Search for invisible particles produced in association with single-top quarks with the ATLAS detector using Run-2 data

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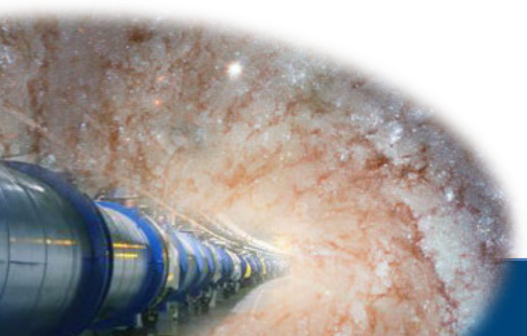
Josep Navarro González, on behalf of the ATLAS collaboration



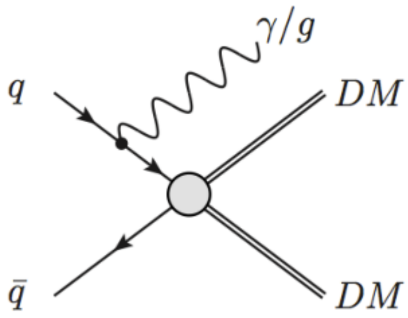
Introduction

- There is long-standing evidence for dark matter (DM) from observations of its gravitational interaction.
- Few properties are known: neutral, massive, weak interaction,… → assume WIMPs here.
- DM searches at colliders are complementary to direct and indirect detection.
- They can directly probe the production mechanism.

- In order to describe the DM production, different approaches can be followed:

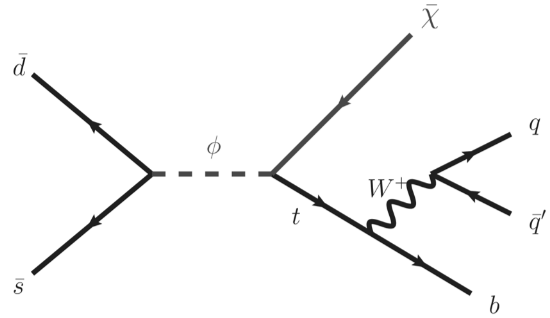
Effective Field Theories (EFT)

- Dark matter production mechanism unspecified
- Mostly considered during Run-1.



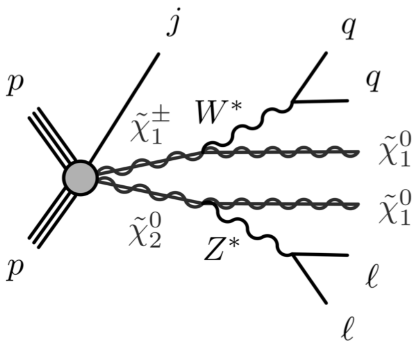
Simplified models

- Signature-driven first-order description of new physics.
- Bridge gap between EFT and complete models.



Complete Models

- Dark matter predicted as part of a complete theory.
- Theoretically "more sound".



Introduction

- As introduced by Matthias Saimpert, searches for dark matter with the ATLAS detector are essential but they have two main difficulties:
  - DM does not interact with the detector → Identify large amount of Missing Energy**.**
  - Not possible to trigger events with DM only → Search in associated production with SM particles.

- Many BSM theories predict production of DM associated with **top quarks**:
  - Heaviest fundamental particle in the SM.
  - Exotics particles (DM mediators) could decay preferentially to top quarks.

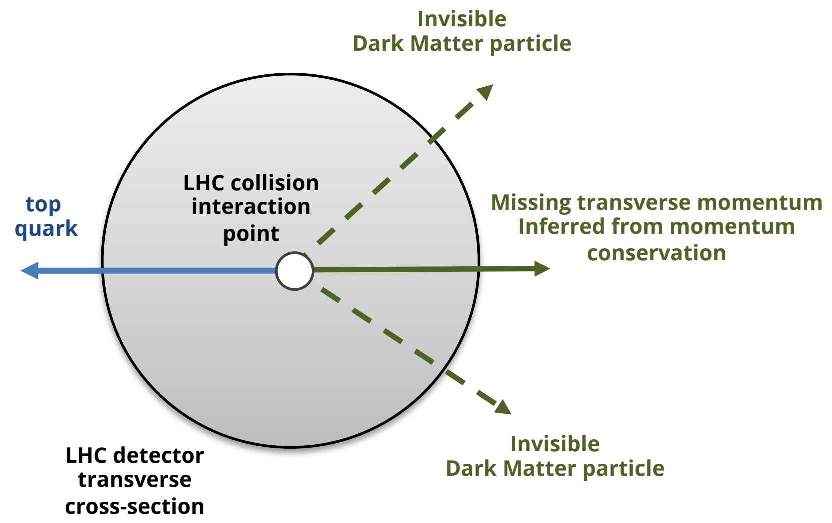
- Two searches targeting different final states are here presented:

1

top quark + **invisible** (*Mono-top*)

Models considered (ATLAS-CONF-2022-036):

- Resonant and Non-Resonant DM production.
  - *Simplified Model.*
  - Add a mediator that couples to SM and DM.
  - Good phenomenology proxy.
- Results are also interpreted in the context of the Vector-Like Quarks model.



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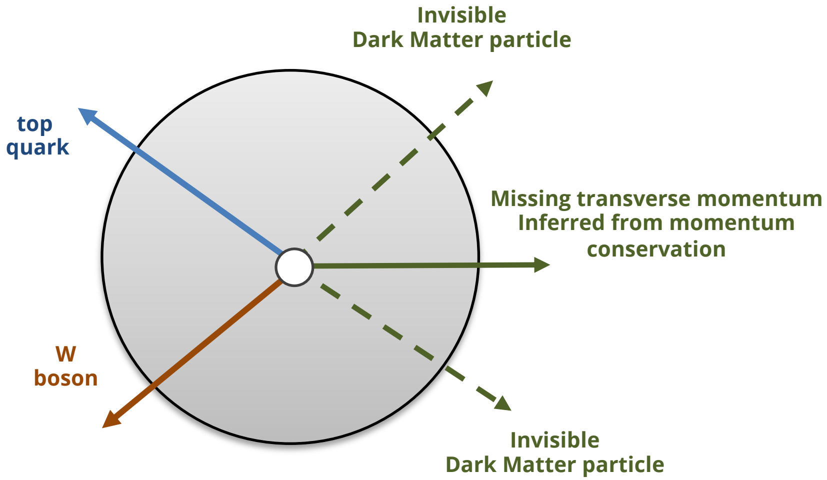
- Two searches targeting different final states are here presented:

2

top quark + W boson + invisible

Model considered (ATLAS-CONF-2022-012):

- Extended two-Higgs-doublet sector together with a pseudoscalar mediator particle (2HDM+a):
  - 2HDMs are an essential ingredient of many well-motivated *complete theories* beyond the Standard Model.
  - Rich and extensive phenomenology.



→ Both searches have been performed using the full LHC Run-2 data (139 fb^{-1} collected during 2015-2018).

1) top quark + invisible (*Mono-top*)

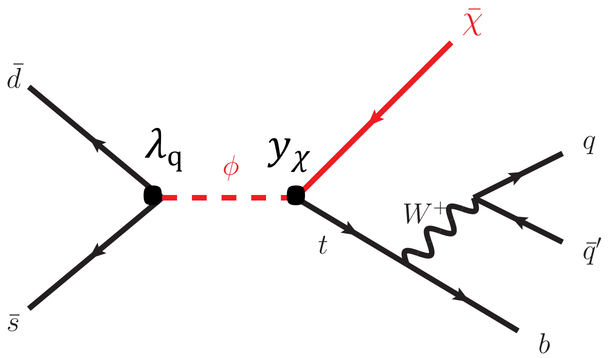
ATLAS-CONF-2022-036

Models considered

- A simplified model for a DM production has been considered using the same baseline last round analysis (arXiv:1812.09743).

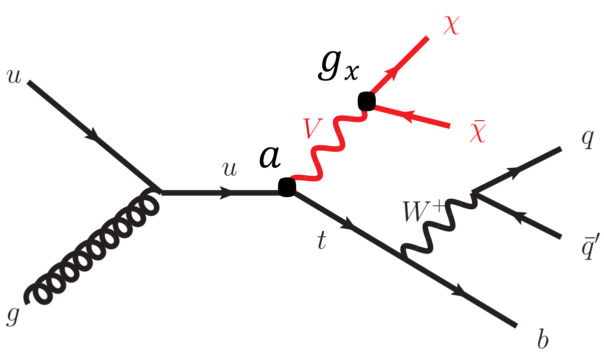
- The single production of Vector-Like Top is also studied, considering the invisible decay of the Z boson.

