Two is not always better than one: Single Top Quarks and Dark Matter

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Alberto Zucchetta

In collaboration with:
Deborah Pinna, Matthew Buckley, Florencia Canelli

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Universität Zürich[UZH]

Dark matter and heavy flavour quarks

D. Pinna, A. Zucchetta, M. Buckley, F. Canelli
arXiv:1701.05195

There are several theories predicting **DM production** at hadron colliders

- different assumptions can be made on the mediator particle and on the kind of interaction (spin, parity, . . .)

→ Spin-0 simplified model: Phys. Rev. D91 015017, arXiv:1507.00966

- scalar and/or pseudo-scalar mediators
- minimal flavour violation, couplings proportional to SM fermions masses
- also used to interpret LHC results

Scalar

$$g_q \frac{\phi}{2} \sum_f y_f \bar{f} f$$

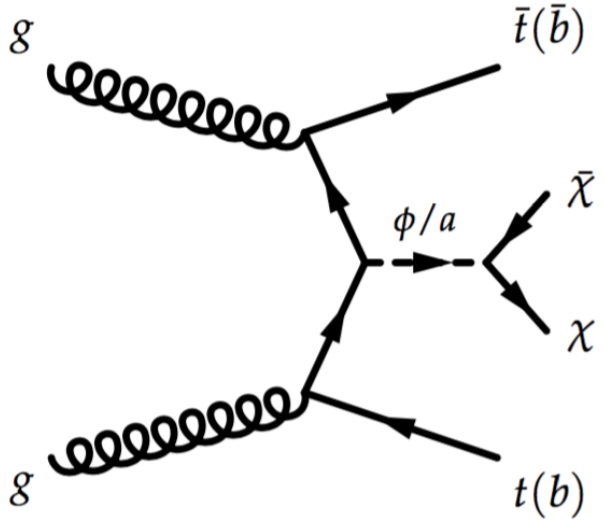
Pseudoscalar

$$g_q \frac{iA}{2} \sum_f y_f \bar{f} \gamma^5 f$$

Channels covered by DM and heavy flavour searches:

- ATLAS $b\bar{b}$+DM (ATLAS-CONF-2016-086)
- CMS $b\bar{b}$+DM (CMS-PAS-B2G-15-007)
- ATLAS $t\bar{t}$+DM (ATLAS-CONF-2016-077)
- CMS $t\bar{t}$+DM (CMS-PAS-EXO-16-005)

Is there something missing?



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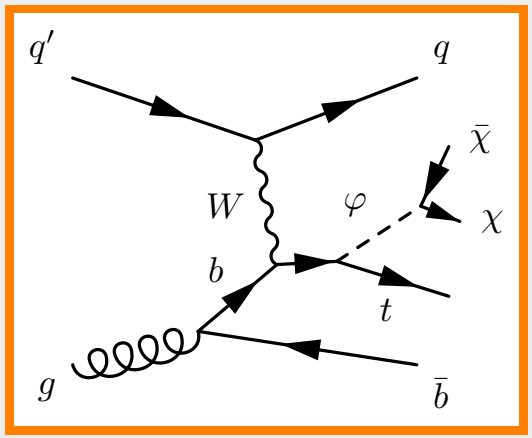
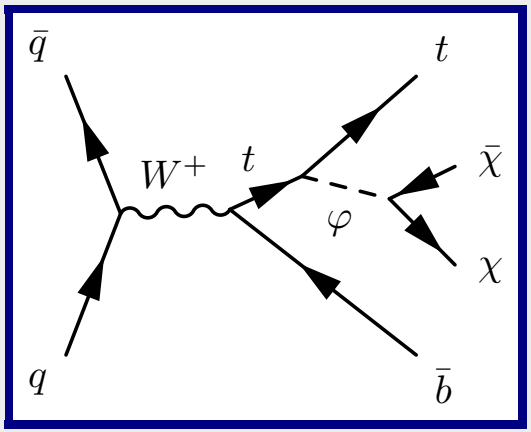
- Same spin-0 simplified model predicts a third, unexplored channel: DM produced with a single top quark (t+DM)

