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Supersymmetric Grand Unified Theories with Different Models

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Abstract:

Super symmetric grand unified theories (SUSY GUTs) are very exciting extensions of the minimal Super symmetric standard model (MSSM). They unify strong and electroweak interactions elucidating the MSSM quantum numbers, account for accuracy gauge coupling unification and steady the weak scale. Then numerous mechanisms for hidden sector Super symmetric breaking and go on to deliver a pedagogical conversation of the several type of Super symmetric unified theories afar the MSSM comprising SUSY GUTs. Their associations for proton decay, R-parity violation, doublet triplet splitting etc. are conferred.

Keywords — **GUT, Minimal Super symmetric standard model, Unification, SUSY.**

1. INTRODUCTION

In modern physics unification is narrowly correlated to symmetry. Apparently dissimilar concepts are connected by symmetry transformations and unified into a single object on which the symmetry group acts. In the case of electrodynamics for instance magnetic and electric fields are connected by Lorentz transformations and form the mechanisms of a single tensor of the Lorentz group. During the procedure of understanding weak connections it converted clear that the underlying symmetries do not have to be manifest. If the symmetries are instinctively broken at some energy scale, the resulting phenomenology below that scale does not even nearly exhibit the sorts of the unified theory above. Indeed weak and electromagnetic connections look very dissimilar at energies below the weak scale, where the SU(2) X U(1) gauge symmetry is broken instinctively. Symmetries play a significant role in the exertion to unify matter and forces also afar the standard model (SM). Such concepts can make remarkable estimates that allow testing them experimentally, even if the symmetry breaking scale is very high.

One probable path is taken by grand unified theories (GUTs). These theories unite strong and electroweak interactions by entrenching the SM gauge group into a simple group like SU(5) or SO(10). Quarks and leptons are united into intricate representations of this group which permits the derivation of their SM quantum numbers. Supersymmetry (SUSY) is a space-time symmetry that unifies fermions and bosons in distinct entities called superfields. This tips to a dramatic progress of the UV-behavior of supersymmetric field theories, for the reason that scalar mass terms are now endangered from the impact of heavy scales by the same chiral symmetries as fermions. It is still clear that SUSY cannot be an exact symmetry of nature for the reason that it prophesies equal masses of fermion and bosons in the same superfield and consequently a plethora of unnoticed scalar particles.

2. THE STANDARD MODEL (SM)

2.1 Gauge Group and Particle Content:

The Standard Model of particle physics has been verified experimentally in numerous ways and to high accuracy during the last decades and turned out to offer a good description of physics at energies lower ∼ 100 GeV. Its scale group is SU(3) × SU(2)L × U(1)Y which is extemporaneously broken down to SU(3) × U(1)EM, as labelled in the Higgs mechanism. Before the symmetry breaking, the model comprises 12 massless gauge bosons in the corresponding adjoint illustrations of the gauge group, three generations of 15 massless fermions and a complex Higgs scalar. The Higgs mechanism gives masses to three of the four gauge bosons of SU(2)× U(1), the left over massless gauge boson is the photon. The fermions also attain a mass upon electroweak-symmetry defiance, excluding for the neutrino, which rests massless.

2.2 Why go beyond the SM?

There are numerous hints that make us trust we have not found the eventual theory yet. Some are rather evident, while others need deeper understanding of the structures of quantum field theories:

• **Gravitation:** Only three of the four known forces in the universe are defined in the SM. The theory of gravity is general relativity (GR). It can be abandoned at the energy scale of today's experimentations in particle physics but if we want to find a theory of all, then there must be one model for all of the four forces

• **Gauge coupling unification:** Using the renormalization group equations (RGEs) for the SM to improve the running of the three gauge couplings, one finds that they meet at energy ~ 1016 GeV. This designates the conceivable presence of higher gauge symmetry at high energies, where the three couplings are united into one.

