PMNS mixing angle implications for the MMS Model

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We extend the Standard Model of particle physics by updating a supersymmetric model of electroweak symmetry breaking. In this model additional Higgs doublets are present that couple directly to the right-handed neutrinos and therefore allow for neutrino masses. This is accomplished in a technically natural manner, that avoids any fine-tuning and the existence of very light scalars. We update this model to include recent discoveries about the θ_{13} mixing angle used to describe the oscillations of neutrinos and analyze the phenomenology in light of recent LHC data. In particular, key decay events brought about by the $\theta_{13} \neq 0$ results will be investigated.

I. INTRODUCTION

The Standard Model (SM) of particle physics has enjoyed countless successes in the half-century since its foundation. Despite these successes, experimental verification of the mechanism that causes electroweak symmetry breaking (Section II A) largely remained elusive. However, with the recent announcement by the ATLAS Collaboration [1] and the CMS Collaboration [2] this is no longer the case. The discovery of a Higgs like scalar around 125 GeV has put the final piece of the SM into place. Still, we know that the SM is not the complete story because it contains some well known problems.

The experimental verification of neutrino flavor oscillations [3] by the Sudbury Neutrino Observatory [4] is one such problem. Flavor oscillations require neutrinos with nonzero mass and yet the SM neutrinos are massless (Section II B). Since the experimental verification of neutrino oscillations a decade ago, there has been significant interest in the creation of SM extensions which solve this problem.

We work with one such extension: a supersymmetric model that has been shown to include neutrino masses. We will first update our model to incorporate recent experimental results from the Daya Bay Collaboration [5], the T2K Collaboration [6], the RENO Collaboration [7] and others that violate assumptions made in the creation of the model (Section II E) . Our research will be one of the first opportunities to update the predictions of a supersymmetric model that includes neutrino masses with these results.

A significant aspect of this research is the opportunity to compare recent results from the Large Hadron Collider (LHC) with the phenomenology of the updated model. One characteristic aspect of our model is that it predicts dramatic multilepton decay events. These decays are a signature of models similar to ours and will be a key component in comparisons with experimental data.

Our investigation will shed light on important characteristics of the Higgs mechanism and will aid in our understanding of how supersymmetry may be involved in this process. Finally, our research will contribute toward the search for an accurate and complete model of the Higgs mechanism that would answer questions like "are there multiple Higgs particles," and if so, "what are their separate properties and how do they contribute to the Higgs mechanism," i.e., does one specific Higgs particle contribute to most of the mechanism or do they evenly share in this process?

II. THEORETICAL PARADIGM

A. Electroweak Symmetry Breaking

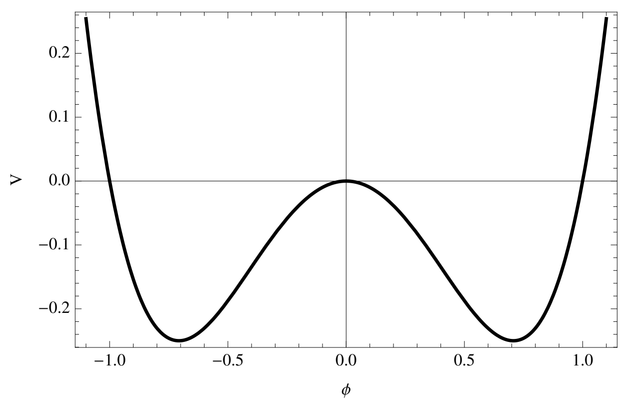

FIG. 1. A 1-D representation of the SM Higgs potential. ϕ corresponds to the field value and V is the potential energy in arbitrary units.

Electroweak symmetry breaking refers to the process by which the scalar particle in the SM, the Higgs boson, "breaks symmetry" in the manner pictured in FIG. 1. In a graph of the potential energy of the Higgs boson, the origin, corresponding to $\phi = 0$ (no field), is an unstable local extrema and as such the vacuum state (lowest possible energy) for the Higgs field does not actually correspond to an absence of field. This allows the Higgs field to pick out what is called a vacuum expectation value (vev). When the Higgs field couples to various particles it is the existence of this vev (a constant term) that leads to particles acquiring mass. For an extensive review of the Higgs mechanism and electroweak symmetry breaking see the review by Sher [8].