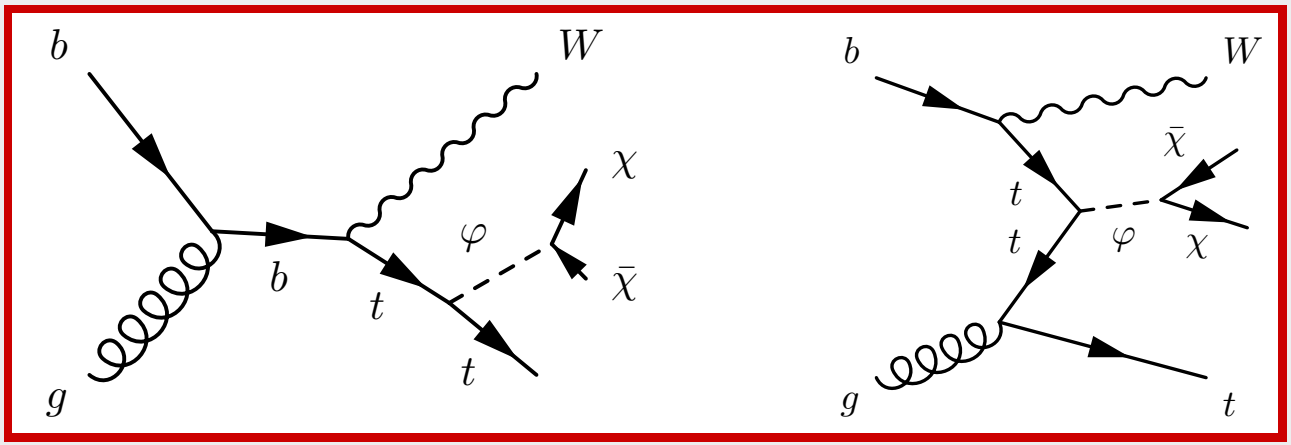
t-channel



s-channel



tW-channel



Dark matter and single top: phenomenology

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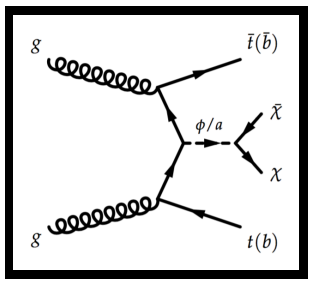
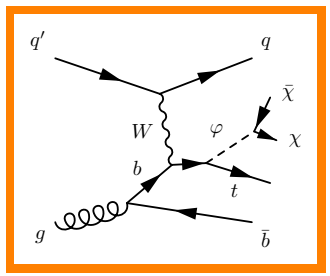
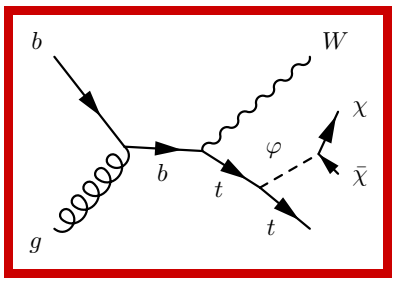
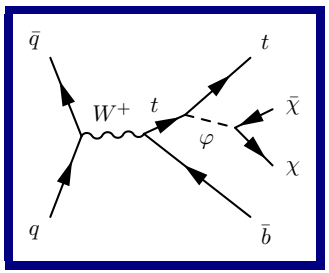
- Unlike in the SM, t+DM processes may have non-negligible cross sections compared to $t\bar{t}$+DM

	$g_\chi = g_\varphi = 1$ $m_\chi,\ m_\varphi$	$t\bar{t}$+DM (pb)	t+DM (pb) t–channel	tW–channel	s–channel	total t+DM	$\frac{\text{t+DM}}{\text{tt+DM}}$
scalar	1, 10	19.76	$27.18 \cdot 10^{-1}$	$73.25 \cdot 10^{-2}$	$7.03 \cdot 10^{-2}$	$35.20 \cdot 10^{-1}$	**0.18**
	1, 20	10.55	$17.03 \cdot 10^{-1}$	$40.44 \cdot 10^{-2}$	$36.29 \cdot 10^{-3}$	$21.43 \cdot 10^{-1}$	**0.20**
	1, 50	$30.06 \cdot 10^{-1}$	$7.00 \cdot 10^{-1}$	$14.09 \cdot 10^{-2}$	$10.10 \cdot 10^{-3}$	$8.51 \cdot 10^{-1}$	**0.29**
	1, 100	$69.60 \cdot 10^{-2}$	$26.83 \cdot 10^{-2}$	$55.49 \cdot 10^{-3}$	$24.74 \cdot 10^{-4}$	$32.62 \cdot 10^{-2}$	**0.47**
	1, 200	$99.16 \cdot 10^{-3}$	$7.37 \cdot 10^{-2}$	$22.15 \cdot 10^{-3}$	$37.6 \cdot 10^{-5}$	$9.62 \cdot 10^{-2}$	**0.97**
	1, 300	$32.21 \cdot 10^{-3}$	$28.88 \cdot 10^{-3}$	$12.04 \cdot 10^{-3}$	$9.87 \cdot 10^{-5}$	$41.02 \cdot 10^{-3}$	**1.27**
	1, 500	$59.00 \cdot 10^{-4}$	$43.85 \cdot 10^{-4}$	$27.61 \cdot 10^{-4}$	$9.01 \cdot 10^{-6}$	$71.55 \cdot 10^{-4}$	**1.21**
	1, 1000	$46.03 \cdot 10^{-5}$	$24.99 \cdot 10^{-5}$	$23.46 \cdot 10^{-5}$	$27.64 \cdot 10^{-8}$	$48.48 \cdot 10^{-5}$	**1.05**
pseudoscalar	1, 10	$44.63 \cdot 10^{-2}$	$15.34 \cdot 10^{-2}$	$66.36 \cdot 10^{-3}$	$19.69 \cdot 10^{-4}$	$22.19 \cdot 10^{-2}$	**0.50**
	1, 20	$40.80 \cdot 10^{-2}$	$14.19 \cdot 10^{-2}$	$61.82 \cdot 10^{-3}$	$16.78 \cdot 10^{-4}$	$20.53 \cdot 10^{-2}$	**0.50**
	1, 50	$30.72 \cdot 10^{-2}$	$10.94 \cdot 10^{-2}$	$50.00 \cdot 10^{-3}$	$10.30 \cdot 10^{-4}$	$16.04 \cdot 10^{-2}$	**0.52**
	1, 100	$19.41 \cdot 10^{-2}$	$7.04 \cdot 10^{-2}$	$35.79 \cdot 10^{-3}$	$47.79 \cdot 10^{-5}$	$10.66 \cdot 10^{-2}$	**0.55**
	1, 200	$86.78 \cdot 10^{-3}$	$31.39 \cdot 10^{-3}$	$19.65 \cdot 10^{-3}$	$13.20 \cdot 10^{-5}$	$51.17 \cdot 10^{-3}$	**0.59**
	1, 300	$42.50 \cdot 10^{-3}$	$15.55 \cdot 10^{-3}$	$11.33 \cdot 10^{-3}$	$46.28 \cdot 10^{-6}$	$26.92 \cdot 10^{-3}$	**0.63**
	1, 500	$59.43 \cdot 10^{-4}$	$22.27 \cdot 10^{-4}$	$19.96 \cdot 10^{-4}$	$41.72 \cdot 10^{-7}$	$42.27 \cdot 10^{-4}$	**0.71**
	1, 1000	$48.33 \cdot 10^{-5}$	$19.09 \cdot 10^{-5}$	$21.44 \cdot 10^{-5}$	$19.31 \cdot 10^{-8}$	$40.56 \cdot 10^{-5}$	**0.84**









