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SO (10) SUSY GUTs AND FERMION MASSES

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SO(10) SUSY GUTs and Fermion Masses

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Abstract: In this talk * I summarize published work on a systematic operator analysis for fermion masses in a class of effective supersymmetric SO(10) GUTs[1] †. Given a minimal set of four operators at M_G , we have just 6 parameters in the fermion mass matrices. We thus make 8 predictions for the 14 low energy observables (9 quark and charged lepton masses, 4 quark mixing angles and $\tan \beta$). Several models, i.e. particular sets of dominant operators, are in quantitative agreement with the low energy data. In the second half of the talk I discuss the necessary ingredients for an SO(10) GUT valid below the Planck (or string) scale which reproduces one of our models. ‡ This complete GUT should still be interpreted as an effective field theory, i.e. perhaps the low energy limit of a string theory.

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†This work is in collaboration with G. Anderson, S. Dimopoulos, L.J. Hall, and G. Starkman.

‡These are preliminary results of work in progress with Lawrence Hall.

1 Introduction

The Standard Model[SM] provides an excellent description of Nature. Myriads of experimental tests have to date found no inconsistency.

Eighteen phenomenological parameters in the SM are necessary to fit all the low energy data[LED]. These parameters are not equally well known. $\alpha, \sin^2(\theta_W), m_e, m_\mu, m_\tau$ and M_Z are all known to better than 1% accuracy. On the otherhand, m_c, m_b, V_{us} are known to between 1% and 5% accuracy, and $\alpha_s(M_Z), m_u, m_d, m_s, m_t, V_{cb}, V_{ub}/V_{cb}, m_{Higgs}$ and the Jarlskog invariant measure of CP violation J are not known to better than 10% accuracy. One of the main goals of the experimental high energy physics program in the next 5 to 10 years will be to reduce these uncertainties. In addition, theoretical advances in heavy quark physics and lattice gauge calculations will reduce the theoretical uncertainties inherent in these parameters. Already the theoretical uncertainties in the determination of V_{cb} from inclusive B decays are thought to be as low as 5%[2]. Moreover, lattice calculations are providing additional determinations of $\alpha_s(M_Z)$ and heavy quark masses[3].

Accurate knowledge of these 18 parameters is important. They are clearly not a random set of numbers. There are distinct patterns which can, if we are fortunate, guide us towards a fundamental theory which predicts some (if not all) of these parameters. Conversely these 18 parameters are the LED which will test any such theory. Note, that 13 of these parameters are in the fermion sector. So, if we are to make progress, we must necessarily attack the problem of fermion masses.

In the program discussed in this talk, we define a procedure for finding the dominant operator set reproducing the low energy data. In the minimal operator sets we have just six parameters in the fermion mass matrices. We use the six best known low energy parameters as input to fix these six unknowns and then predict the rest. These theories are supersymmetric[SUSY] SO(10) grand unified theories[GUTs]. In the next two sections I want to briefly motivate these choices.

2 Why SUSY GUTs?

The answer has two parts. First why SUSY?

1. SUSY can provide at least a technical understanding to the solution of the gauge hierarchy problem, namely, why the ratio $M_W/P_{Planck} \sim 10^{-16}$ is so small[4].
2. It is also a very beautiful symmetry unifying states of different spins[5]. Clearly many of the great successes of particle physics in the last 30 years have involved the discovery of one new symmetry of Nature after the next. In fact all the forces of the SM can be described in terms of local gauge symmetries (local SUSY is supergravity[6]).

Now, why GUTs?

1. Once more this is a beautiful symmetry which unifies the known forces of the SM and also the particles - quarks and leptons[7]. The first consequence of this unification is that electric charge is quantized in the correct way. This success can also be claimed by string theorists, without utilizing a GUT.
2. More importantly, all GUTs make predictions.
 - (a) Given two gauge couplings measured at low energies, the third is predicted[8]. Thus using the experimentally measured values of α and $\sin^2\theta_W$, the strong coupling $\alpha_s(M_Z)$ is fixed. This prediction is in good agreement with SUSY GUTs[9].
 - (b) Nucleon decay is to be expected and in SUSY GUTs the dominant decay modes of the proton are $p \rightarrow K^+\bar{\nu}$ and $p \rightarrow K^0\mu^+$ [10].

In summary, only in SUSY GUTs are these predictions still consistent with the low energy data.

Note, as a direct consequence of a symmetry, in this case a SUSY GUT, we have reduced the number of fundamental parameters in the gauge sector of the theory by 1. Consequently, we have gained one prediction and this prediction agrees remarkably well with the LED[9]. This is a great success. We also have the aesthetic feature of a SUSY GUT DESERT, i.e. once the sparticles and gauginos are observed there is no new physics until the GUT scale $M_G \sim 10^{16}$ GeV. Thus there is a huge discovery potential since now the LED can shed light directly on the physics at M_G .

3 Why SO(10)?

There are two reasons for using SO(10).

1. It is the smallest group in which all the fermions in one family fit into one irreducible representation, i.e. the **16**. Only one additional state needs to be added to complete the multiplet and that is a right-handed neutrino. In larger gauge groups, more as yet unobserved states must be introduced to obtain complete multiplets. Thus we take $\mathbf{16}_i \supset \{U_i, D_i, E_i, \nu_i\}, i = 1, 2, 3$ for the 3 families with the third family taken to be the heaviest. *Since SO(10) Clebschs can now relate U, D, E and ν mass matrices, we can in principle reduce the number of fundamental parameters in the fermion sector of the theory.* We return to this point below.
2. In any SUSY theory there are necessarily two higgs doublets – H_u and H_d . Both these states fit into the **10** of SO(10) and thus their couplings to up and down type fermions are also given by a Clebsch. There are however six additional states in the **10** which transform as a $\mathbf{3} + \bar{\mathbf{3}}$ under color. These states contribute to proton decay and must thus be heavy. The problem of giving these color triplet states large mass of order M_G while keeping the doublets light is sometimes called the second gauge hierarchy

problem. This problem has a natural solution in $SO(10)$ which we discuss later[11].

Note that the gauge group $SO(10)$ has to be spontaneously broken to the gauge group of the SM - $SU(3) \times SU(2) \times U(1)$. This GUT scale breaking can be accomplished by a set of states including $\{ \mathbf{45}, \mathbf{16}, \overline{\mathbf{16}}, \dots \}$. The $\mathbf{45}$ (the adjoint representation) enters into our construction of effective fermion mass operators, thus I will discuss it in more detail in the next section.

I promised to return to the possibility of reducing the number of fundamental parameters in the fermion sector of the theory. Recall that there are 13 such parameters. Using symmetry arguments we can now express the matrices D, E , and ν in terms of one complex 3×3 matrix, U . Unfortunately, this is not sufficient to solve our problem. There are 18 arbitrary parameters in this one matrix. In order to reduce the number of fundamental parameters we must have zeros in this matrix. We thus need new *family symmetries* to enforce these zeros.

4 The Big Picture

Let us consider the big picture(see Fig. 1). Our low energy observer measures the physics at the electroweak scale and perhaps an order of magnitude above. Once the SUSY threshold is crossed we have direct access to the effective theory at M_G , the scale where the 3 gauge couplings meet. Of course the GUT scale $M_G \sim 10^{16}$ GeV is still one or two orders of magnitude below some more fundamental scale such as the Planck or string scales (which we shall refer to as M). Between M and M_G there may be some substructure. In fact, we may be able to infer this substructure by studying fermion masses.

In our analysis we assume that the theory below the scale M is described by a SUSY $SO(10)$ GUT. Between M_G and M , at a scale v_{10} , we assume that the gauge group $SO(10)$ is broken spontaneously

to $SU(5)$. This can occur due to the vacuum expectation value of an adjoint scalar in the X direction (i.e. corresponding to the $U(1)$ which commutes with $SU(5)$) and the expectation values of a 16 and a $\overline{16}$ (denoted by Ψ and $\overline{\Psi}$ respectively). Then $SU(5)$ is broken at the scale $v_5 = M_G$ to the SM gauge group. This latter breaking can be done by different adjoints (45) in the Y , $B-L$ or T_{3R} directions.

