CSIC
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ATLAS Experiment

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Exotic searches at ATLAS (prompt)

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on behalf of the ATLAS collaboration

BLOIS2024 conference

Search for exotics physics

- The Standard Model explains most of the observed phenomena.
- However, theoretical reasons and observational evidences motivate the search for **exotics phenomena**.

Theoretical motivations

- Hierarchy problem
- Flavour puzzle
- GUTs to unify EW and QCD, gravity?
- …

Observational evidences

- Dark Matter
- Baryon asymmetry of the Universe
- Neutrino masses
- …

Search for exotics physics

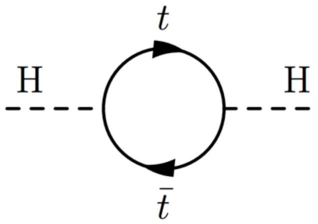
- The Standard Model explains most of the observed phenomena.
- However, theoretical reasons and observational evidences motivate the search for **exotics phenomena**.

Theoretical motivations

Hierarchy problem

$$m_H^2 = m_{H,0}^2 + \delta m_H^2$$

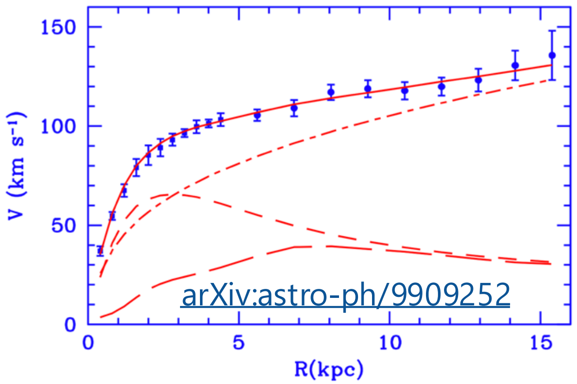
$$\delta m_H^2 \propto \int_0^{\Lambda_c} \frac{d^4p}{p^2} \propto \Lambda_c^2$$



<u>Possible solutions</u>:
Models such as Composite Higgs and Little Higgs, predicting new particles like **vector-like leptons and quarks**.

Observational evidences

Dark Matter



Gravitational lensing, CMB radiation, large scale structure, bullet cluster, etc.

<u>DM candidates:</u>
MACHOs, **Axions**, Dark photons, Kaluza-Klein particles, **Weakly-Interactive Massive Particles (WIMPs)**, etc.

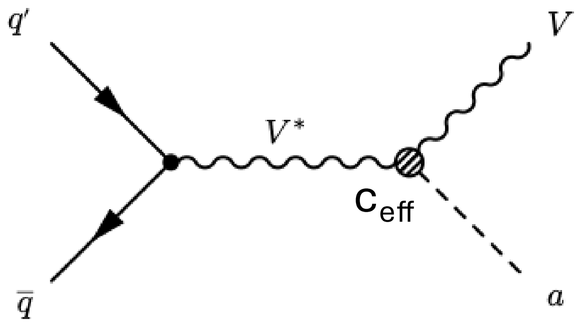
Search for mono-V events decaying hadronically

Paper submitted to JHEP

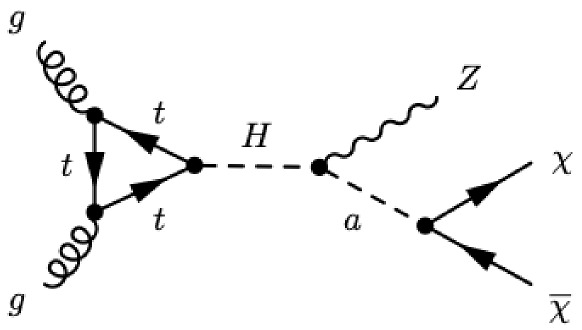
arXiv:2406.01272

Motivation for mono-V searches

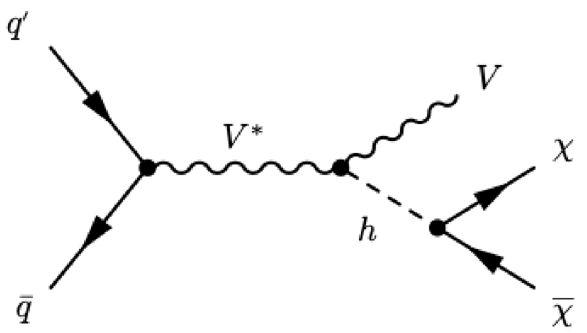
- Since Dark Matter is not expected to interact with the detector, its detection requires the production of additional objects to trigger the event.
- Events with just a single object in the final state and large missing energy transverse (E_T^{miss}) are a clear signature to look for Dark Matter.
- This search is focused on events with a single W/Z boson decaying hadronically.
- Four BSM interpretations explored: Axion-Like Particles (ALPs), Two-Higgs-doublet model with a pseudoscalar, Higgs portal and a simplified model.



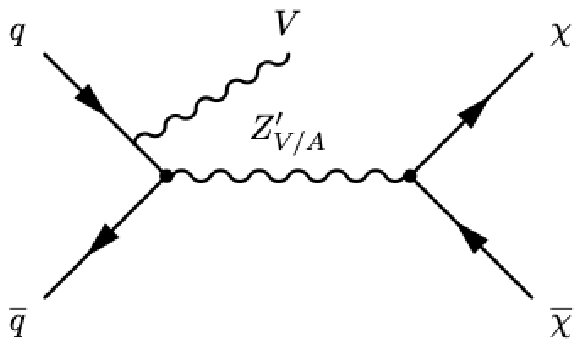
ALPs in association with a V boson (effective scale f_a)



2HDM+a



Higgs portal

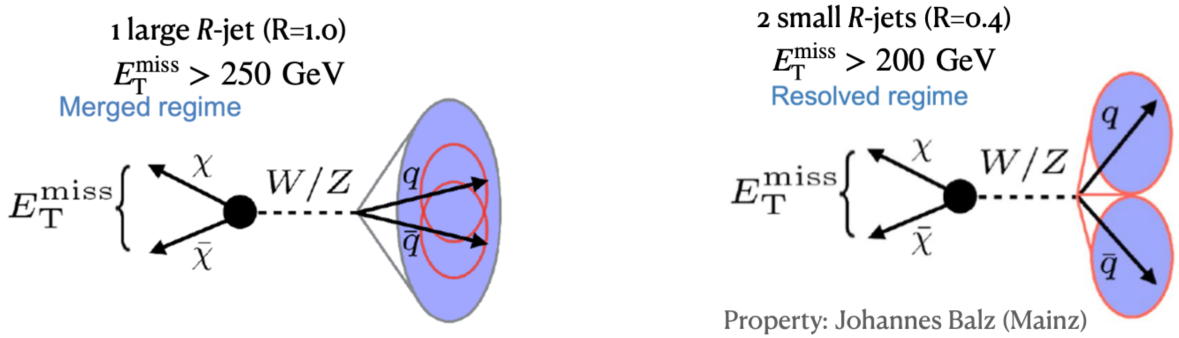


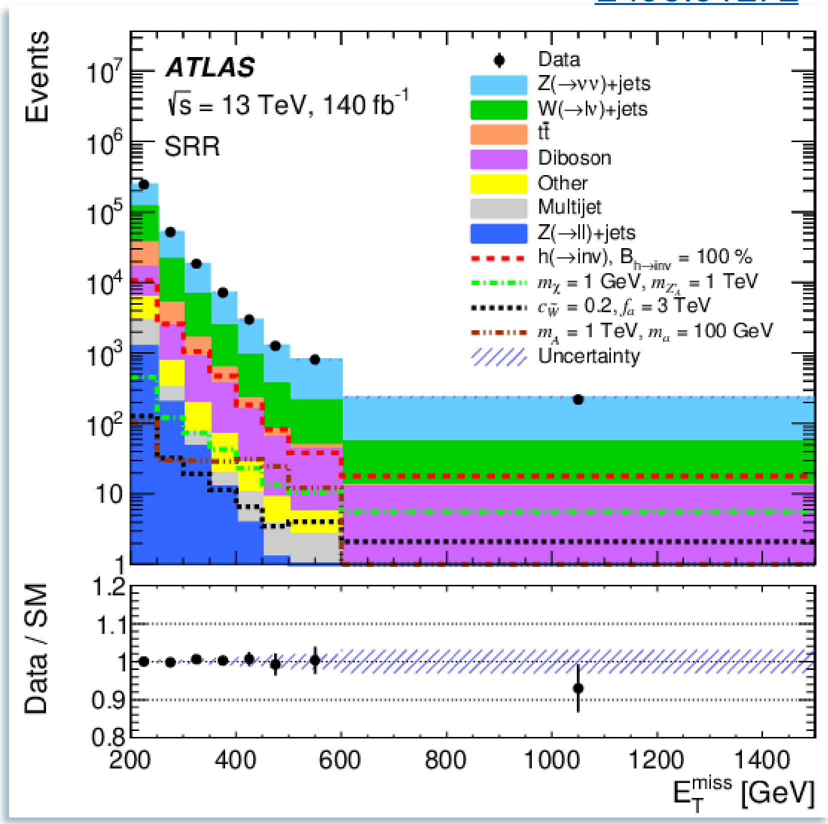
Simplified model (hypothetical mediator decaying to WIMPs)

Strategy for hadronic mono-V search

[2406.01272](2406.01272)

- Depending on the boost of the produced boson:
  - Merged regime: large-R jet p_T > 250 GeV.
  - Resolved regime: reconstructed V ($m_{j1,j2} \in [65,105]$ GeV, $\Delta R_{j1,j2} < 1.4$, $\Delta\phi_{j1,j2} < 140^o$).





