

Lepton Flavor Violation and Dark Sectors

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HQL2018 Yamagata

Plan

Overview of LFV

Some details—models, ways to constrain, etc

Prospects



Dark sectors

A little motivation

Standard scenarios

Less standard scenarios

Symmetries of the (leptonic part of the) standard model

$$\mathcal{L} \supset i\bar{L}_i\gamma^\mu D_\mu L_i + i\bar{e}_i\gamma^\mu D_\mu e_i$$

Possesses $U(3)_L \times U(3)_R$ symmetry

$$L \rightarrow U_L L, \quad e \rightarrow U_R e$$

The Yukawa couplings

$$\mathcal{L} \supset -H\bar{L}_i Y_{ij} e_j + \text{h.c.} \rightarrow -H\bar{L}_i Y_{ii}^d e_i + \text{h.c.}$$

$$\rightarrow -(\bar{e}_L \quad \bar{\mu}_L \quad \bar{\tau}_L) \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix} \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix} + \text{h.c.}$$

break the flavor symmetry

$$U(3)_L \times U(3)_R \rightarrow U(1)_e \times U(1)_\mu \times U(1)_\tau$$

Now let's add (Majorana) neutrino masses

$$\mathcal{L} \supset -\frac{c_{ij}}{\Lambda} (H L_i)^T (H L_j) + \text{h.c.} \rightarrow (m_\nu^d)_{ii} (\nu_L)_i (\nu_L)_i + \text{h.c.}$$

$$\text{breaks } U(3)_L \rightarrow U(1)_1 \times U(1)_2 \times U(1)_3$$

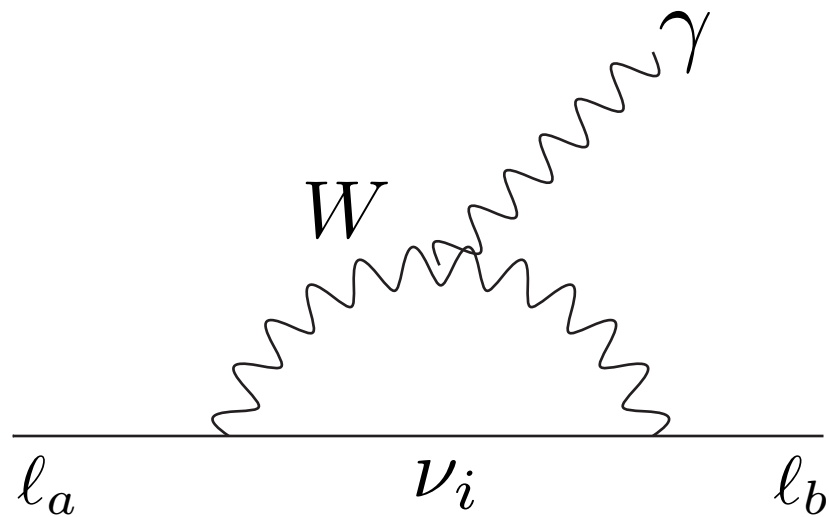
$$\text{Crucially } U(1)_e \times U(1)_\mu \times U(1)_\tau \neq U(1)_1 \times U(1)_2 \times U(1)_3$$

$\Rightarrow$ Charged lepton AND neutrino masses break the flavor symmetry to just lepton number:

$$U(3)_L \times U(3)_R \rightarrow \times U(1)_{e+\mu+\tau}$$

Lepton flavors are not symmetries of SM+neutrino masses!

Minimal Lepton Flavor Violation

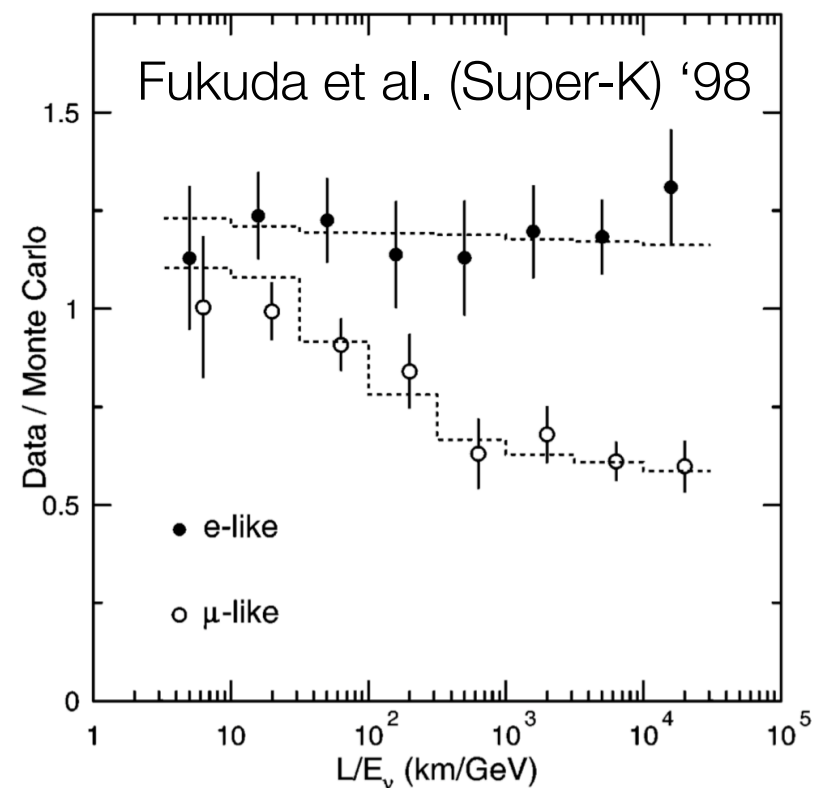


$$\frac{\Gamma(\ell_a \rightarrow \ell_b \gamma)}{\Gamma(\ell_a \rightarrow \ell_b \nu_a \bar{\nu}_b)} \sim \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{ai} \frac{\Delta m_{i1}^2}{m_W^2} U_{ib}^\dagger \right|^2 \lesssim 10^{-53}$$

(Compare to $\sim 10^{35}$ muons produced on Earth in its history)

Neutrino oscillation (LFV...)
also sensitive to mass differences

$$P_{a \rightarrow b} = \sin^2(2\theta) \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$



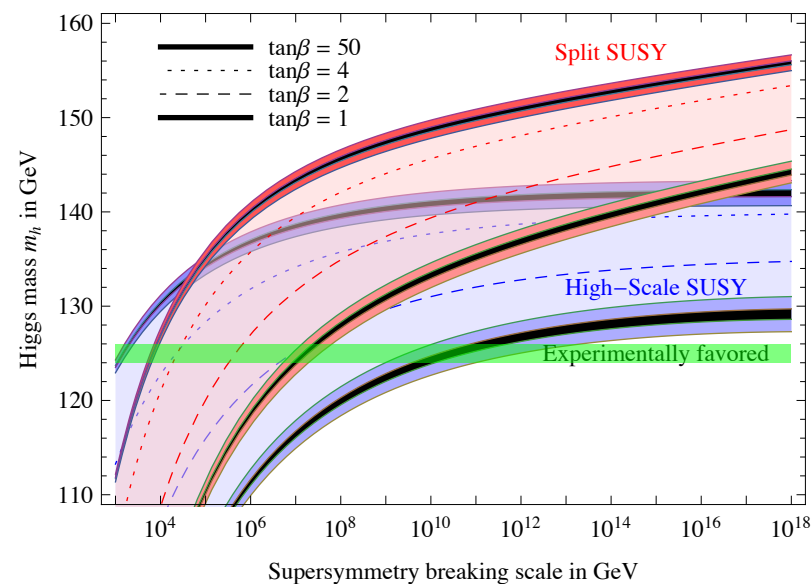
So minimal LFV will never be seen...

But is this an opportunity to conclusively find new physics?

New Physics for LFV

High scale SUSY

Predicted range for the Higgs mass



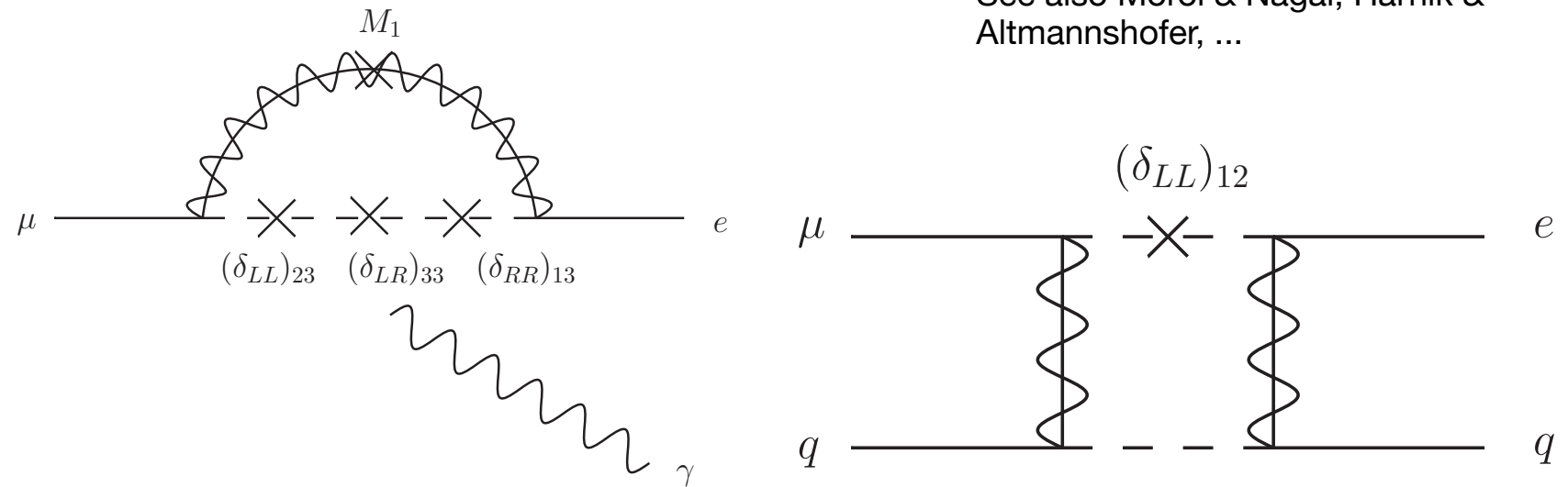
Giudice & Strumia

Arkani-Hamed, Kaplan, & Weiner

Many others

DM, Pospelov, Ritz

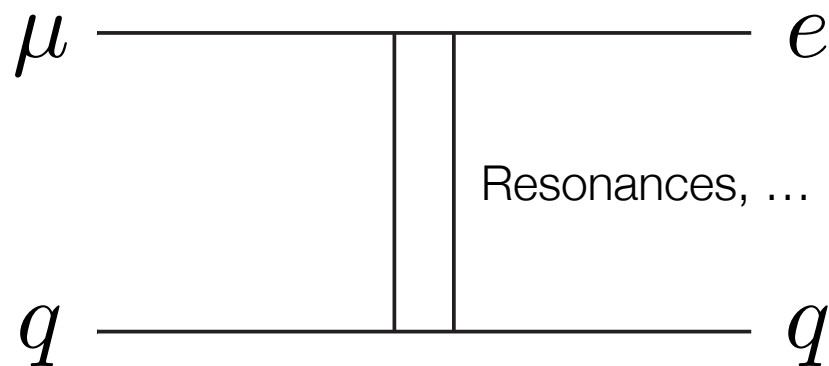
See also Moroi & Nagai, Harnik & Altmannshofer, ...



$$\mathcal{B}(\mu \rightarrow e\gamma) \sim 1 \times 10^{-17} \left(\frac{\tan \beta}{4} \right)^2 \left(\frac{100 \text{ TeV}}{\Lambda_{\text{SUSY}}} \right)^6 \left(\frac{\theta_{e12}^2 M_1}{300 \text{ GeV}} \right)^2$$

$$\mathcal{B}(\mu \rightarrow e)_{\text{Ti, box}} \sim 10^{-16} \left(\frac{100 \text{ TeV}}{\Lambda_{\text{SUSY}}} \right)^4 \left(\frac{\theta_{e12}^2}{1/3} \right)$$

See poster by Rosiek for detailed study in MSSM



Resonances, ...

