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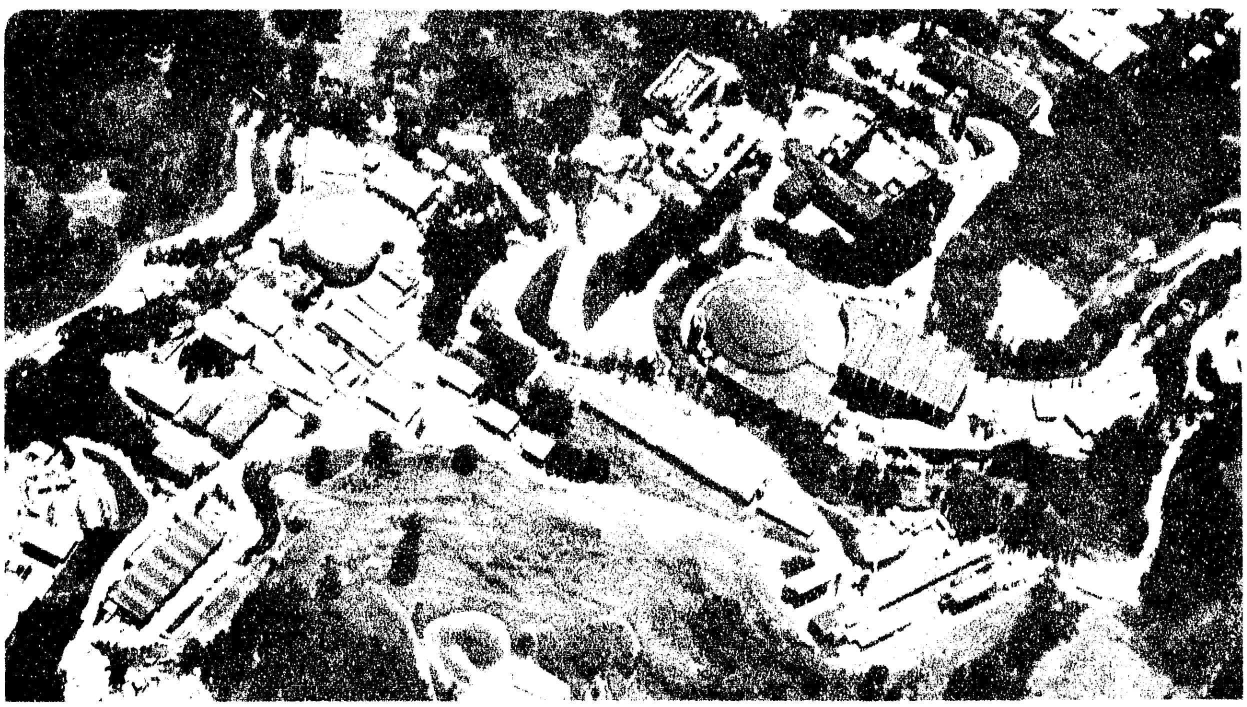

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# Precise Predictions For Neutrino Masses and Mixings [*] [†] [‡]

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[‡]In collaboration with S. Dimopoulos and S. Raby.

Written contributions of theoretical talks are often just edited versions of published technical papers, so nobody bothers to read them. Instead of doing this, I will tell you in plain English the motivation and the results of this work.

It is no exaggeration to say that the majority of particle physics experiments are designed to measure either the masses of the quarks and leptons, or their couplings to the $W$ boson. There is no mystery about why this is so: we are most interested in learning the fundamental parameters of the standard model, and 22 out of 27 of these correspond to quark and lepton masses and mixing.* I am not trying to minimize the importance of the 5 parameters of the gauge sector, which can be taken as $\alpha, \alpha_s, G_F, M_Z$ and $M_H$; but it is a simple fact that the large majority of the fundamental parameters belong to the flavor sector.

Each of the 27 fundamental parameters is represented in the standard model by a coupling constant. Conventional wisdom in particle physics has it that theory got way ahead of experiment, and consequently became a victim of its own success. What do you do after successfully predicting the existence and masses of the $W$ and $Z$ particles? This masks an important point; the triumph of particle theory was the construction of the standard model, not the understanding of the values of the 27 fundamental coupling constants. The prediction of the $Z$ mass was possible because the four observables $\alpha, G_F, \sin^2\theta$ and $M_Z$ depend on only three of the fundamental independent couplings, giving a prediction $M_Z^2 = \pi\alpha/\sqrt{2}G_F \sin^2\theta\cos^2\theta$. The real problem with theory is that it has failed to calculate any of the 27 fundamental coupling constants, while experiments have measured 18 of them. Particle theory has hit a brick wall. It is a victim of its present failures not its previous successes.

