Search for Dark Matter in final states with top quarks in CMS data

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on behalf of the CMS Collaboration
Introduction

- Why search for BSM with top quarks?
  - Decays provide many handles to reduce backgrounds
    - Lots of possibilities to try new techniques to exploit top quark decay and/or \( t\bar{t} \) system properties
- Large (additional) MET a signature of sign of dark matter production
- Associated production with top quarks is the most effective channel for several DM models
- Present CMS DM+\( \text{top(s)} \) results on the 2016 dataset
Mono-top

- Single top quark + MET production is rare in SM
- Two models for DM production[1]
  - via FCNC spin-1 mediator
  - via charged, color scalar mediator

Mono-top

- Large MET $\rightarrow$ boosted t-quark $\rightarrow$ jet substructure!
  - Jet grooming, subjet properties, 3-prong-ness
- Cambridge-Aachen jet clustering with $\Delta R = 1.5$
  - $p_T > 250$ GeV
  - $110$ GeV $< M_{\text{soft drop}} < 210$ GeV [2]
- Subjet b-tagging
- Top tagger using Boosted Decision Tree (BDT)
  - Compatibility of subjets with $m_W$ and $m_t$ via HEPTopTaggerV2 [3]
  - N-subjet-tiness $\tau_3/\tau_2$ [4]
  - Energy Correlation Functions [5,6]

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Mono-top

- **Signal Region:**
  - 1 top-tag and categorize by low and high BDT scores
  - MET > 250 GeV
  - Veto on electron, muon, tau, photon objects
  - $\Delta R(MET, AK4) > 0.5$ for any AK4 jet

- **Control regions:**
  - Dimuon, dielectron, photon $\rightarrow Z(\nu\nu)+$jets
  - Single muon, electron + b-tag $\rightarrow t\bar{t}(1l)$
  - Single muon, electron with no b-tag $\rightarrow W(l\nu)+$jets, $Z(\nu\nu)+$jets

- Simultaneous fit of SR and CRs
Mono-top

- Result on 36 fb\(^{-1}\) collected in 2016
  - FCNC model: \(m_V\) exclusion up to 1.75 TeV
  - Scalar model: \(m_\phi\) exclusion up to 3.5 TeV

CMS-EXO-16-051
Mono-top

- Result on 36 fb$^{-1}$ collected in 2016
  - FCNC model: $m_V$ exclusion up to 1.75 TeV
  - Scalar model: $m_\phi$ exclusion up to 3.5 TeV
- For FCNC model, constraints on couplings between mediator with SM / DM sectors also computed

Limits on coupling of mediator to SM
• Spin-0 mediators with Yukawa couplings to SM particles provide most compelling models for $\bar{t}t+$MET final state
  • Mono-jet production is loop suppressed
  • Pseudoscalar is velocity suppressed for direct detection experiments
• Scalar and Pseudoscalar models developed in LHC Dark Matter Forum[7] (collaboration of ATLAS, CMS, and theory communities)

**tt+DM: Dileptonic**

- Designed for stop pair search, but still good sensitivity to $\bar{t}t+\text{DM}$
- **Selection:**
  - $ee$, $e\mu$, $\mu\mu$ final states
  - At least 2 jets with a least one b-tagged
  - $m_{ll} > 20$ GeV
  - $|m_{ll} - m_Z| > 15$ GeV for $ee$, $\mu\mu$
  - MET $> 80$ GeV
  - MET significance $> 5$ GeV$^{1/2}$
  - $\cos\Delta\phi(\text{MET, jet}_1) < 0.8$
  - $\cos\Delta\phi(\text{MET, jet}_2) < 0.96$
- Events are binned in $M_{T2}(ll)$, $M_{T2}(l\mu l\mu)$, MET
- Control regions for: $t\bar{t}$/single $t$, $t\bar{t}Z$, DY and multiboson
tt+DM: Dileptonic

- Result on 36 fb$^{-1}$ collected in 2016
  - Scalar model: $m_\phi$ excluded up to 100 GeV
  - Pseudoscalar model: $m_a$ excluded up to 50 GeV
- Exclusion of scalar model benchmarks, not yet achieved in other MET+X final states
**tt+DM: Dileptonic**

- New result with several new techniques explored
- Benchmark against tt+DM MET-related variables only analysis
  - Much looser requirements on MET, $M_{T2}(ll)$, $M_{T2}(l\bar{l}b\bar{b})$ than SUS-17-001
  - Categorize events between $M_{T2}(ll) > 110$ GeV and $M_{T2}(ll) < 110$ GeV
- Signal extraction from fit of MET shape


