PhD Progress Report

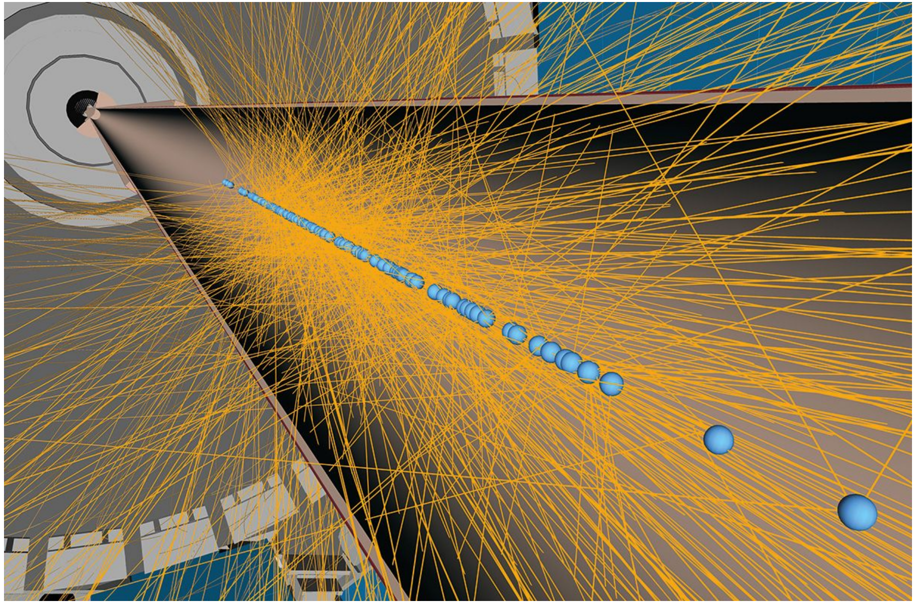
Leonardo Splendori

Supervisors: Arnaud Duperrin, Thomas Strebler

CSI meeting, 20/06/2024

Authorship Qualification Project

Flavour tagging with Graph Neural Networks at High Luminosity LHC

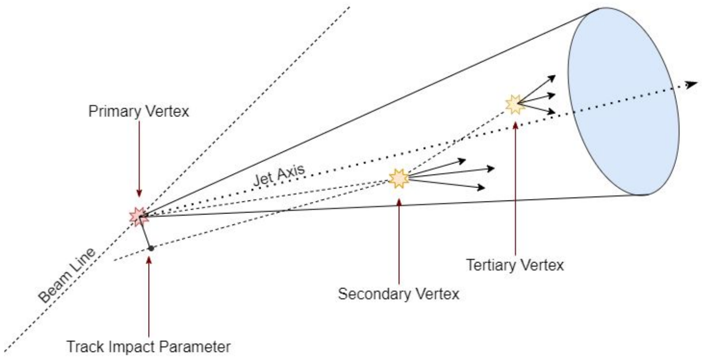


Jet Flavour

Mandatory project to get added to the ATLAS author list.

Main goal: Study the application of current flavour-tagging software in High Luminosity LHC.

Flavour tagging:



Many processes at colliders involve colour-charged objects in the final state. These hadronize and manifest as **hadronic jets.**

Jets are divided into different **flavours** depending on their origin:

- b-jets → From b-hadrons.
- c-jets → From c-hadrons.
- light-jets → Everything else, too similar to each other for more subcategories.

Each flavour can be identified thanks to the different topology and kinematics of the jets.

Flavour Tagging

For physics studies we want to be able to identify the flavour of jets. But this is not simple:

- Many particles.
- Multiple decays happening inside the jet → complex topology.
- LHC is a hadron collider → noisy environment.
- Highly structured data.

