UNIVERSITY OF CALIFORNIA, IRVINE

DEPARTMENT OF PHYSICS AND ASTRONOMY

Reconstructing Scalar Dark Energy: A Collider-Based Simulation Study

Author:

Edward Sahyoun

Supervisor:

Professor Daniel Whiteson

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Abstract

The nature of dark energy remains a mystery in modern physics. Quintessence models that predict the existence of scalar dark energy fields not only explain dark energy but provide a bridge between cosmology and quantum mechanics. This thesis investigates the prospects of detecting the dark energy scalar field, ϕ , by reconstructing its particle, phide, from simulated proton collisions. The analysis reveals asymmetric, broad reconstruction distributions that lack the resolution required for discovery-level feasibility. While the existence of scalar dark energy fields remains unproven, the study provides a phenomenological framework for evaluating detectability through collider-based experimentation.

1. Introduction

1.1 Context

We know less about what causes the expansion of the universe than the interior of black holes. Our universe's expansion is accelerating far beyond what any established theories predict. This phenomenon is attributed to dark energy, a proposed force that permeates throughout space accelerating its expansion. It is seemingly everywhere, including here on Earth, yet we have never interacted with it, let alone comprehended it.

The idea of the universe's repulsive component was theorized long before its discovery. It began in 1917 with Einstein's theory of general relativity introducing the cosmological constant, Λ, which symbolized a repulsive force throughout the universe. It was proposed to balance gravity, but this led to an unstable static universe. The first signs of the universe's expansion were seen by Hubble in 1929, through observations of galaxies and their redshift. In 1998, A. Reiss observed Type Ia supernovae with less luminosity than predicted [1]. This suggested not only an expanding universe but an accelerating one. Prior to this discovery, the prevailing theory was that gravity dominated over this repulsive force, slowing the universe's expansion over time. A. Reiss's discovery of an accelerating universe shifted the narrative, leading to deeper investigations into the phenomenon, which soon became popularized as dark energy.

Today, the most accepted theory for dark energy is the Lambda Cold Dark Matter (ΛCDM) model [2], the standard model of cosmology. It explains the Cosmic Microwave Background, the distribution of galaxies, and the acceleration of the universe through the cosmological constant, Λ. While Einstein introduced the cosmological constant to maintain a static universe, the ΛCDM model reinterprets it as a physical form of dark energy responsible for the universe's accelerating expansion. The model finds dark energy to account for ~68% of the universe's mass-energy composition. While this model is successful in matching observations of large-scale structures and the cosmic background radiation, it still faces many challenges. Key issues, such as the nature of dark matter, dark energy, and the cosmological constant problem remains unresolved. This problem is the major discrepancy between the observed vacuum energy of the universe and the predicted vacuum energy by quantum field theory. QFT predicts vacuum energy approximately 10^{55} times greater than what has been observed [3]. This staggering ratio reveals a fundamental inconsistency between cosmology and quantum theory. Addressing this paradox, is a major step towards a more unified theory and a deeper understanding of reality itself.

1.2 Quintessence Interpretation of Dark Energy

Quintessence is one such approach that combines aspects of both cosmology and QFT, that explains the acceleration of our universe. First proposed in 1998 [4], quintessence models dark energy as a dynamical scalar field. Whereas the cosmological constant doesn't change throughout space and time, quintessence models allow for fluctuations and are not inherently attractive or repulsive. Quintessence models suggest that dark energy became dominant 3.5 billion years after the big bang, drastically increasing the universe's acceleration.

Quintessence theory implies a unique method of detection. From a quantum scalar field, a particle emerges that can potentially interact with the Standard Model. If such couplings exist, even relatively weak ones, they open the door for collider-based detection. In high-energy collisions, these quintessence particles may be produced in association with known particles, escaping detection as missing energy signatures. This provides the basis of a distinct phenomenological signature that can be tested experimentally.

