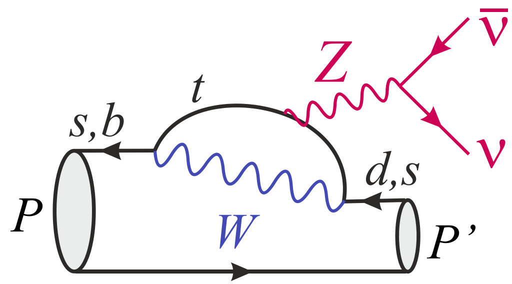
Heidelberg, Germany September 27th, 2017

FCNC portals to the dark sector

Christopher Smith

• Introduction

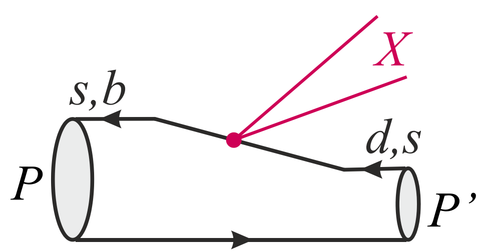
Some of the cleanest FCNC-induced decays produce neutrinos:



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

But neutrinos are undetected, only missing energy is reconstructed.

Could there be something else? Some new dark state X?

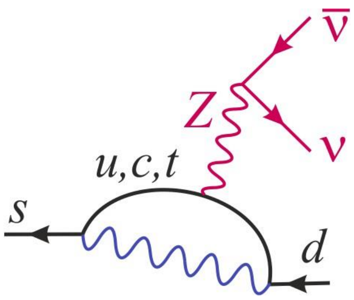


- Outline

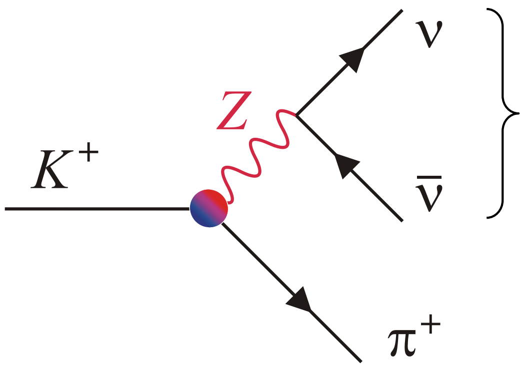
I. Observables and kinematics

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

	SM ($\times 10^{-11}$)	Experiment
$K_L \to \pi^0 \nu\bar{\nu}$	$2.57^{+0.37}_{-0.37}$	$< 2.6 \cdot 10^{-8}$ 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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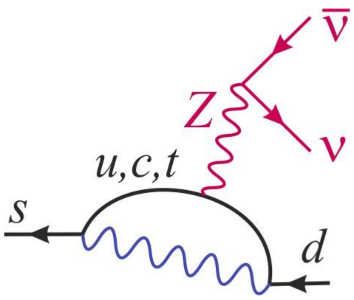
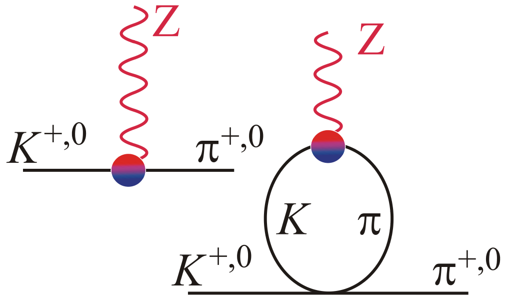


Z penguin & W boxes lead to the interaction $\bar{s}\gamma^{\mu}(1-\gamma_5)d \otimes \bar{\nu}\gamma_{\mu}(1-\gamma_5)\nu$.

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



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

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

Mescia,CS ‘06

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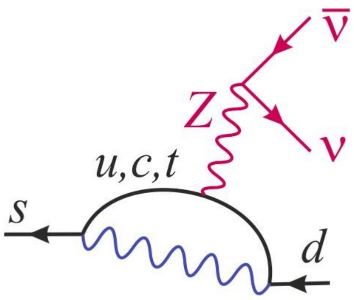
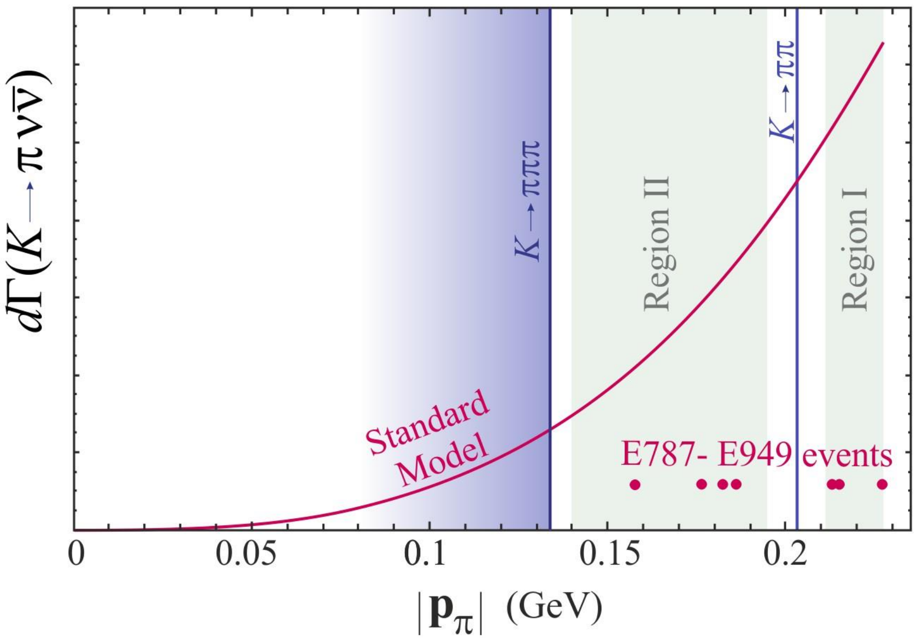


The observable differential rate is

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

Essential for the necessarily aggressive background rejection.



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

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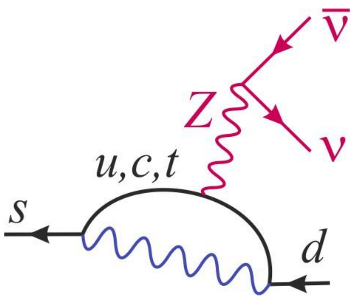
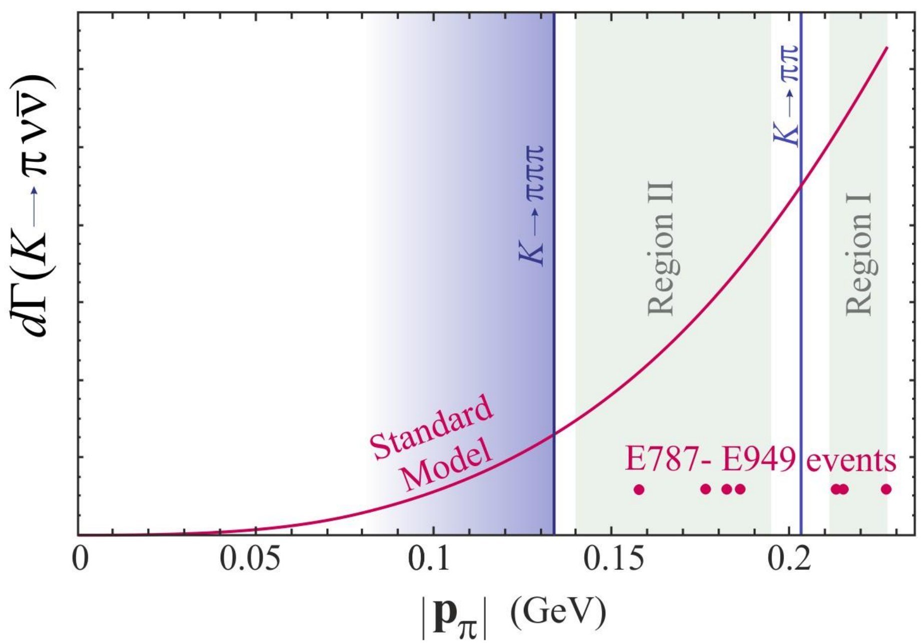


$\times 10^{-11}$	SM	Extrapolated
I	2.3	$14.7^{+13.0}_{-8.9}$
II	3.3	$78.9^{+92.6}_{-51.0}$

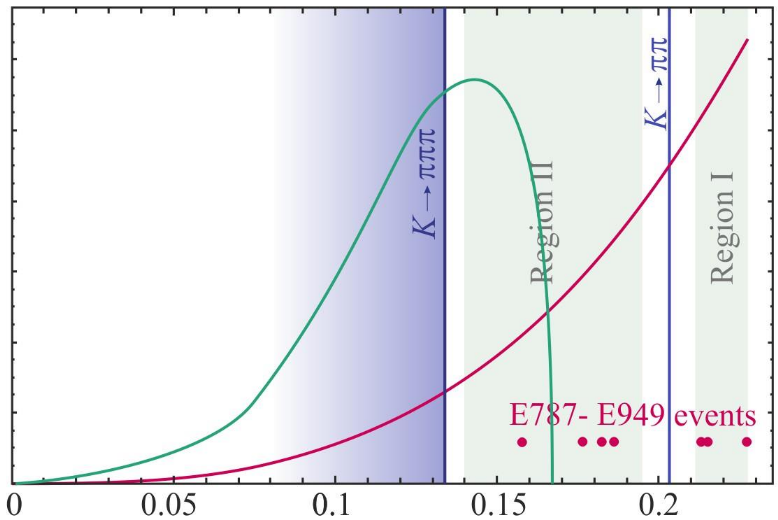


Important message: V-A current assumed & kinematical range limited.

