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Dark matter models coupled to the top quark and discovery potential at LHC

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Abstract

This document presents different dark matter models that couple to the top quark, leading to monotop and same sign top pair production. The main ingredients of each models will be described, as well as the different assumptions and simplifications needed to derive a well defined collider phenomenology. The search strategy and the discovery potential at the LHC will be also discussed for each of these models.

Contents

1. Motivations and models description

In this note, we want to describe the phenomenology of dark matter models involving a strong coupling to the top quark. These models can be classified according to their experimental signatures. Assuming the Standard Model (SM) flavour scheme, the models essentially lead to $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ final state and are described in a separated document. Since we do not know the flavour structure of the dark sector, it is also interesting to relax this constraint and consider a different experimental signatures: monotop final state ($t + E_{\mathrm{T}}^{\mathrm{miss}}$) and a prompt production of two top quarks having the same electric charge (tt)[1]. These two final states are forbidden at the leading order in the Standard Model and become thus a good area to search for any new physics, and in particular dark matter.

1.1. Model structure

As usual, a dark matter candidate χ and a mediator M (vectorial or scalar) are added to the Standard Model to describe the dark sector and its interaction with the Standard Model particles. The full details of the various models are described in [1] but the basics ingredients are the following:

1. the theory is effective and respects the $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ symmetry,
2. the mediator strongly couples to the top quark,
3. the top quark is *singly* produced in association with a new particle X_{new} (dark matter or mediator),

There are two classes of models based on the monotop production mode: resonant and non-resonant production, as shown in Fig. 1. The sections 1.1.1 and 1.1.2 describe the phenomenology leading to such production mechanisms.

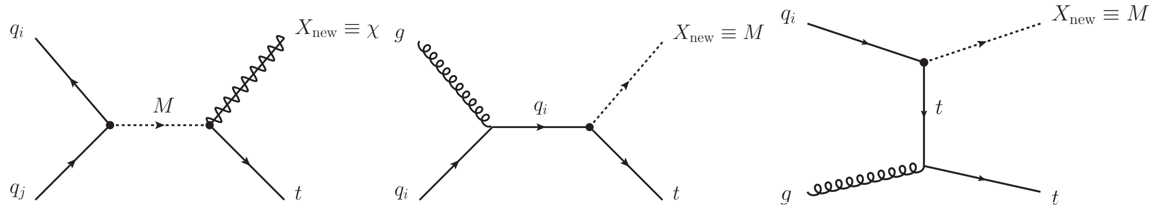

Figure 1: Feynman diagram of leading order processes leading to monotop events: resonant production of t via resonant mediator M decaying into a top quark and X_{new}, which is the dark matter fermion χ (left), and s and t channel non-resonant production of a top quark in association with X_{new}, which is the mediator M (middle and right).

1.1.1. Resonant production

In this case, the mediator M is a couloured charged scalar $\phi^{\pm}$ decaying into a top quark and a spin-1/2 invisible particle, χ (X_{new} is then the dark matter candidate χ). The dynamics of the new sector is then described by the following lagrangian:

$$\mathcal{L}_{\mathrm{int}} = u_i^C \left[\left(g_{ud}^v\right)^{ij} + \left(g_{ud}^a\right)^{ij} \gamma^5 \right] d_j \, \phi^{\pm} + u_k^C \left[\left(g_{u\chi}^v\right)^k + \left(g_{u\chi}^a\right)^k \gamma^5 \right] \chi \tag{1}$$

[1] For simplicity, the notation tt is used to describe both tt and $\overline{tt}$

where the index v (a) stands for vectorial (axial), C means charge conjugate and i, j, k run over the generations (color indices involved in the $\phi^{\pm}$−quarks interaction are not explicitely written). The first term leads to the production of the mediator and the last term allows its decay into a *up* quark and a non interacting fermion (in particular to the top quark when $\left(g_{u\chi}^{v/a}\right)^k$ is sizable mainly for $k = 3$). This model is then described by the masses of the mediator m_ϕ and the invisible fermion m_χ, and the coupling $\left(g_{ud}^{v/a}\right)^{ij}$ and $\left(g_{u\chi}^{v/a}\right)^k$.

