The Two-Higgs Doublet Model and Sonification: Using Sound to Understand the Origin of Mass

R. Michael Winters IV
Physics Department, The College of Wooster, Wooster, Ohio 44691, USA
(Dated: June 9, 2010)

The Two-Higgs Doublet Model is a well studied extension of the Standard Model of particle physics. Most notably, it predicts the existence of five Higgs particles while the Standard Model predicts only one. Of the five Higgs particles, three electrically neutral (h_1, h_2, h_3) and two are charged (H^+, H^-). Contributions of the basis-independent CP-violating Two-Higgs Doublet Model to the oblique parameters (S, T, U, V, W, and X) and the Higgs masses were determined. Correlations between these parameters were sonified using the sound synthesis program SuperCollider. Sonification effectively displayed correlations between groups of four parameters.

I. INTRODUCTION & MOTIVATION

A. Extending the Standard Model

The Standard Model (SM) of particle physics, the operational theory of fundamental particles and their interactions, is not expected to provide a complete description of nature. It must be superseded by a theory which incorporates gravitational interactions near the Plank scale (10^{19} GeV), but may also break down at relatively lower energies. Therefore, although the SM has thus far been an effective theory at the energy scale of 1 TeV, it is not expected to be valid for some high energy scale. Various extensions of the SM have been proposed as explanations for observations such as dark matter and theoretical problems such as Grand Unification.

One popular extension is supersymmetry, which provides a mechanism for the source of dark matter. Incorporating supersymmetry into the Standard Model requires doubling the number of particles because each fundamental particle needs a super-partner. In order to account for the lack of experimental evidence for super-partners, theorists have moved towards more complicated versions of supersymmetry. The simplest possible supersymmetric model that is consistent with the SM is the Minimal Supersymmetric Standard Model (MSSM). It requires two Higgs doublets in its scalar sector.

The Two-Higgs Doublet Model (2HDM) is a model of low-energy particle interactions that is equivalent to the Standard Model except for the addition of one extra-Higgs doublet. Although it is implied by MSSM, it functions independently as well. For this and other reasons, it is one of the most studied extensions of the Standard Model. The extended Higgs sector would appear experimentally as five Higgs particles, whereas the Standard Model predicts only one.

B. Electroweak Symmetry Breaking in the Standard Model

The nature of electroweak symmetry breaking (EWSB) is one of the most important questions in theoretical particle physics. Although the Standard Model has a mechanism for dealing with EWSB, it has not received experimental confirmation. For reasons addressed in section I C, other ways of implementing EWSB are of theoretical interest.

The Standard Model of particle physics is constructed by applying local symmetries to the interactions of fundamental particles. At energies far above the electroweak scale (≈90 GeV), the symmetry group is $SU(3)\times SU(2)\times U(1)$. $SU(3)\times SU(2)\times U(1)$ summarizes the symmetries of the SM in group theoretical notation. $SU(3)$ refers to the three-fold (red/green/blue) color symmetry of the strong force. $SU(2)\times U(1)$ refers to the symmetries of the electroweak force. $SU(2)$ comes from the doublet structure of the particles subject to the weak force, and $U(1)$ is a phase symmetry known as hypercharge. Typically, these symmetry groups require a massless gauge boson (force-carrying particle) corresponding to each generator of the symmetry group. Thus the $SU(2)\times U(1)$ symmetry group requires 4 massless force-carrying particles. However, when the universe evolved to lower energies, this symmetry was spontaneously broken producing masses for the three gauge bosons of the weak nuclear force ($W^{\pm}$, and Z^0), and leaving the force carrier for electromagnetism (the photon) massless.

Spontaneous symmetry breaking requires the existence of a field (the Higgs field) that permeates space and has non-zero vacuum energy. A particle acquires mass when it interacts with this field. This process is known as the "Higgs Mechanism." The energy associated with this interaction is the vacuum expectation value v. If this scalar field exists, it can be used to explain why particles such as fermions have mass.

