Campinas State University

Doctoral Thesis

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

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A thesis submitted in fulfillment of the requirements for the degree of Doctor of Physics

in the

Graduate Program of
"Gleb Wataghin" Institute of Physics

August 4, 2020

"*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

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

by Felipe Torres da Silva de Araujo

Searches for 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 presented. The analyses is performed using data recorded by CMS detector from proton-proton collisions at center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 35.86 fb^{-1}. We put a limit, 95% confidence level, on $H \to \Upsilon(1S, 2S, 3S)+\gamma$ decay branching fraction at (6.8, 7.1, 6.0) $\times 10^{-4}$ and on $Z \to \Upsilon(1S, 2S, 3S)+$ γ decay branching fraction at (2.6, 2.3, 1.3) $\times 10^{-6}$. Contributions to operation, maintenance and R&D of Resistive Plate Chambers (RPC) of CMS are also presented. **EXPANDIR**

Acknowledgements

I would like to thank:

- the Campinas State University for providing the institutional support for this study;
- the Rio de Janerio State University for the cooperation with Campinas State University in their high-energy physics program. This was a key factor for this study;
- the National Council for Scientific and Technological Development (CNPq) for the financial support for this work;
- 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.

Contents

1 Introduction

INTRODUÇÃO

USAR UM PAPER DE CMS MUON PERFORMANCE PARA DIZER PORQUE TRABALHAR COM DETECTORES DE MUONS

2 Rare Z and Higgs decays to quarkonia

2.1 Standard Model and Local Gauge Invariance

Physics understands the matter and how it interacts in terms of two components: four fundamentals forces and elementary particles. From the weakest to the strongest, the fundamental forces are: gravitational, weak, electromagnetic and strong. All share common characteristics like, being mediated by particles [1], being relevant within some effective range and have a associate a charge-like quantity (i.e. intrinsic characteristic of the object) that defines whether or not, particles might be subjected to a specific interaction.

Along with the fundamental interactions, the Standard Model (or simply *SM*) defines every existing matter in the Universe as a set of fundamental quantum objects, with properties that define their interaction. Those objects are said to be fundamental since, in the context of the SM, they are the smallest possible components of matter. We shall refer to them as fundamental particles. There four of those mediating particles (force carriers), gluon (g - for the strong interaction), photon (γ - for the electromagnetic interaction), Z and W (for weak interaction), all of them being vector bosons (spin 1). Besides the interaction mediators, described at Table 2.1, the fundamental particles are divided in two groups (*quarks* and *leptons*), with three generations, each. These are not force carriers, but elementary particles, endowed with charge-like characteristics that allow them to by exchange the vector bosons. Those are the building blocks of Matter in our Universe.

Figure 2.1 summarizes their properties. Table 2.1 presents the relative strength and effective range, for each on of the four fundamental interactions. The gravitational force is not study subject of the Standard Model.

Table 2.1: Relative strength (with respect to the strong force) and effective range of action for the four fundamentals interactions.

	Mediator	Relative Strength	Effective Range
Gravitational	Graviton	10^{-41}	∞
Weak	W and Z bosons	10^{-16}	10^{-18} m
Electromagnetic	Photon	10^{-3}	∞
Strong	gluons	1	10^{-15} m

There are six quark, up and down (u and d - first generation), charm and strange (c and s - second generation), top and bottom (t and b - first generation), in increasing invariant mass order of the generations. Since they interact thought all the three fundamental forces of the SM, they are said to possess electrical charge, flavour and color. Their generational counterparts, the leptons,

[1]There is no evidence of the existence of the Graviton (force carrier associated to the gravitational force), even though, it is theorized by models that wish to comprehend gravity in a quantum perspective.

