Title: Flavor-specific scalars and dark sectors

Date: Nov 13, 2018 01:00 PM

URL: http://pirsa.org/18110038

Abstract: <p>New scalar bosons that are uncharged under the Standard Model have many phenomenological applications, and in particular may serve as mediators between the dark and visible sectors. Such scalars are often taken to have Higgs-like couplings to Standard Model fermions, in order to evade constraints from bounds on flavor-changing neutral currents.
We describe an alternative approach, based on an effective field theory approach in which a new scalar preferentially couples to a single fermion mass eigenstate. In such theories, we show through a spurion analysis that small flavor changing couplings are still technically natural. Examples of our framework include a muon-philic scalar that can explain the observed anomalous magnetic moment of the muon and an up-specific scalar mediator to a dark sector, whose phenomenologies we discuss in detail.<o:p></o:p></p>

Flavor-specific scalars and dark sectors

Ahmed Ismail

University of Pittsburgh

Perimeter Institute seminar

November 13, 2018

with B. Batell, A. Freitas and D. McKeen

Dark sectors: new SM singlet particles

Motivated by hints of new physics / questions in SM

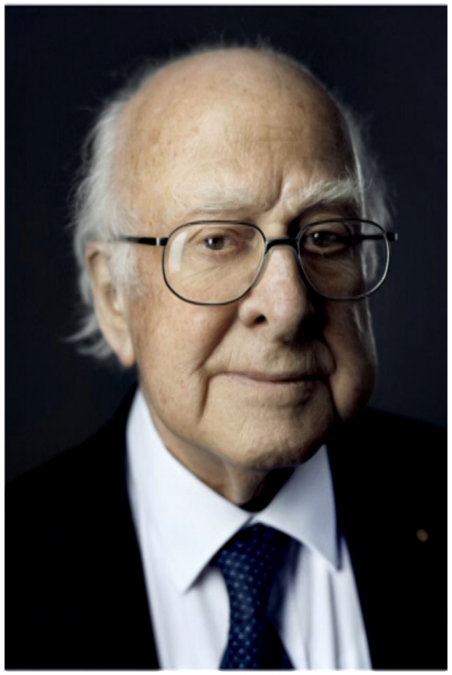
- dark matter
- muon g – 2
- proton radius
- neutrinos

Compared to new vector bosons, no anomaly cancellation issues for scalars

Downside: scalar masses unprotected against quantum corrections

2

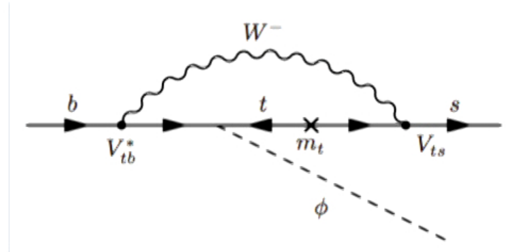
Maybe hierarchies are a fact of life....

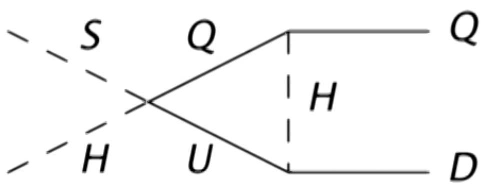


3

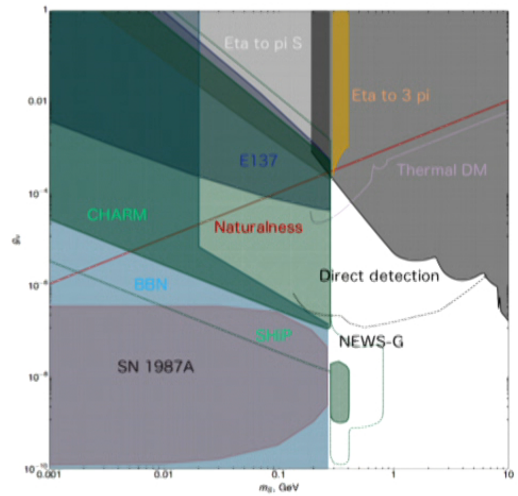
Plan

Fermion-specific scalars as part of light dark sector





Theory of a flavored scalar



Phenomenology:
up-philic
muon-philic

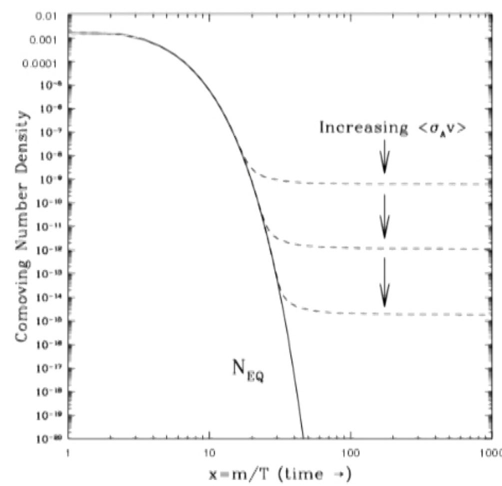
4

Motivating new light scalars from DM

Lots of evidence for dark matter

Canonical WIMP paradigm:

- thermal freezeout of cold relic



Lower limit from needing to annihilate enough

$$\Omega h^2 \sim 0.1 \left(\frac{10 \text{ GeV}}{m_\chi} \right)^2$$

weak interaction

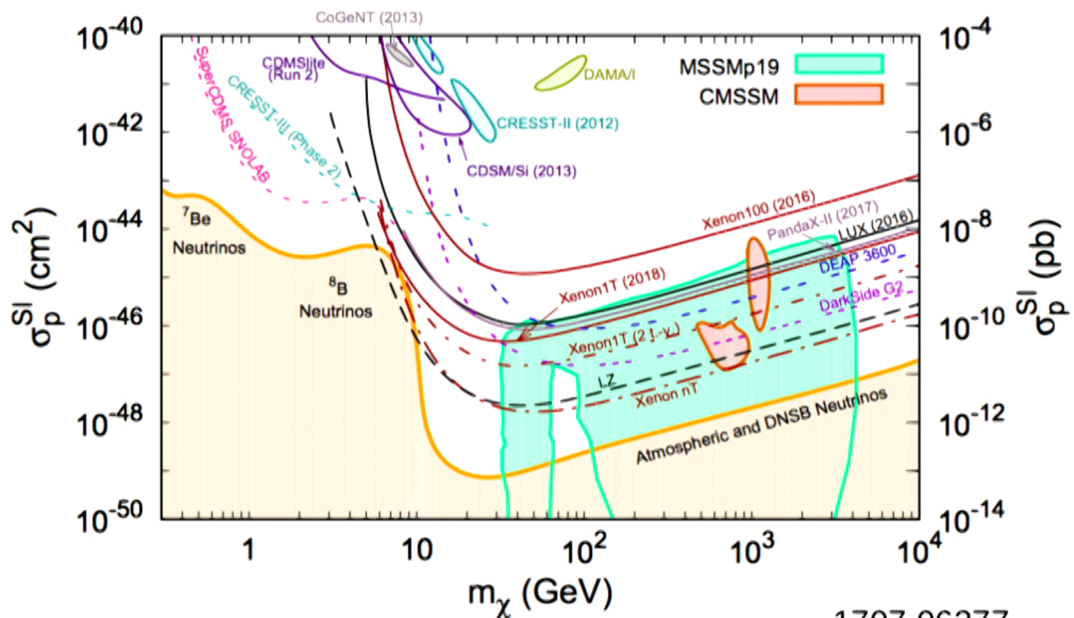
Upper limit from maximum coupling size ~ 100 TeV

