Determining the structure of dark-matter couplings at the LHC

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The latest LHC mono-jet searches place stringent bounds on the $pp \rightarrow \bar{\chi}\chi$ cross section of dark matter. Further properties such as the dark matter mass or the precise structure of the interactions between dark matter and the standard model can however not be determined in this manner. We point out that measurements of the azimuthal angle correlations between the two jets in $2j + \bar{\chi}\chi$ events may be used to disentangle whether dark matter pair production proceeds dominantly through tree or loop diagrams. Our general observation is illustrated by considering theories in which dark matter interacts predominantly with the top quark. We show explicitly that in this case the jet-jet azimuthal angle difference is a gold-plated observable to probe the Lorentz structure of the couplings of dark matter to top quarks, thus testing the CP nature of the particle mediating these interactions.

I. INTRODUCTION

The minimal experimental signature of dark matter (DM) pair production at the LHC would be an excess of events with a single jet in association with large amounts of missing transverse energy ($E_{T, \text{miss}}$). The experimental search for $j + E_{T, \text{miss}}$ events provides bounds on the interaction strength of DM with quarks and gluons, constraining the same parameters as direct detection experiments (see e.g. [1, 2]). These measurements place the leading (and in some cases only) limits on models of DM over certain regions of parameter space.

While the $j + E_{T, \text{miss}}$ channel can be used to constrain the $\sigma(pp \rightarrow \bar{\chi}\chi)$ cross section, it provides insufficient information to determine additional DM properties such as its mass or the precise nature of its interactions with the standard model (SM). In fact, the transverse momentum ($p_T$) spectrum of the $j + E_{T, \text{miss}}$ signal is essentially featureless and almost independent of the chirality and/or the CP properties of the DM couplings to quarks. This suggests that while ATLAS and CMS are well suited to discover light DM, the LHC prospects of using this channel to make more definitive statements about specific DM properties seem to be slim.

In this letter we observe that this unsatisfactory situation may be remedied by studying two-jet final states involving $E_{T, \text{miss}}$. In particular, we will argue that measurements of the azimuthal angle difference in $2j + E_{T, \text{miss}}$ events can possibly show a strong cosine-like or sine-like correlation only if DM pair production is loop induced, whereas tree-level interactions result in a $\Delta \phi_{j1,j2}$ distribution of a quite different shape. In order to illustrate our general observation we will consider DM models that generate the effective operators

$$O_S = \frac{m_t}{\Lambda_S^2} \bar{t} \tilde{\chi}\chi, \quad O_P = \frac{m_t}{\Lambda_P^2} \bar{t} \gamma_5 \tilde{\chi}\chi. \quad (1)$$

Examples of Feynman diagrams with an insertion of $O_{S,P}$ that give rise to a $2j + E_{T, \text{miss}}$ signal are displayed in Fig. 1. For this well-motivated case we will explicitly show that the Lorentz structure of the DM top-quark interactions — and in consequence the CP nature of the mediator inducing (1) — can be disentangled by measuring the normalised $\Delta \phi_{j1,j2}$ distribution. After a discovery of an enhanced mono-jet signal, combining the measurements of the top-loop induced $\sigma(pp \rightarrow j + \bar{\chi}\chi)$ cross section [4, 5] and the $1/\sigma d\sigma(pp \rightarrow 2j + \bar{\chi}\chi)/d\Delta \phi_{j1,j2}$ spectrum of the jet-jet azimuthal angle difference would hence not only allow to determine the suppression scales $\Lambda_{S,P}$ in (1) but also whether the scalar operator $O_S$ or the pseudo-scalar operator $O_P$ is responsible for the observed excess of $j + E_{T,\text{miss}}$ events. Other constraints on effective interactions between DM and top quarks have been discussed for example in [6, 7].