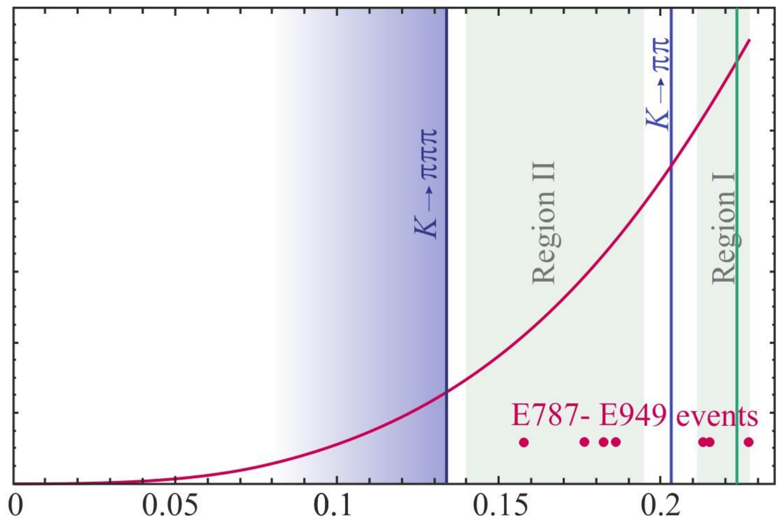
B. The $K \to \pi +$ missing energy decays

Consequence: Using total rates to set limit is wrong!

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



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

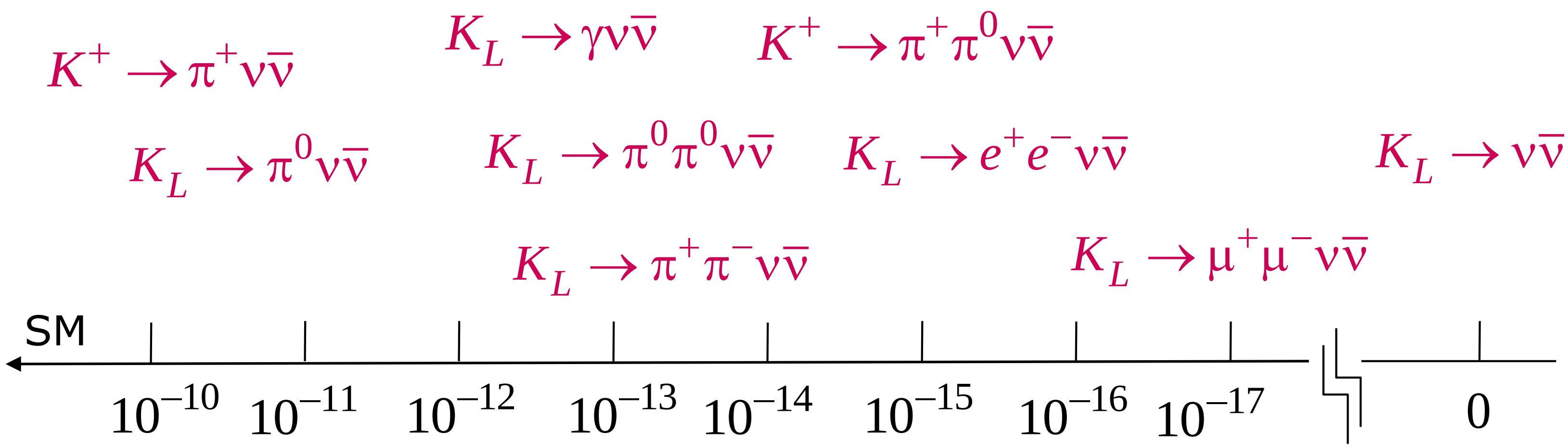


For both K and B decays: - Cuts are usually introduced to reduce BG.
- SM differential rate may be implicit in MC.

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

C. Other 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. Other modes with missing energy

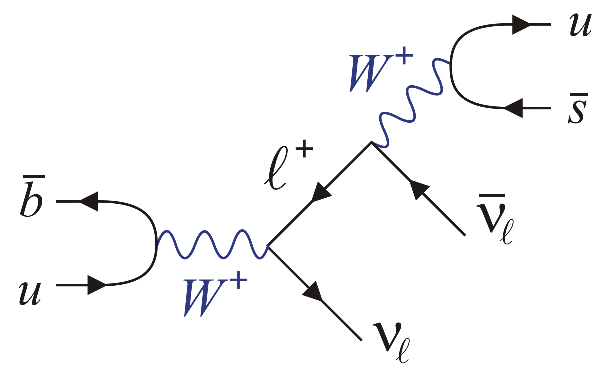
Main B decay modes into neutrino pairs:

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

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

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

Kamenik, CS '09



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:

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

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

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

II. Is there a dark sector?

A. Are there only SM particles at low energy?

Evidently: Anything sufficiently weakly interacting could have escaped detection.

- Many theories have pseudo-Goldstone remnants at low-energy:

Axion	← Peccei-Quinn symmetry
Familon	← Flavor symmetry
Sgoldstinos	← Supersymmetry

- Many theories (e.g. string, ED) have vector boson remnants at low-energy:

  U(1) factors generic in SSB chains

  U(1) symmetries required in place of discrete symmetries

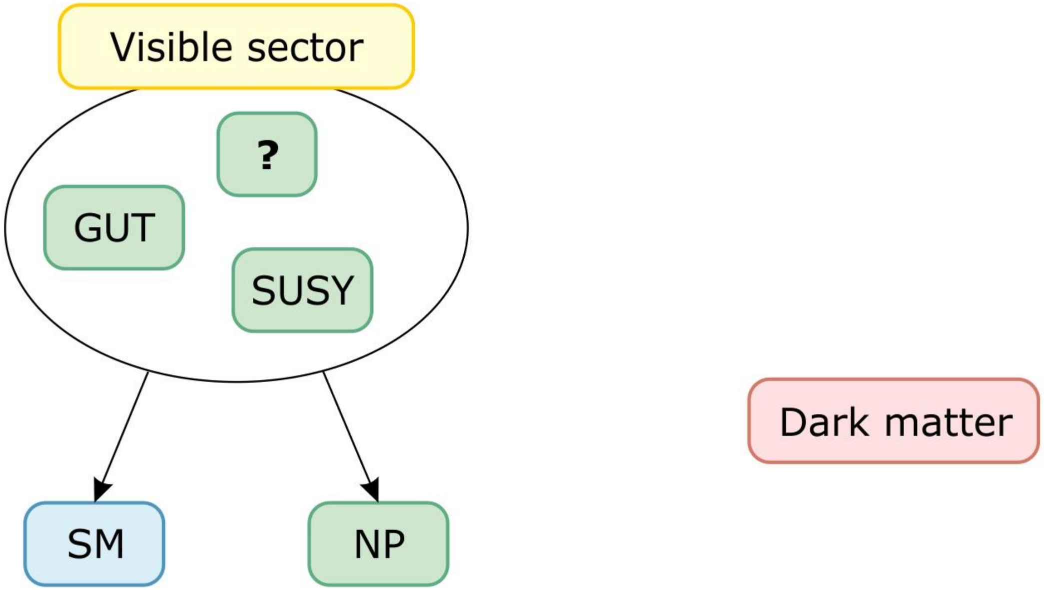
- Many theories have hidden sectors, with messenger connections

  SUSY breaking, mirror worlds, millicharged fermions,...

- Many others: dilaton, radion, majoron, neutralino, sterile ν, gravitino,...

- And finally, of course, there is dark matter in the Universe!

B. How to systematically investigate these scenarios?

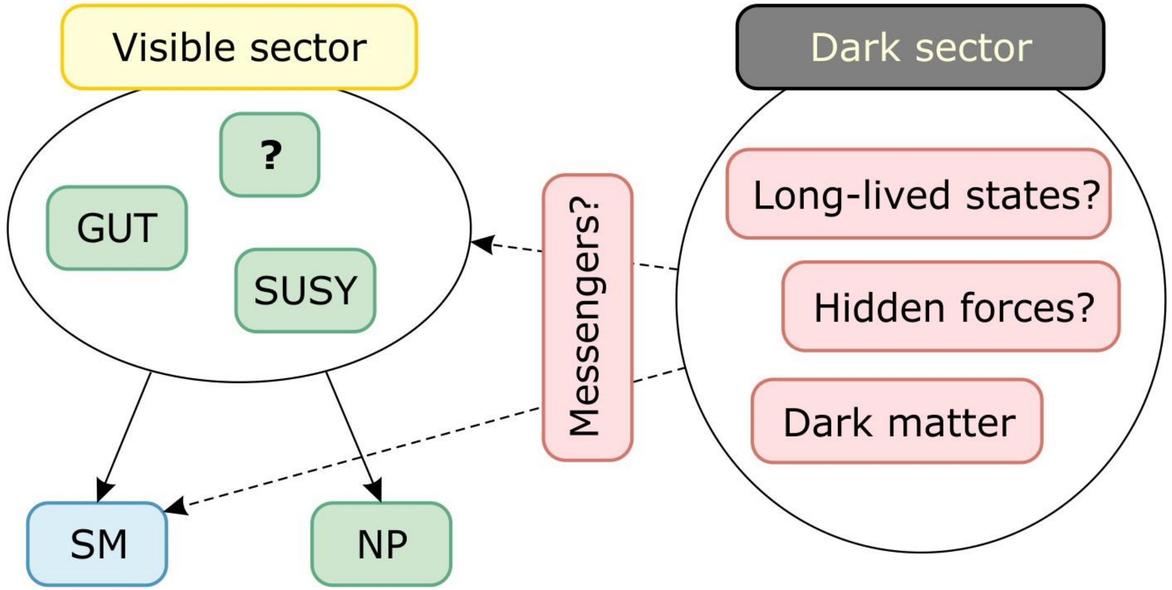


$$\mathcal{L}_{TOT} = \mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2} Q_i[SM] + \ldots$$

Heavy NP can be projected onto 65
effective gauge-invariant operators
built in terms of SM fields.

