Innovations for a Sustainable Tomorrow

LIV.INNO

Developing τ-Identification and Searching for New Physics with the ATLAS Detector

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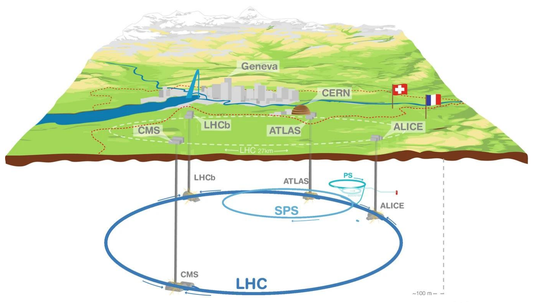
1. The LHC and the ATLAS Detector



[1]

The ATLAS detector is the largest detector at the LHC.

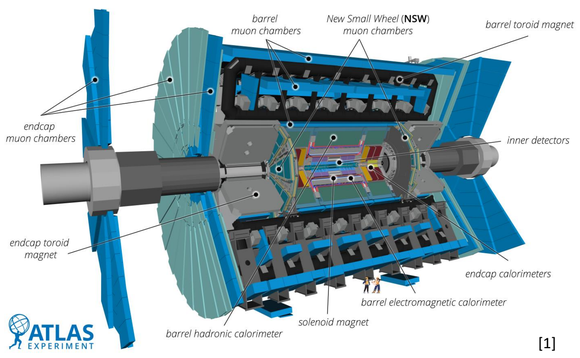
ATLAS is a general-purpose detector whose physics goals range from precision measurements to searching for new physics beyond the Standard Model (BSM).

The detector is built in an onion-structure:
- Inner-detector for charged particle tracking
- Calorimeters measuring the energy of particles
- Muon detector.

The Large Hadron Collider (LHC) is the main European experimental facility for particle physics.

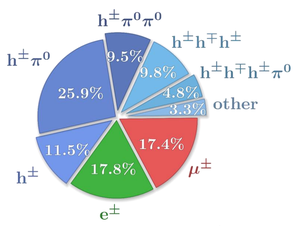
The main collider is a 27km ring approximately 100m underground in France/Switzerland.

There are 4 main interaction points housing the main experiments: ATLAS, CMS, ALICE and LHCb.



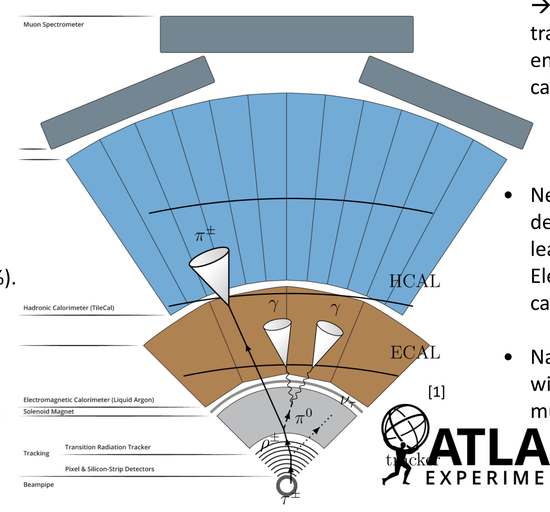
[1]

2. The Tau Lepton Reconstruction



The τ lepton is the 3rd generation charged lepton.
- Mass – 1.777 GeV (~2x proton mass)
- Decay length of 100's μm
- Decay leptonically (35%) and hadronically (65%).

The τ lepton is interesting to study for several reasons:
- Probe to measure Higgs coupling to charged leptons (relatively high branching fraction ~ 6%)
- Many BSM theories preferentially couple to 3rd generation fermions.



[1]

$\tau^{\pm} \to \rho^{\pm}\nu_{\tau} \to \pi^{\pm}\pi^0\nu_{\tau}$

The τ signature is:
- 1 or 3 charged pions → each pion leaves a track and associated energy deposits in calorimeter
- Neutral pions (which decay into photons) leaving deposits in the Electromagnetic calorimeter
- Narrow/collimated jet with low track multiplicity

Tau Reconstruction Chain

Jet Seed/ Tracks & Vertex Association → Track Classification → τ ID / τ Decay Mode Classification / Electron Veto → Energy Calibration (BRT)