Resonant DM production



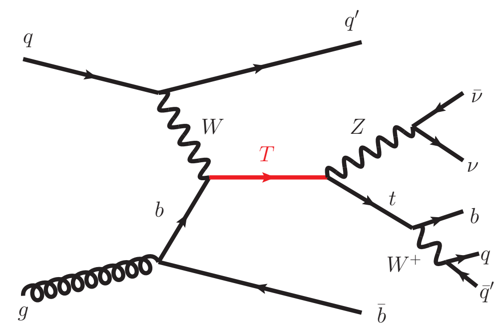
- Colored-charged scalar decaying to a top quark and a DM particle.
- Parameters:
  - Couplings λ_q and y_χ.
  - Masses of the mediator ϕ and the DM particle χ.

Non-Resonant DM production



- Vector mediator couples DM particles.
- Parameters:
  - Couplings a and g_χ
  - Masses of the mediator V and the DM particle χ.

Single Vector-Like Top production



- A model for new fermion generations (coloured spin-1/2).
- Parameters:
  - Overall coupling κ_T (related to W, Z and H couplings).
  - Mass of the VLT.

Event selection

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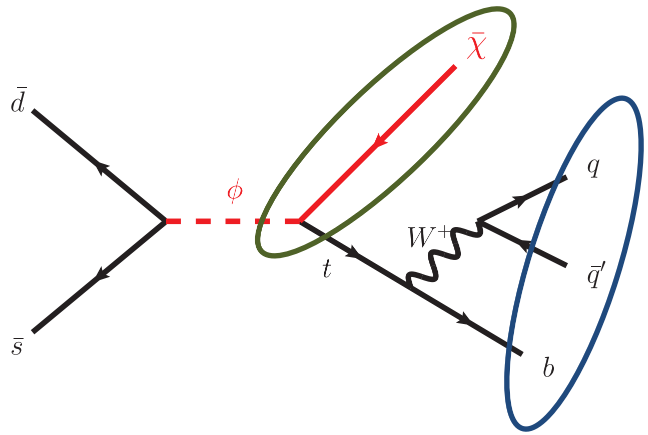


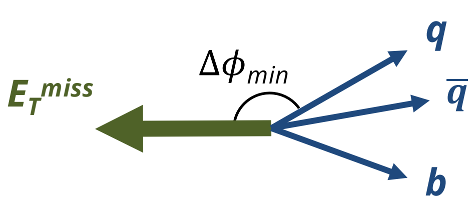
$E_T^{miss} \geq$ **250 GeV**

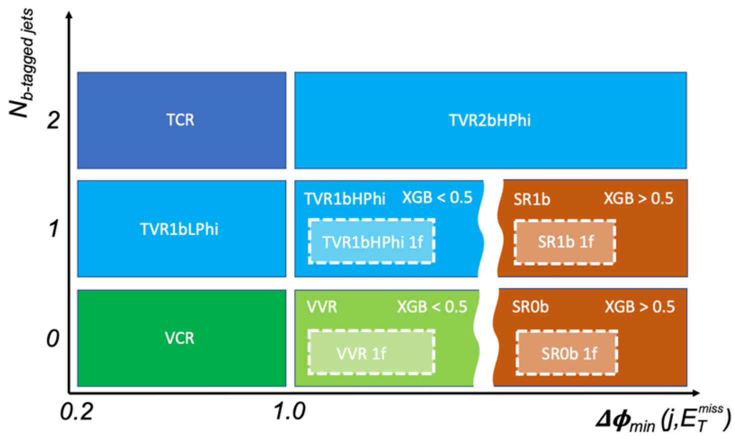
Exactly zero leptons (hadronic channel)

At least one boosted large-R jet associated to the top quark → use top-tagging for S/B separation!

- Main backgrounds: $t\bar{t}$ and **Z/W+jets** → constrained in the control regions.
- Consider a Multivariate Analysis (MVA) approach to discriminate signal (*XGBoost*):
  - E_T^{miss} -based variables and ΔR_{max}^{*} among the most important features in the training.

- Further reduce backgrounds by selection requirement on the *number of b-jets* and $\Delta\phi_{min}$:





* Maximum ΔR between two small-R jets.

Fit to data

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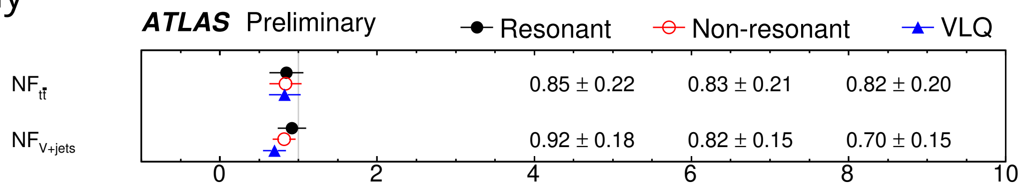
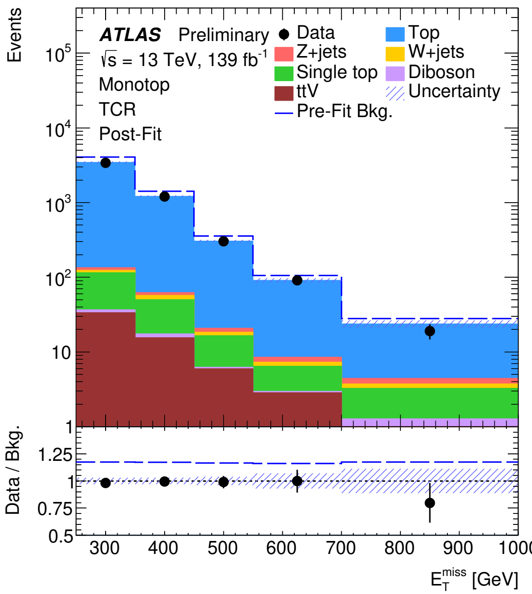
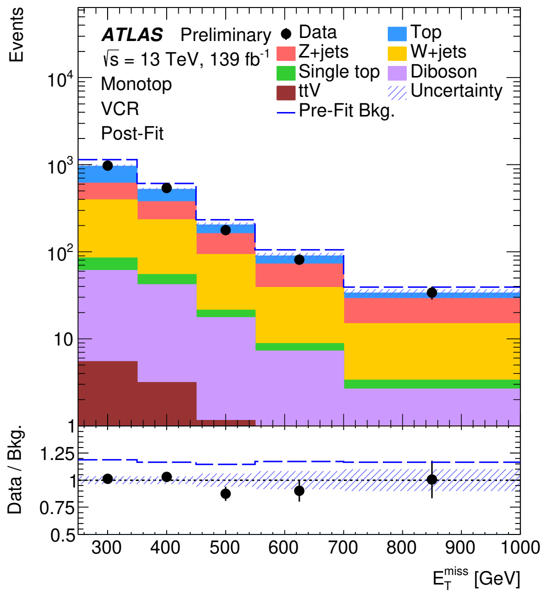
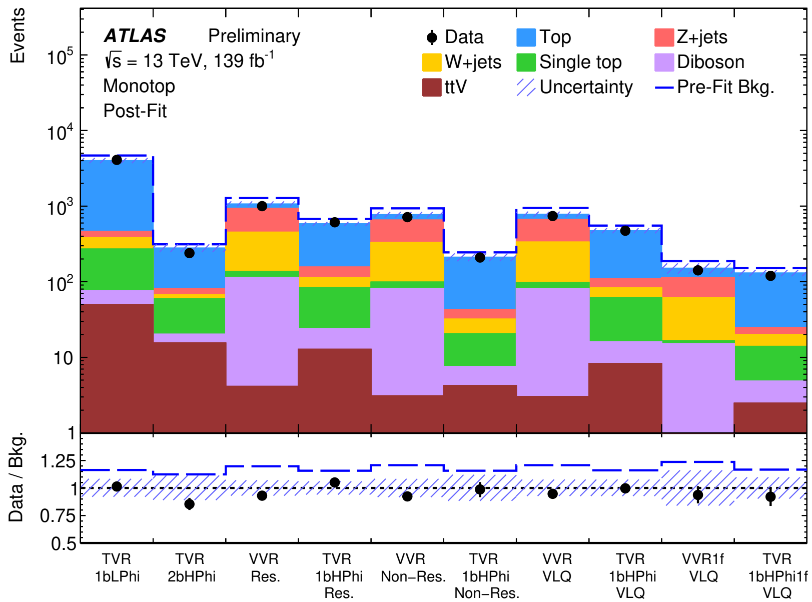
Fit to data under the background-only hypothesis yields to measure the **normalization of the main backgrounds** :



- Values obtained for the 3 different models fit are fully consistent within each other.
- Good description of data in the **control** and **validation** regions of the post-fit background model:







