Non-universal Gaugino Mass Models vis-a-vis LHC and Dark Matter

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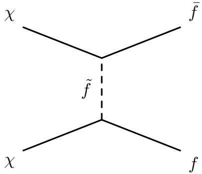
Introduction

- Standard Model(SM) + massive neutrinos is extremely successful in explaining most of the current experimental results
- However problems like Dark matter content of the universe and a theoretical concern called “hierarchy problem” remain unaddressed in SM
- Supersymmetry hence invoked to address these issues particularly the gauge hierarchy problem
- Low energy SUSY in its simplest form, SM+SUSY partners along with an extended Higgs sector, is called Minimal Supersymmetric Standard Model (MSSM)
- It also provides a viable DM candidate in the Lightest Supersymmetric Particle (neutralino)

Introduction

- Constrained MSSM (CMSSM), is a popular version of MSSM which has been studied extensively
- CMSSM has universal gaugino and scalar masses at the Grand Unification (GUT) scale with just five free parameters in the theory - m_0, $M_{1/2}$, $\tan\beta$, $sign(\mu)$, A_0
- LSP is bino through most of the parameter space
- Main annihilation channel for bino is to a pair of fermions via sfermion exchange(bulk annihilation process)



- Bulk annihilation region provides a natural solution to the DM relic density constraint

Introduction

- However LHC sets stringent lower limits on the bino LSP mass as well as sfermion masses in CMSSM through its measurement of the neutral Higgs boson which rules out the bulk annihilation region
- To evade the LHC constraint while accessing the bulk region one has to give up the universality of gaugino masses at GUT scale and assume that the GUT scale bino mass is significantly smaller than the gluino mass
- A heavy gluino at GUT scale ensures that the Higgs mass value from LHC is satisfied while the light GUT scale bino mass makes the bulk region accessible
- One can construct such a model for nonuniversal gaugino masses by assuming that the latter get contributions from SUSY breaking superfields belonging to non-singlet representations of the GUT group

SU(5),SO(10) and E(6) NUGM models

- Gauginos at GUT scale get masses when the F-term of the gauge kinetic function related to the gaugino masses gets a *vev*

$$\frac{\langle F_{\Omega} \rangle_{ij}}{M_{Planck}} \lambda_i \lambda_j$$

- Since the gauginos belong to the adjoint representation of the GUT group and the gaugino mass term in the Lagrangian is bilinear in them, the F-term which breaks the SUSY must belong to the symmetric product of the adjoint rep. with itself
- SUSY breaking superfield could belong to any of the irreps of the symmetric products of the adjoint reps of SU(5), SO(10) and E(6)

$$\begin{aligned} SU(5) \quad &\Rightarrow (24 \otimes 24)_{sym} \quad &= 1 \oplus 24 \oplus 75 \oplus 200, \\ SO(10) \quad &\Rightarrow (45 \otimes 45)_{sym} \quad &= 1 \oplus 54 \oplus 210 \oplus 770, \\ E(6) \quad &\Rightarrow (78 \otimes 78)_{sym} \quad &= 1 \oplus 650 \oplus 2430 \end{aligned}$$

- When the F-term transforms under a non-singlet representation, non-universal gaugino masses arise

SU(5),SO(10) and E(6) NUGM models

- The SUSY breaking field $\Omega^{ij} = \langle F \rangle^{ij} / M_{Planck}$ is then required to be a SM singlet
- One then finds such SM singlets within the irrep of the larger symmetry group
- For example in SU(5) each of the irreps - $1, 24, 75$ and 200 contains a SM singlet which gives a unique prediction for the gaugino mass ratio at the GUT scale
- The scale of the F-term vev is arbitrarily chose, however the ratio of gaugino masses is fixed by group theory
- Each distinct nonuniversal gaugino mass ratio corresponds to a particular model of low energy SUSY
- We analyse all such possible nonuniversal gaugino mass ratios using the experimental constraints from LHC and those on Dark Matter(DM)

