Project Overview

Title:	Measurement of Double Higgs Boson Production in the $bb\gamma\gamma$ Channel with the ATLAS Experiment Using Run 2 and Run 3 Data
Proponent:	Marco Delmastro (DR1 CNRS/IN2P3, LAPP Annecy)
Request:	Funding for a 3-year doctoral contract, covering the period 2025-2028

Scientific Context: The Quest for Higgs Self-Coupling at the LHC, Within Reach with Run 3 Data

The **measurement of the Higgs self-coupling at the LHC** holds paramount importance as it completes the picture of the Standard Model of particle physics by determining its only missing parameter. This endeavor represents the sole method to empirically examine the properties of the Higgs potential in a model-independent manner and promises to illuminate the underlying mechanism of electroweak symmetry breaking and mass generation for vector bosons and fermions. Such a quest is **pivotal to ENIGMASS+ Working Package 1**, which aims to investigate the nature of the vacuum and the mass acquisition process of particles. Currently, with LHC Run 3 in progress and an extension planned for 2026 to collect additional data beyond the initially planned duration, there is an unprecedented opportunity to provide tangible insights well before the High Luminosity Run of the LHC (HL-LHC).

The most effective approach to probing the properties of the Higgs boson's self-coupling at the LHC is through the **search for double Higgs production**. While it was initially anticipated that analyses would require the complete HL-LHC proton-proton (pp) dataset of 3 ab^{-1} to yield meaningful results [1], recent experiences from ATLAS di-Higgs searches with Run 2 data [2] have demonstrated that **significantly more sensitive outcomes can be achieved with smaller datasets**, through both enhanced treatment of the physics objects involved and the application of **machine-learning algorithms** in the analyses.

Fig. 1 presents a summary of the expected sensitivity from the most recent ATLAS di-Higgs analyses compiled in Ref. [2], alongside an extrapolation of their efficacy when applied to the complete datasets from Runs 2 and 3, assuming a conservative total of 400 fb^{-1}. This projection only takes into account enhancements due to increased statistics and already suggests that a limit approaching the Standard Model (SM) signal strength is achievable with this alone. It is conceivable that further refinements in the analyses could realistically position us to potentially observe the HH process by the end of LHC Run 3, particularly through a combined analysis with CMS results.

One of the most promising channels for such a measurement is the $HH \to b\bar{b}\gamma\gamma$ process [3], which maintains one of the highest sensitivities to double Higgs production and is a key focus of the ATLAS Higgs physics program during LHC Run 3. Several improvements to the analysis are envisioned, which will be central to the doctoral project described in this proposal.

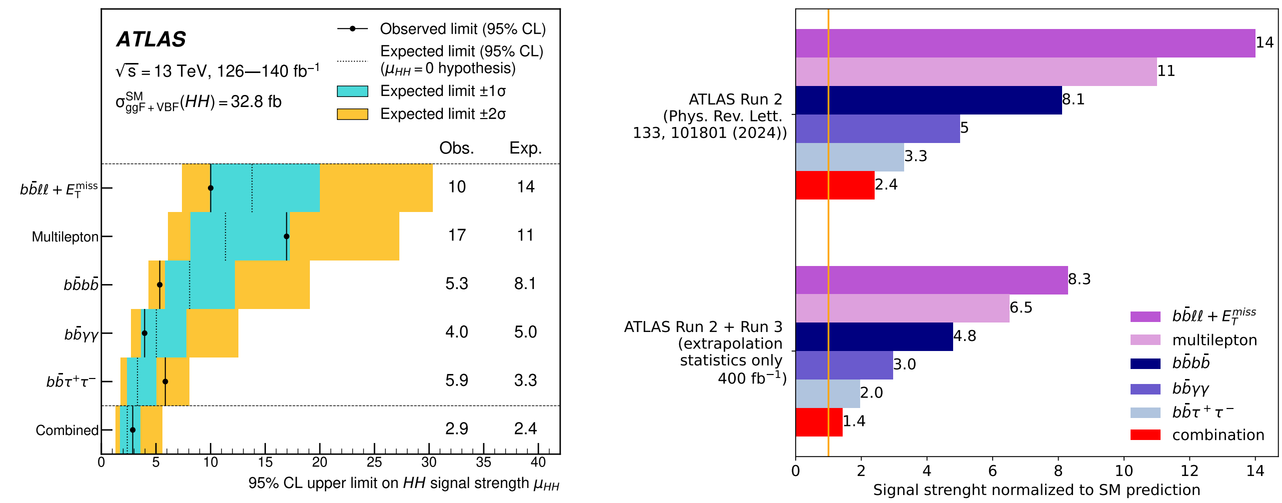

Figure 1: Left: Observed and expected 95% CL upper limits on the signal strength for inclusive ggF HH and VBF HH production from the $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$, multilepton, and $b\bar{b}\ell\ell + E_T^{miss}$ decay channels, and their statistical combination, from Ref. [2]. Right: Extrapolation of the expected sensitivities assuming 400 fb^{-1}of pp collisions in the combined Run 2 + Run 3 datasets, considering only statistical improvement. The orange line at 1 represents the Standard Model (SM) signal strength.