• **Hierarchy problem:** The mass of the W-boson has been experimentally indomitable to be of the order of 80 GeV. Meanwhile it attains its mass via the Higgs mechanism; mW is proportional to the Higgs mass. But the latter obtains radiative corrections that are quadratically divergent. These divergencies have to be annulled "by hand" in every order in perturbation theory, a process mentioned to as fine tuning. Such "accidental" cancellations seem a bit unbelievable and give rise to the question whether there may be another reason for the steadiness of the weak scale.

• **Mass and mixing parameters:** The Standard Model comprises a lot of free parameters, e.g. the masses of quarks and leptons and their weak mixing angles. There are correlations among them, which could be elucidated by supplementary symmetries, which may also decrease the distressingly large number of free parameters in the SM. Family symmetries, given that certain prospects for the form of the PMNS matrix are not under deliberation here, but grand unification will tip to relations among fermion masses.

3. The Minimal Supersymmetric Standard Model (MSSM):

Imposing supersymmetry (SUSY), the gauge fields become constituents of vectorsuperfields and the fermionic fields as well as the Higgs become constituents of chiral superfields. In adding, the other constituents of the superfields, named gauginos, squarks, sleptons and Higgsinos, appear in the lagrangian. Also, a second Higgs field (escorted by its superpartner) has to be familiarized, in order to give masses to leptons and d-type quarks as well as u-type quarks, and to keep the model difference free.

Supersymmetry resolves part of the hierarchy problem stated above. Rendering to the non-renormalization theorem, the radiative corrections to the Higgs mass happening in the SM will be negated by analogous diagrams with superpartners running in the loops. Consequently, if the bare Higgs mass is of the order of 150 GeV, there will be no different alterations pushing it up to the scale of a impetus cut-off. SUSY does not clarify why the weak scale is at its experimentally dogged value, but it does clarify why it stays there. Additionally, supersymmetry anticipates the masses of particles to be the similar as those of their superpartners. Since we have not detected any of these superpartners at the energy scales of the SM particle masses, supersymmetry has to be broken. In order not to spoil the attainment of the renormalization theorem, the terms in the lagrangian breaking supersymmetry have to be soft, i.e. their mass dimension has to be positive. In most of the models found in the works, the breaking of SUSY happens "after" the contravention of the higher gauge symmetry, i.e. at a lower energy scale.

An exciting aspect of some SUSY models is the likelihood to attain a negative squared Higgs mass, essential for unprompted symmetry breaking. The bare squared Higgs mass is expected to be positive, but then strapped into the negative system by radiative corrections. If one writes down all renormalizable expressions allowable by Lorentz and gauge invariance as well as supersymmetry, there will be operators prominent to proton decay. One can forbid these operators to show up in the lagrangian by imposing an supplementary symmetry, named R-parity, well-defined as R = (−1) ^ 3(B−L)+2S. The other open problems specified above are not resolved by SUSY. In addition, there arise numerous new features that need a clarification, e.g. the origin of the soft-breaking terms and the preservation of R-parity. Grand Unified Theories (GUTs) try to find solutions to these open questions.

4. GROUP THEORY:

Grand Unification means embedding the SM gauge group into a larger symmetry group, breaking down the symmetry via the Higgs mechanism and gaining an operative theory at low energies, that comprises leftovers of the structure of the higher symmetry. The mathematical tool for sympathetic these structures and their backtracking is group theory. Here, only some of the most significant features for GUT model building are shortly offered.

4.1 Representations

A illustration of the group G is a map from G into the group of all invertible, n-dimensional matrices GL(n),

$$R: \quad G \longrightarrow GL(n)$$
$$g \longrightarrow R(g),$$

with the properties

$$R(g \circ h) = R(g) \cdot R(h)$$
$$R(e) = 1,$$

where e is the identity element in G and 1 is the identity matrix. A representation is called reducible, if there is an invariant subspace, i.e. if P is the projection operator on that subspace, then $\forall g \in G$

$$P\,R(g)P = R(g)P$$

A representation is complicated if it is not reducible. Irreducible illustrations are significant in physics for the reason that they allow for mixing of all constituents of a field transforming in a precise depiction of a symmetry group.

