Dark $U(1)$

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Abstract. In this talk we will explore the possibility of adding a local $U(1)$ dark sector to the standard model with the Higgs boson as a portal connecting the visible standard model sector and the dark one. We will discuss existing experimental constraint on the model parameters from the invisible width of Higgs decay. Implications of such a dark $U(1)$ sector on phenomenology at the Large Hadron Collider will be addressed. In particular, detailed results for the non-standard signals of multi-lepton-jets that arise from this simple dark sector will be presented.

1. Introduction

Although we all cheered triumphantly the standard model (SM) with the recent discovery of the 126 GeV Higgs-like boson [1, 2], precision measurements of the Higgs properties are necessary in order to differentiate whether this is indeed the SM Higgs or a mixture with other scalar bosons in an extended Higgs sector. Such measurements may not be feasible at the Large Hadron Collider (LHC) but can nevertheless be achieved by the future electron-positron machine like the proposed circular electron-positron collider (CEPC) in China or the International Linear Collider (ILC) in Japan. We will present one simple $U(1)$ extension [3] of the SM to demonstrate that the 126 GeV boson could be a mixture and detailed how studies of its non-standard decay modes at the LHC may lead to the discovery of a hidden dark sector with light particle content.

2. Local Dark $U(1)$

In [3], we extend the electroweak SM by including the original Abelian Higgs model for a dark $U(1)_D$. Similar works can be found in [4, 5, 6, 7, 8, 9]. The bosonic part of the Lagrangian density is

$$\mathcal{L}_B = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{scalar}}$$

with

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} \tilde{W}_\mu \cdot \tilde{W}^{\mu} - \frac{1}{4} B_{\mu \nu} B^{\mu \nu} - \frac{1}{4} C_{\mu \nu} C^{\mu \nu} - \frac{\epsilon}{2} B_{\mu \nu} C^{\mu \nu} ,$$

$$\mathcal{L}_{\text{scalar}} = |D_\mu \Phi|^2 + |D_\mu \chi|^2 - V_{\text{scalar}}(\Phi, \chi) ,$$

and

$$D_\mu \Phi = \left( \partial_\mu + ig \frac{1}{2} \sigma_a W_{a \mu} + i g' B_\mu \right) \Phi ,$$

$$D_\mu \chi = \left( \partial_\mu + ig D_\mu C_\mu \right) \chi .$$
where $\vec{W}^\mu$, $B^\mu$ and $C^\mu$ are the gauge potentials of the $SU(2)_L$, $U(1)_Y$ and $U(1)_D$ with gauge couplings $g$, $g'$ and $g_D$ respectively, and $\epsilon$ is the kinetic mixing parameter between the two $U(1)$s [10]. The scalar potential in (3) is given by

$$V_{\text{scalar}} = -\mu^2_\Phi (\Phi^\dagger \Phi)^2 + \mu_\chi (\chi^* \chi)^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 (\chi^* \chi).$$

(6)

We pick the unitary gauge and expand the scalar fields around the vacuum

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \quad \chi(x) = \frac{1}{\sqrt{2}} (v_D + h_D(x))$$

with the vacuum expectation values $v$ and $v_D$ fixed by minimization of the potential to be

$$v^2 = \frac{\mu^2_\Phi - \frac{1}{2} \lambda_\phi \mu^2_\chi}{\lambda_\Phi - \frac{1}{2} \lambda_\chi \mu^2_\chi}, \quad v_D^2 = \frac{\mu^2_\chi - \frac{1}{2} \lambda_\chi \mu^2_\Phi}{\lambda_\chi - \frac{1}{2} \lambda_\phi \mu^2_\Phi}.$$ 

(8)

The mass matrix $M_S^2$ for the scalar bosons is

$$M_S^2 = \begin{pmatrix} 2 \lambda_\phi v^2 & \lambda_\phi v v_D \\ \lambda_\phi v v_D & 2 \lambda_\chi v_D^2 \end{pmatrix}.$$ 

