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2021 TEV PARTICLE ASTROPHYSICS CONFERENCE

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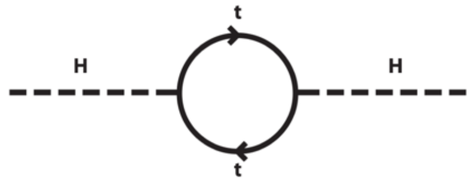
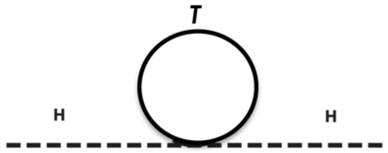
SEARCHES FOR NEW PHENOMENA IN FINAL STATES WITH 3RD GENERATION QUARKS USING THE ATLAS DETECTOR

INTRODUCTION

- The large top Yukawa coupling to the Higgs boson motivates searches **for new physics coupling to top or b-quarks**
- Radiative corrections from the top quark lead to quadratic divergences to the Higgs boson mass
  - Search for a mechanism to cancel those corrections instead of fine tuning





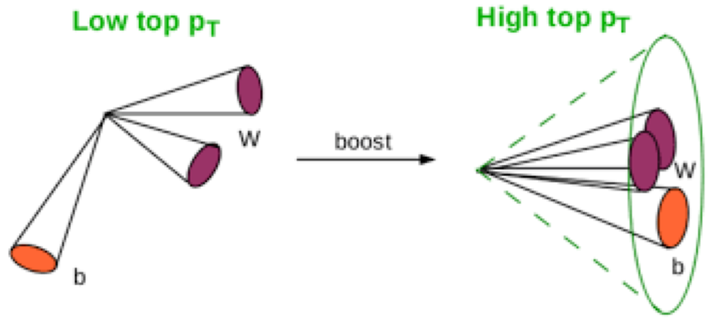
- Many new physics models like Composite Higgs models, extra dimensions etc. predict new particles coupling preferentially to 3rd generation quarks like:
  - Vector-like quarks
  - New heavy gauge bosons like W' and Z' as mediators to new vector charged/neutral current interactions
  - New heavy top resonances
- This talk covers recent searches for these new physics models using data from proton-proton collisions **recorded by the ATLAS experiment at a center of mass energy of 13 TeV collected during the LHC Run 2 (2015-2018)**

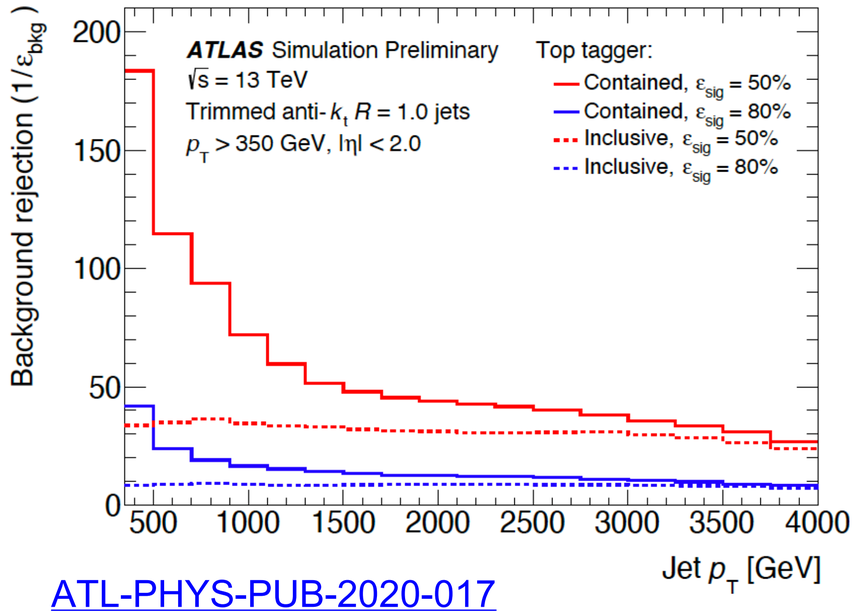
ATLAS EXPERIMENT

IDENTIFICATION OF 3RD GENERATION QUARKS

- All searches presented in this talk **rely on the identification of hadronic jets from top or bottom quarks**
- Important aspect in **rejection of background from multijet events**

- Top quarks from heavy new physics decay produced with high transverse momentum (p_T) → top decay products collimated in single large-Radius jet (R=1.0)
- Jet substructure techniques can be exploited to discriminate those top quarks from multijet events
  - Using variables like number of large-R jet constituents, mass of the jet, etc.
  - Dedicated top tagger in ATLAS trained with a DNN using information about dispersion of the jet constituents (N-subjettiness, splitting scales and energy correlation function)

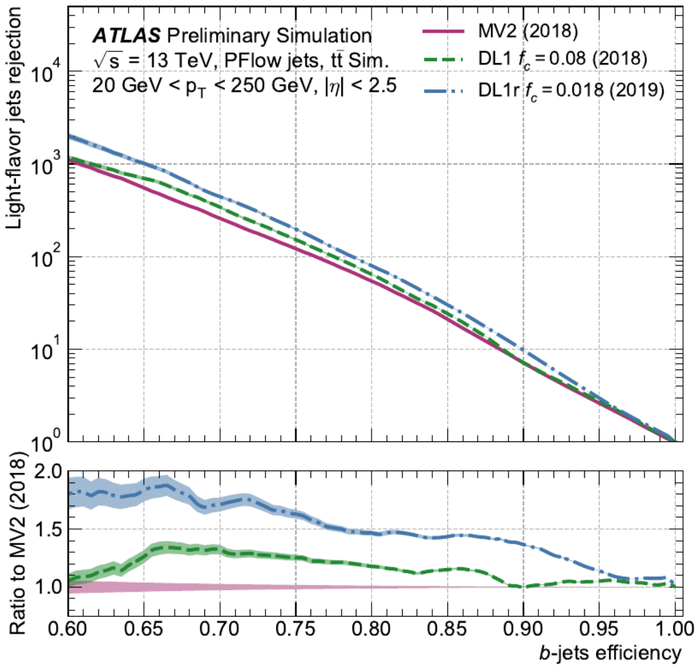




ATL-PHYS-PUB-2020-017

IDENTIFICATION OF 3RD GENERATION QUARKS

- All searches presented in this talk **rely on the identification of hadronic jets from top or bottom quarks**
- Important aspect in **rejection of background from multijet events**
- Properties of b-hadron decay like long lifetime, displaced secondary decay vertices, high mass and decay multiplicity are used in the construction of the ATLAS b-taggers
  - ATLAS uses DNN to train b-taggers, improvement w.r.t previously trained taggers using Boosted Decision Trees
  - Recent version uses in addition recurrent neutral network to exploit correlations between the impact parameters of different tracks in the jet
- Dedicated b-taggers for **particle-flow jets** and **variable-radius track (VRTrack) jets**