- W/Z tagging of the boosted large-R jet using the combined mass, substructure variables and the number of associated tracks.
- 3 signal regions depending on the boosted regime and the tagging criteria.
- Z(-> **νν**)+jets, W(->l**ν**)+jets and top pairs are the dominant backgrounds.
  - Z(->**νν**)+jets estimated in di-leptonic phase space.
  - W(->l**ν**)+jets and ttbar estimated in events with muons and b-jets.
- Likelihood fit to the E_T^{miss} distribution in both signal and control regions.

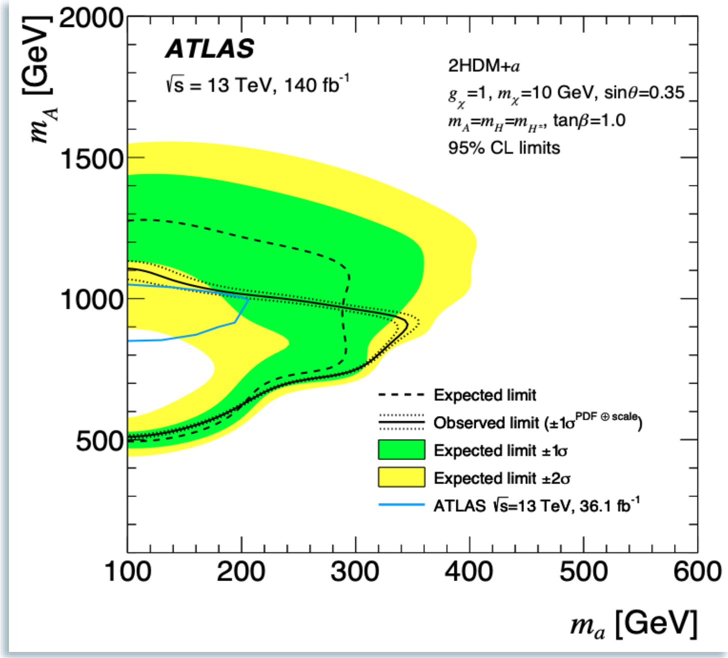
Higgs -> inv
Simplified model
2HDM
ALPs

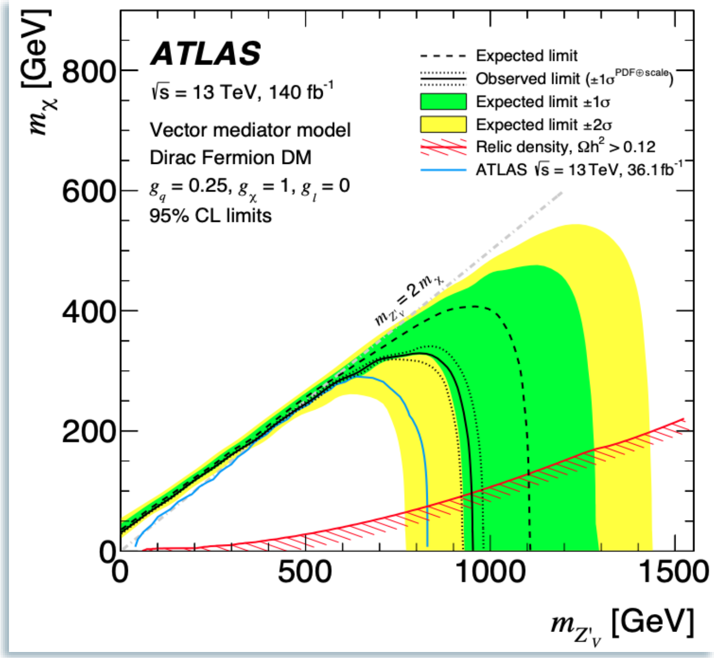
Results

- No significant excess found for any of the signals explored.
- Model-independent (inclusive) limits on the visible cross-section (σ x A x ε): > 0.8 fb excluded for large E_T^{miss} values (>500 GeV).
- Model-dependent exclusion limits on the free-parameters of the models.
  - The ALP search excluded the **ratio c_{eff}/f_a (for a fixed m_{ALP}=1 MeV) for values above 0.11 TeV^{-1}**.
  - 2HDM+a set exclusions in pairs with 2D limit maps fixing the rest of parameters.
  - Higgs to invisible excluded **BR(h-> invisible) > 0.34** .
  - The simplified model allows to set limits on the DM mass and mediator masses, fixing the values of the couplings.

c_{eff} : effective coupling
f_a : effective scale

2HDM+a





Simplified model

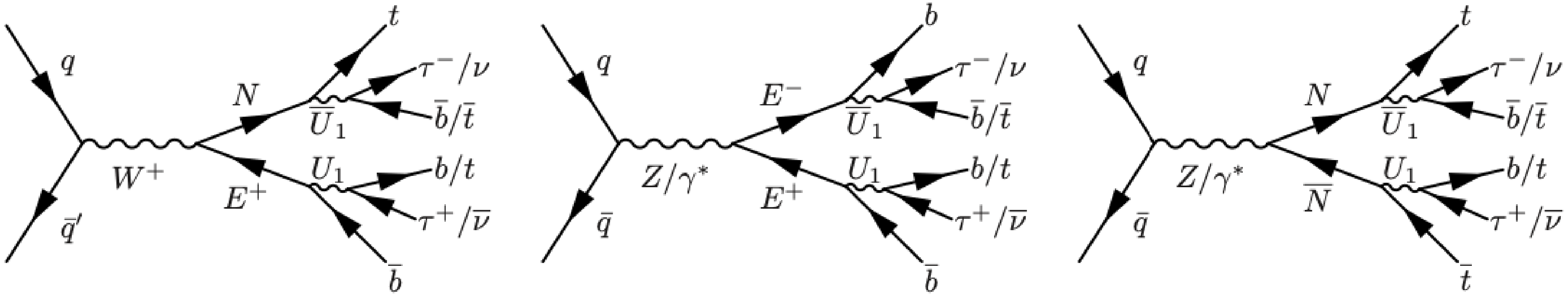
Vector-Like Leptons in the τ channel

Conference note:

ATLAS-CONF-2024-008

Motivation of VLLs

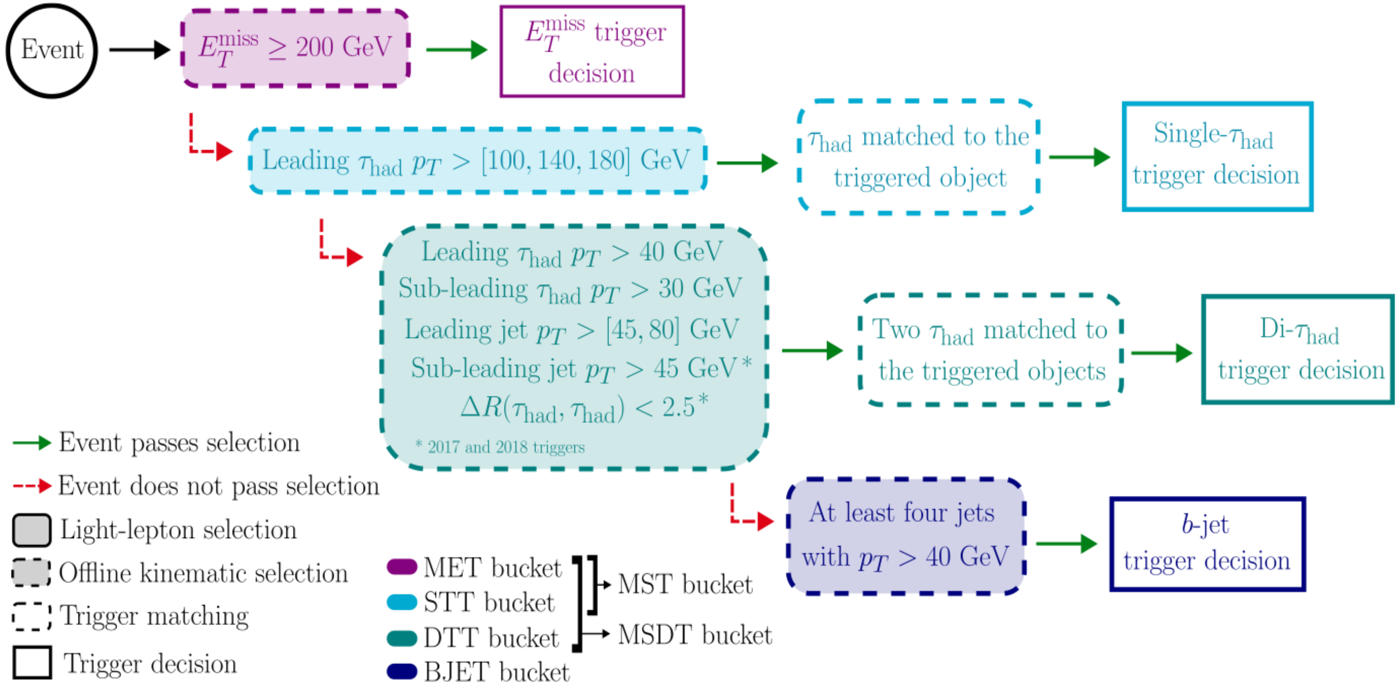
- Vector-Like Leptons are predicted by models that solve the hierarchy problem.
  - This search is based on the 4321 renormalizable model: SU(4)xSU(3)'xSU(2)$_L$xU(1)'
  - Introducing leptoquarks (U_1), 3 new gauge bosons, vector-like leptons (E/N) and quarks (U/D).
- **Vector-like**: same EW transformations for left- and rigth-handed components.
- **Leptons**: colour-singlet, spin-1/2 particles grouped in SU(2) doublets with a neutral and a charged component.
- This search target pair-production of VLLs:



Search focused on τ's

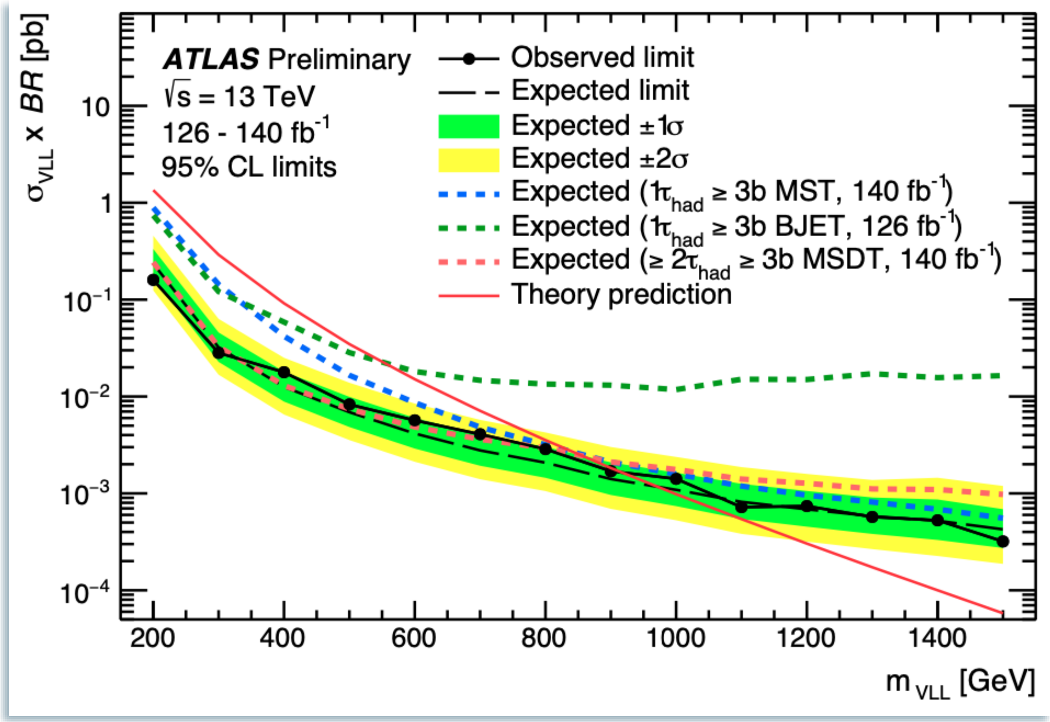
Strategy for VLLs with τ's in the final state

- Different triggers to maximise sensitivity.
  - MET, SingleTauTrig. (STT), DiTauTrig. (DTT), BJTrig. (BJET).
- 5 signal regions for three event categories:
  - $1\tau_{had}$, $3b$ MST & $1\tau_{had}$, $\geq 4b$ MST (MST=MET ∪ STT).
  - $1\tau_{had}$, $3b$ BJET & $1\tau_{had}$, $\geq 4b$ BJET .
  - $\geq 2\tau_{had}$, $\geq 3b$ MSDT (MSDT=MET ∪ STT ∪ DTT).
- 0 leptons + >=1 τ_{had} : Signal & control regions.
- >=1 leptons: Scale & validation regions.
- Main backgrounds: top pair, Z/W+jets
- Neural Network score as discriminant.
  - Different training for the 3 event categories.
- Simultaneous fit over 5 signal regions & 7 control regions.



Results

- No significant excess of data over the expected background is observed.
- Limits presented for the individual and combination of the signal regions.
- The observed (expected) limits exclude masses below 910 (970) GeV at 95% CL.
- Results incompatible with CMS excess.



Earlier study from CMS found a 2.8σ excess at m_{VLL}~600 GeV (CMS result).

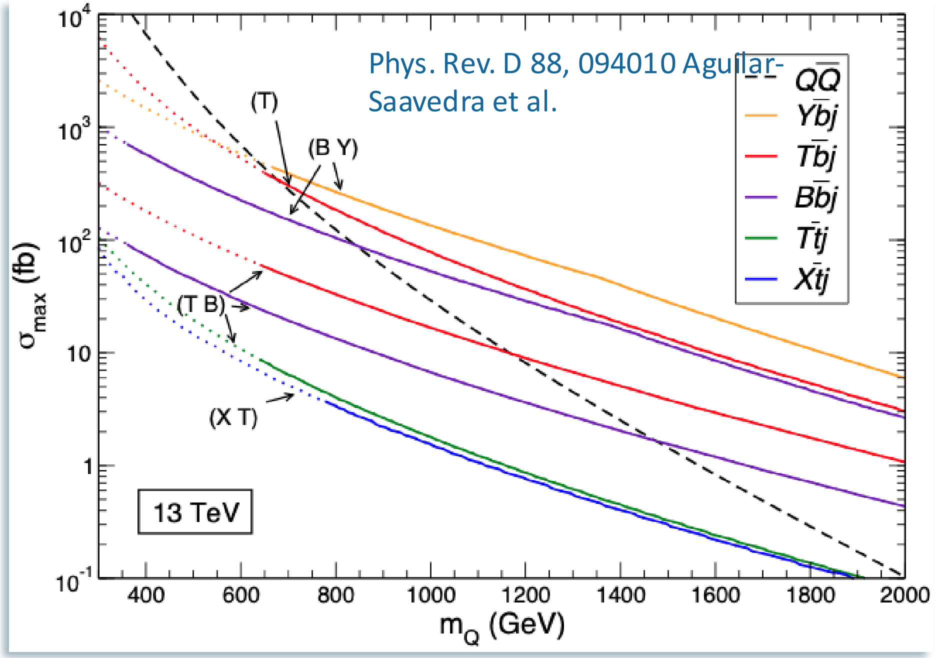
Vector-Like Quarks decaying to *Wb* hadronically