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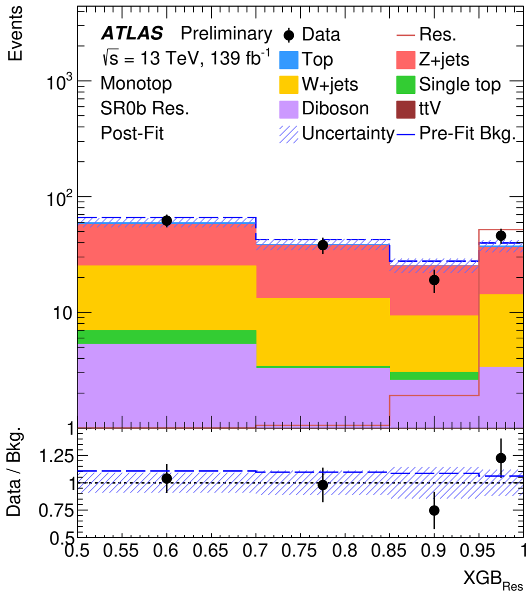
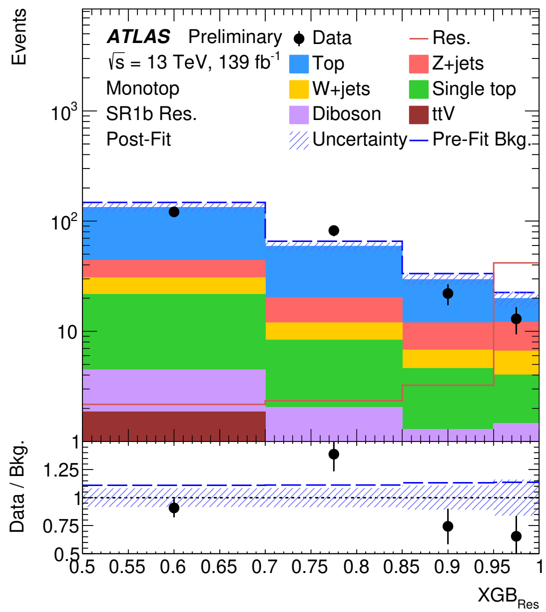
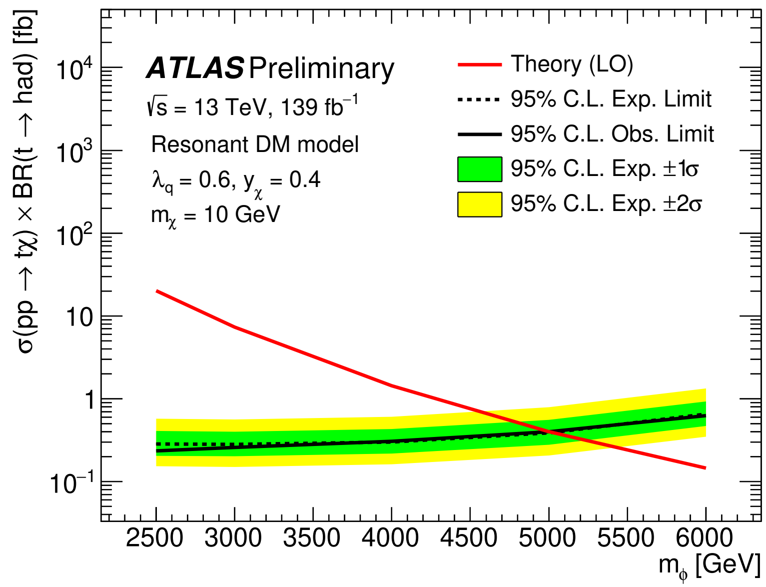
Resonant DM interpretation

- No significant excess above the SM expectation is found in any of the Resonant DM model signal regions:





- Interpret result in terms of expected and observed upper limit on the signal cross section:

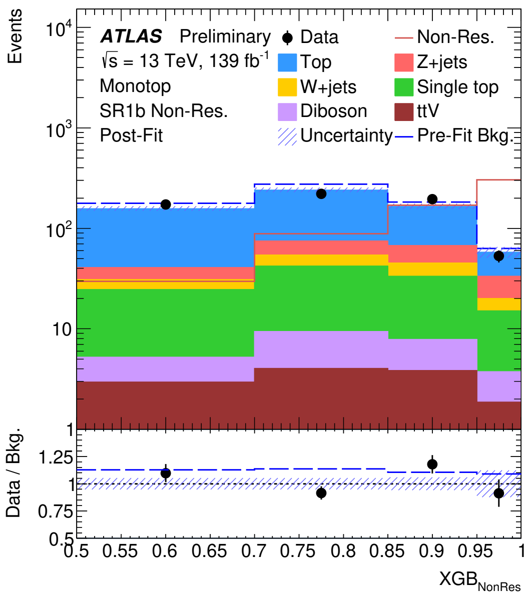


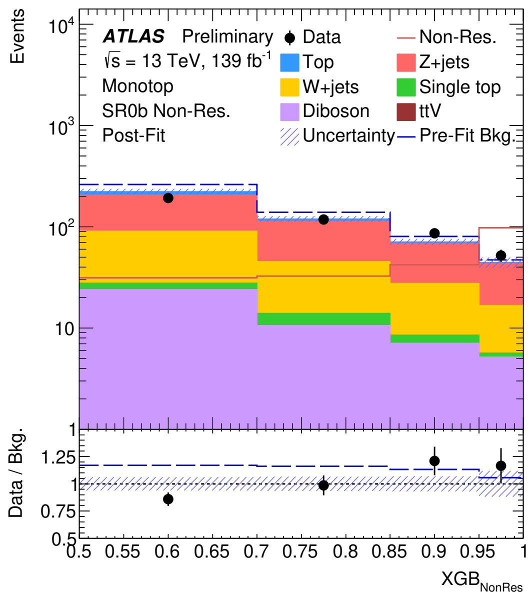
Considering the parameters λ_q = 0.6, y_χ = 0.4 and m_χ = 10 GeV,

the Resonant model is excluded for m_ϕ < 5000 GeV.

Non-Resonant DM interpretation

- No significant excess above the SM expectation is found in any of the Non-Resonant DM model signal regions:





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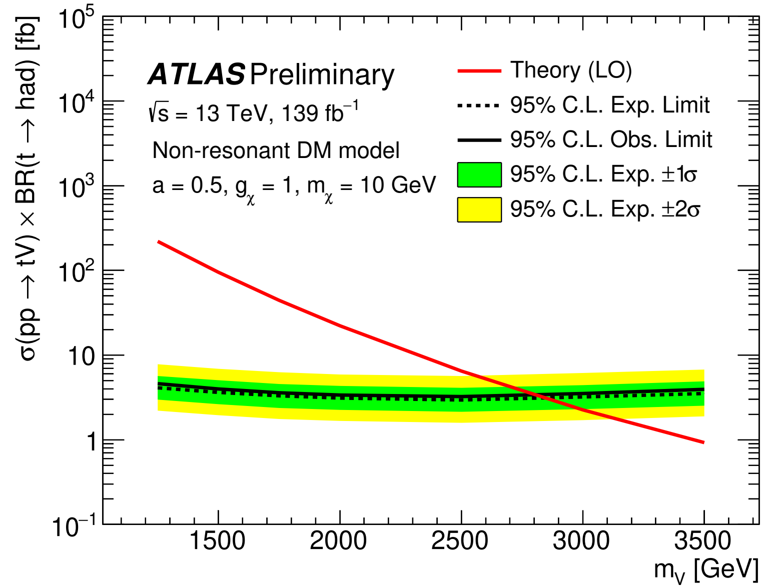
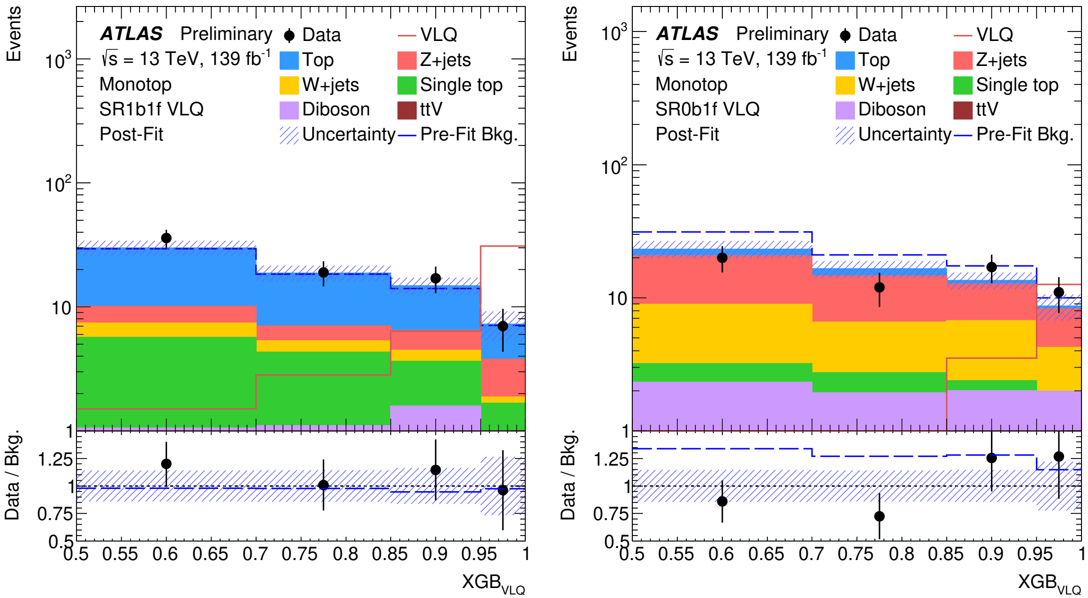