Our work is organised as follows: in Sec. II we introduce the DM interactions which we intend to examine. In Sec. III we calculate the azimuthal angle correlations of the two jets in $2j + \bar{\chi}\chi$ production induced by the operators $O_{S,P}$, including the full top-quark mass dependence of the squared matrix elements. Our calculation is performed at the leading order (LO) in QCD. We will also comment on the applicability of the heavy top-quark ap-

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* For instance, the $p_T$ spectra corresponding to effective vector and axial-vector DM-quark interactions are within the uncertainties present at the next-to-leading order (NLO) plus parton-shower (PS) level indistinguishable.
proximation and the impact of higher-order QCD effects. In Sec. [IV] we discuss the case where the mediator can be resonantly produced, before concluding in Sec. [V]

II. DM INTERACTIONS

In the following we are interested in DM pair production from quark or gluon initial states. We will restrict our discussion to the case where the production proceeds via the exchange of a spin-0 s-channel mediator. We consider the following interactions between DM and top quarks involving a colourless scalar (S) or pseudo-scalar (P) mediator:

\[ \mathcal{L}_S = g_S^s (\bar{\chi} \chi) S + g_S^t \frac{m_t}{v} (\bar{t} t) S, \]
\[ \mathcal{L}_P = ig_P^s (\bar{\chi} \gamma_5 \chi) P + ig_P^t \frac{m_t}{v} (\bar{t} \gamma_5 t) P, \]

(2)

where \( v \simeq 246 \) GeV is the Higgs vacuum expectation value. Notice that we have assumed that the couplings of the mediators to top quarks are proportional to the associated SM Yukawa coupling. This is motivated by the hypothesis of minimal flavour violation (MFV), which curbs the size of dangerous flavour-changing neutral currents and automatically leads to a stable DM candidate [5]. While the DM particle \( \chi \) in [2] is understood to be a Dirac fermion, extending our discussion to Majorana DM or the case of a complex/real scalar is straightforward (see [4] for details).

If the mediator masses \( M_{S,P} \) are large compared to the invariant mass \( m_{\chi \chi} \) of the DM pair, we can describe \( 2j + \chi \chi \) production by means of an effective field theory (EFT). Integrating out the scalar and pseudo-scalar mediator then gives rise to (1) as well as composite operators consisting of four top-quark fields, which we do not consider further. In the case of \( O_S \) the suppression scale \( \Lambda_S \) is related to the mediator mass and the fundamental couplings by

\[ \Lambda_S = \left( \frac{v M_S^2}{g_S^3 g_t^2} \right)^{1/3}, \]

(3)

and an analogous expression with \( S \to P \) holds for \( O_P \).

With the current \( j + E_{T,\text{miss}} \) [3] and \( tt + E_{T,\text{miss}} \) [7] data, one can exclude values of the suppression scale below roughly 150 GeV (170 GeV) in the scalar (pseudo-scalar) case for light DM, which is small compared to typical LHC energies. In order to discuss the validity of the EFT approach (see also [10][15]), we will consider in Sec. [IV] also the simplest ultraviolet (UV) completion, where [14] arises from the full theory (2) after integrating out the fields \( S \) and \( P \). We will see that in this case the analysis becomes more model-dependent, because the predictions now depend on \( g_S^{S,P} \) and \( g_P^{S,P} \) as well as the masses \( M_{S,P} \) and the decay widths \( \Gamma_{S,P} \) of the mediators. Apart from these minor complications our general conclusions will however also hold in the case where the s-channel resonances \( S,P \) can be directly produced in pp collisions.

III. DM PRODUCTION WITH TWO JETS

In our analysis we consider \( 2j + E_{T,\text{miss}} \) production at the LHC with \( \sqrt{s} = 14 \) TeV center-of-mass (CM) energy. We adopt event selection criteria corresponding to the latest CMS mono-jet search [2][5]. In this search events of more than two jets with pseudo-rapidity below 4.5 and transverse momentum above 30 GeV are rejected. In order to suppress QCD di-jet events, CMS puts an angular requirement on the azimuthal distance between the two tagging jets of \( \Delta \phi_{j_1,j_2} < 2.5 \). Our reference signal region is defined by \( |\eta_j| < 2.4 \), \( p_{T,j} > 110 \) GeV and \( E_{T,\text{miss}} > 350 \) GeV, but we will comment on the sensitivity of the signal on the \( p_{T,j} \) and \( E_{T,\text{miss}} \) cuts. To improve the separation between the azimuthal angle distribution of the SM background and the \( 2j + E_{T,\text{miss}} \) signal, we also impose a cut of \( m_{j_1,j_2} > 600 \) GeV on the invariant mass of the di-jet system.