C. The CP-Violating Two-Higgs Doublet Model

CP (Charge-Parity) symmetry states that the laws of physics would be the same if a particle was switched with its anti-particle and left and right handedness were also exchanged. A theory without this property violates CP. In 1964, CP-violation was experimentally verified through the decay of neutral kaons into their antiparticles [3]. Experimenters James Cronin and Val Fitch noticed that the transformation did not occur with exactly the same probability in both directions, showing that nature does not treat left-handed particles the same as right-handed anti-particles.

It has been shown that the Standard Model can explain CP violation by incorporating complex values into the CKM (Cabibbo-Kobayashi-Maskawa) matrix. The CKM matrix is a numerical 3x3 matrix whose values are experimentally determined. Each element of the CKM matrix K_{ij} represents how strongly an up-like quark q_i interacts with a down-like quark q_j. It can be used to explain theoretically why the top quark is more likely to decay into a bottom quark than to a down or strange. A CKM matrix with strictly real values will exhibit no CP-violation.

By adopting complex values for the CKM, the Standard Model provided a sufficient theoretical explanation for the experimental evidence of CP-violation. However, an underlying problem of the SM is that it is not believed to be sufficient to explain the lack of antimatter. The universe contains far more matter than antimatter and the CKM matrix is only a small feature of the Standard Model. The solution to this apparent radical asymmetry is one of the great unsolved problems in contemporary particle physics. The Two-Higgs Doublet Model provides a possible source for CP-violation and, paired with a theory of supersymmetry, also provides a dark matter candidate.

Although supersymmetry requires a multi-Higgs doublet model, the Two Higgs Doublet Model works independently of supersymmetry as well. It is identical to the Standard Model in all respects except the inclusion of one extra Higgs doublet. While the Standard Model's single Higgs doublet is sufficient to explain electroweak symmetry breaking, it does not allow for CP-violation. The 2HDM not only explains EWSB, but also provides another possible source for CP violation.

II. THE BASIS-INDEPENDENT CP-VIOLATING 2HDM

A. Basis-Independence

As featured in the Minimal Supersymmetric Standard Model, the two Higgs doublets can be described by a parameter $\tan\beta$,

$$\tan\beta \equiv \frac{v_2}{v_1} \equiv \frac{\langle\Phi_2^0\rangle}{\langle\Phi_1^0\rangle}, \tag{1}$$

which describes how much of the vacuum expectation value v_1, v_2 is in the first doublet and how much is in the second. However, in the most general 2HDM, this quantity is not well-defined because one can perform a basis transformation that changes how much of the vacuum expectation value appears in each doublet. Therefore, it is important to define the parameters of the theory so that they are "invariant," meaning that they do not depend upon the basis choice of the Higgs doublets.

To explain experimentally observed quantities in terms of the physical parameters of the general model, one needs a way to relate ambiguous or pseudo-invariant parameters to invariant parameters. Only invariant parameters can be candidates for observable quantities because observables should not depend upon the choice of basis (the distribution of the vacuum expectation value).

For the purposes of the present experiment, the basis-independent 2HDM was implemented, but the necessary formalism will not be displayed. It is presented at length in [1].

B. Generating the Physical Higgs Mass-Eigenstates

The following section summarizes the work of Haber and O'Neil [1]. The Two-Higgs Doublet Model has five observable Higgs particles regardless of whether it is CP violating or conserving. The doublet scalar fields of the Higgs basis are parametrized as

$$\begin{aligned} H_1 &= \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + \varphi_1^0 + iG^0\right) \end{pmatrix}, \\ H_2 &= \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(\varphi_2^0 + ia^0\right) \end{pmatrix} \end{aligned} \tag{2}$$

with hermitian conjugates

$$H_1^\dagger = \begin{pmatrix} G^- & \frac{1}{\sqrt{2}}\left(v + \varphi_1^0 + iG^0\right) \end{pmatrix}, \tag{3}$$

$$H_2^\dagger = \begin{pmatrix} H^- & \frac{1}{\sqrt{2}}\left(\varphi_2^0 + ia^0\right) \end{pmatrix}, \tag{4}$$

where $G^\pm$ is the charged Goldstone boson pair and G^0 is the CP-odd neutral Goldstone boson.