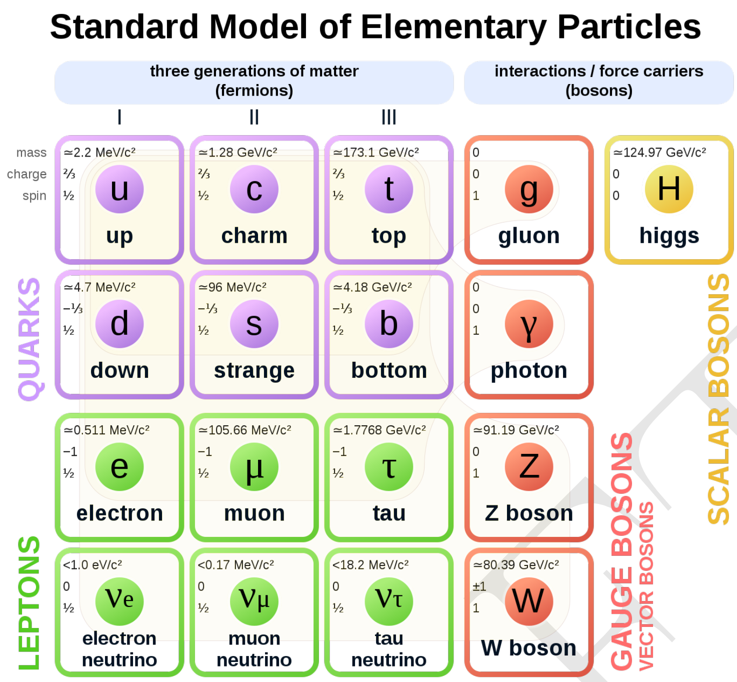

Figure 2.1: Elementary particles of the Standard Model, with their masses charges and spin. Those particles can be divided in two classes: boson (the interaction/force carriers) and the fermions, which are divided in three generations. Source: [1].

don't interact via strong interaction, that is why they are said to have only flavours and electric charge. The leptons are electron and electron neutrino (e and ν_e - first generation), muon and muon neutrino (μ and ν_μ - second generation) and tau and tau neutrino (τ and ν_τ - third generation). The neutrinos, within the SM, are massless, even though, experimental measurements have shown that they actually have mass [2]. Neutrinos are also electrically neutral, meaning that they only interact through weak interactions.

Figure 2.1 also presents the Higgs Boson (H) which is part of the SM and shall be discussed later.

Within the Standard Model, the theoretical basis that describe the fundamental interactions are derived from a common principle: the local gauge invariance. According to Salam and Ward [3]:

> "Our basic postulate is that it should be possible to generate strong, weak and electromagnetic interaction terms [...], by making local gauge transformations on the kinetic-energy terms in the free Lagrangian for all particles."

Taking the Quantum Electrodynamics (QED) as an example: the quantum field theory that describes the x

The fundamental theories that compose the Standard Model are all derived from a fundamental principle call

The electromagnetic force, in the context of fundamental interactions, is describe by a gauge theory called quantum electrodynamics.

Electroweak

Higgs discovery Production modes Decay modes

Yukawa coupling

Higgs results at CMS

The rare decays of the Higgs boson [4, 5] to a quarkonium state and a photon provide a unique sensitivity to the magnitude of the Yukawa couplings of the Higgs boson to quarks [6–8]. These couplings are difficult to access on hadronic collisions through direct decay of Higgs in quark-antiquark, due to the immense background from QCD [9].

Among the channels available to explore Yukawa's couplings of light quarks [7, 8] are those with heavy-quarkonia. The rare modes of decay of the Z boson have attracted attention focused on establishing its sensitivity to New Physics [10], being configured as an alternative environment to investigate the Yukawa couplings of the Higgs boson.

Also, the exclusive rare decays of vector bosons (Z, W) provide a favorable environment for testing the factorization of QCD, thus allowing an approach in a context where the power of corrections are definitely under control. The main focus of this kind of analysis are the hadronic radioactive decays, $Z \to M\gamma$, where M can be a pseudoscalar or a vector meson $(J/\psi, \phi, \Upsilon_n)$.

They offer the perfect way to explore some of the leading order properties of the light-cone distribution amplitudes (LCDAs) [11] of several mesons, but they present a difficulty, considering that in the LHC energy scale the branching ratio of these processes is very small. There are theoretical predictions [12, 13] that point out a branching ratio for several decay channels in the Standard Model, as shown in the Table 2.2.

Physics Processes	Branching Ratio (BR_{SM}):
H$\to \Upsilon(1S)+\gamma$	5.22×10^{-9}
H$\to \Upsilon(2S)+\gamma$	1.42×10^{-9}
H$\to \Upsilon(3S)+\gamma$	9.10×10^{-10}
Z$\to \Upsilon(1S)+\gamma$	4.88×10^{-8}
Z$\to \Upsilon(2S)+\gamma$	2.44×10^{-8}
Z$\to \Upsilon(3S)+\gamma$	1.88×10^{-8}

Table 2.2: Summary of cross section and branching ratio for $H/Z \to \Upsilon(1S, 2S, 3S)+\gamma \to \mu^+\mu^- +\gamma$ analysis. The effective cross-section will be discussed in section **??**.