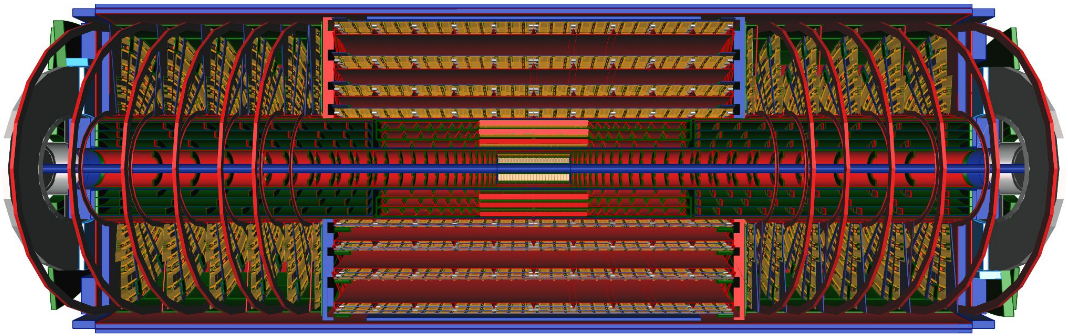
→ **Graph Neural Networks**

Reconstructed Jet → Graph Representation → Tagging Scores

New conditions at High Luminosity LHC:

- Increased pileup.
- New detector components (ITk).

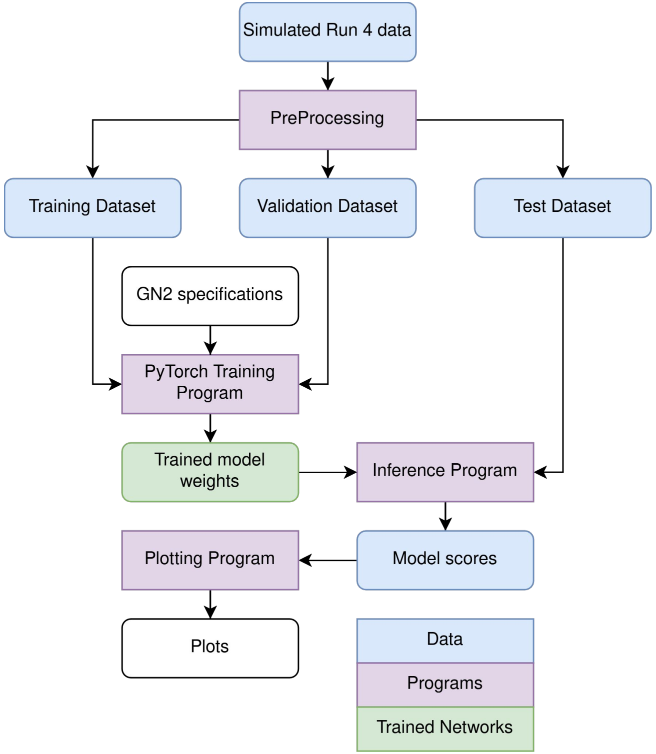
How does the currently used neural network handle these new conditions?



