Search for the production of dark matter in association with top-quark pairs in the single-lepton final state in proton-proton collisions at $\sqrt{s} = 8$ TeV (CMS)

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Summary
Introduction

- Dark Matter (DM) is estimated to account for about 24% of the total mass of the universe
- Five times more abundant than the known baryonic matter
Assume DM has a particle explanation

There is only one new Dirac fermion which is related to DM within LHC energy reach

Fermions interact with quarks via a four-fermion contact interaction, this is described by a EFT Lagrangian

\[ L_{int} = \sum_q \sum_i C_{qi} (\bar{q} \Gamma_i^q q) (\bar{\chi} \Gamma_i^\chi \chi) \] (1)
Introduction

- Exclusion limit for a scalar interaction between DM particles and scalar is the most relaxed of all the interaction types probed so far
- In this interaction the coupling strength is proportional to the mass of the quark:
  \[ L_{int} = \frac{m_q}{M_\chi^3} \bar{q}q\bar{\chi}\chi \] (2)
- Coupling to light quarks $\rightarrow$ suppressed
- Sensitivity to scalar interaction can be improved by searching in final states with third-generation quarks
Objective

- This paper reports on the search of the production of DM particles in association a pair of top quarks
- Consider the scalar interaction only
- Focus on the events with one lepton (electron or muon) in the final state

Figure 1: Dominant diagram contributing to the production of DM particles in association with top quarks at the LHC.
CMS Detector

- Silicon Tracker
- Electromagnetic Calorimeter
- Hadron Calorimeter
- Superconducting Solenoid
- Iron return yoke interspersed with muon chambers

Legend:
- Blue: Muon
- Red: Electron
- Green: Charged hadron (e.g. pion)
- Green dashed: Neutral hadron (e.g. neutron)
- Dotted: Photon
Data and simulated samples: Data

- Data used in this search was recorded with the CMS detector at the LHC with a $\sqrt{s} = 8$ TeV

- Integrated Luminosity corresponds to $19.7 \text{ fb}^{-1}$

- Data was collected using single-electron and single-muon triggers, with the $P_T$ thresholds of 27 and 24 GeV respectively

- Efficiencies of the triggers of the data and the simulation are compared and the correction factors are applied to the simulation
Data and simulated samples: Simulation

- DM signal is generated with MADGRAPH v5.1.5.11
- Dominant standard model (SM) background processes for this search are:
  - $t\bar{t}$+jets
  - $t\bar{t} + \gamma/W/Z$
  - single top quark
  - diboson (WW, WZ, and ZZ)
  - Drell-Yan events
- All these backgrounds, except single top quark and WW events, are generated with MADGRAPH
- Single top quark processes are generated with NLO generator POWHEG v1.0 & WW background are generated with PYTHIA v6.242
- All events are:
  - matched to the PYTHIA parton shower description.
  - passed through detailed simulation of CMS detector based on GEANT4 v9.4
A particle-flow (PF) based event reconstruction is used by CMS, takes into account information from all the subdetectors. All particles in the events are classified into mutually exclusive categories: electrons, muons, photons, charged and neutral hadrons. Electrons (Muons) are selected if they satisfy $P_T > 30$ GeV ($P_T > 30$ GeV) and $|\eta| < 2.5$ ($|\eta| < 2.1$). Jets clustered using anti-$k_t$ algorithm and Jet candidates required to have $P_T > 30$ GeV and $|\eta| < 4.0$. $E_T^{\text{miss}}$ is measured as magnitude of the vectorial $P_T$ sum of all PF candidates, takes into account the jet energy corrections.
Event selection: preselection cut

- In semileptonic $t\bar{t}$ decays, two b quarks and two light quarks are produced (four jets produced, $N_j = 4$)
- Search sensitivity is in fact better by 10% for $N_j \geq 3$ than $N_j \geq 4$
- Require at least one b-tagged jet in the event and only one identified isolated lepton
Event selection: preselection cut

