

ATLAS AND CMS SEARCHES FOR VLO



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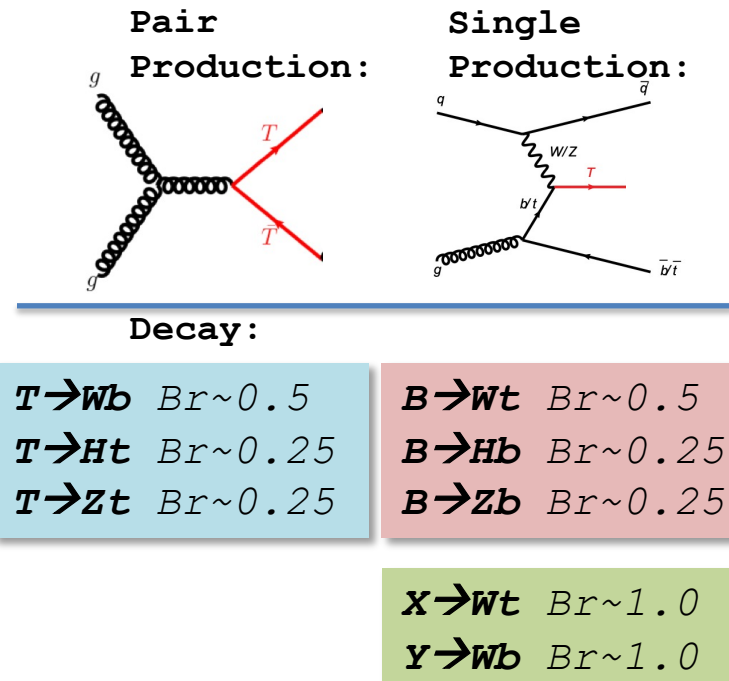
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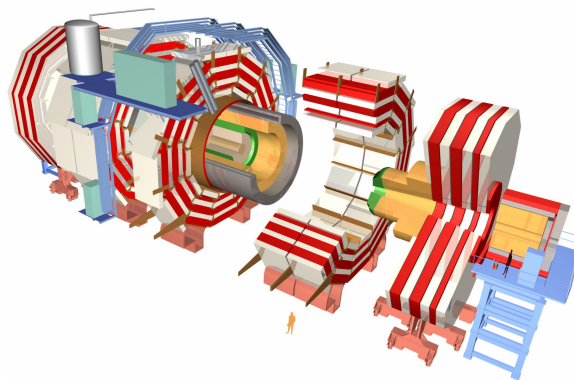
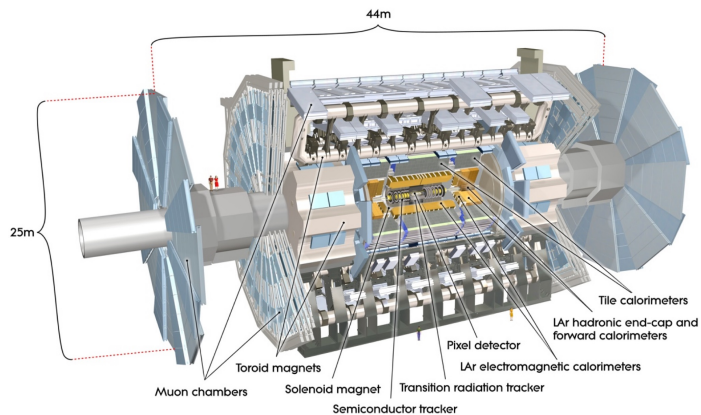
Vector-like quarks in a time of anomalies

- New precision measurements have created an exciting time for direct searches for BSM physics at ATLAS and CMS.
- Vector-like quarks (VLQ) are an important signature in many of the new models.
- **VLQs** are **colored** spin-1/2 fermions but their **L/R-handed** components transform the same way under gauge transformations
 - Evade limitations on quark extensions of the SM
 - Can be “partners” to SM quarks with the same charges (e.g. $T_{2/3}$, $B_{-1/3}$) or can have more exotic charges ($X_{5/3}$, $Y_{-4/3}$...)
 - In simplified models VLQ mix with their SM partners to regulate the Higgs boson mass
 - Assumed to mix predominately with 3rd gen. SM partners
 - Less simple models may include new resonance decaying to VLQ, or VLQ decaying to BSM particle.



Searching for VLQ

- Multitude of complex final states
 - » **Broad program of searches at ATLAS and CMS.**
- Analyses of full Run 2 ($\sim 139 \text{ fb}^{-1}$) dataset discussed today.
- **How to find VLQ?**
 - Exploit new techniques in all-hadronic (boosted) object tagging, event classification of multi-lepton final states, and more.

