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High scale parity invariance as a solution to the SUSY CP problem and an explanation of small ϵ'/ϵ*

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Abstract. It is shown that if the supersymmetric Standard Model (MSSM) emerges as the low energy limit of a high scale left–right symmetric gauge structure, the number of uncontrollable CP violating phases of MSSM are drastically reduced. In particular it guarantees the vanishing of the dangerous phases that were at the root of the so called SUSY CP problem. Such a symmetric gauge structure is independently motivated by the smallness of neutrino masses that arise via seesaw mechanism automatic in the theory. The minimal version of this theory also provides an explanation of the smallness of ϵ'/ϵ as a consequence of the high scale parity invariance.

Keywords. SUSY CP problem; ϵ'/ϵ; neutron edm.

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1. Introduction

Recent evidences for neutrino oscillations imply that the Standard Model must be extended to accommodate small neutrino masses. An elegant model that provides an explanation of the small neutrino masses via the seesaw mechanism is the left–right symmetric model. Two other seemingly unrelated puzzles of the Standard Model, viz., the stability of the Higgs-boson mass and the origin of the electroweak symmetry breaking, seem to require its supersymmetric extension – the MSSM – for a proper resolution. It is therefore natural to consider embedding of the MSSM into a high scale left–right symmetric gauge structure and study any constraints on the properties of MSSM. It was shown in ref. [1] that this high scale SUSY LR model provides a solution to the CP problems of the MSSM. A minimal version of this model has been studied extensively in recent papers by us [2] where we have further noted that the suppression of ϵ'/ϵ observed in experiments also comes out naturally as a consequence of the parity invariance of the theory. There are also a number of other predictions noted in [2] that make the theory testable in the near future. In this talk I give a brief overview of the basic outline of the model and its phenomenological consequences.

Let us first introduce the so called SUSY CP problem of MSSM. In contrast with the Standard Model, the MSSM has more than 30 phases which cannot be rotated away by

*This talk is based on work done in collaboration with K S Babu and B Dutta.

redefinition of the fields in the theory and is therefore plagued with many CP violating amplitudes which are uncontrollably large. Examples are the electric dipole moment (edm) of the neutron, ϵ'/ϵ etc. Thus in the CP violating sector, MSSM takes a giant stride backwards from the SM. This is known as the SUSY CP problem [3,4]. The main sources of the edm problem are the phases in the μ-term, the $B\mu$-term as well as the gluino mass in the conventional MSSM terminology.

As we see below, in the left–right symmetric model with supersymmetry, parity invariance implies that Yukawa couplings are hermitean, the μ terms, the $B\mu$ terms and the gluino masses is real [1]. Thus parity invariance not only drastically reduces the number of phases in the theory but it also sets to zero the three dangerous phases that led to the edm problem of MSSM. This in brief is the solution to the SUSY CP problem, which has been discussed in detail in ref. [1,2]. We now proceed to discuss the minimal version of this theory analysed in ref. [2] which makes the model very predictive in both the supersymmetry as well as the CP violating sector.

The minimal versions of the high scale SUSY LR model contains only one multiplet responsible for fermion masses, i.e. one left–right bidoublet, Φ. Since Φ contains both the H_u and H_d multiplets of the MSSM, it immediately leads to a proportionality between the up and the down Yukawa coupling matrices [2]. This is called up–down unification which implies that quark mixing angles all vanish at the tree-level, but are induced by loop diagrams involving the exchange of supersymmetric particles. This considerably restricts the flavor and CP violating interactions in the model and makes it very predictive without the need for any extra symmetries.

As already discussed, parity invariance of the model above the seesaw scale implies that the familiar μ and B parameters and the gluino mass terms are real [1] for mass scales above v_R; the Yukawa coupling matrices and the SUSY breaking A matrices (the trilinear terms that involves the squarks) are Hermitean. Furthermore the squark sector has only one A matrix, which evolves to the two $A_{u,d}$ matrices of low energy MSSM. We supplement these constraints with the additional assumption of universal scalar masses while keeping the trilinear scalar A terms arbitrary, subject of course to left–right symmetric constraints. The A terms need to remain arbitrary in order to get the correct quark mixings out of radiative corrections. The resulting theory has only one CP phase residing in the A term that ultimately leads to all CP violating phenomena in the quark sector. Thus in terms of CP violating implications, this theory is on par with the KM model.

