PROCEEDINGS OF SCIENCE

Searching for Dark Matter in top quark production with the CMS experiment

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A search for Dark Matter (DM) produced in association with a top quark pair using 137fb^{-1} of 13 TeV pp collision data collected with the CMS experiment at the Large Hadron Collider is presented. No excess was observed, and limits were set on the nominal cross-section for scalar mediators up to 420 GeV, and pseudoscalar mediators up to 400 GeV. Further improvements for an in-progress analysis which also targets DM produced in association with a single top quark are also shown, including the use of neural networks to improve the sensitivity.

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1. Motivation

Astronomical observations show a large difference between the total amount of matter in the universe, inferred from gravitation effects, and the amount of visible matter. Cosmological models suggest this "Dark Matter" (DM) may couple to ordinary matter via a mediator with mass of order 1 TeV (the thermal freeze-out model), and may therefore be produced in 13 TeV collisions at the Large Hadron Collider (LHC).

One such possible candidate is fermionic DM (χ) which couples to the SM via a scalar (ϕ) or pseudoscalar (A) mediator with a yukawa coupling. The lagrangians for this model are [1]:

$$\mathcal{L}_\phi \supset -g_\chi \phi \bar{\chi}\chi - \frac{\phi}{2} \sum_{q=u,d,s,c,b,t} g_q y_q \bar{q} q - \frac{1}{2} m_\phi{}^2 |\phi|^2 - m_\chi |\chi|^2$$

$$\mathcal{L}_A \supset -g_\chi A \bar{\chi}\gamma_5 \chi - \frac{A}{2} \sum_{q=u,d,s,c,b,t} g_q y_q \bar{q} \gamma_5 q - \frac{1}{2} m_A{}^2 |A|^2 - m_\chi |\chi|^2$$

Where the coloured terms represent the free parameters of the model. Such a mediator will naturally couple most strongly to top quarks, since these are the heaviest particles in the SM, and hence would be produced at the LHC in association with a pair of top quarks ($t\bar{t}$+DM), as shown in figure 1. This signature is very similar to pair production of supersymmetric stop squarks which decay to top quarks plus an undetectable neutralino, and the results presented here come from a set of searches designed to target these signatures [3].

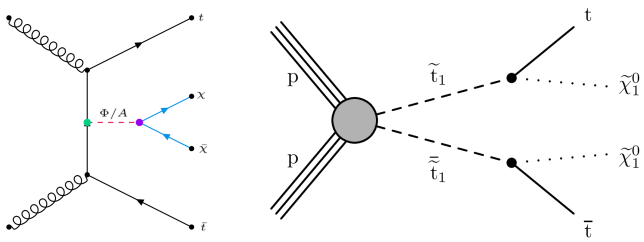

Figure 1: Feynmann diagrams for $t\bar{t}$+DM production (left) and production of a stop squark pair (right).

2. Analysis Strategy

A search was performed for this DM signature using the CMS experiment at the LHC [2]. The search was divided into all-hadronic (AH) [4], semileptonic (SL) [4] and dileptonic (DL) [6] channels, depending on whether the top quark decays included 0, 1 or 2 leptons, respectively.

Since the DM particles cannot be detected, this process is expected to have a large amount of missing transverse momentum (p_t^{miss}), which is the magnitude of the negative vector sum of the transverse momenta of all visible particles, which is, by conservation of momentum, equal to the momenta of the invisible particles. Additionally, imposing cuts requiring decay products consistent with a top decay can help to suppress non-$t\bar{t}$ SM backgrounds. In the SL and AH channels a categorisation is then performed on various kinematic variables intended to suppress the SM $t\bar{t}$ background. A plot of p_t^{miss} in one of the most sensitive region is shown in figure 2. In the DL channel, p_t^{miss} has less discriminating power since the SM $t\bar{t}$ process contains two neutrinos, which also contribute to p_t^{miss}. Therefore a fit is performed on:

$$M_{T2}(ll) = \min_{q_1+q_2=p_t^{miss}} [\max(m_T(p_{l1}, q_1), m_T(p_{l2}, q_2))] \tag{1}$$

This variable is designed to have a kinematic endpoint at the W boson mass for the SM $t\bar{t}$ process, but not for the $t\bar{t}$+DM process as the DM provides an additional source of p_t^{miss}, as can be seen in figure 2.

