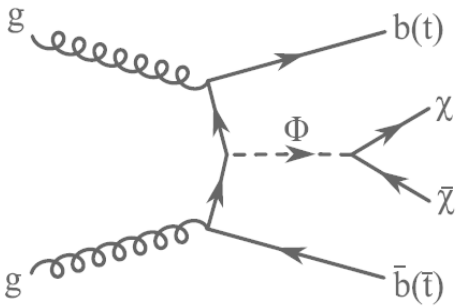


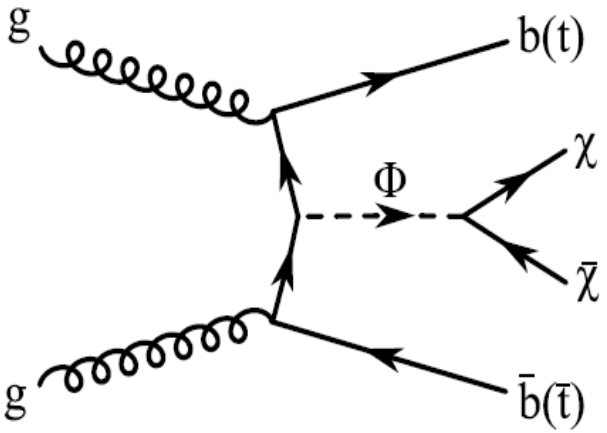

# Search for Dark Matter production in association with heavy flavor quark pairs with CMS

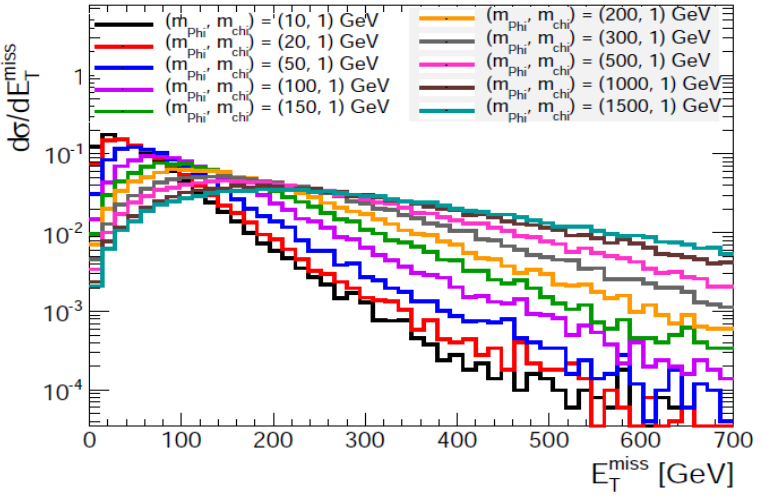
**Kevin Sung** (Northwestern University)

*On behalf of the CMS Collaboration*

# Introduction

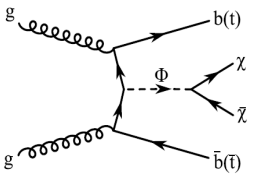
- Under MFV assumption, spin-0 mediators couple to SM via Yukawa couplings, favoring heavy flavor quarks




- Search for DM in $b\bar{b}$+MET and $t\bar{t}$+MET final states in CMS with 2015 dataset (2.2 $fb^{-1}$)
  - Physics Analysis Summaries:
    - $b\bar{b}$+MET: B2G-15-007
    - $t\bar{t}$+MET: EXO-16-005

# Signal Generation



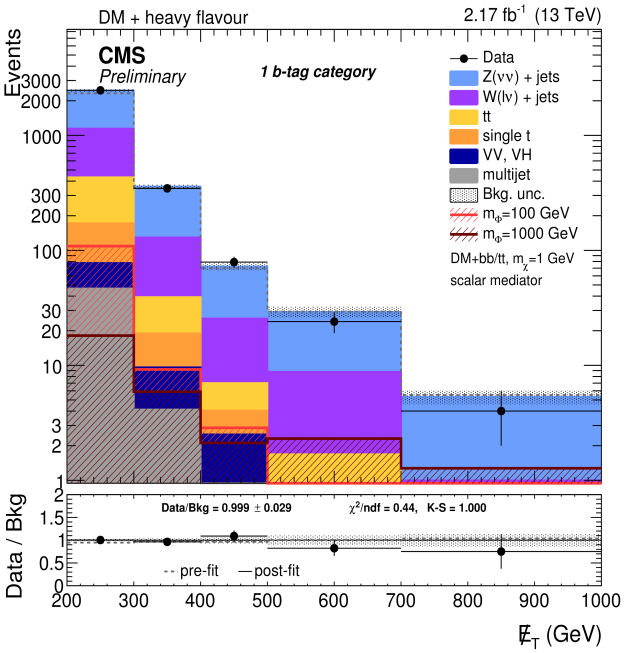

- Generated with MadGraph models studied in LHC DMF (link)
  - No mixing with SM Higgs
  - LO ME up to 1 additional parton, Pythia8 showering, MLM matching
- Scalar and Pseudoscalar mediated production with $g_{DM}=g_{SM}=1$
  - Mediator decays only to Dirac fermion DM pairs
- $b\bar{b}$+DM
  - ME computed with 4-flavor scheme
  - Normalize to cross section computed with 5-flavor scheme
- $t\bar{t}$+DM
  - MadSpin for spin correlations in top decays
  - Normalized to cross sections from LHC DMF discussions (link)

