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 tt 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+top(s) results on the 2016 dataset
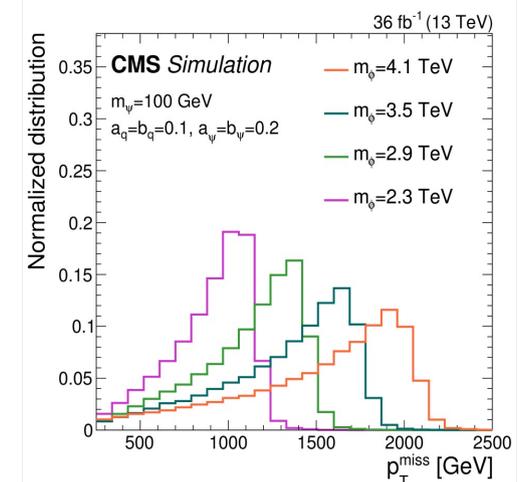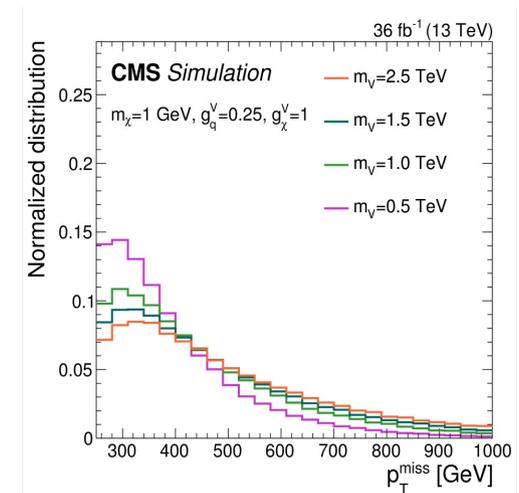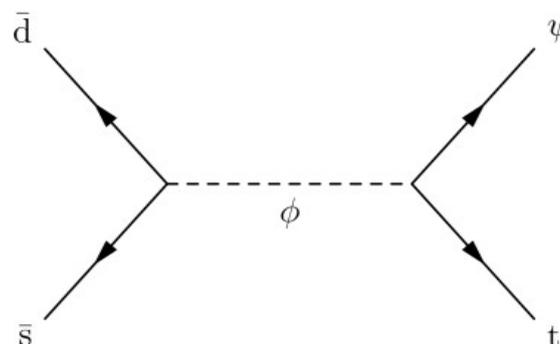
?

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

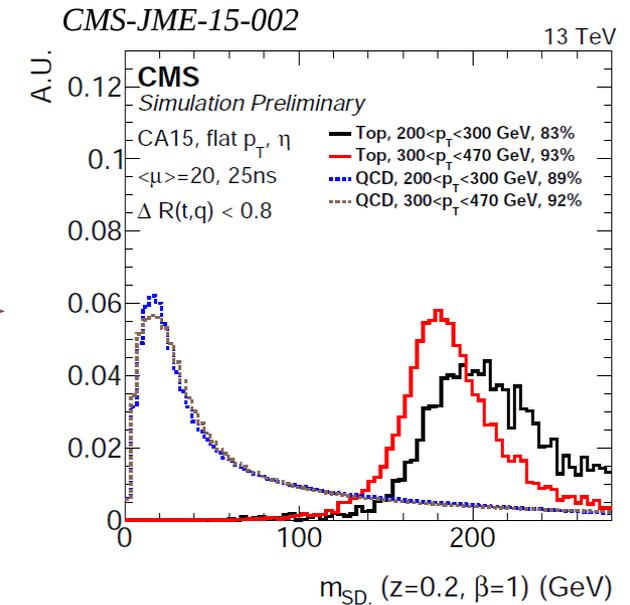FCNC spin-1 mediator
non-resonant production
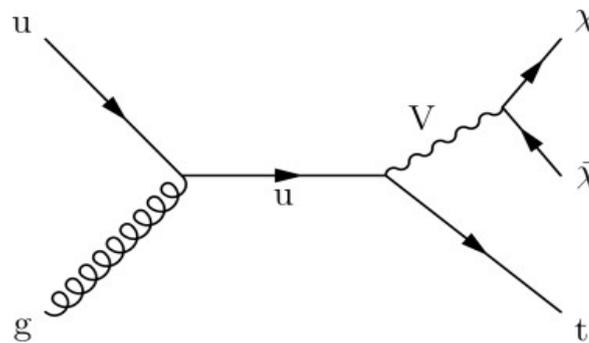
Charged, colored scalar
mediator resonant production

[1] Phys. Rev. D 84, 074025 (2011)

Mono-top

- Large MET ➡ boosted t-quark ➡ **jet substructure!**

  - Jet grooming, subjet properties, 3-prong-ness

- Cambridge-Aachen jet clustering with ΔR=1.5

  - $p_T > 250$ GeV

  - 110 GeV $< M_{soft\ drop} < 210$ 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-subjettiness τ_3/τ_2 [4]