5

Direct detection limited at low mass

Today, DM velocity ~ 10^{-3}

$$q \sim m_\chi v \qquad E_{\rm recoil} = \frac{q^2}{2m_N}$$



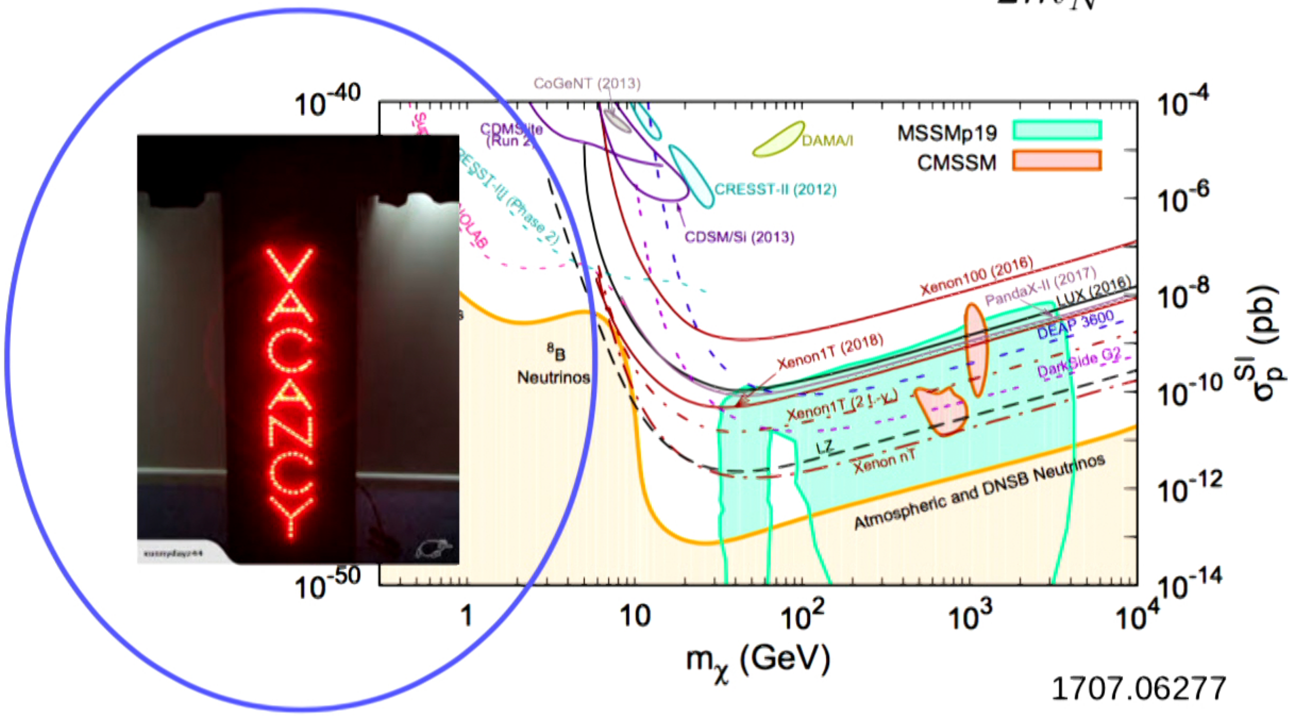
1707.06277

6

Direct detection limited at low mass

Today, DM velocity ~ 10^{-3}

$$q \sim m_\chi v \qquad E_{\rm recoil} = \frac{q^2}{2m_N}$$



1707.06277

7

New mediators

Evade Lee-Weinberg bound with light mediators to go between SM and DM

Fully renormalizable portals:

- vector

$$F_{\mu\nu}F'^{\mu\nu}$$

- scalar

$$|S|^2|H|^2$$

- fermion

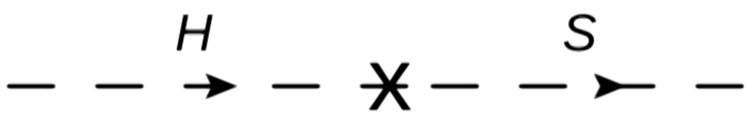
$$\bar{L}HN$$

8

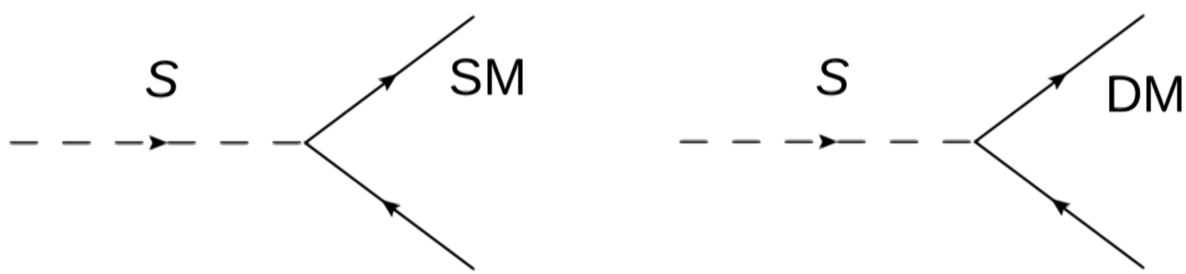
Looking for the dark sector

Renormalizable portals → dark photon, dark Higgs, sterile neutrino

Production through portal coupling



Decay of mediator depends on available modes

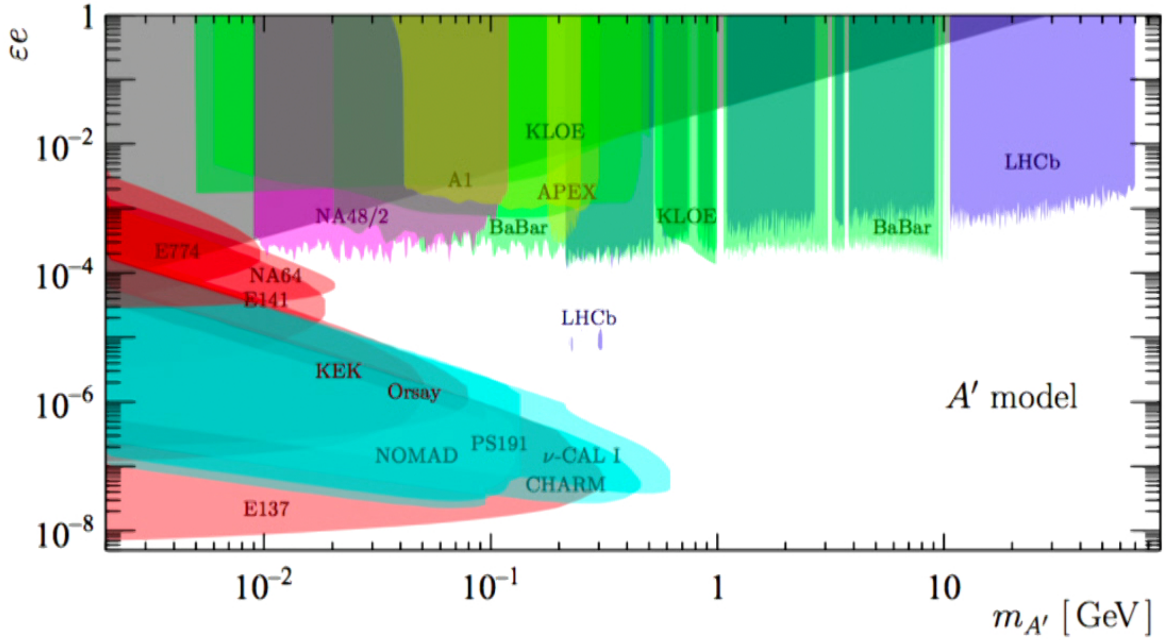


Note visible decay independent of DM itself

9

Example: dark photon

Assuming dark photon decays visibly $\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$



Quark and lepton couplings linked

Ilten et al., 1801.04847

10

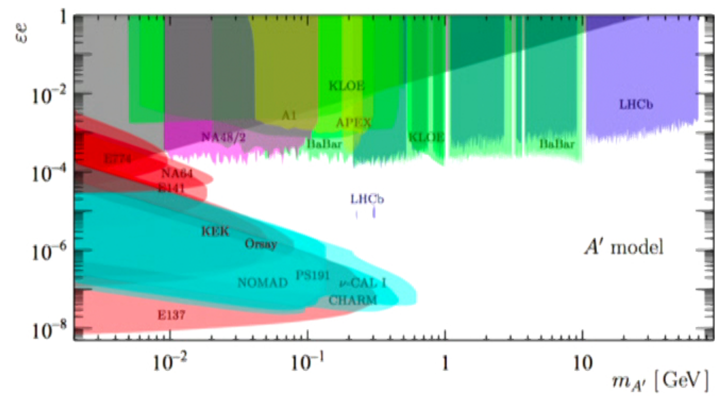
Going beyond fermion universality

Model dependence, e.g. for a kinetically mixed dark photon, all fermions couple proportionally to their charge

How to change?

