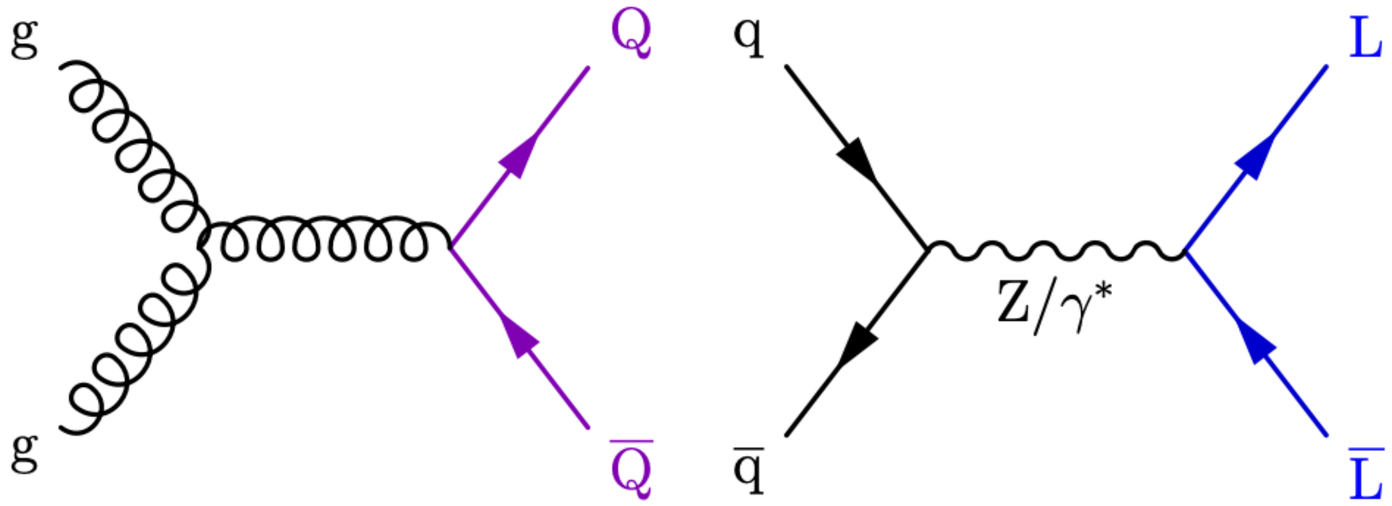
Search for Vector-like Quarks and Leptons

Christina Wang on behalf of the ATLAS & CMS Collaborations

Rencontres de Moriond 2025
Electroweak Interactions & Unified Theories

Motivation for New Vector-like Fermions

- Ample evidence of phenomena that the standard model cannot fully explain with potential hints at the TeV scale:
  - Dark matter
  - Massive neutrinos
  - Light Higgs
- LHC is the most direct probe of nature at the TeV scale
- To address these problems, many BSM models predict new fermions: **vector-like quarks (VLQ)** and **vector-like leptons (VLL)**
  - High mass (GeV to TeV) fermions that are not chiral → left- and right-handed components transform identically under EW symmetry group
  - Arising in different models: little Higgs, composite Higgs, extra dimensions…



Recent Results Covered Today

- **Vector-like quarks**
  - ATLAS
    - Pair-produced vector-like quarks: PhysRevD.110.052009
    - Single vector-like T/Y (fully hadronic): JHEP02(2025)075
    - Single vector-like T: JHEP05(2024)263
    - Combination of searches for singly produced vector-like T: PhysRevD.111.012012
  - CMS
    - Single vector-like T->Ht/Zt (all-hadronic): PhysRevD.110.072012
    - Vector-like quarks review paper: Physics Reports 04(2025) 1115
- **Vector-like leptons**
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    - Search for vector-like electrons and muons: 2411.07134
    - Search for vector-like tau in 4321 model: ATLAS-CONF-2024-008
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    - Search for vector-like leptons with long-lived particle decays: 2503.16699

NEW RPV SUSY results!

Submitted 2 days ago!

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Many new results in the past year!

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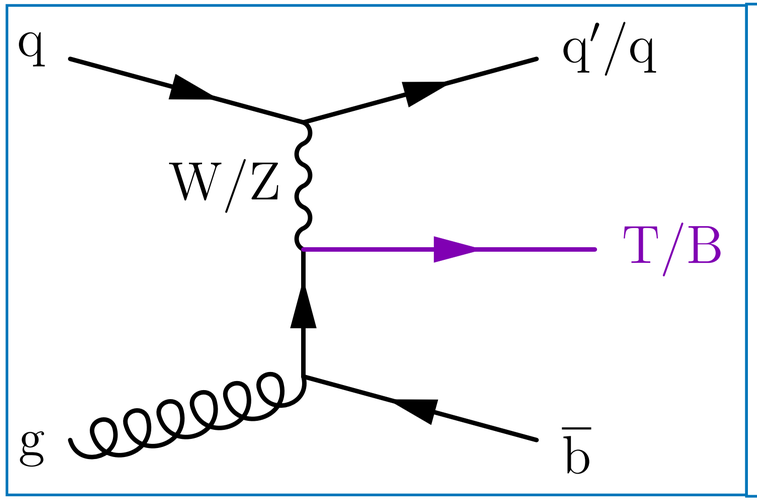
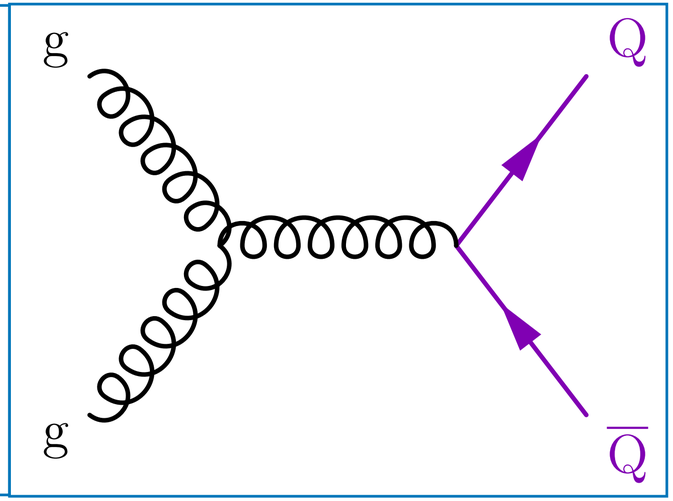
Vector-like Quarks

- Vector-like: Masses don't arise from Yukawa coupling → not constrained by Higgs measurements
- Broad range of final states:
  - Singlet, doublet, or triplet
  - Single/double production
  - Decay to W/Z/H + quark
- Mostly focus on **pair-produced VLQ mixing with light quarks** and **single vector-like top**

Electroweak (single) production



strong (double) production



Decay modes

$T \to bW^+, \quad T \to tZ, \quad T \to tH$

$B \to tW^-, \quad B \to bZ, \quad B \to bH$

$X_{5/3} \to tW^+$

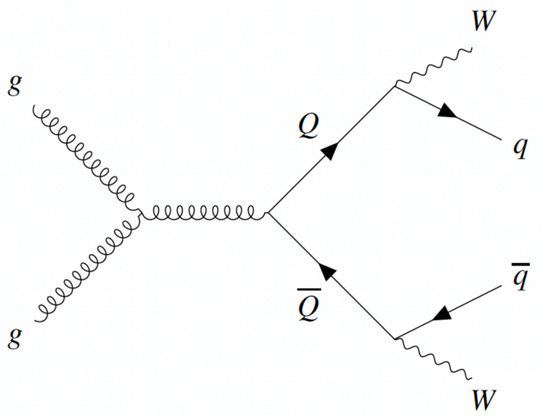
$Y_{4/3} \to bW^-$

Pair-Produced VLQ

Phys. Rev. D 110, 052009

- Considering VLQ mixing with light quarks → **much less explored scenario**
- Require one W decays leptonically and the other hadronically to reduce multi-jet background
- Reconstruct VLQ mass with W_{had} and W_{lep},
- Fit reconstructed mass of the leptonically decaying VLQ (m_{VLQ}^{lep})