The calculation of the azimuthal distance \( \Delta \phi_{j_1,j_2} \) of the \( 2j + E_{T,\text{miss}} \) signal events is performed with the help of GGFLO which is part of VBFNLO [13], modifying the process \( pp \to 2j + h(A) \) appropriately. The GGFLO implementation of the \( 2j + h (A) \) production process is based on the analytical LO results of [19][20] for the scalar Higgs (h) case and of [21] for the pseudo-scalar Higgs (A) case. Our simulations utilise MSTW2008LO parton distributions [22] and jets are constructed according to the anti-k_t algorithm [23] with a radius parameter of \( R = 0.5 \), which corresponds to the value used in the CMS analysis [2].

We start our numerical analysis by showing results obtained for \( \Lambda_{S,P} = 150 \) GeV, a DM mass of \( m_\chi = 50 \) GeV, employing the reference cuts described above. Our choice of parameters will be motivated in Sec. [IV]. The central values of the corresponding \( j + E_{T,\text{miss}} \) and \( 2j + E_{T,\text{miss}} \) signal cross sections are 675 fb and 204 fb (1119 fb and

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2 LHC constraints on the scalar and pseudo-scalar DM-quark interactions involving the light flavours \( q = u, d, s, c, b \) have been discussed in [3][5].

3 Unlike the operator \( \bar{t} t \gamma_5 t \), which is strongly constrained because it contributes to the electric dipole moment of the neutron [9], the purely scalar or pseudo-scalar four-top quark operators resulting from (2) are experimentally not well bounded. The appearance of the operator \( \bar{t} t \gamma_5 t \) can be avoided by taking the spin-0 mediators \( S, P \) to be CP eigenstates.

4 The cuts imposed in the existing ATLAS and CMS analyses will not be suitable for DM searches at the 14 TeV LHC due to triggering limitations [10]. Our work should hence only be considered as a proof of concept. A more realistic study, including NLO corrections, PS effects and hadronisation corrections for both the DM signal and the SM backgrounds, will be presented elsewhere [17].
identify the factorisation scale as $\mu_F = \xi (p_{T,j1}, p_{T,j2})^{1/2}$ and replace the overall factor $\alpha_s^2$ entering the $2j + E_{T,\text{miss}}$ cross section by $\alpha_s (p_{T,j1}, \alpha) \alpha_s^2 (\xi m_\chi)$. We evaluate these quantities for every event generated by our Monte Carlo (MC) and vary $\xi$ in the range $[1/2, 2]$. In the total cross sections the induced scale uncertainties are around $+80\%$ $-40\%$, while the relative shifts in the normalised differential azimuthal angle distributions do not exceed the level of $+5\%$ $-5\%$. We conclude from this that even after considering scale ambiguities, the normalised $\Delta \phi_{j1, j2}$ distribution for $O_S$ is different than that of $O_P$, and both spectra are clearly distinguishable from the SM background.

The distinction in the radiation pattern of $O_S$ and $O_P$ can be most easily understood by employing the heavy top-quark mass approximation and replace the overall factor $\mu_F$ by $\xi (p_{T,j1}, p_{T,j2})^{1/2}$ and replace the overall factor $\alpha_s^2$ entering the $2j + E_{T,\text{miss}}$ cross section by $\alpha_s (p_{T,j1}, \alpha) \alpha_s^2 (\xi m_\chi)$. We evaluate these quantities for every event generated by our Monte Carlo (MC) and vary $\xi$ in the range $[1/2, 2]$. In the total cross sections the induced scale uncertainties are around $+80\%$ $-40\%$, while the relative shifts in the normalised differential azimuthal angle distributions do not exceed the level of $+5\%$ $-5\%$. We conclude from this that even after considering scale ambiguities, the normalised $\Delta \phi_{j1, j2}$ distribution for $O_S$ is different than that of $O_P$, and both spectra are clearly distinguishable from the SM background. 