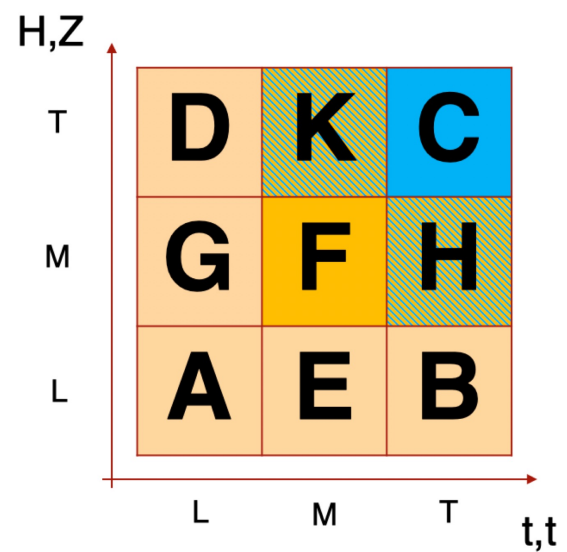
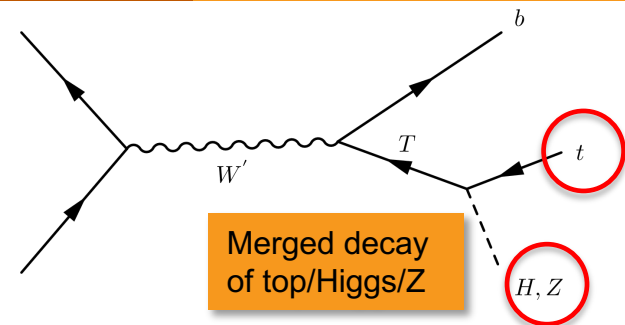


Search for heavy W' $\rightarrow tB$ or bT

CMS-PAS-
B2G-20-002



- Cascade decay of heavy W' boson to VLT/B predicted in Composite Higgs Models
- All hadronic event signature of three energetic jets:
 - 2 AK8 (large radius) jets, $p_T > 400$ GeV, $\Delta R(JJ) > 1.6$ (top/Higgs/Z)
 - 1 b -tagged AK4 jet, $p_T > 200$ GeV, $\Delta R(b, J) > 1.2$
 - Uses variety of boosted heavy resonance techniques
 - Top: $\text{imageTop}_{\text{MD}}$ deep CNN, decorrelated from jet mass, $140 < m_{\text{SD}}(\text{top}) < 220$ GeV
 - Higgs: double b -tag, $105 < m_{\text{SD}}(H) < 140$ GeV
 - Z: low τ_{21} , $65 < m_{\text{SD}}(Z) < 105$ GeV
 - b : DeepFlavour b -tagging (1% light q misID WP)
- QCD multijet background predicted using transfer function in p_T, η
 - Derived from data by inverting the Higgs or Z jet candidate selection in control and validation regions.

