

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

Philipp Gadow (CERN) on behalf of the ATLAS collaboration

SUSY2023 “Alternative theories to SUSY”, Southampton, 17.07.2023



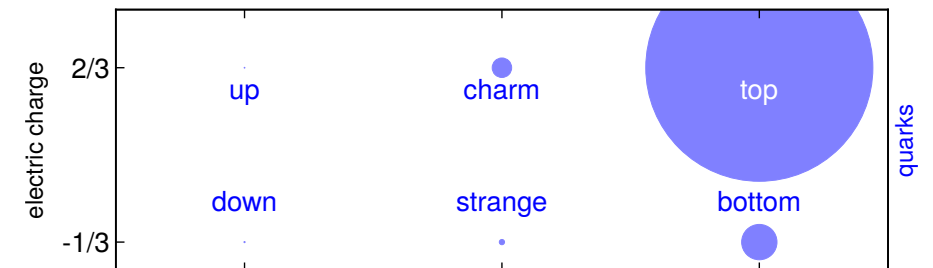
New phenomena

can be probed at the LHC in **final states with top and bottom quarks**. Talk covers:

- Heavy vector bosons and scalars: new gauge bosons or heavy Higgs bosons.
- Vector like quarks (VLQ): new colour-triplet fermions whose both chiralities, transform the same under SM gauge groups („vector-like“), could cancel quadratic divergence in Higgs mass.
- Leptoquarks (LQ): new colour-triplet bosons with both lepton and quark quantum numbers, could explain anomalies in decays of B mesons and the discrepancy between measured and predicted muon anomalous magnetic moment.

Why perform searches with **3rd generation quarks**?

- among the heaviest particles in the Standard Model: very large Yukawa coupling.
- great potential to reduce the Standard Model background due to unique signature.



Detecting 3rd generation quarks: bottom quarks

bottom quark

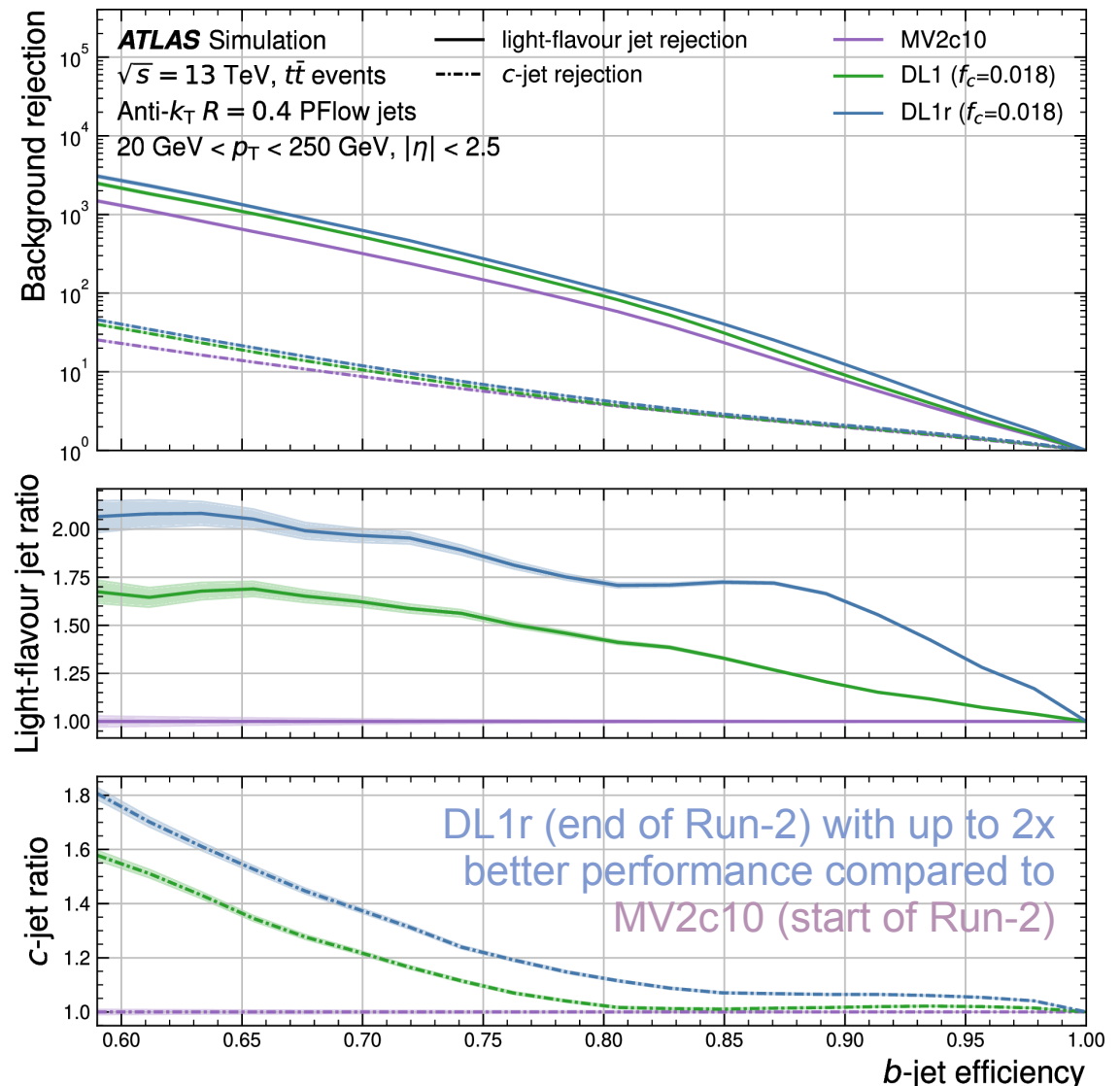


initiates formation of sprays of particles reconstructed as **jets from particle flow objects**.

Unique features of *b*-jets due to large lifetime and mass of B mesons (displaced secondary vertex, high mass and track multiplicity)...

... allow for their identification using multi-variate **machine learning algorithms**. →

Next generation: graph-neural-network algorithm GN2 (not discussed here, ask me about it!)



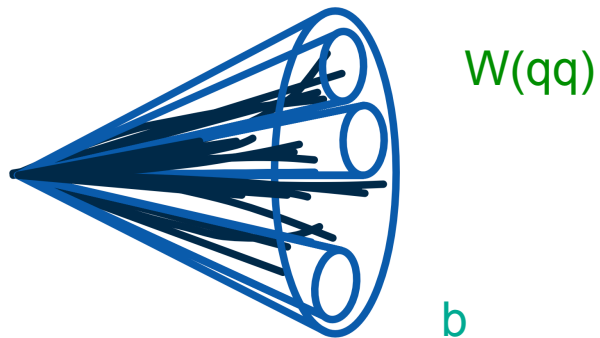
ATLAS Run 2 flavour-tagging algorithms

arXiv 2211.16345

Detecting 3rd generation quarks: top quarks

top quark

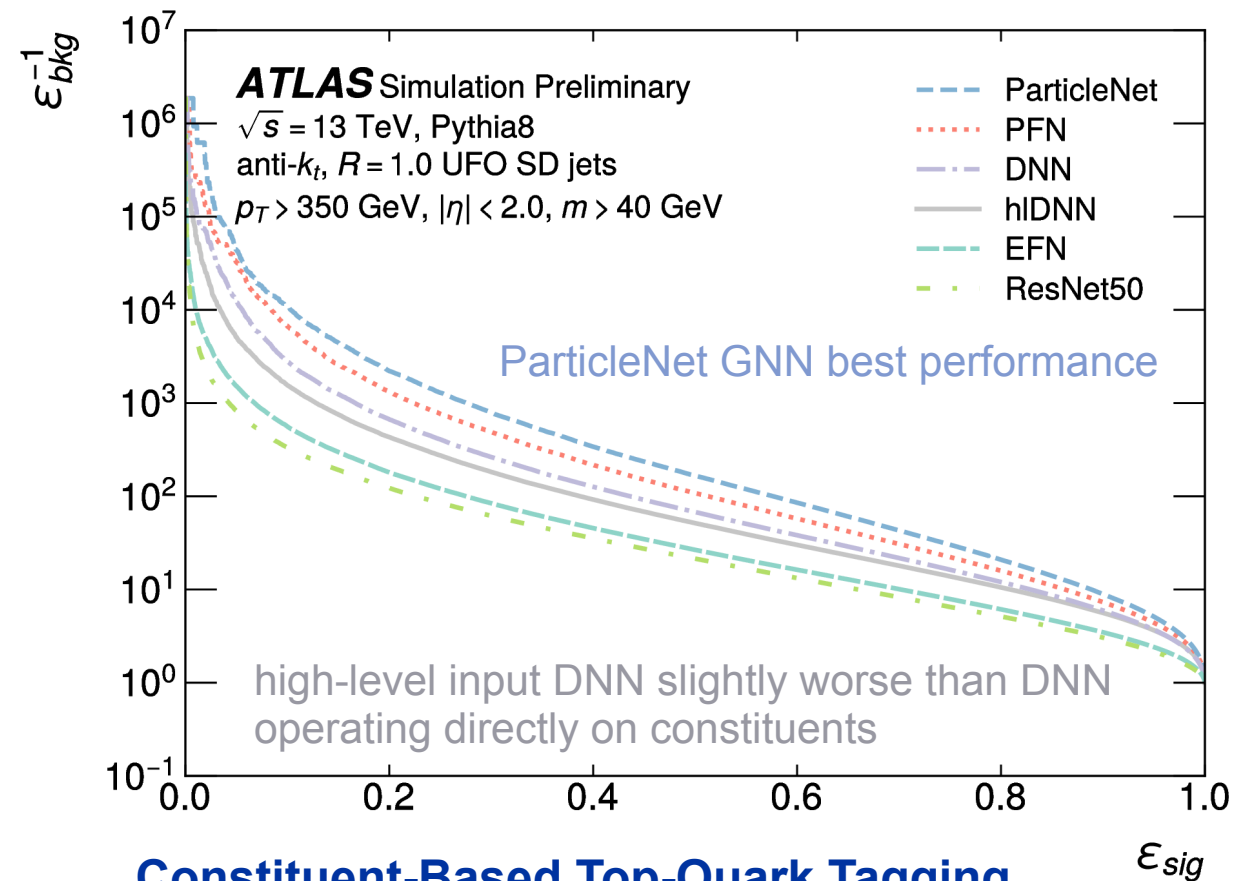
$t \rightarrow W + b$



reconstructed using jets with large-radius parameter (typical $R=1$) to contain full top quark decay.

Often large-radius jets are not reconstructed from calorimeter energy deposits but from small-radius jets.

„Jet reclustering“, see JHEP 02 (2015) 075



Constituent-Based Top-Quark Tagging

Top tagging with constituent-based machine learning models (ParticleNet, ParticleFlow network and Densely connected Neural Network) provides better discrimination than neural network based on high-level variables.

Data set of this note is publicly available!

