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Constraining Dark Matter Interactions with Pseudoscalar and Scalar Mediators Using Collider Searches for Multijets plus Missing Transverse Energy

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The monojet search, looking for events involving missing transverse energy (E_T) plus one or two jets, is the most prominent collider dark matter search. We show that multijet searches, which look for E_T plus two or more jets, are significantly more sensitive than the monojet search for pseudoscalar- and scalar-mediated interactions. We demonstrate this in the context of a simplified model with a pseudoscalar interaction that explains the excess in GeV energy gamma rays observed by the Fermi Large Area Telescope. We show that multijet searches already constrain a pseudoscalar interpretation of the excess in much of the parameter space where the mass of the mediator M_A is more than twice the dark matter mass m_{DM} . With the forthcoming run of the Large Hadron Collider at higher energies, the remaining regions of the parameter space where $M_A > 2m_{\text{DM}}$ will be fully explored. Furthermore, we highlight the importance of complementing the monojet final state with multijet final states to maximize the sensitivity of the search for the production of dark matter at colliders.

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Weakly interacting massive particles (WIMPs) are the most studied and arguably the best motivated candidate for particle dark matter (DM), as they are present in many extensions of the Standard Model (SM). A particularly appealing feature of WIMPs is that they should be detectable with current or near-term experiments [1].

The plethora of DM models poses a challenge of how to interpret DM searches in a generic way. One approach is to classify the DM model by the particle mediating the interaction. A particularly interesting class of models involves the exchange of a spin-0 s -channel scalar or pseudoscalar mediator, since additional scalars and pseudoscalars are a generic prediction of extensions of the SM Higgs sector. Pseudoscalars are also particularly interesting, as they are a common feature in many of the models proposed to explain the spatially extended gamma-ray excess around the Galactic Center observed with the Fermi Large Area Telescope (Fermi-LAT) [2,3].

While scalars and pseudoscalars with a mass below 10 GeV can be probed by flavor-changing observables at colliders [4], heavier pseudoscalars whose dominant interaction is with DM are particularly difficult to detect. Pseudoscalar-mediated interactions result in a suppressed tree-level spin-dependent interaction and an unobservably small loop-level spin-independent interaction at direct detection experiments, making this interaction inaccessible for these experiments [5,6]. The most prominent collider search for DM production at the Large Hadron Collider (LHC) is the monojet search [7–10], which searches for events with a high momentum jet from initial state radiation in combination with significant missing transverse energy (E_T). As we will demonstrate (see also [11–13]), the monojet search has limited sensitivity to pseudoscalar- or scalar-mediated interactions.

In contrast, we show that multijet plus E_T collider searches significantly extend the sensitivity of the LHC to these interactions. These searches are designed to be inclusive and probe a large region of the topological and kinematic phase space, probing jet multiplicities ≥ 2 with several kinematic variables, including E_T and the scalar sum of the jets p_T (H_T). Typically, the multijet plus E_T final state has been used to search for supersymmetry (SUSY) at the LHC. In this Letter, we demonstrate that this final state also has excellent sensitivity to the pair production of DM from pseudoscalar and scalar mediators. This is because the production of pseudoscalar or scalar mediators is typically dominated by gluon fusion [14], which in turn generally leads to events with higher jet multiplicity in the final state [15].

As an example of the utility of the multijet plus E_T searches, we apply our limits to a pseudoscalar model that can account for the Fermi-LAT excess. We show that current limits already exclude much of the Fermi-LAT excess parameter space where the pseudoscalar's mass (M_A) is more than twice the DM mass (m_{DM}). Future limits at $\sqrt{s} = 13$ TeV will fully probe the remaining parameter space where $M_A > 2m_{\text{DM}}$.