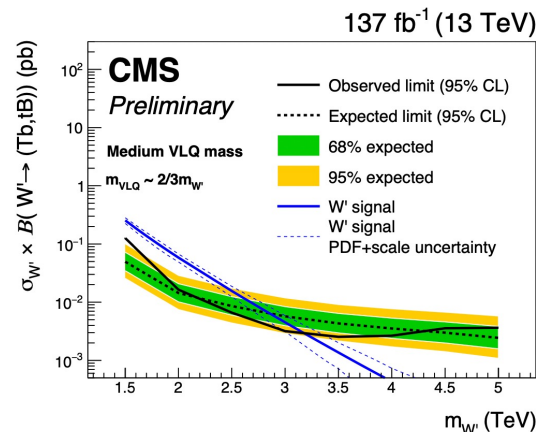


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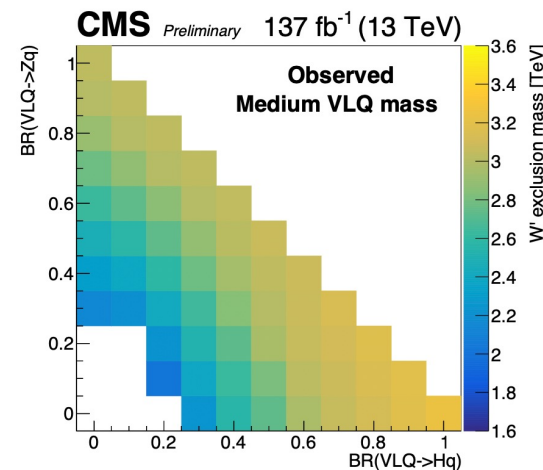
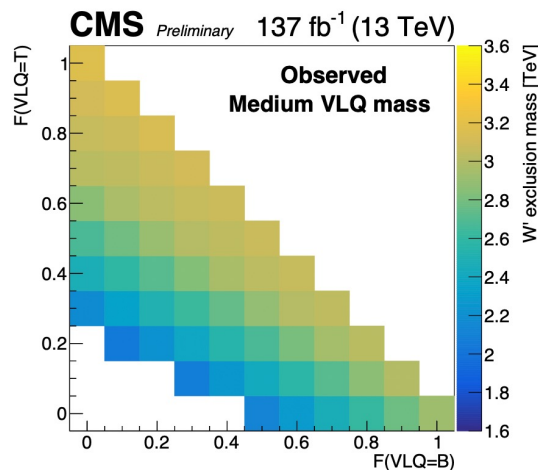
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- Benchmark point:
 - $M(\text{VLQ}) \sim 2/3 M(W')$
 - Equal tB , bT decay
 - $Br(\text{VLQ} \rightarrow Z/H) = 1/2$
- At benchmark point **$M(W') < 3.2 \text{ TeV}$** excluded, 95% CL
- Fraction qT and qB , and $Br(\text{VLQ} \rightarrow Z/H)$ varied from benchmark



For more searches for new, heavy mediators in **Search for high mass mediators in ATLAS and CMS** by Claudio Quaranta and **ATLAS + CMS Searches beyond inclusive resonances in hadronic final states** by Alberto Orso Maria Iorio.

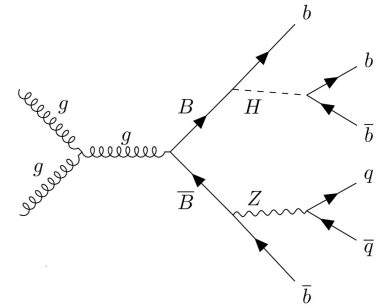
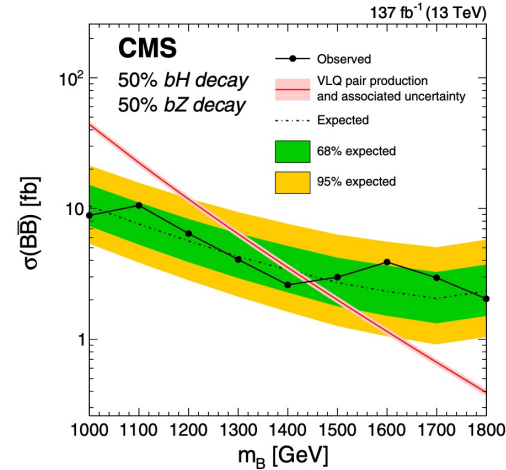




- Three **recent** results for $VL B$ production!

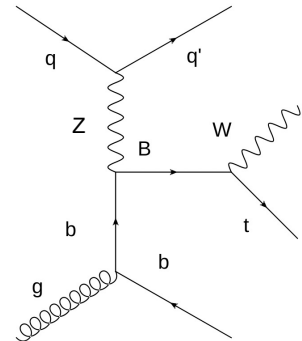
- Dedicated search for production of pair of $VL B$, decay to bZ or bH .

- All hadronic decay using AK4 (small radius) and multiple b -tags or boosted AK8 (large radius) jets with double b -tags.
- $M(B) < 1450$ GeV for the benchmark $B(B \rightarrow bH) = B(B \rightarrow bZ) = 50\%$ excluded at 95% CL.



- **[NEW]** Search for heavy resonance decay to Wt

- All hadronic event signature targeting b^* resonance with $VL B$ interpretation

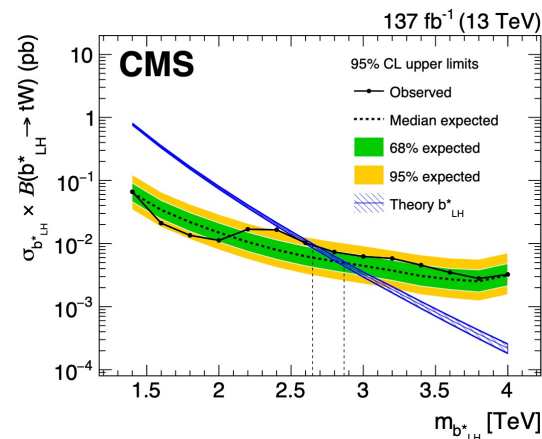
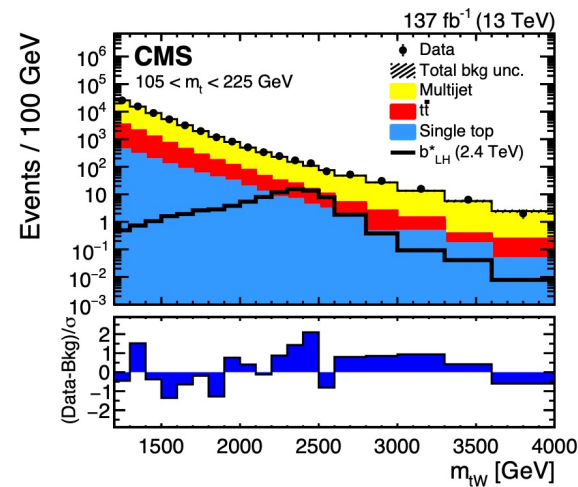