1.1.2. Non-resonant production

For the non-resonant production, the top quark is produced in association with the mediator (X_{new} is then the mediator and not the dark matter candidate). They are two possibilities depending on the nature of the mediator.

First, the mediator can be a scalar field interacting with the SM field and the dark matter candidate as described in this lagrangian:

$$\mathcal{L}_{\text{int}} = u_i^C \left[\left(g_{\phi u}^v\right)^{ij} + \left(g_{\phi u}^a\right)^{ij} \gamma^5\right] u_j \, \phi + \chi^C \left[g_{\phi\chi}^v + g_{\phi\chi}^a \gamma^5\right] \chi \, \phi \tag{2}$$

where the index v (a) stands for vectorial (axial), C means charge conjugate and i, j, k run over the generations. The first term describe the interaction between the mediator and the *up* quarks while the second term leads to the decay the mediator into invisible fermions. In this model, there is necessarily a mixing between ϕ and the Higgs boson field. Additional parameters are then required to describe this new sector. Indeed, on top of the mediator mass and couplings, the mixing matrix of the two scalar field is needed in order to make predictions. For the sake of simplicity, we do not consider this case was the parameters space would be too large.

Another possibility is to consider a vectorial field as mediator with the following dynamics:

$$\mathcal{L}_{\text{int}} = \bar{u}_i \left[\left(g_{Vu}^v\right)^{ij} \gamma^\mu + \left(g_{Vu}^a\right)^{ij} \gamma^5\right] u_j \, V_\mu + \bar{\chi} \left[g_{Vu}^v \gamma^\mu + g_{V\chi}^a \gamma^5\right] \chi \, V_\mu \tag{3}$$

where the index v (a) stands for vectorial (axial) and i, j, k run over the generations. The first term describe the interaction between the mediator and the *up* quarks while the second term leads to the decay the mediator into invisible fermions. The new sector can be defined with the couplings $\left(g_{Vu}^{v/a}\right)^{ij}$, $g_{V\chi}^{a/v}$ and the masses m_V and m_χ. This model can be probed by two experimental signatures depending on the exact scenario: monotop and same-sign top quark production.

Question for theorists: why it cannot mix with Z in case of vectorial mediator ?

1.2. Simplifications

The lagrangians (1) and (3) contains too many degrees of freedom, which makes the LHC phenomenology difficult to predict. In addition, only a certain region of the parameter space can actually be probed with a monotop final state. For these reasons, further simplifications are performed in particular in term of flavour and chiral structure of the model. These simplifications leads to some limitations in the way ATLAS and CMS can constrain the model parameter space and these limitations are also qualitatively discussed below.

1.2.1. Flavour structure

The flavour structure is simplified in order to have a reasonable signal production rate in proton-proton collisions. In case of a scalar mediator, it has to be sufficiently produced so it has to couple with proton content, namely lightest quark which are allowed in equation (1). The monotop final state is sensitive to scenario where ϕ strongly couples to $t\chi$. Correct and/or complete with the monotop paper. In term of parameter space, it means that the monotop final state is not sensitive to some parameters like coupling between the mediator and heavy quarks or scenario in which $\mathrm{BR}(\phi \to t\chi) \ll 100\%$. For the latest, there is a way to recover the sensitivity looking at $u_i d_j \to \phi \to u_i d_j$. Since ϕ must be produced, it has to coupled to quarks and must decay in in the same final state. Experimentally, this would correspond to a di-jet resonance search.

The same kind of simplification is performed for the non-resonant production. The equation (3) is simplified in the parameter space where a monotop final state can be sufficiently produced to be detected at the LHC. The mediator V must be produced from light quark initial state, in a association with a top quark: this signature can mainly probe a high coupling $\left(g^{v/a}_{Vu}\right)^{13}_{Vu} \equiv g^{v/a}_{Vtu}$. Therefore, the sensitivity to other flavour couplings is significantly lower since V is less importantly produced. In addition, the mediator must decay into invisible particles to lead to the searched monotop final state. As a consequence, the sensitivity for scenario where $\mathrm{BR}(V \to \chi\chi) \ll 100\%$. To cope with this second limitation, a same-sign top quark final state $gu \to tV(\to t\bar{u})$ is proposed to cover the cases where V would decay into visible particles. This is case is more likely as the tV production rate increases, and becomes then a key point to constraint this model in a consistent way.