  - Energy Correlation Functions [5,6]
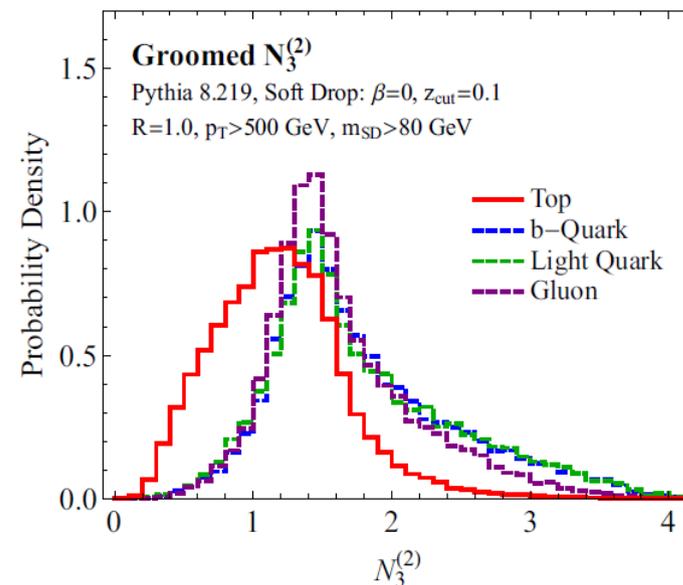

[2] JHEP 05 (2014) 146
[3] arXiv:1503.05921
[4] JHEP 03 (2011) 015
[5] JHEP 06 (2013) 108
[6] JHEP 12 (2016) 153

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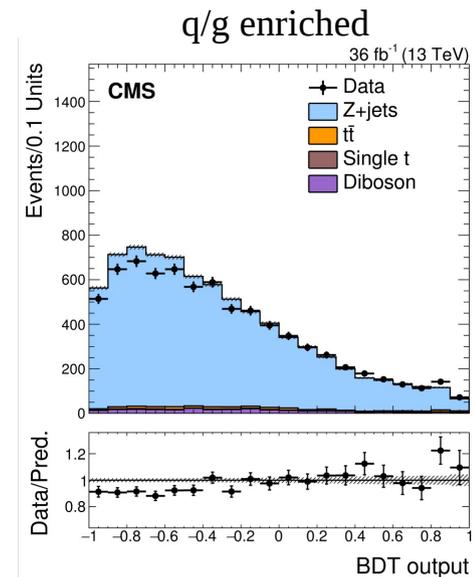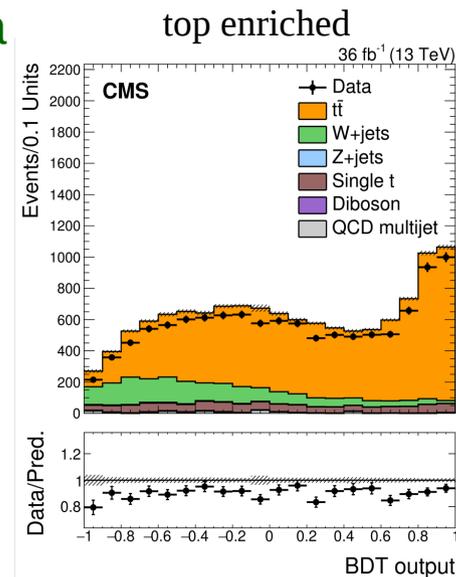 - Energy Correlation Functions [5,6]

JHEP 12 (2016) 153

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top enriched

q/g enriched

Mono-top
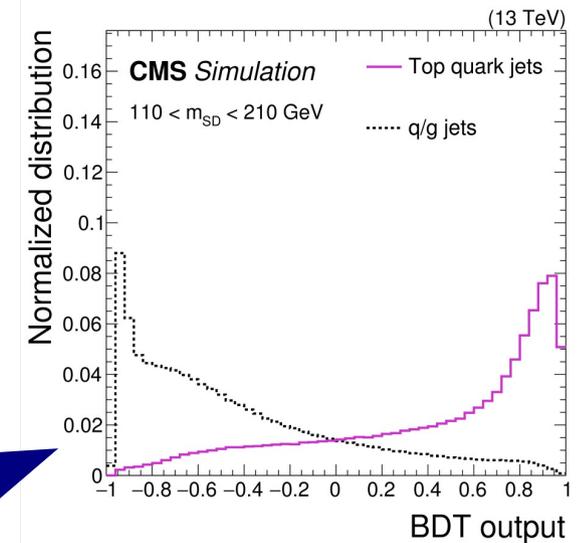
- ## Signal Region:

  - 1 top-tag and categorize by low and high BDT scores

  - MET > 250 GeV

  - Veto on electron, muon, tau, photon objects

  - ΔR(MET, AK4) > 0.5 for any AK4 jet

- ## Control regions:

  - Dimuon, dielectron, photon ➡ Z(νν)+jets

  - Single muon, electron + b-tag ➡ t$\bar{\text{t}}$(1l)

  - Single muon, electron with no b-tag ➡ W(lν)+jets, Z(νν)+jets

- ## Simultaneous fit of SR and CRs
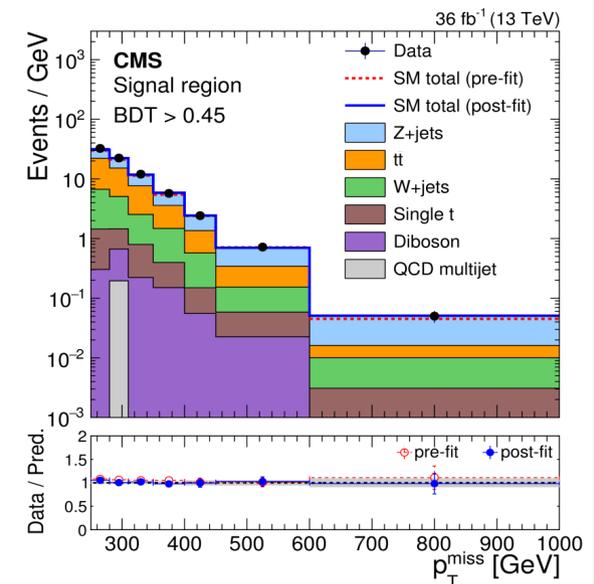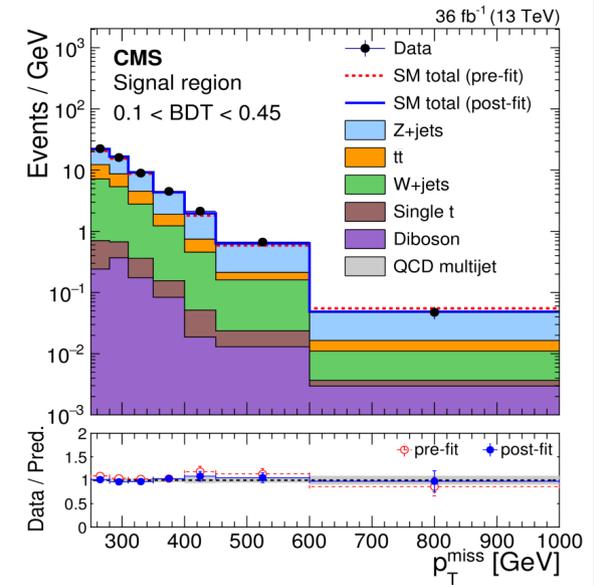
Mono-top

