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1 Motivation

The monojet searches at the LHC (jets with unbalanced transverse momentum p_T) carry information on new particles that go invisible in the detector, and are produced in association with the jets. Such new states may be just long-living or absolutely stable, may or not constitute (part of) the dark matter energy density.

From the collider point of view, the question is to what extent a monojet observation may shed light on the underlying new physics. As the main (unique?) observable is the p_T of the jets, it is particularly interesting to understand the dependence of the differential cross-section, $\mathrm{d}\sigma/\mathrm{d}p_T$, on the masses and couplings of the new particles involved in the process. Here we attempt to discriminate models with or without derivative couplings between the Standard Model (SM) and the new physics sector. The cross-section may have a radically different momentum dependence in the presence of derivative couplings.

One theoretical motivation is provided by Nambu-Goldstone bosons, that are massless scalar particles with derivative couplings only, associated to a global symmetry spontaneously broken at some scale f. They may receive a mass, and non-derivative couplings as well, when an explicit, weak breaking of the global symmetry is introduced at some scale $\epsilon < f$. While all the Nambu-Goldstone boson couplings are proportional to some positive power of $1/f$, the non-derivative ones are also proportional to some positive power of ϵ.

We will focus on extensions of the SM by scalar particles, the lightest state η being stable due to a parity symmetry Z_2: the SM is assumed to be even under Z_2, while η is odd. The only relevant SM invariant that can couple to η^2 is $H^\dagger H$, with H the SM Higgs doublet. This is the so-called Higgs portal to new physics.

2 The minimal model: SM + odd singlet

The minimal model field content is given by SM + η, where η is a gauge singlet real scalar, with Lagrangian

$$\mathcal{L}_\eta = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}\mu_\eta^2\eta^2 - \frac{1}{4}\lambda_\eta\eta^4 - \frac{1}{2}\lambda\eta^2 H^\dagger H + \frac{c}{2f^2}\partial_\mu(\eta^2)\partial^\mu(H^\dagger H)\ . \quad (1)$$

Note that we included the most general renormalizable interactions compatible with a Z_2 symmetry that leaves the SM invariant and acts on the singlet as $\eta \to -\eta$. We also included the only independent dimension-six operator that involves derivatives. We will neglect the several non-derivative dimension-six operators allowed by the symmetries, as their effect is not enhanced at large momentum transfer.

The relevant SM$-\eta$ interactions amount to $h-\eta$ cubic and quartic interactions, where h is the physical Higgs boson,

$$\mathcal{L}_\eta \supset -\frac{1}{4}(v+h)^2\left(\lambda\eta^2 + \frac{c}{f^2}\partial_\mu\partial^\mu\eta^2\right) \ . \tag{2}$$

The cubic interaction induces monojet events, e.g. via gluon fusion, $gg \to gh \to g\eta\eta$. The quartic interaction induces mono-Higgs events, $gg \to h \to h\eta\eta$.

Remark that η is not necessarily the constituent of the dark matter energy density: it may have a lifetime shorter than the age of the Universe, if the Z_2 symmetry is not exact; even if absolutely stable, its relic density may be negligibly small. As a consequence, the constraints from the dark matter relic density, as well as from direct and indirect dark matter searches, do apply only under the requirement that η is the and the only dark matter particle. On the contrary, one cannot decouple the mono-X searches from the Higgs invisible width constraint, that directly applies to $gg \to h \to \eta\eta$. Therefore, it is worth to explore the monojet (and mono-Higgs) signal and its p_T dependence in the full range for the three parameters $\{m_\eta, \lambda, c/f^2\}$, up to the constraint $m_\eta > m_h/2$ to avoid Higgs invisible decays. Note that $m_\eta^2 = \mu_\eta^2 + \lambda v^2/2$. If the mono-X signal were very interesting for the LHC, it would be worth to look for it, even though unrelated to dark matter.

3 SM + even doublet + odd singlet

In the minimal model, the pair of dark states $\eta\eta$ with $m_\eta > m_h/2$ is produced by the exchange of an off-shell SM Higgs boson h. This reduces the cross-section with respect to on-shell production by a factor $\sim m_h^2\Gamma_h^2/(p^2-m_h^2)^2$. This suppression is removed when the mediator is not h, but rather a heavier particle with mass larger than $2m_\eta$. A simple possibility is to consider a two Higgs doublets model (2HDM), with the lightest scalar mass eigenstate mimicking the SM Higgs at 125 GeV. Then, the heavier scalar states can provide the mediator for the $\eta\eta$ production. The Lagrangian reads

$$\mathcal{L}_\eta = \mathcal{L}_{2HDM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}\mu_\eta^2\eta^2 - \frac{1}{4}\lambda_\eta\eta^4 - \frac{1}{2}\lambda_{ij}\eta^2 H_i^\dagger H_j + \frac{c_{ij}}{2f^2}\partial_\mu(\eta^2)\partial^\mu(H_i^\dagger H_j) \ , \tag{3}$$

where a sum over $i,j = 1,2$ is understood, and the matrices λ and c are hermitian. We included the most general renormalizable interactions, plus a dimension-six derivative operator for each pair i,j. [CHECK WHETHER THERE ARE OTHER INDEPENDENT DERIVATIVE OPERATORS.]

The 2HDM model parameter space is vast and it is not obvious what are the best choices to avoid all constraints such as FCNCs and, at the same time, to generate a large monojet signal. [I AM NO EXPERT ON THE PARAMETER SPACE OF 2HDMs AND I HAD NO TIME TO CHECK WHAT ARE THE OPTIONS.]

