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http://lhcp2024.cos.northeastern.edu

ATLAS EXPERIMENT

Searches for VLQ in ATLAS

Vallary Bhopatkar

Oklahoma State University

On Behalf of ATLAS Collaboration

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Photo credit: Alina Mak

Outline

- Vector-like Quarks
- Motivation
- Results using Full Run 2 Data
  - ➢ VLQ pair production search in the Wb+X final state (TT→Wb and Wb, Ht, Zt, BB→Wt and Wt, Hb, Zb)
  - ➢ Search for E_T^{miss} plus boosted single-top-quark (T→Zt)
  - ➢ Search for pair-produced VLQ in Wq + X final State (QQ →Wq +X)
- Summary

Vector-like Quarks

- "Quarks" : Color-triplets, spin 1/2 particles
- "Vector-like": Left and right chirality have the same weak isospin
- Only left-handed charged currents for SM quarks $(\bar{q}\gamma^{\mu}(1-\gamma^{5})q')$
- BOTH left- and right-handed charged currents for VLQs $(\bar{Q}\gamma^{\mu}Q')$
- Physically, this means:
  - Chiral fermions can only get mass through coupling to the Higgs boson
  - VLQs fermions can have mass without coupling to the Higgs boson
    - ➢ Important: This avoids strong constraints from Higgs measurements!
- Couple to SM through mixing with SM quarks

	Q[e]	VLQs singlets		VLQs doublets			VLQs triplets	
	$5/3$			X			X	
Top-partner	$2/3$	(T)		T	T		T	T
Bottom-partner	$-1/3$		(B)		B	B	B	B
	$-4/3$					Y		Y

Motivation

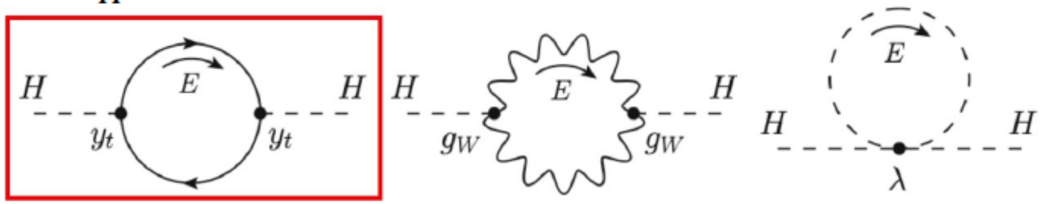
- Unresolved phenomena present within the SM despite its many successes i.e. hierarchy problem, dark matter, strong CP problem, etc.
  - The hierarchy problem is one which may be resolved through the addition of extra particles known as vector-like quarks (VLQs)
- Hierarchy problem in a nutshell: loop diagram contributions from top quark causes quadratic divergences in the Higgs boson mass => unnatural

$$m_H^2 = m_0^2 + \delta m_H^2$$

where

$$\delta m_H^2 \approx -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 + \frac{9}{64\pi^2}g^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 = -\delta_{top}m_H^2 + \delta_V m_H^2 + \delta_H m_H^2$$

with $\delta_{top}m_H^2 \gg m_H^2$ [1]

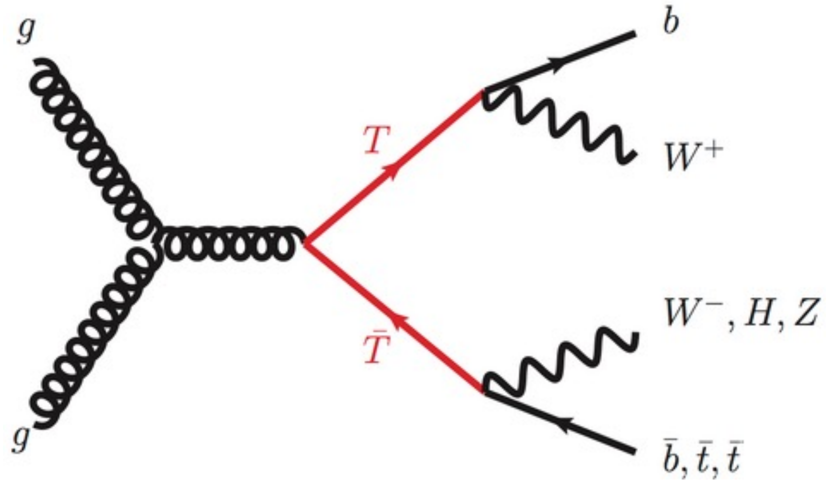


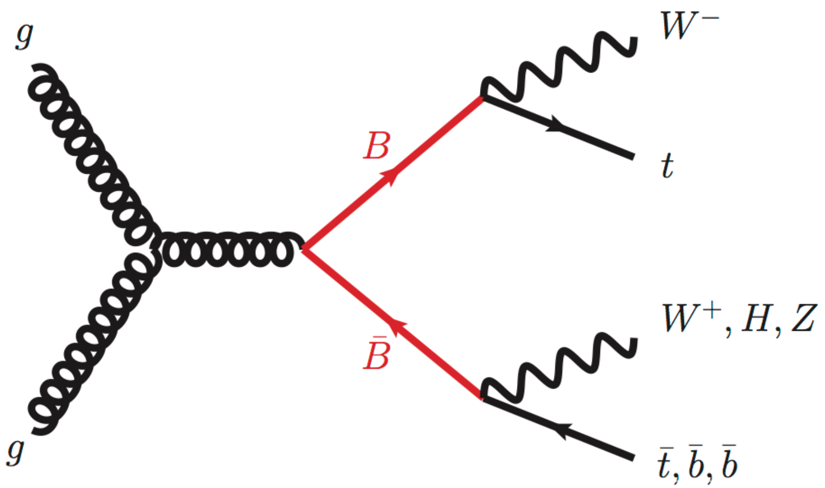
- Having vector-like quarks could naturally cancel the divergent top correction!

VLQ pair production search in the Wb+X final state

VLQ pair production search in the Wb+X final state

[Phys. Lett. B 854 (2024) 138743]



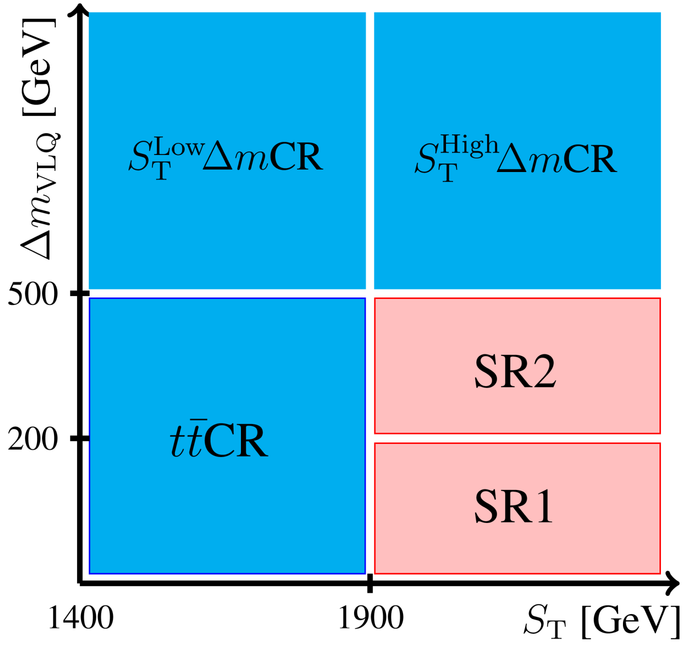


- Optimised for the TT→WbWb channel with one W boson decaying leptonically and the other hadronically.
- Wb has the largest BR for VLTs
- High-pT hadronically decaying W bosons are tagged as a single large-radius (large-R) jets.
- T candidates are reconstructed such that the mass difference between the leptonically and hadronically
- Decaying T candidates is minimised. The mass is the final discriminant variable

