

## Trigger and identification strategies for the search of Higgs boson pair production in the $bb\tau\tau$ final state in the ATLAS experiment

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**Summary.** — Measuring the Higgs boson self-coupling is one of the primary objectives of the High Luminosity Large Hadron Collider (HL-LHC). Optimizing and upgrading the sensitivity to its signals is therefore crucial. During Run 2, the LHC achieved an integrated luminosity of  $140 \text{ fb}^{-1}$  for proton-proton collisions at 13 TeV, and this figure is expected to at least double by the end of the ongoing Run 3. Despite this increase, the low di-Higgs production cross-section requires significantly higher data statistics to observe this process. Hence, improving signal acceptance and efficiency, starting with enhanced trigger selections, is essential to reducing the necessary data volume for this measurement.

This paper presents the latest results of an ongoing study focused on optimizing the trade-off between acceptance in the  $bb\tau\tau$  channel and the total trigger rate within the ATLAS experiment's High-Level trigger. A notable advancement in this research is the introduction of a new  $b + \tau$  trigger, which offers a superior efficiency-rate tradeoff compared to previous upgrades. Additionally, enhancements in identification algorithms through the inclusion of new variables have significantly improved background rejection power. These improvements are part of the comprehensive ATLAS effort to increase sensitivity to Higgs boson self-coupling measurements.

### 1. – Di-Higgs production in $bb\tau\tau$ at ATLAS

The ATLAS [2] and CMS [3] experiments discovered the Higgs boson at the LHC [4] in 2012 [5, 6], confirming the Brout-Englert-Higgs mechanism, which is responsible for giving mass to elementary particles. This landmark discovery completed the Standard Model (SM) of particle physics [7], the theoretical framework that has been remarkably successful in describing the fundamental particles and their interactions.

Despite this achievement, the Higgs self-coupling ( $\lambda_{HHH}$ ) remains an unmeasured parameter. Studying  $\lambda_{HHH}$  is crucial for understanding the Higgs potential and the electroweak symmetry-breaking mechanism, making it a primary objective of the High Luminosity LHC (HL-LHC) [8] upgrade. The SM predicts a specific value for  $\lambda_{HHH}$  based on the Higgs mass and its vacuum expectation value, and any deviations from this prediction could indicate new physics. During LHC Run 2 (2015-2018), ATLAS

investigated di-Higgs production events, focusing on various final states based on Higgs boson decays. Among these, the  $bb\tau\tau$  final state is of particular interest due to its balanced branching ratio and sensitivity to the di-Higgs signal. Using an integrated luminosity of  $140 \text{ fb}^{-1}$  of proton-proton collisions at 13 TeV, this analysis sets an upper limit on the Higgs pair production cross-section at 4.7 times the SM expectation and constrains the Higgs self-coupling modifier to  $-2.7 < k_\lambda < 9.5$  at a 95% confidence level [9].

## 2. – 2024 New trigger approach: $b + \tau$

Although Run 3 is anticipated to double the available data, enhancing the ATLAS detector's performance remains crucial. During Run 2, two di- $\tau$  triggers were used to detect events from the  $HH \rightarrow bb\tau\tau$  process. The first step in optimizing these triggers was to evaluate their efficiency and rate as a function of the transverse momentum ( $p_T$ ) of the  $\tau$  leptons. For Run 2, the di- $\tau$  triggers required two  $\tau$ s with transverse momenta of 35 GeV and 25 GeV, respectively. For the first two years of Run 3 data-taking, new versions of the di- $\tau$  triggers with transverse momentum cuts lowered by 5 GeV were implemented in the ATLAS trigger delayed stream, starting from the 2023 data-taking period. This adjustment provided about a 10% increase in signal efficiency [1]. For the 2024 data-taking year, a novel trigger has been developed, based on the selection of only one  $\tau$  and one  $b$ -jet of the final state.

The new trigger strategy has an intrinsic combinatorial advantage because it requires the identification of only one particle per type, each with two candidates in the final state. In the di- $\tau$  approach, as well as in the di- $b$ -jet strategy, if the identification algorithms in the High-Level Trigger (HLT) of ATLAS fail to correctly select one of the two final  $\tau$  leptons (or final  $b$ -jets), the event is lost.

**Figure 1** shows the invariant mass distribution of the two reconstructed Higgs bosons for the events passing the 2023 di- $\tau$  trigger configuration, the  $b + \tau$  trigger alone, and both trigger strategy in the logic OR configuration, which has the best overall efficiency and shows an improvement respect the di- $\tau$  strategy of 30%. **Figure 2** shows the efficiency of different studied triggers respect their rate on data, and the  $b + \tau$  option clearly offers the best trade off, incrementing the signal acceptance, with a rate that is smaller than the di- $b$  trigger.

## 3. – Upgrades on the Tau Identification

Distinguishing hadronically decaying  $\tau$  leptons from jets originating from Quantum Chromodynamics (QCD) processes is essential for tau identification in the ATLAS experiment. These QCD jets can sometimes be incorrectly reconstructed as tau leptons by the reconstruction algorithms. However, jets from hadronic tau decays tend to be more collimated compared to the QCD background, which allows for using specific discriminating variables to identify genuine  $\tau$  leptons. Machine Learning (ML) algorithms have been particularly successful in addressing this challenge. In 2022, an enhanced track classification (TC) algorithm was developed utilizing the Recurrent Neural Network (RNN) architecture, which is a Deep Learning (DL) algorithm tailored for processing sequences, and is also the current model used to tau identification in ATLAS [10].

