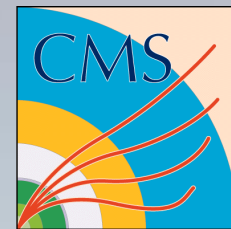




BLV2019: The 2019 International Workshop on Baryon and Lepton Number Violation



Searches for Vector Like Quarks at the LHC

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IHEP/CAS Beijing

On behalf of the ATLAS and CMS Collaborations



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Institute of High Energy Physics
Chinese Academy of Sciences

Vector-like quarks

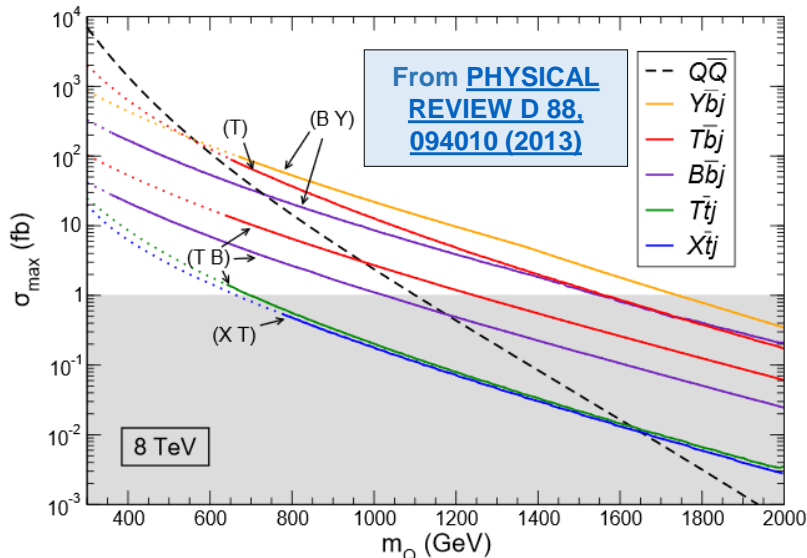


- The **ATLAS and CMS experiments** have an extensive physics program devoted to the **search of vector-like quarks** since Run 1
- Discovery of Higgs boson motivates **search for new physics**
- Possible explanations given by: little Higgs models, extra dimensions models, composite Higgs models, etc.
- These theories predict existence of **heavy vector-like quarks** (VLQ)
- Hypothetical new spin-1/2 particles: left- and right-handed chiralities transform in the same way under the standard model symmetry group

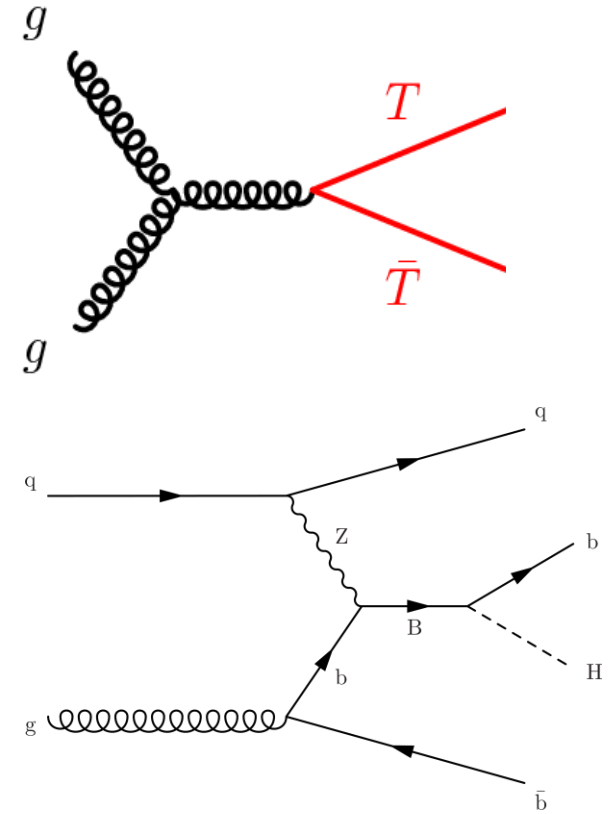
	$T \quad B$	$\begin{pmatrix} X \\ T \end{pmatrix} \quad \begin{pmatrix} T \\ B \end{pmatrix} \quad \begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix} \quad \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
SU(2) _L multiplet	1	2	3
Charge	2/3 -1/3	$\begin{pmatrix} 5/3 \\ 2/3 \end{pmatrix} \quad \begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix} \quad \begin{pmatrix} -1/3 \\ -4/3 \end{pmatrix}$	$\begin{pmatrix} 5/3 \\ 2/3 \\ -1/3 \end{pmatrix} \quad \begin{pmatrix} 2/3 \\ -1/3 \\ -4/3 \end{pmatrix}$



- **Pair-production:**
strong mechanism, the cross section depends only on the **VLQ mass**
- **Single production:**
electroweak mechanism, the cross section depends on **VLQ mass** and on its **couplings** with SM particles

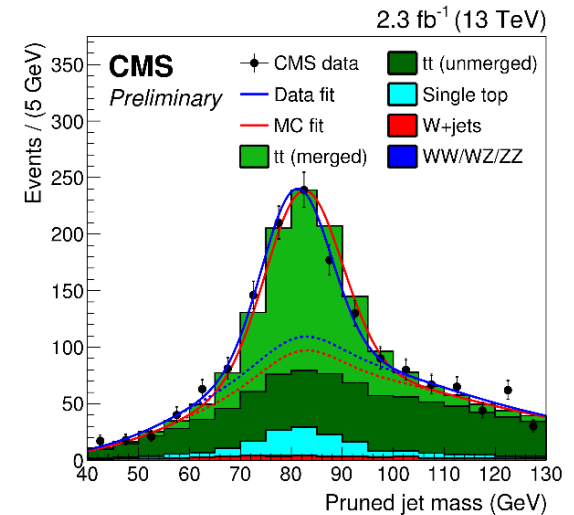
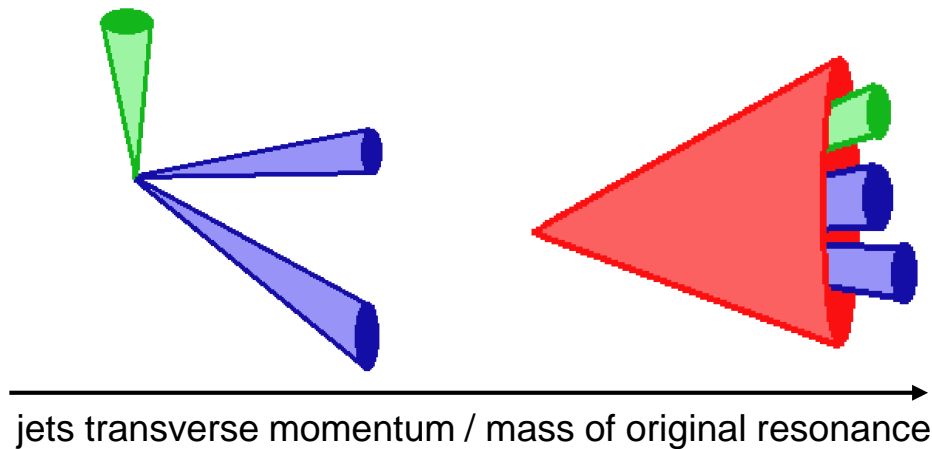