Dark matter and single top: phenomenology

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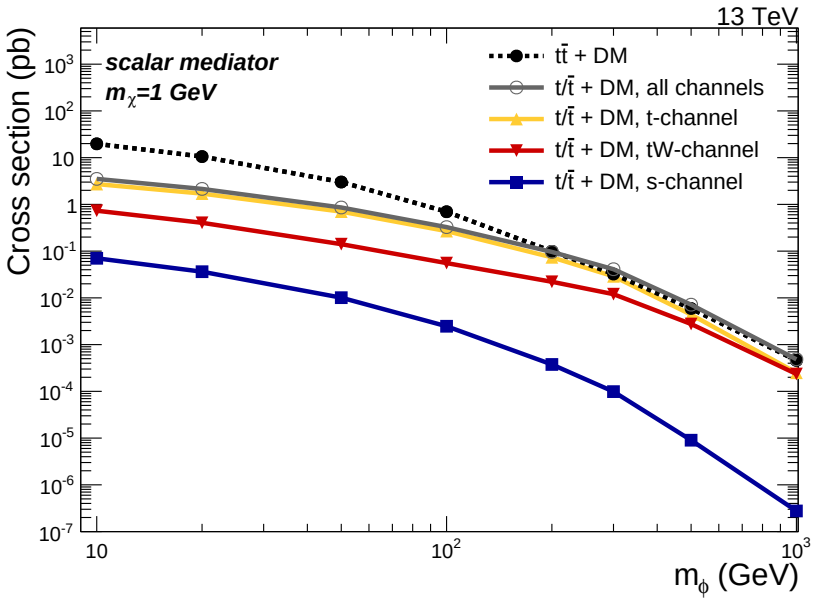
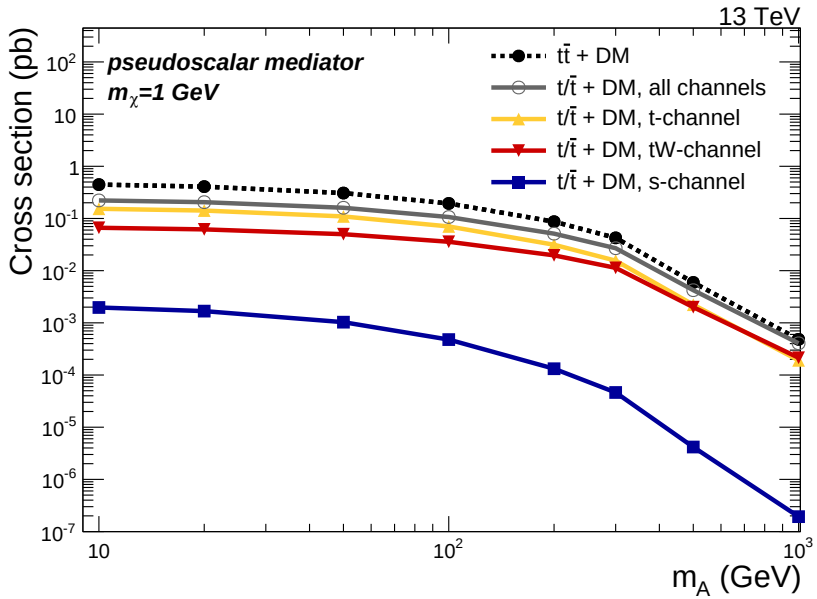
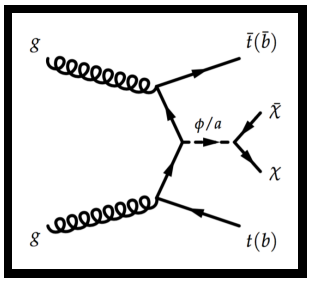
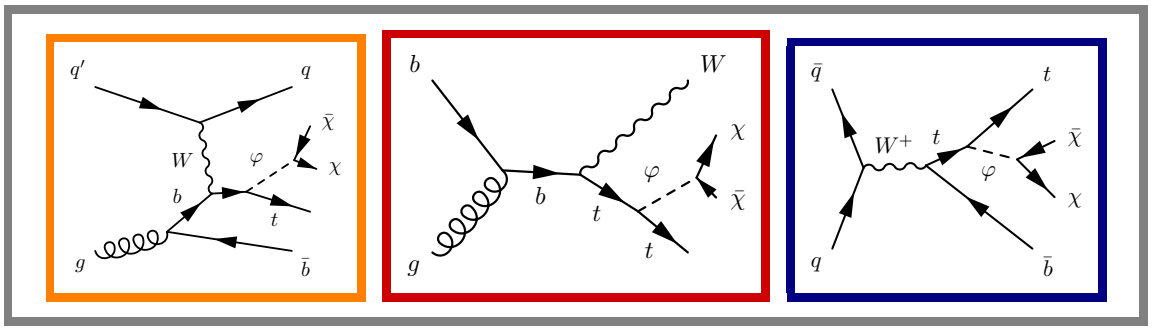
- Unlike in the SM, t+DM processes may have non-negligible cross sections compared to $t\bar{t}$+DM









Dark matter and single top: sensitivity

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What is the impact of the new channel on existing searches?

0. Reference analysis → CMS search for $t\bar{t}$+DM (CMS-PAS-EXO-16-005)
   - Similar final state and topology: top quarks and missing energy
   - Results interpreted within the same model
   - Evaluate the improvement by adding t+DM on top of $t\bar{t}$+DM
1. Validate simulation framework
   - Madgraph (LO) + Pythia (showering) + Delphes (CMS response)
   - 200 000 $t\bar{t}$+DM events generated
   - reproduce $t\bar{t}$+DM yields from CMS-PAS-EXO-16-005 after selection
2. Use simulation framework to produce t+DM samples
   - tW-channel in 5F scheme and t-, s-channels in 4F scheme
   - cross section calculated in 5F scheme
   - tW-, s-channel 200 000 events, t-channel 500 000 events
3. Reproduce analysis selections, and compare t+DM and $t\bar{t}$+DM yields
4. Compute limits improvements

Dark matter and single top: validation

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1. Event selection and comparison with CMS-PAS-EXO-16-005

Hadronic channel (0ℓ)	
$\not{E}_T$	> 200 GeV
number of jets	≥ 4
number of b-jets	≥ 2

Semileptonic channel (1ℓ)	
$\not{E}_T$	> 160 GeV
number of jets	≥ 3
number of b-jets	≥ 1
m_T^W	> 160 GeV
m_{T2}^W	> 200 GeV

Dark matter and single top: validation

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Semileptonic channel (1ℓ)	
$\not{E}_T$	> 160 GeV
number of jets	≥ 3
number of b-jets	≥ 1
m_T^W	> 160 GeV
m_{T2}^W	> 200 GeV