VLQ pair production search in the Wb+X final state

Phys. Lett. B 854 (2024) 138743

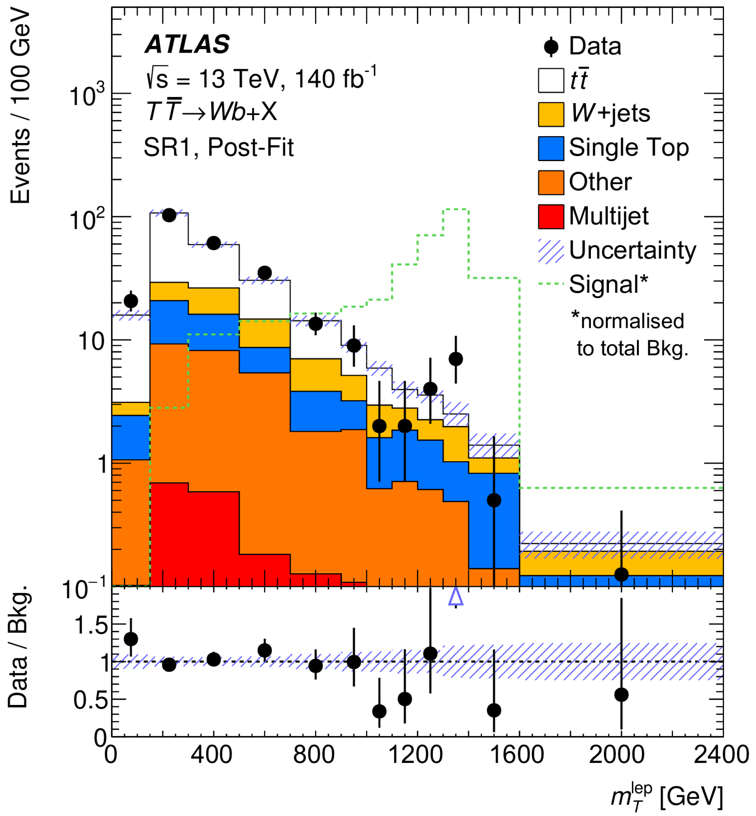
Region Definitions



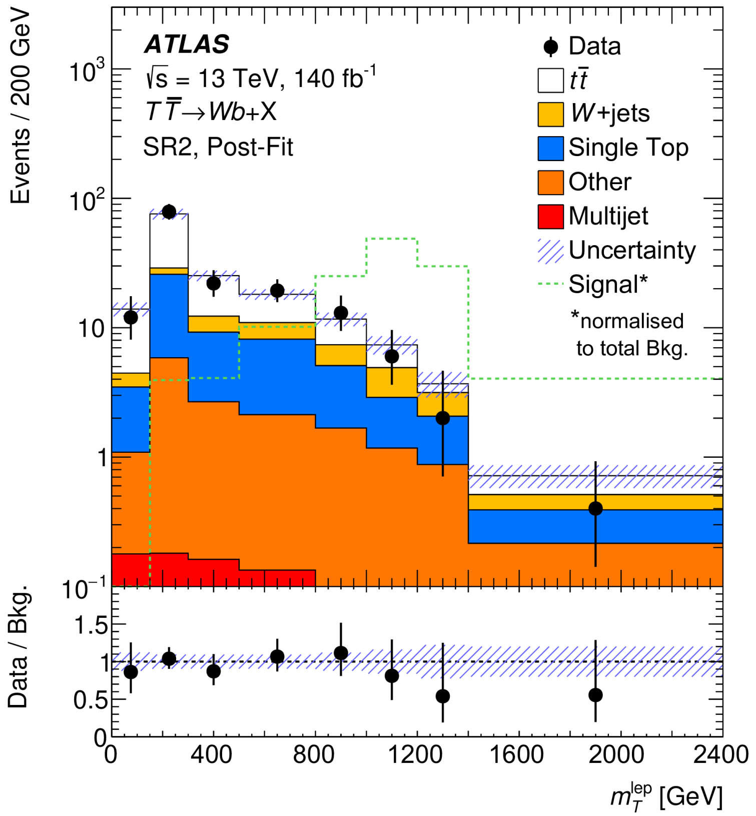
- Top modelling is reweighted
- $t\bar{t}$ and W+jets dedicated CR and final corrections from additional high CRs at high DeltaM
- Multijets are estimated by Matrix-Method.