4.2 Decomposition of Representations and Tensor Products

With the method of Young Tableaux, it is conceivable to decompose a representation into representations of a subgroup. For instance, ruminate decomposition of the 5 and 10 of SU(5) under the SM group,

$\bar{5} = (\bar{3}, 1, +2/3) \oplus (1, 2, -1)$,

$10 = (1, 1, +2) \oplus (\bar{3}, 1, -4/3) \oplus (3, 2, +1/3)$.

In the same manner, a tensor product of two representations of the group under deliberation can be disintegrated into representations of this cluster, e.g. for the 5 and $\bar{5}$ of SU(5)

$$5 \times \bar{5} = 1 + 24.$$

5. GAUGE COUPLING UNIFICATION:

The three gauge couplings of the Standard Model, α_1 of $U(1)_Y$, α_2 of $SU(2)_L$ and α_3 of $SU(3)_C$ do not take on a persistent value for all energies, but run with the scale rendering to their beta functions, which in one-loop calculation read

$d\alpha_i/d(\ln\mu) = -1/2\pi \cdot b_i.\alpha_i^2 \qquad (i = 1, 2, 3)$

where

$$b_i = 3C_2(G_i) - T_R N_\psi.$$

6. GUT MODEL BUILDING:

6.1 Steps of Model Building:

The building of a SUSY GUT needs numerous steps, which are itemized one by one below. In the successive chapters, instances of SUSY GUT models will be given, subsequent each of these steps.

a) Choose a symmetry group G comprising the SM gauge group $SU(3) \times SU(2)_L \times U(1)_Y$ as a subgroup. This might either be one single group, e.g. SU(5), SO(10) or E6, or a product of a number of groups, such as $SU(3)\times SU(3)$ or $SU(4) \times SU(2)_L \times SU(2)_R$, where the latter is frequently denoted to as Pati-Salam group.

b) State the particle content of the model. For fermions and Higgs bosons (and, of course, their superpartners) complicated illustrations of the gauge group are preferred, while the gauge bosons transform in the adjoint. If the particles of the MSSM do not fit into one depiction, they have to be split into numerous ones or new particles have to be added. A new particle that is welcome in numerous cases, is the right-handed neutrino, for the reason that its survival enlargens the symmetry in the sense that all fermions now appear in a left- and right-handed version. In several cases, there is the need for more than two Higgs fields, in imperative to break the GUT symmetry and the electroweak symmetry as well as give masses to fermions and gauge bosons, well-matched with their investigational values. Additionally, assigning fermions to convinced representations, one has to make definite that the model comprises no gauge anomalies.

c) Write down kinetic terms for fermions, Higgses and gauge bosons (and their superpartners, respectively). The covariant derivative (in the event for one single gauge set) reads $D_\mu = \partial_\mu - igA^a_\mu T^a$, where g is the gauge coupling, A^a_μ are the vector gauge bosons and T^a are the generators of the gauge group (a = 1, . . . , dimLie(G)).

d) Write down the superpotential W for the scalar fields and the Yukawa interactions, observance in mind that all terms must be renormalizable, Lorentz- and gauge invariant. The superpotential is accountable for breaking the gauge symmetry down to that of the SM and the Yukawa terms will give mass to fermions afterwards symmetry breakdown.

e) Define the minimum of the scalar potential by stately F-term flatness ($F_i = \partial W/\partial\Phi_i = 0$, where Φ_i are the scalar fields appearing in W). The F-term has to disappear, if one assumes that SUSY still exists at energies underneath the GUT-scale. This is a great simplification in calculation delivered by SUSY, in non-supersymmetric theories outcome the vacuum expectation value (VEV) of the Higgs fields is much more elegant.

f) Compute masses and couplings at the weak scale using the RGEs of the theory. Associations among parameters attained from the theory will be valid at the GUT scale. In order to get relations at the weak scale, the running of parameters has to be taken into account. The form of the RGEs is resolute by the particle content of the theory. If there are intermediary energy scales where new particles seem, the RGEs will change at these scales. In estimate, this change is frequently expected to take place "speedily", i.e. a theta-function is used.