Heavy resonances

Heavy Z' boson search in multi-top-quark final state

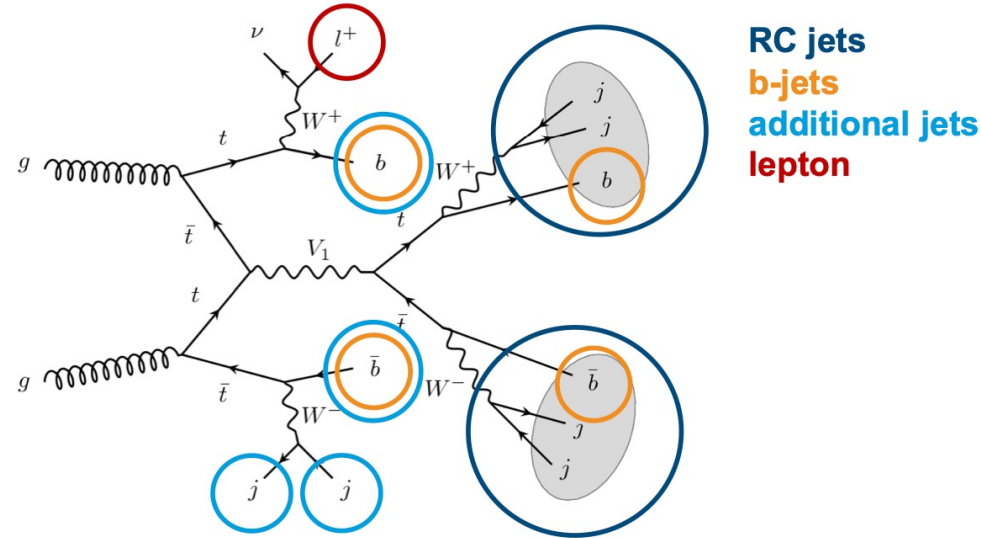
Signal: spin-1 resonance with exclusive coupling to top quarks

$$\mathcal{L} = c_t \bar{t} \gamma_\mu (\cos \theta P_L + \sin \theta P_R) t Z'^\mu$$

coupling strength c_t , chirality parameter θ
 $P_{L/R}$ projection operators

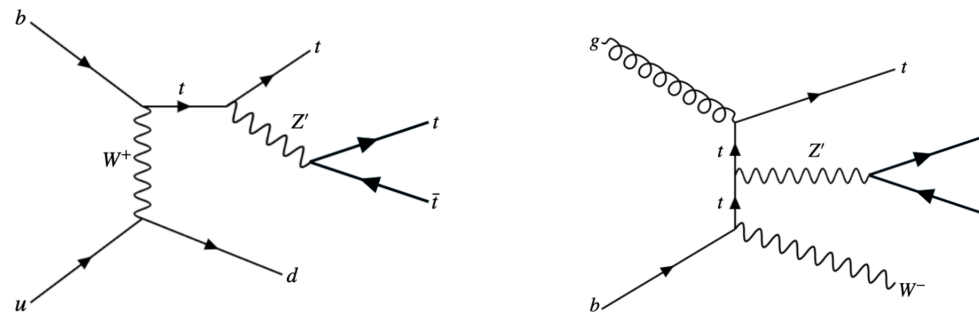
Final states: exactly 1 light lepton (e/ μ) with multiple jets and b-jets.

Reconstruction: Z' resonance decay reconstructed using large-radius reclustered jets with b-tagged sub-jets, top quarks from associated production reconstructed as additional small-radius jets which can be b-tagged.



RC jets
b-jets
additional jets
lepton

four top quark final state

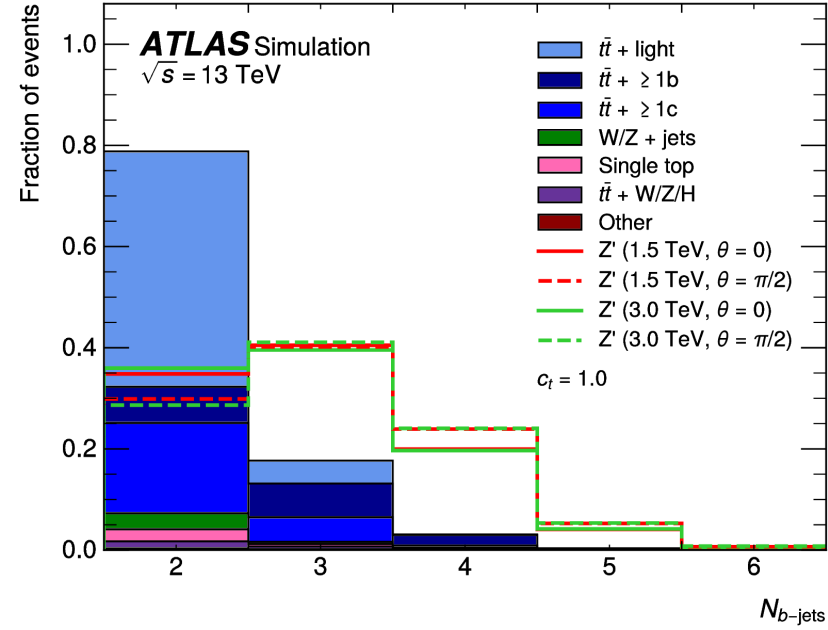
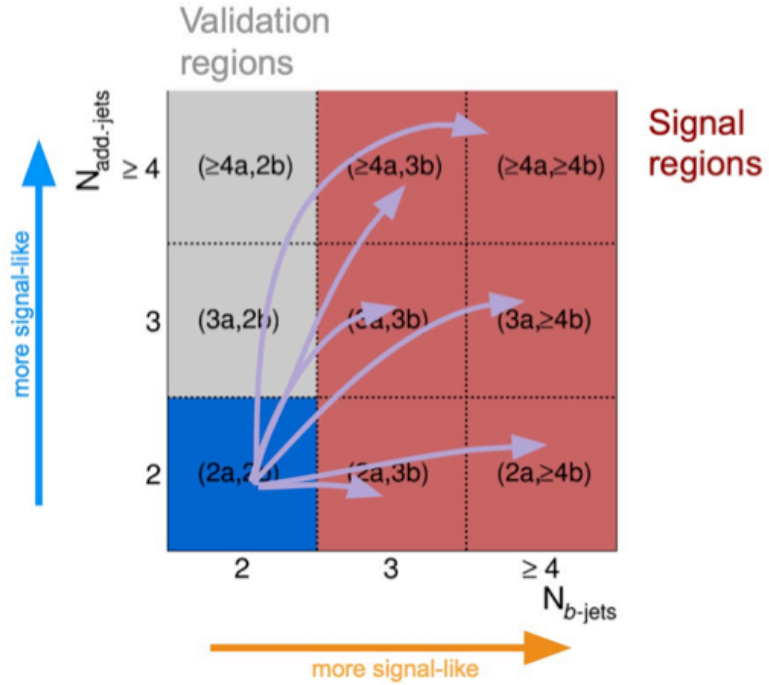
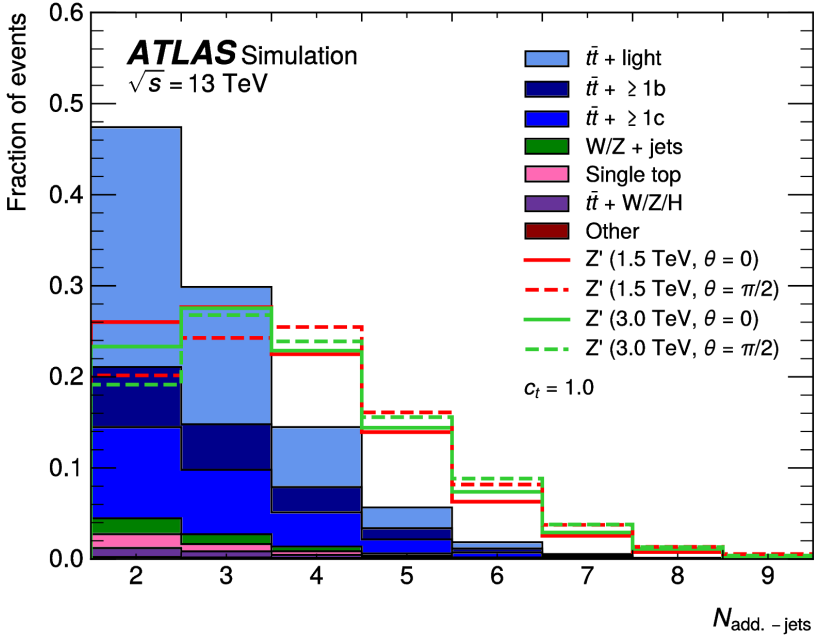


three top quark final states

Search for top-philic heavy resonances in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector

arXiv 2304.01678

Heavy Z' boson search in multi-top-quark final state



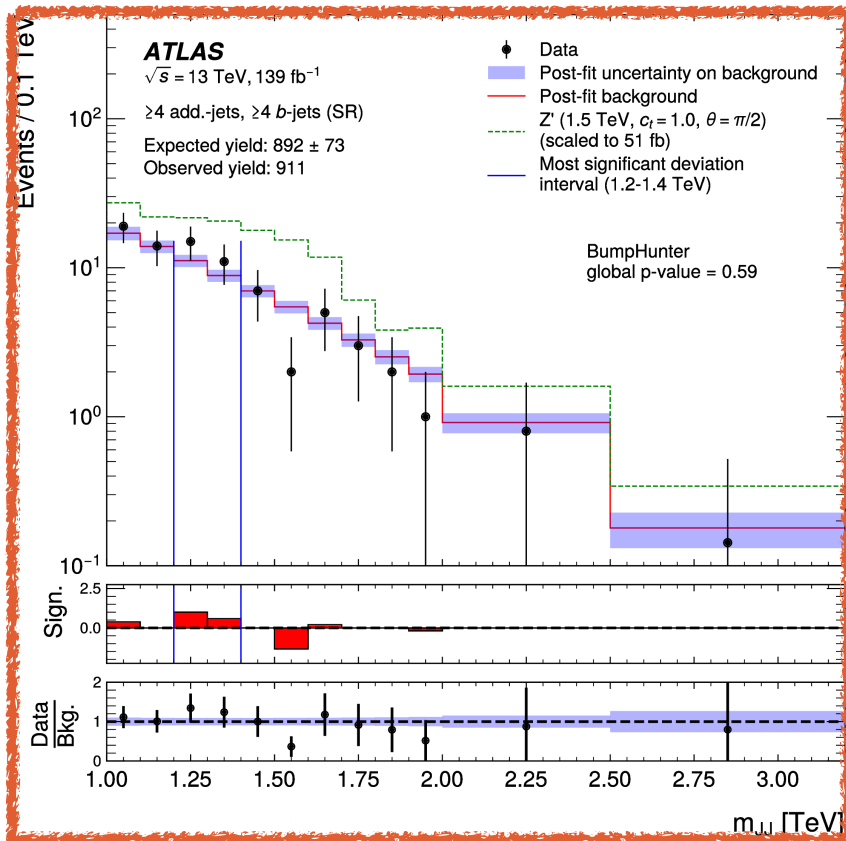
Analysis regions defined by **number of additional jets** and **number of b-jets**.

Background prediction from functional form fit to **source region data** and **MC-based extrapolation**.

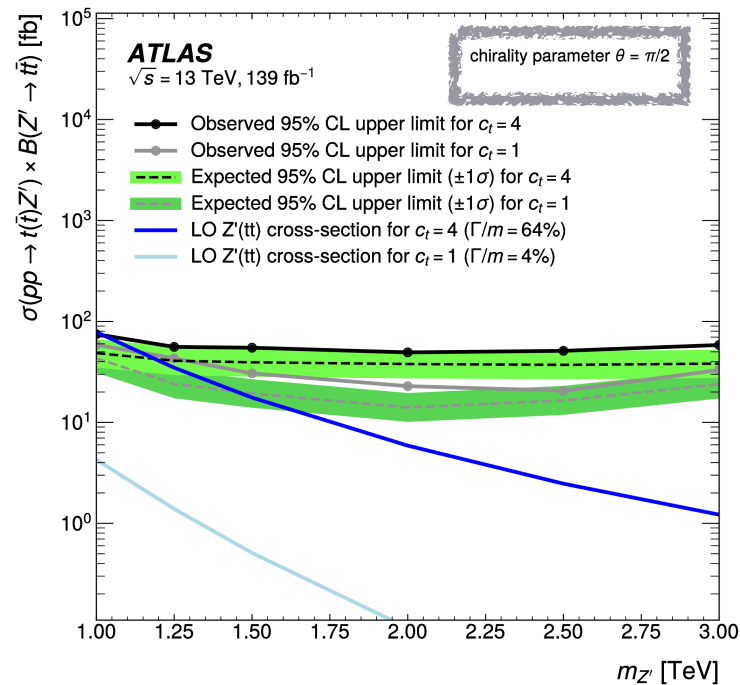
Heavy Z' boson search in multi-top-quark final state

Fit: Profile likelihood fit in 6 regions using **resonance top quark mass** as discriminating variable.

