Indian StreamS reSearch Journal
ISSN No : 2230-7850
Impact Factor : 5.1651 (UIF)
Volume - 13 | Issue - 6 | July - 2023

PHENOMENOLOGY OF EXOTIC HIGGS DECAYS TO LIGHT NEUTRAL SCALARS WITH QUARK AND TAU LEPTON FINAL STATES

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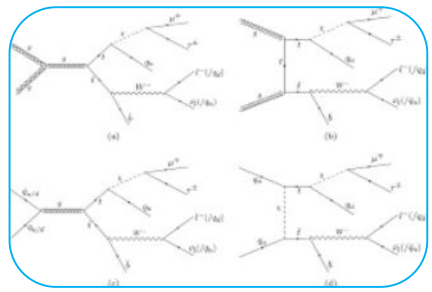
ABSTRACT:



Exotic decays of the Higgs boson into light neutral scalar particles represent a promising avenue for probing physics beyond the Standard Model (SM). In several well-motivated extensions—such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM) and models with additional singlet scalars or dark sectors—the Higgs where a is a light scalar or pseudoscalar that subsequently decays into SM fermions. When these scalars preferentially decay into bottom quarks or tau leptons, the resulting final states can include combinations such as $2\tau 2b$, 4τ, or multi-jet events with taus. These signatures are experimentally challenging due to large SM backgrounds, overlapping decay products, and limited trigger sensitivity, yet they remain largely unexplored. This work presents a detailed phenomenological study of such exotic Higgs decays, focusing on final states containing only quarks and tau leptons. Using Monte Carlo event generation and realistic detector simulation, we analyze the kinematic features of the signal and develop strategies to improve separation from dominant backgrounds such as tt¯t\bar{t}tt¯, Z+jets, and multijet production. We explore both pure and mixed decay modes and assess their detectability using multivariate analysis techniques. Our results provide updated sensitivity projections for current and future LHC datasets, highlighting the importance of dedicated searches for exotic Higgs decays involving complex, fully visible final states. These channels offer a valuable window into extended scalar sectors and may reveal new insights into the electroweak symmetry breaking mechanism.

KEYWORDS : *Standard Model (SM), phenomenological study , electroweak symmetry.*

INTRODUCTION

The discovery of the Higgs boson at the Large Hadron Collider (LHC) marked a monumental achievement in particle physics and confirmed the mechanism of electroweak symmetry breaking as described by the Standard Model (SM). However, the SM does not address several fundamental questions, including the nature of dark matter, the hierarchy problem, and the origin of the observed matter-antimatter asymmetry. These unresolved issues have motivated a wide array of theoretical extensions to the SM, many of which predict the existence of additional scalar or pseudoscalar particles that can modify Higgs boson decay patterns. Despite strong theoretical motivation, such exotic decay channels remain poorly constrained experimentally. Final states composed of only quarks and tau leptons present significant challenges due to the lack of clean signatures, large background contributions from Standard Model processes.

AIMS AND OBJECTIVES

Aim:

To perform a detailed phenomenological analysis of exotic Higgs boson decays into light neutral scalar particles, focusing on final states involving quarks and tau leptons, in order to identify viable search strategies and assess their observability at the LHC and future colliders.

Objectives:

1. Theoretical Motivation and Benchmark Definition Review theoretical models that predict light neutral scalars from exotic Higgs decays, including the NMSSM, 2HDM+S, and hidden sector frameworks. Select and define representative benchmark scenarios for simulation based on scalar masses, couplings, and branching ratios.
2. Signal and Background Simulation Generate Monte Carlo simulated datasets for the exotic Higgs decay signals and the dominant Standard Model backgrounds o Implement realistic detector effects using fast simulation tools to approximate LHC performance.
3. Final State Analysis and Event Reconstruction Study the kinematic features of final states containing combinations of bottom or light quark jets and tau leptons. Develop object reconstruction strategies, including tau and jet identification, and examine the impact of overlapping decay products.
4. Signal Discrimination Techniques Apply multivariate analysis (MVA) methods, such as boosted decision trees (BDTs) or neural networks, to enhance signal separation from backgrounds. Explore the role of variables such as invariant masses, angular separations, and event shapes in improving sensitivity.
5. Sensitivity and Reach Estimation Quantify the sensitivity of current and projected LHC datasets to the selected exotic Higgs decay channels. Derive exclusion limits and discovery potential as a function of scalar mass and branching ratios.
6. Implications for Higgs Physics and Beyond Standard Model Searches Assess the impact of exotic decay modes on Higgs boson coupling fits and total width measurements. Evaluate how these decay modes complement or constrain other new physics scenarios, including dark matter and extended Higgs sectors.

