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Constraints on the Final Fermions of an Exotic Higgs Decay

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1 Abstract

In this paper, I analyze a theoretical decay chain of the Higgs boson to two fermions that involves dark matter particles, predicted by the NMSSM. I used Monte Carlo event generators and mathematical code to simulate this decay chain for varying masses of decay particles, with and without the presence of a particle jet. I found no non-obvious constraint on the angle between the final fermions, but my results illuminate the accuracy of and future applications for this problem-solving method in particle physics.

2 Introduction

For the last fifty years, the Standard Model (SM) has successfully predicted and explained most theoretical phenomena and experimental results involving elementary particles and the fundamental forces of the universe, but it is incomplete (CERN, 2019). The model cannot describe or make predictions about dark matter (DM), the dominant form of material in the universe, whose particles outnumber those of ordinary matter five to one (Garrett, 2010). DM is "dark" in that it does not interact with photons, so we cannot see it; its existence is primarily justified by its gravitational effect on the velocities of astronomical objects. Over the last thirty years, physicists have developed three strategies to verify the existence of DM particles: they may be produced in particle accelerators, their self-annihilation products may be detected in regions of high DM density, or they may be measured after scattering off target nuclei (Undagoitia, 2017).

Production experiments such as The Compact Muon Solenoid (CMS) (Adolphi, 2008) and A Toroidal LHC Apparatus (ATLAS) (Aad, 2008) have searched for DM in the form of "missing energy." If a particle is observed to decay into two smaller particles whose combined energy is less than that of their parent, researchers can conclude that the difference in energies was a particle, potentially DM, that went undetected. Unfortunately, this effort has been widely unsuccessful, and DM particles remain theoretical and left out of the SM. Because high-energy collisions produce a variety of particles that may decay in a variety of ways, perhaps we have not seen any missing energy because we have not studied the decays most likely to produce it.

I propose a theoretical decay chain shown in Figure 1, predicted by the Next to Minimal Supersymmetric Model (NMSSM) that should produce DM in a particle accelerator. Using simulation software, if I can produce distributions of particles that correspond to the distributions observed at accelerators, I can first demonstrate that my chain may lead to the production of some of those observed particles. By then determining some kinematic constraints on the particles, I can provide experimentalists a promising signature to probe in both future experiments and past data. This is the primary goal of this paper: to give physicists a new place to look for DM.

$$\begin{array}{l}
\mathrm{H}\ (\pm Jet) \rightarrow \chi_2\ \chi_1 \\
\qquad\qquad\qquad\ \ \downarrow \\
\qquad\qquad\qquad\ \chi_1\ a_1 \\
\qquad\qquad\qquad\qquad\ \downarrow \\
\qquad\qquad\qquad\quad\ f_1\ f_2
\end{array}$$

Figure 1: Higgs decay to two fermions. χ_1 is the SUSY dark matter candidate, χ_2 is a heavier cousin, a1 is a scalar SUSY particle, and f1 and f2 are the final fermions that a detector might see.

If experimentalists do observe this specific signature, we can deduce that a DM particle was produced, and begin integrating it into the SM. Observing this would also verify all that the NMSSM postulates, including an energy scale at which the strong, weak, and electromagnetic forces become a single, unified force (Lykken, 2010). Additionally, comparing this decay chain with and without the presence of a particle jet may illuminate some constraint on the final products. The more diverse decay chains I test, the more specific a signature I can propose.

The balance of this paper provides a brief background describing theories of physics beyond the standard model (BSM), collider phenomenology and particle jets, and the software and mathematics involved in calculations. The Results section provides figures of the raw Pythia (Sjöstrand, 2008) distributions and those of the final fermions. The Discussion section describes the implications and applications of the data, as well as potential projects for further study.

Physics Beyond the Standard Model

In addition to a lack of explanation of DM, the SM cannot describe gravity (Burgess, 2006), nor why the Higgs boson is so much lighter than a Planck mass (Jegerlehner, 2015), nor why our universe has more matter than anti-matter (Dine, 2003). Many extensions to the SM have been developed to solve these problems, and the most promising of which, implement the principle of “supersymmetry" (Lykken, 2010) or “SUSY.” The Minimal Supersymmetric Standard Model (MSSM) reflects the simplest way to unite SUSY and the SM: it assigns each SM particle a SUSY partner of opposite particle class (e.g. each fermion gets a bosonic partner and vice versa). This additional set of particles includes a promising DM candidate

(Jungman, 1996), one that is abundant, weakly-interacting, and stable – qualities predicted by the previously mentioned astronomical observations. The MSSM also predicts the observed mass of the Higgs. Imperfections in the MSSM galvanized the formulation of the NMSSM, with an even richer Higgs sector (Ellwanger, 2010) that more closely matches observations.