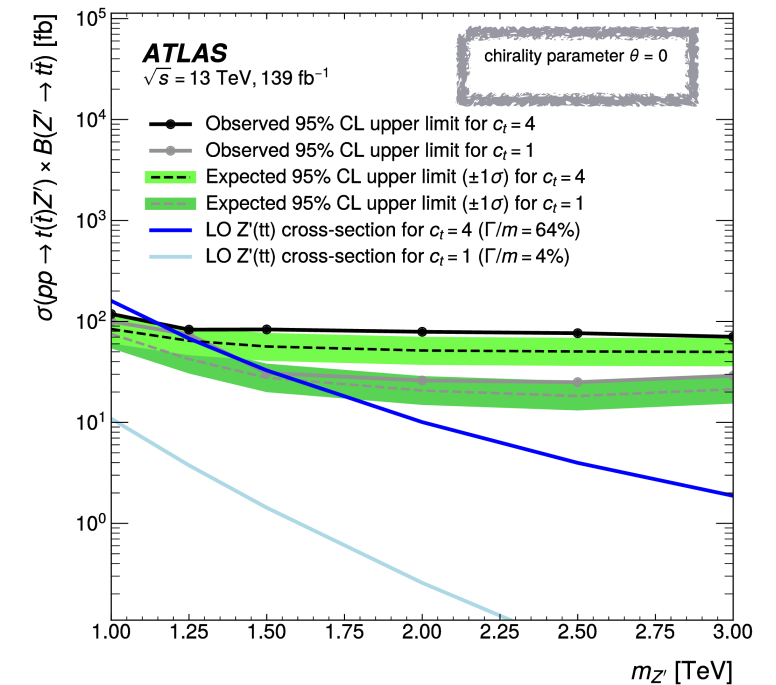
most sensitive signal region



minimal contribution of 3-top channel



maximal contribution of 3-top channel



Limits on cross-section for different coupling strengths and chirality parameter values.

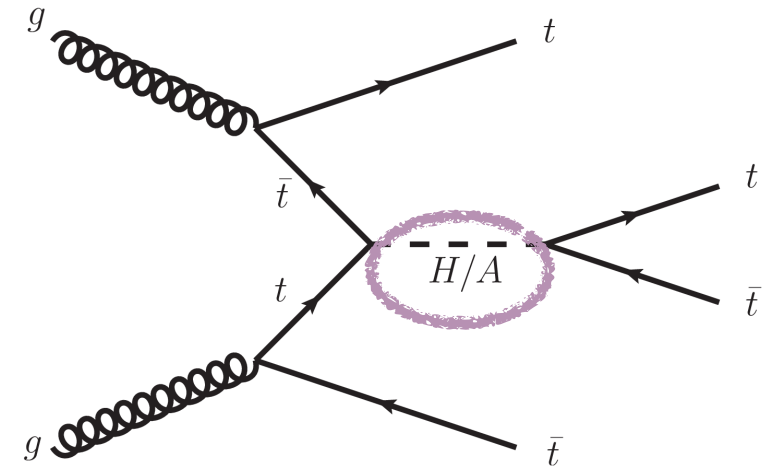
ttH/A decaying to 4-top in multi-lepton final states

Signal: new heavy scalar or pseudo-scalar Higgs boson produced with a top quark pair + decaying into top quark pair, assuming type-II Two-Higgs-Doublet model.

Final states: exactly 2 light leptons with same-sign electric charges or at least 3 light leptons with multiple jets and b-jets.

Backgrounds: low background contamination, mostly top quark pair production + W/Z/H, SM 4-top.

Trigger and event selection: single-lepton or dilepton triggers, exactly two same-sign electric charged leptons or 3+ leptons, veto on Z(ll) events, $m_{ee} > 15$ GeV to reduce low-mass resonance background with electron charge mis-identification.



four top quark
final state

Search for ttH/A \rightarrow tttt production in the multilepton final state in proton-proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector

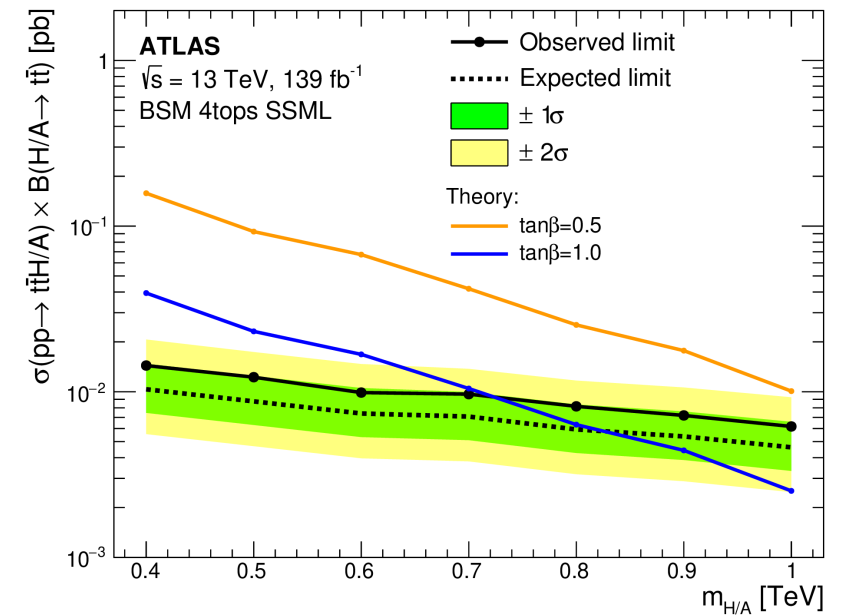
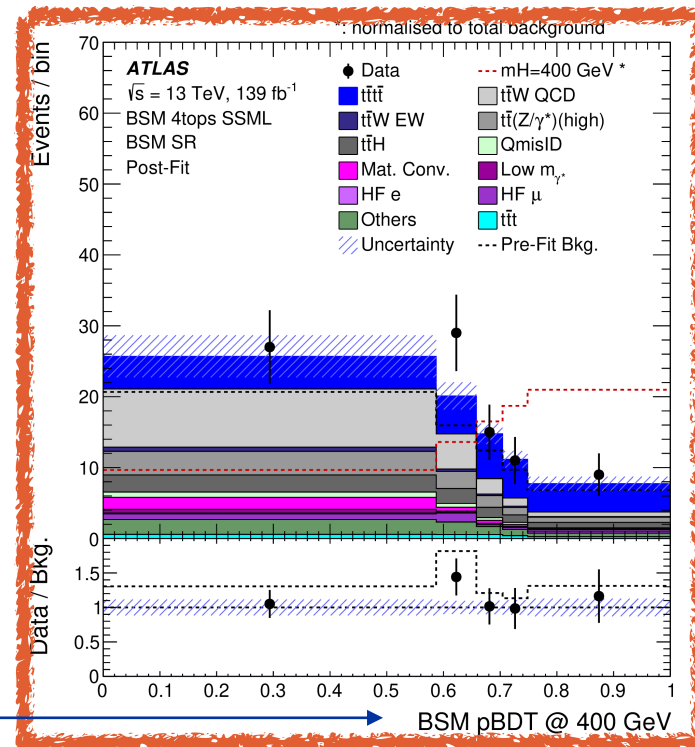
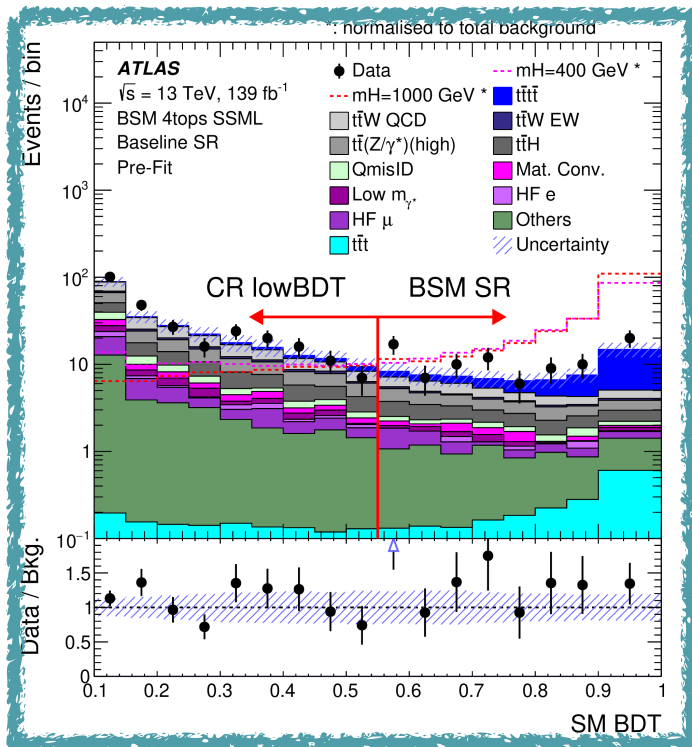
arXiv 2211.01136

ttH/A decaying to 4-top in multi-lepton final states

Fit: strategy based on SM 4-top observation, using **SM BDT to identify 4-top events** and define signal region. Use **BSM BDT parameterised in signal mass** as discriminant in template fit with dedicated control regions to constrain fake lepton and ttW backgrounds.

first find four-top-quark events

then discriminate SM vs BSM



Limits on cross-section between 14 fb and 6 fb across 400 GeV to 1 TeV signal mass.

Vector-like quarks (VLQ)

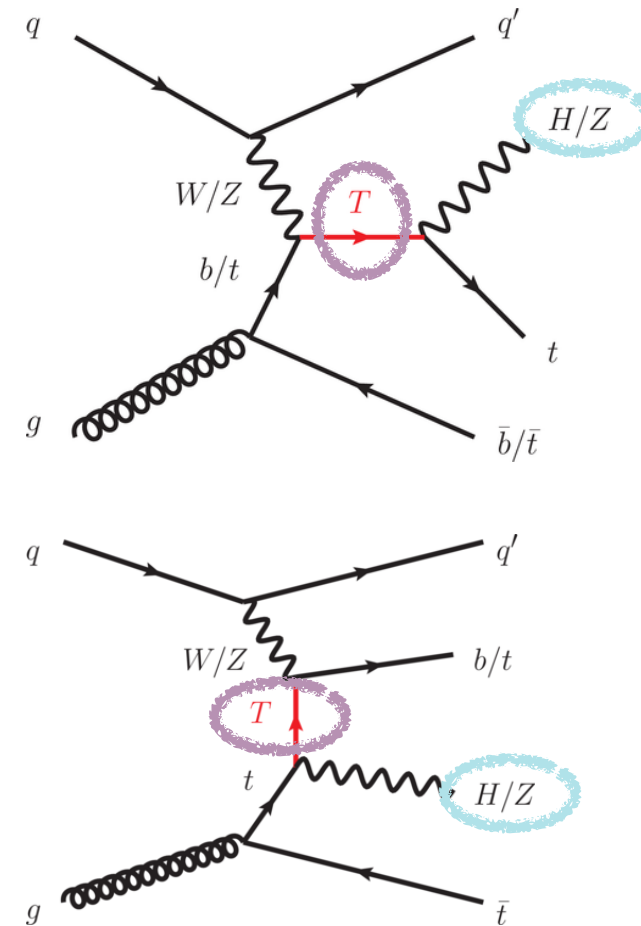
Single VLQ via Ht/Zt decay in 1-lepton channel

Signal: b- or t- associated production of up-type VLQ T

Final states: exactly 1 light lepton with multiple jets and b-jets, assuming top quark decay with leptons and Higgs or Z boson decaying hadronically.

Reconstruction: Heavy particles t, H, and W/Z are reconstructed and tagged with variable radius reclustered (vRC) jets. Leptonic top quark is reconstructed by calculating neutrino p_T using constraints from measured E_T^{miss} and W boson mass.