A being the only source of flavor mixing in the model, its elements A_{ij} are fixed to a narrow range in order to fit the observed CKM angles and the CP phase is fixed by the requirement that the model reproduce the observed value of the kaon CP violating measure ϵ_K. The low energy theory in this case is MSSM, but without the SUSY CP problem and with its parameters restricted to a very narrow range. The value of ϵ'/ϵ is now predicted and we find it to be in good agreement with the recent KTeV [5] and NA48 [6] results. We also predict the electric dipole moment (edm) of the neutron to be $\sim 4 \times 10^{-29}$ ecm.

2. The model

Let us give some details of the model which is based on the $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ local symmetry with the standard assignment where Q, Q^c denote left-handed and right-handed quark doublets and Φ denotes the (2,2,0) Higgs bi-doublet. The $\mathrm{SU}(2)_R \times$

$U(1)_{B-L}$ symmetry could either be broken by $B - L = 2$ triplets – the right-handed triplet Δ^c (accompanied by $\bar{\Delta}^c$ fields, to cancel anomalies and their left-handed partners) or by $B - L = 1$ doublet χ^c (along with $\bar{\chi}^c$ and their left-handed partners). The gauge invariant superpotential involving matter fields is:

$$W = \mathbf{Y}_q Q^T \tau_2 \Phi \tau_2 Q^c + \mathbf{Y}_l L^T \tau_2 \Phi \tau_2 L^c + i(\mathbf{f} L^T \tau_2 \Delta L + \mathbf{f}_c L^{cT} \tau_2 \Delta^c L^c) \; . \quad (1)$$

Below the v_R scale, the $H_{u,d}$ contained in Φ will emerge as the MSSM doublets, but in general in arbitrary combinations with other doublet fields in the model. The single coupling matrix Y_q therefore describes the flavor mixing in the MSSM in both the up and the down sectors leading to the relations

$$Y_u = \gamma Y_d; \qquad Y_\ell = \gamma \, Y_{\nu^D} \quad (2)$$

which we call up–down unification. The parameter γ is unity if the multiplets H_u and H_d of MSSM are contained entirely in $\Phi(2,2,0)$, but γ can differ from one if additional doublets contribute to H_u and H_d. At first sight the first of the relations in eq. (2) might appear phenomenologically disastrous since it leads to vanishing quark mixings and unacceptable quark mass relations. It was shown in ref. [2] that after including the one-loop corrections involving the exchange of supersymmetric particles to the relations in eq. (1), there exists a large range of parameters of MSSM where correct quark mixings as well as masses can be obtained. We explored the parameter space that allowed for arbitrary bilinear squark masses and mixings as well as arbitrary form for the supersymmetry breaking trilinear A matrix but did not address the SUSY CP problem. We focused on a class of solutions for large $\tan\beta \sim 35$–40, corresponding to $\gamma = 1$. The magnitude of $\tan\beta$ can be reduced for $\gamma \geq 1$. In this paper, we focus on a predictive scenario where the scalar masses are universal and all flavor mixing arises from the trilinear A terms. Using small tanβ scenario ($\gamma \gg 1$) we explain the observed CP violation while satisfying the FCNC constraints from the K meson system.

