Universität Zürich UZH

PHYSIK INSTITUT
UNIVERSITÄT ZÜRICH

Prof. Ben Kilminster
Physik-Institut
Universität Zürich
CH-8057
Zurich, Switzerland

Nov. 26, 2018

Report on "**Search for Heavy Resonances Decaying into Two Higgs Bosons or into a Higgs Boson and a W or Z Boson in the** $q\bar{q}(b\bar{b})\ \tau^+\tau^-$ **Final State with the CMS Detector** ", PhD dissertation by Camilla Galloni

Dear Colleagues,

The Higgs boson was discovered in 2012, but a number of mysteries remain and are the highest priorities in particle physics. Among these are the question of how the Higgs boson mass is stabilized, why gravity is so weak compared to other forces, what is the reason for the different couplings of the Higgs boson to the fermions, what is dark matter, what are the additional sources of CP violation necessary to generate the observed baryon asymmetry, and how does the neutrino get a mass. The LHC at CERN can help answer these questions by creating all of the particles and interactions of the standard model, as well as possibly finding cracks in this so-far very predictive model.

The PhD thesis of Ms. Camilla Galloni considers the Higgs boson as a tool to probe for new physics. Ms. Galloni searches for new, heavy particles that would appear as resonances of HH or VH, where H is the Higgs boson and V is a vector (W or Z) boson. These particles may be Randall Sundrum gravitons, copies of the graviton at the TeV-scale that emerge in extra dimensions; radions that stabilize the size of the extra dimension; heavy new vector bosons that extend the SM; or new particles that emerge due to compositeness. These models generally address questions of stabilizing the Higgs boson mass due to new interactions at the TeV scale. They also can help explain the weakness of gravity with respect to the weak scale.

Chapter two of the thesis explains the relevant parts of the standard model needed to be understood in order to do her beyond-standard model search. It is not a comprehensive explanation of the standard model; as one reviewer pointed out, there is not an explanation of the CKM matrix that explains the difference between flavor and mass eigenstates, but this is not so relevant to her searches, which focus on new gauge interactions beyond the SM. Chapter three is a nice review of the new theory models that she tests.

Chapter four is a very quick explanation of the LHC and CMS detector, which can be understood in more detail based on the extensive references provides. Camilla includes a description of some of her own work in order to understand the hit resolution of the pixel detector. The pixel detector is a vital contribution of the UZH group to the CMS experiment, as we have helped design, construct, and commission this detector. Camilla has become an expert on the methods for measuring the pixel hit resolution, and this information allows us to make sure the detector is functioning to its design capabilities. This has been a continuing project for her, and after the installation of the new pixel detector at the beginning of 2017, was high-priority work in which she was frequently asked to provide feedback and understand issues on quick time scales.

Chapter five explains how the objects of the standard model are reconstructed and calibrated. Most of this is work produced by others. However, Camilla has made important contributions in identifying high momentum Higgs bosons decaying to tau leptons. The work she has done has been very important in understanding the proper way to trigger on such events, and how to reconstructed extremely boosted Higgs bosons. Camilla has led the way at the LHC in this type of work, and is probably the leading expert at the LHC on boosted Higgs decays to tau leptons.

Chapter six reviews Camilla's first LHC analysis on searching for resonances decaying to boosted Higgs bosons that decay to two tau leptons and two b quarks in LHC collisions with an 8 TeV center-of-mass energy. This is the most complicated boosted diboson search at the LHC. One Higgs boson decays to boosted b quarks, while one Higgs boson decays to boosted tau leptons. Both of these required significant investigation to figure out how to optimally select and reconstruct these objects. Camilla completed this work by herself, with little supervision. To do this, she had previously helped in a search for heavy resonances decaying to $VH \rightarrow qq\tau\tau$, which she does not include in her thesis, but which was published. However, the analysis of chapter six requires $VH \rightarrow bb\tau\tau$, which is another layer of complexity. Besides her needing to develop an approach for boosted $H \rightarrow bb$ identification, she needed to deal with the low statistics of the signal region, which meant she needed to develop a new way to do the background estimations in control regions. This part took perhaps the most amount of effort. The background modeling regions are based on selection similar to that of the signal region, but differing in isolation of the tau leptons, and with jet masses not expected to have signal. It was pointed out in the external review that this chapter was not as thorough as chapter seven, but this was by design. Since the analysis in chapter six is similar to that of chapter seven, Camilla decided to describe the analysis in more detail in chapter seven.

Chapter seven is entirely Camilla's work. It is a more complicated analysis than in chapter seven because she attempts to do more. The analysis was based on a new center-of-mass energy of 13 TeV, and so she began preparing for this analysis by studying different ways of triggering on the events to improve the efficiency for selecting signal events. She then considers additional decay modes of the tau leptons in order to improve sensitivity. By considering Higgs bosons decaying to tau leptons, where both tau leptons decay hadronically, she selects many more signal events but then has additional sources of background to consider from QCD production of multiple jets. She also develops a technique to fit events both with and without b-tags in order to consider resonances decaying to WH, ZH, and HH. This meant that Camilla had to understand and model many different objects including boosted, hadronically decaying W and Z jets, boosted Higgs jets with b-tags, boosted Higgs jets with two tau leptons, and consider both hadronically and leptonically decaying tau leptons and their associated missing transverse energy. She further split the signal events into categories with higher and lower signal purity, in order to both gain in sensitivity and constrain backgrounds. Camilla also does a more comprehensive evaluation of the data with respect to different signal models and constraints, which required some significant understanding of these models. This chapter is more comprehensive than chapter six, and answers many questions that a reader may have asked after reading chapter six, as one reviewer points out.

To summarize, Camilla's original work can be found in sections 4.2.2.1 (measuring hit resolution in the pixel detector), 5.3.7.5 (identifying highly energetic Higgs bosons that decay to tau leptons), and then all of chapter six (searching for HH resonances in run 1 of the LHC), and chapter seven (searching for VH and HH resonances in run 2 of the LHC).

Camilla has been rewarded by CMS for her work on tau leptons and boosted tau identification, as she has been made convener of the CMS tau identification group. In this role, she is in charge of establishing the quality of tau lepton identification algorithms for the entire experiment. This tau identification group has about ten people working on various aspects of tau leptons. One of these is a younger UZH PhD student, and Camilla has been supervising his work, which requires a quite rigorous analysis of CMS data in many final states, taking into account many systematic uncertainties. So Camilla is becoming one of the leading tau experts on CMS.

In conclusion, the PhD work of Ms. Galloni has been on the CMS pixel detector, on tau lepton reconstruction and identification algorithms, and on searches for new physics decaying to Higgs bosons that decay to tau leptons and b quarks. She has completed two analyses by herself, and is now quite capable in producing a complete collider physics analysis, from trigger all the way to signal interpretation. Her analysis does not have an equivalent at the ATLAS experiment, and on CMS, she is a pioneer in utilizing boosted Higgs to tau lepton pairs in order to search for new physics, making her the leading expert at the LHC on this niche. Her thesis is well written and explains especially well her second analysis in chapter seven. While some parts of the thesis could use a bit more detail, she made some educated decisions on what to cover and what not to cover in detail, and the resulting thesis of close to 200 pages could not be said to be too short. Camilla has proven to be a very practical physicist who can break new ground on experimental techniques and become recognized as an expert by the particle physics community. I very much approve of her thesis and recommend it be accepted and she be granted a PhD.

Sincerely,
Prof. Ben Kilminster