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

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MultiDark
Multimessenger Approach for Dark Matter Detection

Olivefest: Astroparticle Physics Looking Forward

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Work in collaboration with

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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

Supersymmetry

- Higgses do not have a three-fold replication as the rest of the matter

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ - \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix}$$

Y= -1/2

3 families of superfields in **SUSY**

sleptons + leptons squarks + quarks

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

Y= -1/2 Y= +1/2

1+1 Higgs doublet scalars (vector-like) are needed

$$\mathbf{W} = Y_e H_d^T \epsilon L e^c + Y_d H_d^T \epsilon Q d^c - Y_u H_u^T \epsilon Q u^c$$

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

$$L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix} = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} = H_d$$

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)

$$L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix} = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} = H_d$$

- Actually, even H_d cannot be interpreted as a fourth family of leptons since

  - there can be no mixing between particles and sparticles,

  Higgses are NOT sleptons and Higgsinos are NOT leptons

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

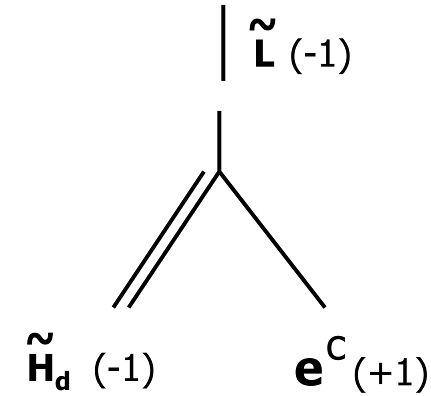
$$\langle H_u^0 \rangle\ ,\ \langle H_d^0 \rangle\ ,\ \langle \tilde{\nu}_i \rangle = \mathbf{0}\ ,\ \langle \tilde{\nu}_i^c \rangle = \mathbf{0}$$

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

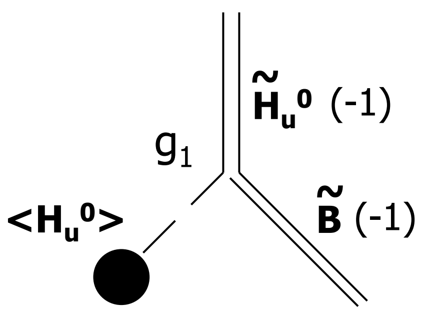
$$W = Y^e_{ij}\, H_d\, L_i\, e^c_j + Y^d_{ij}\, H_d\, Q_i\, d^c_j - Y^u_{ij}\, H_u\, Q_i\, u^c_j$$

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

R_p (particle) = +1
R_p (sparticle) = - 1
i.e. sparticles must appear in pairs



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



$$(\tilde{B}^0, \tilde{W}^0, \tilde{H}^0_1, \tilde{H}^0_2) \Longrightarrow \mathcal{M} = \begin{pmatrix} M_1 & 0 & -\frac{g'\nu_1}{\sqrt{2}} & \frac{g'\nu_2}{\sqrt{2}} \\ 0 & M_2 & \frac{g\nu_1}{\sqrt{2}} & -\frac{g\nu_2}{\sqrt{2}} \\ -\frac{g'\nu_1}{\sqrt{2}} & \frac{g\nu_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g'\nu_2}{\sqrt{2}} & -\frac{g\nu_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix}$$

4 neutralinos: $\tilde{\chi}^0_1 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}^0_1 + N_{14}\tilde{H}^0_2$

2 charginos: $(\tilde{W}^+, \tilde{H}^+)$

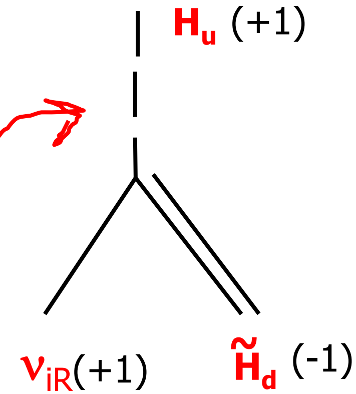
BUT because of the different R_p quantum numbers, there can be no mixing between particles and sparticles, e.g. between neutralinos and neutrinos, …