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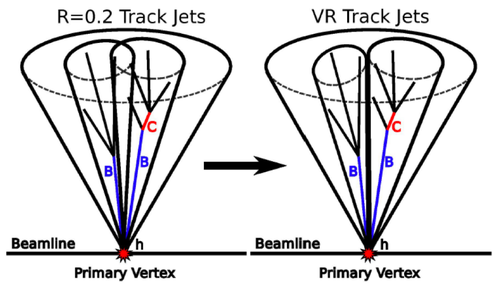
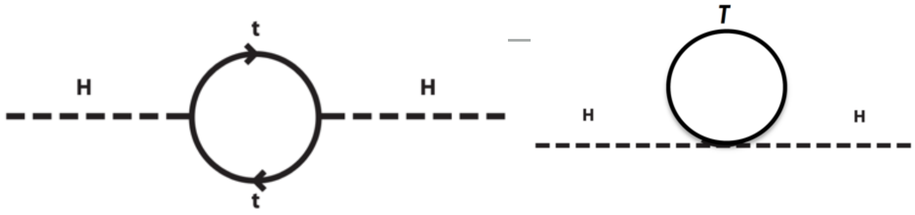
Particle-flow jets: Measurements from **tracker** and **calorimeter** are combined to form signals which ideally represent individual particles.



VRTrack jets

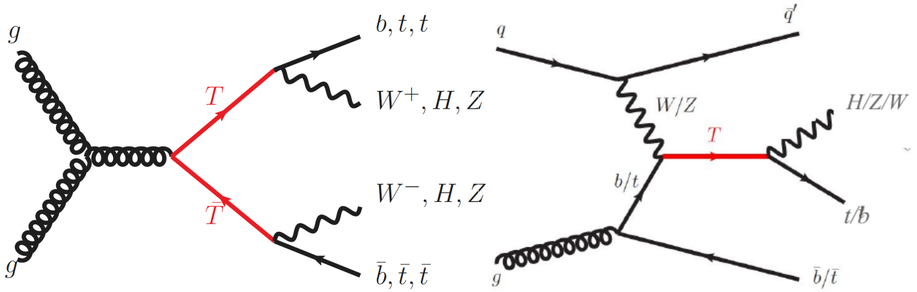
$$R \longrightarrow R_{\text{eff}}(p_{\text{T}}) = \frac{\rho}{p_{\text{T}}}$$

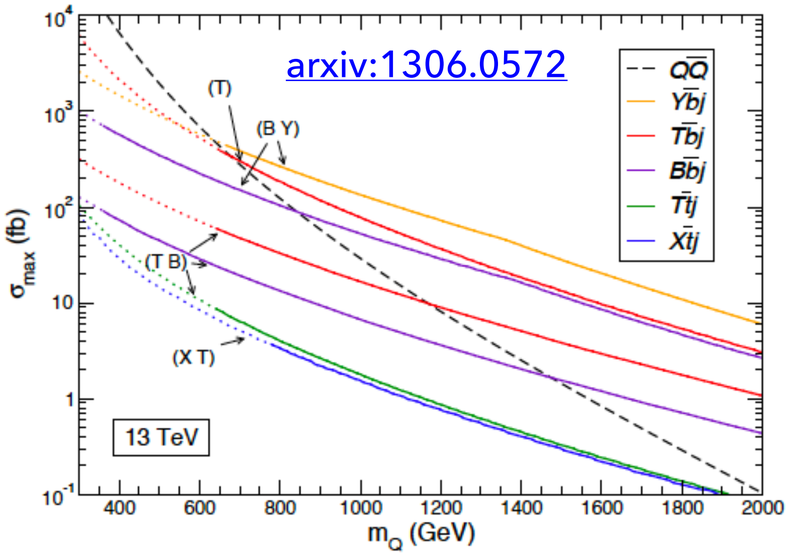
THEORETICAL MOTIVATION– VECTOR-LIKE QUARKS (VLQ)



- Heavy VLQs predicted in many models, especially those aimed at solving the hierarchy problem
- Left and right chiral components have same color & electroweak quantum numbers
  - Singlet, doublet and triplet representations of T, B, and exotic-charged X & Y → define relative couplings to V,H
  - Expected to decay to bosons and mainly to top or bottom quarks
- Pair-produced (QCD) & singly-produced (EW)
  - Pair-production cross-section only dependent on VLQ mass
  - Single-production cross-section also dependent on coupling (κ) to Standard Model particles
  - Single production could dominate for VLQ masses > 1 TeV