The lower part of Fig. 2 also shows that while the pre-

338 fb) for $O_S$ ($O_P$), while the SM background predictions amount to 1289 fb and 330 fb. To put these numbers into perspective we recall that the latest CMS analysis excludes excesses in the mono-jet cross section with $S/B > 0.15$ at 95% confidence level. Given these numbers the mono-jet signals corresponding to $A_{S,P} = 150 \text{ GeV}$ and $m_\chi = 50 \text{ GeV}$ should be easily detectable at the 14 TeV LHC.

The normalised $\Delta \phi_{j1, j2}$ distributions associated to the operators $O_{S,P}$ are displayed in Fig. 2. From the figure it is evident that the scalar operator $O_S$ produces a strong correlation between the two jets, while the distribution that is peaked at $\Delta \phi_{j1, j2} = 0$ and heavily suppressed at $\Delta \phi_{j1, j2} = \pi/2$ (red solid curve). In the case of the pseudo-scalar operator $O_P$ the position of the peak and trough is instead reversed (blue solid curve). The cosine-like (sine-like) modulation in the azimuthal angle distribution corresponding to $O_S$ ($O_P$) should be contrasted with the spectrum of the dominant SM background process, $pp \to 2j + Z(\to \nu \nu)$, which has a minimum at $\Delta \phi_{j1, j2} = 0$ and a maximum in the vicinity of $\Delta \phi_{j1, j2} = 2.5$ (green solid curve). We simulate the background at LO using the POWHEG BOX. PS effects or hadronisation corrections are not included in our SM prediction.

To assess the significance of our findings, we study the scale uncertainties of the results. As advocated in [20], we...
FIG. 3. Normalised $\Delta \phi_{j_1j_2}$ distributions using the event selection criteria $p_{T,j_1} > 350 \text{ GeV}$ and $E_{T,\text{miss}} > 500 \text{ GeV}$. The style and colour coding of the curves follows the one used in Fig. 2.

The behaviour found for $1/\sigma \, da(pp \to 2j + E_{T,\text{miss}})/d\Delta \phi_{j_1j_2}$ is in clear contrast to that obtained in the case of the loop-induced mono-jet cross section for which the limit $m_t \to \infty$ is not a good approximation [4], because the high-$p_T$ jet is able to resolve the sub-structure of the top-quark loop. In fact, also in the case of $\sigma(pp \to 2j + \tilde{\chi} \chi)$, we find that the EFT predictions and the exact results are vastly different. For our standard cuts the infinite top-quark mass approximation overestimates the $2j + E_{T,\text{miss}}$ cross section by a factor of around 7 (10) in the case of the operator $O_S$ ($O_P$).

In order to further illustrate this point we show in Fig. 3 the normalised $\Delta \phi_{j_1j_2}$ distributions for $O_{S,P}$ using again $\Lambda_{S,P} = 150 \text{ GeV}$ and $m_\chi = 50 \text{ GeV}$, but applying the stronger signal cuts $p_{T,j_1} > 350 \text{ GeV}$ and $E_{T,\text{miss}} > 500 \text{ GeV}$. The corresponding $j + E_{T,\text{miss}}$ and $2j + E_{T,\text{miss}}$ cross sections read 214 fb and 87 fb ($O_S$), 344 fb and 141 fb ($O_P$) and 246 fb and 92 fb (SM). One first observes that the infinite top-quark mass limit still furnishes an acceptable description of the full results in this case. Second, the cosine-like and sine-like modulations of the $\Delta \phi_{j_1j_2}$ spectra are less pronounced if the requirements on $p_{T,j_1}$ and $E_{T,\text{miss}}$ are more exclusive. This feature can be understood by recalling that a pure cosine-like or sine-like $\Delta \phi_{j_1j_2}$ spectrum requires that the transverse momenta of the jets are much smaller than the momentum components along the beam direction. For harder $p_{T,j_1}$ cuts this approximation is not as good and as a result the strong jet-jet correlation is less marked. We conclude from this that in order to maximise the power of the $\Delta \phi_{j_1j_2}$ distribution in determining the Lorentz structure of the DM top-quark interactions the $p_{T,j_1}$ and $E_{T,\text{miss}}$ cuts should be as loose as possible. Making this statement more precise would require to perform a detailed analysis of the cut dependencies of both the signal and the background. While such a study is beyond the scope of this letter, we plan to return to this question in a future publication [17].