6.2 Achievements and Problems:

Grand unified theories, containing of only one single gauge assembly, describe the unification of gauge couplings. In supersymmetric versions, the couplings match at ~ 1016 GeV within the current experimental mistakes for the early values at the weak scale. Additionally, quarks and leptons are incorporated being part of the same complicated representation of the gauge set. This leads to predictions for relations amongst their masses. Another accomplishment is the likelihood to comprise the right-handed neutrino in the theory and write down a Majorana mass stint, e.g. in SO(10), where the right-handed neutrino can attain a large Majorana mass upon defiance of left-right symmetry. In these kinds of models, the seesaw mechanism can be smeared, which clarifies the smallness of (left-handed) neutrino masses, permitting for a Dirac mass of the order of the weak scale.

Gravity has not been spoken yet. It is a problematic task to syndicate it with quantum field theory. There are numerous possibilities to comprise a spin 2 particle in the model, which can be recognized as a graviton, e.g. if one cogitates local supersymmetry transformations. String theory may deliver an acceptable framework, but shall not be conversed here.

Even though they suggest answers to most of the tasks stated, grand unified theories give augmentation to new questions. One of them is the so-called doublet-triplet splitting of the Higgs boson. The Higgs field familiarized in a depiction of the GUT group comprises color triplet and electroweak doublet apparatuses. In mandate to break down also the electroweak symmetry of the standard model at a lower energy scale, one has to decouple the triplet constituents from the low-energy concept by giving them a large mass, while the doublet constituents should persist light. This clue to a new fine-tuning problem. A way out of this is delivered by familiarizing an added dimension, which is compactified into an orbifold.

7. SUSY SU(5):

The smallest single gauge group that comprises the SM as a subcategory is SU(5). SU(5) is the set of all five-dimensional unitary matrices with basis one. Its creators are traceless and hermitian (5 × 5) matrices which can be chosen as follows: Take the 10 matrices with one i above the diagonal, one −i below and zeros universally else. Take the 10 matrices with one 1 above the diagonal, one 1 below and zeros everywhere else. Ultimately, take the matrices with n ones on the diagonal, monitored by a single −n (there are four of these, n = 1, ..., 4). These are the 24 generators of SU(5). For SU(N) in general, there are N2 − 1 generators.

7.1 The Superpotential: Subsequent the steps of GUT model building; the next matter to hold is the theory's superpotential. It is generally signified by W and it can be shown that, in order to reserve supersymmetry, it needs to be holomorphic in the scalar mechanisms of chiral superfields. As stated before, this is one of the causes for presenting a second Higgs doublet in the MSSM. For SUSY SU(5), the superpotential is

$$W = W_h + W_Y + W_{SB}.$$

In the subsequent, the three terms are discoursed one by one. W_h is called the hidden sector and contains of soft-terms, that break supersymmetry. W_Y comprises the Yukawa couplings,

$W_Y = y_u$^ab ψ_{10}^a ψ_{10}^b $H_u + y_d$^ ab ψ_{10}a ψ ^b/ 5H_d,

With y_u and y_d being Yukawa coupling matrices. Reminding the distribution of SM particles among the two demonstrations, one sees that the first Yukawa stint gives mass to the u-quark, while the d-quark and the electron receive their masses from the second term. The neutrino rests massless, except the righthanded neutrino is involved into the model as an extra singlet. If there was such an extra singlet νR, one could add a term ψ¯5νRH_u, compliant a Dirac mass for the neutrino. Since νR is a gauge singlet, it can even get an explicit Majorana mass term MRν¯RνR, provided that the background for the see-saw mechanism. WSB is accountable for symmetry breaking,

$$W_{SB} = z\mathrm{Tr}\Phi + x\mathrm{Tr}\Phi^2 + y\mathrm{Tr}\Phi^3 + \lambda H_u \Phi H_d + M H_u H_d$$

