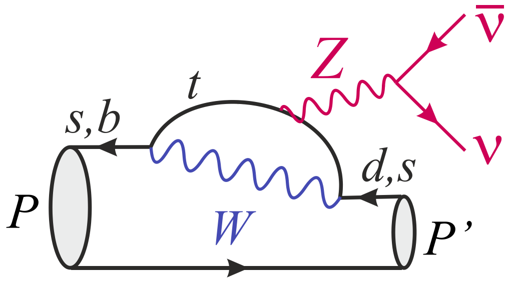
- Real production of DM particles in meson decays?

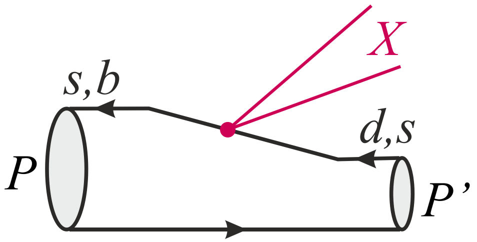
t-channel models: mediator is heavy → Local SM+DM operator

What if DM is light enough to be produced in meson decays?

What if mediator models is extended to describe a new light state?

Look for signatures in some the cleanest FCNC-induced decay:

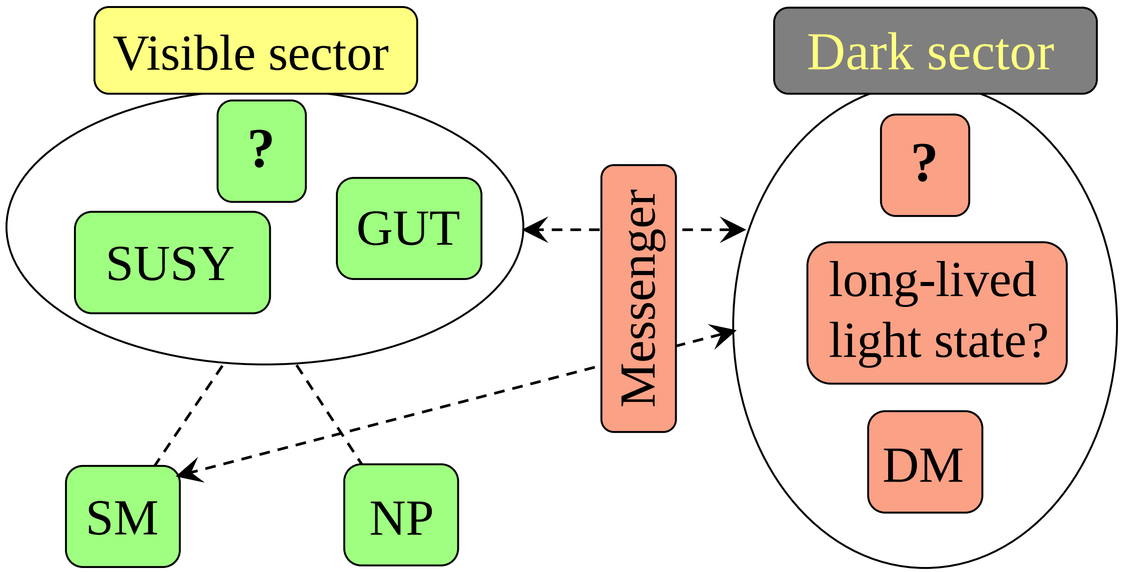




$P = B, K, \pi, \ldots$

Both produce the same final state with missing energy.

