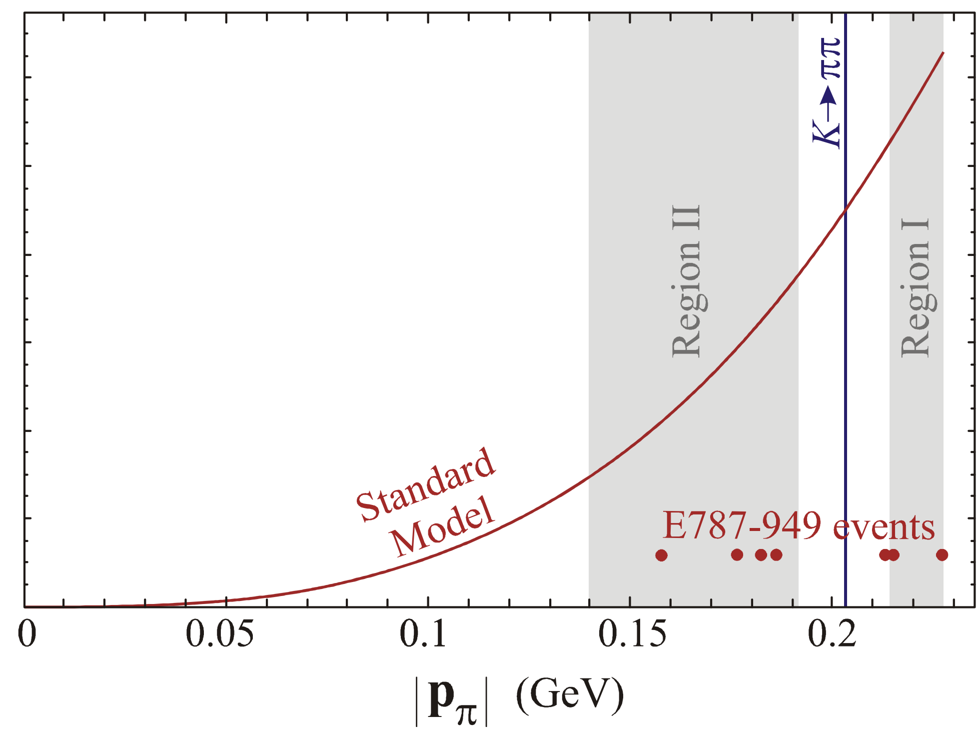
Differential rate essential for the aggressive background rejection.

Its shape depends on the current:

SM:



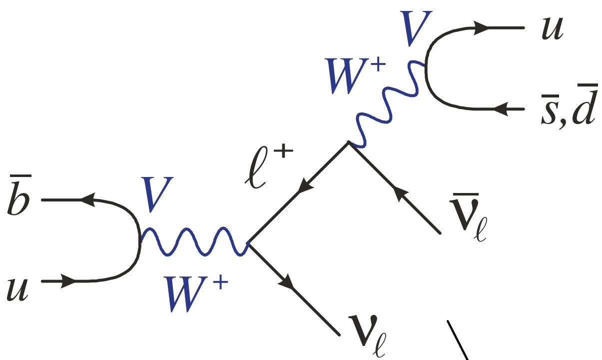
$$\Rightarrow \bar{s}_L\gamma^\mu d_L \otimes \bar{\nu}_L\gamma_\mu\nu_L$$

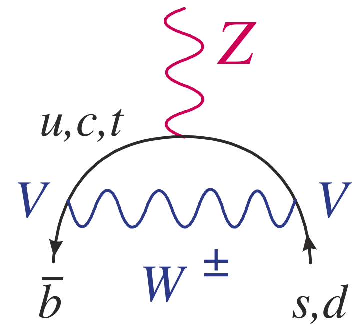


B. The $B^+ \to (\pi^+, K^{(*)+})\nu\bar{\nu}$ *decays*

Kamenik,CS '09

Tree-level contribution entangled with the FCNC for all *charged* rare decays:





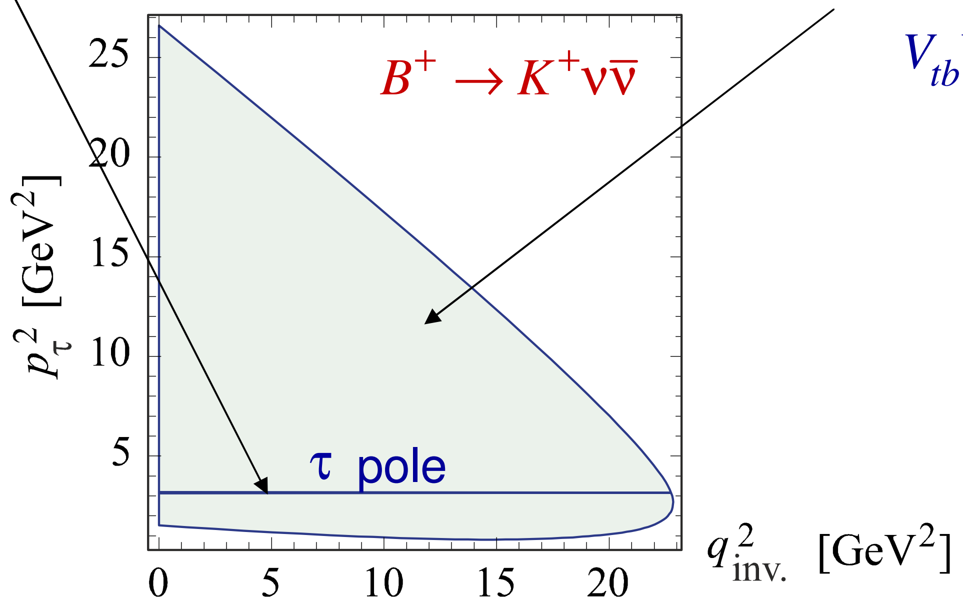
$V_{ub}V_{us}^* < V_{ub}V_{ud}^*$

$V_{tb}V_{ts}^* > V_{tb}V_{td}^*$

Sizeable for $\ell = \tau$ when on-shell.

↓

$B^+ \to \tau^+\nu_\tau$



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

Kamenik,CS '09

$\times 10^{-6}$	τ pole	FCNC	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 $b \to (s,d)\nu\bar{\nu}$. *(seen)*

$B^+ \to \nu_\tau\tau^+[\to \pi^+\bar{\nu}_\tau]$: 2% pollution by the direct $b \to d\nu\bar{\nu}$ transition. *(seen)*

$B^+ \to \nu_\tau\tau^+[\to K^{(*)+}\bar{\nu}_\tau]$: ~ 700% apparent enhancement due to $b \to s\nu\bar{\nu}$. *(soon?)*

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

II. Lepton flavor violation

A. Generalities

- Since neutrino flavors are not seen, one can only measure

$$\Gamma(P \to P'\nu\bar{\nu}) = \sum_{I,J=1,2,3} \Gamma(P \to P'\nu^I\bar{\nu}^J)$$

- When NP respects the SM gauge symmetries, neutrinos are in doublets,

$$L = \begin{pmatrix} \nu_L \\ \ell^- \end{pmatrix},$$

so $P \to P'\nu^I\bar{\nu}^J$ is necessarily correlated with $P \to P'\ell^I\bar{\ell}^J$.

- Given current bounds, $P \to P'\nu^I\bar{\nu}^J$, $I,J=1,2$ should be very suppressed,

but not much is currently known for the third generation...

B. What Minimal Flavor Violation can say

Chivukula,Georgi '87
Hall,Randall '90
D'Ambrosio et al.'02
Cirigliano et al.'05
Colangelo et al.'08
...

The dominant operator is:

$$\mathcal{H}_{eff} = \frac{1}{\Lambda^2} \bar{Q}^I (\mathrm{Y}_u^\dagger \mathrm{Y}_u)^{IJ} Q^J \otimes \bar{L}^I (a_0 1 + a_1 \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu)^{IJ} L^J$$

Quark flavor transition

$$v \mathrm{Y}_u = m_u V_{CKM}$$

Lepton flavor transition

$$v^2 \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu = M_R U_{PMNS} \mathrm{m}_\nu U_{PMNS}^\dagger + \ldots$$

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$$v\mathrm{Y}_u = m_u V_{CKM}$$

$$b \to s : \left|V_{tb}^* V_{ts}\right| \sim 10^{-2}$$

$$b \to d : \left|V_{tb}^* V_{td}\right| \sim 10^{-3}$$

$$s \to d : \left|V_{ts}^* V_{td}\right| \sim 10^{-4}$$

Lepton flavor transition

$$v^2 \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu = M_R U_{PMNS} \mathrm{m}_\nu U_{PMNS}^\dagger + \ldots$$

For $\Lambda \lesssim$ 1 TeV, $\dfrac{\Gamma_{NP}^{LFC}}{\Gamma_{SM}}(P \to P' L^I \bar{L}^I) \lesssim 1$.

