On a reinterpretation of the Higgs field in supersymmetry and a proposal for new quarks

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DSU 2017, Daejeon, July 10-14, 2017
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arXiv: 1701.02652, PLB
The Higgs is intriguing

- the only elementary scalar in the spectrum of the SM
- introduces the hierarchy problem
- no three-fold replication, unlike the rest of the matter

In SUSY the presence of the Higgs(es) is more natural:

- scalar particles exist by construction
- the hierarchy problem can be solved
- models predict the Higgs mass $\lesssim 140$ GeV

**BUT**

- NO explanation is given for the existence of only one family
- Their behaviour is very different from the rest of the matter
Higgses do not have a three-fold replication as the rest of the matter

\[
L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}_{Y = -1/2}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{pmatrix} e_i^c \\ \nu_i \end{pmatrix}_{Y = +1/2}
\]

3 families of superfields in SUSY

\[
W = Y_e H_d^T \epsilon L e^c + Y_d H_d^T \epsilon Q d^c - Y_u H_u^T \epsilon Q u^c
\]

but since \(H_d\) and \(L\) have the same SM quantum numbers, \(Y = -1/2\)

this might lead one to interpret the Higgs superfield \(H_d\) as a fourth family of lepton superfields

\[
L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix} = \begin{pmatrix} H_0^d \\ H_d^- \end{pmatrix} = H_d
\]

Unfortunately, one cannot interpret naturally the superfield \(H_u\) in a similar way, given that it is a doublet with no leptonic counterpart for its neutral component (...right-handed neutrinos)
Higgses are NOT sleptons and Higgsinos are NOT leptons

thus their behaviour is very different, e.g.:

\[ <H_u^0> \neq 0 \ , \ <H_d^0> \neq 0 \ , \]

\[ <\tilde{\nu}_{eL}> = 0 \ , \ <\tilde{\nu}_{\mu L}> = 0 \ , \ <\tilde{\nu}_{\tau L}> = 0 \]

This connection is ONLY posible if R-parity is violated
e.g. the Yukawa couplings of the **MSSM**

\[ W = Y^e_{ij} H_d L_i e^c_j + Y^d_{ij} H_d Q_i d^c_j - Y^u_{ij} H_u Q_i u^c_j \]

have effectively a \( Z_2 \) discrete symmetry (**R parity**)

\[ R_p \text{(particle)} = +1 \]
\[ R_p \text{(sparticle)} = -1 \]

i.e. sparticles must appear in pairs

because of these couplings, there are **mixing** between sparticles, e.g. gauginos & higgsinos

\[
\begin{pmatrix}
\tilde{B}^0, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0
\end{pmatrix}
\]

4 neutralinos:

2 charginos:

\[
\tilde{\chi}^0_1 = N_{11} \tilde{B}^0 + N_{12} \tilde{W}^0 + N_{13} \tilde{H}_d^0 + N_{14} \tilde{H}_u^0
\]

\[
(\tilde{W}^+, \tilde{H}^+)
\]

BUT because of the different \( R_p \) quantum numbers, there can be no mixing between particles and sparticles, e.g. between neutralinos and neutrinos, ...
The gauge-invariant trilinear superpotential containing right-handed neutrinos:

\[
W = Y_{ij}^e H_d L_i e_j^c + Y_{ij}^d H_d Q_i d_j^c - Y_{ij}^u H_u Q_i u_j^c - Y_{ij}^\nu H_u L_i \nu_j^c \\
+ \lambda_{ijk} L_i L_j e_k^c + \lambda_{ijk}^l L_i Q_j d_k^c + \frac{1}{3} \kappa_{ijk} \nu_i^c \nu_j^c \nu_k^c + \lambda_i H_u H_d \nu_i^c.
\]

violates explicitly \( R_p \)

\[
<H_u^0>, <H_d^0>, <\tilde{\nu}_i L>, <\tilde{\nu}_i R> \neq 0
\]

Fields with the same color, electric charge and spin naturally mix, e.g.:

"Neutrinos"

\[
(\tilde{B}^0, \tilde{W}^0, \tilde{H}_d, \tilde{H}_u, \nu_{R_i}, \nu_{L_i}).
\]

