Testing top-bottom-tau unification at the LHC

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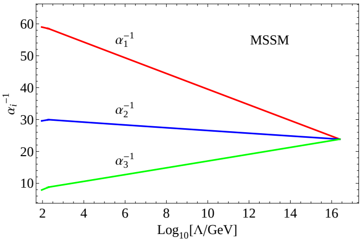
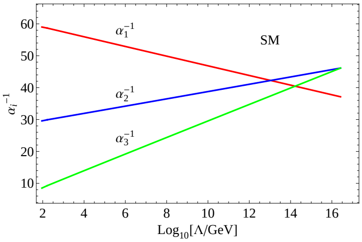
Low Energy Supersymmetry (SUSY)

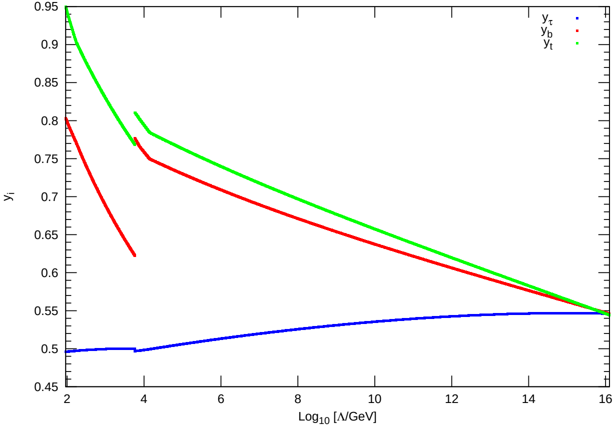
- Resolution of the gauge hierarchy problem;
- Cold dark matter candidate (LSP);
- Radiative electroweak symmetry breaking;
- Predicts new particles accessible at the LHC;
- Unification of the SM gauge couplings.





- SUSY has to be broken. One of the most popular scenarios is gravity mediated SUSY breaking

- SUSY and $t - b - \tau$ Yukawa coupling unification



SO(10) GUT

- The SM fermions: 16 and the MSSM Higgs boson: **10**
- Third family Yukawa coupling **16 16 10** yields

$$Y_t = Y_b = Y_\tau = Y_\nu$$

- It turns out to be difficult in the SO(10) model to reconcile the lightest neutralino primordial abundance with the observed dark matter densities.

H. Baer, S. Kraml, S. Sekmen and H. Summy, JHEP 0803, 056 (2008); Phys. Lett. B 666, 5 (2008)

- $m_{16},\ m_{10},\ M_D,\ M_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
- $m_{16} \equiv$ Universal soft SUSY breaking sfermion mass
- $m_{10} \equiv$ Universal soft SUSY breaking MSSM Higgs mass
- $M_D \equiv$ The Higgs mass splitting $M^2_{H_{u,d}} = m^2_{10} \mp 2M^2_D$
- $m_{1/2} \equiv$ Universal SSB gaugino mass
- $A_0 \equiv$ Universal SSB trilinear interaction
- $\tan\beta = \frac{v_u}{v_d}$
- $\mu \equiv$ SUSY bilinear Higgs parameter

- Random scans was performed over the parameter space

$$
\begin{array}{lll}
m_{16}: & 0 - 20 \text{ TeV} & (1 - 20 \text{ TeV}), \\
m_{10}/m_{16}: & 0 - 1.5 & (0.8 - 1.4), \\
m_{1/2}: & 0 - 5 \text{ TeV} & (0 - 1 \text{ TeV}), \\
A_0/m_{16} & -3 - 3 & (-2.5 - 1.9), \\
M_D/m_{16}: & 0 - 0.8 & (0.25 - 0.8), \\
\tan\beta: & 40 - 60 & (46 - 53).
\end{array}
$$

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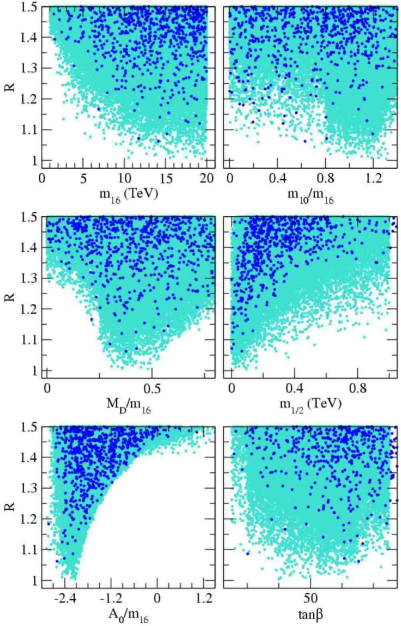
\end{array}
$$