Questions for theorists:

- How well these flavour assumptions are allowed by the other HEP data (proton decay life time, flavour physics, etc ...) ?
- MFV criteria ?

1.2.2. Chiral structure

The main point here is to consider only right handed quark components in order to not simplify the phenomenology. In fact, the representation of the left-handed components under the $\mathrm{SU}(2)_L$ symmetry impose a couplings to *down*-type quarks, since the effective theory is invariant under $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ gauge symmetry). Having a coupling between the mediator and *down*-type quarks fairly complicates the collider phenomenology in term of decay mode. Typically, including the left-handed components of quarks in the lagrangian (3) describing the Vtu vertex would lead to

$$\mathcal{L}_{Vtu} = g^R_{Vtu}\, \bar{t}_R \gamma^\mu u_R\, V_\mu + g^L_{Vtu} \left(\bar{t}_L \gamma^\mu u_L + \bar{b}_L \gamma^\mu d_L\right) V_\mu \tag{4}$$

where $g^{R/L} \equiv 1/2\,(g^v \pm g^a)$ couples only to right-handed/left-handed components. The second term ensure the invariance under $\mathrm{SU}(2)_L$ rotations, and lead to an additional decay mode $V \to b\bar{d} + \bar{b}d$ (on top of $V \to t\bar{u} + \bar{t}u$ and $V \to \chi\chi$).

1.2.3. ATLAS and CMS simplifications

Just check what are the simplifications done in CMS monotop models

2. Collider signatures

As explained in Section 1, there are two types of models that can be constrained the following signatures at the Large Hadron Collider (LHC):

1. $t + E_{\mathrm{T}}^{\mathrm{miss}}$ final state (resonant and non-resonant production)
2. tt final state (non-resonant production)

These two productions are highly suppressed in the SM and makes these channels good candidates to search for new physics. In the current section, details about the global search strategy are given in each cases and the interplay between the two final state is described. Finally, some considerations on practical aspects are discussed, such as parameters scan or PDF and showering modeling for the signal generation.

2.1. Search strategy

2.1.1. $t + E_{\mathrm{T}}^{\mathrm{miss}}$ final state

The search performed during the LHC Run 1 with the ATLAS experiment for the production of single-top quarks in association with missing energy denoted as monotop is briefly described in this section, for more information see Ref. [2]. The search is based on the lepton+jets channel where the W boson coming from the top quark decays leptonically into an electron or a muon in association with a neutrino. The experimental signature of monotop events is given by one isolated charged lepton (electron or muon), large missing transverse energy, and one b-tagged jet as shown in Fig. 2.

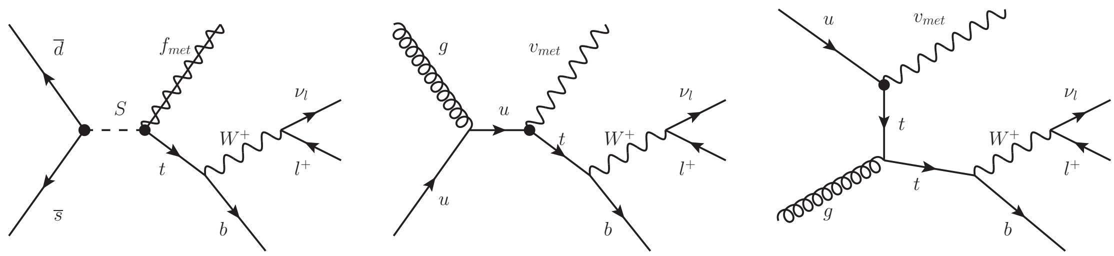

Figure 2: Feynman diagram of leading order processes leading to monotop events with a semi-leptonic topology: production of a coloured scalar resonance S decaying into a top quark and a spin-1/2 fermion f_{met} in the $\mathrm{S1_R}$ model, and s- and t-channel non resonant production of a top quark in association with a spin-1 boson v_{met} in the $\mathrm{S4_R}$ model.