See for example Martin, Phys. Rev. D **79***, 095019 (2009)*

Experimental contraints

- Higgs mass bound from LHC

$$122\ \text{GeV} < M_h < 127\ \text{GeV}$$

- Relic density constraint from WMAP-PLANCK data at 3σ

$$0.1118 < \Omega h^2 < 0.1280$$

- Branching fraction for $B_s \to X_s\gamma$ at 2σ

$$3.05 \times 10^{-4} < \mathrm{BR}(B_s \to X_s\gamma) < 4.05 \times 10^{-4}$$

- Branching fraction for $B_s \to \mu^+\mu^-$ at 2σ

$$0.8 \times 10^{-4} < \mathrm{BR}(B_s \to \mu^+\mu^-) < 6.2 \times 10^{-4}$$

- Ratio of branching fraction for $B_u \to \tau\nu_\tau$ in MSSM to that in SM at 3σ

$$0.46 < \frac{\mathrm{BR}(B_u \to \tau\nu_\tau)_{MSSM}}{\mathrm{BR}(B_u \to \tau\nu_\tau)_{SM}} < 1.78$$

- Anomalous muon magnetic moment, $a_\mu \equiv (g-2)/2$,

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (26.1 \pm 8.0) \times 10^{-10}$$

Parameter scan

- We use the following range of parameters for the scan

$$\begin{aligned} m_0 &\in [100, 2000] \text{ GeV}, \\ M_3^G &\in [800, 2000] \text{ GeV}, \\ \tan\beta &= 10, \\ A_0 &= -1, 0, 1 \text{ TeV} \\ sgn(\mu) &\equiv +, -. \end{aligned}$$

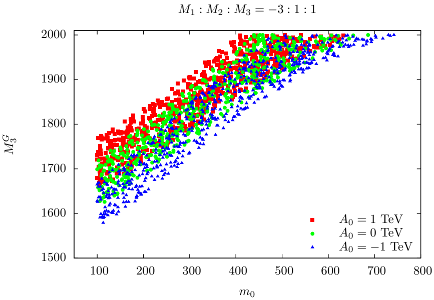
- We use SuSpect two-loop RGE code for obtaining the low energy SUSY spectrum and MicrOmegas for evaluating relic density, muon $(g-2)$ and B-physics constraints

Benchmark scenarios

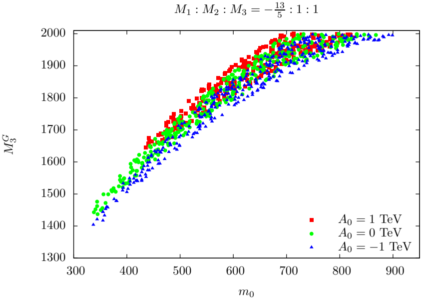
Model no.	$M_1^G : M_2^G : M_3^G$	m_0 (GeV)	M_3^G (GeV)	A_0 (TeV)	$\tan\beta$	sgn(μ)
1	$-\frac{19}{5} : 1 : 1$	182	2038	-1	10	$+$
2	$-3 : 1 : 1$	100	1620	-1	10	$+$
3	$-\frac{13}{5} : 1 : 1$	300	1320	-1	10	$+$
4	$-\frac{22}{5} : 1 : 1$	130	2055	-1	10	$+$
5	$\frac{41}{15} : 1 : 1$	300	1460	-1	10	$+$
9	$10 : 2 : 1$	116	966	-1	10	$+$
10	$\frac{9}{5} : 1 : 1$	1000	1190	-1	10	$+$
11	$-\frac{1}{5} : 3 : 1$	2000	1650	-4	40	$+$
18	$\frac{2}{5} : 2 : 1$	200	1119	-1	10	$+$
19	$-5 : 3 : 1$	789	1719	-3.5	10	$+$
20	$\frac{5}{2} : -\frac{3}{2} : 1$	1900	1740	-1	10	$-$
22	$-\frac{1}{5} : 1 : 1$	150	1355	-1	10	$-$
24	$-\frac{1}{2} : -\frac{3}{2} : 1$	506	800	-3.5	20	$-$

Table: Input parameters at GUT scale for the benchmark point chosen for each of the 13 models. We choose the parameters such that in each case we get a maximal contribution from SUSY to muon $(g-2)$.

