Looking through the Pseudo-Scalar Portal into Dark Matter: Novel Mono-Higgs and Mono-Z Signatures at LHC

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Mono-X signatures are a powerful collider probe of the nature of dark matter. We show that mono-Higgs and mono-Z may be key signatures of pseudo-scalar portal interactions between dark matter and the SM. We demonstrate this using a simple renormalizable version of the portal, with a Two-Higgs-Doublet-Model as electroweak symmetry breaking sector. Mono-Z and mono-Higgs signatures in this scenario are of resonant type, which constitutes a novel type of dark matter signature at LHC.

The nature of dark matter (DM) is an outstanding mystery at the interface of particle physics and cosmology. The current DM candidate paradigm is the so-called Weakly-Interacting-Massive-Particle (WIMP), a particle whose relic abundance is obtained via thermal freeze-out in the early Universe, and with a mass in the range GeV – TeV, around the scale of electroweak (EW) symmetry breaking $v = 246$ GeV. WIMP DM is very well-motivated in connection with new physics close to the EW scale (see \cite{1} for a review) and/or the existence of a hidden sector (singlet under the SM gauge group) which interacts with the SM via a portal \cite{2,3}.

A large experimental effort aims to reveal the nature of (WIMP) DM and its interactions with SM particles, either indirectly by measuring the energetic SM particles product of DM annihilations in space, or directly by measuring the scattering of ambient DM from heavy nuclei. Current best experimental limits on the spin-independent DM interaction cross section with nuclei are very strong, and particularly constraining for DM masses in the range $10 - 100$ GeV. On the other hand, the experimental limits on spin-dependent DM-nucleon interactions are much less stringent, generically favouring a pseudo-scalar mediator of DM-nucleon interactions (which primarily yields spin-dependent interactions) over a scalar mediator.

Direct/indirect probes of DM are complemented by searches at colliders, where pairs of DM particles could be produced. These escape the detector and manifest themselves as events showing an imbalance in momentum, which primarily yields spin-dependent interactions) over a scalar mediator.

The letter is organized as follows: In Section I we introduce and discuss the pseudo-scalar portal scenario, with a Two-Higgs-Doublet-Model as electroweak symmetry breaking sector. In Section II we analyze the mono-Higgs and mono-Z signatures in this context, with very distinct kinematical features from other mono-X scenarios. These signatures constitute a new probe of DM scenarios at LHC, deeply linked to the realization of a non-minimal Higgs sector in Nature.

I. Dark Matter Through the Pseudo-Scalar Portal

The simplest realization of the pseudo-scalar portal occurs within a Two-Higgs-Doublet-Model (2HDM) extension of the SM \cite{23}. For our purposes, we use in the following a simple embedding of DM into such a picture (see e.g. \cite{24}), and consider dark matter to be a Dirac fermion $\psi$ with mass $m_\psi$, which couples to a real singlet pseudo-scalar mediator state $a_0$ via

\begin{equation}
V_{\text{dark}} = \frac{m_{a_0}^2}{2} a_0^2 + m_\psi \bar{\psi} \gamma^5 \psi + y_\psi a_0 \bar{\psi} \gamma^5 \psi \, (1)
\end{equation}

A renormalizable coupling of $a_0$ to the visible sector becomes possible by extending the SM Higgs sector to in-
In particular, for mono-\(pp\) (3), yielding two pseudo-scalar mass eigenstates \(h\) and mono-\(\psi\) \((X = W, Z, h)\), lead to mono-X signatures at LHC. Focusing on mono-Higgs for the purpose of illustration, there exist contributions from \(pp(\bar{q}q) \rightarrow Z^* \rightarrow h a (a \rightarrow \psi \psi)\) and \(pp (gg) \rightarrow A \rightarrow h a (a \rightarrow \psi \psi)\).

The former is kinematically similar to mono-\(h\) signatures in other scenarios \([21,22]\), which are generically suppressed either by the presence of an off-shell or very massive particle in the s-channel. Together with the momentum transfer being cut-off by the parton distribution functions (PDFs), this leads to very small mono-Higgs cross sections, making a mono-\(h\) signature difficult to probe at the 14 TeV run of LHC even with a large integrated luminosity, if it solely arises from this type of contribution.