Why consider 4 particular breaking directions for the 45 and no others? The X and Y directions are orthogonal and span the two dimensional space of $U(1)$ subgroups of $SO(10)$ which commute with the SM. $B-L$ and T_{3R} are also orthogonal and they span the same subspace. Nevertheless we consider these four possible breaking directions and these are the *only directions* which will enter the effective operators for fermion masses. Why not allow the X and Y directions or any continuous rotation of them in this 2d subspace of $U(1)$ directions. The answer is that there are good dynamical arguments for assuming that these and only these directions are important. The X direction breaks $SO(10)$ to an intermediate $SU(5)$ subgroup and it is reasonable to assume that this occurs at a scale $v_{10} \geq v_5$. Whether v_{10} is greater than v_5 or equal will be determined by the LED. The $B-L$ direction is required for other reasons. Recall the color triplet higgs in the 10 which must necessarily receive large mass. As shown by Dimopoulos and Wilczek[11], this doublet-triplet splitting can naturally occur by introducing a $10\ 45\ 10$ type coupling in the superspace potential. Note that the higgs triplets carry non-vanishing $B-L$ charge while the doublets carry zero charge. Thus when the 45 gets a vacuum expectation value[vev] in the $B-L$ direction it will give mass to the color triplet higgs at v_5 and leave the doublets massless. Thus in any $SO(10)$ model which solves this second hierarchy problem, there must be a 45 pointing in the $B-L$ direction. We thus allow for all 4 possible breaking vevs — X , Y , $B-L$ and T_{3R} . Furthermore we believe this choice is “natural” since we know how to construct theories which have these directions as vacua without having to tune any parameters.

Our fermion mass operators have dimension ≥ 4 . *From where would these higher dimension operators come?* Note that by measuring the LED we directly probe the physics in some effective theory at M_G . This effective theory can, and likely will, include operators with dimension greater than 4. Consider, for example, our big picture looking down from above. String theories are very fundamental. They can in principle describe physics at all scales. Given a particular string vacuum, one can obtain an effective field theory valid below the string scale M . The massless sector can include the gauge bosons of $SO(10)$ with scalars in the 10, 45 or even 54 dimensional representations. In addition, we require 3 families of fermions in the 16. Of course, in a string context when one says that there are 3 families of fermions what is typically meant is that there are 3 more 16s than $\overline{16}$ s. The extra $16 + \overline{16}$ pairs are assumed to get mass at a scale $\geq M_G$, since there is no symmetry which prevents this. When these states are integrated out in order to define the effective field theory valid below M_G they will typically generate higher dimension operators.

Consider the tree diagram in Fig. 2. The state 16_2 contains the second generation of fermions. It has off-diagonal couplings to heavy fermions $16_i, \overline{16}_i, i = 1, 2$. If, for example, the vev $45_X > M_G$ then it will be responsible for the dominant contribution to the mass of the states labelled 1 and 2. These two states however mix by smaller off-diagonal mass terms given by the vev 45_{B-L} or the singlet vev (or mass term) denoted by M_G . When these heavy states are integrated out one generates to leading order the operator $O_{22} = 16_2 10 \frac{M_G 45_{B-L}}{(45_X)^2} 16_2$ plus calculable corrections of order $(v_5/v_{10})^2$. *It is operators of this type (which can be obtained by implicitly integrating out heavy 16's) which we use to define our operator basis for fermion masses in the effective theory at M_G .*

5 Operator Basis for Fermion Masses at M_G

Let us now consider the **general operator basis for fermion masses**. We include operators of the form

$$O_{ij} = 16_i (\cdots)_n 10 (\cdots)_m 16_j$$

where

$$(\cdots)_n = \frac{M_G^k 45_{k+1} \cdots 45_n}{M_P^l 45_X^{n-l}}$$

and the 45 vevs in the numerator can be in any of the 4 directions, $X, Y, B - L, T_{3R}$ discussed earlier.

It is trivial to evaluate the Clebsch-Gordon coefficients associated with any particular operator since the matrices $X, Y, B - L, T_{3R}$ are diagonal. Their eigenvalues on the fermion states are given in Table 1.

6 Dynamic Principles

Now consider the dynamical principles which guide us towards a theory of fermion masses.

0. At zeroth order, we work in the context of a SUSY GUT with the MSSM below M_G .
1. We use $SO(10)$ as the GUT symmetry with three families of fermions $\{16_i \ i = 1, 2, 3\}$ and the minimal electroweak Higgs content in one 10. $SO(10)$ symmetry relations allow us to reduce the number of fundamental parameters.
2. We assume that there are also family symmetries which enforce zeros of the mass matrix, although we will not specify these symmetries at this time. As we will make clear in section 12, these symmetries will be realized at the level of the fundamental theory defined below M .

Table 1. Quantum numbers of the four 45 vevs on fermion states.

Note, if u denotes a left-handed up quark, then \bar{u} denotes a left-handed charge conjugate up quark.

	X	Y	B - L	T _{3R}
u	1	1/3	1	0
\bar{u}	1	-4/3	-1	-1/2
d	1	1/3	1	0
\bar{d}	-3	2/3	-1	1/2
e	-3	-1	-3	0
\bar{e}	1	2	3	1/2
ν	-3	-1	-3	0
$\bar{\nu}$	5	0	3	-1/2

3. Only the third generation obtains mass via a dimension 4 operator. The fermionic sector of the Lagrangian thus contains the term $A O_{33} \equiv A 16_3 10 16_3$. This term gives mass to t , b and τ . It results in the symmetry relation — $\lambda_t = \lambda_b = \lambda_\tau \equiv A$ at M_G . This relation has been studied before by Ananthanarayan, Lazarides and Shafi[12] and using m_b and m_τ as input it leads to reasonable results for m_t and $\tan \beta$.
4. All other masses come from operators with dimension > 4 . As a consequence, the family hierarchy is related to the ratio of scales above M_G .
5. [Predictivity requirement] We demand the minimal set of effective fermion mass operators at M_G consistent with the LED.

7 Systematic Search

Our goal is to find the *minimal* set of fermion mass operators consistent with the LED. With any given operator set one can evaluate the fermion mass matrices for up and down quarks and charged leptons. One obtains relations between mixing angles and ratios of fermion masses which can be compared with the data. It is easy to show, however, without any detailed calculations that the minimal operator set consistent with the LED is given by

$$O_{33} + O_{23} + O_{22} + O_{12} \quad - - - \text{“22” texture}$$

or

$$O_{33} + O_{23} + O'_{23} + O_{12} \quad - - - \text{“23’” texture}$$

It is clear that at least 3 operators are needed to give non-vanishing and unequal masses to all charged fermions, i.e. $\det(m_a) \neq 0$ for $a = u, d, e$. That the operators must be in the [33, 23 and 12] slots is not as obvious but is not difficult to show. It is then easy to show that 4 operators are required in order to have CP violation. This is because, with only 3 SO(10) invariant operators, we can redefine the phases of the three 16s of fermions to remove the three arbitrary phases. With one more operator, there is one additional phase which cannot be removed. A corollary of this observation is that this minimal operator set results in just 5 arbitrary parameters in the Yukawa matrices of all fermions, 4 magnitudes and one phase*. This is the minimal parameter set which can be obtained without solving the remaining problems of the fermion mass hierarchy, one overall real mixing angle and a CP violating phase. We should point out however that the problem of understanding the fermion mass hierarchy and mixing has been rephrased as the problem of understanding the hierarchy of scales above M_G .

*This is two fewer parameters than was necessary in our previous analysis (see [13])

From now on I will just consider models with “22” texture. This is because they can reproduce the observed hierarchy of fermion masses without fine-tuning[†]. Models with “22” texture give the following Yukawa matrices at M_G (with electroweak doublet fields on the right)

$$\lambda_a = \begin{pmatrix} 0 & z'_a C & 0 \\ z_a C & y_a E e^{i\phi} & x'_a B \\ 0 & x_a B & A \end{pmatrix}$$

with the subscript $a = \{u, d, e\}$. The constants $x_a, x'_a, y_a, z_a, z'_a$ are Clebschs which can be determined once the 3 operators (O_{23}, O_{22}, O_{12}) are specified. Recall, we have taken $O_{33} = A 16_3 10 16_3$, which is why the Clebsch in the 33 term is independent of a . Finally, combining the Yukawa matrices with the Higgs vevs to find the fermion mass matrices we have 6 arbitrary parameters given by A, B, C, E, ϕ and $\tan \beta$ describing 14 observables. We thus obtain 8 predictions. We shall use the best known parameters, $m_e, m_\mu, m_\tau, m_c, m_b, |V_{cd}|$, as input to fix the 6 unknowns. We then predict the values of $m_u, m_d, m_s, m_t, \tan \beta, |V_{cb}|, |V_{ub}|$ and J .

Note: since the predictions are correlated, our analysis would be much improved if we minimized some χ^2 distribution and obtained a best fit to the data. Unfortunately this has not yet been done. In the paper however we do include some tables (see for example Table 4 in this talk) which give all the predictions for a particular set of input parameters.