Trigger and event selection: single-lepton or E_T^{miss} trigger, exactly 1 lepton, 3 or more jets, at least 1 b-tagged jet, kinematic requirements to suppress multi-jet background and select events close to those expected from signal.



resonant
production

non-resonant
production

Search for single production of vector-like T quarks decaying to Ht or Zt

arXiv 2305.03401

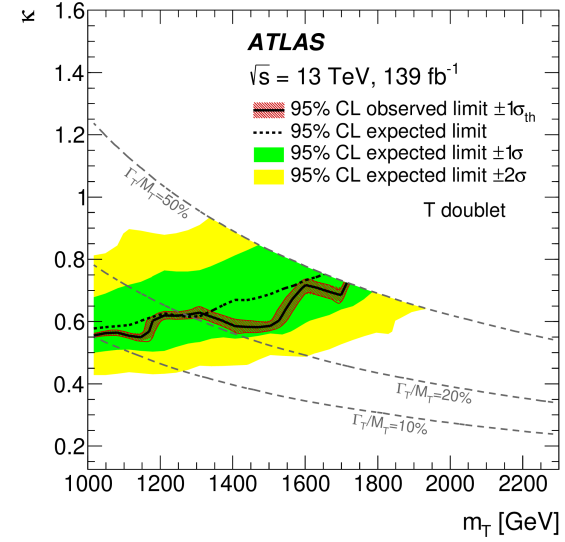
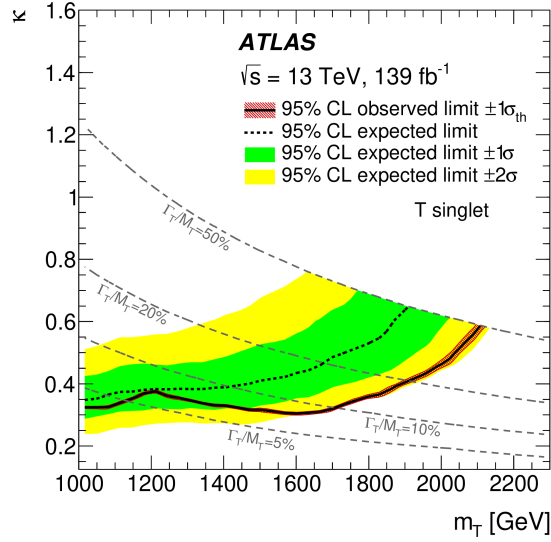
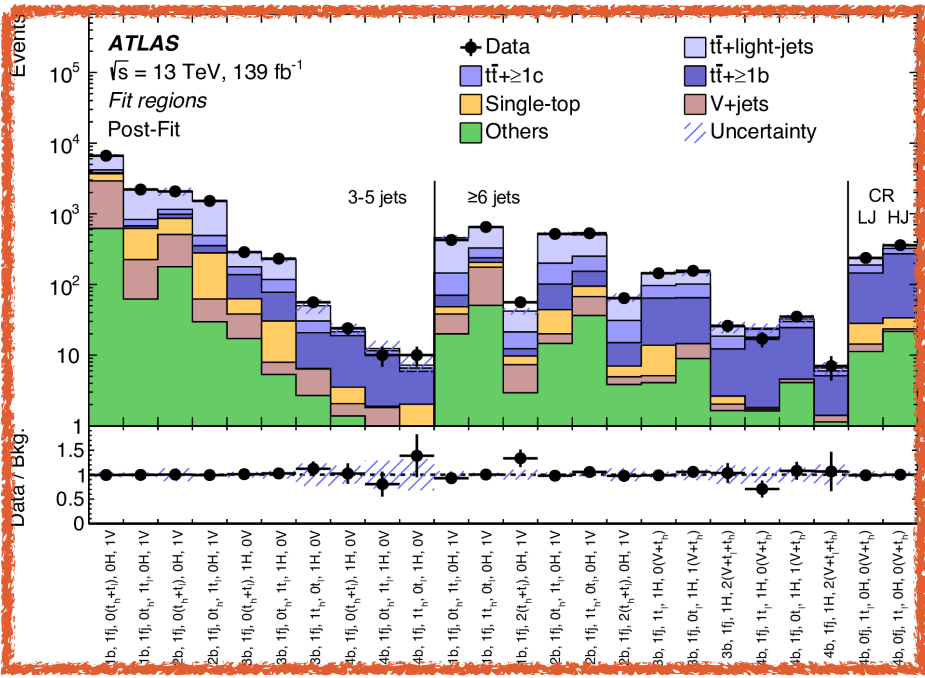
Single VLQ via Ht/Zt decay in 1-lepton channel

Backgrounds: top quark pair production, tW, and W+jets.

MC event simulation corrected using data-driven kinematic reweighting.

Fit: Profile likelihood fit in 24 regions using **effective mass** as discriminating variable.

scalar sum of lepton $p_{T,S}$, jet $p_{T,S}$ and $E_{T,miss}$



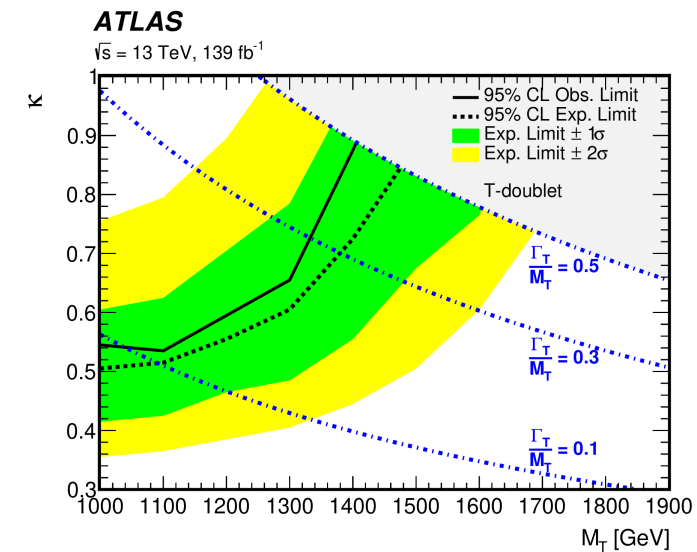
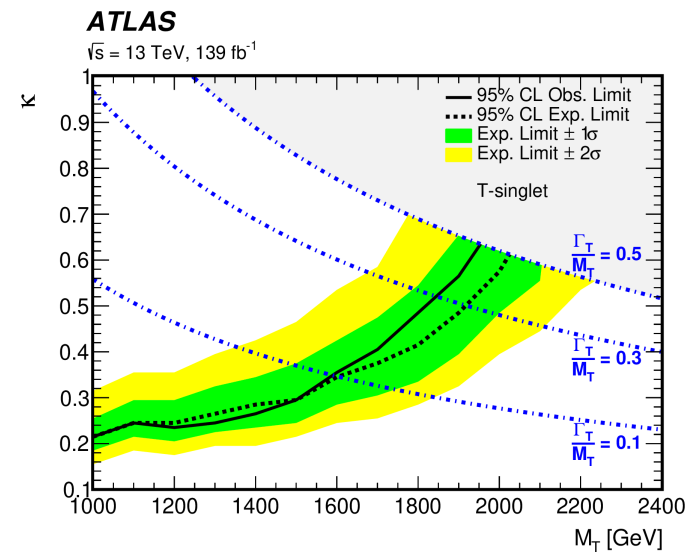
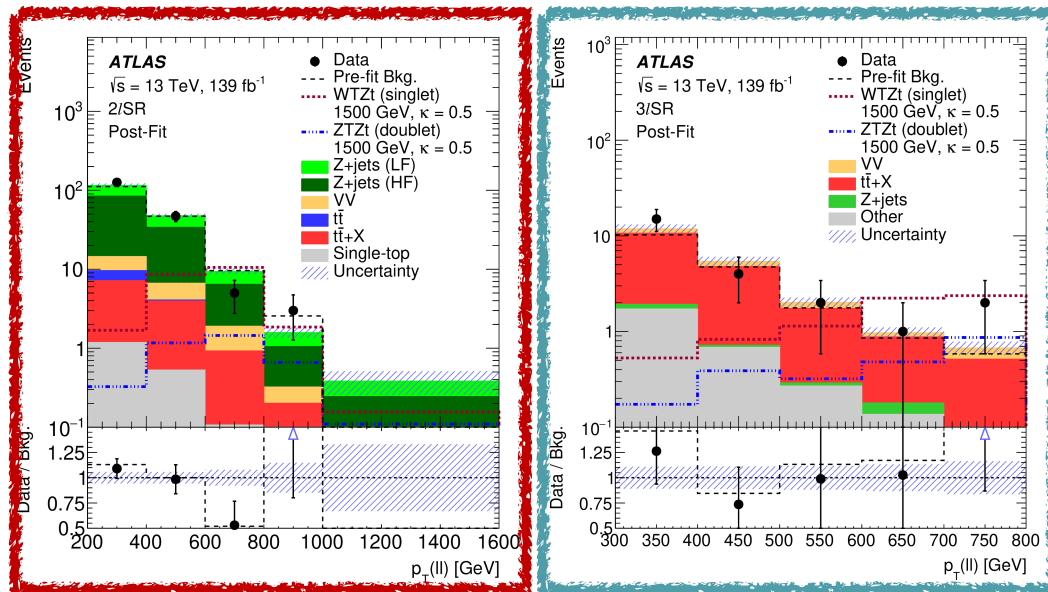
Limits on the universal coupling constant κ as a function of the VLQ mass in the SU(2) singlet and doublet scenarios.

Single VLQ via Zt decay in multilepton channel

Signal: b- or t- associated production of up-type VLQ T with leptonically decaying Z boson

Final states: exactly 2 opposite-electric charged light leptons or 3+ light leptons with multiple jets, forward jets and b-jets.

brand-new result with complementary limits to one-lepton channel analysis



Limits on the universal coupling constant κ as a function of the VLQ mass in the SU(2) singlet and doublet scenarios.

Search for singly produced vector-like top partners in multilepton final states with 139 fb⁻¹ of pp collision data at $\sqrt{s}=13$ TeV with the ATLAS detector

arXiv soon!

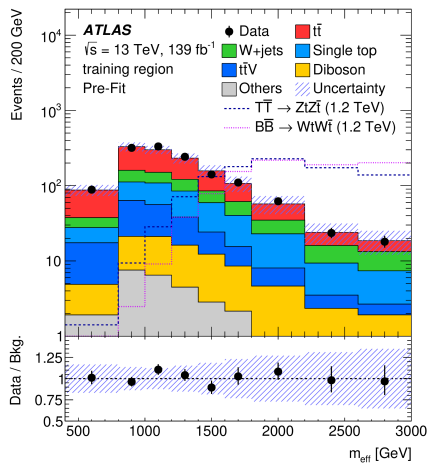
VLQ pair production (Zt+X decay) in 1-lep channel

Signal: vector-like partners T/B of top/bottom quarks, vector-like X with charge +5/3.

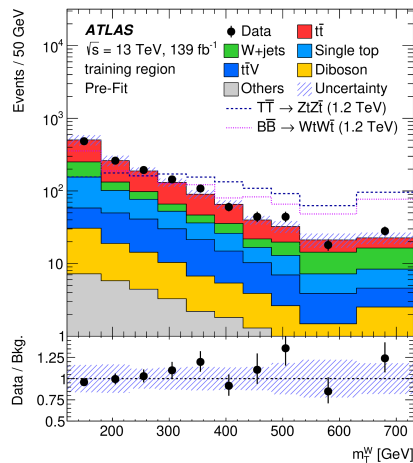
Final states: exactly 1 light lepton, 4+ jets, including 1+ b-jet and large E_{T}^{miss} .

Backgrounds: top quark pair production, W+jets.

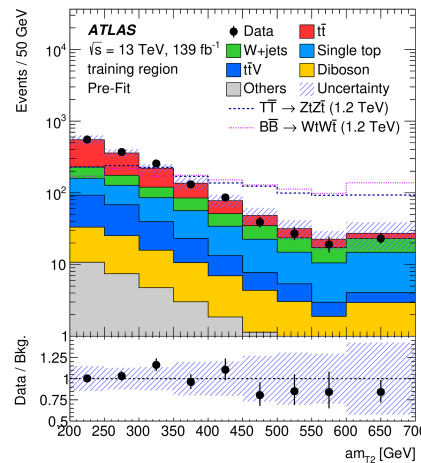
Reconstruction: neural networks for signal/background discrimination trained on several signal hypotheses using 13 input variables, including