(9)

Its eigenvalues are

$$m_{1,2}^2 = \frac{1}{2} \left[ \text{Tr} M_S^2 \pm \sqrt{\left( \text{Tr} M_S^2 \right)^2 - 4 \det M_S^2} \right].$$ 

(10)

The physical Higgs $(h_1, h_2)$ are related to the original $(h, h_D)$ as

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h \\ h_D \end{pmatrix},$$ 

(11)

with the mixing angle

$$\sin 2\alpha = \frac{2m_{12}^2}{m_1^2 - m_2^2}, \quad m_{12}^2 = \lambda_\phi v v_D.$$ 

(12)

We will identify the heavier Higgs $h_1$ with mass $m_1 = 126$ GeV as the new boson observed at the LHC [1, 2], while the lighter one $h_2$ has been escaped detection thus far. The SM Higgs couplings with the SM fermions and gauge bosons are thus modified by a factor of $\cos \alpha$.

3. Constraints

We had computed the following non-standard processes $h_1 \to \gamma_D \gamma_D$, $h_1 \to h_2 h_2$, $h_1 \to h_2 h_2^* \to h_2 \gamma_D \gamma_D$ and $h_1 \to h_2 h_2 h_2 h_2$. Each of $h_2$ in the final state of these processes will decay into two dark photons and each dark photon will give rise to two leptons through its mixing with the photon. We note that $h_2$ can decay to SM fermion or gauge boson pairs as well through its mixing with $h_1$ and hence these modes are suppressed. We take the branching ratio of $h_2 \to \gamma_D \gamma_D$ to be 100%. These non-standard processes will provide multiple leptons in the final state of the standard model Higgs decay [7]. The contribution to the heavier Higgs width from these non-standard processes is

$$\Gamma_{h_1}^{NS} = \sin^2 2\alpha \hat{\Gamma}(h_1 \to \gamma_D \gamma_D) + \Gamma(h_1 \to h_2 h_2) + \Gamma(h_1 \to h_2 h_2^* \to h_2 \gamma_D \gamma_D) + \Gamma(h_1 \to h_2 h_2 h_2 h_2) + \cdots$$ 

(13)

The four lepton modes from the first term $h_1 \to \gamma_D \gamma_D$ followed by $\gamma_D \to ll$ ($l = e, \mu$) were studied in details in [4]. Thus the total width of the heavier Higgs $h_1$ is modified as

$$\Gamma_{h_1} = \cos^2 2\alpha \hat{\Gamma}_\lambda + \Gamma_{h_1}^{NS},$$ 

(14)
where $\hat{\Gamma}_h$ is the width of the SM Higgs $h$, which has a theoretical value of 4.03 MeV. The branching ratio for the non-standard modes of the heavier Higgs decay is

$$B_{h_1}^{NS} = \frac{\Gamma_{h_1}^{NS}}{\Gamma_{h_1}},$$

which should be constrained to be less than 22% or so from global fit results [11].

Now the dark Higgs $h_2$ decays into $\gamma_D\gamma_D$ and SM particles with coefficients $\cos^2 \alpha$ and $\sin^2 \alpha$ respectively, so its branching fraction into $\gamma_D\gamma_D$ is given by

$$B(h_2 \to \gamma_D\gamma_D) = \frac{\cos^2 \alpha \Gamma(h_2 \to \gamma_D\gamma_D)}{\cos^2 \alpha \Gamma(h_2 \to \gamma_D\gamma_D) + \sin^2 \alpha \Gamma_{h_2}^{SM}},$$

where $\Gamma_{h_2}^{SM}$ is the partial decay width of $h_2$ into SM particles. Since $\hat{\Gamma}_{h_2}^{SM}$ are suppressed by a factor of $\sin^2 \alpha$, the above branching fraction is close to unity. Formulas for the various decay rates can be found in [3].

