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Luca Cadamuro

Search for Higgs Boson Pair Production in the $b\bar{b}\tau^{+}\tau^{-}$ Decay Channel

with the CMS detector at the LHC

Doctoral Thesis accepted by
the University of Paris-Saclay, Palaiseau, France

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Author
Dr. Luca Cadamuro
University of Florida
Gainesville, FL, USA

Supervisors
Prof. Dr. Yves Sirois
École polytechnique, CNRS-IN2P3
Palaiseau, France

Dr. Roberto Salerno
École polytechnique, CNRS-IN2P3
Palaiseau, France

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Supervisor's Foreword

The Ph.D. thesis of Mr. Luca Cadamuro was carried out with the CMS experiment at the Large Hadron Collider (LHC) and concerned the search for the pair production of Higgs (H) bosons. It was supervised by myself and co-supervised by Dr. Roberto Salerno at the Laboratoire Leprince-Ringuet (LLR) of the École polytechnique, Palaiseau, France. The thesis presents original contributions in two areas: the deployment of new algorithms for the selection of tau (τ) leptons at trigger level, within the new trigger electronic architecture of CMS, and the first analysis for the production of H bosons pairs at the LHC in the pp $\rightarrow$ HH $\rightarrow$b$\bar{\text{b}}\tau^+\tau^-$ channel, with proton–proton collisions at centre of mass of 13 TeV. This thesis has brought major improvements in both areas.

The thesis first describes the new algorithms developed for the tagging of tau leptons at the hardware level of the triggering system. A new time-multiplexed trigger architecture with a two-layered system, based on large field-programmable gate array (FPGA) configurable integrated circuits, was designed and installed in CMS in 2015 in preparation for the data taking at the LHC with high luminosity and high energy. The aim of this thesis work was to best exploit the capacities of the new trigger electronic architecture of CMS. Luca developed a strategy to reconstruct at trigger level the various possible decay modes of τ leptons involving hadrons and distinguish them from the overwhelming quark and gluon jet background. This used the specific topology of energy deposits in the fine-grained calorimetry expected for both one prong decays ($\tau \rightarrow \pi^{\pm}\pi^{0}\nu_{\tau}$) and three prong decays ($\tau \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu_{\tau}$) of the τ leptons. He implemented the algorithms on the FPGAs, in collaboration with engineers at the LLR and the Imperial College (London, UK). He further commissioned the trigger with the first 13 TeV collisions and showed that the selection efficiency for tau lepton pairs was very significantly improved compared to that of previous CMS data taking. The improvement was shown to represent up to a factor 2.5 in selection efficiency for the H boson decay H $\rightarrow \tau^+\tau^-$. The trigger performance results described in this work have been previously presented by Luca in international conferences, at the EPS High Energy Physics Conference in Vienna, Austria, in July 2015 [1], and at the Innovative Particle and Radiation Detectors (IPRD) conference in Siena, Italy, in October 2016 [2].

The original physics analysis work described in this thesis concerns both the searches for non-resonant and for resonant production of H boson pairs. The search for non-resonant production is motivated on the long term by the measurement of the H boson self-coupling. This self-coupling is fundamentally linked to the H boson potential responsible for the spontaneous breaking of electroweak symmetry via the Brout–Englert–Higgs mechanism. Non-resonant HH production is one of the most important processes to be studied with high luminosity at the LHC. Physics models beyond the standard theory, such as supersymmetry, are strong motivations to search for resonant HH production. Luca focused on the analysis of the $b\bar{b}\tau^+\tau^-$ final state which had been initiated using lower luminosity data taken at 7 and 8 TeV. He presented for the first time a very convincing case for this channel in the competition for sensitivity with other HH decay channels. In particular, he showed that a best sensitivity could be obtained for cases where both tau leptons decay semi-leptonically (often called by language abuse τ "hadronic" decays). Such cases lead to signatures with a pair of tau-induced hadronic jets that can be identified thanks to the new trigger algorithms starting with the high energy data in 2015. The analysis described in this thesis uses the full 35.9 fb^{-1} of data collected in 2016. It introduces event categories depending on τ leptons and b quark jets properties, as well as boosted H event topologies to best exploit the fact that the separation of the two b quarks produced in the H boson decay depends on the Lorentz boost of the H boson. The analysis and interpretation of the results also rely on a very much involved treatment of background and systematics. As of March 2017, when the results were first presented by Luca at the International Conference of Moriond [3], they represented the very best sensitivity obtained so far at the LHC for the HH production.