Parameter which determines the violation of \( R_p \) : \( Y^\nu \)

\( Y^\nu \rightarrow 0 \) the \( \nu^c \) are no longer neutrinos, they are just ordinary singlets like the \( N \) of the NMSSM: \( N H_1 H_2 + NNN \), and R-parity is conserved
A simple re-interpretation of the spectrum

neutrinos/leptons    neutral Higgs  exist in Nature (SM)

neutrinos/leptons    neutral/charged Higgsinos

neutrinos/leptons    neutral/charged Higgses

neutrinos/leptons    neutral/charged Higgses

sneutrinos/sleptons  neutral/charged Higgsinos

sneutrinos/sleptons  neutral/charged Higgses

There are only neutrinos/leptons (and quarks) and their scalar partners

\[
L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad e_i^c, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad d_i^c, \quad u_i^c
\]

\[
H_d = \begin{pmatrix} H_d^0 \\ H_d \end{pmatrix}, \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}
\]

Higgses are vector-like

leptons of a fourth family

In this framework, the first scalar particle discovered at the LHC is a sneutrino belonging to a 4th-family vector-like doublet representation.
Extra bonuses

\[ W = Y_{ij}^e H_d L_i e_j^e + Y_{ij}^d H_d Q_i d_j^c - Y_{ij}^u H_u Q_i u_j^c - Y_{ij}^\nu H_u L_i \nu_j^c + \lambda_{ijk} L_i L_j e_k^c + \lambda_{ijk}^l L_i Q_j d_k^c + \frac{1}{3} \kappa_{ijk} \nu_i^c \nu_j^c \nu_k^c + \lambda_i H_u H_e \nu_i^c. \]

When the right sneutrinos acquire VEVs of order the EW scale, an effective \( \mu \)-term from \( \nu \) is generated (\( \mu \nu \) SSM)

 produc ing higgsino masses beyond the experimental bounds \( \mu \geq 100 \) GeV

solving the \( \mu \) problem: What is the origin of \( \mu \), and why is so small \( \ll M_{\text{Planck}} \)

-as well as effective Majorana masses for neutrinos: EW scale seesaw

\[ m_\nu \sim m_D^2/M_M = (Y_\nu \nu_u)^2/(\kappa v_R) \sim (10^{-6} 10^2)^2/10^3 = 10^{-11} \text{ GeV} = 10^{-2} \text{ eV} \]

Like the electron Yukawa

solving the \( \nu \) problem: How to accommodate the neutrino data
Since R parity is violated, SUSY particles can decay to standard model particles, there is no missing energy as a special signal, and the bounds become significantly weaker.

Interesting LHC phenomenology because of R-parity violation

- Novel signals with displaced vertices, multilepton final states, multijets

...
E.g.: Left Sneutrino LSP

\( \tilde{\nu}_i \) \( i = e, \mu, \tau \)


\( (\tilde{\nu}_e, \mu, \tau \text{ LSP}) \) diphoton + missing energy

\( (\tilde{\nu}_\tau \text{ LSP}) \) diphoton + leptons

\( (\tilde{\nu}_\tau \text{ LSP}) \) multileptons

\( Y_\nu \sim 10^{-6} \to 45 \lesssim m_{\tilde{\nu}_L} \lesssim 300 \text{ GeV} \) in order to observe its production at the LHC

\( m_{\tilde{\nu}_L} \sim 45 - 100 \text{ GeV} \) have decay lengths \( \sim \text{ mm} \)

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Novel signals from novel R-parity violation
Proposal for new quarks

\[ L_i = \begin{pmatrix} \nu_i^c \\ e_i \\ \nu_i \end{pmatrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \\ u_i \end{pmatrix}, \quad Q^c = \begin{pmatrix} d_i^c \\ u_i^c \end{pmatrix}, \]

\[ L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix} \quad L_4^c = \begin{pmatrix} e_4^c \nu_4 \end{pmatrix} \quad Q_4 = \begin{pmatrix} u_4 \\ d_4 \end{pmatrix} \quad Q_4^c = \begin{pmatrix} d_4^c \\ u_4^c \end{pmatrix} \]

For the first 3 families, each lepton representation has its quark counterpart.

