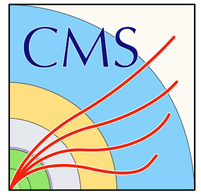
BSM searches with top final states

Junpei Maeda (Kobe University)

on behalf of the ATLAS and CMS Collaborations

The ninth Annual Conference on Large Hadron Collider Physics (LHCP2021)

Online, 7-12 June 2021

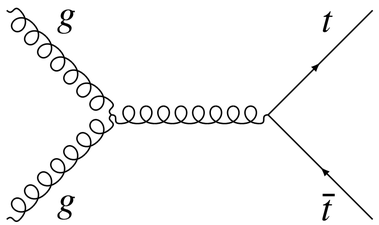


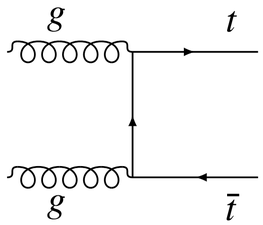
Introduction

LHC as a top factory — able to access BSM searches using a huge sample with the heaviest quark.

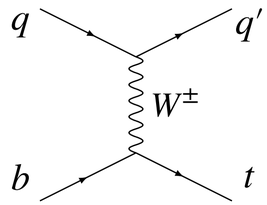
- Many top-related SM measurements are ongoing.

ttbar

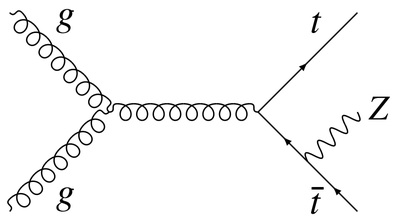


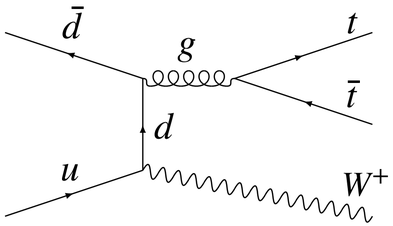


single-top

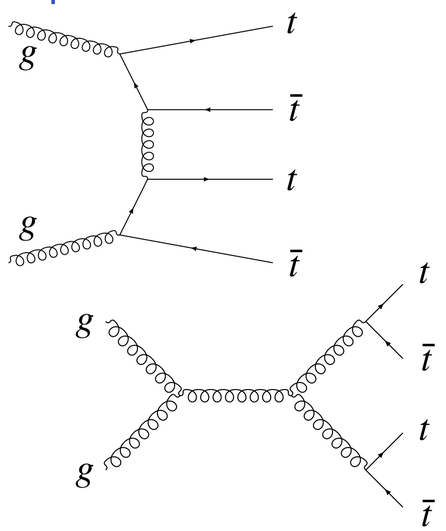


ttbar + V

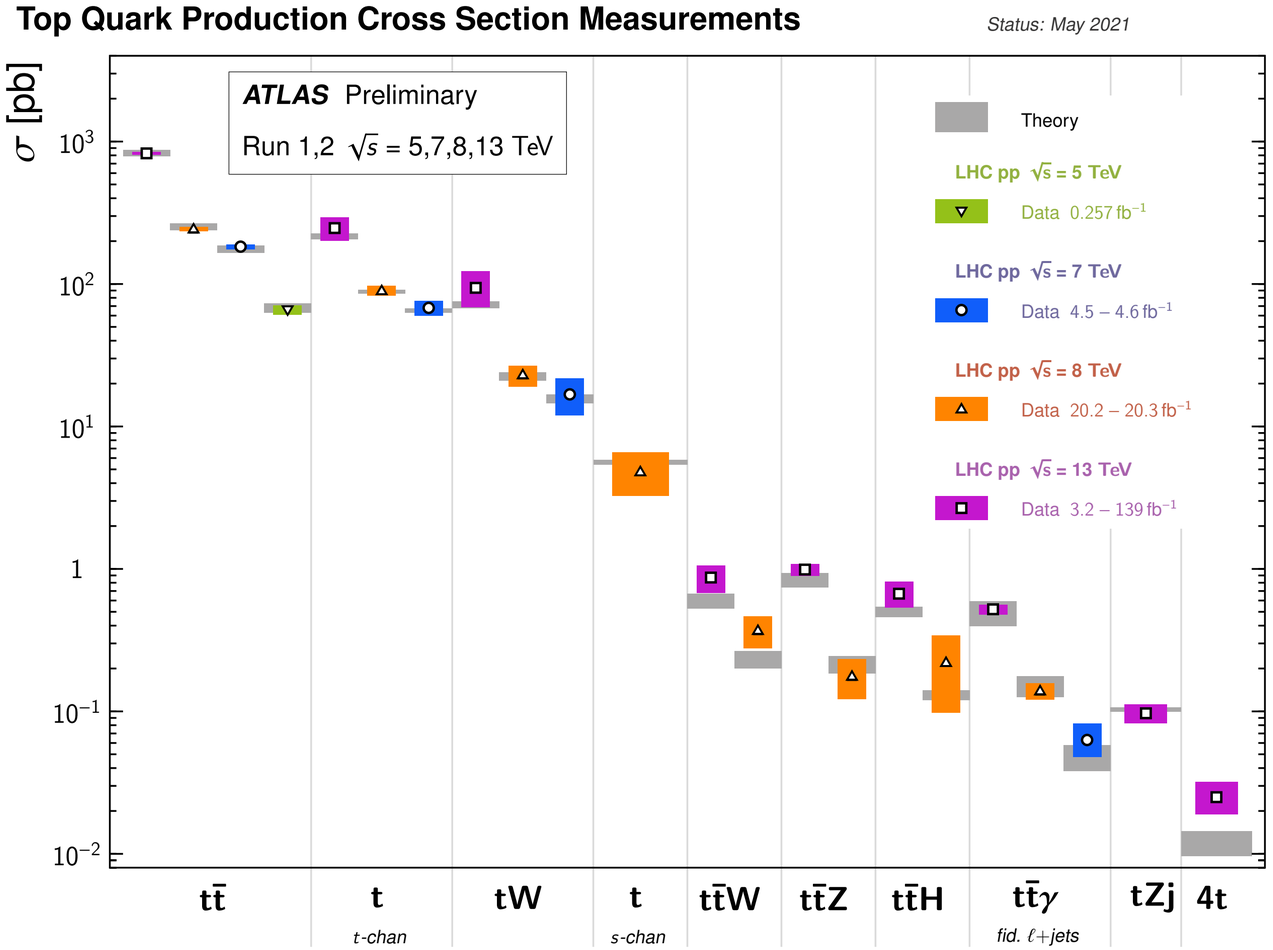




4-tops



- Events of same topologies are expected in many BSM.

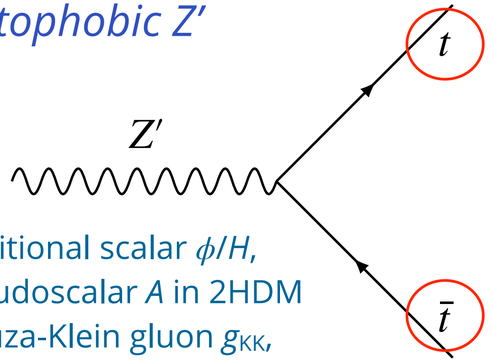


ATL-PHYS-PUB-2021-014

Introduction

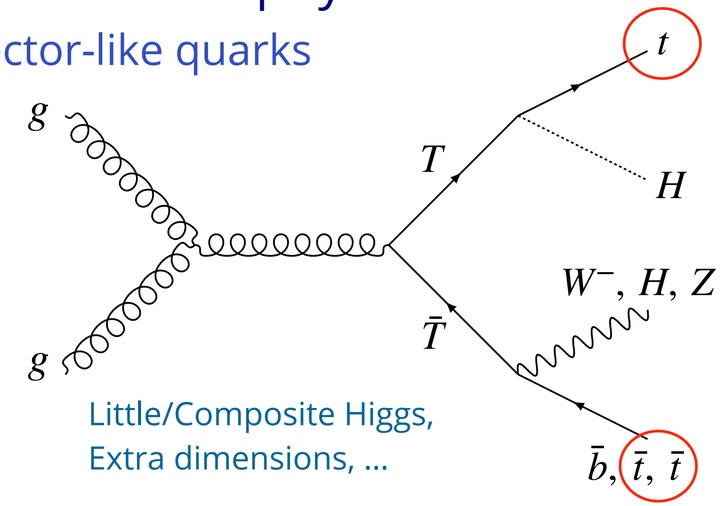
Signatures of top final states may indicate new physics.

Leptophobic Z'



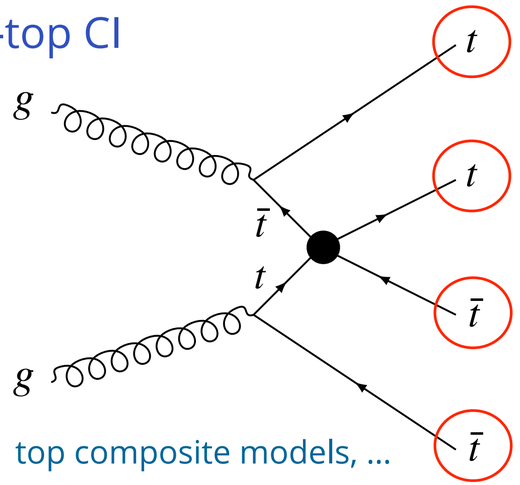
Additional scalar ϕ/H,
Pseudoscalar A in 2HDM
Kaluza-Klein gluon g_{KK},

Vector-like quarks



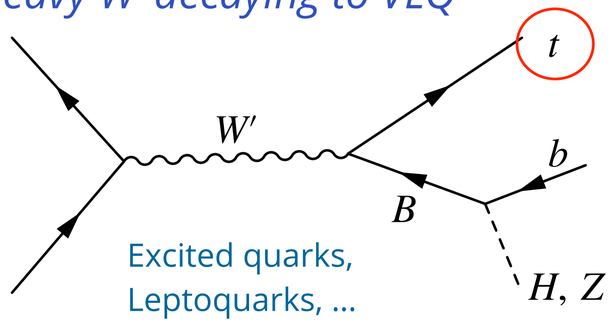
Little/Composite Higgs,
Extra dimensions, ...

4-top CI



top composite models, ...

