Solutions to the strong CP and SUSY phase problems with parity symmetry

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“Minimal Supersymmetric Left-Right Model”
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Why SUSY Left-Right Symmetry?

- Origin of parity violation better understood
- Compelling reason for neutrino mass
- Automatic $R$–parity in SUSY
- Natural solution to the strong CP problem
- Absence of excessive SUSY CP violation
- Pathway to $SO(10)$ unification
Minimal SUSY Left-Right Model

- Gauge group is $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  - Enables one to define parity

- Quarks and leptons:
  \[
  Q(3,2,1,\frac{1}{3}) = \begin{pmatrix} u \\ d \end{pmatrix}; \quad Q^c(3^*,1,2,-\frac{1}{3}) = \begin{pmatrix} d^c \\ -u^c \end{pmatrix} \\
  L(1,2,1,-1) = \begin{pmatrix} \nu_e \\ e \end{pmatrix}; \quad L^c(1,1,2,1) = \begin{pmatrix} e^c \\ -\nu^c_e \end{pmatrix}
  \]

- Higgs fields:
  \[
  \Delta(1,3,1,2) = \begin{pmatrix} \delta^+ \\ \delta^0 \sqrt{2} \\ -\delta^+ \sqrt{2} \end{pmatrix}; \quad \overline{\Delta}(1,3,1,-2) = \begin{pmatrix} \delta^- \\ \overline{\delta}^0 \sqrt{2} \\ -\delta^- \sqrt{2} \end{pmatrix};
  \]
  \[
  \Delta^c(1,1,3,-2) = \begin{pmatrix} \delta_e^- \\ \delta_e^0 \sqrt{2} \\ -\delta_e^- \sqrt{2} \end{pmatrix}; \quad \overline{\Delta}^c(1,1,3,2) = \begin{pmatrix} \overline{\delta}_e^+ \sqrt{2} \\ \delta_e^0 \sqrt{2} \\ -\overline{\delta}_e^+ \sqrt{2} \end{pmatrix};
  \]
  \[
  \Phi_a(1,2,2,0) = \begin{pmatrix} \phi^+_1 \\ \phi_0^a \\ \phi^-_2 \end{pmatrix}_a \quad (a = 1 - 2); \quad S(1,1,1,0)
  \]
Under parity:

\[ Q \rightarrow Q^{c*}, \quad L \rightarrow L^{c*}, \quad W_L \rightarrow W_R^{*}, \quad B \rightarrow B^{*}, \quad G \rightarrow G^{*}, \quad \theta \rightarrow \bar{\theta} \]

\[ \Phi \rightarrow \Phi^\dagger, \quad \Delta \rightarrow \Delta^{c*}, \quad \bar{\Delta} \rightarrow \bar{\Delta}^{c*}, \quad S \rightarrow S^{*} \]

- Yukawa couplings to $\Phi$ and the $\Delta$ terms are hermitian
- Gluino and Bino masses real
- $\mu$ term for $\Phi$ becomes real
- If $\langle \Phi \rangle$ are also real, fermion mass matrix becomes hermitian
  - Can solve the strong CP problem
  - Can solve the SUSY CP problem
Superpotential:

\[
W = Y_u Q^T \tau_2 \Phi_1 \tau_2 Q^c + Y_d Q^T \tau_2 \Phi_2 \tau_2 Q^c + Y_\nu L^T \tau_2 \Phi_1 \tau_2 L^c + Y_t L^T \tau_2 \Phi_2 \tau_2 L^c \\
+ \ i \left( f^* L^T \tau_2 \Delta L + f L^c T \tau_2 \Delta^c \Delta^c \right) \\
+ \ S \left[ \text{Tr} \left( \lambda^* \Delta \bar{\Delta} + \lambda \Delta^c \bar{\Delta}^c \right) + \lambda_{ab} \text{Tr} \left( \Phi_a^T \tau_2 \Phi_b \tau_2 \right) - M_R^2 \right] + W'
\]

\[
W' = \left[ M_\Delta \Delta \bar{\Delta} + M_{\Delta}^* \Delta^c \bar{\Delta}^c \right] + \mu_{ab} \text{Tr} \left( \Phi_a^T \tau_2 \Phi_b \tau_2 \right) + M_S S^2 + \lambda_S S^3
\]

- If \( W' \) is set to zero, there is an enhanced \( R \) symmetry
  - Helps understand the \( \mu \) problem
  - In the SUSY limit, \( \langle S \rangle = 0 \), but after SUSY breaking, \( \langle S \rangle \sim m_{\text{SUSY}} \)
  - Bidoublet mass term of order \( m_{\text{SUSY}} \)
Problem with the minimal model

Desired vacuum:

$$\langle \Delta^c \rangle = \begin{pmatrix} 0 & v_R \\ 0 & 0 \end{pmatrix}, \quad \langle \bar{\Delta}^c \rangle = \begin{pmatrix} 0 & 0 \\ \frac{1}{v_R} & 0 \end{pmatrix}$$