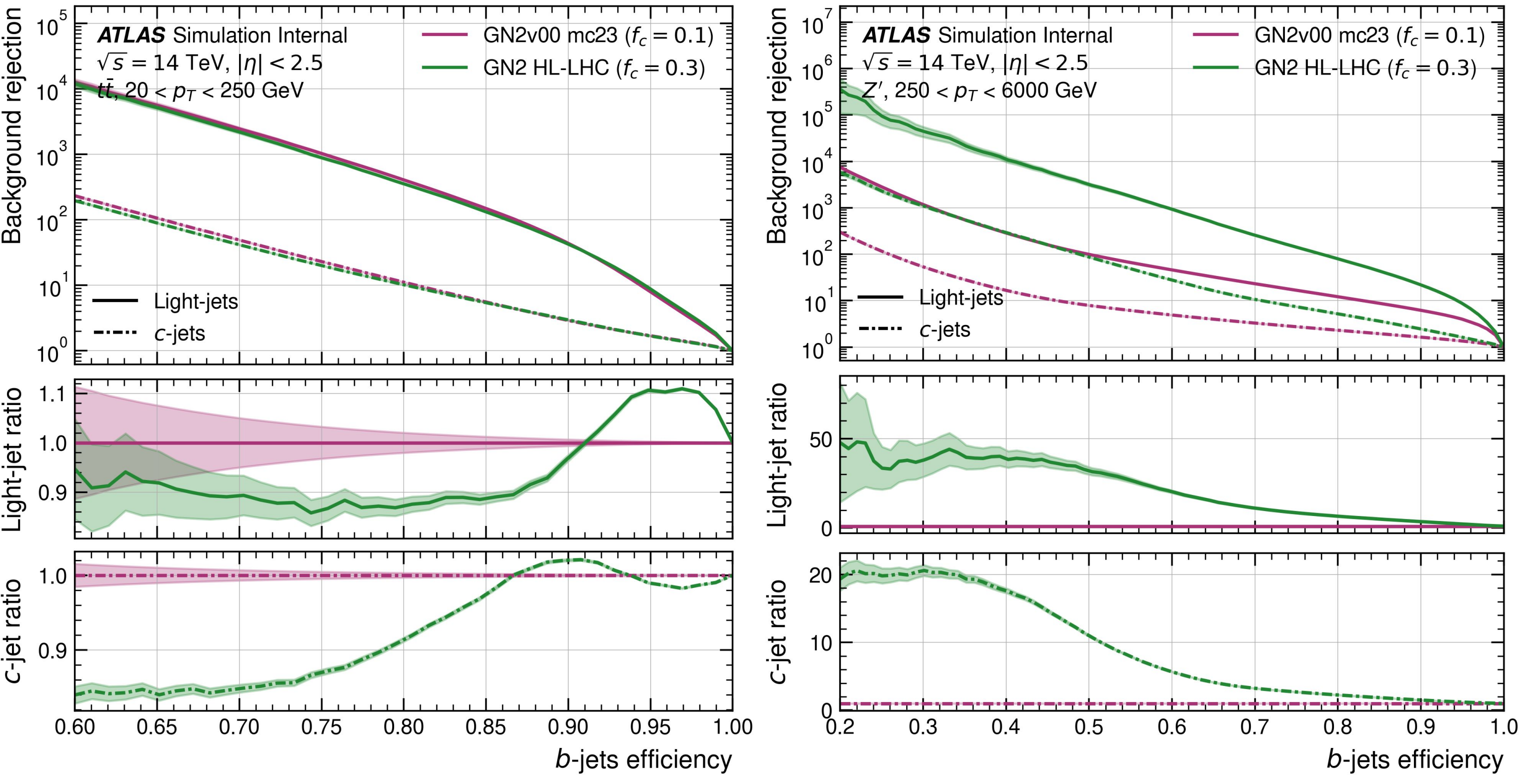
How to train your tagger

Simulated Run 4 data used to train the network. Multiple steps to get results:

- Data pre-processing:
  - Prepares training/validation/test samples.
  - Performs resampling to reduce biases.
- Model training:
  - Actual training of the model using the training/validation samples.
  - Very computationally expensive and time consuming.
- Model evaluation:
  - Model inference is computed on the test sample.
  - Production of performance plots and analyses.