- ## Result on 36 fb^{-1} collected in 2016

  - ### FCNC model: m_V exclusion up to 1.75 TeV

  - ### Scalar model: m_φ exclusion up to 3.5 TeV
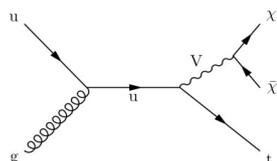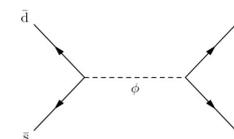
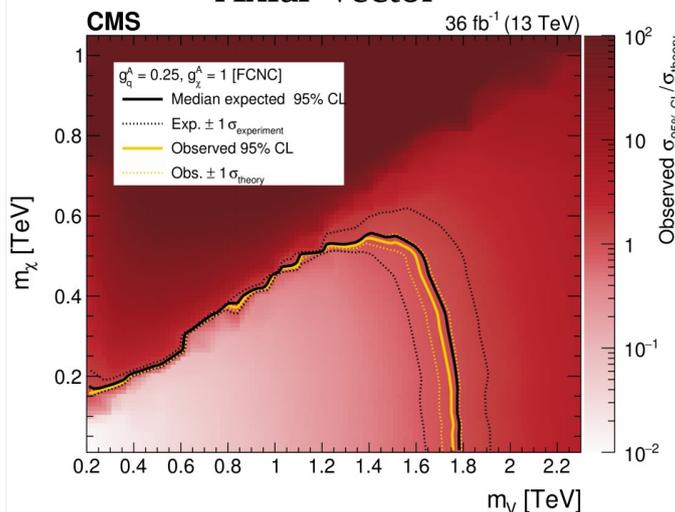Vector
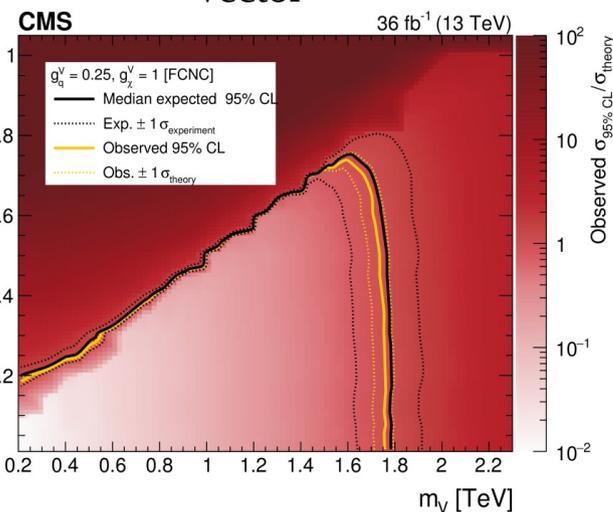
Axial-Vector

Scalar

Mono-top

- Result on 36 fb^{-1} collected in 2016

    - FCNC model: m_V exclusion up to 1.75 TeV
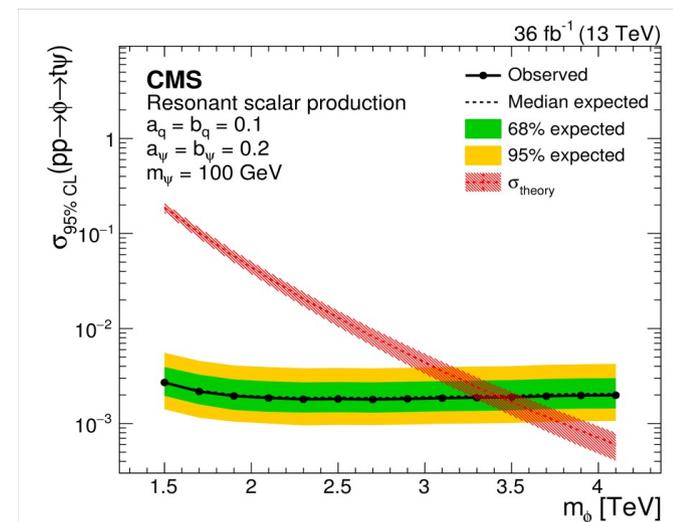
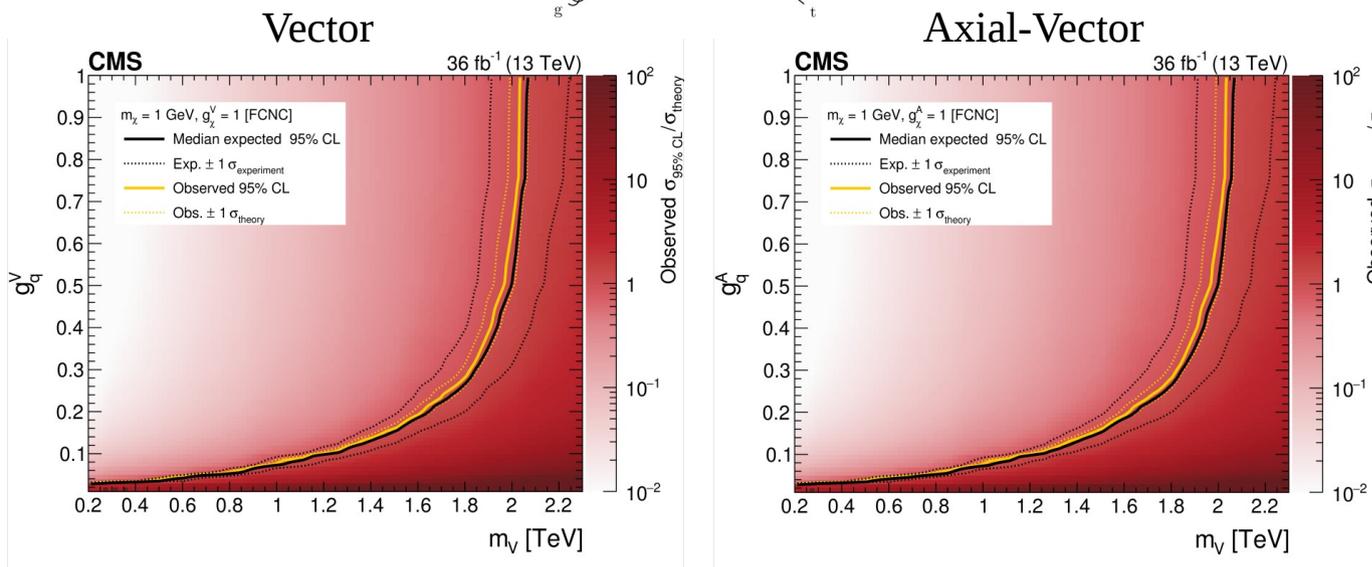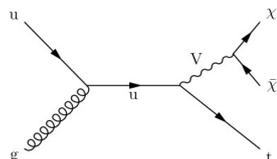   - Scalar model: m_φ exclusion up to 3.5 TeV

- For FCNC model, constraints on couplings between mediator with SM / DM sectors also computed