The essential scenario we aim to is the following. The first Higgs doublet H_1 develops a vev v and contains the SM Higgs boson h_1. The second Higgs doublet

H_2 has no vev and contains two additional neutral states, $H_2^0 = (h_2 + ia_2)/\sqrt{2}$. We are interested in the monojet channel $gg \to gh_2 \to g\eta\eta$, as well as in the mono-Higgs channel $gg \to h_2 \to h_1\eta\eta$ (or the same processes with h_2 replaced by a_2). The necessary ingredients for a large monojet (mono-Higgs) signal are

- A large Yukawa coupling to the top quark, $y_2\overline{t_L}t_R h_2$. The gluon-gluon fusion production of h_2 goes through the top loop, that has a large form factor, as long as $m_{h_2}^2/(4m_t^2) \lesssim 5$ (the bottom loop is very small). The cross-section relative to the h_1 production scales as $|y_2/y_t|^2$, where $y_t \simeq 1$ is the SM top Yukawa coupling.
- A mass $m_{h_2} > 2m_\eta$. In this way one can produce h_2 on-shell, with a larger cross-section.
- Large couplings $h_2\eta\eta$, that are generated by the Lagrangian interactions

$$\mathcal{L}_\eta \supset -\frac{1}{2}(v+h_1)h_2\left[\mathrm{Re}(\lambda_{12})\eta^2 + \frac{\mathrm{Re}(c_{12})}{f^2}\partial_\mu\partial^\mu\eta^2\right] \ . \tag{4}$$

Then, the monojet analysis of the minimal model can be repeated with the obvious replacements of masses and couplings. Besides the three parameters $\{m_\eta, \mathrm{Re}(\lambda_{12}), \mathrm{Re}(c_{12})/f^2\}$, one can also vary m_{h_2} and y_2, that control the h_2 production cross-section.

[AGAIN, 2HDM EXPERTS SHOULD CHECK IF THERE IS SOME OBSTACLE TO CHOOSE THE PARAMETERS AS DONE ABOVE.]

4 SM + odd doublet + odd singlet

Another possibility to extend the minimal model is to enlarge the Z_2-odd sector, to comprise a scalar doublet $\Phi = [\Phi^+, (\phi^0 + ia^0)/\sqrt{2}]$ and a real scalar singlet S. We reserve the name η for the lightest odd state, that may play the role of dark matter. In general, η is a linear combination of S, ϕ^0 and, if CP is violated, a^0. We also assume that Z_2 is not spontaneously broken, that is Φ and S acquire no vev, otherwise η would be unstable.

The most general renormalizable Lagrangian is $\mathcal{L}_{D\leq 4} = \mathcal{L}_{SM} + \mathcal{L}_{S,\Phi} + \mathcal{L}_{S,\Phi,H}$, where

$$\mathcal{L}_{S,\Phi} = \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{1}{2}\mu_S^2 S^2 + D_\mu\Phi^\dagger D^\mu\Phi - \mu_\Phi^2\Phi^\dagger\Phi - V_{quartic}(S,\Phi) \ , \tag{5}$$

$$\begin{aligned}\mathcal{L}_{S,\Phi,H} &= -(gS\Phi^\dagger H + h.c.) - \frac{1}{2}\lambda S^2 H^\dagger H \\ &- \lambda_1(\Phi^\dagger\Phi)(H^\dagger H) - \lambda_2(\Phi^\dagger H)(H^\dagger\Phi) - \frac{1}{2}[\lambda_3(\Phi^\dagger H)^2 + h.c.] \ .\end{aligned} \tag{6}$$

In contrast with the previous models, one non-trivial derivative operator appears already at dimension five,

$$\begin{aligned}\mathcal{L}_{D=5} &\supset \frac{c}{f}(\partial_\mu S)\Phi^\dagger D^\mu H + h.c. \\ &\supset \frac{c}{2f}(\partial_\mu S)(\phi^0 - ia^0)\partial^\mu h + \frac{ic\sqrt{g^2+g'^2}}{4f}(\partial_\mu S)(\phi^0 - ia^0)Z^\mu(v+h) + h.c. \,. \end{aligned} \tag{7}$$

Note that all other dimension-five derivative operators can be reduced to this one, up to non-derivative pieces. Of course there are also dimension-six derivative operators, but in our exploratory study we focus on the leading effect only.

The first term on the right-hand side of Eq. (7) is the analog of Eq. (2). Recall that the odd neutral fields contain a η component, $S = s_S\eta + \ldots$, $\phi^0 = s_\phi\eta + \ldots$, $a^0 = s_a\eta + \ldots$, therefore one recovers a derivative $\eta - \eta - h$ interaction, with coupling $\sim p^2 c/f$. It is suppressed by $1/f$ only, while in the previous models it was suppressed by v/f^2. This leads to a monojet signal slightly enhanced with respect to the minimal model.

More interestingly, the second term on the right-hand side of Eq. (7) includes a derivative $\eta - \eta - Z$ interaction, that can be used to generate monojet events through the Z portal. This is potentially better than the Higgs portal, as the Z boson is easier to produce and has a much larger width, $\Gamma_Z \gg \Gamma_h$. Note that the coupling goes like $p^\mu v/f$, that is it grows linearly with momentum.

The second term on the right-hand side of Eq. (7) also includes a derivative $\eta - \eta - Z - h$ interaction, that allows to produce mono-Higgs events through the Z portal, or vice versa mono-Z events through the Higgs portal. The coupling goes like p^μ/f.