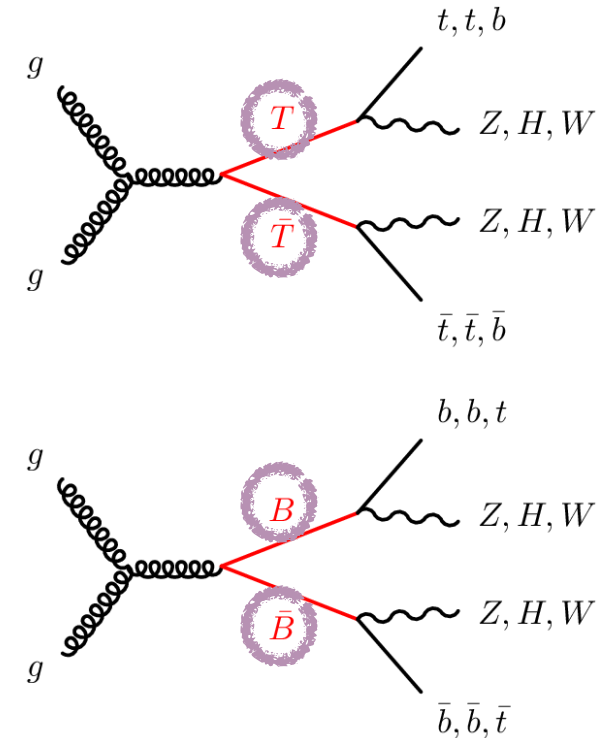
scalar sum of lepton p_{T^S} , jet p_{T^S} and E_{T}^{miss}



transverse mass of lepton and E_{T}^{miss}



asymmetric transverse mass

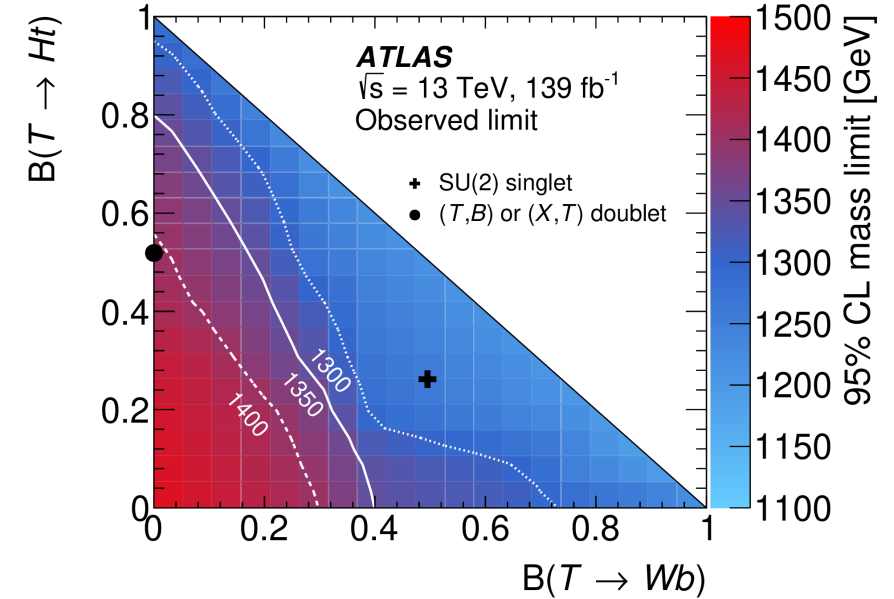
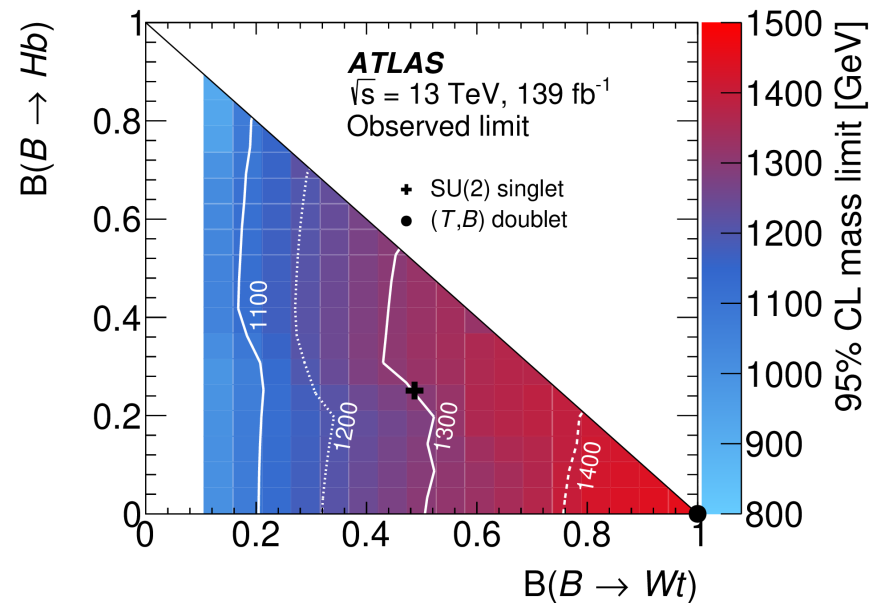
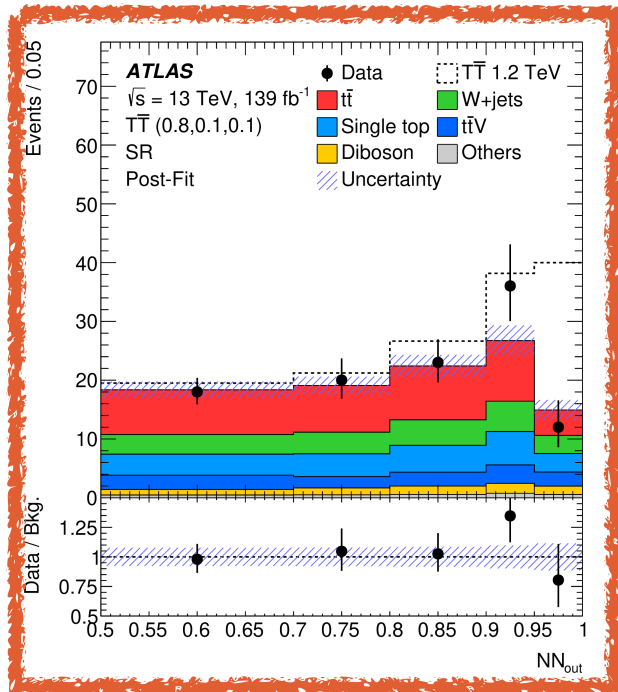


Search for pair-produced vector-like top and bottom partners in events with large missing transverse momentum in pp collisions with the ATLAS detector

arXiv 2212.05263

VLQ pair production ($Zt+X$ decay) in 1-lep channel

Fit: Profile likelihood fit using signal-enriched part of the **binned neural net (NN) output distribution** and total number of events in low- NN_{out} , W +jets and single-top control regions.



Limits are set on the pair-production cross-sections for T and B quarks at 95% CL.

Leptoquarks

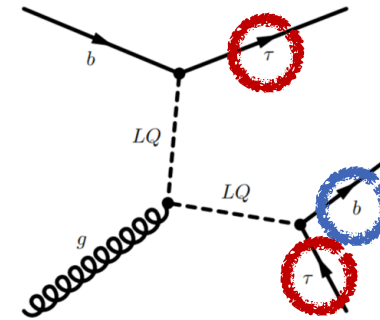
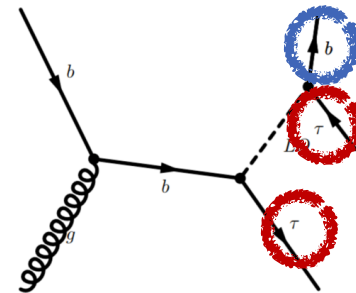
Single scalar leptoquark in b-tau final state

Signal: singly produced leptoquark (LQ) with $B(LQ \rightarrow b\tau) = 1.0$, neglecting interference with SM.

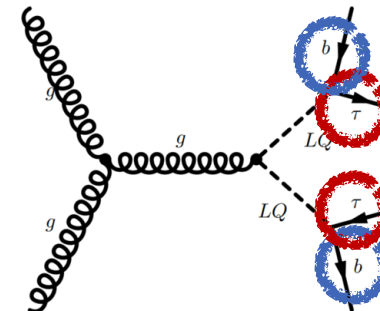
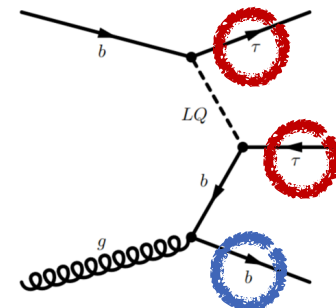
Final states: pair of tau leptons with opposite electric charge + high p_T b-jet.

Reconstruction: two signatures are considered, containing tau pairs in leptonic + hadronic or hadronic + hadronic decay channels.

Trigger and event selection: single lepton and hadronic tau triggers, (1+ hadronic tau and exactly 1 electron/muon) or (2+ hadronic taus and no electron/muon), opposite electric charges of tau candidates, 1 or more b-tagged jets, kinematic requirements, scalar sum of tau candidates and b-jet $S_T > 300$ GeV.



optimised for resonant production

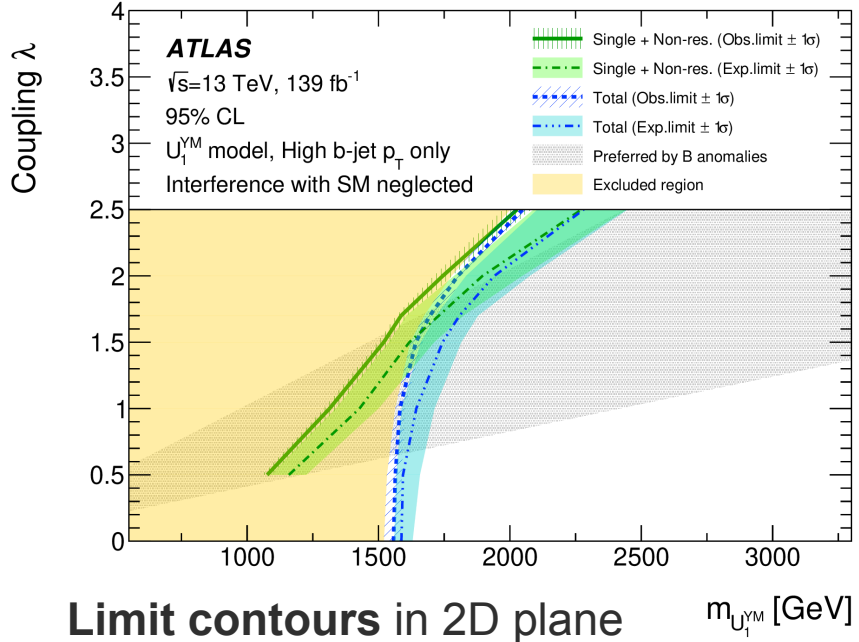
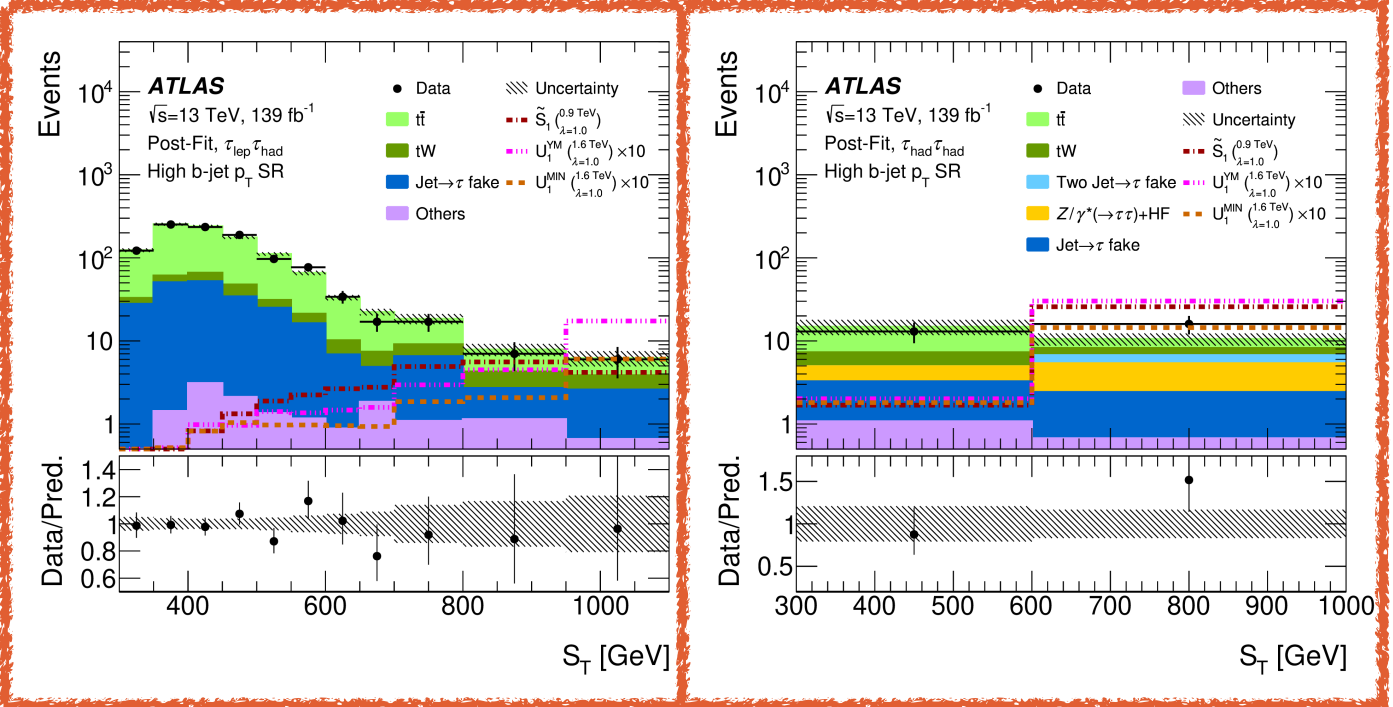


also sensitive to non-resonant production + pair production

Single scalar leptoquark in btau tau final state

Backgrounds: top quark pairs and tW production.