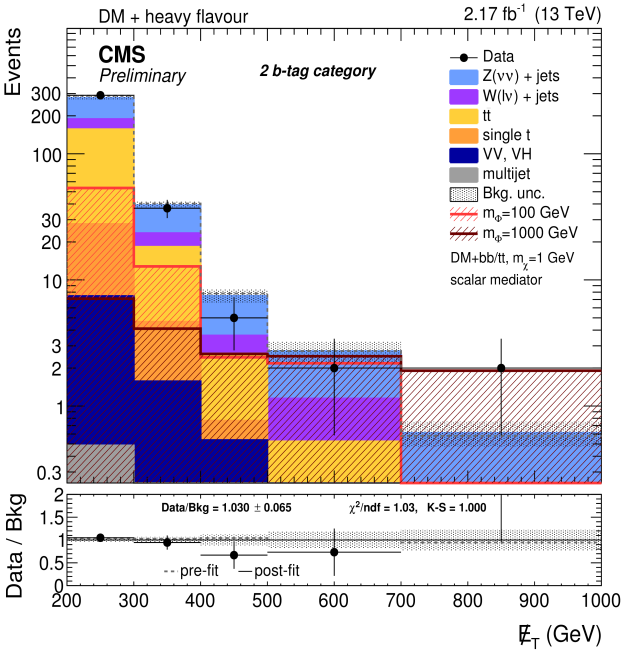
# Analysis Strategy

- MET shape analysis
- Control regions defined to help constrain dominant SM backgrounds: $t\bar{t}$, W+jets, Z+jets
- Simultaneous fit of signal and control regions
  - Natural way to handle signal “contamination” in control regions
  - Using Higgs Combination framework for limit setting
- $b\bar{b}$+MET
  - Signal region split by number of b-tags: single-b, double-b
- $t\bar{t}$+MET
  - Semileptonic and hadronic channels
    - Hadronic channel split by number of top tags: 2 top tags, <2 top tags

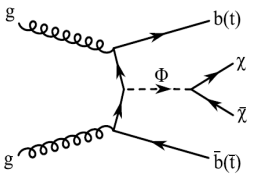
# $b\bar{b}$+MET Search (1)

- Selection
  - ***Two signal regions:***
    - (1) One jet ($p_T$>50) with possibly one additional jet ($p_T$>30) and exactly 1 b-tag
    - (2) Two jets (both $p_T$>50) with possibly one additional jet ($p_T$>30) and exactly 2 b-tags
  - Δφ(jet, MET) > 0.5 for all selected jets
  - Veto on e, μ, τ, γ
  - MET > 200
- Interpretation with $b\bar{b}$+DM signal as well as $b\bar{b}$+DM and $t\bar{t}$+DM signals together
  - Results driven by sensitivity to $t\bar{t}$+DM due to harder MET spectra

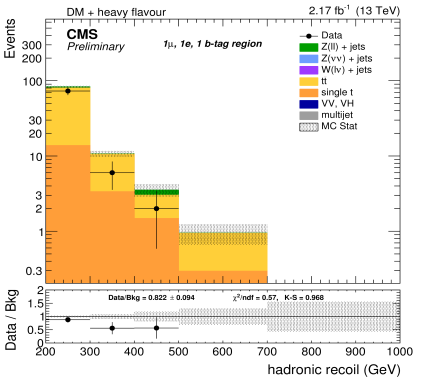


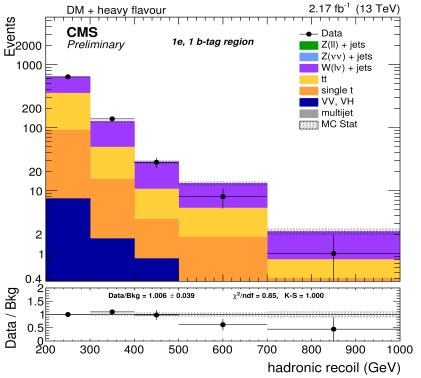
# $b\bar{b}$+MET Search (2)



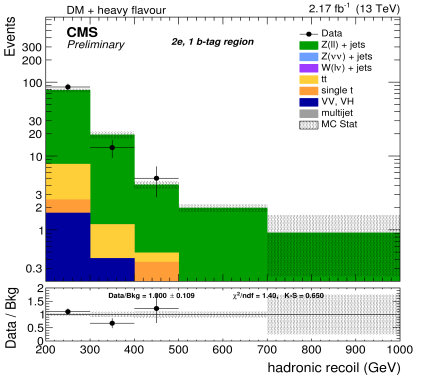

- 5 background enriched regions corresponding 1 b-tag and 2 b-tag categories (i.e. same $N_{jets}$ and $N_b$ cuts)
  - For $t\bar{t}$: eμ events
  - For W+jets: e/μ events with $50 < M_T < 160$
  - For Z+jets: ee/μμ events with $70 < M_{ll} < 110$
- Leptons are removed from the MET calculation (i.e. hadronic recoil)
- Sources of systematics treated as constrained nuisances on normalization (Gaussian prior) or shape
- 3 additional nuisance parameters scale the corresponding $t\bar{t}$, W, Z yields in signal region and bkg enriched regions
  - Nuisances have flat prior




