Searches for new phenomena in final states with 3rd generation quarks using the ATLAS detector

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October 20, 2021

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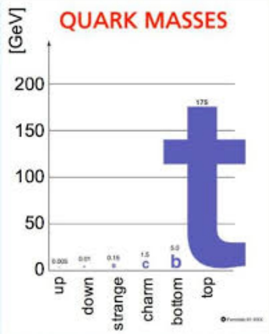
Introduction

Motivation

- Deviations from the SM in lepton flavor universality seen in B physics.
- Third generation quarks a good place to look for new physics. Higher mass → Stronger coupling with the Higgs boson.
- Decays of top and bottom quarks unique in the SM Bottom quarks decay with a displaced vertex while top quarks decay before hadronisation.

A few of the issues SM cannot explain

- Neutrino masses
- Smallness of the Higgs mass
- Dark Matter



Contents

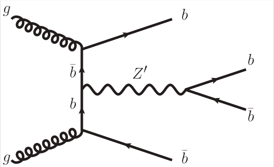
This talk is split into two main parts:

- **Lepton flavor universality**
  - Search for heavy particles with b-tagged dijet mass distribution and additional b-jets
  - Search for third generation leptoquarks decaying to a top quark and a τ lepton
- **Higgs fine-tuning**
  - Pair-production of vector-like top/bottom quarks
  - Single-production of vector-like top/bottom quark
- **Bonus:** Search for $t\bar{t}$ resonances (predicted by both classes of models)

This list is not exhaustive. A complete list of analyses with the full Run-2 data collected by ATLAS can be found here.

Lepton flavor universality

Search for heavy particles with b-tagged dijet mass distribution and additional b-jets arxiv:2108.09059

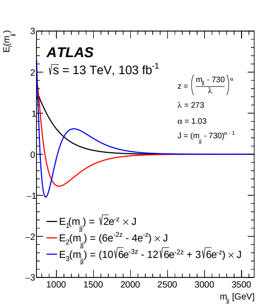


- Search for resonant peaks in $b-$tagged dijet invariant mass spectrum
- Models explaining LFU anomalies also predict Z' and W' coupling to third generation quarks
- First search in this final state probing masses upto 3.6 TeV
- Main source of background: multijet
- Dedicated trijet trigger used
- Innovative data-driven method to estimate background based on orthonormal functions

Background estimation

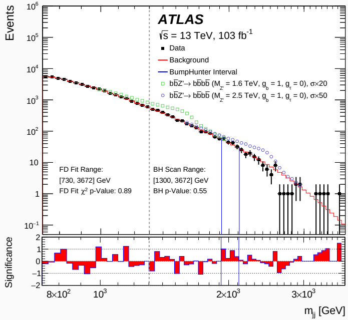
Fit to invariant mass spectrum of the two leading $b-$tagged jets

- Shape impacted by asymmetric thresholds of trijet triggers
- Functional decomposition used
  arxiv:1805.04536
- Power law transformation on m_{jj}
  $$z = \left(\frac{m_{jj} - m_{jj}^0}{\lambda}\right)^{\alpha}$$
- Spectrum modelled by $\Omega(z) = \Sigma_{n=1}^{N} c_n E_n(z)$
- Truncated series given by the optimized (λ, α, N) and c_n determines the background estimate



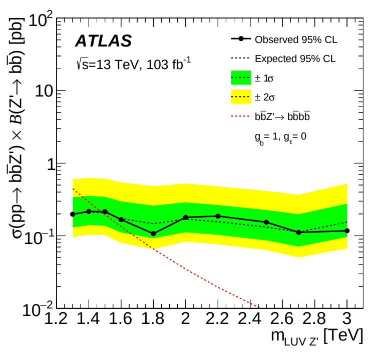
- Pseudodata obtained by scaling events passing pre-selection ith the expected event-level $b-$tagging selection efficiency of multijet events in dat used to make sure background estimate is adequate, and data is not over-fitted

Results

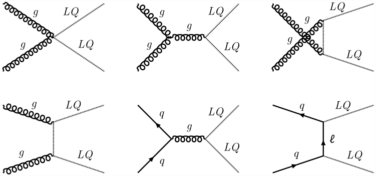


Most significant excess in [1921, 2114] GeV with a p-value of 0.55

Z' bosons between 1.3 and 1.45 TeV excluded at 95% CL

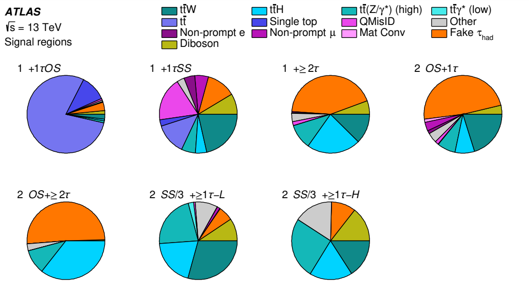


Search for third generation leptoquarks decaying to a top quark and a τ lepton arxiv:2101.11582