MFV solves the *NP flavor puzzles*.

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MFV solves the *NP flavor puzzles*.

Lepton flavor transition

$$v^2 \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu = M_R U_{PMNS}\, \mathrm{m}_\nu U_{PMNS}^\dagger + \dots$$

Can be made large by adjusting the seesaw parameters.

But, $(\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu)^{I \neq J}$ is bounded by $\ell \to \ell' \gamma$:

$$\mathcal{H}_{eff} = \frac{e}{\Lambda^2} E^I \mathrm{Y}_e^{II} (\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu)^{IJ} \sigma^{\mu\nu} L^J H^\dagger F_{\mu\nu}$$

For $\Lambda \lesssim$ 1 TeV, $\frac{\Gamma_{NP}^{LFV}}{\Gamma_{NP}^{LFC}} \lesssim 10^{-4}$.

B. What Minimal Flavor Violation can say

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Quark flavor transition

$$v\mathrm{Y}_u = m_u V_{CKM}$$

Lepton flavor transition

$$v^2 \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu = M_R U_{PMNS} \mathrm{m}_\nu U_{PMNS}^\dagger + \ldots$$

When $I \neq J$, model-independent MFV says:

$$B(K \to \pi L^I \bar{L}^J) < 10^{-15}$$

$$B(B \to (\pi, K) L^I \bar{L}^J) < 10^{-10}$$

This arises because *MFV factorizes quark & lepton flavor groups*.

It may not survive if there is a *direct connection* (leptoquark, unification, ...)

Davidson,Descotes '10, Cirigliano et al.'05

III. R-parity violation

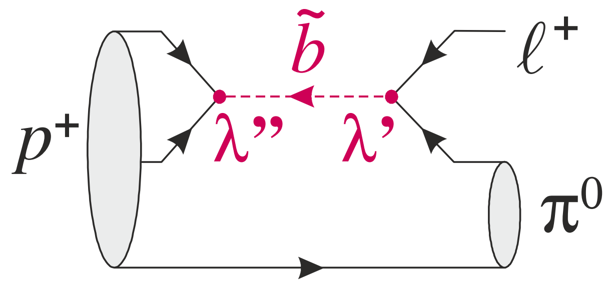
A. The MSSM without R-parity

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

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

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

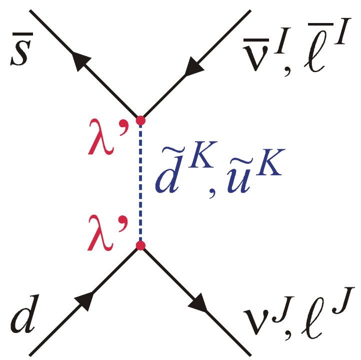
Ex.:



Experimentally, $\tau_{p^+} > 10^{30}$ years, which implies $|\lambda'\lambda''| \leq 10^{-27}$?

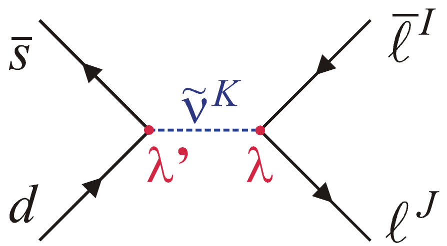
B. Possible effects in rare decays

To avoid proton decay, but get a large signal, discard $\Delta\mathcal{B}=1$ couplings.



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

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



Scalar-pseudoscalar effective couplings:

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

The $\Delta\mathcal{L}$ couplings can induce all $P \to P'\nu^I\overline{\nu}^J$ and $P \to P'\ell^I\overline{\ell}^J$ decays.

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

C. What Minimal Flavor Violation can say

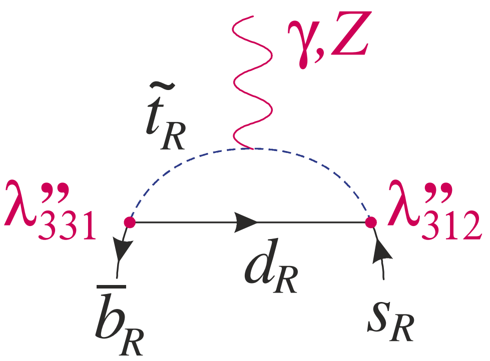
Nikolidakis,C.S. '07

- The $\Delta\mathcal{B}$ couplings are allowed by $\mathrm{Y}_{u,d}$, but $\Delta\mathcal{L}$ couplings are not when $m_\nu = 0$

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

MFV sufficient to pass all the bounds from proton decay.