Considering the parameters a = 0.5, g_χ = 1 and m_χ = 10 GeV,

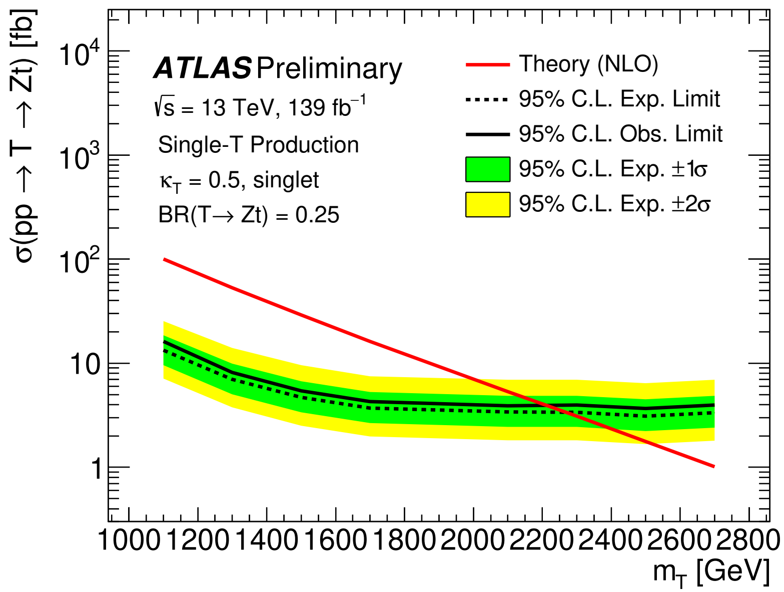
the Non-Resonant DM model is excluded for m_V < 2800 GeV.

Vector-Like Quarks interpretation

- No significant excess above the SM expectation is found in any of the VLQ model signal regions:



- Interpret result in terms of expected and observed upper limit on the signal cross section:



Considering the parameter $k_T = 0.5$ and the Vector-Like Top (VLT) being a singlet,

the VLT masses are excluded for m_T < 2300 GeV.

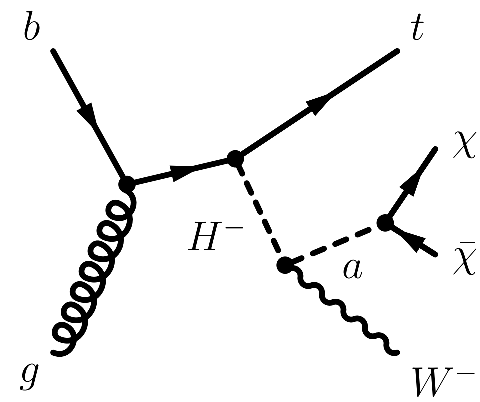
2) top quark + W boson + invisible

ATLAS-CONF-2022-012

Model considered

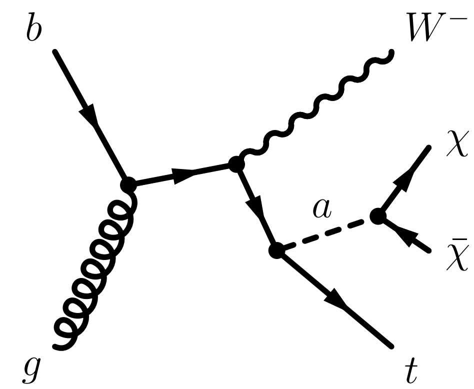
This signature has been searched considering the **2HDM+a** model.

- This theory is an extension of the Standard Model:
  - **Two** Higgs doublets (h (SM Higgs), H, $H^{\pm}$, A).
  - New **pseudoscalar DM mediator (a)** that couples to a fermionic DM candidate**.**

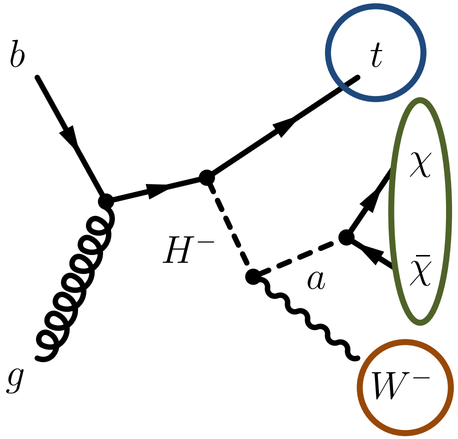


- This model is the simplest ultraviolet-complete and renormalizable extension of the simplified pseudoscalar DM mediator model characterized by a wide range of signature.

- **Several free parameters**:
  - Different masses: $\mathbf{m_H}$, $\mathbf{m_{H^{\pm}}}$, $\mathbf{m_A}$ and $\mathbf{m_a}$.
  - **tanβ**: ratio of the *vev* of the two Higgs doublets.
  - **sinθ**: Mixing angle between the pseudoscalar mediator a and A.



Event selection



1 b-jet (from top decay)

0-1 electrons/muons

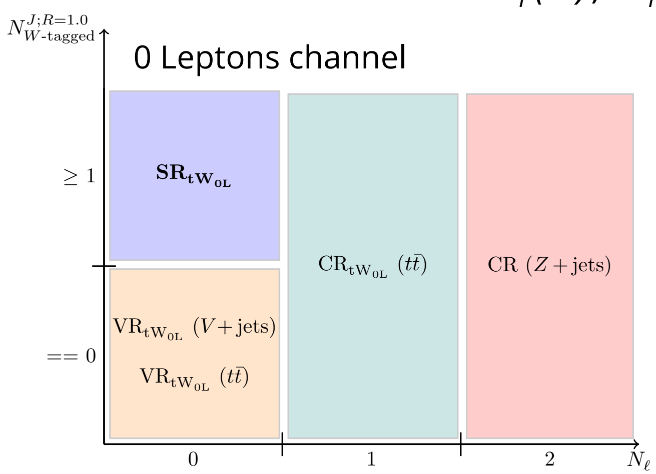
$E_T^{miss} \geq$ 250 GeV

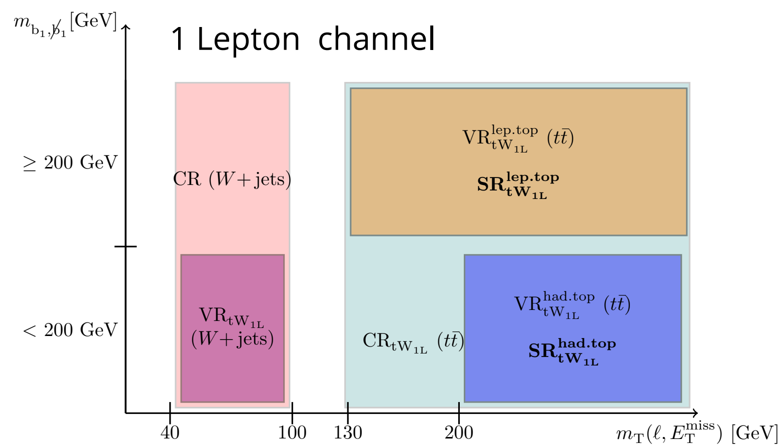
if $H^{\pm}$ >> $m_W + m_a$, W from $H^{\pm}$ has high p_T

→ Use <u>*W*-tagging</u> for S/B separation!

Main backgrounds: $t\bar{t}$, ***Z/W*+jets** and ***ttZ*** → constrained in the control regions.

