Exploring Yukawa and Gauge-Yukawa Unification at the LHC

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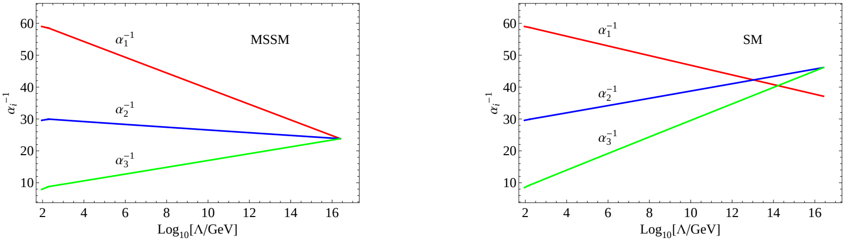
Yukawa and Gauge-Yukawa Unification

(inspired by supersymmetric unified theories)

- b-τ Unification ($SU(5)$ and $SO(10)$)
- t-b-τ Yukawa Unification ($SO(10)$ and $SU(4)_c \times SU(2)_L \times SU(2)_R$
- Gauge-Yukawa Unification (Orbifold GUTs)

Low Scale ($\sim$ TeV) Supersymmetry (SUSY):

- Arguably the most compelling extension of the Standard Model;
- Resolves the gauge hierarchy problem (more or less);
- Provides cold dark matter candidate (LSP);
- Implements radiative electroweak symmetry breaking;
- Predicts new particles accessible at the LHC, and thereby enables unification of the SM gauge couplings;



• b-τ Yukawa Unification

Ilia Gogoladze, S. Raza and Q. Shafi, arXiv:1104.3566 [hep-ph](2011) .

- SUSY $SU(5)$: $\overline{5}_3 \times 10_3 \times \overline{5}_{H_d}$

$$\begin{array}{ccc} \uparrow & & \uparrow \end{array}$$

$$(L, b^c), (Q, \tau^c) \Longrightarrow y_b = y_\tau$$

- SUSY $SO(10)$: $16_3 \times 16_3 \times 10_{u,d}$

Suppose $10_u \equiv H_u$

while $10_d \equiv H_d \cos\delta + \ldots$

$$\Longrightarrow y_b = y_\tau$$

- Quantify b-τ Yukawa unification(YU) by

$$R_{b\tau} = \frac{\max(y_b, y_\tau)}{\min(y_b, y_\tau)}$$

SU(5) in CMSSM framework

- $m_0,\ M_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
- $m_0 \equiv$ Universal soft SUSY breaking sfermion mass
- $M_{1/2} \equiv$ Universal SSB gaugino mass
- $A_0 \equiv$ Universal SSB trilinear interaction
- $\tan\beta = \frac{v_u}{v_d}$
- $\mu \equiv$ SUSY bilinear Higgs parameter > 0

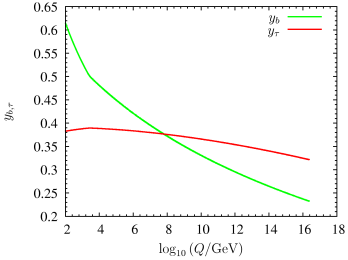
We performed random scans for the following parameter range

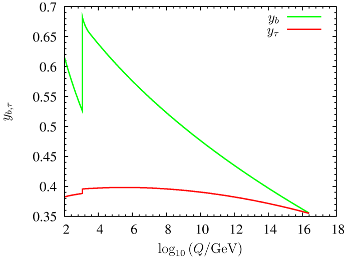
$$
\begin{array}{rcccl}
0 & \leq & m_0 & \leq & 25\,\mathrm{TeV}, \\
0 & \leq & M_{1/2} & \leq & 2\,\mathrm{TeV}, \\
-3 & \leq & A_0/m_0 & \leq & 3, \\
1.1 & \leq & \tan\beta & \leq & 60, \\
\mu > 0, & & & & m_t = 173.3\,\mathrm{GeV}.
\end{array}
$$

