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Jason Tsz Shing Yue

Higgs Properties at the LHC

Implications for the Standard Model and for Cosmology

Doctoral Thesis accepted by
The University of Sydney, NSW, Australia

Springer

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ISSN 2190-5053 ISSN 2190-5061 (electronic)
Springer Theses
ISBN 978-3-319-63401-2 ISBN 978-3-319-63402-9 (eBook)
DOI 10.1007/978-3-319-63402-9

Library of Congress Control Number: 2017948609

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The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Supervisor's Foreword

The groundbreaking discovery of the Higgs boson particle at the CERN Large Hadron Collider (LHC) found fresh physics graduate Jason Yue at the start of his Ph.D. studies in the University of Sydney. This work is a result of his research in one of the most fascinating areas of fundamental physics.

The thesis starts out with a concise introduction to basic theoretical aspects of the Standard Model of particle physics, including discussion on effective field theories and renormalisation, unitarity, gauge invariance and the Higgs mechanism and nonlinear realisation of the electroweak symmetry.

In Chap. 2, the author discusses possible spin and parity assignments for the LHC resonance. The determination of these quantum numbers is an important experimental task for establishing the Higgs mechanism and the related Higgs particle. By utilising theoretical arguments on perturbative unitary and electroweak precision measurements, the author established that generic Higgs impostors with spin-2 and even and odd parities are excluded, leaving the room only for the spin-0 Higgs particle. In view of the fact that spin-2 Higgs impostors with generic interactions are notoriously difficult to exclude by the standard experimental analysis, this result is of a significant importance.

In Chap. 3, Jason analyses anomalous top-quark Higgs Yukawa couplings within the framework of nonlinearly realised electroweak symmetry. Using the collider data, constraints on CP-violating couplings are obtained, and prospects of their measurements in future experiments have been elucidated.

Interactions of the Higgs boson with the heaviest standard model particle, the top-quark as well as Higgs self-interactions may play a very important role in the very early universe. In Chap. 4, Jason studied cosmological implications of the model with anomalous Higgs couplings. He established an intriguing connection between Higgs trilinear coupling and the nature of the electroweak phase transition and the dynamical generation of the matter–antimatter asymmetry in the universe.

The topics studied in Jason Yue's thesis are in the focus of worldwide efforts of experimental and theoretical particle physics communities. I believe this work will be useful for young Ph.D. students as well as experienced researchers.

Sydney, Australia
June 2017

Archil Kobakhidze
Associate Professor

Abstract

The aim of this thesis is to study the properties of the 125 GeV Higgs-like resonance discovered at the Large Hadron Collider (LHC) in 2012 and to elucidate its role in electroweak (EW) symmetry breaking. The first step is to study the spin and charge parity ($J^{\mathcal{CP}}$) assignments for this resonance, which are alternate to the Standard Model (SM) Higgs. In particular, we use unitarity arguments to eliminate the possibility that the new resonance is a spin-2 impostor. Furthermore, it was found that such an impostor leads to large deviations from the observed oblique precision parameters. This resonance must then be a scalar, a pseudoscalar or a mixture of these two cases.

A nonlinearly realised electroweak symmetry may lead to $\mathcal{CP}$-violating top-Yukawa couplings. Collider data was used to put indirect constraints on the modulus, y_t and $\mathcal{CP}$-phase, ξ, which parameterise such couplings. We then studied the LHC potential to probe the $t\bar{t}h$ coupling directly through the $pp \to thj$ channel, focusing on the scalar ($|\xi| = 0$), pseudoscalar ($|\xi| = 0.5\pi$) and maximally mixed ($|\xi| = 0.25\pi$) scenarios. It was found that large QCD backgrounds in $h \to b\bar{b}$ decays make it difficult to observe thj production. Instead, we demonstrated that higher signal significance is expected in $h \to \gamma\gamma$ decays, where signal reconstruction is significantly improved due to cleaner signatures. The lepton forward–backward asymmetry was found to be a good $\mathcal{CP}$-observable. As it measures the polarisation of the produced t-quark, it allows different ξ's to be distinguished.

The last part of this thesis examines the phase transition (PT) of a nonlinearly realised EW gauge symmetry. Electroweak baryogenesis may then generate the observed matter–antimatter asymmetry without augmenting the SM particle content. This is realised by extra sources of $\mathcal{CP}$-violation and first-order PT due to the anomalous top-Higgs and cubic Higgs interactions of the non-standard gauge structure.