Paper submitted to JHEP

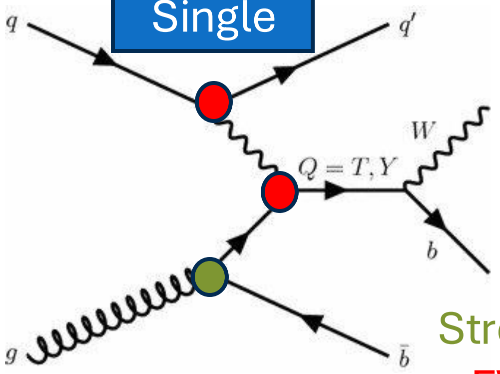
arXiv:2409.20273

Motivation of VLQs

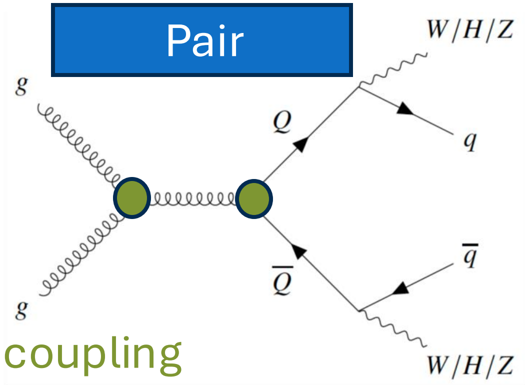
- Vector-Like Quarks (VLQs) appear in some BSM models to solve the mass hierarchy problem.
- Same EW transformations for left- and right-handed components.
- Spectrum of VLQs: $X_{+5/3}$, $\mathbf{T_{+2/3}}$, $B_{-1/3}$, $\mathbf{Y_{-4/3}}$.
- Two production modes at the LHC:
  - Pair production: dominant for low masses, only depend on m_{VLQ}.
  - Single production: dominant for large masses and also depends on EW couplings.
- Simplified model to interpret single-production results.
  - Limits on cross-section, m_{VLQ} and overall coupling κ to SM bosons.



Single



Pair

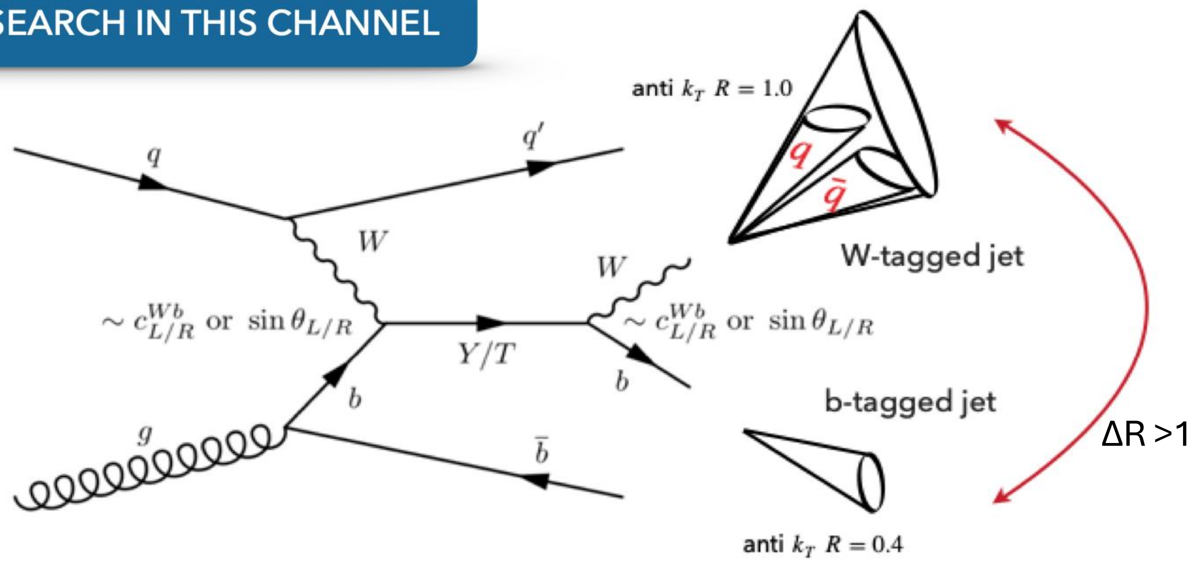


Strong coupling

EW coupling

Strategy for *T/Y* -> *Wb* hadronically

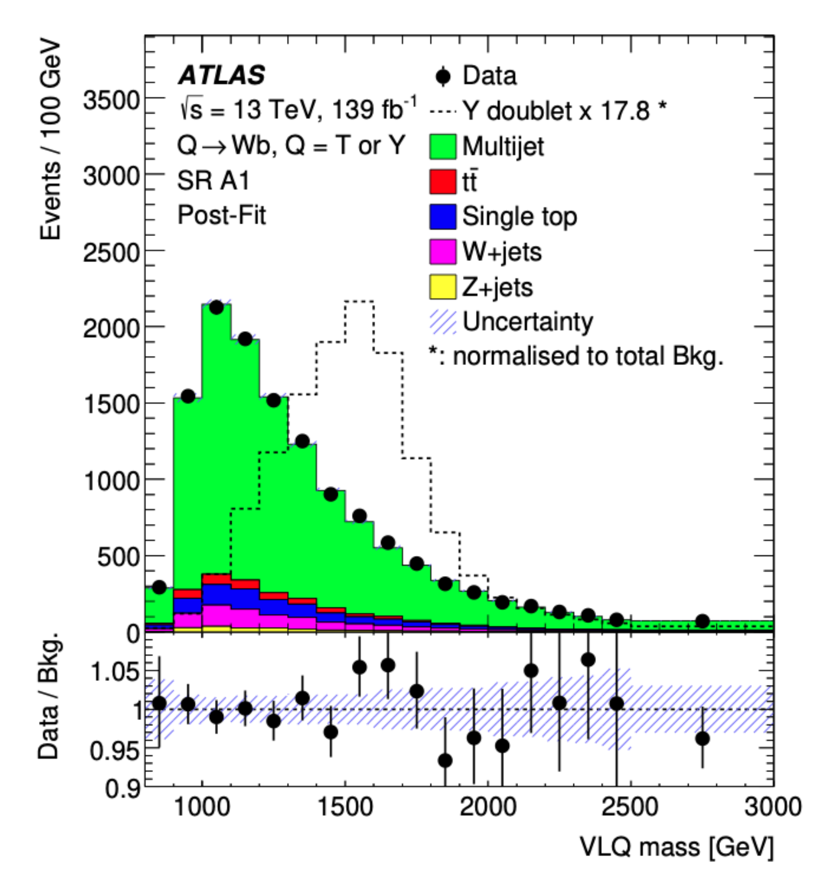
FIRST SEARCH IN THIS CHANNEL



- Discriminant variable signal vs background:

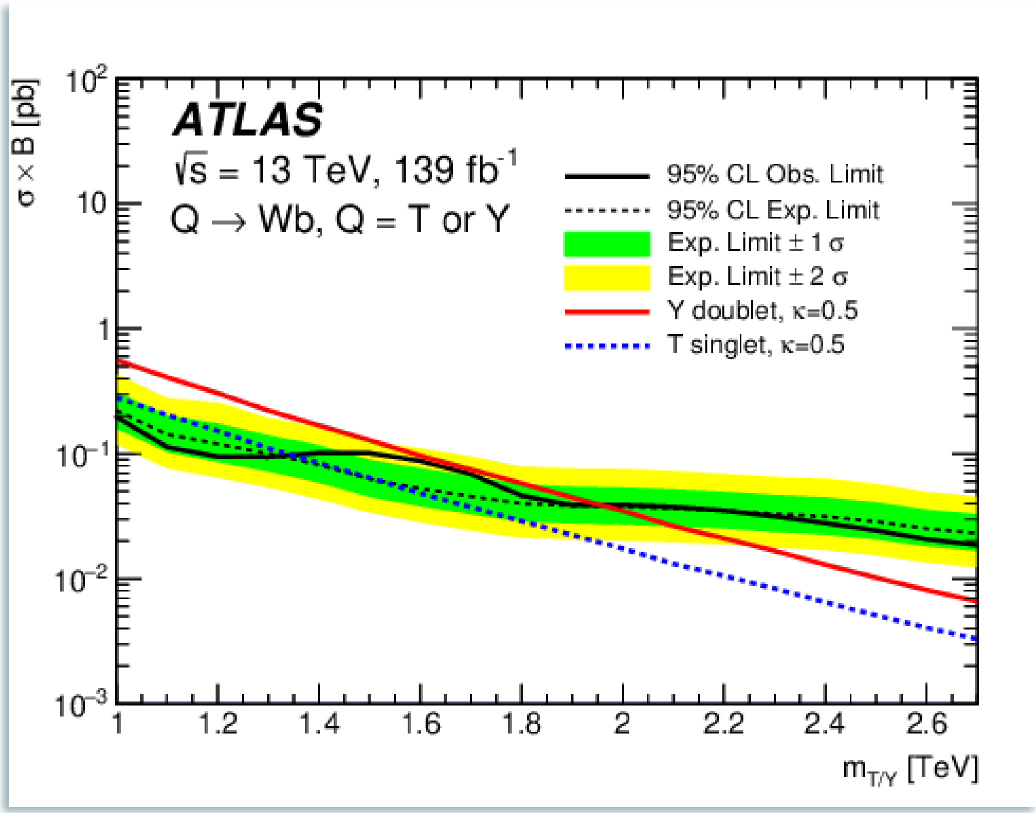
$$m_{VLQ} = p(\text{leading large-R jet}) + p(\text{leading small-R jet})$$

- Multijet production is the main irreducible background.
- Multijet estimate calculated with a data-driven technique:
  - ABCD method: W-tagging working point and b-tag multiplicity to define the plane.