Before EWSB, the Goldstone bosons were observable as propagating particles. However, at this point in the evolution of the universe, the Goldstone bosons are observable only indirectly as the masses of the Z^0 and $W^\pm$ bosons. The neutral Goldstone boson G^0 becomes the mass of the Z^0 boson while $G^\pm$ becomes the mass of the $W^\pm$ boson. If the Higgs sector is CP-conserving, then a^0 will be a mass eigenstate. If the Higgs sector is CP-violating, then φ_1^0, φ_2^0, and a^0 mix to form three additional physically observable particles. Because $H^\pm$ do not mix with φ_1^0, φ_2^0, and a^0 in eqn. (5), $H^\pm$ will become manifest as mass eigenstates regardless of CP conservation. Mass eigenstates will appear as states of definite mass and therefore observable particles. φ_1^0, φ_2^0 will always mix, and therefore cannot be mass eigenstates or states of definite mass.

To determine the mass of these particles, one needs to first examine the terms of the scalar potential that are quadratic in the scalar fields. The scalar potential $\mathcal{V}$ can be written

$$\begin{aligned}\mathcal{V} &= Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] \\ &+\tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \tfrac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) \\ &+Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \{\tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 \\ &+\big[Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2)\big] H_1^\dagger H_2 + \text{h.c.}\}, \qquad (5)\end{aligned}$$

where $Y_{1,2,3}$ and Z_{1-7} are important constants which are potentially complex. The substitution

$$Y_1 = -\tfrac{1}{2} Z_1 v^2\,, \qquad\qquad Y_3 = -\tfrac{1}{2} Z_6 v^2\,, \qquad (6)$$

is a result of minimizing the scalar potential (eqn. 5).

Quadratic and linear terms are relevant because the requirement that the coefficient for linear terms vanishes corresponds to minimizing the scalar potential and results in the simplification used in eqn. (6). Furthermore, because no quadratic terms involving the Goldstone bosons survive, we know that the Goldstone is massless. From the coefficients of eqn. (5), the charged Higgs boson mass is determined to be

$$m_{H^\pm}^2 = Y_2 + \tfrac{1}{2} Z_3 v^2\,. \qquad (7)$$

The three neutral fields mix and the neutral Higgs squared-mass matrix in the φ_1^0–φ_2^0–a^0 basis becomes

$$\mathcal{M} = v^2 \begin{pmatrix} Z_1 & \text{Re}(Z_6) & -\text{Im}(Z_6) \\ \text{Re}(Z_6) & \Lambda_1 & -\tfrac{1}{2}\text{Im}(Z_5) \\ -\text{Im}(Z_6) & -\tfrac{1}{2}\text{Im}(Z_5) & \Lambda_2 \end{pmatrix}, \qquad (8)$$

where

$$\begin{aligned}\Lambda_1 &= \tfrac{1}{2}\left[Z_{34} + \text{Re}(Z_5)\right] + Y_2/v^2, \\ \Lambda_2 &= \tfrac{1}{2}\left[Z_{34} - \text{Re}(Z_5)\right] + Y_2/v^2, \\ Z_{34} &= Z_3 + Z_4, \qquad (9)\end{aligned}$$

and from complex analysis, the simplification

$$\text{Im}(z) = \frac{z-\bar{z}}{2i} \qquad \text{Re}(z) = \frac{z+\bar{z}}{2} \qquad (10)$$

is implied.