Composite Higgs

Leptoquarks, Z', 2HDMs...

Observation is “unambiguous
sign of New Physics”

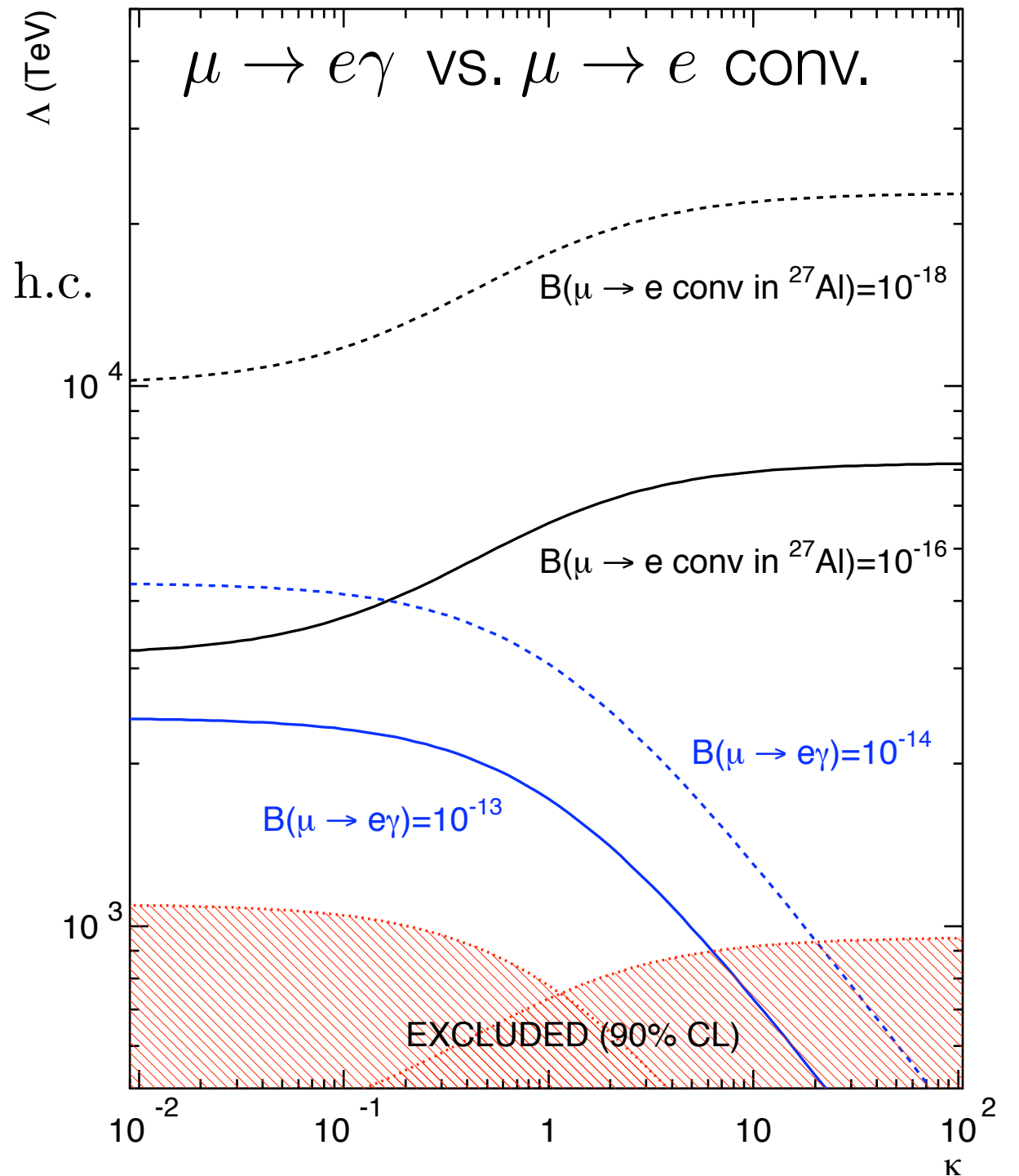
Model independent parameterization

De Gouvea & Vogl 1303.4097

$$\mathcal{L}_{\text{off}}^{\text{LFV}} = \frac{1}{(1+\kappa)} \frac{m_\mu}{\Lambda^2} \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} \\ + \frac{\kappa}{(1+\kappa)} \frac{1}{\Lambda^2} \bar{\mu}_L \gamma^\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L) + \text{h.c.}$$

κ interpolates between transition dipole and 4-fermion operator

Already probing the PeV scale



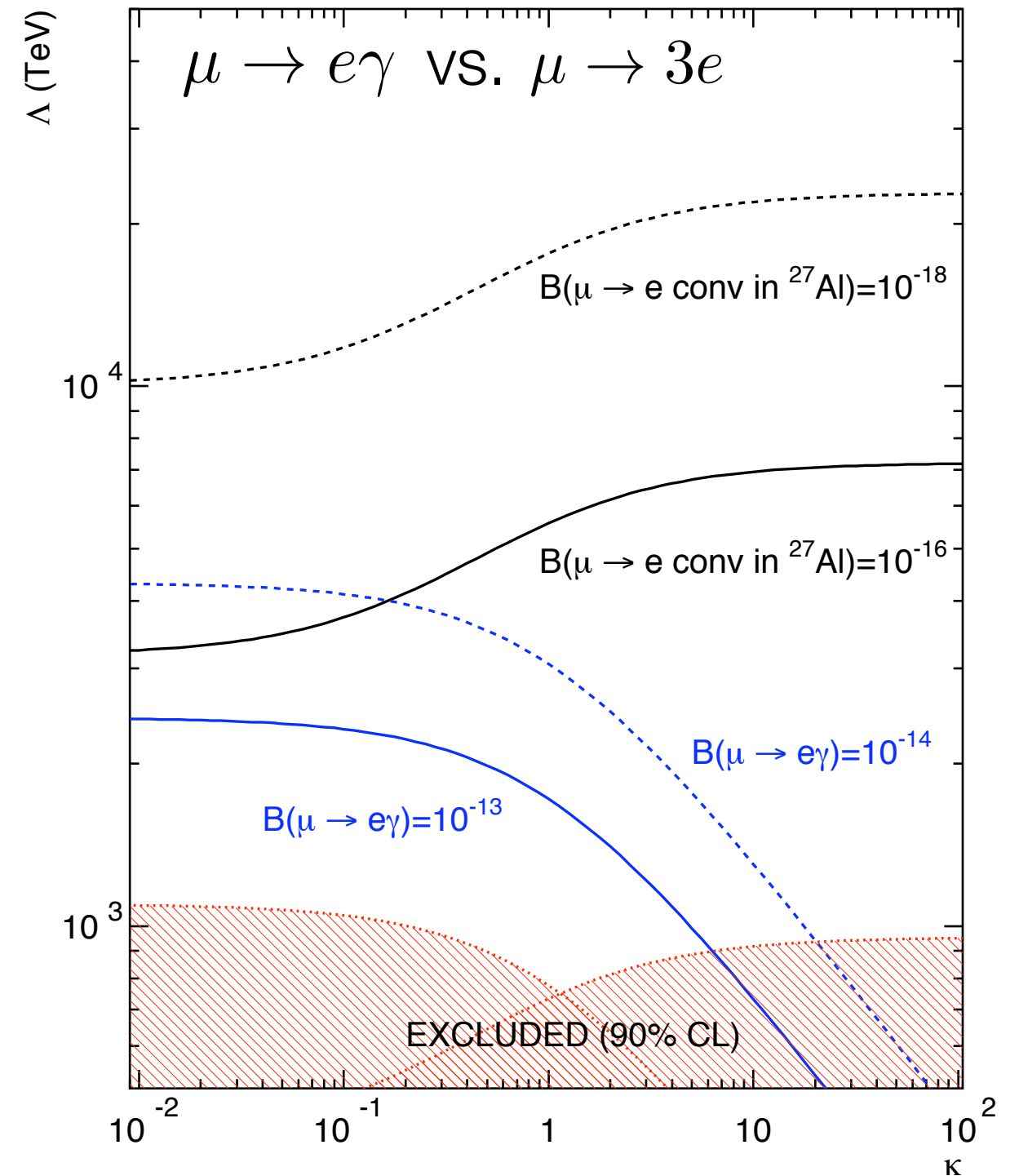
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κ interpolates between transition dipole and 4-fermion operator

Already probing the PeV scale



LFV search status

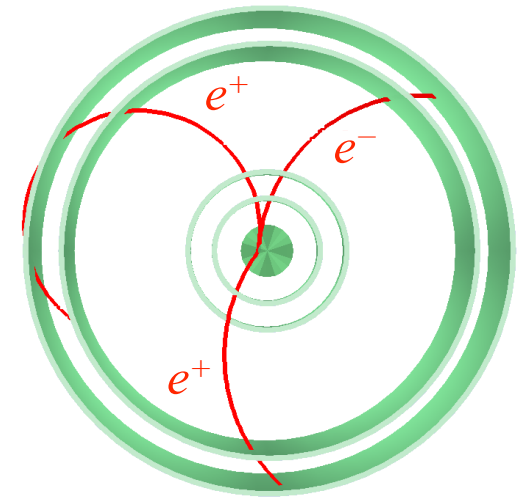
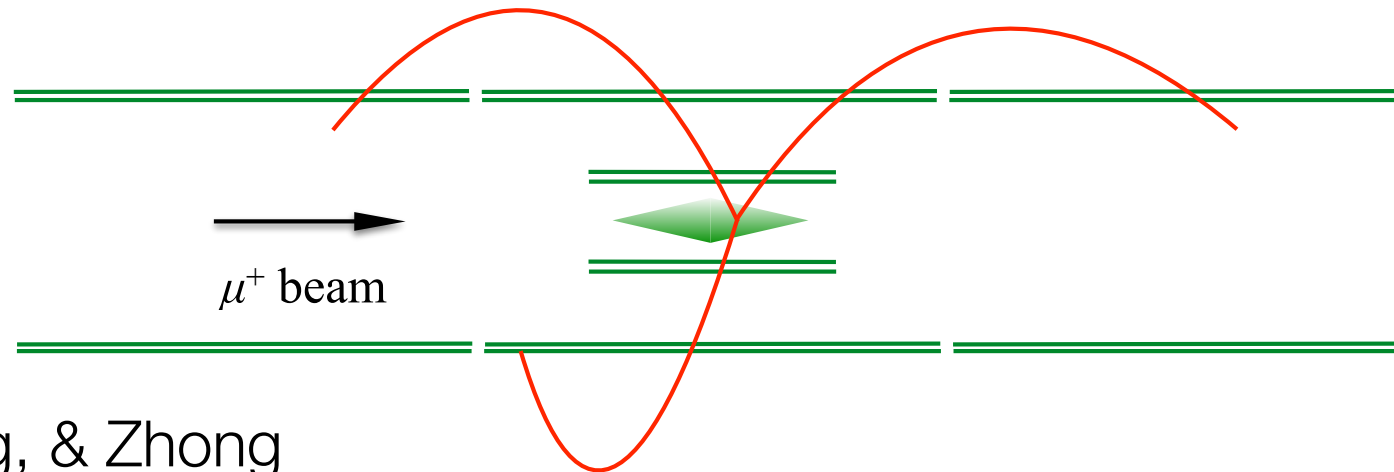
From Heeck '17