Recent studies on exclusive Higgs boson decays [14–16] in final states containing a simple vector meson and a photon have caused interest in these physics topics. It was proposed to use these decays as a possible way to explore non-standard Yukawa couplings of the Higgs boson. Such measures are quite challenging in the LHC environment. The observation of hadronic decays of vector bosons provides could provide a new frontier for the nature of heavy quarkonia production in hadronic collisions.

Along the same lines, the simple exploration of rare SM decays, even in scenarios where anomalous couplings are, in principle, ruled out by direct measurements [17], as in the case of this analysis $(H \to \Upsilon(nS)+\gamma)$, are still important as a stress test of the SM and as reference for future measurements. Specially the later one, when you consider that the small predicted cross sections from Table 2.2, most probably, would imply that an observation of this decay would be unlikely even in the HL-LHC [18].

This measurement is sensitive to the direct and indirect production (Figure 2.2). The *direct* process consists in the decay of boson (Higgs or Z) to a quark anti-quark pair, in which, one of the quarks radiates a photon and the pair hadronizes to a meson (a $\Upsilon(nS)$, for this study), while in *indirect* process, the decay happens to a $\gamma\gamma^{*}(Z)$, with the subsequent decay of the $\gamma^{*}(Z)$ to a quark anti-quark that hadronizes.

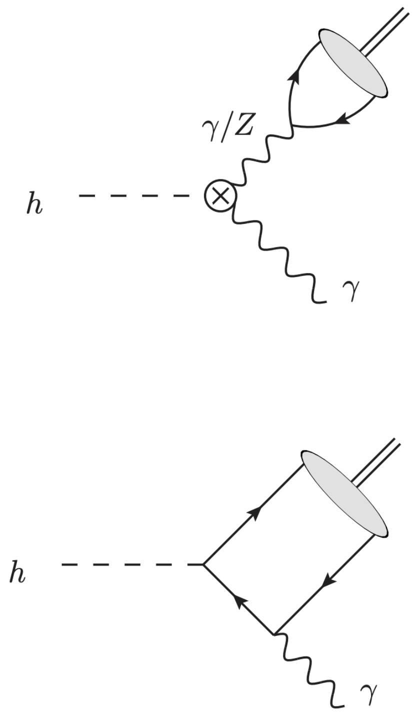

Figure 2.2: Example of leading order diagrams for the indirect (top) and direct production mechanisms. In the diagrams, the h can also be understood as a Z boson.

Clearly, only the direct process is sensible to the Yukawa coupling of the boson with the quarks, but, since both processes are indistinguishable in their final state, the in direct process needs to be taken into account. In this study, a dimuon final state is used to tag the $\Upsilon(nS)$.

Even though there is different theoretical predictions for the cross section of this process and its twin brother ($H \to \mathrm{J}/\Psi + \gamma$), each one taking into account different levels of complexity, the 2013 paper [6], from G. Bodwin, F. Petriello, S. Stoynev and M. Velasco, summarizes very well and in a simpler manner, the most relevant phenomenological results on these decays. For the decay to $J/Psi + \gamma$, the quantum intereference with the indirect amplitude, enhances the directed production, leading to a larger, and potentially observable, cross section. This is not true for the $\Upsilon(nS) + \gamma$ decay, since the interference is destructive, diminishing the cross sections.

Another interesting aspect of this study is that, for both $Hc\bar{c}$ and $Hb\bar{b}$ direct coupling measuremnts are not sensible to the sign of the Yukawa coupling, while the presence of the indirect process in the $H \to M + \gamma$ (M standing for J$/Psi$ or $\Upsilon(nS)$) decays resolve this ambiguity.

Finally, since the $\Upsilon(nS) + \gamma$ decay has a much smaller cross section, because of the destructive quantum interference between direct and indirect production mechanisms, a small deviation in the $Hb\bar{b}$ Yukawa coupling, can lead a large increase in the expected branching ratio, making this channel sensible any non-Standard Model process that might interfere in this final state. This becomes clear when we look to Figure 2.3.