Because all of the coefficients in the mass matrix $\mathcal{M}$ are invariant, the physical Higgs masses will be basis-independent as well. It is necessary to diagonalize $\mathcal{M}$ so that only the eigenvalues lie along the diagonal and only the squared-mass terms are present. By diagonalizing the mass matrix, we are identifying the physical particles since physical particles are states of definite mass. Diagonalization requires defining a new matrix R such that

$$R\mathcal{M}R^T = \mathcal{M}_D \equiv \text{diag}\,(m_1^2\,, m_2^2\,, m_3^2)\,, \qquad (11)$$

where $RR^T = I$ and the m_k^2 are the eigenvalues of $\mathcal{M}$.

The three new neutral Higgs mass-eigenstates are denoted h_1, h_2, h_3 such that

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \varphi_1^0 \\ \varphi_2^0 \\ a^0 \end{pmatrix}\,. \qquad (12)$$

These are the neutral Higgs particles that would actually be observed with masses m_1, m_2, and m_3. Without loss of generality, it is convenient to order h_k such that $m_1 \leq m_2 \leq m_3$.

C. The Oblique Parameters

The Two-Higgs Doublet Model has implications for the values of many experimental parameters. The Large Hadron Collider is optimized to make discoveries at the electroweak scale and should provide experimental evidence for the existence or non-existence of the Higgs particle. As the LHC has become operational again as of the 20th of November 2009, refining experimental predictions and constraints for the 2HDM is a pressing research goal. For this purpose the "Oblique Parameters," S, T, U, V, W, and X are experimentally accessible values which can constrain or disprove a theory. The 2HDM predicts values for the oblique parameters which may or may not be compatible with those measured experimentally.

The S, T, U, V, W, and X parameters are the link between theory and experiment. Experimentally, these parameters can be determined only indirectly through the determination of constants such as M_Z, M_W, and decay rates. However they can also be determined theoretically by arbitrarily varying the constants of the mass matrix $\mathcal{M}$ in eqn. (8) and using the Feynman rules corresponding to the possible vertices of the 2HDM. These Feynmann rules are derived and displayed in [2]. The theoretical upper bounds of the constants in the mass matrix are displayed in Table I.

TABLE I: The theoretical limits of the parameters Z_1, $\text{Re}(Z_5)$, $\text{Im}(Z_5)$, $\text{Re}(Z_6)$, $\text{Im}(Z_6)$, $Z_{34} = Z_3 + Z_4$, and Z_3. These values were varied arbitrarily to produce values for $m_{1,2,3,H^\pm}$ and the oblique parameters. Their bounds are theoretically determined and found in [2].

Theoretical Upper Bound
$\lvert Z_1\rvert < 4\pi$
$\lvert Z_3\rvert < 8\pi$
$\lvert Z_3 + Z_4\rvert < 8\pi$
$\lvert\text{Re}(Z_5)\rvert < 2\pi$
$\lvert\text{Re}(Z_5))\rvert < 2\pi$
$\lvert\text{Im}(Z_6))\rvert < 2\pi$
$\lvert\text{Im}(Z_6))\rvert < 2\pi$

The numerical results generated from these calculations exhibit relationships between the six oblique parameters (S, T, U, V, W, and X) and $m_{1,2,3,H^\pm}$, some of which display correlation. An example of these correlations is displayed in Figs. 1, 2, 3, and 4.

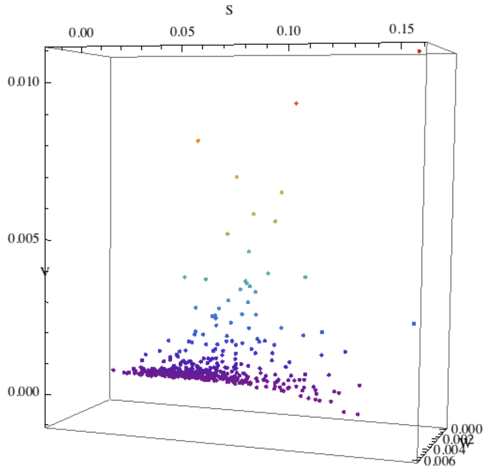

FIG. 1: A plot of 343 values for S, V, and W using the theoretical upper bounds of Table I. Color is being used to perceptually reinforce the W parameter. Each parameter in this set was paired with a perceptual resources from Table II. This mapping is displayed in Table III.