Group	Process	Current	Future
$\Delta(L_e - L_\mu) = 2$	$\mu \rightarrow e\gamma$	4.2×10^{-13} [11]	4×10^{-14} [12]
	$\mu \rightarrow e\bar{e}e$	1.0×10^{-12} [13]	10^{-16} [14]
	$\mu \rightarrow e$ conv.	$\mathcal{O}(10^{-12})$ [15]	10^{-17} [16,17]
	$h \rightarrow e\bar{\mu}$	3.5×10^{-4} [18]	2×10^{-4} [19]
	$Z \rightarrow e\bar{\mu}$	7.5×10^{-7} [20]	...
	had $\rightarrow e\bar{\mu}$ (had)	4.7×10^{-12} [21]	10^{-12} [22]
$\Delta(L_e - L_\tau) = 2$	$\tau \rightarrow e\gamma$	3.3×10^{-8} [23]	10^{-9} [24]
	$\tau \rightarrow e\bar{e}e$	2.7×10^{-8} [25]	10^{-9} [24]
	$\tau \rightarrow e\bar{\mu}\mu$	2.7×10^{-8} [25]	10^{-9} [24]
	$\tau \rightarrow e$ had	$\mathcal{O}(10^{-8})$ [10]	10^{-9} [24]
	$h \rightarrow e\bar{\tau}$	6.9×10^{-3} [18]	5×10^{-3} [19]
	$Z \rightarrow e\bar{\tau}$	9.8×10^{-6} [26]	...
	had $\rightarrow e\bar{\tau}$ (had)	$\mathcal{O}(10^{-6})$ [27,28]	...
$\Delta(L_\mu - L_\tau) = 2$	$\tau \rightarrow \mu\gamma$	4.4×10^{-8} [23]	10^{-9} [24]
	$\tau \rightarrow \mu\bar{e}e$	1.8×10^{-8} [25]	10^{-9} [24]
	$\tau \rightarrow \mu\bar{\mu}\mu$	2.1×10^{-8} [25]	10^{-9} [24]
	$\tau \rightarrow \mu$ had	$\mathcal{O}(10^{-8})$ [10]	10^{-9} [24]
	$h \rightarrow \mu\bar{\tau}$	1.2×10^{-2} [7]	5×10^{-3} [19]
	$Z \rightarrow \mu\bar{\tau}$	1.2×10^{-5} [29]	...
	had $\rightarrow \mu\bar{\tau}$ (had)	$\mathcal{O}(10^{-6})$ [27,28]	...

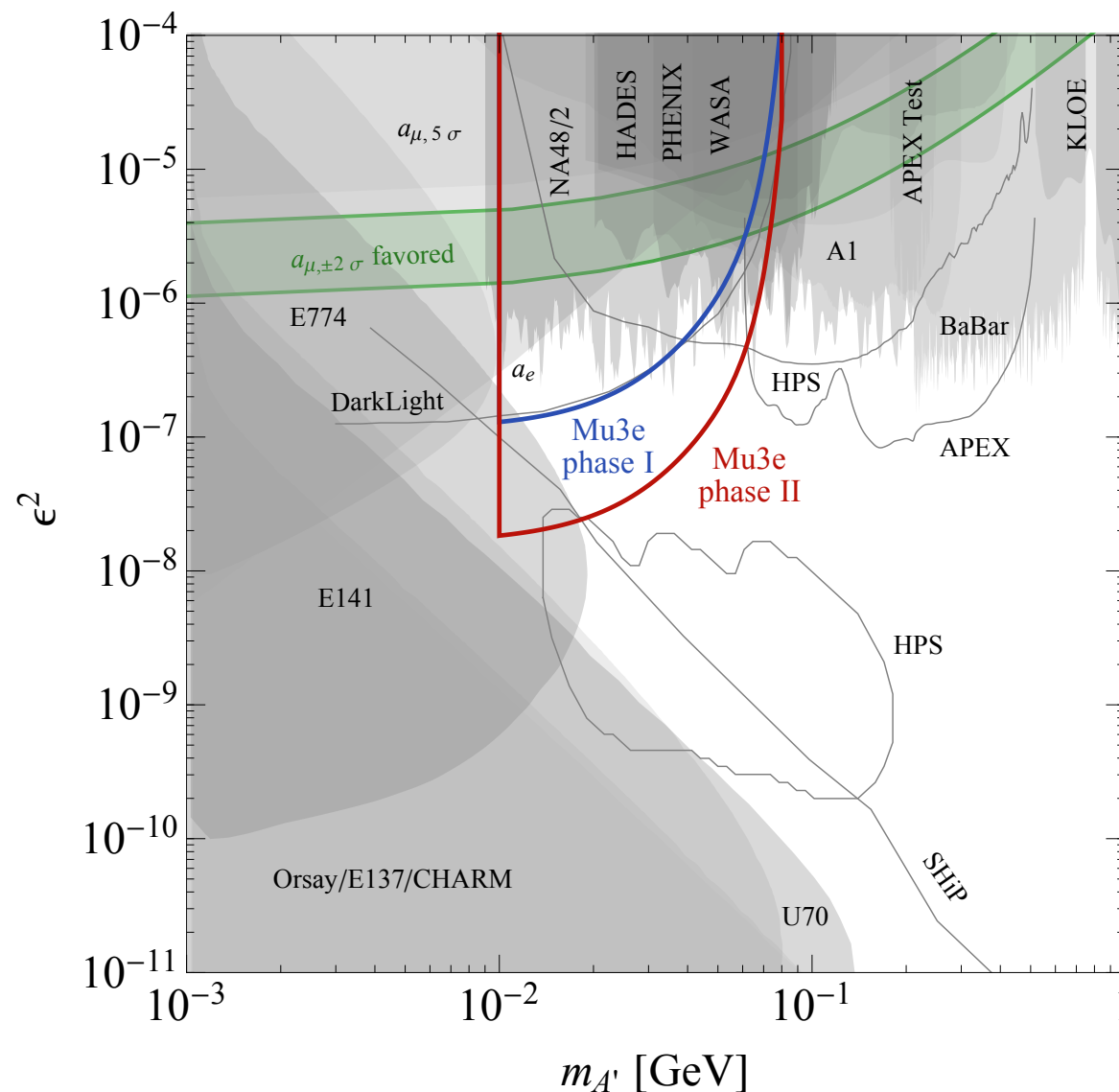
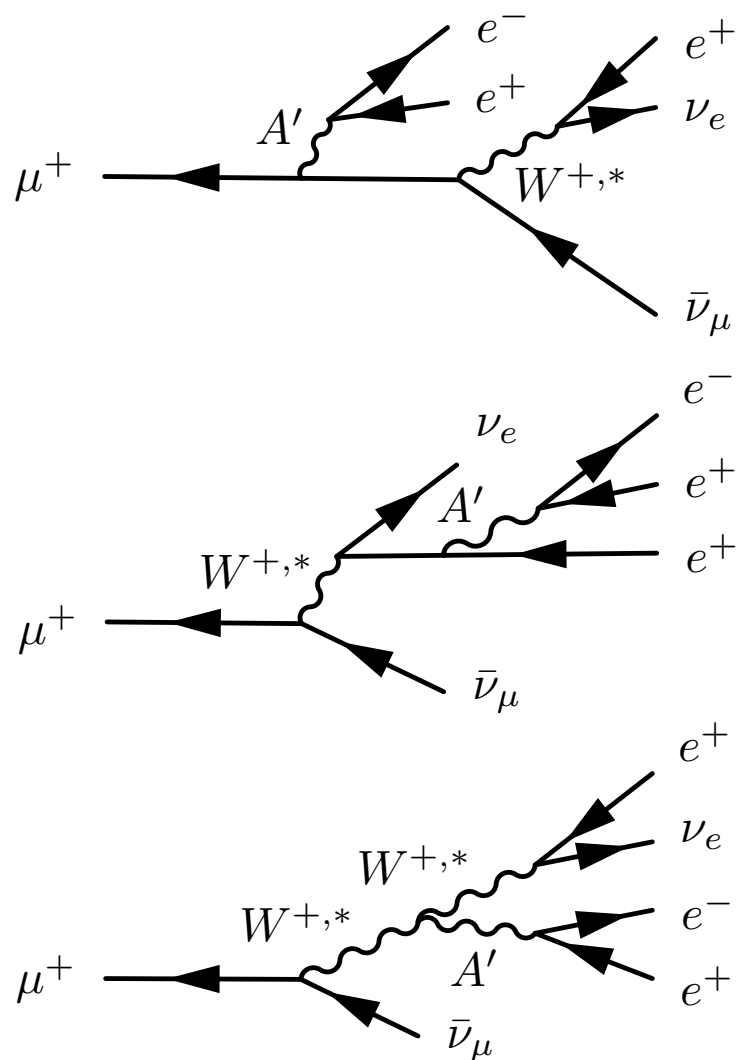
Enormous number of probes. See talks later this session for Mu2e and COMET

What else are we sensitive to at LFV experiments?

Mu3e at PSI



Echenard, Essig, & Zhong
1411.1770



What is A' ?

Model Building a Dark Sector or: what is a “portal”?

Standard Model
gauge
symmetries

$$SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{\text{em}}$$

Standard Model
particle content

$$\left. \begin{array}{l} L = \left(\begin{array}{c} \nu_L \\ e_L \end{array} \right) \quad e_R \\ Q = \left(\begin{array}{c} u_L \\ d_L \end{array} \right) \quad u_R \quad d_R \end{array} \right\} \times 3$$

$$H = \left(\begin{array}{c} \rho^+ \\ v + h + \rho^0 \end{array} \right) \quad G_\mu^a, \quad W_\mu^b, \quad B_\mu \rightarrow G_\mu^a, \quad A_\mu$$