Collider Phenomenology

High-energy particle colliders like the Large Hadron Collider (LHC) at CERN and the Tevatron at Fermi Lab were created in part to explore SUSY and particle physics BSM. As the SUSY particles are predicted to be much heavier than their SM counterparts, these accelerators collide beams of protons at very high speeds in search of them. Many of the particles created in these collisions are short-lived, decaying within microseconds to more stable, less massive particles. These final results are all that particle detectors can see. It is the task of theorists to work backward, using relativistic kinematics and conservation laws to decipher the decay-chains that lead to the final particles.

The existence of the Higgs boson was proved using this method (Aad, 2012). During a run at the LHC, about a billion proton-proton collisions occur each second, producing around one Higgs event (Pralavorio, 2017). The SM predicts that most of these Higgs will decay into bottom quarks, but others into rarer products, such as two photons and two Z-bosons. Under this assumption, experimentalists searched for these particle products within energy-momentum ranges that indicated a previous Higgs and were met with success in 2012. Decays predicted by SUSY models involve SUSY DM candidates, such as the one studied in this paper.

Jets

Many decays seen in particle accelerators involve “jets.” These jets can be described by quantum chromodynamics (QCD), the theory that describes all SM particles that interact through the strong force. QCD imposes “color confinement,” the reason why quarks are never found on their own but in structures like protons (Rangel, 2019). Color confinement requires all processes be colorless, and quarks on their own have color. When proton-proton collisions produce quarks, these quarks create gluons and other quarks around them to cancel out their color-charges, a process called "showering." These particles then recombine to form structures like protons, a process called "hadronization." Eventually, these hadrons decay into smaller, stable particles, and the entire string of events, propagating in some constant direction, is called a "jet."

Simulation Programs

The Monte Carlo event generators MadGraph (Alwall, 2016) and Pythia were used in tandem to produce all of the data analyzed in this study. MadGraph first generated the two processes shown in Figures 2 and 3

$$\mathrm{g}\ \mathrm{g} \rightarrow H$$

Figure 2: Gluons collision to Higgs

$$\mathrm{g}\ \mathrm{g} \rightarrow H + J$$

Figure 3: Gluons collision to Higgs plus jet

and produced 999 events per process. Pythia then showered and hadronized the jets involved. In MadGraph, the jet is a blurry, unspecified stream of particles, and Pythia's algorithm makes these intricate sub-processes much clearer. The data output took the form of a list of Higgs four-momenta, which was then analyzed using Mathematica (Wolfram Research, 2018).

Relativistic Kinematics

To run the Higgs events through my proposed decay chain, I first developed equations for the four-momenta of the initial decay particles in Figure 1 using relativistic relationships between energy, mass, and momentum. These equations are functions of two free parameters: the masses of each particle, which I had the freedom to choose; and the two angles associated with spherical coordinates, which I generated randomly.

I used similar relationships to create a Lorentz matrix from the Higgs four-momenta. The Methods section describes in detail how I then used this matrix to boost the decay into the Center of Mass (CM) Frame, i.e. the frame where the Higgs is at rest. I repeated this process for each decay in the chain to arrive at a list of four-vectors of the two final fermions, and finally, determined the angles between them. I did this process for the decay chains with and without a jet.

3 Procedure

Relativistic Kinematic Equations and Boost Matrix

I analyzed a list of four-momenta of 999 Higgs events of the form

$$P_H = \{E_H, px_H, py_H, pz_H\} \tag{1}$$

generated by Madgraph and Pythia. The four-vector's first component is the total energy of the Higgs, and the others are components of its three-momentum. In general, the equations for the energy and three-momentum of a relativistic particle are

$$E = \gamma mc^2 = \sqrt{m^2c^4 + p^2c^2} \tag{2}$$

and

$$p = \gamma mv \tag{3}$$

where $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ is the Lorentz factor and $\beta = \frac{v}{c}$. In my calculations I set c = 1 for convenience[1]. In doing so, I generated new equations for γ and β that only depend on values I know:

$$\gamma = \frac{E}{m} \tag{4}$$

and

$$\beta = \frac{p}{E}. \tag{5}$$

Because the Higgs are moving in 3D space, there are three spatial components to their momenta, and therefore three beta factors:

$$\beta_x = \frac{p_x}{E}, \beta_y = \frac{p_y}{E}, \beta_z = \frac{p_z}{E}. \tag{6}$$