Search for Heavy Resonance $\rightarrow tW$

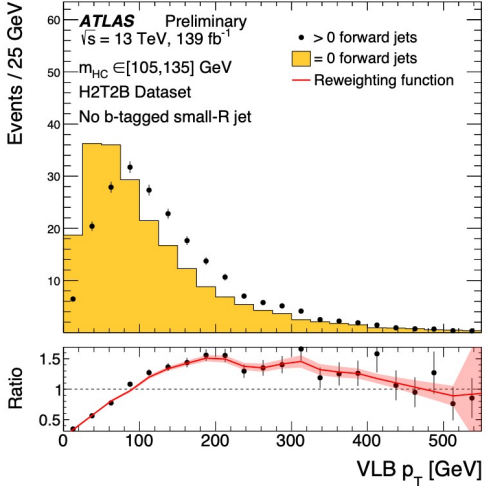
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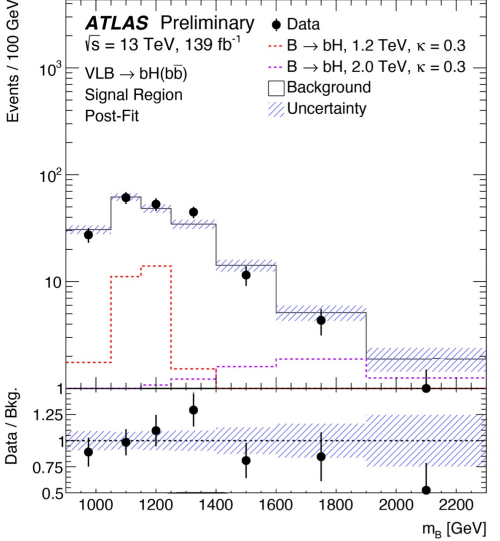
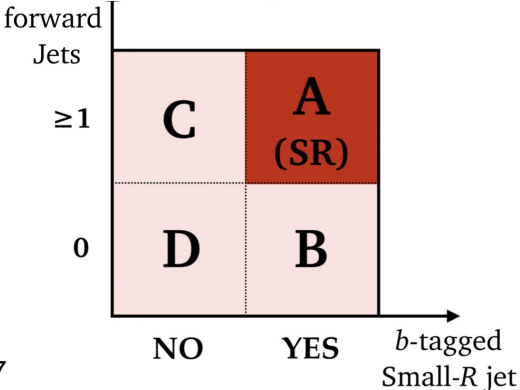
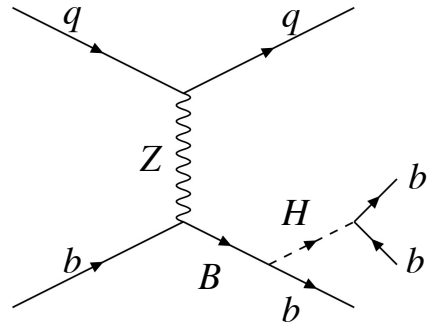
- Events selected with two AK4 jets with $p_T > 400$ GeV, $\Delta y < 1.6$ and $\Delta\phi > \pi/2$.
- Jets tagged as W boson or top quark
 - W : low τ_{21} , $65 < m_{SD}(Z) < 105$ GeV
 - Top : low τ_{32} , $105 < m_{SD}(top) < 220$ GeV, subject b-tagged with DeepCSV algorithm.
- Dedicated $t\bar{t}$ background measurement (2nd top tag)
 - $t\bar{t}$ and single top background from template fit to data, QCD multijet background from data.
- $VL B$ (b/t -associated production) uniformly more/not less sensitive by $\sim 22\%/7\%$ above 1.2 TeV.