- $\Delta\mathcal{B}$ couplings induce *new FCNC* at the loop level:



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

IV. New invisible particles

Kamenik,CS, in prep.

A. Flavor-based classification

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

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

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

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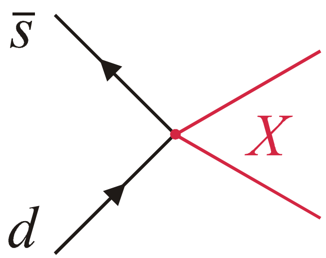
Able to induce the $\Delta F = 1$ quark transition.



$P \to P' X$ natural probes, and the signal may be large.

A. Flavor-based classification

Kamenik,CS, in prep.

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

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

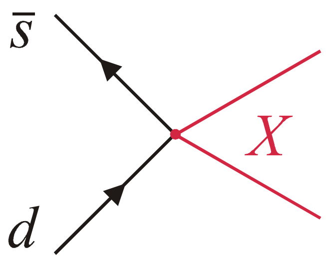
Flavor-blind: $\{\bar{q}^I \Gamma q^I\} X$

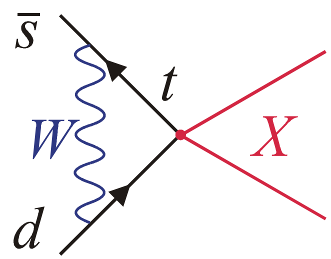
Needs W *bosons* for the weak transitions

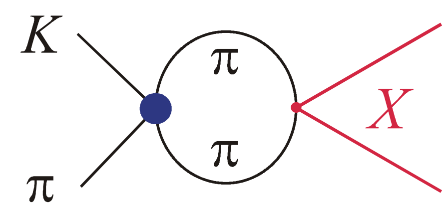
Able to induce the $\Delta F = 1$ quark transition.

Heavy quarks:
New FCNC

Light quarks:
Long-distance effects







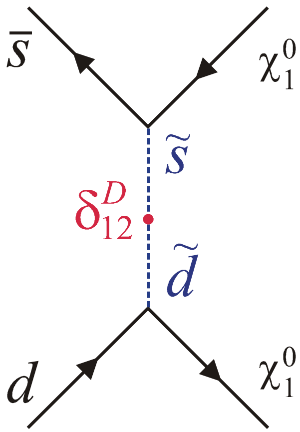
$P \to P' X$ natural probes, and the signal may be large.

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

B. Flavor-breaking scenario: Very light neutralinos

Dreiner et al '09

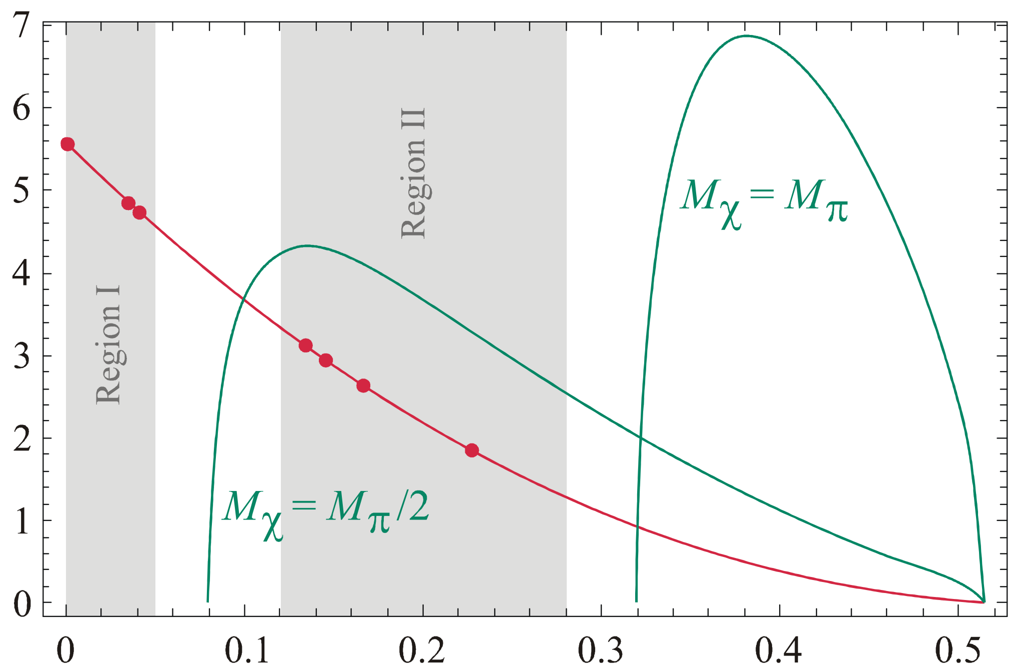
Beyond MFV, the flavor-breaking comes from squark mixings.