Supersymmetry with right-handed neutrinos

The most general gauge-invariant trilinear superpotential containing right-handed neutrinos:

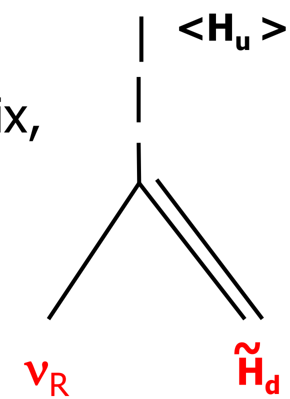
Lopez-Fogliani, C. M., PRL 2006

$$W = Y^e_{ij} H_d L_i e^c_j + Y^d_{ij} H_d Q_i d^c_j - Y^u_{ij} H_u Q_i u^c_j - Y^\nu_{ij} H_u L_i \nu^c_j$$
$$+ \lambda_{ijk} L_i L_j e^c_k + \lambda'_{ijk} L_i Q_j d^c_k + \frac{1}{3}\kappa_{ijk} \nu^c_i \nu^c_j \nu^c_k + \lambda_i H_u H_d \nu^c_i .$$



violates explicitly R_p

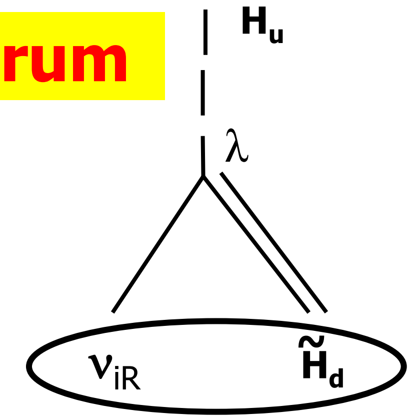
$\langle H_u^0\rangle$, $\langle H_d^0\rangle$, $\langle\tilde{\nu}_i\rangle$, $\langle\tilde{\nu}^c_i\rangle$ $\neq 0$



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

"Neutrinos" $(\tilde{B}^0, \tilde{W}^0, \tilde{H}_d, \tilde{H}_u, \nu_{R_i}, \nu_{L_i}),$

A simple re-interpretation of the spectrum



neutrinos/leptons   neutral Higgs   exist in Nature (SM)

SUSY predicts

neutrinos/leptons   neutral/charged Higgsinos   are mixed

\+   +

sneutrinos/sleptons   neutral/charged Higgses   are mixed

in SUSY with neutrinos/RPV

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

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix} \quad \longrightarrow \quad L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix}$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

Higgses are vector-like leptons of a fourth family

$$\longrightarrow \quad L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix}, \quad L_4^c = \begin{pmatrix} e_4^c \\ \nu_4^c \end{pmatrix}.$$

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

$$W = Y^e_{ij} H_d L_i e^c_j + Y^d_{ij} H_d Q_i d^c_j - Y^u_{ij} H_u Q_i u^c_j - Y^\nu_{ij} H_u L_i \nu^c_j$$
$$+ \lambda_{ijk} L_i L_j e^c_k + \lambda'_{ijk} L_i Q_j d^c_k + \frac{1}{3}\kappa_{ijk} \nu^c_i \nu^c_j \nu^c_k + \lambda_i H_u H_d \nu^c_i .$$

When the right sneutrinos acquire VEVs of order the EW scale, an effective μ-term from ν is generated (μνSSM)

Lopez-Fogliani, C. M., PRL 2006

-producing higgsino masses beyond the experimental bounds μ ≥ 100 GeV

solving the μ problem: What is the origin of μ, and why is so small << M_{Planck}

