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Dark sectors and their signatures in Kaon physics

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Abstract. I review the set of theoretical ideas motivating experimental searches of light physics beyond the Standard Model. Specifically, I give examples of very weakly interacting candidates that can be probed in direct detection experiments. I then discuss a possibility of probing such states in the high-intensity kaon experiments by looking at the rare and radiate decay modes. The interesting modes to pursue include $K^\pm \rightarrow \pi^\pm + \text{missing energy}$, $K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$, as well as Dalitz and double-Dalitz decays of π^0 .

1. Introduction

The discovery of the Higgs boson in the LHC experiments is the triumphant development in particle physics. For a long time the existence of the Higgs boson was anticipated based on indirect electroweak precision tests, and from theoretical self-consistency of the Standard Model. Besides a discovery of the new particle, one can argue that the discovery of the Higgs boson - which for now is fully consistent with being an elementary boson - is also a manifestation of a new force in Nature - the Yukawa-type force. Given that all other forces in nature are of gauge origin, the Higgs discovery is really a "big deal" for our understanding of how the world works.

Another significant outcome of the LHC is the total absence of new physics that was widely anticipated to show its appearance around the 1 TeV energy scale. So far, there are no hints on supersymmetric partners, new gauge bosons with \sim TeV scale masses, or additional missing energy signals. The list of new physics models that is "put in trouble" by the LHC, and/or pushed above the TeV scale goes on and on. Recent excitement about a "di-photon" resonance at 750 GeV turned out to be baseless, as the early excess was nothing else but a statistical fluctuation.

Given that we have such a resounding success of the Standard Model (SM) on one hand, and no new physics indications (so far) on the other hand, one may go back to the "drawing board" and re-assess the possibilities for new physics, as well as our ability to probe it in particle physics experiments.

I make an effort to do so in Figure 1, where the cartoon of the coupling constants and particle masses that mediate the interactions is given. All SM forces have their coupling constants around the $\sim 0.1 - 0.01$ range, and the masses of mediators vary from a photon (massless), to gluon (effectively getting a QCD scale mass via confinement), and W, Z bosons. Interaction strength similar to a Fermi constant, $\sqrt{2}G_F = g_w^2/(8M_W^2)$, is represented by a diagonal line, that divides this parameter space into the "SM backyard" and the "unknown frontier". The high-energy colliders are uniquely positioned to probe the upper-right corner in this picture, where the strength of the coupling constants is significant, and the masses of new hypothetical



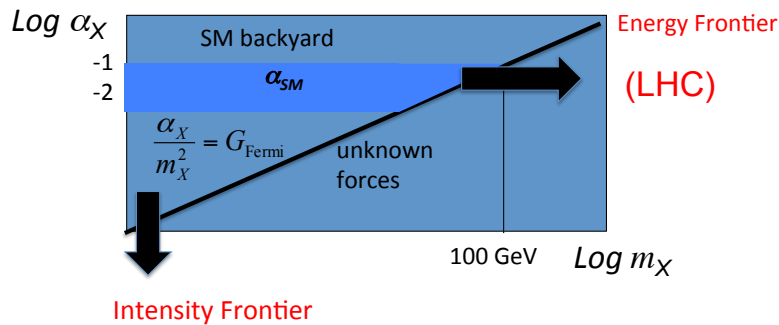


Figure 1. A cartoon representation of the coupling strength vs force mediator mass. The LHC is the way to explore high mass/not-so-small couplings for new forces. The intensity frontier direction (a downward pointing arrow) - very small couplings and masses much below the electroweak scale - is completely orthogonal, and can be explored with the new generation of electron beam facilities.

force carriers are large. Indeed, for a "sequential" Z' (i.e. coupled to the SM fermions the same way as the SM Z boson), the limits from CMS and ATLAS are $m_{Z'} > 2.8\text{TeV}$. This means that the analogue of the Fermi constant for the Z' compared to G_F is $\sim m_Z^2/m_{Z'}^2 < 10^{-3}$. Should a new force with the TeV scale mass mediator exist, its strength is already 1000 times smaller than the weak force! But what happens if there is new physics that is significantly *lighter* than the TeV scale? If there are new gauge bosons with masses on the order of 100 MeV, and couplings $\alpha_X \sim 10^{-6}$ or so, one cannot use the LHC very efficiently to search for such particles. The reason for that is that the production cross section is not growing with energy, as it would be for a TeV scale bosons, but instead is falling rather steeply. Being weakly coupled, such new particles will be completely buried under the SM backgrounds. Therefore, the high-energy colliders have very limited ability to probe light and very weakly coupled sectors.