Note that, although Φ is traceless, the word zTrΦ seems in the superpotential as a Lagrange multiplier. Diminishing the potential, the trace will be forced to evaporate. SUSY needs vanishing of the F-terms:

$$0 = \mathrm{Tr}\,(\partial W/ \partial \varphi_j{}^i)$$

Where

$$\partial W/ \partial \varphi i\ j = z\delta j\ i + 2x\Phi\ i\ j + 3y\Phi\ i\ k\Phi\ k\ j$$

Consequently F-term flatness, composed with the constraint TrΦ = 0, produces the relation

$$z = -\ 3/5. \qquad y\mathrm{Tr}.(\Phi^2)$$

Now there are three explanations to the equation Tr ∂W/∂φi j = 0, one of them corresponding to unbroken SU(5), another one corresponding SU(4) × U(1) as residual symmetry, and the last one corresponding to the

Standard Model SU(3) × SU(2) × U(1) The MSSM Higgs doublets are delimited in H_u and H_d and have to be detached from the triplets by finetuning the parameters x, y and M, to guarantee the doublet masses endure light.

7.2 Fermion masses:

The unification of quarks and leptons into the same representations of SU(5) hints to relations among their masses. From WY it is evident that the d-quark and the electron collect the same mass, since they share the same Yukawa coupling matrix. Of course, this equivalence is only valid at the GUT scale. If the experimentally determined values for the masses at the weak scale are taken as preliminary values of the RGEs, one finds for the masses at the GUT scale around md ≈ 3me. This displays that the SU(5) prediction md = me is a little too strict. Additional result removed from this model is the scale self-governing relation me mμ = md ms, which is also in conflict with the investigational values.

8. SUSY SO(10):

SO(10) is the collection of all orthogonal ten-dimensional matrices with factor one. Its generators are antisymmetric, hermitian (10 × 10) matrices which can be chosen to be the 45 conditions with one i above the diagonal, one −i below and zeros everywhere else. For SO(N) in common, there are N(N − 1)/2 generators. An significant variance amongst SO(10) and SU(5) is the rank of their Lie algebras. While the Lie algebra of SO(10) comprises 5 altering generators, that of SU(5) has only 4, i.e. it has the similar rank as the Lie algebra of the Standard Model gauge group. Subsequently the rank of SO(10) is higher than that of the SM, there are dissimilar ways to break down the equilibrium. Explicitly, there are diverse probable intermediate symmetries of rank 5, e.g. SU(5)×U(1), SU(4) × SU(2)L × SU(2)R or SU(3) × SU(2)L × SU(2)R × U(1).

8.1 Spinors:

SO(10) is very striking as a GUT set ever since all chiral superfields of the MSSM, organized with the right-handed neutrino, fit into (three copies of) its 16 spinor representation. An sophisticated way to signify spinors in SO(2N) is to definite them in SU(N) basis. This is possible for the reason that SU(N) is a subgroup of SO(2N). To see how this is done, consider N operators $\chi_i , \chi^\dagger_i$, obeying

$$\{\chi_i , \chi^\dagger_j \} = \delta_{ij} \quad \{\chi_i , \chi_j\} = 0 \quad \{\chi^\dagger_i , \chi^\dagger_j \} = 0.$$