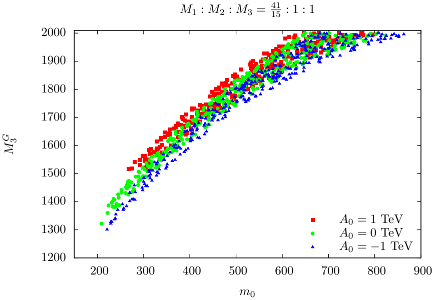
Results : Wino models



$M_1 : M_2 : M_3 = -3 : 1 : 1$



$M_1 : M_2 : M_3 = -\frac{13}{5} : 1 : 1$



$M_1 : M_2 : M_3 = \frac{41}{15} : 1 : 1$

Results : Wino models

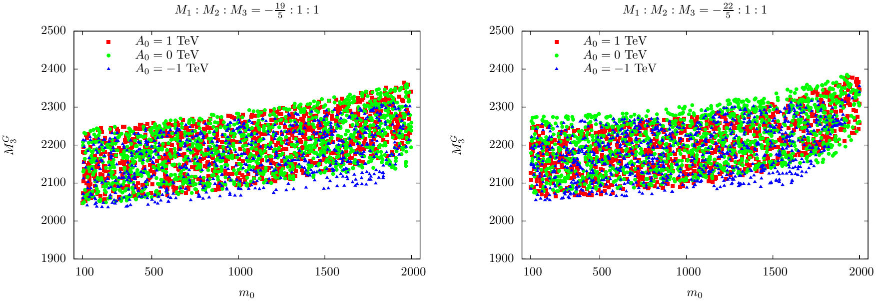
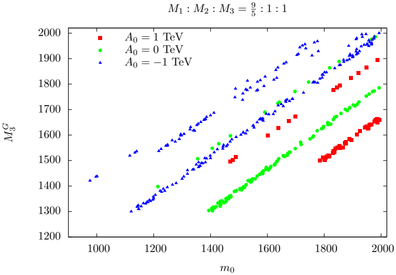


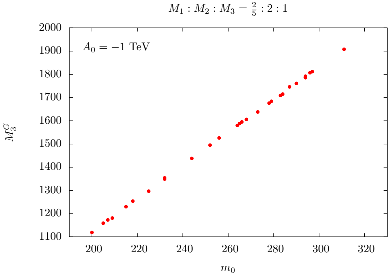
Figure: The allowed parameter space for heavy wino models 1($-19/5 : 1 : 1$) and 4($-22/5 : 1 : 1$) shown in the left and right panels respectively. We extend the scan range for M_3^G upto 3 TeV for these two models. The allowed mass range for M_3^G lies between $\sim 2.0 - 2.4$ TeV while for m_0 it covers the entire range of our scan from $100 - 2000$ GeV.

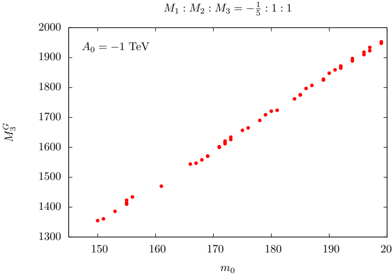
Results : Wino models

- In models 2($-3:1:1$), 3($-13/5:1:1$) and 5 ($41/15:1:1$) the LSP is a wino with mass 1323 GeV, 1073 GeV and 1189 GeV respectively
- In all three models the chargino masses are almost degenerate with the wino LSP masses due to which the chargino co-annihilation processes $\tilde{\chi}_1^0\tilde{\chi}_1^+ \to ZW^+, c\bar{s}, u\bar{d}$ and $\tilde{\chi}_1^-\tilde{\chi}_1^+ \to W^-W^+$ also contribute significantly to the relic density in addition to the annihilation channel $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^-W^+$
- These models come closest to being probed in the direct detection experiments
- Models 1($-19/5:1:1$) and 4($-22/5:1:1$) show a valid parameter space for $M_3 = 2000 - 2400$ GeV, because of the well known result that the correct relic density for wino LSP models is achieved by wino annihilation to W pair by a t-channel chargino exchange with $M_{\text{LSP}} \sim 2$ TeV
  Hisano et al, Phys. Rev. D, (2006)