If the new light particles violate some exact or approximate symmetries of physics at the GeV-scale, such as parity or CP symmetry, one can still limit the corresponding analogue of Fermi constant rather efficiently using the precision symmetry tests at low energy (parity-violation experiments, electric dipole moments, and for certain types of new physics, flavor constraints). But certain types of new physics, such as "dark photon" to be discussed later, are completely "innocuous" as they preserve all discrete and flavor symmetries. In this case, the strength of such a force can be well above the SM G_F , and indeed such forces may be discovered in the SM backyard. To find them, or better to say, probe their existence, one needs a dedicated effort at the "intensity frontier" [1]. On the Figure 1 cartoon, intensity frontier activity is pictured by the arrow in the down-left corner.

To conclude the Introduction: the intensity frontier direction is in many ways an orthogonal direction to the energy frontier. Consequently, the absence of new physics at the LHC does not spell doom on [most of the] efforts at the intensity frontier. A sub-GeV scale is exactly the place where new high-intensity electron beams can have an unparallel sensitivity to light and very weakly coupled New Physics. In the rest of my talk I will go over some motivations for new physics at these low scales. The experiments with kaons, probing very minute standard model branching ratios, are uniquely positioned to probe the dark sectors as well.

2. Portals to light weakly coupled sectors

The portals to light neutral hidden sectors are an effective field theory classification of all lowest dimension operators that mediate interaction between SM and the hidden sector. Symbolically,

we can write this type of contributions to the effective Lagrangian as

$$\Delta\mathcal{L} = \sum c_O O^{\text{SM}} O^{\text{hidden}}. \quad (1)$$

We assume that the hidden sector is not charged under the SM fields, and therefore both O^{SM} and O^{hidden} are SM singlet operators separately. Note, however, that they have to form a Lorentz singlet only in the product directly entering into $\Delta\mathcal{L}$, but separately they can transform under the Lorentz group. Given that, one can write down a set of terms of lowest dimension operators in $\Delta\mathcal{L}$:

$$B_{\mu\nu}F_{\mu\nu} \quad \text{kinetic mixing portal} \quad (2)$$

$$(H^\dagger H)(AS + \lambda S^2) \quad \text{Higgs portal} \quad (3)$$

$$(\bar{L}H)N \quad \text{neutrino portal} \quad (4)$$

$$(\bar{\psi}_{\text{SM}}\gamma_\mu\psi_{\text{SM}})A_\mu \quad \text{generic gauge portal} \quad (5)$$

$$(\bar{\psi}_{\text{SM}}\gamma_\mu\gamma_5\psi_{\text{SM}})\partial_\mu a/f_a \quad \text{axion – like portal} \quad (6)$$

In the expressions above, $B_{\mu\nu}$ is the SM hypercharge field strength, H is the SM Higgs doublet, L is a SM lepton doublet, and ψ_{SM} stands for a generic SM fermion. Particles from dark sector are denoted as A_μ , N and a . $F_{\mu\nu}$ stands for a usual field strength of A_μ .

Notice that the neutral singlet fermion N coupled to a composite SM effective operator of dimension 5/2, $(\bar{L}H)$, naturally leads to masses and mixings in the neutrino sector. Therefore, it is quite possible that nature has "already used" one of these portals, and it makes sense to study possible phenomenological implications or all these structures. Sometimes, one can speculate that these simple structures may be behind certain long-standing anomalies and deviations in particle physics. One bright example is the case of the so-called dark photon, or a new particle coupled via the $\epsilon B_{\mu\nu}F_{\mu\nu}$ portal that can give a *positive* correction to the anomalous magnetic moments of charged leptons. For example, a few tens of MeV mass dark photon with $\epsilon \sim \text{few} \times 10^{-3}$ could account for the long-standing theoretical deficit of about 3×10^{-9} in the muon anomalous magnetic moment [2].