$t\bar{t}$ region in 1-b category



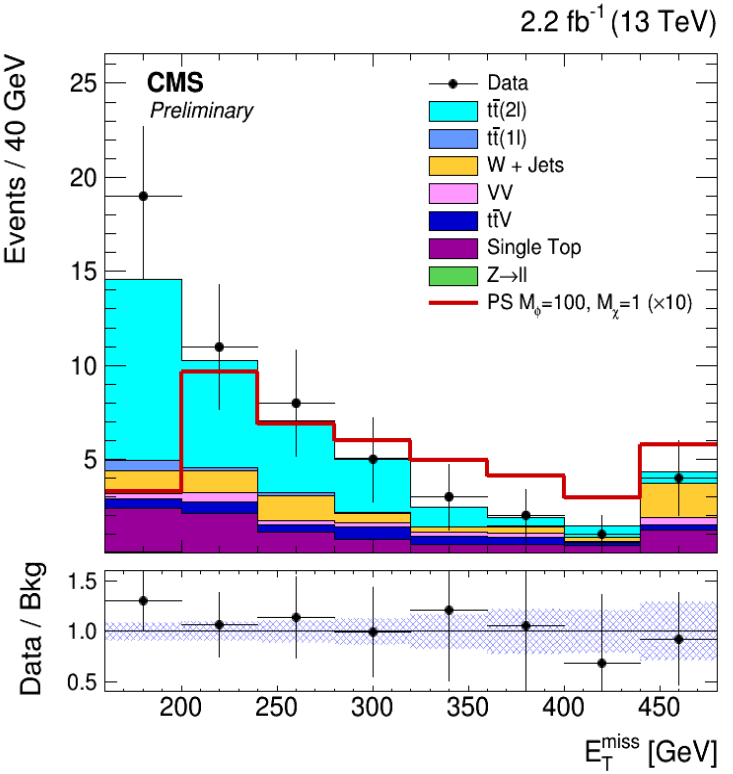

W(e) region in 1-b category




Z(ee) region in 1-b category

# Semilept $t\bar{t}$+MET Search (1)

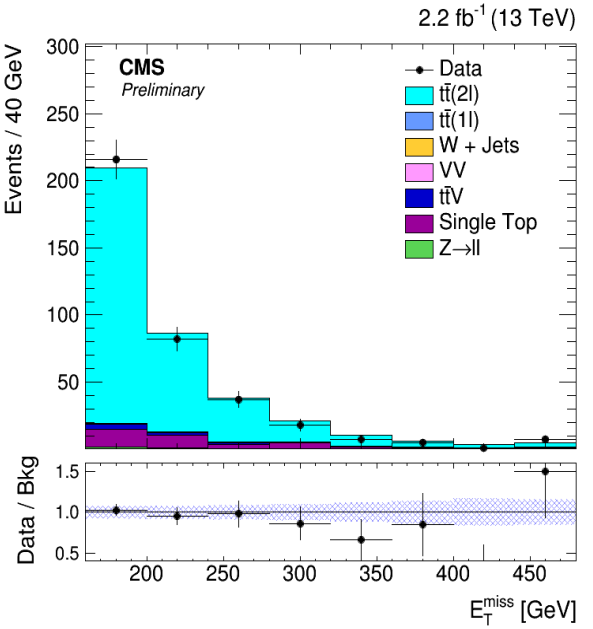
- Selection
  - Single e, μ ($p_T$>30)
  - 3 or more jets ($p_T$>30) with at least 1 b-tag
  - $M_T$ > 160
  - Veto on additional e, μ
  - MT2W > 200 [1]
  - Min-Δφ(jet, MET) > 1.2 for two leading jets
  - MET > 160

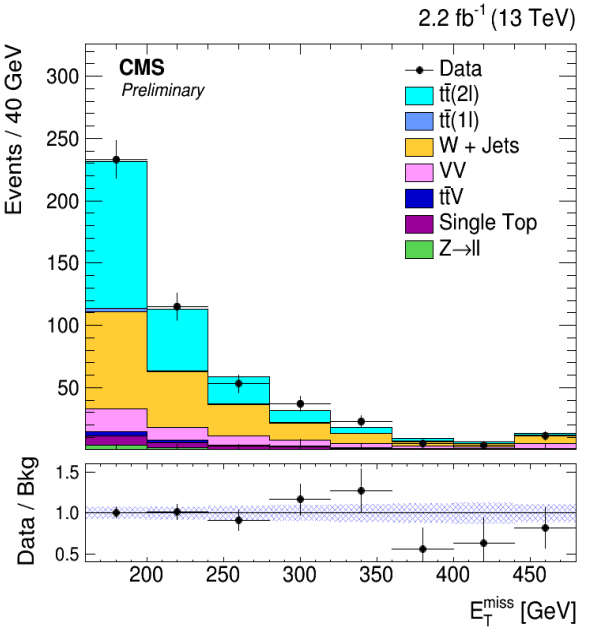



[1] Y. Bai, H.-C. Cheng, J. Gallichio, J. Gu, arXiv:1203.4813

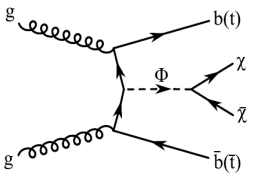
# Semileptonic Channel (2)

- Two background enriched regions:
  - For dileptonic $t\bar{t}$:
    - Two leptons (ee/eμ/μμ)
  - For W+jets:
    - 3 or more jets but *zero b-tag*
    - $M_T > 160$
    - Note there is still significant contribution from dileptonic $t\bar{t}$
- Two unconstrained nuisance parameters (one for dilepton $t\bar{t}$ and one for W+jets) scale the background process across signal and background enriched regions, in addition to the constrained nuisances corresponding to systematics

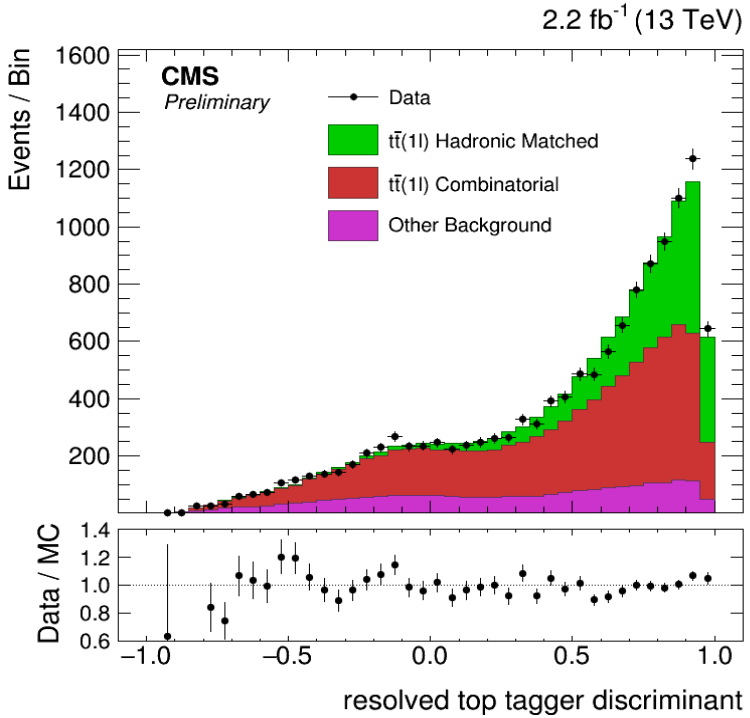


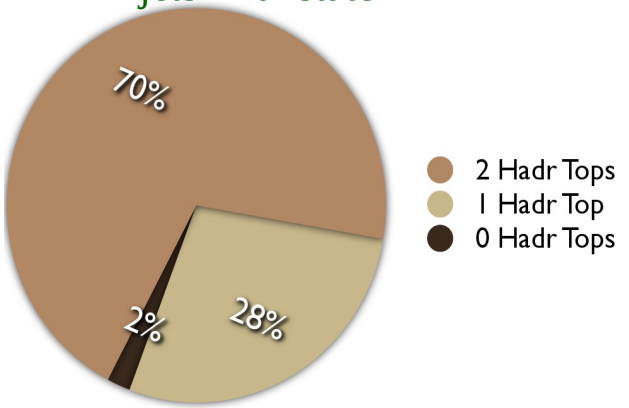
# Hadronic $t\bar{t}$+MET Search (1)