Pair-production through gluon fusion

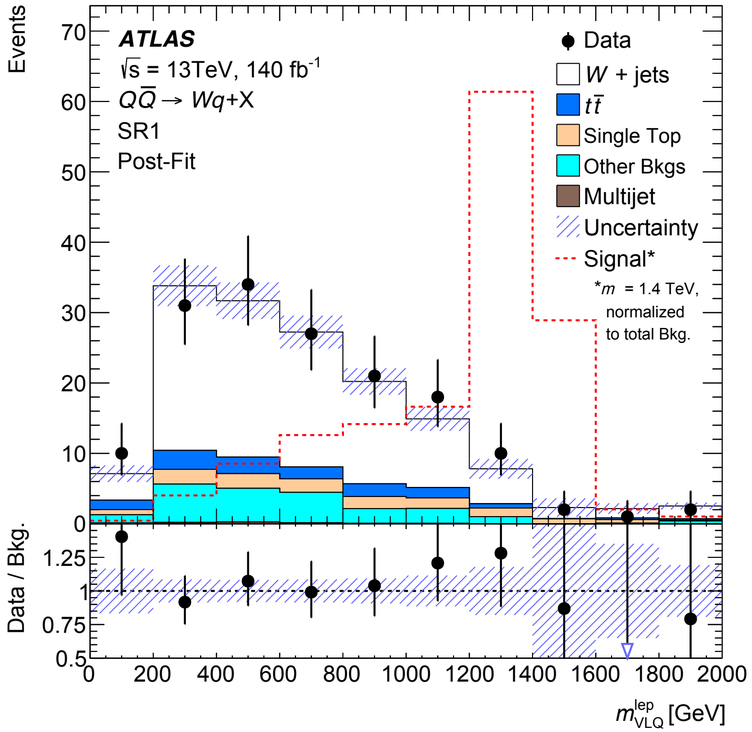


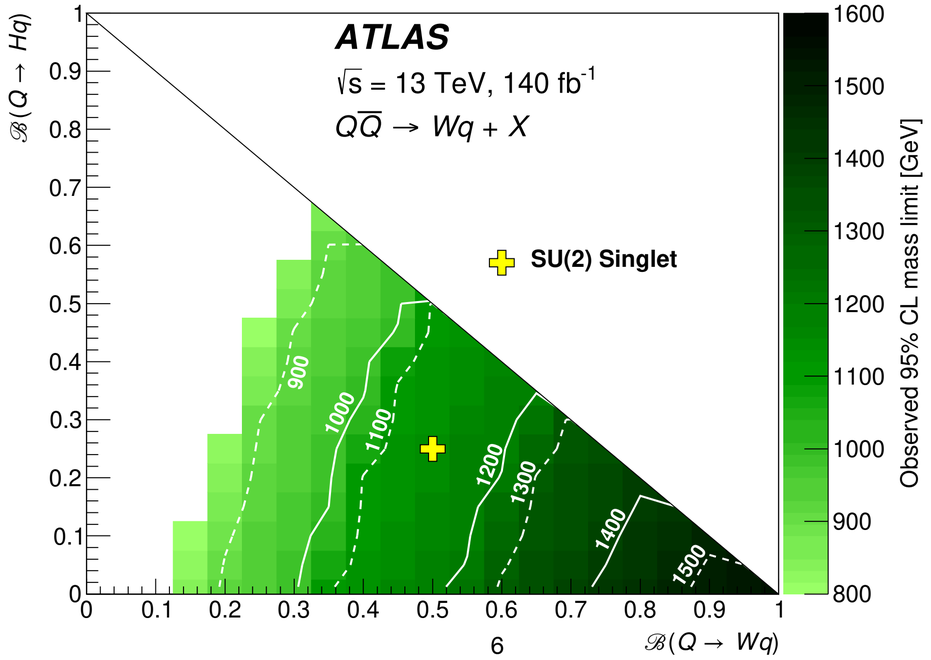
Lepton + p_T^{miss}

Small radius jet

Small radius jet

Large radius jet





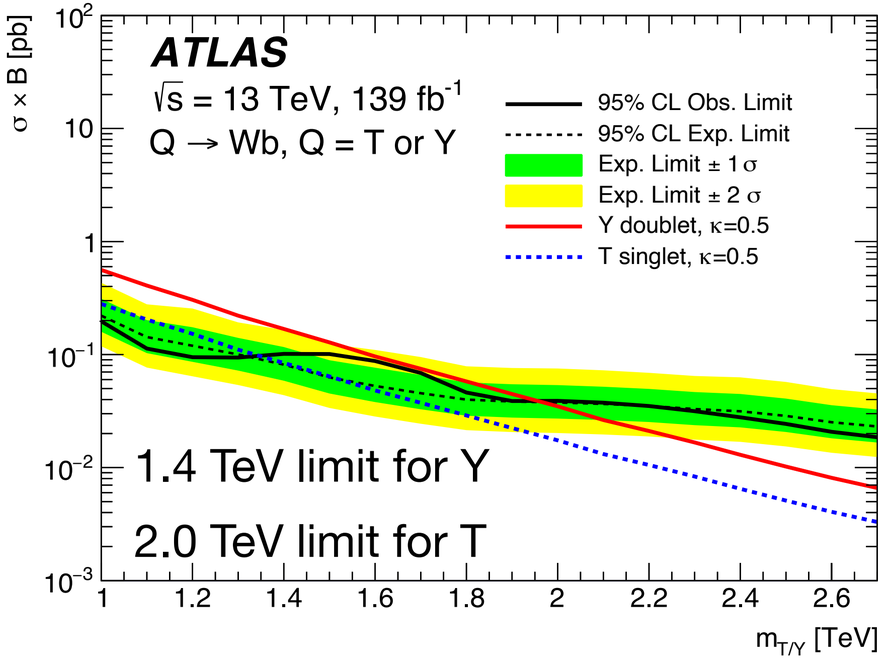
$m_{VLQ} > 1530$ GeV with $B(Q \to Wq) = 1$

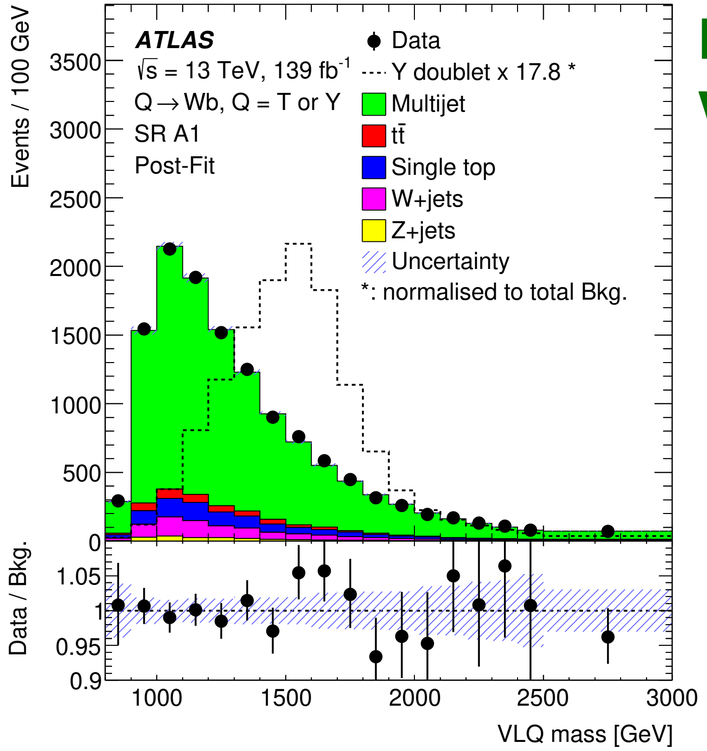
Improved by ~ factor 2 w.r.t. previous limits (Run 1)

Single T/Y→ Wb (All hadronic)

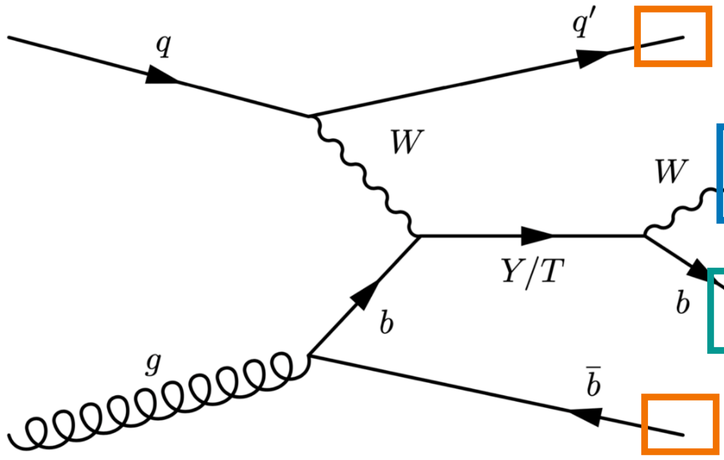
JHEP02(2025)075

- First search using the hadronic ($W \rightarrow q\bar{q}$) decay mode
- Data-driven estimation for QCD multijet background
- Significantly extends mass limits





Reconstruct VLQ mass with W and b-jet



$\geq$ 1 forward jets ($p_T > 40$ GeV)

Large-R, W-tagged jet ($p_T > 500$ GeV)

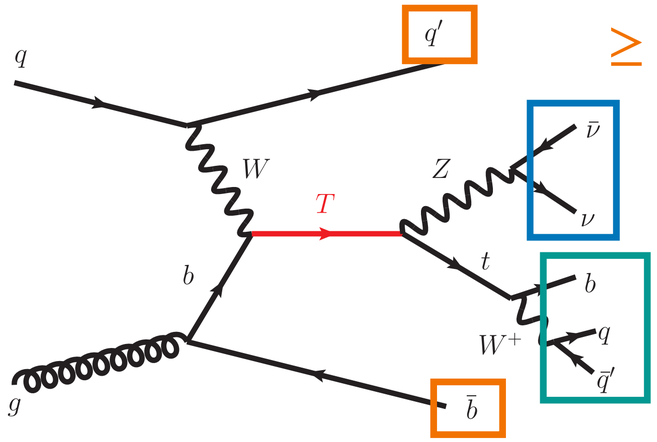
b-tagged jet ($p_T > 350$ GeV)

Zero leptons

Single T Production: Single-top + p_T^{miss}

JHEP05(2024)263

Mono-top signature: single-top + p_T^{miss} final states with interpretations in DM and VLQ production