Buchmüller, Wyler '86

B. How to systematically investigate these scenarios?

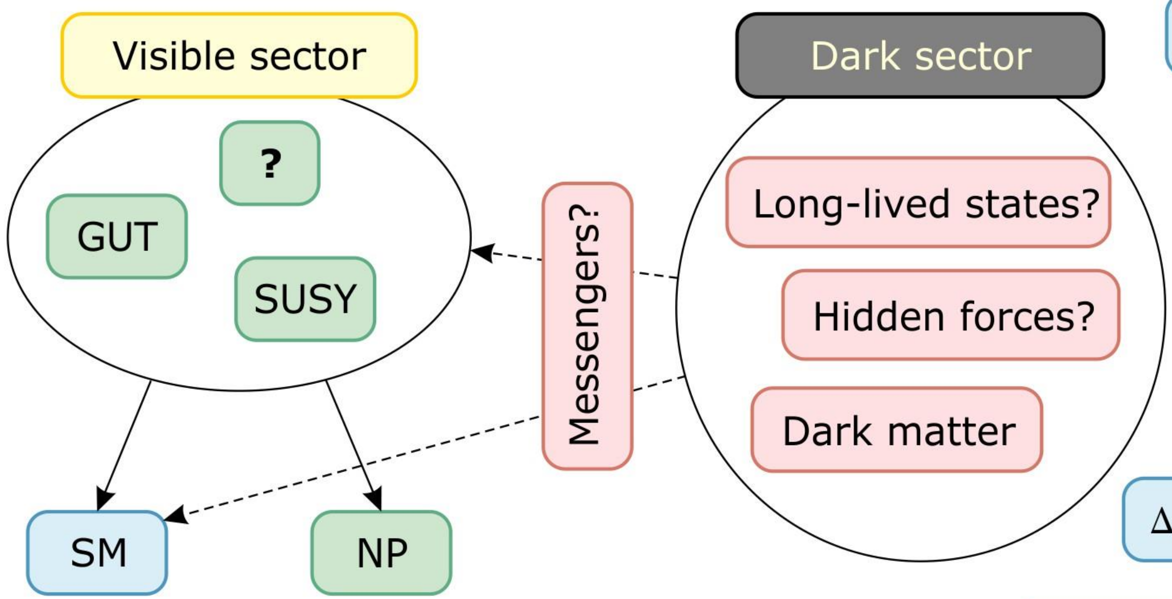


X = dark sector state connected to the SM, or a light messenger.

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

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

B. How to systematically investigate these scenarios?



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

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

Dark gauge invariance?

$\Delta\mathcal{B}$ & $\Delta\mathcal{L}$ = 0 or not?

Coupled to the SM Higgs, gauge boson, and/or fermions?

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

The leading operators must be kept separately for each possibility.

Kamenik, CS '12

C. The operator basis : classification

	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	$H\bar{L}^C\psi$	$\frac{1}{\Lambda^2}\bar{D}Q\bar{L}^C\psi$	$\frac{1}{\Lambda^2}H^\dagger\overleftrightarrow{\mathcal{D}}^\mu H\bar{\psi}\gamma_\mu\psi$	$\frac{1}{\Lambda^2}\bar{Q}\gamma^\mu Q\bar{\psi}\gamma_\mu\psi$
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	$\frac{1}{\Lambda}\mathcal{D}_\mu H\bar{L}^C\Psi^\mu$	$\frac{1}{\Lambda^3}\bar{D}\mathcal{D}_\mu Q\bar{L}^C\Psi^\mu$	$\frac{1}{\Lambda}H^\dagger H\bar{\Psi}^\mu\Psi_\mu$	$\frac{1}{\Lambda^2}\bar{Q}\gamma^\mu Q\bar{\Psi}^\rho\gamma_\mu\Psi_\rho$

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

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

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Portals: those interactions which are renormalizable [Higgs, Neutrino, Vector].

Remark: After the EW SSB, $HL \to \frac{(v+h)\nu_\ell}{\sqrt{2}}$ and $H^\dagger\overleftrightarrow{D}^\mu H \to \frac{ig}{2c_W}(v+h)^2 Z^\mu$.

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Why separate flavored vs. flavorless operators?

B. Dark portals in rare decays

Kamenik,CS, '12

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

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

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

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

Needs W boson for the weak transitions

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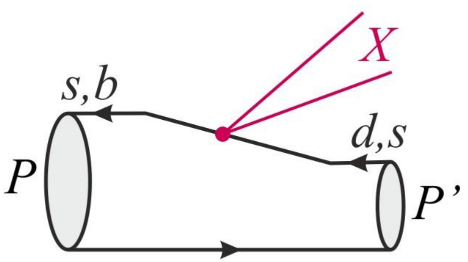
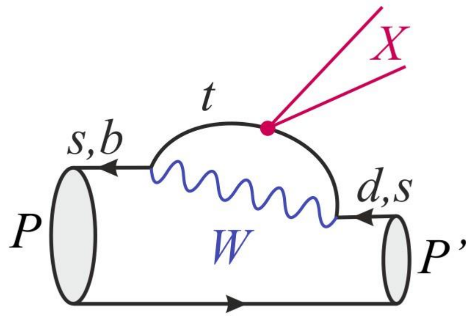
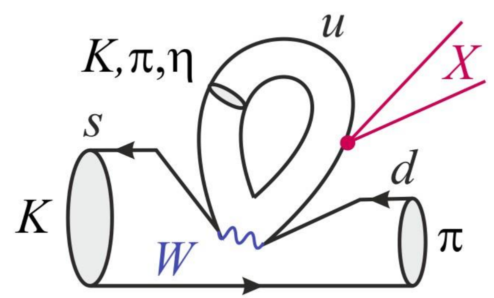
Heavy quarks: New FCNC

Light quarks: Long-distance







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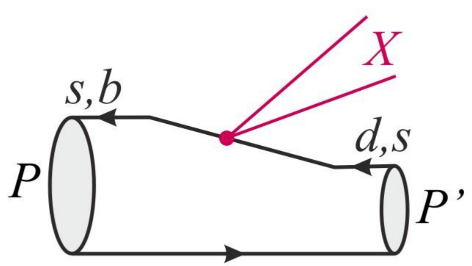
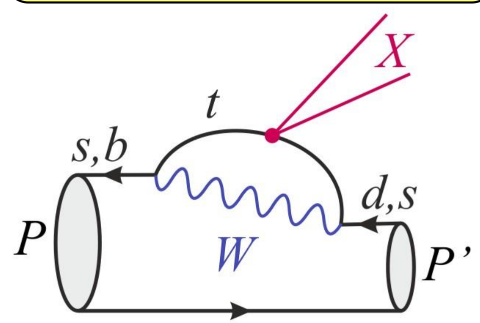
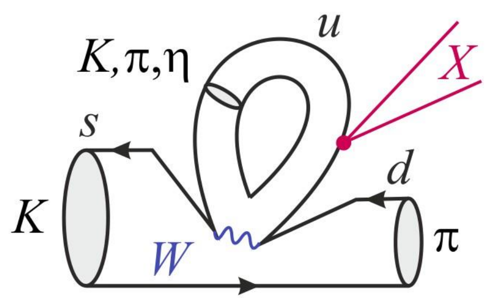






$P \to P'X$ may be large, competitive with $P \to P'\nu\bar{\nu}$

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

B. Dark portals in rare decays

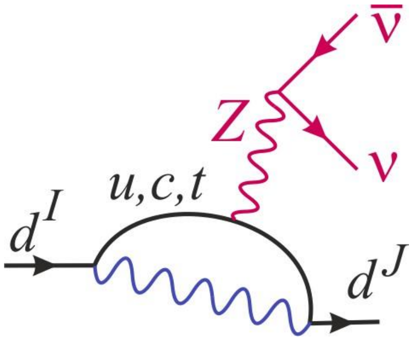
New very light and neutral particles X coupled to the SM particles

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}	$>90\ TeV$		

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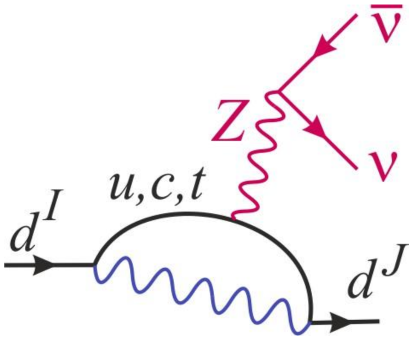
$$\frac{1}{\Lambda^2}\bar{Q}^I\gamma^\mu Q^J\bar{\psi}\gamma_\mu\psi$$

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}	$>8\ TeV$	$>2\ TeV$	
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Λ_{sd}	$>90\ TeV$	$>2\ TeV$	

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Flavor-blind:

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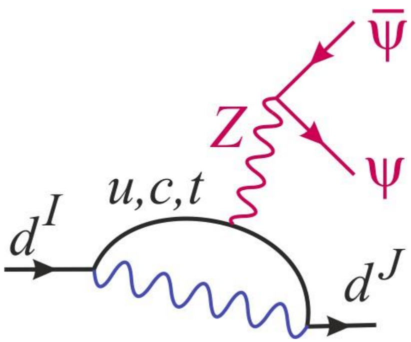
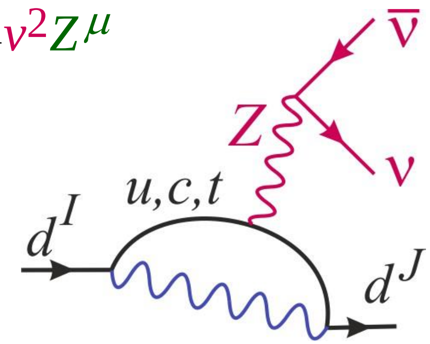


$$\Rightarrow\ \frac{v^2}{\Lambda^2}G_F\frac{g^2}{4\pi}V_{tI}V_{tJ}^\dagger \approx G_F\frac{g^2}{4\pi}V_{tI}V_{tJ}^\dagger\ \Leftarrow$$



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

III. The Higgs vs. FCNC

A. Why the Higgs boson?

- For dimensional reasons, most leading operators involve the Higgs.

