Searching for pseudo Nambu-Goldstone boson dark matter production in association with top quarks

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INTRODUCTION

Models in which dark matter (DM) and the Higgs boson arise as pseudo Nambu-Goldstone bosons (pNGBs) have recently gained considerable attention since they can address two of the most challenging questions of modern physics: the hierarchy problem and the dark matter puzzle. The respective DM candidate is usually said to naturally evade the severe constraints from DM direct detection experiments since it couples predominantly via momentum suppressed operators to the Standard Model (SM). Moreover, its interactions with light SM fermions are suppressed due to their small SM Yukawa couplings. The hierarchy in the SM Higgs sector, however, motivates an investigation of the DM interaction with top quarks, which could be observed at the Large Hadron Collider (LHC).

We study a set of generic operators arising in such models in an effective field theory (EFT) encompassed by two interaction Lagrangians [1, 2]. First,

$$\mathcal{L}_{\chi H} = \frac{c_d}{f^2}\,\partial_\mu|\chi|^2\partial^\mu|H|^2 - \lambda\,|\chi|^2|H|^2\,,$$

where f denotes the energy scale of the breaking of the global symmetry. We refer to these operators as the *derivative* and the *marginal* Higgs portals. Interactions with SM fermions are described by

$$\mathcal{L}_{\chi\psi} = \frac{|\chi|^2}{f^2}\left(c_t y_t \bar{q}_L \tilde{H} t_R + \text{h.c.}\right) + \frac{i}{f^2}\,\chi^*\overleftrightarrow{\partial_\mu}\chi \sum_{\psi=q_L,t_R,b_R} d_\psi \bar{\psi}\gamma^\mu\psi\,.$$

Here, we distinguish between the *Yukawa-type* and the *current-current-type* interaction. The DM scalar is assumed to be complex.

We perform a detailed phenomenological analysis of the LHC reach for pNGB DM production in association with top quarks. Our focus lies on the tX+MET channel. Moreover, we demonstrate how loop-induced effects can lead to a sizeable spin-independent DM-nucleon cross section. Subsequently, we find strong constraints from DM direct detection experiments. Besides, we show that for small DM masses a broad region of the parameter space is ruled out due to precision measurements of the decay width of the SM Higgs boson. We further provide the limits imposed by the DM relic abundance as measured by the PLANCK collaboration. Finally, we use the data from galactic γ−ray spectra in order to pin down the region in the parameter space in which pNGBs are viable DM candidates.

Phenomenology

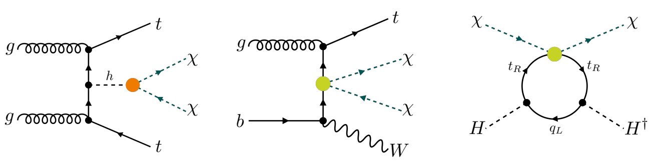

Fig. 1 & 2: Sample processes at leading order that can cause signatures in the tX+MET channels at the LHC.
Fig. 3: Sample diagram for contributions to invisible Higgs decays.

The Lagrangian defined above implies a rich phenomenology accessible through various experiments. For instance, one would expect to observe signatures in the tX+MET channel, as shown representatively in Figs. 1 & 2. Both the DM-Higgs and the DM-fermion operators lead to top quark associated production of DM at the LHC. The ATLAS and CMS collaborations have published several studies on simplified models of DM in these channels (see e.g. [3]) investigating fully hadronic and (semi-)leptonic final states. We implement four different analyses in CHECKMATE and investigate the collider reach on the pNGB DM operators.

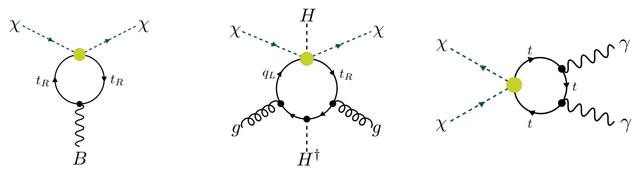

Fig. 4 & 5: Diagrams before EWSB contributing to the low-energy scattering of DM with matter in direct detection experiments.
Fig. 6: Sample diagram for DM annihilation processes relevant indirect detection of DM.