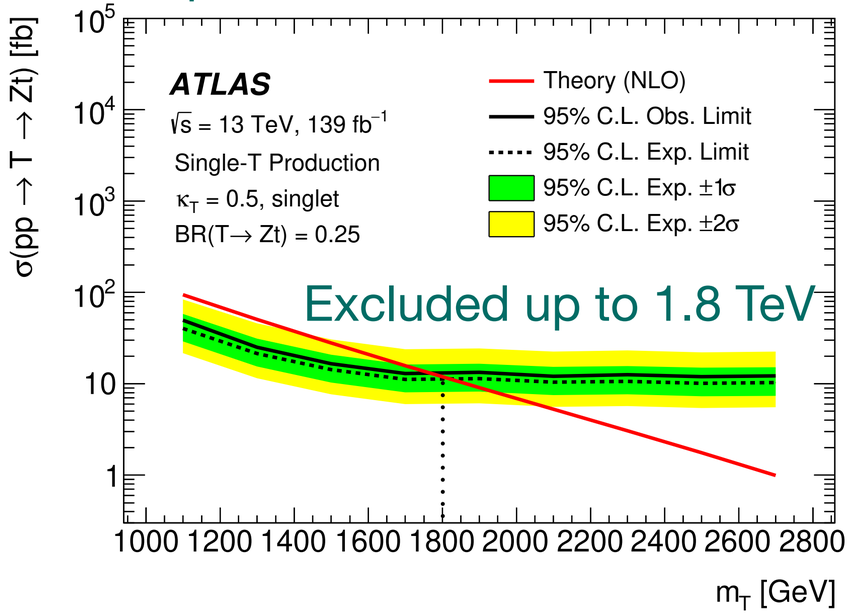
≥ 1 forward (b-tagged) jets

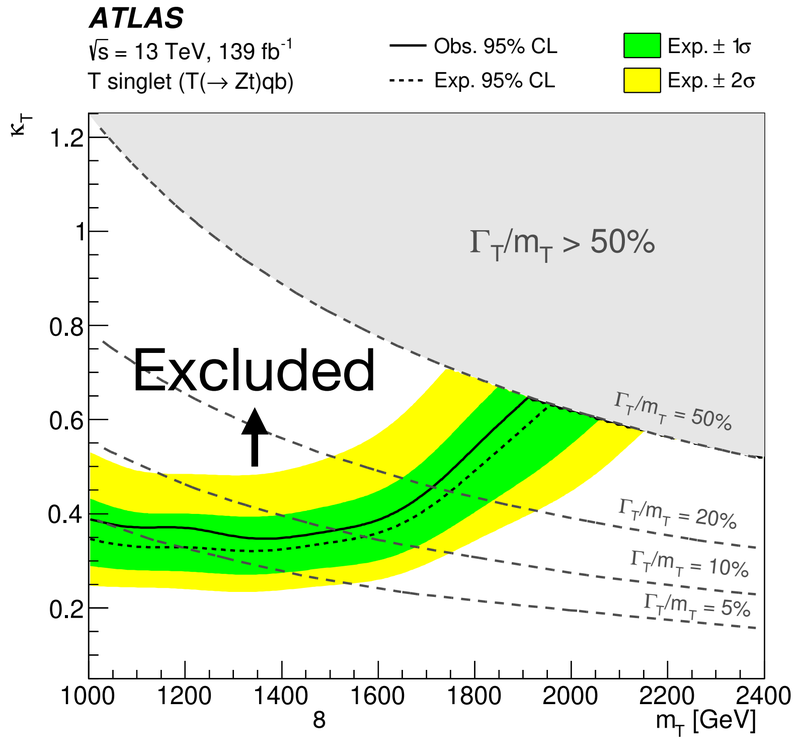
p_T^{miss} > 250 GeV

Zero leptons

One top-tagged large-R jet (p_T > 350 GeV)

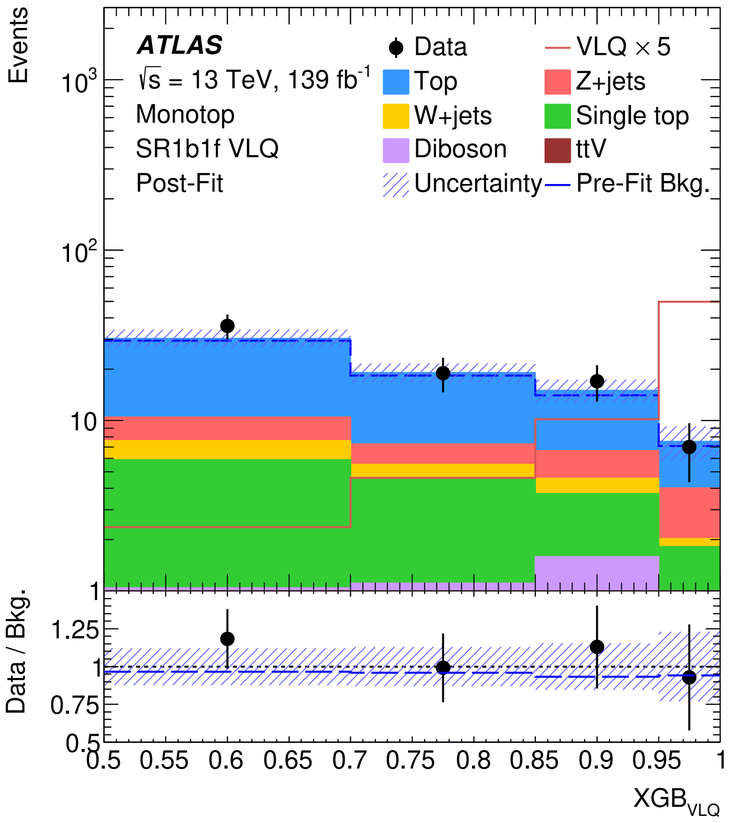
10x improvement in cross section limit





Jet kinematics to train an XGBoost classifier to improve S/B

Fit XGBoost score in CR and SR simultaneously



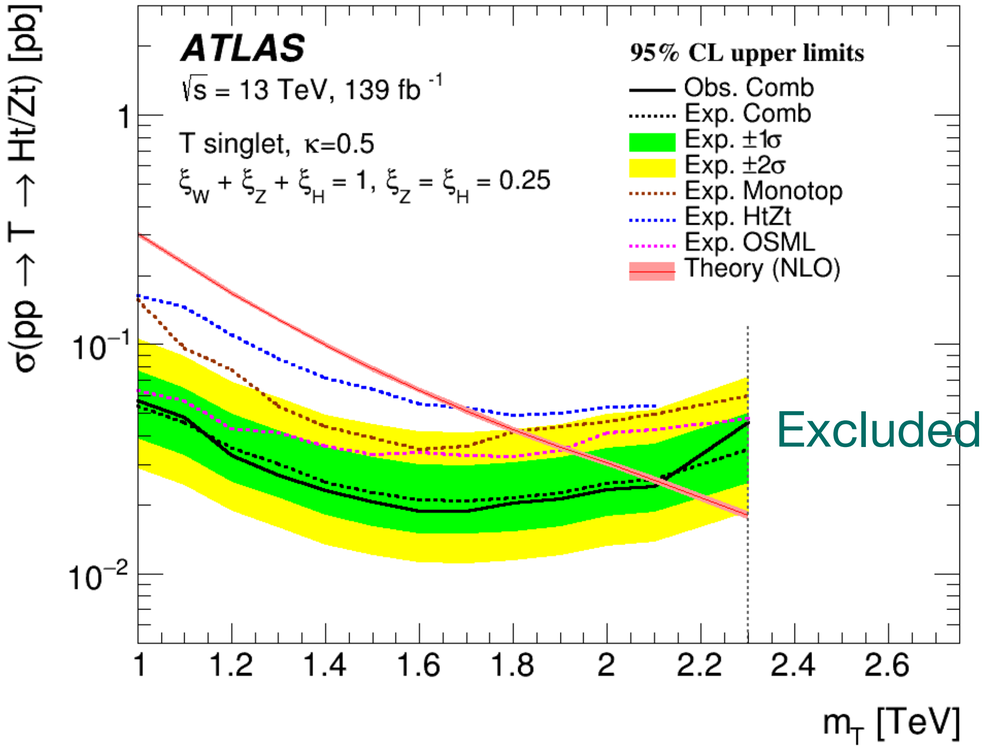
PhysRevD.111.012012

Single Production T Combination

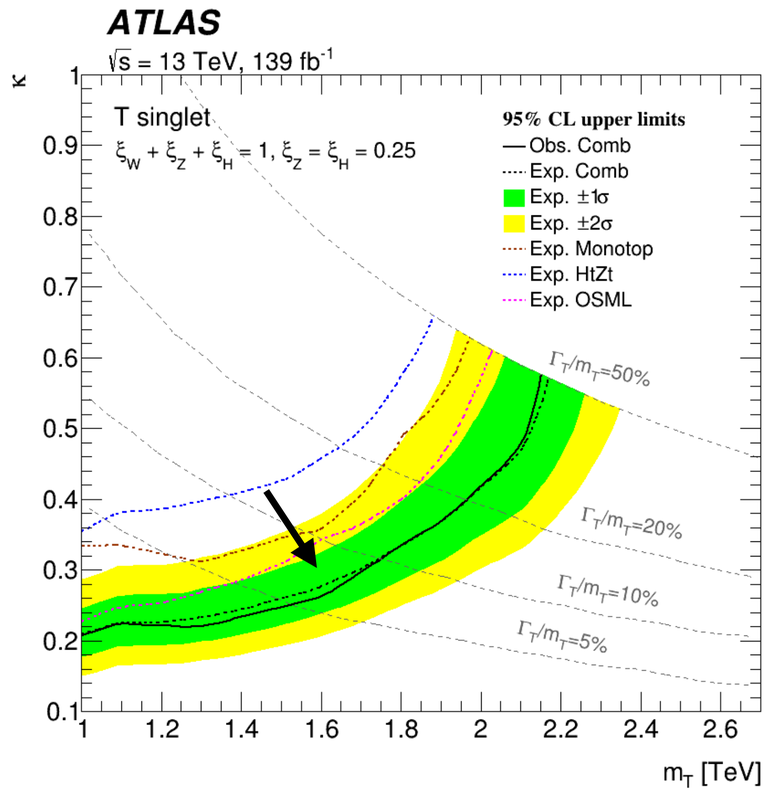
- Combination of three searches for single vector-like top with orthogonal selections
- **Set the most stringent limits to date**