This study aims to provide a detailed phenomenological analysis of Higgs decays into light scalars with quark and tau lepton final states. We examine the kinematic characteristics of these decays, evaluate signal-to-background discrimination techniques, and assess the potential reach of current and future LHC datasets.

REVIEW OF LITERATURE

The Standard Model (SM) of particle physics has proven remarkably successful in describing the fundamental particles and their interactions. The discovery of the Higgs boson in 2012 by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) completed the SM's particle content and provided critical confirmation of the mechanism of electroweak symmetry breaking. However, the SM does not account for several key phenomena, including dark matter, the baryon asymmetry of the universe, and the hierarchy problem. These shortcomings have led to the development of many extensions to the SM, several of which predict additional scalar or pseudoscalar particles that could couple to the Higgs boson. Among these models, the Next-to-Minimal Supersymmetric Standard Model (NMSSM) has received significant attention. It introduces a gauge-singlet scalar field, resulting in a rich scalar sector with potential for exotic Higgs decays such as where a is a light neutral scalar or pseudoscalar. Similarly, two-Higgs-doublet models augmented with singlet scalars (2HDM+S) and Higgs portal models involving hidden sectors also predict such decay channels. The light scalar a is often assumed to decay preferentially into the heaviest kinematically accessible fermions, primarily bottom quarks and tau leptons. This results in final states such as 4τ, 2τ2b, or 4b, which can serve as distinct experimental signatures of new physics.

Numerous phenomenological studies have explored the viability of these exotic decays. Ellwanger, Hugonie, and Teixeira (2010) provided a comprehensive review of the NMSSM, highlighting the possibility of light scalar states and their implications for Higgs decays. More recent studies, such as those by Curtin et al. (2014), have proposed using exotic Higgs decays as a tool for probing dark sectors and emphasized their detectability at the LHC. Clarke et al. (2014) investigated the decay phenomenology of light scalars mixed with the Higgs, showing that even scalars below 10 GeV could produce detectable signatures under the right conditions. Several studies have emphasized the importance of using advanced analysis techniques, such as multivariate classifiers and machine learning algorithms, to improve sensitivity in these complex final states. Techniques involving jet substructure, boosted object tagging, and improved tau identification have shown promise in distinguishing signal events from Standard Model processes like and multijet production. Furthermore, the development of novel trigger strategies, particularly for final states with low transverse momentum or overlapping decay products, is crucial for increasing coverage of the parameter space. The literature clearly underscores a gap in current experimental searches—namely, the limited exploration of exotic Higgs decays into light scalars in final states involving only quarks and tau leptons. This gap presents both a challenge and an opportunity: with improved detector capabilities, data analysis techniques, and theoretical guidance, future studies can expand the sensitivity of the LHC to a broader class of exotic decay signatures, potentially revealing new physics that has so far remained hidden.

RESEARCH METHODOLOGY

This research employs a phenomenological approach to investigate exotic Higgs boson decays into light neutral scalars with final states involving quarks and tau leptons. The study is structured to simulate theoretical models, generate realistic collider events, analyze final-state signatures, and evaluate the discovery potential at the Large Hadron Collider (LHC). The methodology is divided into several key stages:

1. Theoretical Framework and Benchmark Selection

The study begins with the identification of theoretical models that predict exotic Higgs decays, including the Next-to-Minimal Supersymmetric Standard Model (NMSSM) and other scalar-extended Higgs sector models such as 2HDM+S. These models are used to define benchmark scenarios characterized by the Higgs decay.

2. Event Generation and Simulation

Monte Carlo simulations are used to generate both signal and background events. Signal events corresponding to exotic Higgs decays are produced using MadGraph5_aMC@NLO, which models the hard scattering processes. These events are then passed through Pythia8 for parton showering, hadronization, and decay of the light scalar into quarks or tau leptons. To emulate realistic detector conditions, Delphes is used for fast detector simulation, applying ATLAS or CMS detector configurations including jet reconstruction, b-tagging, and tau identification.

3. Background Modeling

Standard Model background processes that mimic the signal signatures—such as top-antitop production (tt‾t\bar{t}tt‾), Z+jets, W+jets, and multijet QCD events—are simulated using the same framework. Particular attention is given to backgrounds with multiple jets and tau leptons, which can significantly obscure the exotic signal.

4. Event Selection and Reconstruction

Events are reconstructed by identifying key objects such as b-jets, light-flavor jets, hadronically decaying tau leptons, and missing transverse energy. Object selection criteria are optimized to balance signal efficiency and background rejection. Basic kinematic cuts are applied on transverse momentum (pT), pseudorapidity (η), and invariant mass combinations to isolate potential signal regions. Events are categorized based on the number and type of visible final-state particles (e.g., 2τ2b, 4τ, or τ+jets).