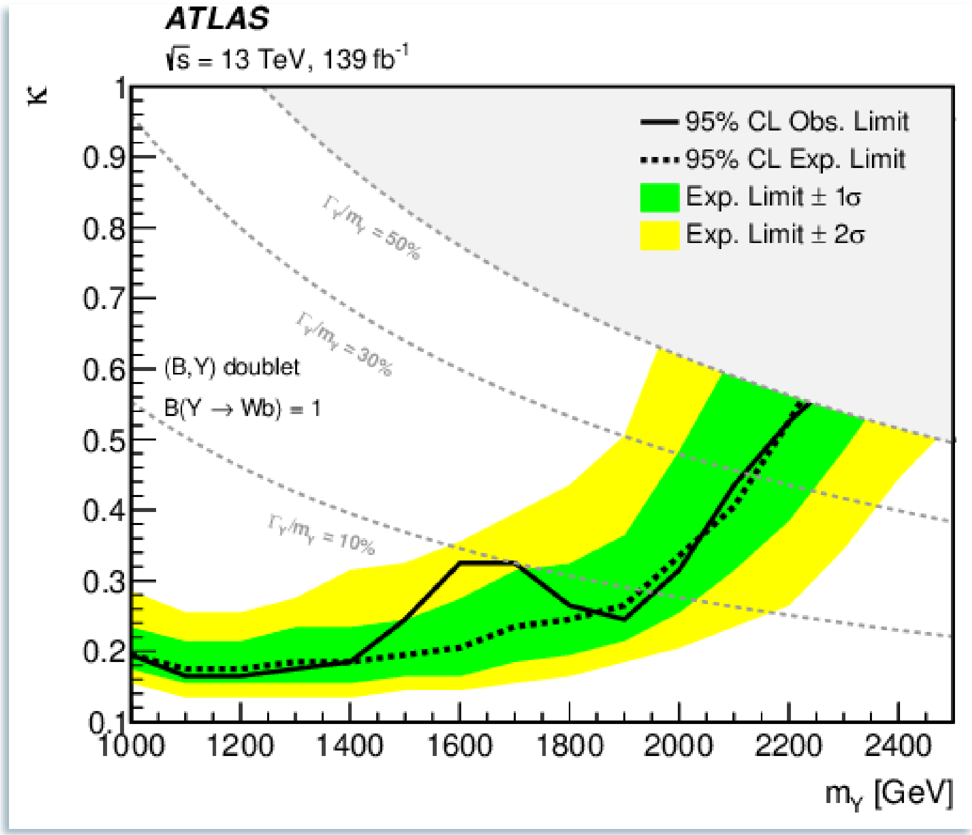


Post-fit distribution of m_{VLQ} fitted to data in the SR for the background-only hypothesis

New Results



For κ = 0.5, masses of T (Y) below 1.4 (1.8) TeV are excluded.



- m_Y excluded up to 2.2 TeV for κ~0.6
- κ > 0.2 excluded in the low mass range.

Note: Assuming BR(T->Wb)=0.5 (T singlet) and BR(Y->Wb)=1.0

Combination of singly-produced Vector-Like Top searches

Paper submitted to PRD:

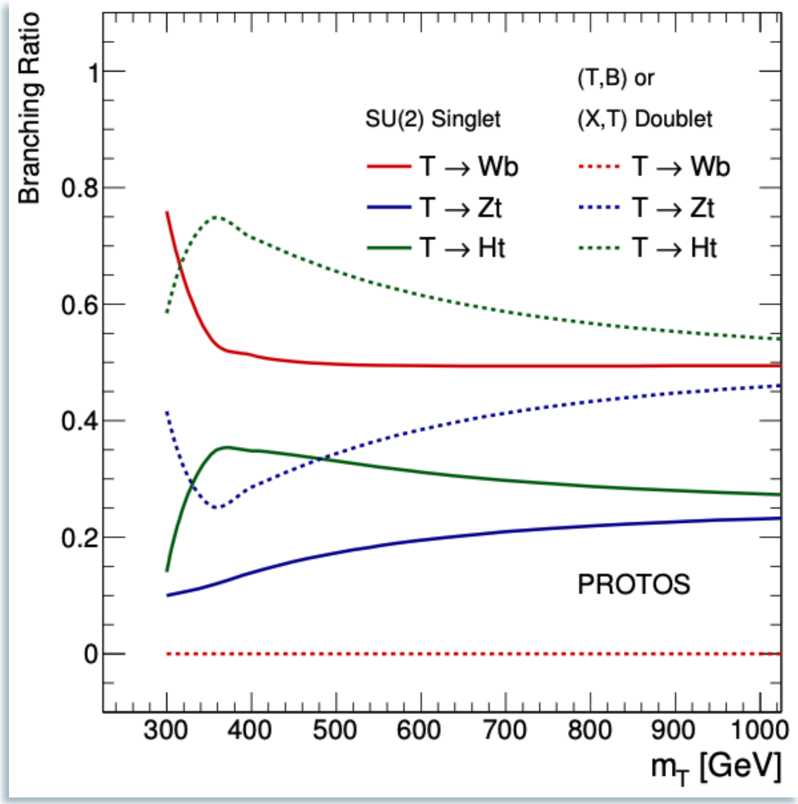
arXiv:2408.08789

Introduction to VLQ combinations

ATLAS EXPERIMENT

- Paper for combination of pair-produced VLQs.
- Wide range of final states coming from a singly-produced VLQ are being explored in the collaboration:
  - B → bH (H→γγ; H→bb)
  - T/Y → Wb (W→ℓ**ν**; W→qq)
  - **T → Ht/Zt** (Z→**νν**; Z→ℓℓ; Z→qq)
- A combination of three searches of vector-like Top (VLT) quarks is shown.
- The VLT quark can exist in a singlet, doublet or triplet of $SU(2)_L$.