Charge breaking vacuum:

$$\langle \Delta^c \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & v_R \\ v_R & 0 \end{pmatrix}, \quad \langle \bar{\Delta}^c \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \frac{1}{v_R} \\ \frac{1}{v_R} & 0 \end{pmatrix}$$

All terms in the potential are identical for the two configurations

Except for the $D$–term which prefers the charge breaking vacuum

Kuchimanchi, Mohapatra (1993)
Suggested solutions

1. **Break $R$–parity.** $\Rightarrow v_R \sim 1$ TeV  
   (Kuchimanchi, Mohapatra, 1993)  
   SUSY dark matter lost

2. **Use higher dimensional operators** $\Rightarrow v_R \sim 10^{11}$ GeV  
   (Aulakh, Melfo, Senjanovic, 1998)  
   (Chacko, Mohapatra, 1998)  
   Solution to strong CP and SUSY CP problems generically lost

3. **Do nothing**  
   (Babu, Mohapatra, 2008)
How the model heals itself

- $\Delta^c$ has Majorana Yukawa couplings with $\nu^c \Rightarrow$
  The effective potential contains new type of terms which drastically modifies the tree-level result

- Tree-level potential has no term of type
  $$\text{Tr}(\Delta^c \Delta^c) \text{Tr}(\Delta^{c\dagger} \Delta^{c\dagger})$$
  Induced by Majorana Yukawa couplings in $V_{\text{eff}}$
  Higher dimensional operators generate similar couplings

- Charge and $R$–parity conserving vacuum can be lower than charge breaking vacuum, if coefficient is positive
Effective Potential

Field–dependent masses of \((\nu^c, e^c)\):

\[
D_{1,2}^2 = \frac{1}{2} \left[ \text{Tr}(\Delta^c \Delta^c) \pm \sqrt{\text{Tr}(\Delta^c \Delta^c)^2 - \text{Tr}(\Delta^c \Delta^c) \text{Tr}(\Delta^c \Delta^c)} \right]
\]

\[
m_{1,2}^2 = |f|^2 D_1^2 + m_{Lc}^2 + \frac{g_R^2}{2} [(D_2^2 - \overline{D_2}^2) - (D_1^2 - \overline{D_1}^2)] - \frac{g^2}{2} [(D_1^2 - \overline{D_1}^2) + (D_2^2 - \overline{D_2}^2)],
\]

\[
\pm |A_f f D_1 + \lambda^* S^* f \overline{D_1}|^2
\]

\[
m_{3,4}^2 = |f|^2 D_2^2 + m_{Lc}^2 + \frac{g_R^2}{2} [(D_1^2 - \overline{D_1}^2) - (D_2^2 - \overline{D_2}^2)] - \frac{g^2}{2} [(D_1^2 - \overline{D_1}^2) + (D_2^2 - \overline{D_2}^2)],
\]

\[
\pm |A_f f D_2 + \lambda^* S^* f \overline{D_2}|^2
\]

\[
m_{F_1}^2 = |f D_1|^2
\]

\[
m_{F_2}^2 = |f D_2|^2
\]

\[
V_{\text{eff}}^{1\text{-loop}} = \frac{1}{64\pi^2} \sum_i (-1)^{2s} (2s + 1) M_i^4 \left[ \log\left(\frac{M_i^2}{\mu^2}\right) - \frac{3}{2} \right]
\]
Diagrams inducing effective potential
\[
x = \frac{\text{Tr}(\Delta^c \Delta^c) \text{Tr}(\Delta^{c\dagger} \Delta^{c\dagger})}{[\text{Tr}(\Delta^{c\dagger} \Delta^c)]^2}
\]

\[
V_{\text{eff}}^{1-\text{loop}} = -\frac{|f|^2 m_L^2 \text{Tr}(\Delta^c \Delta^{c\dagger})}{64\pi^2} \left[ (4 + 2 \ln 2) + 2(a_1 - a_2)g_R^2 \sqrt{1-x} + 2(a_1 + a_2)g'{}^2 + \right.
\]
\[
- \left\{ 2 + (a_2 - a_1)g_R^2 + (a_2 + a_1)g'{}^2 \right\} (1 - \sqrt{1-x}) \ln \left( \frac{|f|^2 \text{Tr}(\Delta^c \Delta^{c\dagger})}{2\mu^2} (1 - \sqrt{1-x}) \right)
\]
\[
+ \left\{ (a_2 - a_1)g_R^2 - (a_2 + a_1)g'{}^2 \right\} (1 + \sqrt{1-x}) + 2\sqrt{1-x} \ln \left( \frac{|f|^2 \text{Tr}(\Delta^c \Delta^{c\dagger})}{2\mu^2} (1 + \sqrt{1-x}) \right)
\]
\[
- 2 \ln \left( \frac{|f|^2 \text{Tr}(\Delta^c \Delta^{c\dagger})}{\mu^2} (1 + \sqrt{1-x}) \right) \right]
\]

\[
V_{\text{quartic}} = -\frac{|f|^2 m_L^2 \text{Tr}(\Delta^c \Delta^c) \text{Tr}(\Delta^{c\dagger} \Delta^{c\dagger})}{128\pi^2 |v_R|^2} \left[ 2 - \{ a_1 - a_2 \} g_R^2 - (a_1 + a_2)g'{}^2 \right] (1 + 2 \ln 2)
\]
\[
+ (a_1 - a_2)g_R^2 \ln \frac{|f v_R|^2}{\mu^2} - \{ 2 - (a_1 - a_2)g_R^2 + (a_1 + a_2)g'{}^2 \} \ln x \right] + ...
\]