- It was introduce a parameter R to quantify Yukawa unification

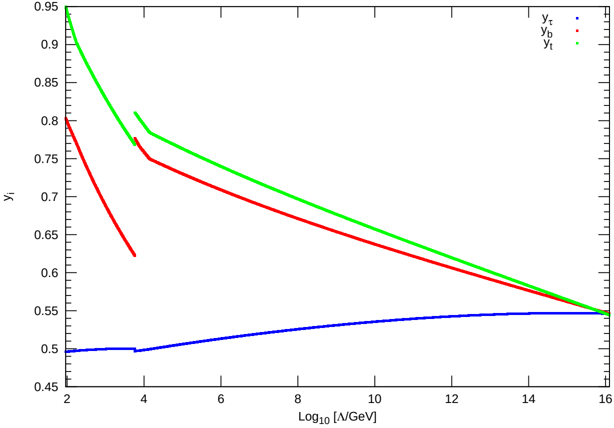
$$R = \frac{\max(y_t, y_b, y_\tau)}{\min(y_t, y_b, y_\tau)}$$

Constraints

$$m_{\tilde{\chi}_1^\pm}\ \text{(chargino mass)} \geq 103.5\ \text{GeV},$$
$$m_h\ \text{(lightest Higgs mass)} \geq 114.4\ \text{GeV},$$
$$m_{\tilde{\tau}}\ \text{(stau mass)} \geq 86\ \text{GeV},$$
$$m_{\tilde{g}}\ \text{(gluino mass)} \geq 220\ \text{GeV},$$
$$BR(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8},$$
$$2.85 \times 10^{-4} \leq BR(b \to s\gamma) \leq 4.24 \times 10^{-4}\ (2\sigma),$$
$$\Omega_{\rm CDM} h^2 = 0.111^{+0.028}_{-0.037}\ (5\sigma),$$
$$3.4 \times 10^{-10} \leq \Delta\alpha_\mu \leq 55.6 \times 10^{-10}\ \ (3\sigma).$$

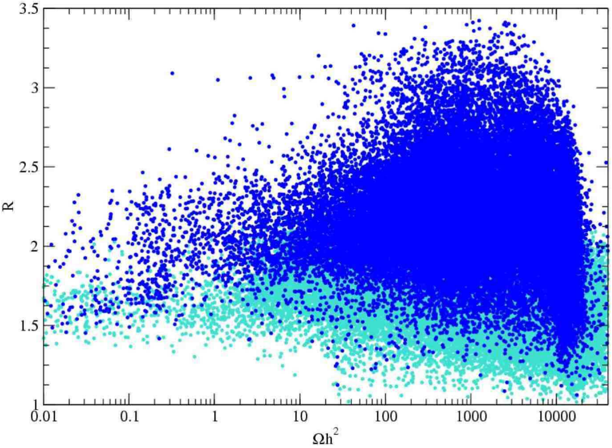

1.5
1.4
1.3
1.2
1.1
1
R
0
5
10
15
20
m16 (TeV)
0
0.4
0.8
1.2
m10/m16
0
0.5
MD/m16
0
0.4
0.8
m1/2 (TeV)
-2.4
-1.2
0
1.2
A0/m16
50
tanβ

- SUSY and $t - b - \tau$ Yukawa coupling unification



Dominant contributions to the bottom quark mass from the gluino and chargino loop

$$\delta m_b \approx \frac{g_3^2}{12\pi^2}\frac{\mu m_{\tilde{g}} \tan\beta}{m_{\tilde{b}}^2} - \frac{y_t^2}{32\pi^2}\frac{\mu A_t \tan\beta}{m_{\tilde{t}}^2} + \ldots$$



H. Baer, S. Kraml, S. Sekmen and H. Summy, JHEP 0803, 056 (2008)

$SU(4)_c \times SU(2)_L \times SU(2)_R$ **(4-2-2)**

I.G, R. Khalid and Q. Shafi, Phys. Rev. D 79, 115004 (2009) .