	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	$H\bar{L}^C\psi$	$\frac{1}{\Lambda^2}\bar{D}Q\bar{L}^C\psi$	$\frac{1}{\Lambda^2}H^\dagger\overleftrightarrow{\mathcal{D}}^\mu H\bar{\psi}\gamma_\mu\psi$	$\frac{1}{\Lambda^2}\bar{Q}\gamma^\mu Q\bar{\psi}\gamma_\mu\psi$
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	$\frac{1}{\Lambda}\mathcal{D}_\mu H\bar{L}^C\Psi^\mu$	$\frac{1}{\Lambda^3}\bar{D}\mathcal{D}_\mu Q\bar{L}^C\Psi^\mu$	$\frac{1}{\Lambda}H^\dagger H\bar{\Psi}^\mu\Psi_\mu$	$\frac{1}{\Lambda^2}\bar{Q}\gamma^\mu Q\bar{\Psi}^\rho\gamma_\mu\Psi_\rho$

A. Why the Higgs boson?

- For dimensional reasons, most leading operators involve the Higgs.

- The Higgs boson is extremely narrow in the SM:

$$R_\Gamma^h = \frac{\Gamma_h^{SM}}{M_h} \approx 3\times10^{-5} \qquad \text{for } M_h \approx 125\ GeV$$

Similar to the spectacular $c\bar{c}$ and $b\bar{b}$ resonances

$$R_\Gamma^{J/\psi} \approx 3\times10^{-5} \qquad R_\Gamma^{\Upsilon(1S)} \approx 0.6\times10^{-5}$$

- What happens if there is a new decay channel? Its rate must be small:

$$\frac{1}{5}\times\frac{\Gamma_h^{SM}}{M_h} > \frac{\Gamma_h^{new}}{M_h} = \frac{1}{8\pi}\left(\frac{M_h^2}{\Lambda_d^2}\right)^{d-4} \Rightarrow \begin{cases} \Lambda_5 > 10\ TeV \\ \Lambda_6 > 1.1\ TeV \\ \Lambda_7 > 0.5\ TeV \end{cases}$$

Naively, for low-dimensional operators, the NP scale has to be rather large!

B. Higgs portal operators

The simplest operators in each case affect the total Higgs decay rate:

$$H_{eff}^{0} = \lambda' H^{\dagger} H \times \phi^{\dagger}\phi$$

$$H_{eff}^{1/2} = \frac{1}{\Lambda} H^{\dagger} H \times \bar{\psi}(1,\gamma_5)\psi$$

$$H_{eff}^{1} = \varepsilon_H H^{\dagger} H \times V_{\mu} V^{\mu} + i\varepsilon'_H H^{\dagger} \overleftrightarrow{\mathcal{D}}^{\mu} H \times V_{\mu}$$

$$H_{eff}^{3/2} = \frac{1}{\Lambda} H^{\dagger} H \times \bar{\Psi}^{\mu}(1,\gamma_5)\Psi_{\mu} + \frac{1}{\Lambda} \mathcal{D}_{\mu} H \overline{L}^{C} \times \Psi^{\mu}$$

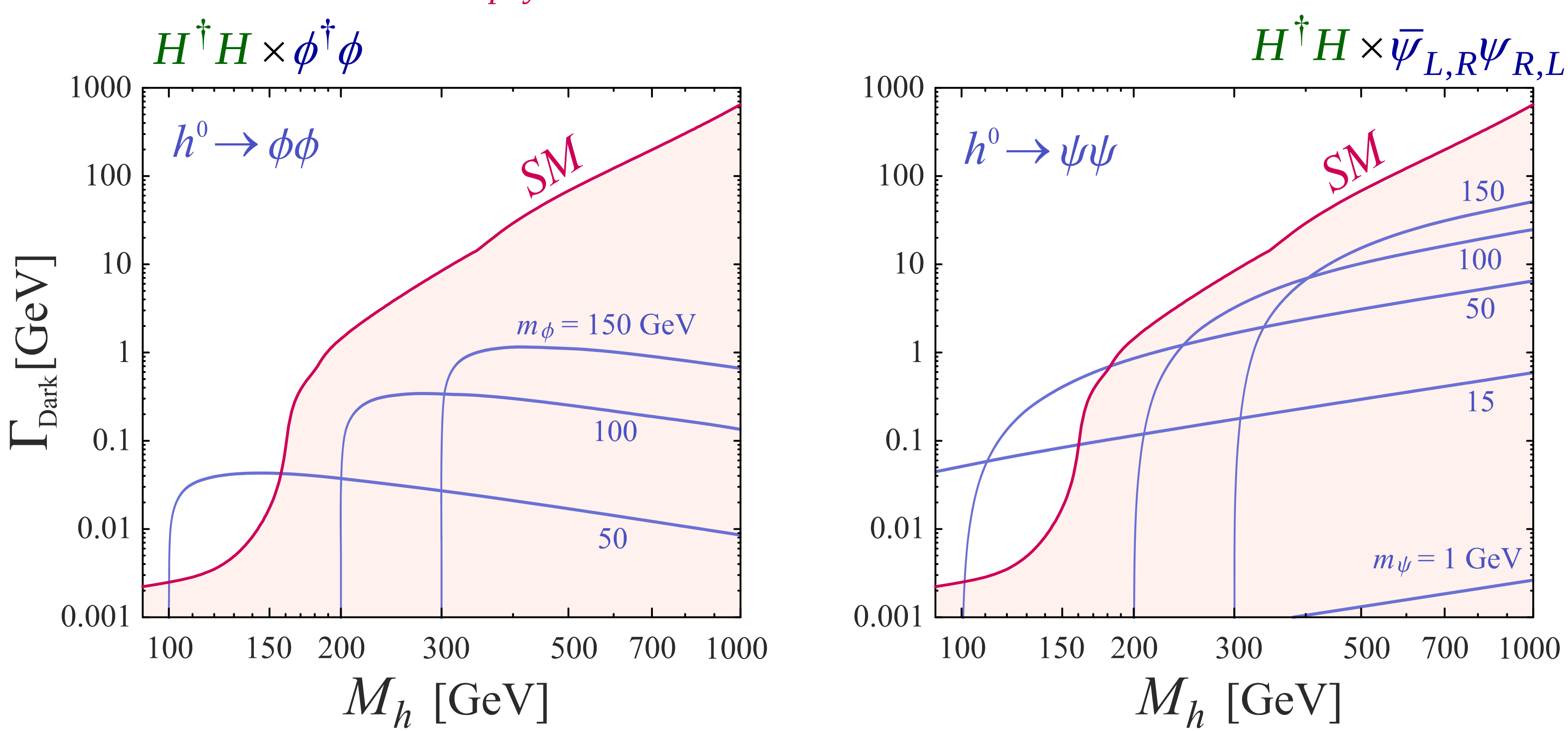
B. Higgs portal operators: Spin 0 and 1/2

Kamenik,CS, '11

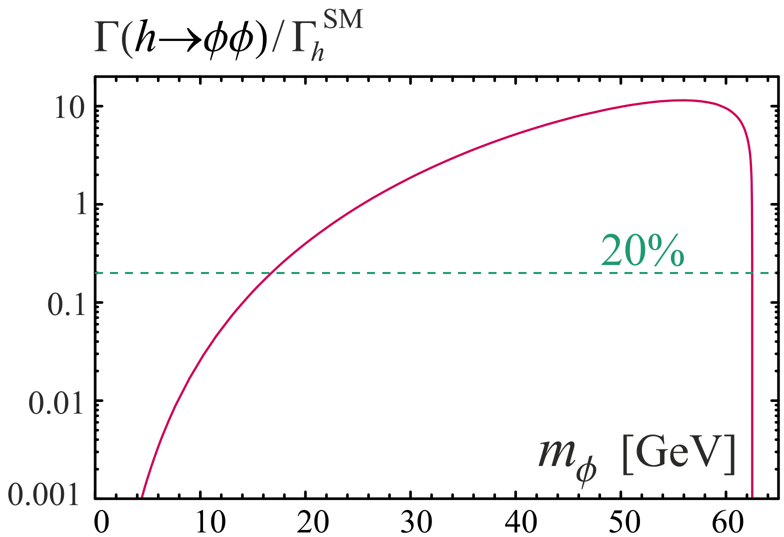
The leading operators induce both a mass correction and an invisible decay rate.