Together, these gamma and beta factors provide all that is needed to Lorentz boost[2] the daughter particles of the Higgs into its CM frame. A Lorentz boost in 3D space takes the matrix form

[1] By choosing natural units where c = $\hbar$ = 1, $mass, inverselength, andinversetimecanbedescribedbyonedimensionlessunit.$

[2] It's technically in *inverse* Lorentz boost.

$$\begin{bmatrix} \gamma & -\gamma\beta_x & -\gamma\beta_y & -\gamma\beta_z \\ -\gamma\beta_x & 1+(\gamma-1)\frac{{\beta_x}^2}{\beta^2} & (\gamma-1)\frac{\beta_x\beta_y}{\beta^2} & (\gamma-1)\frac{\beta_x\beta_z}{\beta^2} \\ -\gamma\beta_y & (\gamma-1)\frac{\beta_y\beta_x}{\beta^2} & 1+(\gamma-1)\frac{{\beta_y}^2}{\beta^2} & (\gamma-1)\frac{\beta_y\beta_z}{\beta^2} \\ -\gamma\beta_z & (\gamma-1)\frac{\beta_z\beta_x}{\beta^2} & (\gamma-1)\frac{\beta_z\beta_y}{\beta^2} & 1+(\gamma-1)\frac{\beta_z^2}{\beta^2} \end{bmatrix}.$$

Step 1: H $\rightarrow \chi_1\ \chi_2$

The first step in my decay chain is the decay of a Higgs boson into χ_1 and χ_2. Since I will be evaluating the daughter particles in the CM frame of their parent, I can use equations for their energy and three-momenta that only depend on the parent's mass (M_{Higgs} = 125 GeV) and their masses (which I am free to choose):

$$E_{\chi_1} = \frac{M_{Higgs}^2 + m_{\chi_1}^2 - m_{\chi_2}^2}{2 * M_{Higgs}}, E_{\chi_2} = \frac{M_{Higgs}^2 + m_{\chi_2}^2 - m_{\chi_1}^2}{2 * M_{Higgs}}. \tag{7}$$

Their three-momenta can be found using equation 3, and I wrote the spatial components of these three-momenta using
spherical coordinates

$$px_{\chi_1} = p_{\chi_1}\sin(\theta)\cos(\phi), \tag{8a}$$

$$py_{\chi_1} = p_{\chi_1}\sin(\theta)\sin(\phi), \tag{8b}$$

and

$$pz_{\chi_1} = p_{\chi_1}\cos(\theta) \tag{8c}$$

where θ is a random polar angle between 0 and π and ϕ is a random azimuthal angle between 0 and 2π. Finally, I wrote out the full expression of the four-momenta of the daughter particles solely in terms of their masses and these angles:

$$P_{\chi_1} = \{E_{\chi_1}, px_{\chi_1}, py_{\chi_1}, pz_{\chi_1}\}, P_{\chi_2} = \{E_{\chi_1}, -px_{\chi_1}, -py_{\chi_1}, -pz_{\chi_1}\}. \tag{9}$$

To boost these four-momenta into the Higgs CM frame, I take their dot product with the boost matrix (with Higgs values plugged in). I am now only interested in χ_2, since it continues to decay:

$$NewP_{\chi_2} = Boost \cdot P_{\chi_2}. \tag{10}$$

Steps 2 and 3 follow similarly. In each step, I generate a new boost matrix based on the gamma and beta factors associated with the mother particle. I (inverse) boost the two daughter particles into the mother's CM frame. My final values are a list of boosted four-vectors of the two final fermions. To determine the angle between them, I use the dot product

$$P_{f1} \cdot P_{f2} = |P_{f1}||P_{f2}{}^{3}| \cos\theta. \tag{11}$$

I looked at two theoretical sets of lepton-antileptons:

$$H \rightarrow \mu\overline{\mu} \tag{12a}$$

$$H \rightarrow \tau\overline{\tau} \tag{12b}$$

where $m_\mu = .1$ GeV and $m_\tau = 1.78$ GeV. I imposed conditions on the masses of the parent particles such that

$$m_{a1} \geq m_{f1} + m_{f2}, \tag{13a}$$

$$m_{X2} \geq m_{X1} + m_{a1}, \tag{13b}$$

and

$$m_H \geq m_{X2} + m_{a1}, \tag{13c}$$

set the mass of χ_1 to 10 GeV[4], and generated about three hundred sets of masses. I ran the Higgs events (999 of them) through each mass-set and took an average of the angles between the final fermions. I present this data in the following section.