Fit Results m_{VLQ} = 1400 GeV

Signal Region 1

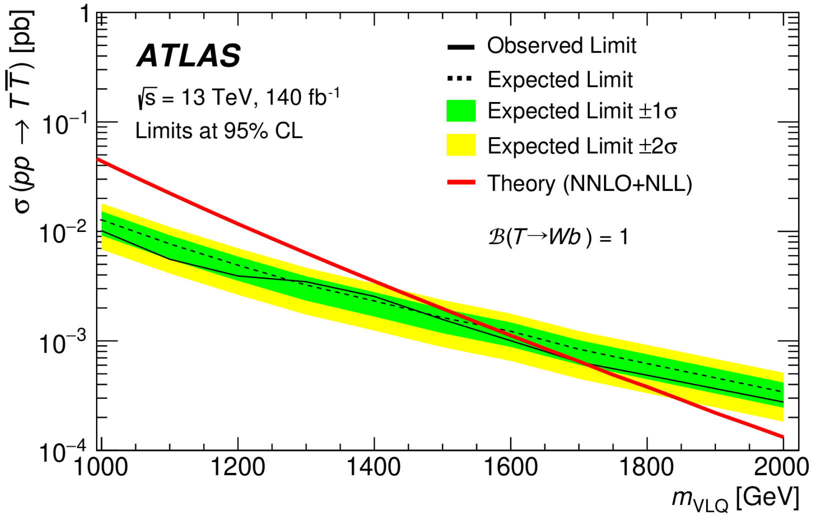


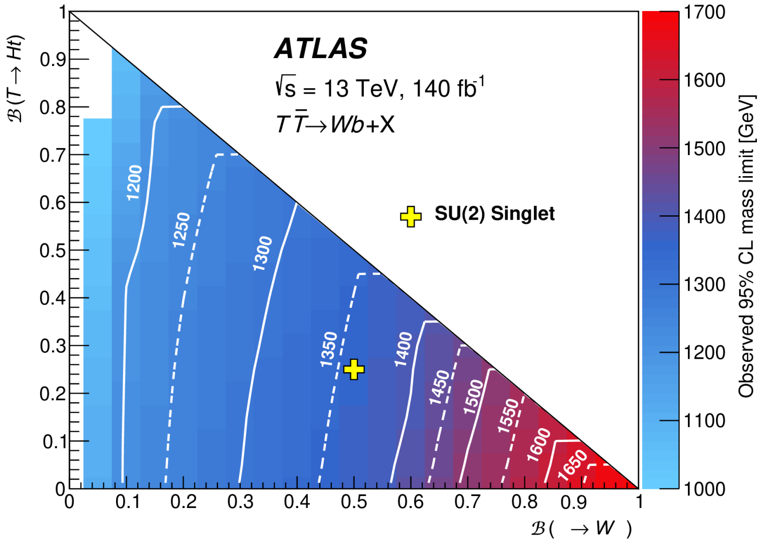
Signal Region 2

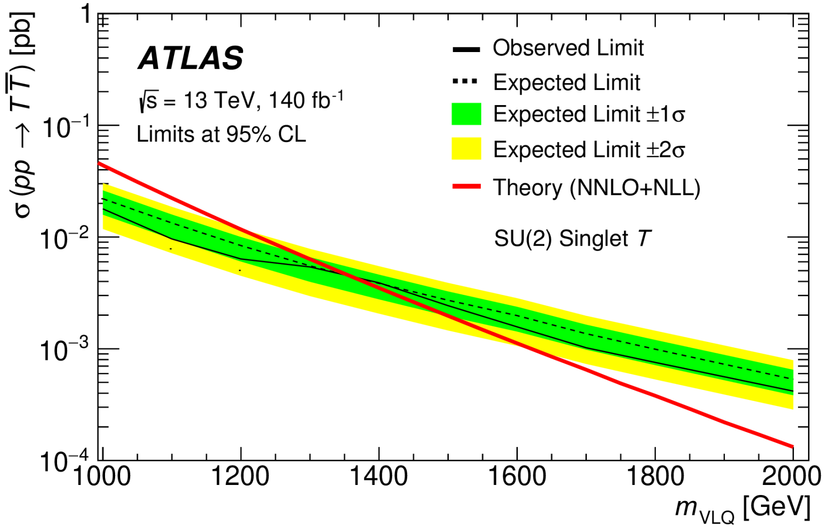


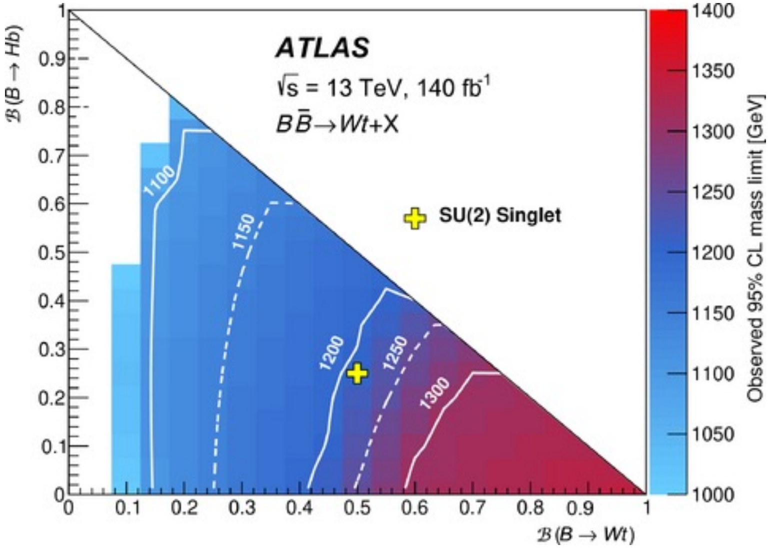
Interpretation: Limits

Phys. Lett. B 854 (2024) 138743









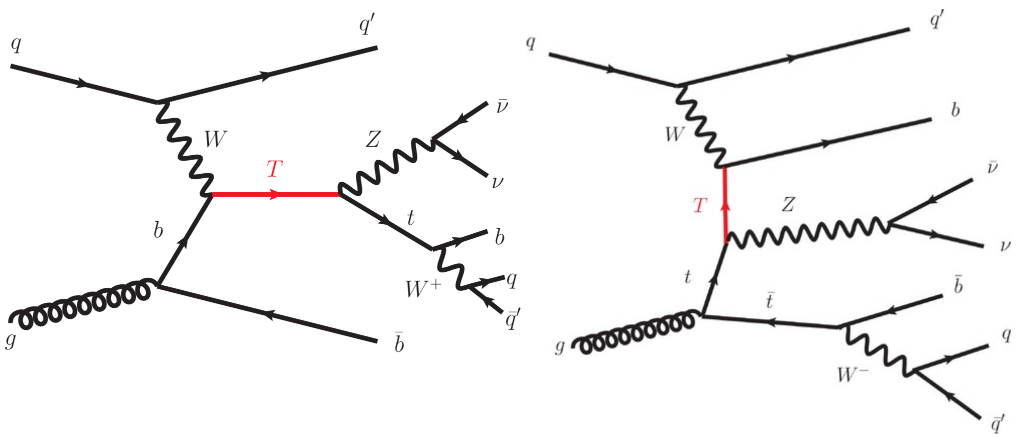
- Limits are set on
  - BR(T⟶Wb) = 1
  - SU(2) Singlet T
- Limits between BRs are also checked.
- Though this analysis is optimized for TT⟶Wb+X, BB⟶Wt+X is also considered.
- **The most stringent limits are set for the scenario BR(T⟶Wb) = 1**

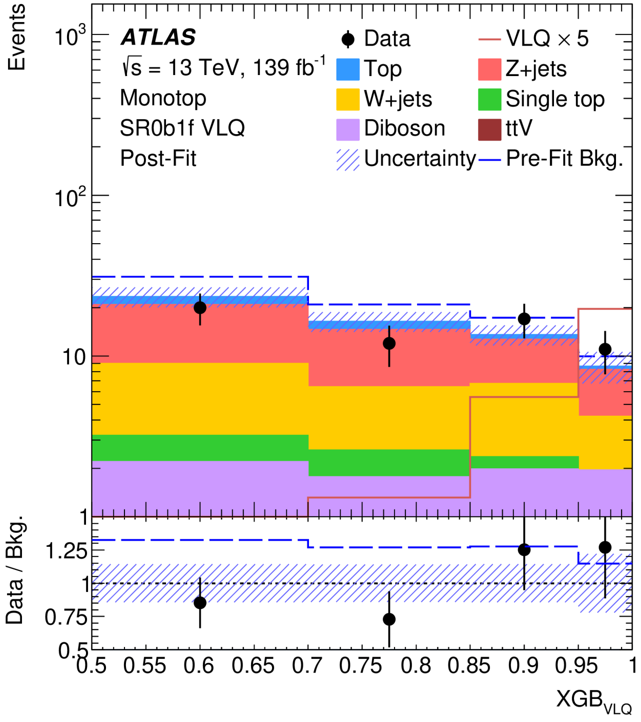
Search for E_T^{miss} plus boosted single-top-quark

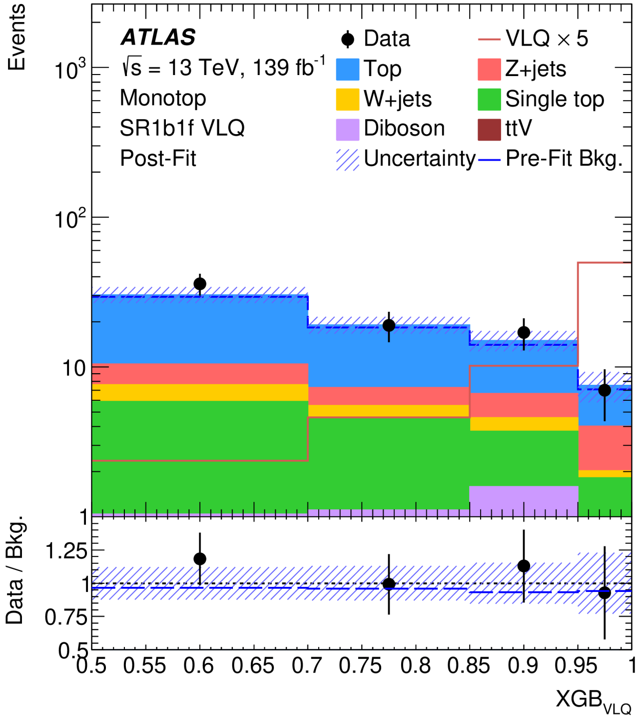
Search for E_T^{miss} plus boosted single-top-quark

JHEP 05 (2024) 263

- A search for new particle in a final state with boosted top quark and MET is performed
  - ➢ The results are interpreted in using simplified model for Dark Matter particle production and the production of single vector-like quark T
- The use of a Deep Neural Network (DNN) based identification of large-R jet originated from hadronically decaying top
- Signal events are separated efficiently from background using extreme gradient-Boosted (XGBOOST) Decision Tree (BDT)
  - ➢ BDT score used as a final discriminant variable