ROC curves

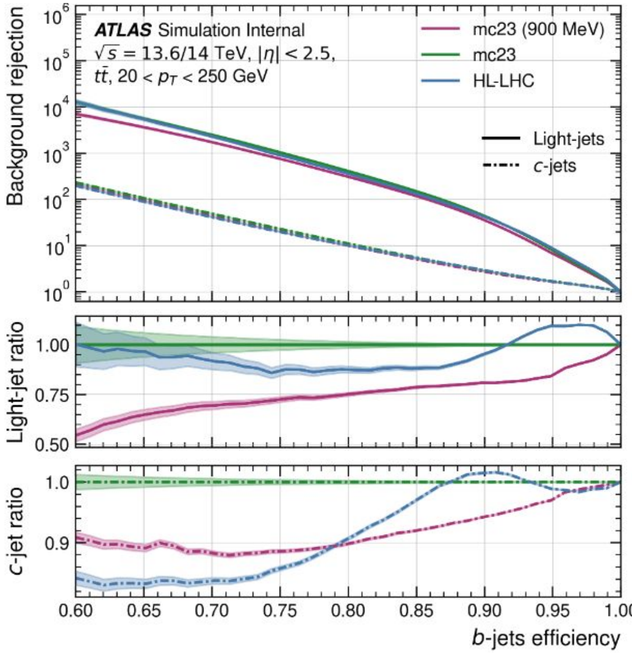


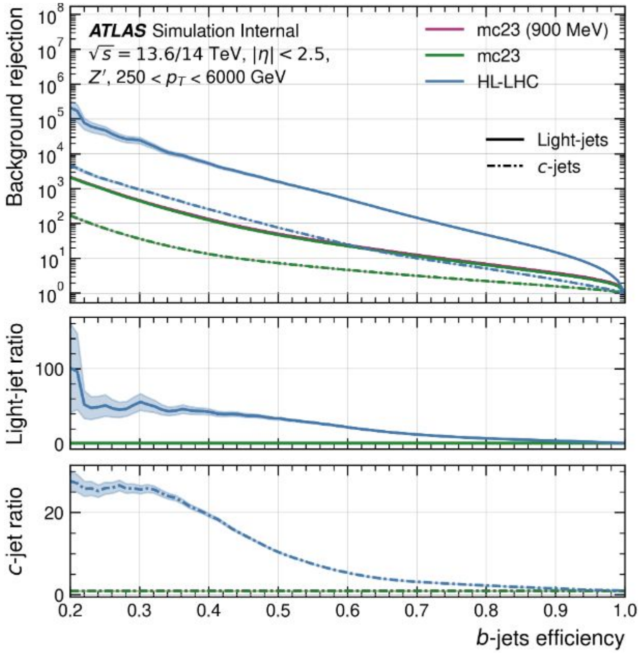
Plots showing the background rejection as a function of the b-jet efficiency.

Run 4 training shows lower rejection on the low pT samples, increased in the high pT region.

Increase most likely attributable to the improved performance of ITk in identifying b/c-hadron decays in those regions.

Investigating performance





There are cuts imposed on the tracks used in jet reconstruction. These cuts are different between Run 3 and Run 4. What impact does this have?

ROC curves showing:

GN2 evaluated on the simulated Run 3 samples with a **pT > 500 MeV** cut (default for Run 3).

GN2 evaluated on the simulated Run 3 samples with a **pT > 900 MeV** track selection. Without retraining.

HL-LHC training of GN2 (evaluated on Run 4 samples).

Shows a negative impact on the tagging performance from the different track selection.
Not an ideal comparison, GN2 for Run 3 was not trained on jets with this selection applied.
Reduction in HL-LHC performance compatible with envelope defined by raising the pT cut.

Pileup tracks

At each bunch crossing, multiple collisions in different points take place (~60 in Run 3, ~200 in Run 4).

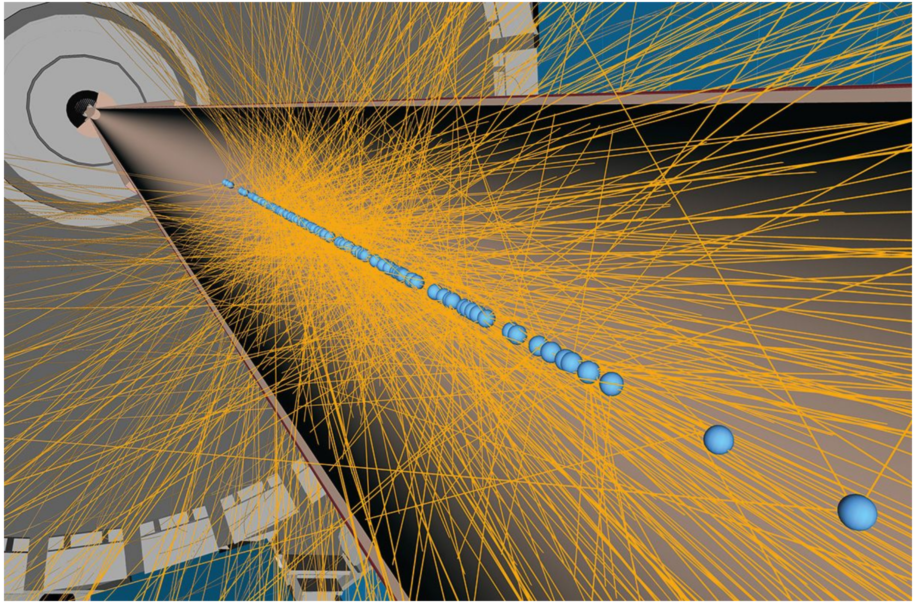
When reconstructing tracks and jets it is possible to mistakenly associate a track to the wrong origin and the wrong jet.

