ICHEP 2022

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

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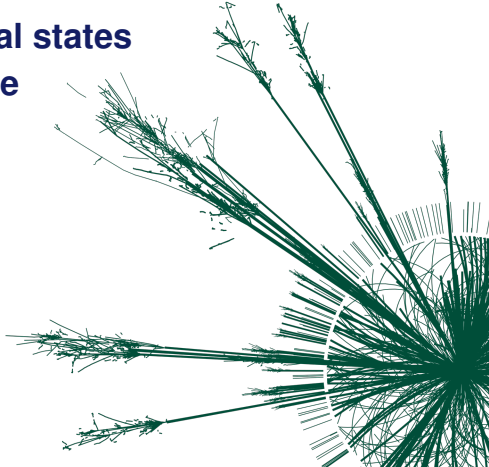
07 July 2022



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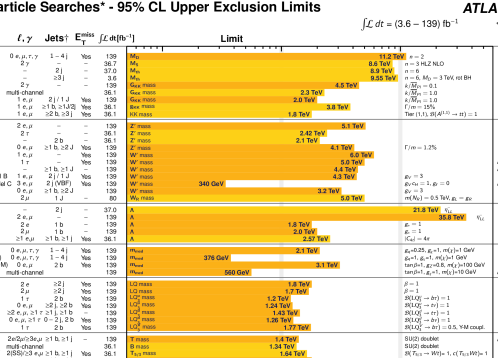
ATLAS EXPERIMENT

Why search for third generation quarks



*Only a selection of the available mass limits on new states or phenomena is shown.
† Small-radius (large-radius) jets are denoted by the letter j (J).

Third generation quarks

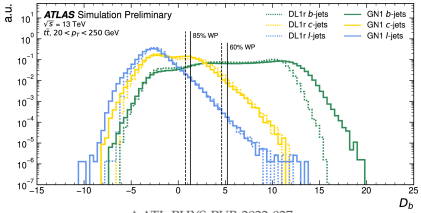
- Offer unique signatures which allows suppression of Standard Model background
- Have a large mass and large Yukawa coupling

In this talk

- Search for single vector-like T
- Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$ production
- Search for mono-top + invisible
- W' resonance to top and bottom

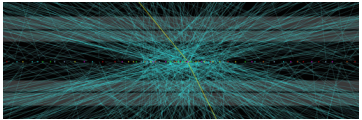
Identification of bottom quarks

- Bottom quarks are longer-lived, hadronise and initiate sprays of particles
- Reconstructed as jets from particle flow objects
- b-jets are distinguishable from light-flavour jets though e.g.
  - Displacement of vertex (typically a few mm)
  - Track multiplicities
  - Large B-hadron mass
- Using machine learning b-jets can be identified
- Continued development of new techniques, e.g. Graph Neural Network

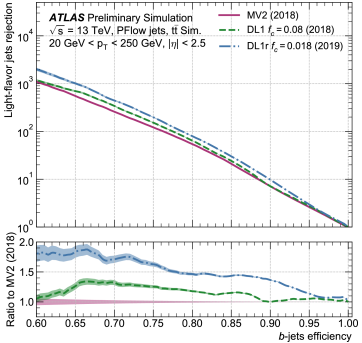


↑ ATL-PHYS-PUB-2022-027

FTAG-2019-005



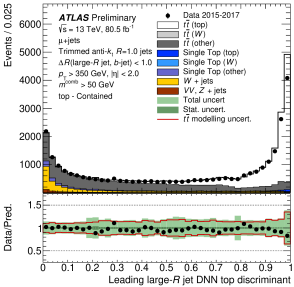
↑ arXiv:1911.07962

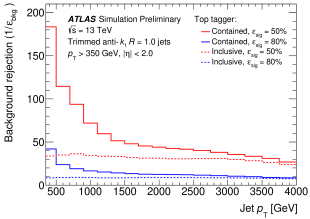


Identification of top quarks

ATL-PHYS-PUB-2020-017

↑ Figure taken from P. Gunnellini





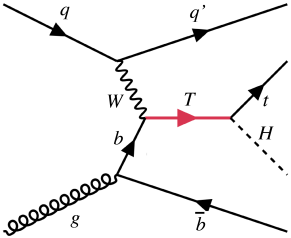
- Top quarks decay almost exclusively via $t \to W + b$
- Hadronically decaying boosted tops can be contained within single large-R jet