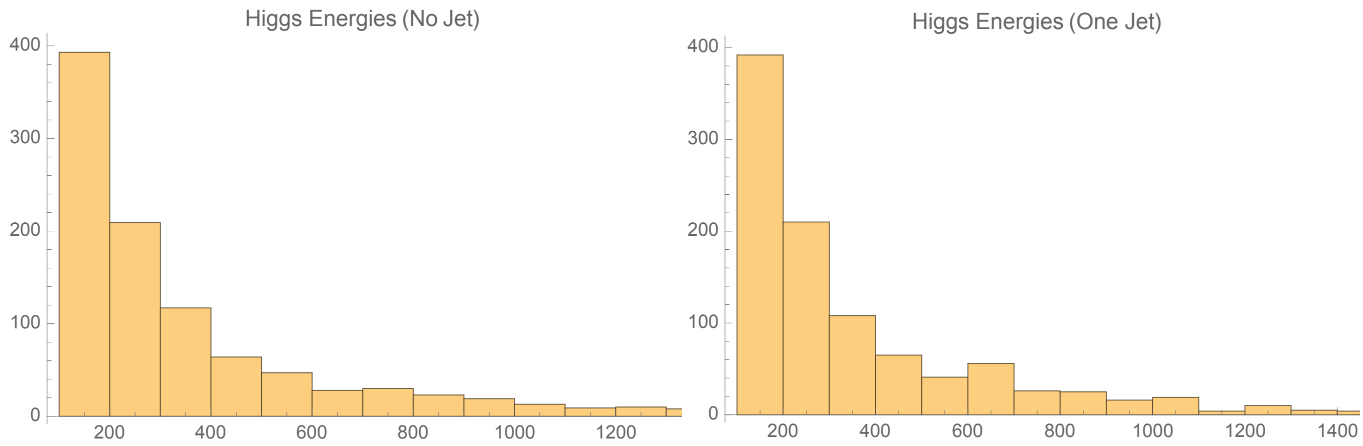
4 Results

Figures 4 and 5 represent raw Pythia data, figures 6 and 7 represent what I produced using Mathematica, and tables 1 and 2 give the statistical values

[3] It is important to note that I only looked at final products where f2 is the antiparticle of f1 ($f2 = \overline{f1}$), meaning it has the same mass and spin but opposite charge.

[4] The mass of this DM candidate is predicted by the NMSSM

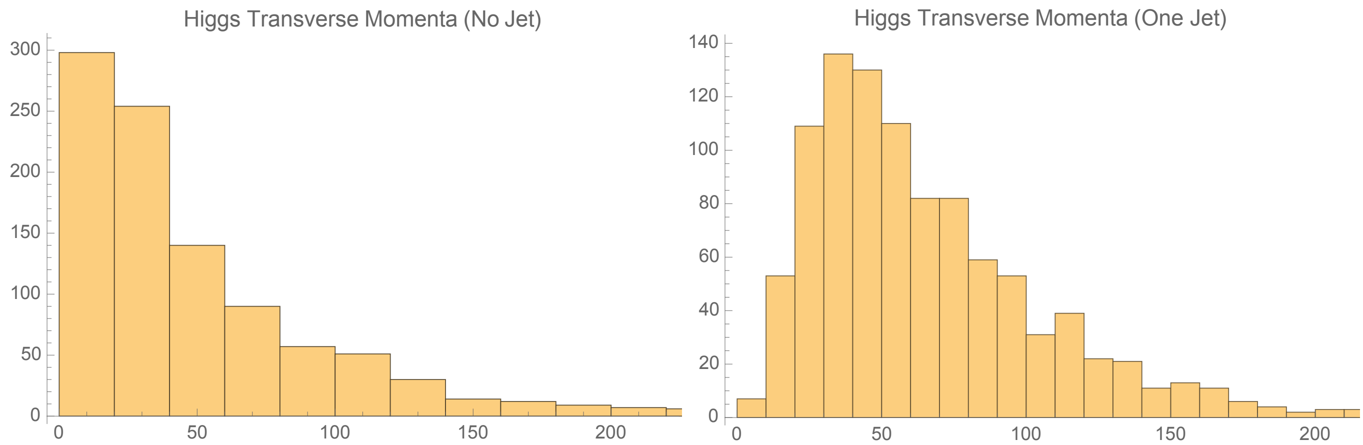
associated with each histogram All energies and momenta are in GeV, and all angles in radians.