We call these **pileup tracks**.

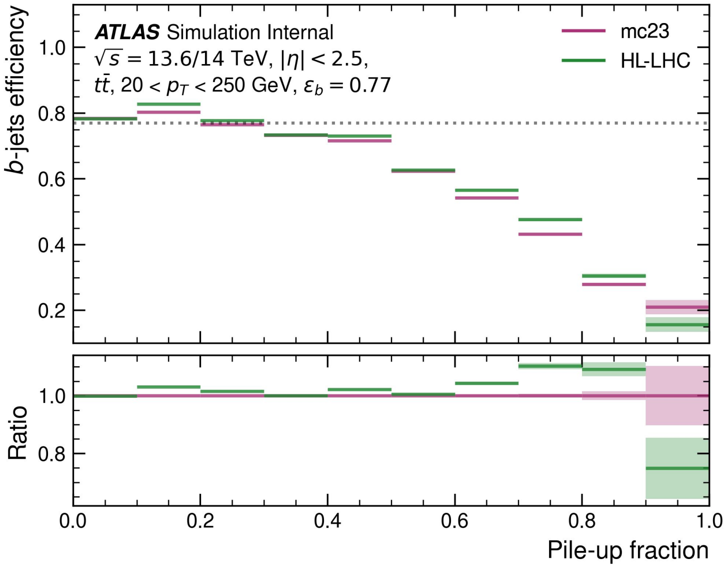
Given the higher number of collisions per crossing we expect **increased pileup** at HL-LHC.

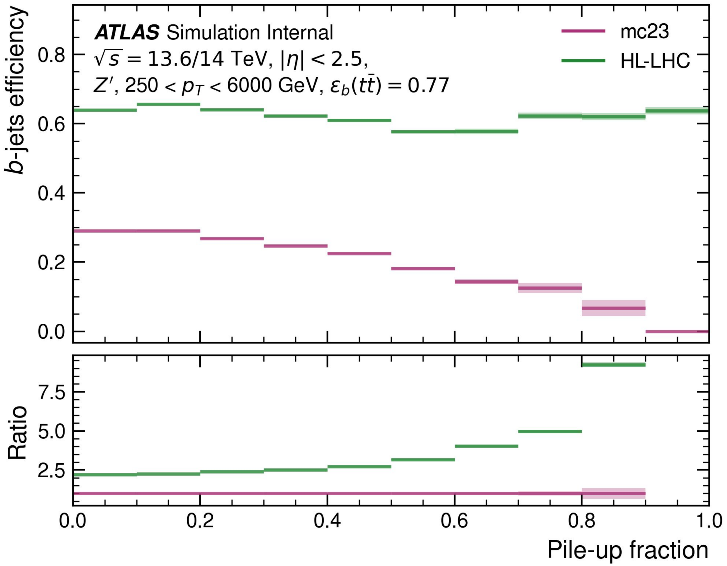
How robust are our taggers against this increase?

To answer we study the b-jet efficiency and light-jet rejection as functions of the concentrations of pile up tracks inside a jet (Pileup fraction).



b-efficiency vs PU fraction





Both Run 3 and HL-LHC b-jet efficiency strongly impacted by PU fraction in the ttbar sample.

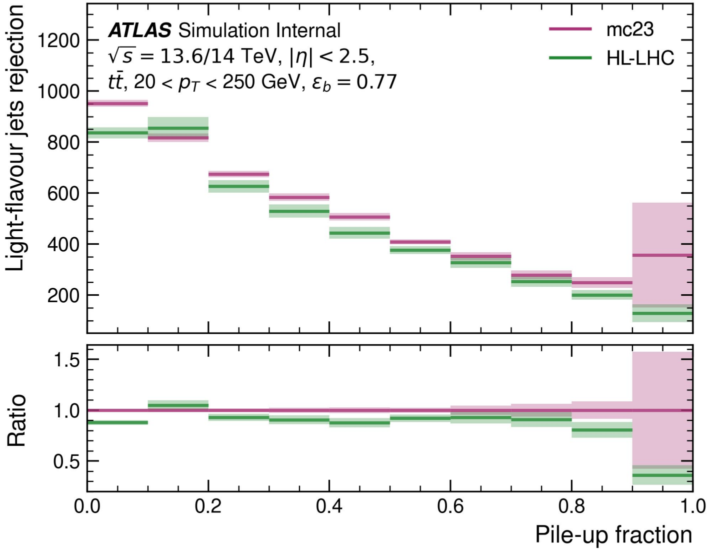
HL-LHC shows improved b-jet efficiency robustness against PU in the Z' sample.