Another important and related issue is the question whether higher-order QCD effects can potentially wash out the observed strong correlations between the two jets. This question can be addressed by relying again on the similarities of the signal process $pp \to 2j + E_{T,\text{miss}}$ and its QCD analog $pp \to 2j + h (A)$. In the latter case it has been shown by explicit calculations (see e.g. [27–29]) that the shape of the lowest order distributions are unchanged and that therefore the jet-jet correlations survive the addition of NLO QCD corrections as well as PS and hadronisation effects. We verified that the latter feature is also present in the case of $1/\sigma \, da(pp \to 2j + \tilde{\chi} \chi)/d\Delta \phi_{j_1j_2}$ by showing our LO results with PYTHIA 6.4 [20]. We find that PS effects result in relative shifts of maximal $\pm 8\%$ in the $\Delta \phi_{j_1j_2}$ distributions and slightly reduce the amplitudes of the cosine-like and sine-like modulations, but do not distort the spectra. Given its stability under radiative corrections, we believe that the normalised spectrum of the azimuthal angle difference $\Delta \phi_{j_1j_2}$ in $2j + \tilde{\chi} \chi$ production is a gold-plated observable for determining the structure of the couplings of DM to top quarks.

IV. DISCUSSION

Until now we have considered an EFT framework to interpret a hypothetical mono-jet signal. This is particularly simple because in such a case the complete information is encoded in the scales $\Lambda_{S,P}$ that suppress the effective couplings [1], making it unnecessary to specify details of the particle mediating the interactions. Given the weakness of the bounds on $\Lambda_{S,P}$ [17], there are however serious concerns regarding the validity of the EFT approach (see also [10] [15] for similar discussions). In this section, we will therefore quantify when the simple-minded limits on the scale of the scalar and pseudo-scalar interactions apply and under which circumstances the EFT framework breaks down. In order to go beyond the effective description, one has to specify a concrete UV completion. In the following, we will assume that the full theory is provided by [2], which implies that the effective interactions [1] are generated by the s-channel exchange of the colourless spin-0 states $S, P$. We will not discuss the case of t-channel exchange of coloured spin-0 mediators, which is interesting in its own right and has been utilised in [31] [32] to construct MFV DM models where the relic carries top flavour.

We follow [15] to determine the minimum value of the couplings $(g_{S,P}^2 m_t^2)^{1/2} = (m_{S,P}^2 m_t^2)^{1/2}$ for which the EFT approach is applicable. First, we derive the limits on the suppression scales $\Lambda_{S,P}$ as a function of the
DM mass $m_\chi$. For concreteness, our analysis is based on the most recent mono-jet search by CMS \cite{7} with an integrated luminosity of 19.5 fb$^{-1}$ at $\sqrt{s} = 8$ TeV, utilising our standard event selection criteria. Second, we calculate $\sigma(pp \rightarrow j + E_{T,\text{miss}})$ in the full theory as a function of both $m_\chi$ and $M_{S,P}$. The actual computation of the top-loop induced $j + E_{T,\text{miss}}$ cross sections is performed by means of the MC codes developed in \cite{4,5}, which give identical results. For each DM mass, the minimum value of $(g_{S,P}^l g_{t}^{S,P})^{1/2}$ consistent with an EFT description is then found from the requirement that the full theory calculation of $\sigma(pp \rightarrow j + E_{T,\text{miss}})$ agrees with the corresponding EFT result to better than 20%. In the whole procedure, we take into account that $\Lambda_{S,P}$ and $M_{S,P}$ are related via (3).

