ANGELA BURGER
LABORATOIRE DE PHYSIQUE DE CLERMONT

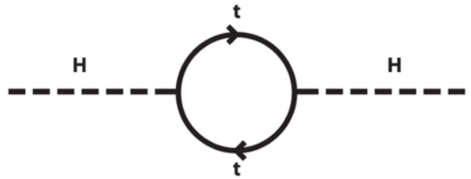
TOP LHC FRANCE 2022

10/05/2022

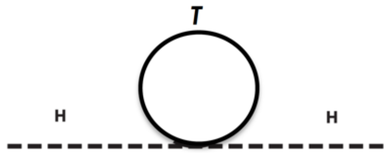
SEARCHES FOR PAIR PRODUCTION OF VECTOR-LIKE QUARKS

INTRODUCTION

- The **large top Yukawa coupling** motivates searches for new physics coupling to top quarks



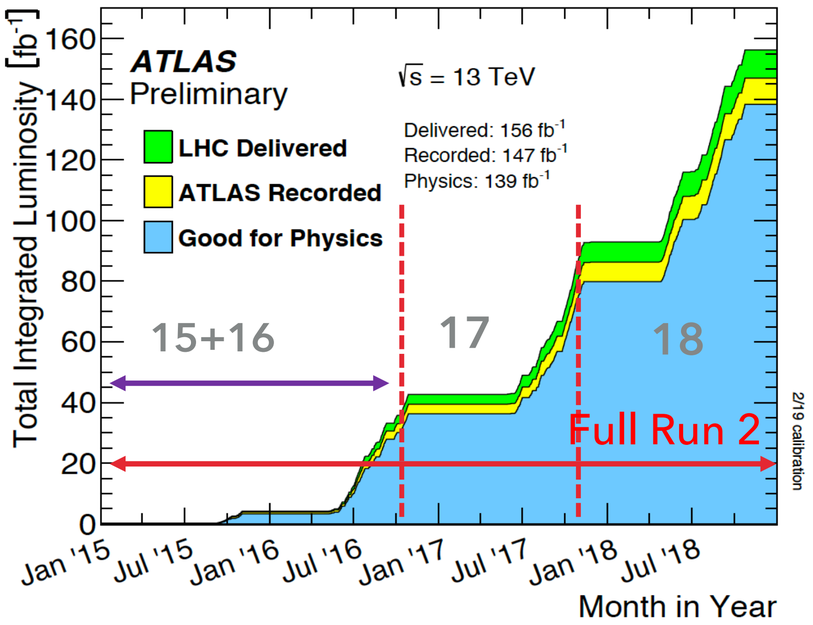
- Radiative corrections from the top quark lead to **quadratic divergences to to the Higgs boson mass**
  - Search for a mechanism to cancel those corrections instead of **fine-tuning**

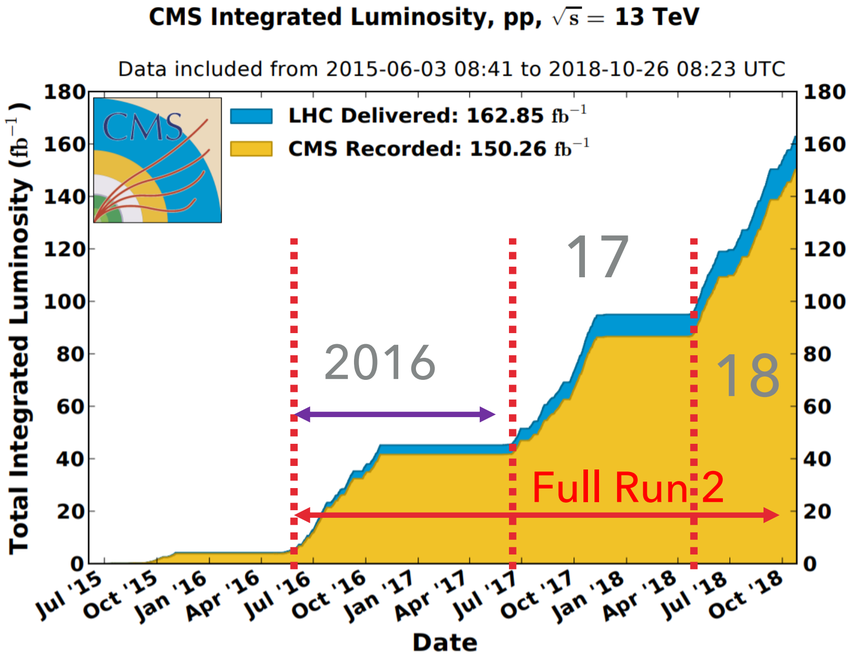


- Many new physics models like composite Higgs models or Little Higgs models predict **new non-chiral quarks**: "**vector-like quarks**"
- This talk covers **recent searches for pairs of vector-like quarks** using data from **ATLAS and CMS** from the Run 2 of the LHC with $\sqrt{s}$ =13TeV
  - Full Run 2 data or a significant part (>35fb^{-1})

ATLAS EXPERIMENT

THE ATLAS AND CMS DATASET FROM LHC RUN 2



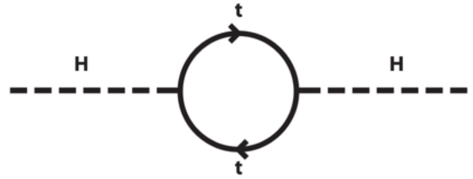


- Analyses in **ATLAS and CMS** use either **(2015+)2016 data** or the "Fun Run 2" covering the years **(2015)2016–2018**
- Only use data "good for physics" with all subsystems fully operational

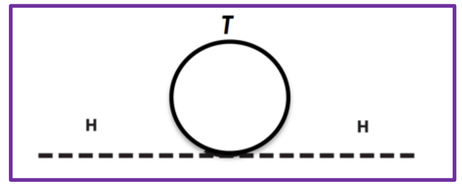
Years	ATLAS	CMS
2015+2016 (VLQ searches concluded)	$36.1 fb^{-1}$	
2016 (VLQ searches concluded)		$35.8 fb^{-1}$
2015–2018 (VLQ searches ongoing)	$139 fb^{-1}$	
2016–2018 (VLQ searches ongoing)		$137 fb^{-1}$

ATLAS EXPERIMENT

VECTOR LIKE QUARKS (VLQS) – THEORETICAL MOTIVATION



- Heavy VLQs predicted in many models, especially those aimed at solving the **Hierarchy Problem**
  - SUSY: scalar top partners ⇔ **VLQs: fermionic top partners**



- Colored, spin ½ fermions
- Both chiralities transform the same under SM gauge groups → **"vector-like"**

SM *V-A* current	VLQ current
$(\bar{q}\gamma^{\mu}(1-\gamma^{5})q')$	$(\bar{Q}\gamma^{\mu}Q')$

- Renormalizability requires the existence of **up to four vector-like quark types**

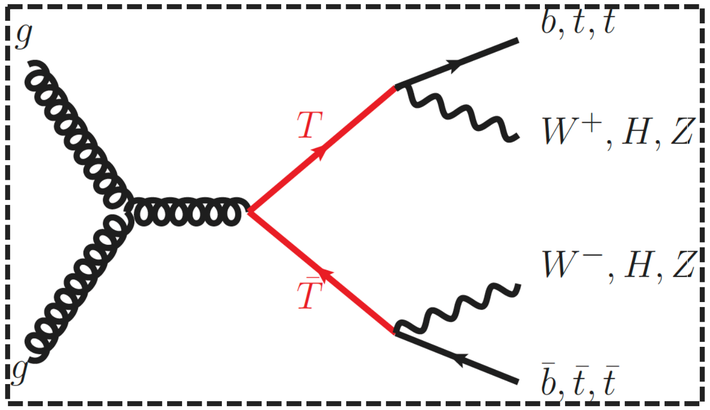
Quark	Y	T	B	X
Charge [e]	5/3	2/3	-1/3	-4/3