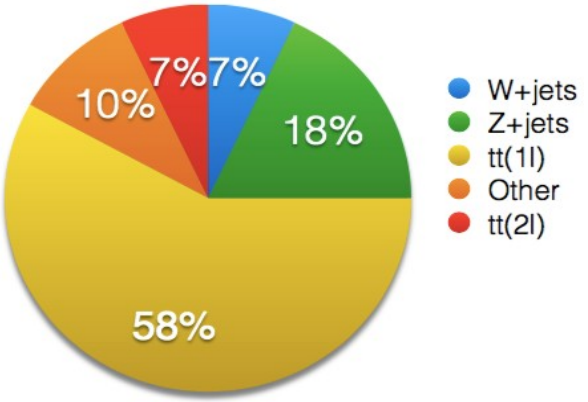



- An MVA discriminant to identify top quark decays to 3 resolved jets is used improve signal purity [2]
  - Employs kinematic fit constrained to $m_t$ and $m_W$
  - Jet properties such as q/g likelihood, angular separation




$t\bar{t}$+DM decay modes in MET+jets final state



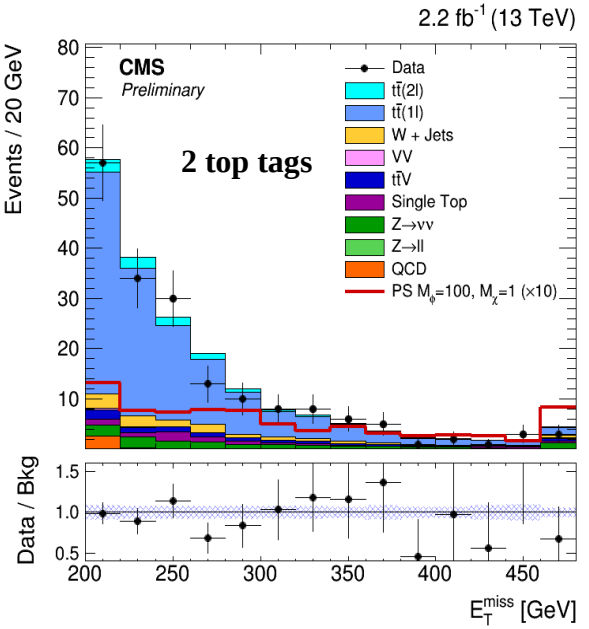



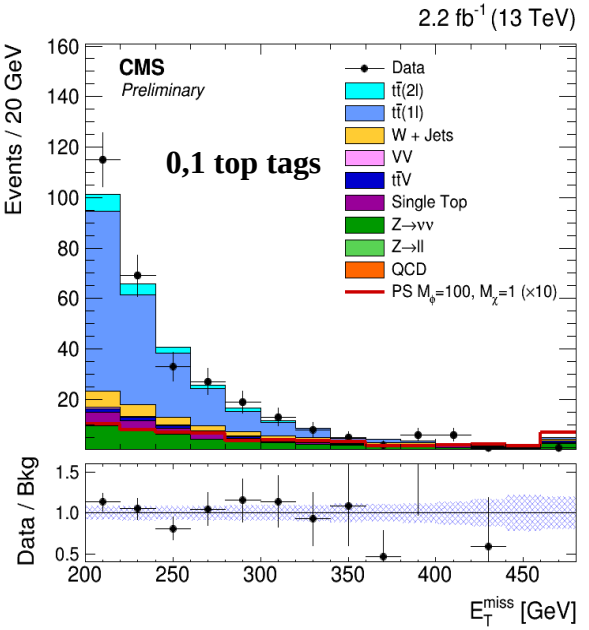

SM backgrounds in MET+jets final state

[2] See talk at 2016 Boost Conference

# Hadronic $t\bar{t}$+MET Search (2)

- An MVA discriminant to identify top quark decays to 3 resolved jets is used improve signal purity [2]
  - Employs kinematic fit constrained to $m_t$ and $m_W$
  - Jet properties such as q/g likelihood, angular separation
- Selection
  - ***Two signal regions:***
    - (1) Two top tags, min-Δφ(jet, MET) > 0.4, 1 b-tag
    - (2) Less than two top tags, min-Δφ(jet, MET) > 1, 4 or more jets with at least 2 b-tags
  - Veto on e, μ
  - MET > 200



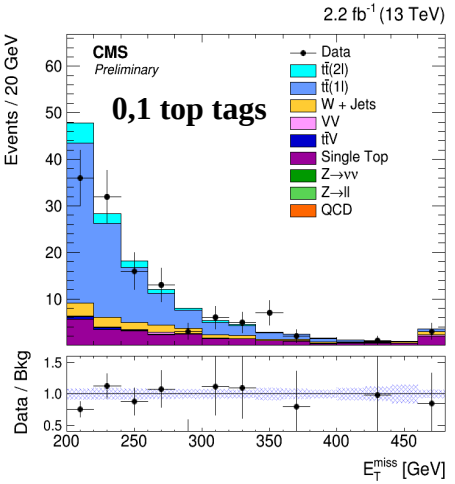




[2] See talk at 2016 Boost Conference

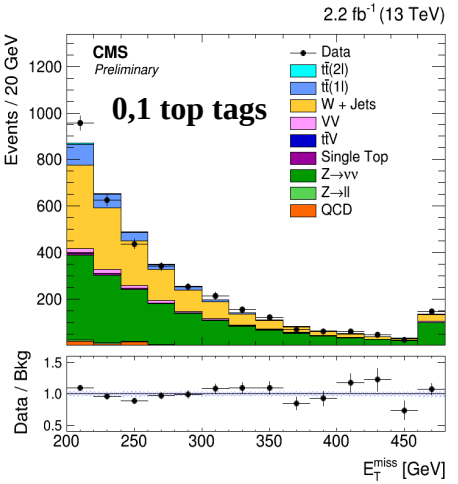
# Hadronic Channel (3)