Constraints

$$
\begin{aligned}
m_{\tilde{\chi}_1^\pm} \text{ (chargino mass)} &\geq 103.5 \text{ GeV}, \\
m_h \text{ (lightest Higgs mass)} &\geq 114.4 \text{ GeV}, \\
m_{\tilde{\tau}} \text{ (stau mass)} &\geq 86 \text{ GeV}, \\
m_{\tilde{g}} \text{ (gluino mass)} &\geq 220 \text{ GeV}, \\
BR(B_s \to \mu^+\mu^-) &< 4.3 \times 10^{-8}, \\
0.53 < \frac{BR(B_u \to \tau\nu_\tau)MSSM}{BR(B_u \to \tau\nu_\tau)SM} &< 2.03 \; (2\sigma), \\
2.85 \times 10^{-4} \leq BR(b \to s\gamma) &\leq 4.24 \times 10^{-4} \; (2\sigma), \\
\Omega_{\mathrm{CDM}} h^2 &= 0.111^{+0.028}_{-0.037} \; (5\sigma), \\
3.4 \times 10^{-10} \leq \Delta\alpha_\mu &\leq 55.6 \times 10^{-10} \;\; (3\sigma).
\end{aligned}
$$

Importance of finite SUSY threshold corrections



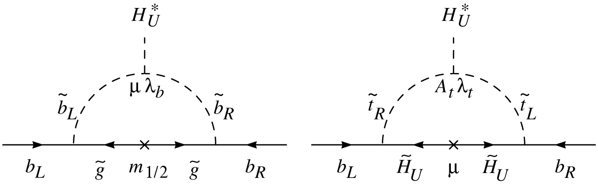


b-τ YU and finite threshold corrections [1]

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

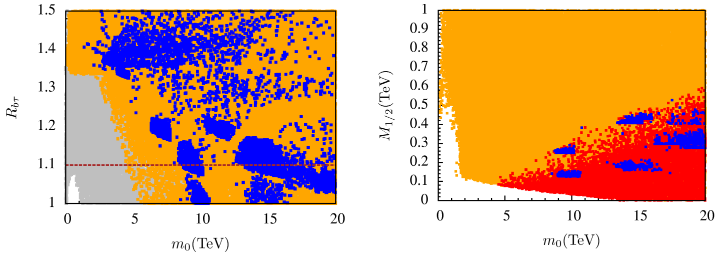
$$\delta y_b \approx \frac{g_3^2}{12\pi^2}\frac{\mu m_{\tilde{g}} \tan\beta}{m_1^2} + \frac{y_t^2}{32\pi^2}\frac{\mu A_t \tan\beta}{m_2^2} + \dots$$

where $m_1 \approx (m_{\tilde{b}_1} + m_{\tilde{b}_2})/2$ and $m_2 \approx (m_{\tilde{t}_2} + \mu)/2$

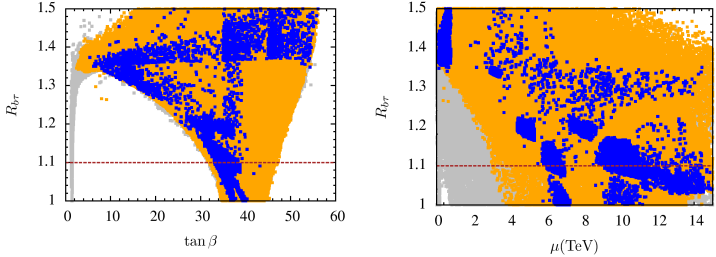


where $\lambda_b = y_b$ and $\lambda_t = y_t$

[1] L. J. Hall, R. Rattazzi and U. Sarid, Phys. Rev.D 50, 7048 (1994)



In $R_{b,\tau} - m_0$ plane gray points are consistent with REWSB and $\tilde{\chi}_1^0$ LSP. Orange points satisfy collider bounds and the blue points are subset of orange points that satisfy WMAP bounds on $\tilde{\chi}_1^0$ DM abundance. In $M_{1/2} - m_0$ plane gray and orange points have the same meaning as in $R_{b,\tau} - m_0$ plane, red points are subset of orange points with $R_{b,\tau} \leq 1.1$, and its subset (blue points) represent solutions satisfy WMAP bounds on $\tilde{\chi}_1^0$ DM abundance



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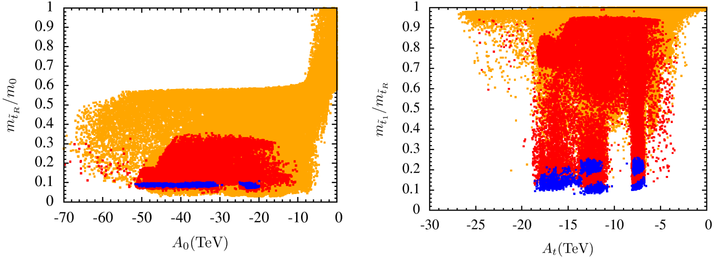