The assumption of universal scalar masses implies that at the Planck scale, the only phase of the SUSY LR theory resides in one of the three off-diagonal entries of the SUSY breaking trilinear coupling matrix A. To understand this, note that parity invariance of the Lagrangian above the v_R scale implies that Arg $(B) =$ Arg $(\mu) = 0$ and $Y_{q,l} = Y^\dagger_{q,l}$ and $A_{q,l} = A^\dagger_{q,l}$. A Hermitean 3×3 matrix has only three independent phases. The quark masses can be diagonalized and made real (since there is only one matrix $\mathbf{Y}_q$ in eq. (1)). Thus in this model there is no CP violation in quark mixings at the tree level. It then follows that redefining the phases of any two quark superfields (in both the right and the left sector) we can make two of the three off diagonal A_{ij}'s real leaving us with only one phase. Thus the tree level MSSM parameters above the v_R scale can be summarized as follows (in the quark–squark sector): $M_u^{(0)} = \gamma \tan\beta M_d^{(0)}$; $M^2_{\tilde{Q}} = M^2_{\tilde{u}^c} = M^2_{\tilde{d}^c} = M^2_{H_{u,d}} = m_0^2 \mathbf{I}$; $M_{\tilde{W}} = M_{\tilde{B}} = M_{\tilde{g}} = M_{1/2}$ and all elements of A are real except A_{13} (with Arg $A_{13} = \delta^p_{13}$). The parameter γ can be different from one if the $SU(2)_L$ doublets in Φ and those in other multiplets in the theory such as χ in the case of the non-renormalizable seesaw model or those in $(2, 2, \pm 2)$ multiplets which may be included in the renormalizable seesaw model so that R-parity conservation remains automatic.

3. Calculations and constraints on the MSSM parameters

To proceed further, one can compute the one-loop corrections to the quark mass matrices. They are given in the refs [7,2]. The up sector corrections can be obtained by replacing (A_d, λ_d, v_d) by (A_u, λ_u, v_u). In the down sector, there are three types of flavor contributions: $M_d = v_d[Y_q(1+c_1\tan\beta)+c_2(A_d/M_{\rm SUSY})+c_3\delta_{33}]$. Here the c_i are dimensionless loop factors. The c_1 and c_2 terms arise from the gluino graph, the c_3 term which contributes significantly only to the b-quark mass is from the chargino graph. M_u is given by $M_u = v_u[Y_q(1+c_1/\tan\beta)+c_2(A_u/M_{\rm SUSY})]$. Clearly there is a mismatch between M_u and M_d, which implies non-zero CKM angles.

Although the scalar masses are assumed to be universal at the Planck scale, the non-diagonal nature of the A matrix will induce via the RGE off-diagonal elements in the up and down squark mass matrices. Since the calculation is going to be done at the SUSY scale of a few hundred GeV, one must extrapolate the parameters down from the Planck scale via the v_R scale down to $M_{\rm SUSY}$. The RGE's for extrapolation below v_R are those of MSSM and are well known [8]. Between $v_R \leq \mu \leq M_{\rm Pl}$, we use the RGE corresponding to the SUSY LR model. We keep only the one-loop terms. The main effect of running from the Planck scale to v_R in the squark sector is to split the third generation squarks slightly from the first two generations due to the large third generation Yukawa coupling. This effect is further amplified via the RGE in the process of running from v_R to the SUSY scale. We work in a basis where the tree-level Yukawa coupling matrix is diagonal. As a result, Yukawa matrices at $M_{\rm SUSY}$ also will be diagonal. However, the superpartner masses which start at the Planck scale as diagonal matrices acquire off-diagonal terms both at the v_R scale and at $M_{\rm SUSY}$. At $M_{\rm SUSY}$, the $\tilde{Q}$, $\tilde{u^c}$ and $\tilde{d^c}$ masses are no longer equal. The off-diagonal entries of these matrices become complex. Similarly, the A-matrix which was Hermitean at the v_R scale also loses its hermiticity. Using these extrapolated quantities, we compute the one-loop corrections to the up and down quark mass matrices and diagonalize them to fit the known quark mixings and masses. We find a range of input parameters at $M_{\rm Pl}$ which leads to the correct quark masses and mixings. We then make sure that the chosen values of the A_{ij}'s do not lead to excessive flavor changing neutral current effects. We have used the constraints quoted in ref. [9,10].

It was shown in ref. [2] that, to get the correct mixing angles, we need to have $\delta_{12,LR} \simeq 4.4\times10^{-3} - 6.2\times10^{-3}$, $\delta_{23,LR} \simeq (0.84-1.8)\times10^{-2}$, where the range comes from varying the parameter $x \equiv M_{\tilde{g}}^2/m_{\tilde{q}}^2$. $\delta_{12,LR}$ is determined from the Cabibbo angle, $\delta_{23,LR}$ from V_{cb}. (Here $\delta_{ij,\alpha\beta} \equiv M^2_{ij,\alpha\beta}/m^2_{\tilde{q}}$ are the flavor violating squark mixing parameters.) On the other hand, from ref. [10], we note that the upper bound on Im$(\delta_{12,LR}) \leq (2$–$4)\times10^{-4}$. It is then clear from this that the phase δ^p_{13} in the A matrix should be of order 1. Our detailed numerical analysis also seems to generate fits to all parameters only for a phase of this order of magnitude.