Monojet and multijet searches.—The benchmark pseudoscalar model that we consider is a simplified model following the ansatz of the minimal simplified dark matter (MSDM) models [16], which have four free parameters: m_{DM} , M_A , and two couplings g_{DM} and g_{SM} . The interaction terms are

$$\mathcal{L}_{\text{int}} = ig_{\text{DM}} A \bar{\chi} \gamma^5 \chi + ig_{\text{SM}} \sum_q \frac{m_q}{v} A \bar{q} \gamma^5 q, \quad (1)$$

where χ is a Dirac fermion, the sum is over all quarks, m_q is the quark mass, and $v = 246$ GeV is the Higgs vacuum expectation value. Motivated by the minimum flavor violation hypothesis [17], we assume that the couplings of the

pseudoscalar to quarks are proportional to m_q . With this coupling structure, the s -channel production of A is dominated by gluon fusion. We adopt a simplified model approach in this work, as it provides a more accurate framework to characterize the results of collider DM searches when the mediator is light enough to be produced [7,8,18]. This simple model can explain the Fermi-LAT excess while remaining consistent with other constraints [6] and is a useful proxy for the structure found in two-Higgs-doublet models (2HDM) and in extended 2HDM that have mixing with a singlet-like pseudoscalar (*à la* the NMSSM) [19].

The MSDM ansatz assumes that the pseudoscalar width Γ_A is fully determined by the decays to quarks, gluons, and DM. The only free parameters affecting Γ_A are the four basic parameters $\{m_{\text{DM}}, M_A, g_{\text{DM}}, g_{\text{SM}}\}$. Expressions for Γ_A are given in Ref. [13]. Γ_A is dominated by DM and top-quark decay (when kinematically allowed), as m_q/v does not suppress these decays. We will focus on the regime where $M_A > 2m_{\text{DM}}$ in which case $\text{BR}(A \rightarrow \chi\bar{\chi})$ is generally large [20]. The collider signatures therefore involve the production of A that decays to a pair of DM particles.

The monojet search at the LHC has been advocated as the primary model-independent search for DM production at colliders [7,8]. Events with a second jet may also be allowed, but events with three or more are rejected to avoid background contamination from processes with high jet multiplicity, like top-quark production.

In contrast, the more inclusive α_T [21], M_{T2} [22], razor [23], or $MHT-H_T$ [24] multijet plus E_T searches place fewer constraints on the phase space. Each event is characterized by the number of jets and hadronic activity H_T , as well as other kinematic variables. These bins are combined in a likelihood fit and allow the multijet searches to take advantage of different signal-to-background compositions in these numerous search regions to attain better sensitivity. For instance, while the CMS monojet analysis employs a single inclusive E_T bin with the E_T threshold ranging between 250 and 550 GeV, the M_{T2} search combines more than 100 exclusive search regions. Similar kinematic selections and jet-multiplicity categorizations are utilized by the α_T and razor searches. These inclusive searches are an important pillar of the search strategy for new physics at the LHC, providing the best possible sensitivity to a large variety of SUSY production and decay topologies [25]. So far, they have largely been ignored for searches involving the pair production of DM. A razor search was previously investigated in Refs. [26,27] but found a small improvement over the monojet search. The search in [26] considered one inclusive signal region, which was optimized for models with a (axial-)vector mediator. Most of the events arising from gluon-induced models, like scalar or pseudoscalar exchanges, were rejected. In contrast, our analysis includes all of the accessible signal regions of the M_{T2} search and maintains excellent performance for a variety of signal models. Unfortunately, Ref. [27] did not consider gluon-induced models, so no direct comparison is possible.

To determine the sensitivity of these collider searches for our model, we reinterpret the CMS monojet [9] and M_{T2} [22] analyses using the POWHEG BOX V2 generator [15,28].