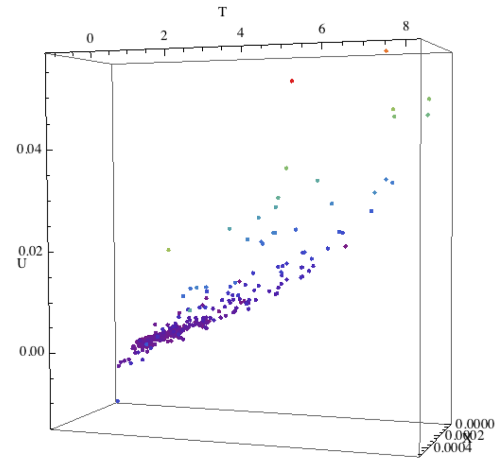

FIG. 3: A plot of 343 values for T, U, and X using the theoretical upper bounds of Table I. Color is being used to perceptually reinforce the X parameter. Each parameter in this set was paired with a perceptual resources from Table II. This mapping is displayed in Table III.

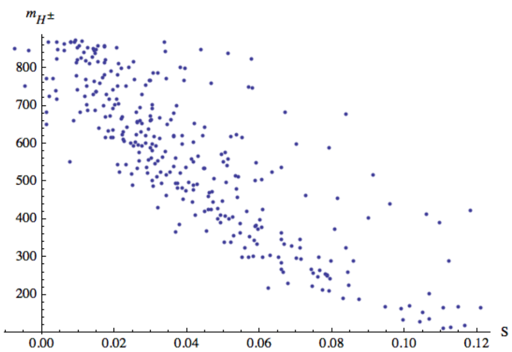

FIG. 2: A plot of values generated for $m_{H^\pm}$ and S. The charged Higgs mass $m_{H^\pm}$ is displayed in units of GeV.

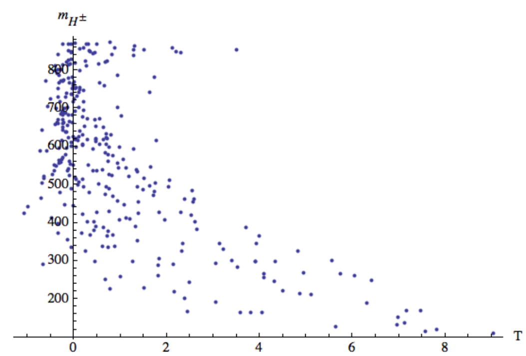

FIG. 4: A plot of values generated for $m_{H^\pm}$ and T. The charged Higgs mass $m_{H^\pm}$ is displayed in units of GeV.

III. SONIFICATION

A. Introduction and Motivation

Visual graphs have developed over time as a simple and accurate means to express information and have been used effectively in the present experiment. However, as computer processing power has blossomed within the past 30 years, new techniques have developed which offer an alternative medium of expression. Our auditory perception remains a largely untapped resource for this purpose and may provide a clear advantage in the representation of complex and high-dimensional data.

In this context, Sonification has emerged as an international field promoting new and exciting display techniques. Defined as the use of non-speech audio to convey information; a simple and well-known example is the Geiger counter, a device which represents the radiation level in its immediate vicinity using audible clicks which vary in number and frequency. Although sometimes Sonification is applied independently of visual display, it also works very well as a supplement. Among its other functions, it is helpful in the sciences where dynamic, complex and high-dimensional data abound. In this environment, as in others, Sonification brings new insight to data through a unique, complex, and perhaps more complete experience. In general, its purpose is to facilitate human-computer interaction through optimal understanding and application of our aural perception.