Heavy W' decaying to VLQ



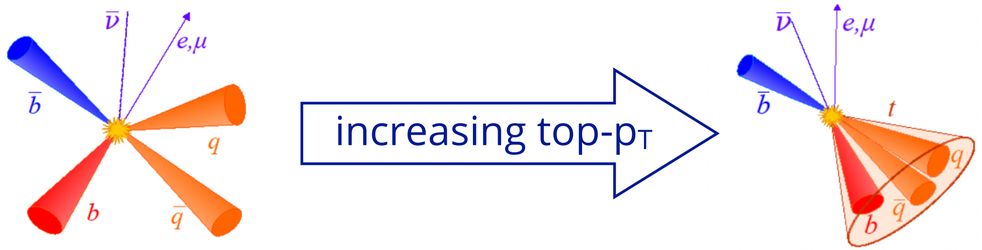
Excited quarks,
Leptoquarks, ...

and many other physics and/or topologies...

This talk will not cover SUSY-related and SM-top measurements that shows BSM signs (e.g. *Lepton Flavour Universality* and *CP Violation*).

Top quark decays to $W^{\pm} + b$ $(V_{tb} \sim 1)$

- Several object ID techniques are needed to tag a top quark.
  - High-pT leptons and/or quark-jets from W, neutrinos identified as MET
  - b-jet tagging, top tagging of boosted-top



$t\bar{t}$ resonance for Z' and g_{KK}

[ATLAS-EXOT-2015-04](), [ATLAS-EXOT-2018-48]()
[CMS-B2G-17-017]()

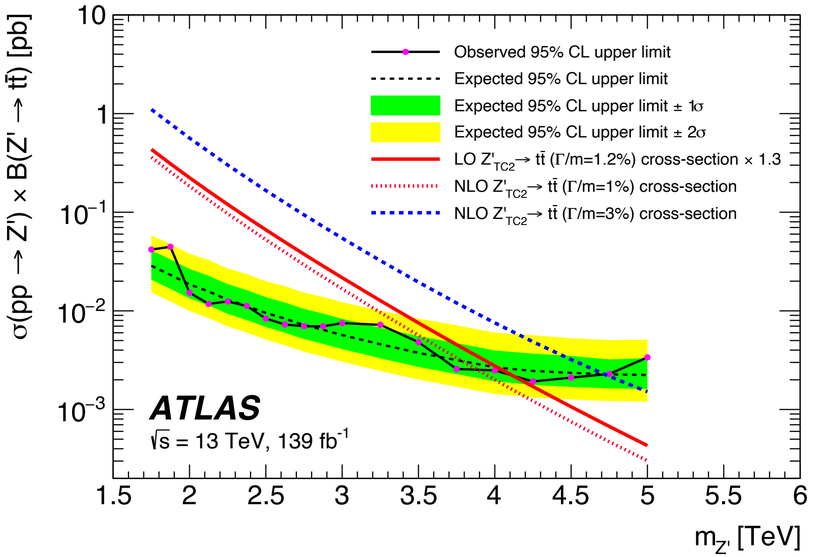
ATLAS full-hadronic channel @ 139 fb^{-1}

- used the DNN top-tagging
- Limits set on Z' in topcolor-assisted-technicolor model

$$m_{Z'} > 3.9\ (4.7)\ \text{TeV} \quad \text{for} \quad \Gamma/m = 1\,(3)\,\%$$

  - only 2015-16 data of 36 fb^{-1} is available for semi-leptonic channel

$$m_{Z'_{\text{TC}}} > 3.0\ \text{TeV} \quad \text{for} \quad \Gamma/m = 1\,\%, \quad m_{g_{\text{KK}}} > 3.8\ \text{TeV} \quad \text{for} \quad \Gamma/m = 15\,\%$$



CMS combined all three channels @ 35.9 fb^{-1}

- Limit set on the Kaluza-Klein gluon in the Randall-Sundrum scenario

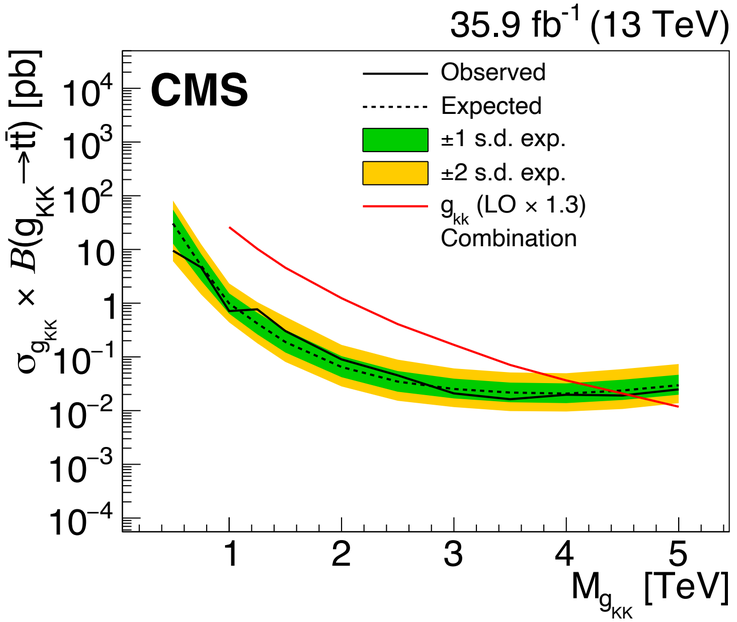
$$m_{g_{\text{KK}}} > 4.55\ \text{TeV}$$

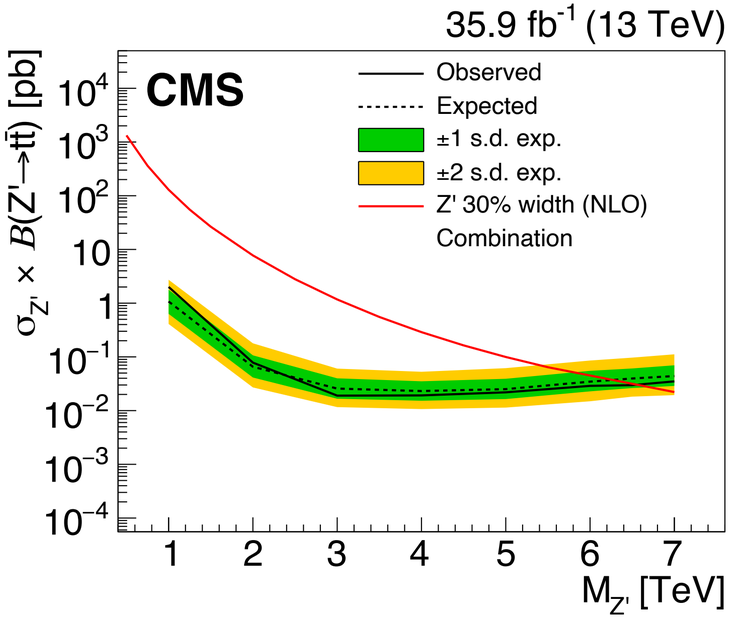
- Limits set on topcolor Z'

$$m_{Z'} > 3.80\ \text{TeV} \quad \text{for} \quad \Gamma/m = 1\,\%$$

$$m_{Z'} > 5.25\ \text{TeV} \quad \text{for} \quad \Gamma/m = 10\,\%$$

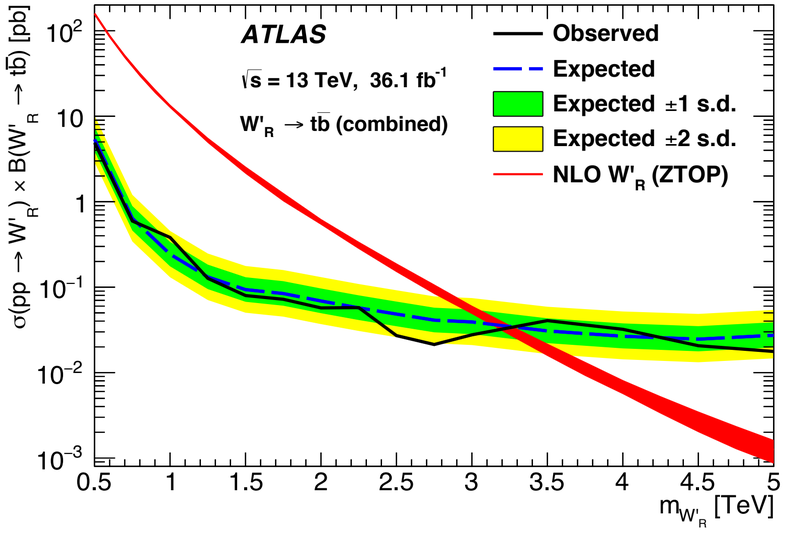
$$m_{Z'} > 6.65\ \text{TeV} \quad \text{for} \quad \Gamma/m = 30\,\%$$

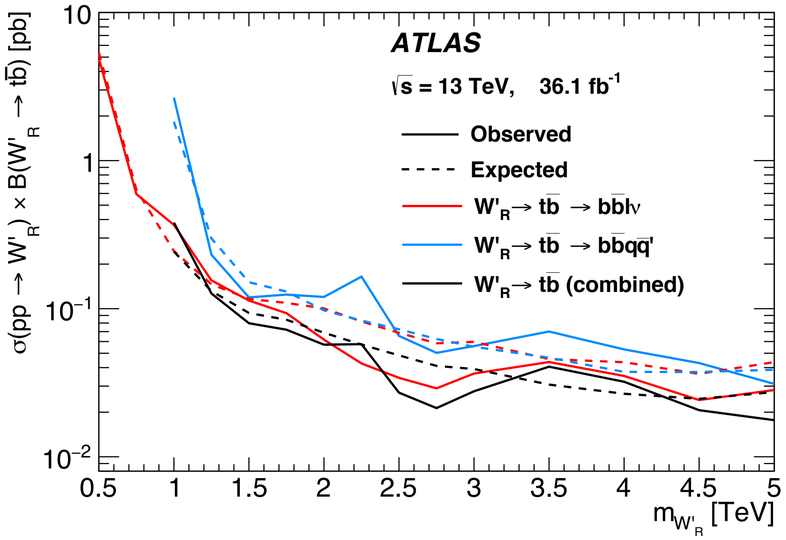




tb resonance for *W′*

[ATLAS-EXOT-2016-18]
[CMS-B2G-20-005]