8 Results

The results for the 3rd generation are given in Fig. 3. Note that since the parameter A is much bigger than the others we can essentially

[†]For more details on this point, see section 9 below or refer to [1].

treat the 3rd generation independently. The small corrections, of order $(B/A)^2$, are however included in the complete analysis. We find the pole mass for the top quark $M_t = 180 \pm 15$ GeV and $\tan\beta = 56 \pm 6$ where the uncertainties result from variations of our input values of the \overline{MS} running mass $m_b(m_b) = 4.25 \pm 0.15$ and $\alpha_s(M_Z)$ taking values .110 – .126. We used two loop RG equations for the MSSM from M_G to M_{SUSY} ; introduced a universal SUSY threshold at $M_{SUSY} = 180$ GeV with 3 loop QCD and 2 loop QED RG equations below M_{SUSY} . The variation in the value of α_s was included to indicate the sensitivity of our results to threshold corrections which are necessarily present at the weak and GUT scales. In particular, we chose to vary $\alpha_s(M_Z)$ by letting $\alpha_3(M_G)$ take on slightly different values than $\alpha_1(M_G) = \alpha_2(M_G) = \alpha_G$.

The following set of operators passed a straightforward but coarse grained search discussed in detail in the paper[1]. They include the diagonal dimension four coupling of the third generation –

$$O_{33} = 16_3 \ 10 \ 16_3$$

The six possible O_{22} operators –

$$O_{22} =$$

$$16_2 \ \frac{45_X}{M} \ 10 \ \frac{45_{B-L}}{45_X} \ 16_2 \quad (a)$$

$$16_2 \ \frac{M_G}{45_X} \ 10 \ \frac{45_{B-L}}{M} \ 16_2 \quad (b)$$

$$16_2 \ \frac{45_X}{M} \ 10 \ \frac{45_{B-L}}{M} \ 16_2 \quad (c)$$

$$16_2 \ 10 \ \frac{45_{B-L}}{45_X} \ 16_2 \quad (d)$$

$$16_2 \ 10 \ \frac{45_X \ 45_{B-L}}{M^2} \ 16_2 \quad (e)$$

$$16_2 \ 10 \ \frac{45_{B-L} \ M_G}{45_X^2} \ 16_2 \quad (f)$$

Note: in all cases the Clebschs y_i (defined by O_{22} above) satisfy

$$y_u : y_d : y_e = 0 : 1 : 3.$$

This is the form familiar from the Georgi-Jarlskog texture[14]. Thus all six of these operators lead to *identical* low energy predictions.

Finally there is a unique operator O_{12} consistent with the LED -

$$O_{12} = 16_1 \left(\frac{45_X}{M} \right)^3 10 \left(\frac{45_X}{M} \right)^3 16_2$$

The operator O_{23} determines the KM element V_{cb} by the relation

$$V_{cb} = \chi \sqrt{\frac{m_c}{m_t}} \times (RG factors)$$

where the Clebsch combination χ is given by

$$\chi \equiv \frac{|x_u - x_d|}{\sqrt{|x_u x'_u|}}$$

m_c is input, m_t has already been determined and the renormalization group[RG] factors are calculable. Demanding the experimental constraint $V_{cb} < .054$ we find the constraint $\chi < 1$. A search of all operators of dimension 5 and 6 results in the 9 operators given below. Note that there only three different values of $\chi = 2/3, 5/6, 8/9$ -

$$O_{23} =$$

$$\chi = 2/3$$

$$(1) 16_2 \frac{45_Y}{M} 10 \frac{M_G}{45_X} 16_3$$

$$(2) 16_2 \frac{45_Y}{M} 10 \frac{45_{B-L}}{45_X} 16_3$$

$$(3) 16_2 \frac{45_Y}{45_X} 10 \frac{M_G}{45_X} 16_3$$

$$(4) 16_2 \frac{45_Y}{45_X} 10 \frac{45_{B-L}}{45_X} 16_3$$

$$\chi = 5/6$$

$$(5) 16_2 \frac{45_Y}{M} 10 \frac{45_Y}{45_X} 16_3$$

$$(6) 16_2 \frac{45_Y}{45_X} 10 \frac{45_Y}{45_X} 16_3$$

$$\chi = 8/9$$

$$(7) 16_2 10 \frac{M_G^2}{45_X^2} 16_3$$

$$(8) 16_2 10 \frac{45_{B-L} M_G}{45_X^2} 16_3$$

$$(9) 16_2 10 \frac{45_{B-L}^2}{45_X^2} 16_3$$

We label the operators (1) - (9), and we use these numbers also to denote the corresponding models. *Note, all the operators have the vev 45_X in the denominator. This can only occur if $v_{10} > M_G$.*

At this point, there are no more simple criteria to reduce the number of models further. We have thus performed a numerical RG analysis on each of the 9 models (represented by the 9 distinct operators O_{23} with their calculable Clebschs $x_a, x'_a, a = u, d, e$ along with the unique set of Clebschs determined by the operators O_{33}, O_{22} and O_{12}). We then iteratively fit the 6 arbitrary parameters to the six low energy inputs and evaluate the predictions for each model as a function of the input parameters. The results of this analysis are given in Figs. (4 - 10).

Let me make a few comments. Light quark masses (u,d,s) are \overline{MS} masses evaluated at 1 GeV while heavy quark masses (c,b) are evaluated at (m_c, m_b) respectively. Finally, the top quark mass in Fig. 3 is the pole mass. Figs. 4 and 5 are self evident. In Fig. 6, we show the correlations for two of our predictions. The ellipse in the m_s/m_d vs. m_u/m_d plane is the allowed region from chiral Lagrangian analysis[15]. One sees that we favor lower values of $\alpha_s(M_Z)$. For each

fixed value of $\alpha_s(M_Z)$, there are 5 vertical line segments in the V_{cb} vs. m_u/m_d plane. Each vertical line segment represents a range of values for m_c (with m_c increasing moving up) and the different line segments represent different values of m_b (with m_b increasing moving to the left). In Figure 9 we test our agreement with the observed CP violation in the K system. The experimentally determined value of $\epsilon_K = 2.26 \times 10^{-3}$. Theoretically it is given by an expression of the form $B_K \times \{m_t, V_{ts}, \dots\}$. B_K is the so-called Bag constant which has been determined by lattice calculations to be in the range $B_K = .7 \pm .2$ [16]. In Fig. 9 we have used our predictions for fermion masses and mixing angles as input, along with the experimental value for ϵ_K , and fixed B_K for the 9 different models. One sees that model 4 is inconsistent with the lattice data. In Fig. 10 we present the predictions for each model, for the CP violating angles which can be measured in B decays. The interior of the “whale” is the range of parameters consistent with the SM found by Nir and Sarid[17] and the error bars represent the accuracy expected from a B factory.

Note that model 4 appears to give too little CP violation and model 9 has uncomfortably large values of V_{cb} . Thus these models are presently disfavored by the data. I will thus focus on model 6 in the second part of this talk.

9 Summary

We have performed a systematic operator analysis of fermion masses in an effective SUSY SO(10) GUT. We use the LED to lead us to the theory. Presently there are 3 models (models 4, 6 & 9) with “22” texture which agree best with the LED, although as mentioned above model 6 is favored. In all cases we used the values of α and $\sin^2 \theta_W$ (modulo threshold corrections) to fix $\alpha_s(M_Z)$.

Table 2 shows the virtue of the “22” texture. In the first column are the four operators. In the 2nd and 3rd columns are the parameters

Table 2. Virtue of “22” texture.

Operator	Parameters	Input	Predictions
O_{33}	$\tan \beta$ A	b τ	t $\tan \beta$
O_{23}	B	c	V_{cb}
O_{22}	E	μ	s
O_{12}	C ϕ	e V_{us}	u d $\frac{V_{ub}}{V_{cb}}$ J

in the mass matrix relevant for that particular operator and the input parameters which are used to fix these parameters. Finally the 4th column contains the predictions obtained at each level. One sees that each family is most sensitive to a different operator[†].

Consider the theoretical uncertainties inherent in our analysis.

1. The experimentally determined values of m_b , m_c , and $\alpha_s(M_Z)$ are all subject to strong interaction uncertainties of QCD. In addition, the predicted value of $\alpha_s(M_Z)$ from GUTs is subject to threshold corrections at M_W which can only be calculated once the SUSY spectrum is known and at M_G which requires knowledge of the theory above M_G . We have included these uncertainties (albeit crudely) explicitly in our analysis.
2. In the large $\tan \beta$ regime in which we work there may be large SUSY loop corrections which will affect our results. The finite corrections to the b and τ Yukawa couplings have been evaluated[18, 19]. They depend on ratios of soft SUSY breaking parameters and are significant in certain regions of parameter space[‡]. In par-

[†]This property is not true of “23” textures.