- **Coupling to third generation quarks** expected to be dominant

ATLAS EXPERIMENT

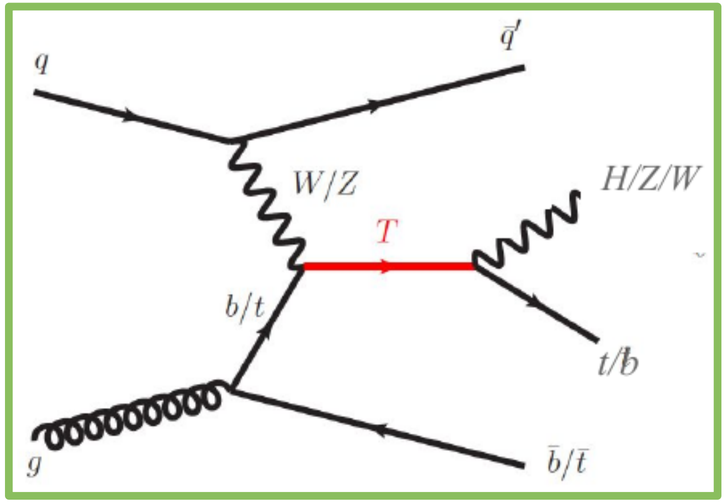
VLQ PAIR VS. SINGLE PRODUCTION

Pair-production via the strong force



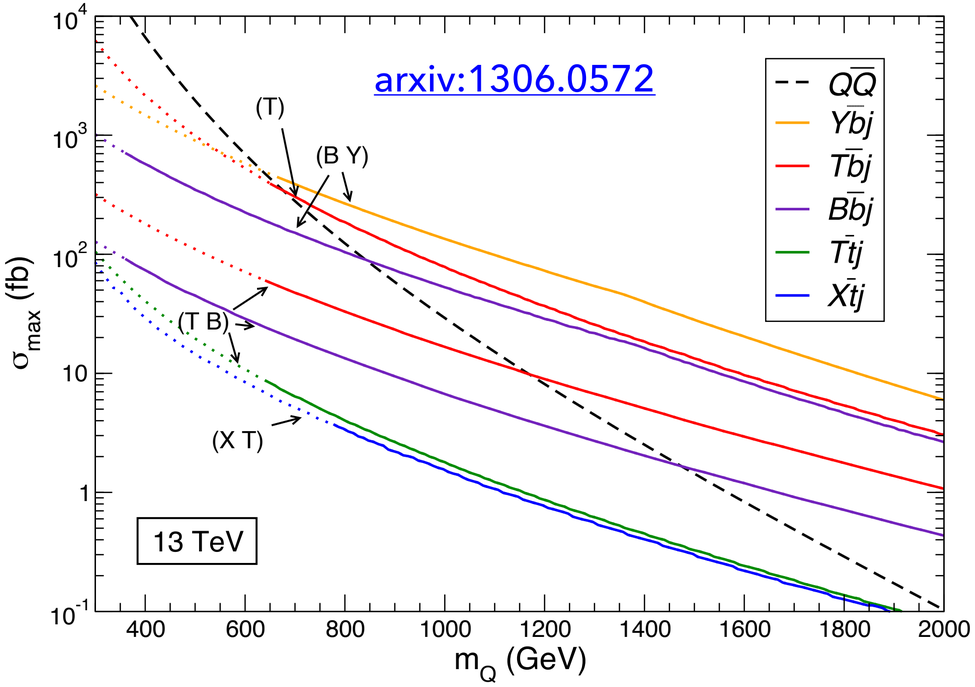
Pair-production cross section **only dependent on VLQ mass**

Single production via the weak interaction



Single production cross section **also dependent on coupling** to Standard Model particles

Single production could dominate for VLQ masses > 1 TeV

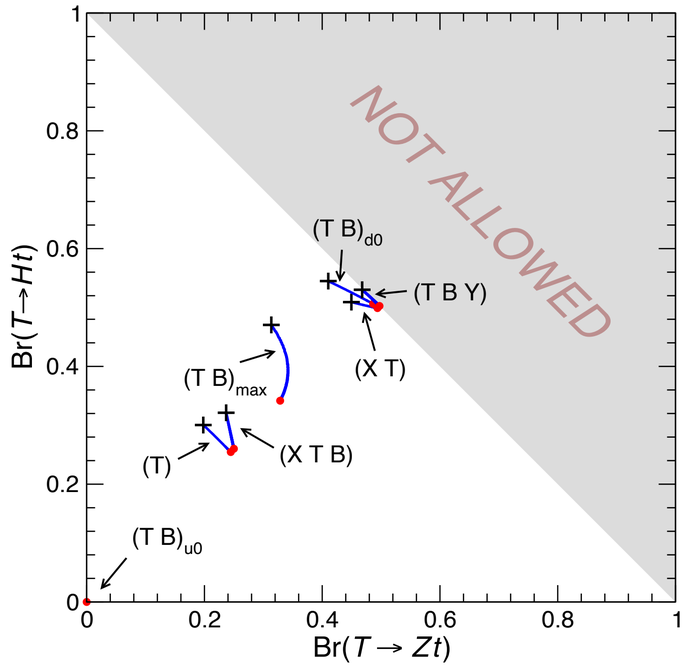


ATLAS EXPERIMENT

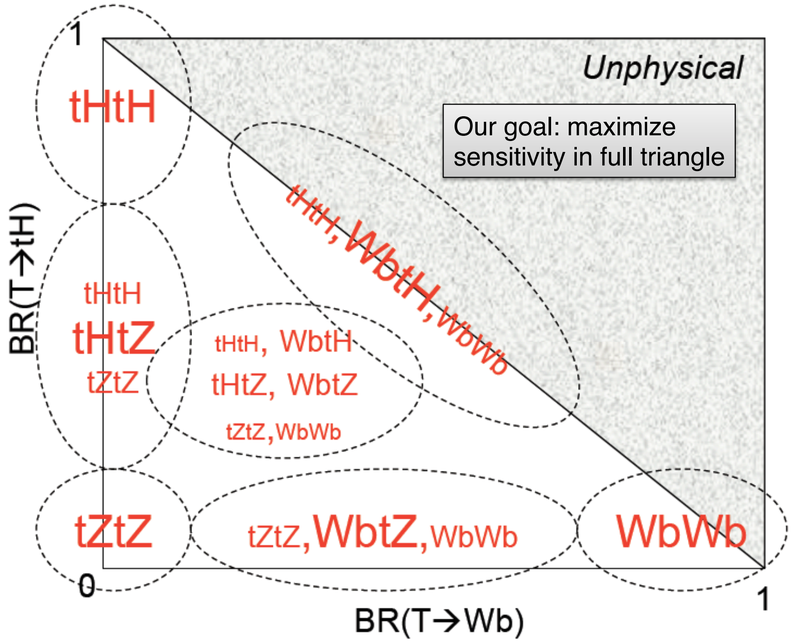
VLQ DECAY CHANNELS

- Expected to decay to **SM bosons and top or bottom quarks**
  - **Singlet, doublet and triplet representations** of **T,B,X,Y quarks** determine the relative couplings to V (=W,Z), H

Q[e]	VLQs singlets	doublets			triplets		
$5/3$		$\begin{pmatrix} X \\ T \end{pmatrix}$			$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$		
$2/3$	(T)		$\begin{pmatrix} T \\ B \end{pmatrix}$			$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$	
$-1/3$	(B)			$\begin{pmatrix} B \\ Y \end{pmatrix}$			
$-4/3$							



- T → Wb, Zt, Ht
- B → Wt, Zb, Hb
- Y → Wb (100%)
- X → Wt (100%)



Test all possibilities!

➔ Extract limits as well as a function of the branching ratio

Exotically charged X and Y quarks can only be discovered in the Wt or Wb channel!

ATLAS EXPERIMENT

VECTOR-LIKE QUARKS: DECAY CHANNELS (T QUARK)

[ATLAS] TT/BB allhadronic (36fb^{-1})

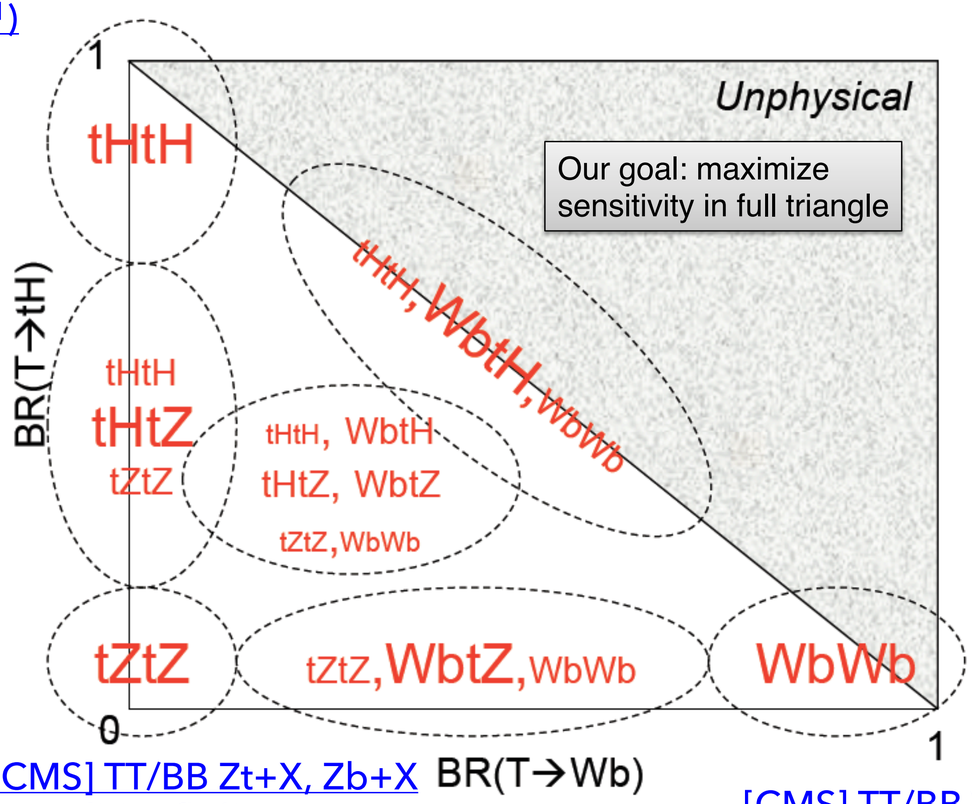
[CMS] TT/BB → Hb/Zb+X allhadronic (137fb^{-1})