Fit: profile likelihood fit using S_T as discriminating variable in regions with b-jet $p_T > 200$ GeV.



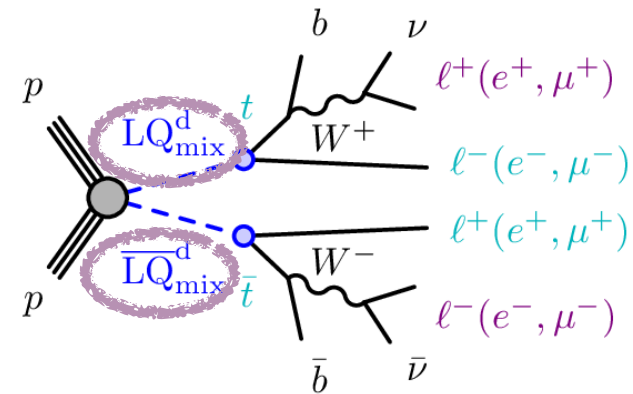
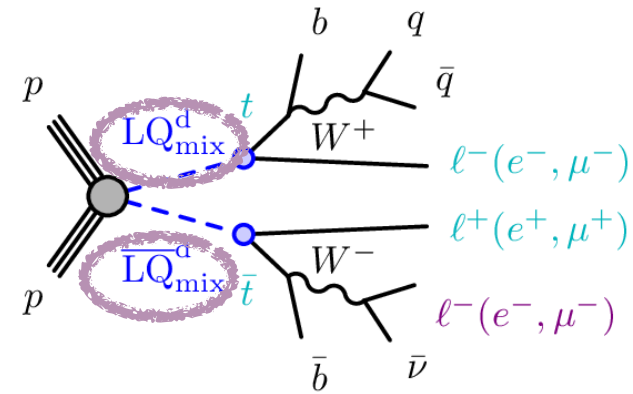
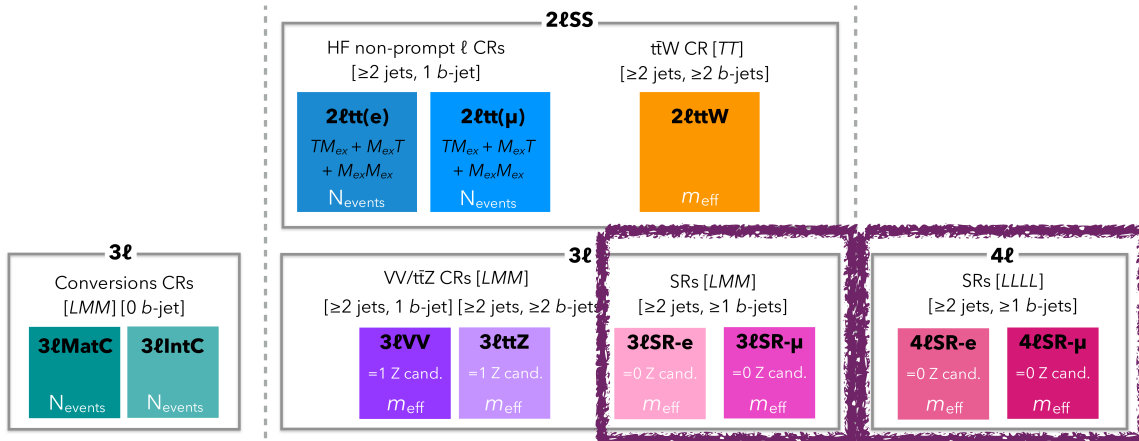
Limit contours in 2D plane of coupling and LQ mass extending from 1.6 TeV to 2 TeV in LQ mass.

Leptoquark pairs decaying to top + electron/muon

Signal: pair-produced leptoquarks decaying into $t\bar{t}$ or $t\bar{t}\mu\mu$ with $B(LQ \rightarrow t\ell) = 1$.

Final states: 3 or 4 light leptons, 2 or more jets, of which at least 1 b-tagged jet.

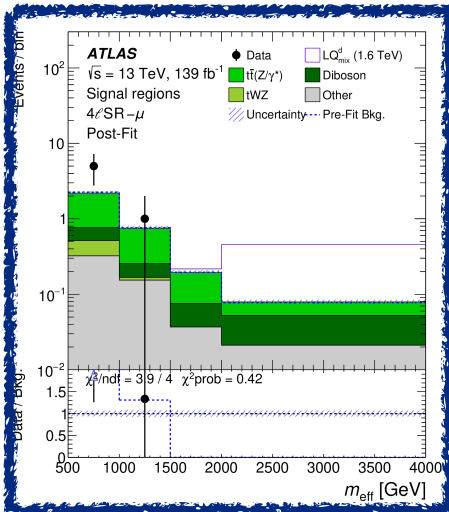
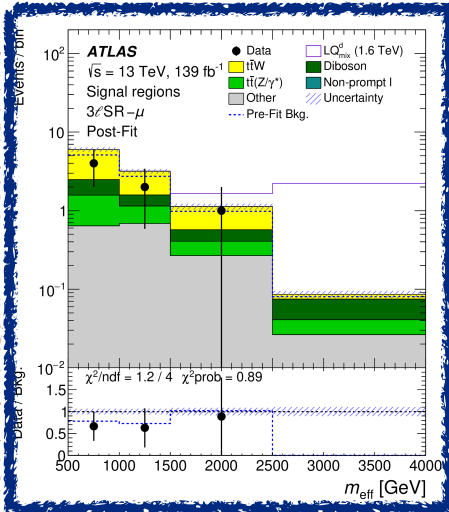
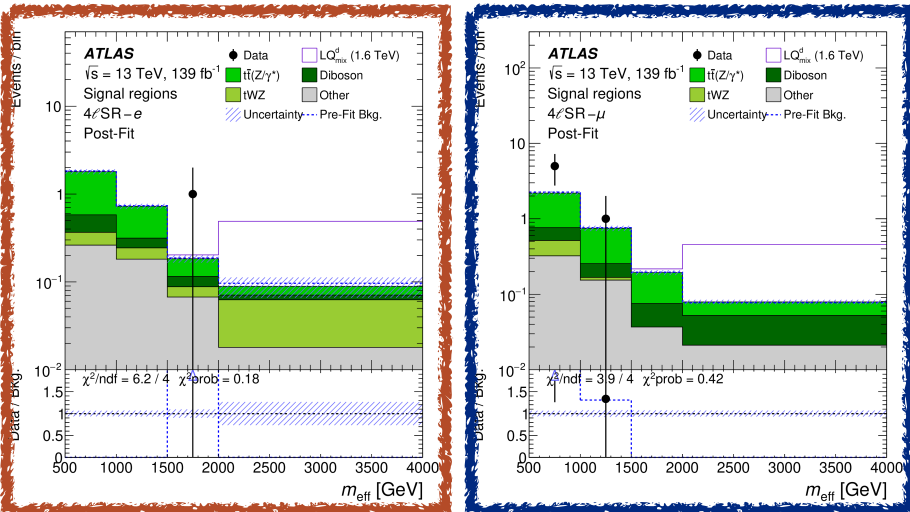
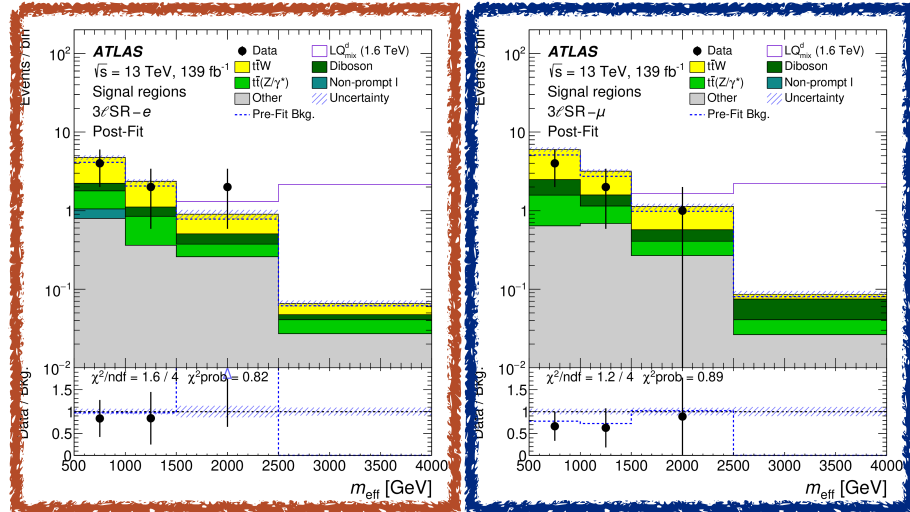
Analysis regions:



Search for leptoquark pair production decaying into $t\bar{t}$ or $t\bar{t}\mu\mu$ in multi-lepton final states in pp collisions at 13 TeV with the ATLAS detector

arXiv 2306.17642

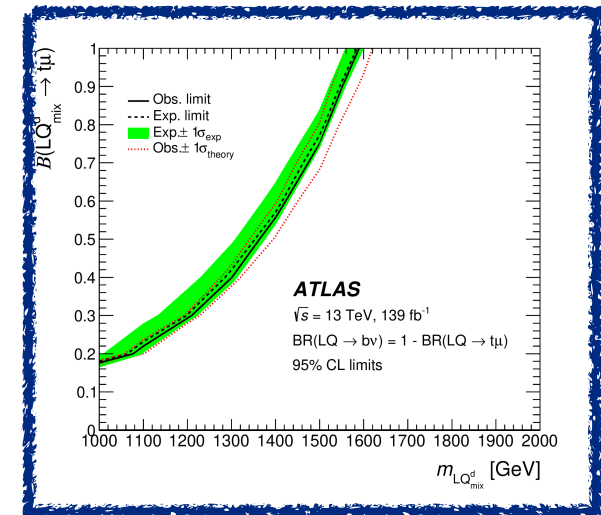
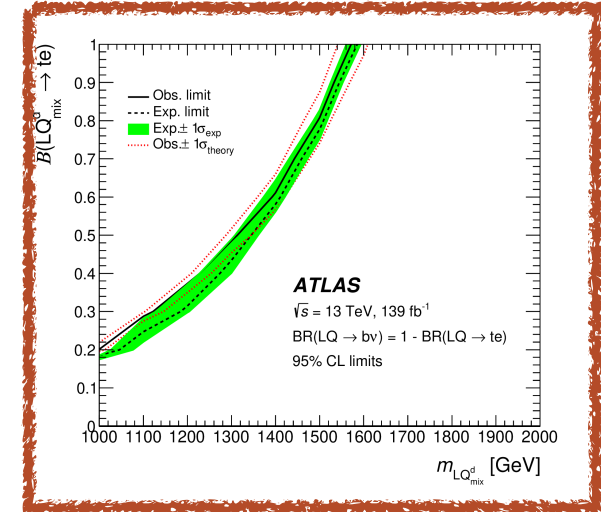
Leptoquark pairs decaying to top + electron/muon