[‡]There is a small range of parameter space in which our results are unchanged[18]. This requires threshold corrections at M_G which distinguish the two Higgs scalars.

ticular it has been shown that the top quark mass can be reduced by as much as 30%. Note that although the prediction of Fig. 3 may no longer be valid, there is still necessarily a prediction for the top quark mass. It is now however sensitive to the details of the sparticle spectrum and to the process of radiative electroweak symmetry breaking[20]. This means that the observed top quark mass can now be used to set limits on the sparticle spectrum. This analysis has not been done. Moreover, there are also similar corrections to the Yukawa couplings for the s and d quarks and for e and μ . These corrections are expected to affect the predictions for V_{cb}, m_s, m_u, m_d . It will be interesting to see the results of this analysis.

3. The top, bottom and τ Yukawa couplings can receive threshold corrections at M_G . We have not studied the sensitivity to these corrections.
4. Other operators could in principle be added to our effective theory at M_G . They might have a dynamical origin. We have assumed that, if there, they are subdominant. Two different origins for these operators can be imagined. The first is field theoretic. The operators we use would only be the leading terms in a power series expansion when defining an effective theory at M_G by integrating out heavier states. The corrections to these operators are expected to be about 10%. We may also be sensitive to what has commonly been referred to as Planck slop[21], operators suppressed by some power of the Planck (or string) scale M . In fact the operator O_{12} may be thought of as such. The question is why aren't our results for the first and perhaps the second generation, hopelessly sensitive to this unknown physics? This question will be addressed in the next section.

10 Where are we going?

In the first half of Table 3 I give a brief summary of the good and bad features of the effective SUSY GUT discussed earlier. Several models were found with just four operators at M_G which successfully fit the low energy data. If we add up all the necessary parameters needed in these models we find just 12. This should be compared to the SM with 18 or the MSSM with 21. Thus these theories, minimal effective SUSY GUTs[MESG], are doing quite well. Of course the bad features of the MESG is that it is not a fundamental theory. In particular there are no symmetries which prevent additional higher dimension operators to spoil our results. Neither are we able to calculate threshold corrections, even in principle, at M_G .

It is for these reasons that we need to be able to take the MESG which best describes the LED and use it to define an effective field theory valid at scales $\leq M$. The good and bad features of the resulting theory are listed in the second half of Table 3.

- In the effective field theory below M we must incorporate the *symmetries* which guarantee that we reproduce the MESG with no additional operators[†] Moreover, the necessary combination of discrete, $U(1)$ or R symmetries may be powerful enough to restrict the appearance of Planck slop.
- Finally, the *GUT symmetry breaking* sector must resolve the problems of natural doublet-triplet splitting (the second hierarchy problem), the μ problem, and give predictions for proton decay, neutrino masses and calculable threshold corrections at M_G .
- On the bad side, it is still not a fundamental theory and there may not be a unique extension of the MESG to higher energies.

[†]This statement excludes the unavoidable higher order field theoretic corrections to the MESG which are, in principle, calculable.

Table 3.

	Good	Bad
Eff. F.T. $\leq M_G$	<u>4 op's. at $M_G \Rightarrow \text{LED}$</u> 5 para's. \Rightarrow 13 observables + 2 gauge para's. \Rightarrow 3 observables <u>+ 5 soft SUSY</u> breaking para's. $\Rightarrow \dots$ Total 12 parameters	<u>Not fundamental</u> <u>No symmetry</u> \Rightarrow Why these operators? (F.T. + Planck slop) <u>Threshold corrections?</u>
Eff. F.T. $\leq M$ $M = M_{\text{string}}$ or M_{Planck}	<u>Symmetry</u> i) gives Eff. F.T. $\leq M_G$ + corrections ii) constrains other operators <u>GUT symmetry breaking</u> i) d - t splitting ii) μ problem iii) proton decay iv) neutrino masses v) threshold corrections at M_G	<u>Not fundamental</u> <u>Not unique?</u>

11 String Threshold at M_S

Upon constructing the effective field theory $\leq M_S$, we will have determined the necessary SO(10) states, symmetries and couplings which reproduce our fermion mass relations. This theory can be the starting point for constructing a realistic string model. String model builders could try to obtain a string vacuum with a massless spectra which agrees with ours. Of course, once the states are found the string will determine the symmetries and couplings of the theory. It is hoped that in this way a *fundamental* theory of Nature can be found. Recent

work in this direction has been reported in this workshop by Joseph Lykken[22]. He has been able to obtain string theories with $SO(10)$, three families plus additional $16 + \overline{16}$ pairs, 45's, 10's and even some 54 dimensional representations. One of the first results from this approach is the fact that only one of the three families has diagonal couplings to the 10, just as we have assumed.

12 Constructing the Effective Field Theory below M_S

In this section I will discuss some preliminary results obtained in collaboration with Lawrence Hall. I will describe the necessary ingredients for constructing model 6. Some very general results from this exercise are already apparent.

- *States* We have constructed a SUSY GUT which includes all the states necessary for GUT symmetry breaking and also for generating the 45 vevs in the desired directions. A minimal representation content below M_S includes $54s + 45s + 3\ 16s + n(\overline{16} + 16)$ pairs + 2 10s.
- *Symmetry* In order to retain sufficient symmetry the superspace potential in the visible sector W necessarily has a number of flat directions. In particular the scales v_5 and v_{10} can only be determined when soft SUSY breaking and quantum corrections are included. An auxiliary consequence is that the vev of W_{visible} vanishes in the supersymmetric limit.
- *Couplings* As an example of the new physics which results from this analysis I will show how a solution to the μ problem, the ratio λ_5/λ_t and proton decay are inter-related.

In Table 4 are presented the predictions for Model 6 for particular values of the input parameters.

Table 4: Particular Predictions for Model 6 with $\alpha_s(M_Z) = 0.115$

Input Quantity	Input Value	Predicted Quantity	Predicted Value
$m_b(m_b)$	4.35 GeV	M_t	176 GeV
$m_\tau(m_\tau)$	1.777 GeV	$\tan \beta$	55
$m_c(m_c)$	1.22 GeV	V_{cb}	.048
m_μ	105.6 MeV	V_{ub}/V_{cb}	.059
m_e	0.511 MeV	$m_s(1GeV)$	172 MeV
V_{us}	0.221	\hat{B}_K	0.64
		m_u/m_d	0.64
		m_s/m_d	24.

In addition to these predictions, the set of inputs in Table 4 predicts:

$$\sin 2\alpha = -.46, \sin 2\beta = .49, \sin 2\gamma = .84, \text{ and } J = 2.6 \times 10^{-5}.$$

Model 6

The superspace potential for Model 6 has several pieces - $W = W_{fermion} + W_{symmetry\ breaking} + W_{Higgs} + W_{neutrino}$.

12.1 Fermion sector

The first term must reproduce the four fermion mass operators of Model 6. They are given by

$$O_{33} = 16_3 10_1 16_3$$

$$O_{23} = 16_2 \frac{A_2}{\tilde{A}} 10_1 \frac{A_2}{\tilde{A}} 16_3$$

$$O_{22} = 16_2 \frac{\tilde{A}}{M} 10_1 \frac{A_1}{\tilde{A}} 16_2$$

$$O_{12} = 16_1 \left(\frac{\tilde{A}}{M} \right)^3 10_1 \left(\frac{\tilde{A}}{M} \right)^3 16_2$$

There are two 10s in this model, denoted by $10_i, i = 1, 2$ and only 10_1 couples to the ordinary fermions. The A fields are different 45s which are assumed to have vevs in the following directions – $\langle A_2 \rangle = 45_Y$, $\langle A_1 \rangle = 45_{B-L}$, and $\langle \tilde{A} \rangle = 45_X$. As noted earlier, there are 6 choices for the 22 operator and we have just chosen one of them, labelled a , arbitrarily here. In Figure 11, we give the tree diagrams which reproduce the effective operators for Model 6 to leading order in an expansion in the ratio of small to large scales. The states $\bar{\Psi}_a, \Psi_a, a = 1, \dots, 9$ are massive $\bar{16}, 16$ states respectively. Each vertex represents a separate Yukawa interaction in $W_{fermion}$ (see below). Field theoretic corrections to the effective GUT operators may be obtained by diagonalizing the mass matrices for the heavy states and integrating them out of the theory.

