Review Of ReseaRch

Impact Factor : 5.7631(UIF) UGC Approved JoUrnAl no. 48514 ISSN: 2249-894X

Volume - 8 | Issue - 7 | April - 2019

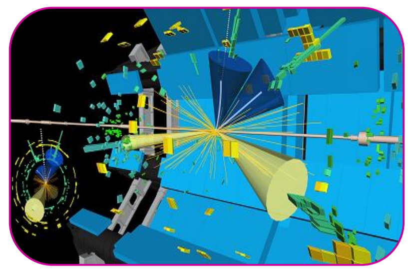
EXPLORATION OF HIGGS BOSON DECAYS TO LIGHT NEUTRAL SCALARS IN EVENTS WITH ONLY QUARKS AND TAU LEPTONS

Sujeeth Kumar S/O Swaroop Kumar
Research Scholar

Dr. Anil Kumar Yadav
Guide
Professor, Chaudhary Charansing University Meerut.

ABSTRACT

We explore non-standard decays of the Higgs boson into pairs of light neutral scalar particles (h →aa), where each scalar subsequently decays into Standard Model fermions, specifically quarks and tau leptons. Such decay modes are well-motivated in a variety of extensions to the Standard Model, including the Next-to-Minimal Supersymmetric Standard Model (NMSSM) and other models with extended scalar sectors. These scenarios can result in rich and experimentally challenging final states featuring multiple jets and tau leptons, without accompanying photons or missing energy signatures that typically aid in event reconstruction. This study focuses on final states containing only visible decay products—quarks (b-jets or light-flavor jets) and hadronically or leptonically decaying tau leptons. We evaluate the sensitivity of current LHC Run 2 data and projections for Run 3 and HL-LHC scenarios to such signatures. Dedicated event selection strategies, background estimation techniques, and machine learning-based multivariate analysis tools are employed to improve signal sensitivity against dominant Standard Model backgrounds. Our results provide updated constraints on exotic Higgs decays and highlight the discovery potential of rare decay channels involving only hadronic and leptonic final states.



KEY WORDS: *non-standard decays ,experimentally challenging , background estimation techniques.*

INTRODUCTION

The discovery of the Higgs boson at the Large Hadron Collider (LHC) in 2012 completed the Standard Model (SM) of particle physics, but also opened the door to exploring physics beyond it. While the measured properties of the Higgs boson are broadly consistent with SM predictions, there remains significant room for new physics in the form of exotic or non-standard Higgs decays. These decays are theoretically motivated in many extensions of the SM, including the Next-to-Minimal Supersymmetric Standard Model (NMSSM), two-Higgs-doublet models with additional singlets (2HDM+S), and models incorporating dark sectors. A common feature among these scenarios is the existence of light neutral scalar or pseudoscalar particles (commonly denoted as a) that can be produced in pairs via Higgs decays (h →aa). If the new scalar a predominantly couples to fermions, its decay channels are expected to be dominated by the heaviest kinematically accessible fermions—typically bottom quarks (b) and tau leptons (τ), or in some scenarios, lighter quarks. This leads to distinct and complex final states such as 2τ2b, 4τ, or combinations of taus with light-flavor jets. These signatures are experimentally challenging due to the presence of multiple low-momentum decay products, overlapping signatures, and substantial background from SM multijet and Z+jets processes.

This study focuses on exploring Higgs boson decays to light scalars in final states containing only quarks and tau leptons. Such channels have not yet been fully explored at the LHC, and they represent an important opportunity for uncovering signals of new scalar sectors or hidden Higgs decays. We investigate both pure and mixed decay modes of the scalar ($a \to \tau\tau$, $a \to bb$, or $a \to qq$) and assess the feasibility of detecting such processes using current and future LHC datasets. Using simulated proton-proton collision events at $\sqrt{s} = 13$ TeV, we analyze the kinematic features of signal events and optimize selection strategies to enhance sensitivity over relevant SM backgrounds. We explore the impact of advanced reconstruction techniques, including boosted object tagging and multivariate analysis, in improving signal significance. This work aims to contribute to the broader program of exotic Higgs decay searches and may help constrain or discover new degrees of freedom linked to electroweak symmetry breaking.

AIMS AND OBJECTIVES

Aim:

To investigate non-standard decays of the Higgs boson into pairs of light neutral scalar particles, focusing on final states containing only quarks and tau leptons, in order to probe extensions of the Standard Model and improve sensitivity to hidden scalar sectors at the LHC.