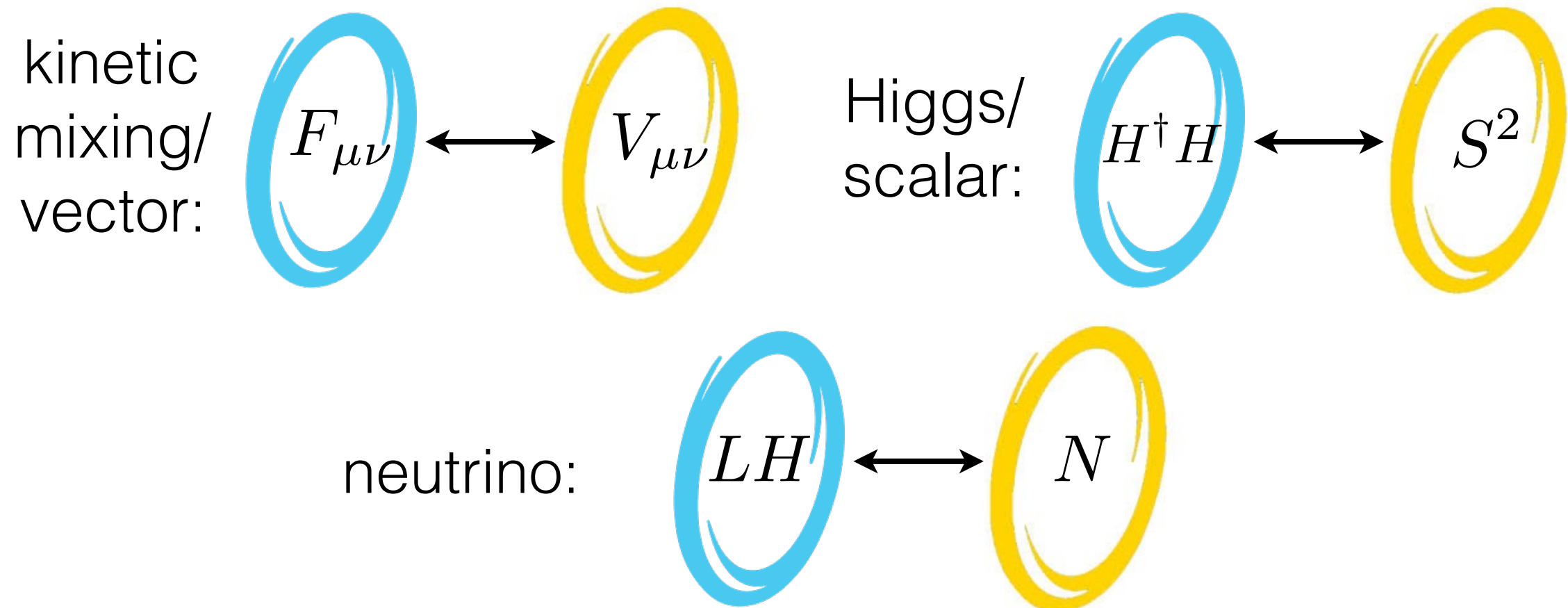
Renormalization: lower dim. operators (fewer fields/particles)
more important at lower energies

Model Building a Dark Sector or: what is a “portal”?

Standard Model symmetries $SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{\text{em}}$

Portals: coupling via stuff uncharged w.r.t. SM

Lead to minimal difficulties incorporating hidden sectors

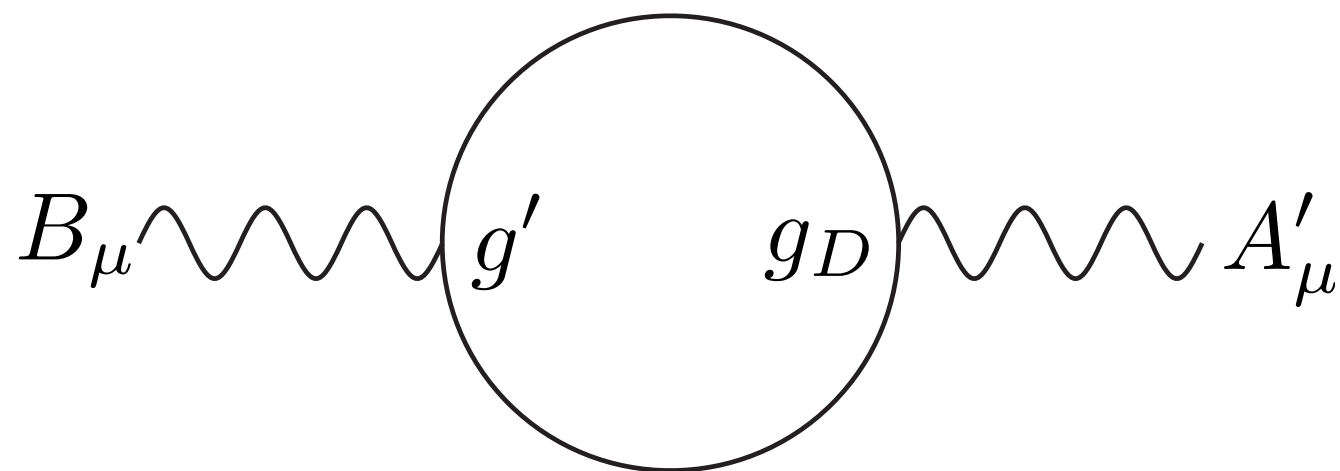


Vector Portal

Okun '82

Galison & Manohar '84

Holdom '86



$$\mathcal{L} \supset -\frac{\epsilon}{2 \cos \theta_W} B_{\mu\nu} F'_{\mu\nu} \rightarrow -\frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu}$$

$$\epsilon \sim \frac{g_D g'}{16\pi^2} \log \frac{M^2}{\Lambda^2}$$

Can have $\epsilon \sim 10^{-3} - 10^{-6}$ $m_{A'} \sim \text{MeV} - \text{GeV}$

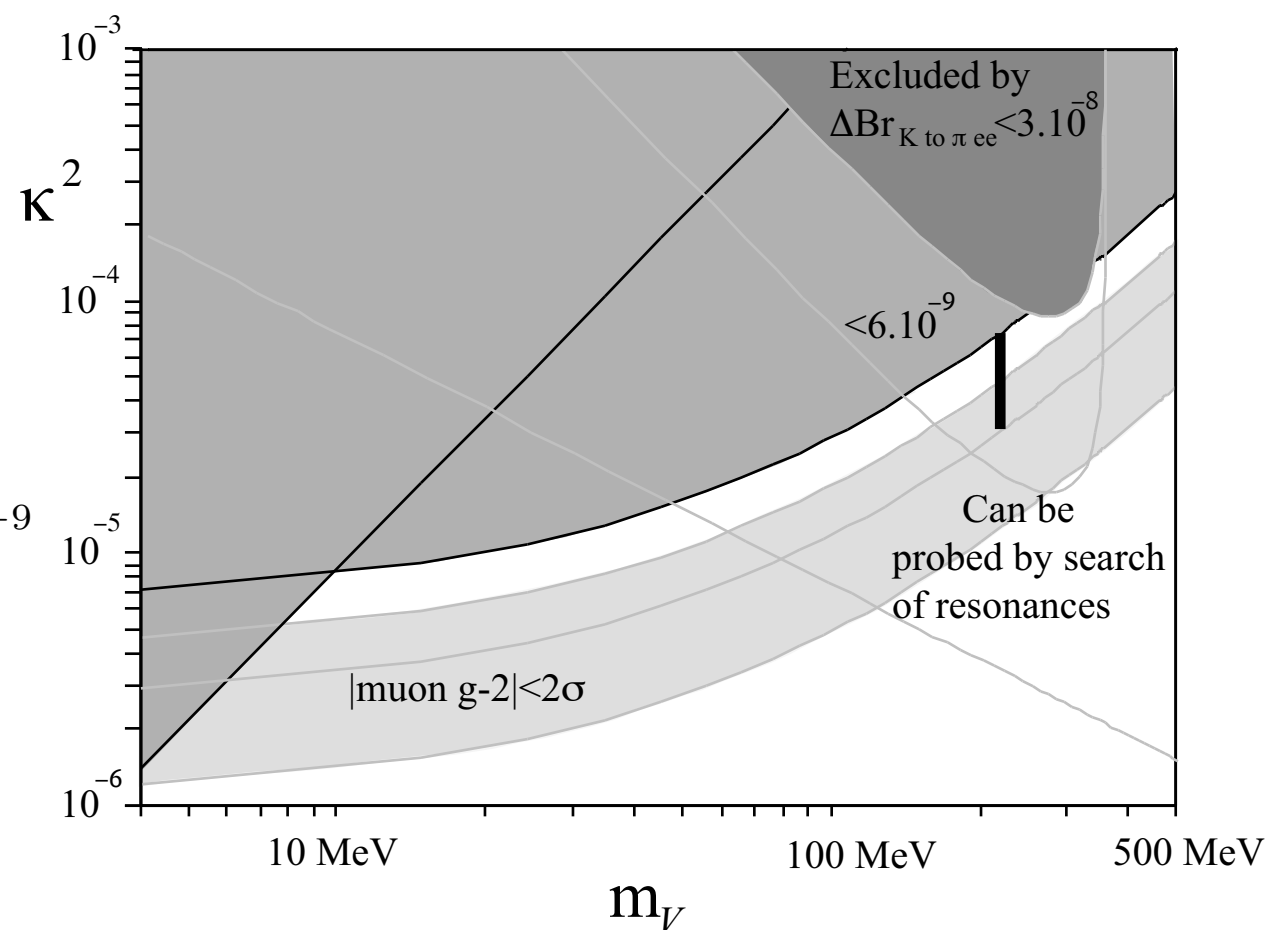
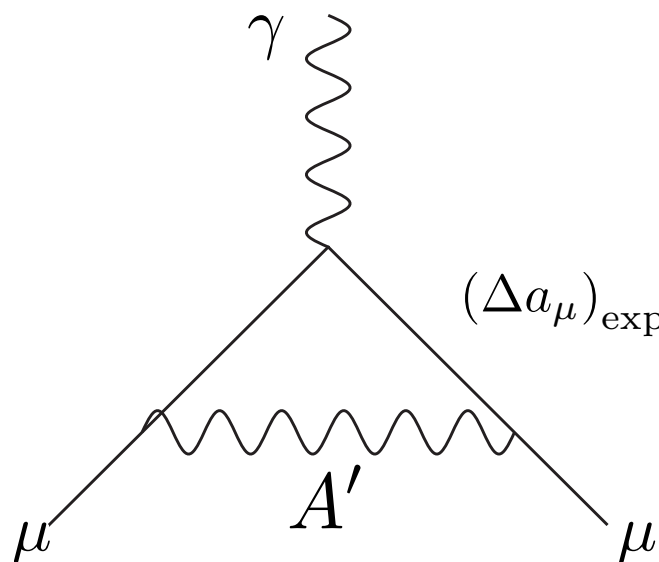
$$\mathcal{L} \supset -\epsilon e A'_\mu (\bar{e} \gamma^\mu e + \bar{\mu} \gamma^\mu \mu + \dots)$$

Pospelov 0811.1030

Contributes
to muon g-2

$$(\Delta a_\mu)_{\text{exp}} - (\Delta a_\mu)_{\text{th}} \simeq (3 \pm 1) \times 10^{-9}$$

(See FNAL and
JPARC g-2 talks)

