Left-right Susy at the TeV Scale

Toby Opferkuch

Based on arXiv:1512.00472 [JHEP 03 (2016) 009]

in collaboration with Martin Hirsch, Manuel E. Krauss, Werner Porod and Florian Staub

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July 28, 2016

What is SARAH and how does it help?

User

Idea for a new model

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Create SARAH input file

↑

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Derive expressions for masses, vertices, RGEs, . . .

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SARAH

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Create SARAH input file

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Idea for a new model

SPheno

SARAH

User

What is SARAH and how does it help?

Collider pheno	Dark matter	Higgs constraints	Vacuum stability	CalcHep, HB, WHIZARD, MG5, MicrOmegas, Vevacious
↑	↑	↑	↑	

Flavour observables, BSM particle and Higgs decays — SPheno

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Calculate running parameters, BSM masses at one-loop, Higgs masses at two-loop, Fine-Tuning — SPheno

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Create model files for MC tools & `Vevacious` as well as Fortran code for `SPheno` — SARAH

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Derive expressions for masses, vertices, RGEs, . . . — SARAH

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Create `SARAH` input file — User

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Idea for a new model — User

Motivation

Theory space beyond the MSSM

Why should we care about SUSY beyond the MSSM?

- Neutrino masses
- Higgs mass measurements

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Appealing features that we'd really like to keep:

- Gauge coupling unification
- Dark Matter

What are the most convincing avenues one should explore?

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SO(10) GUTs

Typical breaking chain

$$\mathrm{SO}(10) \to \mathrm{SU}(5) \times \mathrm{U}(1) \to \mathcal{G}_{\mathrm{S}M}$$

- SM field content fits perfectly in a spinorial **16**-plet
- Spinorial **16**-plet contains a singlet $\Longrightarrow$ Neutrino masses!

Alternate SO(10) breaking chains

Classic SUSY alternative

$$\mathrm{SO}(10) \xrightarrow{M_{\mathrm{GUT}}} \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times U(1)_{B-L} \xrightarrow{M_R} \mathcal{G}_{\mathrm{SM}}$$

If left-right symmetry broken by $\mathrm{SU}(2)_R$ triplets $\Longrightarrow M_R \geq 10^9\,\mathrm{GeV}$

[S. K. Majee, M. K. Parida, A. Raychaudhuri & U. Sarkar (hep-ph/0701109)]

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Models with "sliding" M_R scale can be constructed

- Field content varied to enforce MSSM-like GCU
- M_R can be in TeV range

[C. Arbeláez, R. Fonesca, M. Hirsch & J. Romão (1301.6085)]

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Three variants possible:

Variant I: low scale $\mathrm{U}(1)_R$

$$\mathrm{SO}(10) \xrightarrow{M_{\mathrm{GUT}}} \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times U(1)_{B-L}$$

$$\xrightarrow{\sim M_{\mathrm{GUT}}} \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_R \times \mathrm{U}(1)_{B-L} \xrightarrow{M_R} \mathcal{G}_{\mathrm{SM}}$$

[M. Hirsch, W. Porod, L. Reichert & F. Staub (1206.3516)]

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Three variants possible:

Variant II: low scale Pati-Salam

$$\mathrm{SO}(10) \xrightarrow{M_{\mathrm{GUT}}} \mathrm{SU}(4) \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$$

$$\xrightarrow{M_R} \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L} \to \mathcal{G}_{\mathrm{SM}}$$

Alternate SO(10) breaking chains

Classic SUSY alternative

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Three variants possible:

Variant III: low scale $\mathrm{SU}(2)_R$

$$\mathrm{SO}(10) \xrightarrow{M_{\mathrm{GUT}}} \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L} \xrightarrow{M_R} \mathcal{G}_{\mathrm{SM}}$$

[M. Hirsch, M. E. Krauss, TO, W. Porod & F. Staub (1512.00472)]

So, what's the plan?

1. Construct a complete, concrete GUT-compatible model
2. Consider implications of the *complete model* with the aid of the computer tools `SARAH` & `SPheno`

The Model

Field content, superpotential and all that jazz!