In order to see the range of the MSSM parameters for which our results remain valid, we scale the squark masses, the A matrix and $M_{\tilde{g}}$ by a common factor k, since this keeps the quark mixings unchanged. At first, one might suspect that the SUSY breaking parameter range is not limited in the theory. But since ϵ_K in our model is coming entirely from the SUSY box graph and it scales like $m_{\tilde{q}}^{-2}$, the squarks cannot be too heavy. There is a scaling relation between the CP phase and the SUSY breaking parameters. The ϵ'/ϵ however scales differently. As a result, we are forced to a narrow range of the SUSY breaking masses.

As a concrete example, consider a case with $\tan\beta = 3$, $m_0 = 80$ GeV, and $M_{1/2} = 180$

GeV. For the trilinear A matrix one may choose: $(A_{11}, A_{12}, A_{13}, A_{22}, A_{23}, A_{33}) = (1.2, 1.8, -2.2, -12, 17, 50)$ GeV and $\delta^p_{13} = 0.02$. We determine μ from the radiative breaking of the electroweak symmetry. Its magnitude in the above parameter space is $\mu \simeq 290$ GeV. We choose the sign of μ as preferred by $b \to s\gamma$ decay. For the quark masses and mixings (at m_t), we find that $V_{us} \simeq -0.21$, $V_{cb} \simeq 0.035$, $V_{ub} \simeq -0.0033$, $V_{td} \simeq -0.012$ and $J \simeq 7 \times 10^{-7}$; $M_d = (-0.0042, -0.059, 2.62)$ GeV, $M_u = (-0.0024, 0.61, 162)$ GeV. The top mass (pole) is 172 GeV. The other masses at their respective mass scales (or at 1 GeV for u, d, s) can be obtained by multiplying with the following QCD correction factors η: $\eta_b = 1.59$, $\eta_c = 2.1$, $\eta_s = 2.4$, $\eta_d = 2.4$ and $\eta_u = 2.4$. The fit for the quark masses and mixings is quite satisfactory.

The squark mass matrices are 6×6 with the 3×3 submatrices denoted by M^2_{LL}, M^2_{RR} and M^2_{LR}. These submatrices need to be rotated by the matrices which are used to diagonalize the up and the down quark mass matrices. If the left-handed and the right-handed rotations for the quark masses are given by $U_{l,i}$ and $U_{r,i}$ where i's can be u or d, then we write the rotated down type squark submatrices (for example) as: $U_{l,d} M^2_{LL} U^\dagger_{l,d}$, $U_{r,d} M^2_{RR} U^\dagger_{r,d}$ and $U_{l,d} M^2_{LR} U^\dagger_{r,d}$. We present only the rotated down squark mass matrices in this case since they are the only ones that enter in the discussion of CP violation in K-decays:

$$M^2_{LL} = \begin{pmatrix} 210442 & -1.8 - 198i & -3.5 - 398i \\ -1.8 + 198i & 209509 & -1594 - 0.86i \\ -3.5 + 398i & -1594 + 0.86i & 174085 \end{pmatrix};$$
$$M^2_{RR} = \begin{pmatrix} 193030 & -2.4 - 263.6i & -5.7 - 651i \\ -2.4 + 263.6i & 191835 & -2583 - 1.4i \\ -5.7 + 651i & -2583 + 1.4i & 187244 \end{pmatrix};$$
$$M^2_{LR} = \begin{pmatrix} 180 + 7.2 \times 10^{-5} i & 0.23 + 86.2i & 8.85 + 979.8i \\ 0.23 - 86.3i & 2430 + 0.0062i & 3060 + 1.72i \\ 7.9 - 874.8i & 2718.3 - 1.52i & 3885.6 + 5.0 \times 10^{-4} i \end{pmatrix}. \quad (3)$$

We need these matrices to calculate flavor changing processes. The usual parameters δ_{ij} parameters can be read off from eq. (3) e.g. $\delta^d_{12,LL}$ is the (1,2) entry divided by the (2,2) entry of M^2_{LL} etc. We find that all the flavor changing constraints arising from the SUSY exchange are consistent with the bounds obtained in [9]. The six down type squark masses in this example are given by: $(459, 458, 440, 439, 433 \text{ and } 415)$ GeV and $M_{\tilde{g}} = 501$ GeV. The parameter space of the model is quite constrained, the example above and its overall rescaling (discussed later) are the only solution we have found.