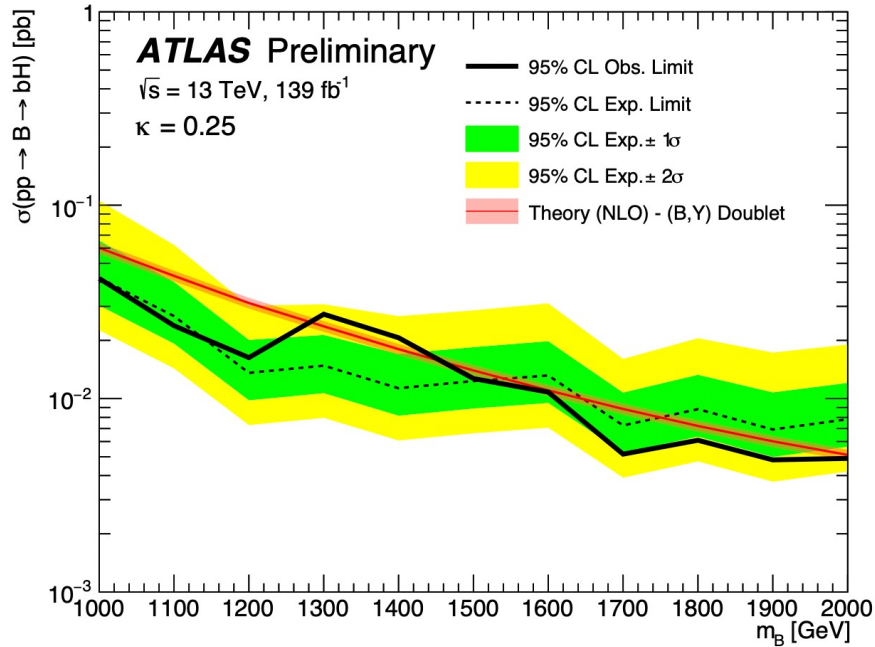
Search for Single Production $VL B \rightarrow bH(bb)$



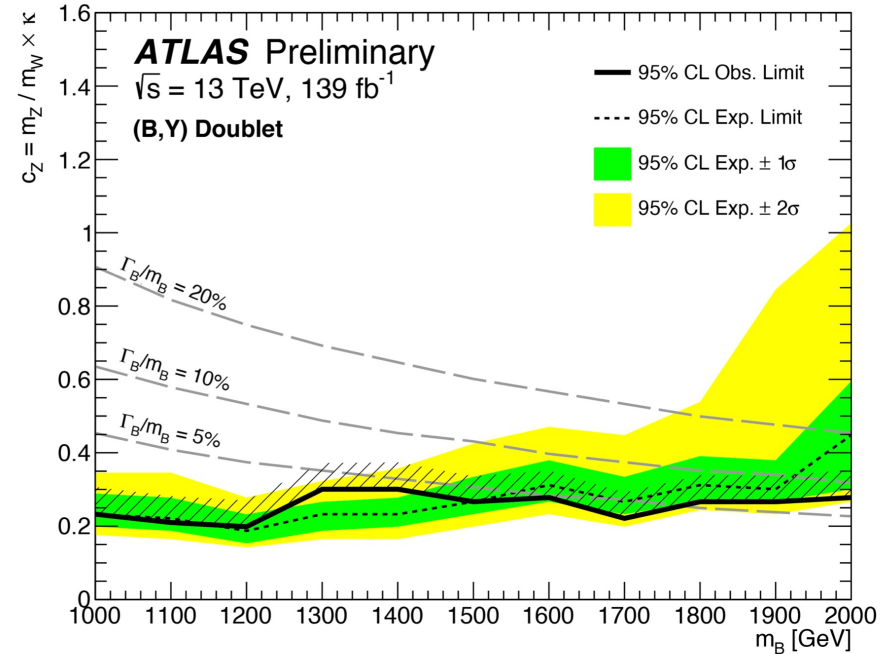
- Dedicated search for $VL B$ with all hadronic event selection.
- Reconstructed Higgs Candidate (HC) based on large radius jet p_T , mass, and associated b -tagged track jets
- Data driven estimation for QCD multijet background using ABCD method
 - $N_A = N_B \times (N_C / N_D)$
- Fit using reconstructed VLB mass: $M(B) = M(HC + jet)$ with $\Delta R(jet, HC) > 2.5$