VLQ pair (left) and single (right) production



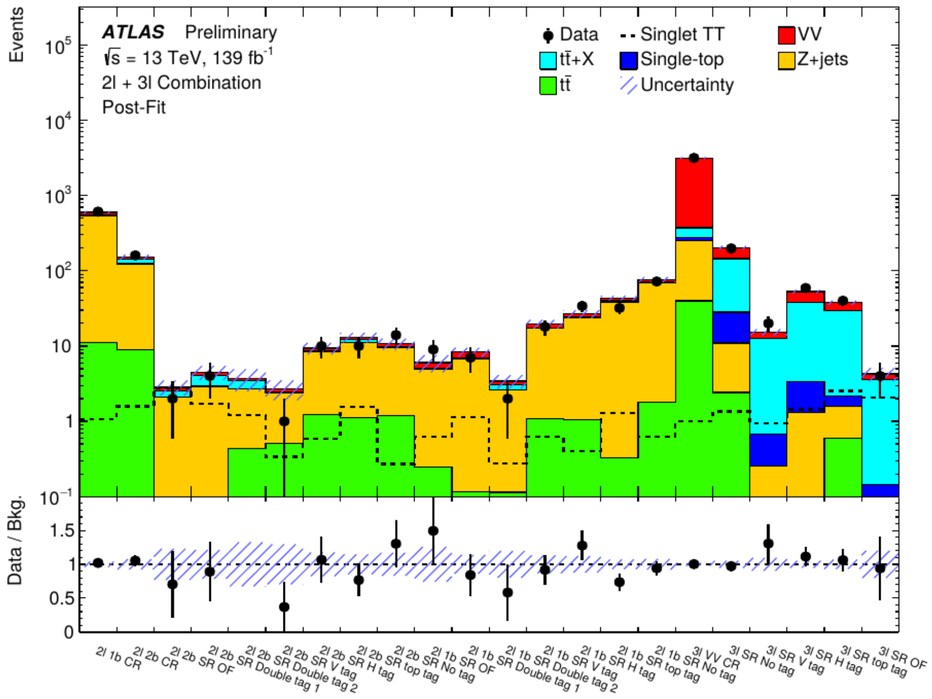


SEARCH FOR PAIR-PRODUCTION OF VECTOR-LIKE QUARKS WITH AT LEAST ONE LEPTONICALLY DECAYING Z-BOSON – ANALYSIS STRATEGY

ATLAS-CONF-2021-024

- Optimized for **TT → Zt+X**
  - Select leptonically decaying Z-boson
  - 2 or 3-leptons in the final state
  - Train **multi-class DNN** on reclustered large-R jet ("MCBOT") to optimize selection for 2nd hadronically decaying VLQ to **top, V (Z,W) or H**
- Define exclusive event categories for signal-sensitive regions, control and validation regions
  - Kinematic properties, b-tag decision and MCBOT decision
- **Combined fit to 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	**1*b* SR** $H_T(\text{jet}) + E_T^{\text{miss}} > 1380$ GeV $= 1$ *b*-jet	**2*b* SR** ≥ 2 *b*-jet	**1*b* CR** $H_T(\text{jet}) + E_T^{\text{miss}} < 1380$ GeV $= 1$ *b*-jet	**2*b* CR** ≥ 2 *b*-jet	**SR** – ≥ 1 *b*-jet	***VV* CR** – $= 0$ *b*-jet
MCBOT categories	7	7	–	–	5	–
Fitted variable	$m(Zb_1)$	$m(Zb_2)$	$H_T(\text{jet}) + E_T^{\text{miss}}$		$H_T(\text{jet}+\text{lep})$	

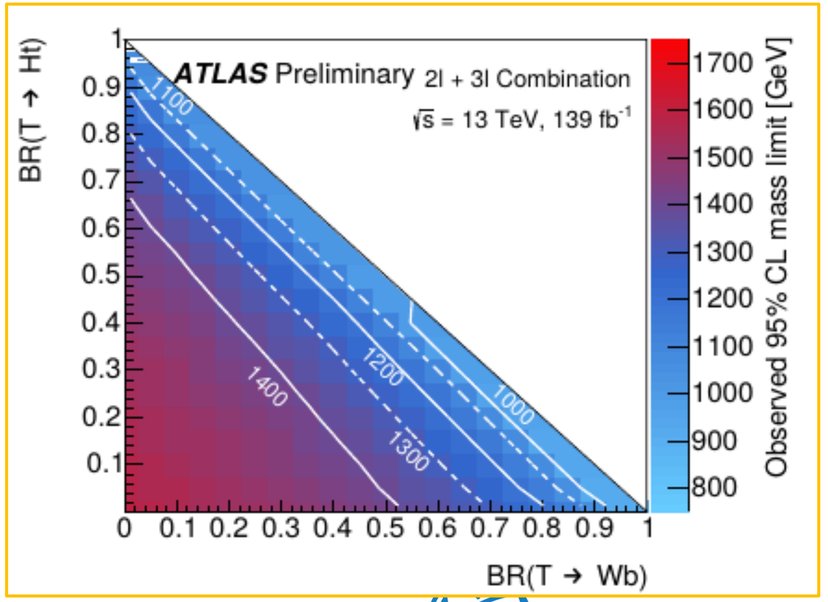


SEARCH FOR PAIR-PRODUCTION OF VECTOR-LIKE QUARKS WITH AT LEAST ONE LEPTONICALLY DECAYING Z-BOSON – RESULTS

ATLAS-CONF-2021-024

- Use ATLAS data of the full Run 2 of the LHC at a center-of-mass energy of 13 TeV (139fb^{-1})
- 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 model and as 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 mass limits by more than 200 GeV compared to previous analysis using 2015+16 data (36fb^{-1})

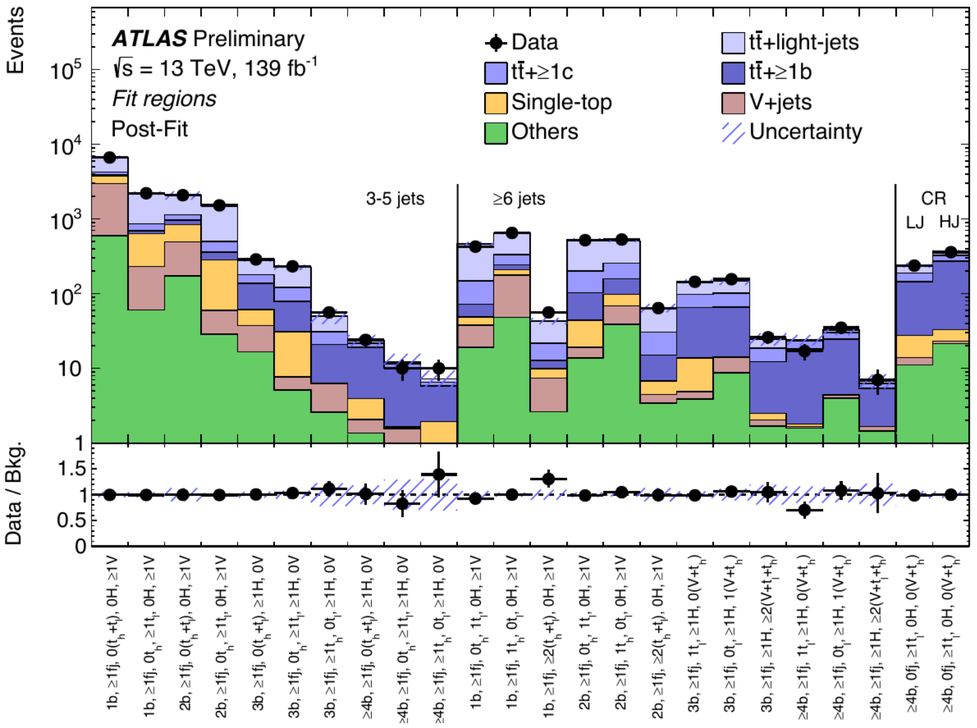
ATLAS EXPERIMENT

SEARCH FOR SINGLE PRODUCTION OF VECTOR-LIKE T QUARKS DECAYING TO Ht OR Zt – ANALYSIS STRATEGY

ATLAS-CONF-2021-040

- Optimize sensitivity to **T → Ht/Zt**
  - top quark decays to t → W(→ lν)+b : **1 lepton in final state**
- Categorization in **exclusive signal-sensitive, control and validation regions** to constrain different signal models and Standard Model backgrounds
  - Number of jets
  - Number of b-tagged jets
- **Properties of reclustered large-R jets** to divide into sensitive regions for **final state containing boosted Higgs, vector bosons or top quarks**
  - Cuts on large-R jet mass, p_T and number of constituents
- Data-driven corrections to dominant MC estimated background using a 2-D reweighting technique
- **Combined fit in all regions to extract the signal and improve background description**
  - Discriminating variable is scalar sum of p_T of all objects in the event