Pair production cross section falls steeply with VLQ mass

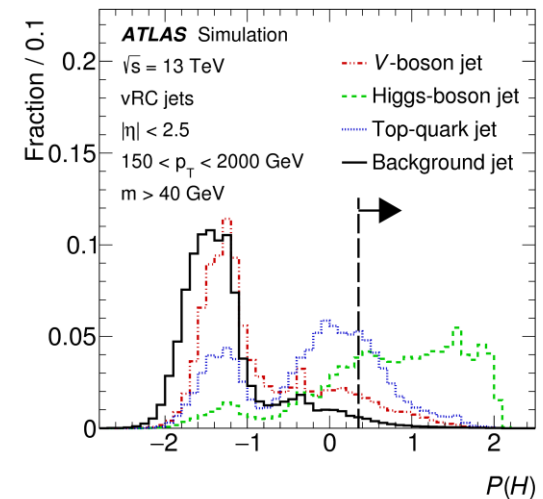


- Common decay modes:
 - $T \rightarrow Wb, Zt, \text{ and } Ht$
 - $B \rightarrow Wt, Zb, \text{ and } Hb$
 - $X \rightarrow Wt$
 - $Y \rightarrow Wb$

- Usage of **wide jets** after *cleaning* from soft/far tracks
- **Jet substructure** to discriminate between 0/2/3 subjets inside the wide jet
- New approaches for both ATLAS/CMS: **machine learning algorithms**



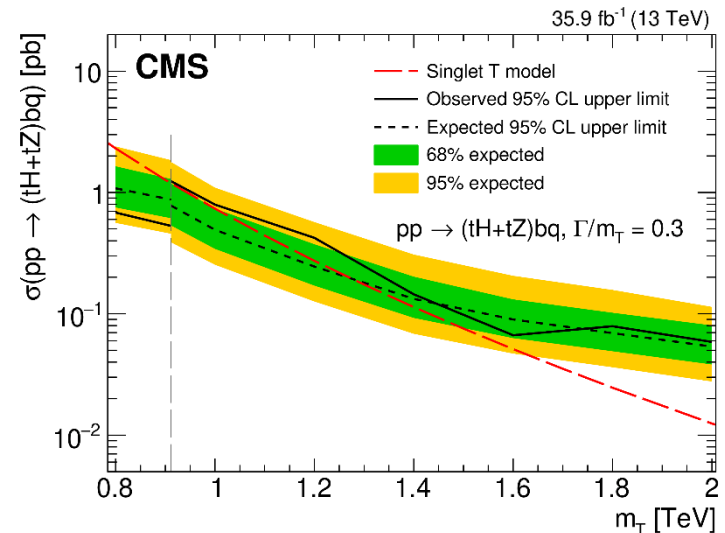
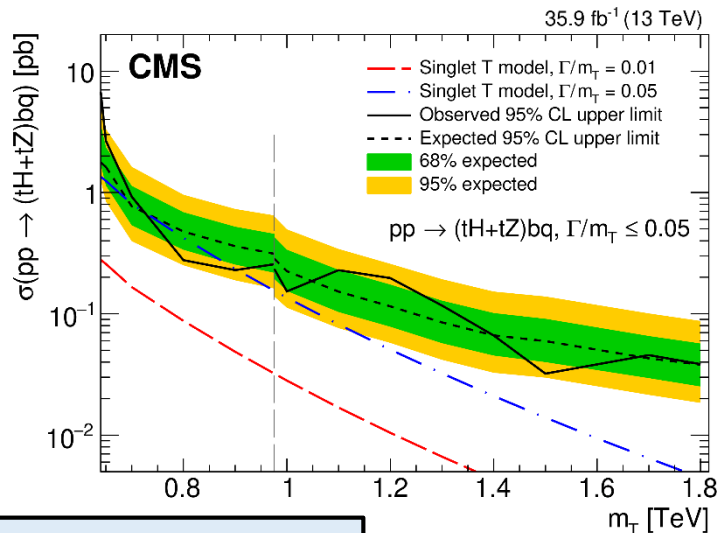
from [here](#)



from [here](#)

Single VLQ production

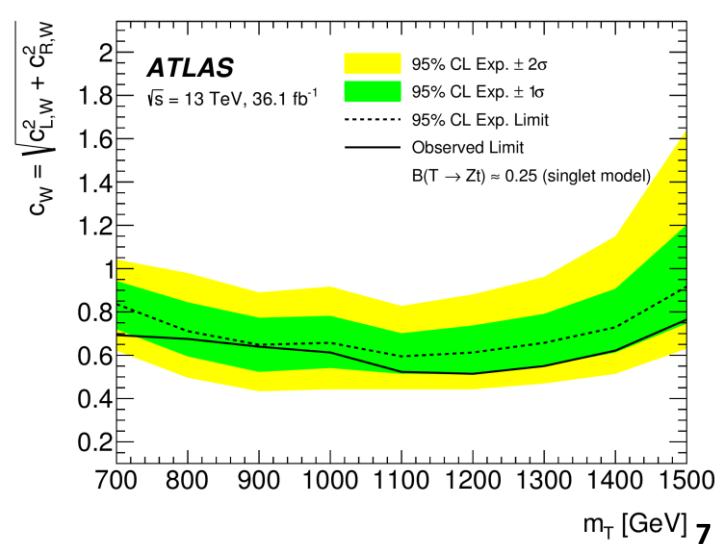
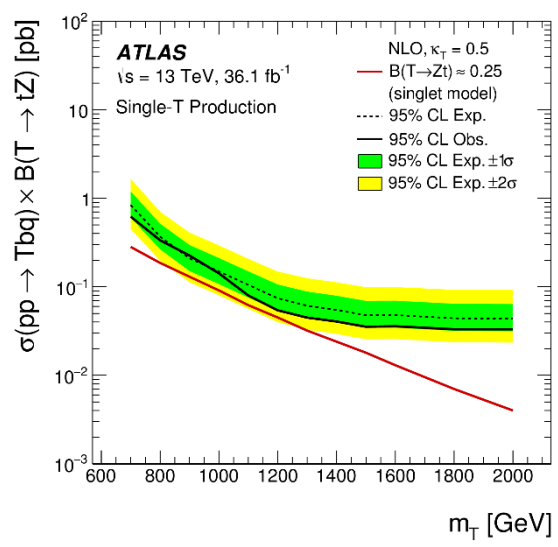
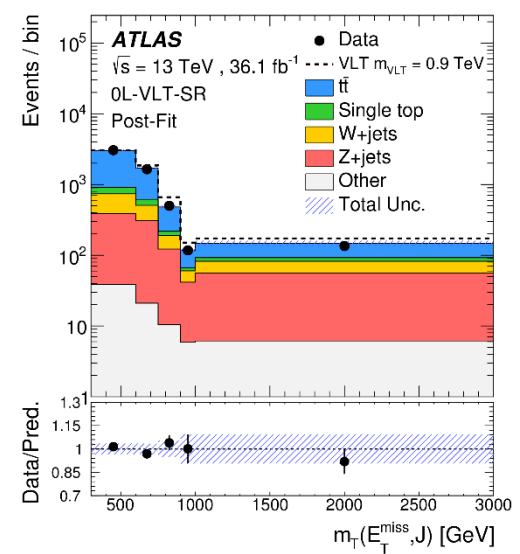
- Single production of **T quark**, decaying to **tH/tZ** with the H/Z to bb
- Two searches targeting separately lower and higher T mass NEW
 - **Low-mass**: at least six jets, with five of them composing the T assigned using χ^2 minimization for top/W/H/Z hypotheses
 - **High-mass**: T quark reconstructed from two wide jets coming from top and H/Z
- Depending on **T width** (between **~0 to 30% of the T mass**), this search has expected sensitivity for T masses up to 1.28 TeV (for singlet T with width of 30%)