This generates, at leading order with exact top-quark mass effects, DM pair production together with one parton via an s -channel pseudoscalar mediator. We use the fixed width approximation, having checked that our results match when the running width is used. We use the MSTW2008LO parton distribution functions with renormalization (μ_R) and factorization scale (μ_F) set to $\mu/2$, where $\mu = \sqrt{m_{\chi\chi}^2 + p_{T,j1}^2} + p_{T,j1}$, $m_{\chi\chi}$ is the invariant mass of the DM pair, and $p_{T,j1}$ is the transverse momentum of the leading jet. Scale uncertainties on the cross section were found to be $\mathcal{O}(\pm 40\%)$ [13]. To be conservative, we do not apply a K factor of 1.6 as used in [11] to account for higher-order corrections, since a computation of the next-to-leading-order corrections with a finite top-quark mass is not available. The events generated by POWHEG are interfaced with PYTHIA 8.180 [29] for parton-shower effects and hadronization. Finally, signal events are passed through DELPHES v3.2.0 [30] for detector simulation.

Figure 1 shows a comparison of the expected 90% confidence level (C.L.) exclusion contours from our monojet and M_{T2} analyses in the $M_A - m_{\text{DM}}$ plane (upper) for two different coupling scenarios, $g_{\text{SM}} = g_{\text{DM}} = 1$ and 3, as well as in the $g_{\text{SM}} - g_{\text{DM}}$ plane (lower) for $m_{\text{DM}} = 45$ GeV and $M_A = 150$ and 250 GeV. This comparison assumes 20 fb^{-1} at 8 TeV. Both planes show that the M_{T2} search possesses significantly better expected sensitivity over the monojet search. In particular, the M_{T2} search has the ability to exclude large regions in the $M_A - m_{\text{DM}}$ plane for both

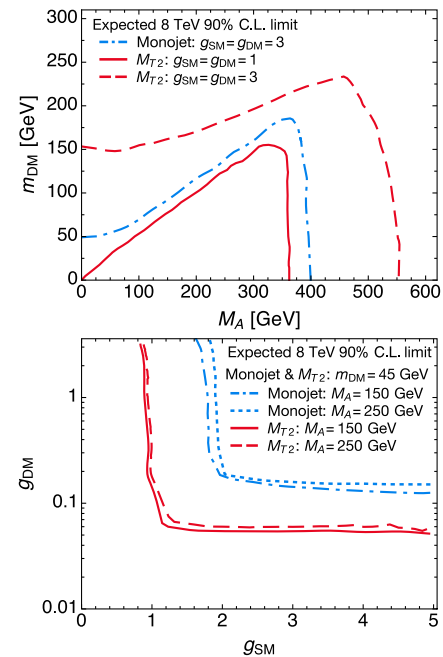


FIG. 1 (color online). Comparison of the expected 90% C.L. exclusion contours from our monojet (blue line) and M_{T2} (red line) analyses. Regions below and above the lines are excluded in the upper and lower panels, respectively. The expected M_{T2} limits are significantly better than the expected monojet limits over the entire parameter space.

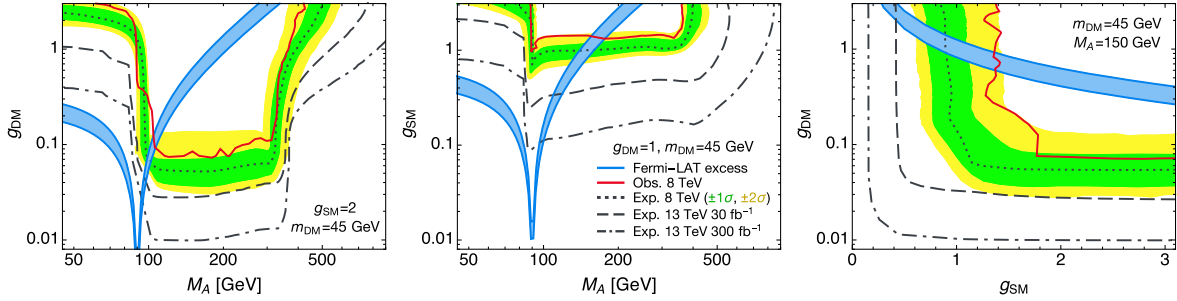


FIG. 2 (color online). Comparison of the region consistent with the Fermi-LAT excess (blue shaded) and the observed (red line) and expected (black dotted line) 90% C.L. exclusion contours of the M_{T2} analysis. The green and yellow shaded regions show the $\pm 1\sigma$ and $\pm 2\sigma$ bands of the expected M_{T2} limits. The black dashed and dot-dashed lines show projected limits at 13 TeV. The region above the lines is excluded. In each panel, we fix $m_{DM} = 45$ GeV and one of $\{M_A, g_{DM}, g_{SM}\}$, as indicated.