Can gauge B – L or inter-generational symmetries instead of having simple kinetic mixing

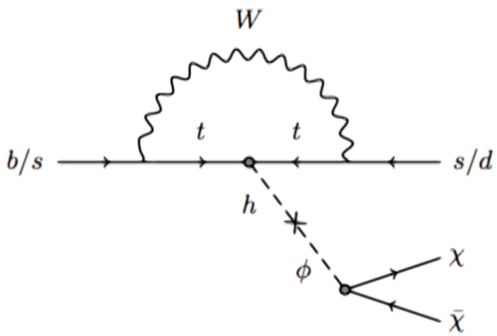
Other options possible but require more particles for anomalies

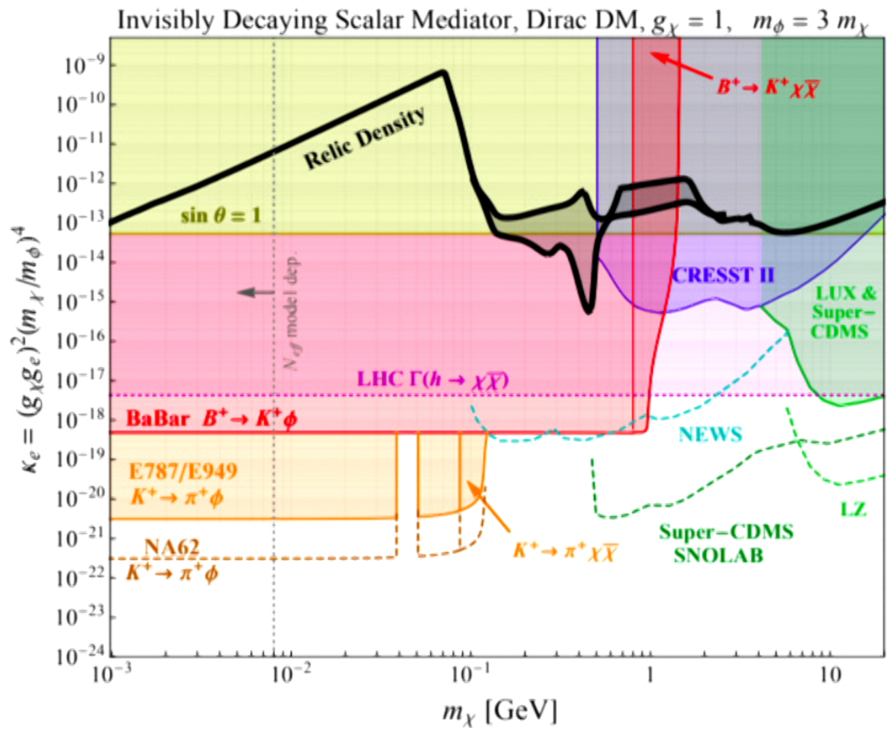


Going beyond fermion universality

Same question arises for other portals

Krnjaic, 1512.04119



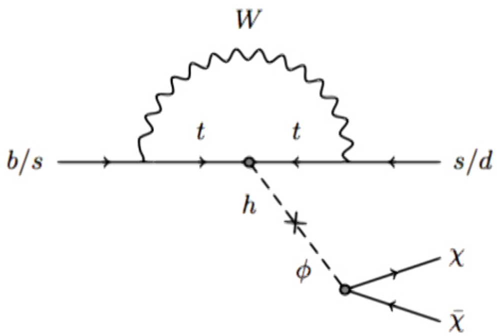


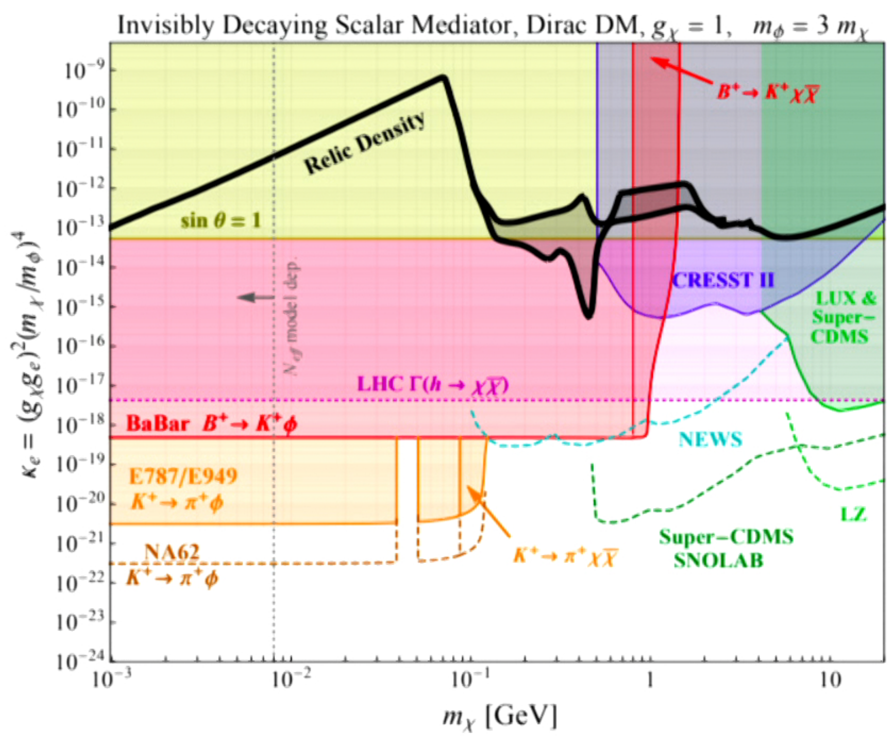
Rare meson decays very constraining

Going beyond fermion universality

Same question arises for other portals

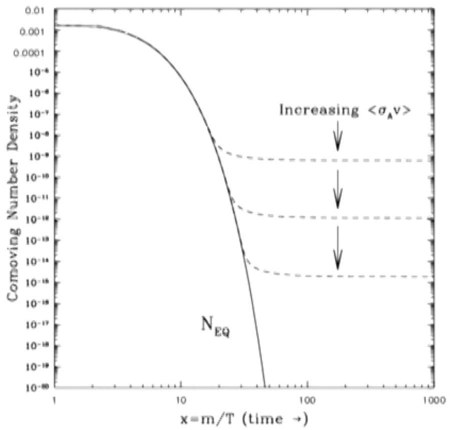
Krnjaic, 1512.04119





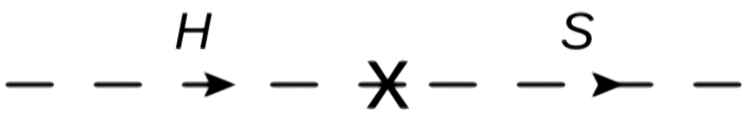
What if scalar mediator had no effective coupling to top quarks?

