Campinas State University

Doctoral Thesis

Search for Z and Higgs boson decaying into $\Upsilon + \gamma$ in pp collisions at CMS/LHC

Author:
Felipe Torres da Silva de Araujo

Supervisor:
Dr. José Augusto Chinellato

Co-Supervisor:
Dr. Alberto Franco de Sá Santoro

A thesis submitted in fulfillment of the requirements for the degree of Doctor in Science, on the field of Physics

in the

Graduate Program of
"Gleb Wataghin" Institute of Physics

July 26, 2021

"*Sometimes science is a lot more art than science. A lot of people don't get that.*"

Rick Sanchez

"*Então, que seja doce. Repito todas as manhãs, ao abrir as janelas para deixar entrar o sol ou o cinza dos dias, bem assim, que seja doce. Quando há sol, e esse sol bate na minha cara amassada do sono ou da insônia, contemplando as partículas de poeira soltas no ar, feito um pequeno universo; repito sete vezes para dar sorte: que seja doce que seja doce que seja doce e assim por diante. Mas, se alguém me perguntasse o que deverá ser doce, talvez não saiba responder. Tudo é tão vago como se fosse nada.*"

Caio Fernando Abreu

CAMPINAS STATE UNIVERSITY

Abstract

"Gleb Wataghin" Institute of Physics

Doctor in Science, on the field of Physics

Search for Z and Higgs boson decaying into $\Upsilon + \gamma$ in pp collisions at CMS/LHC

by Felipe Torres da Silva de Araujo

This thesis presents the study on searches for rare decays of Standard Model bosons to quarkonia. The searches are performed on data collected during the 2016 data taking of the CMS detector, at center-of-mass energy $\sqrt{s} = 13$ TeV. Standard Model Higgs and Z bosons decaying to a $\Upsilon(1S, 2S, 3S)$ and a photon, with subsequent decay of the $\Upsilon(1S, 2S, 3S)$ to $\mu^+\mu^-$ are performed using integrated luminosity of 35.86 fb^{-1} from proton-proton collisions. No significant excess above the background-only assumption is observed. A limit at 95% confidence level, is set on the $Z \rightarrow \Upsilon(1S, 2S, 3S) + \gamma$ decay branching fraction at 2.9, 2.7, 1.4 $\times 10^{-6}$ and on $H \rightarrow \Upsilon(1S, 2S, 3S) + \gamma$ decay branching fraction at 6.9, 7.4, 5.8 $\times 10^{-4}$, using the CL_s method. Contributions given from 2016 to 2018 to the operation, maintenance and R&D for Phase-2 Upgrade of Resistive Plate Chambers (RPC) at CMS are also presented. This includes shift for the system operation, data certification for quality control, upgrade and maintenance of the online software and detector maintenance during the LHC Long Shutdown 2 (LS2.)

Acknowledgements

I would like to thank:

- the Campinas State University for providing the institutional support for this study;
- the Rio de Janeiro State University for the cooperation with Campinas State University in their high-energy physics program. This was a key factor for this study;
- the HEPGRID - High Energy Physics GRID (CMS computing cluster of Rio de Janeiro State University) for providing the computing resources;
- the Ministry of Science, Technology and Innovation" and the "National Council for Scientific and Technological Development – CNPq";
- the European Laboratory for Particle Physics (CERN) for the construction and operation of the Large Hadron Collider (LHC);
- the Compact Muon Solenoid (CMS) collaboration for the construction, operation and provision of the instrumental means for this study;
- my colleagues from CMS-RPC, specially Mehar, Jan, Andres, Nicolas, Gabriella, Mapse and Kevin. Such welcome environment, created a lot of learning opportunities, which I will take for life;
- my colleagues from Rio de Janeiro University, specially my friends, Eliza, Sandro, Dilson and Sheila. This work is gladly shared with them;
- my advisor, Prof. José Augusto Chinellato. His kindness, guidance and trust in my work made this a reality. I will thankfully take his lessons to my carrier;
- my co-advisor, Prof. Alberto Santoro, with all my admiration for his successful carrier and achievements as scientist. My pleasure to be his friend;
- my wife, Yasmin, for her love, unrestricted support and dedication. Without her, this study would never be possible;
- my mother, Doralice, for her unconditional love, support and inspiration.

Contents

List of Figures

List of Tables

List of Abbreviations

CERN	European Laboratory for Particle Physics
LHC	Large Hadron Collider
CMS	Compact Muon Solenoid
SM	Standard Model
R9	Photon R9 is a shower shape variable defined as the fraction of energy deposited in the 5x5 square surrounding the Super Cluster seed of the reconstructe
LS1, LS2	Long-Shutdown 1 and 2. Long periods of maintenance and upgrade (spread over few year), in between data taking periods (Run). The LHC timescale is: Run1, LS1, Run2, LS2, Run3, ...
ECAL	Electromagnetic Calorimeter
HCAL	Hadronic Calorimeter
FEWZ	Fully Exclusive W and Z Production

For my mother…

1 Introduction

The Standard Model (SM) have been proven successful over the last decades by its accordance with results from many particle physics experiments, the Super Proton Synchrotron (SPS) [1] and its experiments created the experimental conditions to the discovery of the electroweak bosons, $W^{\pm}$ and Z. The Tevatron experiments (D0 , from Fermilab) allowed the discovery of the top quark. These were 3 of the four heaviest components of the SM. The missing piece was the, so called, Higgs Boson, or any other explanation to the mass of the other SM particles.