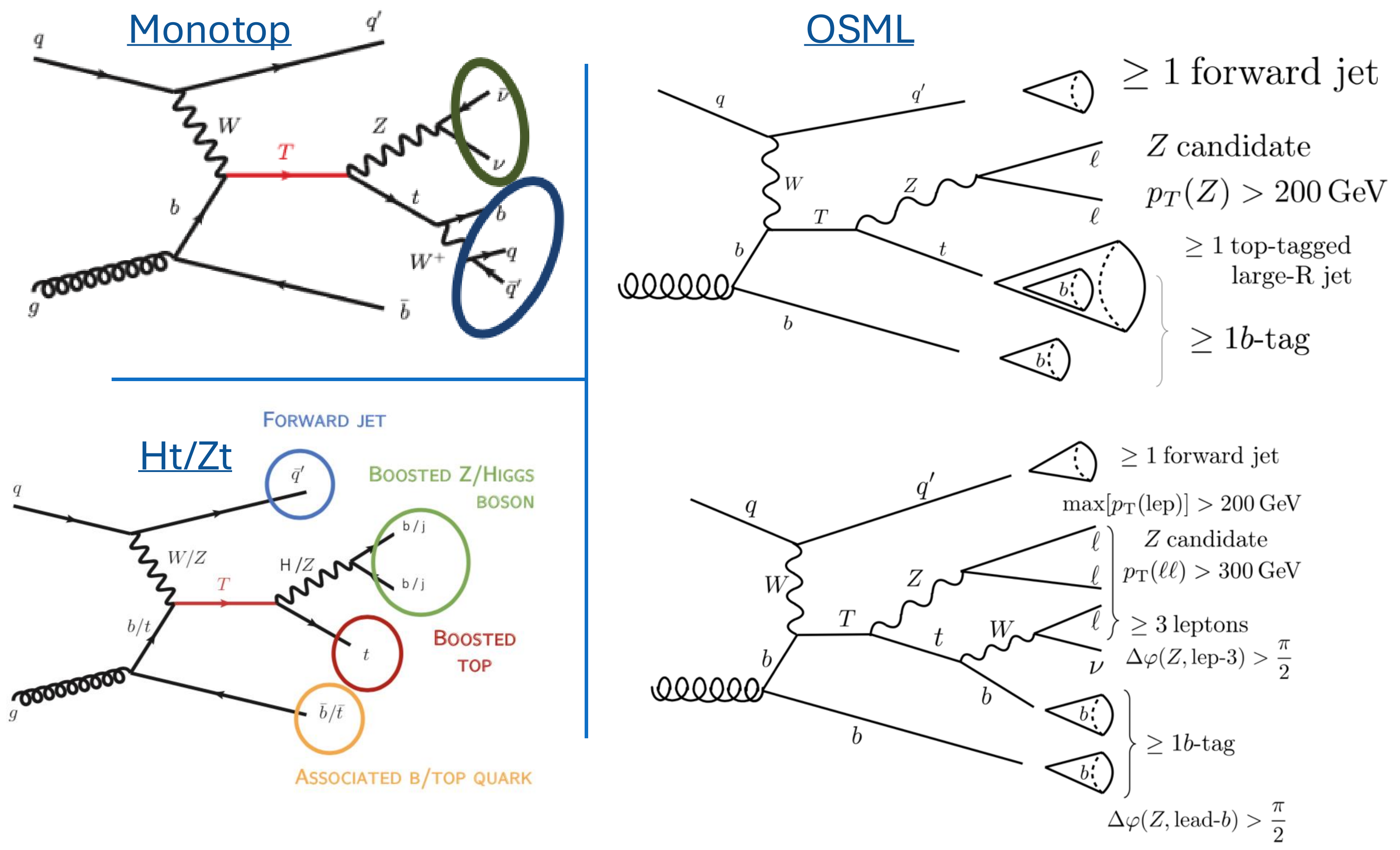
Multiplet	T	B	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
Hypercharge	$+2/3$	$-1/3$	$+1/6$	$+7/6$	$-5/6$	$+2/3$	$-1/3$
Weak isospin	0	0	1/2	1/2	1/2	1	1
Color charge	1	1	1	1	1	1	1



T singlet: BR(T->Zt)=BR(T->Ht)=0.25
T doublet: BR(T->Zt)=BR(T->Ht)=0.5

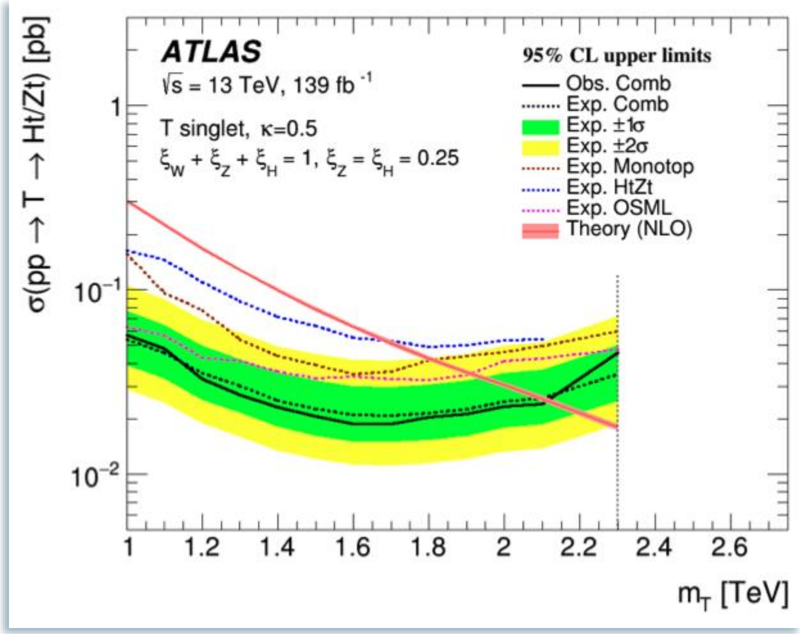
Combination strategy

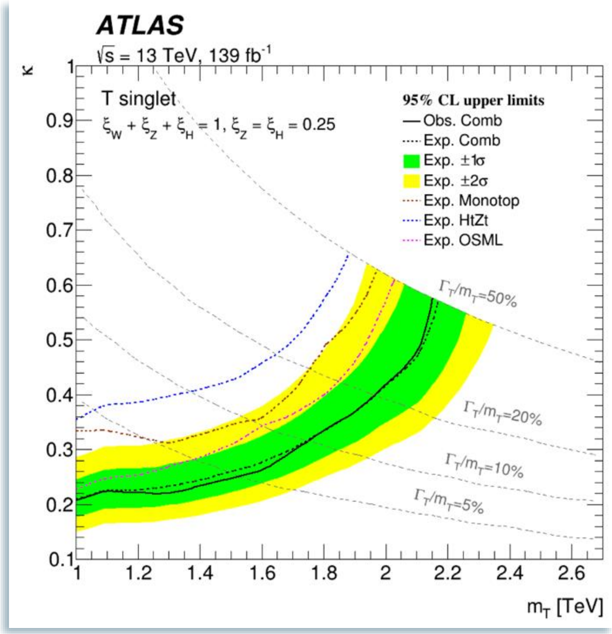
- Three analyses with **orthogonal final states**:
  - Monotop: 0 lepton.
  - Ht/Zt: 1 lepton.
  - OSML: 2 or 3 leptons.
- Common systematics are correlated among the analyses.
- Centralised framework to combine workspaces, perform fitting and plotting.

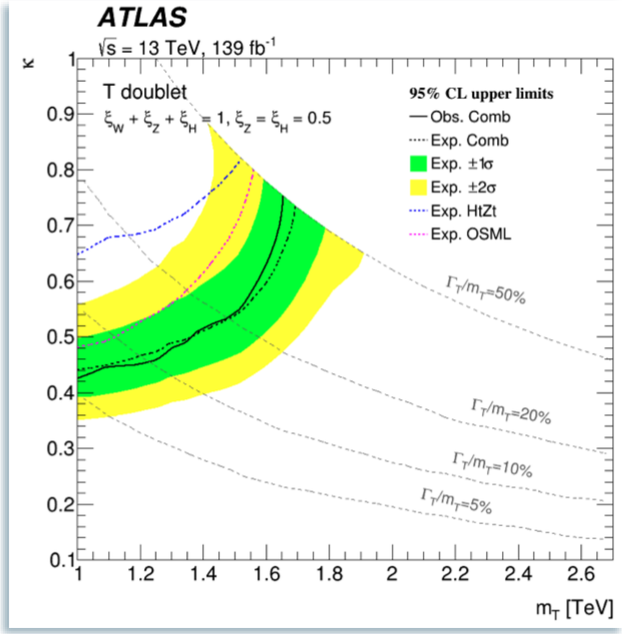


Results

- The combination significantly improved the limits obtained from the individual analyses.
  - For κ values of 0.5, the excluded cross-section improved around a 50% (20%) and the mass limit increased ~200 (~150) GeV, for the singlet (doublet) interpretation.
- Upper limits set for T singlet (doublet):
  - The cross-section for single production is constrained to be below 0.02 pb for κ~0.3 (0.7) .
  - Coupling parameter κ is contrained to be below 0.2 (0.4) for lower masses, excluding masses up to 2.2 (1.7) TeV for κ ~0.5 (0.7).







Conclusions

ATLAS EXPERIMENT

Some of the latest exotics searches in ATLAS have been shown, mainly related to the Dark Matter and the hierarchy problems:

- ❑ Mono-V hadronic search.
- ❑ Search for Vector-Like Leptons in the multi-tau and multi-bjets channel.
- ❑ Search for singly-produced Vector-Like T/Y decaying to Wb hadronically.
- ❑ Combination of singly-produced Vector-Like Top searches.

No significant excess of data over the expected background is observed.