Besides couplings to the SM, which is absolutely crucial for production of the dark sector particles, the dark sector states can interact among themselves. For example, interactions among dark particles, such as $(\bar{N}\gamma_\mu N)A_\mu$, which e.g. may lead to the decay of the dark photons into the dark fermionic states.

All of these hidden sector options have found vivid discussions in recent literature, with many potentially interesting applications to astrophysics and cosmology, collider physics and beam dump experiments [1]. In the rest of this talk, I will discuss the implications of the portal framework, and possible signatures of light particles in the kaon decay experiments.

3. Dark photons and dark scalars in the kaon decay experiments

To probe light weakly coupled states one needs high-luminosity yields of the SM particles, and rather precise detectors. Modern experiments with kaons generally fit this description. It is no surprise that some of the most exquisite limits come directly from studying kaon decays, or from the decays of the kaon decay products. Below, I go over the list of some decays and comment on their applications to the hidden sectors.

- $K^+ \rightarrow \pi^+$ +missing energy, $K^+ \rightarrow \pi^+e^+e^-$. It is entirely possible that a light particle coupled either via the Higgs or kinetic mixing portals would be produced in an underlying $K^+ \rightarrow \pi^+X$ decays. Subsequently, X can decay to a lepton pair. However, if the decay length is too long, as it would happen with a light scalar coupled via $\sim ASH^\dagger H$ portal and effective mixing to the SM Higgs below $\sim 10^{-3}$, the actual X decay may occur outside a

detector. (Same signature will also occur if X decays invisibly, e.g. to a pair of light dark matter particles.) This may lead to a spectacular signatures of the underlying two-body decay for $K^+ \rightarrow \pi^+$ +missing energy, and even a relatively modest excess of events may lead to a clear discovery. The details of constraints on light scalars mixed with the Higgs can be found in e.g. Ref. [3]. NA62 is poised to improve these bounds by a wide margin. If, on the other hand, the X particle is a vector, it is likely to decay quickly, in which case the invariant mass spectrum of e^+e^- may reveal a presence of a resonance via the bump hunt search.

- $K^+ \rightarrow \mu^+\nu e^+e^-$, $K^+ \rightarrow \mu^+\nu\mu^+\mu^-$. Rare radiative leptonic decays may be a signature of particles that couple predominantly to leptons [4]. In the above processes, kaons are a "controlled source of muons", and the underlying process $K^+ \rightarrow \mu^+\nu X$ may reveal itself in the spectrum of extra charged lepton pairs. Especially interesting is the regime of very small invariant masses, where such processes may be hidden behind substantial backgrounds from other kaon decay modes.
- $\pi^0 \rightarrow \gamma X \rightarrow \gamma e^+e^-$, $\pi^0 \rightarrow XX \rightarrow e^+e^-e^+e^-$. Dalitz and double-Dalitz decays of pions can be studied in the kaon beam experiments as well. In fact, a recent analysis of NA48/2 data [5] has contributed rather significantly into the dark photon story. It has shown that the Dalitz decays of π^0 show no unexpected peaking structures, setting very tight limits on the model, and excluding the remainder of the $g-2$ relevant parameter space in the minimal model. It is worth pointing out that a recent model [6] has been constructed to specifically circumvent these bounds. By "flipping" the dark charges of u and d quarks, one can eliminate the $\pi^0 \rightarrow X\gamma$ decays. However, $\pi^0 \rightarrow XX$ will remain, and can be analyzed for a "double peak" in the spectrum of four charged leptons.
- $K^+ \rightarrow \pi^+\pi^0 e^+e^-$. This decay can also be sensitive to the $K^+ \rightarrow \pi^+\pi^0 X$ models, and since the analysis of this decay mode is ongoing by the NA48 collaboration, it is also make sense to perform a search of peaking structures in the lepton pair invariant mass spectrum. This decay mode will also be sensitive to particles suggested in [6].

To conclude, kaon physics will remain vital for the searches of light weakly coupled particles. Future experiments, such as NA62, will make further significant progress in probing a variety of light particles coupled to the SM via well-motivated portals.

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