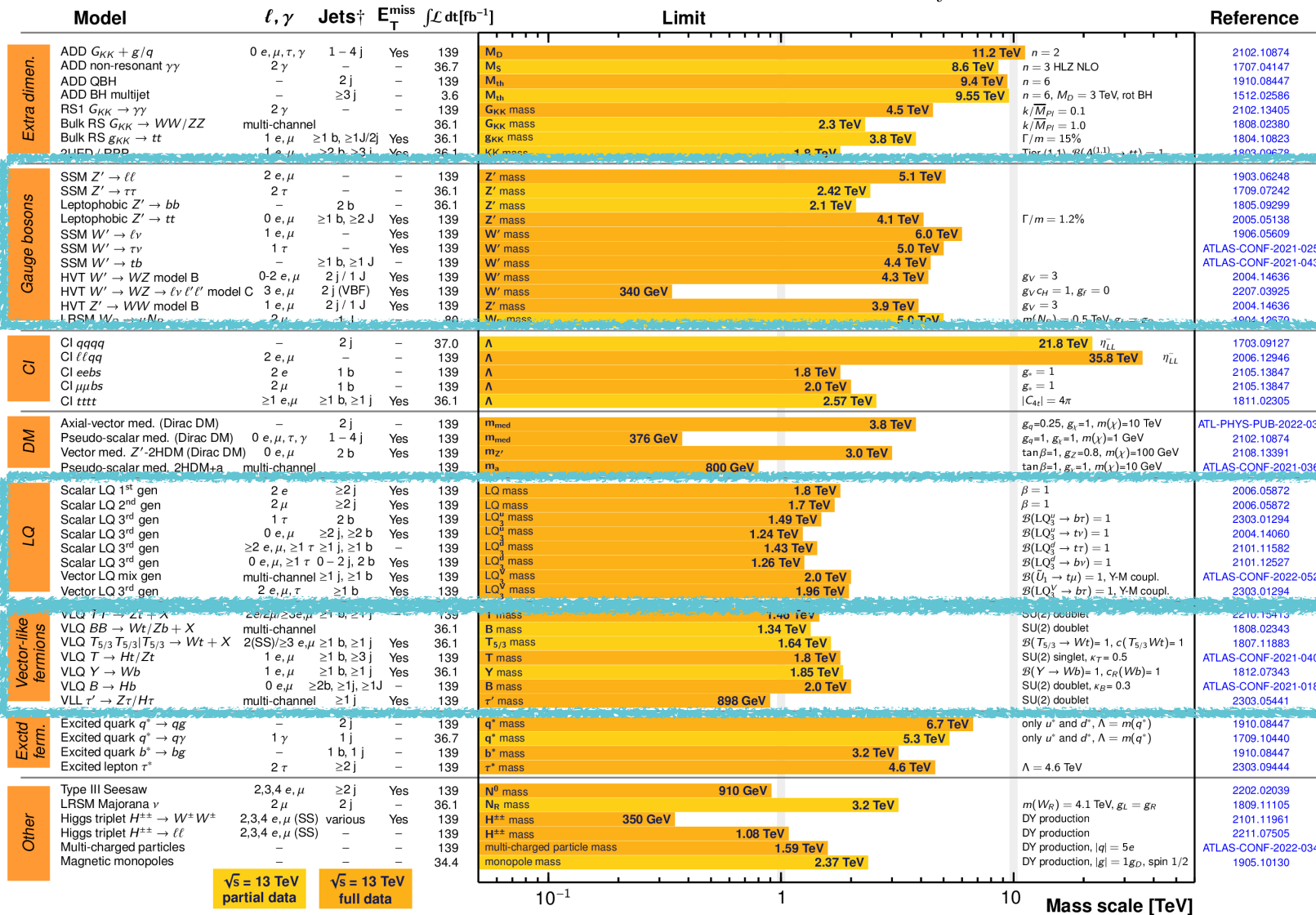


Fit: profile likelihood fit using **effective mass** as discriminating variable for each signal hypothesis ($tete/t\mu t\mu$) with

- all control regions and 3ISR-e + 4ISR-e signal regions for $B(\text{LQ} \rightarrow te)$ interpretation, or
- all control regions and 3ISR- μ + 4ISR- μ signal regions for $B(\text{LQ} \rightarrow t\mu)$ interpretation.

Limits on the cross section for the LQ_{mix}^d pair production as a function of the assumed signal mass and branching fraction.





*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).

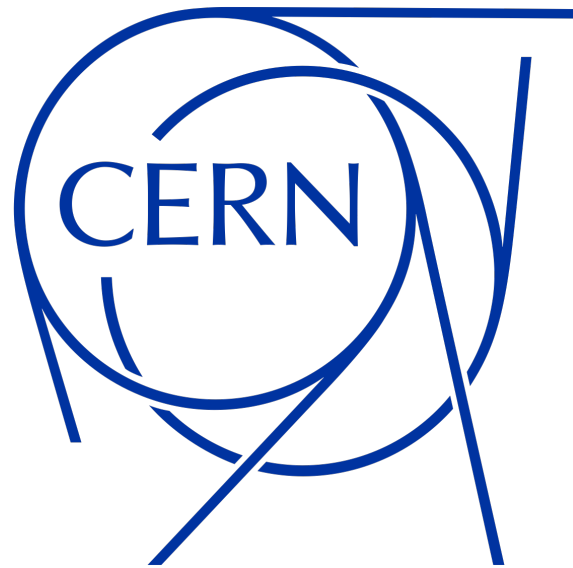
Conclusions

Novel techniques for reconstruction and signal/background discrimination provide increased sensitivity.

ATLAS covers a wide range of searches involving 3rd generation quarks, including searches for

- heavy resonances
- vector-like quarks
- leptoquarks

and constrains the viable parameter space of the respective models.



One more thing...



ATLAS CONF Note

ATLAS-CONF-2023-021

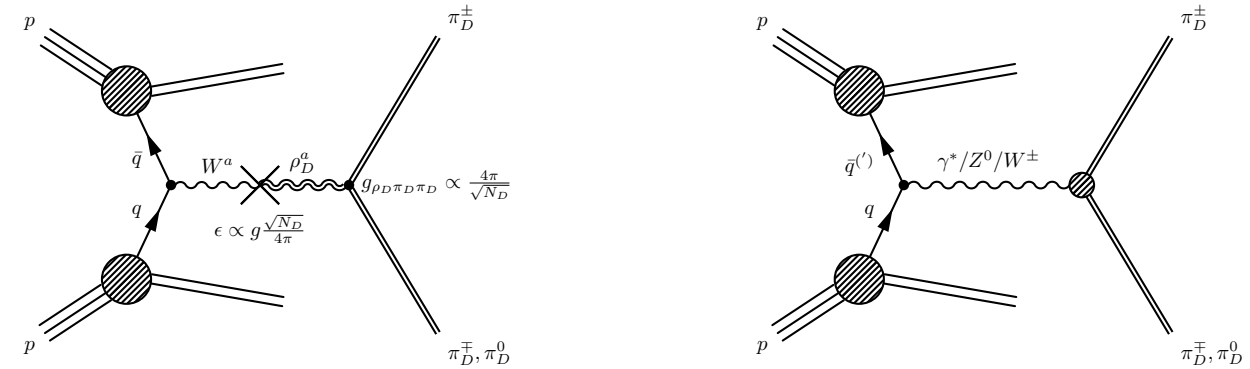
16th May 2023



Search for dark mesons decaying to top and bottom quarks with the ATLAS detector in 140 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13 \text{ TeV}$

The ATLAS Collaboration

very interesting result, not directly addressed by classes of models mentioned in abstract but relevant given final states containing top and bottom quarks



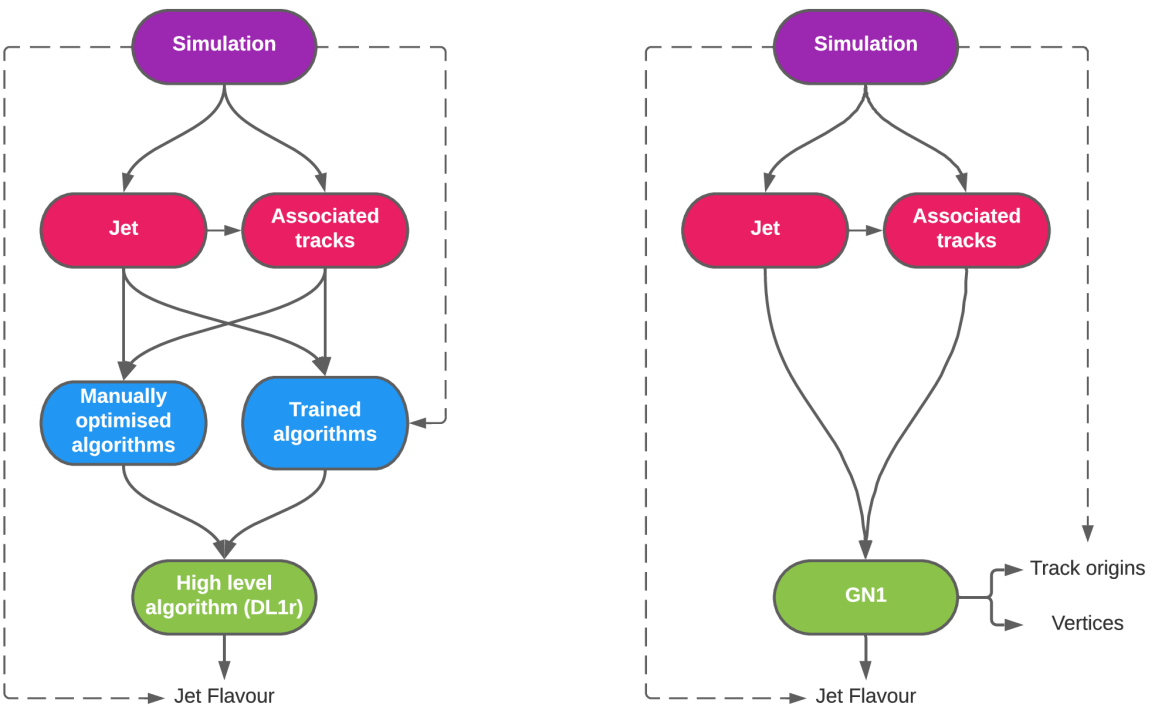
A search for dark mesons originating from strongly-coupled, $SU(2)$ dark flavour symmetry conserving models and decaying gaugephobically to pure Standard Model final states containing top and bottom quarks in fully hadronic topologies is performed. The analysis of the full Run 2 proton–proton collision data sample corresponding to 140 fb^{-1} collected at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector at the Large Hadron Collider yields no significant excess over the Standard Model background expectation. The two-dimensional signal space of dark pion masses m_{π_D} and dark rho masses m_{ρ_D} is scanned. For $m_{\pi_D}/m_{\rho_D} = 0.35$, dark pions with masses $m_{\pi_D} < 434 \text{ GeV}$ are excluded, while for $m_{\pi_D}/m_{\rho_D} = 0.25$ the exclusion covers the mass range $280 \text{ GeV} < m_{\pi_D} < 522 \text{ GeV}$.

Search for dark mesons decaying to top and bottom quarks with the ATLAS detector in 140 fb^{-1} of proton-proton collisions at $\sqrt{s}=13 \text{ TeV}$