$$\underline{W_{fermion}}$$

$$16_3 16_3 10_1 + \bar{\Psi}_1 A_2 16_3 + \bar{\Psi}_1 \tilde{A} \Psi_1 + \Psi_1 \Psi_2 10_1$$

$$+ \bar{\Psi}_2 \tilde{A} \Psi_2 + \bar{\Psi}_2 A_2 16_2 + \bar{\Psi}_3 A_1 16_2$$

$$+ \bar{\Psi}_3 \tilde{A} \Psi_3 + \Psi_3 \Psi_4 10_1 + M \sum_{a=4}^9 (\bar{\Psi}_a \Psi_a)$$

$$+ \bar{\Psi}_4 \tilde{A} 16_2 + \bar{\Psi}_5 \tilde{A} \Psi_4 + \bar{\Psi}_6 \tilde{A} \Psi_5$$

$$+ \Psi_6 \Psi_7 10_1 + \bar{\Psi}_7 \tilde{A} \Psi_8 + \bar{\Psi}_8 \tilde{A} \Psi_9 + \bar{\Psi}_9 \tilde{A} 16_1$$

- *Note that the vacuum insertions in the effective operators above cannot be rearranged, otherwise an inequivalent low energy theory would result. In order to preserve this order naturally we demand that each field carries a different value of a $U(1)$ family charge*

(see Fig. 11). Note also that the particular choice of a 22 operator will affect the allowed U(1) charges of the states. Some choices may be acceptable and others not.

- Consider $W_{fermion}$. It has many terms, each of which can have different, in principle, complex Yukawa couplings. *Nevertheless the theory is predictive because only a very special linear combination of these parameters enters into the effective theory at M_G . Thus the observable low energy world is simple, not because the full theory is particularly simple, but because the symmetries are such that the effective low energy theory contains only a few dominant terms.*

12.2 Symmetry breaking sector

The symmetry breaking sector of the theory is not particularly illuminating. Two 54 dimensional representations, S, S' are needed plus several singlets denoted by $S_i, i = 1, \dots, 7$. They appear in the first two terms and are responsible for driving the vev of A_1 into the B-L direction, the third term drives the vev of the $\overline{16}, 16$ fields $\overline{\Psi}, \Psi$ into the right-handed neutrino like direction breaking SO(10) to SU(5) and forcing \tilde{A} into the X direction. The fourth and fifth term drives A_2 into the Y direction. Finally the last two terms are necessary in order to assure that all non singlet states under the SM gauge interactions obtain mass of order the GUT scale. All primed fields are assumed to have vanishing vevs. Note if $\langle S \rangle_3 \approx M_S$ then two of these adjoints state may be heavy. Considerations such as this will affect how couplings run above M_G .

$$\underline{W_{symmetry\ breaking}}$$

$$A'_1(SA_1 + S_1A_1) + S'(S_2S + A_1A_2)$$

$$\begin{aligned}
& +\tilde{A}'(\bar{\Psi}\Psi + S_3\tilde{A}) \\
& +A'_2(S_4A_2 + S\tilde{A} + (S_1 + S_5)\tilde{A}) \\
& +\bar{\Psi}'A_2\Psi + \bar{\Psi}A_2\Psi' \\
& +A'_1A_1\tilde{A} + S_6\tilde{A}'^2
\end{aligned}$$

12.3 Higgs sector

The Higgs sector is introduced below. It does not at the moment appear to be unique, but it is crucial for understanding the solution to several important problems – doublet-triplet splitting, μ problem and proton decay – and these constraints may only have one solution. The $10_1 A_1 10_2$ coupling is the term required by the Dimopoulos-Wilczek mechanism for doublet-triplet splitting. Since A_1 is an anti-symmetric tensor, we need at least two 10s.

The couplings of 10_1 to the 16s are introduced to solve the μ problem. After naturally solving the doublet-triplet splitting problem one has massless doublets. One needs however a small supersymmetric mass μ for the Higgs doublets of order the weak scale. This may be induced once SUSY is broken in several ways.

- The vev of the field A_1 may shift by an amount of order the weak scale due to the introduction of the soft SUSY breaking terms into the potential. In this theory the shift of A_1 appears to be too small.
- There may be higher dimension D terms in the theory of the form, eg.

$$\frac{1}{M_{Pl}} \int d^4\theta 10_1^2(A_2^*)$$

$$\begin{array}{c}
\bar{5}_1 \quad \bar{5}_2 \quad \bar{5}_\Psi \quad \bar{5}_{\Psi'} \\
\begin{array}{c} 5_1 \\ 5_2 \\ 5_\Psi \\ 5_{\Psi'} \end{array} \quad \left(\begin{array}{cccc} 0 & A_1 & 0 & \Psi \\ A_1 & S_7 & 0 & 0 \\ 0 & 0 & 0 & A_2 \\ \bar{\Psi} & 0 & A_2 & 0 \end{array} \right)
\end{array}$$

Higgs doublets In the doublet sector the vev A_1 vanishes. Since the Higgs doublets in 10_1 now mix with other states, the boundary condition $\lambda_b/\lambda_t = 1$ is corrected at tree level. The ratio is now given in terms of a ratio of mixing angles.

Proton decay The rate for proton decay in this model is set by the quantity $(M^t)_{11}^{-1}$ where M^t is the color triplet Higgsino mass matrix. We find $(M^t)_{11}^{-1} = \frac{S_7}{A_1^2}$. This may be much smaller than $\frac{1}{M_G}$ for S_7 sufficiently smaller than M_G . Note there are no light color triplet states in this limit. Proton decay is suppressed since in this limit the color triplet Higgsinos in 10_1 become Dirac fermions (with mass of order M_G), *but they do not mix with each other.*

12.4 Symmetries

The theory has been constructed in order to have enough symmetry to restrict the allowed operators. This is necessary in order to reproduce the mass operators in the effective theory, as well as to preserve the vacuum directions assumed for the 45s and have natural doublet-triplet splitting. Indeed the construction of the symmetry breaking sector with the primed fields allows the 45s to carry nontrivial U(1) charges. This model has several unbroken U(1) symmetries which do not seem to allow any new mass operators. It has a discrete Z_4 R parity in which all the primed fields, $S_{6,7}$ and 10_2 are odd and $16_i, i = 1, 2, 3$ and $\bar{\Psi}_a, \Psi_a, a = 1, \dots, 9$ go into i times themselves. This guarantees that the odd states (and in particular, 10_2) do not couple into the

. Then supergravity effects might induce a non-vanishing vev for the F term of A_2 of order the $m_W M_G$. This will induce a value of μ of order $m_W M_G / M_{Pl}$. The shift in the F-terms also appear to be negligible.

- One loop effects may induce a μ term once soft SUSY breaking terms are introduced[23]. In this case we find $\mu \sim \frac{A\lambda^4}{16\pi^2}$ where λ^4 represents the product of Yukawa couplings entering into the graph of Figure 12.

$$\begin{aligned} & \underline{W_{Higgs}} \\ & + \bar{\Psi}' A_2 \Psi + \bar{\Psi} A_2 \Psi' \\ & + 10_1 A_1 10_2 + \mathcal{S}_7 10_2^2 \\ & + \bar{\Psi} \bar{\Psi}' 10_1 + \Psi \Psi' 10_1 \end{aligned}$$

Note that the first two terms already appeared in the discussion of the symmetry breaking sector. They are included again here since as you will see they are important for the discussion of the Higgs sector as well. It is the latter mechanism which has been entertained in the above model. As a result of these couplings to $\bar{\Psi}, \Psi$ the Higgs doublets in 10_1 mix with other states. The mass matrix for the SU(5) $\bar{5}, 5$ states in $10_1, 10_2, \Psi, \Psi', \bar{\Psi}, \bar{\Psi}'$ is given below.

fermion mass sector. There is in addition a Family Reflection Symmetry (see Dimopoulos- Georgi, [9]) which guarantees that the lightest supersymmetric particle is stable. Finally, there may be a continuous R symmetry which would be useful in controlling Planck slop. These conclusions are still preliminary and must be checked.

Neutrino sector The neutrino sector seems to be very model dependent. It will constrain the symmetries of the theory, but I will not discuss it further here.

13 Conclusion

In this talk, I have presented a class of supersymmetric $SO(10)$ GUTs which are in *quantitative* agreement with the low energy data. With improved data these particular models may eventually be ruled out. Nevertheless the approach of using low energy data to ascertain the dominant operator contributions at M_G seems robust. Taking it seriously, with *quantitative* fits to the data, may eventually lead us to the correct theory.