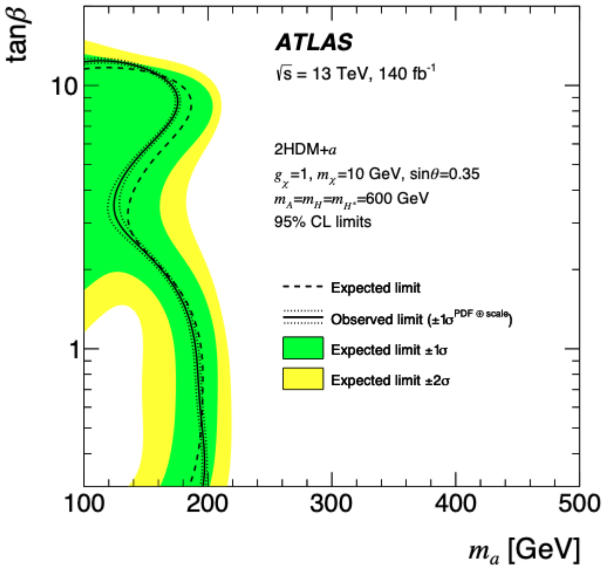
Stringent limits are set in several cases and combinations offer large improvements over analyses in individual channels.

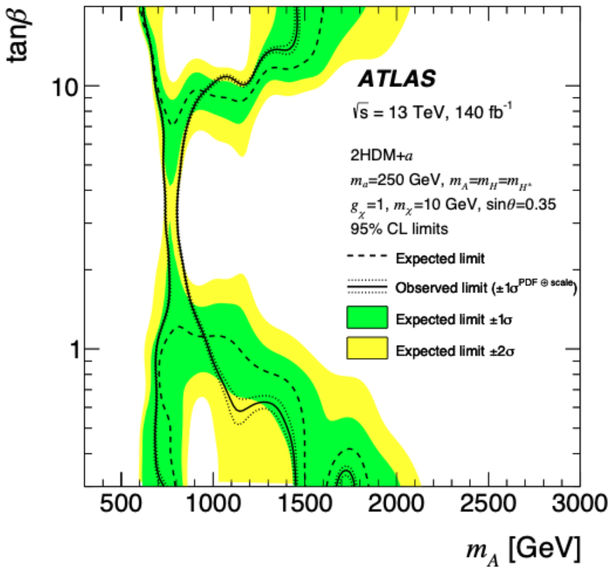
More analyses are being finalised soon… keep tuned!

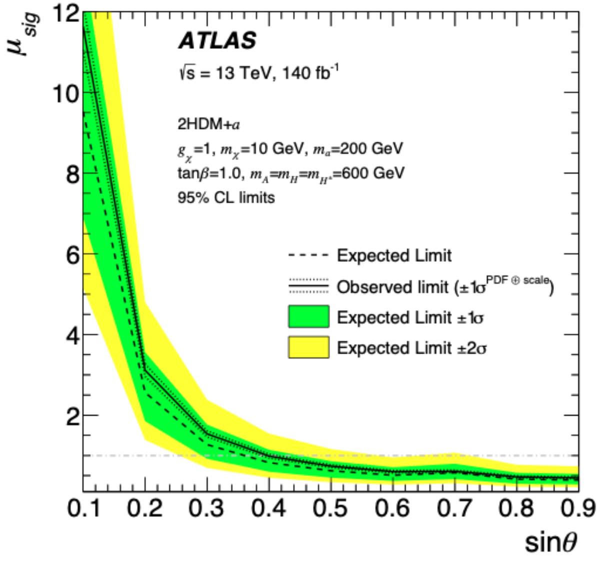
Back-up slides

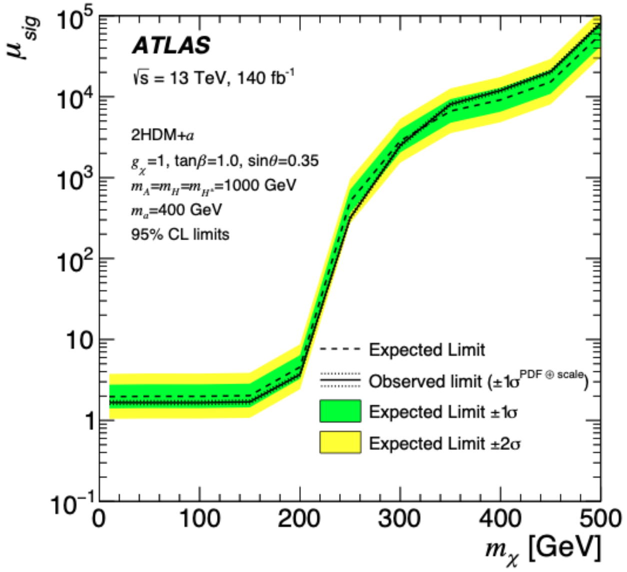
Mono-V search

- 2HDM+a model set limits to the cross-section and 5 parameters:
  - g_χ, m_χ, $mA=mH^+=mH^-$, $\sin\theta$, $\tan\beta$





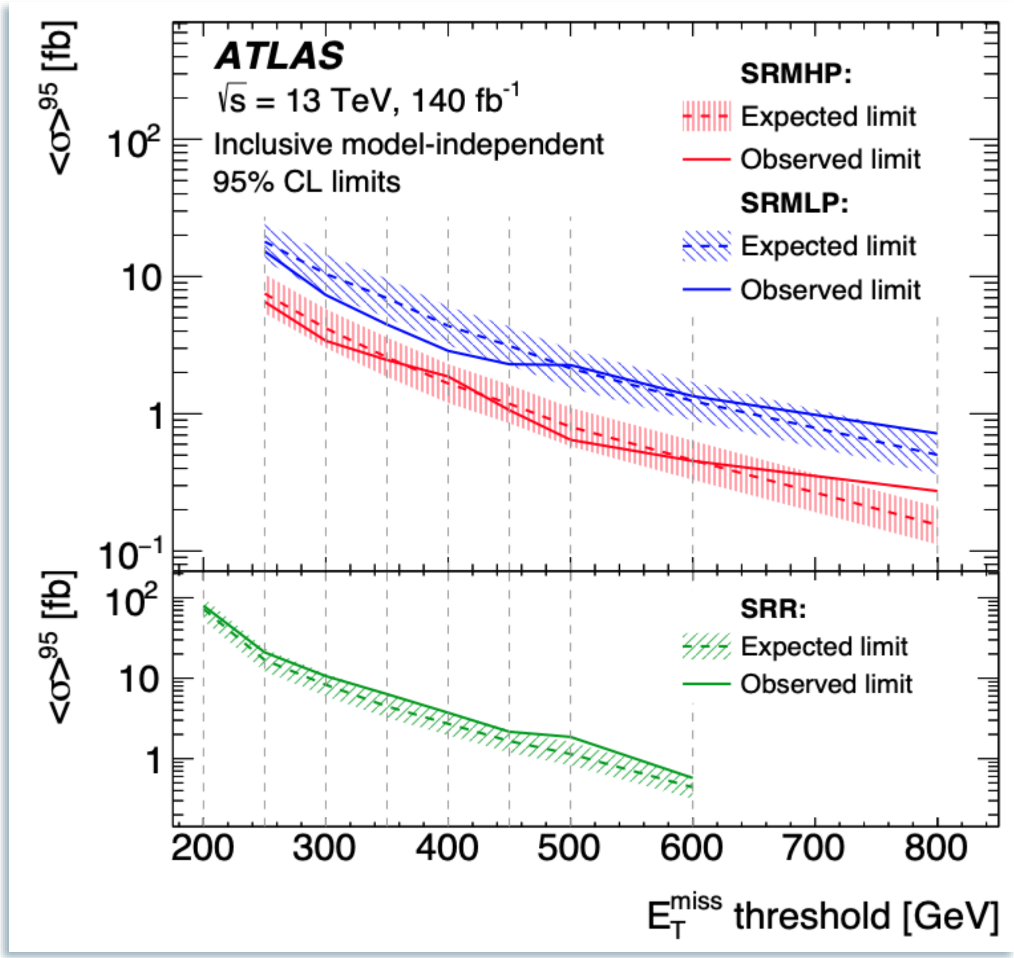




Mono-V search

- Model independent limits on the inclusive visible cross-section:

SRR: resolved.
SRMHP: merged with high purity.
SRMLP: merged with low purity.