→ Tau Identification

Signal

Prompt τ_{had}

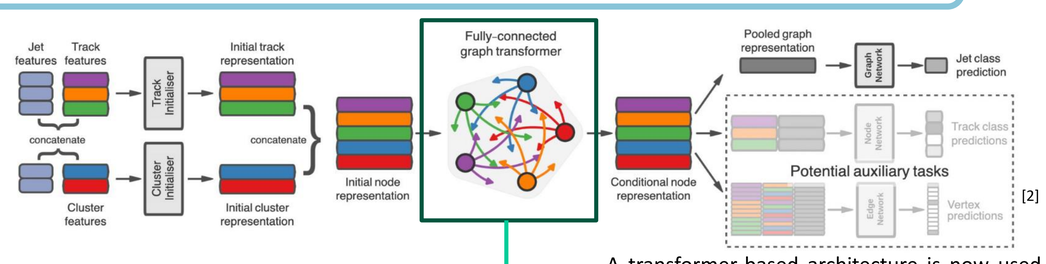
Background

Light quark/gluon initiated jet | b/c initiated jet

One of the key challenges is to distinguish the τ_{had} from the large QCD background.

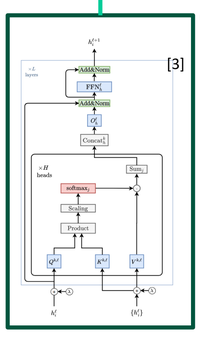
This task is tackled using a neural network which is optimised with appropriate inputs.

3. Machine Learning Techniques: GNN's



[2]

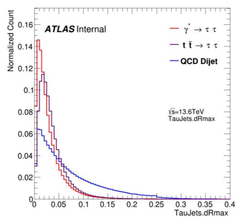
A transformer-based architecture is now used to discriminate τ_{had} from the QCD background.



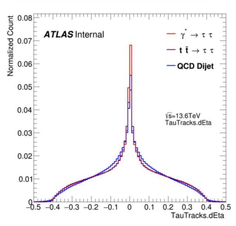
[3]

- Transformers form a conditional representation based on the constituents of the τ_{had}
- Leveraging the "attention"-mechanisms which is an integral feature of current LLMs
- Current input features related to: high-level jet features, tracks and calorimeter cluster features
- Further studies to improve performance related to τ_{had} substructure inputs called "Particle Flow Objects"

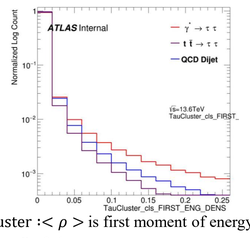
	Fully Conv Network	Recurrent NN	DeepSets NN	Transformer
Variable Input Size	X	✓	✓	✓
Permutation-invariance to input	X	X	✓	✓
Relational structure between inputs	X	X	X	✓



Jet: ΔR_{max} is maximum ΔR between core tracks and τ_{had}

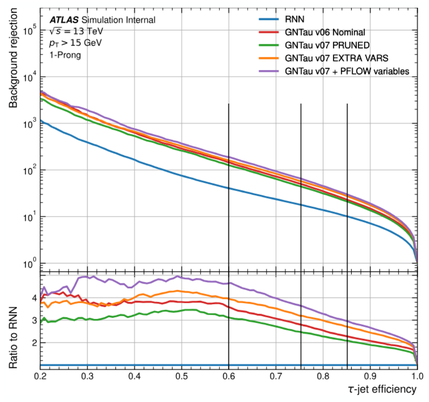


Track: $\Delta\eta$ is angular distance between track and τ_{had}

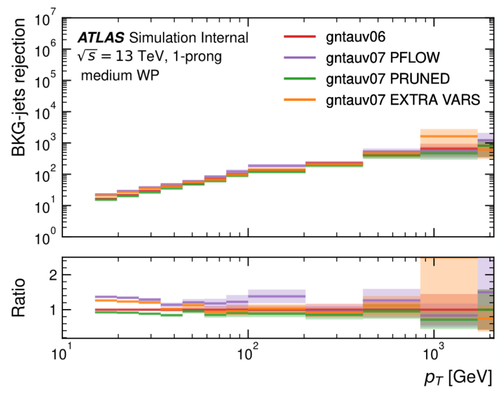


Cluster :< ρ > is first moment of energy density → "mass" of cluster

4. GNN Performance

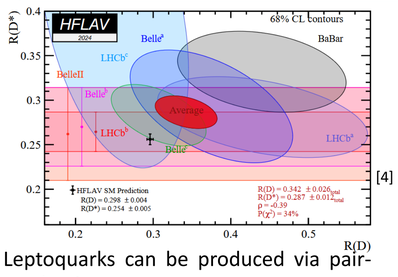


Receiver Operating Curve (ROC) shows the background rejection as a function of the signal efficiency (higher is better)
- Recurrent Neural Network (blue) is the previous nominal neural network architecture
- GNTau v06 (RED) is the nominal transformer-based network which performs much better than RNN
- v07 PFLOW (purple) shows a newer model with additional input features with a performance boost of ~30% across relevant signal efficiencies