$g_{SM} = g_{DM} = 1$ and 3, up to $M_A = 350$ and 550 GeV, respectively, for small m_{DM} . In contrast, for $g_{SM} = g_{DM} = 1$ the monojet analysis does not find any limit, while the reach in M_A for $g_{SM} = g_{DM} = 3$ is more than 150 GeV less than for M_{T2} . The lower panel shows that, for $M_A > 2m_{DM}$, the multijet plus E_T analysis is expected to probe couplings down to $g_{DM} \approx 0.05$ and $g_{SM} \approx 1$. In comparison, the monojet search possesses sensitivity for $g_{DM} \gtrsim 0.12$ and $g_{SM} \gtrsim 2$, consistent with the findings in [13].

Based on these results, we conclude that multijet plus E_T searches exhibit better sensitivity than the monojet analysis over the entire parameter space. The improved sensitivity of M_{T2} is a result of categorizing the search in bins of jet multiplicity and several kinematic variables, allowing for differences in signal and background in these various categories to be exploited. We find that the low and medium H_T categories for two jets provide a large fraction of the sensitivity for our pseudoscalar model. However, significant additional sensitivity is gained by the inclusion of low and medium H_T categories with 3–5 jets. The higher-jet bins are particularly important for our model, since $\sim 60\%$ and $\sim 30\%$ of the events in the low and medium H_T categories, respectively, have gluon-fusion (gg) and quark-gluon (qg) production, which typically produce more jets in the final state. The remaining $\sim 10\%$ of events are from quark antiquark ($q\bar{q}$) or gluon heavy-quark initial states. Having demonstrated the enhanced sensitivity of M_{T2} over the monojet search, in the following we will show only limits from the M_{T2} analysis.

Constraining the Fermi-LAT excess.—The Fermi-LAT observation of a spatially extended gamma-ray excess around the Galactic Center has generated great interest, since it may be explained by annihilating DM. Unfortunately, many indirect detection signals, including the Fermi-LAT excess, do not give irrefutable evidence for DM because of large astrophysical uncertainties [31]. For instance, Ref. [32] suggests that the excess could be explained by point sources (PS) that lie just below the current Fermi-LAT threshold. While detecting members of the PS population would corroborate an astrophysical origin for the excess, a complementary signal in direct detection or collider experiments is required to corroborate a DM origin.

A plethora of models involving a pseudoscalar mediator have been proposed to explain the Fermi-LAT excess [6,33]. As pseudoscalar-mediated interactions are suppressed at direct detection experiments, colliders are the most promising way to independently test a pseudoscalar-mediated explanation for the gamma-ray excess. We therefore investigate the implications of the M_{T2} limits on the model defined by Eq. (1), which can explain the Fermi-LAT excess.

We fit to the Fermi-LAT excess energy spectrum in [3], assuming the DM halo follows a generalized Navarro-Frenk-White profile with $\gamma = 1.26$, $r_s = 20$ kpc, $r_\odot = 8.5$ kpc, and $\rho_\odot = 0.4$ GeV cm $^{-3}$. We shower the annihilation products with PYTHIA 8.186 [29]. For this model, we obtain $m_{DM} = 44.9^{+5.3}_{-4.6}$ GeV. As in Ref. [3], we find that values up to $m_{DM} \approx 65$ GeV provide a reasonable fit (p value > 0.05). For $m_{DM} = 45$ GeV and the halo parameters mentioned, the preferred annihilation cross section is $\langle\sigma v\rangle = 3.2 \pm 0.4 \times 10^{-26}$ cm 3 s $^{-1}$. This is a factor of 2 larger than values in Ref. [3], because we assume χ is a Dirac fermion while Ref. [3] assumed a Majorana fermion.