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}

JHEP05(2024)263
Phys. Rev. D 109 112012
JHEP08(2023)153



Excluded up to 2.1 TeV

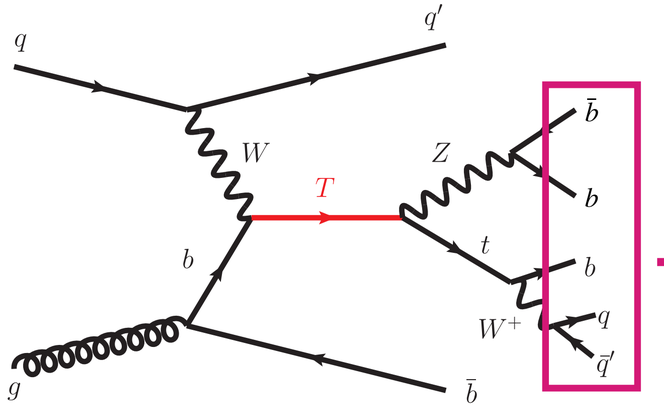


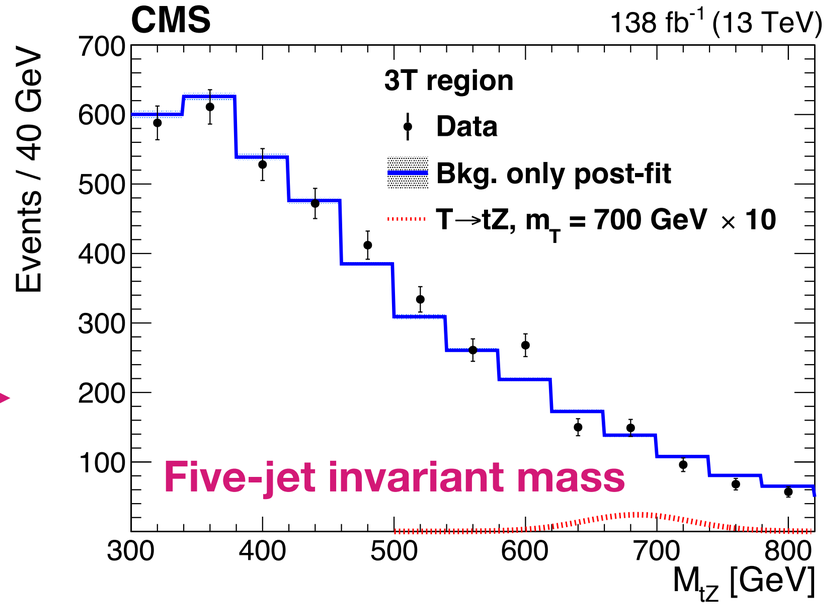
PhysRevD.110.072012

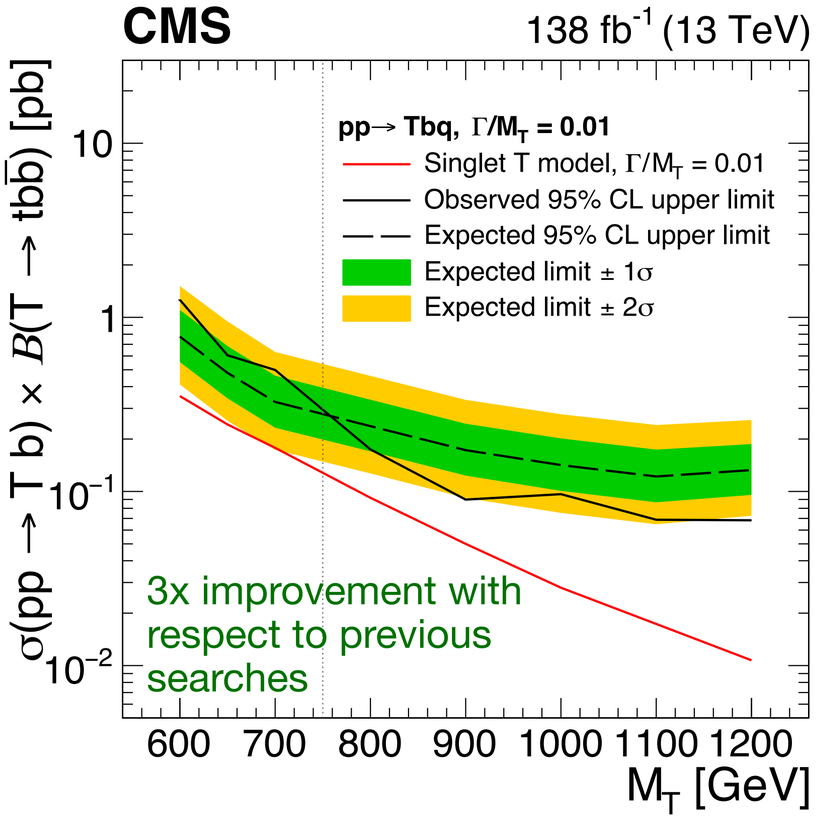
Single T Production (All Hadronic)

- T singlet with narrow width approximation ($\Gamma/m < 1\,\%$)
- Reconstruct the T quark by iterating through all possible jet combinations
  - multi-step minimization to reduce deviations from the expected masses of Z/H, W, and the top quark

