IL NUOVO CIMENTO **47 C** (2024) 118
DOI 10.1393/ncc/i2024-24118-8

Colloquia: IFAE 2023

Trigger studies for the search of Higgs boson pair production in the ATLAS experiment(*)

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received 13 February 2024

Summary. — The estimation of the Higgs boson self-coupling is possible at the Large-Hadron Collider studying di-Higgs events. The full Run 2 data-taking period reached an integrated luminosity of 140 fb^{-1}, that is expected to at least double at the end of the ongoing Run 3 of the LHC, but given the small di-Higgs production cross-section, much higher data statistics is expected to be needed to observe this process from the simple extrapolation of the current results. For this reason, improvements in the signal acceptance and efficiency, starting from improvements in the trigger selections, are crucial to reduce the amount of data needed for this measurement. The preliminary results of an ongoing study to find the best trade-off between acceptance in the $bb\tau\tau$ channel and the total trigger rate, at both the Level-1 and High Level triggers of the ATLAS experiment will be presented. In particular the latest results of the optimization, and its possible future upgrades, will be discussed as part of the ATLAS global effort to increase the sensitivity to the Higgs boson self-coupling measurements.

1. – Di-Higgs production at ATLAS, LHC

The Higgs boson was discovered at the LHC [1] in 2012 [2,3], and it assumes a key role within the theoretical framework of foundamental particle physics, as it is responsible for giving mass to other particles through the so known Brout-Englert-Higgs mechanism. The Higgs discovery was the missing piece of the Standard Model (SM) of particle physics [4], which is a theoretical model that has enjoyed remarkable success in explaining the fundamental particles and their corresponding interactions.

The ATLAS [5] and CMS [6] experiments have been able to measure with remarkable precision the cross section of the Higgs boson production and decays [7,8] using the data collected during the LHC Run2 (2015 – 2018). However there remain several aspects of the Higgs sector that require further scrutiny. Of particular significance in this context is the study of the Higgs potential, which is a critical ingredient to achieve a deeper comprehension of the electroweak symmetry-breaking mechanism, with substantial implications in other fields of physics, like astro-particles and cosmology [9].

(*) IFAE 2023 - "Poster" session

The shape of the Higgs potential around its minimum determines the Higgs self-coupling (λ_{HHH}), which is a parameter of the SM that can be measured at the ATLAS detector through the study of the production of Higgs pair events, mainly due to gluon-gluon fusion process [10]. The Higgs mass and the vacuum expectation value of the Higgs field give a SM prediction of this parameter, and deviations from it could provide insights into new physics.

2. – HH in $bb\tau\tau$ analysis and procedure description

Depending on the branching ratio of the Higgs boson decays, different final states can be defined to detect di-Higgs events inside the ATLAS detector. The $bb\tau\tau$ signature is particularly interesting because it strikes a balance between a good branching ratio (BR = 7.3% [10]) and high sensitivity to the di-Higgs signal. The ATLAS analysis of the Run2 data, corresponding to an amount of data of 140 fb^{-1} of integrated luminosity, allowed to define at 95% confidence level the upper limit on the Higgs pair production cross section that is 4.7 times the SM expectation [11], and constrained the allowed range of the Higgs boson self-coupling modifier to $-2.7 < k_\lambda < 9.5$ at 95% CL. Despite the Run 3 is expected to double the statistics collected in previous data-taking period, it is important to improve the performance of the ATLAS detector and the introduction of a new delayed stream for the trigger setup has opened up exciting possibilities for improving the efficiency of detecting rare decays such as $HH \to bb\tau\tau$. This innovation has allowed us to introduce new trigger mechanisms with higher rates, significantly enhancing our ability to identify and study these elusive processes. Naturally, there exists an upper limit to the rate that the ATLAS detector can accommodate. Consequently, for every trigger, the delicate balance between optimizing the efficiency in detecting the signal of interest and managing the overall event rate that is recorded must be meticulously determined.