Global minimum problem is solved
Solving the SUSY CP problem

SUSY models generically lead to large EDM for neutron and electron

\[ d_n^e \approx 10^{-23} \sin \phi \ e - \text{cm} \]

Hermitian Yukawa couplings and \( A\)-terms \( \Rightarrow \)

\[ \sin \phi = 0 \ \text{at} \ v_R \]

RGE induced EDM \( d_n^e \approx 10^{-29} \ \text{e-cm} \)
Solving the strong CP problem

\[ \bar{\theta} = \theta_{QCD} + \text{Arg}\{\text{Det}(M_uM_d)\} - 3\text{Arg}(M_{\tilde{g}}) . \]

Leads to \( d_n^e \sim 10^{-16} \bar{\theta} \)
\[ \Rightarrow \bar{\theta} \leq 10^{-9} \]

- Parity makes \( \theta_{QCD} = 0 \)
- Quark Yukawa matrices hermitian
- gluino mass is real
  \[ \Rightarrow \bar{\theta} = 0 \text{ at tree level} \]
  \( \text{(if } \langle \Phi \rangle \sim \text{ real}) \)
Loop corrections to theta-bar

\[ \delta \bar{\theta} \approx \left( \frac{\ln(M_R/M_W)}{16\pi^2} \right)^4 \left[ c_1 \text{ImTr} \left( Y_u^2 Y_d^4 Y_u^4 Y_d^2 \right) + c_2 \text{ImTr} \left( Y_d^2 Y_u^4 Y_d^4 Y_u^2 \right) \right] \]

\[ \delta \bar{\theta} \approx 3 \times 10^{-27} (\tan \beta)^6 (c_1 - c_2) \]

Loop corrections preserve solution to strong CP problem

KB, Dutta, Mohapatra (2000)
Predictions of the minimal model

1. A pair of light doubly charged Higgs and Higgsino below TeV

Pseudo–Goldstone of $SU(2)_R$ symmetry breaking

Doubly charged Higgs boson mass matrix:

$$M_{δ++}^2 = \begin{pmatrix} -2g_R^2(\nu_R^2 - \bar{\nu}_R^2 + \frac{X}{2}) - \frac{\bar{\nu}_R}{\nu_R} Y & Y^* \\ Y & 2g_R^2(\nu_R^2 - \bar{\nu}_R^2 + \frac{X}{2}) - \frac{\nu_R}{\bar{\nu}_R} Y \end{pmatrix}$$

$$Y = λA_λ S + |λ|^2(\nu_R \bar{\nu}_R - \frac{M_R^2}{λ})^*$$

One doubly charged Higgs is massless at $\nu_R$

Acquires mass only via RGE

Mass $\leq (2 - 3)M_1$
Predictions of the minimal model (cont.)

2. Two pairs of Higgs doublets must remain light below $v_R$. Otherwise CKM mixing vanish, even with two Yukawa coupling matrices for quarks.

Calculable SUSY flavor violation

Proportional to $Y_u^\dagger Y_u$ in down sector

Flavor structure identical to CKM structure

Neutral Higgs mediated FCNC

Similar to CKM structure

Requires one pair of Higgs to be heavier than 10 TeV
3. CKM mixings arise only after radiative corrections

Bidoublet Higgsino mass matrix:

\[
m_\Phi = \begin{pmatrix} \mu_{11} & \mu_{12} \\
\mu_{21} & \mu_{22} \end{pmatrix}
\]

At \( v_R \), \( \mu_{12} = \mu_{21} \) due to parity

Quark Yukawa couplings do not create asymmetry in \( \mu_{ij} \)

However, leptonic Yukawa couplings cause asymmetry \( \mu_{12} \neq \mu_{21} \) since \( \nu^c \) decouple at \( v_R \)

\[
\frac{d}{dt}(\mu_{12} - \mu_{21}) = \frac{\mu_{12} + \mu_{21}}{32\pi^2} \text{Tr}(Y_\nu^\dagger Y_\nu - Y_\ell^\dagger Y_\ell),
\]

Parametrically quark mixings are small, while leptonic mixings are not small
Predictions of the minimal model (cont.)

4. In the simplest version, $(\Delta, \, \bar{\Delta})$ remain light below TeV

$(\Delta, \, \bar{\Delta})$ Higgsino degenerate at $v_R$

Coupings of these particles probe right–handed neutrino mass structure

Rich collider phenomenology
Summary and conclusions

- Minimal SUSY left–right model works!
- Global minimum problem cured by effective potential
- Simple solution to SUSY CP and strong CP problems
- Predicts two sub–TeV doubly charged Higgs
- Left–handed triplet fields naturally light
- Rich collider phenomenology
- Much more works remains to be done

Thank you!