- The SM fermions: $\psi_{\mathbf{i}} = (\mathbf{4}, \mathbf{2}, \mathbf{1})$ and $\psi_{\mathbf{i}}^{\mathbf{c}} = (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2})$
- The MSSM Higgs boson: $\mathbf{H} = (\mathbf{1}, \mathbf{2}, \mathbf{2})$
- Third family Yukawa coupling $\psi \, \psi^{\mathbf{c}} \; \mathbf{H}$ yields

$$Y_t = Y_b = Y_\tau = Y_\nu$$

- Left-right symmetric 4-2-2 model
- Asymptotic relation between the three MSSM gaugino masses

$$M_1 = \tfrac{3}{5} M_2 + \tfrac{2}{5} M_3$$

- It has one additional parameter in the SSB parameter space compared to the SO(10) model

We have performed random scan for the following parameter range

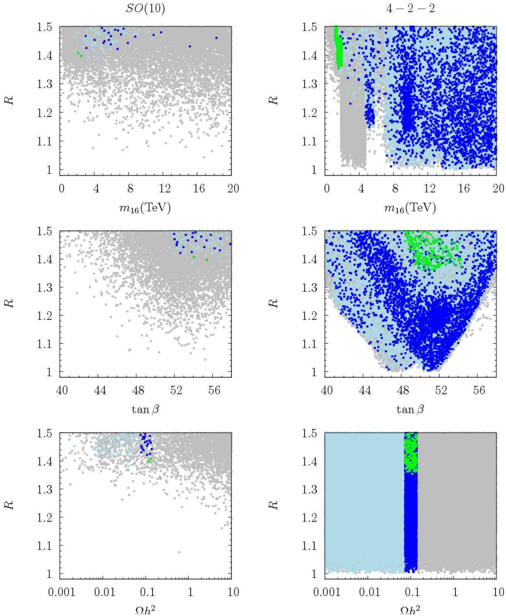
$$
\begin{aligned}
0 &\leq m_{16} \leq 20\,\mathrm{TeV}, \\
0 &\leq M_2 \leq 1\,\mathrm{TeV}, \\
0 &\leq M_3 \leq 1\,\mathrm{TeV}, \\
-3 &\leq A_0/m_{16} \leq 0, \\
0 &\leq M_D/m_{16} \leq 0.95, \\
0 &\leq m_{10}/m_{16} \leq 1.5, \\
40 &\leq \tan\beta \leq 58, \\
\mu > 0, & \quad m_t = 172.6\,\mathrm{GeV}.
\end{aligned}
$$

Constraints

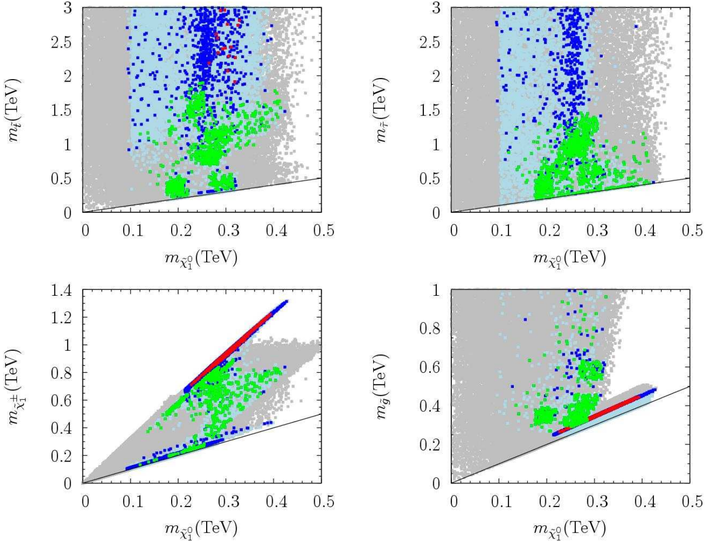
$$m_{\tilde{\chi}_1^\pm} \text{ (chargino mass)} \geq 103.5 \text{ GeV},$$
$$m_h \text{ (lightest Higgs mass)} \geq 114.4 \text{ GeV},$$
$$m_{\tilde{\tau}} \text{ (stau mass)} \geq 86 \text{ GeV},$$
$$m_{\tilde{g}} \text{ (gluino mass)} \geq 220 \text{ GeV},$$
$$BR(B_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-8},$$
$$2.85 \times 10^{-4} \leq BR(b \rightarrow s\gamma) \leq 4.24 \times 10^{-4} \ (2\sigma),$$
$$\Omega_{\rm CDM} h^2 = 0.111^{+0.028}_{-0.037} \ (5\sigma),$$
$$3.4 \times 10^{-10} \leq \Delta\alpha_\mu \leq 55.6 \times 10^{-10} \ (3\sigma).$$