Preface—The Higgs Discovery

> *Thus invariance principles [of symmetry] provide a structure and coherence to the laws of nature just as the laws of nature provide a structure and coherence to the set of events.*
>
> —D.J. Gross [1]

The discovery of a Higgs resonance, $h(125)$[1], was announced by ATLAS and CMS in 2012 [2, 3]. In the Standard Model (SM) of particle physics, the Higgs boson plays an instrumental role in giving masses to the particles whilst keeping gauge invariance [4–8]. This reconciliation with gauge symmetry principles is an important step in successfully describing the fundamental particles and their interactions. The Higgs discovery follows from analysing the 5 fb^{-1} and 20 fb^{-1} of data collected in 7 and 8 TeV pp-collisions respectively. This was mainly driven by the $h \rightarrow \gamma\gamma$ and $h \rightarrow ZZ^*$ decay channels where they individually reached significances of $> 4\sigma$ and $> 5\sigma$ respectively. The same resonance was identified with $> 2\sigma$ excess in the $h \rightarrow WW^*$ channel within the same mass region, but with a lower resolution. The combination of these channels resulted in a local excess of $> 5\sigma$, suggesting that a random statistical fluctuation is unlikely[2].

The high mass resolution in the $h \rightarrow \gamma\gamma, ZZ^*$ channels was exploited by the collaborations to yield the first combined measurement of the Higgs mass [9] (cf. Fig. 1):

$$m_h = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV}.$$

In the forthcoming years, the focus of the community is to pin down the role that $h(125)$ plays in the electroweak (EW) symmetry breaking. The first step in characterising the Higgs-like resonance is to establish its spin and $\mathcal{CP}$-properties ($J^{\mathcal{CP}}$),

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[1] We will subsequently use this interchangeably with h to denote the resonance.

[2] A 5σ significance corresponds to a probability or p-value of $\sim 10^{-7}$ assigned to obtaining the current data without the resonance.

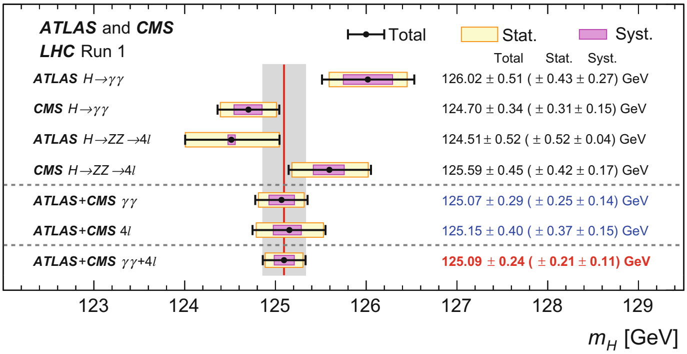

Fig. 1 Combination of the ATLAS and CMS measurements on the mass of the Higgs-like resonance using the $h \rightarrow \gamma\gamma$ and $h \rightarrow ZZ^*$ decay channels. *Source* [9]

which are the quantum numbers[3] dictating the Lorentz structure of the possible interactions. This is the subject of our work in [10–12]. The related cosmological implications of such a resonance were subsequently explored in [13]. This thesis will be devoted to explaining this series of works.

In Chap. 1, we review the role that the Higgs boson plays in the context of gauge invariance, unitarity and renormalisability. In particular, the Higgsless theory is well described by an effective chiral theory where the electroweak symmetry $SU(2)_L \otimes U(1)_Y$ is nonlinearly realised. A scalar is required to unitarise the perturbative scattering amplitudes whilst retaining the perturbative regime, whereas the unitarisation by vector or tensor resonances will eventually lead to a strongly coupled theory[4]. Also, spontaneous symmetry breaking with a vector or tensor resonance should lead to a vacuum that violates Lorentz symmetry.

Current experimental data is consistent with a SM scalar of even parity ($J^{\mathcal{P}} = 0^+$). The $J = 1$ case can be eliminated by the Landau–Yang theorem, but exclusion limits on the $J = 2$ alternative hypothesis are based on minimal graviton-like couplings. Although the discovery was made solely in the diboson channels, the existence of such scalar couplings to massive bosons is taken as an indication that the minimal Higgs mechanism indeed operates in the SM gauge sector. In recognition of this contribution, Higgs and Englert shared the Nobel Prize in 2013.