Vector   Axial-Vector

Limits on coupling of mediator to SM

t̄t+DM

- Spin-0 mediators with Yukawa couplings to SM particles provide most compelling models for t̄t+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)


[7] arXiv:1507.00966

t̄t+DM: Dileptonic
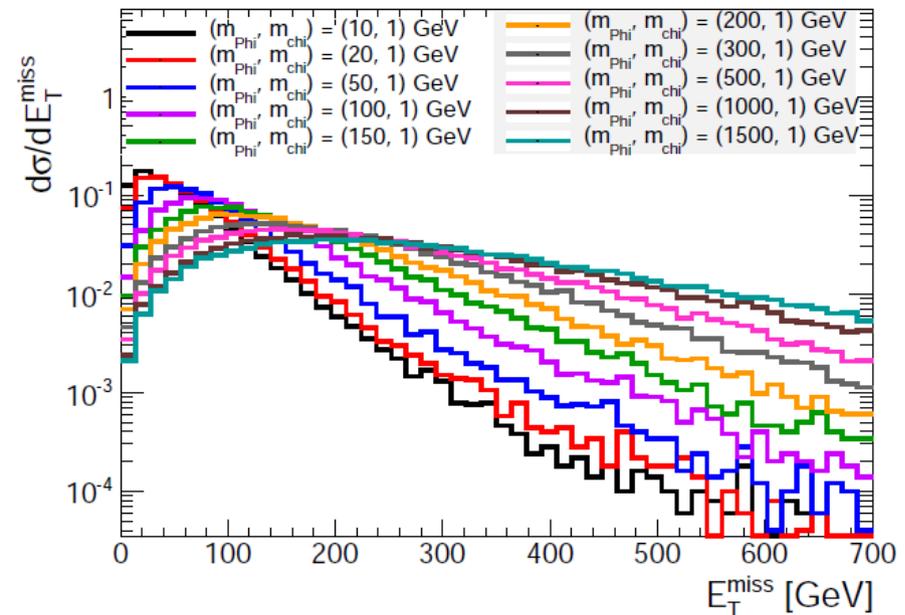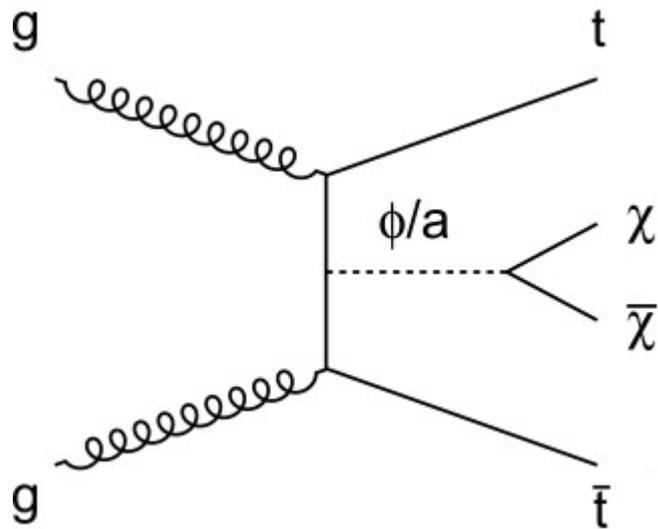
- Designed for stop pair search, but still good sensitivity to t̄t+DM

- Selection:

  - ee, eμ, μμ final states

  - At least 2 jets with a least one b-tagged

  - $m_{ll} > 20$ GeV

  - $|m_{ll} - m_Z| > 15$ GeV for ee, μμ

  - MET > 80 GeV

  - MET significance > 5 GeV$^{1/2}$

  - $\cos\Delta\varphi(MET, jet_1) < 0.8$

  - $\cos\Delta\varphi(MET, jet_2) < 0.96$

- Events are binned in $M_{T2}(ll)$, $M_{T2}(lblb)$, MET

- Control regions for: t̄t/single t, t̄tZ, DY and multiboson

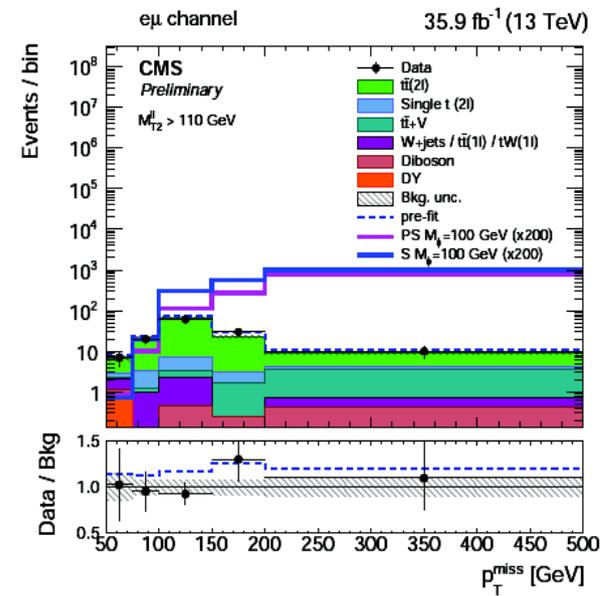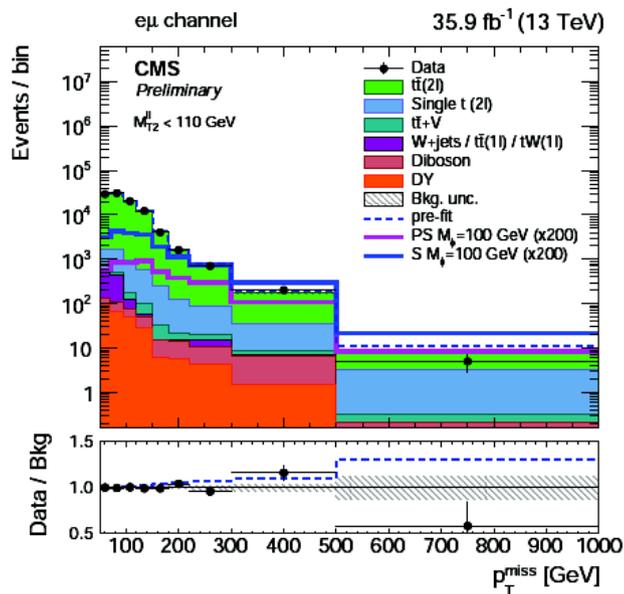# $t\bar{t}$+DM: Dileptonic
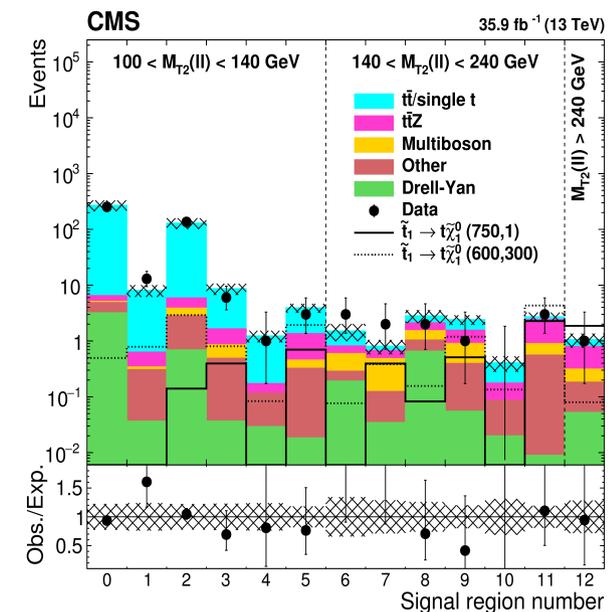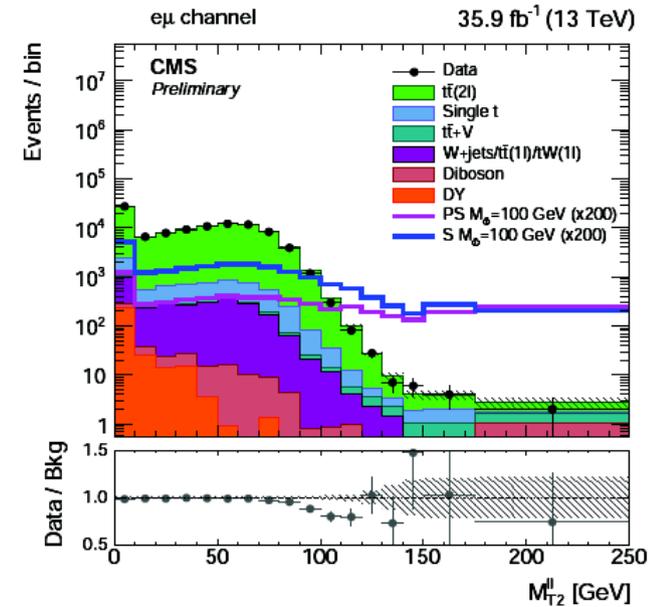
- **Result on 36 fb^{-1} collected in 2016**