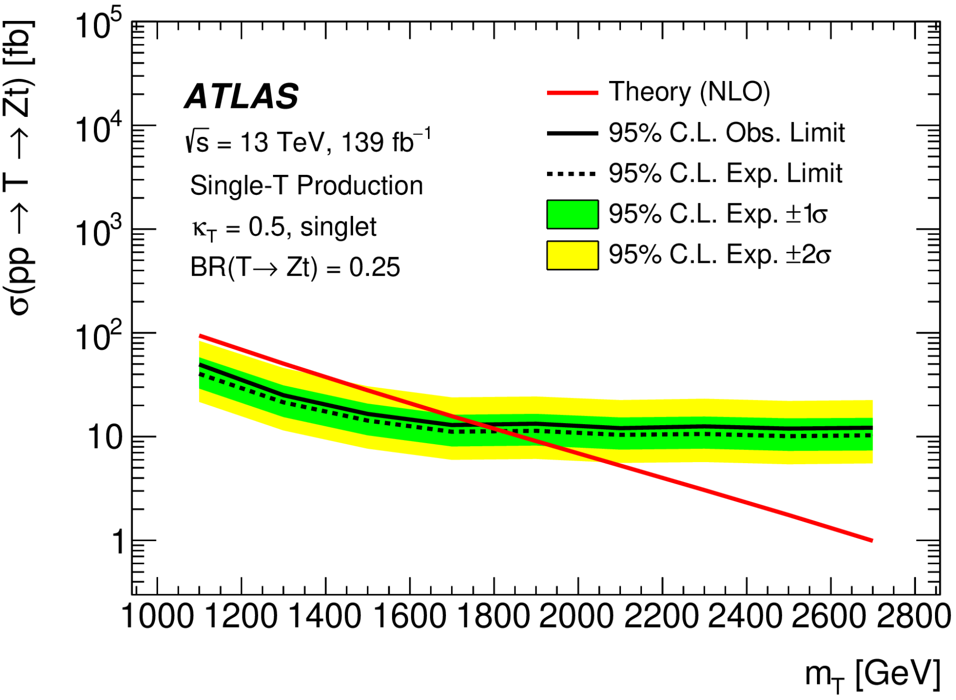


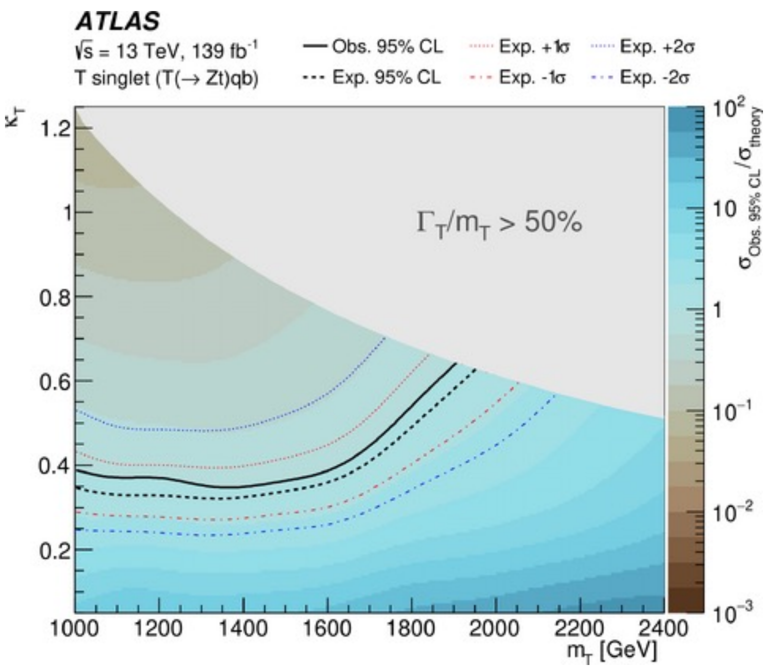


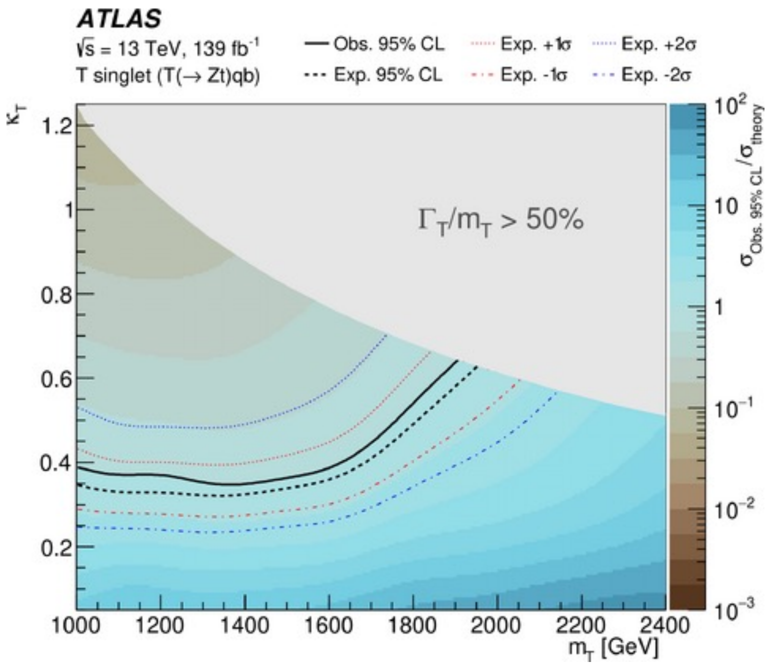
Search for E_T^{miss} plus boosted single-top-quark

JHEP 05 (2024) 263

- No significant excess above SM expectation is found
  - ➢ Results interpretation=> expected and observed upper limit on the signal cross-section as function of model parameters
- Due to improved and refined object reconstruction and used of XGBoost algorithm the limits improved significantly compared to previous results (~400 GeV)







VLQ pair production search in the Wq+X final state

VLQ pair production search in the Wq+X final state

- Full Run 2 analysis searching for Vector-Like Quarks decaying to Wq+X

$$pp \rightarrow Q\bar{Q} \rightarrow Wq+X$$

where q is a light quark

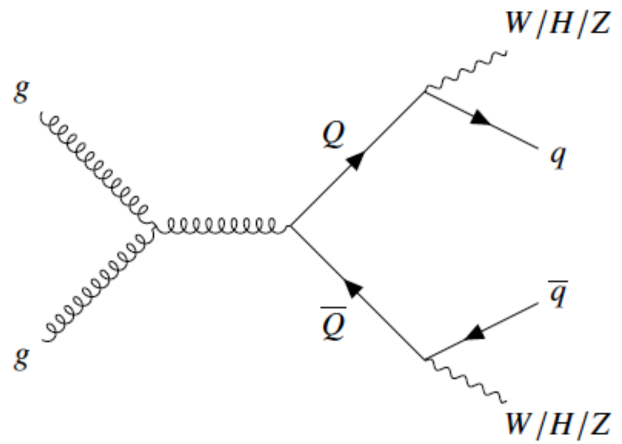
- Complements searches where it is assumed that q is a third-generation quark
- Previous analysis performed during Run 1
- Require at least one lepton (ℓ=e/μ) from leptonic W decay

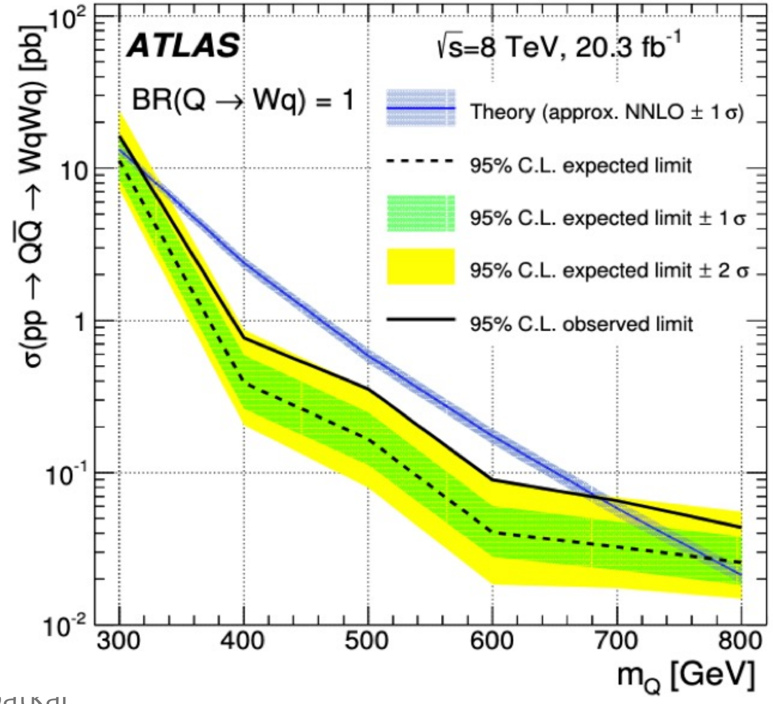
$$Q \rightarrow Wq \rightarrow \ell\nu q$$