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[3] Here J refers to spin, and $\mathcal{C}$ to charge conjugation, where the particle is exchanged for its antiparticle; $\mathcal{P}$ refers to spatial inversion of the particle wavefunction. The eigenvalues associated with these two operators may be either positive or negative.

[4] Although it was shown in [14, 15] that a heavy vector state can replace the Higgs in unitarising the scattering of the weak gauge bosons, but this is only so up to a cut-off of $\Lambda \sim 3$ TeV. A more massive scalar or an infinite tower of vector-like resonances (e.g. in extra dimensions or composite scenarios, possibly related via the AdS/CFT conjecture) will then be required to unitarise such theory (cf. e.g. [16, 17]).

Chapter 2 will correspond to our work [10], where we give a theoretical argument against a spin-2 impostor with generic couplings. This is based on the fact that such a resonance should lead to unitarity violation if it is to mimic the SM Higgs decay rate to weak bosons and if no further particles are found. The electroweak precision observables are also shown to be incompatible with such a replacement of the SM Higgs with the impostor.

Having ruled out the $J = 1$ and $J = 2$ scenarios, one can focus on distinguishing a pure scalar hypothesis against a pure pseudoscalar hypothesis. The preference of the 0^+ case over the 0^- case is not unexpected, given that the resonance discovery is made in the diboson modes. Pseudoscalar couplings to massive vector bosons are loop suppress relative to the tree-level scalar mass terms induced by the Higgs mechanism (cf. Chap. 3). As such, the fermion sector should provide a more democratic probe to the $\mathcal{CP}$-structure of the new resonance.

In order to show that the minimal Higgs mechanism is also operative in the Yukawa sector, one has to first verify that the Higgs boson couples proportionally to the masses of the fermions, which is required to retain the $SU(2)_L$ structure in the SM. Global fits where the Higgs couplings to the bosons and fermions are allowed to scale from those in the SM by respective constants κ_i, reveal that this is indeed the case (cf. Fig. 2). Subsequently, there will be a preference to decay into heavy fermions. Although the top-quark mass is the largest of the fermions, on-shell $h \to t\bar{t}$ decays are forbidden since $m_h < 2m_t$. The most favourable fermion decay channels are then $h \to b\bar{b}$ and $h \to \tau\tau$ but no direct fermion coupling could yet be established. There are only evidence for the $\tau\tau$ mode at ATLAS (4.5σ) [19] and CMS (3.2σ) [20].

The dominant Higgs production and decay mode have also been measured to be consistent with the SM prediction. This is evident in Fig. 3, where μ_i parameterises

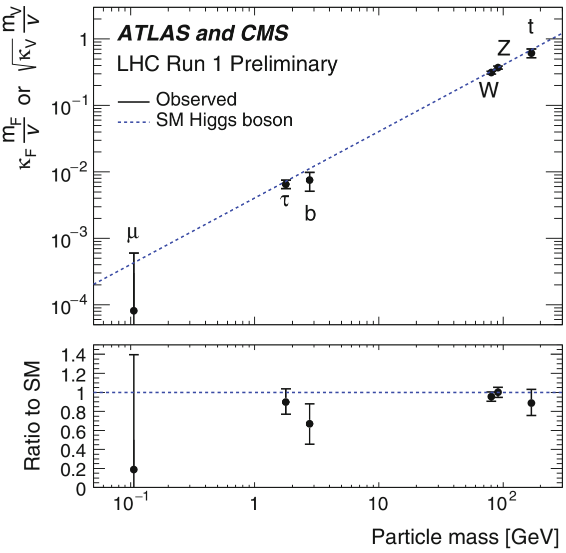

Fig. 2 ATLAS and CMS measurements of Higgs couplings and masses of the various SM particles. Should the Higgs be solely responsible for generating these masses, the couplings should be proportional to the masses. *Source* [18]