Final state: ≥ 6 jets with 3 b-jets





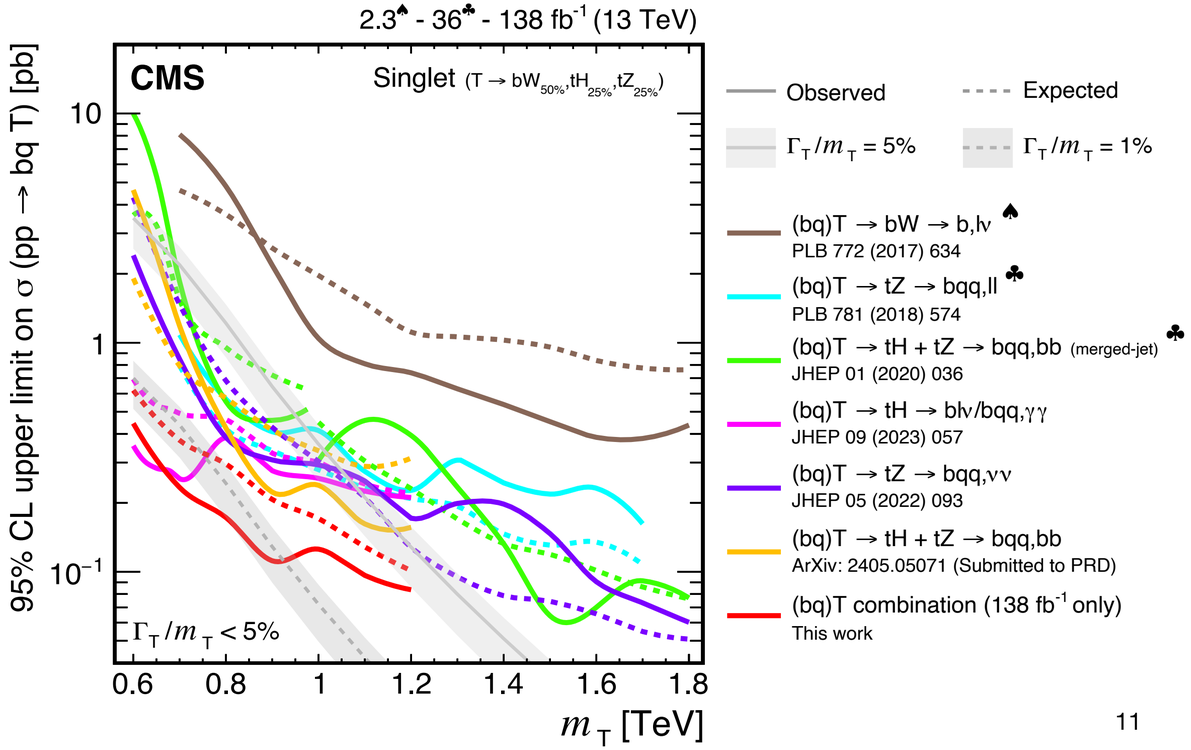


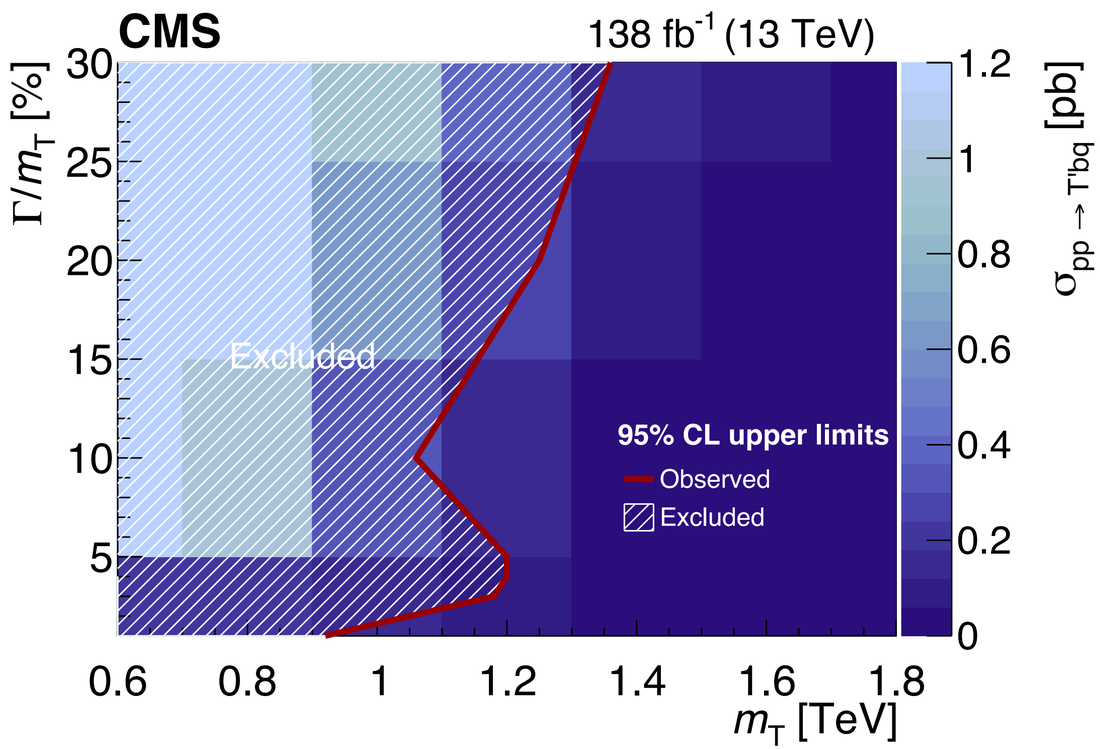
Obtained a stronger limit by a factor of three than 2016 results

Physics Reports 04(2025) 1115

VLQ Combination

- Review paper for searches on vector-like quarks, vector-like leptons, and heavy neutral leptons
- Overview, complementary, and partial combination of different final states are presented
- Combination of three searches under **narrow width approximation** for single T quark production in different final states

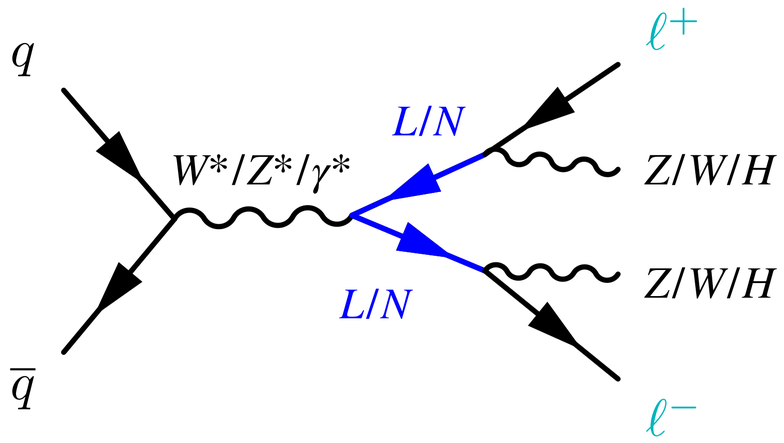


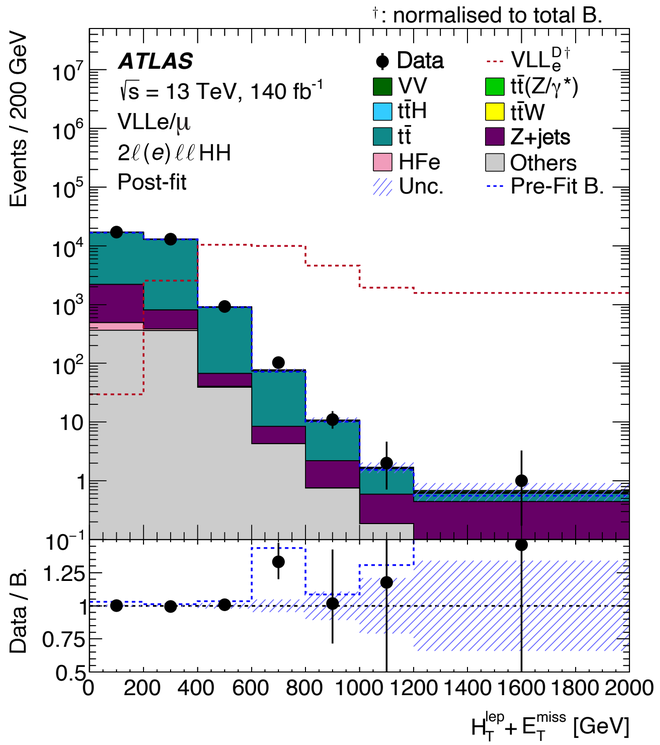


2411.07134

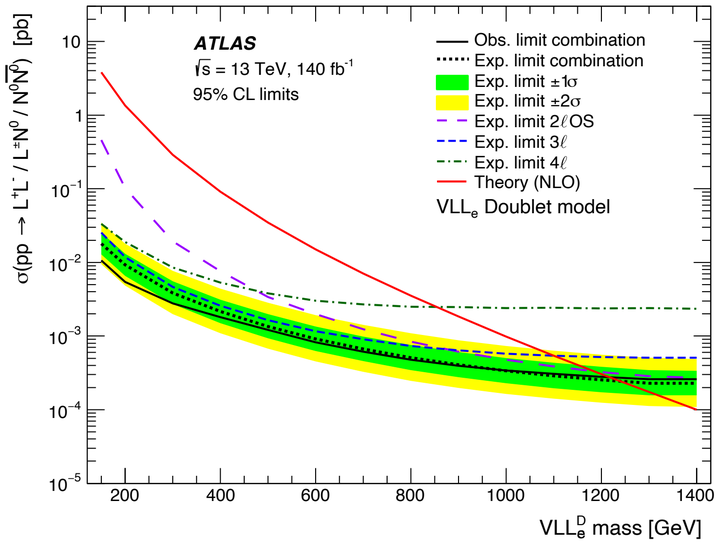
Vector-like Electrons and Muons

- VLLs → Color-singlet counterparts of VLQs
- Much less explored due to lower cross-section: only few LHC searches for VLL exist
- **First Run 2 search for vector-like e/μ:**
  - 3 categories: opposite-sign dileptons, three-lepton, or four-lepton categories
- Multi-class DNN trained separately in each category to further categorize events based on topologies
- Fit signal and control regions simultaneously to constrain the normalization of the main backgrounds