- Background enriched regions respective to both signal categories:
  - For semileptonic $t\bar{t}$:
    - e/μ events with $M_T < 160$
  - For W/Z+jets:
    - Events with *zero b-tag*
  - For W+jets:
    - e/μ events, $M_T < 160$, and *zero b-tag*
  - For Z+jets:
    - ee/μμ events with $60 < M_{ll} < 120$
    - 0,1 top tag category only
- Three unconstrained nuisance parameters (semileptonic $t\bar{t}$,W+jets, Z+jets)

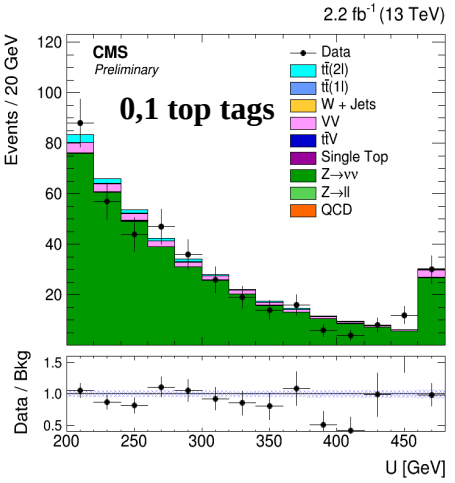
$t\bar{t}$(1l) region



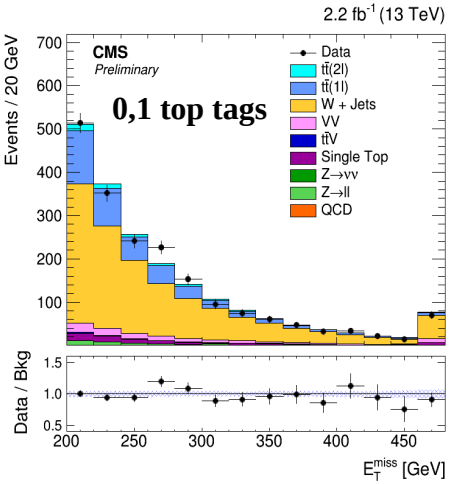

W/Z+jets region



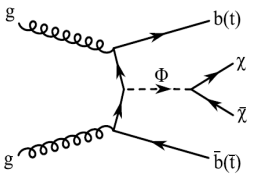

Z+jets region




W+jets region

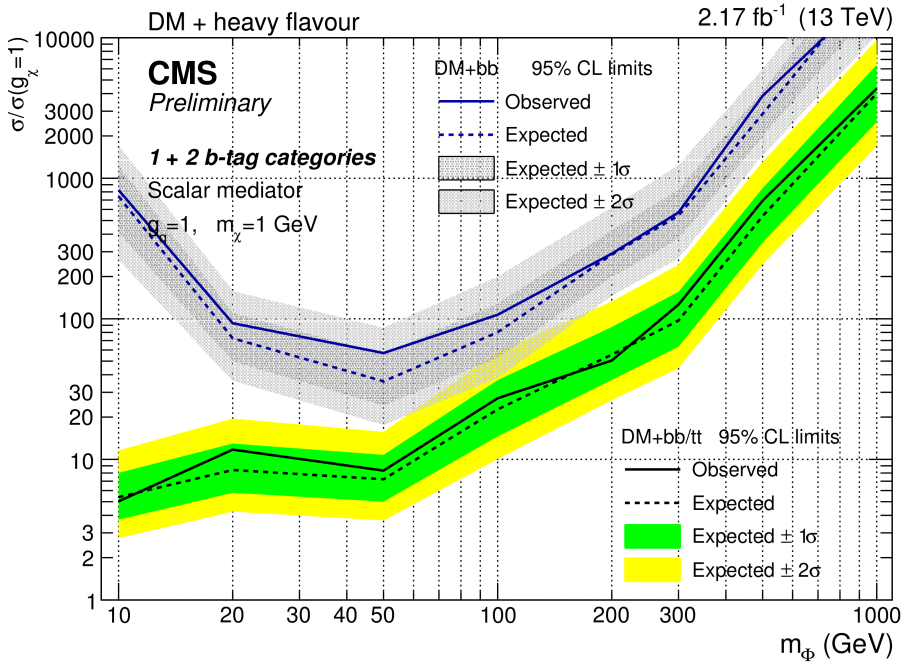


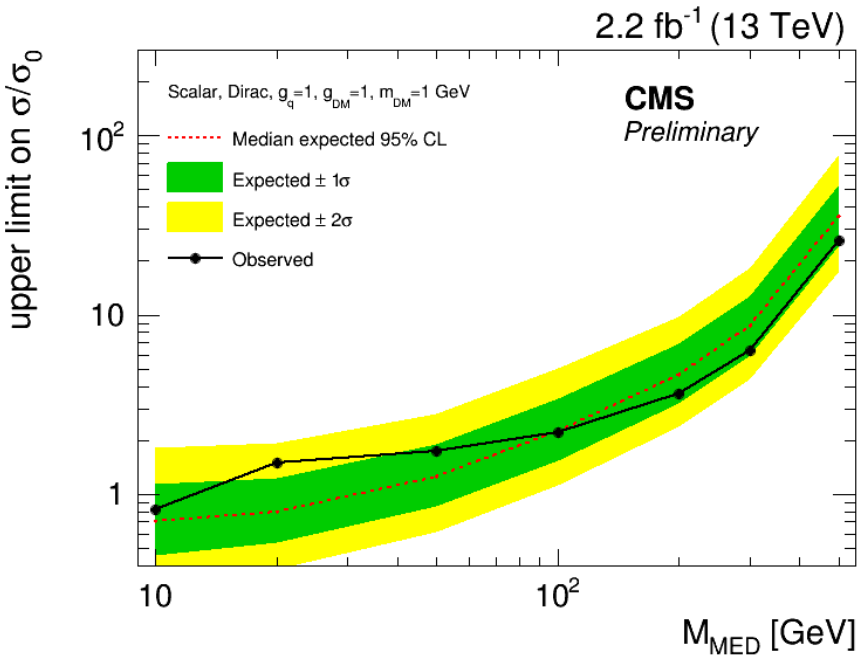
# Summary




- Dark Matter search in $b\bar{b}$+MET and $t\bar{t}$+MET final states performed in CMS with 2015 dataset
- Interpretation with $b\bar{b}$+DM and $t\bar{t}$+DM signals
  - Results are driven by sensitivity to $t\bar{t}$+DM