Effective couplings: $\bar{s}\gamma^\mu(1\pm\gamma_5)d \otimes \bar{\chi}\gamma_\mu\gamma_5\chi$ $(\delta_{LL},\delta_{RR})$

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

$K^+ \to \pi^+\chi_1^0\chi_1^0$



(similar for $B \to P\chi_1^0\chi_1^0$)

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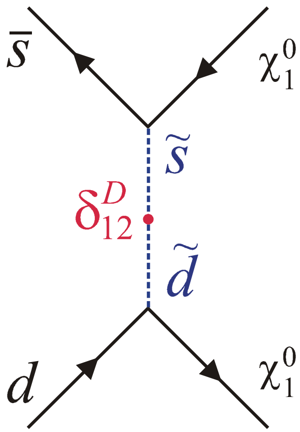
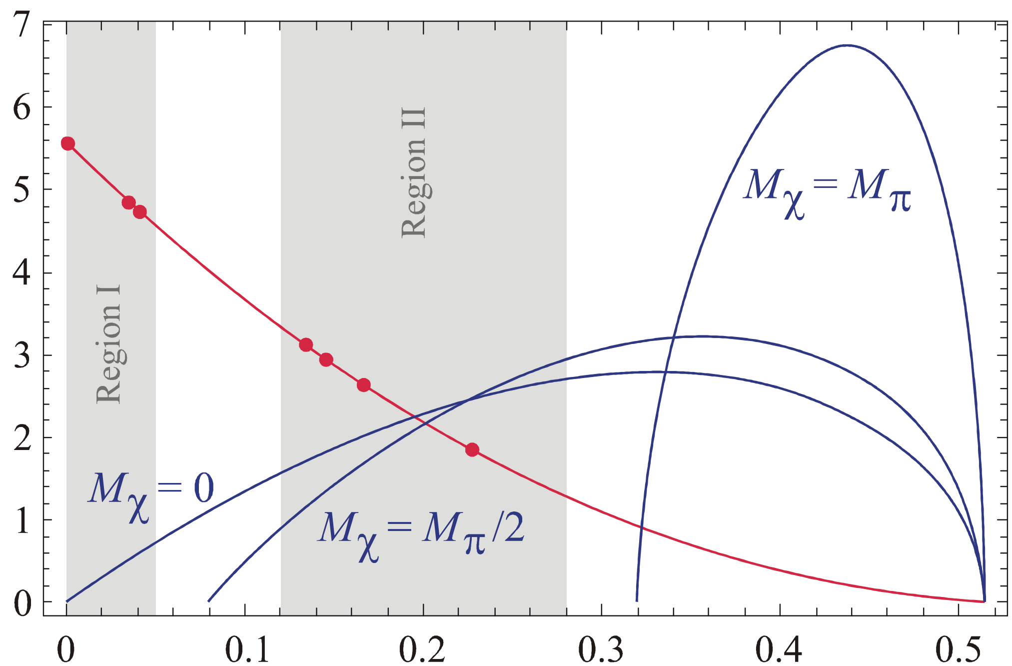


Effective couplings: $\bar{s}\gamma^\mu(1\pm\gamma_5)d \otimes \bar{\chi}\gamma_\mu\gamma_5\chi \quad (\delta_{LL},\delta_{RR})$

$\bar{s}(1\pm\gamma_5)d \otimes \bar{\chi}(1\pm\gamma_5)\chi \quad (\delta_{LR})$

$K^+ \to \pi^+\chi_1^0\chi_1^0$

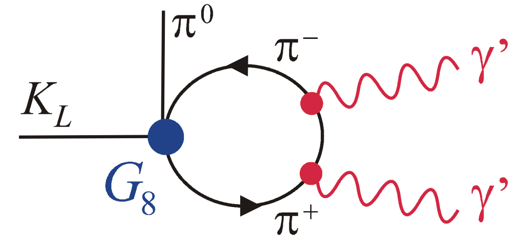


(similar for $B \to P\chi_1^0\chi_1^0$)

Kamenik,CS, in prep.