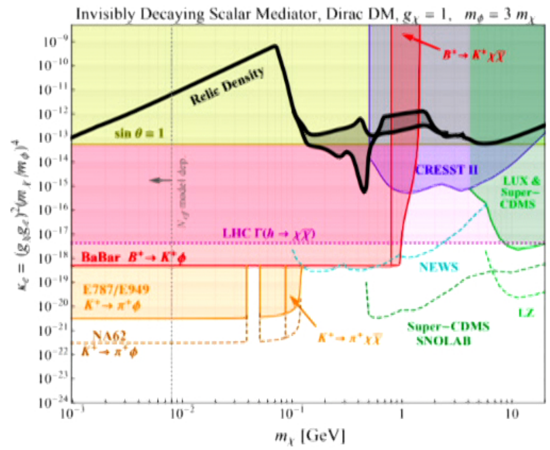
Summary – motivation



Go beyond WIMPs, look at light dark sectors

Implies the existence of new mediators between SM and DM



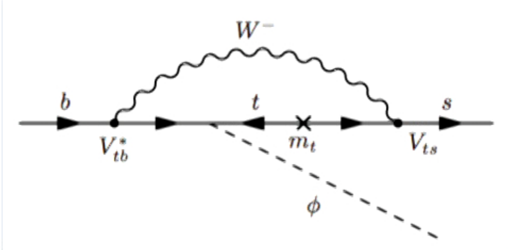


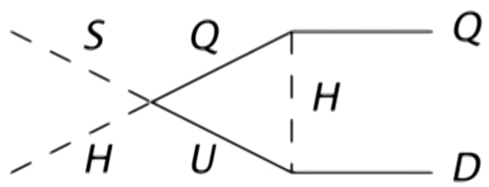
Simplest portals are very predictive

Today: generalize scalar portal with fermion-specific couplings

Plan

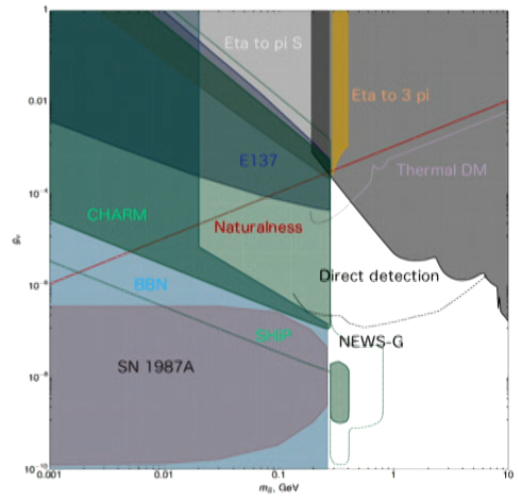
Fermion-specific scalars
as part of light dark sector





Theory of a flavored
scalar

Phenomenology:
up-philic
muon-philic



15

Adding a new flavored scalar

Want to not just reproduce dark Higgs → direct fermion coupling

Renormalizable operator forbidden for SM singlet

$$\frac{c_S}{M} S\bar{Q}H_c U \qquad\qquad \frac{d_S}{M}\partial_\mu S\bar{U}\gamma^\mu U$$

Can change these into each other with field redefinitions

$$U \to U(1 - id_S)/M$$

Induces non-derivative operator with strength proportional to Yukawa

Flavor symmetries

Consider non-derivative operator $\frac{c_S}{M} S\bar{Q}H_c U$

Coefficient is matrix in flavor space, generically leads to flavor-changing neutral currents

Recall: SM without Yukawas has flavor symmetry

$$U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$$

Minimal flavor violation hypothesis: Yukawas are only source of flavor symmetry breaking $\rightarrow c_S \sim Y_u$

17

Beyond Minimal Flavor Violation

MFV = new physics preserves $U(3)^3$ of quark sector

Next-to-minimal flavor violation = new physics couples only to third generation, respecting $U(2)^3$

Agashe, Papucci, Perez, Pirjol hep-ph/0509117

Meson mixing is proportional to misalignment between interaction basis of new physics and Yukawas

Generalize: a coupling to a single quark preserves $U(2)^2 \times U(3)$

Spurion analysis

Take flavor and shift symmetries associated with *S*

Estimate sizes of all operators in EFT in terms of leading couplings

$$\frac{c_S}{M} S\bar{Q}H_c U \qquad\qquad m_S^2 S^2$$

- Flavor changing operators
- Scalar potential

19

Flavor for up-philic scalar

Orientation of single up-type quark interacting with scalar in mass eigenbasis determines FCNCs

- e.g. *S* coupling to O(1) mixture of *u* and *c* mass eigenstates faces stringent *D* meson bounds

$$(c_S)_{12}/M \lesssim (10^8 \text{ GeV})^{-1}$$

→ *Assume* that chiral symmetry broken by *S* interactions = symmetry broken by up quark mass

$$c_S \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

quark mass eigenbasis

$$U(3)^2 \to U(2)_Q \times U(2)_U \times U(1)_{u+q^1}$$

Flavor for up-philic scalar

All flavor violation now goes as Y_d with appropriate CKM elements; in basis with diagonal up Yukawas,

$$Y_d = V_{\rm CKM} Y_d^D$$

In up sector, have flavor-violating correction

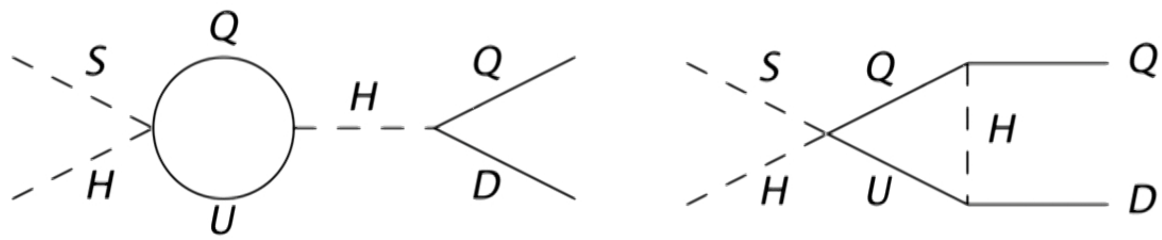
$$\frac{1}{M}\left(V_{\rm CKM} Y_d^D (Y_d^D)^\dagger V_{\rm CKM} c_S^\dagger\right) S\bar{Q} H_c U$$

Small down-type Yukawas, off-diagonal CKM elements yield negligible D mixing

$$c_S/M \lesssim (1\ {\rm GeV})^{-1}$$

Flavor for up-philic scalar

Down-type scalar couplings induced at loop level



Both flavor-conserving and flavor-violating couplings go as $Y_u\, Y_d\, c_S$ and are loop suppressed

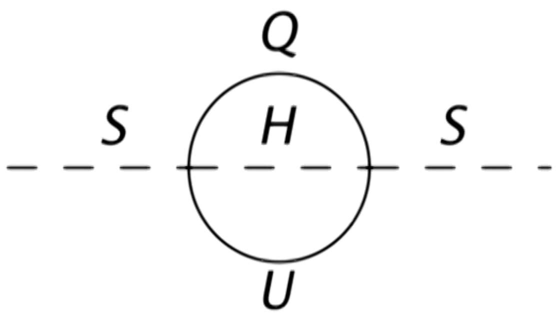
$$\frac{1}{M}\left(V_{\rm CKM}^\dagger c_S (Y_u^D)^\dagger V_{\rm CKM} Y_d^D\right) S\bar{Q}HD$$

Tend to be less important for up-philic case

Other induced couplings – scalar potential

New scalar suffers from usual hierarchy problem

Assume new physics regulates divergence at scale *M*



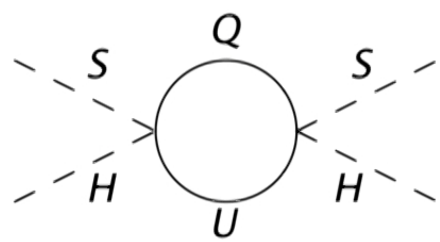
$$\delta m_S^2 \lesssim m_S^2$$

$$\begin{aligned} c_S &\lesssim (16\pi^2)\frac{m_S}{M} \\ &\approx (3\times 10^{-3})\left(\frac{m_S}{0.1\ \mathrm{GeV}}\right)\left(\frac{5\ \mathrm{TeV}}{M}\right) \end{aligned}$$