## Scalar results

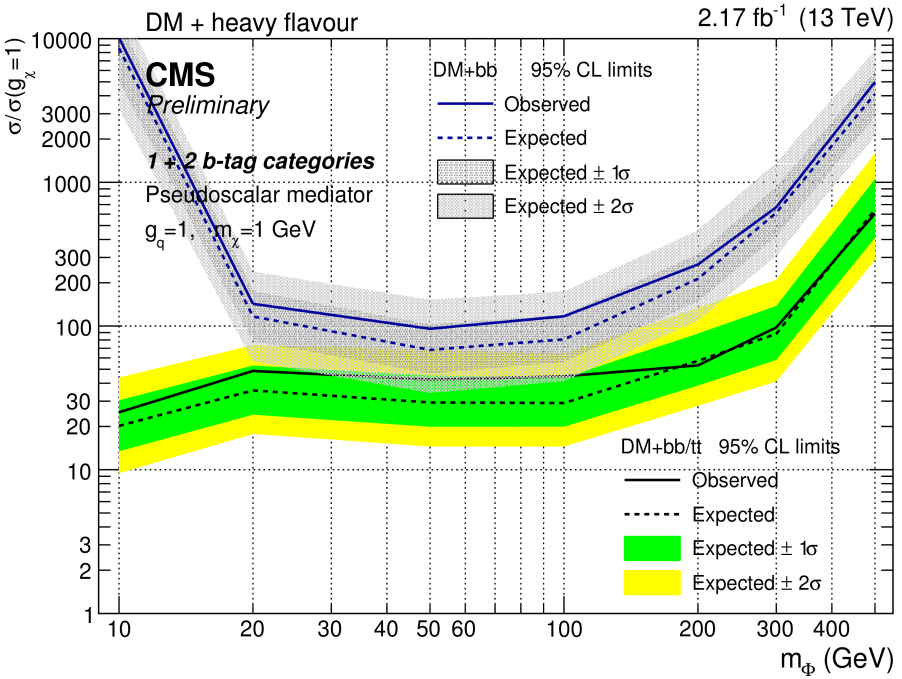


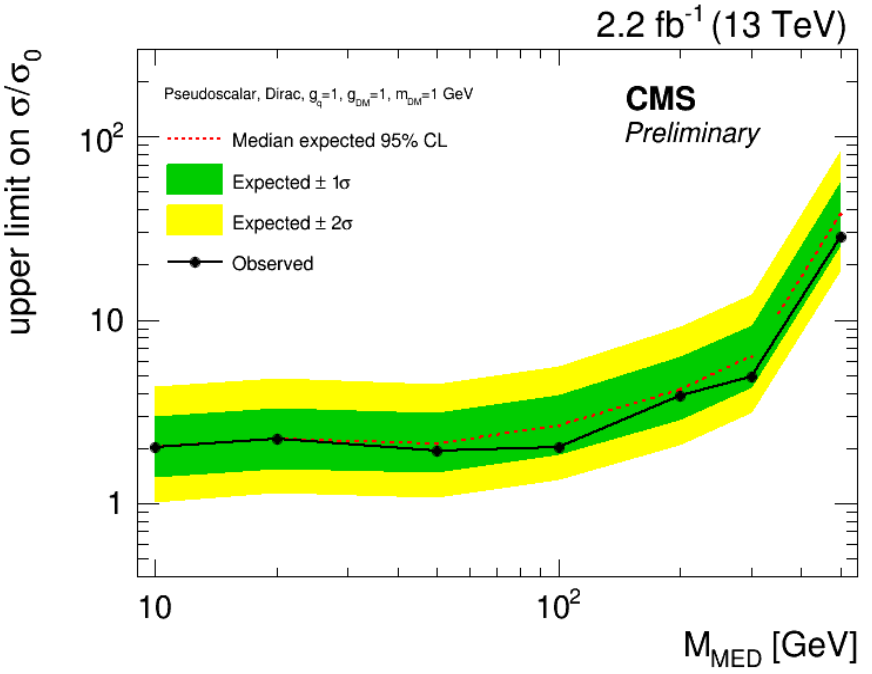



# Summary

- Dark Matter search in $b\bar{b}$+MET and $t\bar{t}$+MET final states performed in CMS with 2015 dataset
- Interpretation with $b\bar{b}$+DM and $t\bar{t}$+DM signals
  - Results are driven by sensitivity to $t\bar{t}$+DM