- Construct dark-$p_T$
  - When $t\bar{t}(2l)$ kin-reco fails, relax assumption that MET comes only from neutrinos and allow a $3^{rd}$ contribution: dark-$p_T$
    - For signal, this estimates the mediator $p_T$

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NEW CMS-EXO-17-014

CMS-EXO-17-014

35.9 fb$^{-1}$ (13 TeV)

Events / 200 GeV

Data / Bkg

Data / Bkg

(reconstructed) mediator $p_T$ [GeV]

Data / Bkg
\( \tilde{t}\tilde{t}+\text{DM: Dileptonic} \)

- **Construct dark-\( p_T \)**
  - When \( t\bar{t}(2l) \) kin-reco fails, relax assumption that MET comes only from neutrinos and allow a 3rd contribution: **dark-\( p_T \)**
    - For signal, this estimates the mediator \( p_T \)
- **Construct Artificial Neural Network (ANN) discriminant for \( t\tilde{t}+\text{DM} \)**
  - \( \text{Dark-}p_T \)
  - MET-related variables: MET, \( M_{T2}(ll) \)
  - Angular variables: \( \Delta\phi(\text{MET}, ll) \)
- **Signal extraction from fit of ANN shape**
tt+DM: Dileptonic

- Construct BDT discriminant for tt+DM
  - Kin-reco probability to be consistent with tt(2l)
  - MET-related variables: MET, M_{T2}(ll), M_{T2}(l\bar{l}b\bar{b})
  - Angular variables: \Delta\varphi(MET, ll), \Delta\eta(ll), \cos\Phi_{ll}
    - Can additionally distinguish between scalar or pseudoscalar
- Much looser requirements on MET, M_{T2}(ll), M_{T2}(l\bar{l}b\bar{b}) than SUS-17-001
- Signal extraction from fit of BDT shape
• Signal normalization updated to NLO cross sections
• Result of BDT analysis on 36 fb\(^{-1}\) collected in 2016
  • Scalar model: \(m_\phi\) excluded up to 86 GeV
  • Pseudoscalar model: no observed exclusion
  • ~20% better than MET-shape strategy, ~10% better than ANN strategy
Summary and Outlook

- DM + top(s) is driving the sensitivity of several DM models
- Much of mediator mass phase space for benchmark models have been excluded, now to consider constraints on other parameters (i.e. couplings between DM and SM)
- Update to $t\bar{t}$+DM in all-hadronic and l+jets channels, as well as full combination of $t\bar{t}$+DM channels, are coming soon
- Further developments on various top tagging techniques on-going
- Models of spin-0 mediator that accounts for co-existence with BEH are available for future interpretations [8,9]

Backup
**tt+DM: All-hadronic**

- Top quark $p_T$ relatively soft in $t\bar{t}+\text{DM}$
- Top tagging on tri-jets
  - BDT discriminator
    - Fit probability from kinematic fitter
    - $q/g$ discriminator
    - b-tag discriminant
    - Pair-wise angular separation
- More details in **Boost 2016 conference talk**
- With large MET requirement, main background is $tt(1\ell)$
  - Ask for 2 top tags to reduce bkg
**tt+DM: All-hadronic**

- **Signal Region**
  - No leptons
  - 4 or more jets
  - MET > 200 GeV
  - Categorize on 2 top tags or <2 top tags
    - Require 1 b-tag or 2 b-tags
    - Min Δφ-(jet_i,MET) > 0.4 or 1.0

- **Control regions for tt(1l), W(lν)+jets, Z(νν)+jets**
  - tt(1l) CR: single lepton + b-tag(s) selection
  - W(lν)/Z(νν)+jets CR: no lepton, zero b-tag
  - W(lν)+jets CR: single lepton, zero b-tag
  - Z(ll)+jets CR: dilepton, zero b-tag

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**CMS-EXO-16-005**

![Graphs and data plots showing tt+DM: All-hadronic signal region and control regions.]
\[ \bar{t}t + \text{DM: lepton+jets} \]

- **Signal Region**
  - One muon (or electron), \( p_T > 30 \text{ GeV}, |\eta| > 2.4 \) (or 2.5)
  - 3 or more jets, at least one b-tagged
  - \( M_T > 160 \text{ GeV} \)
  - \( M_{T2}^W > 200 \text{ GeV} \)
  - \( \text{Min}_{i=1,2} \Delta \phi (\text{jet}_i, \text{MET}) > 1.2 \)
  - \( \text{MET} > 160 \text{ GeV} \)
- **Control regions for \( \bar{t}t(2\ell) \) and W+jets**
  - \( \bar{t}t(2\ell) \) CR: dilepton selection
  - W+jets CR: single lepton, zero b-tag