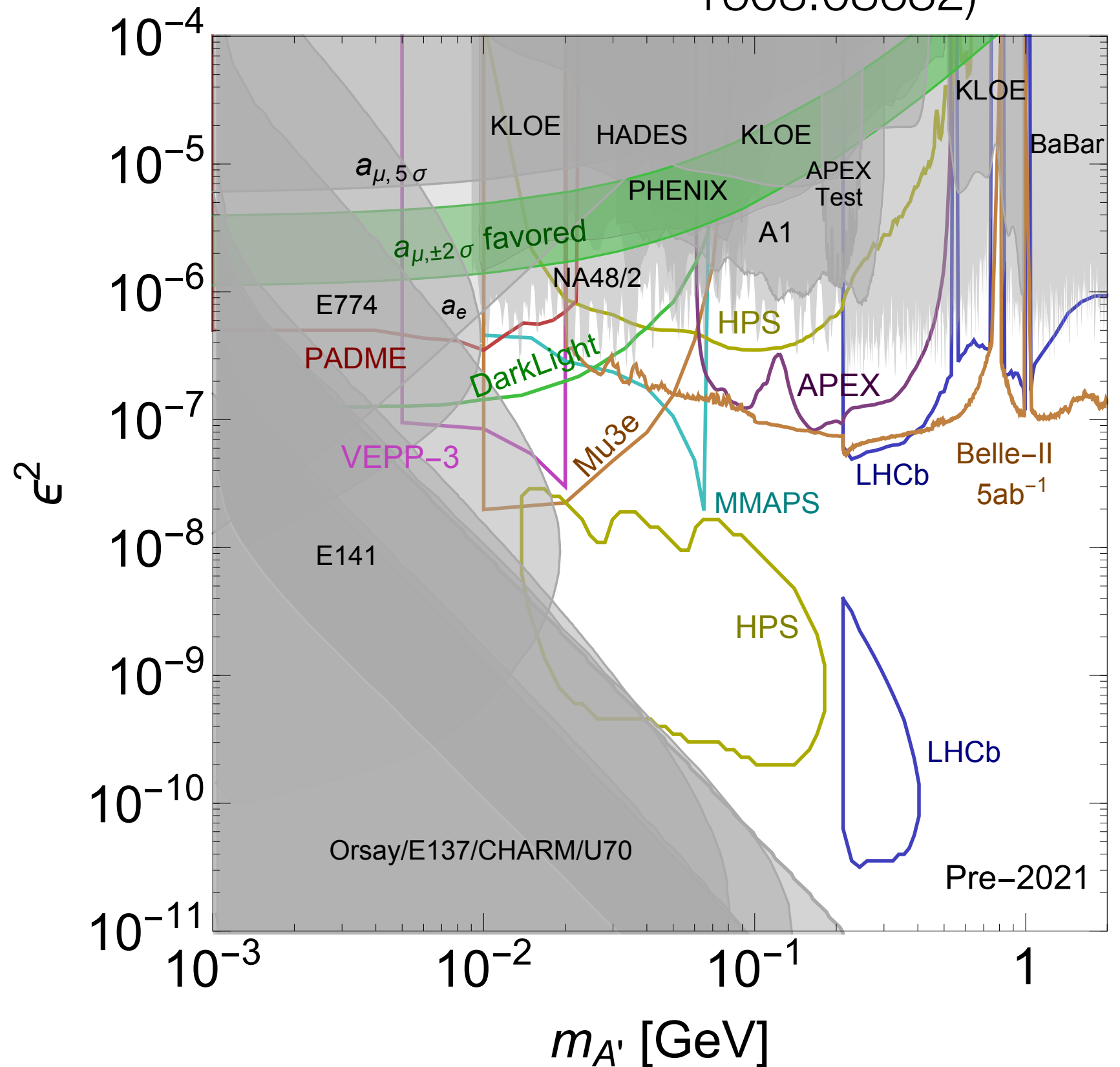
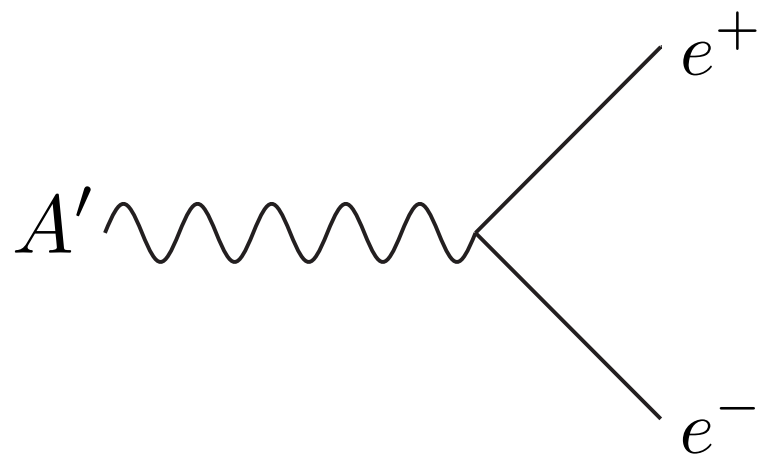


Vector Portal

(Dark sectors 2016
1608.08632)

And now...

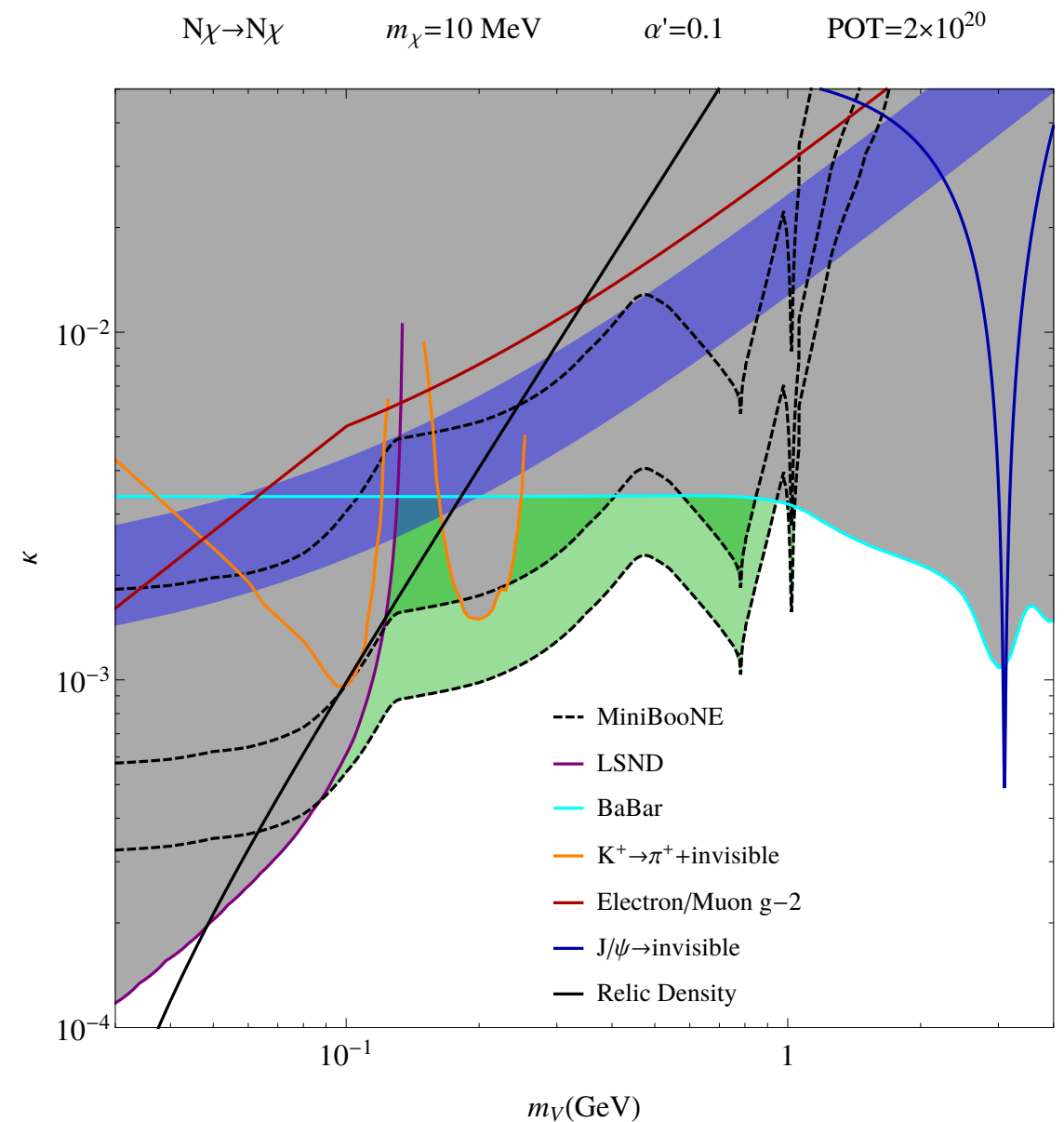
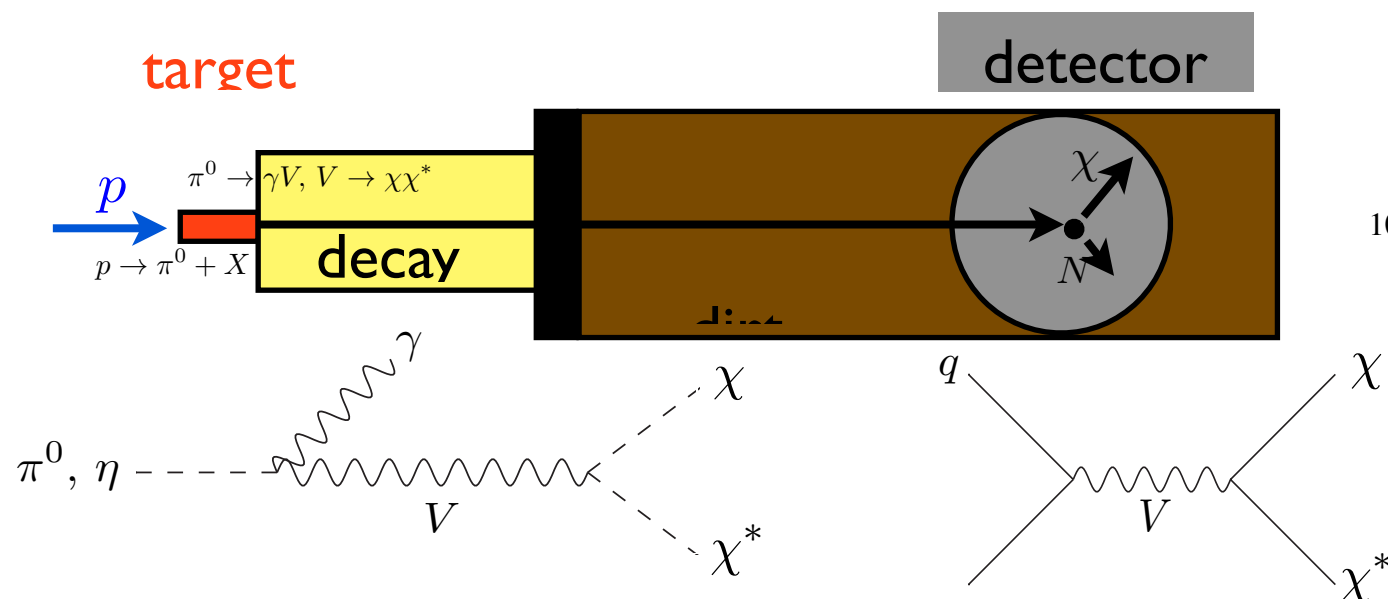
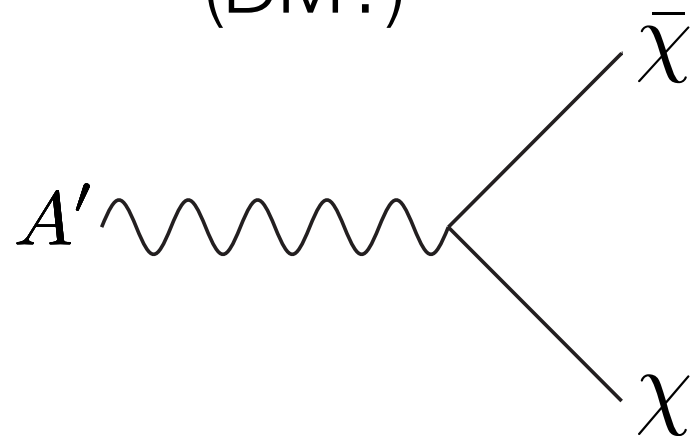
Dark photon decays
to visible stuff e.g.



Vector Portal

Couple dark photon to dark sector: $\mathcal{L} \supset -g_D A'_\mu \bar{\chi} \gamma^\mu \chi$

Dark photon decays
to invisible stuff
(DM?)