C. Flavor-blind scenario: Weakly-coupled "dark photon"

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



Problem 1: The EW transition strongly suppresses the rate.

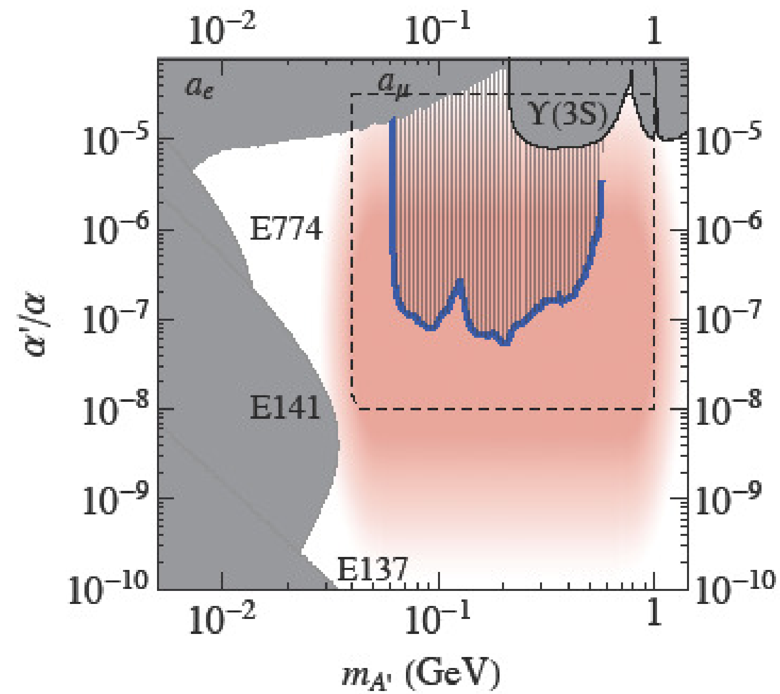
$$Br(K_L \to \pi^0 \gamma\gamma)^{\rm exp} = 1.273(34) \times 10^{-6}$$

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

A bound in the 10^{-13} range means

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

which is already excluded...



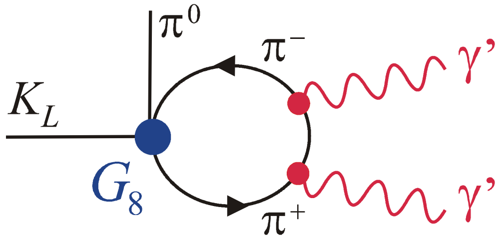
From Essig et al, ArXiv:1001.2557

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

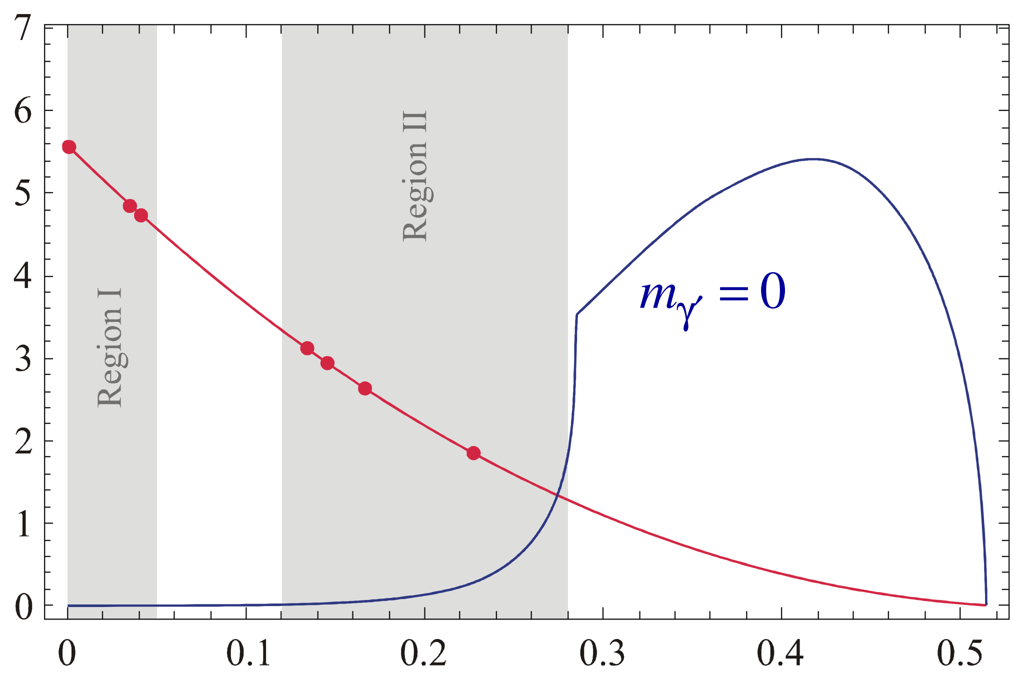
Kamenik,CS, in prep.