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

$$m_\nu \sim m_D^2/M_M = (Y_\nu v_u)^2/(k\, v_{\nu^c}) \sim (10^{-6}\, 10^2)^2/10^3 = 10^{-11}\ \text{GeV} = 10^{-2}\ \text{eV}$$

Like the electron Yukawa

solving the ν problem: How to accommodate the neutrino data

Extra bonuses

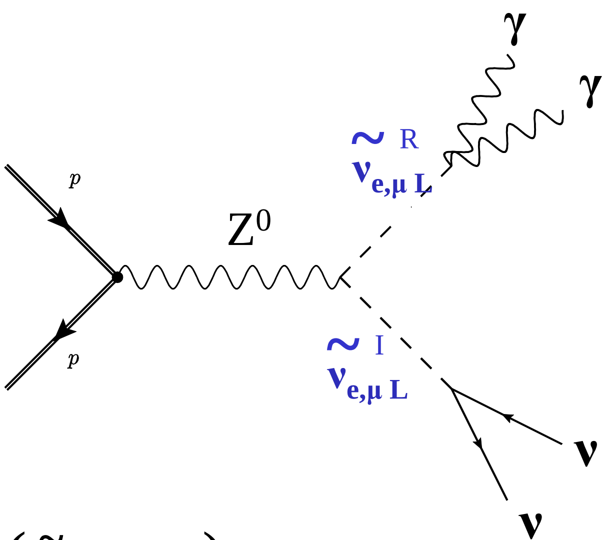
- Since R parity is violated, SUSY particles can decay to standard model particles, there is no missing energy as a special signal, and the bounds become significantly weaker

- Interesting LHC phenomenology because of R-parity violation

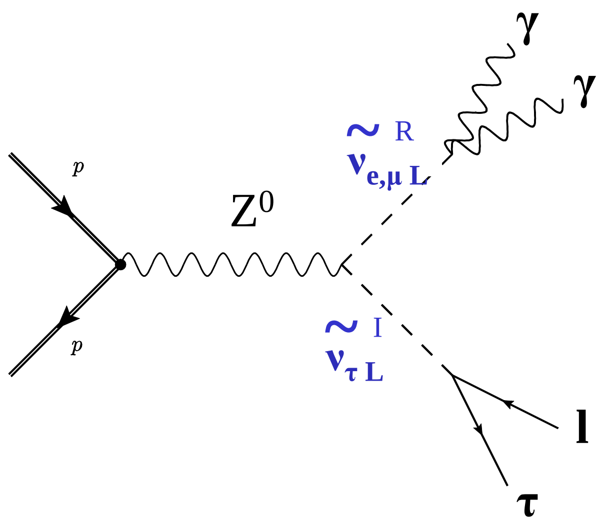
  - Novel signals with displaced vertices,
    multilepton final states,
    multijets
    …

E.g.: **Left Sneutrino LSP**

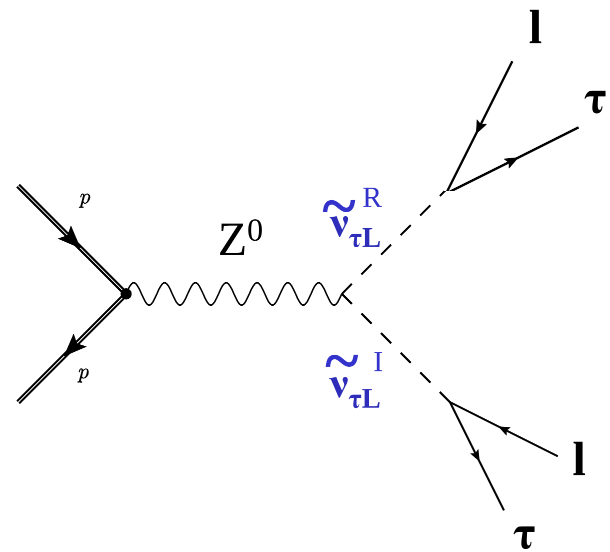
Ghosh, Lara, Lopez-Fogliani, C.M., Ruiz de Austri, in preparation