- Use trimmed anti-k_t $R = 1.0$ jets built from topological clusters
- Tagging via fully-connected feed-forward Deep Neural Network
- Input: jet mass, momentum, various jet moments
- Achieve strong rejection of background processes

  $\Rightarrow$ Improvements provide sensitivity gains beyond luminosity

Search for single production of a vector-like T quark

arXiv:2201.07045



Premise

- Vector like quarks (VLQ) could address hierarchy problem
- Have limits > 1 TeV for VLQ from previous LHC results
- Single VLQ production dominates at large masses

Analysis strategy

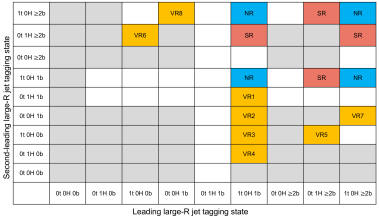
- Search $T \to Ht$ with hadronic top decay and $H \to bb$
- Reconstruct as 2 large-R jets with b-tagged subjets

Object tagging

- Higgs-tag: $100 < m_{\text{jet}} < 140$ GeV, two-body jet structure (via τ_{21})
- Top-tag: $140 < m_{\text{jet}} < 225$ GeV, DNN top tagger (80% working point (WP))
- B-tag: DNN-based DL1 tagger (70% WP), 0/1/2+ b-tagged subjets

Region definition

- Based on 9x9 tagging state table



Search for single production of a vector-like T quark

arXiv:2201.07045

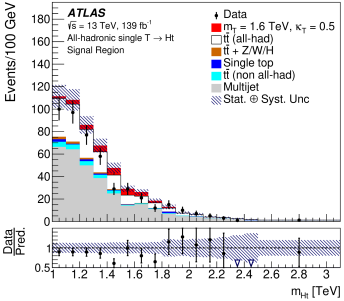
Backgrounds

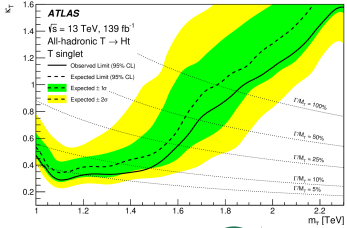
- Dominated by QCD multijet → estimated from data using ABCD method
- All-hadronic $t\bar{t}$ from simulation, constrained to data in 2 top-tag normalisation regions

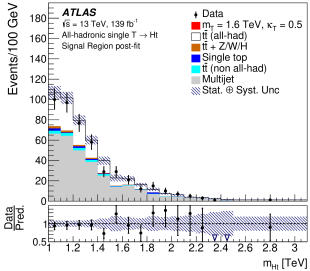
Results

- Binned-likelihood fit of dijet mass distributions
- Fit performed simultaneously in signal and normalisation regions
- No excess observed

  ⇒ Set limits as function of T mass and coupling κ







Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$

ATLAS-CONF-2022-008

Premise

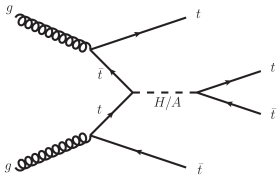
- Targets 2HDM type-II $t\bar{t}H \to t\bar{t}t\bar{t}$ signal and interpretation on low $\tan\beta$ region* in the alignment limit $\sin(\beta - \alpha) \to 1$
- All couplings similar to SM Higgs, $H/A \to t\bar{t}$ decay dominates