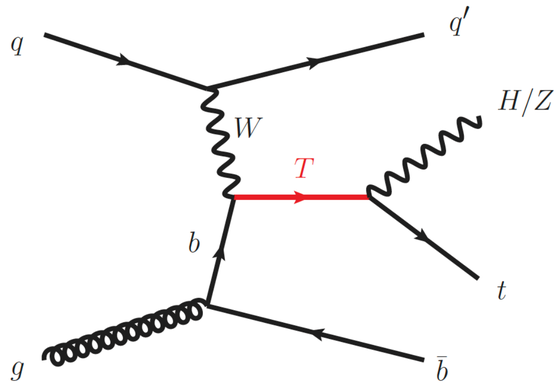
Baseline selections on jet and *b*-tag multiplicity			
Jet multiplicity	*b*-tag multiplicity	Channel name	Targeted signal
3–5	1–2	LJ, 1-2b	$T \to Zt$
3–5	≥3	LJ, ≥3b	$T \to Ht$
≥6	1–2	HJ, 1-2b	$T \to Zt$
≥6	≥3	HJ, ≥3b	$T \to Ht$

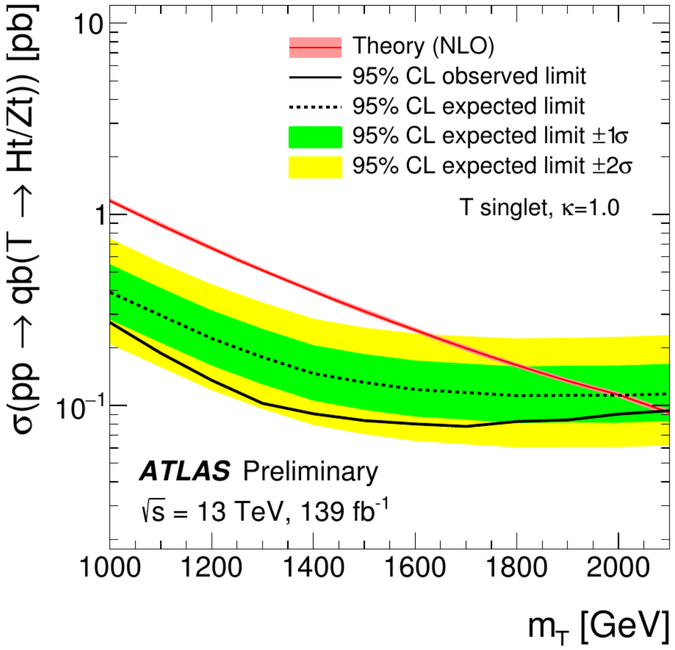


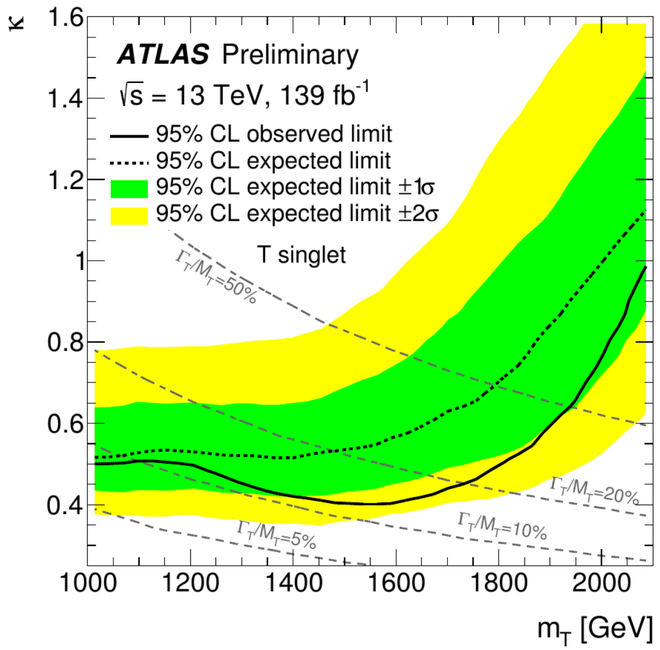
SEARCH FOR SINGLE PRODUCTION OF VECTOR-LIKE T QUARKS DECAYING TO Ht OR Zt – RESULTS

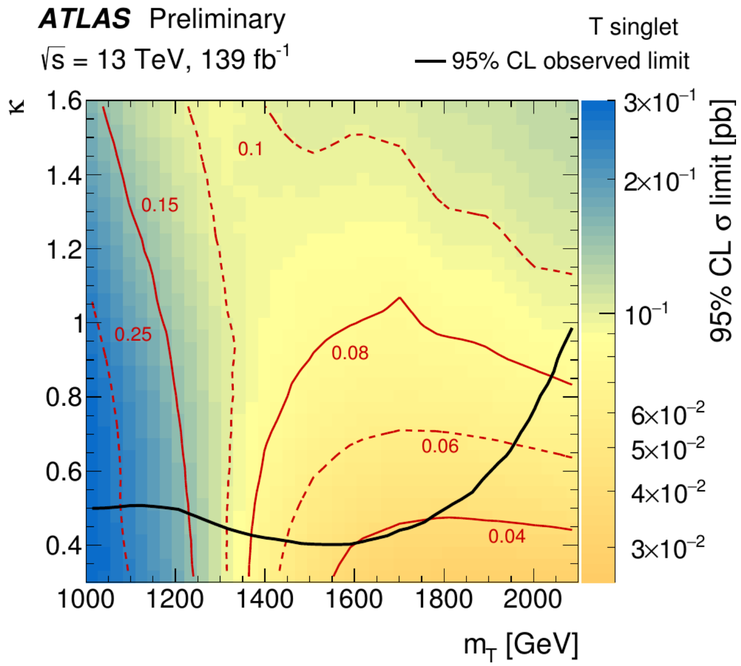
ATLAS-CONF-2021-040

- Use ATLAS full Run 2 data set
- **No deviation from the background only hypothesis**
- Interpretation in terms of the **universal coupling constant (κ)** , which determines the production cross section and total decay width for a given mass
- Sensitivity limited by ttbar and single top modeling







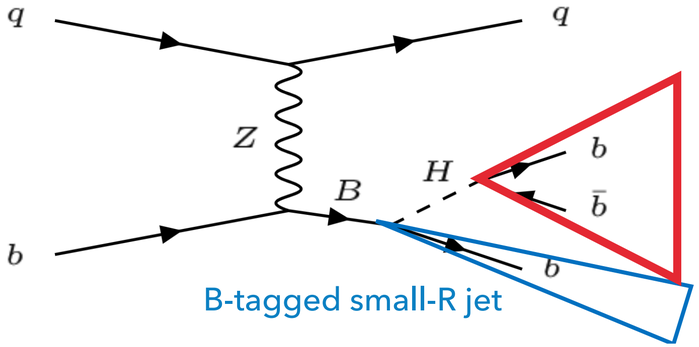


SEARCH FOR SINGLE VECTOR-LIKE B QUARK PRODUCTION AND DECAY VIA B ⟶ bH(bb)