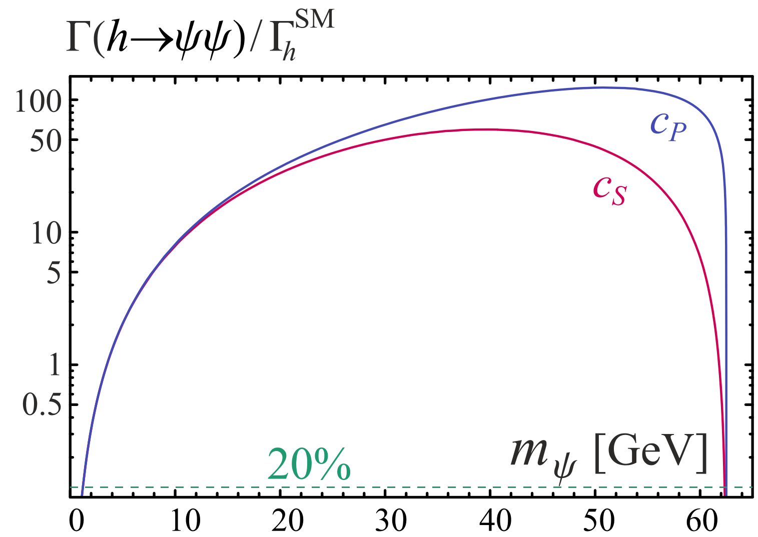
$$H^\dagger H \to \tfrac{1}{2}(v^2 + 2vh + h^2)$$

$$m_{phys} \gtrsim \delta m \qquad \Gamma(h \to \not{E})$$



B. Higgs portal operators: Spin 0 and 1/2





To escape the invisible Higgs width constraints:

- Dark state must be sufficiently light,
- Its mass must come from the Higgs.

B. Higgs portal operators: Spin 1 and 3/2

The leading operators break a dark gauge invariance:

$$H_{eff}^{1} = \varepsilon_H H^\dagger H \times V_\mu V^\mu + i\varepsilon'_H H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times V_\mu$$

$$H_{eff}^{3/2} = \frac{c_\Psi}{\Lambda} H^\dagger H \times \bar{\Psi}^\mu (1, \gamma_5) \Psi_\mu + \frac{c'_\Psi}{\Lambda} \mathcal{D}_\mu H \bar{L}^C \times \Psi^\mu$$

Consequently, decay rates are singular in the massless limit:

$$\sum_{pol} \varepsilon_k^\mu \varepsilon_k^\nu = -P_V^{\mu\nu}$$

$$\sum_{spin} u_k^\mu \bar{u}_k^\nu = -(\not{k} + m_\Psi)\left(P_\Psi^{\mu\nu} - \tfrac{1}{3} P_\Psi^{\mu\rho} P_\Psi^{\nu\sigma} \gamma_\rho \gamma_\sigma\right)$$

$$P_X^{\mu\nu} = g^{\mu\nu} - \frac{k^\mu k^\nu}{m_X^2}$$

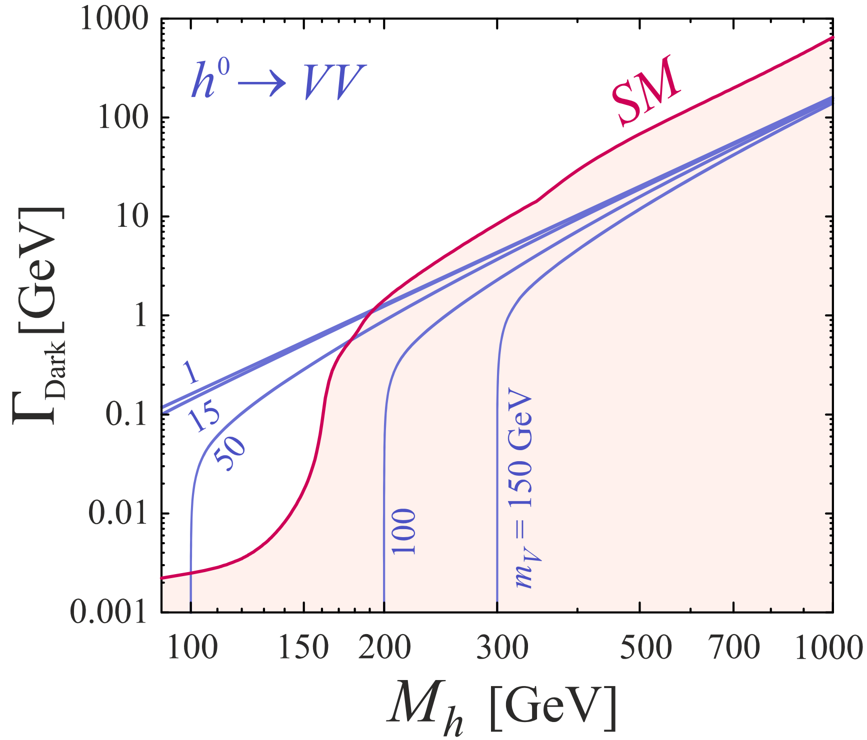
Same situation for the SM gauge boson:

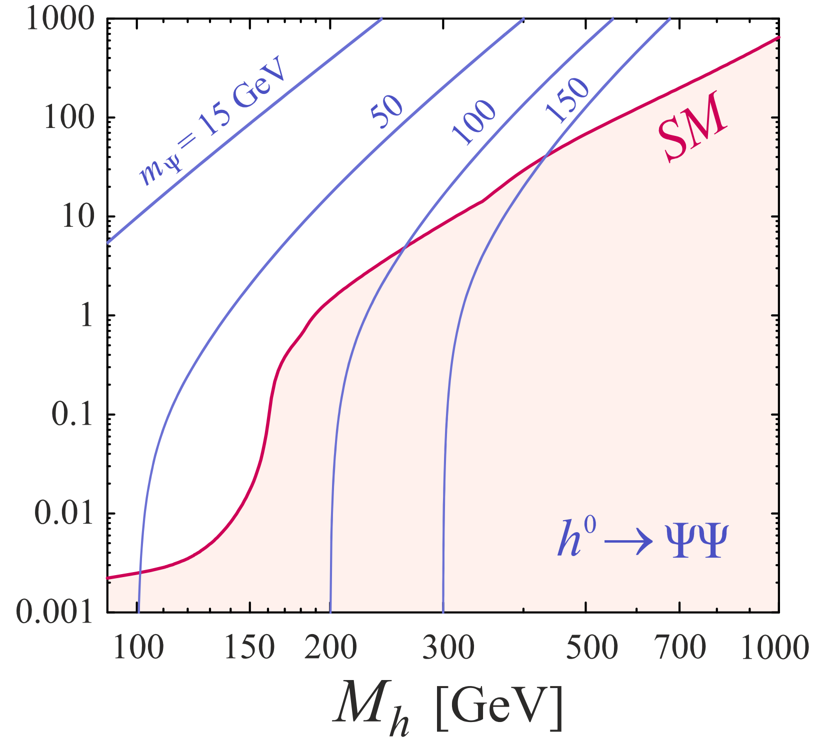
$$\Gamma(h \to WW) \sim (g^4 v^2) P_W^{\mu\nu} P_{W,\mu\nu} \xrightarrow{M_W \to 0} \frac{g^4 v^2}{M_W^4} + \ldots \xrightarrow{M_W \sim gv} \frac{1}{v^2} + \ldots$$

One way to make sense of the singularity is: $m_V \sim \varepsilon_H v_{dark}$ with $v_{dark} \geq v$.

B. Higgs portal operators: Spin 1 and 3/2

Kamenik,CS, '11



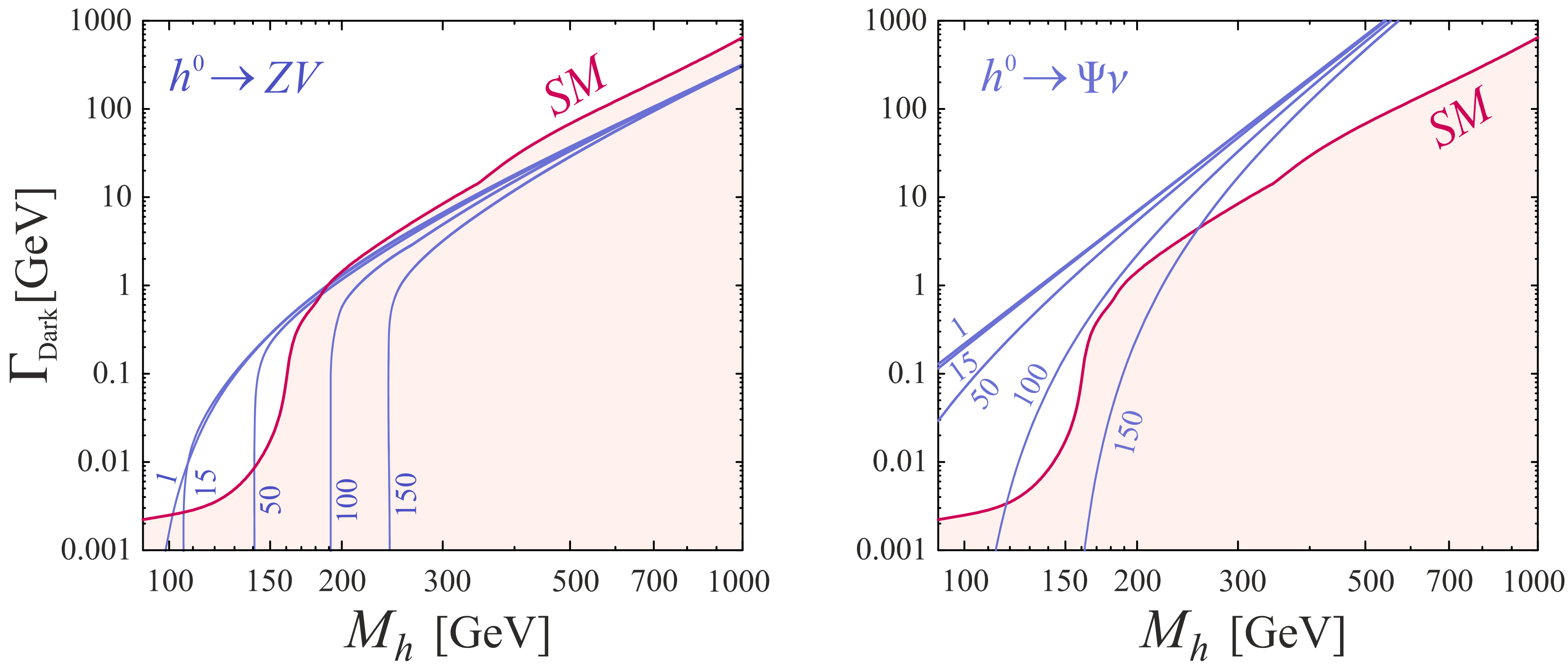


The $h \to VV$ rate always large for the 125 GeV higgs boson.