Reduce backgrounds by selection requirements on various transverse mass variables such as $m_T(W)$, $m_T(l, E_T^{miss})$, am_{T2}, etc…





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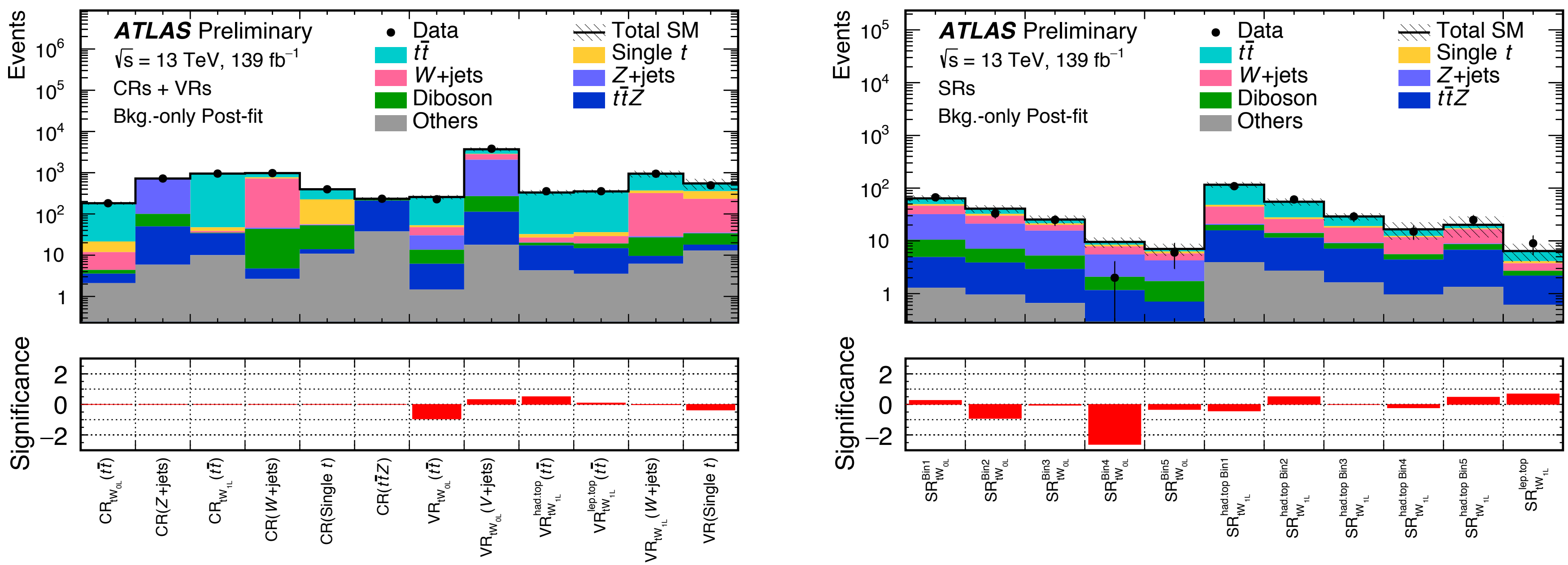
Fit to data

Fit to data under the background-only hypothesis yields to measure the **normalization of the main backgrounds.**

- Good description of data in the **control** and **validation** regions of the post-fit background model.

- No significant excess above the SM expectation is found in any of the **signal regions**.



2HDM+a interpretation

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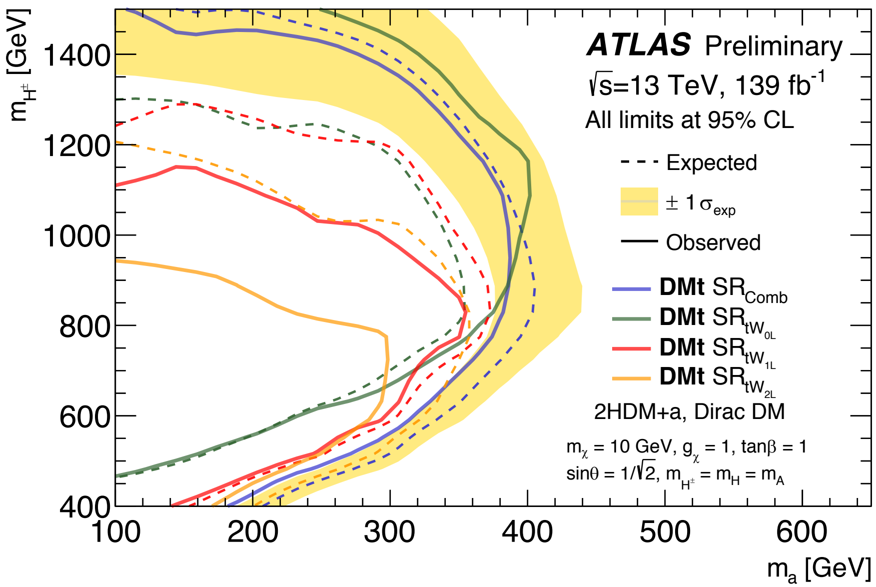
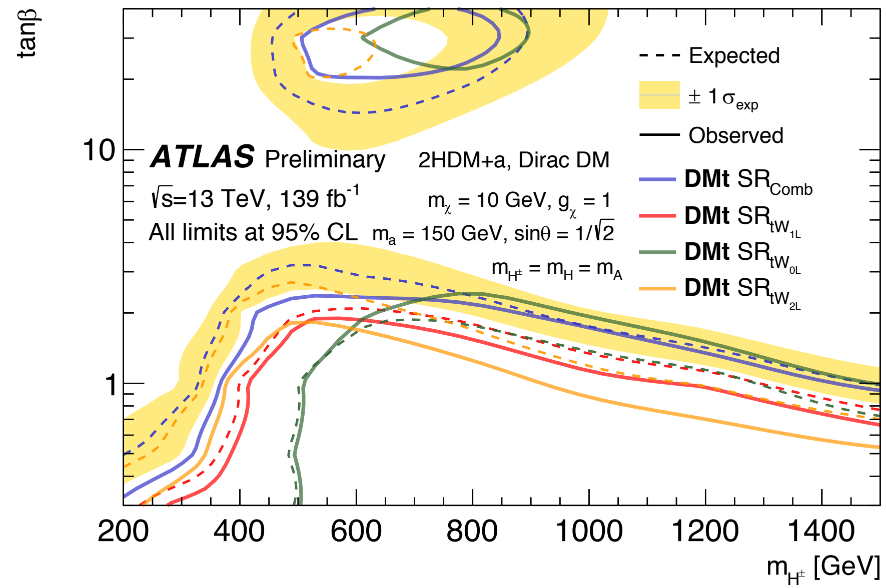
- Interpret result in terms of expected and observed exclusion limits on the 2HDM+a model.
- Combined with previous analysis (arXiv:2011.09308) 2L channel.





- 0L/1L channel with strongest exclusion for $m_{H^\pm} > 700$ GeV.
- 2L channel (dominant for $m_{H^\pm} < 700$ GeV).
- **The 2HDM+a model is excluded for masses between m_a=100-400 GeV and $m_{H^\pm}$=400–1500 GeV.**

Conclusions

- Different searches for invisible particles produced in association with single-top quarks using full Run-2 data have been presented.

- The results have been interpreted in the context of different scenarios:

  - DM simplified model (Monotop Resonant and Non-resonant production).
  - Single Vector-Like Top production.
  - 2HDM+a model.

- No signal excess has been found in any of the the searches.

- For the different models considered, the most stringent constraints up to date have been provided. More results covering a wider parameter space are about to come.

- Stay tuned!

- Thanks for your attention!!

BACKUP

Monotop production at the LHC

- **Monotop signature**:

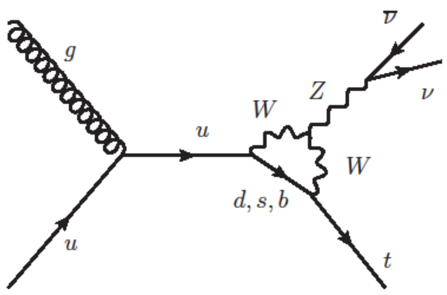
  + A single top quark
  + Large amount of missing energy (one or several undetected neutral particles)

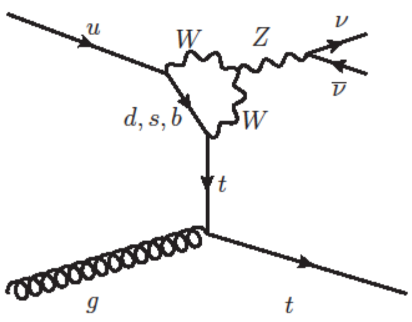
  DM candidate ! ← Stable and/or weakly interacting with ordinary matter?

• No such process is possible in the SM at tree level.

• Production of such signatures can only be possible at next-to-leading order (NLO).