The minimal coupling strengths determined in this manner are indicated by the red solid curves and bands in Fig. 4. The width of the bands reflects the dependence of the predictions on the relative width of the mediators, which we vary in the range $\Gamma_{S,P}/M_{S,P} \in [1/(8\pi), 1/3]$ to obtain the shown results. We see that for the EFT to work the couplings of the s-channel mediators to DM and top quarks have to be strong and that increasingly larger values of $(g_{S,P}^l g_{t}^{S,P})^{1/2}$ are needed for an accurate description, if the DM mass lies at or above the weak scale. In fact, in the case of $\mathcal{O}_S$ ($\mathcal{O}_P$) the theory becomes necessarily non-perturbative for $m_\chi \gtrsim 490$ GeV ($m_\chi \gtrsim 580$ GeV) as indicated by the blue dashed curves in the plots. It is important to realise that the values $M_{S,P}$ for which the EFT is applicable are below a TeV if DM is light. To give an example, for $m_\chi = 50$ GeV the displayed EFT limits correspond to $M_S \simeq 370$ GeV and $M_P \simeq 310$ GeV, respectively, if one assumes that the relative widths are $\Gamma_{S,P}/M_{S,P} = 1/3$.

The DM relic abundance also depends on the couplings $g_{S,P}^l$ and the masses $M_{S,P}$. However, this observable is sensitive to the full particle content of the underlying UV theory, because the mass spectrum determines the number and the strengths of the DM annihilation channels. This feature makes the prediction for $\Omega_\chi h^2$ more model-dependent than the mono-jet cross sections analysed above. For simplicity, we will assume that the couplings and the particle content are completely specified by (2), meaning that only annihilation processes with top quarks and gluon pairs in the final state are possible. We also allow for either scalar or pseudo-scalar interactions but not both.

Using the relevant formulas for the annihilation cross sections given in \cite{4} and requiring that the relic abundance saturates the observed value $\Omega_\chi h^2 = 0.119$ \cite{33}, we find the green dotted curves in the panels of Fig. 4. The parameter regions to the left and right of the curves correspond to DM overproduction and underproduction in the early universe. From the intersections of the non-perturbativity bounds and the relic density constraints, we obtain the following limit $m_\chi \gtrsim 40$ GeV ($m_\chi \gtrsim 10$ GeV) in the case of the operator $\mathcal{O}_S$ ($\mathcal{O}_P$). Combining all constraints we then find the yellow coloured wedges, which correspond to strongly-coupled theories with weak scale DM masses. Numerically, we arrive at $(g_{S,P}^l g_{t}^{S,P})^{1/2} \in [3.9, 4\pi]$ and $m_\chi \in [40, 470]$ GeV ($g_{S,P}^l g_{t}^{S,P})^{1/2} \in [2.2, 4\pi]$ and $m_\chi \in [10, 580]$ GeV). The parameters $\Lambda_{S,P} = 150$ GeV and $m_\chi = 50$ GeV used in Sec. \cite{3} to simulate the $\Delta\phi_{i,j}^{1/2}$ distributions have hence been specifically

![Fig. 4](image_url)

**FIG. 4.** Upper panel: The red solid curve and band indicates the minimum value of $(g_{S,P}^l g_{t}^{S,P})^{1/2}$ for which the LHC bounds on $\Lambda_S$ hold. The perturbative limit on this combination of couplings is indicated by the blue dashed curve, while the green dotted curve marks the parameter space where the DM relic density agrees with observation. Lower panel: The analogous bounds on $(g_{S,P}^l g_{t}^{S,P})^{1/2}$. In both panels the region of parameter space compatible with all constraints is coloured yellow. See text for further explanations.
chosen so that the EFT approach applies and the universe is not over closed. We emphasise that while large regions of parameter space are excluded due to DM overproduction, these bounds can be ameliorated if DM has large annihilation cross sections to other SM particles or (in particular) new hidden sector states. Such additional annihilation channels can reduce the tension between the LHC mono-jet limits and the relic density constraints significantly.