The $h \to \Psi\Psi$ rate is huge whatever the Higgs mass (harder singularity).

B. Higgs portal operators: Spin 1 and 3/2

Kamenik,CS, '11



The $h \to ZV$ rate is also affecting the total width.

The $h \to \nu\Psi$ rate again huge because of its harder singularity.

C. Dark gauge invariance

	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	$H\bar{L}^C\psi$	$\frac{1}{\Lambda^2}\bar{D}Q\bar{L}^C\psi$	$\frac{1}{\Lambda^2}H^\dagger\overleftrightarrow{\mathcal{D}}^\mu H\bar{\psi}\gamma_\mu\psi$	$\frac{1}{\Lambda^2}\bar{Q}\gamma^\mu Q\bar{\psi}\gamma_\mu\psi$
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	$\frac{1}{\Lambda}\mathcal{D}_\mu H\bar{L}^C\Psi^\mu$	$\frac{1}{\Lambda^3}\bar{D}\mathcal{D}_\mu Q\bar{L}^C\Psi^\mu$	$\frac{1}{\Lambda}H^\dagger H\bar{\Psi}^\mu\Psi_\mu$	$\frac{1}{\Lambda^2}\bar{Q}\gamma^\mu Q\bar{\Psi}^\rho\gamma_\mu\Psi_\rho$

C. Dark gauge invariance

1. If the Higgs doublet is charged under the dark U(1):

$$D^\mu H = \left(D^\mu - i\frac{\lambda}{2} V^\mu \right) H \quad \Rightarrow$$

$$\mathcal{L}_{Higgs} \supset D_\mu H^\dagger D^\mu H - i\frac{\lambda}{2} H^\dagger \overleftrightarrow{D}^\mu H \times V_\mu + \frac{\lambda^2}{4} H^\dagger H \times V_\mu V^\mu$$

Both the renormalizable operators appear!

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EW SSB

$$\mathcal{L}_{kin} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{M_Z^2}{2}\left(1+\frac{h}{v}\right)^2 (Z_\mu + \lambda V_\mu)(Z^\mu + \lambda V^\mu)$$

Z-V mass diagonalization (unitary)

The dark vector remains massless, and decouples from the Higgs!

C. Dark gauge invariance: Soft breaking

2. If the dark gauge symmetry is softly broken by a vector mass:

$$D^\mu H = \left(D^\mu - i\frac{\lambda}{2} V^\mu \right) H \;\Rightarrow$$

$$\mathcal{L}_{Higgs} \supset D_\mu H^\dagger D^\mu H - i\frac{\lambda}{2} H^\dagger \overleftrightarrow{D}^\mu H \times V_\mu + \frac{\lambda^2}{4} H^\dagger H \times V_\mu V^\mu + \frac{\bar{m}_V^2}{2} V_\mu V^\mu$$

EW SSB

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EW SSB

$$\mathcal{L}_{kin} = \frac{1}{2}\partial_{\mu}h\partial^{\mu}h + \frac{M_{Z}^{2}}{2}\left(1+\frac{h}{v}\right)^{2}(Z_{\mu}+\lambda V_{\mu})(Z^{\mu}+\lambda V^{\mu}) + \frac{\overline{m}_{V}^{2}}{2}V_{\mu}V^{\mu}$$

Z-V mass diagonalization (unitary)

$$\mathcal{L}_{Higgs} \supset \frac{1}{2}\partial_{\mu}h\partial^{\mu}h + \frac{M_{Z}^{2}}{2}\left(1+\frac{h}{v}\right)^{2} Z_{\mu}Z^{\mu} + M_{Z}^{2}\frac{h}{v}\left(2\varepsilon Z_{\mu}V^{\mu} + \varepsilon^{2}V_{\mu}V^{\mu}\right) + \frac{m_{V}^{2}}{2}V_{\mu}V^{\mu}$$

With $\varepsilon \approx \chi s_{W} m_{V}^{2} / M_{Z}^{2}$, the couplings to light vectors remain very suppressed!

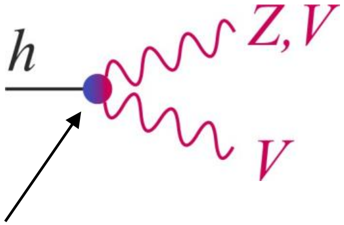
C. Dark gauge invariance: Kinetic mixing

3. If the vector field couples to the SM through the kinetic mixing:

$$\delta\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu} + \frac{\bar{m}_V^2}{2} V_\mu V^\mu$$

B-V redefinition (non-unitary)

$$\mathcal{L}_{Higgs} \supset D_\mu H^\dagger D^\mu H - i\frac{\lambda}{2} H^\dagger \overleftrightarrow{D}^\mu H \times V_\mu + \frac{\lambda^2}{4} H^\dagger H \times V_\mu V^\mu + \frac{\bar{m}_V^2}{2} V_\mu V^\mu$$



$$\varepsilon \approx \chi s_W m_V^2 / M_Z^2$$

$$\begin{cases} \delta\rho \Rightarrow \varepsilon < 0.03 \\ B(h \to VV) \leq 10^{-6} \\ B(h \to ZV) \leq 10^{-3} \end{cases}$$

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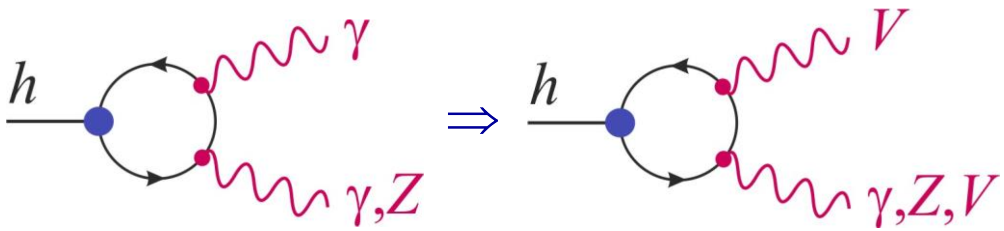
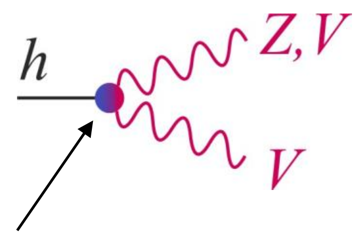
$$\mathcal{L}_{Fermions} \supset \chi c_W J_\mu^{em} \times V^\mu$$





$$\varepsilon \approx \chi s_W m_V^2 / M_Z^2$$

$$\begin{cases} B(h \to VV) \approx \chi^4 B(h \to \gamma\gamma) \\ B(h \to (\gamma, Z)V) \approx \chi^2 B(h \to \gamma\gamma) \end{cases}$$

$$\Rightarrow \chi \leq 0.1$$

$$\begin{cases} \delta\rho \Rightarrow \varepsilon < 0.03 \\ B(h \to VV) \leq 10^{-6} \\ B(h \to ZV) \leq 10^{-3} \end{cases}$$

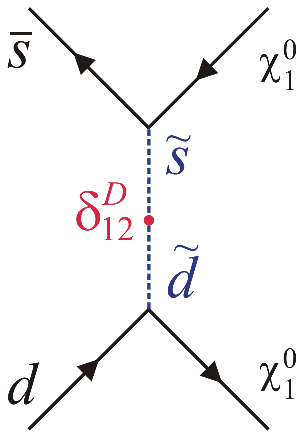
Dark gauge invariance permits to circumvent Higgs constraints!