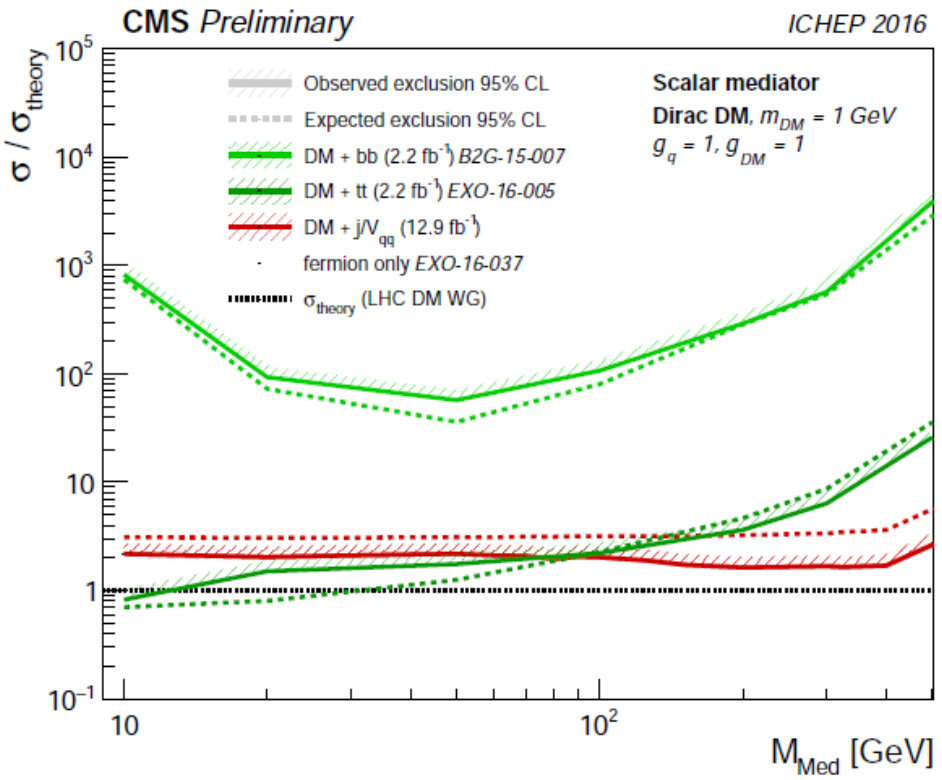
## Pseudoscalar results

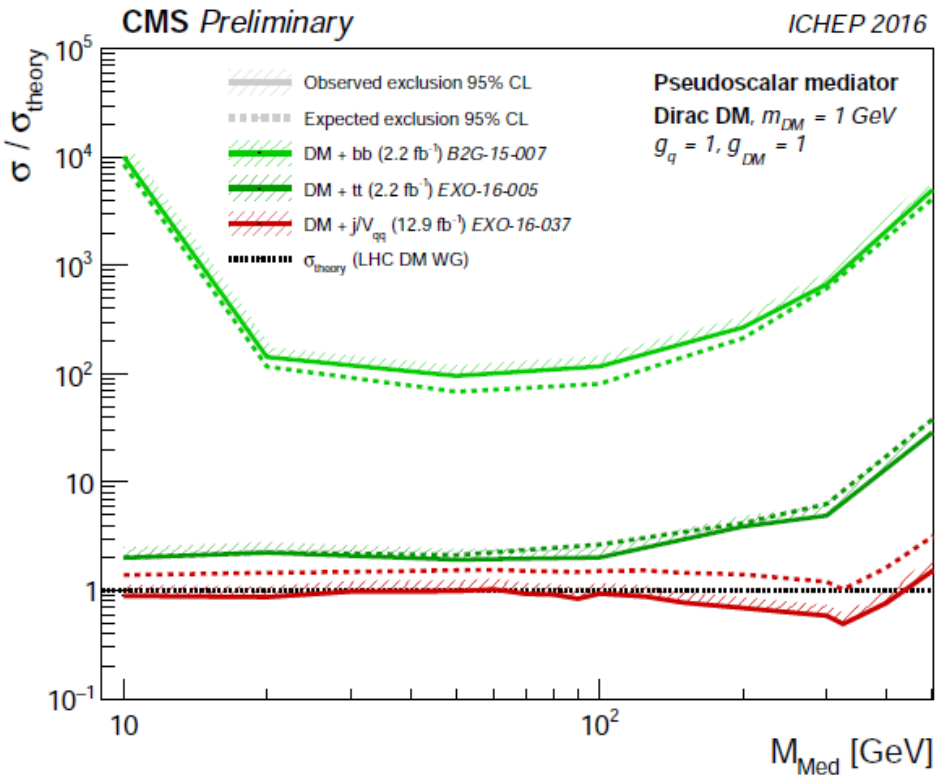


# Summary

- Dark Matter search in $b\bar{b}$+MET and $t\bar{t}$+MET final states performed in CMS with 2015 dataset
- Interpretation with $b\bar{b}$+DM and $t\bar{t}$+DM signals
  - Results are driven by sensitivity to $t\bar{t}$+DM




From DP-2016/057

# *Backup Slides*

# Signal Region Yields

- Background-only post-fit yields for SM backgrounds
- Uncertainties include statistical and systematics

$b\bar{b}$+MET

| Process | single $b$-tag | double $b$-tag |
|---|---|---|
| $t\bar{t}$ | 284 ± 28 | 145 ± 11 |
| W+jets | 829 ± 59 | 38.5 ± 5.5 |
| Z+jets | 1613 ± 64 | 111 ± 6.7 |
| Single t | 105 ± 16 | 23.6 ± 4.0 |
| Diboson | 38.7 ± 6.6 | 9.2 ± 1.6 |
| QCD | 52 ± 22 | 0.53 ± 0.22 |
| SM Expected | 2922 ± 96 | 327 ± 15 |
| Data | 2919 | 337 |
| PS DM+$t\bar{t}$ 50,1 | 1.21 ± 0.38 | 1.34 ± 0.34 |
| PS DM+$b\bar{b}$ 50,1 | 3.44 ± 0.94 | 0.55 ± 0.22 |
| S DM+$t\bar{t}$ 100,1 | 2.22 ± 0.53 | 2.11 ± 0.64 |
| S DM+$b\bar{b}$ 100,1 | 2.21 ± 0.66 | 0.49 ± 0.15 |

Semileptonic $t\bar{t}$+MET

| Process | |
|---|---|
| $t\bar{t}$ | 25.7 ± 2.2 |
| W+jets | 6.9 ± 1.6 |
| Z+jets | 0.14 ± 0.06 |
| Single t | 8.9 ± 2.0 |
| $t\bar{t}$+V | 3.41 ± 0.52 |
| Diboson | 2.11 ± 0.51 |
| SM Expected | 47.1 ± 3.5 |
| Data | 53 |
| S 10,1 | 9.1 ± 4.3 |
| S 100,1 | 4.64 ± 0.56 |
| PS 100,1 | 4.36 ± 0.29 |