A. How to probe systematically these signatures?

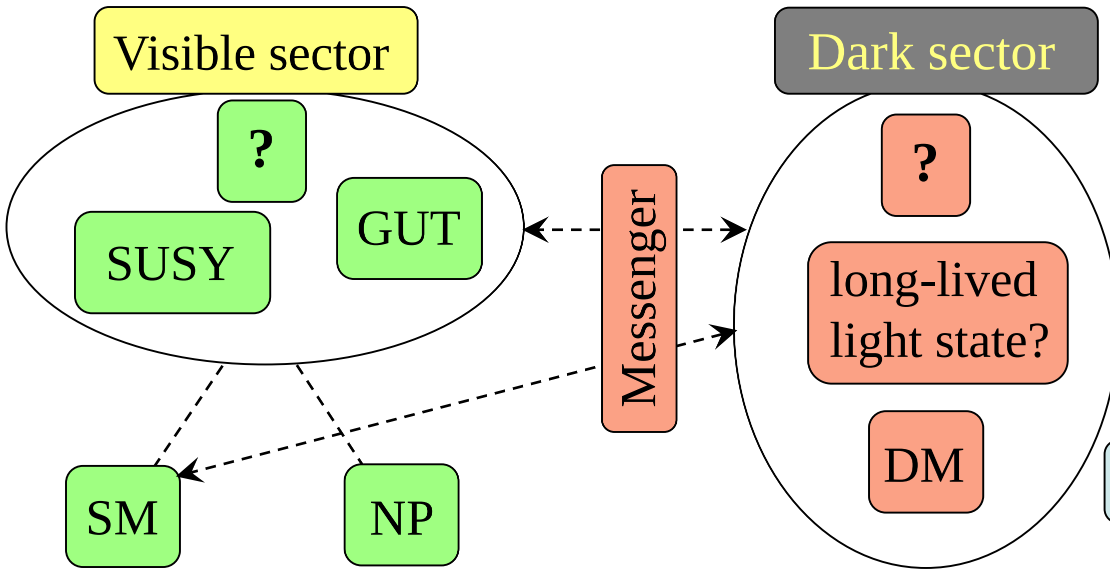


X = dark sector state connected to the SM, or a light messenger.

$$\mathcal{L}_{TOT} = \mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2} Q_i[SM] + \ldots \quad + \sum_{d\geq 3} \frac{c_i}{\tilde{\Lambda}^{d-4}} Q_i'[SM + X] + \ldots$$

Very weakly interacting → Consider X to be neutral, but include all possible interactions as gauge-invariant effective operators.

A. How to probe systematically these signatures?



spin 0, 1/2, 1, 3/2,...?

Charged/neutral?
Majorana/Dirac?
Abelian or not?

Dark gauge-invariance?

Baryon & lepton numbers?

$$\mathcal{L}_{TOT} = \mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2} Q_i[SM] + \ldots$$

Coupled to the SM Higgs, fermions, gauge bosons?

The leading operators must be kept separately for each possibility.

Kamenik, CS '11

A. How to probe systematically these signatures?

	Neutral		Charged	
	Flavorless	Flavored	Flavorless	Flavored
ϕ : scalar	$\Lambda H^\dagger H\phi$	$\frac{1}{\Lambda}\bar{Q}\gamma^\mu Q\partial_\mu\phi$	$H^\dagger H\phi^\dagger\phi$	$\frac{1}{\Lambda^2}\bar{Q}\gamma^\mu Q\phi^\dagger\overleftrightarrow{\partial}_\mu\phi$
ψ : spin 1/2	$H\overline{L}^C\psi$	$\frac{1}{\Lambda^2}\bar{D}Q\overline{L}^C\psi$	$\frac{1}{\Lambda^2}H^\dagger\overleftrightarrow{\mathcal{D}}^\mu H\bar{\psi}\gamma_\mu\psi$	$\frac{1}{\Lambda^2}\bar{Q}\gamma^\mu Q\bar{\psi}\gamma_\mu\psi$
V^μ : vector	$H^\dagger\overleftrightarrow{\mathcal{D}}^\mu HV_\mu$	$\bar{Q}\gamma^\mu QV_\mu$	$H^\dagger HV_\mu V^\mu$	$\frac{1}{\Lambda^2}\bar{Q}\gamma^\mu QV^\nu V_{\mu\nu}$
V^μ : gauge	$B^{\mu\nu}V_{\mu\nu}$	$\frac{1}{\Lambda^2}H\bar{D}\sigma^{\mu\nu}QV_{\mu\nu}$	$\frac{1}{\Lambda^2}H^\dagger HV_{\mu\nu}V^{\mu\nu}$	$\frac{1}{\Lambda^4}\bar{Q}\gamma^\mu\mathcal{D}_\nu QV_{\mu\rho}V^{\rho\nu}$
Ψ^μ :spin 3/2	$\frac{1}{\Lambda}\mathcal{D}_\mu H\overline{L}^C\Psi^\mu$	$\frac{1}{\Lambda^3}\bar{D}\mathcal{D}_\mu Q\overline{L}^C\Psi^\mu$	$\frac{1}{\Lambda}H^\dagger H\bar{\Psi}^\mu\Psi_\mu$	$\frac{1}{\Lambda^2}\bar{Q}\gamma^\mu Q\bar{\Psi}^\rho\gamma_\mu\Psi_\rho$