Moreover, the pNGB DM operators alter the decay width of the Higgs boson. It receives tree-level contributions from both the marginal and derivative Higgs portals, but loop-induced interactions open up sensitivity also to the Yukawa-type coupling with the top quark (see Fig. 3). We compute the partial width $\Gamma(h \longrightarrow \chi\chi^*)$ and infer limits on the couplings from recent measurements of the total Higgs decay width.
At low energies, the pNGB DM Lagrangian induces effective interactions with the SM gauge bosons (see Figs. 4 & 5), which can be described by the EFT Lagrangian

$$\mathcal{L}_{\chi V} = \frac{iec_A}{16\pi^2 f^2}\,\chi^*\overleftrightarrow{\partial_\mu}\chi\,\partial_\nu F^{\mu\nu} + \frac{g_s^2 d_G}{16\pi^2 f^2}\,|\chi|^2 G^a_{\mu\nu}G^{a,\mu\nu}\,.$$

We compare the implied spin-independent DM-nucleon cross section to the 90% CL limits published by the XENON collaboration.
For $m_b < m_\chi \lesssim m_W$, the tree-level annihilation of DM into a pair of bottom quarks provides the dominant contribution to the DM relic abundance. The s-wave contribution is suppressed by the small mass of the bottom quark and hence dominated by the p-wave contribution. For larger DM masses, the s-wave annihilations of DM into pairs of electroweak gauge bosons, Higgs bosons, and top quarks determine the abundance in the early universe.
In the present universe, pNGB DM in galactic centers could annihilate into pairs of monochromatic photons via s-channel exchange of a Higgs boson or the direct $\chi\chi^* \longrightarrow \gamma\gamma$ transition via a top quark loop (see Fig. 6). We consider the latest data on γ-ray lines from dwarf spheroidal galaxies (dSphs) as published by the Fermi-LAT and the DES collaborations in order to account for the limits imposed by indirect detection experiments.

PRELIMINARY RESULTS AND DISCUSSION

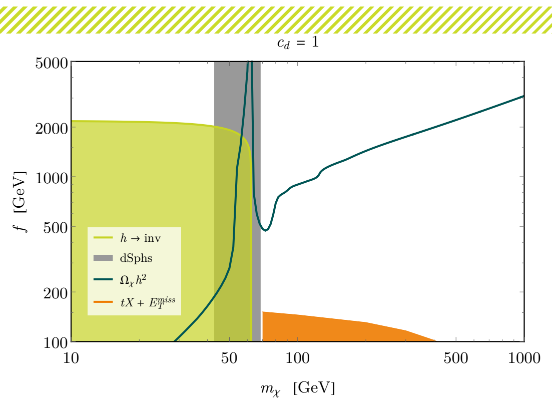

Fig. 7: Exclusion limits for the derivative Higgs portal.

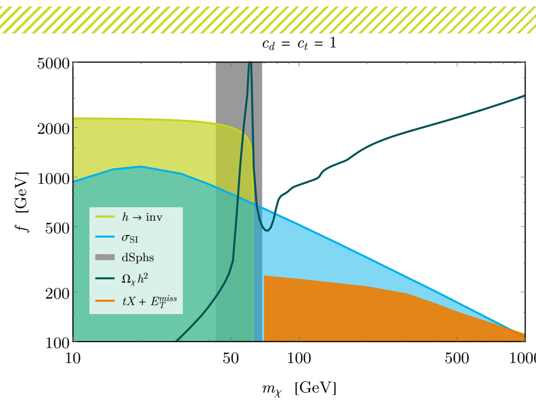

Fig. 8: Exclusion limits for the combined derivative Higgs portal and the Yukawa-type interaction.

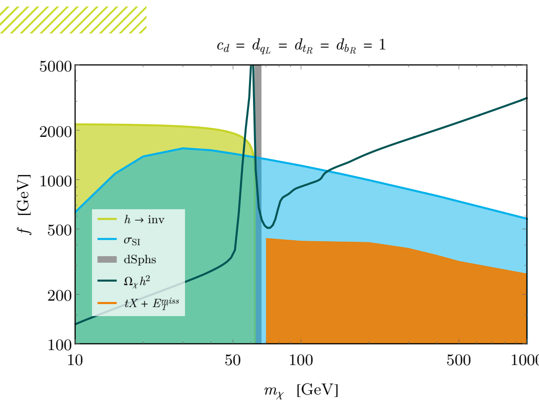

Fig. 9: Exclusion limits for the combined derivative Higgs portal and the current-current-type interaction.

In Figs. 7-9, exclusion limits in the m_χ-f-plane are displayed for different coupling scenarios. We observe that the different search strategies lead to complementary bounds on the parameter space.
For the derivative Higgs portal in Fig. 7, we find that tX+MET searches at the LHC can probe otherwise inaccessible regions of the parameter space. However, the sensitivity is not sufficient to test models that can explain the entire observed DM relic abundance. Direct detection is not sensitive to the derivative Higgs portal, but it dominates the collider bounds whenever other operators are added to the analysis (see Figs. 8 & 9). pNGB DM with $m_\chi \gtrsim 100\,\text{GeV}$ still cannot be excluded along the line that fulfills the relic density constraint. In all scenarios under consideration, the region $m_\chi \lesssim m_h/2$ is mostly ruled out by the invisible width of the Higgs and indirect detection constraints.
In conclusion, pNGBs remain attractive candidates for DM since they can explain the observed DM relic abundance in the universe based on theoretically motivated and simple assumptions. Neither colliders nor direct detection experiments achieve the necessary sensitivity to exclude weak scale DM masses.

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