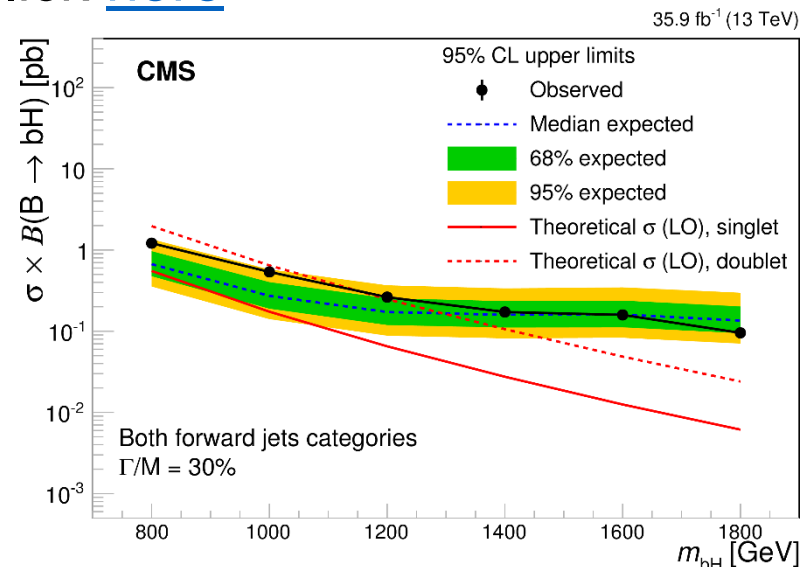
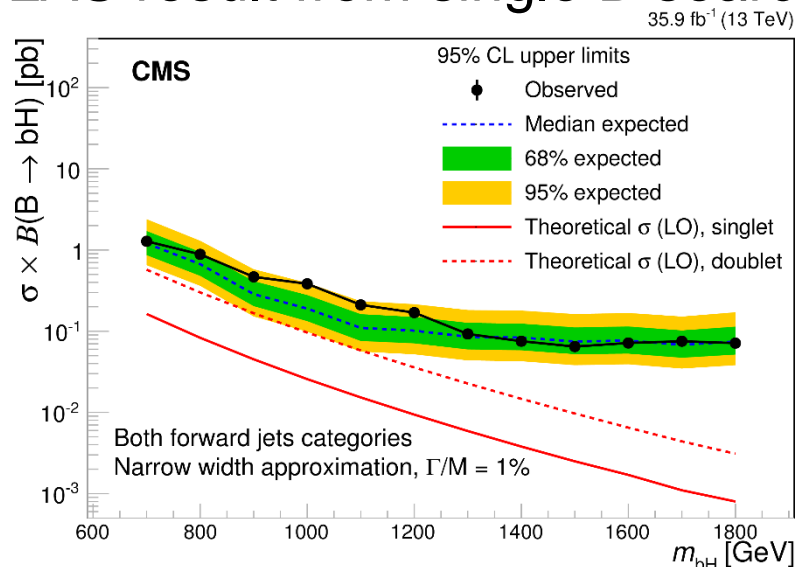


- Single production of **T quark**, decaying to **tZ** with:
 - **1 top tagged jet (trimming + τ_{32} , see [here](#))**
 - **$E_T^{miss} > 200$ GeV (from $Z \rightarrow \nu\nu$)**
 - **1 forward jet + additional cuts to reduce background**
- Multijet background estimated from data, other contributions from control regions included in the fit
- Study of the **coupling** between T quark and SM particle: **c_W** for the **WTb vertex**

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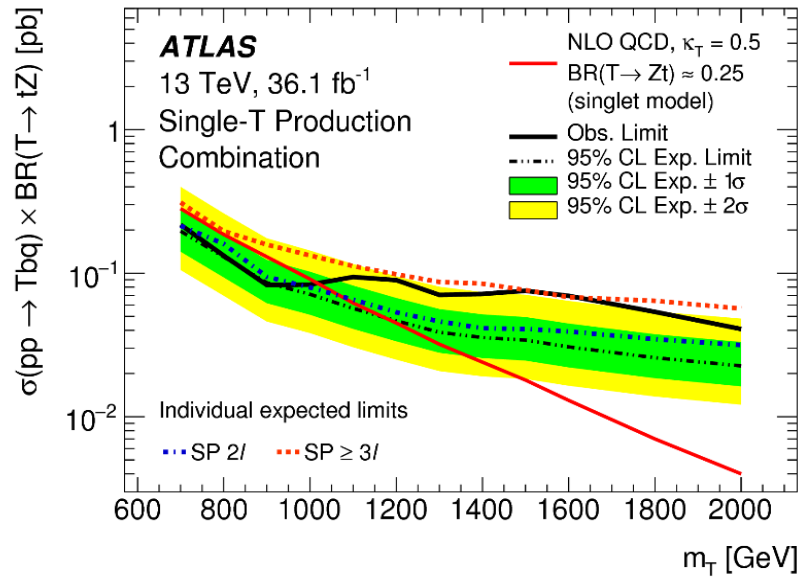
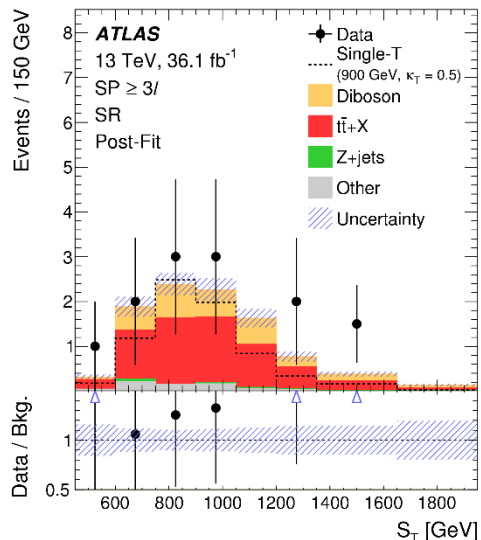
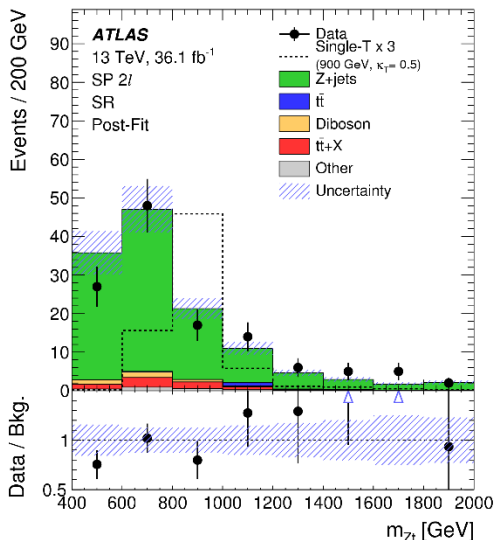