• For example, the direct production of a **top quark** and a **Z boson decaying into a pair of neutrinos**, without any additional quark, is suppressed by the Glashow–Iliopoulos–Maiani (GIM) mechanism:



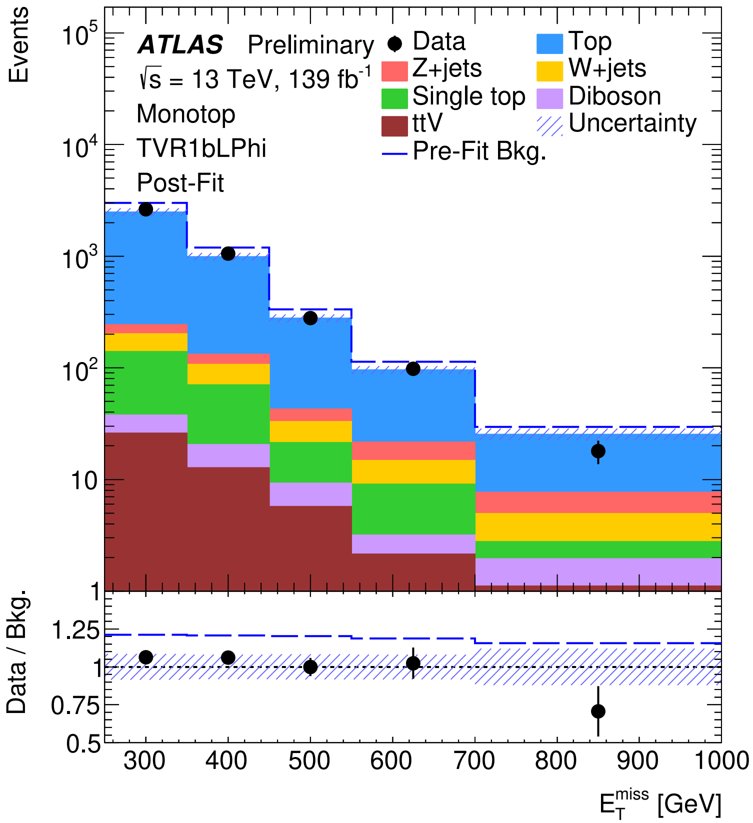


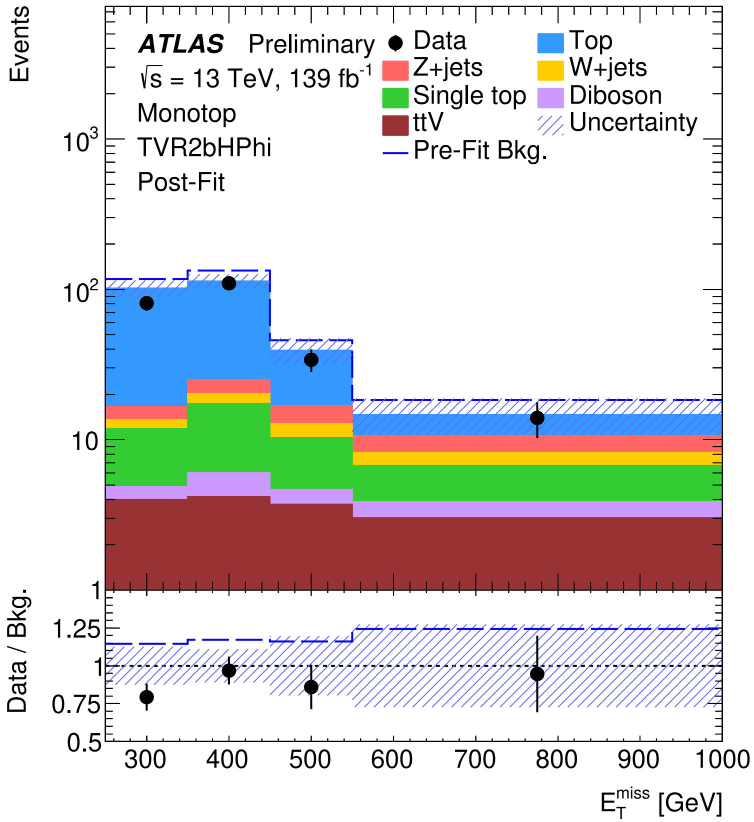
Monotop: XGB features

Variable	Description	Resonant DM model	Non-resonant DM model	VLQ
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum	✓	✓	✓
Ω	$E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet p_{T} balance: $\frac{E_{\mathrm{T}}^{\mathrm{miss}}-p_{\mathrm{T}}(J)}{E_{\mathrm{T}}^{\mathrm{miss}}+p_{\mathrm{T}}(J)}$	✓	✓	✓
$\mathrm{N}_{\mathrm{jets}}$	Small-R jet multiplicity	✓	✓	✓
ΔR_{max}	Maximum ΔR between two small-R jets	✓	✓	✓
$m_{\mathrm{T,min}}(E_{\mathrm{T}}^{\mathrm{miss}},b\text{-jet})$	Transverse mass of $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest b-tagged jet.	✓	✓	✓
$m_{\text{top-tagged jet}}$	Mass of the large-R top-tagged jet	✓		✓
$\Delta p_{\mathrm{T}}\ (J,\text{jets})$	Scalar difference of large-R jet p_{T} and the sum of p_{T} of all small-R jets.	✓	✓	
H_{T}	Sum of all small-R jet p_{T}		✓	✓
$H_{\mathrm{T}}/E_{\mathrm{T}}^{\mathrm{miss}}$	Ratio of H_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$		✓	✓
$\Delta E(E_{\mathrm{T}}^{\mathrm{miss}},J)$	Energy difference between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the large-R jet		✓	✓
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},J)$	Angular distance in the transverse plane between $E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet		✓	✓
$p_{\mathrm{T}}(\mathrm{J})$	Large-R jet p_{T}			✓
$m_{\mathrm{T}}(E_{\mathrm{T}}^{\mathrm{miss}},J)$	Transverse mass of the $E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet			✓
$\Delta\phi(b\text{-tagged jet},J)$	Angular distance in the transverse plane between the large-R jet and the leading b-jet			✓

Monotop: background modelling

A good modelling is observed in the different validation regions:





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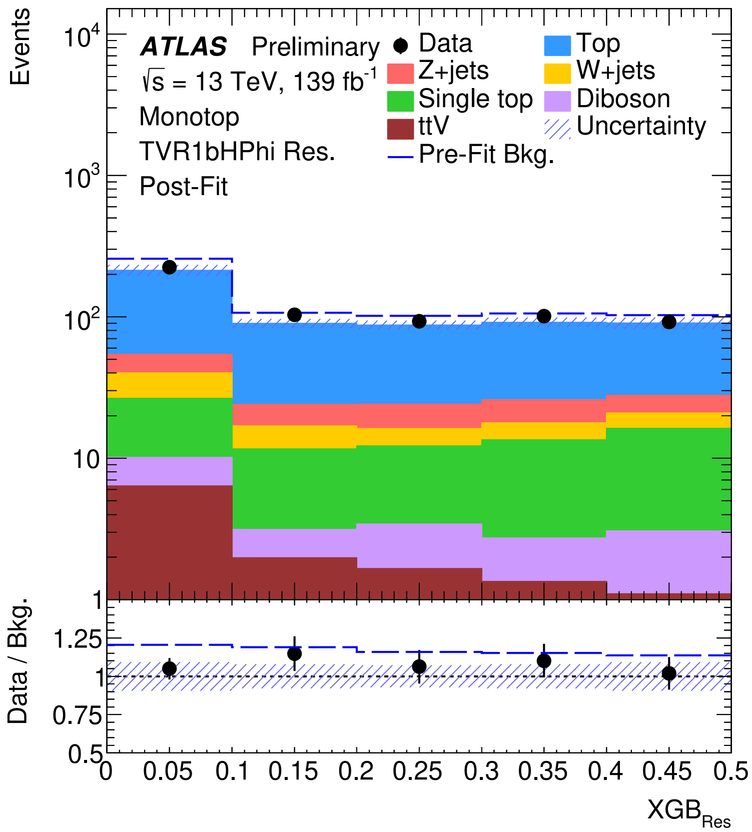
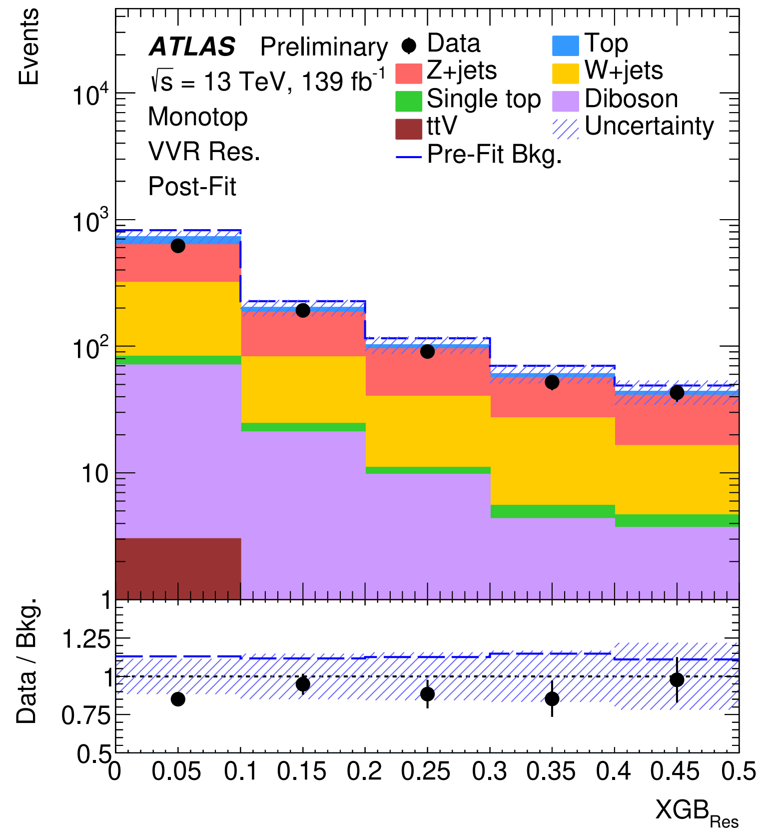
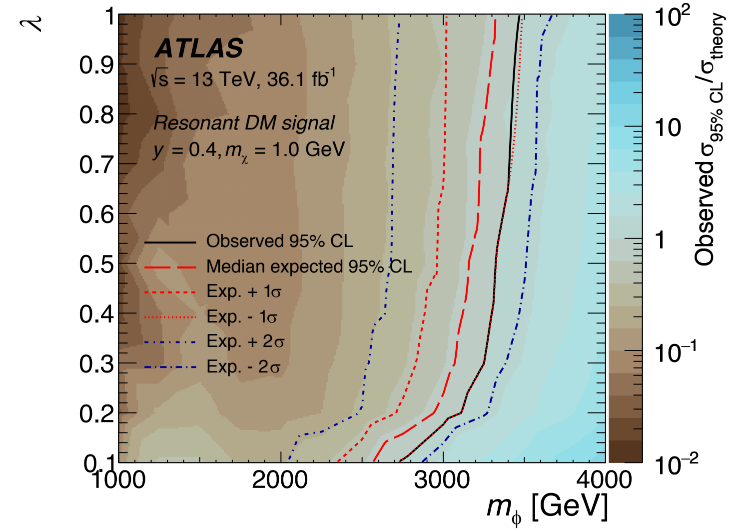