- Check consistency between CMS analysis and DELPHES parametrization:

	$t\bar{t}$+DM	
m_χ, m_φ (GeV)	CMS	Delphes
$m_\chi = 1,\ m_\phi = 10$	20 ± 12	23.9 ± 2.3
$m_\chi = 1,\ m_\phi = 100$	10.0 ± 3.0	10.1 ± 0.42
$m_\chi = 1,\ m_A = 100$	8.5 ± 1.4	8.03 ± 0.13

	$t\bar{t}$+DM	
m_χ, m_φ (GeV)	CMS	Delphes
$m_\chi = 1,\ m_\phi = 10$	9.1 ± 4.3	8.8 ± 1.8
$m_\chi = 1,\ m_\phi = 100$	4.64 ± 0.56	4.78 ± 0.38
$m_\chi = 1,\ m_A = 100$	4.36 ± 0.29	4.61 ± 0.13

Dark matter and single top: kinematics

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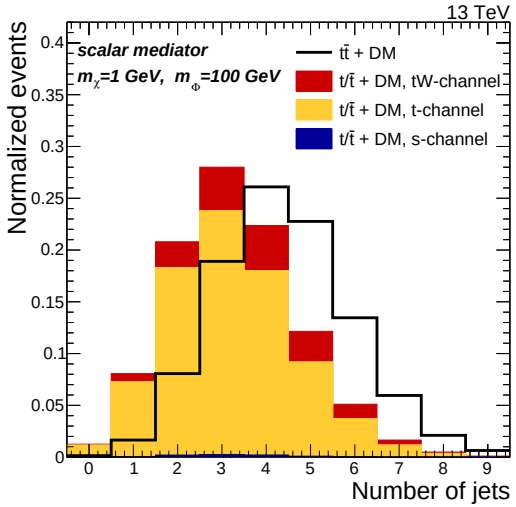
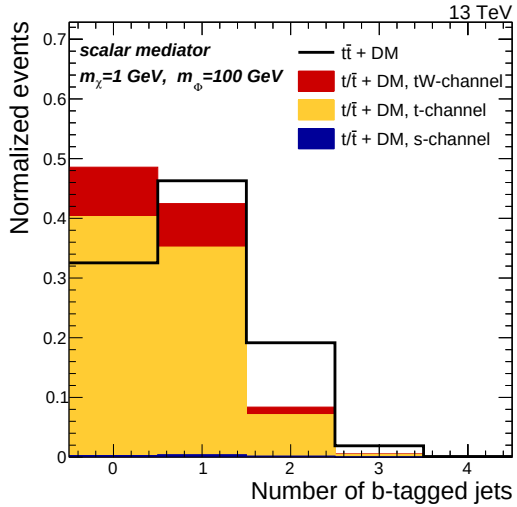
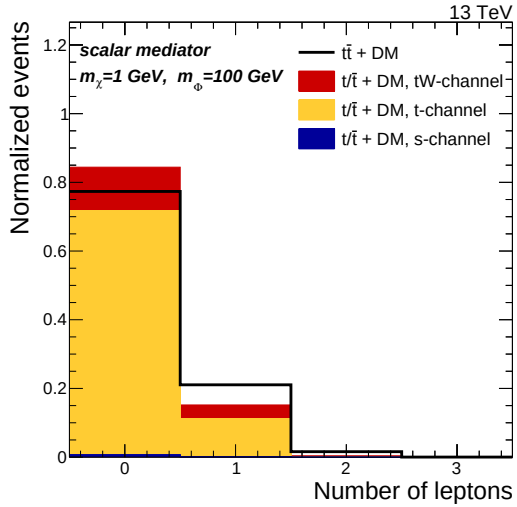
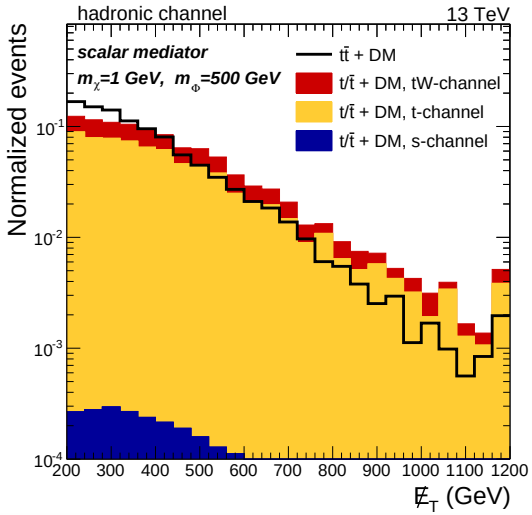
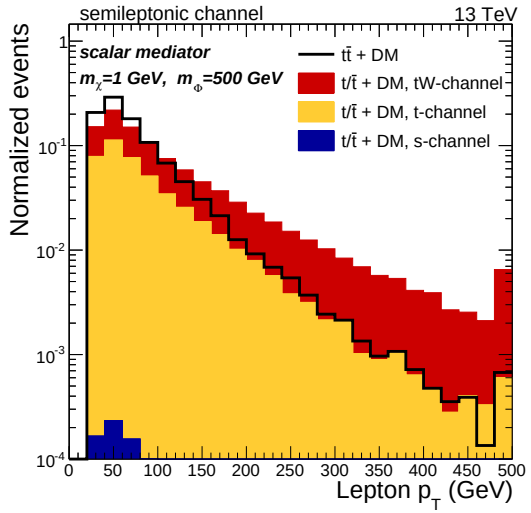


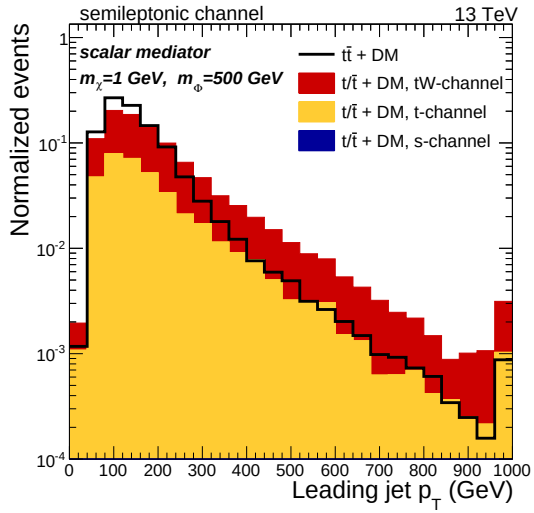




- Object multiplicity is different
  - one less top quark in the final state
- t+DM spectra tend to be "harder" than $t\bar{t}$+DM for $m_\Phi \gtrsim 100$ GeV
  - initial state is different (gluon-gluon for $t\bar{t}$+DM , quark-gluon for t+DM)