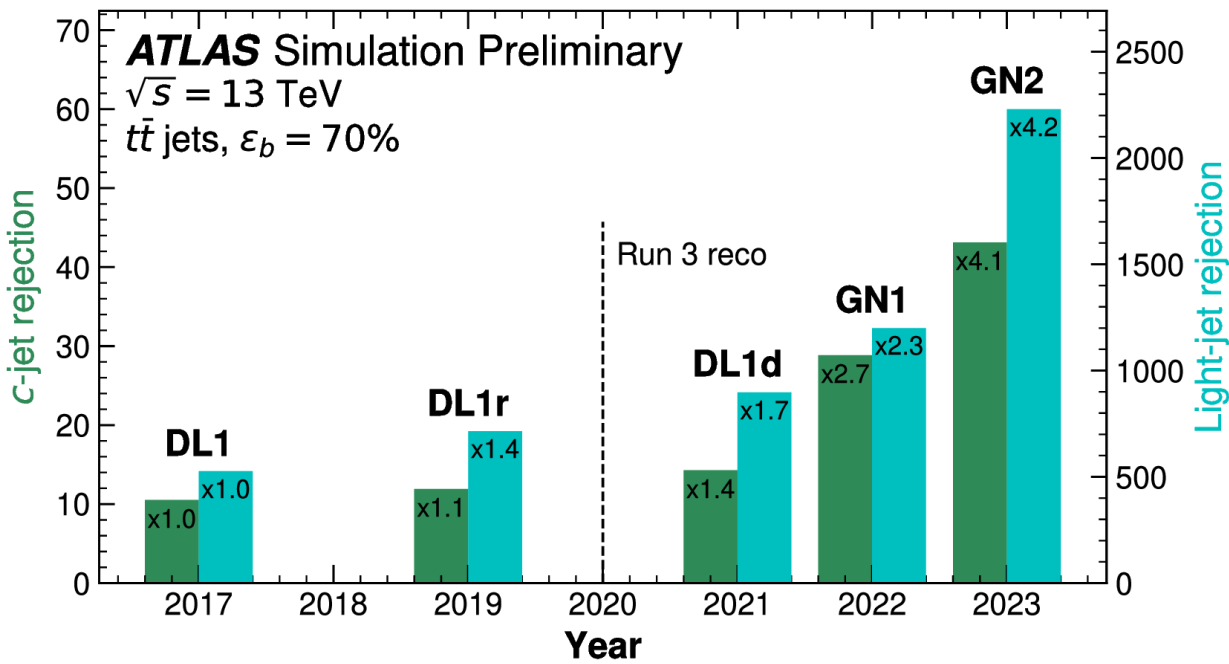


Next generation ATLAS flavour tagging algorithm

New approach to algorithm design



Performance improvements

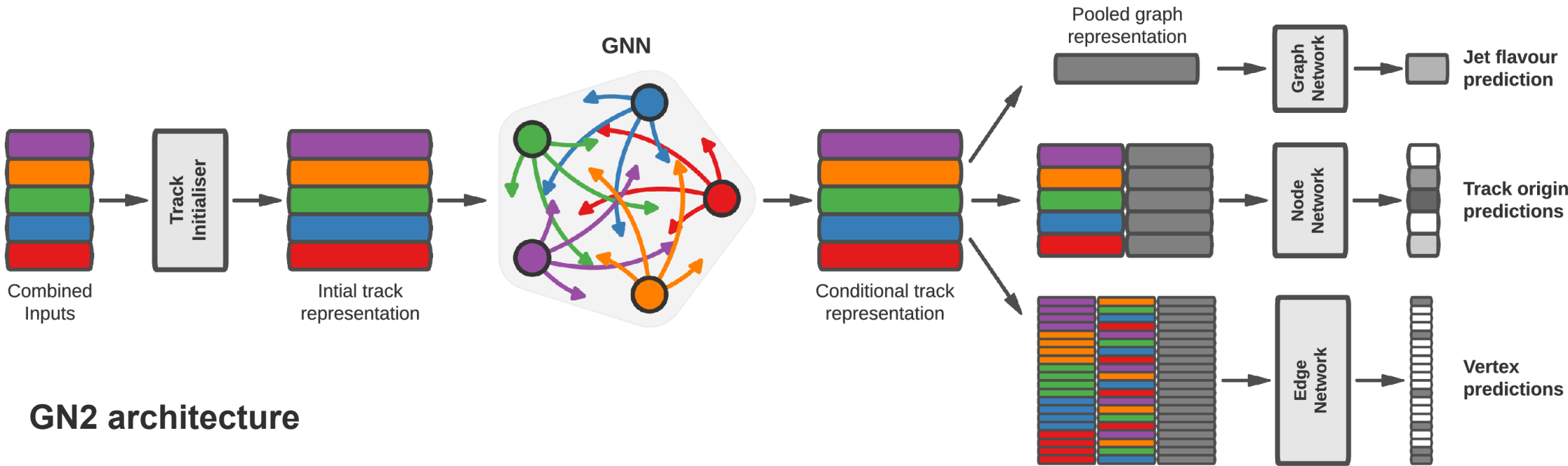


Graph Neural Network Jet Flavour Tagging with the ATLAS Detector

Jet Flavour Tagging With GN1 and DL1d. Generator dependence, Run 2 and Run 3 data agreement studies





Next generation ATLAS flavour tagging algorithm



GN2 architecture

EP-IT Data Science Seminar: <https://indico.cern.ch/event/1232499>

ATLAS Open Data for top quark tagging

Help About ▾

ATLAS Top Tagging Open Data Set

ATLAS collaboration

Cite as: ATLAS collaboration (2022). ATLAS Top Tagging Open Data Set. CERN Open Data Portal. DOI:[10.7483/OPENDATA.ATLAS.FG5F.96GA](https://doi.org/10.7483/OPENDATA.ATLAS.FG5F.96GA)

Dataset Derived Datascience ATLAS CERN-LHC

Description

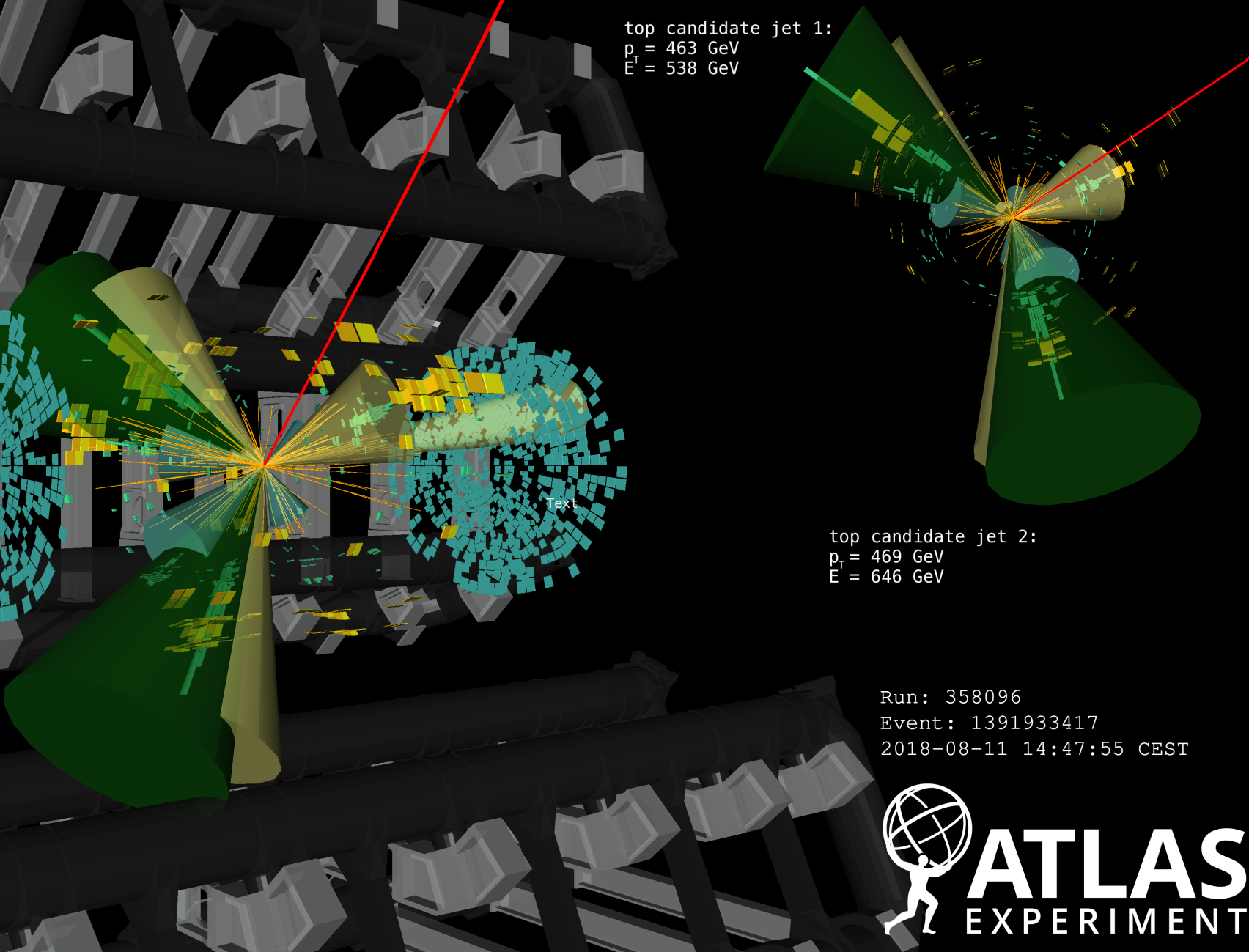
Boosted top tagging is an essential binary classification task for experiments at the Large Hadron Collider (LHC) to measure the properties of the top quark. The ATLAS Top Tagging Open Data Set is a publicly available data set for the development of Machine Learning (ML) based boosted top tagging algorithms. The data are split into two orthogonal sets, named train and test and stored in the HDF5 file format, containing 42 million and 2.5 million jets respectively. Both sets are composed of equal parts signal (jets initiated by a boosted top quark) and background (jets initiated by light quarks or gluons). For each jet, the data set contains:

- The four vectors of constituent particles
- 15 high level summary quantities evaluated on the jet
- The four vector of the whole jet
- A training weight
- A signal (1) vs background (0) label.

There is one rule in using this data set: the contribution to a loss function from any jet should always be weighted by the training weight. Apart from this a model should separate the signal jets from background by whatever means necessary.

<http://opendata.cern.ch/record/15013>





Heavy resonance decaying to top quarks produced in association with a top quark pair

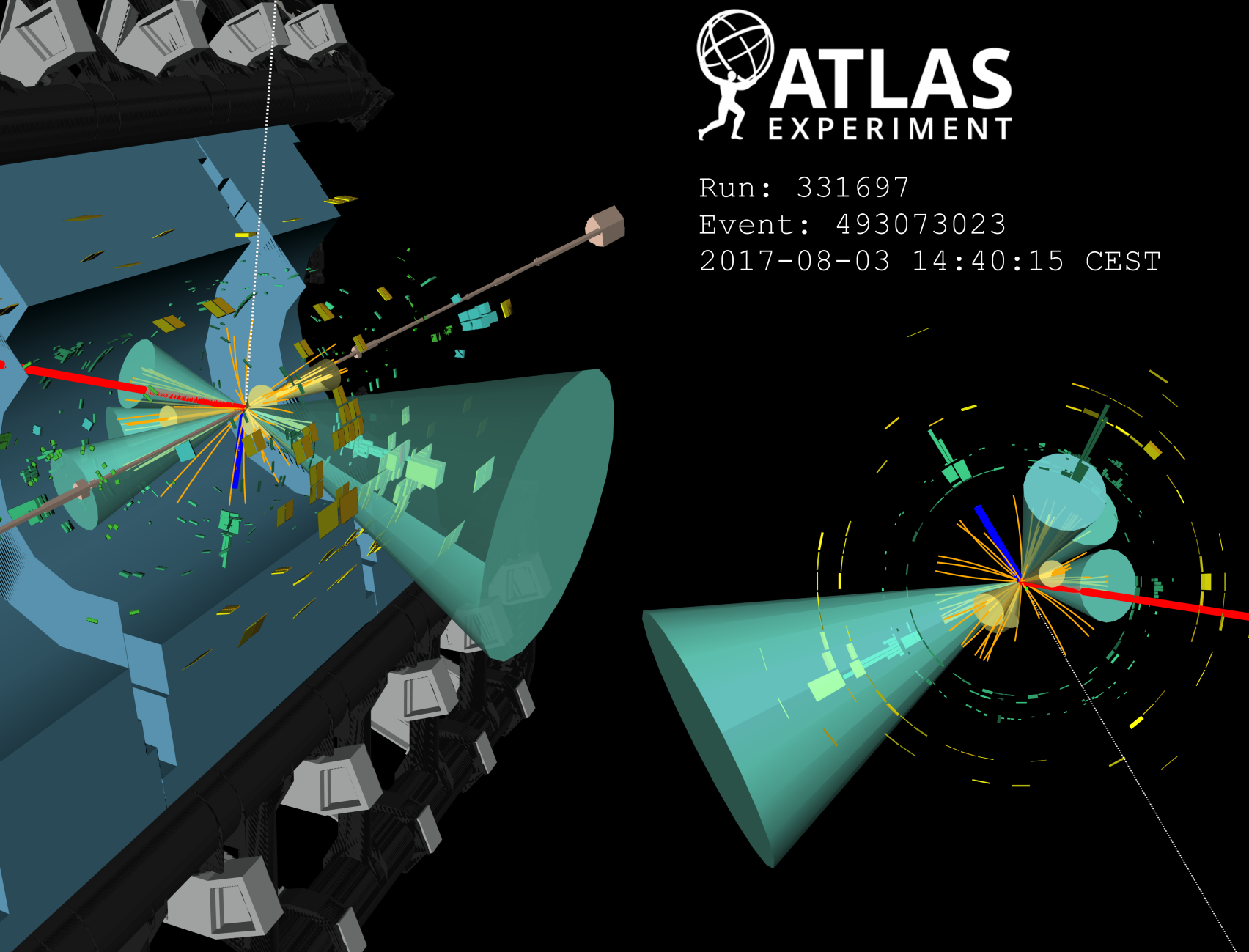


Run: 331697

Event: 493073023

2017-08-03 14:40:15 CEST

ttH/A decaying to four top quarks in multi-lepton final states





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