- Signal normally has larger $E_T^{miss}$ than the backgrounds because of the two DM particles
- Events required to have $E_T^{miss} > 160$ GeV
- The cuts discussed so far are called the preselection cut
Event selection: final selection

- After preselection, the main backgrounds are $t\bar{t}$ and $W+$ jets
- QCD multijet background cut greatly due to preselection cut

To improve search sensitivity:

- $E_T^{\text{miss}} > 320$ GeV
- $M_T > 160$ GeV, where for background $M_T < M_W$ and for signal $M_T > M_W$
- $M_{T2}^W > 200$ GeV
- In addition, jets and $\vec{p}_T^{\text{miss}}$ are usually more separated in $\phi$ in signal events than in $t\bar{t}$ background, therefore a min $\Delta\phi(j_{1,2}, \vec{p}_T^{\text{miss}}) > 1.2$
- All of the above selection cuts are optimized based on expected significance for DM masses between 1 and 1000 GeV
Event selection

- Distributions of $E_T^{\text{miss}}$, $M_T$, $M_W^T$ and $\min \Delta \phi(j_{1,2}, \vec{p}_T^{\text{miss}})$
- Distributions after applying all other selections, this is so that we can see power of discrimination.
- In distributions, the $t\bar{t} + \text{jets}$ and $W + \text{jets}$ backgrounds have been adjusted by Scale Factors (SF)
Background Estimation

- Two control regions (CR) defined to extract these SF
- CR1 is the preselection cuts with the additional requirement of $M_T > 160$ GeV (SF applied in figure)
- Dominated by $t\bar{t}$ jets background
Background Estimation

- Two control regions (CR) defined to extract these SF
- CR2 is the same as CR1 except there is no b-tag requirement (SF applied in figure)
- Increase amount of $W+\text{jets}$ events.
Background Estimation: Conclusion

- The subdominant backgrounds are subtracted from data distributions and obtain a sample which only has $t\bar{t} + \text{jets}$ and $W + \text{jets}$ background contributions.

- The $t\bar{t} + \text{jets}$ and $W + \text{jets}$ SFs are obtained by matching the data from the $M_T$ distributions in CR1 and $E_T^{\text{miss}}$ distributions in CR2.

- The SF for $t\bar{t} + \text{jets}$ and $W + \text{jets}$ are $1.11 \pm 0.02(\text{stat})$ and $1.26 \pm 0.06(\text{stat})$ respectively.
Systematic Uncertainties

- Main systematic uncertainties sources are the normalization uncertainty of other background in deriving the SF and the CR tests.
- Other uncertainties include the Jet energy scale & resolution and the b-tagging correction factors.

Table 1: Systematic uncertainties from various sources and their impact on the total background prediction.

<table>
<thead>
<tr>
<th>Source of systematic uncertainties</th>
<th>Relative uncertainty on total background (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% normalization uncert. of other bkg in deriving SFs</td>
<td>10</td>
</tr>
<tr>
<td>SF_{W+jets} (CR tests)</td>
<td>13</td>
</tr>
<tr>
<td>\text{t}\bar{t}+jets top-quark $p_T$ reweighting</td>
<td>3.9</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>4.0</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>3.0</td>
</tr>
<tr>
<td>b-tagging correction factor (heavy flavour)</td>
<td>1.0</td>
</tr>
<tr>
<td>b-tagging correction factor (light flavour)</td>
<td>1.8</td>
</tr>
<tr>
<td>Pileup model</td>
<td>2.0</td>
</tr>
<tr>
<td>PDF</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Results: Number of Expected Events

- Data agrees with our background within the uncertainties

Table 2: Expected number of background events in the SR, expected number of signal events for a DM particle with the mass $M_\chi = 1$ GeV, assuming an interaction scale $M_* = 100$ GeV, and observed data. The statistical and systematic uncertainties are given on the expected yields.