In our numerical work, we will restrict our interest where both the dark photon and dark Higgs have masses smaller than 126 GeV. In particular, we will pay special attention to the small mass region where their masses are in the range of 0.5 to a few GeV. In this range, final states of $\tau$ pair and light quarks pairs (pion and kaon pairs) from the dark photon decay are also possible, but they are harder to detect at the LHC.

In Fig. 1, we plot the contour of the non-standard branching ratio $B_{h_1}^{NS} = 0.1$ (left) and 0.2 (right) of the heavier Higgs $h_1$ in the $(m_{\gamma_D}, m_2)$ plane up to 126 GeV in both axes for $\sin^2 \alpha = 0.0009$ and $g_D = 0.05, 0.1, 0.2, 0.4$ and 0.8.

In Fig. 2, we plot the contour of the non-standard branching ratio $B_{h_1}^{NS} = 0.1$ (left) and 0.2 (right) of the heavier Higgs $h_1$ in the $(m_{\gamma_D}, m_2)$ plane for the small mass region of 0.5 to 5 GeV in both axes for $\sin^2 \alpha = 0.0009$ and $g_D = 0.005, 0.009, 0.013$ and 0.017.

4. Signals of Multi-Lepton-Jets
Next, we will present our study of some collider signatures for the model. In particular, we will focus on the 4 lepton-jet and 2 lepton-jet modes in our analysis. We consider the following four processes which may lead to signals of multi-lepton-jets at the LHC:
Figure 2. Contour plot of the non-standard branching ratio $B_{h_1}^{NS} = 0.1$ (left) and 0.2 (right) of the heavier Higgs $h_1$ in the small mass region of 0.5 to 5 GeV in the $(m_{\gamma D}, m_2)$ plane for $\sin^2\alpha = 0.0009$ and $g_D = 0.005, 0.009, 0.013$ and 0.017.

(I) $pp \rightarrow h \rightarrow ZZ \rightarrow l^+l^-l^+l^-$

(II) $pp \rightarrow VV \rightarrow l^+l^-l^+l^-$ \quad (VV = ZZ, \gamma\gamma, Z\gamma)$

(III) $pp \rightarrow h_1 \rightarrow XX \rightarrow l^+l^-l^+l^-$ \quad (XX = ZZ, \gamma_D\gamma_D, h_2h_2)$

(IV) $pp \rightarrow h_1 \rightarrow h_2h_2 \rightarrow \gamma_D\gamma_D\gamma_D\gamma_D \rightarrow l^+l^-l^+l^-l^+l^-l^+l^-$

where $l = e$ or $\mu$. Processes (I) and (II) are coming entirely from the SM, process (III) can arise from either SM (with modified Higgs-ZZ coupling) or the dark portal (see Fig. 3), and process (IV) is purely from the dark portal (see Fig. 4).

Figure 3. Some topologies of 4 (left) and 2 (right) lepton-jets for process III. The 4 lepton-jets can also be coming from the SM of process I with $h_1$ replaced by the SM $h$. The immediate state of $h_2h_2$ for the 2 lepton-jets is not shown since the branching ratio for $h_2 \rightarrow l^+l^-$ is very tiny.

Figure 4. Some topologies of 4 (left) and 2 (right) lepton-jets for process IV.
Table 1. Several benchmark points of the dark portal used to calculate the signals of multilepton-jets. ($\epsilon = 10^{-4}$ and $\sin^2\alpha = 10^{-3}$)

| Benchmark Point | $g_D$ | $M_{\gamma D}$ | $m_2$ | $\text{Br}_{h_1 \rightarrow \text{DarkStuff}}$ | $\text{Br}_{h_2 \rightarrow \gamma D \gamma D}$ | $\text{Br}_{\gamma D \rightarrow l\bar{l}-l\bar{l}}$ |
|-----------------|------|---------------|------|---------------------------------|-------------------------------|------------------|
| A               | 0.005| 1.5           | 4    | $\sim 16\%$                    | 99%                           | 50%              |
| B               | 0.009| 1.8           | 10   | $\sim 20\%$                    | 100%                          | 50%              |
| C               | 0.005| 1.5           | 40   | $\sim 15\%$                    | 99%                           | 50%              |
| D               | 0.005| 1.8           | 40   | $\sim 11\%$                    | 99%                           | 50%              |

In what follows, we will use the 4 benchmark points listed in Table 1 for analysis.