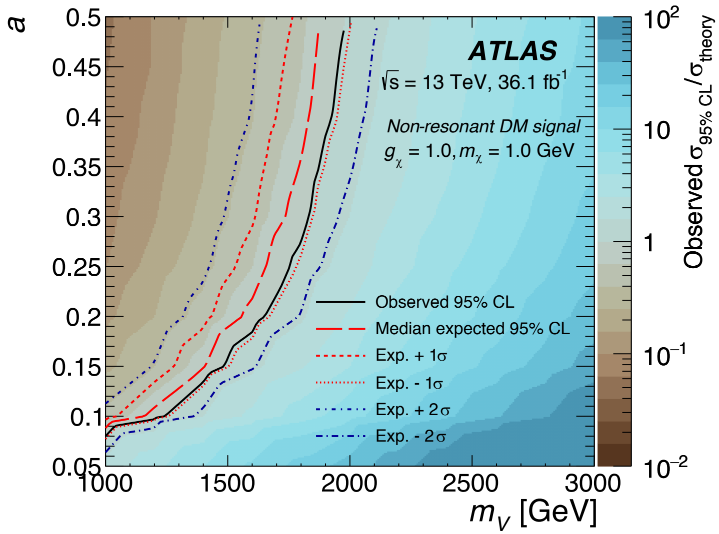
Last round analysis results (Monotop)

- Dataset: 2015-206 (**36.1 fb^{-1}**).
- **Cut based** analysis.
- **Topological** jets were used.
- Combined **leptonic** (negligible contribution) and **hadronic** channels.
- Monotop: Excluded $\boldsymbol{m_\phi}$ **up to 3.4 TeV** and $\boldsymbol{m_V}$ **up to 2 TeV**.
- VLQ: No m_T exclusion for k_T = 0.5.

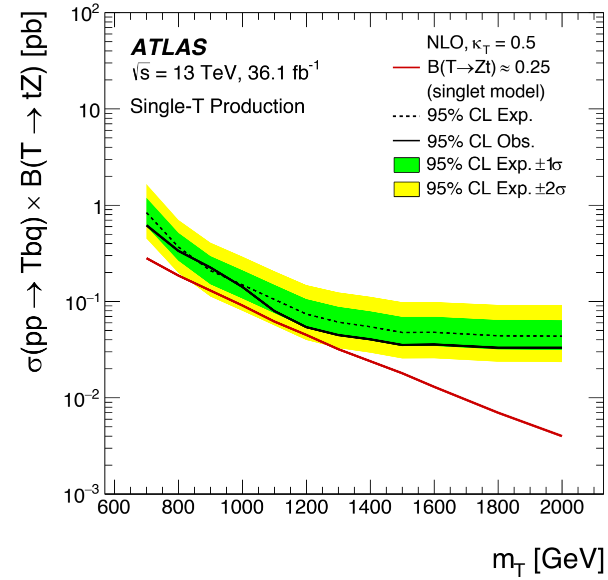
Resonant model



Non-resonant model



VLQ model



t + W + invisible region definitions

Variable	$\text{CR}_{\text{tW}_{0\text{L}}}$ $(t\bar{t})$	$\text{CR}_{\text{tW}_{1\text{L}}}$ $(t\bar{t})$	CR $(W+\text{jets})$	CR $(Z+\text{jets})$
Trigger	$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}}$	Single-lepton
$E_{\text{T}}^{\text{miss}}$ [GeV]	$\geq$250	$\geq$250	$\geq$250	$\leq$ 120
$E_{\text{T},\ell\ell}^{\text{miss}}$ [GeV]	–	–	–	$\geq$ 250
$\mathcal{S}_{E_{\text{T}}^{\text{miss}}}$	–	–	$\geq$ 15	–
$\mathcal{S}_{E_{\text{T},\ell\ell}^{\text{miss}}}$	–	–	–	$\geq$ 14
$\min[\Delta\phi(\text{jet}_{1-4}, E_{\text{T}}^{\text{miss}})]$	$\geq$ 0.5	$\geq$ 0.5	$\geq$ 0.5	–
$\min[\Delta\phi(\text{jet}_{1-4}, E_{\text{T},\ell\ell}^{\text{miss}})]$	–	–	–	$\geq$ 0.5
Number of baseline leptons	1	1	1	2
Number of signal leptons	1	1	1	2 (SF-OS)
$p_{\text{T}}^{\ell_1}$ [GeV]	$\geq$ 30	$\geq$ 30	$\geq$ 30	$\geq$ 30
$p_{\text{T}}^{\ell_2}$ [GeV]	–	–	–	$\geq$ 20
Number of signal jets	$\geq$4	$\geq$3	$\geq$3	$\geq$4
$p_{\text{T}}^{\text{j}_1}$ [GeV]	$\geq$ 100	$\geq$ 30	$\geq$ 30	$\geq$ 100
$p_{\text{T}}^{\text{j}_2}$ [GeV]	$\geq$ 60	$\geq$ 30	$\geq$ 30	$\geq$ 60
$p_{\text{T}}^{\text{j}_3}$ [GeV]	$\geq$ 60	$\geq$ 30	$\geq$ 30	$\geq$ 60
$p_{\text{T}}^{\text{j}_4}$ [GeV]	$\geq$ 40	–	–	$\geq$ 40
Number of b-tagged jets	$\geq$1	$\geq$2	$\geq$1	$\geq$1
$p_{\text{T}}^{\text{b}_1}$ [GeV]	$\geq$ 50	$\geq$ 50	$\geq$ 50	$\geq$ 50
$p_{\text{T}}^{\text{b}_2}$ [GeV]	$\leq$ 50	$\geq$ 50	$\leq$ 50	$\leq$ 50
Number of W-tagged jets $(N_{W\text{-tagged}}^{J;R=1.0})$	$\geq$ 1	–	$=0$	$\geq$ 0
$\Delta R_{W-\text{tagged},\text{b}_1}$	$\geq$ 1.0	–	–	–
$m_{W-\text{tagged},\text{b}_1}$ [GeV]	$\geq$ 220	–	–	–
$\text{m}_{\ell\ell}$ [GeV]	–	–	–	$\in$ [81,101]
$m_{\text{T}}(b_1, E_{\text{T},\ell\ell}^{\text{miss}})$ [GeV]	–	–	–	$\geq$ 180
$m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}})$ [GeV]	$<$ 130	$\geq$ 130	$\in$ [40,100]	–
am_{T2} [GeV]	$<$ 180	$<$ 180	$\geq$ 180	–
$m_{\text{W}}^{\text{had}}$ [GeV]	–	–	$<$ 60	–