Let me end this long talk with a short story. I have been reading a very interesting biography of Rutherford. It describes how, as a fresh post-doc, Niels Bohr went to work with J.J. Thomson at the Cavendish Laboratory. He was interested in working with J.J. on a theory of the atom. Bohr however didn't stay at the Cavendish for long; within the year he left to go to Manchester to work with Rutherford. Rutherford, of course, had recently proposed his theory of the atom to explain how alpha particles could be scattered in the backward direction upon hitting a thin metal foil.

The following excerpt, quoted from Rutherford : Simple Genius by D. Wilson, describes Bohr's feelings at the time.

In interviews later in his life Bohr explained that to Thomson, models were mere analogies and fundamental problems of little inter-

est. *Thomson did not demand consistency among the different models he employed nor did he worry about quantitative agreement between experiments and calculations based on the models*; indeed, in Bohr's words "things needed not to be very correct, and if it resembled a little, then it was so" as far as J.J. was concerned.

The italics are mine. I hope the moral of this story is evident.

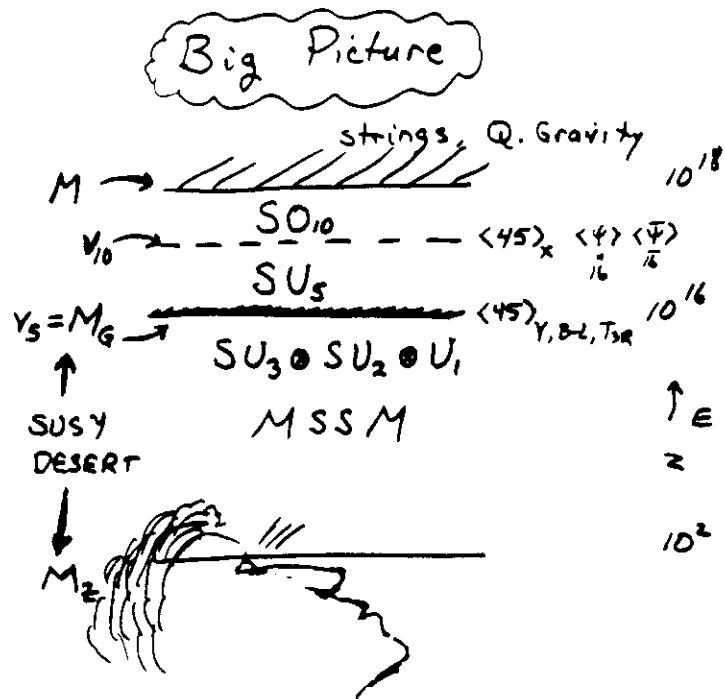
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M SO_{10} $16_1, 16_2, 16_3 + n(16 + \overline{16})$

some $10, 45, 54$

Figure 1

O_{22}

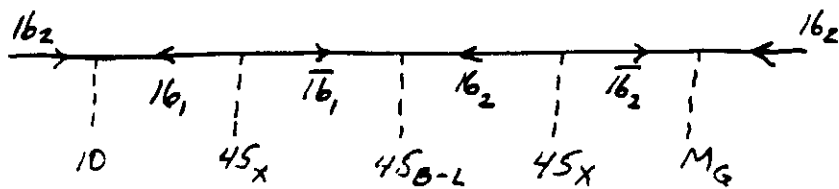


Figure 2

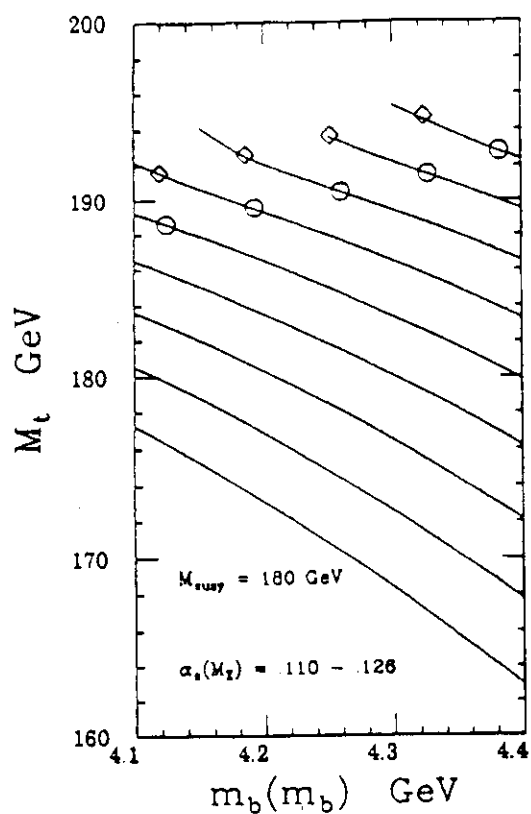


Figure 3a Top Mass Prediction

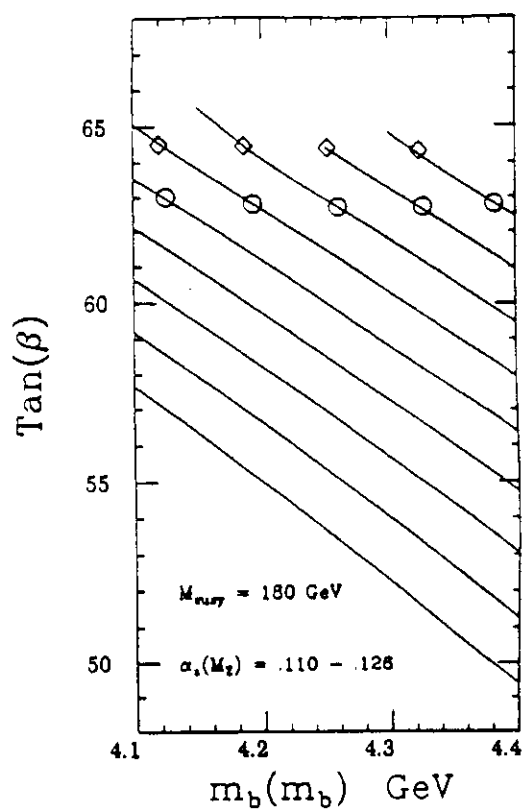


Figure 3b Prediction for $\tan\beta$

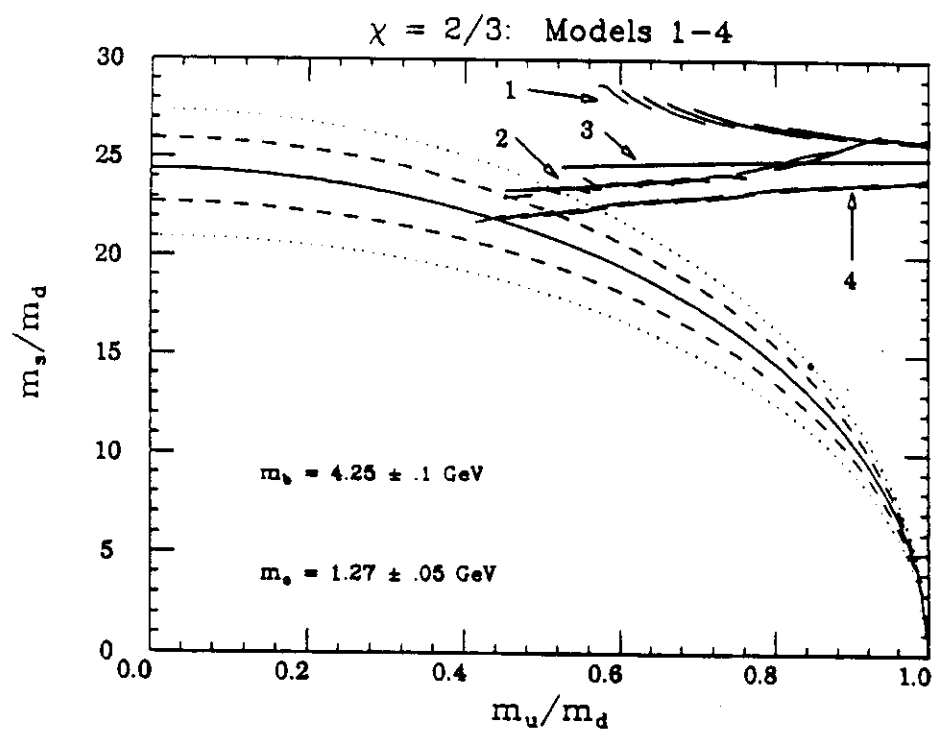


Figure 4a Prediction for $\frac{m_s}{m_d}$ and $\frac{m_u}{m_d}$.