All these operators -and many more- contribute to the rare decays.

Each has its own signatures in terms of channels and kinematics.

B. Naïve estimates of the reach?

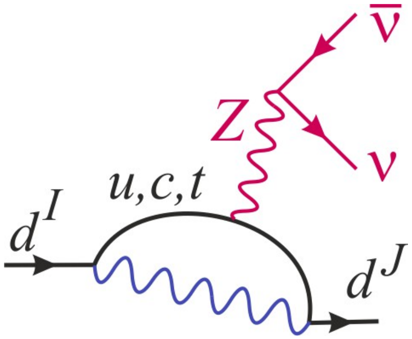
New very light and neutral particles X coupled to the SM particles

Flavor-changing:

$$\frac{1}{\Lambda^2}\bar{Q}^I\gamma^\mu Q^J\bar{\psi}\gamma_\mu\psi$$

Assuming its contribution is similar to the SM one:

$$\frac{1}{\Lambda^2} \approx G_F\frac{g^2}{4\pi}V_{tI}V_{tJ}^\dagger \Leftarrow$$



	Generic		
Λ_{bs}	$>8\ TeV$		
Λ_{bd}	$>20\ TeV$		
Λ_{sd}	$>90\ TeV$		

B. Naïve estimates of the reach?

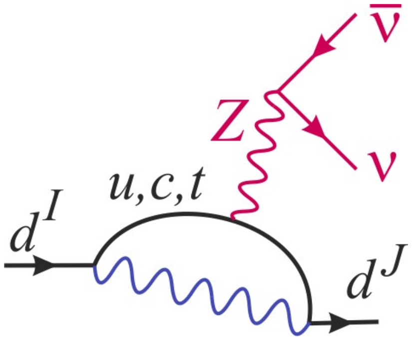
New very light and neutral particles X coupled to the SM particles

Flavor-changing:

$$\frac{1}{\Lambda^2}\bar{Q}^I\gamma^\mu Q^J\bar{\psi}\gamma_\mu\psi$$

Assuming Minimal Flavor Violation holds:

$$\frac{1}{\Lambda^2}V_{tI}V_{tJ}^\dagger \approx G_F\frac{g^2}{4\pi}V_{tI}V_{tJ}^\dagger \Leftarrow$$



	Generic	MFV	
Λ_{bs}	$> 8\ TeV$	$> 2\ TeV$	
Λ_{bd}	$> 20\ TeV$	$> 2\ TeV$	
Λ_{sd}	$> 90\ TeV$	$> 2\ TeV$	

B. Naïve estimates of the reach?

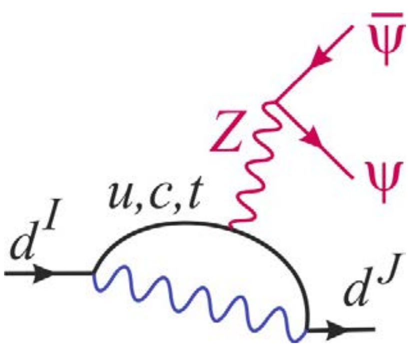
New very light and neutral particles X coupled to the SM particles

Flavor-changing:

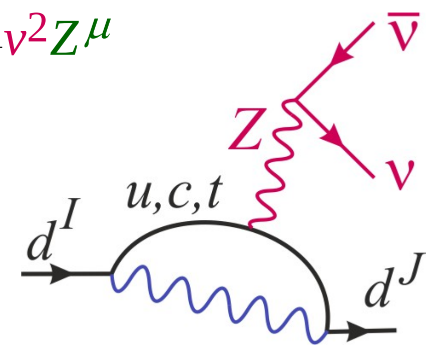
$$\frac{1}{\Lambda^2}\bar{Q}^I\gamma^\mu Q^J\bar{\psi}\gamma_\mu\psi$$

Flavor-blind:

$$\frac{1}{\Lambda^2}\underbrace{H^\dagger\overleftrightarrow{\mathcal{D}}^\mu H}_{\frac{ig}{2c_W}v^2 Z^\mu}\bar{\psi}\gamma_\mu\psi$$



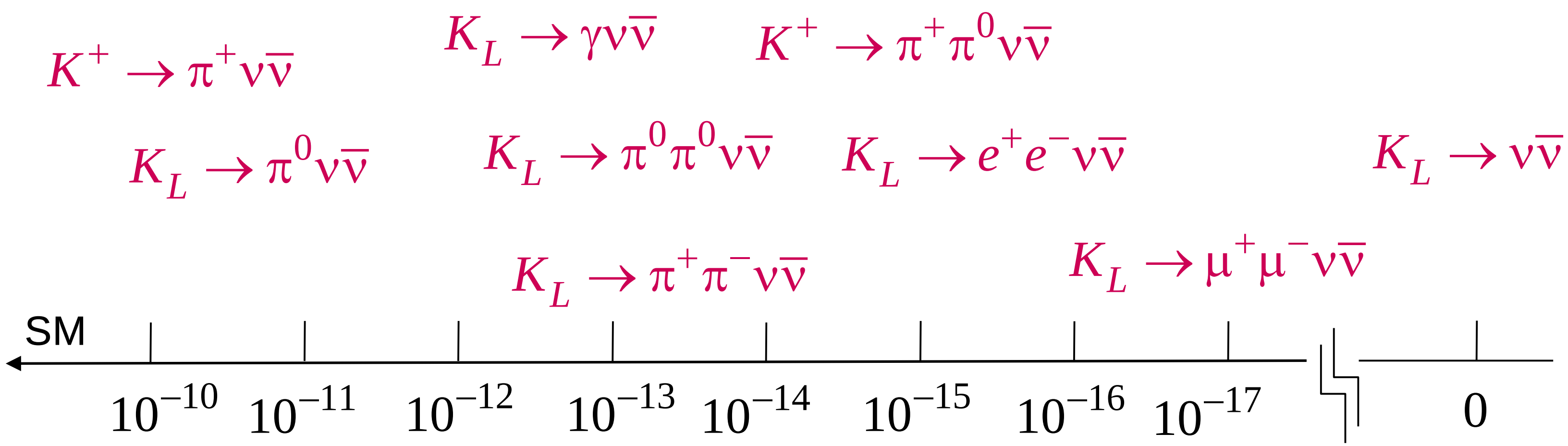
$$\Rightarrow \frac{v^2}{\Lambda^2}G_F\frac{g^2}{4\pi}V_{tI}V_{tJ}^\dagger \approx G_F\frac{g^2}{4\pi}V_{tI}V_{tJ}^\dagger \Leftarrow$$



	Generic	MFV	Flavorless
Λ_{bs}	$>8\ TeV$	$>2\ TeV$	$>0.2\ TeV$
Λ_{bd}	$>20\ TeV$	$>2\ TeV$	$>0.2\ TeV$
Λ_{sd}	$>90\ TeV$	$>2\ TeV$	$>0.2\ TeV$

C. What are the players: Rare decay modes with missing energy

Some K decay modes with good sensitivity:



Remarks:
- K_S modes: opposite CP, similar width, but much smaller BR.
- Leptonic modes essentially Dalitz pairs from real photons.
- Charged-current modes $K^+ \to (\pi)\ell^+\nu$ can also play a role.