- Single production of **B quark**, decaying to **bH** with the H to bb
- Final state with:
 - **one high-pt b-tagged jet**
 - **one boosted Higgs to bb**
 - presence of **forward jets**
- **Main background is multijets**: estimation done completely from data
- Study of the **B width** between ~ 0 to 30% of the B mass
- ATLAS result from single B search: click [here](#)



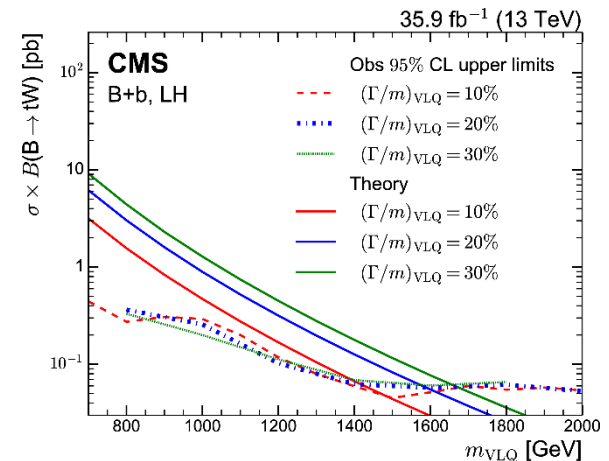
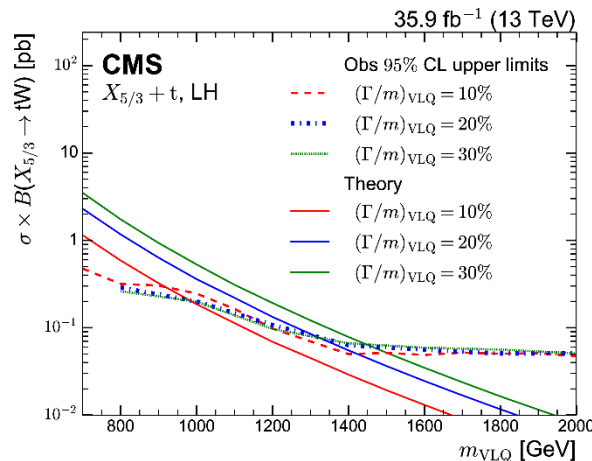
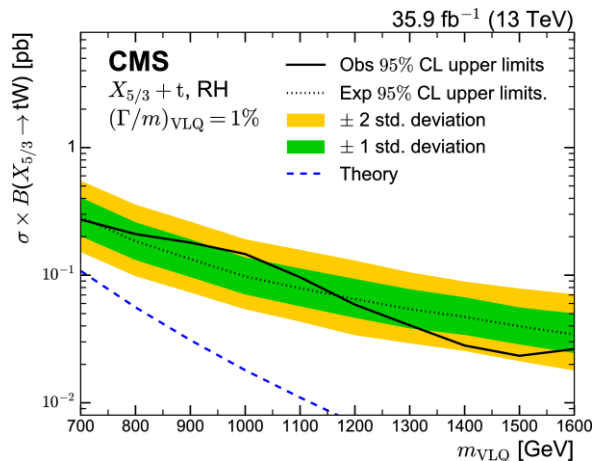
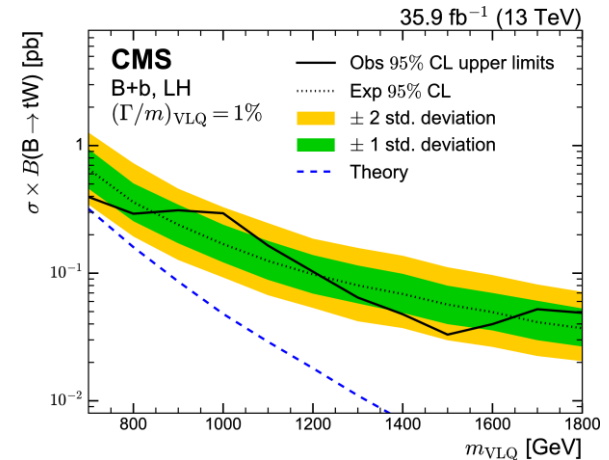
- Single production of **T quark**, decaying to **tZ** with:
 - **2 leptons + 1 top tagged jet (trimming + τ_{32})**
 - **or 3 leptons**
 - **1 forward jet + additional cuts to reduce background**
- Contribution from main backgrounds taken from simulation and corrected from control samples
- With a coupling **$k_T=0.5$** , **single T** excluded for masses **below 1.05 TeV**

[Phys. Rev. D 98 \(2018\) 112010](#)





- Search for **single vector-like B or $X_{5/3}$** with the **VLQ decaying to tW**, with one muon or electron in the final state
- Ten categories depending on number of **top tagged jets, W tagged jets, b tagged jets**
- **Forward jet** required in the signal region
- Background estimated from control region with zero jets in the forward region
- **Limits for:** Bb LH/RH, Bt RH and $X_{5/3}$ +t LH (width = 1%, 10%, 20%, 30%)



Pair VLQ production



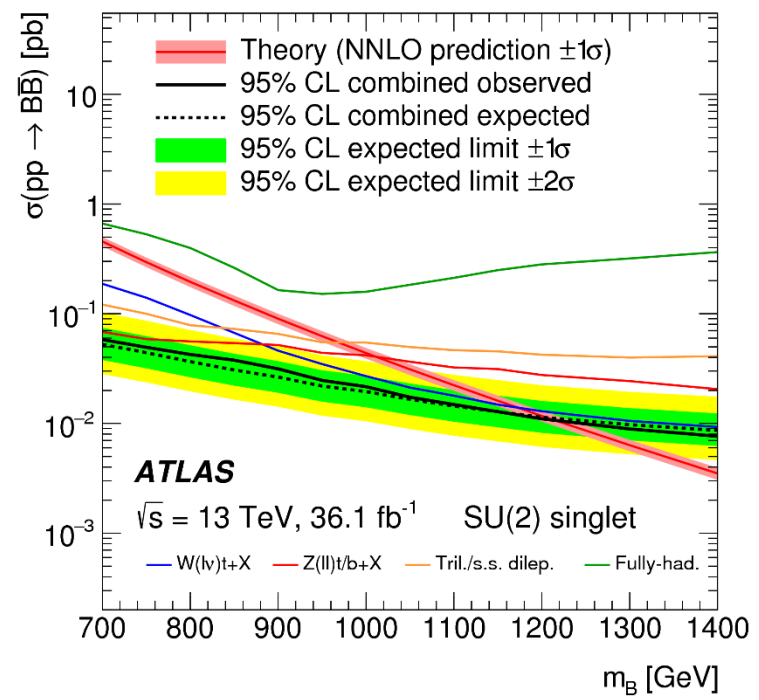
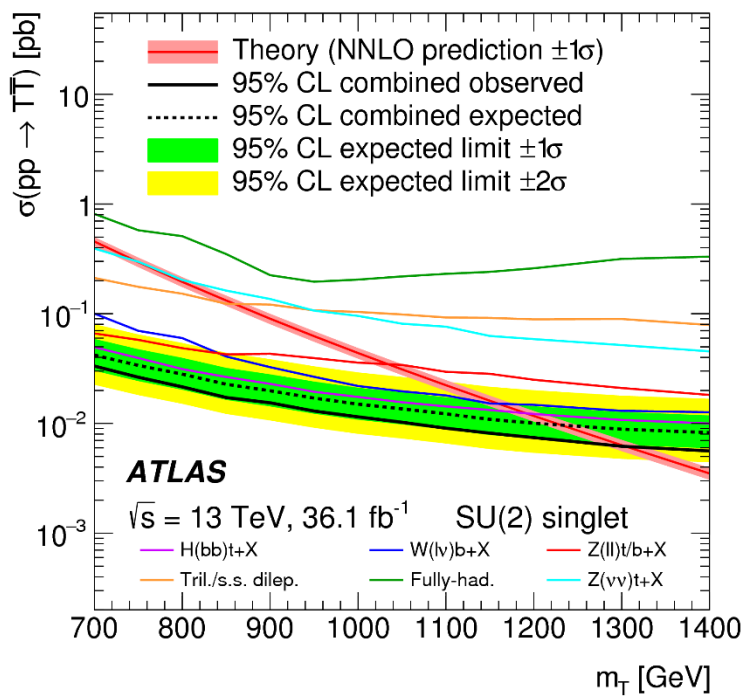
ATLAS **combination** of several analyses of VLQ pair production:

1. 1 lepton or transverse missing energy + 6 jets targeting **TT** \rightarrow **Ht** + **X**, with **H** \rightarrow **bb**
2. 1 lepton + 3 jets + 1 W-jet targeting **TT** \rightarrow **WbWb**
3. 1 lepton + 4 jets + 1 top-jet targeting **BB** \rightarrow **Wt** + **X**
4. transverse missing energy + top tagged jets targeting **TT** \rightarrow **Zt** + **X**, with **Z** \rightarrow **$\nu\nu$**
5. 2/3 leptons + 2 b-jets targeting **TT** \rightarrow **Zt** + **X** or **BB** \rightarrow **Zb** + **X** with the **Z** decaying to dilepton
6. same sign dilepton or trilepton targeting **TT** \rightarrow **HtHt** or **B** \rightarrow **WtWt**
7. fully hadronic final state with low transverse missing energy targeting **TT** \rightarrow **HtHt** or **B** \rightarrow **HbHb**

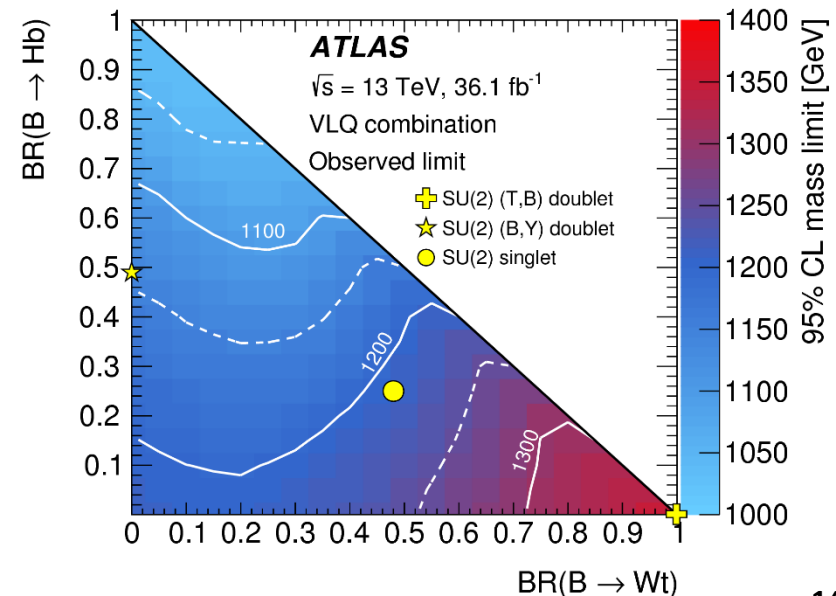
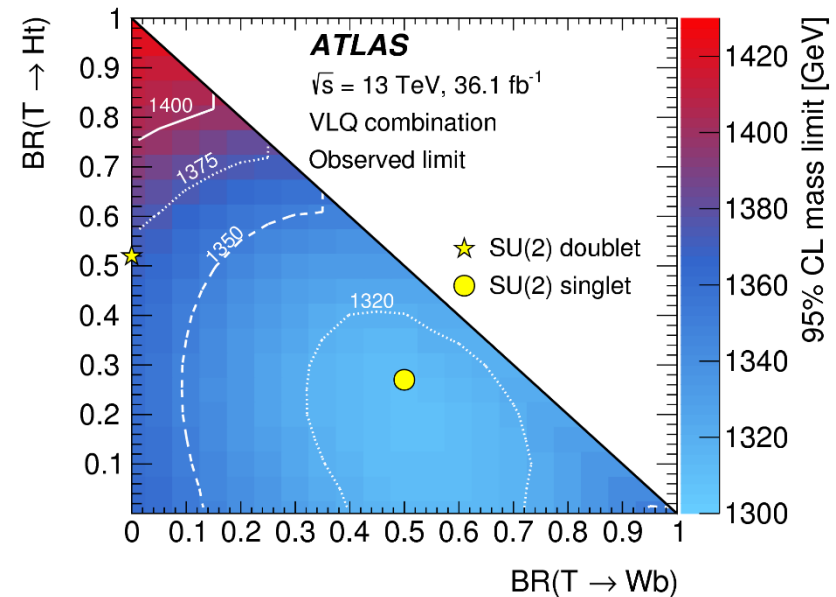
Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$ [16]	$HtH\bar{t}$	-
$W(\ell\nu)b + X$ [30]	$WbW\bar{b}$	-
$W(\ell\nu)t + X$ [32]	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$ [33]	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$ [35]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [36]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic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



- For a **singlet (doublet) T**, masses below **1.31 (1.37) TeV** are excluded
- A **singlet B** excluded for masses below **1.22 TeV**
- A **doublet B** excluded for masses below **1.37 TeV** for (T,B) doublet, and **1.14 TeV** for (B,Y) doublet