The number of events versus the total invariant mass $M_{\text{Invariant}}$ for the four processes I, II, III and IV at the LHC-14 without any cuts are shown in Fig. 5 for the benchmark point B. We can see that before imposing any cuts the number of events around the Higgs boson resonance for the two processes III (red) and IV (yellow, 8 leptons) from the dark portal can stand above the SM processes of I (blue) and II (black). However away from the resonance region, the 4 leptons SM background from process I (black) is 2 to 3 order of magnitudes above the signals from process IV (green).

For the kinematic cuts for the 2 and 4 lepton-jets, we follow Refs. [4, 7] and [12]. For the basic cuts that we will impose in all processes, we have

**Basic cuts:**

- (4 leptons case) $p_T \geq 20, 10, 10, 10$ GeV, $|\eta| < 2.3$;
- (8 leptons case) $p_T \geq 20, 10, 10, 0, 0, 0, 0, 0$ GeV, $|\eta| < 2.3$,

where $p_T$ and $\eta$ are the transverse momenta and pseudo-rapidity of the lepton respectively. On top of the basic cuts, we employ the following lepton-jet cuts

- 4 lepton-jet cuts: $\Delta R_{d_{ij}} > 0.7$, $\Delta R_{l_{ij}} < 0.2$, $M_{\text{Invariant}} = M_{h_i} \pm 10$ GeV;
- 2 lepton-jet cuts: $\Delta R_{d_{ij}} > 0.7$, $\Delta R_{l_{ij}} < 0.2$, $M_{\text{Invariant}} = M_{h_i} \pm 10$ GeV.

Here $\Delta R_{d_{ij}}$ denotes the cone radius between two different lepton-jets and $\Delta R_{l_{ij}}$ denotes the cone radius between two different leptons in the same lepton-jet, as depicted in Fig. 6. $M_{\text{Invariant}}$ denotes the invariant mass of all final state particles due to the decay chain of the SM Higgs boson resonance, give or take 10 GeV from the central value of 126 GeV.
We now discuss the impact of imposing the multi-lepton-jet cuts on the cross sections. The topologies of imposing the 4 and 2 lepton-jet cuts for processes III and IV are shown in Figs. 3 and 4 respectively. In Table 2, we show the cross sections of the 4 processes at the LHC-14 with the basic, 4 and 2 lepton-jet cuts for the 4 benchmark points listed in Table 1. The following statements can be drawn from the results shown in Table 2:

- The 4 and 2 lepton-jet cuts have strong and different impact for the SM processes I and II. For process I, since the intermediate state is the $Z$ boson with a relatively high mass, its decay products can be produced at a relatively large angle with respect to the original $Z$ boson direction. Thus it favors 4 lepton-jets in the final state (see left diagram in Fig. 3) and 2 lepton-jets is vanishing small for process I. On the other hand, SM process II has a cross section of about 700 times larger than process I with just the basic cuts imposed. Imposing the 4 and 2 lepton-jet cuts reduce the cross section of process II by a factor of $4.7 \times 10^{-3}$ and $1.1 \times 10^{-3}$ respectively. We note that the $ZZ$ intermediate state in process II arises from the tree level parton processes of quark-quark annihilation while in process I it is connected with the loop-induced gluon fusion mechanism of Higgs production.