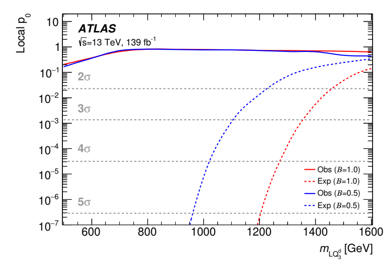
- Similarities between quark and lepton sectors suggest a **possible underlying symmetry connecting the two sectors.**
- Thus some extensions of SM predict leptoquarks (LQ) with non-zero Baryon and Lepton numbers.
- LQ can have spin-0 or spin-1. Spin-0 LQs couple to quarks and leptons via Yukawa interactions, and **can also mediate processes that violate LFU**.
- **Pair-production of LQ** via ggF and $q - \bar{q}$ annihilation considered.
- Corresponding cross-sections are proportional to the mass of the LQ.
- A **narrow width** of roughly 0.2% assumed.
- The search considers the process $LQ_3^d \bar{LQ}_3^d \rightarrow t\tau t\tau$

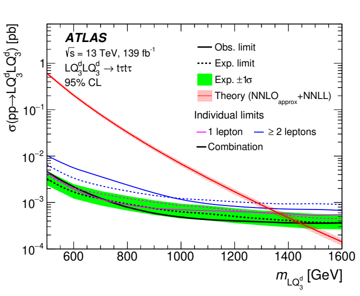
Backgrounds



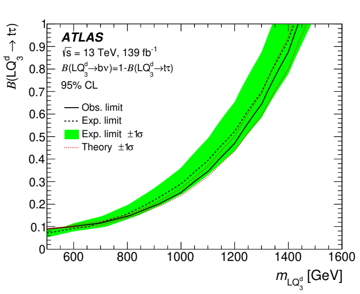
- At least one light lepton, one hadronically decaying τ, ≥ 2 jets, ≥ 1 $b-$jet.
- Several final states based on multiplicity and flavor of lepton candidate.
- Main sources of background: $t\bar{t}$ with or without fake lepton or τ.
- Masses scanned: 500-1600 GeV
- Simulations with corrections derived from data used for both, reducible and irreducible backgrounds.
- m_{eff} used as the discriminating variable in the signal regions.

Results





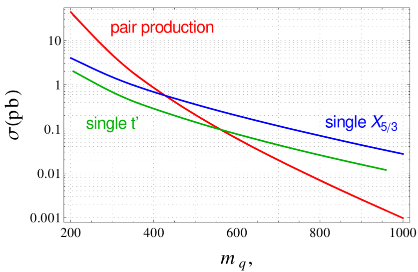
- Sensitivity dominated by $1\ell + \geq 1\tau$, with improvements from $2\ell\text{OS} + \geq 1\tau$ and $2\ell\text{SS}/3\ell + \geq 1\tau$
- Expected sensitivity for $\mathcal{B} = 1$ is $> 5\sigma$ for $m < 1.21$ TeV and $> 3\sigma$ for $m < 1.36$ TeV.
- Assuming $\mathcal{B} = 1$, $m_{LQ_3^d} < 1.43$ TeV excluded at 95% CL.
- Sizeable sensitivity for $\mathcal{B} = 0.5$ as well.



Higgs fine-tuning

Composite-Higgs models and vector-like quarks

- The Higgs boson is a composite pseudo-Nambu-Goldstone boson (pNGB) from spontaneous breaking of a global symmetry in a new strongly coupled sector
  $\rightarrow$ This protects the Higgs mass.
- Models with partial compositeness predict **new vector-like fermions**.
- Simplest extensions with VLQ (T and B)
- VLQs assumed to decay via **charged and neutral currents** to 3rd generation quarks.



- **QCD pair-production:** Mass-independent, dominant at low mass
- **Single-production:** Scales with coupling, model dependent, significant at high mass.