The classification scores produced by this new algorithm significantly improve the identification performance of various models. Two different architectures (RNN and Transformer) were tested with and without the inclusion of the track classification scores

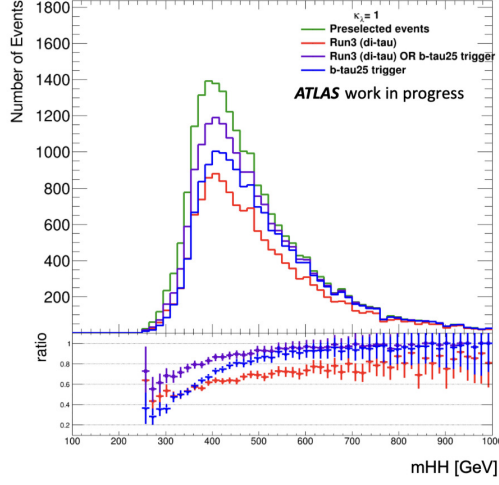


Fig. 1: Invariant mass distribution of the two reconstructed Higgs bosons for events passing the 2023 di- $\tau$  trigger, the  $b + \tau$  trigger alone, and both trigger strategies in the logic OR configuration. The acceptance efficiency improves by 30% with the OR configuration with respect to the di- $\tau$  strategy.

as inputs. The Receiver Operating Characteristic (ROC) curves for these models were obtained, demonstrating that the best option is the Transformer with the track classifier scores. This configuration improves the rejection power against background events by 130% more rejection power at 60% signal efficiency with respect to the baseline models.

The results are summarized in **Table I** and in **Figure 3**, which shows the rejection power, defined as the inverse of the true fake rate, for the RNN and the Transformer with and without the track classification score as input. The rejection power is given for two different working points, which are defined depending on the selected efficiency on signal, which is studied on taus decaying in only one charged pion (therefore labelled ad 1-prong).

#### 4. – Conclusion

The optimization of triggers for detecting  $HH \rightarrow bb\tau\tau$  events has seen significant advancements in the transition from Run 2 to Run 3 data-taking at the LHC. The development and integration of the  $b + \tau$  triggers introduced a new approach, resulting

TABLE I.: Rejection power for 0.60 and 0.85 signal efficiencies of the RNN and the Transformer. The two models have been trained on 1-prong taus with and without using the TC score.

Working points (Efficiency)	RNN wout TC	Transf. wout TC	RNN w TC	Transf. w TC
0.60	124	132	304	308
0.85	46	49	58	60

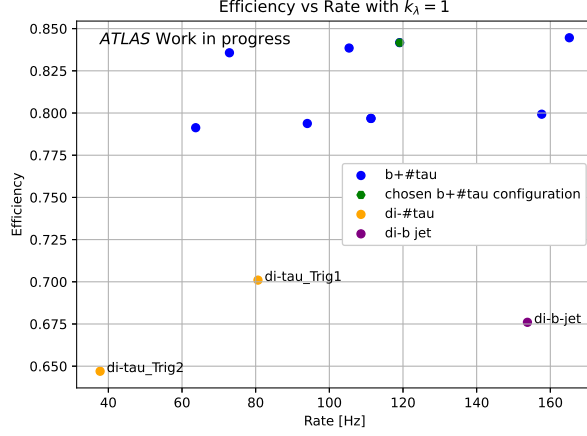


Fig. 2: Efficiency of different triggers relative to their rate estimated on data, with the  $b + \tau$  trigger offering the best tradeoff. The efficiency has been computed on SM  $HH \rightarrow b\bar{b}\tau\tau$  signal samples.

in a 30% gain in overall efficiency when compared to 2023 triggers currently in use at ATLAS. This innovative trigger strategy leverages the combinatorial advantage of requiring the identification of only one type of particle, thus increasing the likelihood of capturing di-Higgs events.

Another crucial upgrade is the introduction of the track classification score into the tau identification algorithms. This enhancement provides better rejection power compared to the existing algorithms used in ATLAS. The use of ML techniques, including Recurrent Neural Networks and Transformers, further improves tau identification performance, with both architectures showing increased rejection power when incorporating track classification scores.

Together with the expected increase in statistics from Run 3 data-taking, these improvements significantly enhance our ability to detect and study the  $HH \rightarrow b\bar{b}\tau\tau$  process.

\* \* \*

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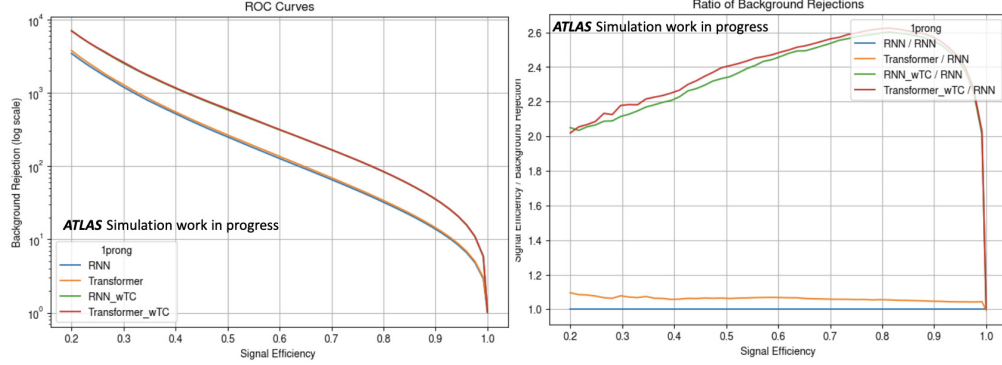


Fig. 3: Left: The ROC curves for the RNN and the Transformer models trained with and without using the TC score. Right: The ratio of each ROC respect the smaller one, which is given by the RNN without the TC score.

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