To study trigger performance the procedure is to apply on the simulated data the online reconstruction, identification and selection algorithms to emulate the trigger of interest. However, in this way the obtained trigger efficiency does not reflect the effective efficiency for the analysis, where many additional offline selection criteria are applied. What it is really of interest in this kind of studies is the effectiveness that a trigger can have on the related analysis, so the offline selections on taus and b-jets that will be applied on the reconstructed objects of each event passing the triggers are also applied on the simulated data, and the effective trigger efficiency is calculated using the following formula:

$$\epsilon_{trigger} = \frac{\textit{Number of events passing offline requirements AND Trigger}}{\textit{Number of events passing offline requirements}} \tag{1a}$$

3. – Studied Triggers

During Run2 two di-τ triggers were used to detect events from the $HH \to bb\tau\tau$ process. Therefore the first study was to try to optimize these kind of triggers, checking the efficiency and the rate as a function of the transverse momentum (p_T) of the τs. For the Run3 data-taking new versions of the di-τ triggers with p_T cuts lowered by 5 GeV have been implemented in the ATLAS trigger delayed stream and have been running starting from the 2023 data-taking, providing about 10% increase in signal efficiency. Another interesting improvement is given by the inclusion in the analysis of a trigger

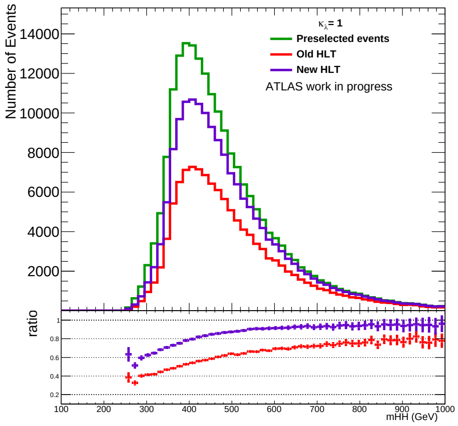

Fig. 1. – Efficiency of old HLT, used in Run 2, and of the new HLT used currently in Run 3, composed of new di-τ triggers and di-b jets trigger.

requiring two b-jets in the final state (di-b-jets). It has been implemented in the delayed stream and has been running starting from the 2022 data-taking, and because it doesn't have direct requirements on taus, it has assured another 30% of improvement on the overall efficiency of the optimized di-τ triggers.

Figure 1 shows the invariant mass distribution of the two reconstructed Higgs bosons for the events passing offline analysis requirements (Preselected) and for the events passing the Run 2 triggers and the new combination of improved triggers for Run 3.

4. – Tau Identification

Tau identification is crucial within the ATLAS experiment to effectively distinguish hadronically decaying tau leptons from jets that originate from Quantum Chromodynamics (QCD) processes but are mis-reconstructed as tau leptons by the reconstruction algorithms. The jets produced by hadronic tau decays are more collimated than QCD background, so it is possible to extract discriminating variables to identify real tau leptons, and the Machine Learning (ML) algorithms have already given great success in this kind of problems. Currently the tau identification in ATLAS is based on a Recurrent Neural Network [12], which is a Deep Learning (DL) algorithm, developed for the processing of temporal series. A different approach has been tested, based on the Geometric DL, that could be able to leverage the graph structure of the input to extract more discriminant information. Table I shows the rejection power, defined as the inverse of the true fake rate, for the RNN and for two new tested models: a Graph Neural Network (GNN) and a Transformer, for taus decaying in 1-prong case (with only one charged pion).

5. – Conclusion

The optimization of triggers for the detection of $HH \to bb\tau\tau$ events has seen significant advancements as we transitioned from Run 2 to Run 3 data-taking at the LHC. The

TABLE I. – *Rejection power depending on different efficiencies on signal, of the RNN, GNN and Transformer algorithms, tested on* 1*-prong taus.*

Working points (Efficiency)	tight (0.6)	medium (0.75)	loose (0.85)	very loose (0.95)
RNN	129	47	22	7.9
GNN	130	48	23	8.0
Transformer	145	52	24	8.5

careful refinement of di-τ triggers and the integration of the di-b-jets trigger has enhanced the overall efficiency of a total 50% gain. However, another interesting upgrade could be given by the introduction of new tau-identification algorithms, which provide better rejection power than the current algorithm used in ATLAS. Together with the expected statistic that the Run 3 will collect in the next years of data-taking, this improvements could significantly enhance our ability to detect and study the $HH \rightarrow bb\tau\tau$ process, leading to a tighter upper limit on di-Higgs production and more stringent constraints on the Higgs boson self-coupling.

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The author acknowledges Dr A. Betti and Prof. S. Giagu for their help.

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