  - Scalar model: m_φ 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*
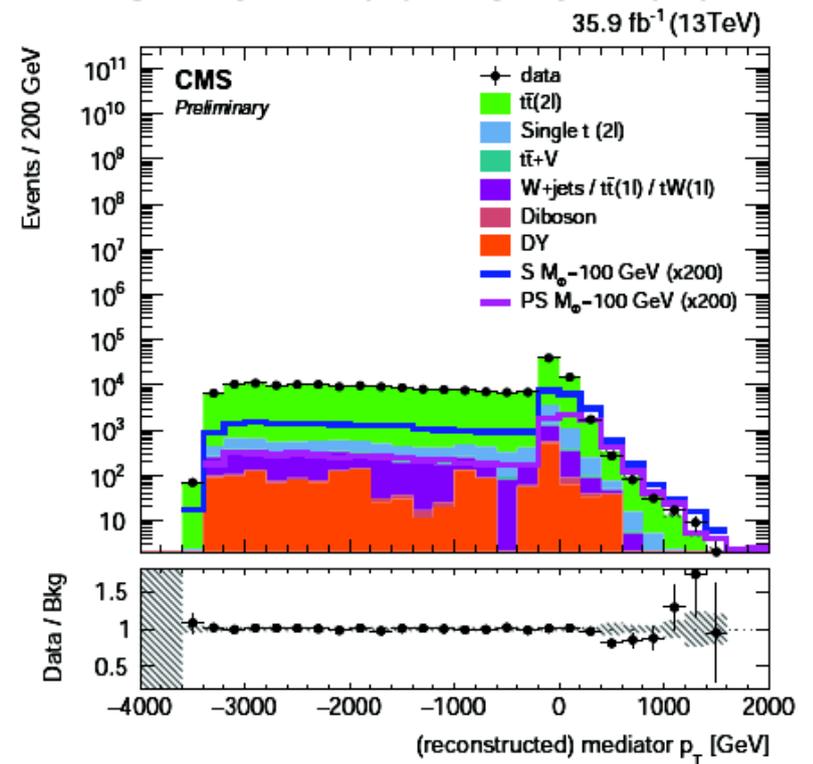
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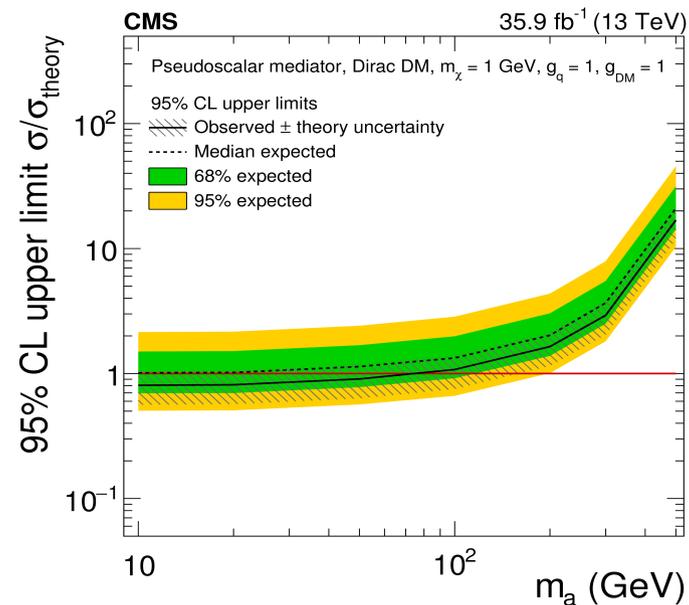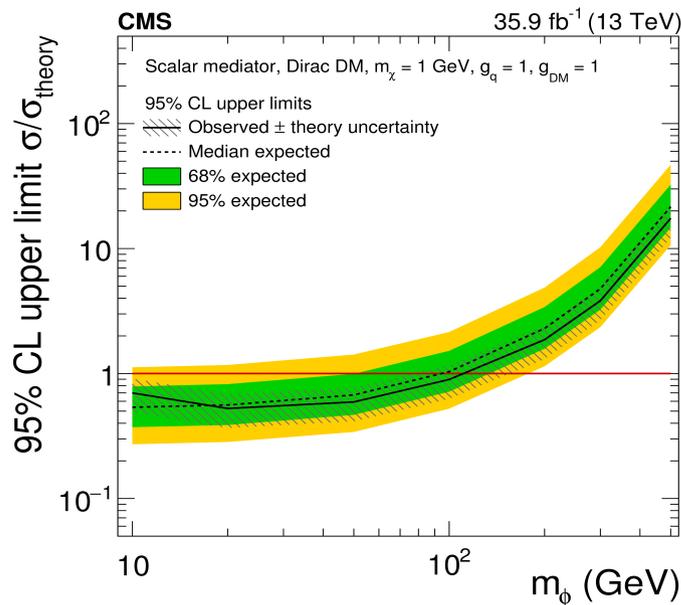
- **New result with several new techniques explored**