With 10 observable parameters S, T, U, V, W, X, m_1, m_2, m_3, $m_{H^\pm}$, and 7 theoretical parameters Z_1, $\mathrm{Re}(Z_5)$,

$\mathrm{Im}(Z_5)$, $\mathrm{Re}(Z_6)$, $\mathrm{Im}(Z_6)$, Z_{34}, and Z_3, the 2HDM serves as an instance of complex, high-dimensional data. While it is possible to display high dimensionality visually (e.g., color, symbol size, shape) it is often difficult to interpret. Sonification provides the potential of displaying this high-dimensionality as a sonic experience. At minimum, sonification provides a complementary resource to visual display. At its best, instead of viewing these 17 related parameters as 136 two-dimensional list plots, they might conceivably be experienced in a single sound space.

B. Perceptual Resources

Auditory perception functions very differently from visual perception. While visual perception is used extensively by most humans, human auditory perception is naturally used to convey complex linguistic content. When thinking of the somewhat arbitrary collection of sounds which create meaning in a natural language, a very narrow range of our auditory perception provides easy understanding and expression for the majority of linguistic mental content. Although sound may offer a broad palette of resources to convey data, an understanding of our auditory perception is fundamental to successful sonification.

In the present experiment, pitch, loudness, spatialization, timbre, duration, and time scale were manipulated as perceptual resources for data representation. Table II links these resources with a corresponding qualitative question to help understand its use. Although there are undoubtably other resources available for auditory representation, they were not used. The addition of timbre (tone color), duration, and time scale offered a considerable step forward from previous experience [4] and the resources of Table II were thought to be sufficient for effective representation of the desired data set.

TABLE II: A table of perceptual resources used in the present experiment to express data through sound.

Perceptual Resource	Qualitative Question
Pitch	How high or low was the sound?
Loudness	How loud or soft was the sound?
Spatialization	Where was the source of the sound?
Timbre	What did it sound like?
Duration	How long did the sound last?
Time Scale	How long since the last sound?

C. Experimentation

Although 17 parameters exist, for the sake of simplicity, only the 10 observable parameters were analyzed. Although these parameters are dependent upon the theoretical parameters, the observables were the focus of the present experiment. To find the correlations between the 10 observable parameters, 45 2-D plots were analyzed (ie. m_1-S, V-W).

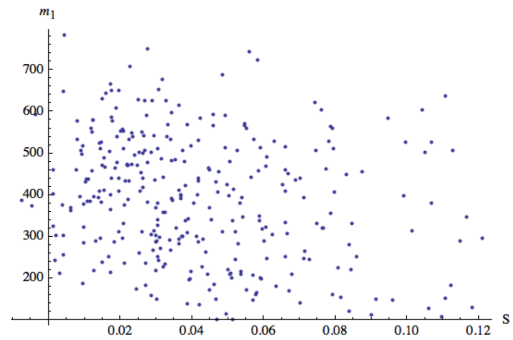

FIG. 5: A plot of values generated for m_1 and S. The least Higgs mass m_1 is displayed in units of GeV. There is no correlation between these parameters.

The correlation between the parameters SVWm_1, SVW$m_{H^\pm}$, TUXm_1, and TUX$m_{H^\pm}$ were chosen for sonification. These groups were chosen firstly because of the mutual correlations between the S,V, and W parameters as displayed in Fig. 1, as well as the mutual correlations between T, U, and X as displayed in Fig. 3. The variable m_1 was chosen because of its importance as the least Higgs mass, the most likely particle to be observed at the LHC. The variable $m_{H^\pm}$ was chosen because of its interesting correlations with the oblique parameters S and T. Because m_1 lacks correlation with these variables the result was two sound files identical in some respects but clearly different in others. These correlations are displayed in Figs. 2 and 4 and 5