Minimal particle content consistent with sliding left-right scale and low energy observations

$$W = \underbrace{Y_{Q_a} Q\, \Phi^a Q_c + Y_{L_a} L\, \Phi^a L_c}_{\text{Yukawa terms}} + \underbrace{\mu_\Phi^{ab} \Phi_a \Phi_b}_{\mu\text{-terms}}$$

Field	Gen.	$\mathcal{G}_{LR}$
Q	3	$(\mathbf{3}, \mathbf{2}, \mathbf{1}, +\frac{1}{3})$
Q_c	3	$(\overline{\mathbf{3}}, \mathbf{1}, \mathbf{2}, -\frac{1}{3})$
L	3	$(\mathbf{1}, \mathbf{2}, \mathbf{1}, -1)$
L_c	3	$(\mathbf{1}, \mathbf{1}, \mathbf{2}, +1)$
Φ	2	$(\mathbf{1}, \mathbf{2}, \mathbf{2}, 0)$

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$$+ \quad \underbrace{\mu_{\chi_c} \bar{\chi}_c \chi_c}_{\mathrm{SU}(2)_R\ \mu\text{-term}}$$

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$$+ \underbrace{\mu_{\chi_c} \bar{\chi}_c \chi_c}_{\mathrm{SU}(2)_R\ \mu\text{-term}} + \underbrace{M_\delta \delta_d \bar{\delta}_d + M_\Psi \Psi \Psi_c}_{\text{vector-like masses}}$$

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δ_d	1	$(\mathbf{3}, \mathbf{1}, \mathbf{1}, -\frac{2}{3})$
$\bar{\delta}_d$	1	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1}, +\frac{2}{3})$
$\Psi,\ \Psi_c$	2	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \pm 2)$
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$$+ \underbrace{Y_{\delta_d} Q_c \bar{\chi}_c \delta_d}_{\text{quark mixing \& tadpole-consistency}} + \underbrace{Y_\Psi L_c \bar{\chi}_c \Psi_c}_{\text{lepton mixing \& GCU}}$$

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$$+ \underbrace{Y_S L_c\chi_c S + \frac{\mu_S}{2}S^2}_{\text{inverse see-saw}}$$

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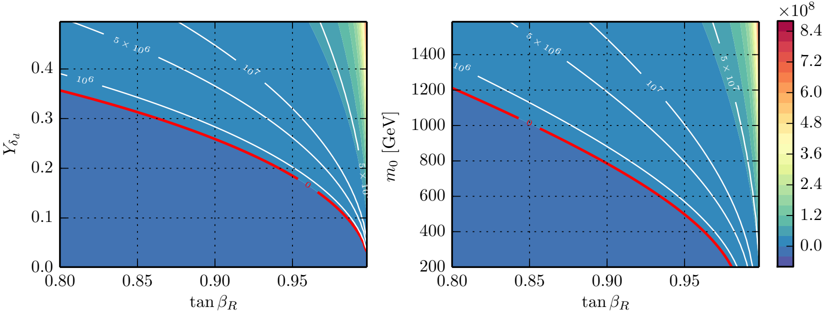
Breaking the left-right phase

After minimisation of potential $\mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ breaking requires

$$|\mu_{\chi_c}|^2 \simeq \frac{1}{1-t^2_{\beta_R}}\left(m^2_{\chi_c} t^2_{\beta_R} - m^2_{\bar{\chi}_c}\right) - \frac{1}{2}M^2_{Z'} > 0$$

Condition requires $Y_{\delta_d} > 0$ and either large m_0 and or A_0 assuming one-loop running of soft-masses



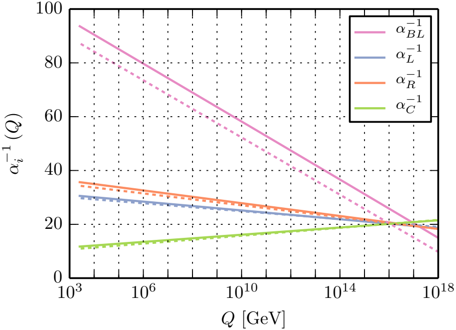
Consistency prefers $t_{\beta_R} \lesssim 1$ (also non-tachyonic sfermion masses $t_{\beta_R} < 1$)

Gauge coupling unification

Large unification scale
$M_{\rm GUT}^{2-\rm loop} = 10^{17}\,\rm GeV > M_{\rm GUT}^{1-\rm loop}$

Behaviour arises from large threshold corrections:

- Large logarithms arising from heavy right-sector particles
- Large beta coefficient $\beta_{g_{BL}} = 29/2$



- Dashed: one-loop RGEs
- Solid: two-loop RGEs & one-loop thresholds

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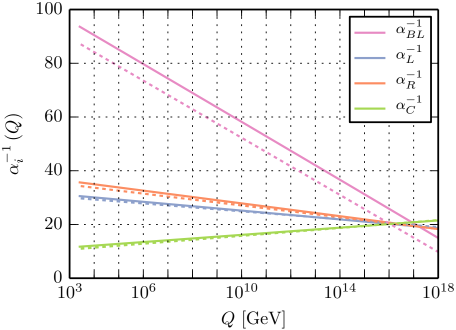

Consequence

Requiring GCU predicts $M_R \lesssim 10\,\text{TeV}$

- Dashed: one-loop RGEs
- Solid: two-loop RGEs & one-loop thresholds

The upshot?

1. Constructed a complete, consistent high-scale model with GCU & mSUGRA-like boundary conditions
2. Extra matter required for GCU essential for successful symmetry breaking pattern
3. Distinctive phenomenology in comparison to the MSSM (stay tuned though, more to come!)

Backup Slides

Quark masses and mixing

To fit all masses and mixings **more than one bi-doublet is required!**

$$M_d = \begin{pmatrix} \frac{v_d}{\sqrt{2}} Y_Q & \frac{v_{\bar{\chi}_c}}{\sqrt{2}} Y_{\delta_d} \\ \tilde{m} & M_{\delta_d} \end{pmatrix} \quad \text{with} \quad V_{\text{CKM}}^{4\times 4} = \tilde{U}_L^u (U_L^d)^\dagger$$

Choose basis where $\tilde{U}_L^u$ is diagonal $\Longrightarrow Y_Q$ is also diagonal

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See-saw approximation: $M_{\delta_d} \gg m_b$

$$M = \frac{v_{\bar{\chi}_c}^2 Y_{\delta_d} Y_{\delta_d}^\dagger}{2} - \tilde{y}\tilde{y}^\dagger \qquad (1)$$

$$M = V_{\text{CKM}}^* \text{diag}(m_d^2, m_s^2, m_b^2) V_{\text{CKM}}^T - 1/2 v_d^2 Y_Q Y_Q^\dagger$$

$$\tilde{y} = \frac{v_u Y_Q \tilde{m}^\dagger + M_{\delta_d}^* v_{\bar{\chi}_c} Y_{\delta_d}}{\sqrt{2(|\tilde{m}|^2 - M_{\delta_d}^2)}}$$

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Linear algebra to the rescue!

$$\det(A + uv^T) = (1 + v^T A^{-1} u)\det(A)$$

Applied to RHS of (1): $\det(A) = 0$
Applied to LHS of (1):

$$\frac{v_d^2}{2} Y_Q^2 = V_{\text{CKM}}^* \text{diag}(m_d^2, m_s^2, m_b^2) V_{\text{CKM}}^T$$

The Higgs sector

$\mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ through doublets

$$\chi_c = \begin{pmatrix} \chi_c^0 \\ -\chi_c^- \end{pmatrix} \qquad \bar{\chi}_c = \begin{pmatrix} \bar{\chi}_c^+ \\ -\bar{\chi}_c^0 \end{pmatrix}$$

with VEVs

$$\chi_c^0 = \frac{1}{\sqrt{2}} \left(\sigma_{\chi_c} + i\varphi_{\chi_c} + v_{\chi_c} \right)$$
$$\bar{\chi}_c^0 = \frac{1}{\sqrt{2}} \left(\bar{\sigma}_{\bar{\chi}_c} + i\bar{\varphi}_{\bar{\chi}_c} + v_{\bar{\chi}_c} \right)$$

and definitions

$$v_R^2 = v_{\chi_c}^2 + v_{\bar{\chi}_c}^2$$
$$t_{\beta_R} = \tan\beta_R = \frac{v_{\chi_c}}{v_{\bar{\chi}_c}}$$