Pair-production of vector-like quarks with at least one leptonically decaying Z boson and a 3^{rd} generation quark

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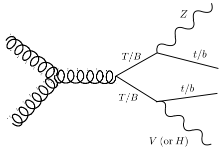
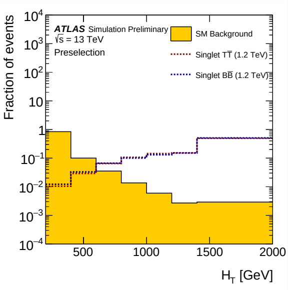
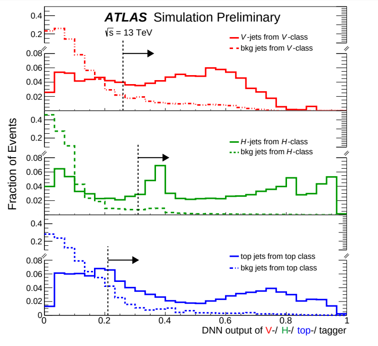


- Optimized for decays to a leptonically-decaying Z boson and a third generation SM quark.
- Events characterized by high-p_T Z boson, $b-$tagged jets, high-p_T large-R jets, exactly 2ℓ or $\geq 3\ell$, boosted W, Z, H, and t.
- Categorization done using a **neural-network based boosted object tagger.**

Multi-Class Boosted Object Tagger (MCBOT)



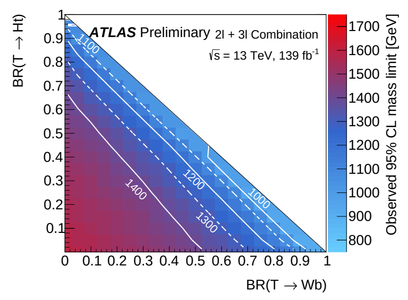
- Analysis exploits the high multiplicities of jets, large-R jets, and $b-$jets in addition to requirements on p_T^Z and H_T to suppress backgrounds.
- Large-R jets reclustered from calibrated R=0.4 jets used as input to MCBOT to identify hadronically decaying V, H, and top quark.
- Based on multi-class DNN trained using RC jets from $Z' \to t\bar{t}$ and $W' \to WZ$ simulations, with multijet as background.
- Three signal labels (V, H, top) are obtained by matching the RC jet to the corresponding boson or top quark at generator-level within $\Delta R < 0.75$.

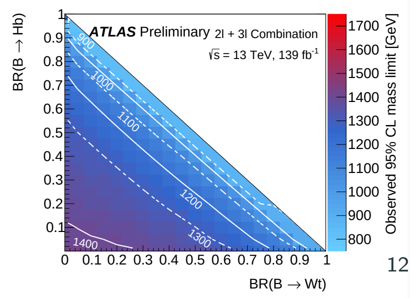


Results

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)

- No significant excesses
- Combined results **exclude T masses upto 1.27 and 1.46 TeV** for singlet and doublet configurations
- Combined results **exclude B masses upto 1.20 and 1.32 TeV** for singlet and doublet configurations
- These limits are better than the previous searches by more than 200 GeV.





Search for single production of vector-like T and B quarks

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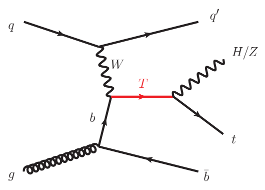
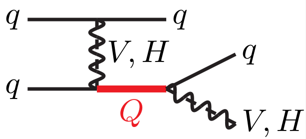
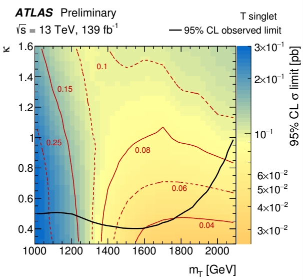


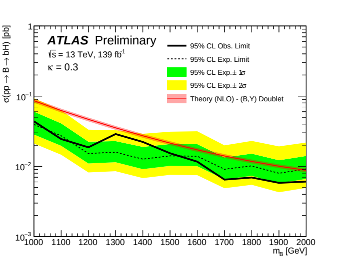


- $T \to Ht$ or $T \to Zt$
- Leptonic top, and hadronic boosted H/Z
- Events classified into low (3-5) or high (≥ 6) jet multiplicity
- At least one forward jet
- m_{eff} used to further discriminate signal and background

- $B \to Hb$, $H \to bb$
- Higgs candidates (HC) reconstructed as single large-R jets
- VLB candidates formed by combining HC with small-R $b-$jet
- Additional requirements used to exploit jet sub-structure