Most stringent mass exclusion limit to-date

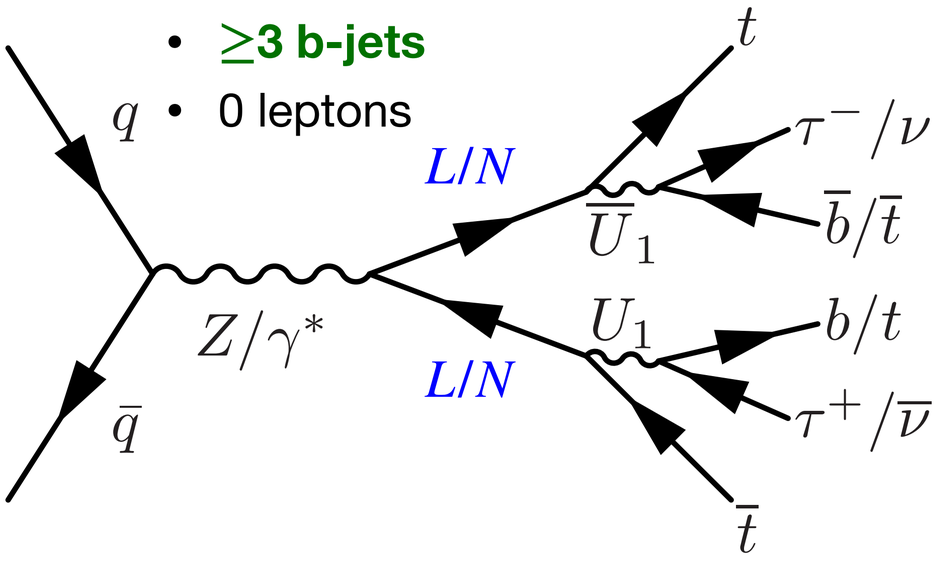


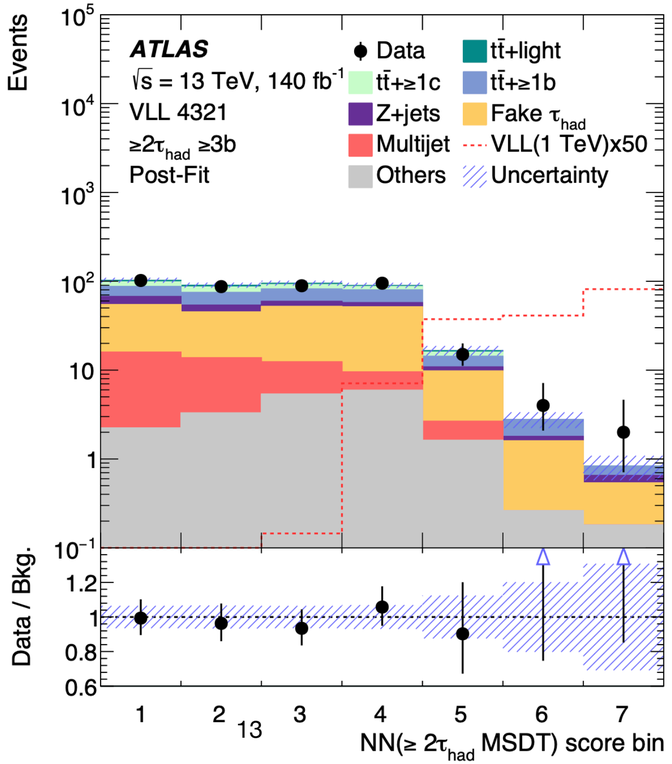
ATLAS-CONF-2024-008

Vector-like Tau in 4321 Model

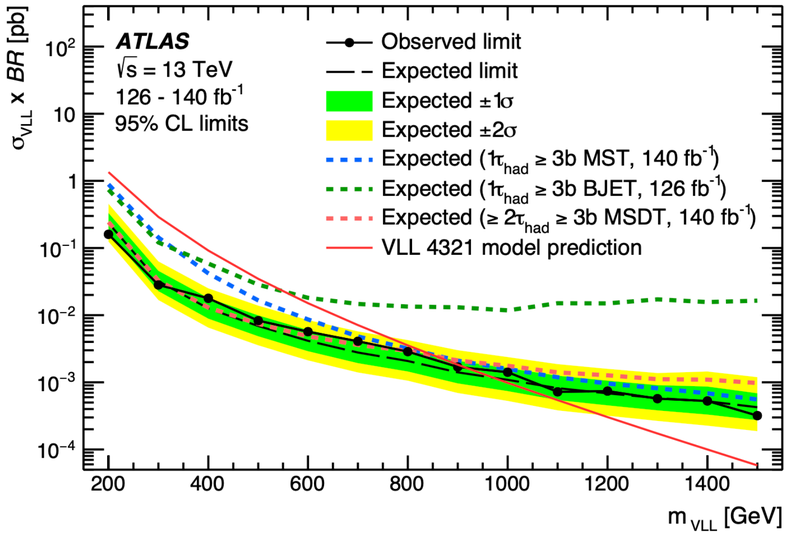
- 4321 model: a renormalizable and ultraviolet-complete extension of the SM
  - VLL decays into a 3rd gen quark and vector leptoquark (U_1)
- Categorization into 5 signal regions based on number of τ_h and b-jets
- Neural network trained separately in each category → NN score is main discriminant
- Does not confirm excess observed by CMS (2208.09700)

- ≥1 τ_h
- **≥3 b-jets**
- 0 leptons





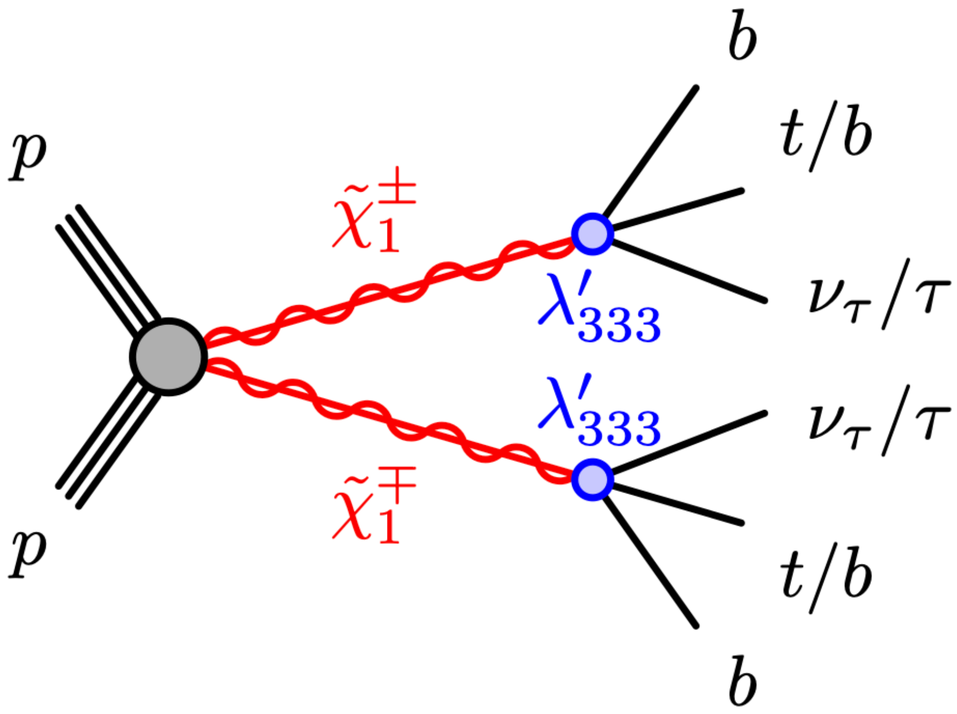
VLL below 910 GeV excluded



ATLAS-CONF-2024-008

RPV SUSY Interpretation (NEW!)

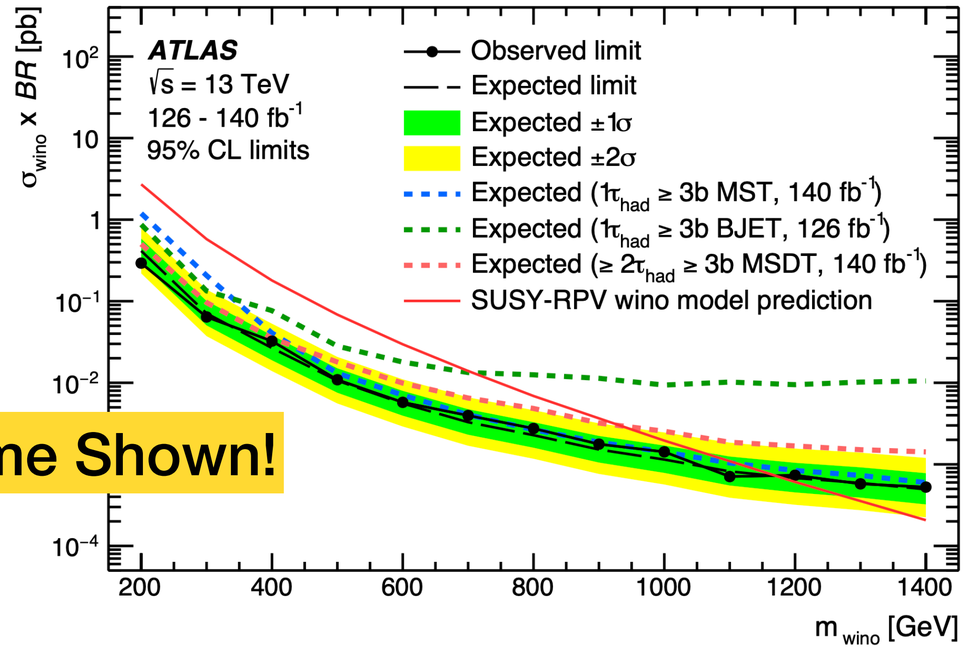
- New interpretations for R-parity violation SUSY with similar final states
  - Accomodate flavor anomalies
- First exclusive search to 3rd generation fermions



- ≥1 τ_h
- **≥3 b-jets**
- 0 leptons

Significantly extend mass exclusion:

- Higgsino: 585 → 880 GeV
- Wino: 670 → 1170 GeV

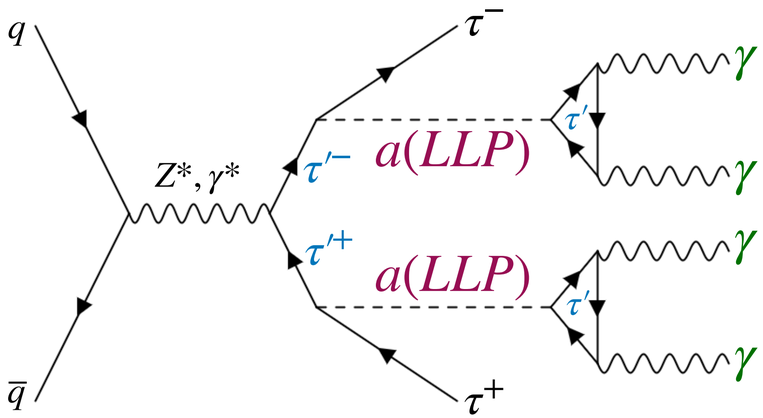


First Time Shown!