$(\tilde{\nu}_{e,\mu}$ LSP$)$ diphoton
\+ missing energy



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



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

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

DISPLACED

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

Proposal for new quarks

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \qquad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \qquad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \qquad \begin{matrix} d_i^c \\ u_i^c \end{matrix},$$

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

$$L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix}_{Y=-1/2}, \; L_4^c = \begin{pmatrix} e_4^c \\ \nu_4^c \end{pmatrix}_{Y=+1/2}, \quad Q_4 = \begin{pmatrix} u_4 \\ d_4 \end{pmatrix}_{Y=+1/6}, \; Q_4^c = \begin{pmatrix} d_4^c \\ u_4^c \end{pmatrix}_{Y=-1/6},$$

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

$$\begin{aligned} W \;=\;& Y_{ij}^e \, H_d \, L_i \, e_j^c + Y_{ij}^d \, H_d \, Q_i \, d_j^c - Y_{ij}^u \, H_u \, Q_i \, u_j^c - Y_{ij}^\nu \, H_u \, L_i \, \nu_j^c \\ +\;& \lambda_{ijk} \, L_i \, L_j \, e_k^c + \lambda'_{ijk} \, L_i \, Q_j \, d_k^c + \frac{1}{3}\kappa_{ijk} \, \nu_i^c \, \nu_j^c \, \nu_k^c + \lambda_i \, H_u \, H_d \, \nu_i^c \\ +\;& \underline{\lambda'_{i4k} \, L_i \, Q_4 \, d_k^c + Y_{4k}^d \, H_d \, Q_4 \, d_k^c - Y_{4k}^u \, H_u \, Q_4 \, u_k^c + Y_{j4k}^Q \, Q_j \, Q_4^c \, \nu_k^c + Y_{44k}^Q \, Q_4 \, Q_4^c \, \nu_k^c} \end{aligned}$$

Mass term for the new quarks

We note in passing...

Strings?

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

arXiv: 1705.02526

Work in collaboration with

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J. A. Aguilar-Saavedra
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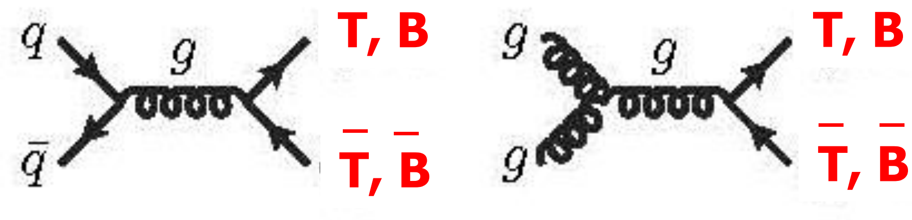
Detection of heavy vector-like quarks (T B) at the LHC

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



+ ...

$T \longrightarrow W^+ b$ $\quad T \longrightarrow Z\, t$ $\quad T \longrightarrow h^0\, t$

$B \longrightarrow W^- t$ $\quad B \longrightarrow Z\, b$ $\quad B \longrightarrow h^0\, b$

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

k=1 $\longrightarrow$ MSSM like

k=1,2 $\longrightarrow$ μνSSM $\tilde{\nu}_R$

$T \longrightarrow H^+ b$ $\quad T \longrightarrow H_k^0\, t$ $\quad T \longrightarrow P_k^0\, t$