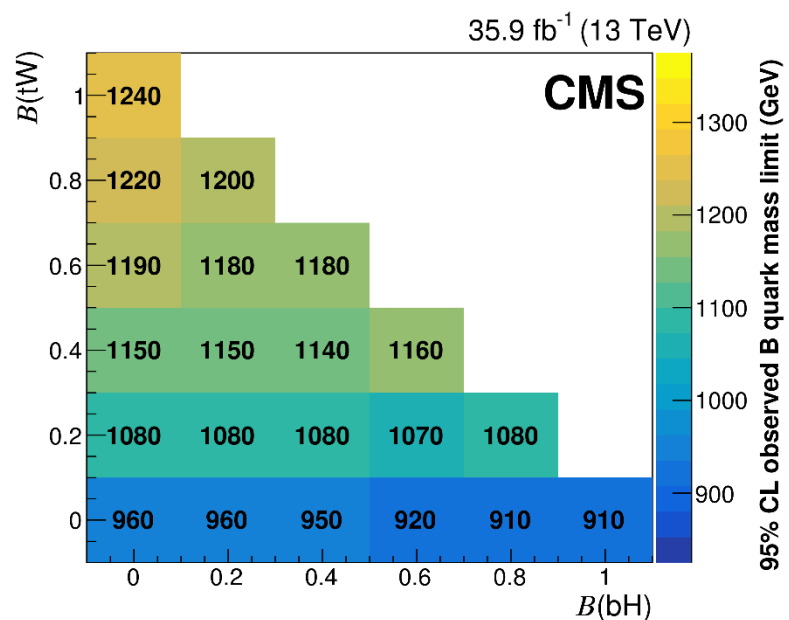
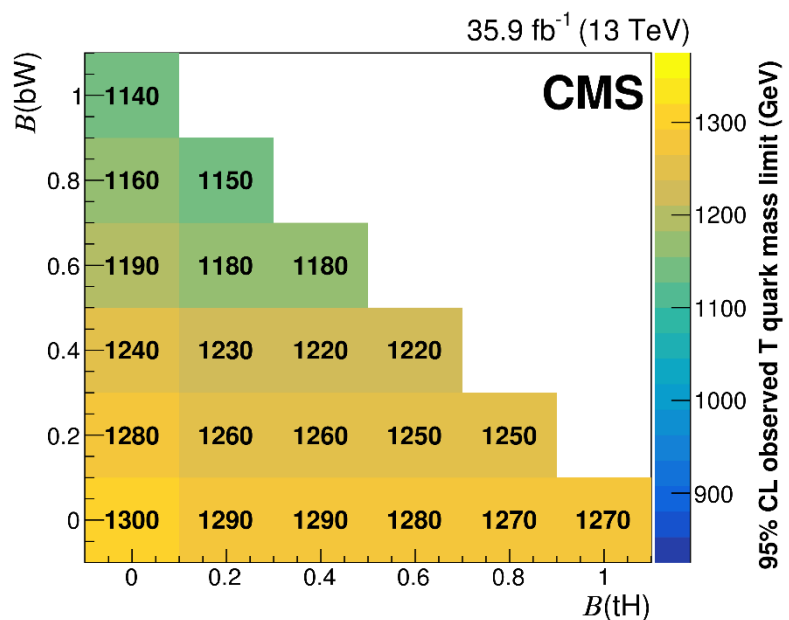


- Combination is **significantly more sensitive than any one analysis**
- In the SU(2) singlet, observed limit on TT improved by up to a factor of ~ 1.7
 - increase of 110 GeV in the observed mass exclusion
- Regardless of the branching ratio:
 - **T quark** excluded for masses below **1.31 TeV**
 - **B quark** excluded for masses below **1.03 TeV**





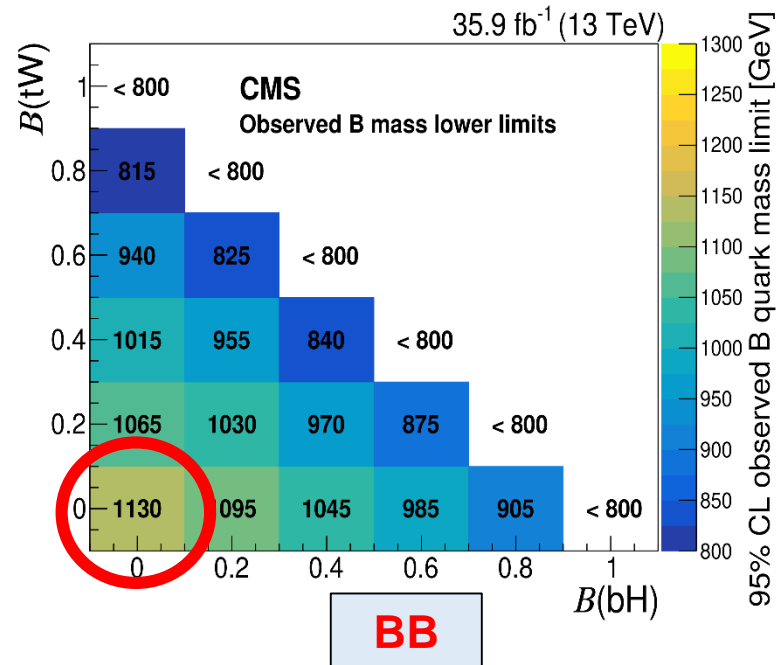
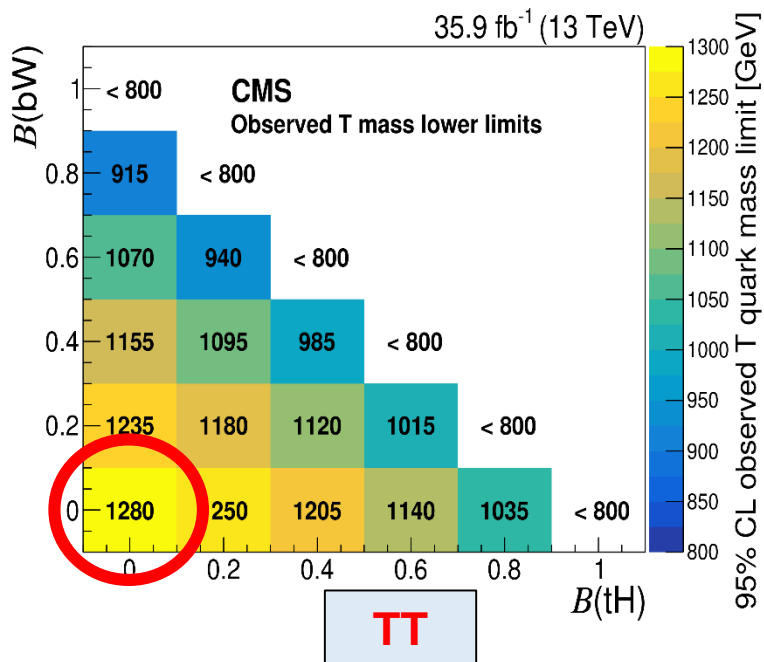
- Search for **TT or BB production**:
 - **single lepton**, optimized for signal events with $T \rightarrow bW$ or $T \rightarrow tH$, with a lepton from top decay and boosted W or H tagged jet
 - **same sign leptons**, most sensitive to signal events with $T \rightarrow tH$, with the Higgs decaying to WW and one W decaying leptonically
 - **trilepton**, highly sensitive to VLQ pair production with at least one $T \rightarrow tZ$, $B \rightarrow bZ$, or $B \rightarrow tW$ decay





- Dedicated analysis looking for TT/BB in final state with **opposite sign dilepton**
- Analysis sensitive to final states with **T → tZ** and **B → bZ**
- Final states with boosted jets
- Assuming 100% BR to Z boson, **T (B) masses excluded below 1280 (1130) GeV**