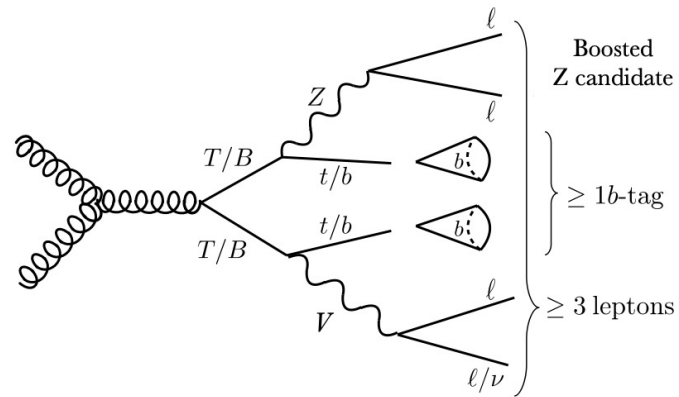
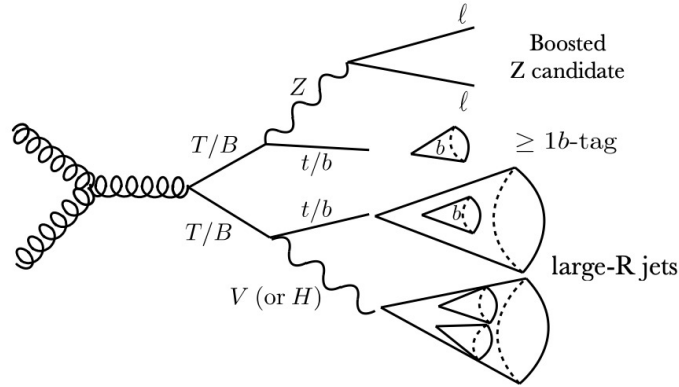
Search for VL B Single Production



- Excludes VL B up to 2 TeV in doublet representations for moderate couplings



- Interpretation: Limits on coupling as a function of VLB mass for doublet representation

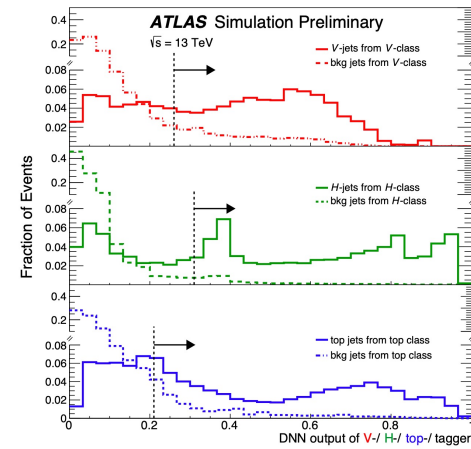
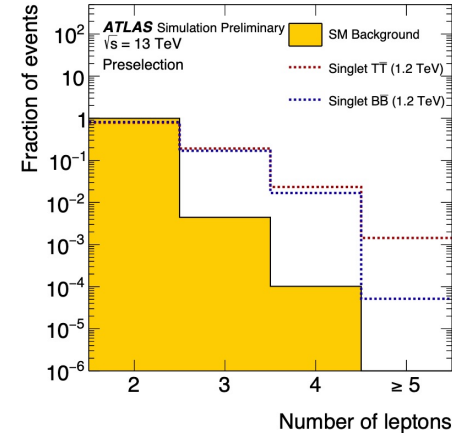


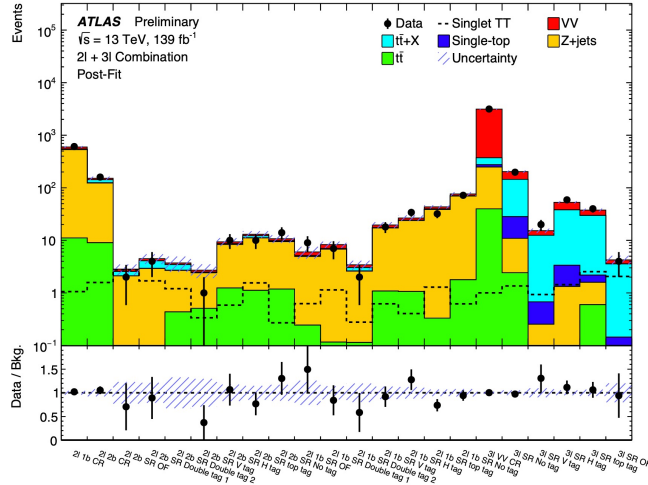
- **[NEW]** Focus on same flavor, opposite sign multi-lepton final states.

- Leptonic Z boson tagged, significantly reduces SM backgrounds.
- 2 and >2 lepton channels.