- For process III since the dark photon mass is small (1.5 GeV for benchmark points A and C, and 1.8 GeV for benchmark points B and D) the contribution from intermediate state of $\gamma_D\gamma_D$ will give rise mainly to 2 lepton-jets (see right diagram in Fig. 3). Thus imposing the 4 lepton-jet cuts for process III will suppress this intermediate state and only the contribution from $ZZ$ intermediate state will survive (see left diagram in Fig. 3). Since this $ZZ$ contribution is very similar to the SM process I, they should have very similar cross sections after imposing 4 lepton-jet cuts as clearly seen in Table 2. On the other hand, imposing 2 lepton-jet cuts will suppress the $ZZ$ intermediate state but keep the $\gamma_D\gamma_D$. However, the contribution of $ZZ$ intermediate state for process III is negligible. The 2 lepton-jet cross sections of process III are several orders of magnitudes larger than the corresponding cross sections of SM process II.

- For process IV, with just basic cuts its cross section is about a factor 4 (benchmark points A and B) to 5 (benchmark points C and D) smaller than that of process III. However, due to the small mass of the dark photon (compared with Z boson mass), one can has either 4 or 2 lepton-jets in the final state. Imposing the 4 and 2 lepton-jet cuts in addition to the basic cuts for process IV have more nontrivial effects on the cross section depending on the benchmark points. For 4 lepton-jets the cross sections can reach about 3 and 1 femtobarn for benchmark points C and D respectively. For 2 lepton-jets, the cross section can reach 2 femtobarn for benchmark point A only. At these benchmark points, these cross sections are an order of magnitude larger than the corresponding cross sections of the SM process II. Other benchmark points have negligible cross sections for 4 and 2 lepton-jets as can be clearly seen in the last column of Table 2.

![Figure 6. Graphical illustrations for the kinematic cuts on the cone radius $\Delta R$ of final state leptons. The 2 and 4 lepton-jet cases are shown in the left and right figures respectively.](image-url)
Table 2. Cross sections (in unit of fb) at the LHC-14 for the background processes (I and II) and dark sector processes (III and IV) with the basic cut only and basic plus 4 and 2 lepton-jet cuts at the 4 benchmark points defined in Table 1.

| Cuts                          | Benchmark Points | I     | II    | III   | IV    |
|-------------------------------|------------------|-------|-------|-------|-------|
| Basic                         | A                | 0.118 | 70.7  | 95.3  | 23.2  |
|                               | B                | 0.118 | 70.7  | 204   | 45.8  |
|                               | C                | 0.118 | 70.7  | 96.7  | 19.2  |
|                               | D                | 0.118 | 70.7  | 68.3  | 13.1  |
| Basic + 4 Lepton-Jets         | A                | 9.63×10⁻³ | 0.337 | 9.86×10⁻³ | ≤10⁻¹⁰ |
|                               | B                | 9.63×10⁻³ | 0.337 | 9.80×10⁻³ | ≤10⁻¹⁰ |
|                               | C                | 9.63×10⁻³ | 0.337 | 9.93×10⁻³ | 3.05   |
|                               | D                | 9.63×10⁻³ | 0.337 | 9.84×10⁻³ | 0.92   |
| Basic + 2 Lepton-Jets         | A                | ≤10⁻¹⁰ | 0.08  | 95.3  | 1.75  |
|                               | B                | ≤10⁻¹⁰ | 0.08  | 201   | ≤10⁻¹⁰ |
|                               | C                | ≤10⁻¹⁰ | 0.08  | 95.8  | ≤10⁻¹⁰ |
|                               | D                | ≤10⁻¹⁰ | 0.08  | 68.2  | ≤10⁻¹⁰ |

5. Summary
To conclude we have demonstrated that non-standard signals of multi-lepton-jets from SM Higgs decay can be used to probe the existence of light particles in the dark sector. Further studies with detector responses taking into account may therefore be worthwhile. Besides the familiar electromagnetic $U(1)$ in our visible world, perhaps such a simplest abelian symmetry may be realized in the dark sector as well.

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