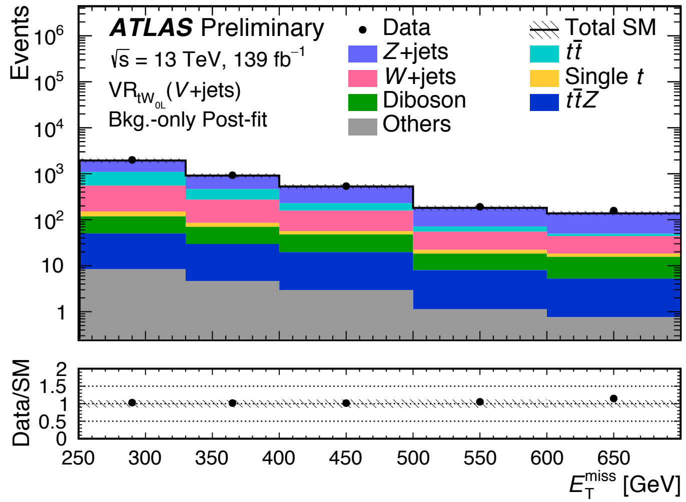
t + W + invisible region definitions

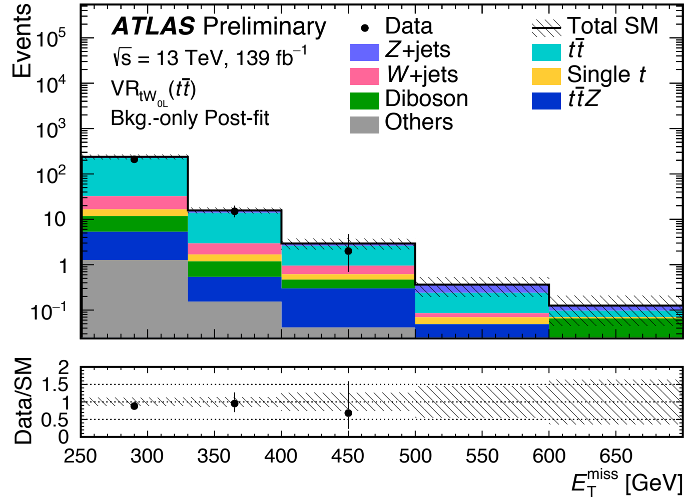
Variable	CR (Single t)	CR ($t\bar{t}Z$)
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single-lepton
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\geq$200	–
$E_{\mathrm{T},\ell\ell}^{\mathrm{miss}}$ [GeV]	–	≥ 140
$\min[\Delta\phi(\mathrm{jet}_{1-4}, E_{\mathrm{T}}^{\mathrm{miss}})]$	≥ 0.5	–
Number of baseline leptons	2	3
Number of signal leptons	2 (OS)	3 (at least one SF-OS pair)
$p_{\mathrm{T}}^{\ell_1}$ [GeV]	≥ 25	≥ 30
$p_{\mathrm{T}}^{\ell_2}$ [GeV]	≥ 20	≥ 20
$p_{\mathrm{T}}^{\ell_3}$ [GeV]	–	≥ 20
Number of signal jets	≥ 1	≥ 3
$p_{\mathrm{T}}^{\mathrm{j}_1}$ [GeV]	≥ 50	≥ 30
$p_{\mathrm{T}}^{\mathrm{j}_2}$ [GeV]	–	≥ 30
$p_{\mathrm{T}}^{\mathrm{j}_3}$ [GeV]	–	≥ 30
Number of b-tagged jets	$\geq$1	≥ 2
$p_{\mathrm{T}}^{\mathrm{b}_1}$ [GeV]	≥ 50	≥ 30
$p_{\mathrm{T}}^{\mathrm{b}_2}$ [GeV]	–	≥ 30
$\mathrm{m}_{\ell\ell}$ [GeV]	≥ 40, $\notin$ [71,111] if SF	$\in$ [71,111] for at least one SF-OS pair
m_{T2} [GeV]	< 100	–
$m_{b\ell}^{\mathrm{min}}$ [GeV]	> 170	–
$m_{b\ell}^{\mathrm{t}}$ [GeV]	> 150	–

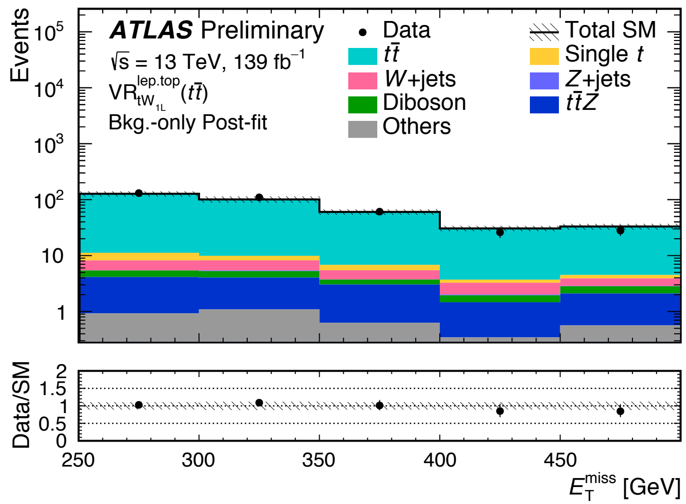
t + W + invisible region definitions

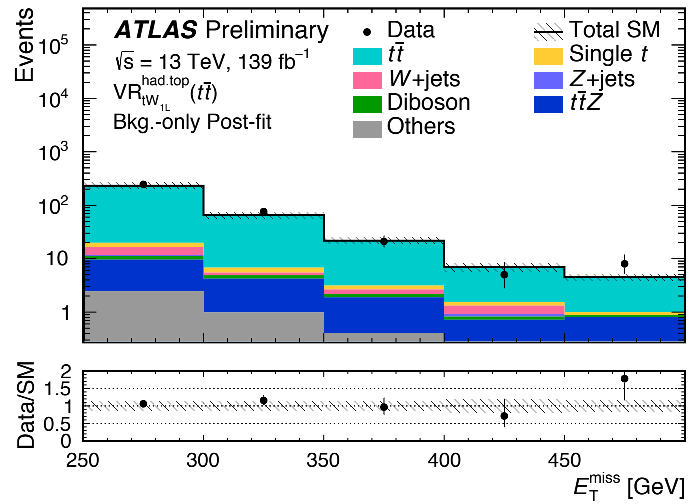
Variable	$\mathrm{SR}_{\mathrm{tW}_{0\mathrm{L}}}$	$\mathrm{SR}^{\mathrm{lep.top}}_{\mathrm{tW}_{1\mathrm{L}}}$	$\mathrm{SR}^{\mathrm{had.top}}_{\mathrm{tW}_{1\mathrm{L}}}$
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	≥ 250	≥ 250	≥ 250
$\mathcal{S}_{E_{\mathrm{T}}^{\mathrm{miss}}}$	≥ 14	≥ 15	-
$\min[\Delta\phi(\mathrm{jet}_{1-4}, E_{\mathrm{T}}^{\mathrm{miss}})]$	≥ 0.9	≥ 0.5	≥ 0.5
Number of baseline leptons	0	1	1
Number of signal leptons	0	1	1
$p_{\mathrm{T}}^{\ell_1}$ [GeV]	-	≥ 30	≥ 30
Number of signal jets	≥ 4	≥ 2	≥ 3
$p_{\mathrm{T}}^{\mathrm{j}_1}$ [GeV]	≥ 100	≥ 50	≥ 50
$p_{\mathrm{T}}^{\mathrm{j}_2}$ [GeV]	≥ 60	≥ 30	≥ 30
$p_{\mathrm{T}}^{\mathrm{j}_3}$ [GeV]	≥ 60	-	≥ 30
$p_{\mathrm{T}}^{\mathrm{j}_4}$ [GeV]	≥ 40	-	-
Number of b-tagged jets	≥ 1	≥ 1	≥ 1
$p_{\mathrm{T}}^{\mathrm{b}_1}$ [GeV]	≥ 50	≥ 50	≥ 50
$p_{\mathrm{T}}^{\mathrm{b}_2}$ [GeV]	≤ 50	≤ 50	≤ 50
Number of W-tagged jets ($N^{J;R=1.0}_{W\text{-tagged}}$)	≥ 1	≥ 1	-
$p_{\mathrm{T}}^{J;R=1.0}$ [GeV]	≥ 200	≥ 200	-
$\Delta R_{W-\mathrm{tagged},\mathrm{b}_1}$	≥ 1.0	-	-
$m_{W-\mathrm{tagged},\mathrm{b}_1}$ [GeV]	≥ 220	-	-
$m_{\mathrm{T}}(\mathrm{b}_1, E_{\mathrm{T}}^{\mathrm{miss}})$ [GeV]	≥ 180	-	-
$m_{\mathrm{b}_1,\mathrm{b}_1}$ [GeV]	-	≥ 200	≤ 200
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$ [GeV]	-	≥ 130	≥ 200
am_{T2} [GeV]	-	≥ 180	≥ 180
$m_{\mathrm{W}}^{\mathrm{had}}$ [GeV]	-	-	≥ 60

t + W + invisible background modelling









t + W + invisible background modelling