Without a specific time dependence of any of the variables, one must be chosen as a substitute. Unlike visual display, auditory display must have an explicit time relation. A sonic space must evolve in time or it cannot exist at all. The the sonic evolution might be stagnant (i.e. a constant tone of arbitrary duration), but a time relation must exist. The parameters S and T were chosen as substitutes. Therefore, for the groups SVWm_1 and SVW$m_{H^\pm}$, the values of V, W, and m_1 or $m_{H^\pm}$ evolve in time proportionally to their relation with S. Similarly, for the groups TUXm_1 and TUX$m_{H^\pm}$, values of U, X, and m_1 or $m_{H^\pm}$ evolve in time proportionally to their relation with T.

IV. USING SUPERCOLLIDER

Though the program 'Mathematica' can generate sound, it proved insufficient as a tool for sonification of the present data set. The program 'SuperCollider' offered the clear choice for sonification, but was explored only after Mathematica because it required learning a new program. Florian Grond of the Ambient Intelligence Group at Bielefeld University offered an effective and compelling prototype in SuperCollider which was modified and used as the basis for all further sonification.

Lists which ordered SVWm_1, SVW$m_{H^\pm}$, TUXm_1, and TUX$m_{H^\pm}$ with respect to S and T were exported from Mathematica as comma-sperated value (.csv) files. These files were imported by SuperCollider and each variable was normalized independently to a value between 0 and 1. With these parameters in mind, the algorithm generated for sound synthesis incorporated all of the resources of Table II. Therefore each element of the list (i.e. SVWm_1) corresponded to a sound of particular pitch, loudness, spatialization, timbre, duration, and time scale.

Although many of the resources of Table II are relatively easy to explain, timbre is complex and requires additional discussion. In the SuperCollider programming language, 'Unit Generators' (UGens) are a fundamental tool for sound synthesis. A simple example of a UGen is 'SinOsc,' a perfect sine wave. Its arguments include frequency of oscillation, phase, and amplitude. These arguments can be adjusted to vary with time with respect to some variable.

For the present experiment, sound synthesis involved the 'Formant' UGen. This UGen generates a set of harmonics around a formant frequency at a given fundamental frequency. Formants can be thought of as important to distinguishing between particular vowel sounds in human speech and singing. While keeping a fundamental tone, vowels nevertheless sound different because they have different formant frequencies. The arguments of the 'Formant' UGen include fundamental frequency, formant frequency, and pulse width frequency. Although all three of these arguments were used, only formant frequency and pulse width frequency were considered to correspond to timbre.

V. SONIFICATION OF THE OBLIQUE PARAMETERS AND m_1, $m_{H^\pm}$

Parameters from SVWm_1, SVW$m_{H^\pm}$, TUXm_1, and TUX$m_{H^\pm}$ were mapped onto the perceptual recourses from Table II in a manner which sought to maximize perceptual comprehension of the data sets. This mapping is displayed in Table III. The corresponding visual graphs are displayed in Figs. 1-5. For sonification, only data points which satisfied

$$\begin{aligned} \mathrm{Im}(m_1) = \mathrm{Im}(m_2) = &\mathrm{Im}(m_3) = \mathrm{Im}(m_{H^\pm}) = 0, \\ &m_{H^\pm} > 100 \text{ GeV, and} \\ &m_1 > 100 \text{ GeV} \end{aligned} \qquad (13)$$

were employed. The first condition discards any unphysical Higgs particles, while the second and third conditions limit the number of extraneous data points.

In each case, the difference in the level of correlation between S-m_1 and S-$m_{H^\pm}$ or T-m_1 and T-$m_{H^\pm}$ was found to be easily perceivable. Although duration was also used to express m_1, $m_{H^\pm}$ (see Table III), the most clear difference in the soundfiles was the change in timbre over time for S-$m_{H^\pm}$ and T-$m_{H^\pm}$. There was no characteristic change in timbre in either S-m_1 or T-m_1.