We introduce a parameter R to quantify Yukawa unification

$$R = \frac{\max(y_t, y_b, y_\tau)}{\min(y_t, y_b, y_\tau)}$$



$SO(10)$
$4-2-2$
R
m_{16}(TeV)
$\tan\beta$
Ωh^2
1.5
1.4
1.3
1.2
1.1
1
0 4 8 12 16 20
40 44 48 52 56
0.001 0.01 0.1 1 10



Points in green satisfies all constraints. Red points represents $R \leq 1.1$

	Point 1	Point 2	Point 3
m_{16}	14110	8429	13124
M_2	832.03	1020.2	689.4
M_3	0.7945	60.542	9.6261
$\tan\beta$	50.82	46.41	51.17
M_D/m_{16}	0.4543	0.5595	0.3323
m_{10}/m_{16}	0.7741	1.1584	1.3048
A_0/m_{16}	-2.4487	-2.1527	-1.8226
m_h	123	126	127
m_H	7569	2163	9882
m_A	7520	2150	9818
$m_{H^\pm}$	7571	2175	9883
$m_{\tilde{\chi}^\pm_{1,2}}$	**887**,13869	**975**,4047	**712**,3750
$m_{\tilde{\chi}^0_{1,2}}$	**283**, 885	**319**,974	**228**,712
$m_{\tilde{\chi}^0_{3,4}}$	13879,13879	4049,4049	3784,3785
$m_{\tilde{g}}$	**325**	**365**	**265**
$m_{\tilde{u}_{L,R}}$	14126,13916	8435,8361	13140,12841
$m_{\tilde{t}_{1,2}}$	5337,5726	**1911**,2640	4931,5310
$m_{\tilde{d}_{L,R}}$	14126,14203	8435,8455	13141,13249
$m_{\tilde{b}_{1,2}}$	5237,5653	2521,2767	4115,5146
$m_{\tilde{\nu}_1}$	13988	8409	12926
$m_{\tilde{\nu}_3}$	10598	6577	9535
$m_{\tilde{e}_{L,R}}$	13988,14376	8408,8514	12926,13500
$m_{\tilde{\tau}_{1,2}}$	6412,10581	4270,6573	5580,9559
μ	14100	4110	3840
$\Omega_{LSP}h^2$	0.095	0.112	0.116
R	**1.00**	1.07	1.09

Yukawa unification with negative μ term

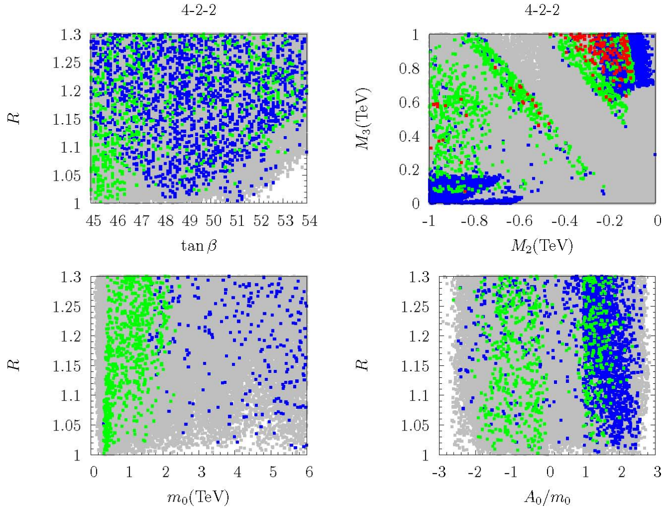
- Yukawa unification prefers $\mu < 0$
- Dominant contributions to the bottom quark mass from the gluino and chargino loop

$$\delta m_b \approx \frac{g_3^2}{12\pi^2}\frac{\mu m_{\tilde{g}} \tan\beta}{m_{\tilde{b}}^2} - \frac{y_t^2}{32\pi^2}\frac{\mu A_t \tan\beta}{m_{\tilde{t}}^2} + \ldots$$

- Dominant contribution to the muon anomalous magnetic moment for large $\tan\beta$ case is $\Delta\alpha_\mu^{SUSY} \propto \mu M_2 \tan\beta/\tilde{m}^4$
- In 4-2-2 model with left-right symmetry, M_2 and M_3 are free parameters
- We can have $\mu < 0$, $M_2 < 0$ and $M_3 > 0$

We have performed random scan for the following parameter range

$$
\begin{aligned}
0 &\leq m_0, M_{H_u, M_{H_d}} \leq 20\,\mathrm{TeV}, \\
1\,\mathrm{TeV} &\leq M_2 \leq 1\,\mathrm{TeV}, \\
0 &\leq M_3 \leq 1\,\mathrm{TeV}, \\
-3 &\leq A_0/m_{16} \leq 3, \\
45 &\leq \tan\beta \leq 55, \\
\mu > 0, &\quad \mu < 0, \quad m_t = 172.6\,\mathrm{GeV}.
\end{aligned}
$$