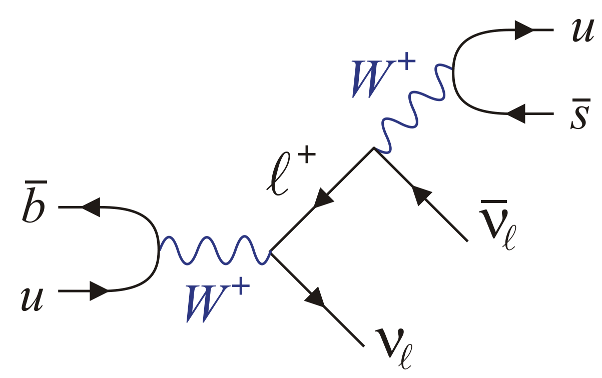
C. What are the players: Rare decay modes with missing energy

Main B decay modes into neutrino pairs:

$$B \to (\pi, \rho, K, K^*, \ldots)\nu\bar{\nu} : 10^{-5} - 10^{-6}$$

$$B \to \nu\bar{\nu}(\gamma) : 10^{-9}$$

Beware of $B^+ \to \nu[\bar{\tau} \to (\pi, \rho)\bar{\nu}]$
hiding the FCNC process:



Indirect bounds: $B(P \to YZ) \gg B(P \to Y\nu\bar{\nu}) \Rightarrow$ Bound on $B(Z \to E_{miss})$.

[provided m_Z^2 lies within the signal region!]

Examples:

$$K \to \pi\pi \gg K \to \pi\nu\bar{\nu} \quad \Rightarrow \pi^0 \to E_{miss}$$

$$B \to K^* J/\psi \gg B \to K^*\nu\bar{\nu} \quad \Rightarrow J/\psi \to E_{miss}$$

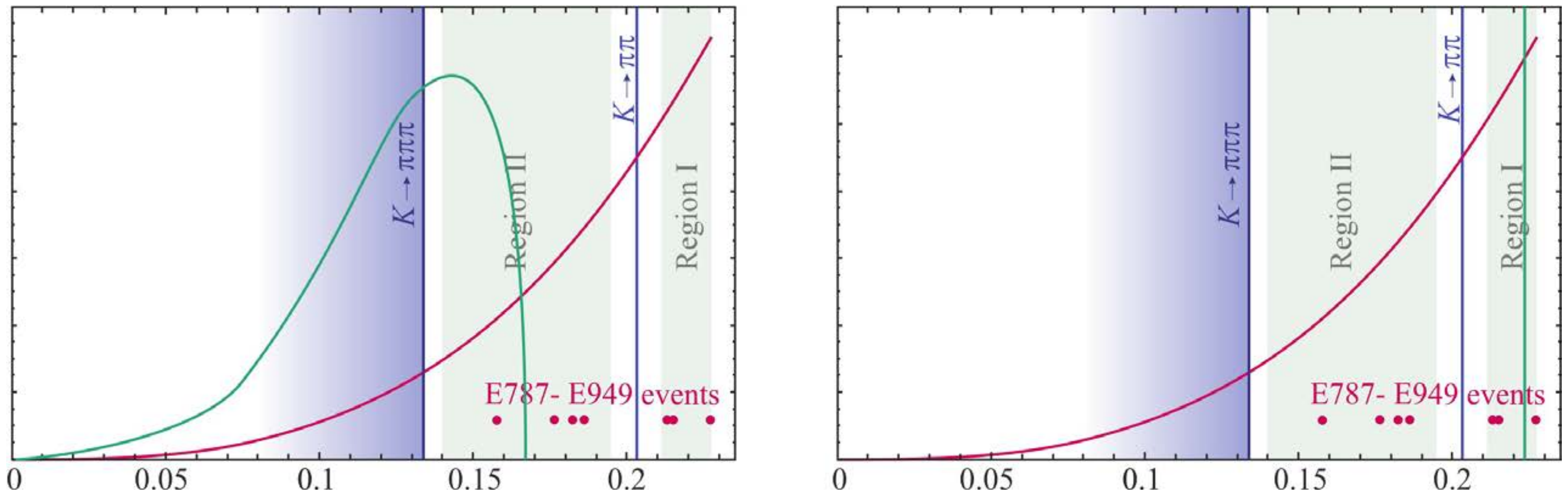
$$B^+ \to \rho^+ D \gg B^+ \to \rho^+\nu\bar{\nu} \quad \Rightarrow D^0 \to E_{miss}$$

D. A word of caution: Beware of the kinematics!!!

Background rejection: V-A current assumed & kinematical range limited.