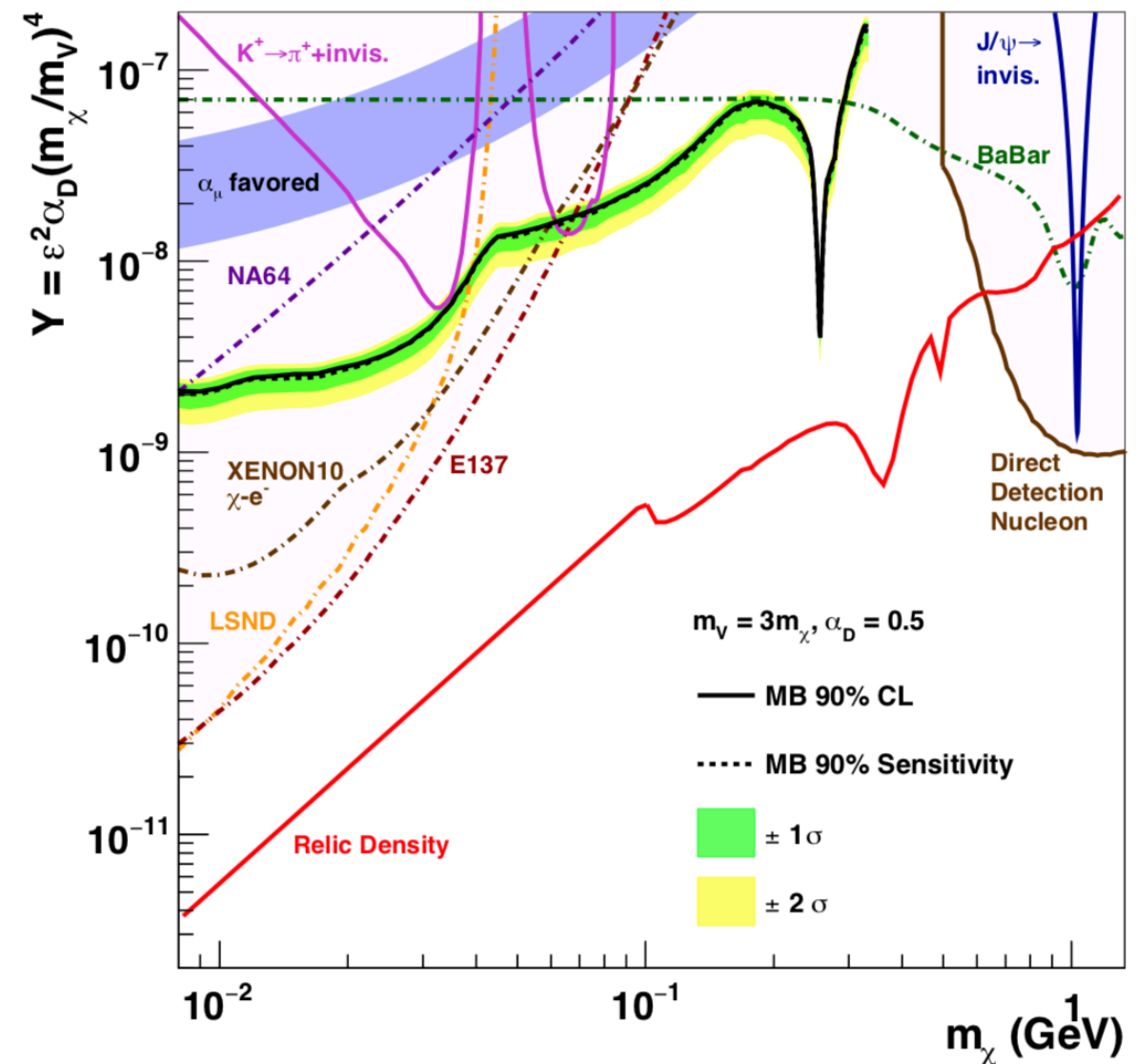
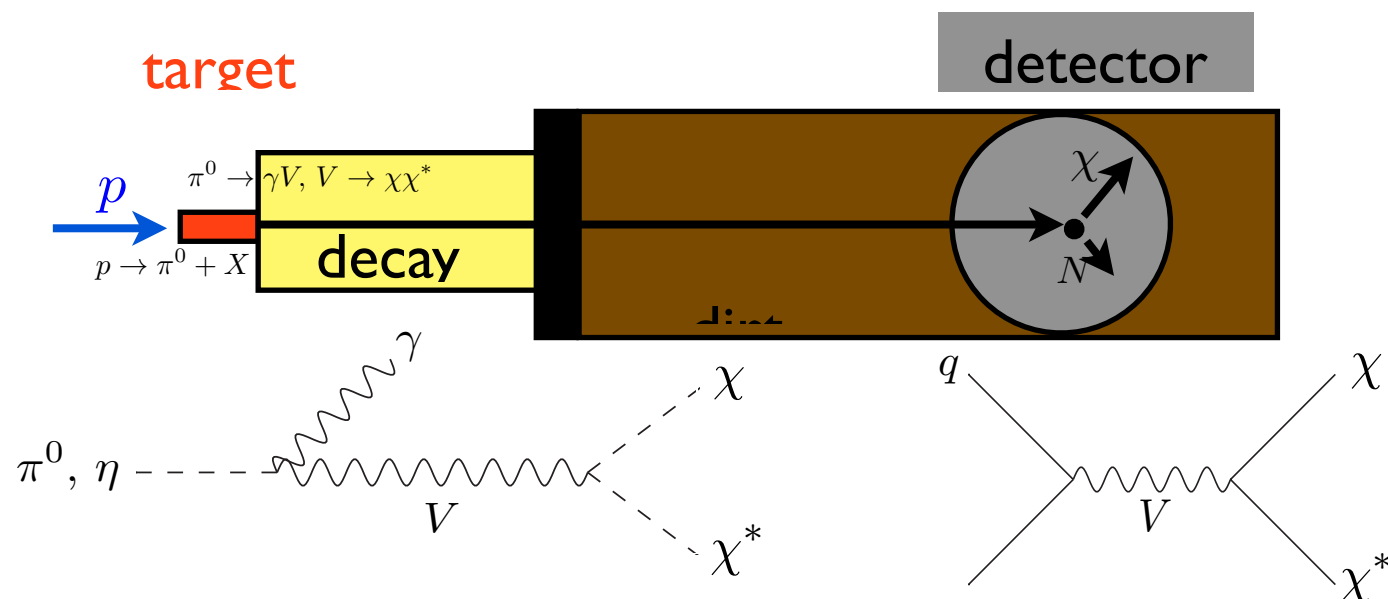
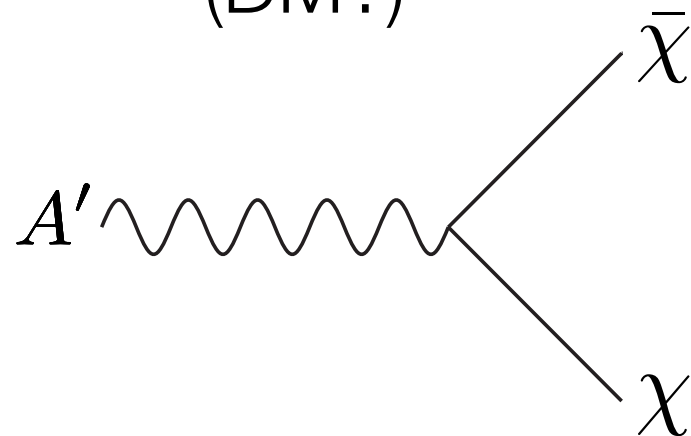


Batell, deNiverville, DM, Pospelov, & Ritz 1405.7049
See also Dobrescu, Fruguele, Coloma

Vector Portal

Couple dark photon to dark sector: $\mathcal{L} \supset -g_D A'_\mu \bar{\chi} \gamma^\mu \chi$

Dark photon decays
to invisible stuff
(DM?)

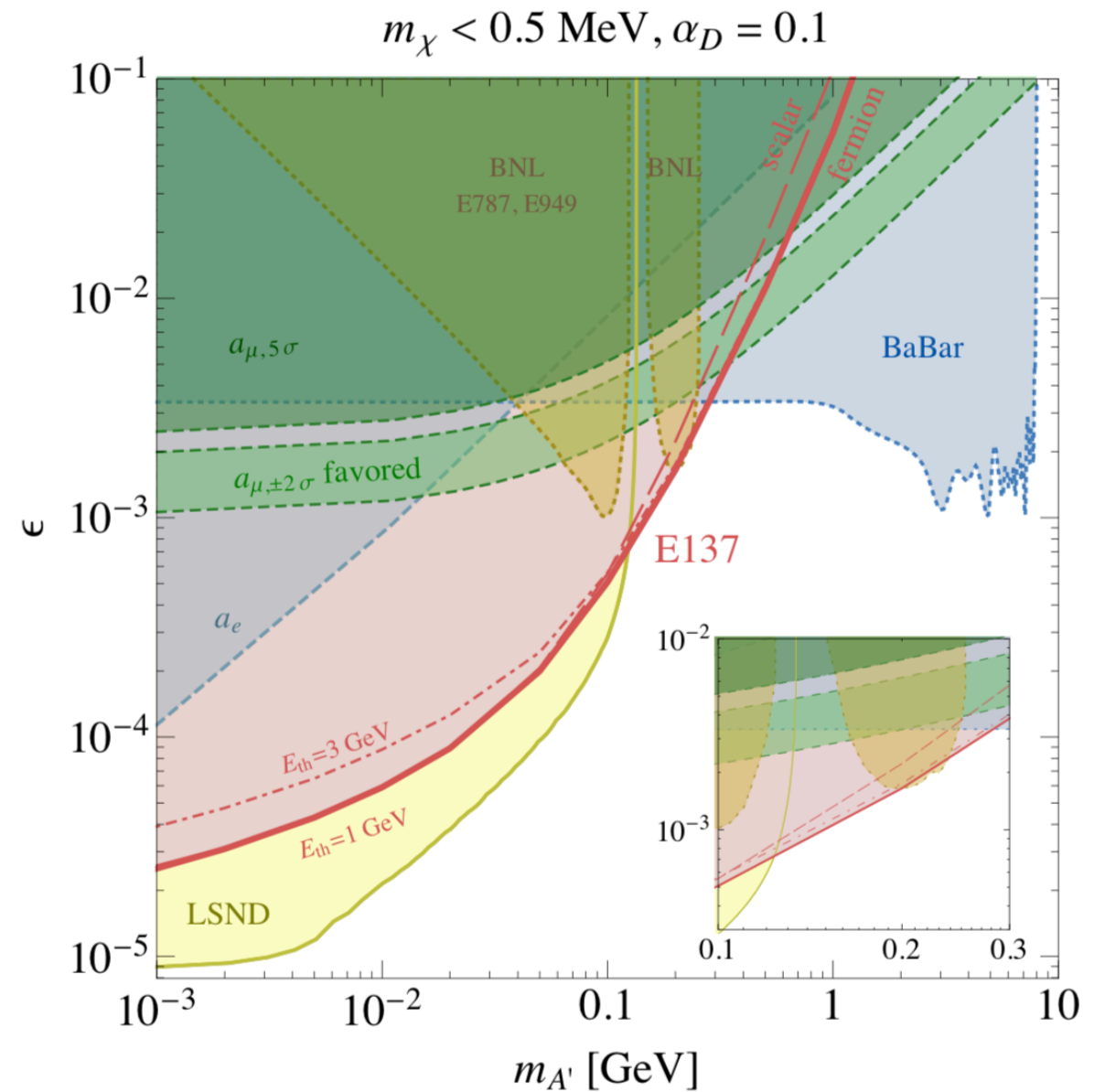
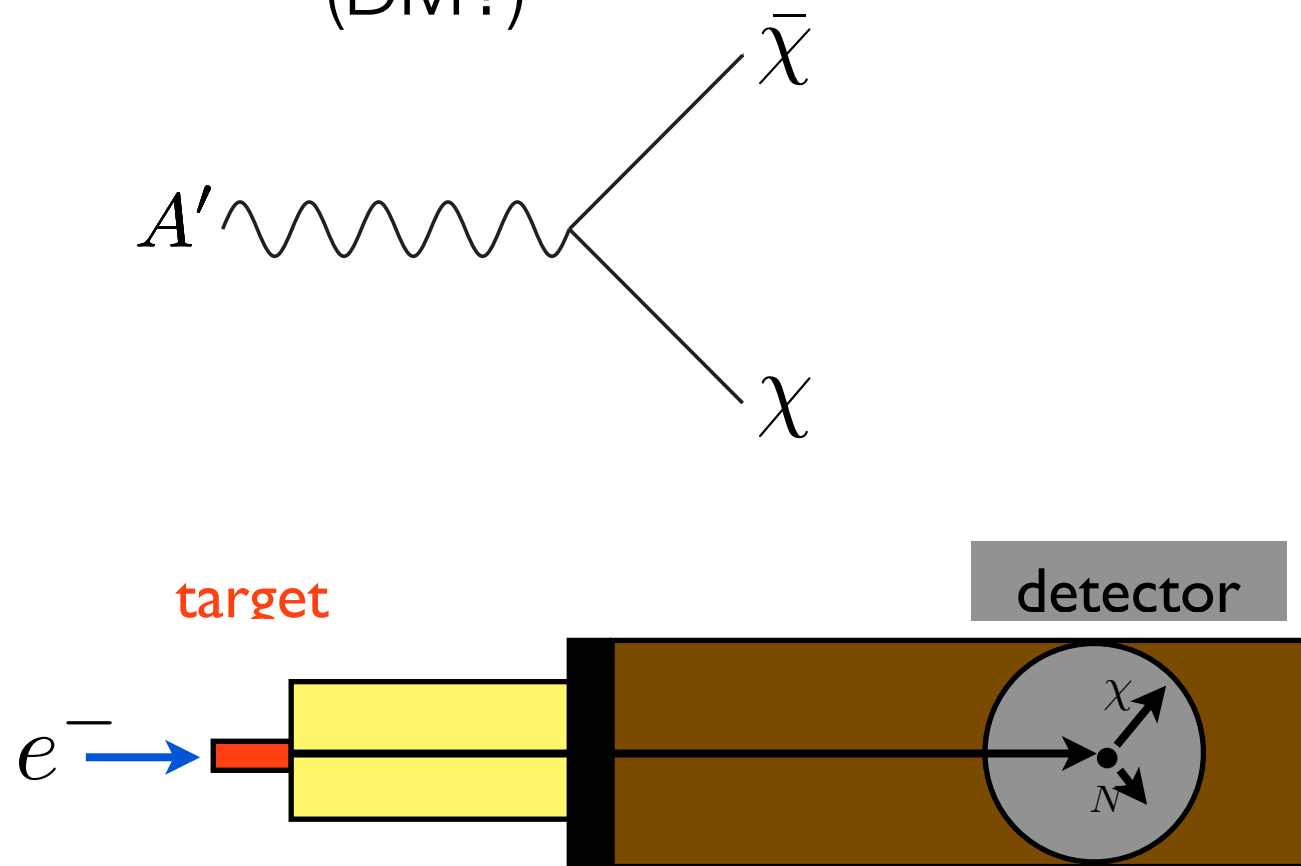