4. CP violation

Turning now to CP violation, as mentioned before, the value of ϵ_K is used to determine the input phase of the theory. The rephasing invariant J-parameter is of order $\sim 7 \times 10^{-7}$. If the CKM phase is to explain ϵ_K, the value needed is $J \sim 2 \times 10^{-5}$. Thus ϵ_K has a purely supersymmetric origin here. The dominant contribution is from gluino box graph involving the LL and RR terms in the squark mass matrix. These LL and RR terms also have their origin in the off-diagonal A terms through the RGE. All parameters in our model are then essentially fixed. We have tried to vary them to see the effect and find that fitting the quark mixings essentially implies that we must vary m_0, $m_{1/2}$ and A by a common factor k relative to the example just given. The value of ϵ_K is sensitive to k since the CKM contribution to the real part of Δm_K is insensitive to it whereas the imaginary part of the matrix element which receives its dominant contribution from the supersymmetric box graphs scales like $m_{\tilde{q}}^{-2}$. Thus the only freedom allowed in our choice of squark and gaugino masses is whatever comes from the uncertainty in the hadronic matrix elements. Using the 12 elements of the LL and RR mass matrices, we find that the experimental bound on ϵ_K is nearly saturated. We use ref. [10] to find the QCD corrected bound on $\sqrt{[|\mathrm{Im}(\delta^d_{12,LL}\delta^d_{12,RR})|]}$ which is $\sim 1.5 \times 10^{-4}$ for $m_{\tilde{q}} \sim 460$ GeV and $x \sim 1.2$.

Turning next to ϵ'/ϵ, the dominant contributions here are from the penguin diagrams. The CP-violating $\Delta I = 1/2$ penguin Hamiltonian arising from the exchange of squarks is proportional to the difference $\delta_{12,LR} - \delta^*_{21,LR}$. This vanishes above the v_R scale due to the constraints of parity symmetry. However, the RGE running makes this difference nonzero. The diagram for the operator $\bar{d}^\alpha_L \sigma^{\mu\nu} t^A_{\alpha\beta} s^\beta_R G^A_{\mu\nu}$ is formed by the squark line $\tilde{d}_L - \tilde{b}_L - \tilde{s}_R$ in the loop formed by the squark and gluino lines. The magnitudes of the mixings are given by $\delta_{13,LL}$ and $\delta_{32,LR}$. Similarly we have the other diagram where the operator $\bar{d}^\alpha_R \sigma^{\mu\nu} t^A_{\alpha\beta} s^\beta_L G^A_{\mu\nu}$ is formed by the squark line $\tilde{d}_R - \tilde{b}_R - \tilde{s}_L$. We have to subtract one diagram from the other to calculate ϵ'/ϵ and we predict $\epsilon'/\epsilon \simeq 3 \times 10^{-3}$ for the above squark mass matrix and the lattice value for the hadronic matrix elements.