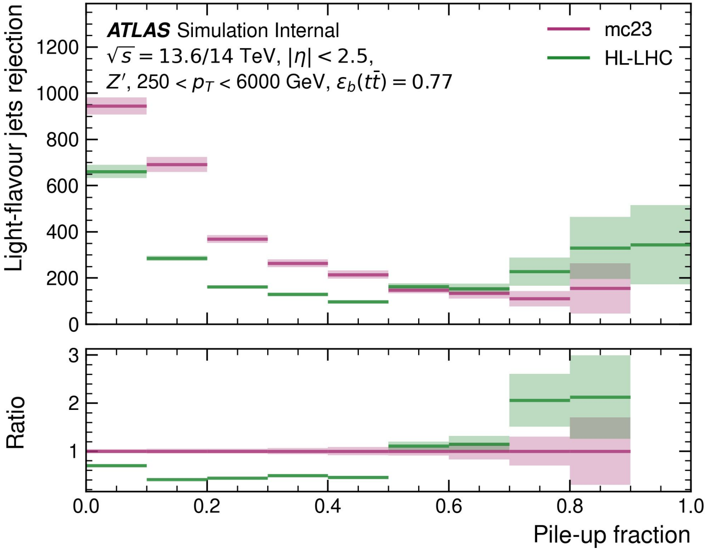
b-jet efficiency as a function of PU fraction.

PU fraction computed as the ratio between the number of PU tracks inside a jet and the total number of tracks inside the same jet.

Plots are made by imposing a cut on the discriminant giving a 77% efficiency on the full ttbar sample. Then by plotting the efficiency and PU fraction.

Rejection vs PU fraction





light-jet rejection as a function of PU fraction.

Plots are made by imposing a cut on the discriminant giving a 77% efficiency on the full ttbar sample. Then by plotting the rejection and PU fraction.

Run 3 and HL-LHC taggers show similar rejection in the low pT region, with PU also having a similar impact.

Larger difference in the high pT region, both in terms of pure rejection power and PU dependence.

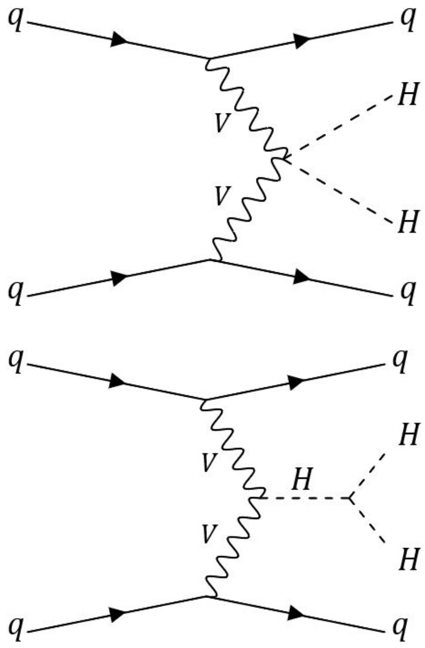
Conclusion and next steps

- Similar **response to pileup** between the Run 3 and Run 4 trainings. Differences mostly at high pT.
- Part of the performance loss at low pT can be explained by the **different track selection**.
- Pipeline and documentation created to ease these tasks.

Next steps:
- Incorporating the trained model into the ATLAS software pipelines.
- Investigate methods to improve performance of HL-LHC training.
- Investigate interplay of tracking and vertex finding for PU robustness.