(a) E no jet

(b) E one jet

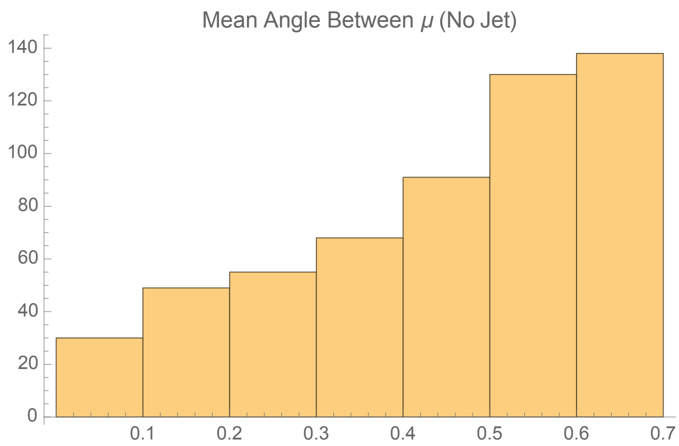
Figure 4: Higgs Energies



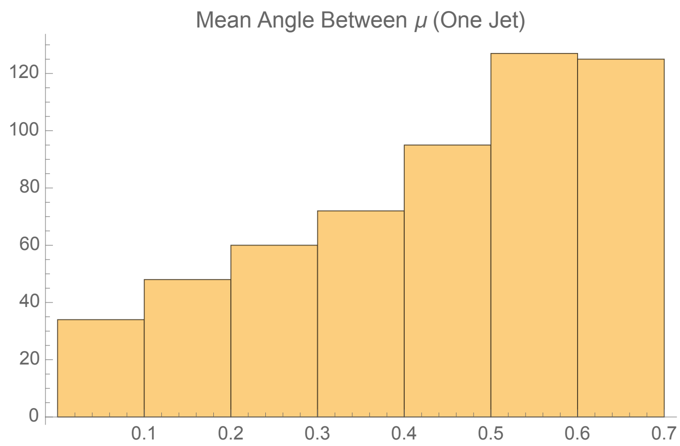
(a) pT no jet

(b) pT one jet

Figure 5: Higgs Transverse Momenta

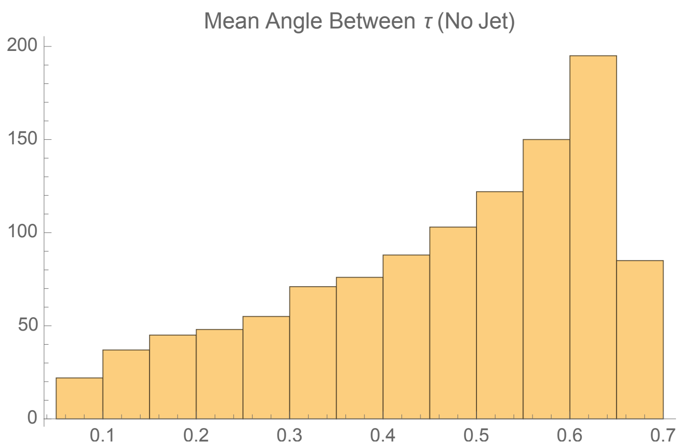


(a) muon angle no jet

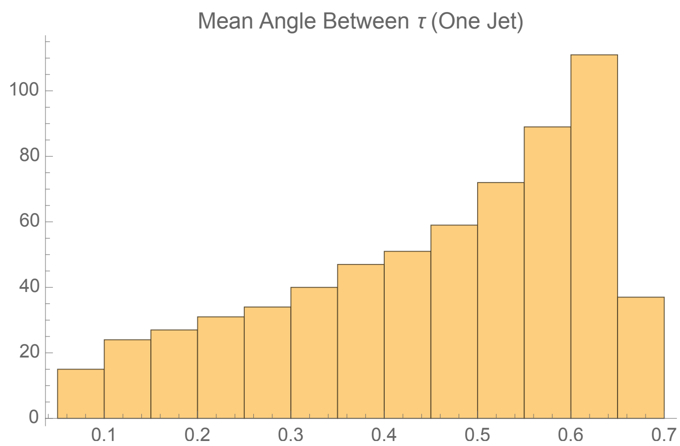


(b) muon angle one jet

Figure 6: Average Angle Between Muons



(a) tau angle no jet



(b) tau angle one jet

Figure 7: Average Angle Between Taus

Quantity	Maximum	Minimum	Mean	Variance
Higgs Energies	4250.	125.1	390.1	1506
Higgs pT	533.8	0.6097	56.52	4263
Angle btwn 561 Muons	0.6709	0.0250	0.4426	0.0326
Angle btwn 1097 Taus	0.6705	0.0535	0.4620	0.0264

Table 1: Events with no jet

Quantity	Maximum	Minimum	Mean	Variance
Higgs Energies	3493	125.6	384.2	1396
Higgs pT	461.8	4.673	67.59	2216
Angle btwn 561 Muons	0.6665	0.0281	0.4322	0.0328
Angle btwn 637 Taus	0.6661	0.0519	0.4529	0.0270

Table 2: Events with one jet

5 Discussion

Figures 4 and 5 reveal how the presence of a particle jet affects the energies and transverse momenta (pT) of the Higgs events produced by Pythia. On average, the Higgs bosons produced in tandem with a jet have lower energies and higher pT. This can be explained via energy and momentum conservation. Conservation of energy ensures that the energy of the interacting gluons and outcoming products must be the same. The more particles produced via the interaction, the smaller their average energies will be. Similarly, momentum must be conserved. If the gluon-interaction axis is labeled the z-axis, the x and y components of the momenta of the products must be equal and opposite, so that their total momentum has only a z-component. According to this, you may wonder why Higgs bosons produced without a jet have any transverse momenta at all. This comes from the Pythia process.

When Pythia produces Higgs events via gluon-gluon collisions, it includes some initial (small) radiation for the Higgs to scatter off of, shown in following Feynman diagram (figure 8).

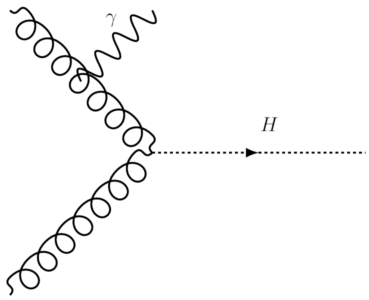


Figure 8: Gluon collision to Higgs with initial radiation

The energy of this initial radiation is smaller than that of the particle jets simulated, so it still stands that the Higgs produced with jets should, and did, have higher pT.