Let us now discuss the parameter space where we can have the right amount of CP violation in ϵ'/ϵ. One simple way is if we change m_0, $M_{1/2}$ and the matrix A in our example by a common factor of k, then V_{CKM} and the fermion masses will remain the same. However one needs to change the phase in order to fit ϵ_K but ϵ'/ϵ might go out of the experimental range. For example if we use $k = 2$, which corresponds to $m_{\tilde{q}} = 900$ GeV, we find that the phase δ^p_{13} is near 0.1 to fit ϵ_K, however our prediction of ϵ'/ϵ becomes a factor 2.5 smaller than what we had before. If k is decreased to 0.5 (corresponds to $m_{\tilde{q}} = 230$ GeV), then the prediction of ϵ'/ϵ becomes a factor of 3 larger. The detailed predictions for the CP violating parameters ϵ'/ϵ along with the neutron edm d^e_n for various choices of k are given in table 1. We see from the table that k somewhere between 0.7 to 2 is acceptable. This is the allowed spread in the squark mass parameters and the other SUSY breaking parameters i.e. squark and gluino masses somewhere between 300 GeV to a TeV. Note that the ratio of the gluino mass to the squark mass is essentially fixed, it is about 1.2 in all the fits. This prediction could serve as a crucial test of the model. We also find that $\tan\beta$ cannot be increased beyond about 6. Larger $\tan\beta$ would require larger value of the off diagonal elements of A (to fit V_{cb}, V_{us} etc). Through RGE, this would yield a SUSY

Table 1. The predictions for ϵ'/ϵ and neutron edm for different values of k. $k = 1$ corresponds to $m_0 = 80$ GeV and $m_{1/2} = 180$ GeV.

k	ϵ'/ϵ	Neutron edm (ecm)
0.5	1.0×10^{-2}	5.0×10^{-29}
1.0	3.1×10^{-3}	5.2×10^{-29}
1.5	2.4×10^{-3}	6.0×10^{-29}
2.0	1.2×10^{-3}	7.0×10^{-29}

contribution to Δm_K that is beyond the experimental limit. Note that the contribution to Δm_K will grow as $(\tan\beta)^2$, so there is really very little room for $\tan\beta \geq 6$.

As for the electric dipole moment of the neutron, we first note that, at the v_R scale, the diagonal Yukawa matrices and hermitean A matrices imply that the neutron edm would vanish in this limit. However once we extrapolate down to the weak scale, the situation changes and we get a nonvanishing, but small edm for neutron as in table 1.

To calculate neutron edm we have considered 3 operators [4]: $O_1 = -\frac{i}{2}\bar{q}\sigma_{\mu\nu}\gamma_5 q F_{\mu\nu}$, $O_2 = -\frac{i}{2}\bar{q}\sigma_{\mu\nu}\gamma_5 T_a q G^a_{\mu\nu}$ and $O_3 = \frac{1}{6} f_{abc} G^a_{\mu\rho} G^{b\rho}_{\nu} G^c_{\lambda\sigma}\epsilon^{\mu\nu\lambda\sigma}$, where G^x_{yz} is the gluon field strength and f_{abc} are the Gellmann coefficients. The effective Lagrangian with the Wilson coefficients is given by: $L = \sum_{i=1}^{3} C_i(Q) O_i(Q)$. We evaluate the C_is at the weak scale and then we multiply by η_i in order to evaluate them at 1.18 GeV. We use $\eta_1 \sim$ 1.53 and η_2=η_3=3.4. Finally we use naive dimensional analysis [11] to calculate the quark edms ($d_q = C_1(1.18) + \frac{e}{4\pi} C_2(1.18) + \frac{1.18\,e}{4\pi} C_3(1.18)$) and then use the quark models to calculate the neutron edm. We estimate $d^e_n \simeq 10^{-28}$–10^{-29} ecm.

A rough intuitive way to see this number is to note that the dominant contribution to d^e_n comes from the A_{11} term which is complex and use the naive estimate from the formula $\frac{\alpha_s}{4\pi}\left(\frac{m_{\tilde{g}}}{m^2_{\tilde{q}}}\right)\mathrm{Im}[\delta_{11,LR}]$. This is a direct consequence of the asymptotic parity invariance of the theory, which leads to hermitean A terms (and of course real μ and $B\mu$ terms). Since the edm is a diagonal operator even after renormalization group extrapolation down to the weak scale, the phases in the diagonal elements of A-terms appear only above two loops resulting in a suppressed edm of neutron.

In conclusion, we have found that the requirement that MSSM be embedded into a supersymmetric left-right framework above a high scale imposes very stringent constraints on the parameters of the MSSM. First it solves the SUSY CP problem, it predicts the value of ϵ'/ϵ in agreement with experiment and the edm of neutron comfortably consistent with the present upper limits. We also find the super-partner masses to be in a very narrow range with the gluino mass not much different from the squark masses.

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