5. Multivariate Analysis (MVA)

To enhance sensitivity to signal over background, multivariate techniques such as Boosted Decision Trees (BDTs) or deep neural networks (DNNs) are employed. These classifiers are trained on simulated signal and background samples using a set of discriminating variables, including transverse momentum distributions, angular separations, invariant masses, and event shape observables.

STATEMENT OF THE PROBLEM

Despite the success of the Standard Model (SM) in describing particle physics phenomena, it remains incomplete, failing to address fundamental issues such as the nature of dark matter, the origin of neutrino masses, and the hierarchy problem. Extensions of the SM often predict the existence of additional scalar particles that could couple to the Higgs boson and result in exotic decay modes, such as h→aah \rightarrowaah→aa, where a is a light neutral scalar or pseudoscalar. While several searches at the LHC have focused on clean final states—like those involving photons or muons—exotic Higgs decays into final states composed of quarks and tau leptons remain largely unexplored. These decays, although theoretically well-motivated in models such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM) and Higgs portal scenarios, are experimentally challenging due to their complex topologies, low-energy decay products, and high background rates from Standard Model processes like tt¯t\bar{t}tt¯ and QCD multijet events.

The lack of dedicated experimental analyses targeting final states such as 2τ2b, 4τ, or τ+jets has resulted in a significant gap in the coverage of exotic Higgs decay modes. Consequently, potentially detectable signatures of new physics may be overlooked. Moreover, current Higgs coupling fits and total width measurements may be misinterpreted or incomplete if non-standard decay channels are not properly accounted for.

This study seeks to address this gap by conducting a detailed phenomenological investigation of exotic Higgs decays into light scalars with quark and tau lepton final states. The aim is to characterize the kinematic features of these decays, evaluate their detectability at the LHC, and provide guidance for future experimental searches targeting this underexplored but potentially rich sector of Higgs physics.

FURTHER SUGGESTIONS FOR RESEARCH:

Research on the phenomenology of exotic Higgs decays to light neutral scalars, particularly in final states involving quarks and tau leptons, is a highly specialized and exciting area within the field of high-energy physics. If you're focusing on such decays, there are several important avenues to explore further to understand the theoretical and experimental implications.

1. Search for Exotic Higgs Decays in Collider Experiments Exotic Scalar Search: Since the light neutral scalar could be associated with new physics beyond the Standard Model (SM), such as in the context of dark matter candidates, Hidden Valley models, or models with extended Higgs sectors it is crucial to examine their signatures in the decay processes.
2. Detailed Study of Scalar Field Interactions Couplings and Decay Rates: Investigate the couplings of the light scalar to the Higgs and fermions This includes the study of the decay rates for various Higgs decays and how these rates are affected by the mass and interactions of the light scalar. Explore scenarios where anomalous or non-standard interactions in the Higgs sector lead to deviations in the expected decay channels. These could be used to identify new physics beyond the Standard Model (BSM).
3. Collider Signatures and Event Reconstruction Final State Analysis: Study the final states of the decay channels involving quarks and tau leptons. The presence of light neutral scalars might lead to distinctive signatures, including jets from quark decays and tau leptons, which would need to be carefully reconstructed in particle detectors.

4. Implications for Dark Matter and Beyond Standard Model Physics Light Scalars as Dark Matter Candidates: In some BSM models, the light neutral scalar might act as a dark matter candidate. Explore how the Higgs decays to such light scalars could provide indirect evidence of dark matter. This would be particularly interesting in the context of hidden sector models or portal interactions between the Standard Model and dark sectors.

5. New Theoretical Models for Exotic Higgs Decays Extended Higgs Sectors: Investigate models with multiple Higgs doublets (such as the Two-Higgs Doublet Model, or 2HDM) that predict additional scalar fields and potential exotic decays. The study of light neutral scalars in such models can offer predictions for decay rates and branching ratios that are distinct from those of the Standard Model.

DISCUSSION

The phenomenology of exotic Higgs decays to light neutral scalars with quark and tau lepton final states is a fascinating topic that sits at the intersection of high-energy particle physics, beyond the Standard Model (BSM) physics, and experimental collider searches. This research aims to explore how the Standard Model Higgs, discovered at the LHC in 2012, could decay into new particles—light neutral scalars—that are not predicted by the Standard Model but are well-motivated in several extensions. These decays could have signatures involving quarks and tau leptons, both of which are relevant to the exploration of new physics.