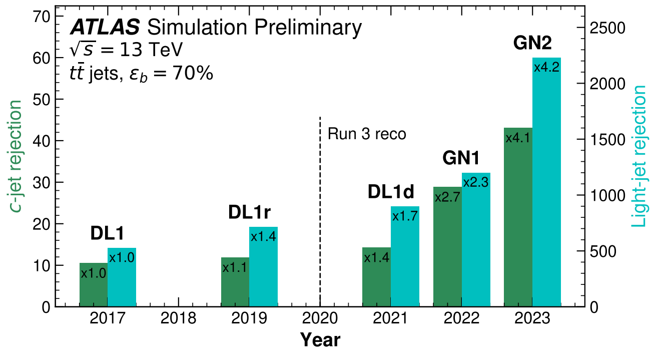

Figure 2: Comparison of the c-jet and light-jet rejection capabilities of various b-tagging algorithms employed by the ATLAS experiment over the years, targeting a tagging efficiency of 70%. The DL1 algorithm is used as a benchmark to gauge the improvement in rejection rates. From Ref. [5].

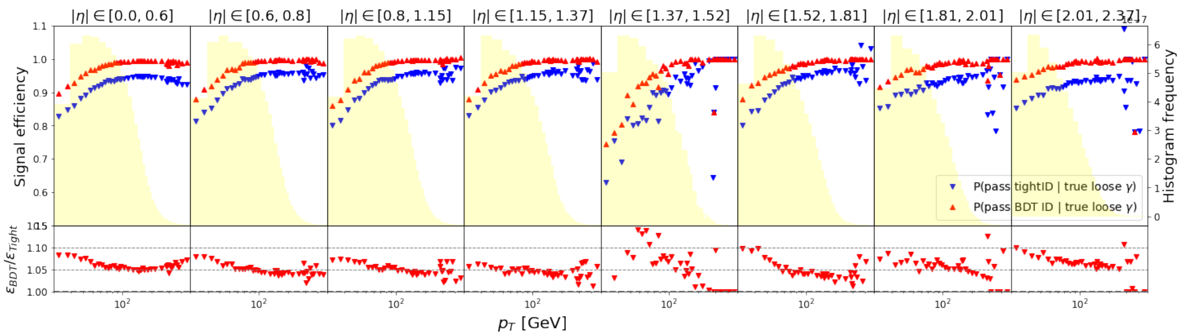

Figure 3: Comparison of photon identification efficiencies between ATLAS's cut-based selection and a new BDT-based approach, selecting a working point with equivalent background rejection across various photon p_{T} and η bins, evaluated using a ggH simulated sample. From Ref. [6].

Objectives of the Proposed PhD Project: Measuring Double Higgs Boson Production in the $b\bar{b}\gamma\gamma$ Channel with the ATLAS Experiment Using Run 2 and Run 3 Data

The proposed doctoral project aims to develop a new ATLAS search for the $HH \to b\bar{b}\gamma\gamma$ process utilizing the comprehensive LHC Runs 2 and 3 datasets. The selected student will join the ATLAS LAPP group in October 2025 under the guidance of the proponent, with the goal of completing their PhD by Summer 2028. This timeline will enable the student to participate in the latter part of Run 3 data collection during their first year of PhD, thus qualifying as an ATLAS author, and subsequently focus on analyzing the complete Run 2 and 3 datasets during the final two years of their PhD. This period is anticipated to coincide with the consolidation of Run 3 data, to which the student will contribute by improving the performance of photon identification and calibration in ATLAS, and by developing various enhancements to the $HH \to b\bar{b}\gamma\gamma$ analysis to fully utilize the Run 2 and Run 3 dataset. Below is a selection of the anticipated developments:

- **Use of the New Machine-Learning-Based GN2 b-Tagger.** Recent advancements in the flavor tagging of QCD jets have been achieved by ATLAS [4]: the new GN2 tagger currently enhances the rejection of light-flavor jets by approximately a factor 3 compared to the DL1r tagger previously employed by the Run $HH \to b\bar{b}\gamma\gamma$ analysis [3], while maintaining the same b-jet selection efficiency (Fig. 2). This new tagger will be incorporated into the Run 2 and Run 3 analyses, while efforts are also made to calibrate it.