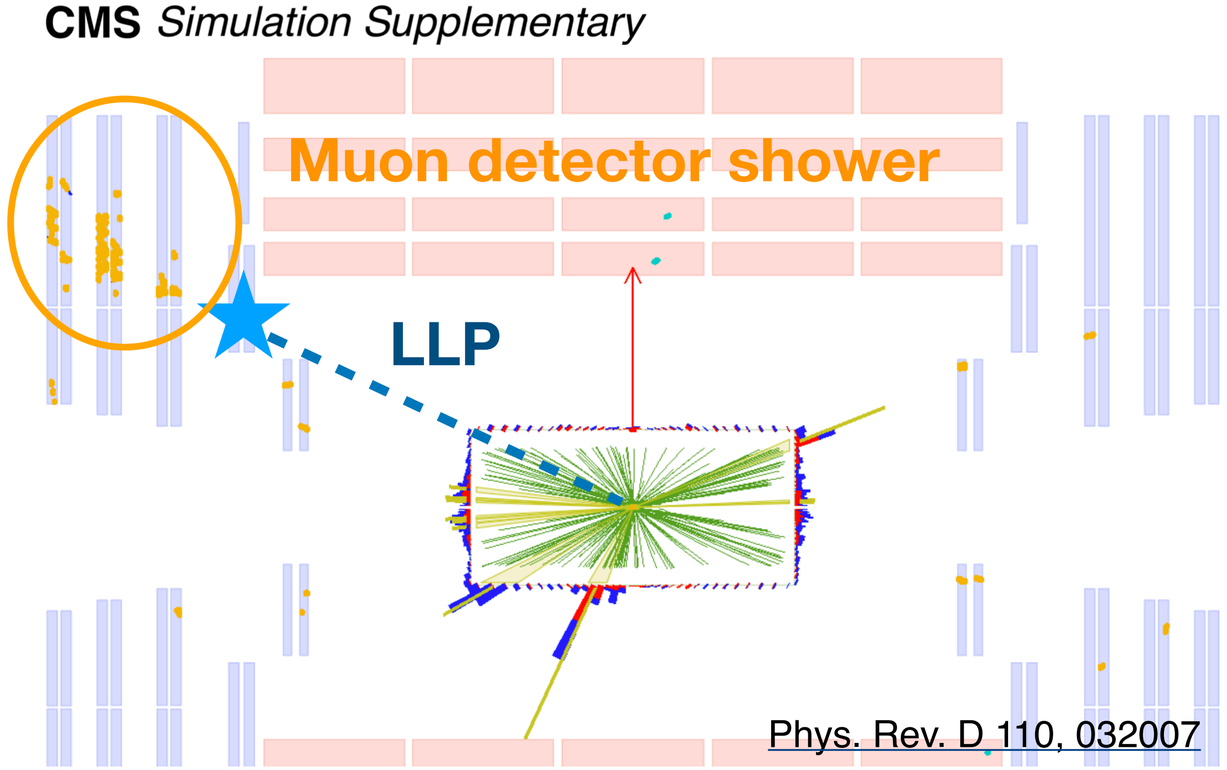
2503.16699

VLL with Long-lived Particle Decays

A heavy VLL(τ') singlet decays into a prompt τ lepton and a light long-lived pseudoscalar a (JHEP 07 (2023) 079)



- $p_T^{miss} > 200$ GeV
- ≥ 1 τ_h with $p_T > 30$ GeV
- ≥ 1 **muon detector shower**



Phys. Rev. D 110, 032007

- Steel interleaved with active chambers → **sampling calorimeter**
- Excellent background suppression from shielding material

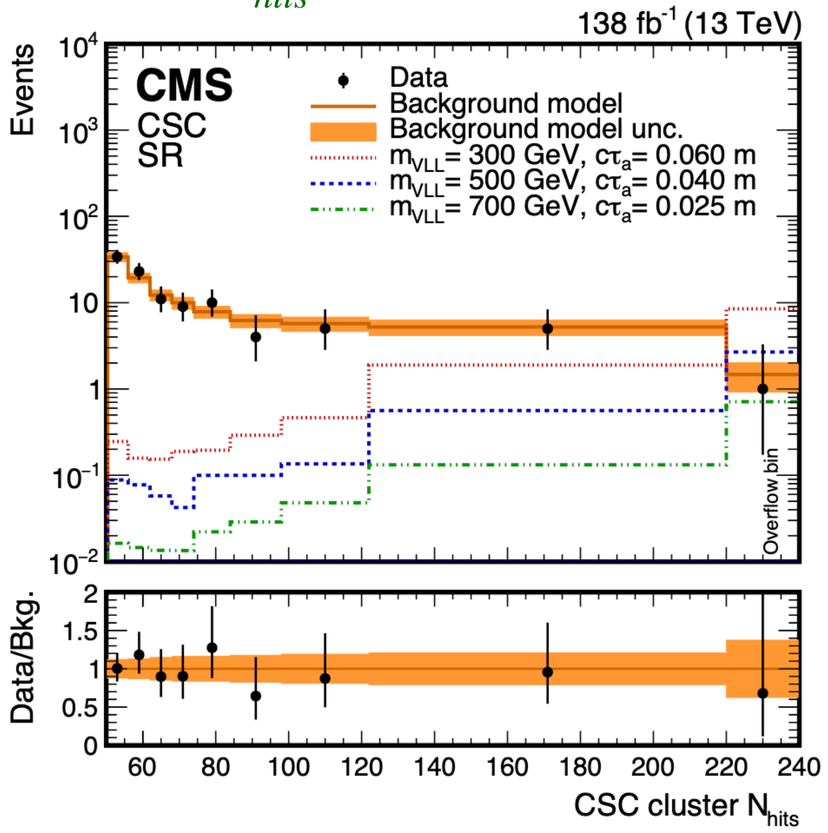
More on LLPs by Sagar Addepalli tomorrow!

2503.16699

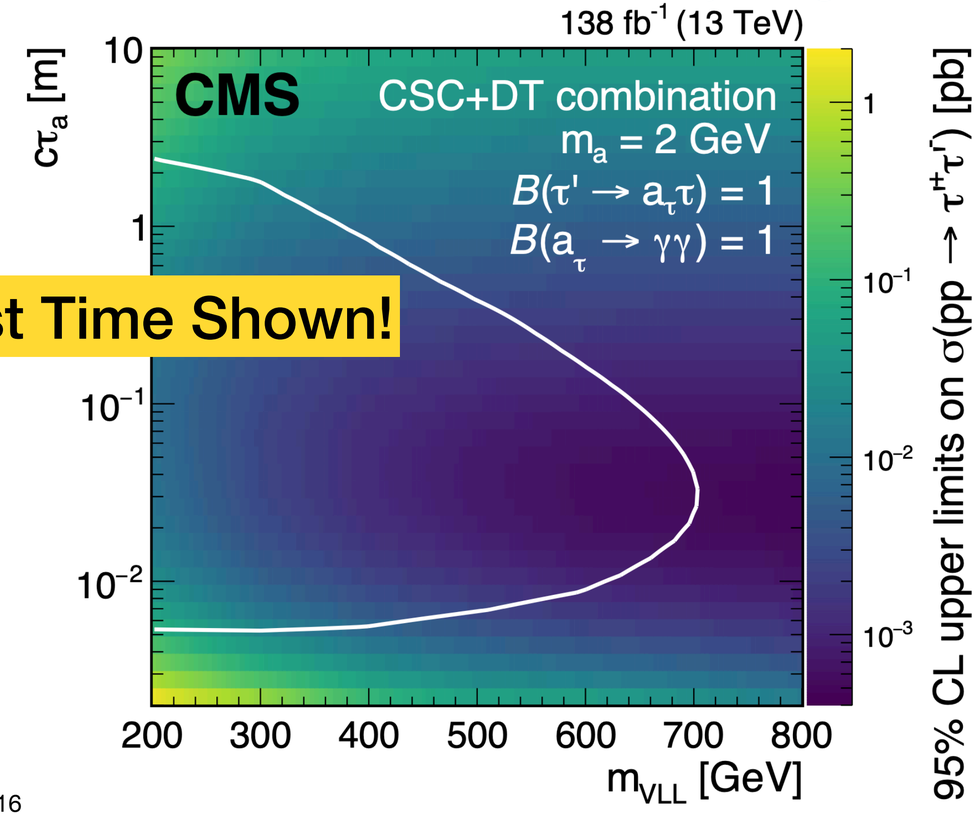
VLL with Long-lived Particle Decays

- Data-driven background estimation (Alphabet method)
  - Fit data in control region (out-of-time cluster region) and signal region simultaneously with a constant transfer factor
- **First limit on VLL cross section as a function of the VLL mass and pseudoscalar lifetime. Exclude up to VLL with masses up to 690 GeV**

N_{hits} in clusters



Limit wrt VLL mass and decay length



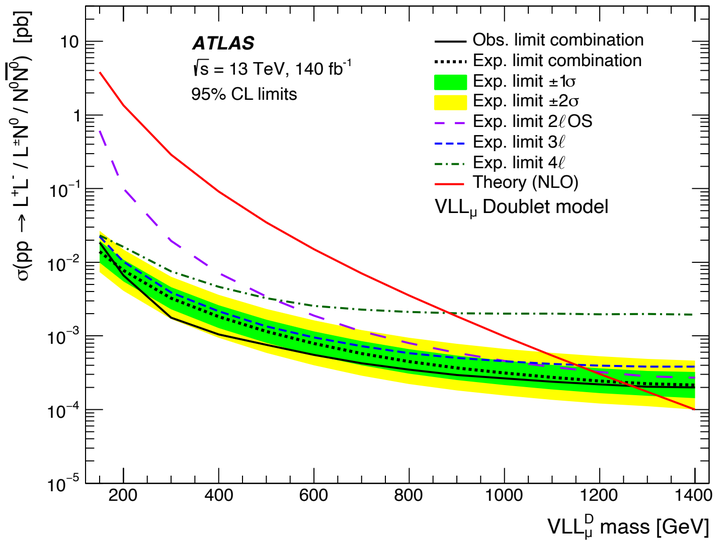
Summary

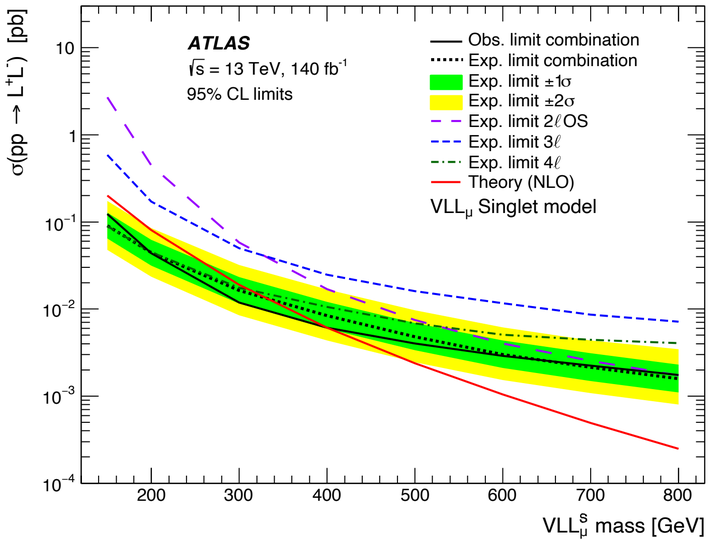
- VLQs and VLLs are a compelling extension to the SM and there has been a broad search program at ATLAS & CMS
- There are still unexplored regions of parameter space
  - Electroweak pair production of VLQ and VLL
  - Coupling with 1st and 2nd gen fermions and additional psuedoscalar/scalar bosons
  - Beyond minimal models to explore more complete models
- Efforts to understand complementarity and combine various searches
- Continuing efforts in innovating analysis techniques will further enhance the sensitivity