The energy of the Higgs bosons should propagate through the entire chain; if Higgs produced with jets have smaller energies, their daughter particles will also have smaller energies, and the final fermions will me moving slower. Slower particles should, on average, have a larger angle of separation. This can be seen in figures 6 and 7. Additionally, daughter particles of higher mass should have a larger angle separation. As can be seen in figures 6a vs 6b or 7a vs 7b, on average the taus are farther apart than the muons. These results can be explained via length contraction– a consequence of relativistic motion.

Lorentz boosting a particle in, for example, the z-direction, will shorten the z-component of its momentum, so inverse-boosting it will lengthen its z-component. The larger the momentum (or beta factor) of a1, the more powerful its inverse-boost, the smaller the pT of the fermions, and the closer together they will be. Thus, I have sound explanation for all of my data.

In each run, the average angle between the final fermions ranged from near zero to slightly below $\frac{\pi}{4}$ radians, or about 40 degrees, as expected. This does not reveal any non-obvious constraint on the angles between the final fermions due to the presence of a jet. Using the same Mathematica notebook, I can now look at Higgs events that involve multiple jets, or even constrain the energies and pT of the jets to higher values. I can also look at decays involving fermions that aren't leptons, or use a slightly different mass for a1. There are many useful ways to modify this process, which I hope to do utilize in the future.

6 Conclusion

I used Monte Carlo event generators and mathematical code to simulate a decay of the Higgs boson that involves dark matter. I found that producing a jet in tandem with the Higgs boson lowers the energies of the Higgs events and raises their transverse momenta, trickling down through the decay chain to shrink the angle between the final fermions. Though my results did not illuminate a non-obvious constraint on the angles between the final decay products due to the presence of a Jet, the process is easily applied to other useful decays.

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