23

Other induced couplings – scalar/Higgs

For low *M*, diagrams with Higgs vevs dominate naturalness constraints



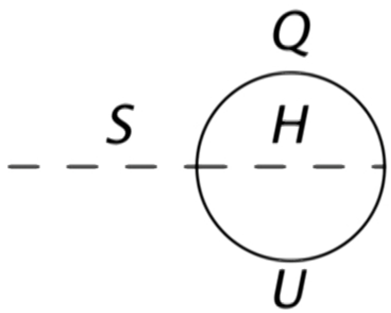
$$\delta m_S^2 \lesssim m_S^2 \rightarrow c_S \lesssim (4\pi\sqrt{2})\frac{m_S}{v}$$

→ small Higgs-*S* mixing

24

Other induced couplings – scalar vev

Protected by combination of *S* shift symmetry and chiral symmetry



$$v_S \approx -\frac{\delta_S}{2m_S^2} \sim \frac{c_S^\dagger Y_u}{2(16\pi^2)^2}\left(\frac{M}{m_S}\right)^2 M$$

S vev generally larger than scalar mass for $M >> m_s$

S^n operators for $n > 2$ don't significantly affect scalar potential when generated radiatively

25

Other induced couplings – scalar vev

Immediately gives correction to quark mass which is technically natural but still dangerous for $m_s \ll M$

$$\delta m_u \sim \frac{c_S^2}{2(16\pi^2)^2} \left(\frac{M}{m_S}\right)^2 m_u$$

Leads to same bound on c_s as S mass correction

$$\mathrm{c}_S \lesssim (16\pi^2)\frac{m_S}{M}$$

Summary – building a scalar theory

Can build theories with new scalars that preferentially couple to a single fermion without huge FCNC

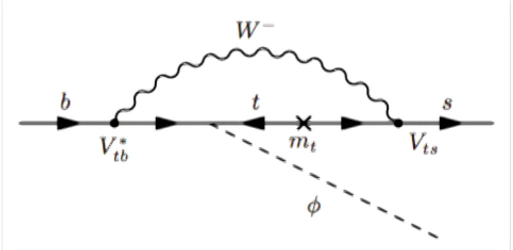
Initial alignment of couplings is required, but then well preserved up to small Yukawas due to MFV-inspired symmetry principle

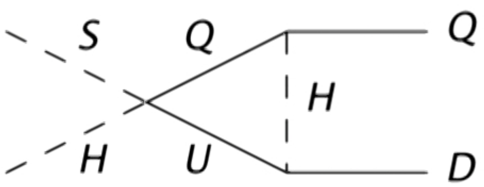
Effective theory is eventually resolved, with different UV completions possible

Imposing naturalness implies small coupling size

Plan

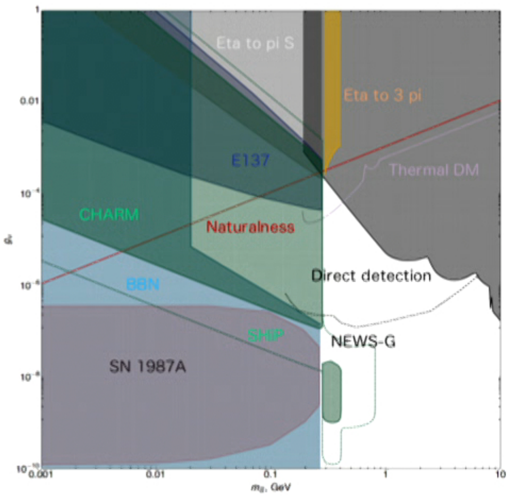
Fermion-specific scalars as part of light dark sector





Theory of a flavored scalar

Phenomenology:
up-philic
muon-philic



28

Searching for an up-philic scalar

Take *S* to be the mediator between us and some DM χ

$$\frac{c_S}{M} S\bar{Q}H_c U \qquad\qquad g_\chi S\bar{\chi}\chi$$

Effective coupling of *S* to up quarks $\quad g_u = \dfrac{c_S v}{\sqrt{2}M}$

DM coupling less constrained → BR($S \to \chi\chi$) = 0 or 1

$m_\chi < m_S / 2$: *S* decays invisibly

$m_\chi > m_S / 2$: *S* can only decay to SM particles

29

Visible decays of the scalar

$m_S < 2\, m_\pi$: *S* decays to photons, can be long-lived

S above pion threshold but below QCD scale: use scalar form factors extracted from scattering data

$$g_{S\pi\pi} = \frac{7}{9}\frac{g_u}{m_u + m_d}\Gamma_\pi$$

$$\Gamma_\pi((p+p')^2) = \langle \pi(p)\pi(p')|m_u \bar{u}u + m_d \bar{d}d|0\rangle$$

m_S > few GeV: parton level calculation

DM annihilation

m_χ > ~GeV: annihilate to free quarks

$$\sigma v(\bar{\chi}\chi \to \bar{u}u) = \frac{3g_u^2 g_\chi^2 m_\chi^2 v^2}{8\pi(m_S^2 - 4m_\chi^2)^2}$$

Again, use form factor for sub-GeV annihilation

$$\sigma v(\bar{\chi}\chi \to \pi\pi) = \frac{49|\Gamma_\pi(4m_\chi^2)|^2 g_u^2 g_\chi^2 m_u^2 v^2 \sqrt{1 - m_\pi^2/m_\chi^2}}{1728\pi(m_u + m_d)^2(m_S^2 - 4m_\chi^2)^2}$$

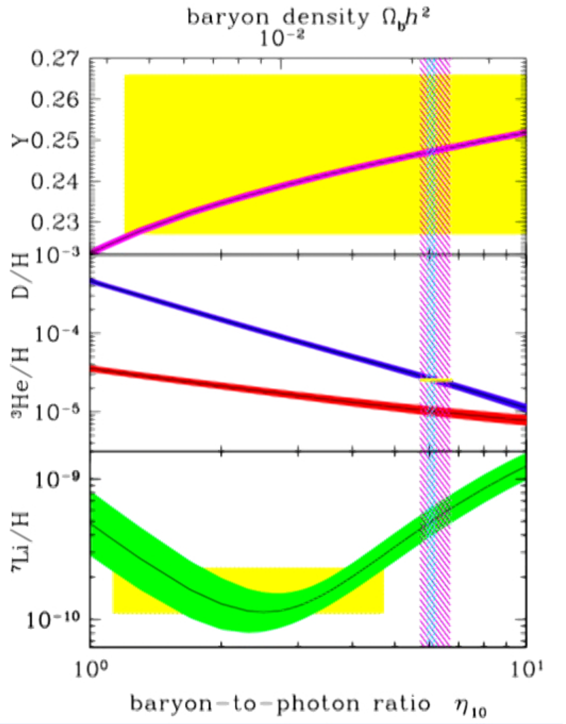
p-wave, avoiding CMB constraints

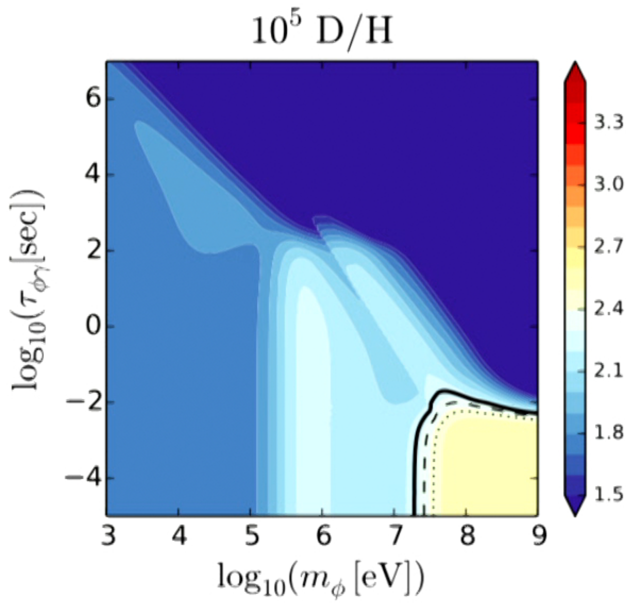
$m_\chi > m_S$: secluded annihilation, $\chi\chi \to S\,S$