In contrast, for \(m_A > m_h + m_a\) the kinematics of the latter process is very different, due to \(A\) being resonantly produced. In this case, the 4-momentum of \(h\) and \(a\) is kinematically fixed, and \(E_T\) is bounded from above by

\[
E_T^\text{max} = \frac{1}{2m_A} \sqrt{(m_A^2 - m_h^2 - m_a^2)^2 - 4m_h^2 m_a^2}. \tag{6}
\]

The \(E_T\) distribution from this process is a steeply rising function with a sharp cut-off at \(E_T^\text{max}\), a very distinct feature of these scenarios. At the same time, this contribution to mono-\(h\) is resonantly enhanced \(w.r.t\) the former one, generically yielding a much larger cross section. Furthermore, it is important to stress that in this scenario the resonant contribution is proportional to \(s_{3\beta-\alpha}^2\) and thus maximal in the 2HDM alignment limit of a SM-like Higgs \(h\) (as favoured by ATLAS and CMS analyses), whereas the off-shell contribution is proportional to \(c_{3\beta-\alpha}^2\), vanishing in that limit.

Before we continue, let us briefly comment on the fact that such resonant mono-\(h\) signatures may also occur in a pure 2HDM through the process \(pp(\bar{q}q) \rightarrow A \rightarrow h Z (Z \rightarrow \nu\nu)\). We stress that the phenomenology in the presence of the pseudo-scalar portal to DM is radically different from that of the pure 2HDM. First, contrary to the case of the DM portal, the interaction yielding a mono-\(h\) signature in the 2HDM vanishes for a SM-like Higgs \(h\), as discussed above. Second and most important, for a pure 2HDM the same process with \(Z \rightarrow \ell\ell\) is a much more sensitive probe of the existence of \(A\) than the mono-\(h\) signature. This constitutes a generic, crucial way of disentangling a resonant \(X + E_T\) signature where \(E_T\) originates in a dark sector (e.g. \(a \rightarrow \psi \psi\)) from that where the \(E_T\) comes from \(Z \rightarrow \nu\nu\), as the latter will have to be accompanied by a much more sensitive \(Z \rightarrow \ell\ell\) counterpart, while the former will not.

For our phenomenological analysis, we choose a Type II 2HDM benchmark \(\tan \beta = 3, c_{3\beta-\alpha} = 0.05\) (close to the 2HDM alignment limit) with \(s_\theta = 0.3\), corresponding

\[
V_{\text{portal}} = i \kappa A H_1^* H_2 + h.c. \tag{3}
\]

The scalar spectrum of the 2HDM contains a charged scalar \(H^\pm = \cos \beta \phi_1^± - \sin \beta \phi_2^±\) and two neutral CP-even scalars \(h = \cos a h_2 - \sin a h_1, H_0 = -\sin a h_2 - \cos a h_1\). We identify \(h\) with the 125 GeV Higgs state, which is SM-like in the limit \(\beta - a = \pi/2\) (see e.g. \([20]\) for a review of 2HDM). For \(\kappa \neq 0\), the would-be neutral CP-odd scalar \(A_0 = \cos\beta \eta_2 - \sin\beta \eta_1\) mixes with \(a_0\) through \(2\beta\), yielding two pseudo-scalar mass eigenstates \(a, A\)

\[
A = c_\theta A_0 + s_\theta a_0, \quad a = c_\theta a_0 - s_\theta A_0 \tag{4}
\]

with \(c_\theta \equiv \cos \theta\) and \(s_\theta \equiv \sin \theta\). We consider in the following the case in which the singlet-mediated a is lighter than \(A\) (\(m_A > m_a\)), and \(m_a > 2m_\psi\) such that the decay \(a \rightarrow \psi \psi\) is possible. In terms of the mass eigenstates, the interactions (1) and (3) become

\[
V_{\text{portal}} = \frac{(m_A^2 - m_a^2) s_{2\theta}}{2} \left( c_{\beta-\alpha} H_0 - s_{\beta-\alpha} h \right) \tag{5}
\]

Gauge interactions of the two doublets \(H_i\) yield the relevant interactions \(aZh \propto s_\theta c_{\beta-\alpha}, AZh \propto c_\theta c_{\beta-\alpha}, aZH_0 \propto s_\theta s_{\beta-\alpha}, AZH_0 \propto c_\theta s_{\beta-\alpha}, aW^\pm H^\mp \propto s_\theta s_{\beta-\alpha}, aW^\pm H^\mp \propto c_\theta s_{\beta-\alpha}\), while \(V = V_{2\text{HDM}} + V_{\text{portal}}\) yields \(aAh \propto s_\theta s_{\beta-\alpha}, a\psi \psi \propto c_\theta, a\bar{\psi} \psi \propto s_\theta\).