- Benchmark against t̄t+DM MET-related variables only analysis

  - Much looser requirements on MET, $M_{T2}(ll)$, $M_{T2}(lblb)$ 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

t̄t+DM: Dileptonic

- **Construct dark-p_T**
  NEW *CMS-EXO-17-014*

  - When t̄t(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

t̄t+DM: Dileptonic
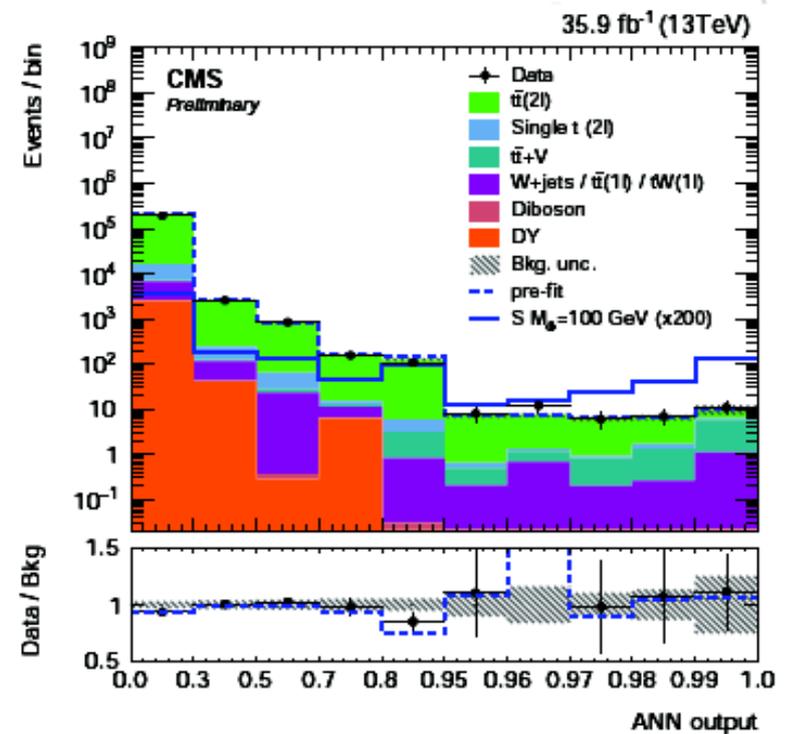
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    - For signal, this estimates the mediator p_T

- Construct Artificial Neural Network (ANN) discriminant for t̄t+DM

  - Dark-p_T

  - MET-related variables: MET, M_{T2}(ll)

  - Angular variables: $\Delta\varphi$(MET, ll)

- Signal extraction from fit of ANN shape

t̄t+DM: Dileptonic

CMS-EXO-17-014

- **Construct BDT discriminant for t̄t+DM**

  - Kin-reco probability to be consistent with t̄t(2l)

  - MET-related variables: MET, M_{T2}(ll), M_{T2}(lblb)

  - Angular variables: $\Delta\varphi$(MET, ll), $\Delta\eta$(ll), cos Φ_{ll}

    – *Can additionally distinguish between scalar or pseudoscalar*

- **Much looser requirements on MET, M_{T2}(ll), M_{T2}(lblb) than SUS-17-001**

- **Signal extraction from fit of BDT shape**

t̄t+DM: Dileptonic
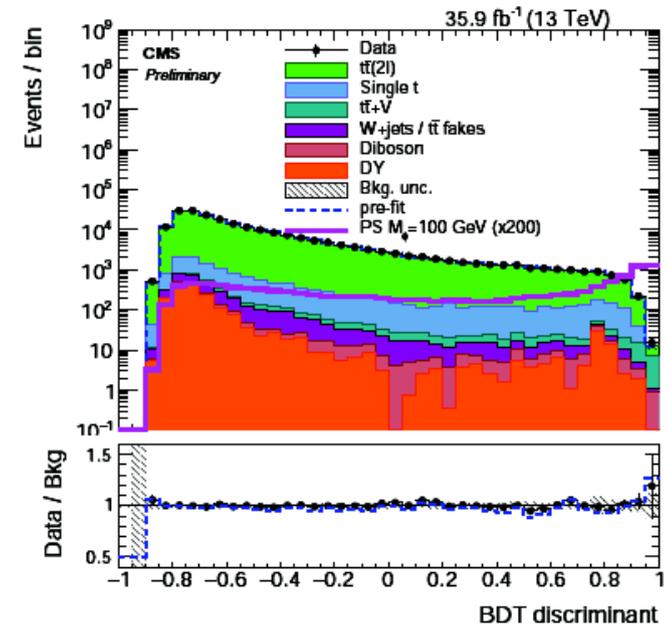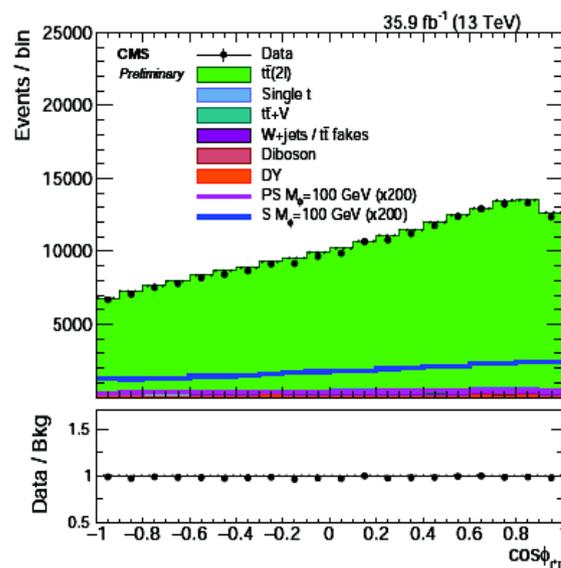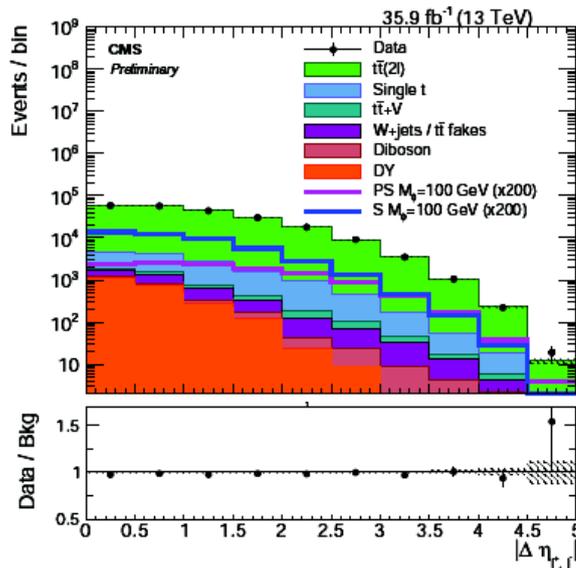
- Signal normalization updated to NLO cross sections