2. Methods

2.1 Phenomenology

The primary objective of this thesis is to test the feasibility of a particular model of the proposed dark energy scalar field, phi [5], by measuring its consistency with the Standard Model through simulated particle collisions. It is important to note that this isn't seeking proof of existence, but proof of concept. If this research shows that the model is feasible, then it would be worth the effort to search for it in actual collider data.

From the scalar field emerges a boson, referred to as phide. While phide can, in theory, be produced and decay in a variety of ways, this thesis focuses on the specific case where it is produced alongside a top quark (top) pair and decays into a bottom quark (bottom) pair. This is denoted as,

p p > t t~ phide, phide > b b~

and its Feynman diagram is,

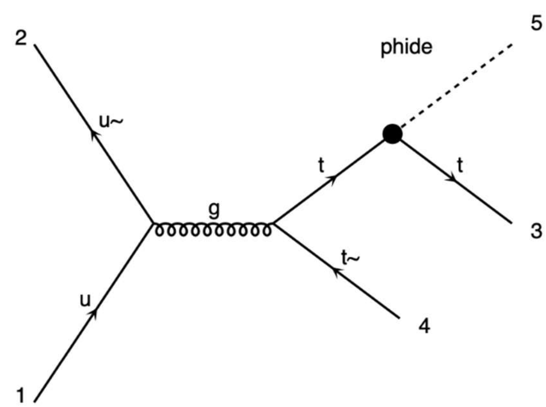

Figure 1: Feynman diagram of phide production.

Because phide is a hypothetical particle, its exact mass is unknown; therefore, it is assigned a specific mass in simulation. This mass acts as a reference point for evaluating the model's feasibility. Specifically, feasibility is assessed by how accurately the simulated decay products reconstruct compared to phide's set mass. Furthermore, phide's reconstruction accuracy is not the only variable in measuring the entire model's feasibility. If the model interacts consistently with the SM, then the other collision products and their subsequent decay products should be reconstructed accurately. The primary decay mode of the top is into a W boson and bottom [6]; therefore, the top quark and W boson reconstruction accuracies are the remaining variables to quantify the model's feasibility.

In high-energy collisions, products like the top quark and phide are not directly observed because they almost instantly decay into subsequent particles. This decay chain only gets detected once it reaches the more stable particles like photons, leptons, or jets. A jet is a collimated spray of particles that originates from a decay chain of quarks. Modern detectors record the information of these final-state particles by their momentum and direction. And it is the kinematics of that data that allows us to work backward from the final-state particles to the original collision products. The two-particle decay invariant mass equation is particularly relevant for this research,

$$M_{phide} = \sqrt{m_1^2 + m_1^2 + 2(E_1E_2 - \overline{p_1} \cdot \overline{p_2})}$$

This equation is especially relevant here because every key variable decays into two products. The W boson either decays down the leptonic path, two leptons, or the hadronic path, two light quarks (detected as jets). The top decays into a W boson and a bottom as mentioned above, and phide decays to two bottoms. The bottom quark cannot be reconstructed reliably because it often hadronizes into a jet before detection, and a single jet is not reliable enough to recover the original particle.

2.2 Collision Simulation Software

To simulate the proton collisions and their resulting products, a framework containing both the Standard Model and the proposed dark energy model must be established. This virtual framework handles the process from event generation to decay processes to detection.

The process begins at event generation through the software, MadGraph. It takes the input, p p > t t~ phide, phide > b b~, and simulates the initial interaction and its decay structure. While MadGraph handles the fundamental components, it does not simulate the remaining details. The software Pythia handles this by simulating radiation, hadronization for jets, and further particle interactions. Together MadGraph and Pythia produce realistic final-state products that are ready to be detected.

Detection is achieved through the software, Delphes, which simulates the behavior of modern detectors such as ATLAS of the LHC. It observes the final-state particles and records their kinematics, which is stored in a file for analysis. This data is used to reconstruct the phide, the top quark, and the W boson, to ultimately determine the feasibility of the dark energy model.