- Optimized for a large-R jet (q' q'') from hadronic W decay

$$Q \rightarrow Wq \rightarrow (q'\,q'')\,q$$

- Sensitive to $Q \rightarrow Z/Hq \rightarrow (q'\,q'')\,q$



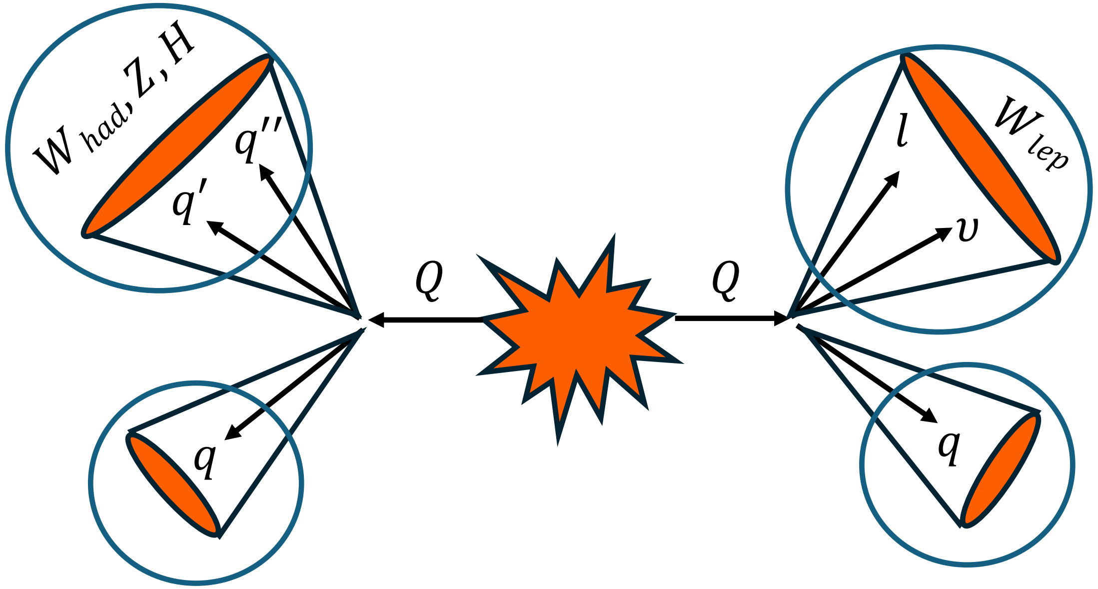


Phys. Rev. D 92, 112007 (2015)

Event Selection and VLQ Reconstruction

- Select only events that allow the possibility of reconstructing the pair - produced VLQ candidates
- Reconstruct neutrino
  - Calculate p_Z^ν
  - Use W boson mass as a constraint
- Reconstruct W bosons
  - Leptonic W: lepton + reconstructed neutrino
  - Hadronic W: leading W-tagged large-R jet
    - No W-tag ⇒ large-R jet mass closest to W mass
- Reconstruct VLQ candidates
  - Use (at most) the 3-leading small-R jets to reconstruct the VLQ ⇒ Minimize ΔM_{VLQ}

Variable	Cut	Purpose
Preselection		
$N_{\text{large-R jets}}$	≥ 1	Hadronic decaying W candidate
$p_T^{\text{large-R jet}}$	≥ 200 GeV	Required for the W-tagger
$N_{\text{small-R jets}}$	≥ 2	Quarks from VLQ decay
$p_T^{\text{small-R jet0}}$	≥ 200 GeV	Boosted objects
p_T^{lep}	≥ 60 GeV	Leptonic VLQ decay
MET	≥ 250 GeV	Neutrino from $W \to \ell\nu$ decay
ΔR(small-R jet, large-R jet)	> 1.0	Overlap removal



Background Modeling

- Backgrounds are:
  - W+jets
  - $t\bar{t}$
  - Single top
    - Dominant bkgs in decreasing order
    - Data-driven shape correction
  - Multijet
    - Data-driven normalization correction
  - Other bkgs
    - (diboson, Z + jets, ttV)
    - Estimated from MC
- 3 Reweighting Regions (RwR), 3 Validation Region (VR) and 2 Signal Regions are defined

- Derive correction on S_T in RwRs
  - Known mis-modelling in MC
    - Shape correction: fit S_T distribution to $\boldsymbol{P_0 + e^{P_1 x}}$, where x = S_T
    - Normalization correction: scale MC to data over S_T distribution
  - Iterative procedure

$$c = \frac{\text{data−other MC}}{\text{MC to correct}}$$

Step	MC being Corrected	Other Corrections Used
1	Multijet	-
2	$t\bar{t}$ and single top	(1)
3	W + jets	(1,2)
4	Multijet	(2, 3)
5	$t\bar{t}$ and single top	(3, 4)
6	W + jets	(4, 5)

Background Modelling

arXiv:2405.19862
Submitted to PRD

- Derived and applied corrections in Reweighting Regions (RwR) using S_T Variable
- Validated the correction in the Validation Regions using reconstructed m_{lep}^{VLQ}