The analysis strategy used in this search is based on a cut-and-count approach which is used to extract the monotop signal. The azimuthal angle difference between the charged lepton and the b-jet ($|\Delta\phi(l, b)|$) and low transverse W mass ($m_{\mathrm{T}}(W)$) are used to define the final signal regions:

- For the resonant case, the optimized signal region is $m_{\mathrm{T}}(W) > 210$ GeV and $|\Delta\phi(l, b)| < 1.2$ in addition to the signal region selection
- For the non-resonant case, the optimized signal region is $m_{\mathrm{T}}(W) > 250$ GeV and $|\Delta\phi(l, b)| < 1.4$ in addition to the signal region selection

The main background contributions to the signal regions is the top-antitop quark pair production ($t\bar{t}$) in particular dilepton $t\bar{t}$ events. The main systematic uncertainties are those related to the jet energy scale, the b-tagging efficiency, the effect of the choice of PDF on signal and background acceptance, the effect of the choice of MC generator and of additional radiation on $t\bar{t}$ modelling, and the effect of the limited size of the samples.

In the absence of deviation with respect to the SM predictions, this search gives upper limits on the production cross-section at 95% CL for two signal models, producing right-handed top quarks together with exotic objects giving rise to missing energy. In the case of the production of a 500 GeV spin-0 resonance, the excluded effective coupling is below a_R= 0.15, for a mass of the invisible spin-1/2 state between 0 and 100 GeV. In the case of non-resonant production, the a_R= 0.2 effective coupling is excluded for a mass of the invisible spin-1 state between 0 and 650 GeV.

The monotop search in the hadronic channel will be considered in Run 2.

2.1.2. tt final state

The main feature of this final state is to have a non-zero electric charge. In order to exploit this, this is essential to consider the events where both top quarks decay into leptons. The relevant final state probing this model is then $\ell^+\ell^+ + X$, where X depends on the exact process ($X = j + 2b$-jets for all diagrams of Figures 3 and 4 but the t-channel, $X = 2b$-jets for the t-channel of Figure 4). The cross-sections involving valence quarks are of are higher than the one involving see quarks. Thus, the positively charged top quark pairs are largely more produced.

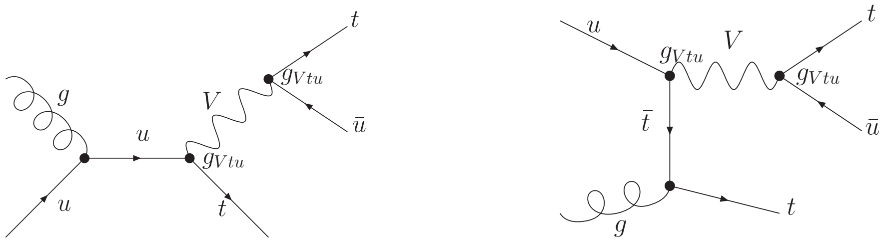

Figure 3: Feynman diagram of leading order processes leading to the $tt\bar{u}$ via the V production and its decay into $t\bar{u}$.

Figure 4: Feynman diagram of leading order processes leading to the $tt\bar{u}$ (left) and to the tt production (right), both via V exchange in the t-channel.

The typical background for this final state is mainly instrumental via a wrong charge reconstruction but can also be physical. Indeed, the $t\bar{t}V$ production can yield to a same-sign lepton pair together with b-jets. On the other hand, the $t\bar{t}$ production is large enough to make the charge mis-reconstruction rate relevant. Finally,"trident" electrons (photon radiation and conversion) can also contribute to this final state.

The Run 1 analysis exploiting the $\ell^+\ell^+ + b$−jets signature [3] is able to exclude a typical cross-section of 10 fb for a FCNC Higgs signal (similar to the tt production of Figure 4). Given the cross-sections of the described model, this final state is quite sensitive to a wide range of parameters.