[ATLAS] TT → Ht/Zt (lepton+ETmiss+jets or lepton+ETmiss) (36fb^{-1})

{CMS] TT/BB in final states with leptons (35fb^{-1})

[ATLAS] TT (2l SS+b-jets) (36fb^{-1})

[ATLAS] TT → Z(vv)t+X (lepton, ETmiss+jets) (36fb^{-1})



[CMS] TT/BB Zt+X, Zb+X (OS 2l) (35fb^{-1})

[ATLAS] TT/BB → Zt/Zb+X (2 OSSF leptons) (139fb^{-1})

[ATLAS] TT/BB → Zt/Zb+X Z→ll (2 or 3 leptons) (36fb^{-1})

[ATLAS] BB → Wt +X (1lepton, ETmiss, jets) (36fb^{-1})

[CMS] XX → WtWt (SSML, 1L) (36fb^{-1})

[CMS] TT/YY → WbWb (lepton,ETmiss,jets) (35fb^{-1})

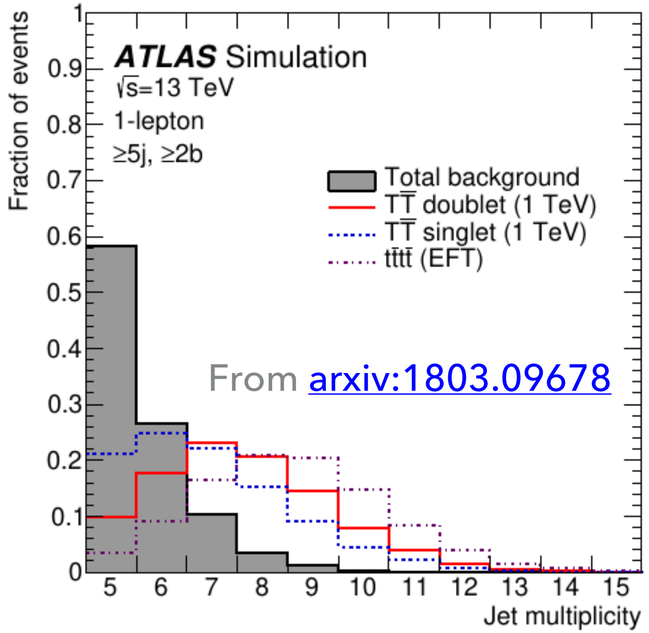
[ATLAS] TT/YY → WbWb (1 lepton+jets) (36fb^{-1})

[CMS] TT/BB Wb+X allhadronic (35fb^{-1})

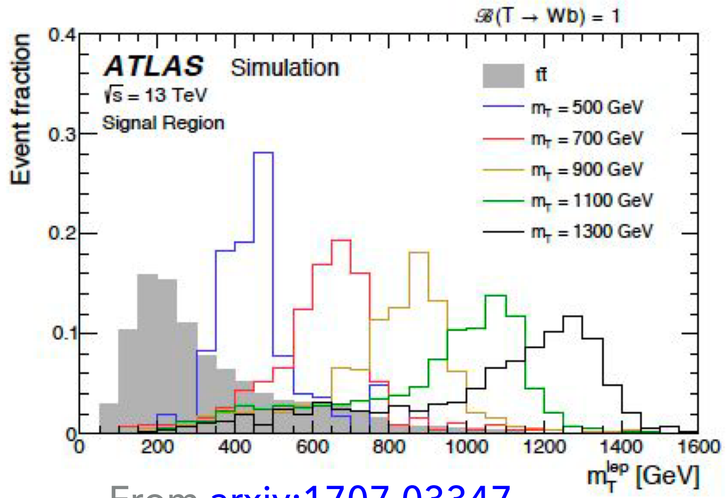
ATLAS EXPERIMENT

PROPERTIES OF PAIR-PRODUCED VLQS EXPLOITED IN SEARCHES

- Resonance peak at **high reconstructed invariant masses**
  - If final state can be reconstructed
- Massive particle decay (~TeV) → **large scalar sum of object p_T in the event** (H_T, m_{eff}, S_T)
- **Large object multiplicity**
- **B-jets**
- **Boosted W/Z/H bosons or top quarks**
  - Hadronic decay reconstructed in single large-Radius jet (R=0.1)
  - Identification:
    - DNN/BDT taggers (ATLAS/CMS/custom)
    - Cut-based (jet mass, p_T, number of constituents)

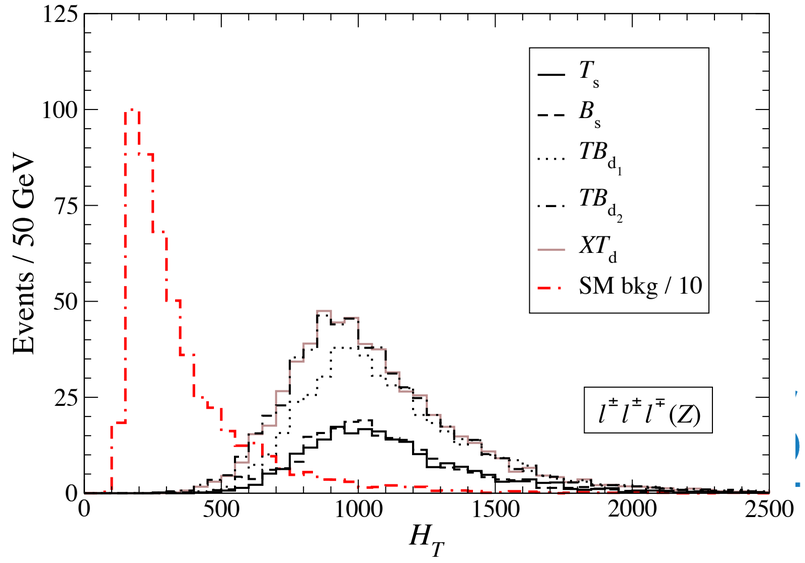


From arxiv:1803.09678



From arxiv:1707.03347

From arxiv:0907.3155



TYPICAL SEARCH STRATEGIES

1) Search for excess over background

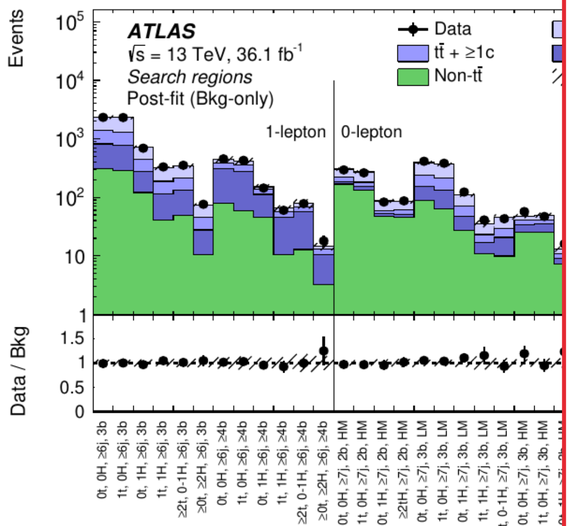
- Possible to reconstruct final state
- Bump in invariant mass spectrum

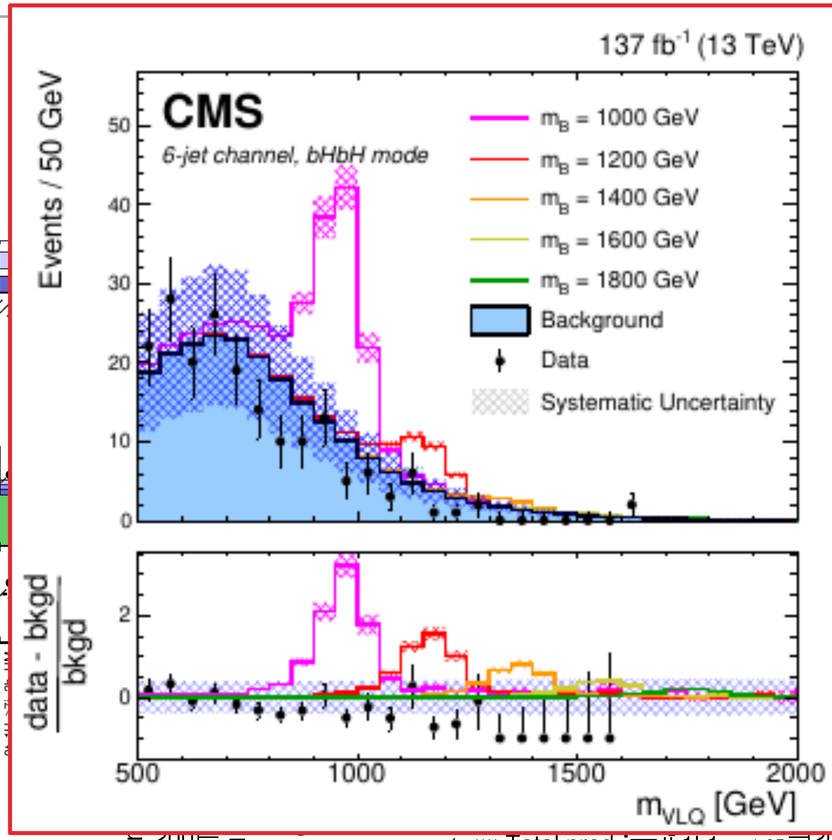
2) "Divide and conquer"