C. Flavor-blind scenario: Weakly-coupled "dark photon"

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



Problem 2: The LD dynamics strongly suppresses the rate below $2m_\pi$.

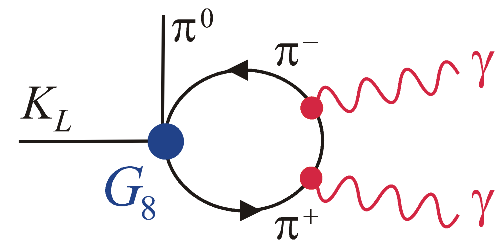


So there is very little sensitivity, no matter the mass of γ'.

Kamenik,CS, in prep.

C. Flavor-blind scenario: Weakly-coupled "dark photon"

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



Solution ? Look for $K_L \to \pi^0 \gamma \gamma'$ with $m_{\gamma\gamma'} > 2m_\pi$!

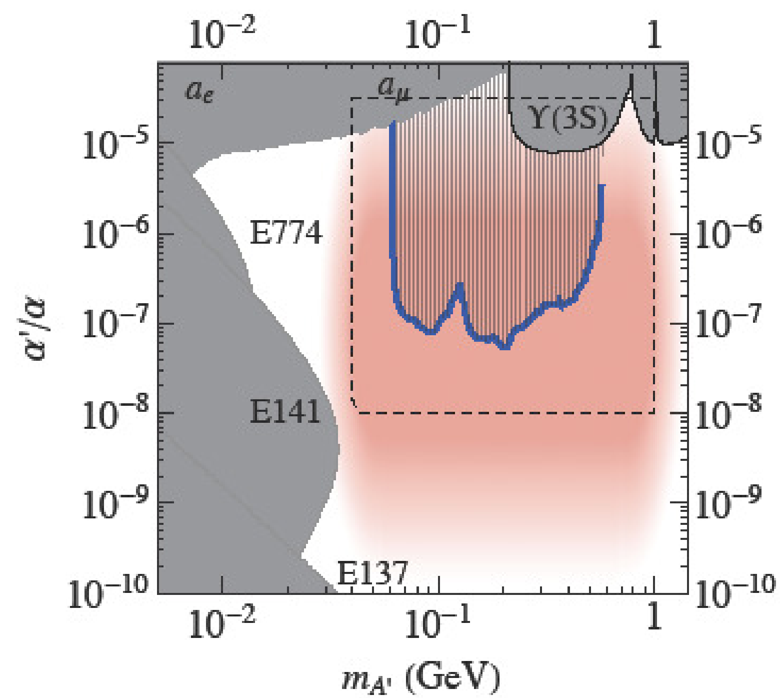
$$Br(K_L \to \pi^0 \gamma\gamma)^{\text{exp}} = 1.273(34) \times 10^{-6}$$

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

A bound in the 10^{-13} range means

$$\alpha' / \alpha < 10^{-7} \ ,$$

Competitive with $e^- \to e^- \gamma' [\to e^+ e^-]$!



From Essig et al, ArXiv:1001.2557

Conclusion

The rare $P \to P'\nu\bar{\nu}$ decays naturally probe several classes of NP effects:

On the quark side, NP flavor structures could induce the FCNC transitions:

The rare decays, suppressed in the SM, are ideal probes.

On the leptonic side, LFV or R-parity violating effects are possible.

No effect within generic MFV → *Test for the MFV principle*.

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

Competitive with flavor-blind experiments for a large class of particles.