B. Fermion Masses

Fermion mass terms appear in the potential energy term of the Lagrangian as $m\overline{\psi}\psi$. Consider the projection operators given by,

$$P_R = \frac{1}{2}(1+\gamma^5),$$

$$P_L = \frac{1}{2}(1-\gamma^5),$$

where 1 represents the identity matrix of appropriate dimensions and γ^5 is,

$$\begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}.$$

These operators project out the right-handed and left-handed components of a fermion ψ. A particle's "handedness" is determined by its chirality: the projection of its spin onto its momentum. Note that,

$$\begin{aligned} P_R + P_L &= 1, \\ P_R^2 &= P_R, \\ P_L^2 &= P_L, \\ P_L P_R = P_R P_L &= 0. \end{aligned}$$

Define $\psi_R = P_R\psi$ and $\psi_L = P_L\psi$. It can be shown that,

$$\begin{aligned} m\overline{\psi}\psi &= m(\overline{\psi}_R + \overline{\psi}_L)(\psi_R + \psi_L), \\ &= m\overline{\psi}_R\psi_L + h.c., \end{aligned}$$

where $h.c.$ is the Hermitian conjugate. This shows that fermion mass terms can be written as the left-handed component of ψ times the right-handed component. However, in the SM there are no right-handed neutrinos. Therefore, the SM neutrinos are massless because there can be no interaction between their left-handed and right-handed components.

C. Our Model

We consider the Marshall-McCaskey-Sher (MMS) model [9] which is the supersymmetric version of the Davidson-Logan model [10]. In the MMS model the Minimally Supersymmetric Model (MSSM) is extended by adding two additional Higgs doublets and three additional right-handed neutrino fields. The additional Higgs doublets couple to these right-handed neutrino fields and their vevs are made small (on the order of an eV) to give the correct neutrino masses.

A key aspect of the MMS model is that the supersymmetric partners of the Higgs bosons, the Higgsinos, can have dramatic multilepton decay events that can be detected at the LHC and Tevatron. For example, it is possible for a pair of charged Higgsinos ($\chi^{\pm}$) created in a $p^+ + p^+$ reaction at the LHC to decay into up to 10 leptons.

D. PMNS Matrix

The Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS matrix) is a 3×3 unitary matrix used to describe the interactions of the quantum states of freely propagating leptons. The physically observable states of the neutrinos, ν_1, ν_2, and ν_3 are only realized after the eigenstates, ν_e, ν_μ and ν_τ, are operated on by the PMNS matrix, given by [11],

$$U_{ij} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{13}s_{23} & -c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{23}c_{13} \end{pmatrix},$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$ and θ_{ij} are three parameters (θ_{12}, θ_{13}, and θ_{23}) used to describe the propagation between various eigenstates. Thus, the physically observable states are found by operating on the neutrino eigenstates with U_{ij},

$$U_{ij}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

E. Mixing Angles

Until the Daya Bay results [5], θ_{13} was thought to be 0. In particular, MMS chose,

$$\theta_{12} = 34^\circ \quad \theta_{13} = 0^\circ \quad \theta_{23} = 45^\circ,$$

and as such their PMNS matrix reduced to

$$U_{ij} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}c_{23} & c_{12}c_{23} & s_{23} \\ s_{12}s_{23} & -c_{12}c_{23} & c_{23} \end{pmatrix} = \begin{pmatrix} 0.83 & 0.56 & 0 \\ -0.4 & 0.59 & 0.71 \\ 0.4 & -0.59 & 0.71 \end{pmatrix}.$$

A nonzero value of θ_{13} significantly affects U_{ij} and thus the phenomenology of any model that makes this assumption. For example, if θ_{12} and θ_{23} are held constant and θ_{13} is increased to 15° the PMNS matrix becomes,

$$U_{ij} = \begin{pmatrix} 0.80 & 0.54 & 0.26 \\ -0.55 & 0.48 & 0.68 \\ 0.24 & -0.69 & 0.68 \end{pmatrix}.$$

In our case, these discrepancies will manifest themselves in the possible decay chains of the Higgsinos.