Results

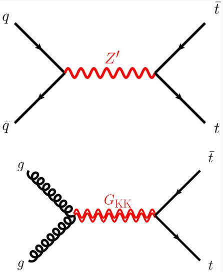


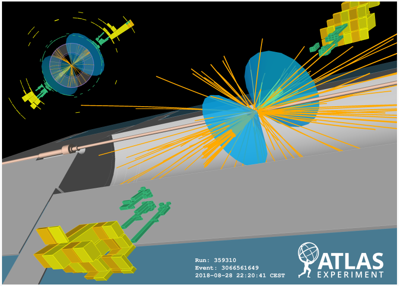


- No significant excesses
- Limits on **T quark mass** are stronger at higher couplings, and reach 2.07 TeV (expected 2.0 TeV) at $\kappa = 1.0$
- At 1.6 TeV, all κ values above 0.4 are excluded

- No significant excesses
- Largest discrepancy between data and background prediction observed at $\mathbf{m_B = 1.3}$ **TeV**, with a local p-value of 0.03
- Resonances with $\kappa = 0.3$ excluded across the full mass range

Search for $t\bar{t}$ resonances in fully hadronic final states arXiv:2005.05138





- $t\bar{t}$ resonances are predicted by 2HDMs, Randall-Sundrum (RS) models with warped extra dimensions etc.
- This analysis is optimized for $m_{t\bar{t}} > 1.4$ TeV.
- Highly boosted tops, so difficult to individually identify decay products of the top quark.
  A deep neural network (DNN) developed to solve this problem.
- DNN is applied to large-R jets to identify boosted top quarks, using jet sub-structure information.

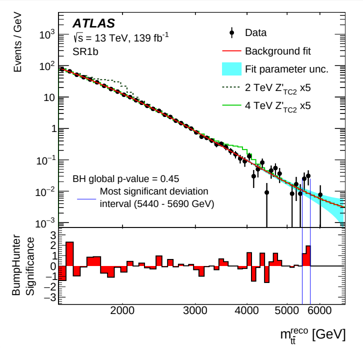
Event selection

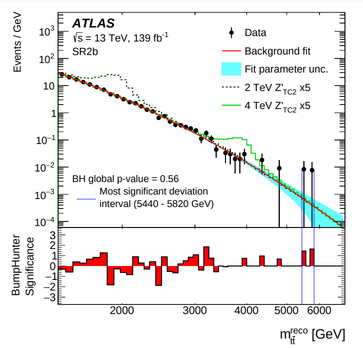
- Resonance (Z'_{TC2}) mass range considered in the RS model: 1.75 TeV $-$ 5 TeV
- Signal region divided into two: 1 or 2 $b-$jets associated with the large-Radius(=1.0) jets.
- Model-independent results obtained by bump-hunting on $m_{t\bar{t}}$ spectrum.

Selection cuts:

- At least two large-R jets (J) which are top-tagged using the DNN
- $p_T^{\text{leading jet}} > 500$ GeV
- $p_T^{\text{sub-leading jet}} > 350$ GeV
- $m_{JJ} > 1.4$TeV
- Leading and sub-leading jets required to be back-to-back in the transverse planes
- Rapidity distance required to be less than 1.8 to reject multijet background

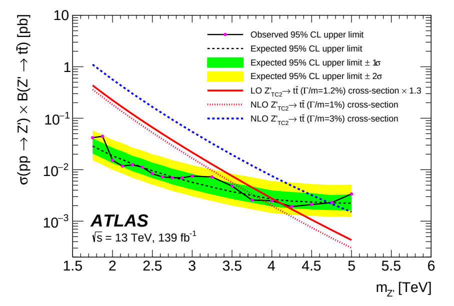
Results I





- Using a fully data driven background, global function fitted in the SR.
- The Functional form and uncertainties estimated using a template built with MC + Data driven mixture.
- Most significant deviation in **5.44 – 5.69 TeV for 1 b–jet** signal region and **5.44 – 5.82 TeV for 2b–jets** signal region with the corresponding **global p-values of 0.45 and 0.56**, respectively.

Results II



- For a Z' signal with a width $\Gamma/m = 1.2\%$, **masses up to 4.1 TeV are excluded at 95% CL**.
- Below 4.5 TeV, the expected sensitivity is limited by the statistical uncertainty of the background prediction.
- Above 4.5 TeV, systematic uncertainty dominates over the statistical uncertainty in the $2b-$jet channel.

Summary

Lepton flavor universality

- Deviations in LFU from the SM suggested by Belle and LHCb.
- Models attempting to ease the tension predict new particles such as heavy vector bosons and leptoquarks.
- Searches for Z' and spin-0 LQ presented here.
- No significant excesses seen but several new and innovative methods were developed.
- Limits on the masses with more data and newer methods stronger than before.

Higgs fine-tuning

- Composite Higgs models provide a way to ensure a small Higgs mass.
- These models predict the existence of vector-like quarks.
- Searches for third generation vector-like quarks produced singly and in pairs presented here.

Backup