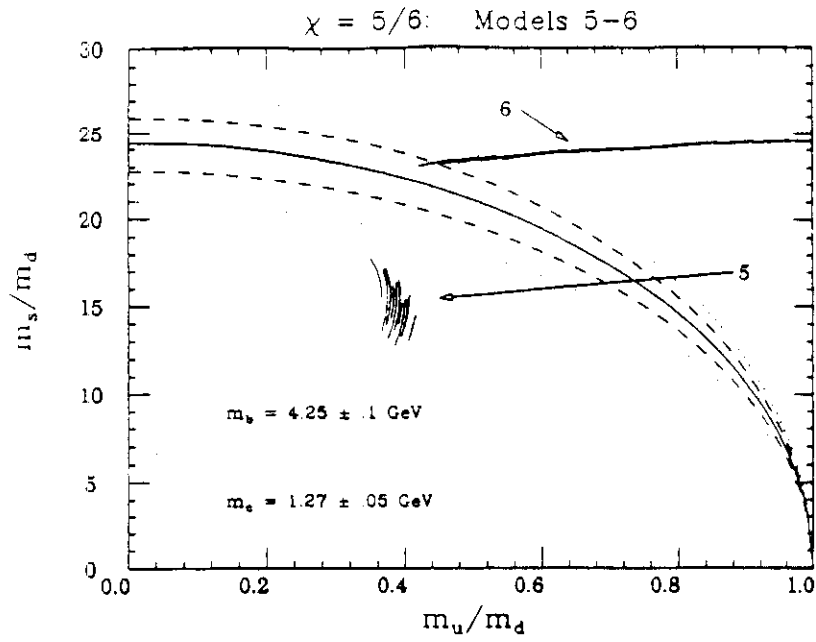


Figure 4b Prediction for $\frac{m_s}{m_d}$ and $\frac{m_u}{m_d}$.

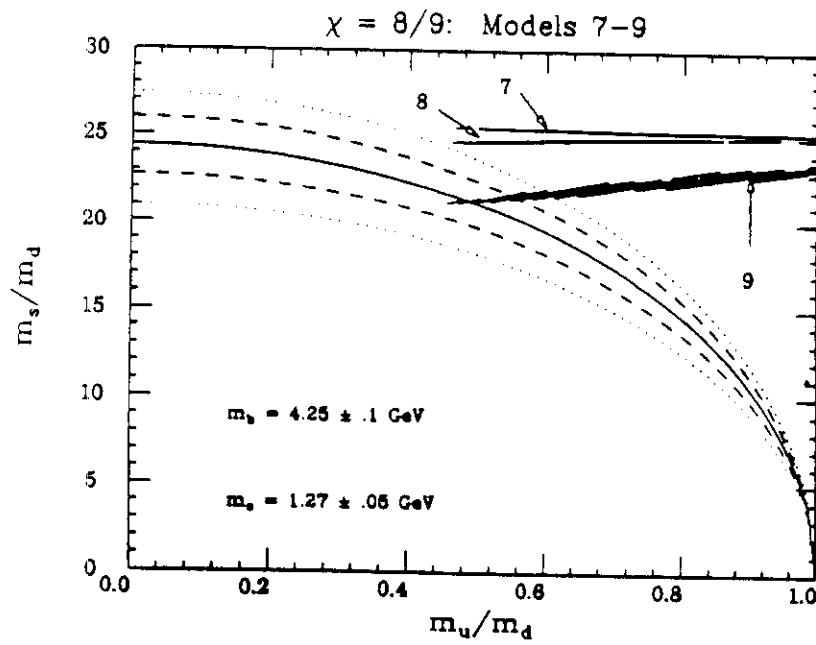


Figure 4c Prediction for $\frac{m_s}{m_d}$ and $\frac{m_u}{m_d}$.

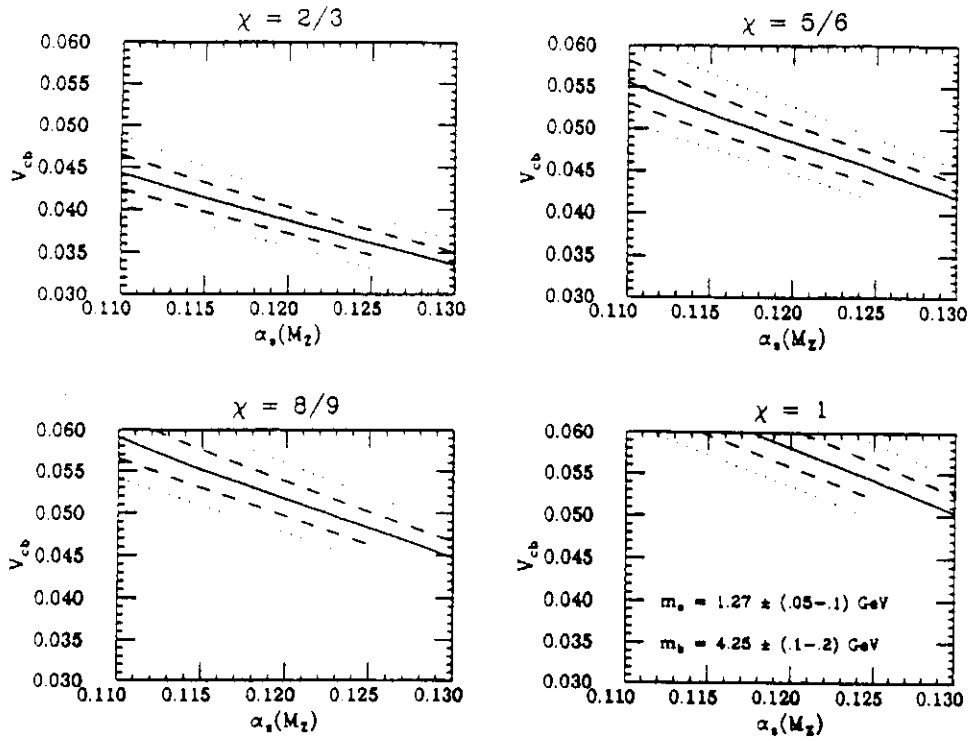


Figure 5 Prediction for V_{cb}

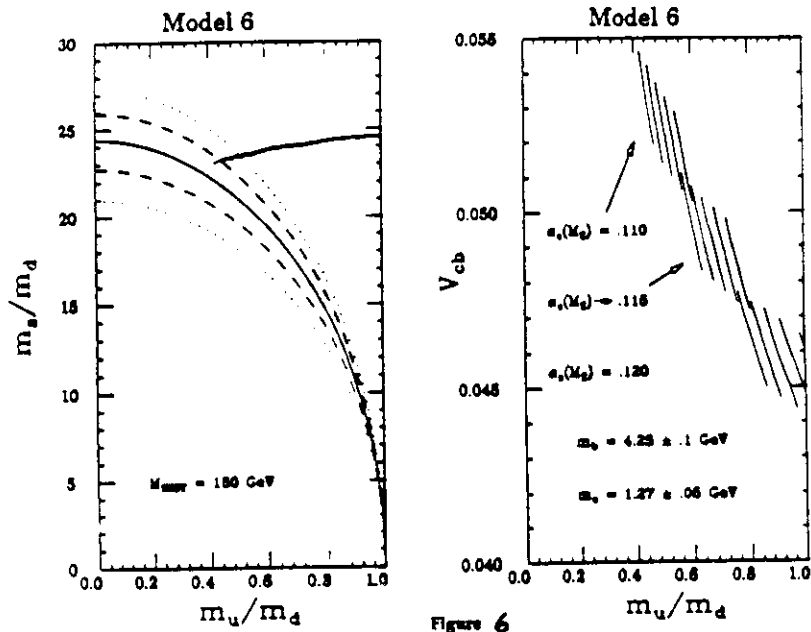


Figure 6

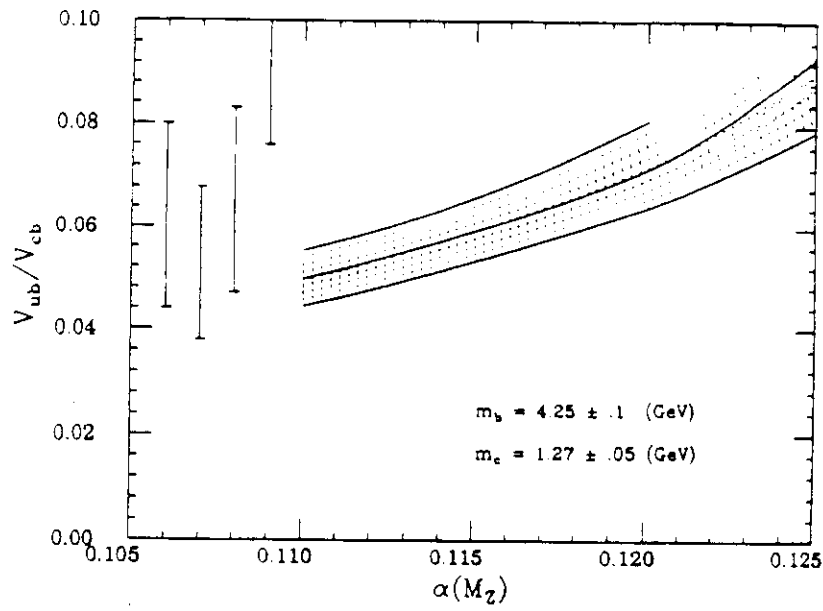


Figure 7 Prediction for $\frac{V_{ub}}{V_{cb}}$.