Physics analysis

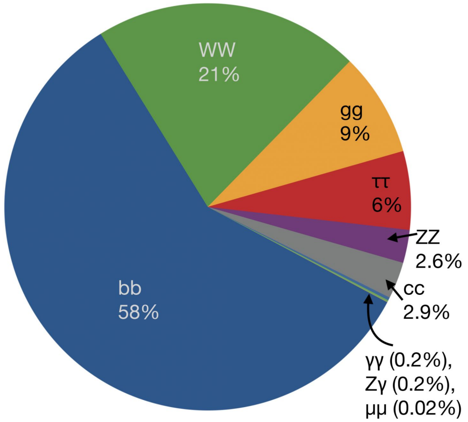
Probing the Higgs boson pair production through Vector Boson Fusion at the LHC in the ATLAS experiment



Di-Higgs in the $bb\tau\tau$ channel

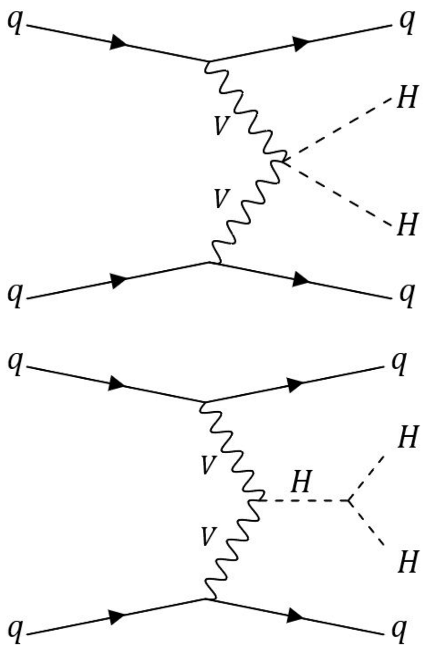
Measurements of **Higgs boson pair production** are a very important test of the Higgs mechanism.

Rare processes require high statistics to be studied.



Access to both the **Higgs self coupling** and the **VVHH vertex** is anticipated for the High Luminosity LHC upgrade.

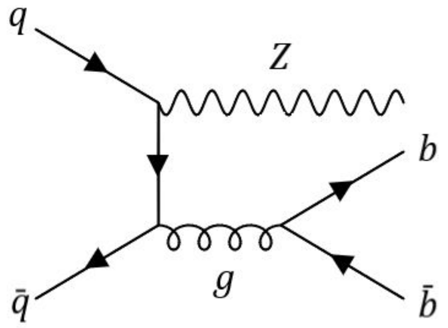
With data from **Run 3** of LHC it is already possible to place constraints on the VVHH coupling.

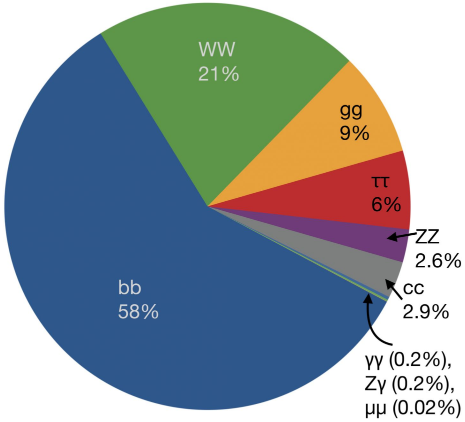


Di-Higgs in the bb$\tau\tau$ channel

One Higgs boson decaying into a b-jet pair, and the other into a tau-antitau pair.

The most significant backgrounds are top-antitop pair production, QCD jets and Z + jets processes.





Significant due to the mass dependent Higgs coupling. Decays into heavier products have **larger branching ratios**.

This channel is a compromise between having **high statistics** and a **clean signal**.

Contributions to the analysis

Worked started as small contributions, mainly due to to the AQP being the main focus of the first year. But slowly ramping up.

Technical contributions to the development of the frameworks used for the analysis. Fixing issues with software deployment pipelines.

Multivariate signal extraction is used in diHiggs analyses. **Boosted Decision Trees** are used to extract possible signals:

- Implementation of observable used in previous analyses into the current framework.
- Porting of existing decision trees into the framework used for the latest analyses.