IV. Flavored portals

A. 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} .

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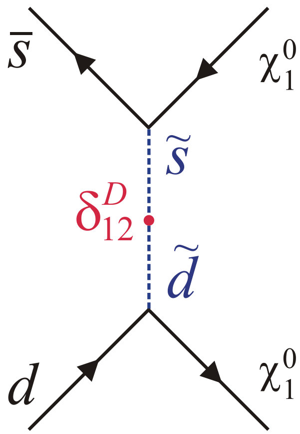
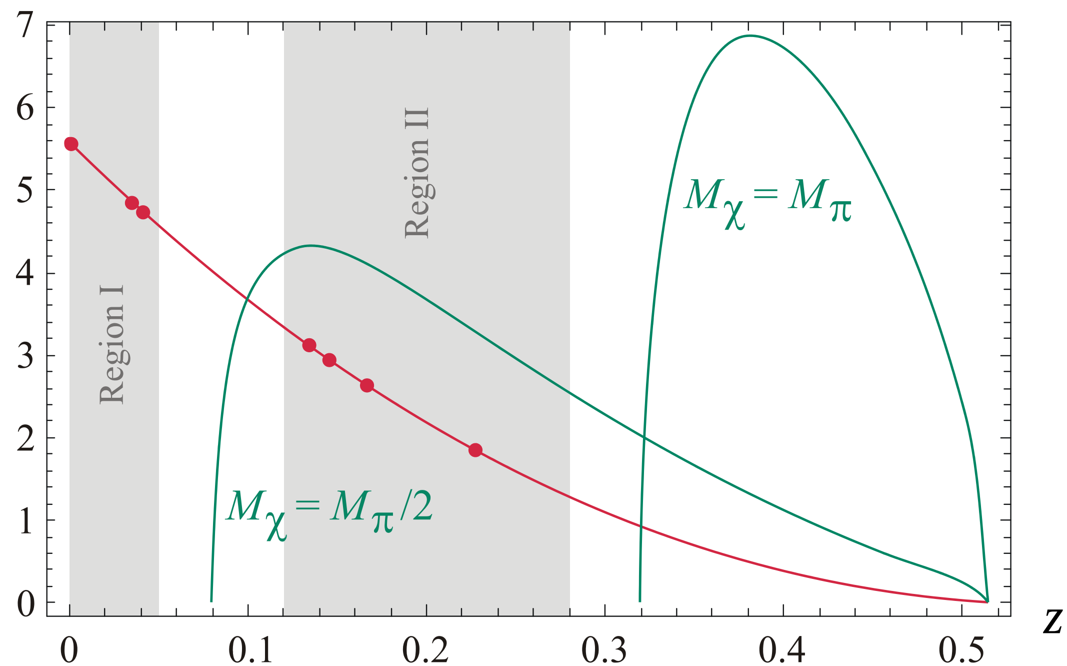


Effective couplings: $\boxed{\bar{s}\gamma^\mu(1\pm\gamma_5)d \otimes \bar{\chi}\gamma_\mu\gamma_5\chi}$

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

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



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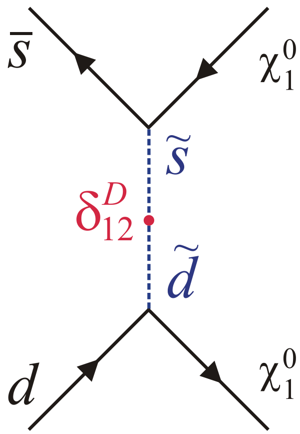

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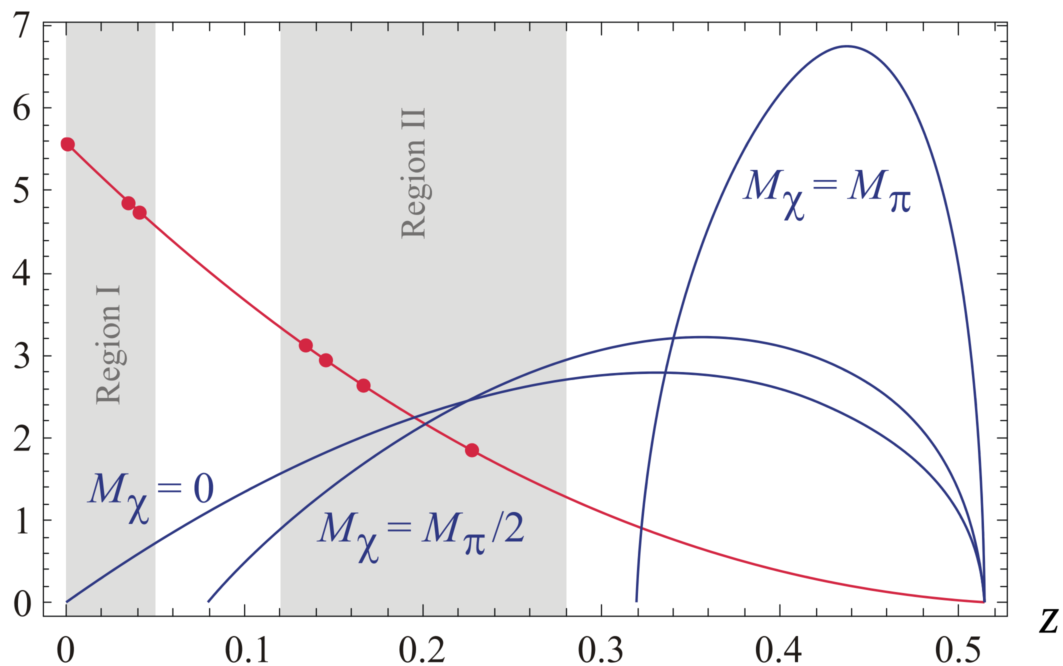

B. Flavor-diagonal scenario: Sterile neutrinos

Consider a hidden fermion with $\mathcal{B}$ or $\mathcal{L}$ breaking couplings:

$$\mathcal{H}_{eff} = \underbrace{H\bar{L}^C\psi + \frac{1}{\Lambda^2}\bar{E}L\bar{L}^C\psi + \frac{1}{\Lambda^2}\bar{D}Q\bar{L}^C\psi}_{\text{Sterile neutrino?}} + \underbrace{\frac{1}{\Lambda^2}\bar{D}^C D\bar{U}^C\psi}_{\text{Sterile baryon?}} + \ldots$$

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Very small!
(neutrino masses)

FCNC: $\frac{1}{\Lambda^2}\bar{s}d\bar{\nu}^C\psi$

Rare modes like $K \to \pi\nu\psi$
should lead to $\Lambda > O(100\,TeV)$.

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Very small!
(neutrino masses)

FCNC: $\frac{1}{\Lambda^2}\bar{s}d\bar{\nu}^C\psi$

Charged current: $\frac{1}{\Lambda^2}\bar{s}u\bar{\ell}^C\psi$ induces $B, K \to \ell\psi$.

Already very constraining, with for example:

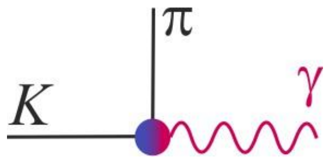
$$\frac{\Gamma(K \to e\nu_e + e\psi)}{\Gamma(K \to \mu\nu_\mu + \mu\psi)} \Rightarrow \Lambda > 80\,TeV$$

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

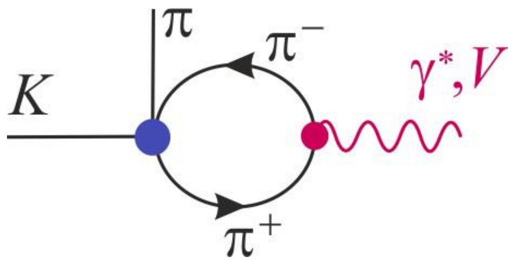
Kamenik,CS, '12

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

Problem 1: The one-photon emission is suppressed.



: Forbidden by Lorentz & gauge invariance.



: Rate proportional to m_V^2 / m_K^2.

No constraints for light dark photons!

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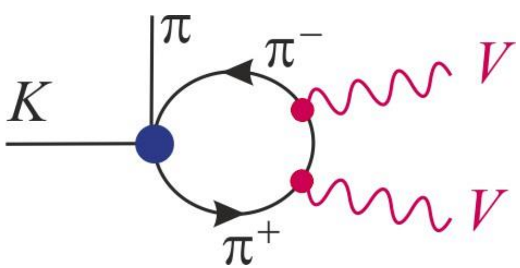
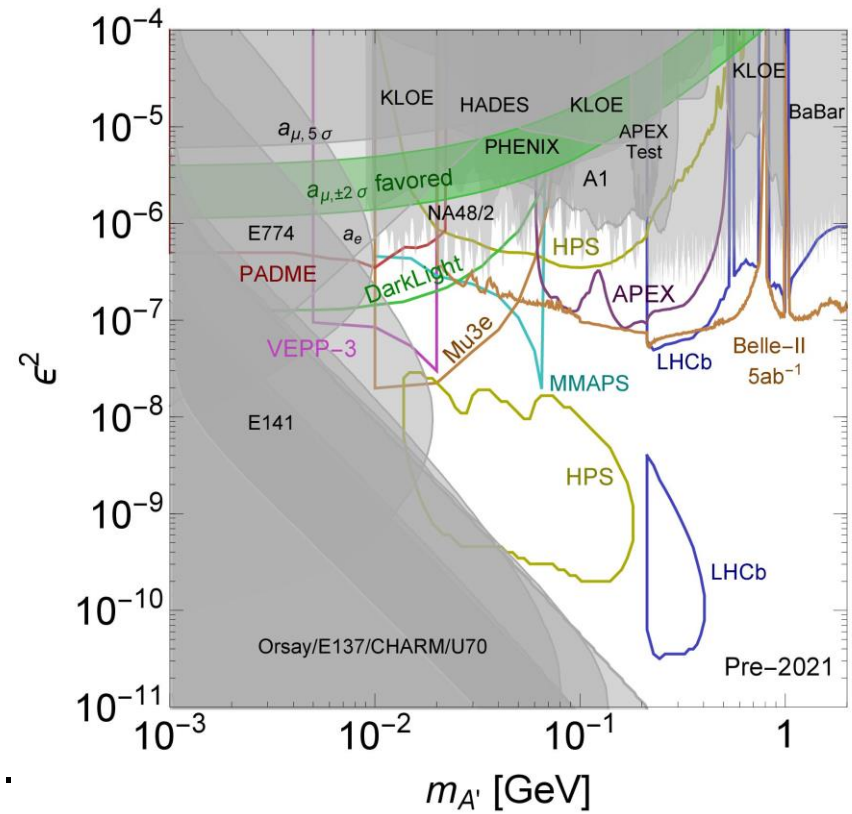
Problem 2: The EW transition strongly suppresses the rate.