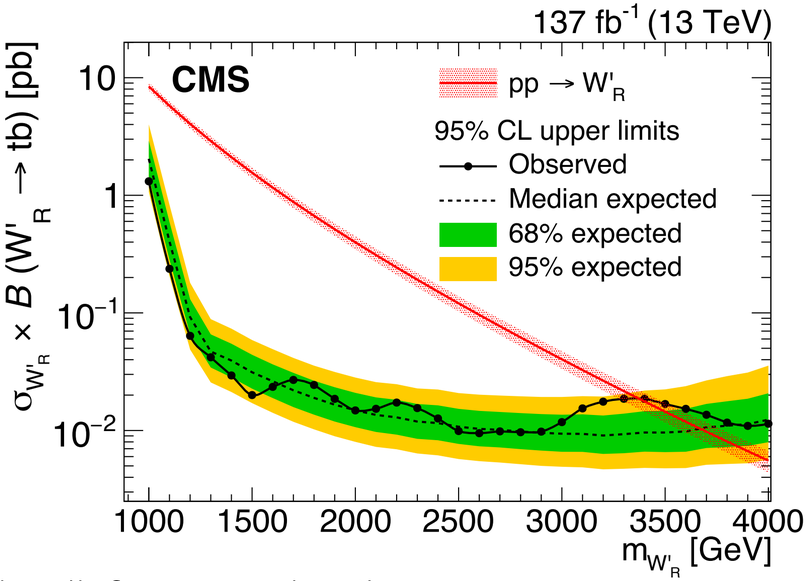


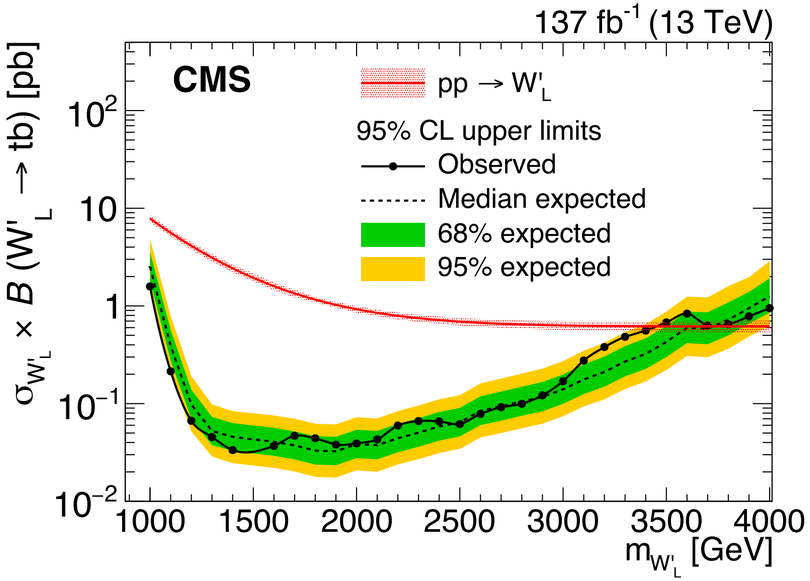
ATLAS @ 36.1 fb^{-1}

- searched for only right-handed W′
- combined lepton+jet channel with full-hadronic channel
- $m_{W'_R} > 3.25$ TeV

CMS hadronic channel @ 137 fb^{-1}

- limits on both right (left)-handed *W′*
- $m_{W'_{R,\,L}} > 3.4$ TeV

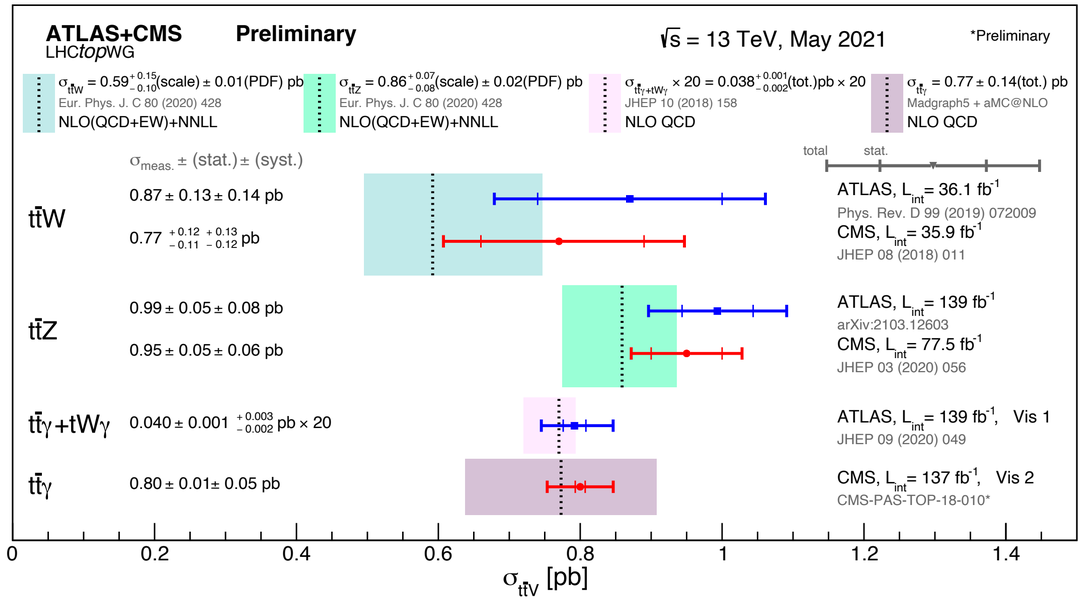




see *T. Novak's* and *A. O. M. Iorio's* resonance search talk for more details

BSM searches with $t(\bar{t}) + X$

ATLAS-PHYS-PUB-2021-013



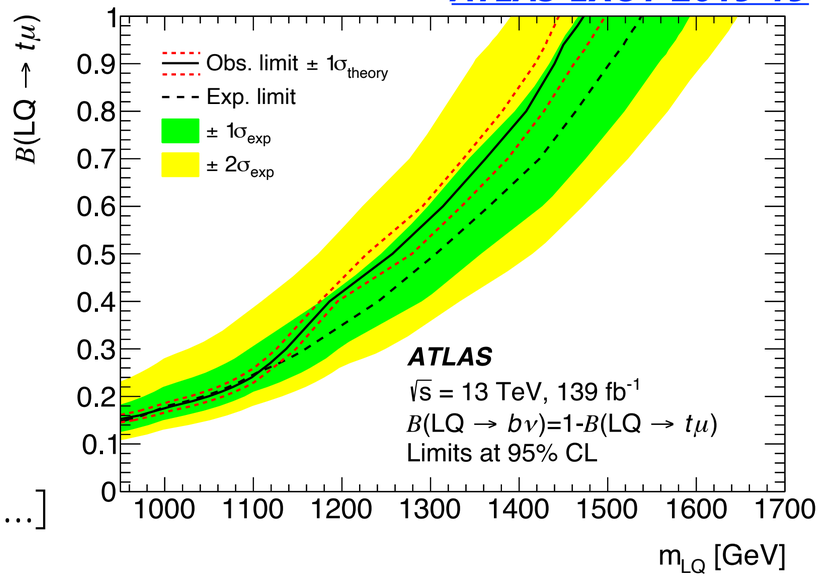
Associated production with a boson is very rare process.

- see *P. J. Falke's talk* for more details
- important topologies to BSM, e.g.
  - Excited fermions, Leptoquarks, Vector-Like Quarks, …

No evidence of BSM so far:

- Excited bottom: $b^* \to tW$ [*CMS-B2G-19-003*, *CMS-PAS-B2G-20-010*]
  - see *A.O.M. Iorio's talk for the resonance search*
- Leptoquarks [*ATLAS-EXOT-2019-15*, *ATLAS-EXOT-2019-19*, …]
  - see *E. Carquin Lopez's talk*
- Vector-Like Quark (VLQ) searches:
  - $T \to Zt, T \to Ht, T \to Wb, B \to Wt$ [*ATLAS-EXOT-2017-14*, *CMS-B2G-19-004*, …]
  - $W' \to Tb\,(tB)$ [*CMS-PAS-B2G-20-002*]
  - see next slide and *T. R. Andeen's VLQ talk*

ATLAS-EXOT-2019-19



They are also sensitive to EFT operators (e.g. *tt*+*Z* related to *tZ* coupling)

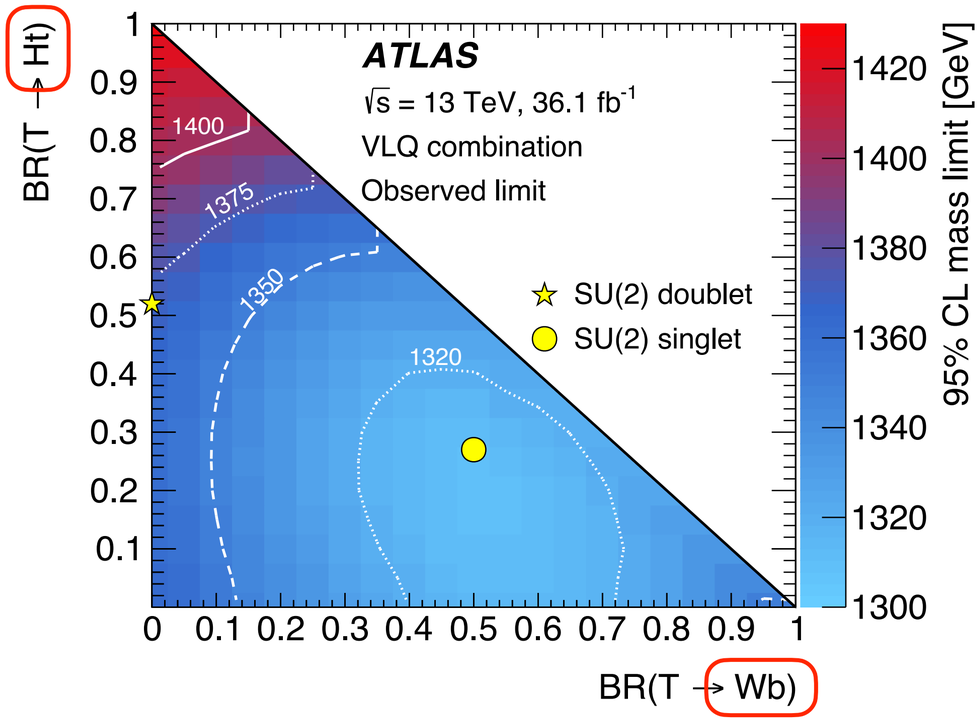
- see *L. Barranco Navarro's* and *J. Gonzalez's* talks in this session [*CMS-TOP-19-001*, …]