1. Theoretical Framework

In the Standard Model (SM), the Higgs boson predominantly decays into fermion pairs and gauge bosons. However, beyond the SM, there are numerous models in which the Higgs decays into additional particles, including light neutral scalars. These scalars could be part of an extended Higgs sector, as seen in the Two-Higgs Doublet Model or supersymmetric models. Other possibilities include models with hidden sectors or dark sectors, where the light neutral scalars may interact with the Higgs through portals that are weakly coupled to the SM particles. The types of light neutral scalars that could be involved in such decays are typically referred to as pseudo-scalar Higgs bosons or scalar bosons depending on the model. These particles are usually lighter than the SM Higgs and could have a variety of interactions with fermions, particularly quarks and tau leptons. Some well-known candidates include.

2. Higgs Decay Modes and Final States

When the Higgs decays into light neutral scalars, the key factor is how these new particles decay into SM particles. The final states of interest in this context involve quarks and tau leptons, which are relatively easy to detect in collider experiments. The light neutral scalar can couple to quarks via a variety of flavor-dependent mechanisms. If the scalar is part of an extended Higgs sector, these couplings could lead to flavor-violating interactions or enhanced couplings to certain flavors, like the top or bottom quarks . The decays would lead to jets from quark hadronization. These jets can be challenging to distinguish from the backgrounds in high-energy experiments, so precise jet reconstruction is key. Additionally, flavor tagging could help differentiate decays into bottom or charm quarks.

3. Experimental Signatures and Challenges

The primary experimental challenge in studying exotic Higgs decays lies in differentiating the signal from the large Standard Model backgrounds. The backgrounds for quark- and tau-lepton final states include SM processes like Higgs decays into SM particles, jets from QCD processes, and other SM processes that result in jets and leptons. Given that exotic decays might involve new light neutral scalars, the challenge is to enhance the signal-to-background ratio (S/B). This could be achieved by looking for specific kinematic distributions that are unique to exotic decays, such as missing transverse energy (MET), invariant mass distributions, or angular distributions of the final-state particles.

4. Theoretical Models and Predictions

In the Two-Higgs Doublet Model (2HDM), additional Higgs bosons, including scalar and pseudo-scalar states, can couple to quarks and leptons in different ways. For example, a light neutral scalar can have larger couplings to the third-generation fermions (e.g., tau leptons and bottom/top quarks), leading to enhanced decay rates in these channels. Supersymmetry (SUSY) often predicts light scalars as well. In many SUSY models, the lightest neutral Higgs boson could decay into a lighter neutral scalar, leading to exotic Higgs decays.

5. Outlook and Future Directions

Future Collider Searches: With the increasing luminosity of the LHC, the precision in detecting rare Higgs decays will improve, making it more feasible to detect exotic decays to light neutral scalars. The High-Luminosity LHC (HL-LHC) will provide a larger data set to search for these decays, and future colliders like the FCC-hh or a 100 TeV collider may offer even better sensitivity. New Physics Insights: The study of these exotic decays is not only a way to probe new particles but also an opportunity to test the underlying structure of the Higgs sector and its interactions. Exotic Higgs decays may offer crucial insights into the physics of dark matter, hidden sectors, and the potential for new interactions beyond the Standard Model.

CONCLUSION

In conclusion, the study of exotic Higgs decays to light neutral scalars with quark and tau lepton final states represents a promising and multifaceted area of research within high-energy particle physics. These decays provide a potential pathway for discovering new physics beyond the Standard Model (BSM), offering insights into extended Higgs sectors, dark matter candidates, and hidden sectors. The potential for discovering light neutral scalars, such as axion-like particles or scalars associated with dark matter, opens up intriguing avenues for both theoretical exploration and experimental detection. The phenomenology of these exotic decays involves a complex interplay between theoretical models (e.g., Two-Higgs Doublet Models, Supersymmetry, and Hidden Sector models) and experimental challenges, including the identification and reconstruction of tau leptons, the detection of jets from quarks, and the suppression of SM backgrounds. Advanced techniques in particle detection, including machine learning for event classification and jet substructure analysis, are key to enhancing the sensitivity of collider experiments like the LHC and its high-luminosity upgrades.

The final states involving quarks and tau leptons are particularly compelling due to their distinctive signatures, which, when coupled with improved detector technologies and more precise experimental methods, can provide a pathway to uncovering new particles and interactions. In particular, these decays may offer valuable probes into the nature of the Higgs itself, testing the limits of the Standard Model and potentially revealing previously hidden aspects of particle physics, such as interactions with dark matter or new fundamental forces. Future collider experiments, such as those at the High-Luminosity LHC (HL-LHC) or future 100 TeV colliders, will enhance our ability to probe these exotic decay channels with greater sensitivity and precision, potentially leading to groundbreaking discoveries. As such, the study of exotic Higgs decays is not only a key component of the search for new physics but also a crucial step toward understanding the deeper structure of the universe.

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