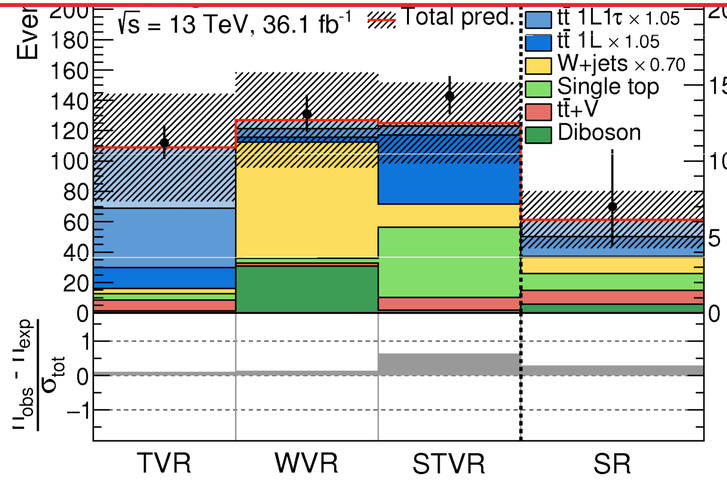
- Maximize sensitivity to several possible signal topologies
- Construct several signal and control region, combined fit to all regions

3) Cut-and-count analysis or construction of multivariate discriminant

- Count events: expected background and data events in signal region
- Fit to BDT/DNN-based discriminant







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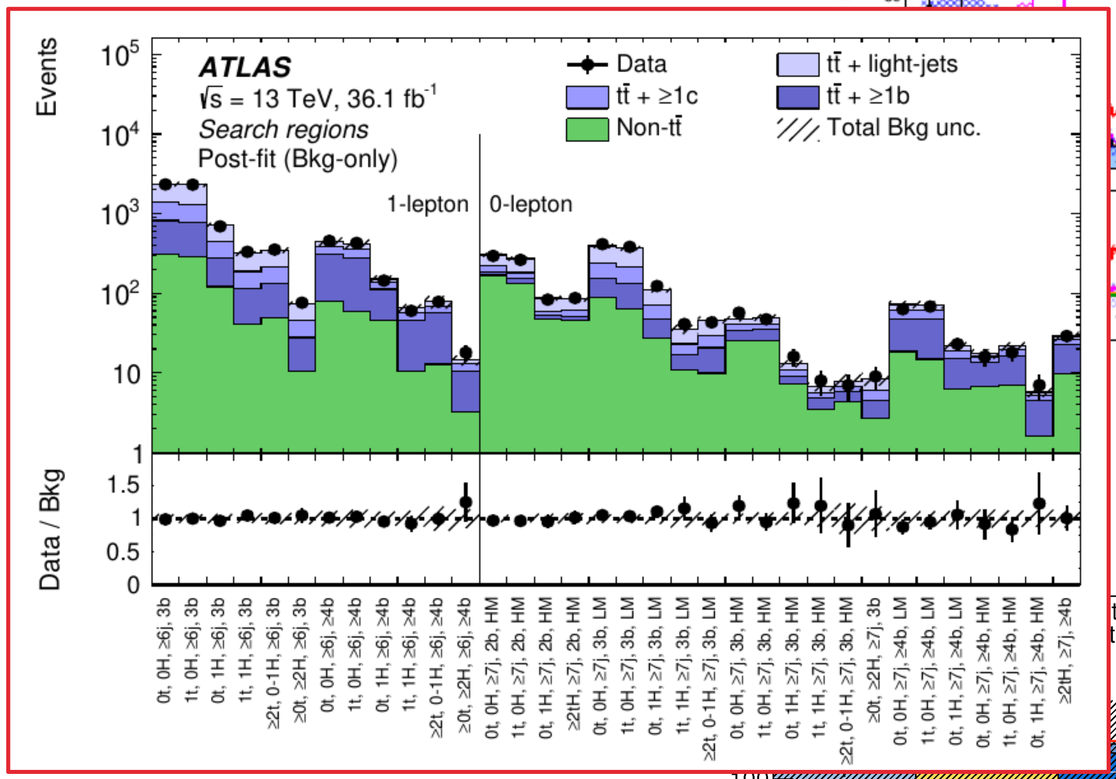