Orange points satisfy all collider bounds.The red points are subset of orange points and represent $R_{b,\tau} \leq 1.1$. Points in blue color show neutralino-stop co-annihilation solutions

	'Perfect" $R_{b,\tau}$	NLSP $\tilde{t}$	$NLSP\tilde{t}$
m_0	15220	10040	17920
$M_{1/2}$	177	152	521
$\tan\beta$	37	39	37
A_0/m_0	-2.36	-2.32	-2.33
$sgn(\mu)$	$+$	$+$	$+$
m_h	115	120	115
m_H	6036	4566	9752
m_A	5997	4537	9688
$m_{H^\pm}$	6037	4568	9753
$m_{\tilde\chi^0_{1,2}}$	124,272	97,209	290,592
$m_{\tilde\chi^0_{3,4}}$	10379,10379	6836,6836	12347,12347
$m_{\tilde\chi^\pm_{1,2}}$	275,10406	211,6840	598,1239
$m_{\tilde g}$	796	640	1680
$m_{\tilde u_{L,R}}$	15170,15214	10000,10030	17892,17942
$m_{\tilde t_{1,2}}$	153,5930	114,4076	328,7894
$m_{\tilde d_{L,R}}$	15170,15222	10000,10036	17892,17951
$m_{\tilde b_{1,2}}$	6060,8357	4152,5752	8097,11159
$m_{\tilde\nu_1}$ 15223	10041	17929	
$m_{\tilde\nu_3}$	12744	8453	15082
$m_{\tilde e_{L,R}}$	15211,15208	10032,10032	17911,17909
$m_{\tilde\tau_{1,2}}$	9843,12771	6619,8474	11801,15130
$\sigma_{SI}(\mathrm{pb})$	3.28×10^{-12}	5.85×10^{-12}	7.93×10^{-13}
$\sigma_{SD}(\mathrm{pb})$	3.90×10^{-12}	2.39×10^{-11}	1.77×10^{-12}
$\Omega_{CDM}h^2$	0.11	0.09	0.1
$R_{b\tau}$	1.00	1.02	1.09

NLSP stop search at LHC

- NLSP stop decay: decay $\tilde{t} \to c + \tilde{\chi}_1^0$ dominates for small $m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ K.I.Hikasa and M.Kobayashi, Phys. Rev. D 36, 724 (1987).
- model-independent search: mono-jet(photon)+missing energy

$$pp \to \tilde{t}\tilde{t}^* + j(\gamma)$$

M.Carena, A.Freitas and C.E.M.Wagner, JHEP 10(2008)109.

- $b - \tau$ Yukawa unification model with $m_{\tilde{g}} \leq 1$ TeV and $m_{\tilde{q}} \geq 10$ TeV: top-pair+missing energy

$$pp \to \tilde{g}\tilde{g} \to t\tilde{t}^* t\tilde{t}^* + c.c. + t\tilde{t}^*\bar{t}\tilde{t} \Rightarrow$$

SS/OS dilepton/1 lepton/0 lepton+2b-jets+jets+large missing energy

- Constraints from LHC with 35^{-1} pb @ 7 TeV ATLAS Collaboration, arXiv: 1103.4344 [hep-ex]

  Upper limits at 95% C.L. on the number of signal events:
  0 lepton +b-jets+jets+$\not{E}_T$: 10.4
  1 lepton +b-jets+jets+$\not{E}_T$: 4.7
  The number of signal events for benchmark point 1,2,3 after applying the same selection cuts as ATLAS

35 pb^{-1}	Point 1	Point 2	Point 3
0 lepton	1	9	0
1 lepton	0	2	0

  All three benchmark points are allowed by current data.