- DNN “*MCBOT*” identification of boosted objects

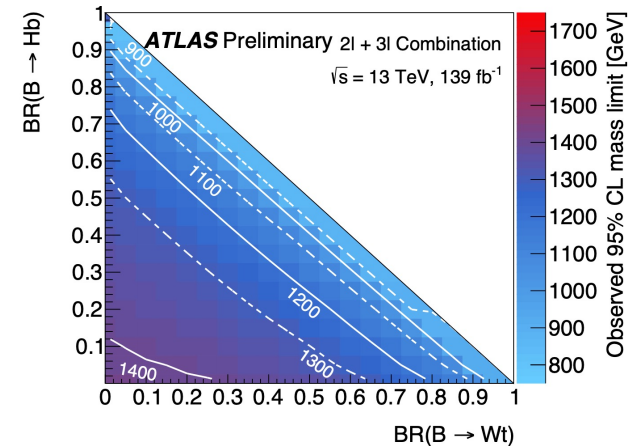
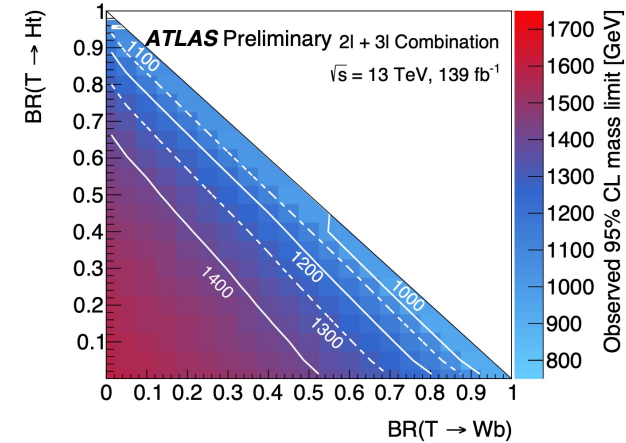
- Input of large radius jets
- Determine probability for hadronic $top/Higgs/W/Z$ simultaneously.





- **Trilepton channel:**
 - Use scalar sum of jets and leptons p_T (H_T) as the observable
- **Dilepton channel:**
 - Use $M(Zb)$ as observable.
 - Signal region requires $H_T + \text{MET} > 1380 \text{ GeV}$
- 19 total separate regions based on hadronic *top/Higgs/W/Z* tag multiplicity


Model	Observed (Expected) Mass Limits [TeV]		
	2 l	3 l	Combination
$T\bar{T}$ Singlet	1.14 (1.16)	1.22 (1.21)	1.27 (1.29)
$T\bar{T}$ Doublet	1.34 (1.32)	1.38 (1.37)	1.46 (1.44)
100% $T \rightarrow Zt$	1.43 (1.43)	1.54 (1.50)	1.60 (1.57)
$B\bar{B}$ Singlet	1.14 (1.21)	1.11 (1.10)	1.20 (1.25)
$B\bar{B}$ Doublet	1.31 (1.37)	1.07 (1.04)	1.32 (1.38)
100% $B \rightarrow Zb$	1.40 (1.47)	1.16 (1.18)	1.42 (1.49)



Summary

- First crop of VLQ search analyses using full Run 2 dataset are arriving.
 - Not mentioned: Vector-like *Lepto*Quarks ([see CMS-EXO-19-015](#))
- Interesting and complex final states are still waiting to be explored.
- The $O(\text{TeV})$ energy range still in the early stages of exploration
 - An exciting time is before us!