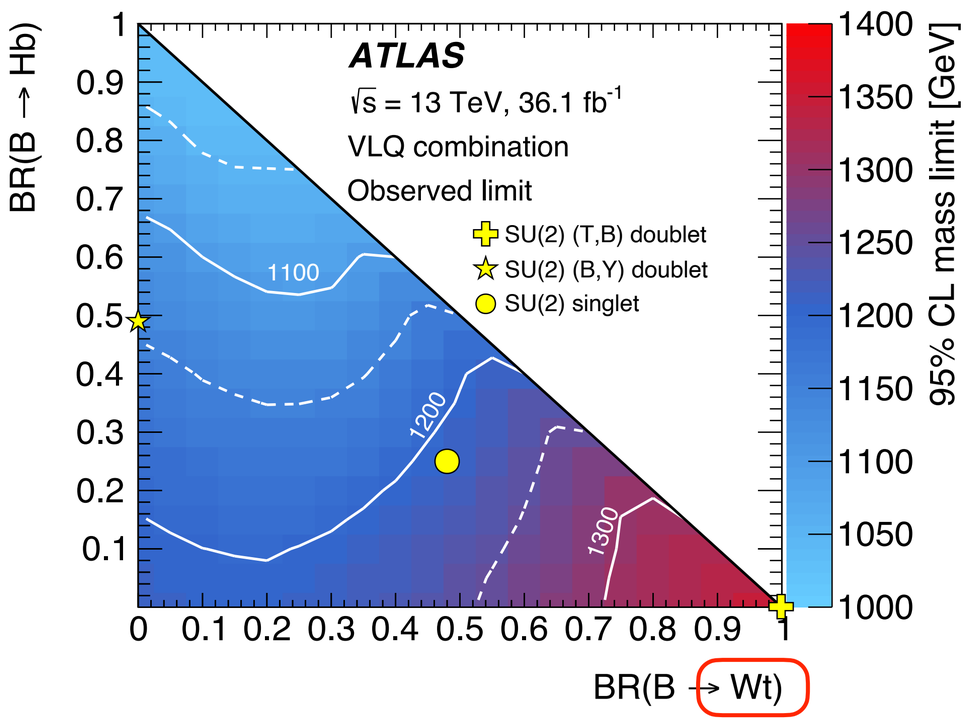
VLQ searches and top final states

Vector-like quarks are expected to decay into final states with third generation quarks.

- Combination of individual searches can cover all possible sets of VLQ decays.
- No evidence yet, but the VLQ mass limits are above TeV scale.
- Toward more high-mass region with high statistics data, a good top tagging may be one of key tool.
- See the latest result of VLQ in *T. R. Andeen's talk* on Thursday.

Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$ [16]	$HtH\bar{t}$	-
$W(\ell\nu)b + X$ [30]	$WbW\bar{b}$	-
$W(\ell\nu)t + X$ [32]	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$ [33]	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$ [35]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [36]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic [37]	$HtH\bar{t}$	$HbH\bar{b}$



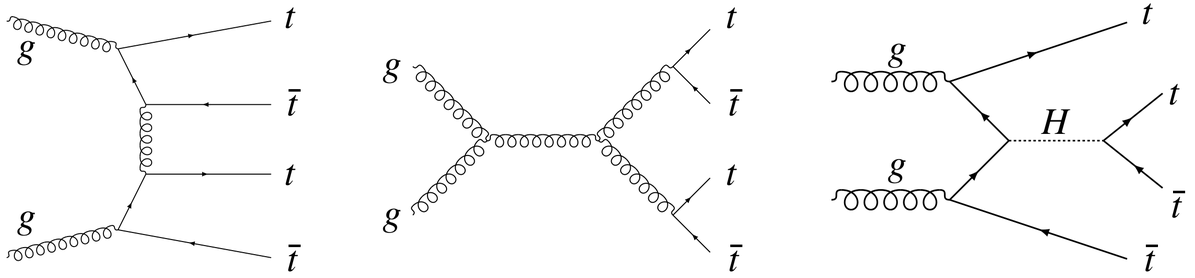


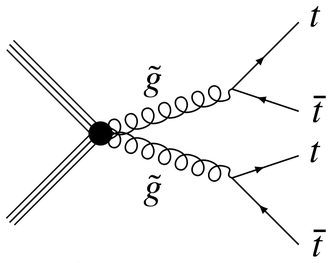
4-top production: $pp \to t\bar{t}t\bar{t}$

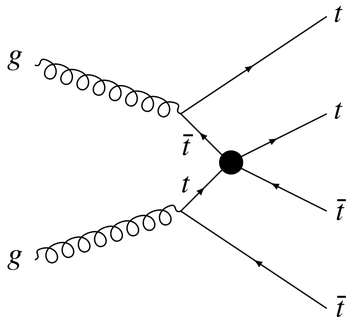
[ATL-CONF-2021-013](#)
[CMS-TOP-18-003](#)
[ATL-PHYS-PUB-2021-013](#)

Very rare process

- $\sigma_{\mathrm{SM}}^{t\bar{t}t\bar{t}} \sim 12.0 \pm 2.4$ fb at NLO QCD+EW at $\sqrt{s} = 13$ TeV
- Sensitive to the top-Higgs Yukawa coupling
- Sensitive to many BSM models, e.g.
  - Gluino pair production in SUSY
  - Heavy scalar/pseudoscalar boson in 2HDM
  - Four-fermion contact interaction within EFT
  - e.g. *ATLAS-EXOT-2016-13*

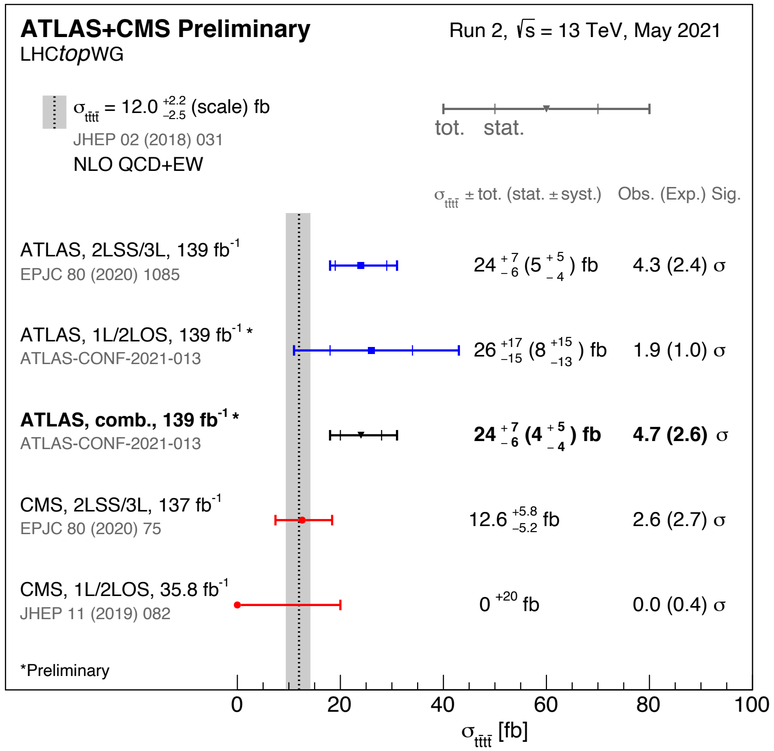






The measured production cross section to be:

- $\sigma^{t\bar{t}t\bar{t}} = 24^{+7}_{-6}$ fb @ ATLAS
  - with a signal significance of 4.7σ (2.6σ expected) over background-only hypothesis
  - consistent within 2.0 standard deviations with the Standard Model expectation
- $\sigma^{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2}$ fb @ CMS
  - in good agreement with SM
  - set to exclusion limits to several physics models
- see *A. Kong's talk* for more details

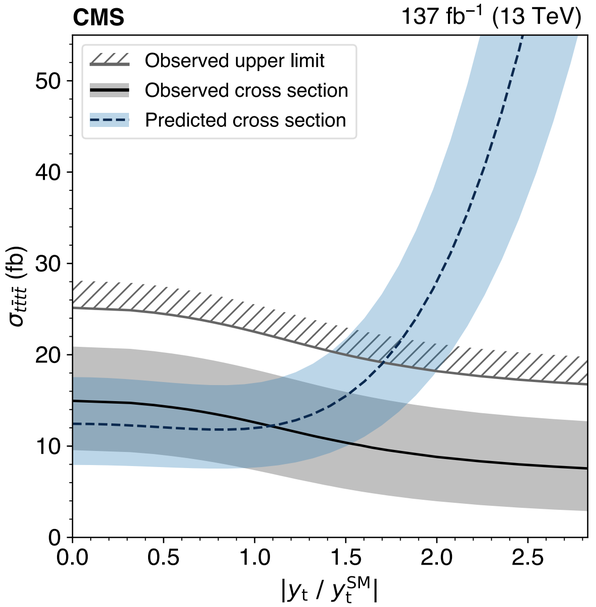


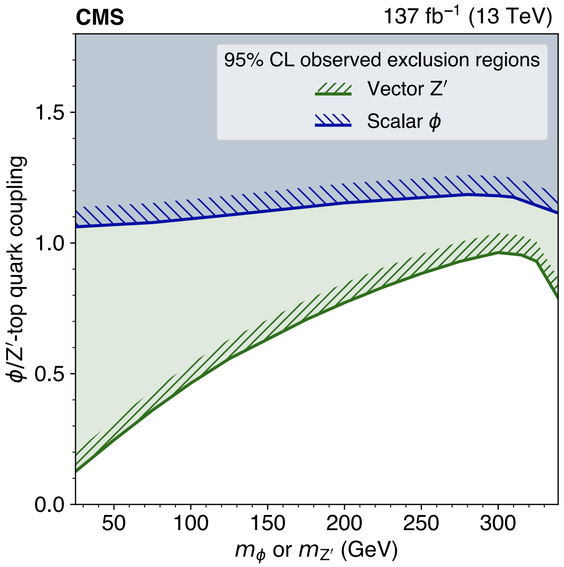
4-top production: $pp \rightarrow t\bar{t}t\bar{t}$

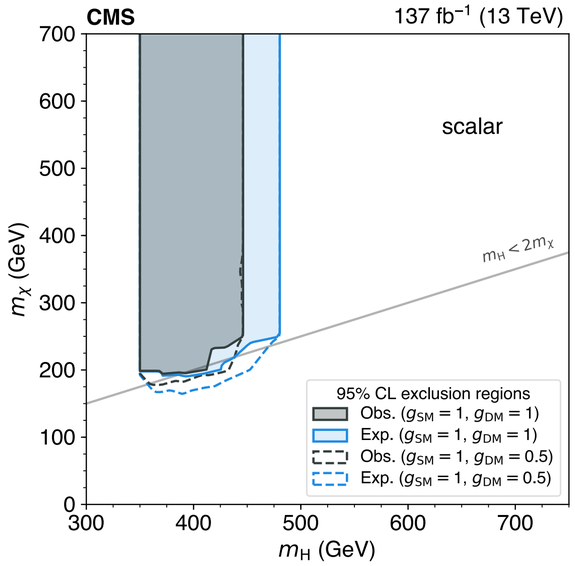
[CMS-TOP-18-003]