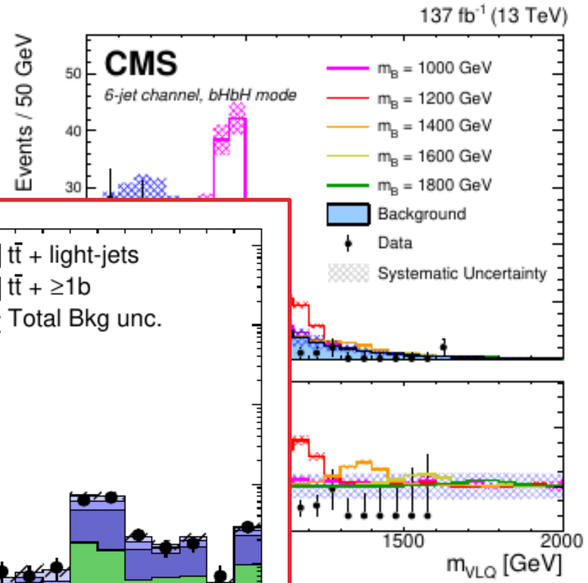

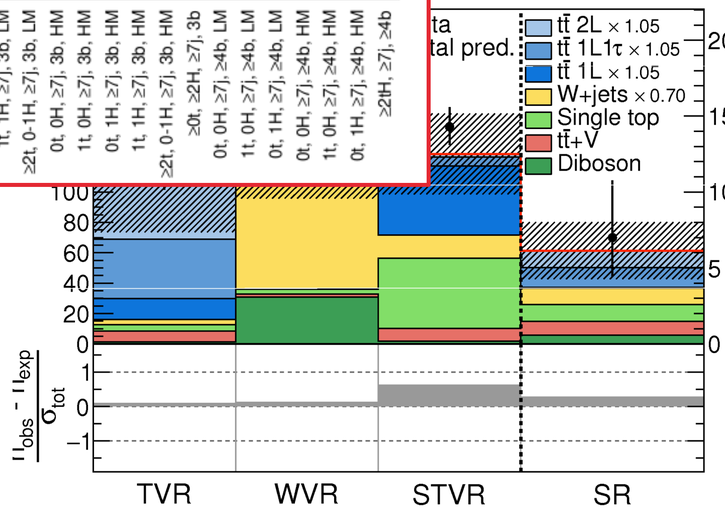

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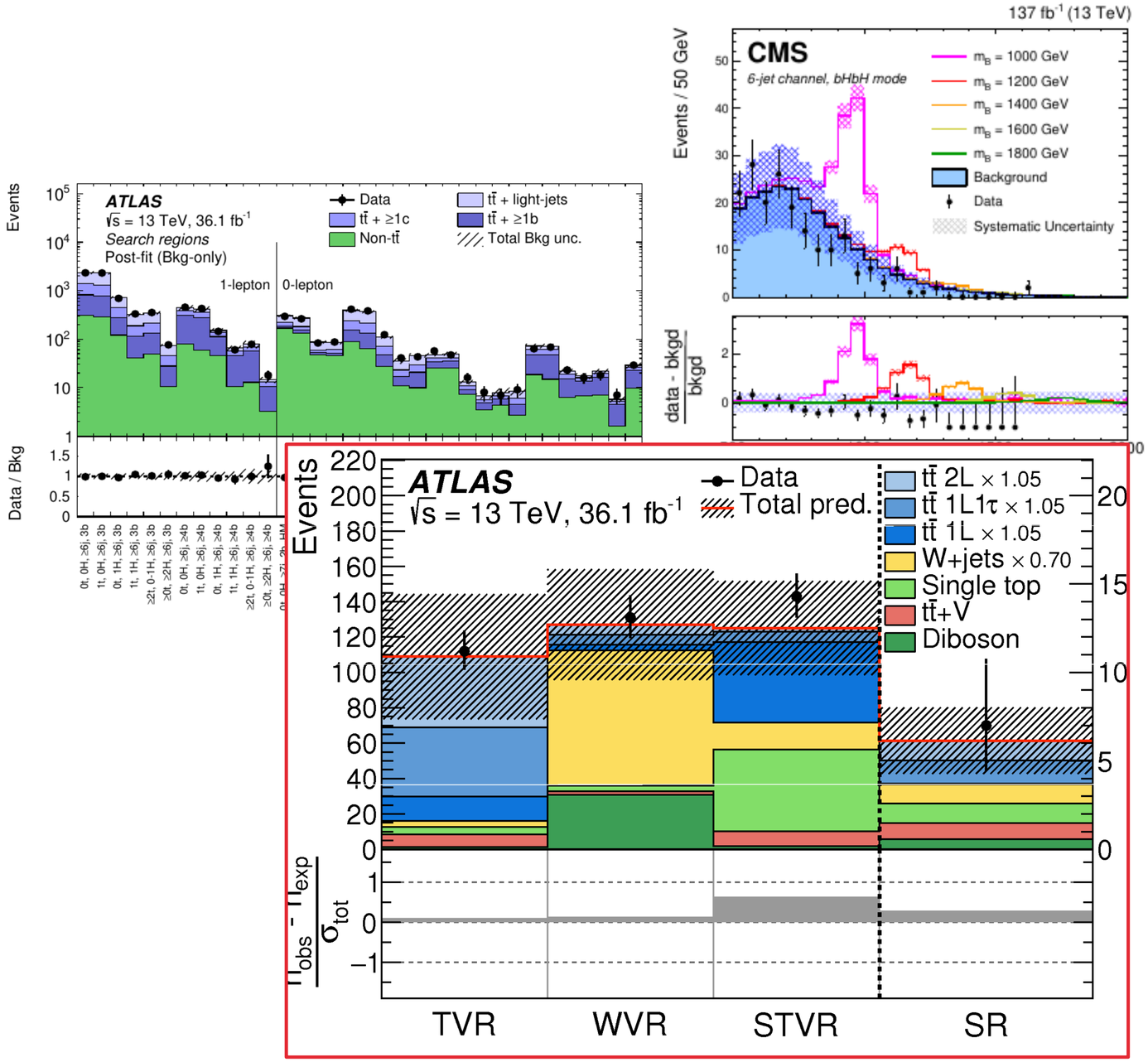
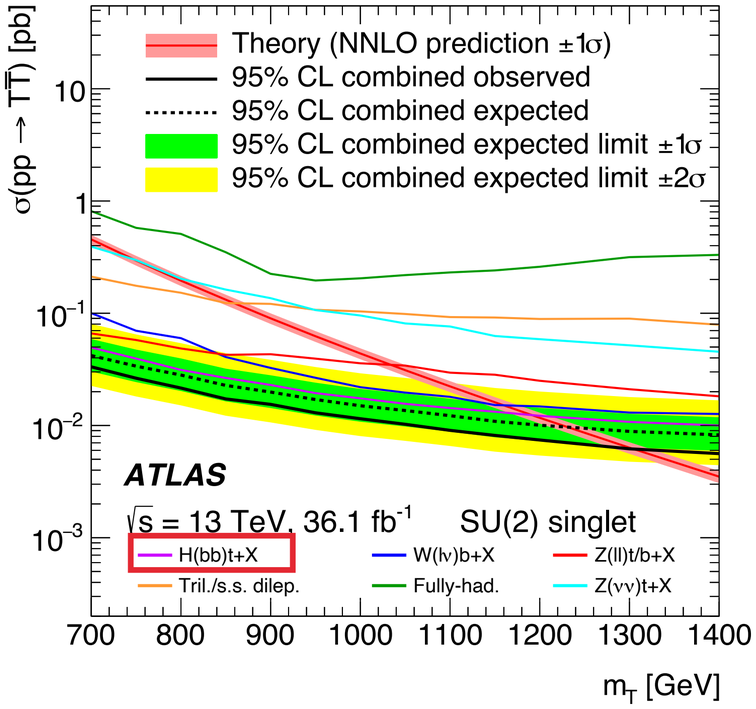


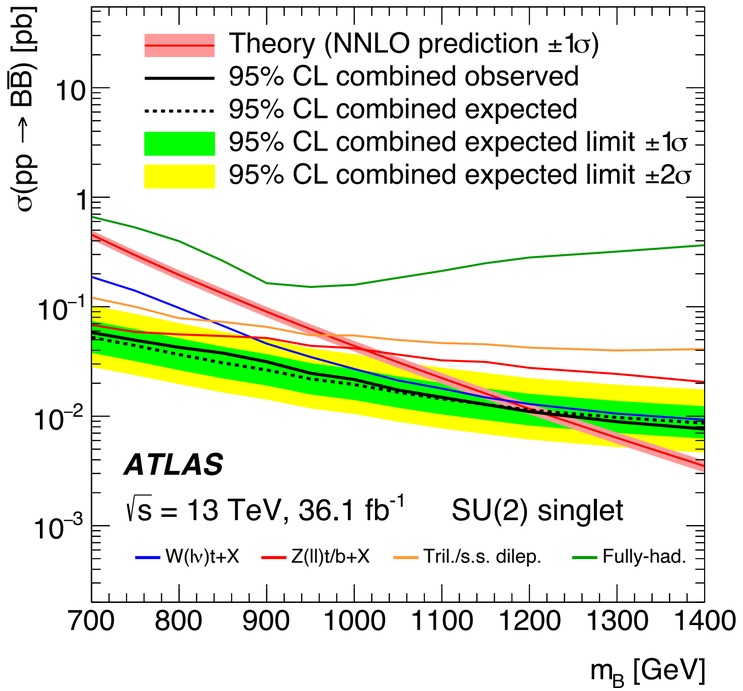
SEARCHES USING 2016 OR 2015+2016 DATA

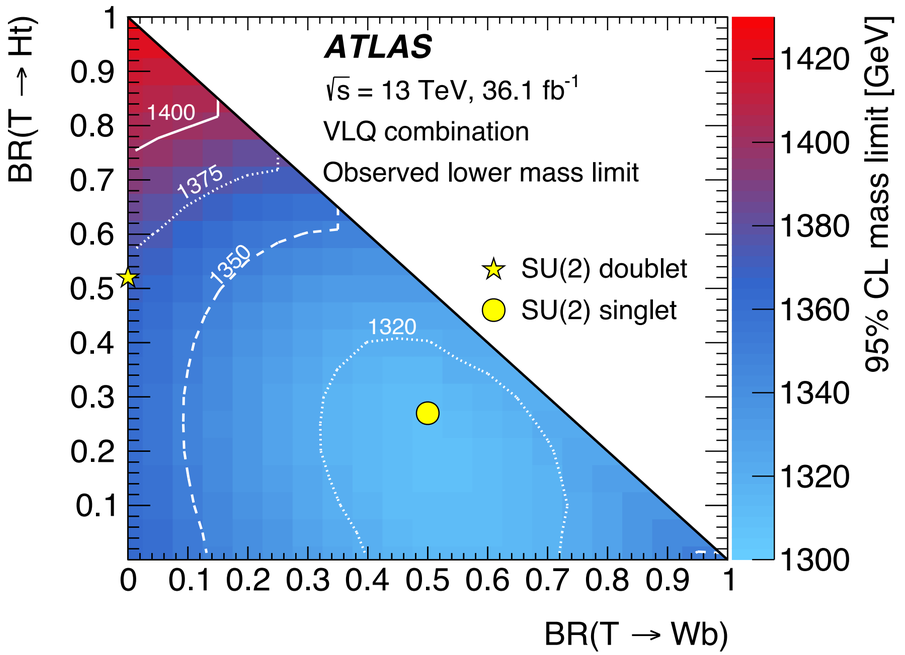
ATLAS EXPERIMENT

[ATLAS] VLQ PAIR COMBINATION – 2015+2016 DATA (36FB^{-1})

arxiv:1808.02343







- After 2015+2016 data analysis was concluded, **combination of ATLAS VLQ pair production searches resulted in the most stringent limits on VLQ masses**
  - Significantly stronger exclusion limits than any of the single analyses
  - T(B) masses **below 1.31 (1.03) TeV for any combination of decays into SM particles excluded**
  - Limit as function of branching ratio showed high **complementarity of VLQ searches**