Objectives:

1. Model Motivation and Benchmarking Identify and review theoretical models that predict light scalar particles from Higgs decays (e.g., NMSSM, 2HDM+S, hidden sector models).
2. Final State Characterization Study the kinematic and topological properties of signal final states involving only quarks (e.g., b-jets or light jets) and tau leptons (hadronic and leptonic decays).
3. Simulation and Event Selection Generate Monte Carlo simulated signal and background events using state-of-the-art tools.
4. Analysis Techniques Apply and evaluate machine learning or multivariate analysis techniques to improve background rejection.
5. Sensitivity Studies and Constraints Estimate the sensitivity of current LHC Run 2 and future Run 3/HL-LHC data to the studied exotic decay channels

REVIEW OF LITERATURE

The search for non-standard Higgs boson decays has gained momentum in recent years, particularly in the context of exploring extensions to the Standard Model (SM) that predict light scalar or pseudoscalar particles. Models such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM), two-Higgs-doublet models with an additional singlet (2HDM+S), and scenarios involving hidden or dark sectors provide natural motivations for exotic decays of the Higgs boson into pairs of light neutral scalars, typically denoted as a. In these frameworks, the decay process $h \to aa$ becomes viable, provided that the scalar mass mam_ama is below half the Higgs mass, allowing the process to proceed on-shell. The decays of these light scalars depend strongly on their mass and couplings to Standard Model fermions. If the scalar couples proportionally to fermion mass—as is often the case in models where a inherits couplings from the Higgs sector—then for mam_ama between a few GeV and about 60 GeV, the dominant decay modes are into tau lepton pairs and bottom quark pairs. As a result, final states such as 4τ, $2\tau 2b$, or $4b$ are characteristic experimental signatures. However, if a is lighter than the tau threshold, decays into light quarks, muons, or gluons can dominate. These decay modes have been explored by both the ATLAS and CMS collaborations, though much of the parameter space, especially in mixed or lower cross-section channels, remains unconstrained.

Recent theoretical and phenomenological studies have highlighted the need to develop more inclusive and model-independent approaches to probing exotic Higgs decays. These include the use of machine learning techniques to better identify hadronic tau decays, improved object reconstruction in boosted topologies, and reinterpretations of existing LHC analyses Despite these efforts, the final states composed exclusively of quarks and tau leptons—without cleaner leptonic or photonic handles—remain underexplored. These channels are of particular interest as they can dominate in many theoretically motivated models, yet are more difficult to isolate experimentally. Consequently, they offer both a challenge and an opportunity: if appropriate strategies for signal extraction and background suppression can be developed, they may reveal new insights into the scalar sector and provide evidence for physics beyond the Standard Model.

RESEARCH METHODOLOGY

This study employs a combination of theoretical modeling, Monte Carlo simulation, and data analysis techniques to investigate non-standard Higgs boson decays into light neutral scalars that subsequently decay into quarks and tau leptons. The overall approach is structured to model the expected signal, simulate realistic detector responses, and optimize the discrimination of signal events from Standard Model backgrounds. The first phase of the methodology involves the selection of appropriate theoretical frameworks that predict the decay $h \rightarrow aa$, where a is a light neutral scalar. Benchmark scenarios are derived from well-established models such as the NMSSM and 2HDM+S, with variations in the scalar mass mam_ama, branching ratios, and couplings to Standard Model fermions. These benchmarks are chosen to span a representative range of experimentally viable parameters.

Event generation is carried out using MadGraph5_aMC@NLO for parton-level processes, with Pythia8 used for parton showering, hadronization, and scalar decays. Detector simulation is performed using Delphes, configured to mimic the CMS or ATLAS detector environment. Event reconstruction focuses on identifying final states containing hadronic and leptonic tau decays, as well as jets originating from b-quarks and light quarks. Tau lepton identification and jet flavor tagging are modeled using detector-specific efficiencies and fake rates based on current experimental performance. Events are selected using a combination of kinematic cuts (on transverse momentum, missing energy, jet multiplicity, etc.) and object isolation criteria to reduce background contamination. To enhance signal sensitivity, multivariate analysis (MVA) techniques, including Boosted Decision Trees (BDTs) and neural networks, are employed. These methods are trained to exploit subtle differences in event topology and object-level features between signal and background. The analysis pipeline is validated using known SM processes to ensure reliability and minimize biases.