2.3 Data Analysis

2.3.1 Event Selection

Processing the raw data into the reconstructed mass consists of two primary concepts: event selection and reconstruction candidate selection. Event selection ultimately determines how the collision decayed into its final-state products. As this thesis only considers phide decay into a bottom quark pair, the degree of variability is determined by the top quark decay modes. The number of jets and leptons will classify events into three possibilities: complete hadronic, complete leptonic, or one of each. In practice, detectors can produce enough jets and leptons to make all decay modes plausible for a single event. This implies a single event can be categorized into any combination of these modes, resulting in eight possible decay configurations for a given event. The goal of the analysis is to minimize categorization into multiple possibilities, to ensure reliable reconstruction.

Kinematic cuts are one of the most effective ways to achieve this. They filter out jets with low momentum and unrealistic directions. These cuts are essential to filter out background radiation which can be detected as jets. The simulation parameter cards and full analysis scripts are available at [7].

2.3.2 Reconstruction Candidate Selection

This process determines the reconstructed mass that will be presented for the given particle for each event. This can be approached in many ways. This analysis will use a standard combinatorial technique in conjunction with χ^2 minimizing to select the best set of masses. Since it isn't possible to know exactly where the jets originate, we look at every possible jet assignment. Each permutation reconstructs two W bosons and two top quarks using the two-particle invariant mass equation, and these reconstructed masses are compared to their known values using χ^2. Whichever permutation has the lowest χ^2 is the overall most accurate combination, and ultimately determines which reconstructed masses are presented.

3. Results

3.1 Biased Reconstruction Distributions

Phide masses from 100GeV to 600GeV in intervals of 100GeV were simulated. The following histograms show the reconstructed mass distributions under biased selection conditions. These conditions use the set phide mass to bias the reconstructed mass towards the preset value. Specifically, by adding a term to χ^2 that measures the accuracy of the reconstructed phide.