- **Development of a Novel ML-Based Photon Identification to Increase the $H \to \gamma\gamma$ Signal Efficiency.** Preliminary studies conducted within the ATLAS LAPP group have indicated that an increase of 5-10% in-photon selection efficiency is achievable while retaining the same level of background rejection by adopting a Boosted Decision Tree (BDT) selection criterion in lieu of the traditional cut-based methodology currently employed by ATLAS (Fig. 3). This enhancement has been shown to improve the expected significance of the Run 2 $HH \to b\bar{b}\gamma\gamma$ legacy analysis by 7% [6]; further gains are anticipated by applying more sophisticated ML techniques.

- **Continuous Calibration of the New ML-Based Photon Identification.** In ATLAS, photon identification has traditionally been calibrated to a working point of fixed efficiency, partly due to limitations imposed by the residual mismodeling of the electromagnetic shower development in the ATLAS calorimeter, leading to significant retuning of the simulation for meaningful data comparison. Fine-tuning the shower development against data would facilitate the calibration of any value of the ML discriminant, effectively permitting its direct application in the $HH \to b\bar{b}\gamma\gamma$ analysis without the need to select a pre-defined (and potentially suboptimal) working point. This approach has been shown to offer additional improvements (up to a 10% increase in signal efficiency [6]), although a consistent calibration has yet to be achieved.

- **Kinematic Fit of the $b\bar{b}\gamma\gamma$ System to Enhance the $H \to b\bar{b}$ Mass Resolution.** This technique is already successfully deployed in other ATLAS Higgs analyses, for instance, the $ZH/H \to b\bar{b}$ measurement [7], where a kinematic fit of the $\ell\ell b\bar{b}$ system significantly refines the $m_{b\bar{b}}$ resolution, the lepton pair $\ell\ell$ origining from the Z decay and providing a mass resolution well under control. A similar enhancement is anticipated for the $b\bar{b}\gamma\gamma$ system thanks to the excellent $m_{\gamma\gamma}$ resolution.
- **Matrix Element Method to Enhance Global Signal-to-Background Discrimination.** Utilizing information about the kinetic properties of the $HH \to b\bar{b}\gamma\gamma$ process, derived directly from hard interaction simulations, can help construct optimal observables for distinguishing the signal from the irreducible background (e.g. as proposed in Ref. [8]).

The project will also explore the **separate treatment of various HH production modes** to heighten the analysis sensitivity. The final measurement aims to be robust against deviations from SM predictions and to maximize sensitivity when **interpreted within the framework of Effective Field Theories (EFTs)**, such as the SMEFT [9] or the HEFT [10] models.

The analysis will unfold within the broader context of ATLAS's search for di-Higgs production across various decay channels, with participation in the **Run 2 and Run 3 di-Higgs combination** expected.

Research Team and Organizational Considerations

The PhD project will be hosted by the ATLAS LAPP group, renowned for its commitment to Higgs physics measurements at the LHC, particularly in the $H \to \gamma\gamma$ channel. This group has previously guided a PhD thesis focused on the search for the $HH \to b\bar{b}\gamma\gamma$ process using only Run 2 data [11].

The proponent has held pivotal roles as the coordinator of the ATLAS EGamma group, which oversees the development of electron and photon reconstruction, identification, and calibration algorithms; the ATLAS HGam group, whichunites all analyses targeting the $H \to \gamma\gamma$ final state; and the ATLAS Higgs group, which coordinates all measurements related to the ATLAS Higgs physics program. Presently, the proponent also leads the LHC Higgs Combination Group.

A postdoctoral researcher (Z. Wu, at LAPP until the end of 2025) is actively collaborating with the proponent on calibrating the GN2 b-tagging algorithm and will provide the necessary overlap to support the selected student to commence their work on this topic by the end of 2025. Another postdoctoral researcher (O. Kurdysh) initiated their collaboration with the proponent in October 2024 and will contribute to the $HH \to b\bar{b}\gamma\gamma$ analysis until 2027. An ongoing ANR project aiming to interpret Higgs measurements within EFT is led by N. Berger at LAPP, with a new postdoctoral researcher soon joining the ATLAS LAPPteam to focus on this area. Consequently, a robust collaborative environment will surround the student alongside the proponent, ensuring a vibrant and dynamic research setting.

LAPP's geographical proximity to CERN, approximately 50 km and a 35-minute drive away, will facilitate significant involvement of the student both in data acquisition and detector operation until 2026 and in attending ATLAS (di)Higgs Group meetings throughout their PhD.

A Master's level internship in Spring 2025 is planned to preliminarily identify a suitable candidate for the project.

References

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