There is one particular feature, not yet exploited, that can be used to extract the $tV(\to t\bar{u})$ production: the transverse momentum of the leading jet is quite high and will definitely help to disantangle the signal and the Standard Model backgrounds, further increasing the sensitivity of this channel. As a consequence, the results shown in section 2.1.3 are quite conservative.

2.1.3. Combination of tt and $t + E_{\mathrm{T}}^{\mathrm{miss}}$ analysis for the non-resonant production

The interesting point in combining the tt and $t + E_{\mathrm{T}}^{\mathrm{miss}}$ analysis is to cover invisible and the visible V decay simultaneously. The visible decay must be taken into account simply because V is produced from visible particles. More the production is large, more the visible decay should be relevant. In order to see the interplay, it is necessary to express the two constaints in the same parameter space.

Assuming that the phenomenology is fully described by σ_{tV}, σ_{tt}, $\sigma_{tt\bar{u}}^{\mathrm{virt}}$ and $\mathrm{BR}(V \to \chi\chi)$, the experimental cross-sections for each final state can be predicted:

$$\sigma_{t+E_{\mathrm{T}}^{\mathrm{miss}}} = \sigma_{tV} \times \mathrm{BR}(V \to \chi\chi) \tag{5}$$

$$\sigma_{tt+X} = \sigma_{tV} \times \frac{1 - \mathrm{BR}(V \to \chi\chi)}{2} + \sigma_{tt\bar{u}}^{\mathrm{virt}} + \sigma_{tt} \tag{6}$$

where σ_{tV} correspond to the 2 diagrams of Figure 3, $\sigma_{tt\bar{u}}^{\mathrm{virt}}$ (σ_{tt}) corresponds to the left (right) diagram of Figure 4.IMPORTANT COMMENT: this split is in principle not correct, but needed. Not correct because all $gu \to tt\bar{u}$ amplitudes must interfer. Needed because only the real production is scaled by $\mathrm{BR}(V \to \chi\chi)$, in which we are precisely interested. This needs to be further discussed with theorists. The factor 2 comes from the fact that $\mathrm{BR}(V \to t\bar{u}) = \mathrm{BR}(V \to \bar{t}u)$. In practice, the selection efficiency will be different for each process, since they have quite different topology. We neglect this aspect in this simplified discussion.

If we neglect the term $\sigma_{tt\bar{u}}^{\mathrm{virt}} + \sigma_{tt}$ in equation (5), it becomes easy to compute the excluded area in the plane $(\sigma_{tV}, \mathrm{BR}(V \to \chi\chi)$ by each of the channel. Considering the excluded cross-section in the monotop analysis ($\sigma_{t+E_{\mathrm{T}}^{\mathrm{miss}}}^{\mathrm{excl}}$) and in the same-sign top analysis ($\sigma_{tt+X}^{\mathrm{excl}}$), it comes:

$$\left(\sigma_{tV}^{\mathrm{excl}}\right)_{\mathrm{monotop}} > \frac{\sigma_{t+E_{\mathrm{T}}^{\mathrm{miss}}}^{\mathrm{excl}}}{\mathrm{BR}(V \to \chi\chi)} \tag{7}$$

$$\left(\sigma_{tV}^{\mathrm{excl}}\right)_{\mathrm{sstop}} > \frac{2 \times \sigma_{tt+X}^{\mathrm{excl}}}{1 - \mathrm{BR}(V \to \chi\chi)} \tag{8}$$

According to the monotop and same-sign top analysis performed durin the Run 1, the cross-sections limits for $m_V \sim 500$ GeV are:

$$\sigma^{\text{excl}}_{t+E_T^{\text{miss}}} \sim 250 \text{ fb} \quad (9)$$
$$\sigma^{\text{excl}}_{tt+X} \sim 10 \text{ fb} \quad (10)$$

By putting these numbers into equations (7), we obtain the excluded areas in the $(\sigma_{tV}, \text{BR}(V \to \chi\chi))$ plane for each analysis as shown in figure 5. The power of the same-sign signature offers a nice way to complete the monotop analysis for $\text{BR}(V \to \chi\chi) \lesssim 0.85$ and to exclude large part of the parameter space.