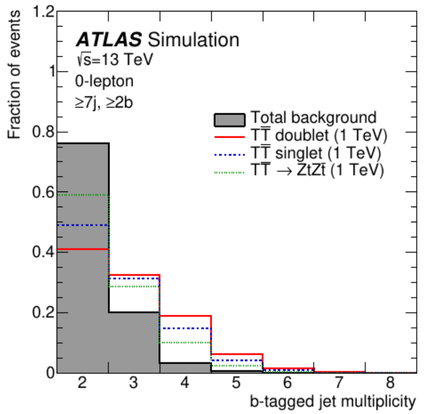
ATLAS EXPERIMENT

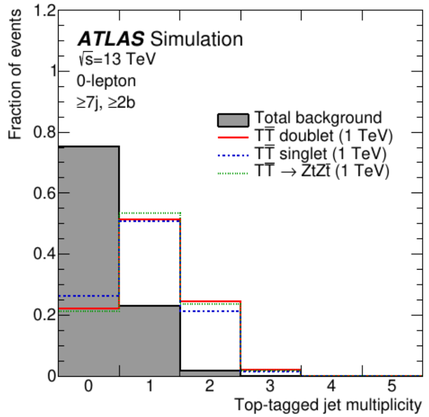
[ATLAS] SEARCH FOR PAIRS OF T QUARKS DECAYING TO FINAL STATES WITH MULTIPLE B-QUARKS

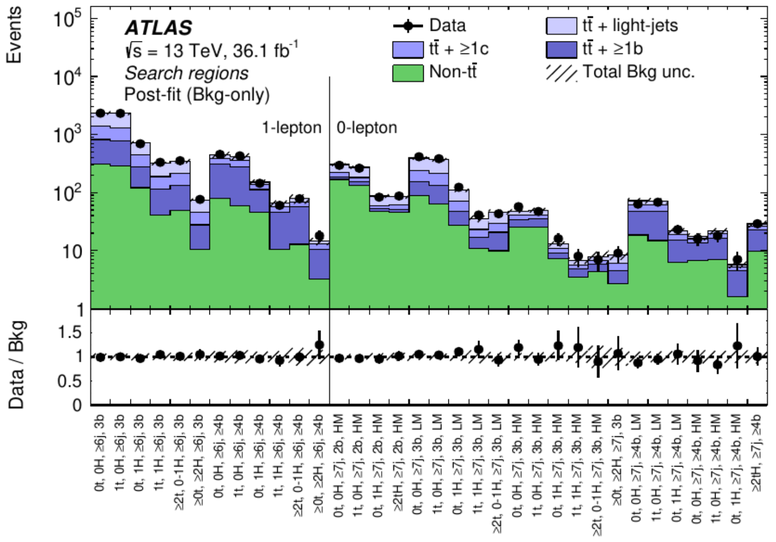
arxiv:1803.09678

- Optimized for decay **T → Ht+X or T → Zt+X** where **H → bb or Z → νν**
- **Two channels:**
  - **0 lepton:** large E_T^{miss} and N(jets)>=7
  - **1 lepton**: e or μ and N(jet) >=5
- **"Divide and conquer":** classify according to
  - Jet multiplicity
  - B-tagged jet multiplicity
  - Number of top and/or Higgs-tagged large-R jet (cut-based identification)
- **Regions with higher multiplicity of top and Higgs tagged jets and b-jet multiplicity drive sensitivity**
- **Regions with lower sensitivity help to constrain the background**
  - Multi-jet estimate data-driven, others estimated with MC

Preselection requirements		
Requirement	1-lepton channel	0-lepton channel
Trigger	Single-lepton trigger	E_T^{miss} trigger
Leptons	=1 isolated e or μ	=0 isolated e or μ
Jets	≥5 jets	≥6 jets
b-tagging	≥2 b-tagged jets	≥2 b-tagged jets
E_T^{miss}	$E_T^{miss} > 20$ GeV	$E_T^{miss} > 200$ GeV
Other E_T^{miss}-related	$E_T^{miss} + m_T^W > 60$ GeV	$\Delta\phi_{min}^{4j} > 0.4$





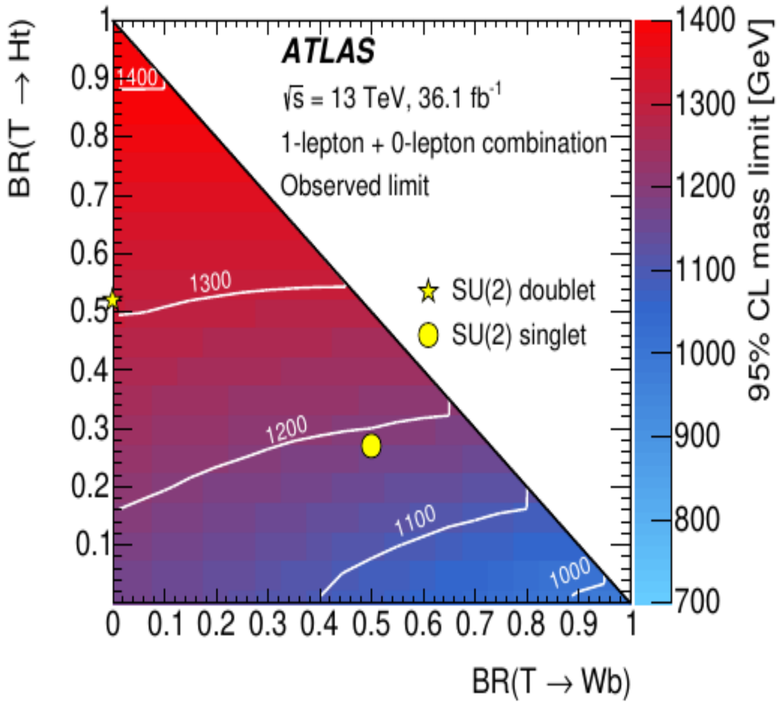


[ATLAS] SEARCH FOR PAIRS OF T QUARKS DECAYING TO FINAL STATES WITH MULTIPLE B-QUARKS

arxiv:1803.09678

- **Combined maximum likelihood fit** to extract signal and to constrain background in all search regions
  - ttbar +HF background floated in the fit
  - Region splitting **allows to constrain other backgrounds within their assigned uncertainty** as nuisance parameters
- **Scalar sum of object p_T** in event ("m_{eff}") is **discriminant** in fit
- **1 lepton** channel especially sensitive to **Br(T → Ht)=1** and **0 lepton** channel to **Br(T → Zt)=1**
- Limits as function of VLQ mass and branching ratio: **exclusion limits between 0.99-1.43 TeV**

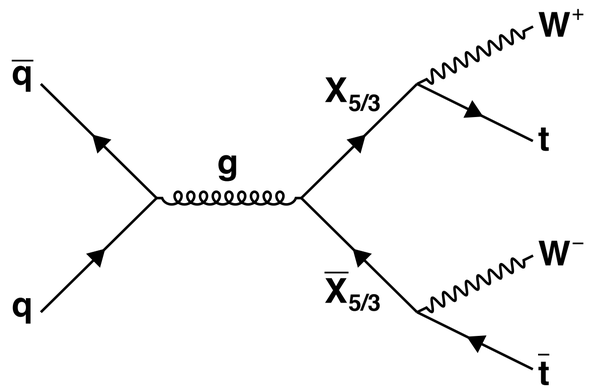
95% CL lower limits on T quark mass [TeV]				
Search	$\mathcal{B}(T \to Ht) = 1$	$\mathcal{B}(T \to Zt) = 1$	Doublet	Singlet
1-lepton channel	1.47 (1.30)	1.12 (0.91)	1.36 (1.16)	1.23 (1.02)
0-lepton channel	1.11 (1.20)	1.12 (1.17)	1.12 (1.19)	0.99 (1.05)
Combination	**1.43 (1.34)**	**1.17 (1.18)**	**1.31 (1.26)**	**1.19 (1.11)**
Previous Run-1 ATLAS $T\bar{T} \to Ht$+X search [25]				
1-lepton channel	0.95 (0.88)	0.75 (0.69)	0.86 (0.82)	0.76 (0.72)