Dark matter and single top: efficiency and yield

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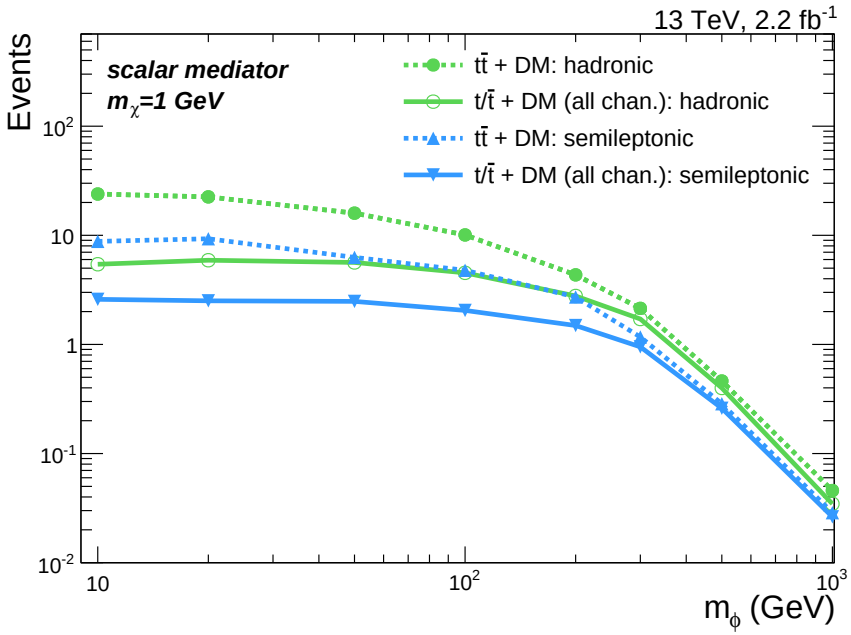
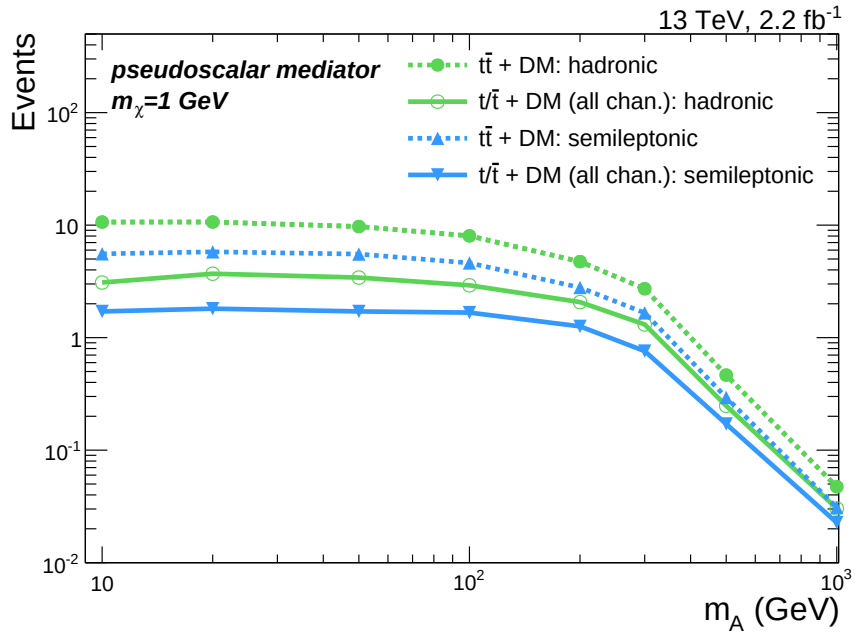
2. Simulate $t\bar{t}$+DM , t+DM samples with Madgraph+Pythia+DELPHES
3. Compare t+DM and $t\bar{t}$+DM signal yields after applying the same selections as in CMS-PAS-EXO-16-005
   - significant t+DM yields contribution ($\gtrsim 30\%$) even after selection





Note: selections optimized for events with **two** top quarks!