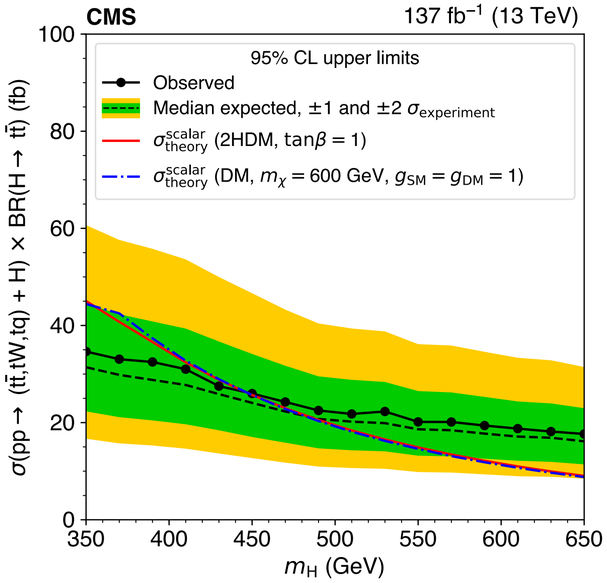
Interpretation by CMS using the $t\bar{t}t\bar{t}$ result:

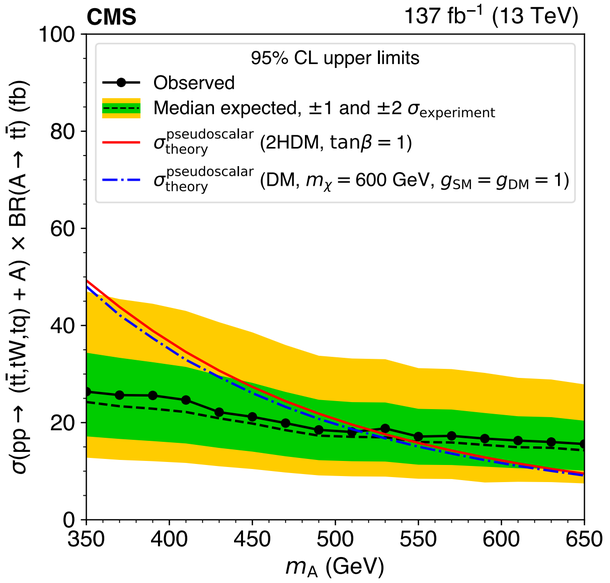
- to constrain the top quark Yukawa coupling y_t
- to constrain the oblique parameter of Higgs in EFT
- to set limits on the production of a heavy scalar or pseudoscalar boson in Type-II 2HDM and simplified dark matter models. excluded:
  - Scalar: $350 < m_H < 470$ GeV
  - Pseudoscalar: $350 < m_A < 550$ GeV
- to set on couplings of the top quark to new light particles









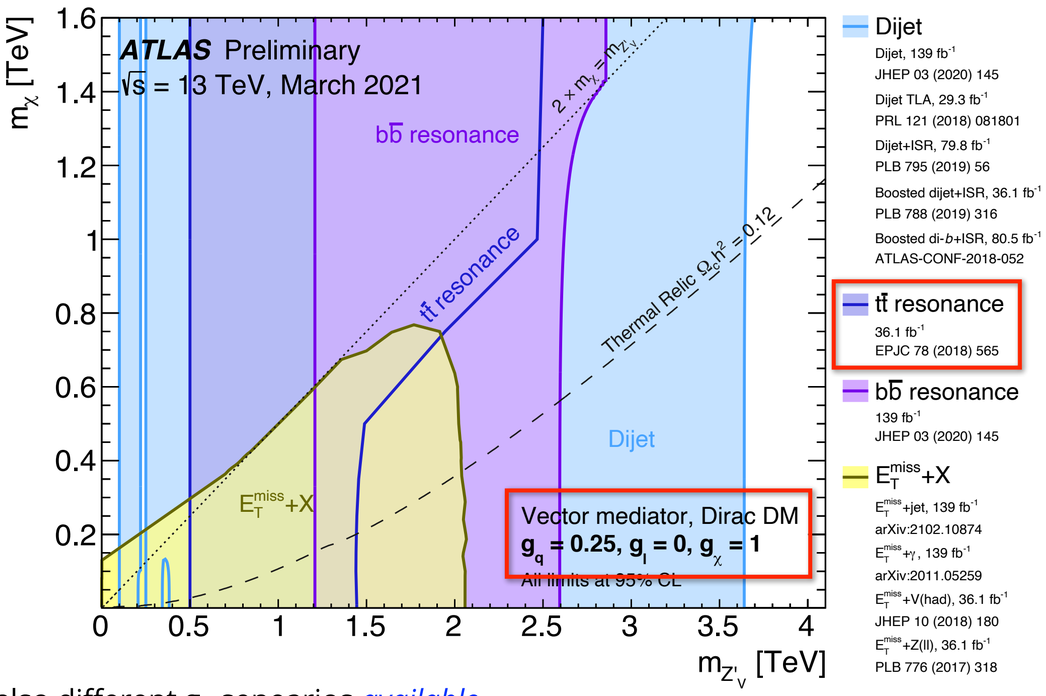


ATL-PHYS-PUB-2021-006

Interpretation on Dark Matter

interpreted $t\bar{t}$ resonance results as dark matter search

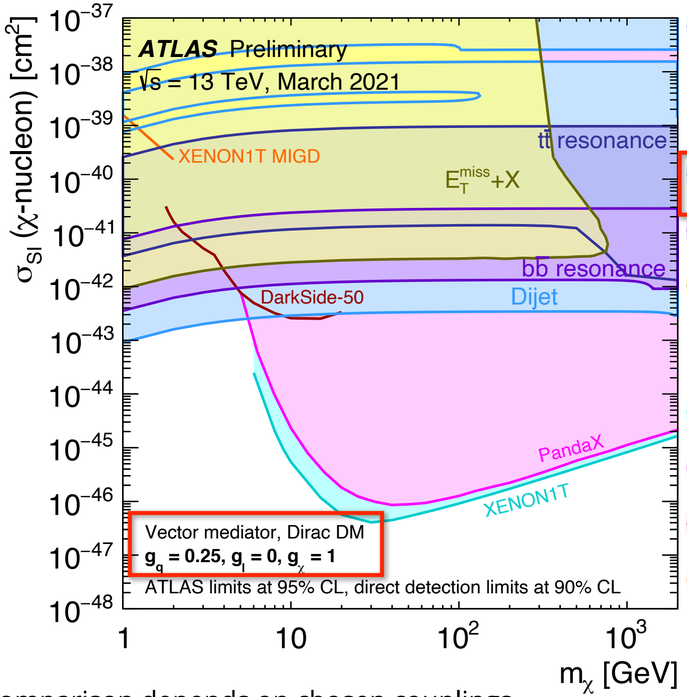
Vector mediator

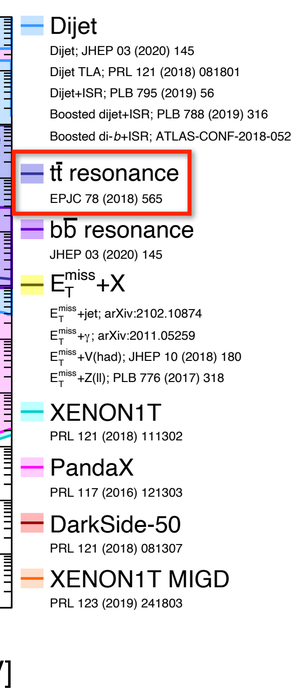


also different g_q senearios *available*

interpret

Comparison to direct detection experiments





⚠ comparison depends on chosen couplings

Other dark matter searches with top quarks have been reported.

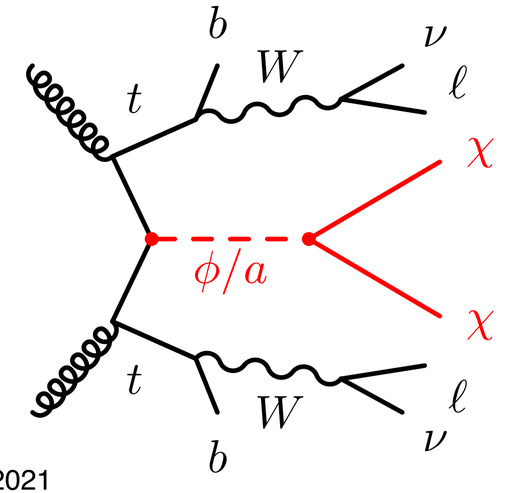
- Searches for dark matter in $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ final states [*ATLAS-SUSY-2018-08*, *CMS-EXO-16-049*, and *CMS-EXO-18-010*]
- Searches for dark matter produced in association with a single-top [*ATLAS-EXOT-2018-43* and *CMS-EXO-18-010*]

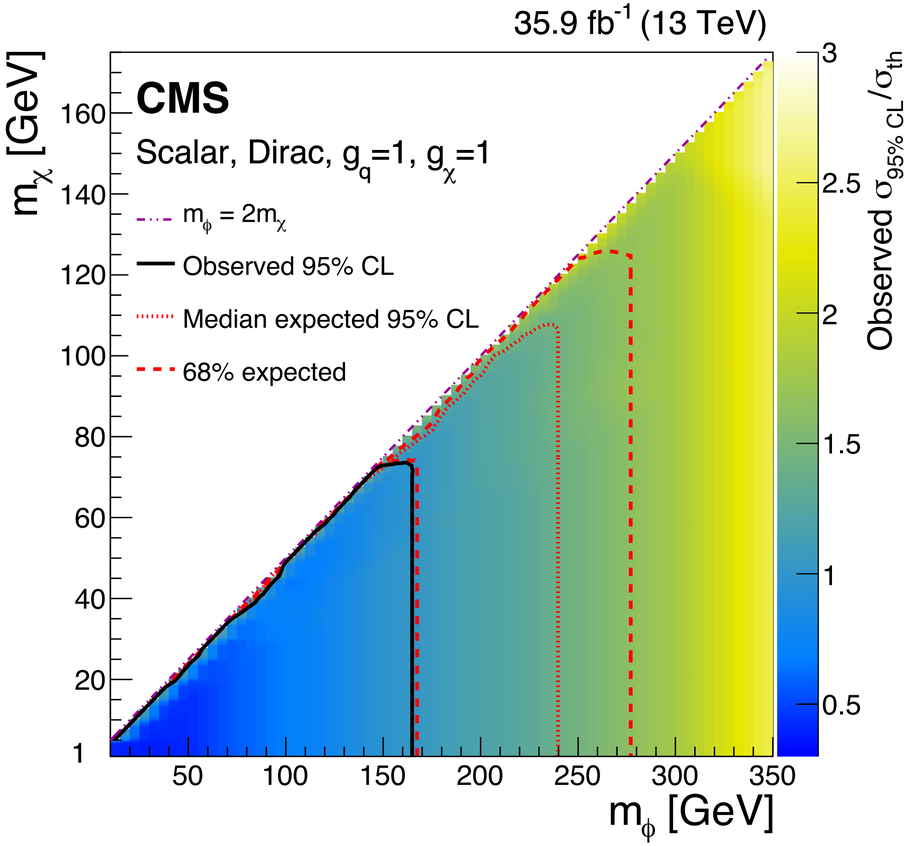
Dark matter in $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$