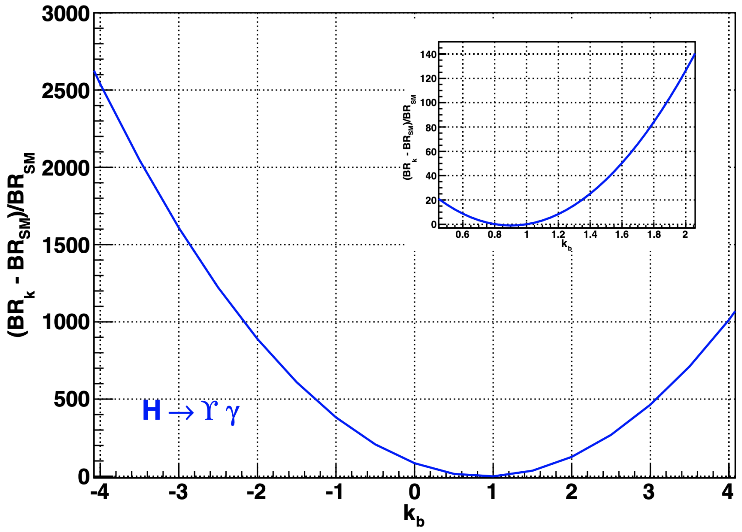

Figure 2.3: Expected relative variation of the branching ratio for the $H \rightarrow \Upsilon(nS) + \gamma$ to k_b, where $k_b = g(Hb\bar{b})/g(Hb\bar{b})_{SM}$ is the ratio for the observed and expected Yukawa coupling oh $Hb\bar{b}$. [6]

2.2 Recent results

The ATLAS experiment [19] already have two results on this decays [20, 21]. The first one corresponds to data taken from 2015, while the former one, corresponds to data from 2016 (the same data taking period to which this study refers).

The what concerns the most updated result, the study corresponded to 36.1 fb^{-1} at $\sqrt{s} = 13$ TeV and no significant excess was found by the experiment. Upper limits for the were obtained, assuming the Standard Model branching fractions predictions, at 95% confidence level, according to table 2.3.

Decay	$\mathcal{BF}$ at 95% CL
H$\rightarrow J/\Psi + \gamma$	$< 4.5\times10^{-4}$
H$\rightarrow \Psi(2S) + \gamma$	$< 2.0\times10^{-3}$
H$\rightarrow \Upsilon(1S) + \gamma$	$< 4.9\times10^{-4}$
H$\rightarrow \Upsilon(2S) + \gamma$	$< 5.9\times10^{-4}$
H$\rightarrow \Upsilon(3S) + \gamma$	$< 5.7\times10^{-4}$
Z$\rightarrow J/\Psi + \gamma$	$< 2.3\times10^{-6}$
Z$\rightarrow \Psi(2S) + \gamma$	$< 4.5\times10^{-6}$
Z$\rightarrow \Upsilon(1S) + \gamma$	$< 2.8\times10^{-6}$
Z$\rightarrow \Upsilon(2S) + \gamma$	$< 1.7\times10^{-6}$
Z$\rightarrow \Upsilon(3S) + \gamma$	$< 4.8\times10^{-6}$

Table 2.3: Observed upper limits, by the ATLAS experiment, on the branching fractions for the Higgs and Z decays (last result). Detailed comparisons with the results obtained in this study will be presented in chapter **??**.

It is worth it to mention that the ATLAS papers present a broader analysis, including the decays to $J/\Psi + \gamma$ and $\Psi(2S) + \gamma$.

CMS [22] also have a result on $J/\Psi + \gamma$ and $\Psi(2S) + \gamma$ decay channel, of the Higgs and Z boson [23]. The observed upper limit on the branching fraction for these decays are presented in table 2.4.

Channel	Polarization	$\mathcal{BF}$ at 95% CL
	Unpolarized	$< 1.4 \times 10^{-6}$
Z$\rightarrow J/\Psi + \gamma$	Transverse	$< 1.5 \times 10^{-6}$
	Longitudinal	$< 1.2 \times 10^{-6}$
H$\rightarrow J/\Psi + \gamma$	Transverse	$< 7.6 \times 10^{-4}$

Table 2.4: Observed upper limits, by CMS, on the branching fractions for the Higgs and Z decays. The number are compatible with the ones obtained by ATLAS. The results presented for different polarization scenarios of the J/Ψ.

No result on the Z and Higgs decays to $\Upsilon(nS) + \gamma$ have been published by CMS, yet.

The results presented here, are a subset of a broader topic related to the rare decays of Standard Model (SM) boson, involving quarkonia. Sticking only to CMS results, we can cite:

- Search for Higgs and Z boson decays to J/ψ or Υ pairs in proton-proton collisions at $\sqrt{s}$ = 13 TeV [24].
- Observation of the Z $\rightarrow \psi\ell^+\ell^-$ decay in pp collisions at $\sqrt{s} = 13$ TeV [25]. This one specifically, is the first observation a such decay, involving a Z boson.

verificar resultados se outros foram publicados.

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