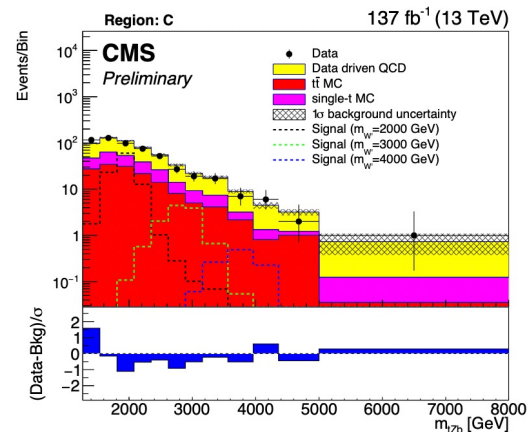
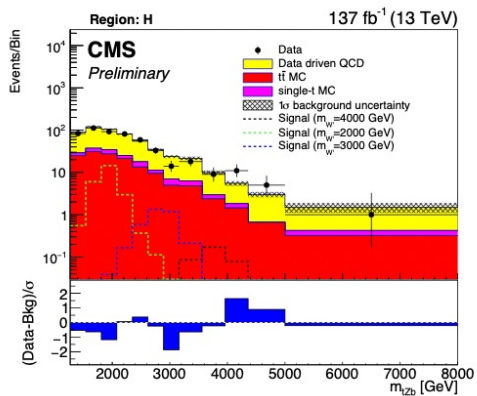
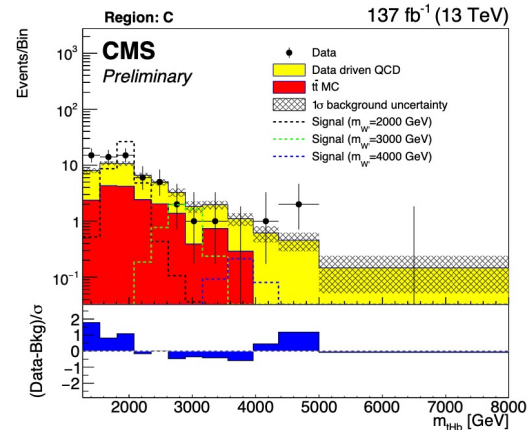
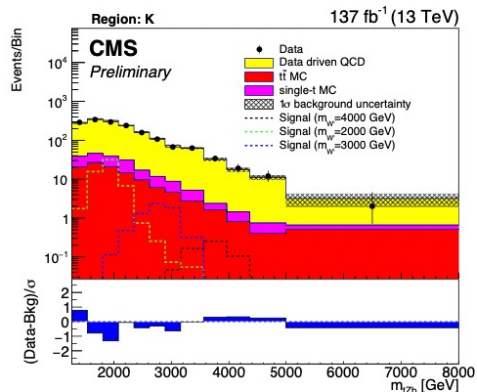
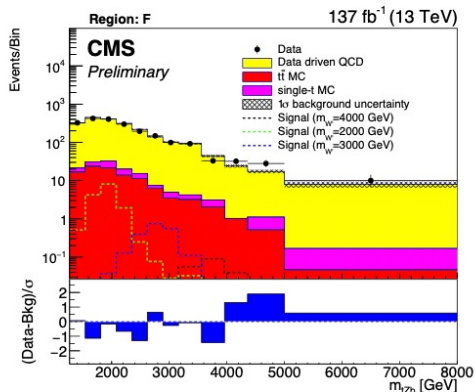
For more searches for LQ see
**ATLAS + CMS searches for
leptoquarks** by Edson Lopez



Just starting on the
path to new
discoveries...

Bonus Slide

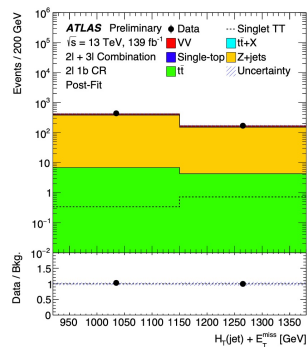
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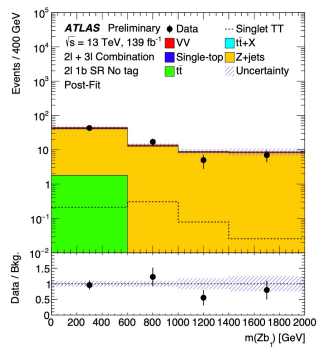
Search for VL T and B Pair Production

M (Z candidate + b-tag jet) in 1 b-tag regions

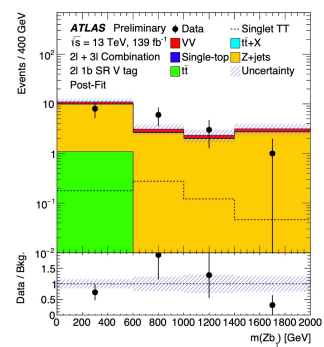
M (Z candidate + sub-leading b-tag jet) in >1 b-tag regions



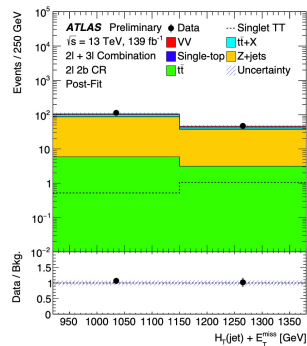
(a)



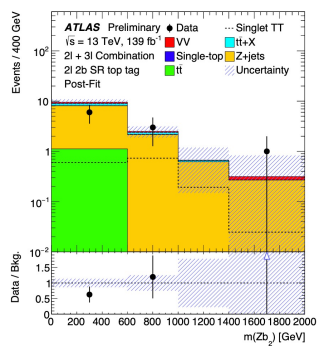
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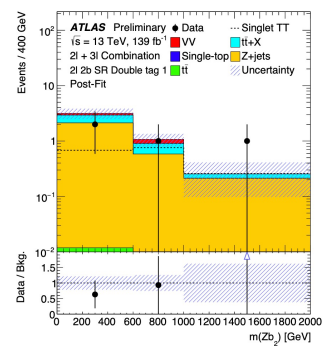
(c)



(d)



(e)



(f)

Search for VL T and B Pair Production