The annihilation cross section for $\chi\bar{\chi} \rightarrow A \rightarrow q\bar{q}$ is

$$\langle\sigma v\rangle_q = \frac{3m_q^2}{2\pi v^2} \frac{g_{DM}^2 g_{SM}^2 m_{DM}^2}{(M_A^2 - 4m_{DM}^2)^2 + M_A^2 \Gamma_A^2} \sqrt{1 - \frac{m_q^2}{m_{DM}^2}}. \quad (2)$$

This equation allows us to map $\langle\sigma v\rangle = \sum_q \langle\sigma v\rangle_q$ to the parameters in our model. The shaded blue bands in Fig. 2 show the region consistent with the Fermi-LAT excess. In all panels, we assumed $m_{DM} = 45$ GeV and $\langle\sigma v\rangle = 1.4\text{--}3.3 \times 10^{-26}$ cm 3 s $^{-1}$. The lower value follows from variations in the halo parameters, principally ρ_\odot , which may be as large as 0.56 GeV cm $^{-3}$ [34] (the annihilation flux Φ scales as $\Phi \propto \rho_{DM}^2 \langle\sigma v\rangle$). The upper value follows from the Fermi-LAT 95% C.L. upper limit on $\langle\sigma v\rangle$ from dwarf spheroidal galaxies [35].

To compare the region consistent with the Fermi-LAT excess with the M_{T2} search, we establish both expected and observed 90% C.L. limits. These are given by the dotted black and solid red lines, respectively, in Fig. 2. To quantify the compatibility of the expected and observed limits, we also determine the expected $\pm 1\sigma$ and $\pm 2\sigma$ bands (shaded green and yellow, respectively) with a toy experiment technique using the reported background uncertainties in

Ref. [22]. The expected and observed limits also include a 20% systematic uncertainty on the signal yield, which is typical for these searches [9,22]. For both bands we have validated our implementation with the M_{T2} public results and find good agreement. Based on the expected sensitivity of the M_{T2} search shown in Fig. 1, we have chosen $g_{SM} = 2$ (left), $g_{DM} = 1$ (middle), and $M_A = 150$ GeV (right) to illustrate the constraints the M_{T2} search places on the Fermi-LAT excess. A resonance feature when $M_A \approx 2m_{DM}$ is seen in both the Fermi-LAT region and the M_{T2} limit in the $M_A - g_{DM}$ and $M_A - g_{SM}$ planes. Outside this region, the excess is consistent with $g_{DM} \sim g_{SM} \sim \mathcal{O}(1)$. Owing to the off-shell suppression of the production cross section, these searches cannot place relevant constraints on the region below $M_A < 2m_{DM}$.

Our observed limit for the M_{T2} search is approximately 2σ weaker than our expected limit. This is compatible with Ref. [36], where the observed limit for direct production of light squarks is also weaker than expected. In contrast, expected and observed limits are similar for the monojet analysis. This suggests that the weaker limit is caused by statistical fluctuations in the background estimates in some of the phase space regions probed by the M_{T2} search that are inaccessible to the monojet search. Of course, we cannot exclude the possibility that a DM signal causes the weaker limit, but given that this is a 2σ effect, additional data are required to draw any significant conclusion.

Even with a $\sim 2\sigma$ weaker observed limit than expected, the M_{T2} search still excludes a significant fraction of the Fermi-LAT excess region for $2m_{DM} \lesssim M_A \lesssim 400$ GeV. For $g_{SM} = 2$, M_{T2} excludes all of the excess region above $M_A = 107$ GeV (left panel), while for $g_{DM} = 1$ mediator masses compatible with the excess above 177 GeV (middle panel) are excluded. The right panel shows that M_{T2} is able to exclude all of the excess region for $g_{DM} < 0.93$ for an illustrative mediator mass of $M_A = 150$ GeV. In these panels, we assumed that $m_{DM} = 45$ GeV, but similar conclusions are found for values up to $m_{DM} = 65$ GeV. In fact, Fig. 1 demonstrates that the M_{T2} limits have little dependence on m_{DM} for $m_{DM} \lesssim 125$ GeV.