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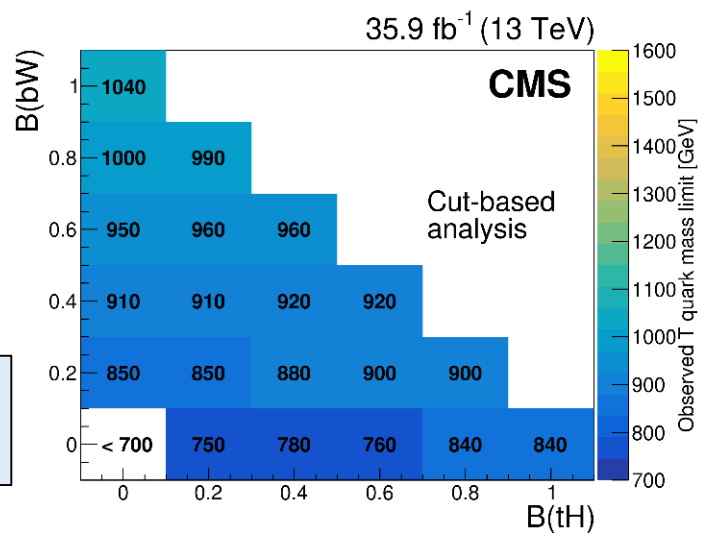




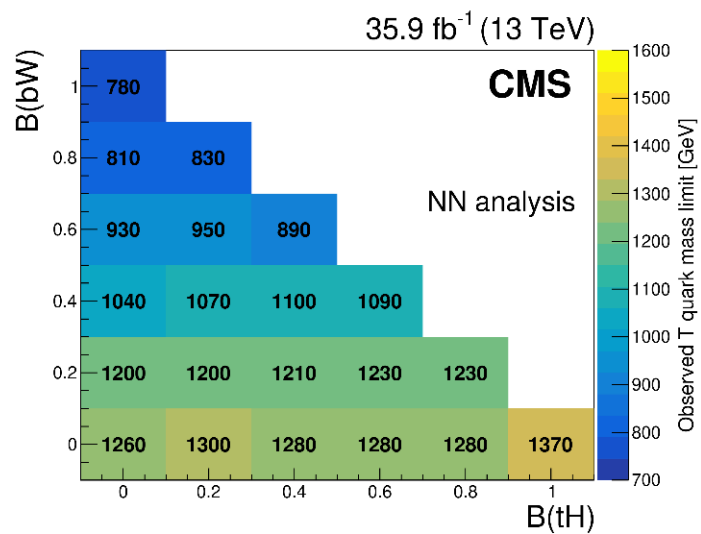
- Two searches for pair production of T or B in fully hadronic final states:
 1. **cut-based analysis targeting T \rightarrow bW decay mode**
 2. **analysis based on NN algorithm**, used to tag candidate jets as originating from top, b, light quarks, or W, Z, H bosons
- In the cut-based analysis, **control regions from data used to measure QCD multijet background** yields and shapes
- In the NN analysis, estimation from **the misidentification rates for each of the six categories of jets**

[Phys. Rev. D 100 \(2019\) 072001](https://arxiv.org/abs/1905.07200)

- Cut-based most sensitive to bW decay, NN to other decays



Cut based

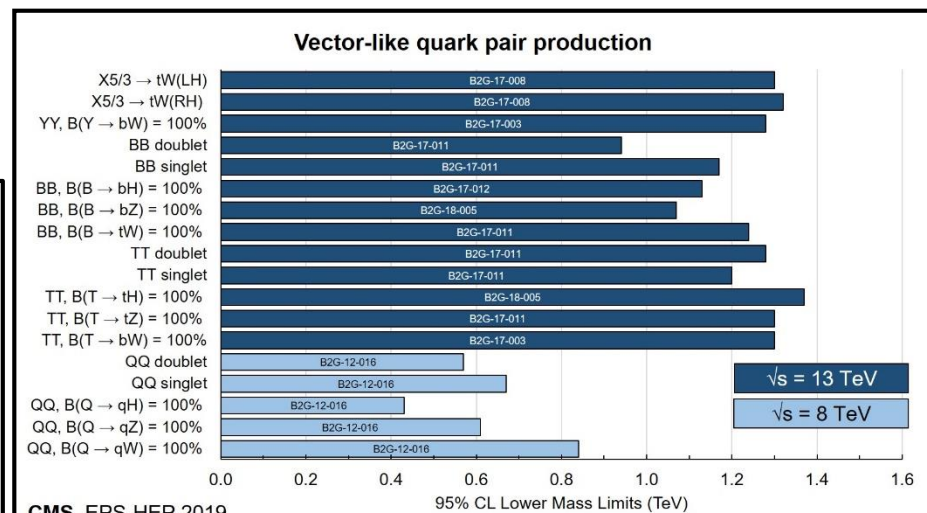
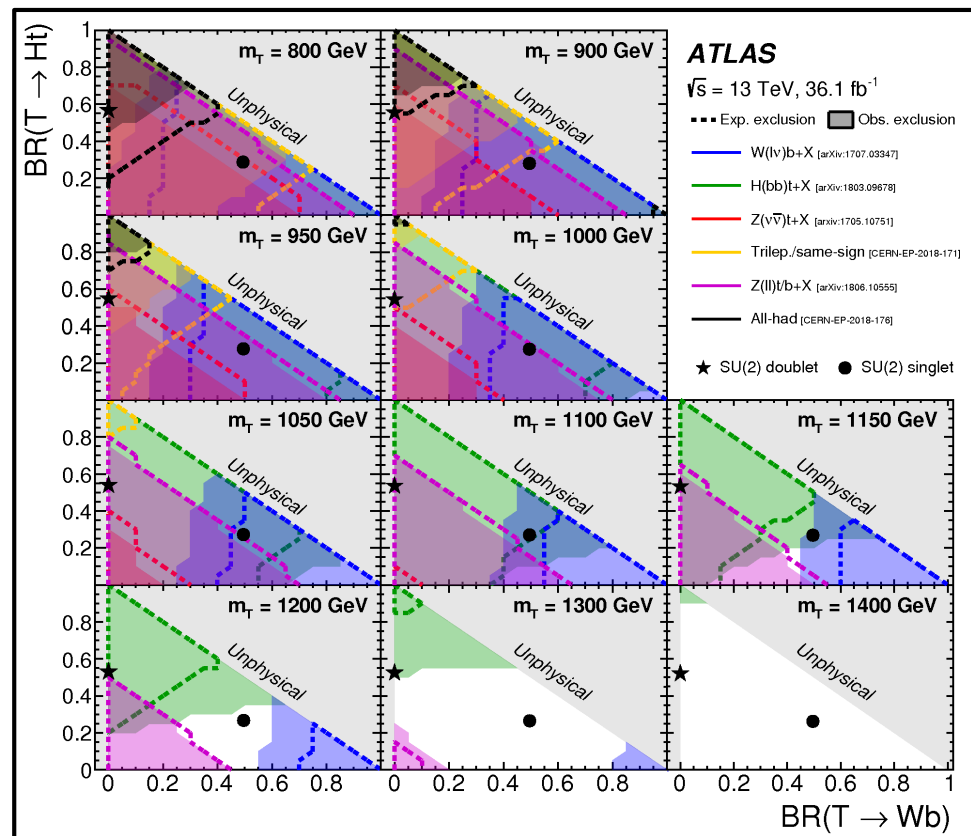