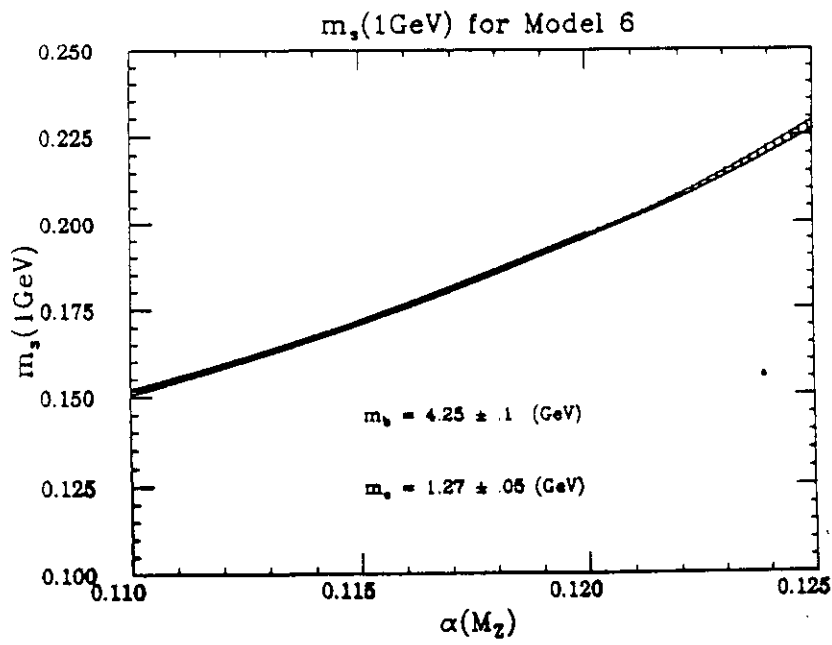


Figure 8 Prediction for m_s .

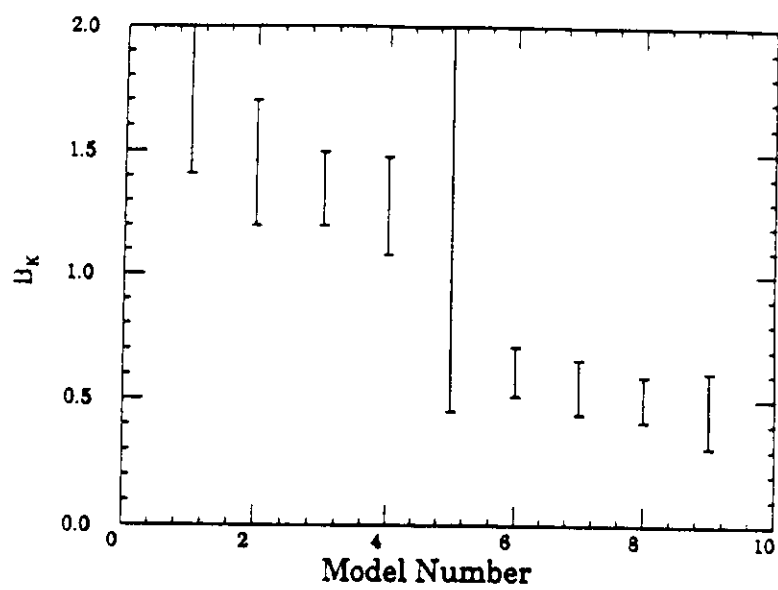


Figure 9

CP Violation in B DECAY

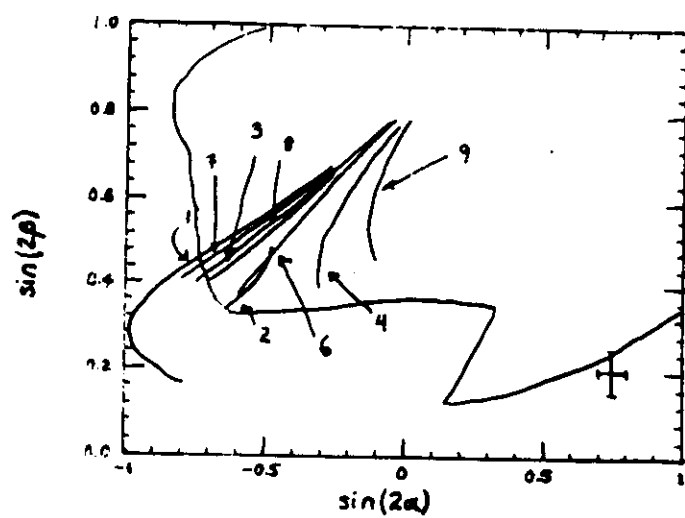


Figure 10

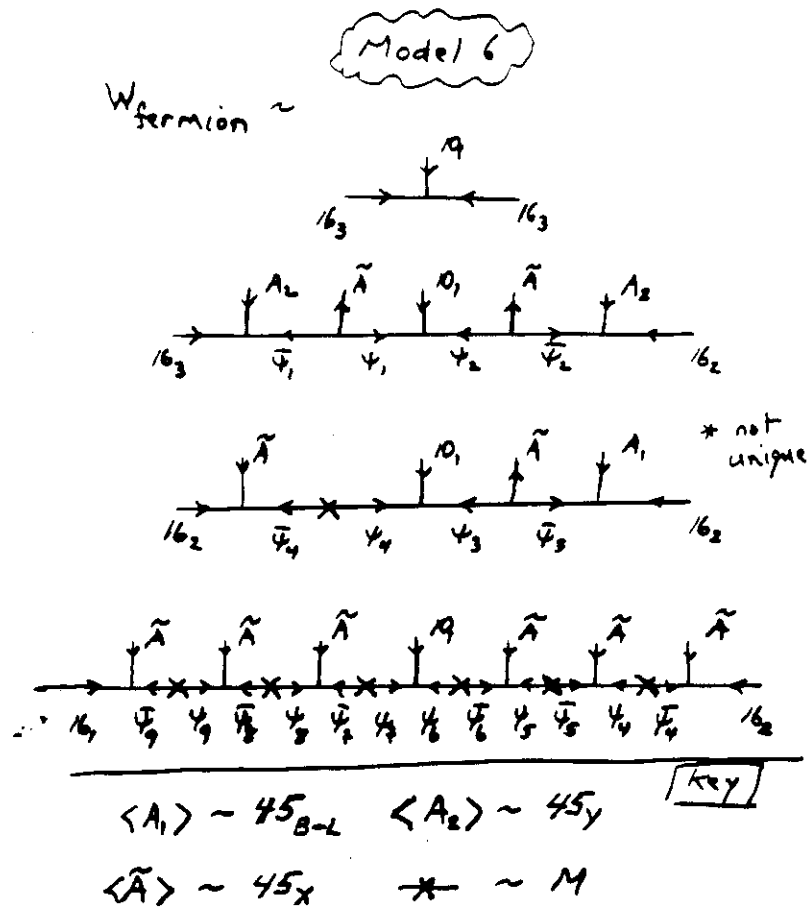


Figure 11

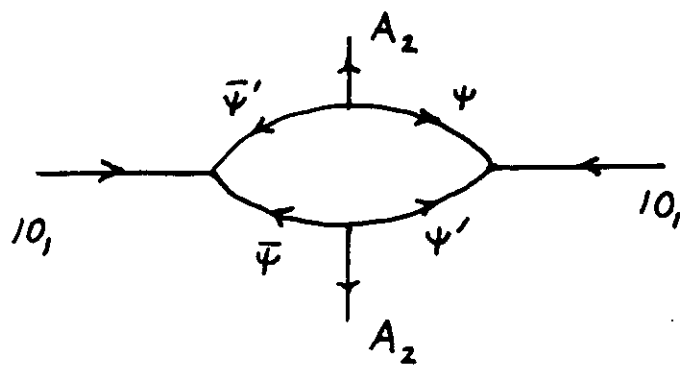


Figure 12