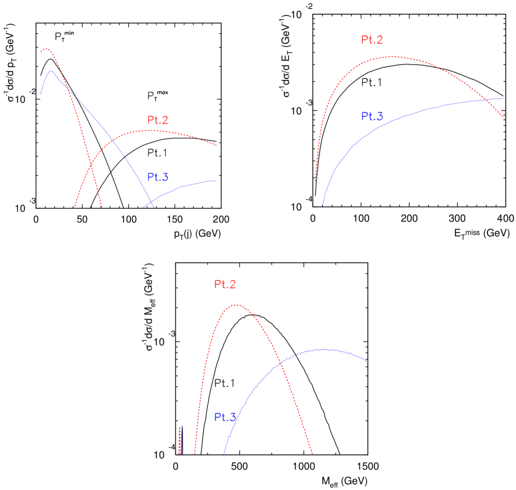
1 fb^{-1}	Point 1	Point 2	Point 3
0 lepton	67	206	4
1 lepton	5	17	1

In preparation with M.A.Ajaib, B.He and T.Li.

- future search channel: same sign top

$$pp \to \tilde{g}\tilde{g} \to t\tilde{t}^* t\tilde{t}^* + c.c. \to \ell^{\pm}\ell^{\pm} + bb + cc + \not{E}_T \qquad (1)$$

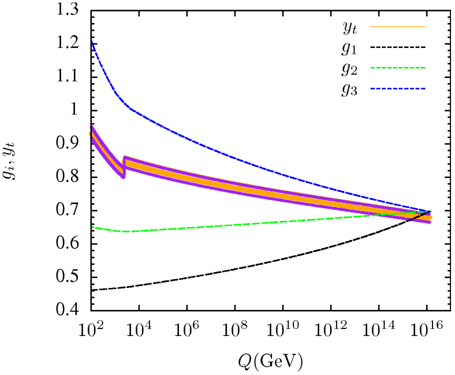
S.Kraml and A.R.Raklev, Phys. Rev. D 73, 075002 (2006); S.P. Martin, Phys. Rev. D 78, 055019 (2008).



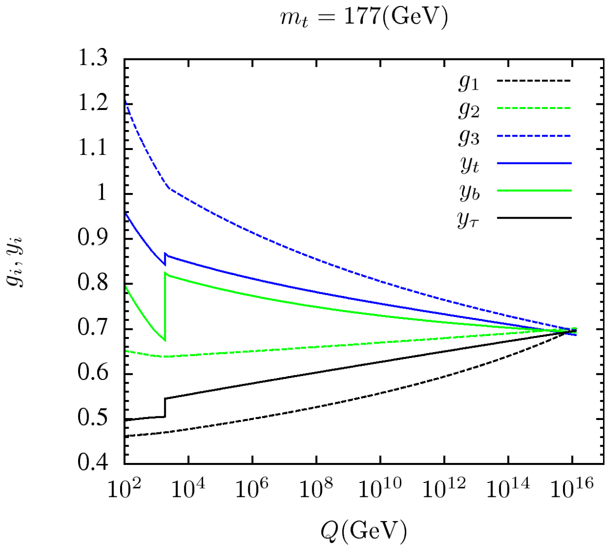
In preparation with T.Li and K.Wang.

Gauge-Yukawa Unification in 4-2-2 from Orbifold Compactification

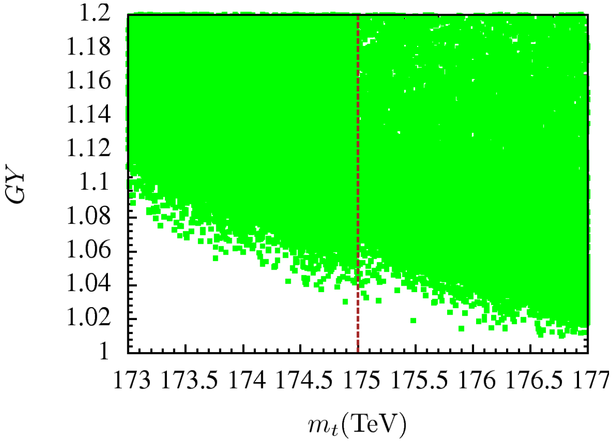
Example: I. Gogoladze, Y. Mimura and S. Nandi, Phys. Lett. B **562**, 307 (2003); I. Gogoladze, Y. Mimura, S. Nandi and K. Tobe, Phys. Lett. B **575**, 66 (2003); T. Kobayashi, S. Raby and R. J. Zhang, Nucl. Phys. B **704**, 3 (2005).