The difference in correlation between S-m_1 and S-$m_{H^\pm}$ is displayed in Figs. 2 and 5. The difference in correlation between T-m_1 and T-$m_{H^\pm}$ is similar in that like S-m_1, T-m_1 is not correlated. Because there is no correlation between T and m_1, the graph for T-m_1 is not displayed. The difference between SVW and TUX was not as easy to differentiate, but careful listening could always indicate which was the correct data set. The most obvious auditory difference between the data sets is visually apparent in Figs. 1 and 3. There is a collection of points in the lower right hand region of SVW that is not present in TUX.

TABLE III: A table of perceptual resources used in the present experiment to express data through sound. 'Mapping' refers to which parameter of the data set TUX or SVW corresponds to the perceptual resource (e.g. S or T, V or U)

Perceptual Resource	Mapping
Pitch	U/V
Loudness	X/W
Spatialization	T/S
Timbre	m_1, $m_{H^\pm}$
Duration	m_1, $m_{H^\pm}$
Time Scale	X/W

VI. CONCLUSION & FUTURE WORK

A. Conclusion

Theoretical calculations involving the basis-independent CP-violating Two-Higgs Doublet Model revealed correlations between the oblique parameters and the five Higgs particles $m_{1,2,3,H^\pm}$. A disproportionate number of correlations exist between the oblique parameters and $m_{H^\pm}$ compared to $m_{1,2,3}$. Sonification was shown to be effective as a means to differentiate correlated data sets involving four parameters (SVWm_1, SVW$m_{H^\pm}$, TUXm_1, and TUX$m_{H^\pm}$).

B. Future Work

The relationships between the seven theoretical parameters Z_1, Re(Z_5), Im(Z_5), Re(Z_6), Im(Z_6), Z_{34}, and Z_3 and the 10 observable parameters S, T, U, V, W, X, $m_{1,2,3,H^\pm}$ should be explored and analyzed for correlations. Although their importance might be secondary to the observables, the present experiment is not complete without this additional analysis.

The current experiment was also limited by experience with SuperCollider and Sonification in general. With more time and experience, more sophisticated sonifications could be created. In addition to displaying our data better, this level of sophistication would be consistent with that of other researchers. Further research and inquiry into auditory perception would provide a more concrete understanding and application of the perceptual resources of Table II.

VII. ACKNOWLEDGEMENTS

I would like to thank Dr. Deva O'Neil for her help and guidance in understanding and applying the Two-Higgs Doublet Model. In addition to her insightful teaching, her enthusiasm for the application of Sonification to this research was tremendously helpful. I'd also like to thank Dr. Hermann and especially Florian Grond of the Ambient Intelligence Group at Bielefeld University for their direction as experts in Sonification and introducing me to SuperCollider.

[1] H. E. Haber and D. O'Neil, "Basis-independent methods for the two-Higgs-doublet Model. II: The significance of tan(beta)," Phys. Rev. D **74**, 015018 (2006) [arXiv:hep-ph/0602242].

[2] D. O'Neil, "Phenomenology of the Basis-Independent CP-Violating Two-Higgs Doublet Model [Dissertation]," arXiv:0908.1363 [hep-ph].

[3] J. H. Christenson, J. W. Cronin, V. L. Fitch and R. Turlay, "Evidence For The 2 Pi Decay Of The K(2)0 Meson," Phys. Rev. Lett. **13**, 138 (1964).

[4] R. Winters, "Musical Mapping of Chaotic Attractors." (2009) www3.wooster.edu/physics/jris

[5] I. Maksymyk, C. P. Burgess and D. London, "Beyond S, T and U," Phys. Rev. D **50**, 529 (1994) [arXiv:hep-ph/9306267].

[6] H. E. Haber. "Introductory low-energy supersymmetry," arXiv:hep-ph/9306207.