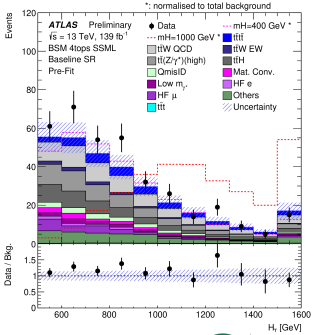
Analysis strategy

- Two channels: 2 same-sign leptons and at least three leptons
- Dedicated control regions to constrain dominant backgrounds
- Separation of signal and background done with MVA techniques

Region definition

- $H_T = \sum p_T^l + \sum p_T^{\text{jet}} \geq 500$ GeV
- ≥ 6 jets and ≥ 2 b-jets





*$\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets

Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$

ATLAS-CONF-2022-008

Backgrounds

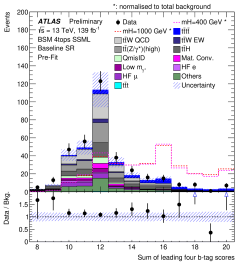
- Standard Model $t\bar{t}t\bar{t}$ (constrained with 20% x-sec uncertainty)
- $t\bar{t}W/t\bar{t}\gamma^*/t\bar{t}Z/t\bar{t}H$ + jets
- Charge mididentification, Non-promt leptons, photon conversion, Fake leptons

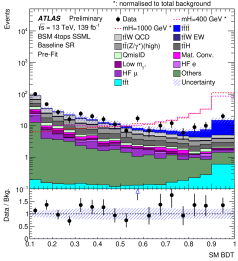
Signal selection

- Two stagged boosted decision trees
- First (SM BDT) to extract $t\bar{t}t\bar{t}$-like events
- Best discrimination from sum of pseudocontinuous b-tag scores
- Second uses output score of first as input along H_T, event shape, E_T^{miss} to separate out BSM $t\bar{t}t\bar{t}$ (pBDT)

Investigated Signals

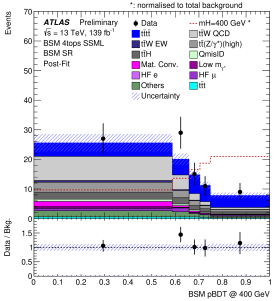
- Search for heavy Higgs in range of 400 GeV to 1 TeV

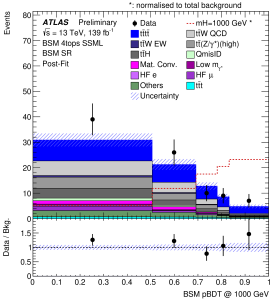


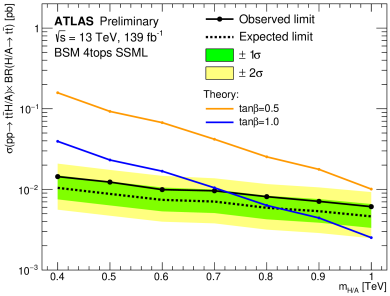


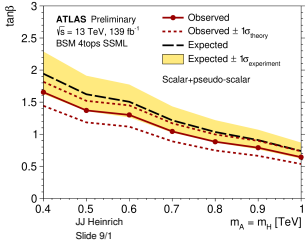
Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$

ATLAS-CONF-2022-008









Results

- Good separation of BSM signal against backgrounds
- Binned-likelihood fit in all signal and control regions
- No excess in data observed

  $\Rightarrow$ Set 95% CL limits on $t\bar{t}H/A$ cross-section and also translate into $\tan\beta$ versus mass plane

Search for mono-top + invisible

ATLAS-CONF-2022-036

Premise

- Mono-top signatures from top-associated dark matter (DM) production (res/non-res) or vector-like T
- Best sensitivity in hadronic top decay channel

Object tagging

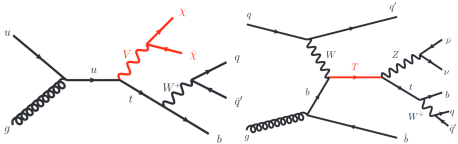
- Tops: Use DNN top tagger (50% working point)
- Bottoms: Use DL1r algorithm (77% working point)