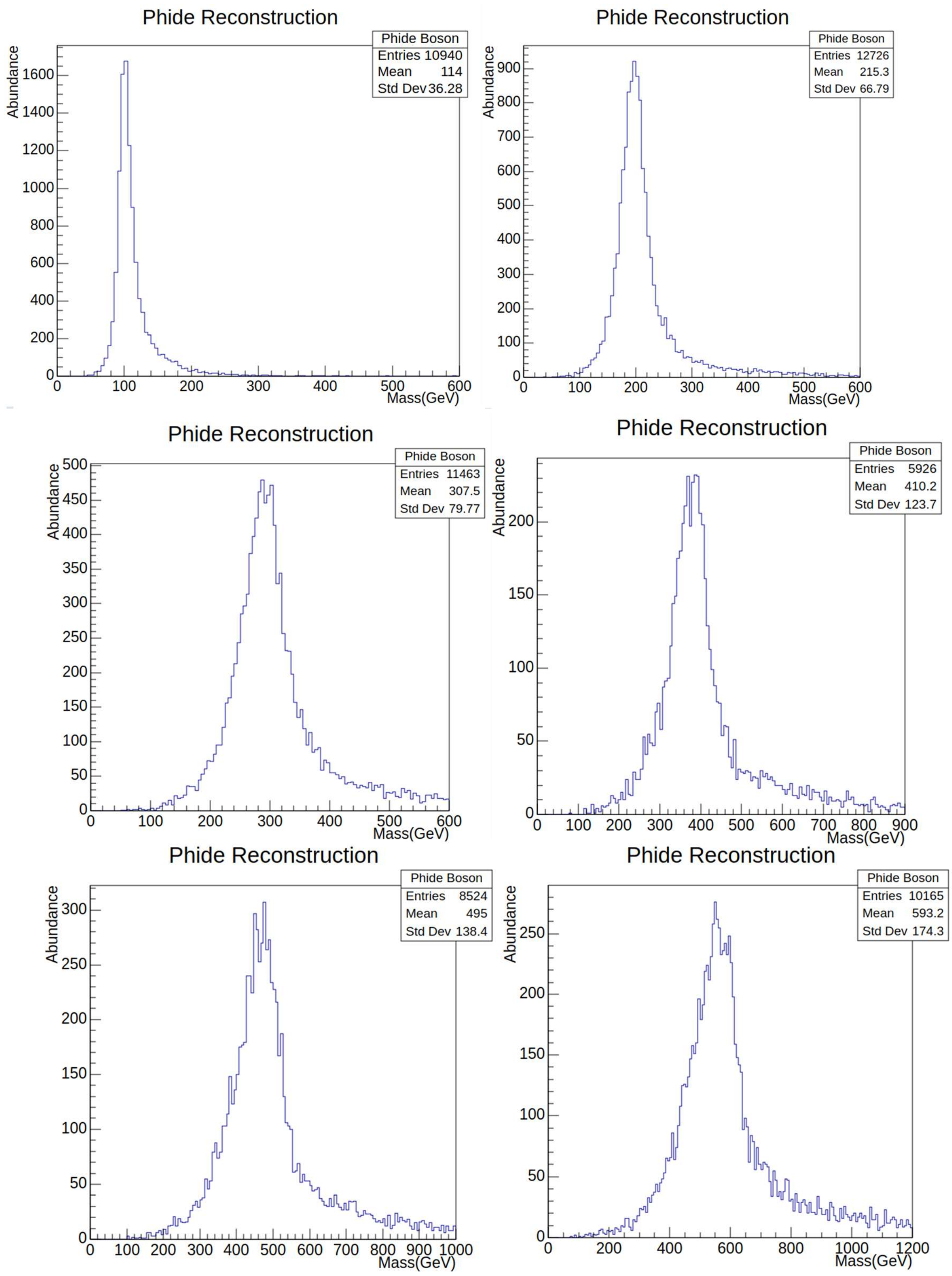

Figure 2: Biased Phide Reconstructions

Each histogram has a distinct peak forming near their preset Phide mass. The best performing mass is 300GeV as its reconstruction distribution has the smallest standard deviation-to-mean ratio at 25.9%. To get a more accurate representation of this distribution's mean and standard deviation, a Gaussian distribution was fitted to the data. The fitted distributions of the 300GeV phide, and the corresponding W and top quark distributions are presented below.

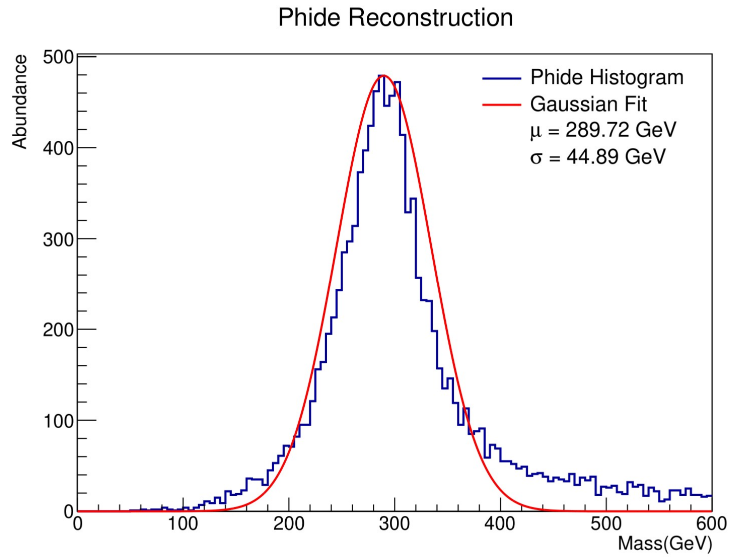

Figure 3: Fitted Phide Reconstructions

With the Gaussian fitting, the 300GeV phide was reconstructed to $289.72 \pm 44.89 GeV$.