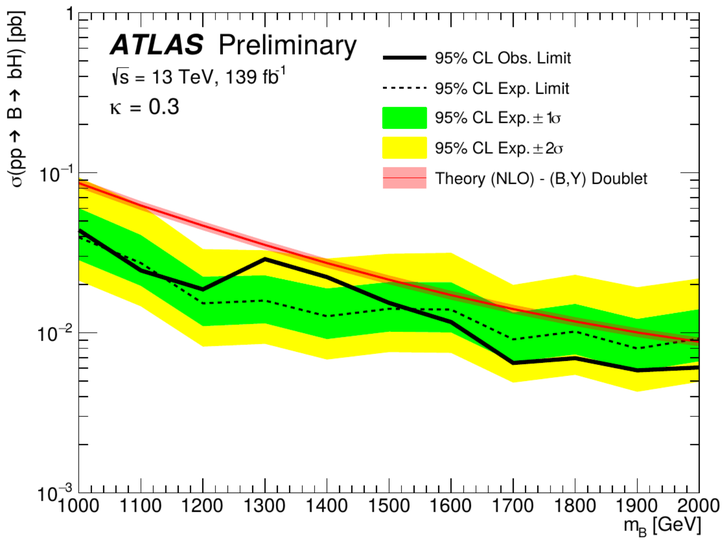
ATLAS-CONF-2021-018

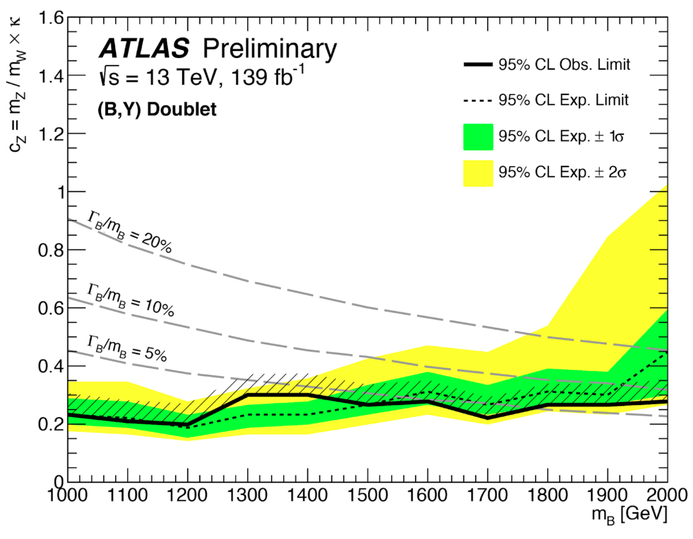
- Identification of **3 b-jets important for dominant (90%) multijet background suppression**
- **Identify boosted Higgs boson** using the jet mass, 2-pronged jet structure and associated b-tagged variable-radius track jets
- Purely data-driven background estimate using several orthogonal auxiliary regions
- **Binned maximum-likelihood fit to reconstructed VLB mass**
- Limits on VLB production set in different coupling scenarios and as a function of the VLB mass using the ATLAS Full Run 2 dataset

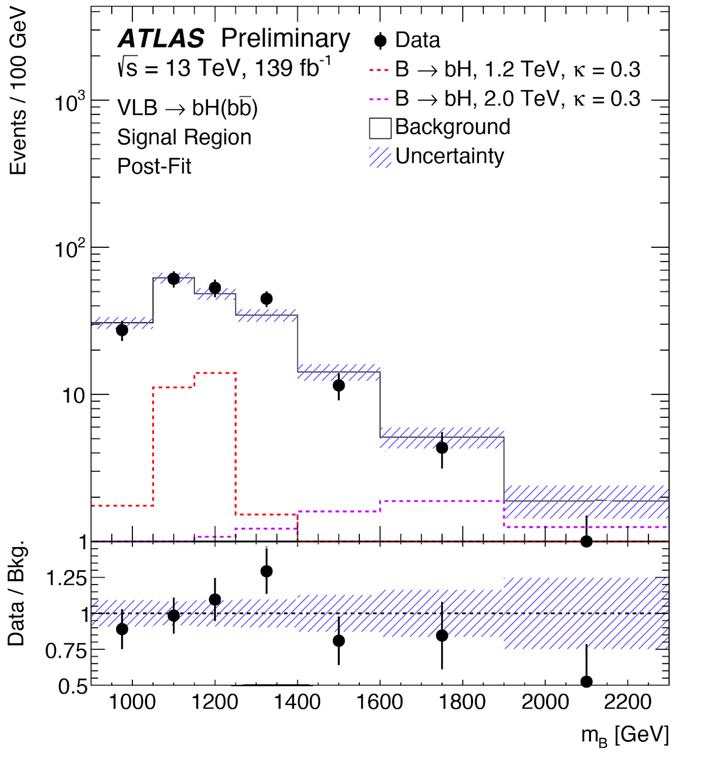
Reclustered large-R jet with two matched b-tagged variable radius track jets



Expand substantially the region of the VLB parameter space probed at collider experiments (previous limits: for (B,Y) double scenario @1.2TeV)