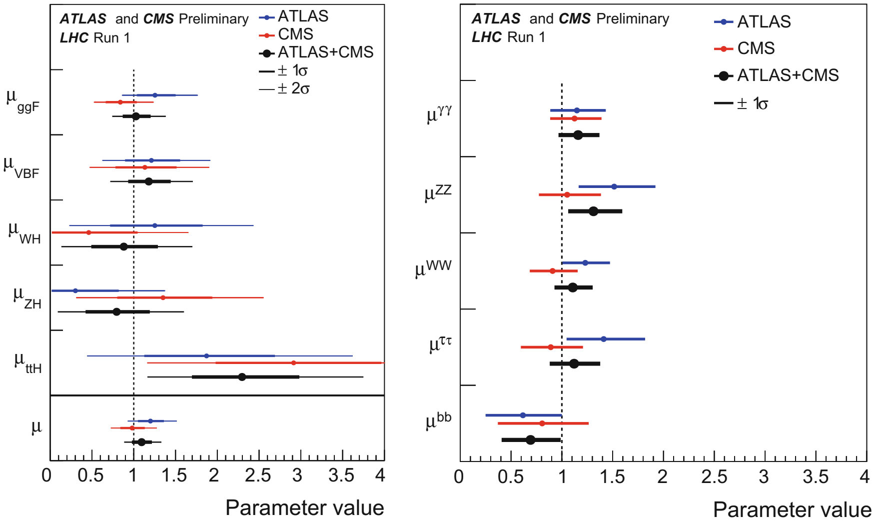

Fig. 3 ATLAS and CMS measurements of the Higgs production (left) and decay (right) rate, as measured with the normalisation μ_i with respect the SM prediction. *Source* [18]

the normalisation of the measured rate with respect to that of the SM. As gluon fusion production ($gg \to h$) and diphoton decay ($h \to \gamma\gamma$) are mediated predominantly by t-quark loops in the SM, the consistency of the data with $\mu_{ggF} = \mu^{\gamma\gamma} = 1$ hint at the existence of the top-Yukawa coupling.

Assuming a scalar hypothesis, current measurements of the Higgs couplings still allow departures from a linear electroweak gauge structure. As such, the new resonance can be a singlet under the nonlinearly realised electroweak symmetry[5]. An important ramification is that the singlet is possibly not a $\mathcal{CP}$-eigenstate. Chapter 3 is devoted to explaining [11, 12], which focuses on the collider consequences of a $\mathcal{CP}$-violating top-Yukawa coupling. Information about such a sector may then be obtained from the decay and production rates, as well as kinematic variables. In particular, a global fit of the modulus and $\mathcal{CP}$-violating phase on the anomalous top-Higgs coupling is included. Subsequently, the polarisation of the top-quark in the $pp \to thj$ channel can be inferred from its decay products.

Finally, there are long-standing observations which are not addressed in the SM, namely (i) the baryon asymmetry in the universe, (ii) the neutrino masses and mixings, (iii) dark matter, (iv) gravitational interactions, and (v) the stability of the electroweak scale and Higgs mass. Chapter 4 follows our work [13], where we address the issue of baryogenesis. We study the phase transition within the effective field theory of the nonlinearly realised EW gauge group and explain how the

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[5] Although one can also approach to explain the deviations using higher dimensional operators from the SM effective field theory.

observed baryon asymmetry is accommodated. This is achieved via extra sources of $\mathcal{CP}$-violation from the top-Higgs sector, which together with anomalous cubic Higgs couplings drives a strongly first-order phase transition. The conclusion and outlook is finally presented in Chap. 5.

Taipei, Taiwan Dr. Jason Tsz Shing Yue

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Acknowledgements

I am most indebted to my advisor Archil Kobakhidze, without whom this series of works is not possible. I thank him for introducing the physics topics to me as well as sending me to various schools and conferences. My graititude also goes towards my co-supervisor Lei Wu, who has helped me in many aspects of the phenomenological works. I am also grateful for the experienced advices that I have received from Michael Schmidt and Kristian McDonald during my studies. A special thanks to the residents of Room 342—particularly Neil Barrie, Adrian Manning, Suntharan Arunasalam, Cyril Lagger and Carl Suster for the countless discussions on physics and other matters. I should also thank the particle physics centre CoEPP and the Australian Research Council for supporting this research.

I will cherish the many memories I share with my friends during my Ph.D. studies—especially those with Eric Lee, Marcello Solomon and Angelica Lau. I am also thankful to my unlce Valen, for his encouragments. Last but not least, I would like to thank my family—Eric, May and Jimmy, for their love and support during my academic endeavours.

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