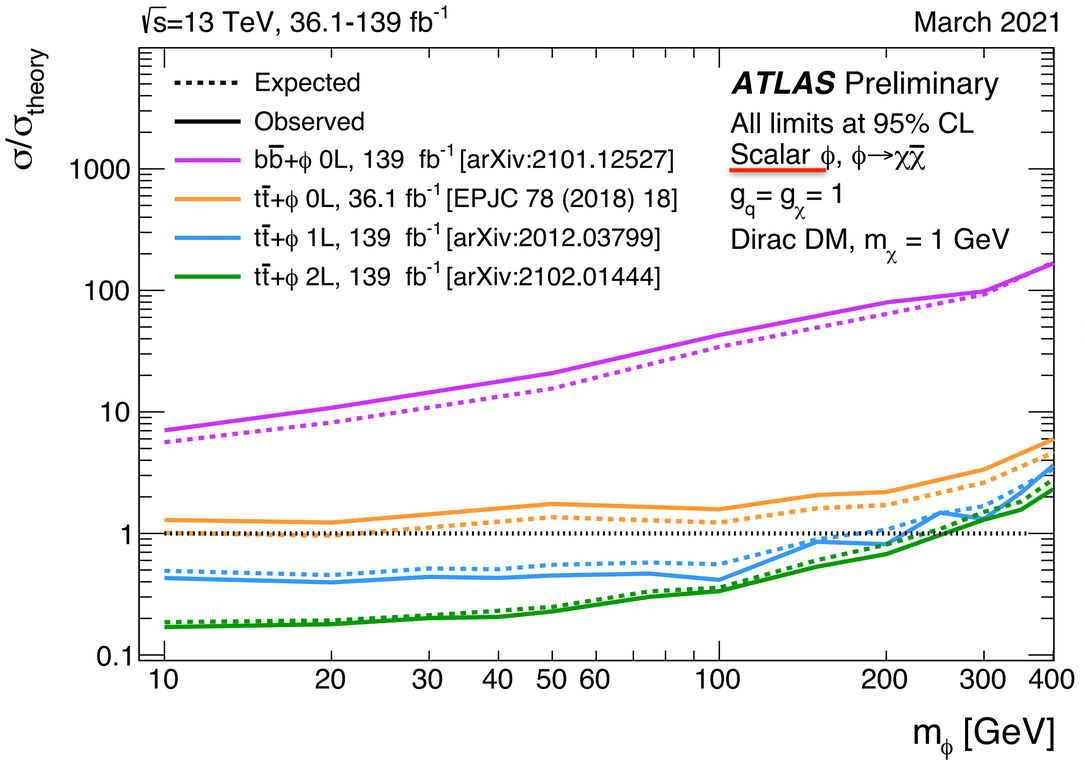
ATLAS-SUSY-2018-08
CMS-EXO-16-049, CMS-EXO-18-010

Simplified benchmark models with scalar (S) / pseudo-scalar (P) mediators which couple both to the SM and to the DM.

- This assumption implies that the interaction between any new neutral spin-0 state and the SM matter is proportional to the fermion masses via Yukawa-type couplings.
- also sensitive to invisible Higgs decays (ttH production) [ATL-CONF-2020-052]







scalar:

$$m_\phi > 250 \text{ GeV}$$

pseudoscalar:

$$m_a > 300 \text{ GeV}$$

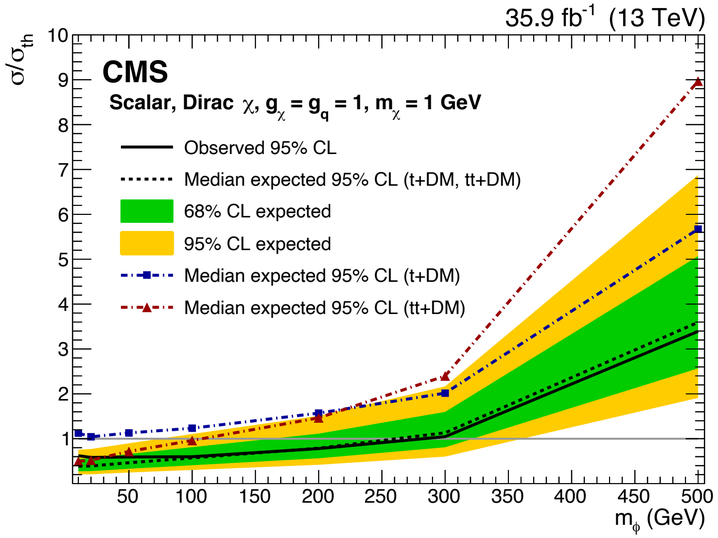
ATL-PHYS-PUB-2021-006

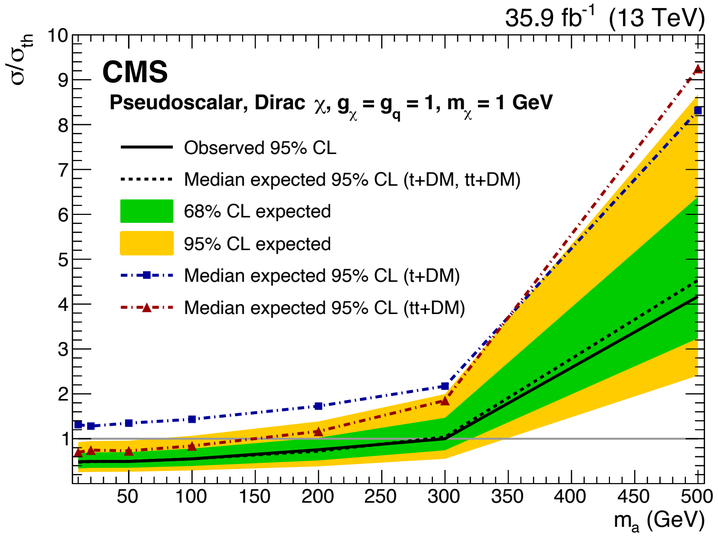
Dark matter associated with single top

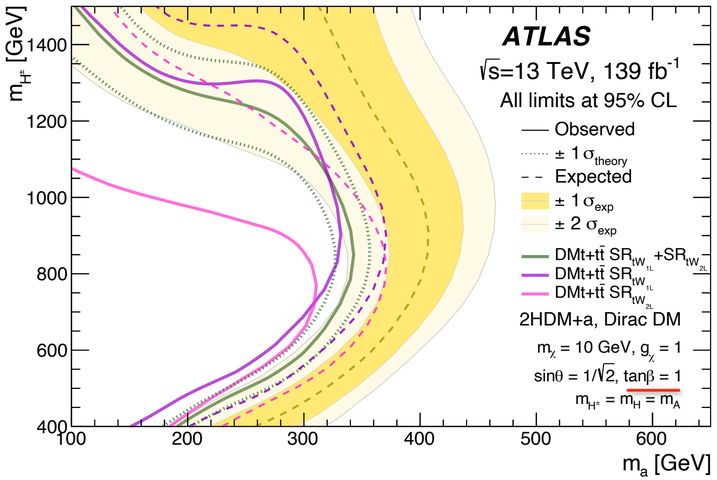
[ATLAS-EXOT-2018-43](#)
[CMS-EXO-18-010](#)

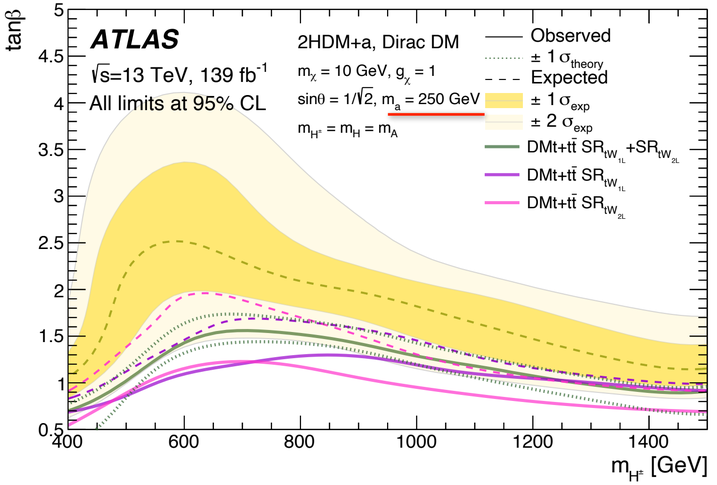
Focusing on 2-Higgs double extended sector + pseudo-scalar DM mediator