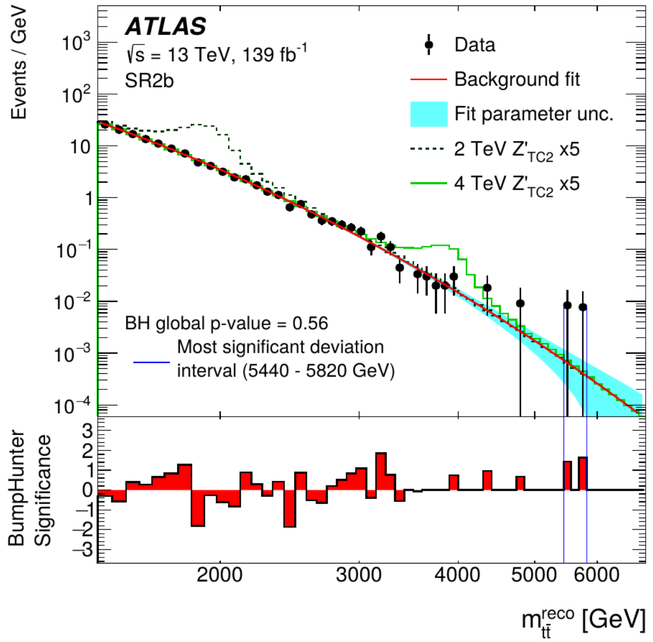


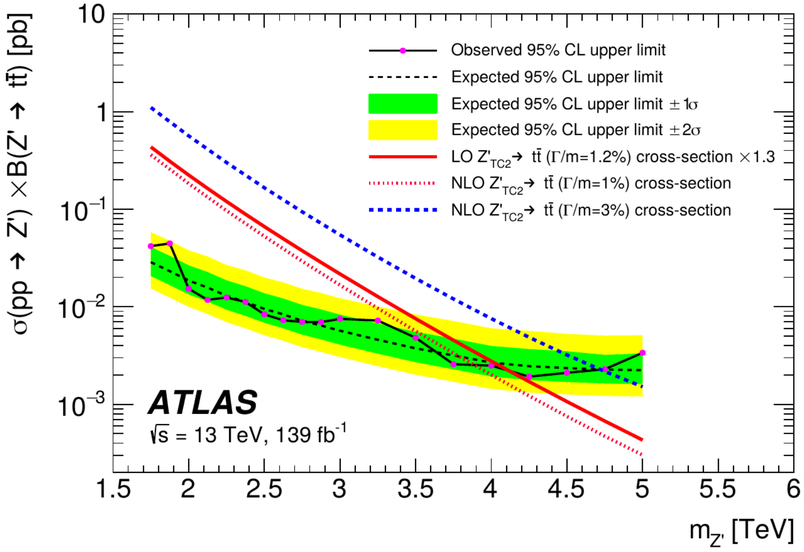


SEARCH FOR TTBAR RESONANCES IN THE FULLY HADRONIC FINAL STATE

JHEP 10 (2020) 61

- Resonant ttbar production predicted by many models
  - Topcolor-assisted-technicolor model (TC2) is used as a benchmark model
  - Model-independent search using Bump-Hunter to search for a localized excess in the m(tt) spectrum
- Selection of **two high-p_T large-R jets**, kinematic cuts ensure multijet event suppression and back-to-back topology
- Analysis regions for **signal extraction and derivation of background functional representation** classified according to:
  - DNN Top-tag of leading and sub-leading large-R jet
  - b-tagged VRTrack jet assigned to 0/1/2 large-R jets
  - **2 top-tags and 1 or 2 associated b-tags characterize signal region**
- Parameterize smoothly falling background spectrum using an analytic function



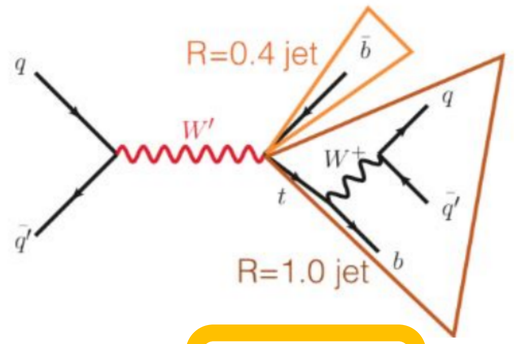


Improvements on cross section limit w.r.t analysis on 2015+2016 data by 65% at 4 TeV

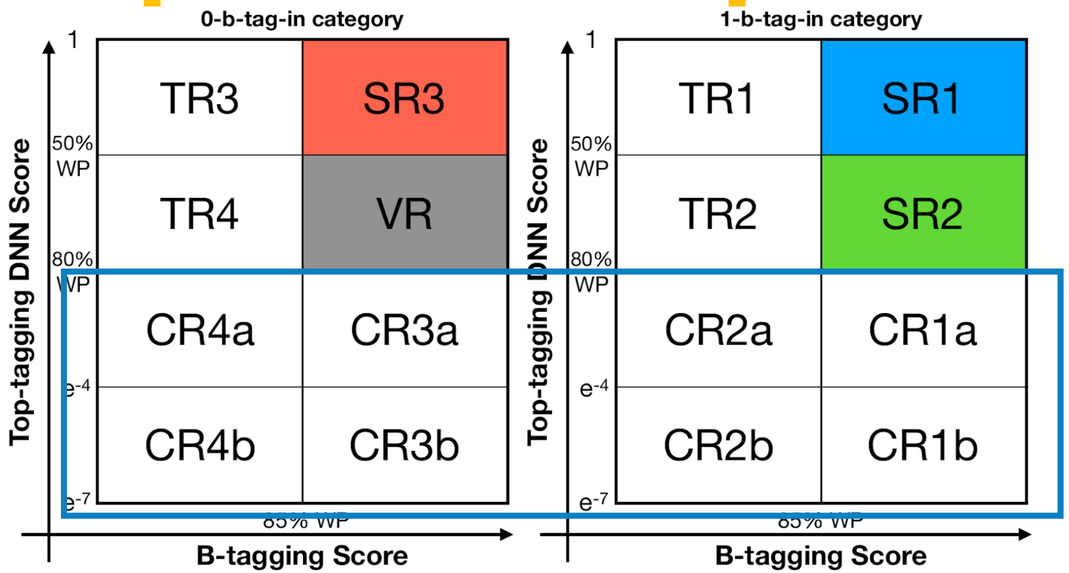
SEARCH FOR VECTOR BOSON RESONANCES DECAYING TO A TOP QUARK AND A BOTTOM QUARK IN HADRONIC FINAL STATES – STRATEGY

ATLAS-CONF-2021-043

- Search for new heavy W′ gauge bosons decaying to a (boosted) top quark and a b-quark
- Analysis profits from improved top and b-quark identification and improved multijet estimate
- Analysis regions classified according to
  - DNN top tag category
  - b-tag from W′ decay
  - b-tagged jet in large-R jet
- Multijet background estimated with data-driven method relying on transfer factors derived in control region to extrapolate from another control region to signal region
- **Combined fit to all three signal-sensitive regions of ttbar and multijet estimate and signal model in W′(t+b) invariant mass distribution**