The $HH \rightarrow b\bar{b}\tau^+\tau^-$ from this thesis, combined with new CMS $\rightarrow bb\gamma\gamma$ and $\rightarrow b\bar{b}b\bar{b}$ results, was highlighted at the ICHEP Conference 2018 as representing a major progress in the field, together approaching by close to a factor 10 the prediction of the standard theory for the self-coupling. The final results from this thesis were submitted for publication in summer 2017 and published since then [4].

Palaiseau, France
July 2018

Prof. Dr. Yves Sirois
Directeur de Recherche
École polytechnique
CNRS-IN2P3

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Abstract

This thesis describes a search for Higgs boson pair (HH) production using proton–proton collision data collected at $\sqrt{s} = 13\,\text{TeV}$ with the CMS experiment at the CERN LHC. Events with one Higgs boson decaying into two b quarks and the other decaying into two τ leptons ($\text{HH} \rightarrow \text{b}\bar{\text{b}}\tau^+\tau^-$) are explored to investigate both resonant and non-resonant production mechanisms. HH production gives access to the Higgs boson trilinear self-coupling and is sensitive to the presence of physics beyond the standard model.

A considerable effort has been devoted to the development of an algorithm for the reconstruction of τ leptons decays to hadrons (τ_h) and a neutrino for the Level-1 calorimeter trigger of the experiment that has been upgraded to face the increase in the centre-of-mass energy and instantaneous luminosity conditions expected for the LHC Run II operations. The algorithm implements a sophisticated dynamic energy clustering technique and dedicated background rejection criteria. Its structure, optimisation and implementation, its commissioning for the LHC restart at 13 TeV, and the measurement of its performance are presented. The algorithm is an essential element in the search for HH production.

The investigation of the $\text{HH} \rightarrow \text{b}\bar{\text{b}}\tau^+\tau^-$ process explores the three decay modes of the $\tau^+\tau^-$ system with one or two τ_h in the final state. A dedicated event selection and categorisation is developed and optimised to enhance the sensitivity, and multivariate techniques are applied for the first time to these final states to separate the signal from the background. Results are derived using an integrated luminosity of $35.9\,\text{fb}^{-1}$. They are found to be consistent, within uncertainties, with the standard model background predictions. Upper limits are set on resonant and non-resonant HH production and constrain the parameter space of the minimal supersymmetric standard model and anomalous Higgs boson couplings. The observed and expected upper limits are about 30 and 25 times the standard model prediction, respectively, corresponding to one of the most stringent limits set so far at the LHC.

Finally, prospects for future measurements of HH production at the LHC are evaluated by extrapolating the current results to an integrated luminosity of 3000 fb^{-1} under different detector and analysis performance scenarios.

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As this thesis comes to its conclusion, I wish to thank all the people that have accompanied me during these three years that marked an incredibly enriching period of my life.

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My deepest gratitude is for my supervisors, Yves and Roberto, whose endless and thorough guidance has been essential to shape this work.

Without Yves, this thesis would not even have started, and I thank him for his support since the very beginning of the Ph.D. His vision of physics and his enthusiasm have been an extraordinary motivation to carry on this project, and he has been a point of reference throughout all its development.

And I am indebted to Roberto for all the time that he dedicated to me, following my work day by day. He formed me as a physicist, and I learned how to prepare, develop and present an original scientific work. A lot of this thesis, in its form and its results, owes to the discussions that we had throughout these three years.

Thanks to all the members of the Laboratoire Leprince-Ringuet that have accompanied me in the adventure of the Ph.D. Thanks to the students, the postdocs and the permanent researchers for the knowledge that they shared with me in all the interesting discussions at work, in the *cafétéria* or at the canteen. Thanks also to the IT and administrative teams for their prompt help that allowed this thesis to run smoothly.

This work is however only a small contribution to the huge programme of exploration of particle physics performed at CMS. It is a privilege and an honour for me to be part of such an important project. I am in particular grateful to the members of the L1 trigger team from the LLR and UK groups. And I would like to thank the colleagues from LLR and the Italian institutes of Milano, Bari and Pisa for the path that we walked together in the exploration of Higgs boson pair production.

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