31

Big Bang Nucleosynthesis

If light enough, *S* decays increase effective baryon/photon ratio at start of BBN





Millea, Knox, Fields 1501.04097

32

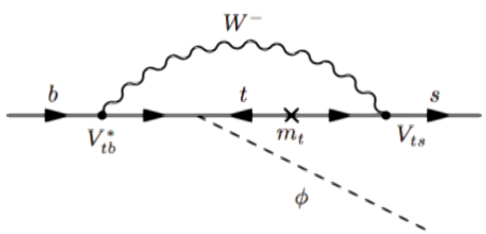
Meson decays to scalars

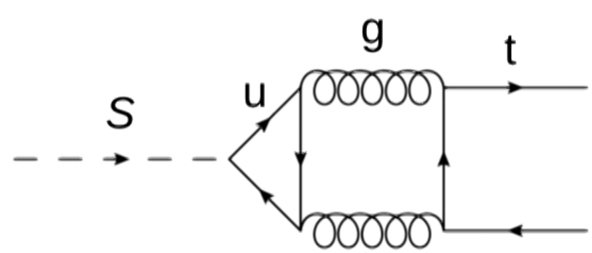
M $\rightarrow$ M' + photons, when $S \rightarrow \gamma\gamma$

M $\rightarrow$ M' + 2π, above pion threshold

Mesons M, M' are B, K, η, π

Unlike dark Higgs, top coupling only arises from loops





Much weaker limits from B $\rightarrow$ K + S

33

Scalar production from eta decays

Estimate $\eta \to \pi S$ from chiral QCD

$$\mathcal{L} \supset \frac{f^2}{4}\mathrm{tr}[(D_\mu\Sigma)^\dagger D^\mu\Sigma] + \frac{f^2}{4}\mathrm{tr}\left[\Sigma^\dagger\chi + \chi^\dagger\Sigma\right]$$

$$\Sigma = e^{2i\pi/f} \qquad \chi = 2B\begin{pmatrix} m_u + g_u S & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

$$B \approx 2.6 \text{ GeV}$$

S-meson-meson couplings are all of order $g_u B$

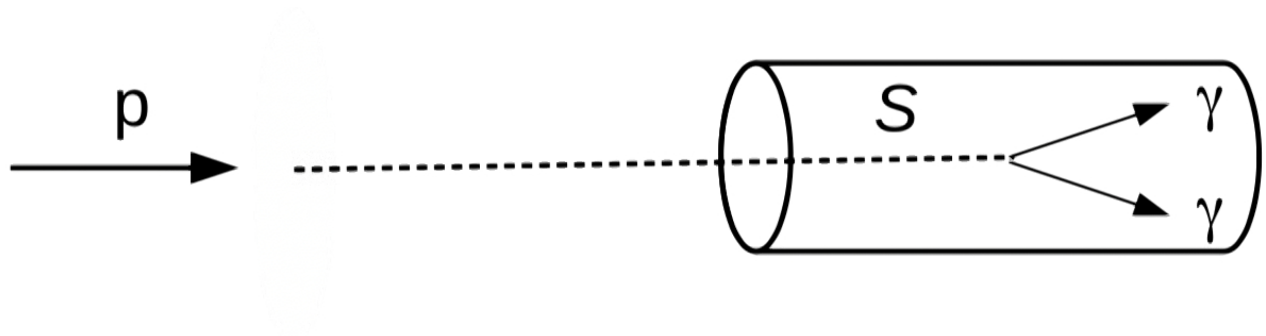
- can do same for kaon decays

Ignores higher derivative terms

Eta decays at beam dumps

$$\mathrm{BR}(\eta \to \pi S) \sim 10^{-3} \left(\frac{g_u}{10^{-4}}\right)^2$$ *S* light

Produce η at proton beam dump, then look for decay products of *S*: photons, or pions if low coupling



e.g. CHARM used a 400 GeV proton beam and looked ~500 m downstream; can recast ALP search

35

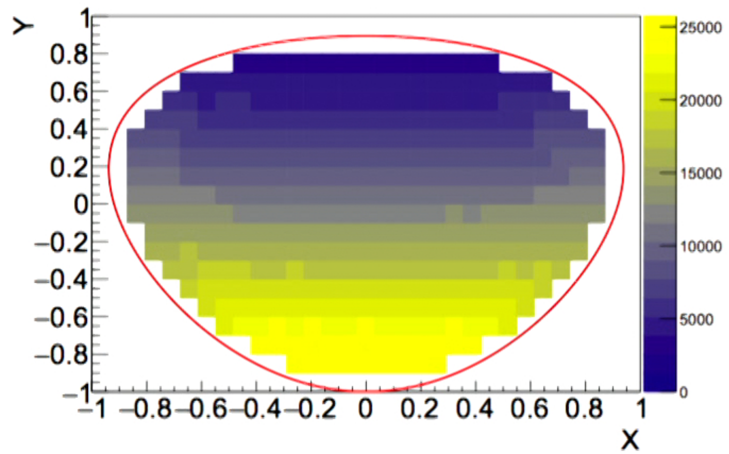
Eta precision measurements

Studying η properties can constrain *S*

$\eta \rightarrow 3\pi$ Dalitz analysis useful in small window for *S* between 2 m_π and m_η - m_π

Also $\eta \rightarrow \pi \gamma \gamma$

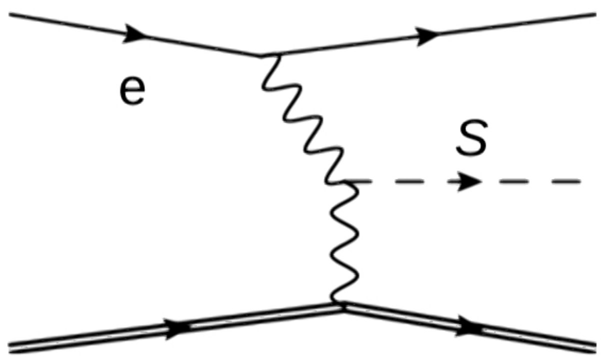
$\eta \rightarrow \pi$ + invisible not searched for currently, though fully invisible decays are limited at ~10^{-4} BR



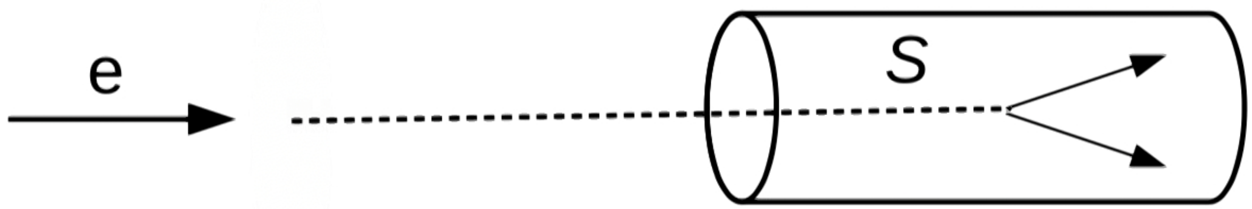
KLOE 3π
1601.06985

Electron beam dump searches

Use induced photon coupling to recast axion-like particle analyses when S has long-lived decay to $\gamma\gamma$