I. Gogoladze, R. Khalid, S. Raza, Q. Shafi: To appear in JHEP.

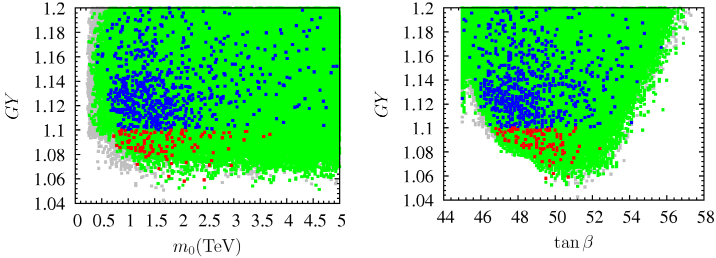


$m_t = 177(\text{GeV})$
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
g_i, y_i
g_1
g_2
g_3
y_t
y_b
y_τ
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
$Q(\text{GeV})$



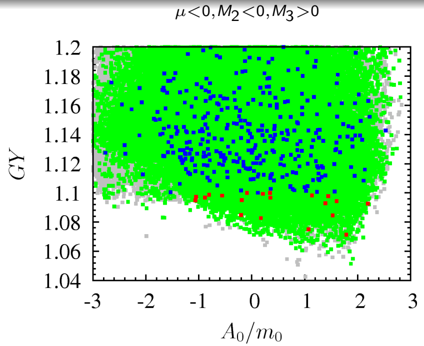
$$GY = \frac{max(g_1, g_2, g_3, y_t, y_b, y_\tau)}{min(g_1, g_2, g_3, y_t, y_b, y_\tau)}$$

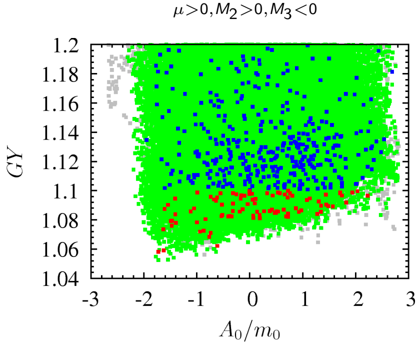
Opposite sign gauginos



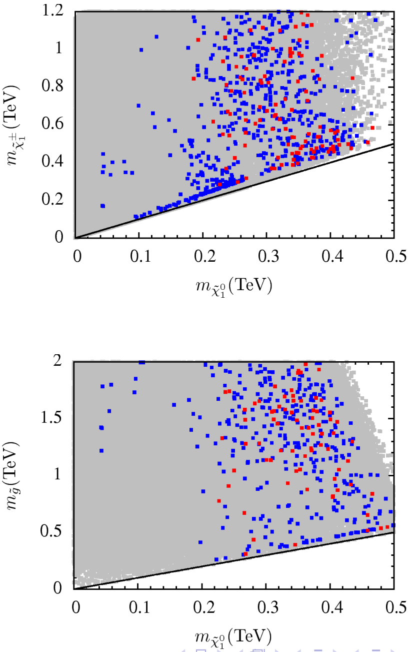
Gray points are consistent with REWSB and $\tilde{\chi}_1^0$ LSP. Green points are consistent with all bounds except Ωh^2. Blue points consistent with all bounds. Red points represent $GY \leq 1.1$

$\delta y_b \propto \mu A_t \implies$
For $\mu < 0, A_0 > 0$,
and
for $\mu > 0, A_0 < 0$





Opposite sign gauginos. Gray points are consistent with REWSB and χ_1^0 LSP. Blue points are consistent with all bounds. Red points have gauge-Yukawa unification to within 10%



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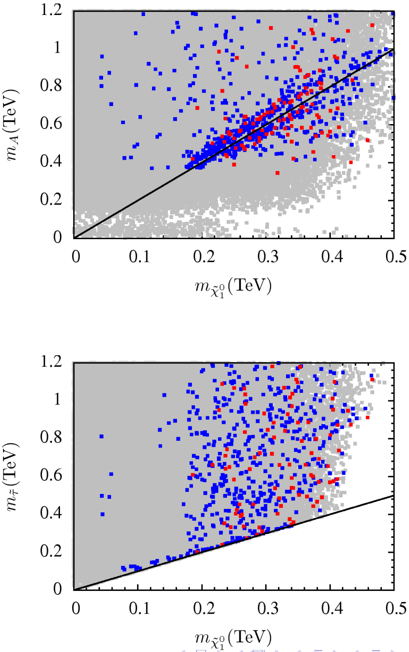