VLLs in the multi-τ and multi-bjets channel

ATLAS EXPERIMENT

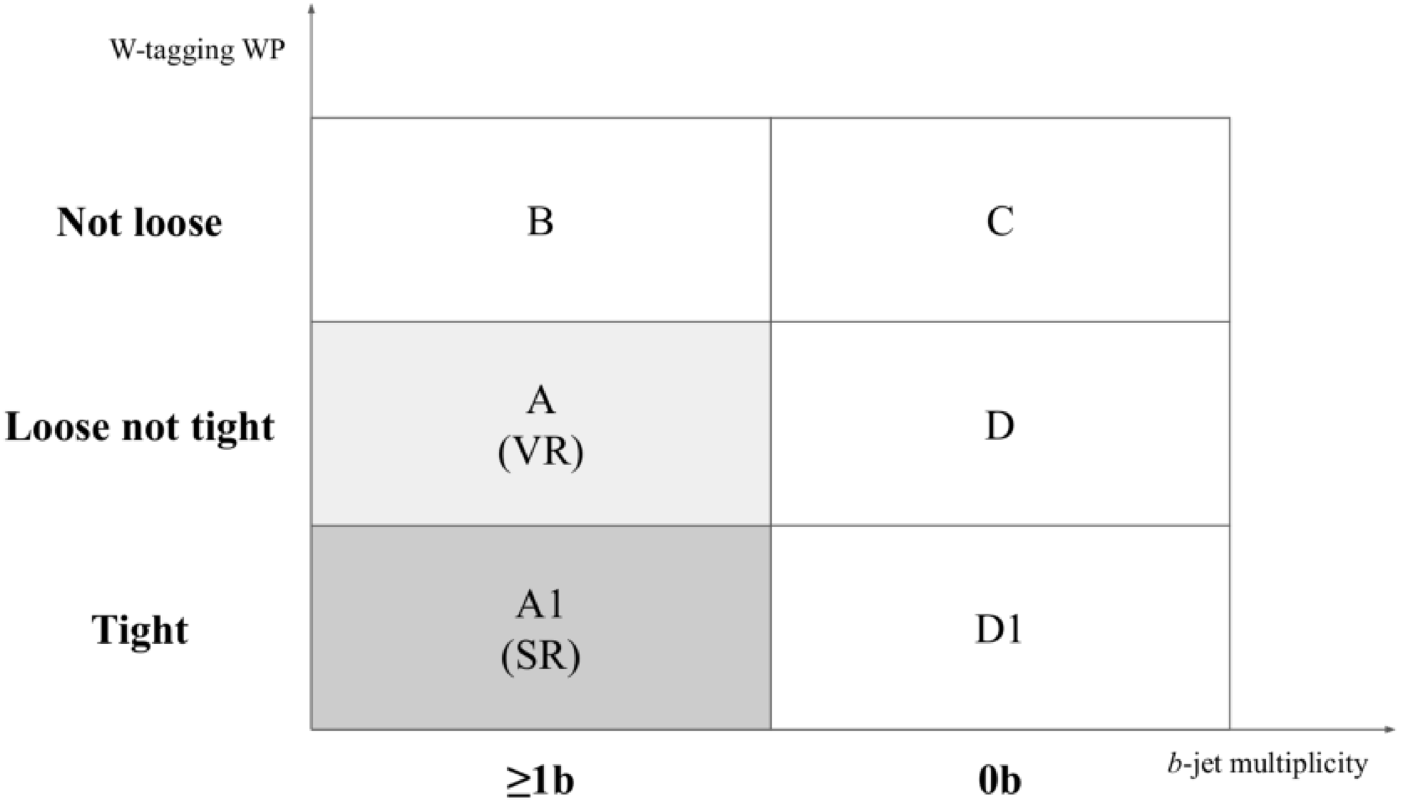
- Training setup:
  - Mass-parameterised Neural Network
  - 2 dense layers (35 nodes each) and 2 nodes in the output layer.
- A different training was performed for the three event categories.
- The variables given to the NN are shown in this table.
- The signal regions definitions are:

Variable	Event category		
	$1\tau_{had} \geq 3b$ MST	$1\tau_{had} \geq 3b$ BJET	$\geq 2\tau_{had} \geq 3b$ MSDT
n^{trig}	✓		✓
$p_{T,0}^{\tau_{had}}$	✓	✓	✓
$p_{T,1}^{\tau_{had}}$			✓
$p_{T,2}^{\tau_{had}}$			✓
N_{jets}	✓	✓	✓
$N_{\tau_{had}}$			✓
$H_{T,jets}$	✓	✓	✓
E_T^{miss}	✓	✓	✓
$m(\tau_{had,0}, \tau_{had,1})$			✓
$m(\tau_{had,0}, b_0)$	✓	✓	✓
$m(b_0 b_1, \tau_{had,0})$	✓	✓	✓
$m(b_0 b_1, E_T^{miss})$	✓	✓	✓
Σb^{PCB}	✓		✓
$n^{\tau_{had}ID}$			✓
$\min(\Delta\phi(E_T^{miss}, \text{jets}))$	✓	✓	✓
$\min(\Delta\phi(E_T^{miss}, \tau_{had}))$	✓	✓	✓
$N_{trk}^{\tau_{had}}$	✓	✓	✓
$Q_{\tau_{had,0}}$	✓	✓	✓
$\Sigma Q_{\tau_{had}}$			✓

Signal Region	$1\tau_{had}3b$ MST	$1\tau_{had} \geq 4b$ MST	$1\tau_{had}3b$ BJET	$1\tau_{had} \geq 4b$ BJET	$\geq 2\tau_{had} \geq 3b$ MSDT		
Trigger bucket	MET ∪ STT		BJET		MET	STT	DTT
Number of τ_{had}	1				≥ 2	2 (OS) or ≥ 3	
τ_{had} identification	Tight				≥ 1 Loose	≥ 1 Medium	≥ 2 Medium
Number of b-tags @77%	3	≥ 4	3	≥ 4	≥ 3		
Number of jets	≥ 4				≥ 3		
NN score distribution	NN ($1\tau_{had}$ MST)		NN ($1\tau_{had}$ BJET)		NN ($\geq 2\tau_{had}$ MSDT)		

Search for singly-produced VLQs decaying to *Wb*

- ABCD plane:
  - Need to estimate the multijet background in the signal region A1.
  - Non-multijet background is extracted from simulations at each bin.



$$N_{\mathrm{A/A1}}^{\text{multijet estimate}}[i] = R_{\mathrm{corr}}[i] \times (N_{\mathrm{B}}^{\mathrm{Data}}[i] - N_{\mathrm{B}}^{\text{SM MC backgrounds}}[i]) \times \frac{(N_{\mathrm{D/D1}}^{\mathrm{Data}}[i] - N_{\mathrm{D/D1}}^{\text{SM MC backgrounds}}[i])}{(N_{\mathrm{C}}^{\mathrm{Data}}[i] - N_{\mathrm{C}}^{\text{SM MC backgrounds}}[i])}$$

Combination of singly-produced VLT searches

- Different techniques, and therefore, different sources of systematics are possible for each analyses.
- Uncorrelated scheme for the non-common uncertainties.
- Orthogonal analyses according to the lepton multiplicity

Analysis	Target signal	Decay channels	Discriminants
Monotop	$Wb/Zt \to T \to Zt$	$Zt \to \nu\nu bqq$ (0ℓ)	BDT score
HtZt	$Wb/Zt \to T \to Ht/Zt$	$Ht/Zt \to bbb\ell\nu/qqb\ell\nu$ (1ℓ)	m_{eff}
OsML	$Wb/Zt \to T \to Zt$	$Zt \to \ell\ell b\ell\nu$ (3ℓ), $Zt \to \ell\ell bqq$ (2ℓ)	Z boson p_{T}

Category	Monotop	HtZt	OsML	Correlating
Lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties				
Electron uncertainties		✓	✓	All
Muon uncertainties		✓	✓	All
$E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties	✓	✓	✓	All
Jet uncertainties				
JES uncertainties	✓	✓	✓	All
JER uncertainties	✓	✓	✓	HtZt and OsML
JMS uncertainties		✓		None
JMR uncertainties	✓	✓		None
Tagging uncertainties				
Flavor-tagging uncertainties	✓	✓	✓	Monotop and OsML
Top-tagging uncertainties	✓			None
W/Z-tagging uncertainties	✓			None
Background modeling uncertainties (constrained)	✓	✓	✓	None
Background normalization factors (unconstrained)				
$t\bar{t}$ normalization	✓			None
V+jets normalization	✓			None
Z+light-jets normalization			✓	None
Z+heavy-flavor normalization			✓	None
$t\bar{t}V$ normalization			✓	None
VV normalization			✓	None