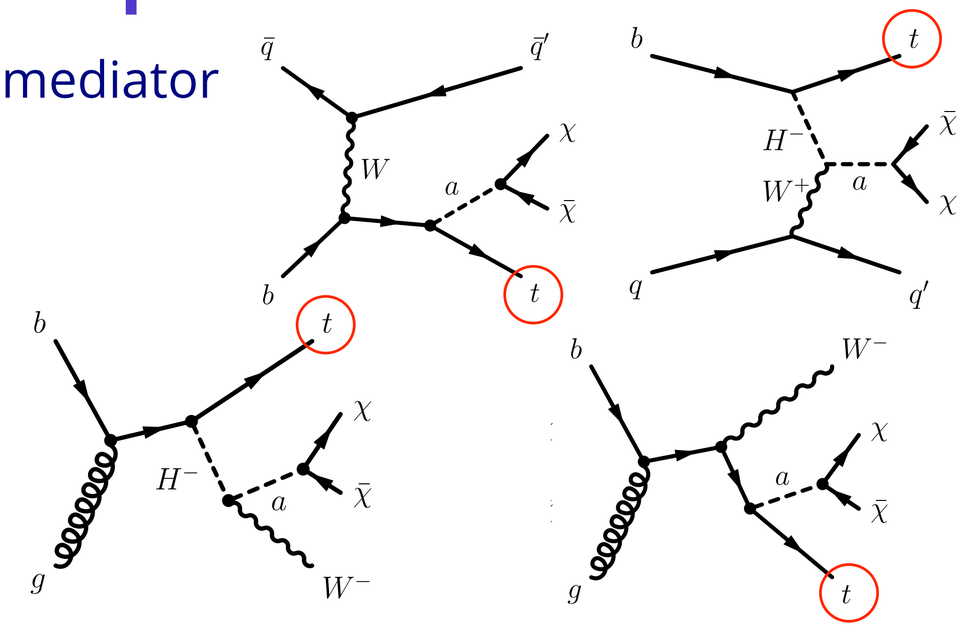
- CP-odd boson (a, A), CP-even boson (h, H), and charged-Higgs ($H^{\pm}$)











CMS @ 35.9 fb-1

- combined searches w. ttbar and single-top
- $m_{\phi} > 290$ GeV, $m_{a} > 300$ GeV

ATLAS @ 139 fb-1

- combined searches w. ttbar and single-top
- excluded some phase spaces in m_{a}, $m_{H^{+}}$, and $\tan\beta$ plane

see *M. Toscani's talk* for details

$\tan\beta$: ratio of the vaccum expectation values of the two Higgs doublets

Summary

Top quark may be one of the key tools to search for physics Beyond the Standard Model in LHC.

Many search results with top final states have been released.

- No direct evidence of new physics, in either model-independent or model-dependent searches
- The EFT interpretation becomes more important.

The search growing interest towards more rare signal.

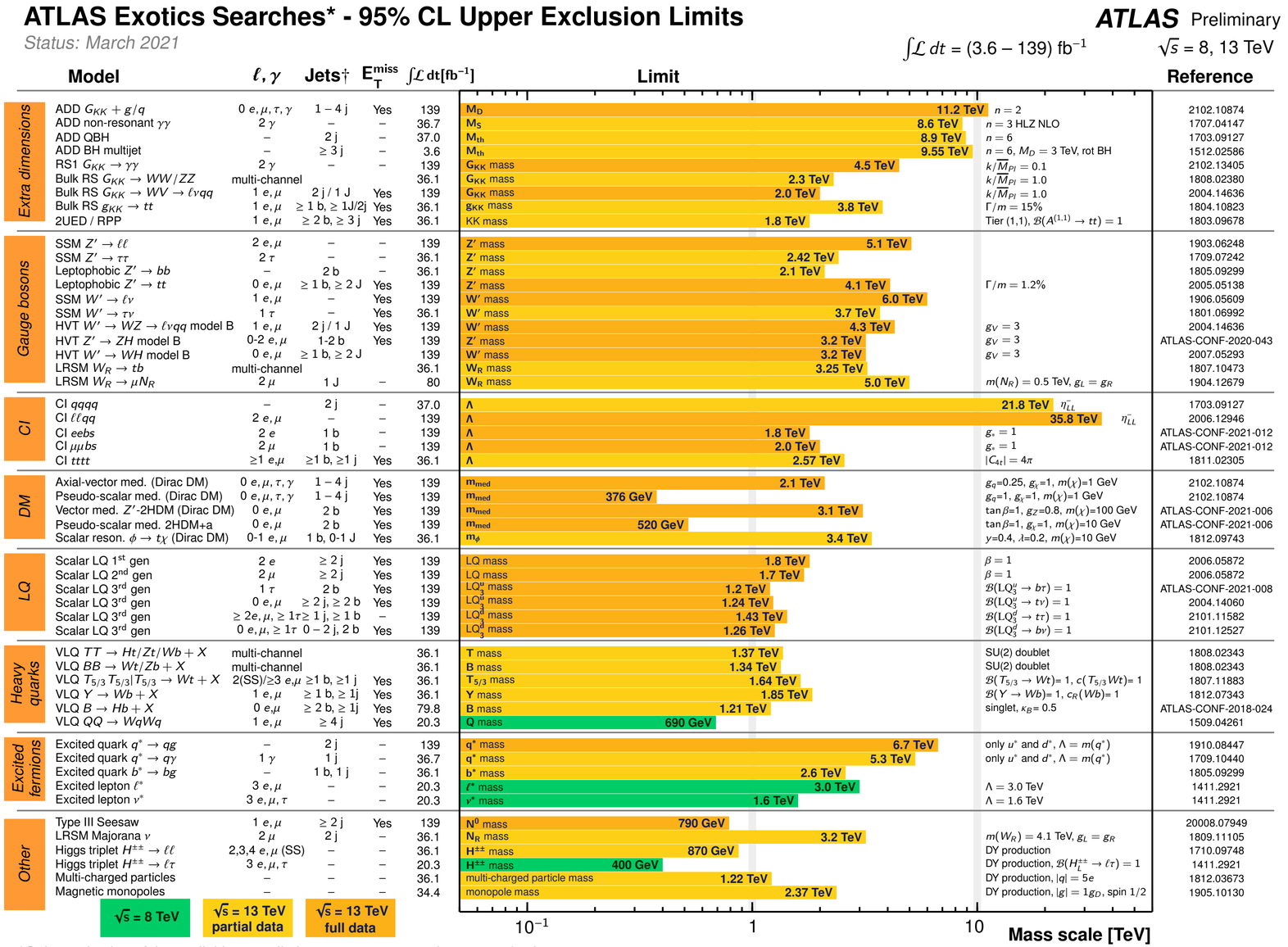
- More data will come in LHC Run 3 and HL-LHC.
- We should push to understand our detectors and to develop new techniques of analyses (e.g. top-tagging).

The program to search for BSM with top quarks is far from complete.

- More full Run 2 analysis to come. Stay tuned!

Backup slides

Exotics Summary in ATLAS

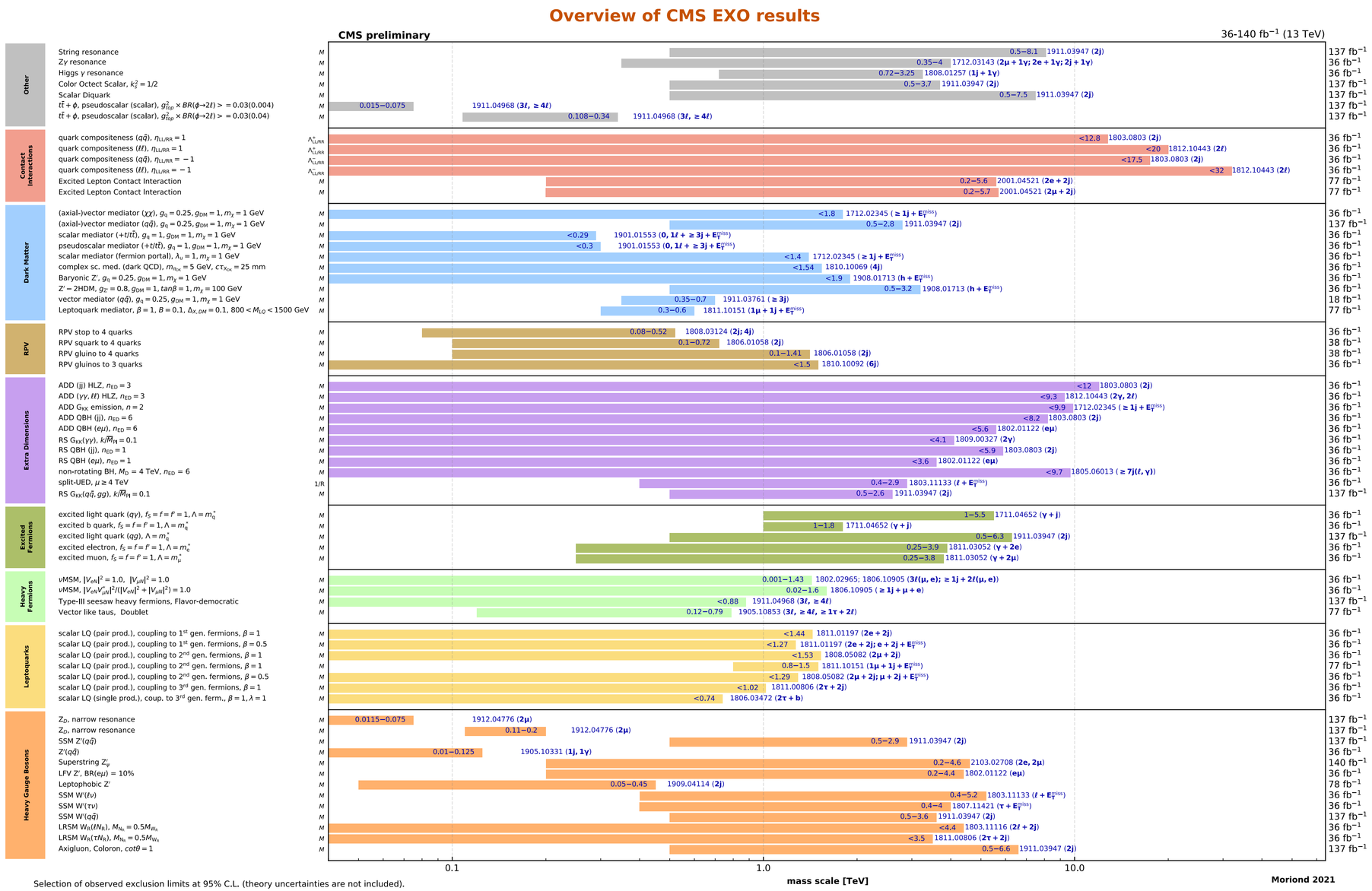


*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Exotics summary in CMS

[CMS Exotica Summary for 13 TeV]