extrapolation using transfer factors



calculation of transfer factors & uncertainties

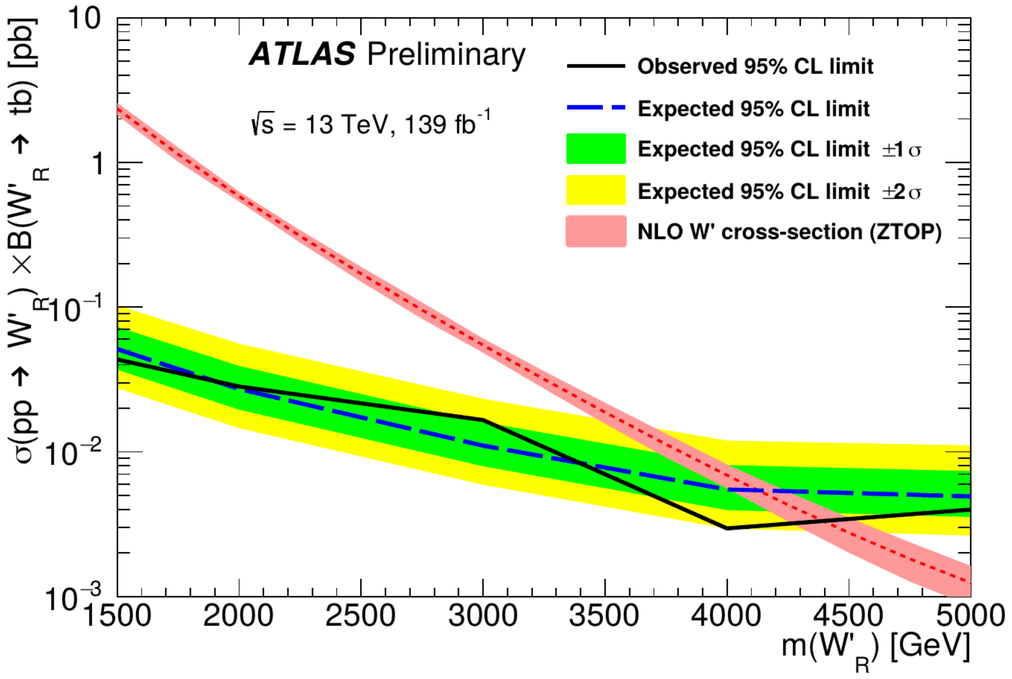
ATLAS EXPERIMENT

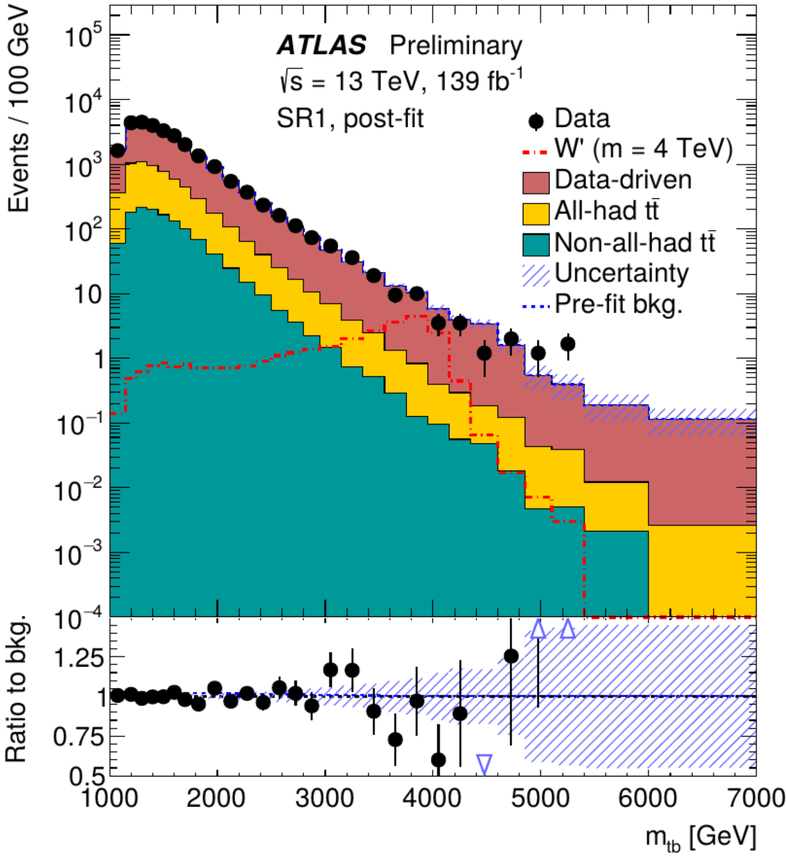
SEARCH FOR VECTOR BOSON RESONANCES DECAYING TO A TOP QUARK AND A BOTTOM QUARK IN HADRONIC FINAL STATES – RESULT

ATLAS-CONF-2021-043

- Search uses 139fb^{-1} of Full Run 2 data from the ATLAS experiment
- W′ with right-handed coupling excluded below a mass of 4.4TeV
  - Sensitivity limited by statistical uncertainties

Improvement of the mass limit by 1TeV w.r.t previous result using 2015+2016 data (36fb^{-1})





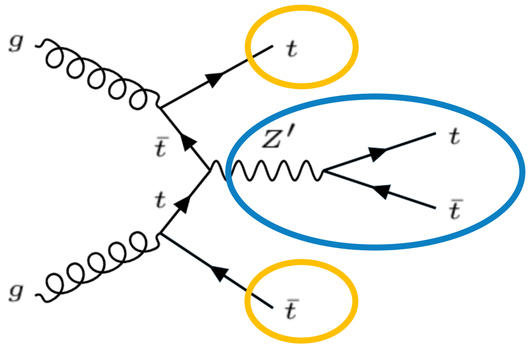
ATLAS EXPERIMENT

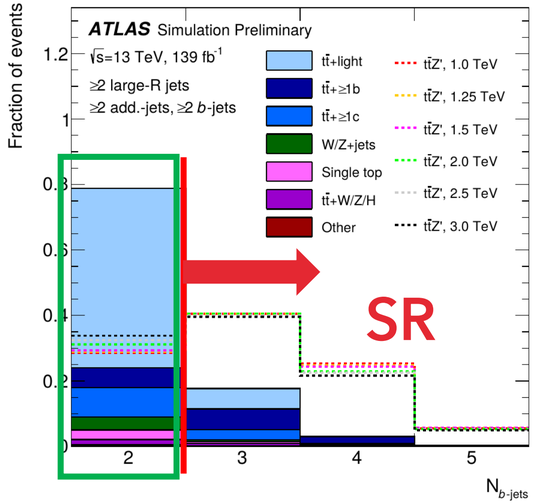
SEARCH FOR HEAVY RESONANCES IN FOUR-TOP-QUARK FINAL STATES

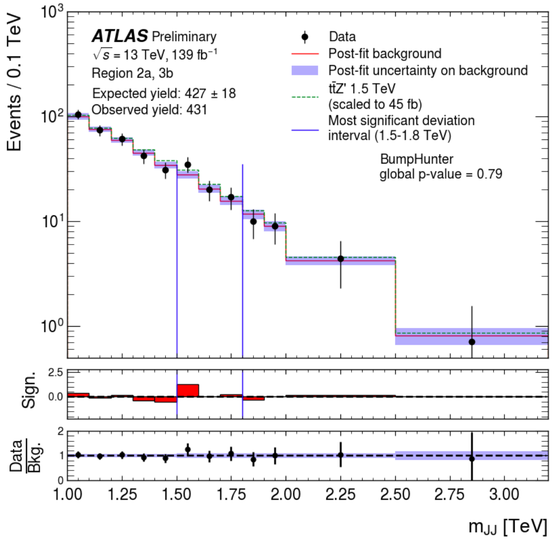
ATLAS-CONF-2021-048

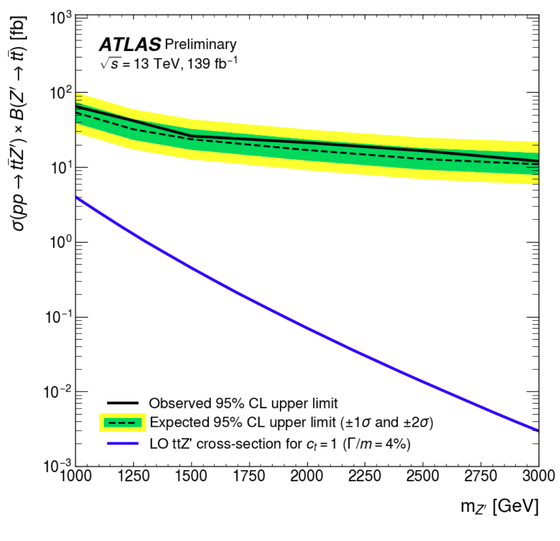
- Search for **new top-philic resonances** using the full Run 2 dataset
- Final state with 1 lepton to suppress multijet background
- Z′ resonance reconstructed from two large-R jets from boosted top quarks
  - Cuts on p_T, mass and number of constituents to identify as top quark
- Define signal and control regions according to multiplicity of additional jets and b-jets
- **Estimate background (ttbar + jets)** by extrapolating from control regions with 2 additional jets and 2 b-jets to signal regions using MC-derived extrapolation factors
- Profile-likelihood fit to further constrain the background
- **Scan m(tt) spectrum using Bump-Hunter and use also a model-dependent search for color-singlet top-philic Z′**
- Dominant uncertainty on ttbar background prediction at low Z′ masses, statistical uncertainties at higher mass points