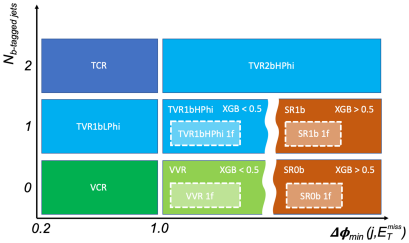
Event selection

- Require 0 leptons and one top-tagged jet with $350 < p_T^{\text{jet}} < 2500$ GeV and $40 < m_{\text{jet}} < 600$ GeV
- $E_T^{\text{miss}} > 250$ GeV

Region definition

- Regions defined based on number of b-tagged jets and minimal angle jet-E_T^{miss}



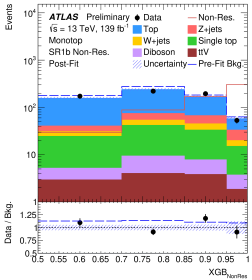


Search for mono-top + invisible

ATLAS-CONF-2022-036

Backgrounds

- Dominant backgrounds from $t\bar{t}$ and V+jets
- Have dedicated control regions to constrain backgrounds to data
- Minor backgrounds: single-top, multiboson



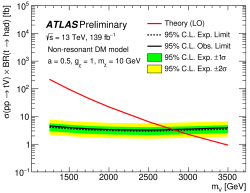
Signal regions

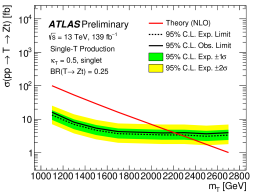
- Use extreme gradient BDT to discriminate signal and background
- Three different versions trained for VLQ, resonant and non-resonant DM

Results

- Profile-likelihood fit to event yields in control region and corresponding XGBOOST score in signal regions
- No excess in data found

  ⇒ Set 95% CL limits on production cross-section



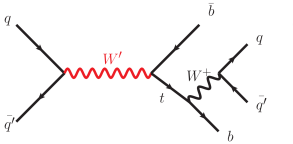


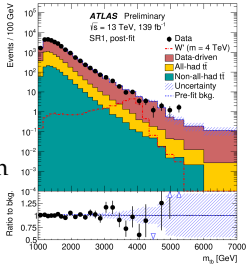
ATLAS heavy resonance searches

ATLAS-CONF-2021-043, ATLAS-CONF-2021-048

- Multiple BSM theories predict new gauge bosons on the TeV scale to address the hierarchy problem

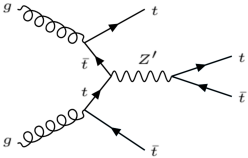
- Search for right-handed leptophobic W' with same coupling strength as SM W

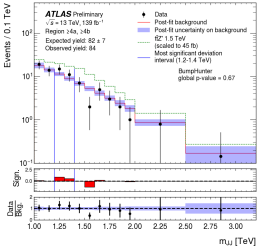




- Hadronic t identified from fat jets with DNN tagger
- tb invariant mass used as discriminant
- Data-driven background estimate
- W' with masses < 4.4 TeV (4.1 TeV exp.) excluded

- Search for heavy Z' in association with a top-pair where $Z' \to t\bar{t}$





- Looking at lepton+jets final state ($l = e, \mu$)
- Reconstruct fully hadronic Z' resonance from large-R jets
- Data-driven background estimate, fit of m_{jj}
- No excess observed $\Rightarrow$ Limits set

Conclusions

- ATLAS has a broad physics programme involving 3rd generation quarks
- 3rd generation quarks offer unique signatures which allow suppresssion of background
- Reconstruction and identification via highly sophisticated machine learning algorithms
- Continued improvements provide sensitivity gains beyond luminosity increase

- Roll-out of new results based on the full Run 2 dataset is still ongoing
- Reported on four recent ATLAS results:
  - Search for single vector-like T
  - Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$ production
  - Search for mono-top + invisible
  - W' resonance to top and bottom
- All searches reported here show no significant deviation from Standard Model expectation
- Continuing to push limits and sensitivities to unprecedented values