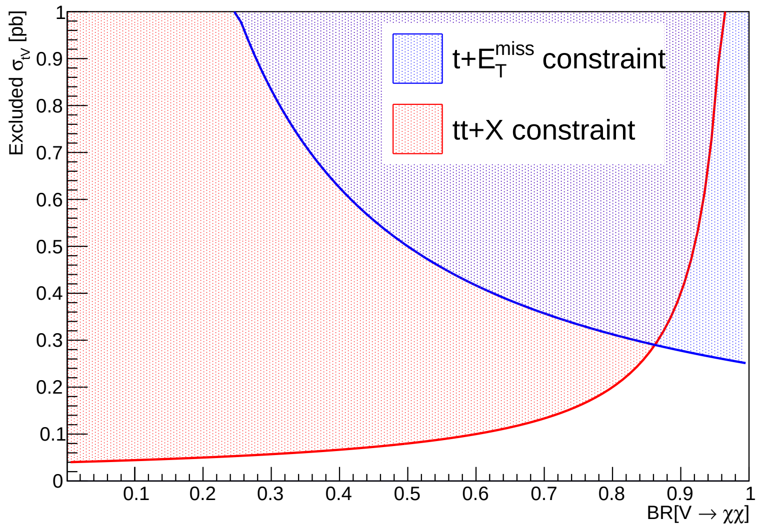

Figure 5: All cross-sections above the curves are excluded cross-section by the monotop analysis (blue) and the $\ell^+\ell^+$ (red) as a function of $\text{BR}(V \to \chi\chi)$. For $\text{BR}(V \to \chi\chi) \lesssim 0.85$, the monotop only excludes large cross-sections while the $\ell^+\ell^+$ takes over in order to recover some sensitivity.

In practice, equations (5) show that figure 5 underestimate the sensibility of the $tt + X$ analysis since the terms $\sigma^{\text{virt}}_{tt\bar{u}}$ and σ_{tt} were neglected. The additional sensitivity brought by these terms might depend on the event selection, due to the different event topology (for instance, leading jet softer). Also, the way to interpret the two analysis in the same parameter plane becomes less obvious when $\sigma^{\text{virt}}_{tt\bar{u}}$ and σ_{tt} are involved. In this case, the couplings g^R_{Vtu} and m_V might be a good option but this has to be properly defined Need discussion with theorists.

2.2. Relevant model parameters

Which parameters impact the kinematics (this is the only relevant aspect form the experimental point of view)? Some studies would be nice to put in this documents about:

- mediator mass
- mediator width → no effect (or parametrizable effects, plots are ready and need to be included)

- **which parameters** impact our experimental sensitivity? Which plane should be scanned?

What are the relevant numerical range to explore? First guess would be to follow the mono-top analysis.

2.3. Practical implementation

From a practial point of view, the simulation of these processes can be done with MadGraph [ref], using the monotop model [ref]. Currently, this model doesn't contain the full set of parameters (coupling to dark matter is missing for the non-resonant vectorial mediator) but remains operational to generate the relevant signals. Concerning the soft physics modeling (PDFs and showering), we propose to use MSTW2008 and Pythia for the central values.

Question for DM forum:

- Do we want to give more details about the Madgraph implementation, the couplings value in the param_card, etc ... ?
- I am not aware of any work on systematic variation due to scale, PDF choice, showering (Maybe some was done in the monotop analysis?). Then I am not completely what to put here.

References

[1] I. Boucheneb et al., *Revisiting monotop production at the LHC* (2014), arXiv: 1407.7529 [hep-ph].

[2] *Search for a single-top quark produced in association with missing energy in proton-proton collisions at* $\sqrt{s} = 8$ TeV *with the ATLAS detector*, Eur. Phys. J. C **75:79** (2015), arXiv: 1410.5404 [hep-ex].

[3] *Analysis of events with b-jets and two leptons of the same charge or three leptons in pp collisions at* $\sqrt{s} = 8$ *TeV with the ATLAS detector* ().

Appendix

A. Cross-sections

B. Mediator width effects

C. Hadron level kinematic distributions