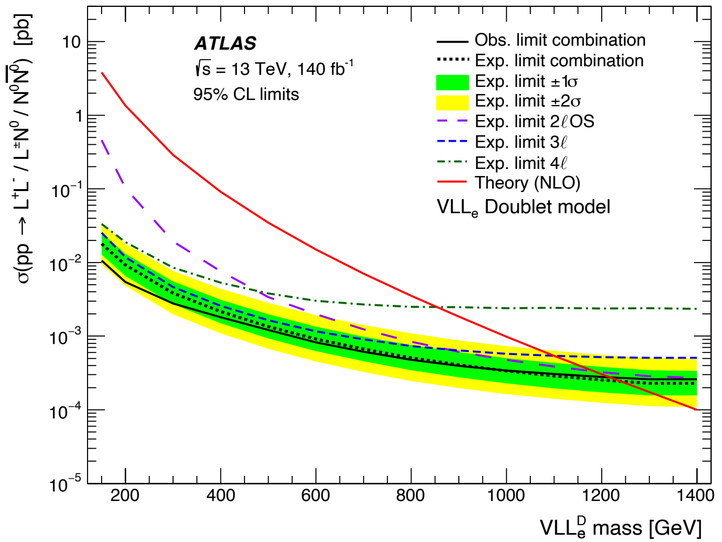
Backup Slides

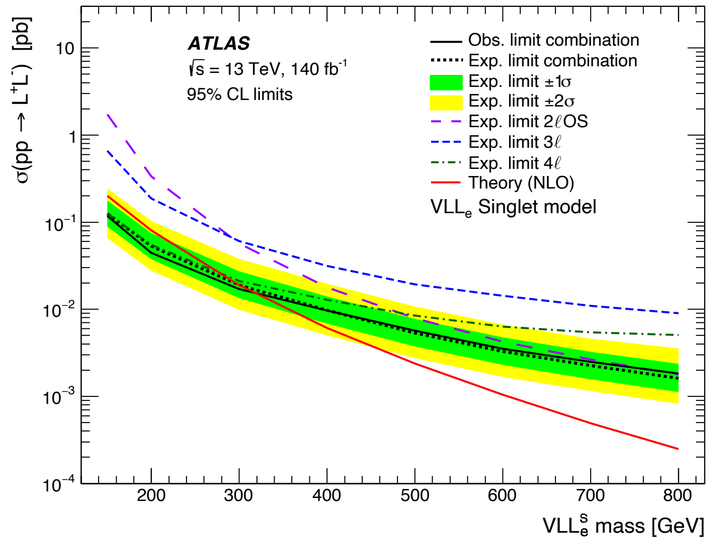
Vector-like Electrons & Muons

- Similar sensitivity for electron and muon types
- Much better sensitivity for doublet models due to more leptons in events
  - 3- and 4-lepton category much more sensitive
- Singlet:
  - $L^{+/-} \rightarrow \nu W / lZ / lH$
- Doublet:
  - $L^{+/-} \rightarrow lZ / lH$
  - $N \rightarrow lW$

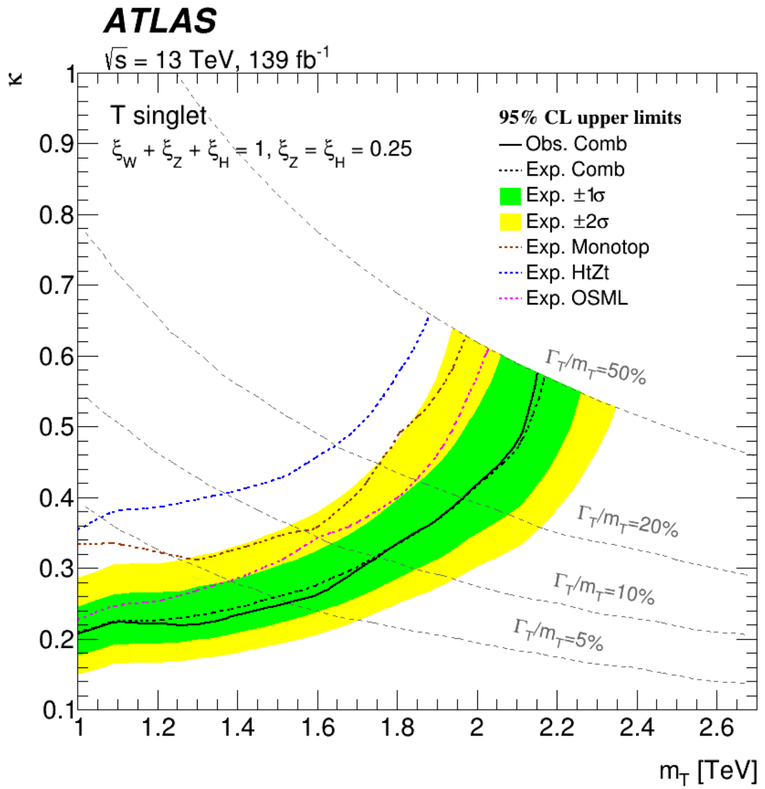


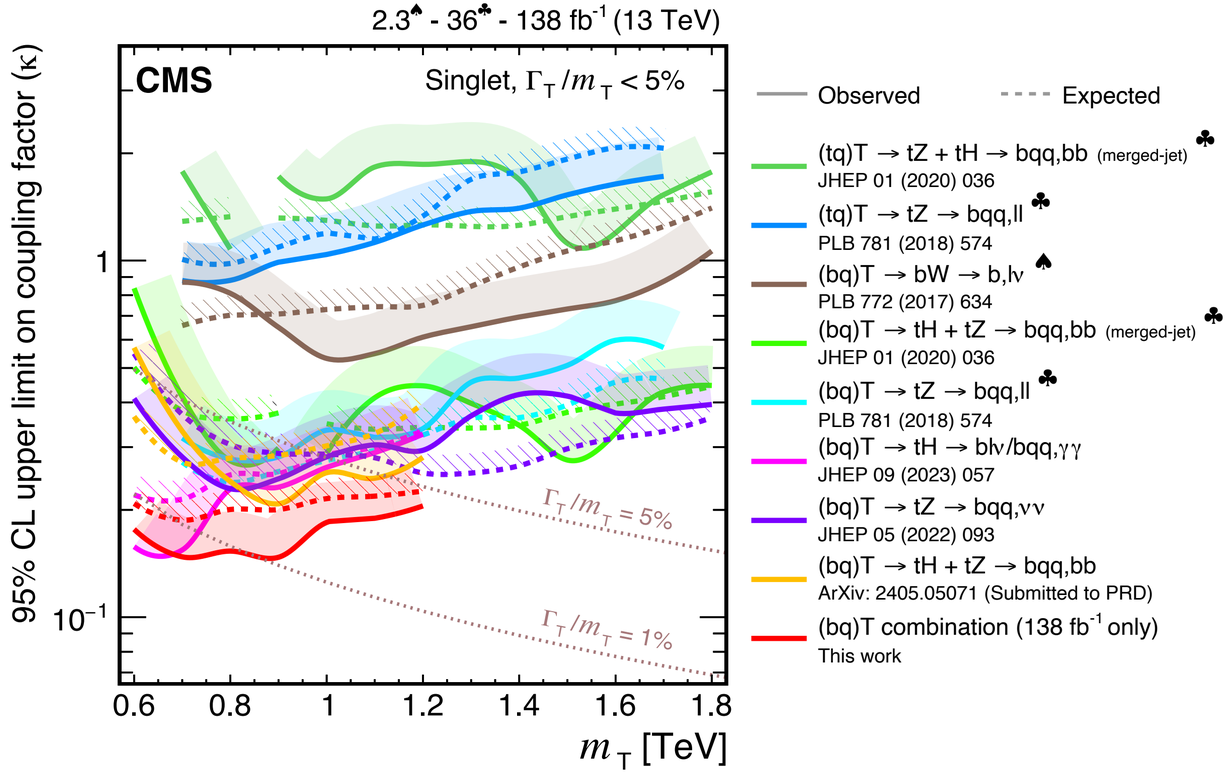






Single Top Comparison





- Similar sensitivity from 1—1.4TeV
- CMS had a focus on narrow width and lower mass VLQ
- ATLAS focused on wider width and higher masses