MiniBooNE 1702.02688 (PRL)

Vector Portal

Couple dark photon to dark sector: $\mathcal{L} \supset -g_D A'_\mu \bar{\chi} \gamma^\mu \chi$

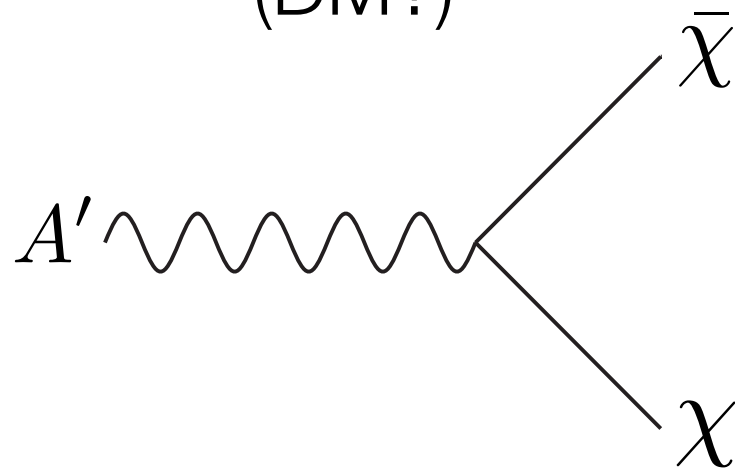
Dark photon decays
to invisible stuff
(DM?)



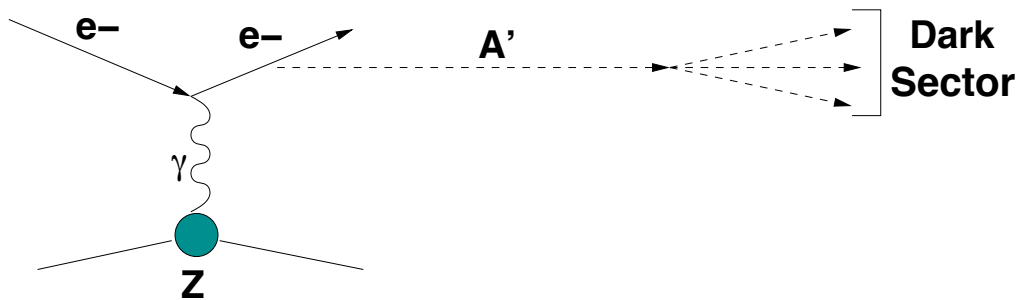
Vector Portal

Couple dark photon to dark sector: $\mathcal{L} \supset -g_D A'_\mu \bar{\chi} \gamma^\mu \chi$

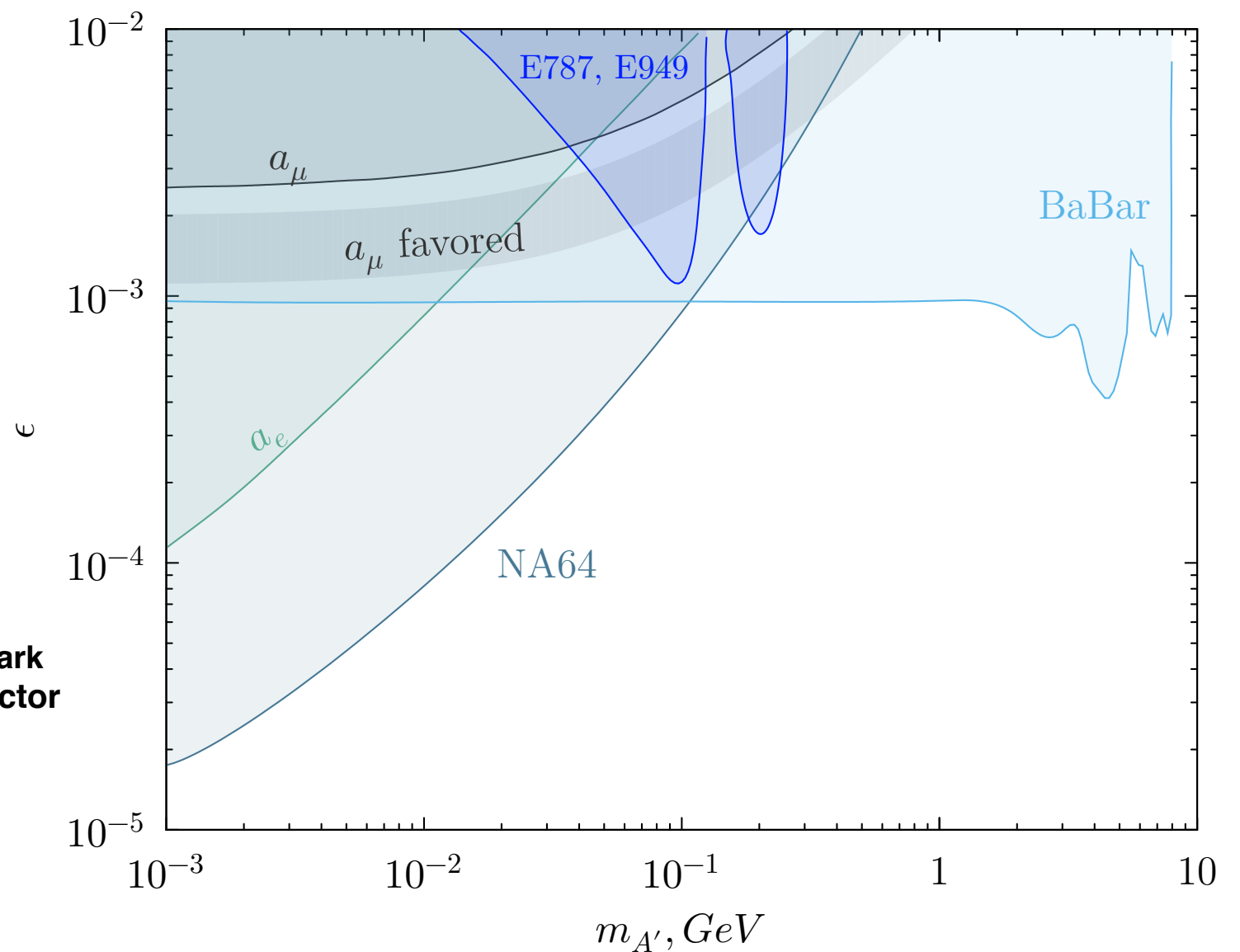
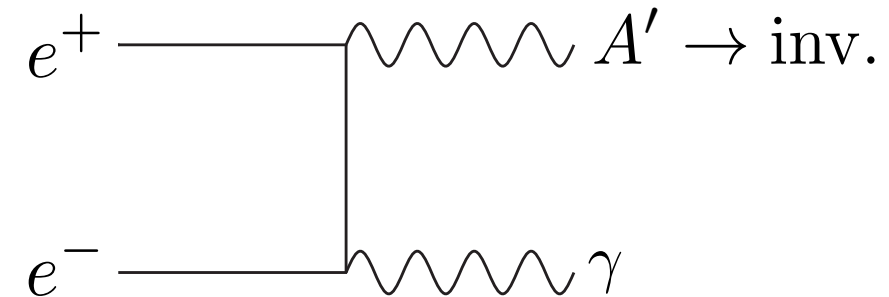
Dark photon decays
to invisible stuff
(DM?)