Neural network

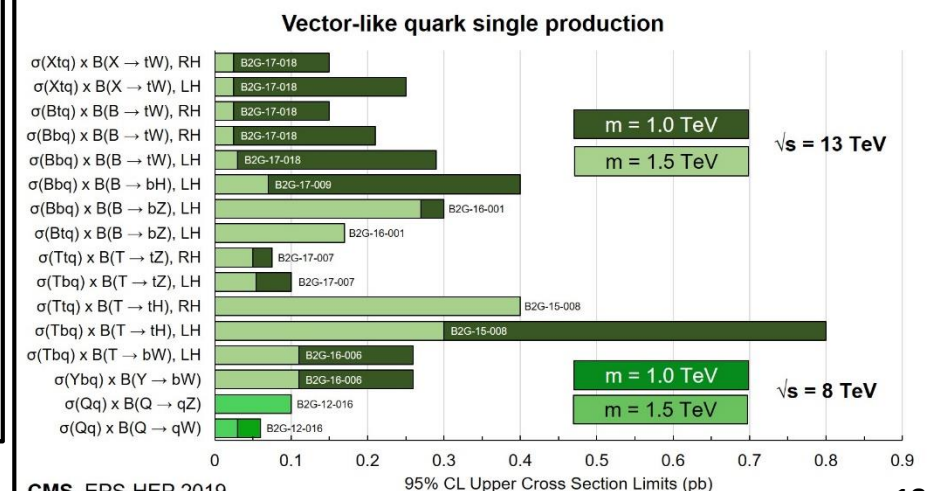


These and more results on vector-like quarks have been investigated at ATLAS and CMS:

- **B2G group at CMS (click [here](#))**
- **ATLAS public page (click [here](#))**



CMS, EPS-HEP 2019



CMS, EPS-HEP 2019



- The **ATLAS and CMS experiments** have an extensive physics program devoted to the search for vector-like quarks
- A selection of searches has been presented
 - **single production of VLQs**
 - **pair production of VLQs**
- Unfortunately no hint of new physics has been found
- Shown **VLQ mass limits are above 1 TeV** and have been obtained using early Run 2 data → collaborations working hard to release **full Run 2 results** that will expand current results
- Furthermore Run 3 is starting soon: **new energy frontiers to explore!**

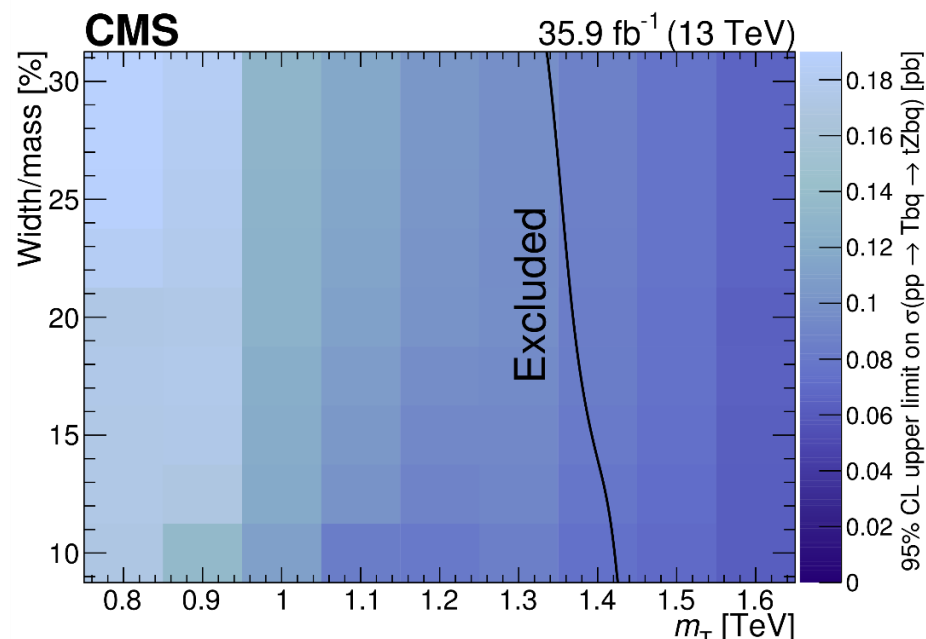
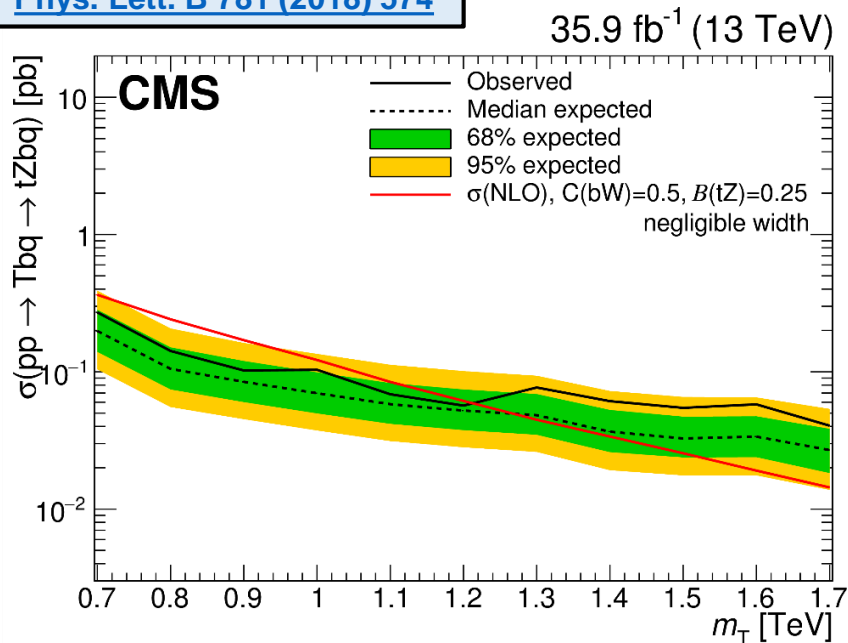
An aerial photograph of a city street intersection at dusk. The scene is illuminated by streetlights and building lights, creating a warm, golden glow. The text "Thank you for your attention" is overlaid in a large, bold, red, italicized font within a white rectangular box with a black border. The background shows a complex street layout with multiple lanes and crosswalks, surrounded by various buildings, including a prominent classical-style building on the left and a modern building on the right. The sky is a soft, hazy blue, suggesting the time is either early morning or late evening.

***Thank you for your
attention***

BACKUP

- Single production of T quark, decaying to tZ with the **Z to leptons and the top quark to hadrons**
- **10 categories** defined, depending on the Z decays / top reconstruction / presence of forward jets
- T quark **widths from negligible to 30%** of T mass are studied
- Left-handed singlet T produced with a b quark excluded below the mass of 1.2 TeV (coupling of 0.5)

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- Search for: $pp \rightarrow TT \text{ or } YY \rightarrow bWbW \rightarrow bl\nu bqq$
- Final states with a single isolated muon or electron, missing transverse momentum, and at least four jets with high transverse momenta
- W jet tagging is used to improve sensitivity at higher masses
- A **constrained kinematic fit** for the considered signal decay process is performed
- **Background** estimated from simulation with corrections from data