Alternatively, the interactions above lead to mono-\(h\) and mono-\(W, Z\) signatures at LHC in various possible ways, which we discuss in detail in the next Section. In particular, for \(m_A > m_h + m_a, m_H > m_Z + m_a, m_{H^\pm} > m_{W^\pm} + m_a\), this scenario yields a novel signature: “resonant mono-\(h, W, Z\)” respectively via the processes \(pp \rightarrow A \rightarrow h a, pp \rightarrow H_0 \rightarrow Z a, pp \rightarrow H^\pm \rightarrow W^\pm a\), with the mediator \(a\) subsequently decaying into DM.
to a moderate mixing between the visible and dark sectors, and $y_{\psi} = 0.2$. For the mediator and DM masses we choose respectively $m_a = 80 \text{ GeV}$, $m_{\psi} = 30 \text{ GeV}$. The DM annihilation cross section in this case is of or-
diagram{fig:cmssv2_04a}

terest for a correct DM relic density [24], and we
is kinematically forbidden. The grey region lies below the
event selection of [15]. A similar Figure may be obtained in
the place $(m_{H_0}, m_a)$ for resonant mono-Z.

In the following, taking as benchmark values $m_{H_0} = m_A = 300, 500, 700 \text{ GeV}$, which we denote respectively
as benchmarks A, B, C, we discuss the existing bounds
from the 8 TeV LHC run and explore the 14 TeV LHC
run prospects for resonant mono-Z, Z.

**Mono-Higgs**

Current ATLAS and CMS mono-Z searches focus on the $h \rightarrow \gamma \gamma$ decay of the 125 GeV Higgs boson. For
our analysis we use the selection criteria from the LHC 8 TeV run data analysis by ATLAS [12], which selects events with two photons with leading (subleading) transverse momentum $P_T^{\gamma} > 35 \text{ (25) GeV}$, rapidity $|y_{\gamma}| < 2.37$
and in the invariant mass window $m_{\gamma\gamma} \in [105, 160] \text{ GeV}$. In addition, the photon pair is required to have been produced in association with a sizable amount of missing
transverse momentum, $E_T > 90 \text{ GeV}$, and such that $P_{T}^{\gamma\gamma} > 90 \text{ GeV}$ (to suppress background events where $E_T$ is caused by mismeasurement of energies of identified physical objects). ATLAS yields a 95% C.L. upper bound on the cross section of 0.70 fb, while our 8 TeV signal samples for $m_A = 300, 500, 700 \text{ GeV}$ generated with

**Mono-Z**

The recent ATLAS search [12] constraints mono-Z sig-
natures with $Z \rightarrow \ell^+\ell^-$ using the available LHC 8 TeV

**TABLE I.** Expected number of events after event selection
(see text for details) and signal region cuts for mono-$h$ with
$h \rightarrow \gamma \gamma$, for LHC 14 TeV with $\mathcal{L} = 300 \text{ fb}^{-1}$. Signal
benchmarks A, B, C are described in Section II.

| $A$ | $B$ | $C$ | $Z\gamma\gamma$ | $Z\gamma\gamma$ |
|-----|-----|-----|----------------|----------------|
| $m_{\gamma\gamma} < [120, 130] \text{ GeV}$ | 161 | 26 | 6 | 34 | 97 | 32 |
| $E_T, P_T^{\gamma\gamma} > 80 \text{ GeV}$ | 105 | 24 | 5 | 13 | 32 | 12 |
| $E_T, P_T^{\gamma\gamma} > 180 \text{ GeV}$ | 4 | 14 | 4 | 2 | 3 | 2 |
| $E_T, P_T^{\gamma\gamma} > 280 \text{ GeV}$ | $< 30$ | 0.3 | 15 | 0.5 | 15 | 0.5 |

In Figure 1 we show the value of $E_T^{\text{max}}$ for resonant mono-$h$ in the $(m_A, m_{\psi})$ plane, which highlights the fact
that, while current searches are not sensitive to $m_A \lesssim 250 \text{ GeV}$ (as $E_T^{\text{max}} < 90 \text{ GeV}$), the value of $E_T^{\text{max}}$ rapidly increases with $m_A$, making the signature $p p \rightarrow h \bar{\psi}\psi \ (h \rightarrow \gamma\gamma)$ promising for masses $m_A \gtrsim 300 \text{ GeV}$ at the LHC 14 TeV run. For our analysis of resonant mono-Z prospects at LHC 14 TeV, we generate our signal and background event samples with MADGRAPH5_AMC@NLO. These are based on a signal simulation in the solid-brown region observable constraints, and for each value of $m_A$ we adjust $\mu$ in (2) to be within the region compatible with vacuum stability, perturbativity and unitarity.

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run data. Their analysis selects events with two opposite sign (opposite charges) electrons/muons in the invariant mass window $m_{\ell\ell} \in [76, 106]$ GeV, with $P_T^{\ell} > 20$ GeV and rapidity $|y| < 2.5$ (2.47) for muons (electrons). The rapidity of the di-lepton system has to satisfy $|y^{\ell\ell}| < 2.5$, and event selection further requires

$$\Delta\phi(E_T, P_T^{\ell\ell}) > 2.5, \quad |P_T^{\ell\ell} - E_T| / P_T^{\ell\ell} < 0.5. \quad (7)$$

Four signal regions are defined, corresponding respectively to $E_T > 150$ GeV, 250 GeV, 350 GeV and 450 GeV. The ATLAS analysis yields respective 95% C.L. observed upper bound on the cross section of 2.7 fb, 0.57 fb, 0.27 fb and 0.26 fb. Our three signal benchmark scenarios, A, B, C, satisfy these bounds, and as we show in the following they are very promising for the 14 TeV run of LHC.