In 2012, during CMS' Run1, at center-of-mass energy $\sqrt{s} = 7$ and 8 TeV, researchers from CMS [2] and ATLAS [3], two collaborations with experiments located at the Large Hadron Collider (LHC), a 27 km long circular proton-proton collider build and operated by CERN, announced the discovery a new particle [4, 5], with characteristics compatibles with the Brout-Englert-Higgs boson, completing the SM picture proposed up to fifty years ago. In 2013, Francois Englert and Peter Higgs were awarded with the Noble Prize for *"for the [...] discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider" [6].*

On top of the success of the Higgs program at CMS, there is much to be understood, e.g. pin down the coupling constants of the Higgs boson with all three generations of quarks and leptons, its mass and its full width, evaluate non-zero CP-odd components in Higgs interactions, investigate double Higgs production and its self-coupling constant and possible extensions of the SM close to the Higgs sector and explore rare decays of Higgs. The former one, specially rare decays involving quarkonia, ,such as $H \to M\gamma$, where M is a meson state, are a very good scenario to investigate the Higgs interaction with other SM particles other than the direct decay. This one would be overwhelmed by the immense background coming from QCD events. The same analogy can be extended to the Z boson, which also serves as a benchmark for the Higgs study.

The present study corresponds to 35.86 fb^{-1} of data taken by CMS during 2016, during the Run2, at center-of-mass energy $\sqrt{s} = 13$ TeV, in which an upper limit on the branching fraction for $H/Z \to \Upsilon(1S, 2S, 3S)(\to \mu\mu) + \gamma$ is determined.

Because of its narrow resolution, muons play a special role not only for this study, but for CMS, in general. Not only the Higgs studies heavily depends of muonic final states (for decay channels, such as $H \to \mu\mu$ and $H \to ZZ \to 4l$ and identification of the production modes), but also muon final states are very important to a whole broad of physics process accessible at CMS/LHC. The Figure 1.1 presents the distribution of dimuon invariant mass reconstructed from different double muon triggers, with different requirements in pseudorapidity and transverse momentum. It is clear how the muons at CMS broaden the set of interesting process giving access to light quark hadrons to high transverse momentum phenomena.

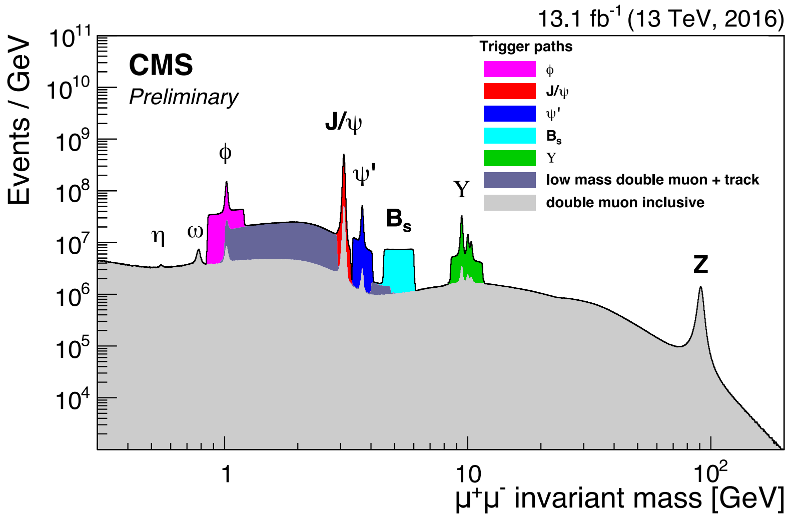

Figure 1.1: Dimuon mass distribution collected with various dimuon triggers. The light gray continuous distribution represents events collected with inclusive dimuon triggers with high p_T thresholds. The dataset corresponding to an integrated luminosity of 13.1 fb^{-1} was collected during the 25 ns LHC running period at 13 TeV in 2016. Source: [7].

In this scenario, a contribution to the muon system of CMS is a meaningfully one to the collaboration. In this document it is described the contributions given to Resistive Plate Chamber (RPC) subdetector, including its commissioning, instrumentation for its upgrade, operation and maintenance.