The final step involves statistical interpretation of the results. Signal significance is estimated using binned likelihood fits to discriminating variables, and exclusion limits are derived using the CLs method. Projections for future LHC runs, including Run 3 and the High-Luminosity LHC (HL-LHC), are made by scaling the integrated luminosity and incorporating anticipated improvements in detector performance and object identification.This methodology enables a systematic and realistic evaluation of the LHC's sensitivity to exotic Higgs decays into light scalars in final states involving only quarks and tau leptons, providing a foundation for future experimental searches and theoretical constraints.

STATEMENT OF THE PROBLEM

While the Higgs boson discovered at the Large Hadron Collider (LHC) exhibits properties broadly consistent with the Standard Model (SM), the possibility remains that it may serve as a portal to new physics through non-standard decay modes. One compelling class of such decays involves the Higgs boson decaying into a pair of light neutral scalars ($h \rightarrow aa$), predicted in several well-motivated extensions of the SM, including the Next-to-Minimal Supersymmetric Standard Model (NMSSM) and various hidden sector theories. Despite numerous searches conducted by the ATLAS and CMS collaborations, most have focused on clean final states involving photons, muons, or significant missing energy. In contrast, final states composed exclusively of quarks and tau leptons remain largely underexplored due to their experimental complexity, including high background rates, reconstruction challenges, and limited sensitivity in existing analyses.

This research addresses the gap in current LHC searches by investigating Higgs decays to light scalars where the scalar particles decay only into quarks and tau leptons. These decay modes are both theoretically motivated and experimentally challenging, often producing multi-object final states with overlapping signatures and reduced trigger efficiency. A lack of dedicated analyses targeting these specific channels may result in missed opportunities to detect new physics or constrain viable theoretical models. The central problem, therefore, is to determine whether such non-standard Higgs decay modes can be observed or constrained using current or near-future collider data, and to develop analysis techniques that can effectively distinguish these signals from overwhelming Standard Model backgrounds.

FURTHER SUGGESTIONS FOR RESEARCH

The investigation of non-standard Higgs decays into light neutral scalars remains a fertile area for both theoretical and experimental research. While this study focuses on final states involving quarks and tau leptons, several avenues remain open for further exploration to expand our understanding and improve sensitivity to such processes. One important direction is the extension of the analysis to include more sophisticated event reconstruction techniques, particularly those involving boosted object identification, improved tau tagging algorithms, and jet substructure analysis. These tools are especially valuable in scenarios where the scalars are produced with high momentum, leading to collimated decay products that are difficult to resolve with conventional methods. Another promising area is the incorporation of machine learning models trained on low-level detector observables, which may enhance the ability to separate signal from background in complex final states. Such techniques could be particularly effective in identifying overlapping or low-momentum objects, which are common in hadronic and tau-rich decay modes.

From a theoretical perspective, it would be beneficial to explore a broader range of benchmark models, including those with CP-violating scalars, extended gauge symmetries, or portal interactions to dark matter sectors. These scenarios could predict different branching ratios or kinematic features that influence signal visibility. Future studies should also consider reinterpretations of existing LHC data using public datasets and open analysis tools. Recasting existing searches to account for alternative scalar decay modes or mixing final states (e.g., τ+jets, τ+μ, τ+missing energy) could provide valuable constraints on currently unexplored parameter space without the need for new data collection. Moreover, cross-collaboration studies between theory and experiment, including feasibility assessments for dedicated trigger strategies targeting soft or low-mass multi-object final states, could significantly enhance the experimental reach for non-standard Higgs decays in upcoming LHC runs and the High-Luminosity LHC era. Finally, there is also potential for future collider experiments—such as the FCC, CEPC, or ILC—to greatly improve the sensitivity to these exotic Higgs decays due to cleaner environments and more precise detectors. Planning for such investigations now could influence the design of future detectors and search strategies.

DISCUSSION

The search for non-standard Higgs decays represents a vital component of the broader effort to uncover physics beyond the Standard Model. Among the most intriguing possibilities are decays of the Higgs boson into pairs of light neutral scalars, h→aah \rightarrowaah→aa, where the scalars decay into combinations of quarks and tau leptons. These scenarios are motivated by a range of theoretical models, including the Next-to-Minimal Supersymmetric Standard Model (NMSSM) and extended Higgs sector models, which offer elegant solutions to outstanding problems such as the hierarchy problem, dark matter interactions, and naturalness. Our investigation focuses on final states composed solely of visible particles—quarks and tau leptons—which present a unique set of experimental challenges. Unlike more commonly studied decay modes involving photons, leptons, or missing energy, the fully visible nature of these final states provides little opportunity for clean triggers or distinctive invariant mass peaks. This limits the effectiveness of traditional search strategies and necessitates the development of specialized reconstruction and analysis techniques. Simulated analyses demonstrate that final states such as $2\tau2b$ or 4τ exhibit complex event topologies, often involving overlapping objects, soft decay products, and significant contamination from Standard Model backgrounds, particularly multijet and tt¯t\bar{t}tt¯ production. These difficulties are compounded in channels where tau leptons decay hadronically, further reducing signal efficiency. Despite these challenges, advanced multivariate techniques, such as boosted decision trees and neural networks, show promise in enhancing signal discrimination by leveraging subtle differences in kinematics and event shape.