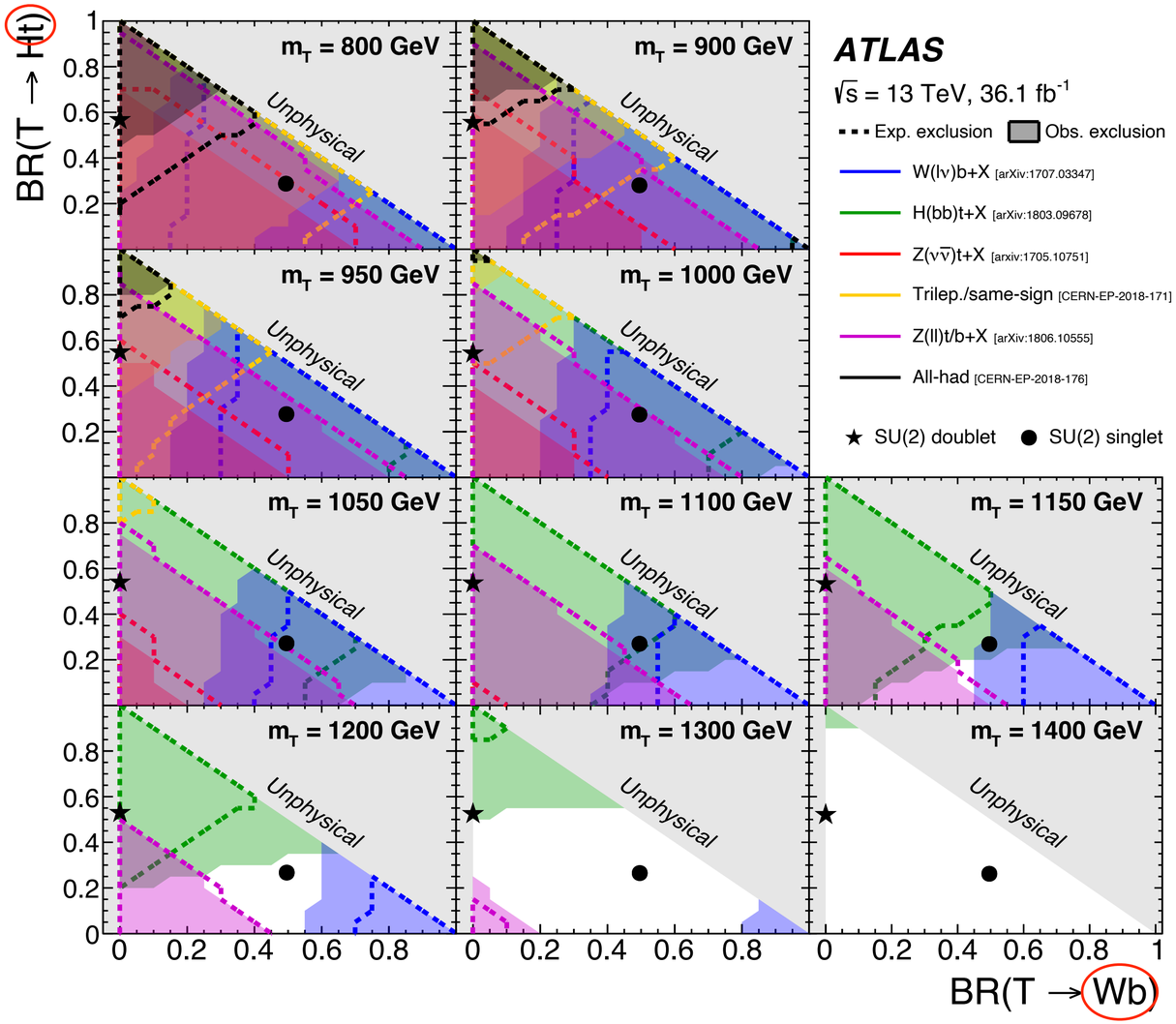


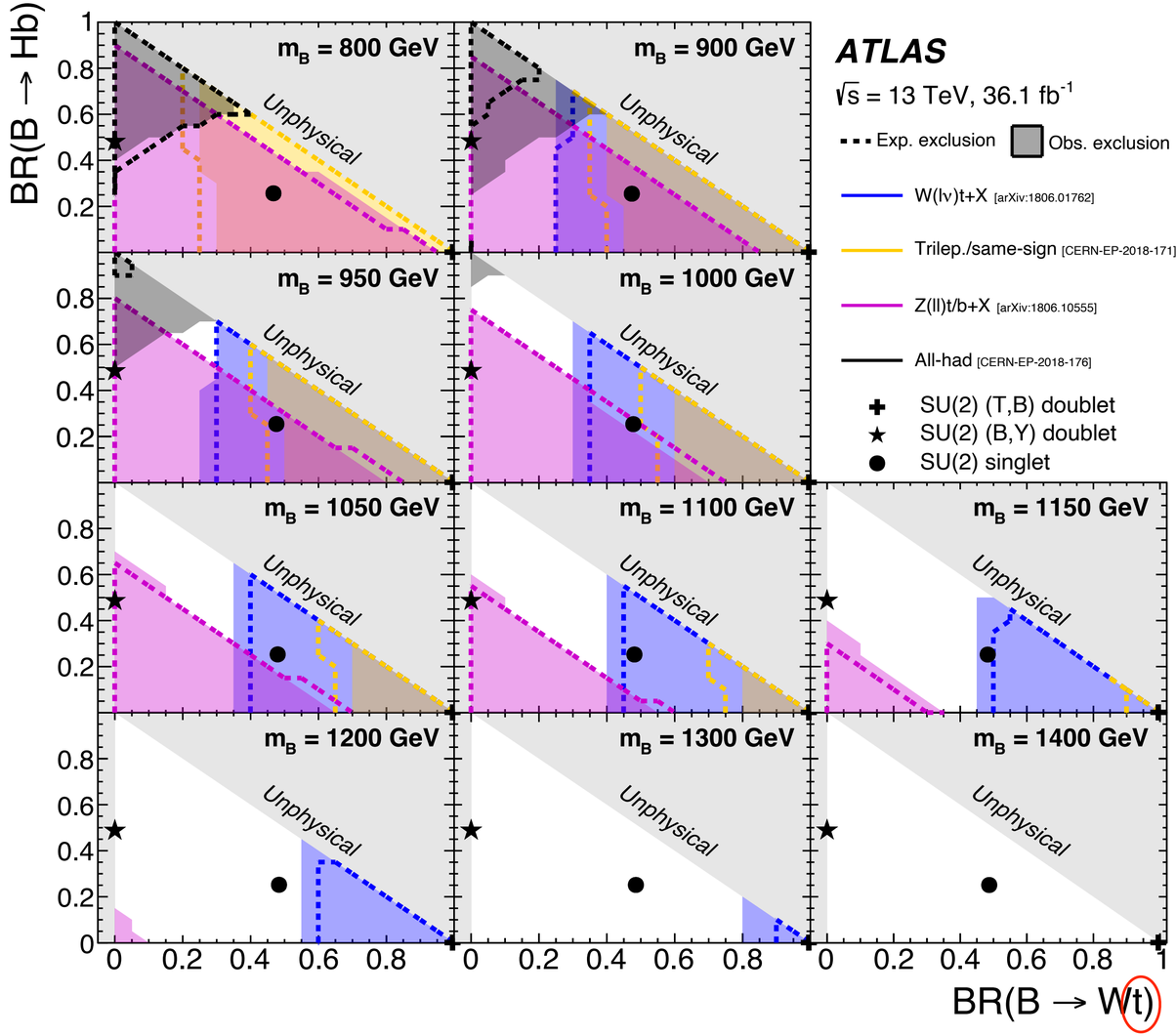
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

VLQ searches and top final states

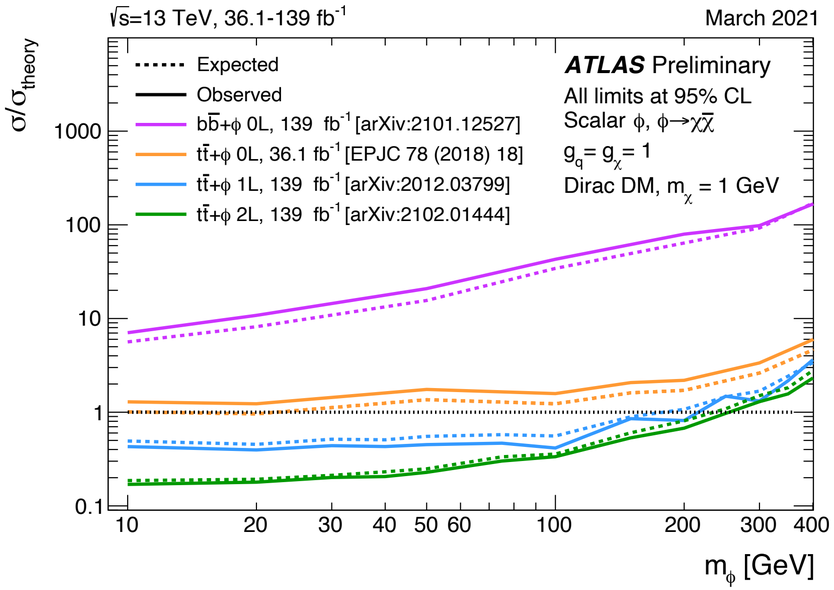
ATLAS-EXOT-2017-17

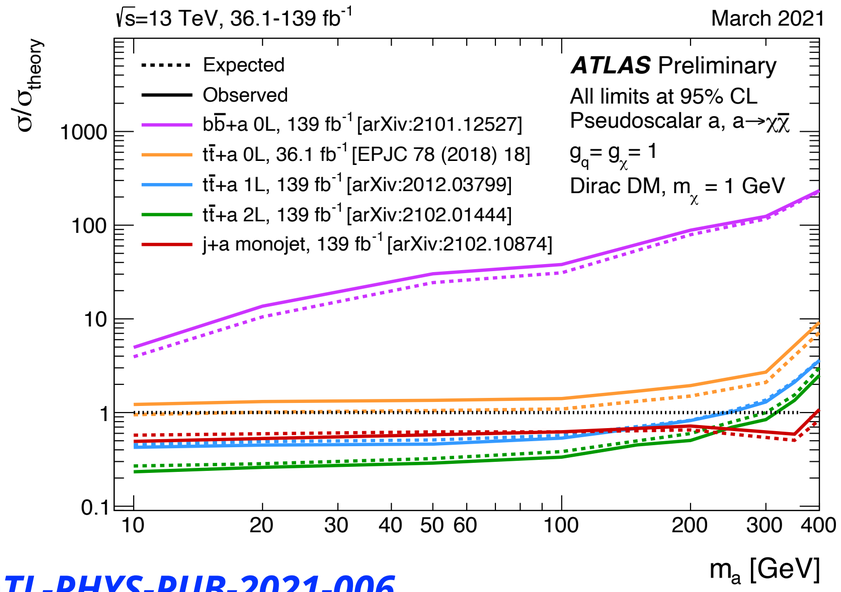
Top final state is the most effective signature to search for Vector-Like Quarks.





Dark matter in $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$





[ATL-PHYS-PUB-2021-006]

[ATL-CONF-2020-052]