<table>
<thead>
<tr>
<th>Source</th>
<th>Yield ($\pm$stat $\pm$syst)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt</td>
<td>8.2 $\pm$ 0.6 $\pm$ 1.9</td>
</tr>
<tr>
<td>W</td>
<td>5.2 $\pm$ 1.8 $\pm$ 2.1</td>
</tr>
<tr>
<td>Single top</td>
<td>2.3 $\pm$ 1.1 $\pm$ 1.1</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.5 $\pm$ 0.2 $\pm$ 0.2</td>
</tr>
<tr>
<td>Drell–Yan</td>
<td>0.3 $\pm$ 0.3 $\pm$ 0.1</td>
</tr>
<tr>
<td>Total Bkg</td>
<td>16.4 $\pm$ 2.2 $\pm$ 2.9</td>
</tr>
<tr>
<td>Data</td>
<td>18</td>
</tr>
</tbody>
</table>
Results: Cross section limits

- Obtain the signal efficiencies for various masses of $M_\chi$ and also the upper limit of the cross section at a 90 CL interval which range from 20 to 55 fb

Table 3: Expected number of signal events in SR assuming an interaction scale $M_\star = 100$ GeV, signal efficiencies, and observed and expected limits at 90% CL on production cross sections for $pp \rightarrow tt + \chi\bar{\chi}$, for various DM particle masses.

<table>
<thead>
<tr>
<th>$M_\chi$ (GeV)</th>
<th>Yield ($\pm$stat $\pm$syst)</th>
<th>Signal efficiency (%) ($\pm$stat $\pm$syst)</th>
<th>$\sigma_{\exp}^{\lim}$ (fb)</th>
<th>$\sigma_{\obs}^{\lim}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$38.3 \pm 0.7 \pm 2.1$</td>
<td>$1.01 \pm 0.02 \pm 0.05$</td>
<td>$47^{+21}_{-13}$</td>
<td>55</td>
</tr>
<tr>
<td>10</td>
<td>$37.8 \pm 0.7 \pm 2.1$</td>
<td>$1.01 \pm 0.02 \pm 0.05$</td>
<td>$46^{+21}_{-13}$</td>
<td>54</td>
</tr>
<tr>
<td>50</td>
<td>$35.1 \pm 0.6 \pm 1.9$</td>
<td>$1.20 \pm 0.02 \pm 0.06$</td>
<td>$39^{+18}_{-11}$</td>
<td>45</td>
</tr>
<tr>
<td>100</td>
<td>$30.1 \pm 0.4 \pm 1.7$</td>
<td>$1.46 \pm 0.02 \pm 0.07$</td>
<td>$32^{+14}_{-9}$</td>
<td>37</td>
</tr>
<tr>
<td>200</td>
<td>$18.0 \pm 0.2 \pm 1.0$</td>
<td>$1.73 \pm 0.02 \pm 0.08$</td>
<td>$27^{+12}_{-8}$</td>
<td>32</td>
</tr>
<tr>
<td>600</td>
<td>$1.26 \pm 0.02 \pm 0.07$</td>
<td>$2.40 \pm 0.03 \pm 0.11$</td>
<td>$19^{+9}_{-6}$</td>
<td>23</td>
</tr>
<tr>
<td>1000</td>
<td>$0.062 \pm 0.001 \pm 0.003$</td>
<td>$2.76 \pm 0.04 \pm 0.13$</td>
<td>$17^{+8}_{-5}$</td>
<td>20</td>
</tr>
</tbody>
</table>
Results: Limitations of EFT

- The EFT approximation is only valid when momentum transfer is small compared to the mediator mass.
- The couplings should not exceed the perturbative limit.
- Both conditions depend on the details of the new physics approximated by EFT.
Summary

- Search for production of dark matter particles in association with top quarks in single lepton events in the CMS detector at $\sqrt{s} = 8$ TeV.
- No excess of events above the SM expectation is found and place cross section upper limits.
- See in figure below that upper limits on cross section are more sensitive for masses below 6 GeV than the direct DM detectors (at 90 CL level).