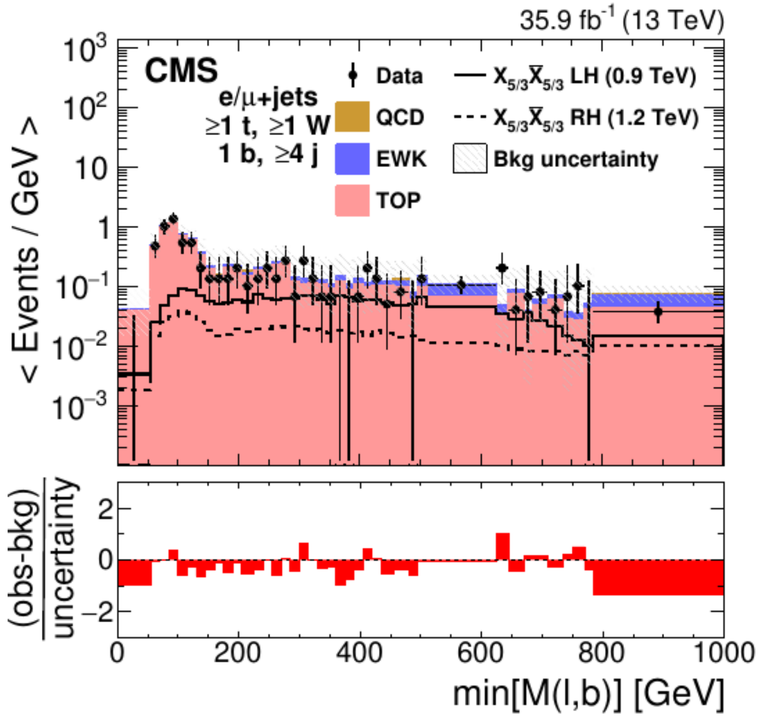


[CMS] SEARCH FOR PAIR OF X QUARKS IN SAME-SIGN DI-LEPTON AND SINGLE LEPTON FINAL STATES

arxiv:1810.03188

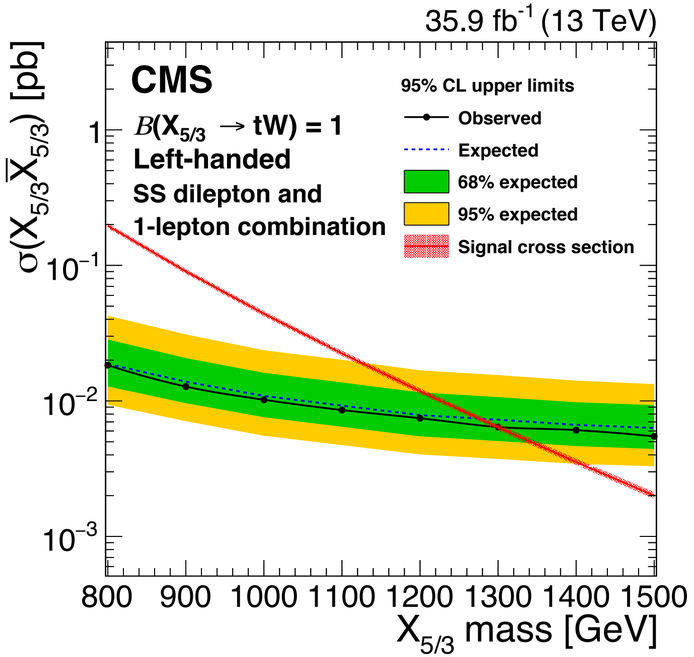
- Target **XX → WtWt** (only decay channel for **X quark**!)
- **2 analysis channels:**
  - **"SSML":** >=2 lepton, >= 1 same-sign lepton pair (e,μ), large sum of object pT and object multiplicity
    - Prompt background estimated using MC, data-driven estimate for charge mis-ID and fake lepton background
    - **Cut-and-count strategy**
  - **"1L":** ==1 electron or muon, large E_T^{miss} and N(jet)
    - Background estimate using MC, constrained using control regions included in fit
    - **Split signal region in 16 categories** (top, W and b-tag multiplicities, lepton flavour)
    - **Simultaneous fit to SR and CR** to discriminating variable

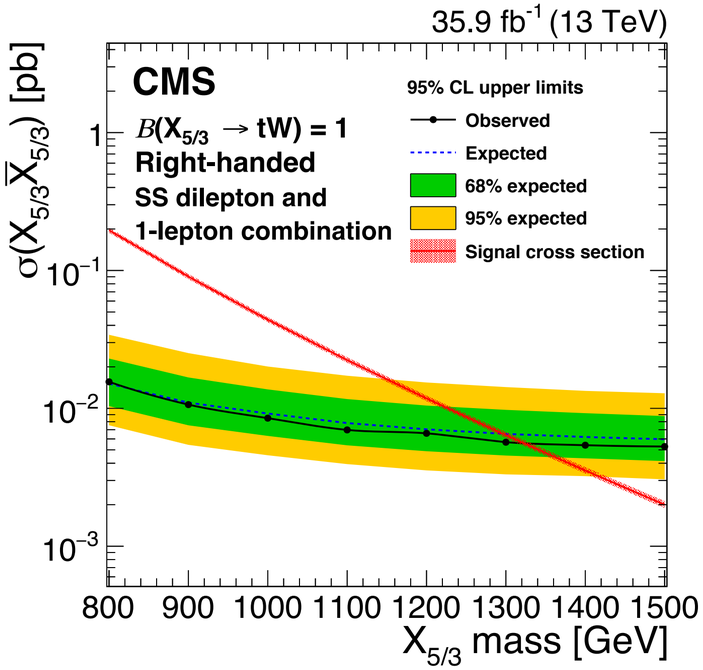




[CMS] SEARCH FOR PAIR OF X QUARKS IN SS DI-LEPTON AND SINGLE LEPTON FINAL STATES

arxiv:1810.03188





- Limits extracted for right (RH) and left-handed (LH) couplings to W (results very similar)
  - « SSML »: 1.16 TeV (RH) and 1.10 TeV (LH)
  - « 1L »: 1.32 TeV (RH) and 1.30 (LH) TeV
- **Combination: 1.33 TeV (RH) and 1.30 (LH) (sensitivity driven by 1L final state)**

ATLAS EXPERIMENT

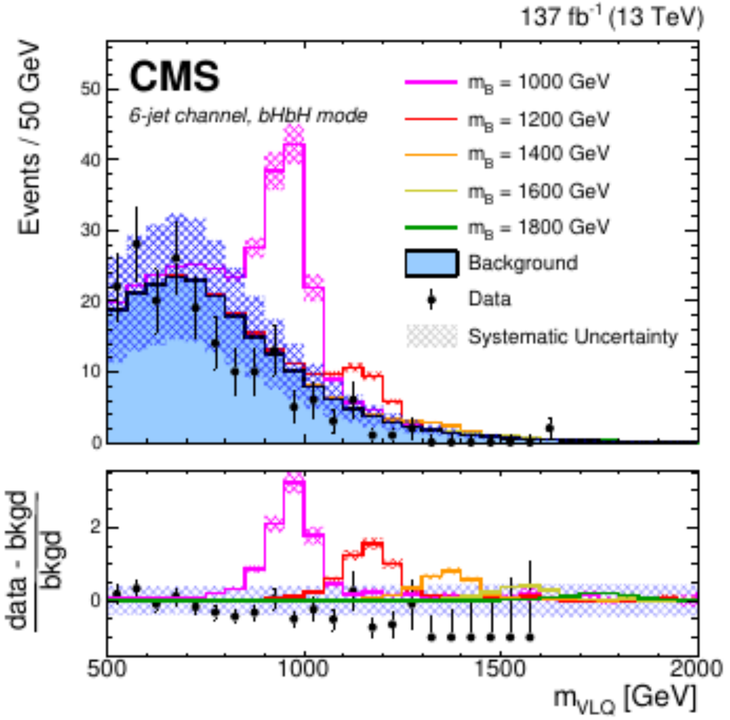
RECENT SEARCHES USING THE FULL RUN 2 DATASET

[CMS] SEARCH FOR PAIR OF B QUARKS IN FULLY HADRONIC STATES

arxiv:2008.09835

- Optimized for **B→ bH and/or B → bZ**
- Main features of the event selection
  - **High jet multiplicity**
  - **High scalar sum of jet pT** (H_T)
  - **B-tagged** jets and **double-b-tagged large-R jets** (channel dependent)
- **Background from multi-jet events** fitted in signal-depleted region and extrapolated to the search region
- Reconstruct the VLQ mass using a modified χ^2 metric (channel-dependent → classify according to the lowest χ^2)
  - Cut on χ^2 value to reject background

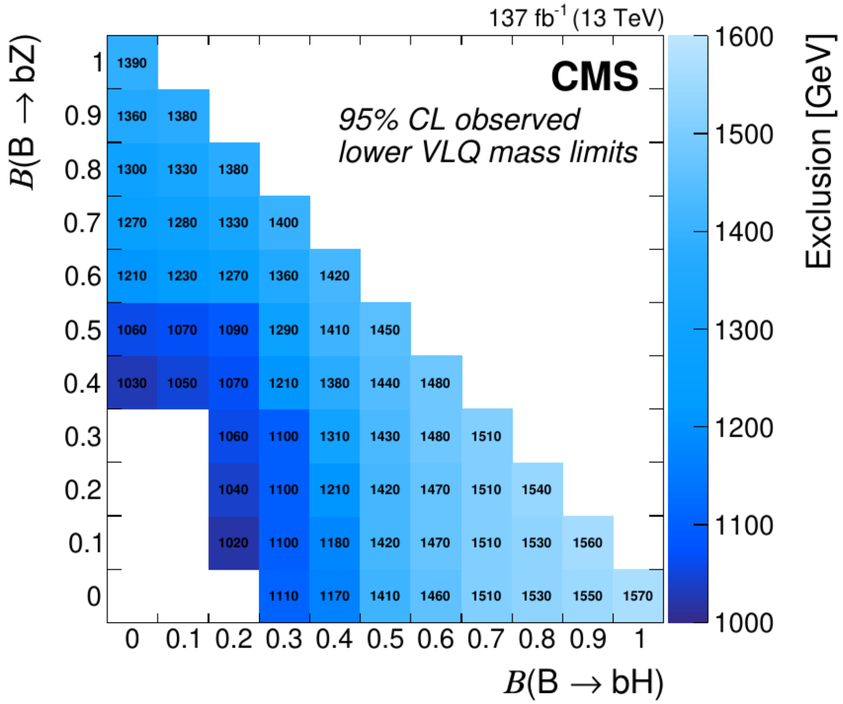
Jet multiplicity	Tag	bHbH	bHbZ	bZbZ
4 jets	Single b	2	2	2
	Double b	1	1	0
5 jets	Single b	3	3	3
	Double b	0	0	0
6 jets	Single b	4	4	3