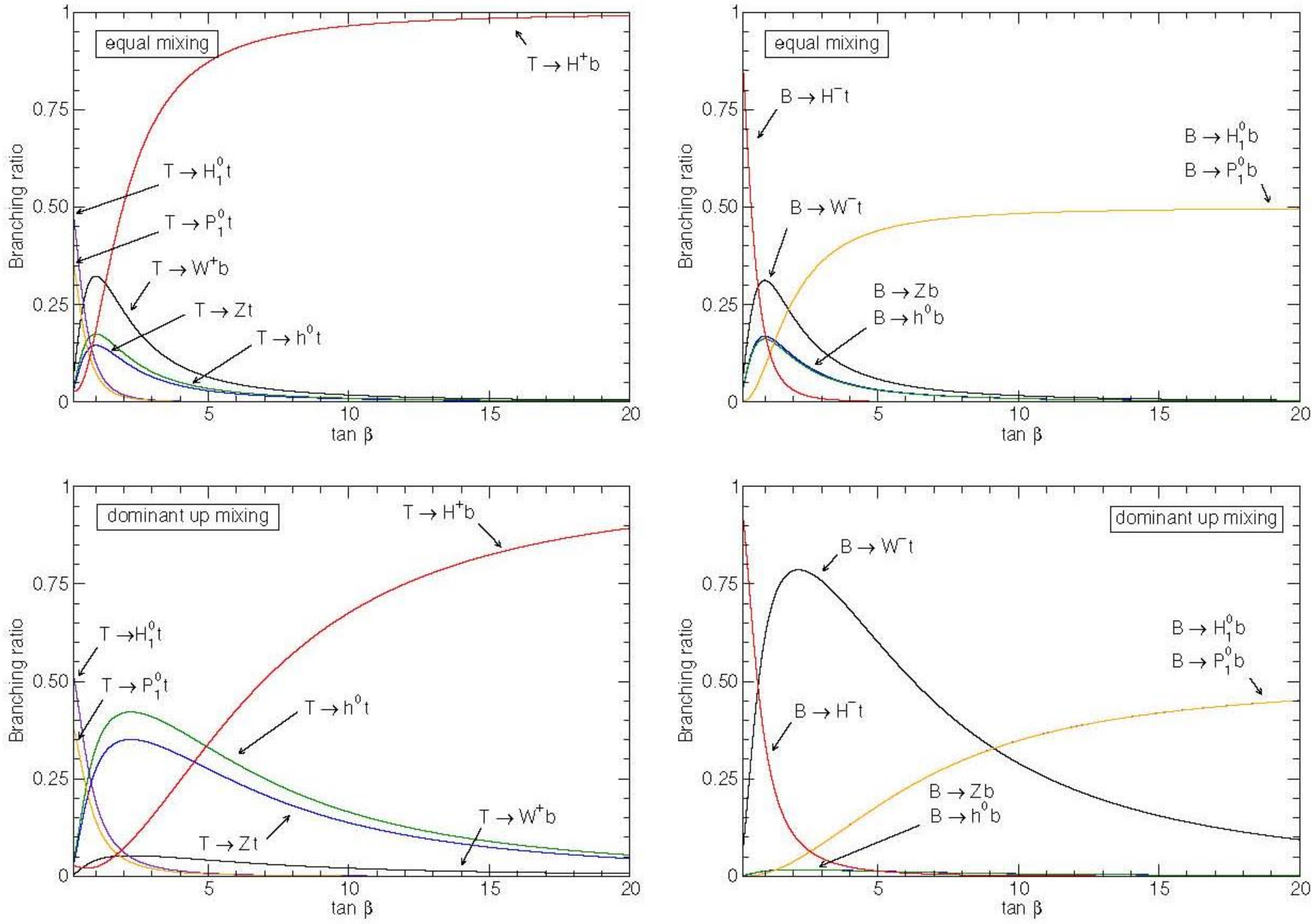
$B \longrightarrow H^- t$ $\quad B \longrightarrow H_k^0\, b$ $\quad B \longrightarrow P_k^0\, b$

New signals can be produced:

$T \longrightarrow t\, \bar{t}\, t$ $\quad T \longrightarrow h^0 h^0\, t$

$B \longrightarrow t\, \bar{t}\, b$ $\quad B \longrightarrow h^0 h^0\, b$

Detection of heavy vector-like quarks (T B) at the LHC



$T \longrightarrow t\,\bar{b}\,b$

$B \longrightarrow t\,\bar{t}\,b$

$B \longrightarrow h^0 h^0 b$

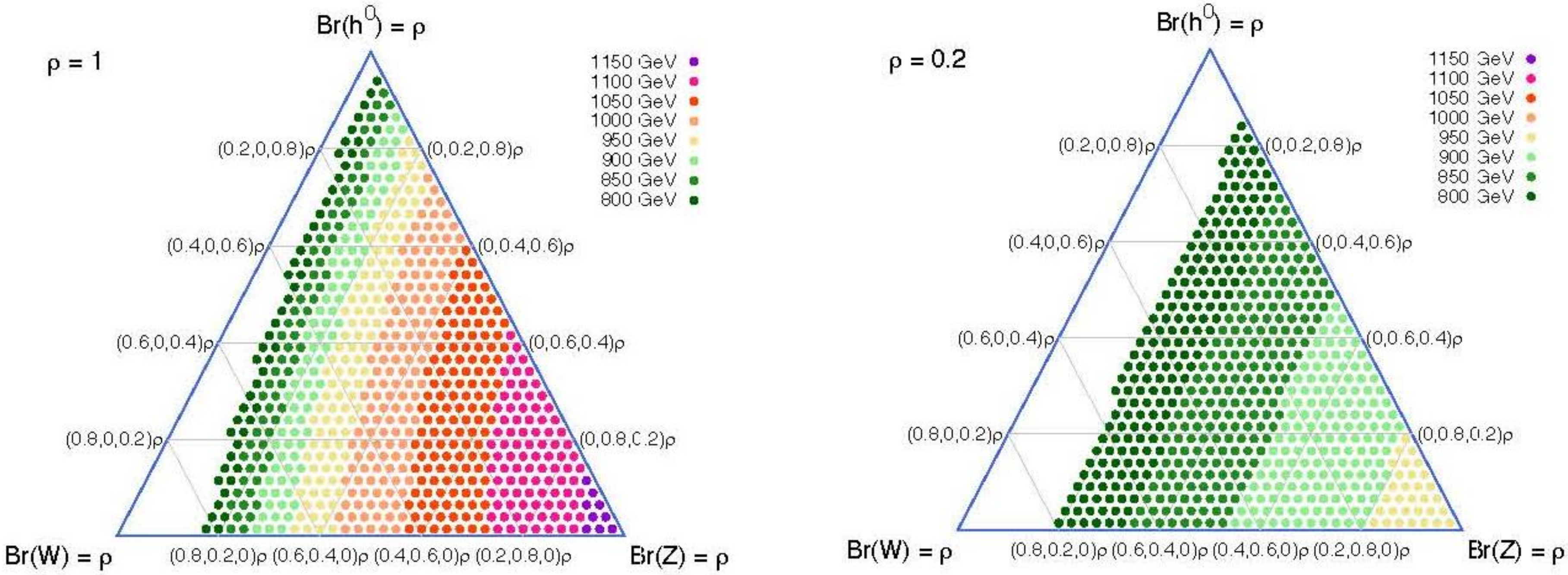


Figure 6: Lower limits on the T quark mass for several values of ρ from a recast of the limits of the heavy quark search in ref. [59].

$$\mathrm{Br}(W) + \mathrm{Br}(Z) + \mathrm{Br}(h^0) = \rho\,,$$

Conclusions

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

- Interesting theoretical advantages:

  - solves the μ problem
  - solves the ν problem
  - reinterpretion 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

$\mathbf{T} \longrightarrow t\,\bar{t}\,t \quad \mathbf{T} \longrightarrow h^0\,h^0\,t \quad \mathbf{B} \longrightarrow t\,\bar{t}\,b \quad \mathbf{B} \longrightarrow h^0\,h^0\,b$

THE END

Happy birthday Keith!

from MultiDark