Consequence: Using total rates to set limit is wrong!

$K^+ \to \pi^+ XX$ $K^+ \to \pi^+ X$



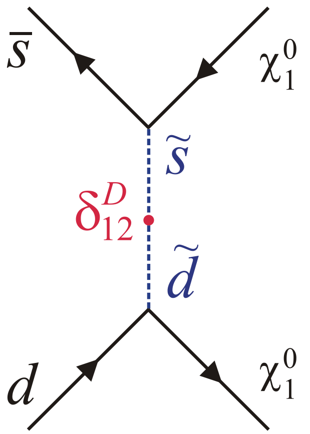
For both K and B decays:
- Cuts are usually introduced to reduce BG.
- SM differential rate may be implicit in MC.

At the very least, look for reconstructed rate discrepancies between SR.

D. A word of caution: Beware of the kinematics!!!

Dreiner et al ‘09

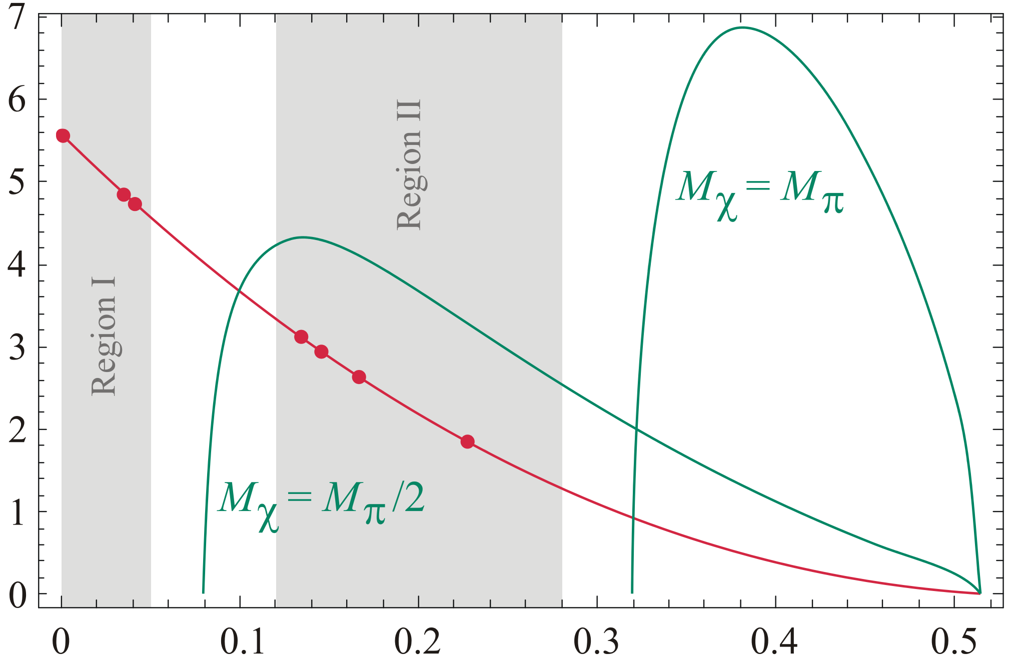
Beyond MFV, the flavor-breaking comes from squark mixings.



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

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

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



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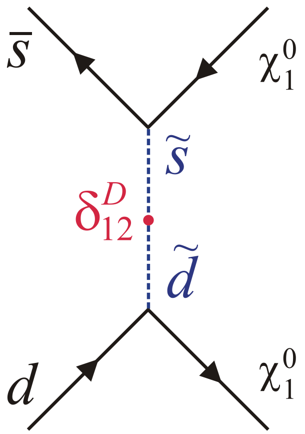

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