- Result of BDT analysis on 36 fb^{-1} collected in 2016

  - Scalar model: m_φ excluded up to 86 GeV

  - Pseudoscalar model: no observed exclusion

  - ~20% better than MET-shape strategy, ~10% better than ANN strategy

Summary and Outlook
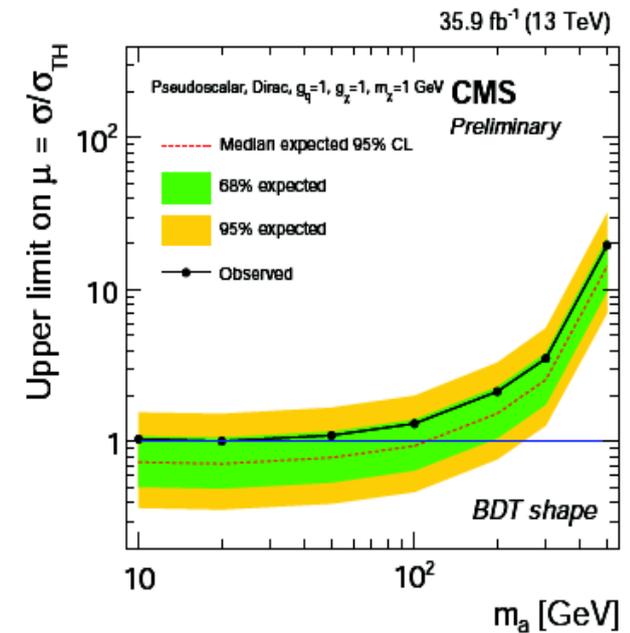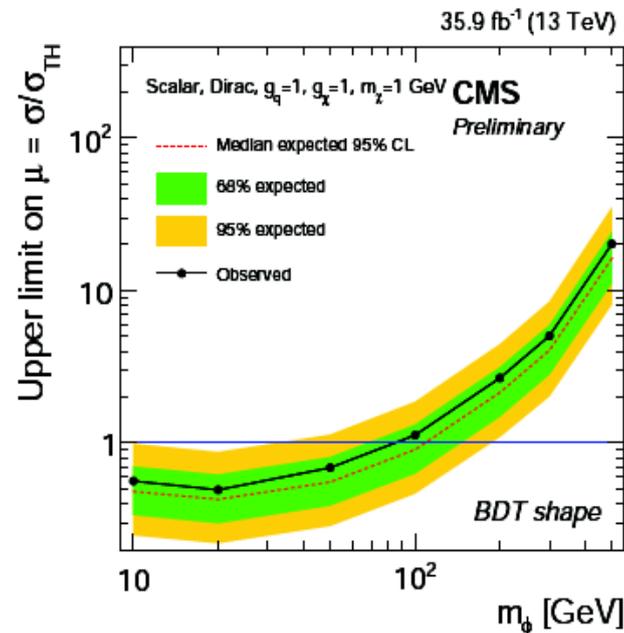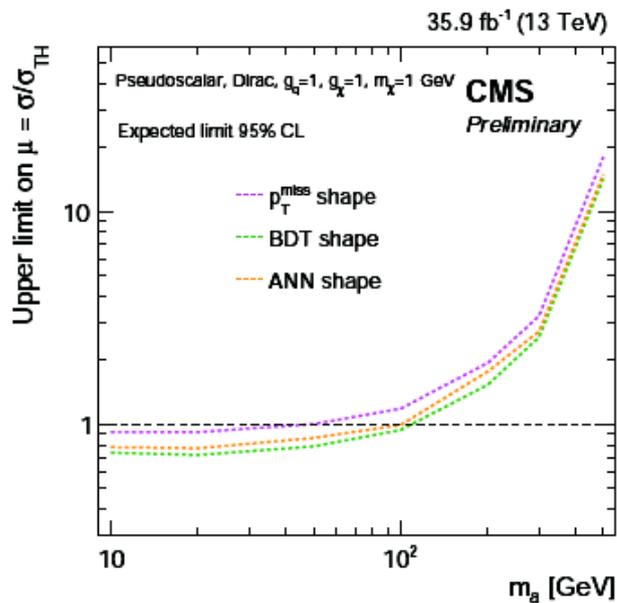
- DM + top(s) is driving the sensitivity of several DM models

- 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$\bar{\text{t}}$+DM in all-hadronic and l+jets channels, as well as full combination of t$\bar{\text{t}}$+DM channels, are coming soon

- Further developments on various top tagging techiques on-going

- Models of spin-0 mediator that accounts for co-existence with BEH are available for future interpretations [8,9]

[8] arXiv:1607.06680
[9] JHEP 05 (2017) 138

Backup

t$\bar{\text{t}}$+DM: All-hadronic

- Top quark p_T relatively soft in t$\bar{\text{t}}$+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(1l)