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

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

A bound in the 10^{-12} range means $\alpha'/\alpha < 10^{-3}$, completely excluded...

From Dark Sectors 2016 Workshop Report, ArXiv:1608.08632

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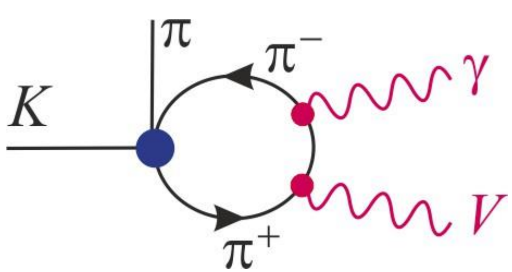

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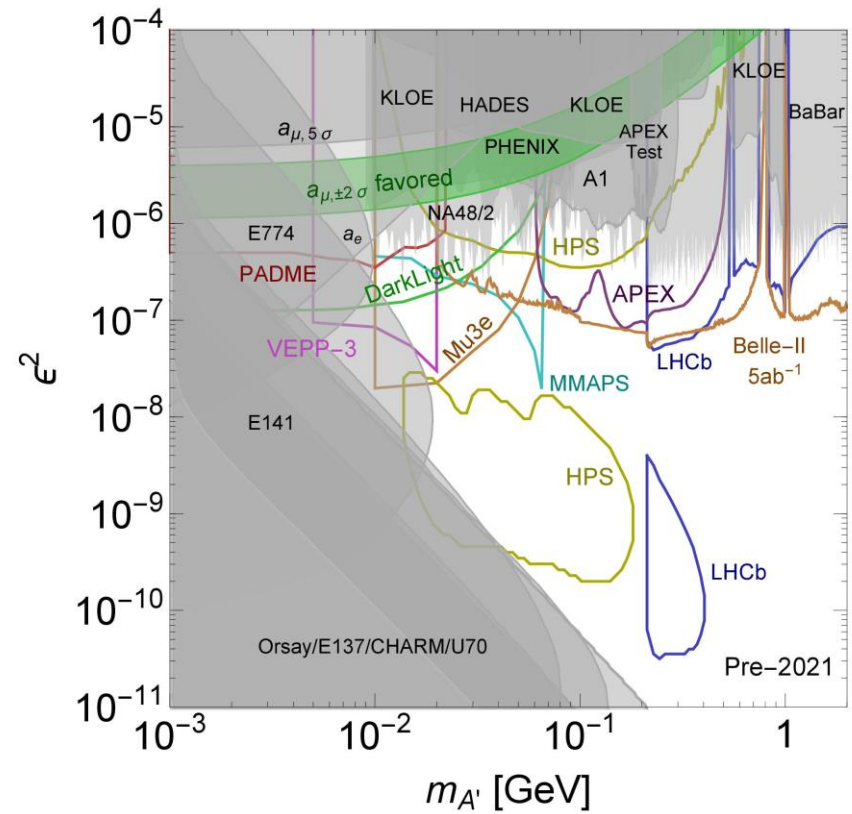
$$\to Br(K_L \to \pi^0\gamma V) \approx \frac{\alpha'}{\alpha}\times 10^{-6}$$

A bound in the 10^{-12} range means $\alpha'/\alpha < 10^{-6}$, slightly better, BUT...



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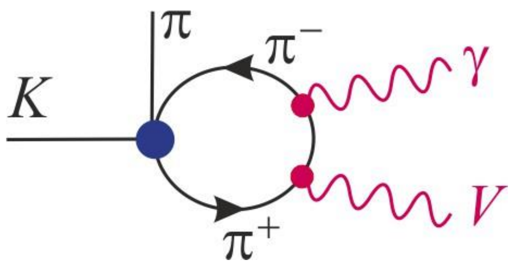
Problem 3: The LD dynamics strongly suppresses the rate below 2π.



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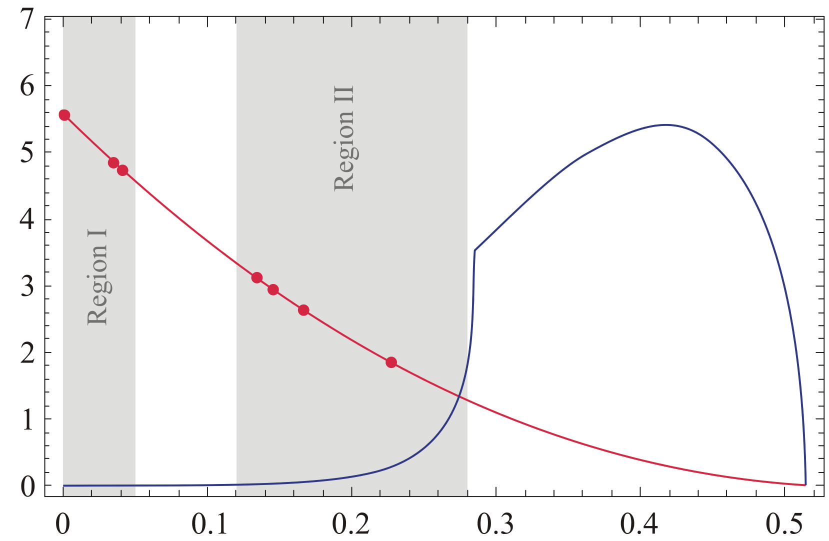

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Problem 4: Even-parity modes are sensitive only to "true" dark photons.

Most general flavorless coupling: aligned with QED or baryon number

$$\mathcal{H}_{eff}^{q=u,d,s} \supset e \bar{q} \gamma_\mu \mathbf{Q}' q \times V^\mu, \; \mathbf{Q}' = \varepsilon \mathbf{Q} + \varepsilon' \mathbf{1}$$

In the LO effective theory (ChPT), the baryon number piece drops out:

$$D^\mu \mathbf{U} = \partial^\mu \mathbf{U} - ieA^\mu [\mathbf{Q}, \mathbf{U}] - ieV^\mu [\mathbf{Q}', \mathbf{U}] = \partial^\mu \mathbf{U} - ie(A^\mu + \varepsilon V^\mu)[\mathbf{Q}, \mathbf{U}]$$

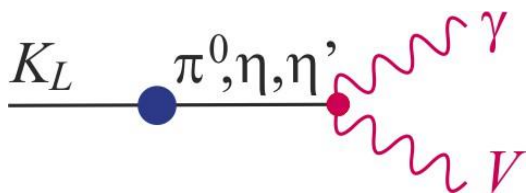
It only survives in the WZW anomalous interaction.

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

Kamenik,CS, '12

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

Solution: Look for different final states! The most promising is



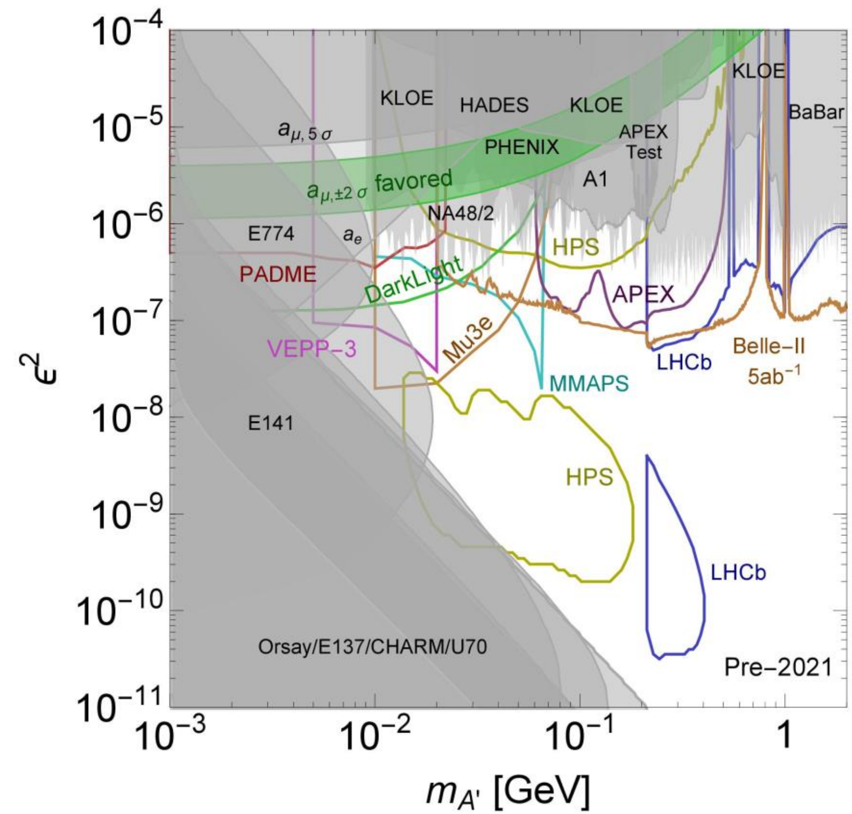
$$Br(K_L \to \gamma\gamma)^{\rm exp} = 5.47(4)\times 10^{-4}$$

$$\to\ Br(K_L \to \gamma V) \approx \frac{\alpha'}{\alpha}\times 10^{-4}$$

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

$$\alpha'/\alpha < 10^{-8}\ ,$$

which would be highly competitive!



(Note: $K_L \to \pi^0 \nu\bar{\nu}$ requires excellent photon capabilities)

Conclusion

1. Many scenarios predict new light states.

   But there are really a lot of possibilities!

   Rare K and B decay modes have a role to play in this search.

2. Sensitivity depends on the theory and experiment:

   To each type of new particle corresponds some specific kinematics.

   Experimental cuts & background estimations have to be dealt with.

3. Alternative decay modes should not be forgotten.

   Charged current, modes with extra photons, baryons,...