To illustrate how the Fermi-LAT excess parameter space might be probed in the future, we also provide projected sensitivities of the M_{T2} search. The basis for these extrapolations are the 8 TeV limits, which are rescaled assuming that the underlying performance of the search in terms of signal efficiency and background suppression remains unchanged. These assumptions were also used in Ref. [16] and form the basis of Collider reach [37]. Figure 2 shows the projected limits for an early start-up scenario assuming 13 TeV and 30 fb^{-1} (black dashed line) and a long-term scenario with 13 TeV and 300 fb^{-1} (black dot-dashed line). The increase in energy and luminosity will enable this search to significantly increase its sensitivity. Assuming that search performance is maintained, it will be possible to probe almost all of the region $M_A > 2m_{DM}$ compatible with the Fermi-LAT excess.

Finally, we see that the projected limits do not constrain the region $M_A < 2m_{DM}$. This implies that this search will not be able to probe the ‘‘cascade-annihilation’’ models that

explain the Fermi-LAT excess (see, e.g., [38]). In these models, a pair of mediating particles are produced on shell, requiring $M_A < m_{DM}$.

Discussion.—Although the monojet search is the most prominent search for DM at the LHC, we have shown that the multijet plus E_T search, M_{T2} , provides more stringent constraints on DM production for a pseudoscalar mediator. The additional sensitivity of the multijet search originates from binning the search into categories of jet-multiplicity and kinematic variables like H_T and M_{T2} , as well as from extending to higher jet multiplicities than the one- or two-jet final state probed by the monojet search. This is especially relevant for gluon-fusion-produced signal models, including the pseudoscalar model discussed here and models with a scalar mediator. POWHEG has the exact top-quark mass dependence for DM pair production and one parton in the final state. Topologies with higher jet multiplicities rely on the parton shower for additional jets, which could introduce uncertainty not fully accounted by our analysis. To estimate the impact of the parton shower producing too many energetic jets, we performed a reweighting of the jet-multiplicity distribution of the signal events. As an extreme variation, we consider the scenario where all 3–5 jet events are moved to the two-jet categories (while keeping other kinematic variables fixed) and find that the resulting limit is still contained in the expected $\pm 1\sigma$ bands in Fig. 2. The robustness of the M_{T2} search against such variations arises from the design criteria of inclusive searches, which typically require that final states with differing jet multiplicity have a similar sensitivity. Therefore, signal events assigned to the wrong category contribute to the analysis with a similar weight and thus maintain the overall performance of the search. Although we find that our conclusions are unchanged by this reweighting, it would be highly desirable to have theoretical tools that include the full top-quark mass dependence in events with multiple partons in the final state.

The Fermi-LAT gamma-ray excess remains an enigma. It may be straightforwardly explained with simple DM models involving the exchange of an s -channel pseudoscalar mediator, but unfortunately, the Fermi-LAT data are not sufficient to exclude mundane explanations with astrophysical sources. A DM signal in a complementary experiment is required to confirm a DM origin. Confronting the M_{T2} limits against parameter space favored by the Fermi-LAT excess shows that the LHC provides crucial input on pseudoscalar models. We demonstrated that, for $M_A > 2m_{DM}$, much of the parameter space is already constrained. Our 13 TeV projections indicate that essentially all of the region $M_A > 2m_{DM}$ will be probed by the next LHC run.

As multijet searches consider events with at least two jets in the final state, the overlap with monojet searches, which allow up to two jets in the final state, is small. For this reason, we strongly recommend that the phase space covered by monojet and multijet searches is combined in a single search to further improve the sensitivity of the LHC to DM production.

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