If coupling to top quark dominant, Z′ can only be produced in association to ttbar





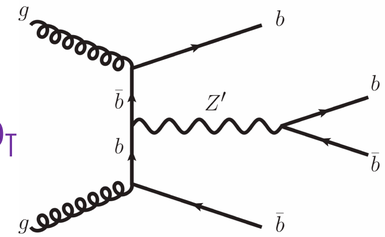


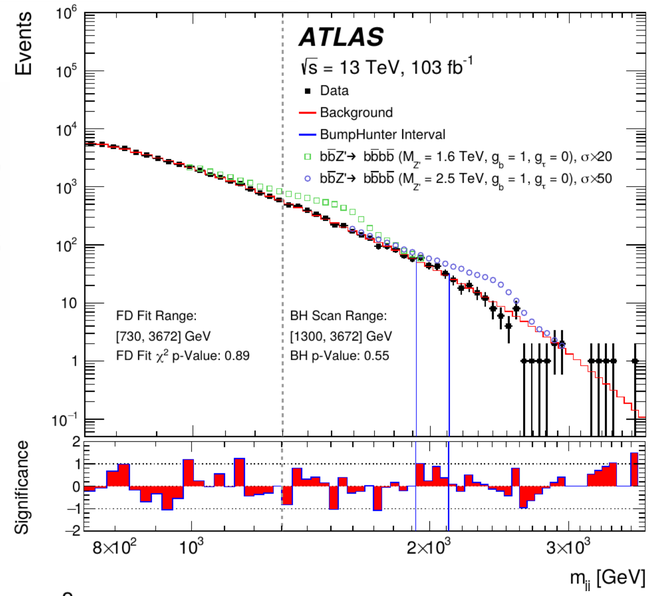


SEARCH FOR HEAVY PARTICLES IN THE b-TAGGED DIJET MASS DISTRIBUTION WITH ADDITIONAL b-JETS

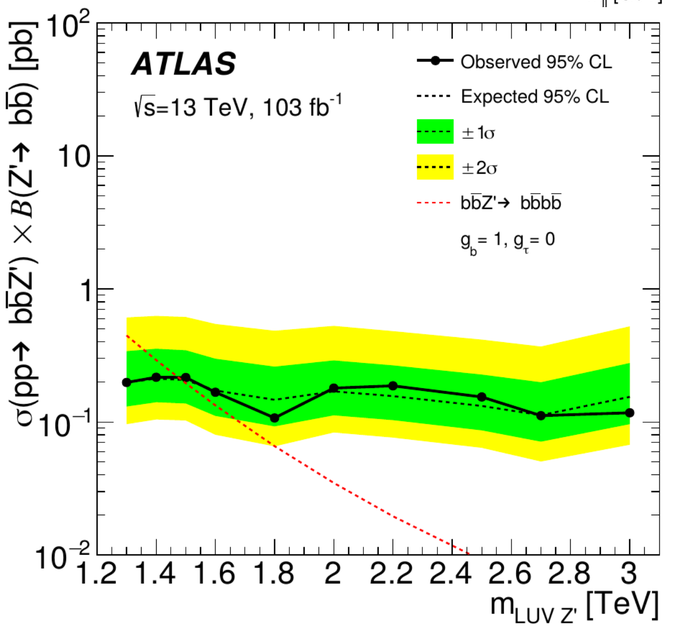
arXiv:2108.09059

- New W' and Z′ could explain the lepton-flavour universality deviations from LHCb & Belle recent results
- The two jets leading in p_T (from Z′ → bb decay) and either 3rd of 4th jet in p_T are b-tagged to **reduce multijet background**
  - **Previous searches did not include additional b-jets**





- Use **new trijet trigger with asymmetric p_T thresholds**, introduced in 2017 → use 103fb^{-1} of 2017 & 2018 ATLAS data
- Dominant background from multijet events
  - Estimate fully data-driven
  - **Functional decomposition (FD) method** using truncated series of a sum of orthonormal basis exponential functions to describes the background spectrum
- **Scan of reconstructed Z′(→ bb) invariant mass spectrum using Bump-Hunter**



Additional b-jets increase the sensitivity by 20-50% at a mass scale of 1.3-3 TeV

SUMMARY

- Many recent searches published with **final states containing 3rd generation quarks** using full or a large part of **ATLAS data collected during Run 2** of the LHC
- Models predicting **vector-like quarks, top resonances and heavy gauge bosons** are probed
- Improved top and b-quark identification techniques help to reject background from multijet events and to increase the sensitivity to new physics
- Nevertheless, the data is compatible with the Standard Model and no deviation has been found
- **Exclusion limits were set, good improvements have been observed w.r.t previous analyses using 2015+2016 data only**

Eagerly anticipating Run 3 data to probe further into the O(TeV) regime!

ATLAS EXPERIMENT

BACKUP

LIST OF PRESENTED ANALYSES

- Search for pair-production of vector-like quarks in *pp* collision events at √s =13 TeV with at least one leptonically-decaying *Z* boson and a third-generation quark with the ATLAS detector (ATLAS-CONF-2021-024)
- Search for single production of vector-like *T* quarks decaying to *Ht* or *Zt* in *pp* collisions at √s =13 TeV with the ATLAS detector (ATLAS-CONF-2021-040)
- Search for single Vector-Like *B* -quark production and decay via $B \rightarrow bH(bb)$ in pp collisions at √s =13 TeV with the ATLAS detector (ATLAS-CONF-2021-018)
- Search for tt resonances in fully hadronic final states in *pp* collisions at √s = 13 TeV with the ATLAS detector (JHEP 10 (2020) 61)
- Search for vector boson resonances decaying to a top quark and a bottom quark in hadronic final states using *pp* collisions at √s =13 TeV with the ATLAS detector (ATLAS-CONF-2021-043)
- Search for heavy resonances in four-top-quark final states in *pp* collisions at √s=13 TeV with the ATLAS detector (ATLAS-CONF-2021-048)
- Search for heavy particles in the *b*-tagged dijet mass distribution with additional *b*-tagged jets in proton-proton collisions at √s=13 TeV with the ATLAS experiment (arXiv:2108.09059)

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