NA64 1710.00971 (PRD)



BaBar 1702.03327 (PRL)



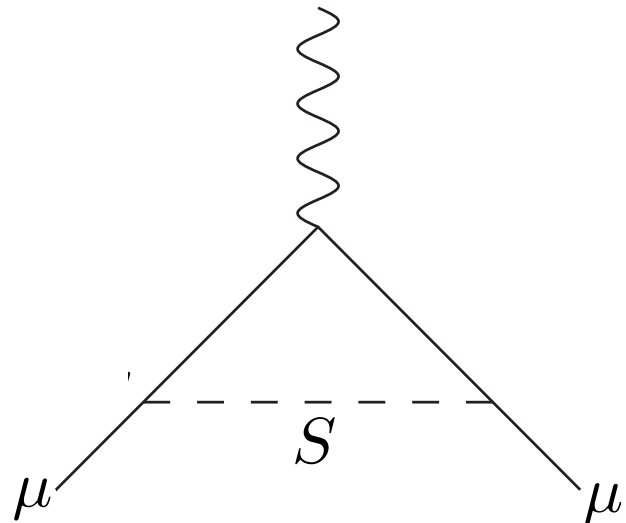
Scalar Portal

Vector portal very constrained even for invisible decays as e.g. $g-2$ solution. What if instead we coupled a **scalar** to leptons?

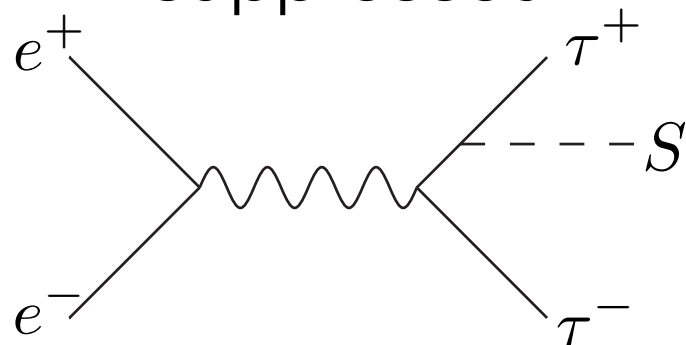
$$\mathcal{L} \supset A |H|^2 S$$



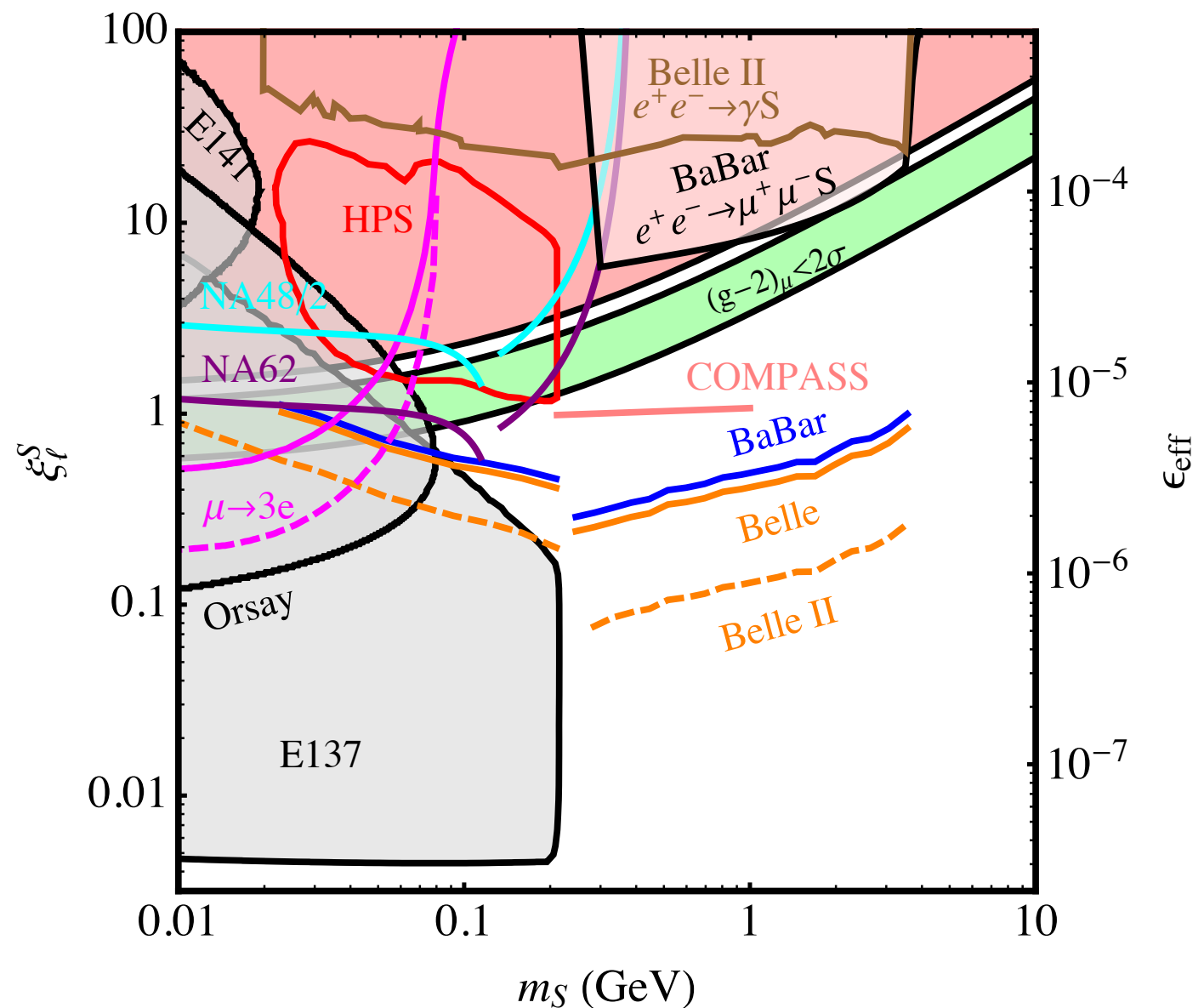
$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 + \xi_\ell S \sum_{l=e,\mu,\tau} \frac{m_\ell}{v} \bar{l}l,$$



Coupling to electrons relatively suppressed



Batell, Lange, DM, Pospelov, & Ritz 1606.04943



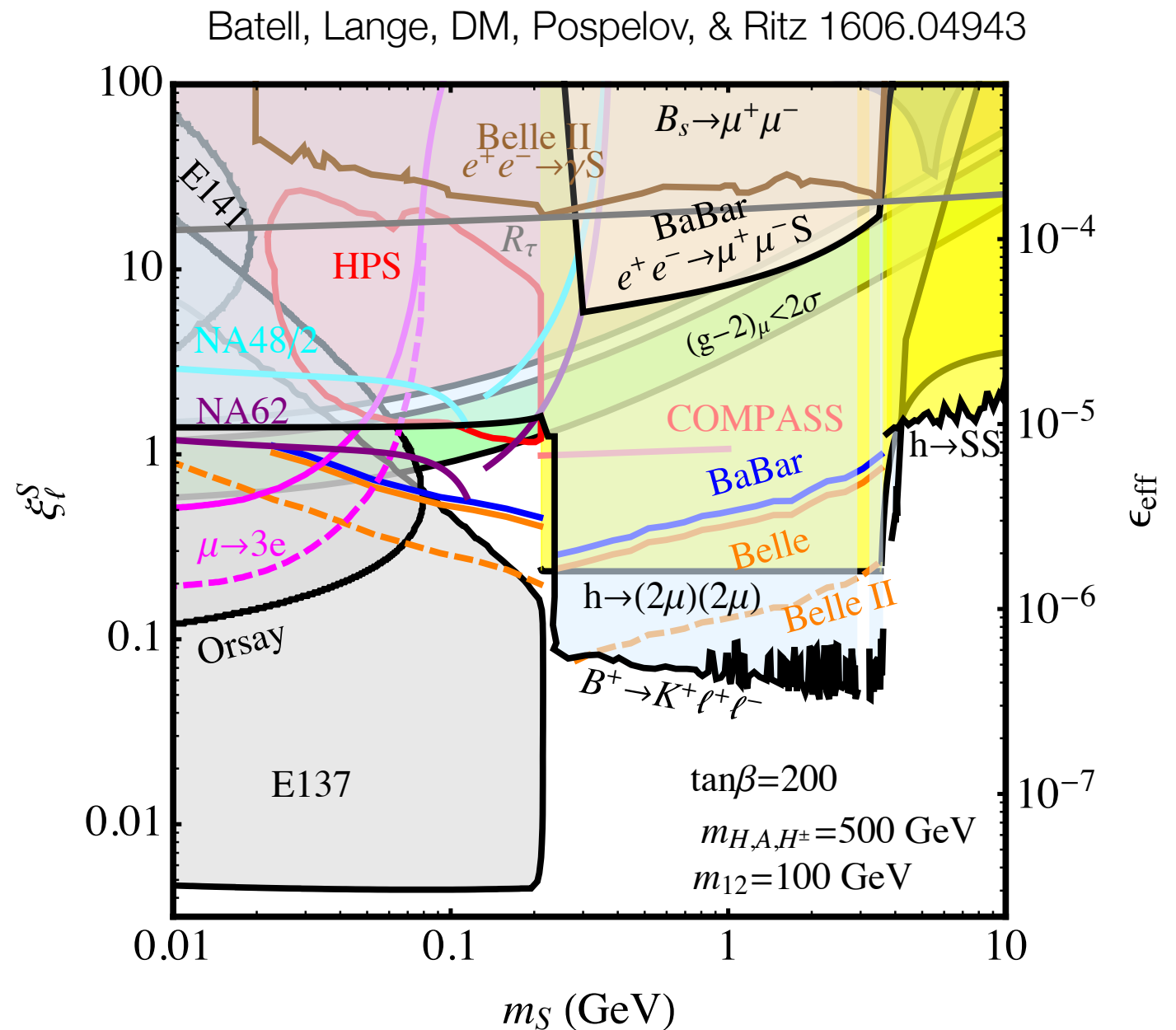
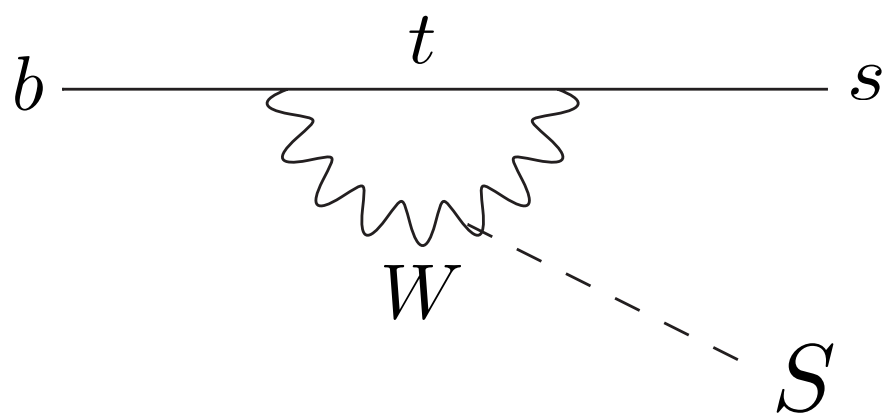
Scalar Portal

A UV completion involves
lepton-specific 2HDM

$$\mathcal{L} \supset \left[A_{11} H_1^\dagger H_1 + A_{22} H_2^\dagger H_2 + A_{12} \left(H_1^\dagger H_2 + H_2^\dagger H_1 \right) \right] \varphi \\ - \left(\bar{L} Y_e H_1 e_R + \bar{Q} Y_d H_2 d_R + \bar{Q} Y_u \tilde{H}_2 u_R + \text{h.c.} \right)$$

(See Chen, Davoudiasl,
Marciano, Zheng for a different
UV completion)

Residual FCNC in quark sector



Summary

LFV exists

In the SM (with neutrino masses) it is unobservable

Lots of BSM models predict LFV—
observation is “unambiguous” sign of NP

Dark sectors well motivated

Study of them has exploded

Standard scenarios already
constrained, sensitivity to more
involved models