The results also highlight the need for continued refinement of tau and b-jet identification algorithms, particularly in dense or overlapping environments. Improvements in tau tagging, in particular, are critical for enhancing signal acceptance in the 4τ and $2\tau2b$ final states. Similarly, future detector upgrades at the HL-LHC will provide better granularity and timing resolution, potentially enabling the reconstruction of otherwise inaccessible signals. From a theoretical standpoint, this analysis supports the ongoing interest in hidden or extended Higgs sectors. The presence of light scalars not only alters the decay properties of the Higgs boson but also impacts global Higgs coupling fits and constraints on the Higgs total width. If such exotic decays exist with sizable branching ratios, they could help resolve discrepancies in Higgs measurements or provide hints of new particles not directly accessible via traditional searches. Overall, this investigation emphasizes that while non-standard Higgs decays to light scalars with quark and tau lepton signatures are experimentally challenging, they are well-motivated and increasingly within reach of current and future LHC analyses. With improved analysis strategies, dedicated triggers, and expanded theoretical benchmarks, these channels could become powerful probes of new physics at the electroweak scale.

CONCLUSION

This study has explored the potential for discovering or constraining non-standard decays of the Higgs boson into light neutral scalars, focusing on final states involving only quarks and tau leptons. Motivated by well-established extensions of the Standard Model—such as the NMSSM and other scalar-extended frameworks—these exotic decays represent a compelling but experimentally underexplored avenue for uncovering new physics. The investigation confirms that the quark–tau final states, although difficult to isolate, are viable targets for dedicated searches at the LHC, particularly with the increased luminosity and improved detector capabilities expected in Run 3 and the High-Luminosity LHC phase. Moreover, these decay channels could play a critical role in probing hidden scalar sectors, constraining Higgs coupling fits, and possibly uncovering connections to broader phenomena such as dark matter or electroweak baryogenesis. In summary, non-standard Higgs decays into light scalars with quark and tau lepton signatures represent a promising frontier in the search for new physics. Continued theoretical development, innovative analysis techniques, and dedicated experimental efforts will be essential to fully exploit this opportunity and potentially reveal physics beyond the Standard Model.

REFERENCES

1. ATLAS Collaboration. (2015). Search for Higgs boson decays to beyond-the-Standard-Model light bosons in four-muon final states with the ATLAS detector at $\sqrt{s} = 8$ TeV.
2. CMS Collaboration. (2019). Search for a light pseudoscalar Higgs boson produced in association with bottom quarks in pp collisions at $\sqrt{s} = 13$ TeV. Phys.
3. Ellwanger, U., Hugonie, C., & Teixeira, A. M. (2010). The Next-to-Minimal Supersymmetric Standard Model (NMSSM): theoretical motivation and phenomenology. Phys.

4. Curtin, D., Essig, R., Gori, S., & Shelton, J. (2014). Illuminating Dark Photons with High-Energy Colliders. JHEP 02, 157. arXiv:1312.4992
5. Clarke, J. D., Foot, R., &Volkas, R. R. (2014). Phenomenology of a very light scalar (100 MeV < m < 10 GeV) mixing with the SM Higgs.
6. CMS Collaboration. (2023). Search for exotic decays of the Higgs boson to a pair of light pseudoscalars in final states with two muons and two b quarks in proton–proton collisions at $\sqrt{s}$ = 13 TeV. JHEP 03, 011. arXiv:2206.06362
7. Bauer, M., Foldenauer, P., &Jaeckel, J. (2018). Hunting All the Hidden Photons. JHEP 07, 094.
8. Djouadi, A. (2008). The anatomy of electro-weak symmetry breaking. II. The Higgs bosons in the minimal supersymmetric model.
9. CMS Collaboration. (2017). Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state .
10. ATLAS Collaboration. (2021). Search for Higgs boson decays into pairs of light (pseudo)scalar particles.