The SO(2N) Clifford algebra consists of 2N gamma matrices,

$$\Gamma_{2i} = 1/\sqrt{2}\,(\chi_i + \chi^\dagger_i)$$
$$\Gamma_{2i-1} = i/\sqrt{2}\,(\chi_i - \chi^\dagger_i)$$

fulfilling

$$\{\Gamma_\mu, \Gamma_\nu\} = \delta_{\mu\nu}1. \quad (20)$$

The chirality operator in SO(2N) is definite as

$$1/2\,(1 \pm \Gamma_0), \text{ where } \Gamma_0 \equiv i^N \Gamma_1\Gamma_2 \cdots \Gamma_N ,$$

8.2 Particle Content:

The point that all MSSM chiral superfields fit into the 16 spinor of SO(10) can be seen by modest counting: There are 3 up- and 3 down quarks (one for each color), 1 charged and 1 neutral lepton, adding up to 8 fields. Multiplication by two, secretarial for the charge conjugates, yields 16. In the SU(5) basis familiarized in the preceding section, the way in which the particles appear in the representation develops clear. $\bar\psi_i$, equivalent to $\bar 5$, and ψ_{ij} , corresponding to 10, comprise the fields as in SU(5), the singlet ψ_0 is the right-handed neutrino. Via the diverging rule for the 16, this interprets into SM language,

$$16 = (3, 2, 1/3)q_L \oplus (1, 2, -1)l_L \oplus (\bar 3, 1, -4/3)u^c_L \oplus (\bar 3, 1, 2/3)d_L \oplus (1, 1, 0)\nu^c_L \oplus (1, 1, 2)e^c_L .$$

The Higgs sector is much more elegant than in SU(5). There are numerous opportunities to choose representations for Higgs fields, compliant numerous predictions for fermion masses. Of course, one needs to keep the number of free parameters in the model as low as possible to acquire high predictivity, but since all fermions are joint in one representation, a small number of Higgs fields generally results in mass relations that are too restrictive and not well-suited with the experimental values.

8.3 Fermion Masses:

The superpotential of the theory, as in SU(5), comprises Yukawa terms, collaborations of Higgs fields and SUSY soft-breaking terms. The requisite of F-term flatness, i.e. conserving SUSY below the GUT scale, yields the minimum of the scalar potential and thus the VEVs of the Higgs fields, whose electroweak doublet constituents give masses to the fermions. All Dirac masses are attained from linear mixtures of the VEVs of components of the 10 and the 126, while the Majorana mass for the right-handed neutrino is delivered by a linear combination of 10 and 126. The VEVs giving mass to d-quarks and indicted leptons point in the same direction, and, in case of a governing 126 component, it is possible to attain the relation md = 3me (26) at the

GUT scale, which is in good covenant with the experimental values at the electroweak scale. Now, the 3 in front of the charged lepton mass is a Clebsch-Gordan coefficient, a relic of the decomposition of the 16 into color trios and singlets.

CONCLUSION

Supersymmetric grand unified theories offer many possible answers to questions posed by the Standard Model. They elucidate gauge coupling unification and can be useful in obtaining relations among fermion masses. Supersymmetry solves (at least part of) the hierarchy problem and tips to models with particle gratified symmetric in fermionic and bosonic degrees of freedom. On the other hand, SUSY GUT models give rise to new tasks, such as the doublet-triplet excruciating in the Higgs sector or evading large proton decline amplitudes. Also the number of free parameters has not been abridged extraordinarily associated to the Standard Model. The SO(10) model with the minimal Higgs content familiarized in the last section has 23 real parameters, whereas the SM with extra massive (Majorana) neutrinos comprises 27. Besides, gravity is not yet comprised in the theory and neither have family symmetries been addressed. Solving the problems related to SUSY GUTs is a new challenge and has been pursuited in the current years. Additional symmetry groups (discrete and continuous) have been presented to accommodate family symmetries. In supergravity, local SUSY invariance tips to the presence of spin 2 particles, which can be recognized as the graviton. Additionally, extra dimensions have been considered in order to attain the doublet-triplet splitting or elucidate the hierarchy amongst the weak and the Planck scale. But all these models are escorted by new open queries and we are still distant from discovering the vital theory.

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