Hadronic $t\bar{t}$+MET

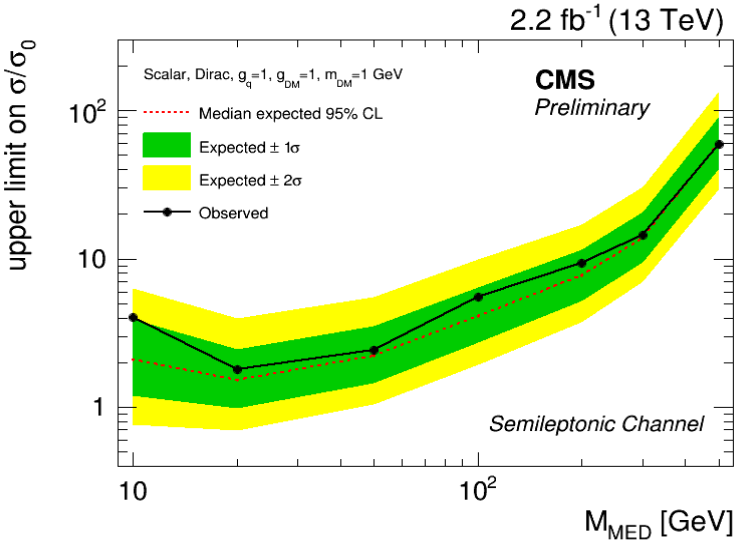
| Process | 2 top tags | 0,1 top tags |
|---|---|---|
| $t\bar{t}$ | 145 ± 14 | 195 ± 20 |
| W+jets | 12.1 ± 1.4 | 23.5 ± 4.6 |
| Z+jets | 13.0 ± 1.3 | 44 ± 13 |
| Single t | 7.5 ± 1.5 | 19.4 ± 2.1 |
| $t\bar{t}$+V | 8.12 ± 0.78 | 6.7 ± 1.0 |
| Diboson | 1.02 ± 0.34 | 3.32 ± 0.35 |
| QCD | 3.0 ± 2.5 | 0.10 ± 0.09 |
| SM Expected | 189 ± 14 | 292 ± 25 |
| Data | 181 | 305 |
| S 10,1 | 19.7 ± 6.2 | 16.3 ± 5.5 |
| S 100,1 | 10.16 ± 0.82 | 7.29 ± 0.68 |
| PS 100,1 | 7.74 ± 0.39 | 6.05 ± 0.33 |

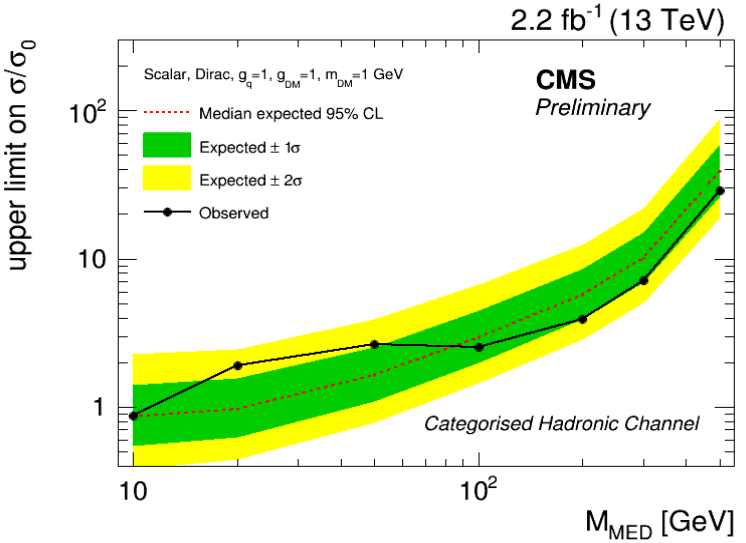
# $t\bar{t}$+MET Limits

- $t\bar{t}$+MET results split by semileptonic and hadronic channels

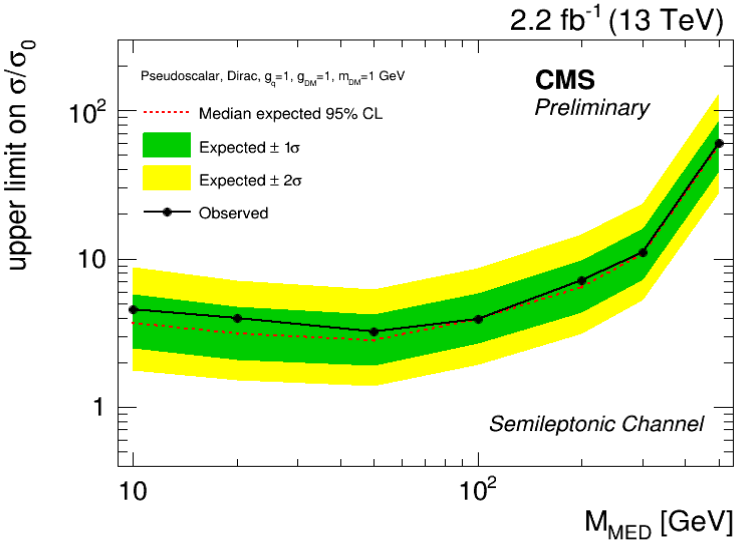
**Semileptonic** | **Hadronic**

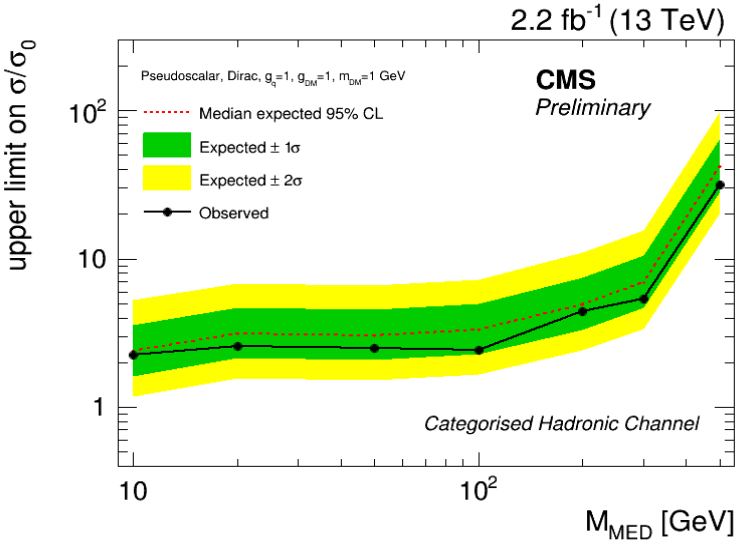
**Scalar results**




**Pseudoscalar results**



# Resolved Top Tagger

- MVA discriminant to identify tri-jet combinations from top quark decays
- Training a BDT with simulated $t\bar{t}$ events
- Input variables:
  - Kinematic fit probability
  - b-tag discriminant
  - Quark/gluon likelihood
  - $\Delta R(j_1,b)$, $\Delta R(j_2,b)$
  - $\Delta\varphi(j_1,b)$, $\Delta\varphi(j_2,b)$
- Efficiencies in MC calibrated with $t\bar{t}$ events in data
- Tops in $t\bar{t}$+DM production generally have moderate $p_T$