In analogy, we add to the 4th family a vector-like quark doublet representation as counterpart of the vector-like lepton/Higgs doublet representation.

\[ W = Y_{ij} e_i^c H_d L_i e_j + Y_{ij} d_i^c H_d Q_i d_j^c - Y_{ij} u_i^c H_u Q_i u_j - Y_{ij} H_u Q_i L_i \nu_j^c \]

\[ + \lambda_{ijk} L_i e_j e_k^c + \lambda'_{ijk} L_i Q_j d_k^c + \frac{1}{3} \kappa_{ijk} \nu_i^c \nu_j^c \nu_k^c + \lambda_i H_u H_d \nu_i^c \]

\[ + \lambda'_{i4k} L_i Q_4 d_k^c + Y_{4k} d_i^c H_d Q_4 d_k^c - Y_{4k} u_i^c H_u Q_4 u_k^c + Y_{4k} Q_j Q_4 \nu_k^c \]

Mass term for the new quarks.
The presence of extra vector-like matter is a common situation in string constructions: Orbifolds, Branes,…

Font, Ibañez, Nilles, Quevedo, 88; Font, Ibañez, Quevedo, Sierra, 90
Casas, Katehou, C.M., 87; Casas, C.M., 88
Cvetic, Shiu, Uranga, 01

…
Novel signatures for vector-like quarks

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arXiv: 1705.02526, JHEP
Detection of heavy vector-like quarks (T B) at the LHC

Many searches for heavy quark pair or single production focus on the standard decay modes:

- \( T \rightarrow W^+ b \)
- \( T \rightarrow Z t \)
- \( T \rightarrow h^0 t \)
- \( B \rightarrow W^- t \)
- \( B \rightarrow Z b \)
- \( B \rightarrow h^0 b \)

New BRs are possible in models with non-minimal scalar sectors, modifying the analyses:

- \( T \rightarrow H^+ b \)
- \( T \rightarrow H_k^0 t \)
- \( T \rightarrow P_k^0 t \)
- \( B \rightarrow H_k^0 b \)
- \( B \rightarrow P_k^0 b \)

New signals can be produced:

- \( T \rightarrow t \bar{t} t \)
- \( T \rightarrow h^0 h^0 t \)
- \( B \rightarrow t \bar{t} b \)
- \( B \rightarrow h^0 h^0 b \)
Detection of heavy vector-like quarks (T B) at the LHC

\[ T \rightarrow t \bar{b} \ b \]

\[ B \rightarrow t \bar{t} \ b \]

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Novel signals from novel R-parity violation

B \rightarrow h^0h^0b
The lower limits on the (T,B) quark masses are less stringent

\[ \text{T} \rightarrow W^+ b \quad \text{T} \rightarrow Z t \quad \text{T} \rightarrow h^0 t \quad \text{Br}(W) + \text{Br}(Z) + \text{Br}(h^0) = \rho = 1 \]

New decay modes \[ \text{Br}(W) + \text{Br}(Z) + \text{Br}(h^0) = \rho < 1 \]

Figure 6: Lower limits on the T quark mass for several values of \( \rho \) from a recast of the limits of the heavy quark search in ATLAS-CONF-2016-101

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Novel signals from novel R-parity violation
Conclusions

SUSY with right-handed neutrinos naturally produces R-parity violation

- Interesting theoretical advantages:
  - solves the $\mu$ problem
  - solves the $\nu$ problem
  - reinterpretation of the Higgs(es) as a “4th family” of lepton superfields

- Interesting LHC phenomenology:
  - Novel signals with displaced vertices, multilepton final states, multijets, diphoton + leptons, diphoton + missing energy

  new vector-like quarks:

  $T \rightarrow t \bar{t} t$  $T \rightarrow h^0 h^0 t$  $B \rightarrow t \bar{t} b$  $B \rightarrow h^0 h^0 b$
DSU 2005

SURVIVORS OF THE WORKSHOP PREPARED TO ENTER IN THE DARK SIDE OF THE UNIVERSE

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