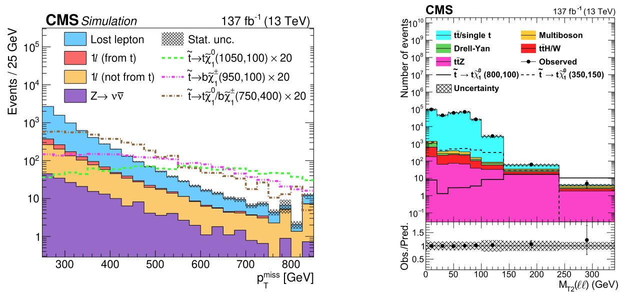

Figure 2: Left: p_t^{miss} distribution in the SL channel. Right: $M_{T2}(ll)$ distribution in the DL channel

3. Results

No excess was observed in the fit compared to the expected SM backgrounds, so exclusion limits were set on the cross-section, as shown in figure 3. Since the couplings of the mediators do not affect the kinematics but only the cross-section, these were set to $g_q = g_\chi = 1$. Similarly the mass of the DM was set to $m_\chi = 1$GeV, since the DM mass has very little impact on kinematics for $m_\chi < m_{\phi/A}/2$, while for $m_\chi > m_{\phi/A}/2$ the mediator becomes off-shell, dramatically reducing the cross-section to the point that there is no sensitivity.

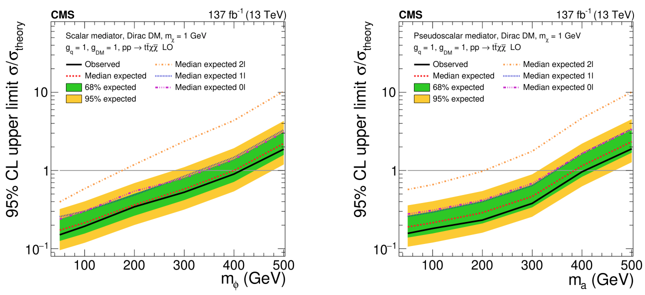

Figure 3: Limits on the crossection of the $t\bar{t}$+DM process for various masses of the scalar (left) and pseudoscalar (right) mediators

4. Future Plans

4.1 Single top + DM

DM can also be produced in association with a single top quark, with the dominant mechanisms being either t-channel production or production of a top quark and a W boson (tW + DM), and a DM mediator emitted from one of the top quark lines. For lower mediator masses, the single top + DM cross-sections are much lower than for $t\bar{t}$ + DM, however the single top + DM cross-section falls more slowly as function of mediator mass, becoming comparable with the $t\bar{t}$ + DM cross-section for a 500 GeV mediator (see [7]). Therefore relaxing some selection cuts to also target these signatures can dramatically improve the sensitivity of the analysis. The t-channel process also includes a quark which is typically emitted in a forward direction, so introducing a categorisation on the number of forward jets can further improve sensitivity.

4.2 Neural Networks

The dilepton channel usually gives the weakest limits of all the channels due to the low branching ratio, and the large SM $t\bar{t}$ background. However this channel does have the advantage of a fairly "clean" final state, which gives access to more information, for example:

- Spin correlation observables: since top quarks decay before they can hadronise, their spin information is transferred to their decay products, and hence top spin correlations can be inferred from the angle between the leptons (in the rest frame of their parent tops). The emission of DM alters the spin correlations of the tops, especially for the pseudoscalar mediator, which flips the spin of the top quark from which it is emitted.

- Single top observables: certain observables, such as $\Delta\phi(llb, p_t^{miss})$ differentiate single top processes from $t\bar{t}$. Since $t\bar{t}$ is also the dominant background in regions targetting the single top + DM signal, these can help to differentiate this signal from the dominant background.

- "Dark" p_t: since the DM provides an additional source of p_t^{miss}, it is possible that one cannot assign all of the p_t^{miss} to the neutrinos when attempting to reconstruct the $t\bar{t}$ system. The kinematic reconstruction algorithm [8] used allows for this, and the remaining unassigned p_t^{miss} is expected to be higher for the signal compared to the SM $t\bar{t}$ background.

It has been shown in a previous work [9] that training a neural network on such variables, in addition to $M_{T2}(ll)$ and p_t^{miss}, can provide a significant improvement in the limits.

References

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