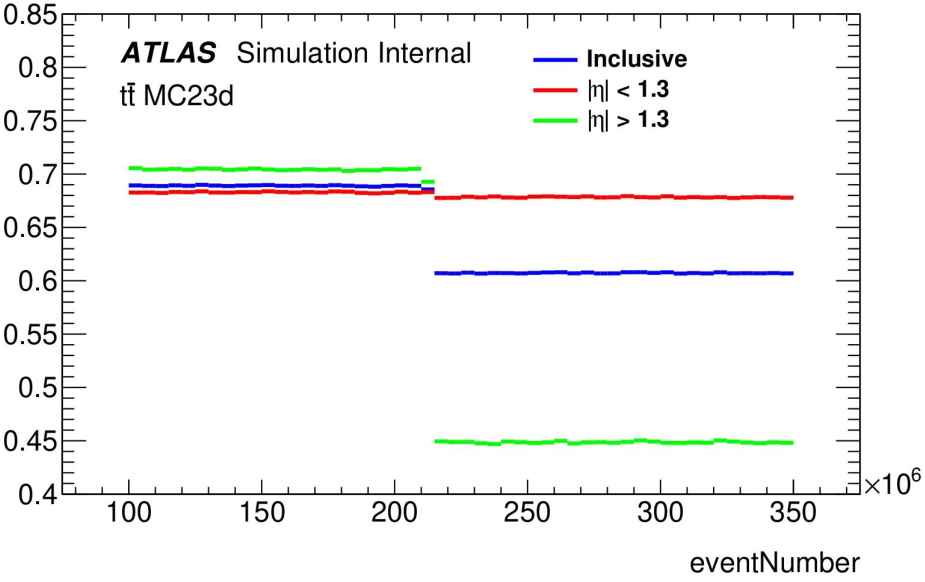
Table 27: Input variables used for the VBF BDT training in the $\tau_{\text{had}}\tau_{\text{had}}$ channel.

Variable	Description
m_{HH}	Invariant mass of the HH system, reconstructed from the τ-lepton pair (using the MMC) and b-tagged jet pair
m_{bb}	Invariant mass of the b-tagged jet pair system
$m_{\tau\tau}^{\text{MMC}}$	Invariant mass of the τ-lepton pair system, calculated using the MMC
$\Delta R(b,b)$	The ΔR between the two b-tagged jets
$\Delta R(\tau,\tau)$	The ΔR between the two visible τ decay products
VBF $\eta_0 \times \eta_1$	Product of the pseudorapidities of the leading and sub-leading VBF jets
$\Delta\eta_{jj}^{\text{VBF}}$	The $\Delta\eta$ between the two VBF jets
$\Delta\phi_{jj}^{\text{VBF}}$	The $\Delta\phi$ between the two VBF jets
$\Delta R_{jj}^{\text{VBF}}$	The ΔR between the two VBF jets
m_{jj}^{VBF}	Invariant mass of the VBF jet system
thrust$(\tau\tau jf)$	Thrust, taking into account the τ-lepton pair and central and forward jets
circ$(\tau\tau jf)$	Circularity, taking into account the τ-lepton pair and central and forward jets
$\eta(\tau_0)$	Pseudorapidity of the leading $\tau_{\text{had-vis}}$
$\eta(\tau_1)$	Pseudorapidity of the sub-leading $\tau_{\text{had-vis}}$

Contributions to the analysis

Recently, a simulation bug has caused samples used by the analysis team to be contaminated:

- Analysed the impact of the bug on the relevant samples.
- Compiled a list of all affected samples.
- Implemented a workaround to eliminate the affected samples until new ones are produced.



Plot showing the trigger efficiency as a function of the *eventNumber* mc variable. Issue is present at the 32 bit integer limit /10. Caused by a bug in data conversion.

Conclusion and next steps

- Work started with small contributions, slowly ramping up.
- Contributed to solving problems with the development pipelines.
- Implementation of observables and BDTs used by previous analyses.
- Study of muon trigger efficiency issue and development of a workaround.

Next steps and future timeline:

- Finalising testing and merging of latest fix.
- October 2024: Full switch to physics analysis work (AQP completion date).
- Summer 2025: Target date by analysis group for early Run 3 public results.
- 2025-2026: Focus on boosted VBF categories.