EW-breaking through bi-doublets

$$\Phi^a = \begin{pmatrix} H_d^{a0} & H_u^{a+} \\ H_d^{a-} & H_u^{a0} \end{pmatrix}$$

with VEVs

$$H_d^{a0} = \frac{1}{\sqrt{2}} \left(\sigma_d^a + i\varphi_d^a + v_\Phi^{d_a} \right)$$
$$H_u^{a0} = \frac{1}{\sqrt{2}} \left(\sigma_u^a + i\varphi_u^a + v_\Phi^{u_a} \right)$$

and definitions

$$v_L^2 = (v_\Phi^{d_1})^2 + (v_\Phi^{d_2})^2 + (v_\Phi^{u_1})^2 + (v_\Phi^{u_2})^2$$
$$v_\Phi^{u_1} = v_L \sin\beta \sin\beta_u, \;\; v_\Phi^{d_1} = v_L \cos\beta \sin\beta_d$$
$$v_\Phi^{u_2} = v_L \sin\beta \cos\beta_u, \;\; v_\Phi^{d_2} = v_L \cos\beta \cos\beta_d$$

PHENOMENOLOGY

Higgs phenomenology

D-term contributions raise absolute upper bound

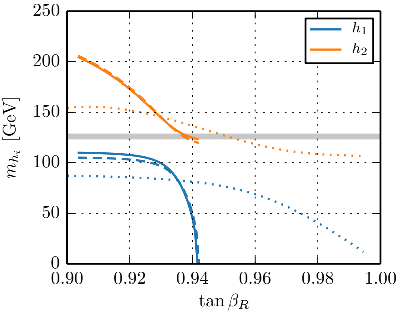
$$m^2_{h,\text{tree}}\Big|^{t_{\beta_R}\to 1} \leq \frac{1}{4}(g_L^2 + g_R^2)\, v_L^2$$

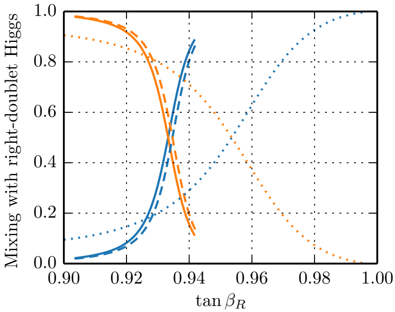
[K. Huitu, P. Pandita & K. Puolamaki (hep-ph/9708486)]

[K. Babu & A. Patra (1412.8714)]

After level-crossing

$$m^2_{h,\text{tree}}\Big|^{t_{\beta_R}\to 0} \leq \frac{1}{4}\left(g_L^2 + \frac{g_{BL}^2 g_R^2}{g_{BL}^2 + g_R^2}\right) v_L^2 = M_Z^2$$

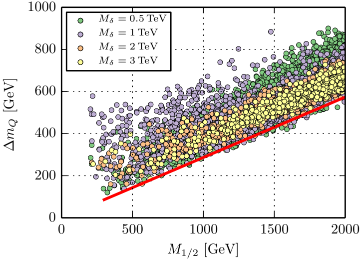




Squark mass spectrum

Splitting between squark soft-masses proportional to $M_{1/2}$

$$\Delta m_Q^2 \equiv (m_Q^{(3,3)})^2 - (m_{Q_c}^{(3,3)})^2$$
$$\simeq 8.2 \times 10^{-2} M_{1/2}^2$$



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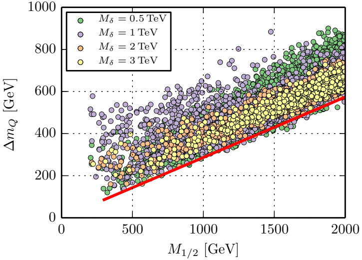
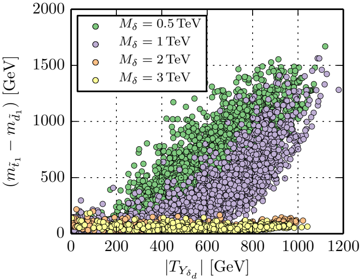


Generically $m_{\tilde{b}_1} < m_{\tilde{t}_1}$

Arises as:

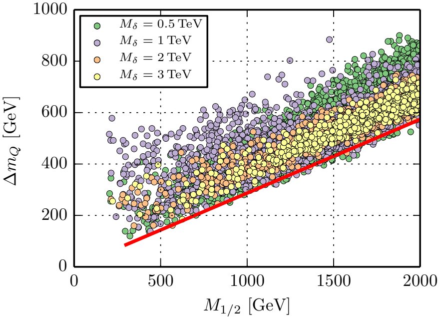
- $\tilde{b}_1$ is large mixture of $\tilde{b}_R$ and $\tilde{\delta}_d$
- Large mixing due to parameters Y_{δ_d}, v_R and A_0 for fixed M_δ



Soft-mass spectrum

Splitting between squark soft-masses proportional to $M_{1/2}$

$$\Delta m_Q^2 \equiv (m_Q^{(3,3)})^2 - (m_{Q_c}^{(3,3)})^2$$
$$\simeq 8.2 \times 10^{-2} M_{1/2}^2$$



MSSM:

$$m_q^2(M_{\rm SUSY}) \simeq m_0^2 + 5.2 M_{1/2}$$
$$m_d^2(M_{\rm SUSY}) \simeq m_0^2 + 4.8 M_{1/2}$$
$$m_u^2(M_{\rm SUSY}) \simeq m_0^2 + 4.8 M_{1/2}$$
$$m_l^2(M_{\rm SUSY}) \simeq m_0^2 + 0.50 M_{1/2}$$
$$m_e^2(M_{\rm SUSY}) \simeq m_0^2 + 0.15 M_{1/2}$$

$SU(2)_R$ Model:

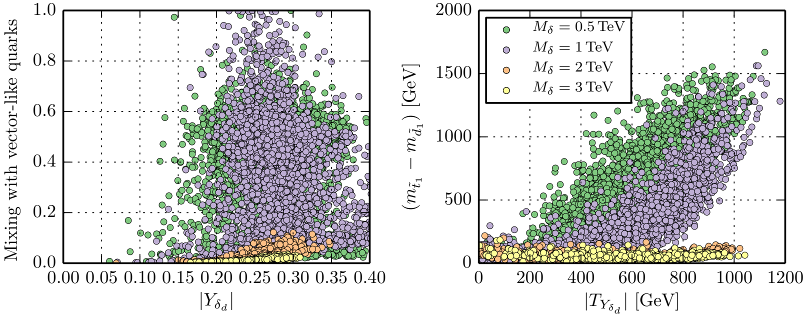
$$m_Q^2(M_{\rm SUSY}) \simeq m_0^2 + 3.6 M_{1/2}$$
$$m_{Q^c}^2(M_{\rm SUSY}) \simeq m_0^2 + 3.5 M_{1/2}$$
$$m_L^2(M_{\rm SUSY}) \simeq m_0^2 + 0.44 M_{1/2}$$
$$m_{L^c}^2(M_{\rm SUSY}) \simeq m_0^2 + 0.36 M_{1/2}$$

Squark spectrum

Generically $m_{\tilde{b}_1} < m_{\tilde{t}_1}$

Arises as:

- $\tilde{b}_1$ is large mixture of $\tilde{b}_R$ and $\tilde{\delta}_d$
- Large mixing due to parameters Y_{δ_d}, v_R and A_0 for fixed M_δ



Parameter values from figures

Higgs mass figures

Parameter	Value
m_0	$1.2\,\mathrm{TeV}$
$M_{1/2}$	$1.2\,\mathrm{TeV}$
A_0	$1\,\mathrm{TeV}$
$\mu_\Phi^{(2,2)}$	$-2\,\mathrm{TeV}$
v_R	$7\,\mathrm{TeV}$
$\tan\beta$	15
$\tan\beta_u$	10
$\tan\beta_d$	0
M_δ	$1\,\mathrm{TeV}$
$Y^i_{\delta_d}$	0.09

Squark mass figures

Parameter	Value
m_0	$[0.2, 2]\mathrm{TeV}$
$M_{1/2}$	$[0.2, 2]\mathrm{TeV}$
A_0	$[0, 3]\mathrm{TeV}$
$\mu_\Phi^{(2,2)}$	$[-3, 3]\mathrm{TeV}$
v_R	$[6.5, 9]\mathrm{TeV}$
$\tan\beta_R$	$[0.8, 1]$
$\tan\beta$	$[1, 30]$
$\tan\beta_u$	$[1, 30]$
$\tan\beta_d$	0
$Y^i_{\delta_d}$	$[-0.15, 0.15]$