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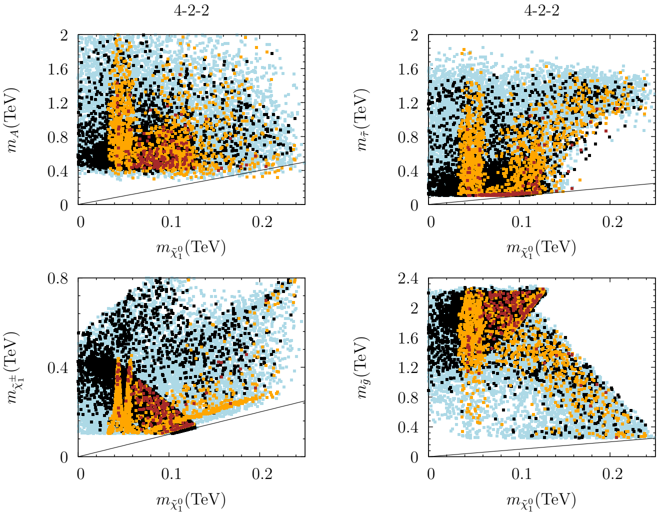
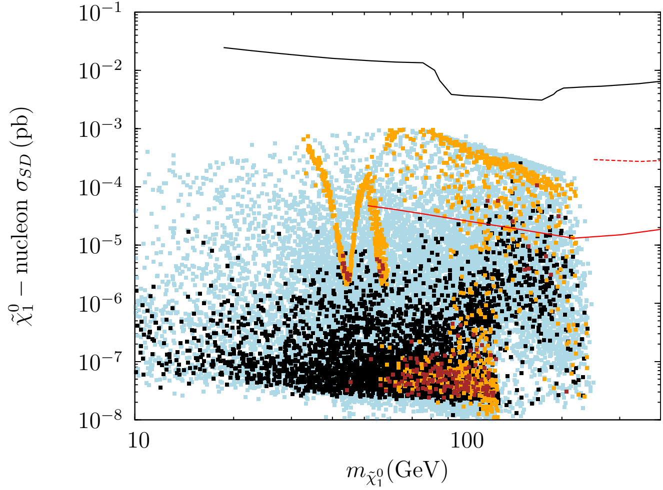


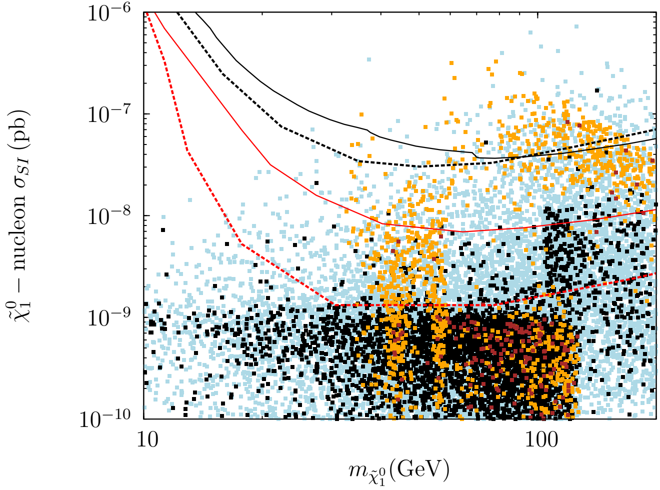
Brown points satisfies all constraints and $R \leq 1.1$

Dark matter direct detection



Brown points satisfies all constraints and $R \leq 1.1$

Dark matter direct detection



Brown points satisfies all constraints and $R \leq 1.1$

Summary

- We considered an L-R symmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ model with gravity mediated supersymmetry breaking. We find that in this case $t - b - \tau$ Yukawa coupling unification is consistent with neutralino dark matter abundance and with all constraints from collider experiments (except $(g-2)_\mu$)for $\mu > 0$. For $\mu < 0$ we can have Yukawa unification satisfying all current constraints.
- The model for $\mu > 0$ predicts a very characteristic sparticle spectrum: very heavy sfermions (> 5 TeV) but relatively light gluinos (around 300 GeV).
- We have shown for $\mu < 0$ case Yukawa unification can be achieve with relatively light sparticle spectrum $O(600)$ GeV.
- It is possible to have observation on the dark matter direct detection experiments.

Happy birthday Goran!