The preceding discussion should have made clear that the applicability of the LHC mono-jet limits on $\Delta S,P$ is limited. This raises the question of whether the jet-jet azimuthal angle difference in $2j + E_{T,\text{miss}}$ remains a good observable to probe the structure of the DM top-quark interactions also beyond the EFT framework. To answer this question we study a simplified $s$-channel model described by $g_{S,P}^{c,t} = 1$, $M_{S,P} = 500\,\text{GeV}$ and $m_c = 200\,\text{GeV}$ and the shown predictions correspond to our reference cuts. The meaning of the coloured curves is analogue to the one in Fig. 2.

The signal strength in $j + E_{T,\text{miss}}$ production depends sensitively also on the total widths $\Gamma_{S,P}$ of the mediators $S,P$. In the case of the scalar mediator, we obtain the following results for the partial decay widths

$$\Gamma(S \rightarrow \ell \bar{\ell}) = \left(\frac{m_1}{v} g_S^2\right)^2 \frac{3}{8\pi} M_S \left(1 - \frac{4m_1^2}{M_S^2}\right)^{3/2},$$

$$\Gamma(S \rightarrow \chi \chi) = \left(g_S^2\right)^2 \frac{1}{8\pi} M_S \left(1 - \frac{4m_1^2}{M_S^2}\right)^{3/2},$$

$$\Gamma(S \rightarrow gg) = \left(\frac{m_1}{v} g_S^2\right)^2 \frac{\alpha^2}{2\pi^3} M_S^2 \left|F_S \left(\frac{4m_1^2}{M_S^2}\right)\right|^2,$$

where

$$F_S(\tau) = 1 + (1 - \tau) \arctan^2\left(\frac{1}{\sqrt{\tau - 1}}\right).$$

The analog expressions for the pseudo-scalar mediator are obtained from the replacements $S \rightarrow P$ and $3/2 \rightarrow 1/2$ in the exponents, and the relevant form factor reads

$$F_P(\tau) = \arctan^2\left(\frac{1}{\sqrt{\tau - 1}}\right).$$

Using the above values for the couplings and masses, we arrive at $\Gamma_S/M_S = 3.1\%$ and $\Gamma_P/M_P = 6.4\%$, which implies that we are dealing with narrow resonances. The corresponding values of the mono-jet cross sections at the 14 TeV LHC are $\sigma(pp \rightarrow j + S(\rightarrow \chi \chi)) \approx 9\,\text{fb}$ and $\sigma(pp \rightarrow j + P(\rightarrow \chi \chi)) \approx 25\,\text{fb}$, if our standard signal cuts are applied. For the $2j + E_{T,\text{miss}}$ signal cross sections we find instead $\sigma(pp \rightarrow 2j + S(\rightarrow \chi \chi)) \approx 5\,\text{fb}$ and $\sigma(pp \rightarrow 2j + P(\rightarrow \chi \chi)) \approx 16\,\text{fb}$, respectively. At the 14 TeV LHC with an integrated luminosity of 300 fb$^{-1}$ one hence expects to see more than 1000 signal events, which should allow for a measurement of the $\Delta \phi_{j_1,j_2}$ distribution in the $2j + E_{T,\text{miss}}$ sample.

In Fig. 5 we show the normalised azimuthal angle distributions corresponding to our explicit DM models. We see that the strong cosine-like (sine-like) correlation between the two tagging jets in $2j + E_{T,\text{miss}}$ survives in the full theory with resonant scalar (pseudo-scalar) exchange. This shows that, unlike the mono-jet cross section, which depends strongly to the exact model realisation, the normalised $\Delta \phi_{j_1,j_2}$ distribution is rather insensitive to the precise structure of the underlying theory, and therefore provides a unique way to probe the anatomy of possible couplings between DM and top quarks.