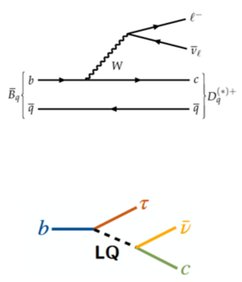
Plot showing the background rejection as a function of the transverse momentum, p_T.
- Performance of transformer-based network is better across entire phase space
- The PFLOW network predominantly low-p_T (<100 GeV) → region the substructure algorithms are optimised for.

5. Searching for New Physics: Leptoquarks



[4]

Leptoquarks can be produced via pair-production



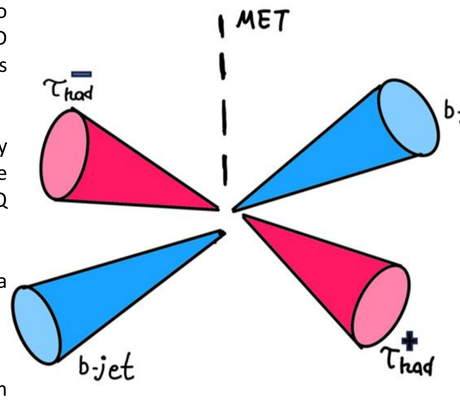
This is particularly good channel to probe as it is dependent solely on QCD production and therefore the search is model independent.

Due to BSM models preferentially coupling to 3rd generation fermions we focus on a final-state where each LQ decays into a bτ.

Hence the signature we focus on is a final state with:
- 2 b-jets
- 2 τ_{had}
- Missing transverse momentum (MET)

The Standard Model (SM) is a very successful theory with numerous measurements validating its predictions. However, there are several tensions: neutrino masses, flavour anomalies, g-2, hierarchy problem and many more.

Leptoquarks (LQs) are hypothetical particles with both baryon and lepton quantum numbers. Such states a predicted by a wide variety of BSM models and alleviate many of these tensions.



The analysis aims to utilize the:
- Larger Centre of Mass (CoM) energy of the LHC beam
- Twice the dataset of previous data-taking period
- Better b/ τ_{had} tagging from improved architecture
- Focussed analysis on the high- p_T phase space

6. Signal Extraction

The signal is extracted by measuring a variable which is highly discriminating against the background.

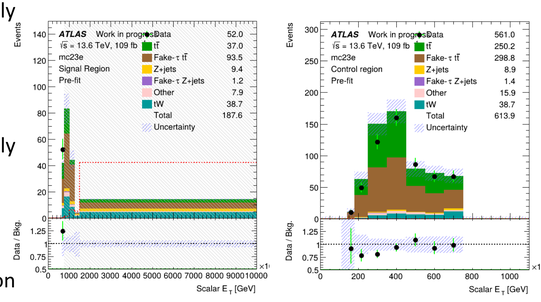
The red curve in the Signal Region (SR) shows the expected LQ signal.

A statistical model is built and tested against the background only hypothesis to determine the significance of our observations.

Background modelling is important to identify a signal process (LQ).

A control-region (CR) is defined to understand our modelling in a region with no expected signal contribution.

The dominant background is top pair-production followed by Z+heavy flavour jets. To constrain these backgrounds further dedicated CRs are defined in high purity regions to correct the Data/Monte Carlo.



Scalar E_T : Sum transverse energy of 2 b-jets and 2 τ_{had} in the event.

7. Next Steps

Tau Identification:
- Validation studies on new inputs (undertaken by Liverpool tau group)
- Increase robustness of network to other signal processes and MC generators (ongoing ATLAS group efforts)

Leptoquark Analysis:
- Fit studies to understand sensitivities across the mass grid
- Incorporate systematic uncertainties
- Complete the analysis

References

[1] ATLAS Collaboration, https://atlas.cern/Resources/Schematics
[2] ATLAS Collaboration, Transforming Jet Flavour Tagging. arXiV: 2505.19689
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[4] HFLAV, https://hflav-eos.web.cern.ch/hflav-eos/semi/summer23/html/RDsDsstar/RDRDs.html
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