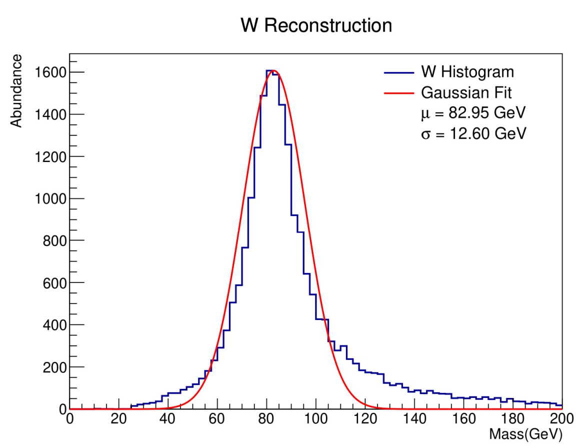

Figure 4: Fitted W Boson Reconstruction

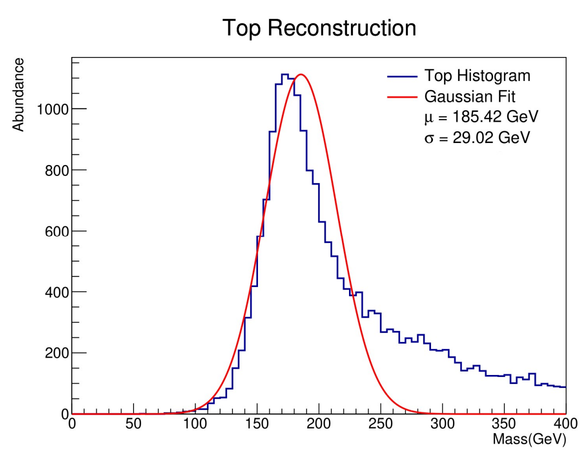

Figure 5: Fitted Top Quark Reconstruction.

The W Boson reconstructed to $82.95 \pm 12.60 GeV$ and the top quark reconstructed to $185.42 \pm 29.02 GeV$.

3.2 Unbiased Phide Reconstruction

The biased selections are ideal for internal comparison; however, they do not suffice for phenomenological searches to quantify feasibility. Therefore, an unbiased reconstruction was conducted for the 300GeV phide to ultimately quantify feasibility. The histogram is presented in Figure 6.

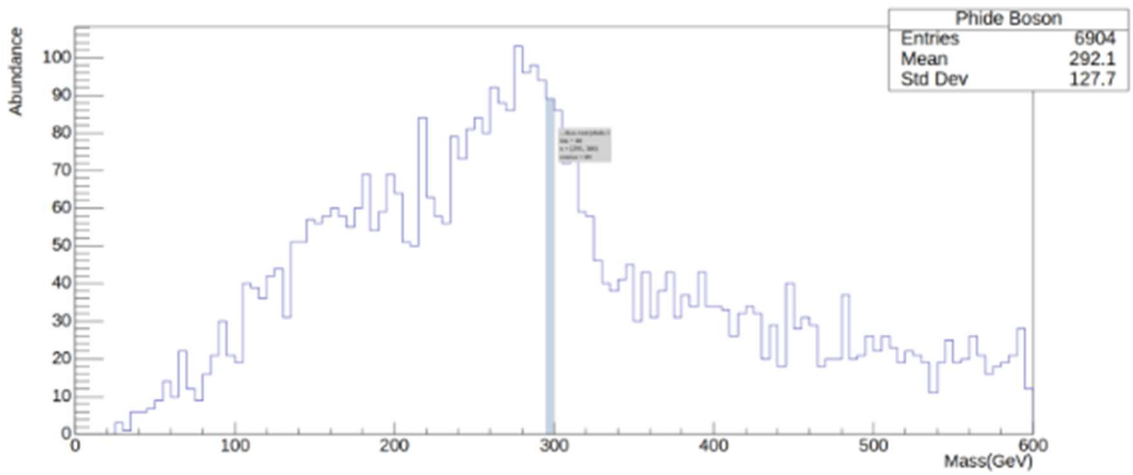

Figure 6: Unbiased Phide Reconstruction

This distribution peaked in the [275,280) GeV bin, and its mean is $292.1 \pm 127.7 GeV$.