As in the case of the EFT calculations, we also see from the latter figure that the $m_1 \rightarrow \infty$ approximations of the $\Delta \phi_{j_1,j_2}$ spectra describe the exact results reasonably well. We furthermore find that the heavy top-quark

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Normalised $\Delta \phi_{j_1,j_2}$ distributions arising from a full theory calculation. The used parameters are $g_{S,P}^{c,t} = 1$, $M_{S,P} = 500\,\text{GeV}$ and $m_c = 200\,\text{GeV}$ and the shown predictions correspond to our reference cuts. The meaning of the coloured curves is analogue to the one in Fig. 2.}
\end{figure}

\footnote{We recall that the dominant SM backgrounds due to $pp \rightarrow j + Z(\rightarrow \ell \ell \nu\nu)$ and $pp \rightarrow 2j + Z(\rightarrow \ell \ell \nu\nu)$ have cross sections of 1289 fb and 330 fb, respectively.}
mass limit describes the total $2j + E_{T,\text{miss}}$ cross sections much better in the full theory than in the EFT framework. Numerically, we obtain for the standard cuts that the ratio of EFT to exact cross sections is around 1.4 for both scalar and pseudo-scalar interactions. The observed feature is explained by the fact that in the full theory the $\sigma(pp \rightarrow 2j + E_{T,\text{miss}})$ cross section is dominated by invariant masses $m_{\chi\chi}$ close to $M_S \rho$, while in the EFT calculation the momentum transfer to the DM pair can be (and is on average) much larger. The quality of the heavy top-quark mass approximation however degrades rapidly with the amount of off-shellness [4], which explains why for the total cross sections the $m_t \rightarrow \infty$ limit works fairly well in the case of the simplified model, while it fails badly in the EFT approach.

V. CONCLUSIONS

While mono-jet searches provide already stringent constraints on the pair-production cross sections of DM and may lead to a future discovery at the LHC, even the observation of an unambiguous $j + E_{T,\text{miss}}$ signal will not be enough to determine details of the nature of DM such as the mass of the DM candidate or the structure of its couplings to quarks and gluons. This is due to the fact that while the $p_T$ spectrum of the signal is somewhat harder than that of the background, the enhancement of the high-$p_T$ tail is fairly universal, in the sense that it is independent of the type of interactions that lead to the $j + E_{T,\text{miss}}$ events.

In this letter we have pointed out that some of the limitations of the LHC DM searches can be overcome by studying the jet-jet azimuthal angle difference in final states with two jets and a large amount of missing transverse energy. We showed in particular that if the $2j + E_{T,\text{miss}}$ signal arises from Feynman diagrams involving top-quark loops, measurements of the normalised $\Delta\phi_{j_1,j_2}$ distribution would provide a powerful handle to disentangle whether the DM top-quark interactions are of scalar or pseudo-scalar type. In contrast to the prediction of the mono-jet cross section that is highly model-dependent, we emphasised that the strong angular correlation between the two tagging jets is present irrespective of whether the calculation is performed in an EFT or in a simplified DM model with scalar and pseudo-scalar exchange in the $s$-channel. This feature combined with the stability of the suggested observable under QCD corrections, makes $1/\alpha (pp \rightarrow 2j + \chi\chi) / d\Delta\phi_{j_1,j_2}$ a gold-plated observable to determine the Lorentz structure of the DM top-quark couplings and/or to test the CP properties of the associated mediators.

The method outlined in our work is more general as, after a DM discovery through a $j + E_{T,\text{miss}}$ signal at the LHC, it can in principle be used to tell apart whether DM pair production proceeds dominantly via tree or loop graphs. Only in the latter case, measurements of the azimuthal angle difference in $2j + E_{T,\text{miss}}$ events can potentially show a strong cosine-like or sine-like modulation, while tree-level exchange of spin-0 and spin-1 mediators will lead to a distribution with a rather different $\Delta\phi_{j_1,j_2}$ dependence. In the case of discovery, it is hence imperative that ATLAS and CMS study the differential distributions of final states beyond $j + E_{T,\text{miss}}$.

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