S_T Distribution

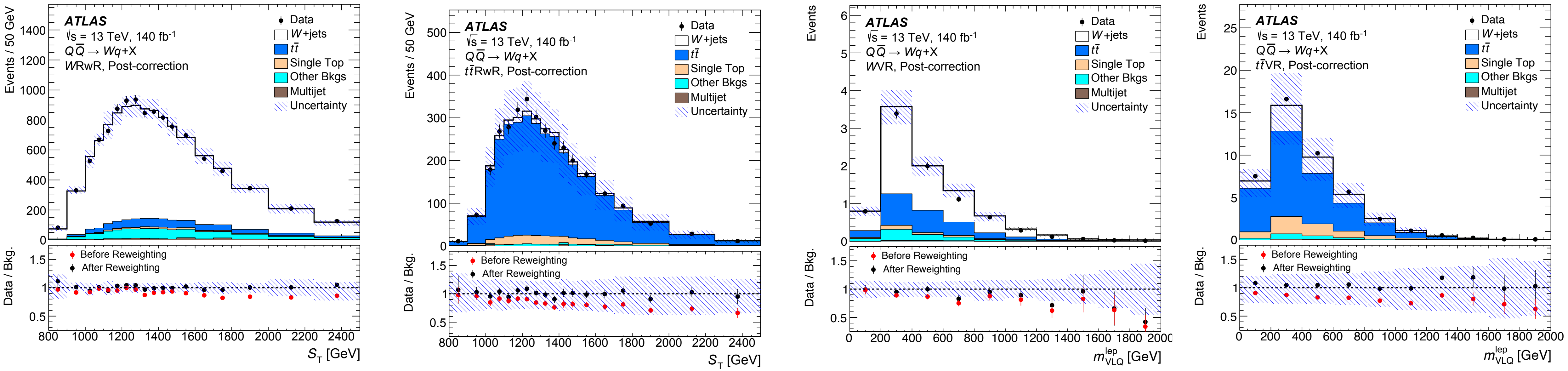
m_{lep}^{VLQ} Distribution

W+Jets RwR

$t\bar{t}$ RwR

W+Jets VR

$t\bar{t}$ VR



Fit Results $m_{VLQ} = 1400$ GeV

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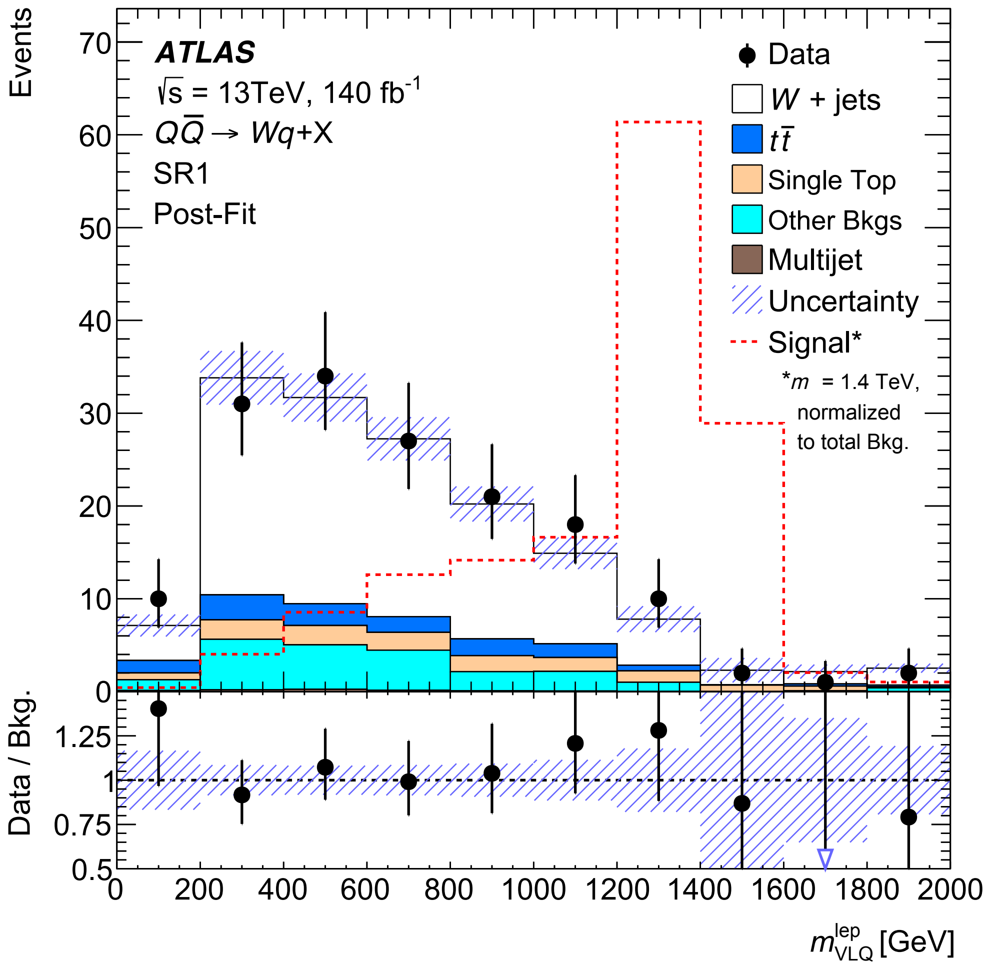
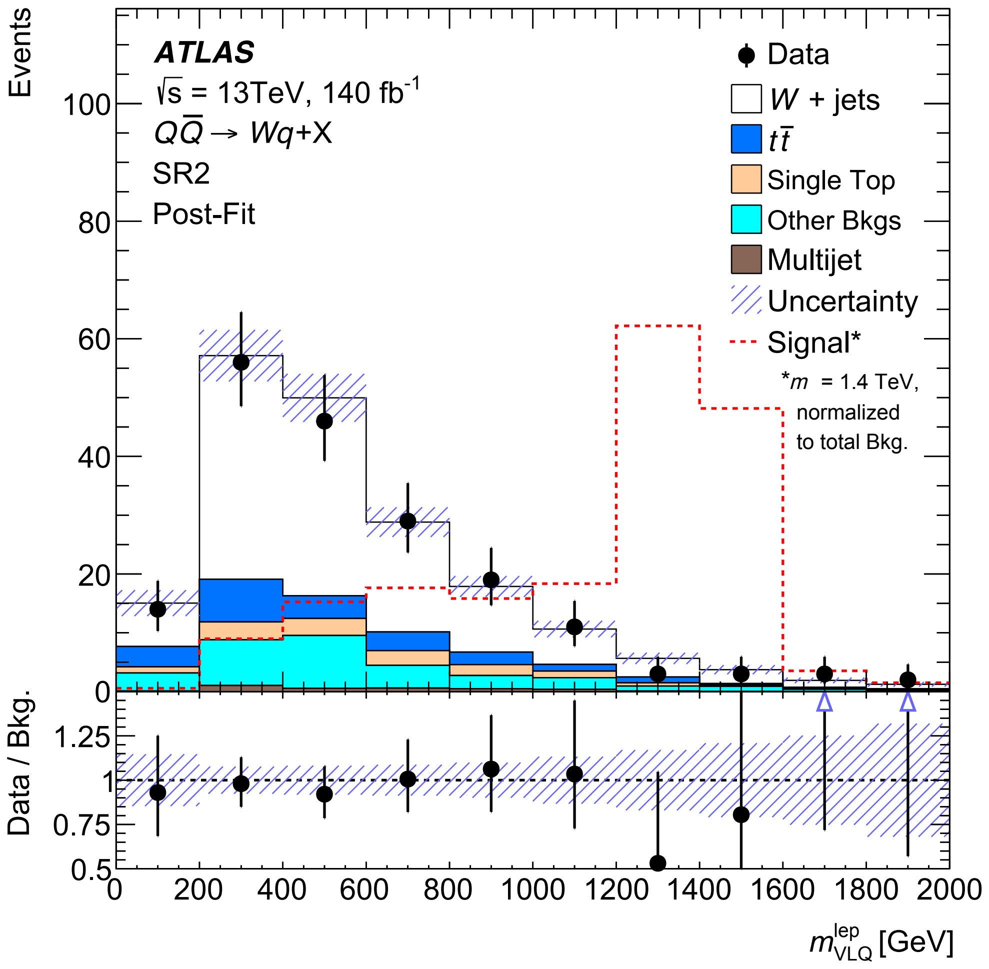
Signal Region 1