These sparticles will decay into sneutrinos (supersymmetric partners of the neutrinos) which are also unstable. It is the subsequent decays of these sneutrinos that will be significantly affected by the mixing angles because the final decay products will be various leptons. This is important because it is these decays that will be observed at colliders.

As an example, consider the decay possibilities of the $\chi^{\pm}$ given in tables I and II. The probabilities of the four most likely products have changed but the most interesting result comes from the appearance of $e^{\pm}$. For this example, with $\theta_{13} = 0$, decays into electrons or positrons would be impossible.

$\chi^{\pm}$	Products	Probability (%)
1	$\tau^{\pm}$	40
2	$\mu^{\pm}$	23
3	$\mu^{\pm}\tau^{+}\tau^{-}$	13
s 4	$\tau^{\pm}\tau^{+}\tau^{-}$	8
5	$\tau^{\pm}\mu^{+}\mu^{-}$	4

TABLE I. The five largest decay possibilities of the $\chi^{\pm}$ for $\theta_{12} = 34°$, $\theta_{13} = 0°$, and $\theta_{23} = 45°$.

$\chi^{\pm}$	Products	Probability (%)
1	$\tau^{\pm}$	38
2	$\mu^{\pm}$	21
3	$\mu^{\pm}\tau^{+}\tau^{-}$	11
4	$\tau^{\pm}\tau^{+}\tau^{-}$	7
5	$e^{\pm}$	3

TABLE II. The five largest decay possibilities of the $\chi^{\pm}$ for $\theta_{12} = 34°$, $\theta_{13} = 15°$, and $\theta_{23} = 45°$.

We will likely investigate the implications for decay products for a range of mixing angles. There are significant uncertainties in the θ_{13} and even θ_{23} values in the literature [12]. The point is that $\theta_{13} \neq 0$ opens up entirely new decay branches which may contain characteristic decay possibilities that will be easily searchable in the experimental data.

III. RESOURCES

Due to the theoretical nature of our field, our research will be performed without the explicit need for laboratory equipment. We will use MATLAB, which is available through the Physics and Astronomy Department, to compute decay probabilities similar to those given above.

Apart from the standard literature sources, the only outside resources will be experimental data from various experiments at the LHC. This freely available information will largely come from the Particle Data Group [13].

IV. BUDGET

No funds will be necessary for the completion of this project.

V. TIMELINE

Objective	Target Date (2013)
1. Model Updated	Aug. 1
2. Analyze Phenomenology	Aug. 20
3. Compare with LHC Data	Oct. 7
4. Refine Parameter Space	Oct. 16
5. Model Complete	Oct. 24
6. First Draft Complete	Nov. 20
7. Final Draft Complete	Dec. 2

This project will largely be completed in three stages.

The first stage (1-2) will be largely theoretical work. We will first update the model to include the $\theta_{13} \neq 0$ results. This will involve investigating the various decay chains of the Higgsinos and quantifying the possible products. Specifically we will investigate the phenomenology of the updated model and examine specific differences in the decay predictions brought about by $\theta_{13} \neq 0$.

The second stage (3-5) will focus on comparing our predictions to experimental results. We will compare the phenomenology of our model with recent LHC data and look for instances in which prediction conflicts with experiment. As mentioned, our model predicts multilepton decay events which should be easily searchable in the experimental data. Where applicable we will refine the parameter space of the model to coincide with bounds set by experiment. This stage is not limited to predictions related to the $\theta_{13} \neq 0$ results but is a chance to compare general predictions of the MMS model (completed in 2010) with more recent experimental data.

The final stage (6-7) will consist of summarizing results and writing Timothy Hayward's Physics 420 senior research paper.

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