Dark matter and single top: sensitivity

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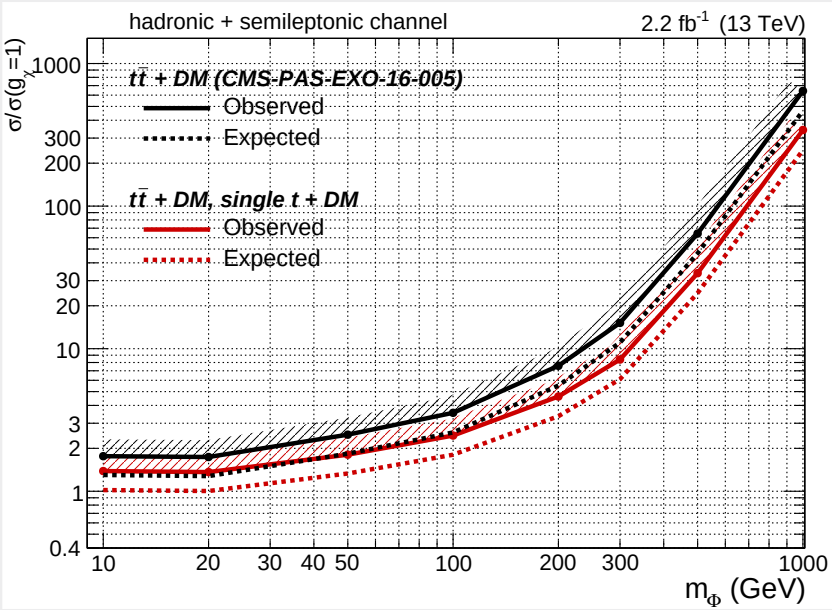
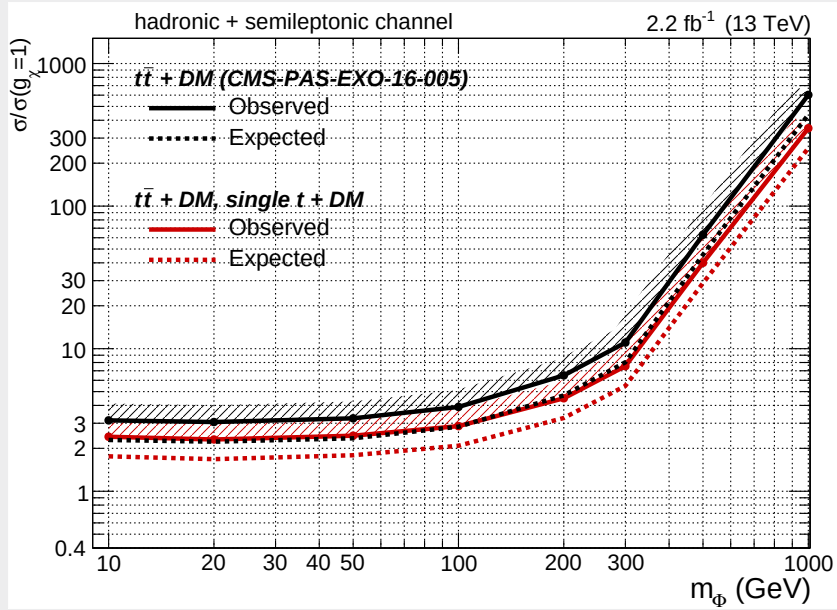
4 Impact on existing limits: improvements obtained including t+DM in addition to the $t\bar{t}$+DM signal

- use CMS $t\bar{t}$+DM analysis as reference
- no shape information $\rightarrow$ counting experiment
- data and SM bkg events (plus unc.) from CMS-PAS-EXO-16-005

Scalar



Pseudoscalar



Improvement between 30% to factor 2 by adding t+DM to $t\bar{t}$+DM

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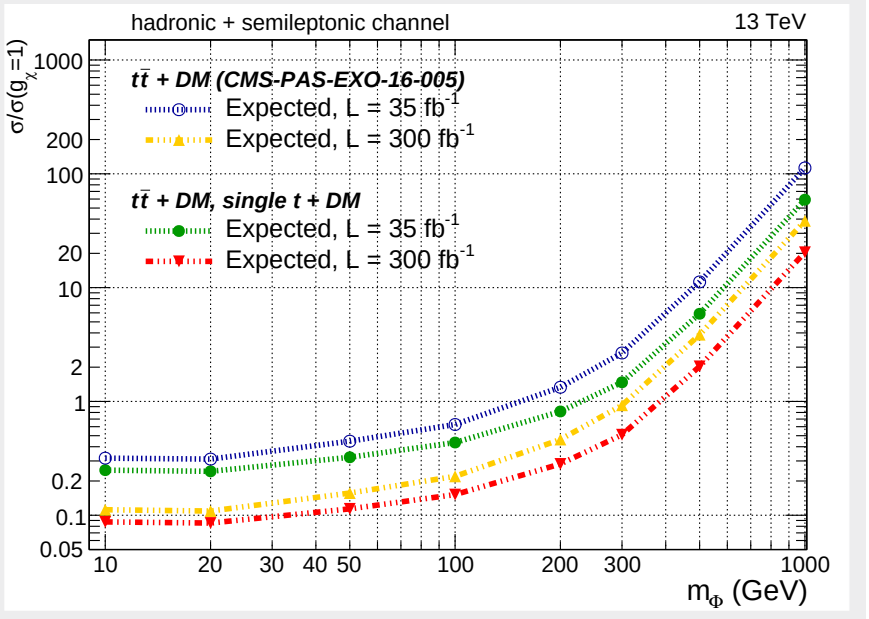
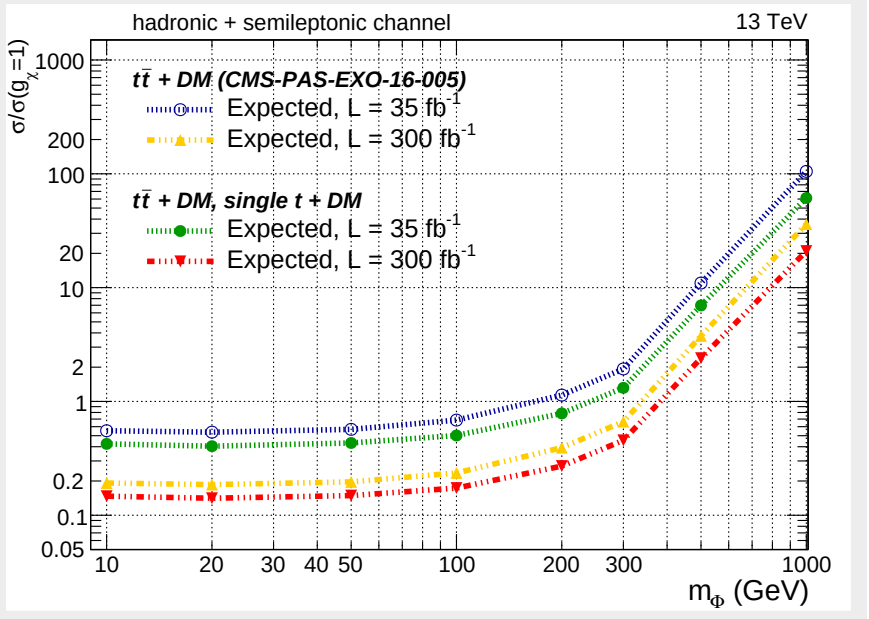
4 **Impact on existing limits**: improvements obtained including t+DM in addition to the $t\bar{t}$+DM signal

- Sensitivity projection for:
  - 2016 dataset of 35 fb^{-1}
  - End of 2023 dataset of 300 fb^{-1}
- Simplified assumptions on the uncertainty scaling (bkg $\propto \sqrt{\mathcal{L}}$, signal $\propto \mathcal{L}$)