This document is organized as follows: Chapter 1 is this introduction. Chapter 2 is devoted to a review of the theoretical foundations of this study and the motivations for the study of Rare Z and Higgs decays involving quarkonia. Chapter 3 is a review of the collider and experimental setup, LHC and CMS respectively. Chapter 4 is a reviews of the Resistive Plate Chamber technology for muon detection at CMS and the details of the contributions given to this subdetector. Chapter 5 is a detailed description of the data sample and the applied analysis procedure, as well as the statistical modeling and the branching fraction upper limit extraction. Chapter 6 presents a summary and perspectives for future developments.

Wherever figures and tables sources are not provided, the source is the author himself.

In this document, the convention of natural units is implicitly used: the vacuum speed of light (c), the reduced Planck constant ($\hbar$) and electric permittivity (ϵ_0) are normalized to unity. In this way, SI units are:

- mass $([m]) = \text{GeV}$,
- energy $([E]) = \text{GeV}$,
- momentum $([p]) = \text{GeV}$,
- time $([t]) = 1/\text{GeV}$,
- length $([s]) = 1/\text{GeV}$.

The summation convention is also followed. In this notation, $y = A^i B_i$ stands for $y = \sum_{i=0}^{n} A^i B_i = A^1 B_1 + A^2 B_2 + A^3 B_3 + ... + A^n B_n$.

2 Conclusion and perspectives

In this document it was presented an analysis of the $H/Z \to \Upsilon + \gamma$, with 2016 data sample of the CMS detector, at center-of-mass energy $\sqrt{s} = 13$ TeV. The obtained upper limits (Table ??), show good agreement with the Standard Model predictions and are compatible with previous measurements from other LHC experiments. Future developments of this analysis would be the measurement of the same upper limits considering the fully available statistics of CMS Run2 (2016, 2017 and 2018), the extrapolation of these results to the expected full CMS luminosity (3000 fb^-1) and an evaluation, using DELPHES [8], of the sensitivity of future colliders, such as the International Linear Collider (ILC) [9] or the FCC [10], to this decay.

Table 2.1: Summary table for the limits on branching ratio of Z $\to \Upsilon(1S, 2S, 3S)\gamma$ and H $\to \Upsilon(1S, 2S, 3S)\gamma$ decays.

95% C.L. Upper Limit

	$\mathcal{B}(Z \to \Upsilon\gamma)$ [$\times 10^{-6}$]		
	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Expected	$1.6^{+0.8}_{-0.5}$	$2.0^{+1.0}_{-0.6}$	$1.8^{+1.0}_{-0.6}$
Observed	2.9	2.7	1.4
SM Prediction [$\times 10^{-8}$]	4.8	2.4	1.9
	$\mathcal{B}(H \to \Upsilon\gamma)$ [$\times 10^{-4}$]		
	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Expected	$7.3^{+4.0}_{-2.4}$	$8.1^{+4.6}_{-2.8}$	$6.8^{+3.9}_{-2.3}$
Observed	6.9	7.4	5.8
SM Prediction [$\times 10^{-9}$]	5.2	1.4	0.9

For the Resistive Plate Chambers, it was presented contributions given to the RPC system of CMS, during the development of this study, including its maintenance and R&D. The main challenge for the next generation of detector based on this technology is research on new gas mixtures that do not included in its composition, green houses gases. There are already developments in this direction [11].

Bibliography

1. The Super Proton Synchrotron. `https://cds.cern.ch/record/1997188` (Jan. 2012).
2. Chatrchyan, S. *et al.* The CMS experiment at the CERN LHC. *JINST* **3,** S08004 (2008).
3. Collaboration, T. A. *et al.* The ATLAS Experiment at the CERN Large Hadron Collider. *Journal of Instrumentation* **3,** S08003–S08003. `https://doi.org/10.1088%2F1748-0221%2F3%2F08%2Fs08003` (Aug. 2008).
4. Chatrchyan, S. *et al.* Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett.* **B716,** 30–61. arXiv: `1207.7235 [hep-ex]` (2012).
5. Aad, G. *et al.* Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B* **716,** 1–29. ISSN: 0370-2693. `http://www.sciencedirect.com/science/article/pii/S037026931200857X` (2012).
6. NobelPrize.org. *The Nobel Prize in Physics 2013* `https://www.nobelprize.org/prizes/physics/2013/summary/`.
7. Collaboration, C. *Selected heavy flavor distributions from CMS with 2016 data at 13 TeV* tech. rep. CMS-DP-2016-016 (June 2016). `https://cds.cern.ch/record/2160343`.
8. Ovyn, S., Rouby, X. & Lemaitre, V. DELPHES, a framework for fast simulation of a generic collider experiment. arXiv: `0903.2225 [hep-ph]` (Mar. 2009).
9. Aihara, H. *et al.* The International Linear Collider. A Global Project. arXiv: `1901.09829 [hep-ex]` (Jan. 2019).
10. Abada, A. *et al.* FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3. *Eur. Phys. J. ST* **228,** 755–1107 (2019).
11. Rigoletti, G. *et al.* Studies of RPC detector operation with eco-friendly gas mixtures under irradiation at the CERN Gamma Irradiation Facility. *PoS* **EPS-HEP2019,** 164 (2020).