I do not know how to construct a fundamental theory which would allow a first principles calculation of coupling constants. Does this mean I have no hope of making predictions? No. It is always possible to obtain predictions by *reducing the number of free parameters*. The Balmer formula provides a superb illustration of this. A large number of observables (the hydrogenic spectral wavelengths) are described by a single free parameter (the Rydberg constant).

*Since this is a Conference on neutrino physics, I will take the standard model to contain the usual minimal field content (no right handed neutrinos), but allow for dimension five operators of the form $\ell_i\ell_j HH$ to generate neutrino masses. Here $\ell_i$ is a lepton doublet and $H$ the Higgs. The counting includes three phases in the leptonic mixing matrix, but ignores $\bar{\theta}$.

Twenty eight years after this incredibly successful formula was written down, it played a dominant role in leading Bohr to his atomic model in which he could compute the Rydberg, $\mathcal{R} = 2\pi^2 m Z^2 e^4/h^3$. This crowning achievement was the birth of the quantum theory of atomic structure. It may will be that a predictive scheme for fermion masses, depending on far fewer than the 22 flavor couplings of the standard model, is a prerequisite for the development of a fundamental theory of fermion masses.

Progress has been made in reducing the number of parameters in the gauge sector. In grand unified theories (GUTs) the three independent gauge couplings become related [1]. This implies predictions for the weak scale gauge couplings $g_i(M_W)$, i = 1...3, of the form [2]:

$$g_i(M_W) = C_i\ \eta_i\ g_G \tag{1}$$

where $g_G$ is the GUT gauge coupling, $C_i$ are numerical group theory constants and the $\eta_i$, which are radiative corrections computed with the renormalization group, depend on mass ratios such as $M_W/M_G$, where $M_G$ is the GUT scale. Let me define the number of predictions of any sector of a theory by

$$\text{Predictions} = (\text{Independent observables}) - (\text{Free parameters})\,. \tag{2}$$

How many predictions occur in the gauge sector of GUTs? While the $C_i$ are purely numerical group theory constants, the $\eta_i$ depend on ratios of various mass scales. If there are two or more mass ratios on which the $\eta_i$ depend, then there are no predictions: together with $g_G$ there are three or more free parameters for the three observables $g_i$. The only hope is for the maximally predictive possibility that the $\eta_i$ depend only on the single mass ratio $M_W/M_G$, in which case there will be one prediction, usually chosen to be the weak mixing angle $\sin^2\theta$.

There are many possible GUTs which have no new scale other than $M_G$. How many different predictions for $\sin^2\theta$ can they give? The answer is just two: .211 without supersymmetry and .233 with weak-scale supersymmetry [3]. What is the accuracy of these predictions? There are GUT/supersymmetric model-dependent corrections which are typically around .002 [4]. Since the standard model is *consistent* with any value of $\sin^2\theta$ from 0 to 1, I think that it is very significant that the minimal supersymmetric scheme predicts precisely the experimental value of .233 ± .001. Many people shrug this off, but let's face it, it *is* significant.

The successful prediction of $\sin^2\theta$ resulted from requiring a larger symmetry than dictated by experiment. It is well known that this same enlargement of the gauge symmetry can also yield predictions in the flavor sector. Flavor observables at the weak scale, $F_a(M_W)$, can be given by predictions of the form

$$F_a(M_W) = C_a\,\eta_a \tag{3}$$

where $C_a$ are again purely numerical group theory constants, while the dynamical factors $\eta_a$ depend on several parameters, including $\alpha_s$ and mass ratios such as $M_W/M_G$. The first such prediction was for $m_b/m_\tau$[5]. However, we now know that in this case $\eta_a$ depends on $m_t$ and $\alpha_s$, leading to uncertainties of 30% and 10% respectively. Hence this successful prediction is much less significant than $\sin^2\theta$, especially as one successful prediction out of so many flavor parameters is not convincing.

Recently Savas Dimopoulos, Stuart Raby and I have constructed a scheme with only 8 independent flavor parameters [6]: we predict 14 of the 22 quark and lepton masses and mixings.† Our scheme is based on two sets of symmetries: an S0(10) supersymmetric gauge symmetry and the family symmetry of Georgi and Jarlskog [7]. We have used these two types of symmetries, GUT and family, because they are the only known tools available for obtaining predictive flavor theories, other than just phenomenological guesswork. Others have obtained predictions using GUT and family symmetries. In particular Harvey, Ramond and Reiss [8] studied the Georgi-Jarlskog family symmetry in the context of S0(10). However, their theory had a complicated Higgs sector so that only four flavor predictions of the type of equation (3) could be made, and furthermore the $\eta_a$ were not calculated. Our scheme is by far the most predictive that has ever been written down. It may not be *the* most predictive, and it may not be correct, but it *can* be tested.