Scalar



Pseudoscalar



Improvement between 30% to factor 2 by adding t+DM to $t\bar{t}$+DM

Concluding remarks

- Considered for first time single top and DM associated production (spin-0 simpl. model with MFV)
- We demonstrated that this process can have a sizable contribution to heavy-flavoured DM searches ($\gtrsim 30\%$)
- The sensitivity of new process has been assessed:
  - include t+DM on top of $t\bar{t}$+DM within CMS-PAS-EXO-16-005 search
  - exclusion limits improvements up to a factor 2 - even in future scenarios
- Study documented in arXiv:1701.05195, submitted to PRD
- Further improvements expected with a dedicated analysis for t+DM

Backup slides

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Dark matter and single top: sensitivity

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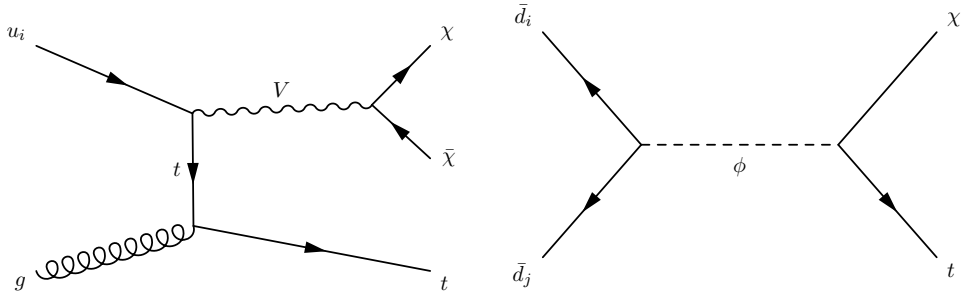
Assess the sensitivity of the t+DM process at LHC experiments:

- **CMS-PAS-EXO-16-040**: CMS boosted "mono-top" search, different topology and phase space (2 body decay, FCNC, boosted)
  - Different model, cannot add t+DM to $t\bar{t}$+DM easily



- **CMS-PAS-B2G-15-007, ATLAS-CONF-2016-086**: b,bb+DM also retain some sensitivity, but efficiency is very low (lepton veto, low jet multiplicity)
- **CMS-PAS-EXO-16-005, ATLAS-CONF-2016-077**: the $t\bar{t}$+DM probes a similar phase space $\rightarrow$ best candidate to test the t+DM potential
  - Use CMS $t\bar{t}$+DM analysis as reference, and evaluate the improvement by adding t+DM on top of $t\bar{t}$+DM

Monojet comparison

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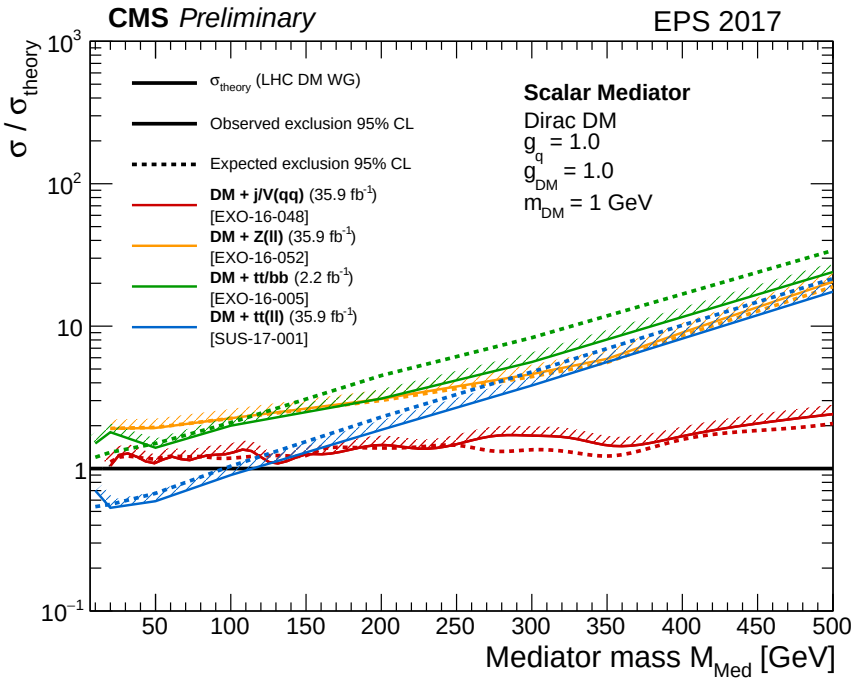