[CMS] SEARCH FOR PAIR OF B QUARKS IN FULLY HADRONIC STATES

arxiv:2008.09835

- Limits extracted in **binned maximum-likelihood fit** to the **reconstructed VLQ mass** in each channel
- Limits extracted in the range 1000 < m(VLB) < 1800 GeV as a function of the VLQ mass and the branching ratio of the VLQ
- **Exclude VLBs up to 1570 GeV** (Br(B → Hb)=1)



Limits improve the previous results by several hundred GeV

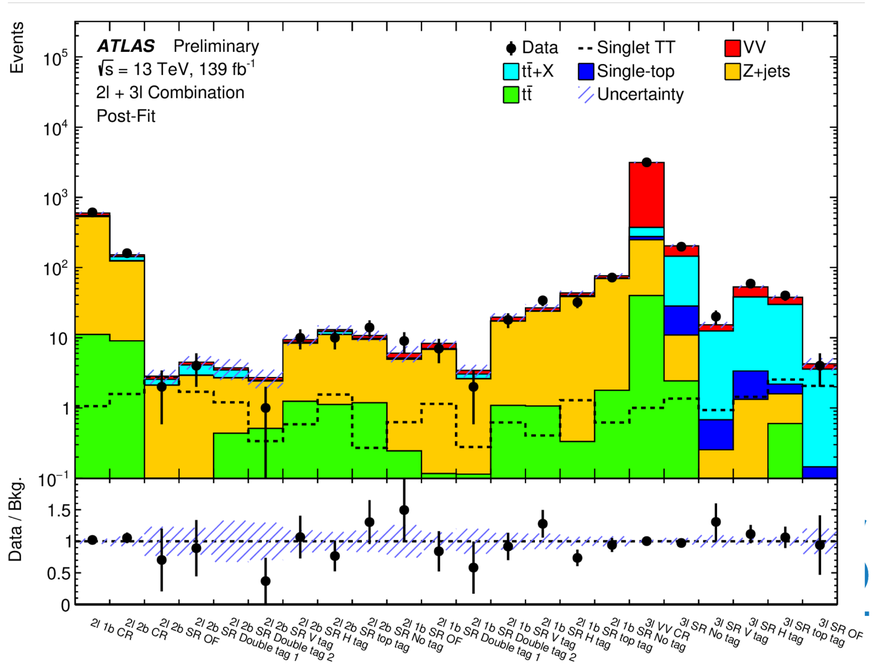
ATLAS EXPERIMENT

[ATLAS] SEARCH FOR PAIR-PRODUCTION OF VLQS WITH AT LEAST ONE LEPTONICALLY DECAYING Z-BOSON

ATLAS-CONF-2021-024

- Optimized for **TT → Zt+X**
  - Z → ee or Z → μμ
  - **2 or 3 leptons** in final state
- Train **multi-class DNN** on large-R jets (“**MCBOT**”) to optimize selection for **2nd hadronically decaying VLQ** to **top, V(Z,W) or H**
- “**Divide and conquer**”: Categories based on kinematic properties, b-tag and MCBOT decision for signal-sensitive regions, control and validation regions
- **Combined fit performed in all regions** to discriminating variable to extract signal and constrain background estimated by Monte-Carlo

Preselection	≥ 2 central jets at least two SF leptons with $p_T > 28$ GeV at least one pair of OS-SF leptons $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV					
Channel definitions	**2ℓ** $= 2\ell$ $p_T(\ell\ell) > 300$ GeV $H_T(\text{jet}) + E_T^{\text{miss}} > 920$ GeV				**3ℓ** $\geq 3\ell$ $p_T(\ell\ell) > 200$ GeV $H_T(\text{jet} + \text{lep}) > 300$ GeV	
Region definitions	**$1b$ SR** $H_T(\text{jet}) + E_T^{\text{miss}} > 1380$ GeV $= 1$ b-jet	**$2b$ SR** ≥ 2 b-jet	**$1b$ CR** $H_T(\text{jet}) + E_T^{\text{miss}} < 1380$ GeV $= 1$ b-jet	**$2b$ CR** ≥ 2 b-jet	**SR** – ≥ 1 b-jet	***VV* CR** – $= 0$ b-jet
MCBOT categories	7	7	–	–	5	–
Fitted variable	$m(Zb_1)$	$m(Zb_2)$	$H_T(\text{jet}) + E_T^{\text{miss}}$		$H_T(\text{jet} + \text{lep})$	

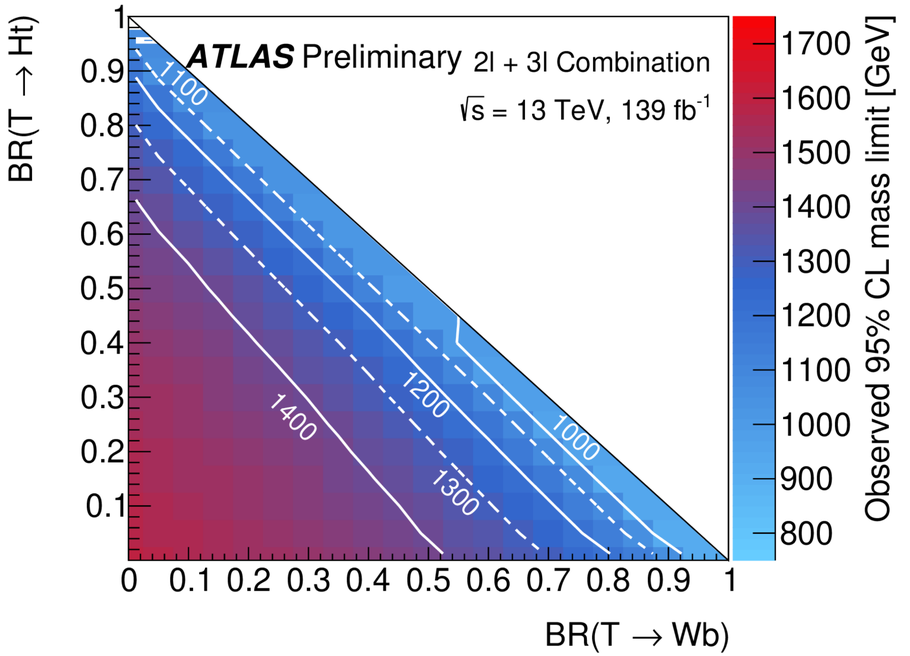


[ATLAS] SEARCH FOR PAIR-PRODUCTION OF VLQS WITH AT LEAST ONE LEPTONICALLY DECAYING Z-BOSON

ATLAS-CONF-2021-024

- No deviations from the background-only model observed
  - Sensitivity limited by statistical uncertainties
- Higher sensitivity to VLB in 2-lepton final state and to VLT in 3-lepton final state
- Set limits in singlet and doublet mode and as a function of the VLT(B) branching ratio to SM bosons

Model	Observed (Expected) Mass Limits [TeV] 2ℓ	3ℓ	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% $T \to Zt$	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% $B \to Zb$	1.40 (1.47)	1.16 (1.18)	1.42 (1.49)



Extend the excluded B & T masses by more than 200 GeV compared to previous analysis using 2015+2016 data (36fb-1)

CONCLUSION

- Many results on searches for vector-like quarks using either a part or the full ATLAS or CMS Run 2 dataset
- Results target different vector-like quark types, searches **complementary to cover the full branching ratio plane**
- No excess over the Standard Model prediction found, limits on T, B, X, Y vector-like quarks are set (as a function of mass & branching ratio)
- Searches using 2015+2016 data excluded **VLQs up to about 1.4 TeV**, **combination exclude T(B) quarks for any combination of decays to Standard Model particles below a mass of 1.31 (1.03) TeV**
- Analyses using the **full Run2 dataset of ATLAS and CMS significantly increase these limits up to about 1.6 TeV** (depending on the decay mode)

Watch out for new results! → Analyses using full Run 2 dataset in progress, many interesting results to come!

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BACKUP

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