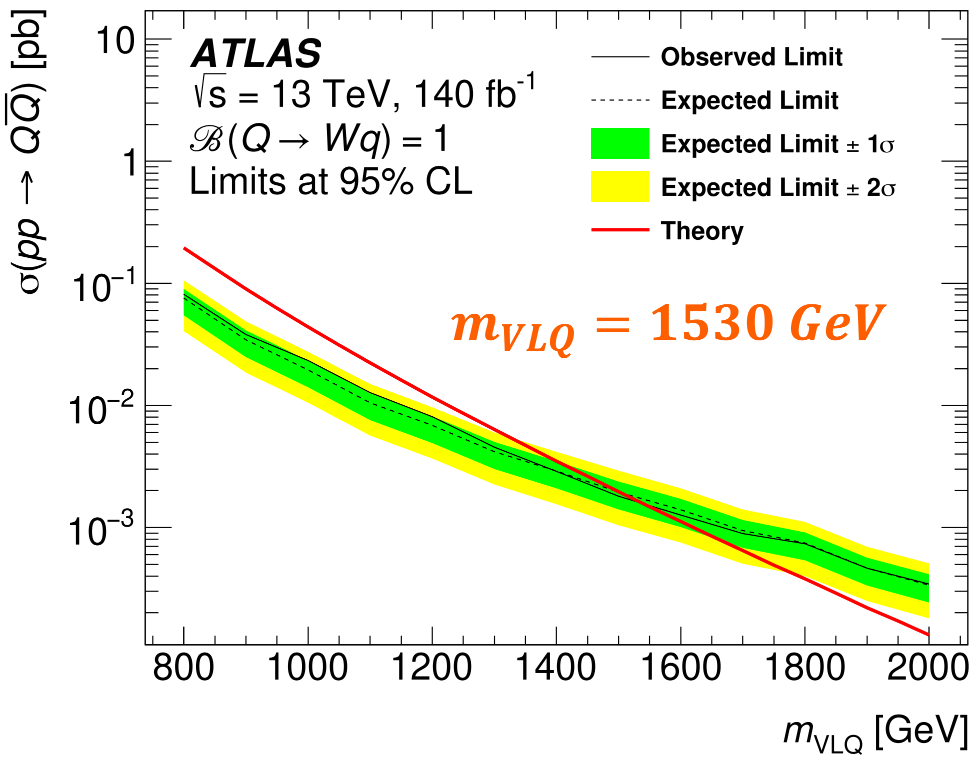
Signal Region 2

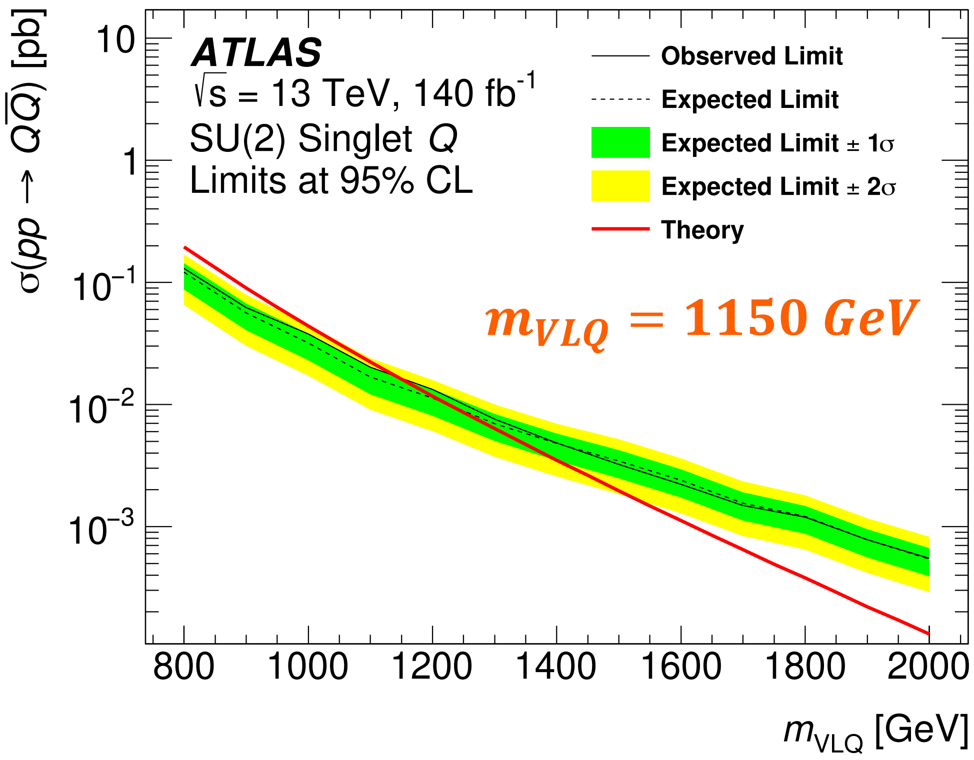


Limits

arXiv:2405.19862
Submitted to PRD

$\mathcal{B}R(Q \to Wq) = 1$ | **$SU(2)$ Singlet Model**





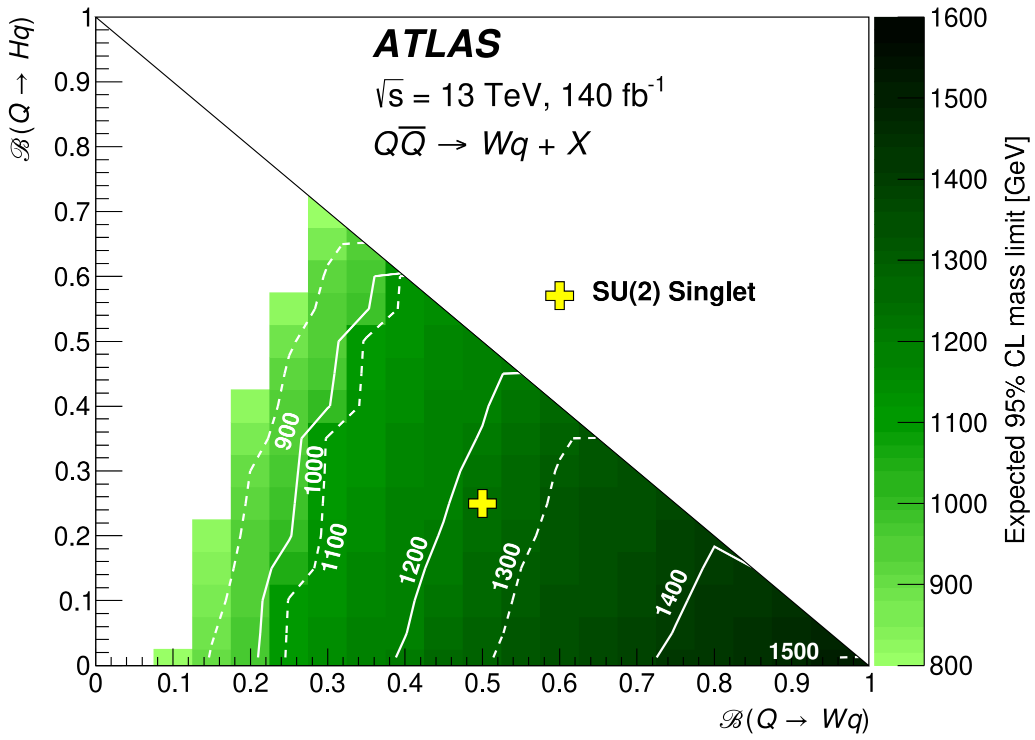
With increased center-of-mass energy and integrated luminosity, as well as improved analysis tools, We have more than doubled the excluded mass limit (1530 GeV) by using the full Run 2 dataset for $\mathcal{B}(Q \to Wq) = 1$ in contrast with the Run 1 result (~700 GeV)

Limits for Single VLQs

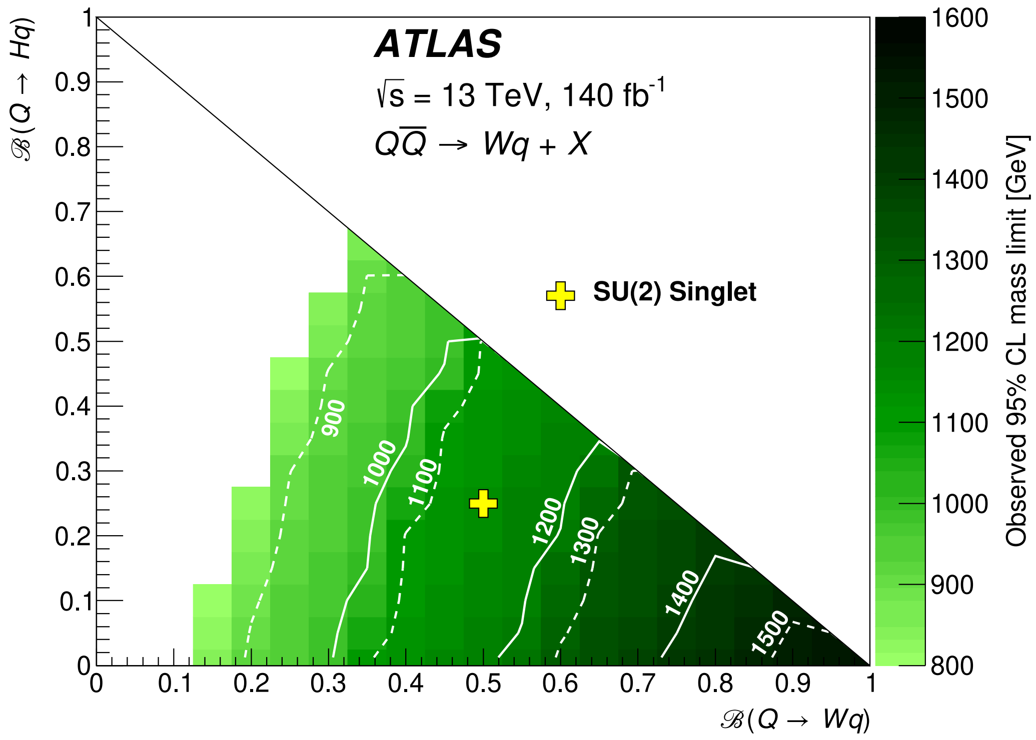
arXiv:2405.19862
Submitted to PRD

- Lower limits on the VLQ mass for various branching ratio (BR) configurations at 95% CL