4. Analysis

4.1 Phide Reconstruction Accuracy

Figure 6 reveals a distinguished peak near the preset mass of 300GeV; however, not to the extent of the previous figures because they used biased reconstructions. The peak of the distribution is about 7.5% off the known value, and there is a significantly broader distribution relative to the biased reconstructions. Furthermore, there is a distinguished asymmetry with the front-loading of entries before the peak and the heavy tail following it.

The standard deviation-to-mean ratio is 43.7% compared to the 15.9% of the fitted, biased 300GeV reconstruction. Comparing these ratios to estimate relative accuracy, this suggests a 69% loss in accuracy when reconstruction is not biased. A Gaussian fitting for the unbiased distribution is not appropriate due to the distribution asymmetry, and further complex fittings were not pursued given the degraded signal quality from the unbiased conditions.

4.2 Sources of Error

The front loading of entries before the peak in Figure 6 is likely due to low-energy radiation getting misidentified as a jet, despite the kinematic cuts filtering out many of the low-energy background. This radiation is typically right at the cusp of being filtered; however, increasing the threshold past the limit starts to remove real jets and reduce accuracy anyway. The heavy tail also likely originates from background radiation. Many times, radiation can be close enough to the real jets, so that its energy is absorbed into its neighboring jet and gets presented as a single higher energy jet. Another possibility is the occasional high-energy radiation that alone gets mistaken for a complete jet. The disparity between the biased and unbiased graphs demonstrates the overemphasis on agreement with the preset mass, despite the χ^2 term being the only difference in the analysis. This inherently reshapes the distribution by favoring jets for an ideal phide mass.

5. Discussion

Comparing biased reconstructions of each phide mass, the 300GeV phide performed the best. For its biased and fitted distribution, its reconstructed mass is $289.72 \pm 44.89GeV$, corresponding to 3.42% error. While this is a very accurate reconstruction, it is artificially amplified by bias; therefore, it cannot be used to evaluate the model's feasibility. For an objective assessment, the unbiased distribution must be used to evaluate the model.

The unbiased distribution for the 300GeV phide yielded a reconstructed mass of $292.1 \pm 127.7 GeV$. While the mean alone may suggest a more accurate reconstruction, the distribution itself tells a different story. The distribution is very broad, with a standard deviation-to-mean ratio of 43.7%, and there are apparent asymmetries such as front-loading before the peak and a heavy tail.

From a phenomenological standpoint, the unbiased distribution suggests that the model is not currently feasible for discovery-level sensitivity. However, the biased distributions suggest the model may hold potential. Achieving discovery-level sensitivity may be accomplished through refining the theoretical model for phi, the dark energy scalar field, or refining the experimental techniques for reconstruction.

6. Conclusion

This thesis aimed to evaluate the feasibility of the dark energy scalar field, phi, through the simulation of particle collisions and reconstructing its associated particle, phide. This follows the theory of Quintessence to explain the nature of dark energy and bridge the gap between cosmology and quantum mechanics. Although feasibility was not definitively established, it was also not ruled out entirely. Furthermore, it establishes a framework for testing its feasibility within the context of particle physics experiments. This investigation contributes to the broader effort of exploring alternatives to models such as ΛCDM, leaving the nature of dark energy unresolved, and contributing to potential Standard Model extensions. Quintessence remains a plausible theory that bridges the gap between these two successful theories, and collider-based detection methods maintain their utility in further exploration.

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