  - Ask for 2 top tags to reduce bkg

t̄t+DM: All-hadronic
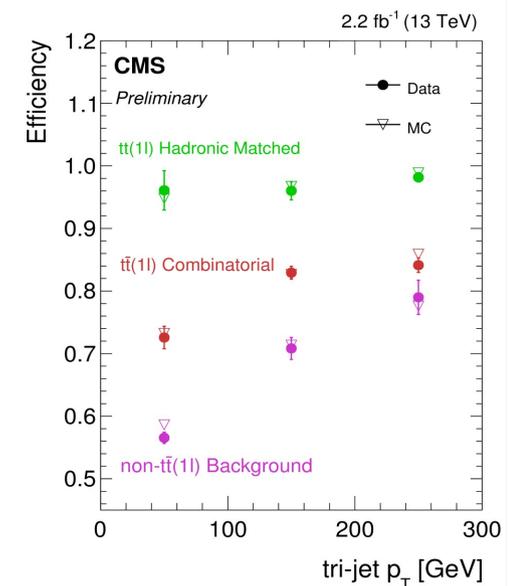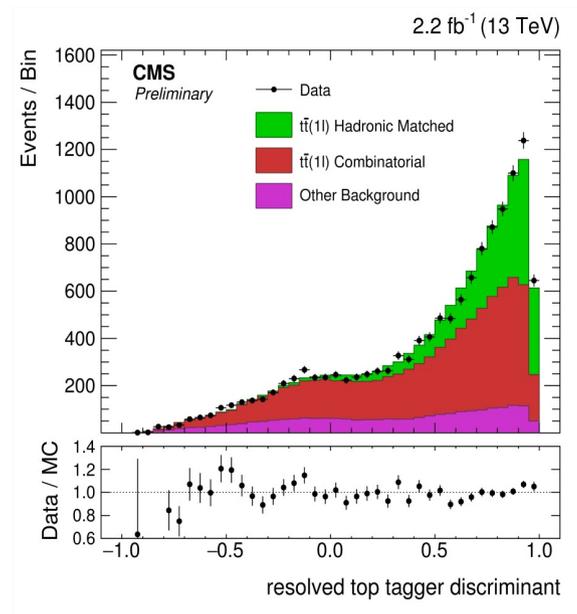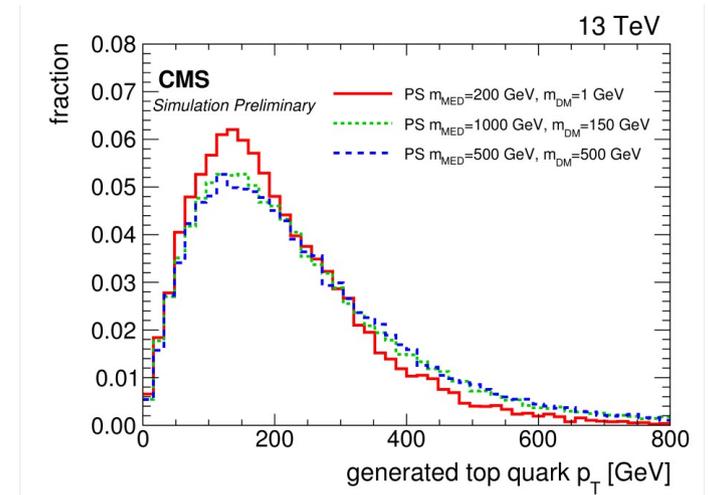
CMS-EXO-16-005

- **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 t̄t(1l), W(lν)+jets, Z(νν)+jets

  - t̄t(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

t̄t+DM: lepton+jets

CMS-EXO-16-005
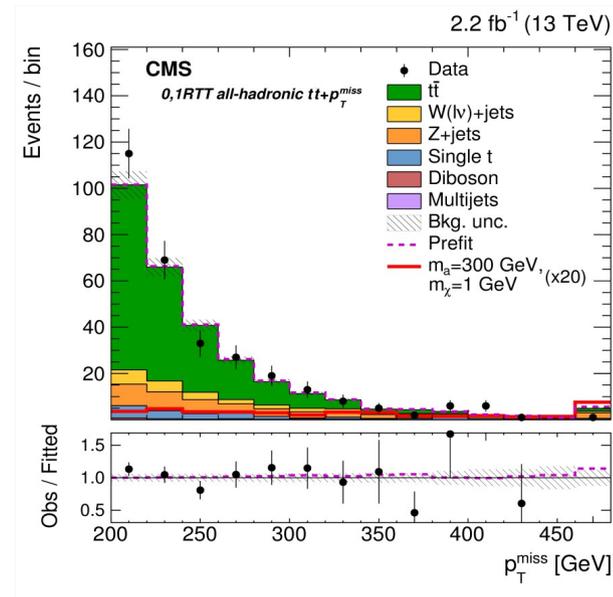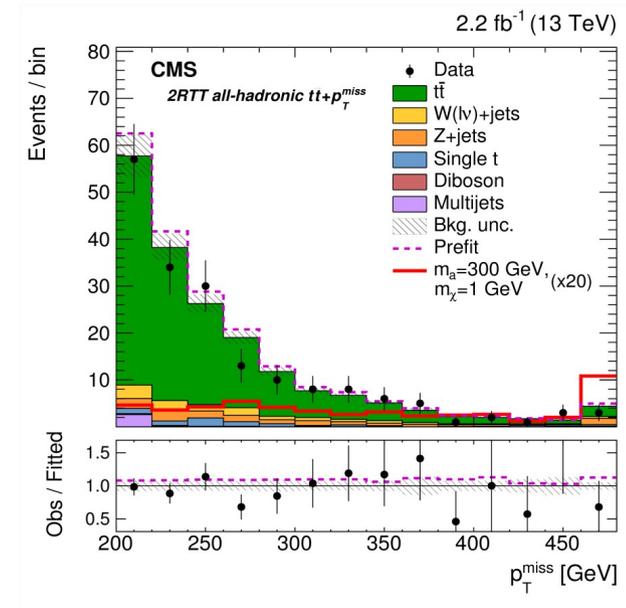
- ## Signal Region

  - One muon (or electron), $p_T > 30$ GeV, $|\eta| > 2.4$ (or 2.5)

  - 3 or more jets, at least one b-tagged

  - $M_T > 160$ GeV

  - $M_{T2}^W > 200$ GeV

  - $\text{Min}_{i=1,2}\,\Delta\varphi\text{-(jet}_i\text{,MET)} > 1.2$

  - MET > 160 GeV

- ## Control regions for tt(2l) and W+jets

  - t̄t(2l) CR: dilepton selection

  - W+jets CR: single lepton, zero b-tag