For our resonant mono-$Z$ analysis at LHC 14 TeV, we follow a similar procedure to the one described for the mono-$h$ case in the previous section, using MadGraph5_aMC@NLO, Pythia and Delphes for our signal $pp \rightarrow Z a (Z \rightarrow \ell^+\ell^-, a \rightarrow \nu\overline{\nu})$ and background event samples. The SM irreducible backgrounds are $ZZ \rightarrow \ell^+\ell^- \nu\overline{\nu}$ and $WW \rightarrow \ell^+\ell^- \nu\overline{\nu}$, while $WZ \rightarrow \ell\nu\ell^-\nu$ and $t\overline{t} \rightarrow b\ell^+\ell^+\nu\overline{\nu}$ are the most important reducible backgrounds. NLO cross sections are estimated via K-factors: $K \approx 1.2, 1.79, 1.68$ respectively for $ZZ, WZ$ and $WW$ [35], $K \approx 1.5$ for $t\overline{t}$ [34] and $K \approx 2.36, 1.88, 1.75$ respectively for our signal benchmarks A, B, C via Sushi. Our event selection follows [12] and is discussed above, and we define three signal regions $E_T, P_T^{Z\gamma} > 90$ GeV, 190 GeV, 290 GeV to respectively maximise sensitivity to benchmarks A, B, C.

In Table II we show the expected signal and background events for LHC at 14 TeV with an integrated luminosity $L = 100$ fb$^{-1}$, after event selection and in the various signal regions. Neglecting systematic uncertainties, an approximate significance $S/\sqrt{S+B} \sim 12.8, 18.7, 9.2$ is obtained in the respective optimal signal region for benchmarks A, B, C. In Figure 2 (RIGHT), we show the $E_T$ distribution for signal and background after event selection.

| Event selection | A | B | C | ZZ | WW | WZ | $t\overline{t}$ |
|-----------------|---|---|---|----|----|----|------------|
| $E_T > 90$ GeV  | 2009 | 1130 | 254 | 282 | 10100 | 12670 | 16680 |
| $E_T > 190$ GeV | 1500 | 1105 | 279 | 2660 | 253 | 3530 | 5660 |
| $E_T > 290$ GeV | 4.5 | 733 | 254 | 414 | < 0.1 | 357 | 30 |
| $E_T > 290$ GeV | 1.5 | 11 | 158 | 81 | - | 57 | < 0.1 |

TABLE II. Expected number of events after event selection (see text for details) and in the signal region for mono-$Z$ with $Z \rightarrow \ell^+\ell^-$, for LHC 14 TeV with $L = 100$ fb$^{-1}$. Signal benchmarks A, B, C are described in Section II.

Finally, although not discussed in his work, resonant mono-$W$ signatures are also possible in this setup, but the suppressed production of $H^\pm$ compared to $A/H_0$ makes them much less promising.
III. Discussion and Outlook

The analysis of the previous Section shows that resonant mono-Higgs and mono-$Z$ are promising signatures for the 14 TeV run of LHC with $\mathcal{L} = 100 - 300$ fb$^{-1}$, with mono-$Z$ in particular being a very sensitive probe of pseudo-scalar portal scenarios like the one discussed here. Moreover, not only these signatures constitute a window into the DM sector, but are also potential discovery modes for the heavy states of the non-minimal scalar sector (here $A, H_0$), as their “usual” decay modes (e.g. in a pure 2HDM) will get suppressed by the presence of the new decay channels into the dark sector.

Finally, there are other possible avenues for exploring these pseudo-scalar portal scenarios, like mono-jet searches on $pp (gg) \rightarrow a j (a \rightarrow \bar{\psi}\psi)$, which we do not explore here, but will most certainly be complementary to the ones introduced in this work. One other aspect I explore here, but will most certainly be complementary to the ones introduced in this work. One other aspect I want to thank the organizers of the Les Houches 2015 Workshop “Physics at TeV Colliders” where this workshop was held, and also Ken Mimasu, Veronica Sanz, Seyda Ipek and Belen Lopez-Laguna for very useful discussions. J.M.N. is supported by the People Programme (Marie Curie Actions) of the European Union Seventh Framework Programme (FP7/2007–2013) under REA grant agreement PIEF-GA-2013-625809.

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