	A-Funnel	NLSP $\tilde{g}$	NLSP $\tilde{\tau}$	B-H mixed DM	Same Sign gauginos
m_0	2063	3246	729	1769	7171
M_1	747	1034	-418	985	583
M_2	1742	1819	-1455	1938	939
M_3	-744	-143	1138	-443	49
$\tan\beta$	50	48	47	50	53
A_0/m_0	-1.73	1.94	-0.19	-0.61	-2.53
m_{Hu}	2191	1162	657	1328	4557
m_{Hd}	2797	3286	1294	2330	6722
m_t	174.3	174.1	174.2	174.4	173.1
sgn μ	+1	+1	-1	+1	+1
m_h	117	119	119	116	121
m_H	597	1739	694	1102	987
m_A	594	1728	689	1095	983
$m_{H^\pm}$	605	1742	701	1106	993
$m_{\tilde{\chi}^0_{1,2}}$	340, 528	459, 1530	193, 1040	428, 492	296, 907
$m_{\tilde{\chi}^0_{3,4}}$	529, 1492	2708, 2710	1058, 1256	503, 1629	6694, 6694
$m_{\tilde{\chi}^\pm_{1,2}}$	534, 1478	1531, 2709	1050, 1247	497, 1618	909, 6686
$m_{\tilde{g}}$	1750	516	2503	1128	340
$m_{\tilde{u}_{L,R}}$	2732, 2485	3445, 3209	2451, 2260	2319, 1946	7186, 7110
$m_{\tilde{t}_{1,2}}$	1355, 1793	1788, 2091	1846, 2091	1153, 1643	1948, 2607
$m_{\tilde{d}_{L,R}}$	2733, 2511	3445, 3276	2452, 2272	2321, 1982	7186, 7195
$m_{\tilde{b}_{1,2}}$	1336, 1781	1485, 2065	1801, 2074	924, 1635	2407, 2852
$m_{\tilde{\nu}_1}$	2335	3412	1177	2148	7161
$m_{\tilde{\nu}_3}$	1841	2814	1048	1835	5218
$m_{\tilde{e}_{L,R}}$	2336, 2115	3412, 3335	1181, 784	2149, 1854	7160, 7251
$m_{\tilde{\tau}_{1,2}}$	540, 1836	1911, 2815	202, 1059	947, 1833	2129, 5204
σ_{SI}(pb)	9.1×10^{-9}	4.7×10^{-12}	2.7×10^{-10}	2.5×10^{-8}	1.1×10^{-12}
σ_{SD}(pb)	5.6×10^{-6}	5.4×10^{-10}	9.0×10^{-8}	3.4×10^{-5}	7.8×10^{-12}
$\Omega_{CDM}h^2$	0.09	0.1	0.11	0.08	0.10
R	1.05	1.07	1.08	1.04	1.13
GY	1.05	1.09	1.09	1.06	1.14

Summary of b-τ Yukawa Unification

- We have investigated b-τ Yukawa unification in the mSUGRA/CMSSM (YCMSSM) framework and find that it is consistent with the NLSP stop scenario and also yields the desired LSP neutralino relic abundance.
- YCMSSM predicts that there are just two 'light' (LHC accessible) colored sparticles, namely the NLSP stop with mass $\sim 100 - 330\,\mathrm{GeV}$, and the gluino which is $\sim 600 - 1700\,\mathrm{GeV}$
- The Chargino and a second neutralino are about a factor 2-3 lighter than the gluino. The remaining squarks as well as all sleptons have masses in the multi-TeV range.
- Regarding the fundamental CMSSM parameters, we find that $5\,\mathrm{TeV} \lesssim m_0 \lesssim 20\,\mathrm{TeV}$, $m_0/M_{1/2} \sim 30 - 50$ or so, $\tan\beta \approx 35 - 40$, $|\mu| \sim 3 - 15\,\mathrm{TeV}$ and $|A_0/m_0| \sim 2.2 - 2.4$.

Summary of Gauge-Yukawa Unification

- Bino-Higgsino dark matter (Good for direct and indirect searches)
- By varying m_t within 1σ of its central value, we can find bino-gluino and stau coannihilation regions and the A resonance solution and bino-Higgsino mixed dark matter solution.