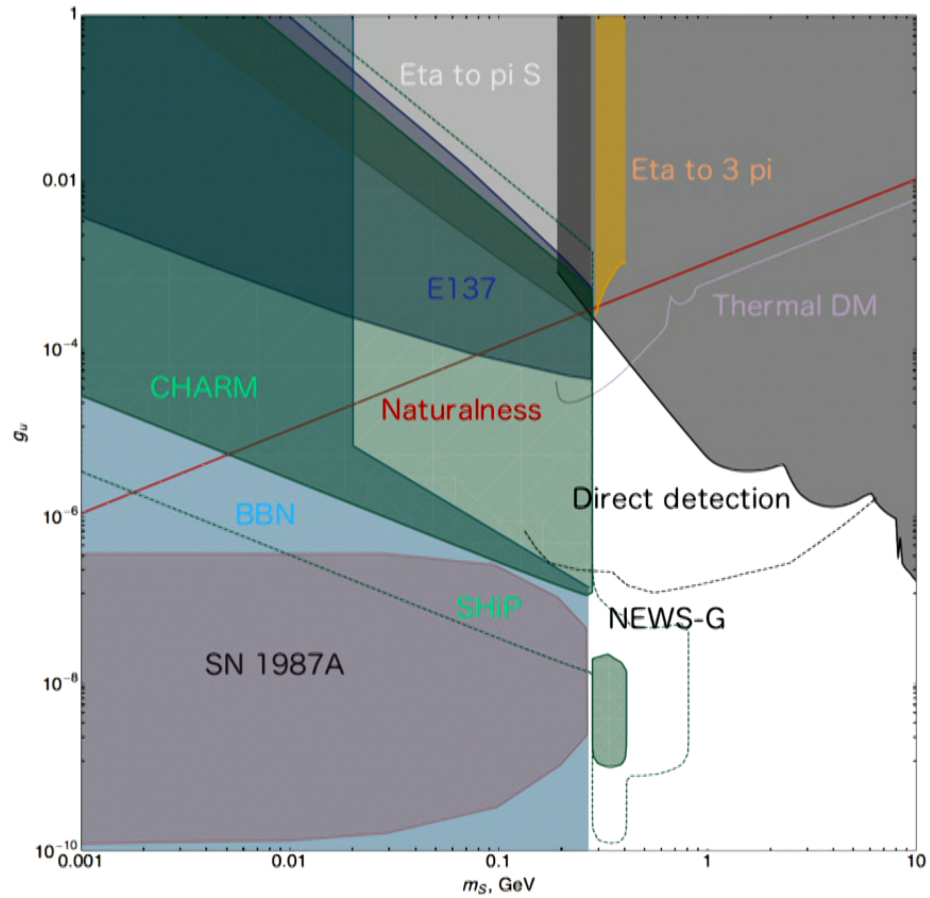


Relevant for electron beam dumps such as E137 at SLAC



37

Up-philic S decaying visibly



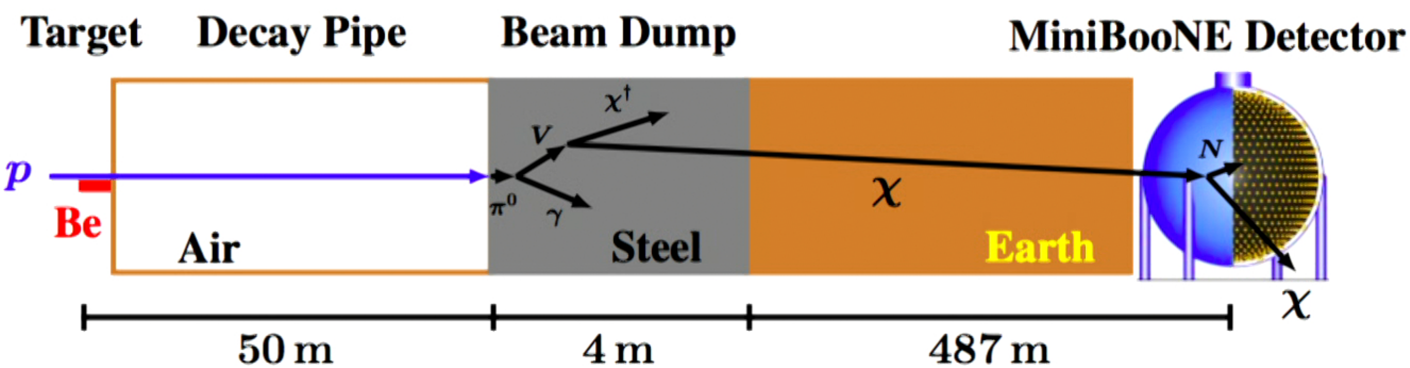
38

S decaying to dark matter

Rare meson decays: M → M' + invisible

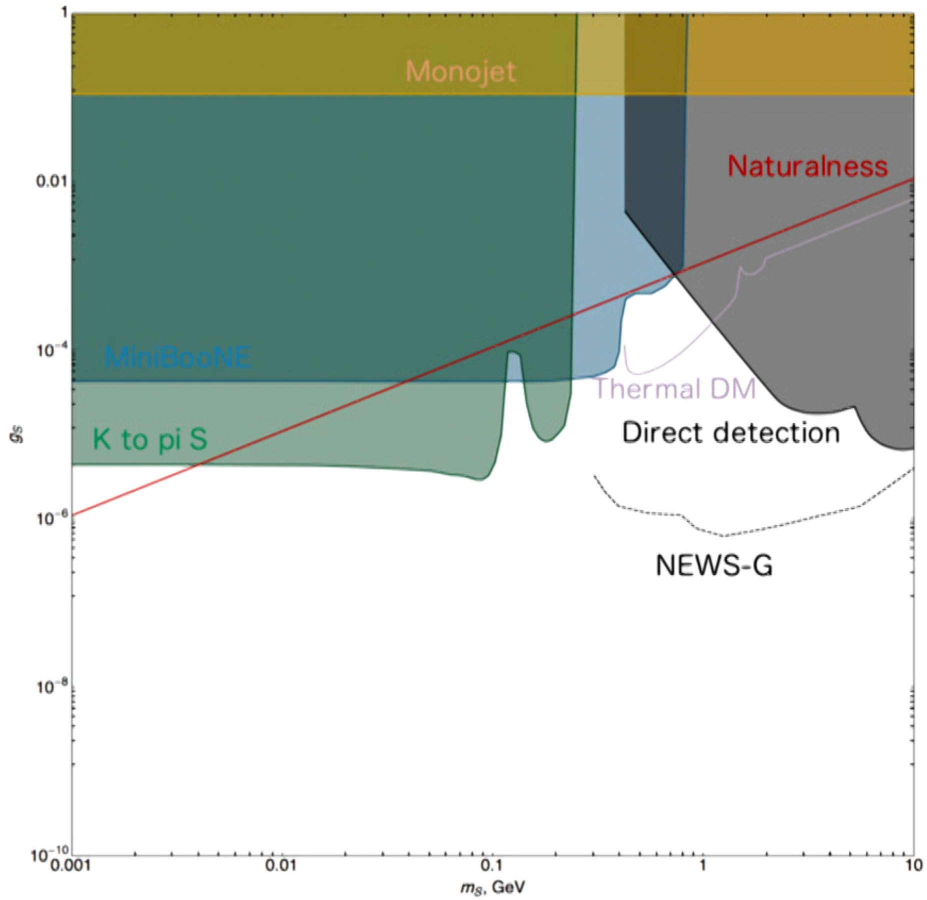
Use precision measurements, e.g. K → π ν ν

Or: produce DM beam, look for recoil downstream in large detector Batell, Pospelov, Ritz 0906.5614