What is the level of accuracy of our predictions? This is determined by the experimental uncertainties of the inputs used to determine our free parameters.

†In fact since the theory is supersymmetric there is an extra flavor parameter: $\tan\beta$, the ratio of vevs. We predict 14 of the 23 total flavor parameters.

For example we use $\sin\theta_c$, $m_c$ and $m_u/m_d$ as inputs, and these are known only to 1%, 10% and 30% respectively. Hence our predictions have accuracies which are typically 1-30% depending on which inputs they are sensitive to.

Six of our 14 predictions occur in the charged fermion sector. Our scheme may well be probed via the top mass. We are unable to give a very precise determination of $m_t$ because it depends on imputs $\alpha_s$, $m_c$ and $V_{cb}$ which all have 0(10%) uncertainties. However, we will need to rethink if $m_t$ is outside the range $165 \pm 25$ GeV. A crucial and definitive test of our scheme will occur if the angles $\alpha, \beta, \gamma$ of the unitarity triangle of the $KM$ matrix are accurately determined through CP violating decays of neutral B mesons at a B factory.

The neutrino masses and mixings are completely determined in terms of the charged fermion masses and mixings, with the one exception of the overall mass scale of the neutrino masses. We do not know any way of predicting this scale. As far as we know, this is the first time anything about the neutrino masses and mixings has been predicted using the known quark and charged lepton masses and mixings as input. We predict every element of the $3 \times 3$ lepton mixing matrix, and both neutrino mass ratios $m_{\nu_\tau}/m_{\nu_\mu}$ and $m_{\nu_\mu}/m_{\nu_e}$. In constructing our scheme for neutrino masses we have made several assumptions, each motivated by the desire to obtain a maximum number of predictions. The assumptions concern our choice of symmetries and how these symmetries are broken.

Our predictions for neutrino masses and mixings are shown in the table. The $3 \times 3$ mixing matrix has been approximated by rotations $\theta_{e\mu}, \theta_{\mu\tau}$ and $\theta_{e\tau}$, and we have not shown the effects from CP violation. There are two versions of our scheme, which we label I and II.

In model I $\theta_{\mu\tau}$ is sufficiently large that the Fermilab E531 results imply that $m_{\nu_\tau} \leq 2.5$ eV. This means that it is unlikely that planned neutrino oscillation experiments will be able to detect the neutrino masses of this model. Although the neutrinos are all too light to be the dark matter, the value of $\theta_{e\mu}$ does allow a resolution of the Cl, Kamiokande and Gallex solar neutrino experiments by MSW oscillations, at the 90 % confidence level. Our value of $\theta_{e\mu}$ implies that, as the error bars on the Ga experiments are decreased, a low number of about $50 \pm 10$ SNUs will result. To test this region of parameter space in the lab would require a long baseline $\nu_\mu \nu_\tau$ oscillation search with sensitivity to smaller mixing angles than the present proposals.

In model II $\theta_{\mu\tau}$ is just beyond the E531 limits. This is very exciting because it means that the upcoming $\nu_\mu\nu_\tau$ oscillation searches [9] will probe a large range of $\Delta m^2$ in this model. In particular if the $\nu_\tau$ makes a significant contribution to the dark matter in the universe, then O(50) events will be seen and $\sin^2 2\theta_{\mu\tau}$ will be determined to be within 15% of $3.10^{-3}$.

Grand unified theories are only interesting if they are testable. The successful weak mixing angle prediction is the first crucial step, but is not sufficient. Observation of proton decay could yield important information about GUT scale physics, but is unlikely to provide a significant numerical test. If the flavor structure of GUTs is simple enough, there can be very many predictions of quark and lepton masses and mixings. This may be the only real hope for definitive progress on GUTs.

| | I | II |
|---|---|---|
| $\theta_{e\mu}$ | $(6.5 \pm .3)10^{-2}$ | $.15 \pm .04$ |
| $\theta_{\mu\tau}$ | $.081 \pm .008$ | $-.027 \pm .003$ |
| $\theta_{e\tau}$ | $(5.7 \pm .6)10^{-4}$ | $(1.9 \pm 0.2)10^{-4}$ |
| $m_{\nu_\tau}/m_{\nu_\mu}$ | $208 \pm 42$ | $1870 \pm 370$ |
| $m_{\nu_\mu}/m_{\nu_e}$ | $(3.1 \pm 1.0)10^3$ | $38 \pm 12$ |
| $m_{\nu_\tau max}$ | 2.5 eV | 710 eV |

**Table**

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