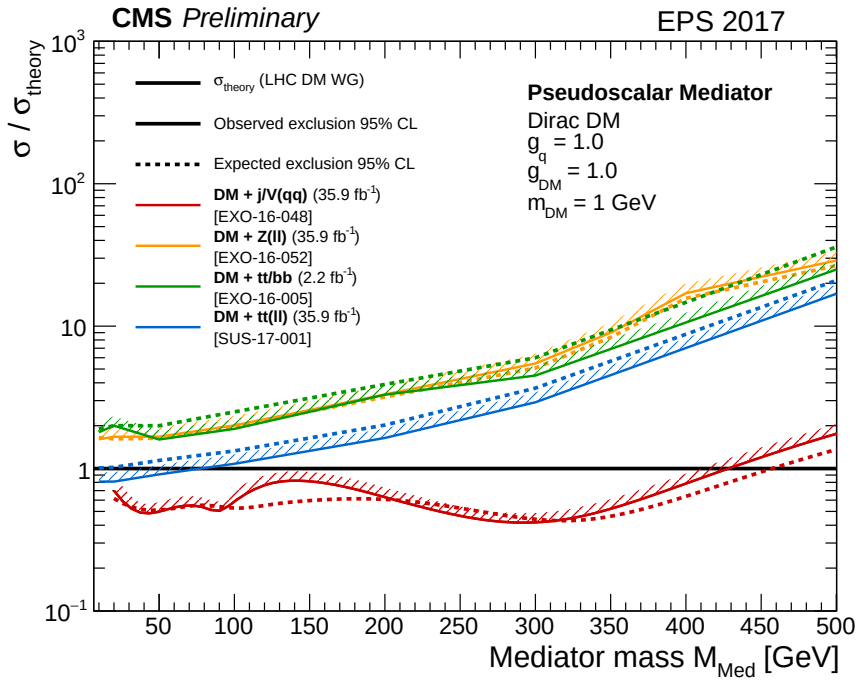

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	SR $\not{E}_T$ >200
$t\bar{t}$	214 ± 20
WJets	24.9 ± 4.0
Drell-Yan	0.44 ± 0.14
SingleTop	20.4 ± 2.9
QCD	0.10 ± 0.04
ZToNuNu	52.6 ± 7.0
ttV	6.3 ± 1.6
VV	5.17 ± 0.96
Backgrounds	324 ± 22
Data	333
scalar m_{MED} = 10 GeV, m_{DM} = 1 GeV	20 ± 12
scalar m_{MED} = 100 GeV, m_{DM} = 1 GeV	10.0 ± 3.0
pseudoscalar m_{MED} = 100 GeV, m_{DM} = 1 GeV	8.5 ± 1.4

	2 top tags	<2 top tags
$t\bar{t}$	145 ± 14	194 ± 20
WJets	12.1 ± 1.4	23.5 ± 4.6
Drell-Yan	0.15 ± 0.04	0.25 ± 0.09
SingleTop	7.5 ± 1.5	19.4 ± 2.1
QCD	3.0 ± 2.5	0.10 ± 0.09
ZToNuNu	12.9 ± 1.3	44 ± 13
ttV	8.12 ± 0.78	6.7 ± 1.0
VV	1.02 ± 0.34	3.32 ± 0.35
Backgrounds	189 ± 14	292 ± 25
Data	181	305
scalar m_{MED} = 10 GeV, m_{DM} = 1 GeV	19.7 ± 6.2	16.3 ± 5.5
scalar m_{MED} = 100 GeV, m_{DM} = 1 GeV	10.16 ± 0.82	7.29 ± 0.68
pseudoscalar m_{MED} = 100 GeV, m_{DM} = 1 GeV	7.74 ± 0.39	6.05 ± 0.33

CMS-PAS-EXO-16-005

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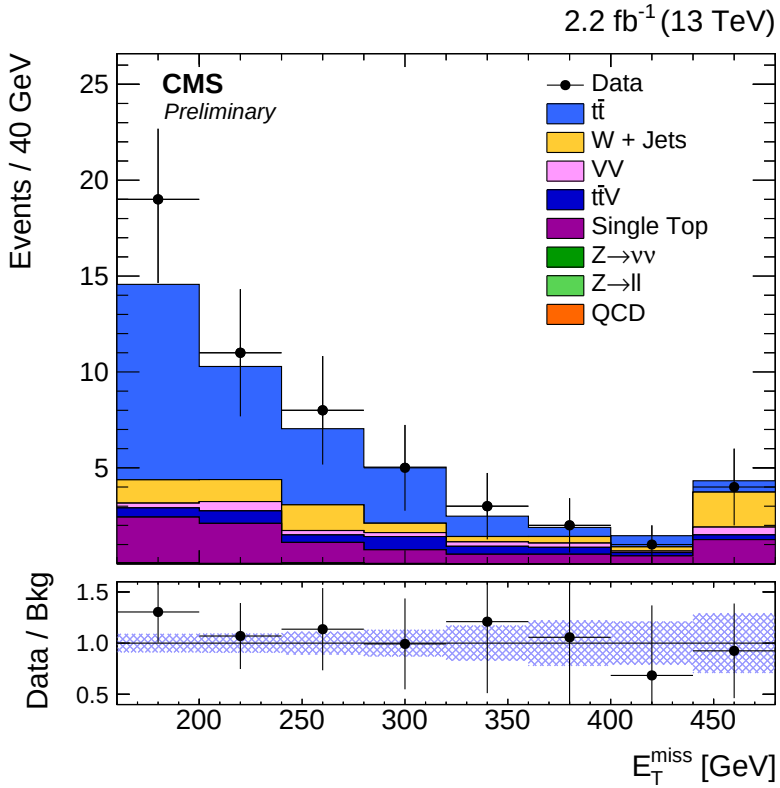

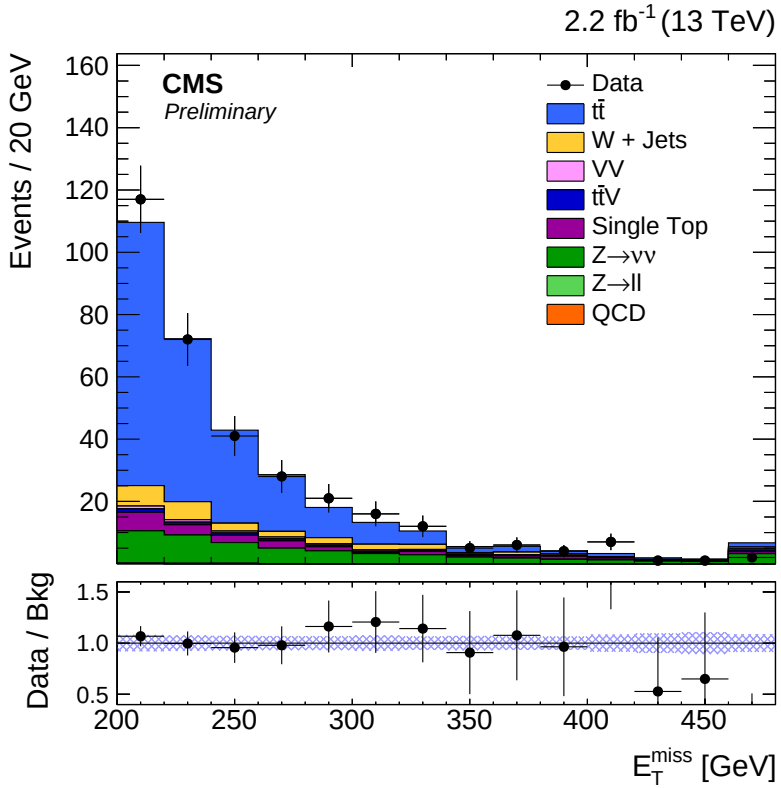

CMS-PAS-EXO-16-005

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