Monojet production at LHC from initial state radiation

Up-philic S decaying invisibly



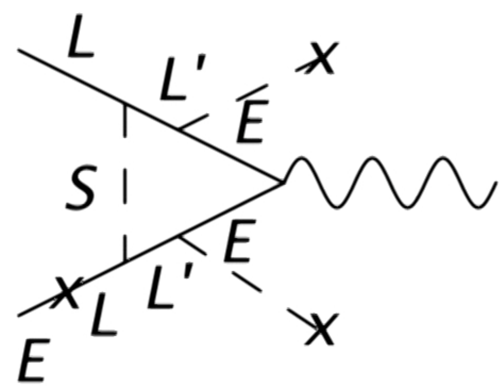
Muon-philic scalar

Can explain muon g – 2 measurement

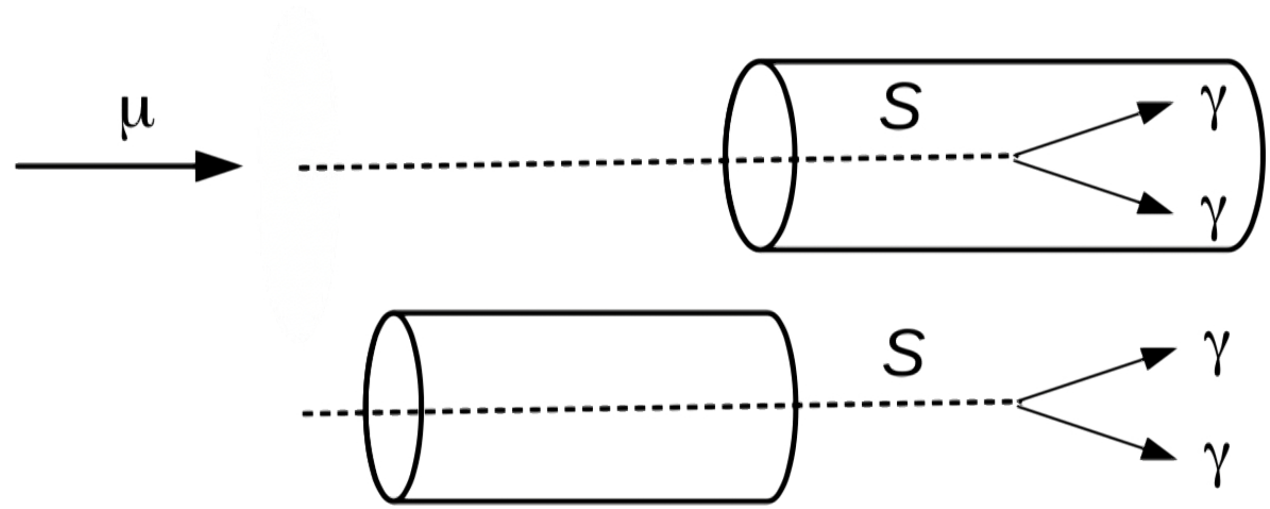
Chen, Davoudiasl, Marciano, Zhang 1511.04715; Batell et al. 1606.04943

Different possible UV completions (vector-like fermion pictured)

Easily long-lived below muon threshold, unlike generic leptophilic scalar

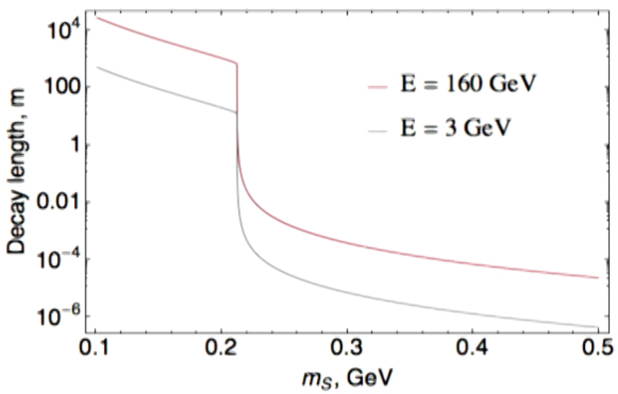


Muon beam signatures



Look for visible decay or missing momentum from long-lived *S*

Chen, Pospelov, Zhong 1701.07437



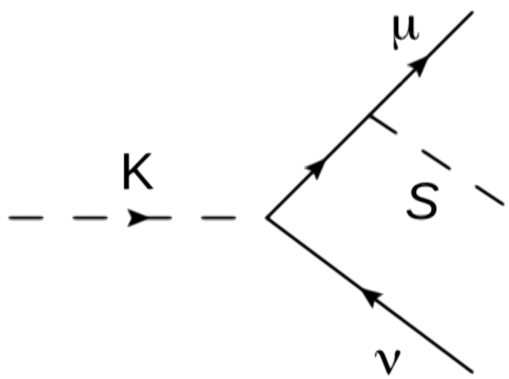
42

Proton, electron beam signatures

Proton beam dump production from rare kaon decays

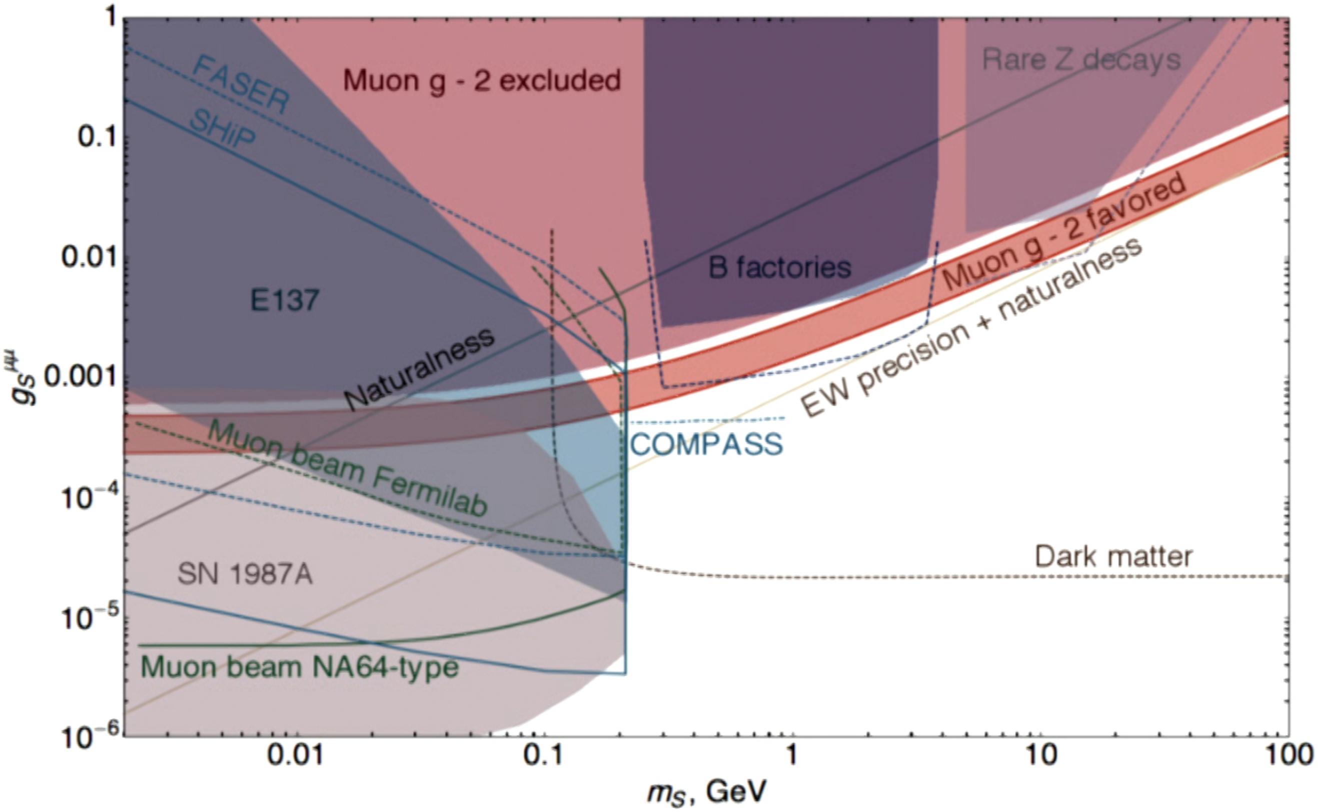
e.g. at SHiP, ~10^{18} kaons produced, detector is between 55 and 125 m downstream

Need kaon to decay before being stopped



Electron beams: as for up-philic scalar, produce *S* through induced photon coupling

Muon-philic S decaying visibly



45

Summary

Generalization of MFV allows fermion-specific new scalar, with suppressed flavor signatures

Useful for building new dark sector models

Technical naturalness suggests small couplings

Up-specific: weaker meson decays than usual dark Higgs, but still tested by beam dumps, cosmology, and direct detection

Muon-specific: best parameter space left for explaining g – 2 is at higher mediator masses, above a GeV

46