Expected



Observed



Summary

- Latest summary of the ATLAS Run-2 results for Vector-like Quarks are presented
    - Pair-production and single production searches are performed
    - Limits are set on VLQ masses and couplings for singlet
    - Scan over branching ratios of VLQs to other possible decay channels also considered
- No significant excess has been observed and hence each of the analyses set the strongest limit
- Full list of recent ATLAS results can be found here

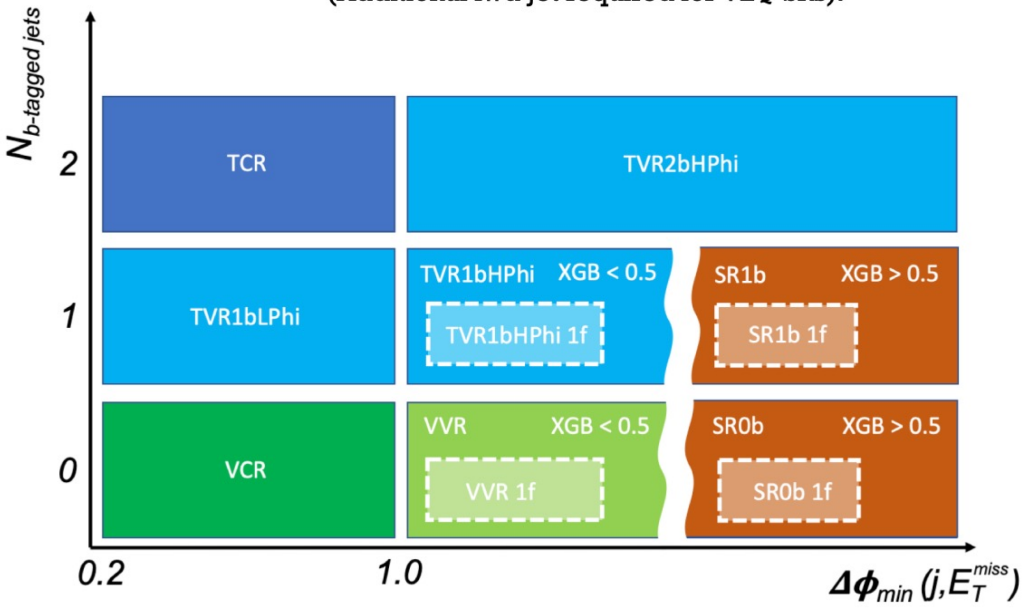
Stay Tuned for the upcoming Run-3 results!!

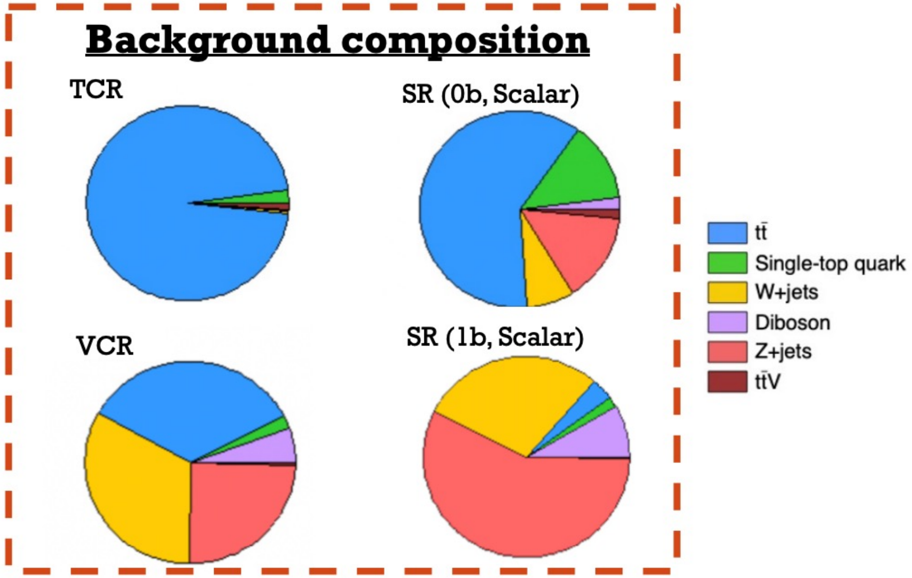
Backup

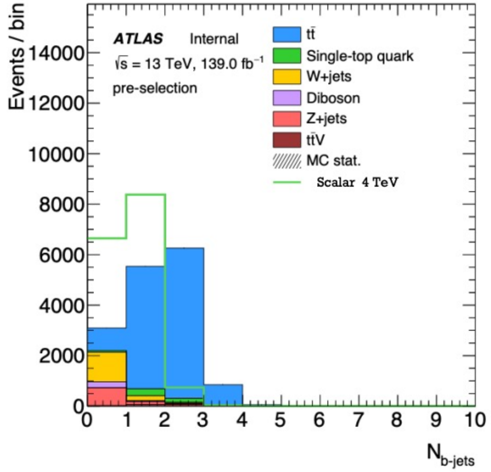
Search for E_T^{miss} plus boosted single-top-quark

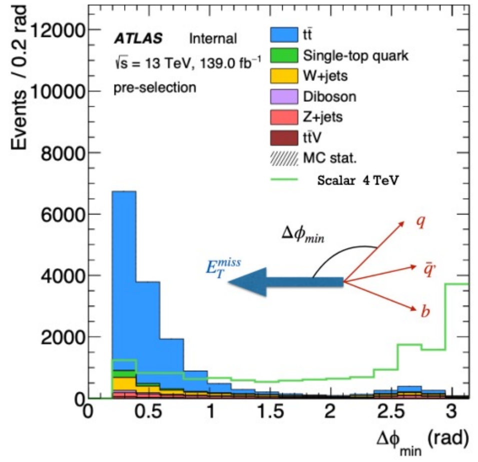
REGIONS DEFINITIONS

- CRs for ttbar and for V+jets.
  - Independent of MVA strategy.
  - Common for the 3 models.
- The XGB scores provide higher sensitivity in SRs.
  - SRs defined for XGB>0.5 for each trained BDT.
    - SR0b Scalar, SR1b Scalar.
    - SR0b Vector, SR1b Vector.
    - SR0b1f VLQ, SR1b1f VLQ.
    (Additional fwd jet required for VLQ SRs).









https://indico.cern.ch/event/1323891/

Search for E_T^{miss} plus boosted single-top-quark

	$N_{b\text{-tagged jets}}$	$\Delta\phi_{\min}(j, E_{\mathrm{T}}^{\mathrm{miss}})$	XGBoost score	$N_{\text{forward jets}}$
TCR	≥ 2	$\in [0.2, 1]$	—	—
TVR1bLPhi	1	$\in [0.2, 1]$	—	—
TVR1bHPhi (1f)	1	≥ 1	< 0.5	— (≥ 1)
TVR2bHPhi	≥ 2	≥ 1	—	—
VCR	0	$\in [0.2, 1]$	—	—
VVR (1f)	0	≥ 1	< 0.5	— (≥ 1)
SR0b (1f)	0	≥ 1	≥ 0.5	— (≥ 1)
SR1b (1f)	1	≥ 1	≥ 0.5	— (≥ 1)

Variable	Description	Scalar DM mediator	Vector DM mediator	VLQ
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum	✓	✓	✓
Ω	$E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet p_{T} balance: $\frac{E_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}(J)}{E_{\mathrm{T}}^{\mathrm{miss}} + p_{\mathrm{T}}(J)}$	✓	✓	✓
N_{jets}	Small-R jet multiplicity	✓	✓	✓
$\Delta R_{\max}$	Maximum ΔR between two small-R jets	✓	✓	✓
$m_{\mathrm{T,min}}(E_{\mathrm{T}}^{\mathrm{miss}}$, b-tagged 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	✓		✓
Δp_{T} (J, 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_{T}(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-tagged jet, J)	Angular distance in the transverse plane between the large-R jet and the leading b-tagged jet			✓