Results : Bino models


$M_1 : M_2 : M_3 = \frac{9}{5} : 1 : 1$


$M_1 : M_2 : M_3 = \frac{2}{5} : 2 : 1$


$M_1 : M_2 : M_3 = -\frac{1}{5} : 1 : 1$

Results : Bino models

- In model 10 ($9/5:1:1$) the DM is a 934 GeV bino LSP; chargino mass is close to the LSP mass and chargino coannihilation processes, $\tilde{\chi}_1^0\tilde{\chi}_1^+ \to t\bar{b}$; $\tilde{\chi}_1^-\tilde{\chi}_1^+ \to t\bar{t}, b\bar{b}$ are important for relic density
- NLSP mass is close at 970 GeV and the NLSP coannihilation processes, $\tilde{\chi}_1^0\tilde{\chi}_2^0 \to b\bar{b}$ and $\tilde{\chi}_2^0\tilde{\chi}_2^0 \to b\bar{b}$ makes a significant contribution to the DM annihilation, hence the parameters A_t and A_b significantly affect the parameter space for achieving the correct relic density
- In model 19 ($-5:3:1$) the LSP is predominantly bino with higgsino mixture ($N_{11} = 0.826, N_{13} = 0.449, N_{14} = 0.338$) of mass 159 GeV
- The processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-, ZZ$ contribute to the relic density
- In model 24 ($-1/2:-3/2:1$) the LSP is a bino of mass 178 GeV and the main annihilation channel is the stau coannihilation $\tilde{\chi}_1^0\tilde{\tau} \to A\tau$; $\tilde{\tau}\tilde{\tau} \to \tau\bar{\tau}, AA$; $\tilde{\chi}_1^0\tilde{\tau} \to Z\tau$ which are all an order of magnitude larger than the annihilation channel $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau\bar{\tau}$
- The stau coannihilation channels are boosted up by taking the stau mass 184.5 GeV close to the LSP mass

Results : Bino models

- Models $18(2/5 : 2 : 1)$ and $22(-1/5 : 1 : 1)$ also show a very small parameter space in the stau coannihilation region
- These two models require the $\tilde{\tau}_1$ mass to be taken very close to the LSP mass (within 5 GeV) and in that sense are more fine tuned than the rest of the successful models

Results : Higgsino models

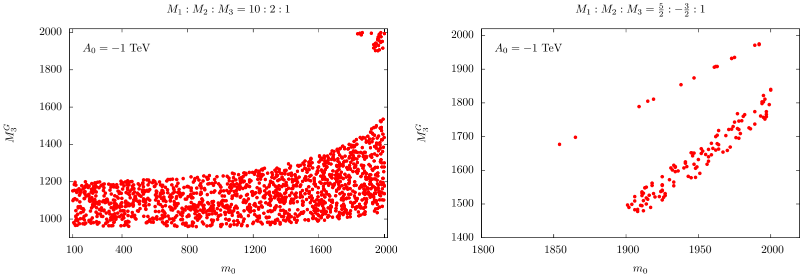


Figure: The allowed parameter space satisfying the low energy constraints except muon $(g-2)$ for heavy higgsino DM models 9(10 : 2 : 1) and model 20(5/2 : −3/2 : 1) with $A_0 = -1$ TeV. For model 9(10 : 2 : 1) the allowed mass range for m_0 spans the entire range of scan from $100 - 2000$ GeV with M_3^G between $\sim 950 - 1550$ GeV. For model 20(5/2 : −3/2 : 1) the allowed mass range for m_0 is $\sim 1850 - 2000$ GeV with M_3^G between $\sim 1400 - 2000$ GeV. These models do not work for $A_0 = 0, 1$ TeV.

Results : Higgsino models

- In model 9 (10 : 2 : 1) the LSP is a higgsino and the relic density is via the chargino coannihilation processes $\tilde{\chi}_1^0\tilde{\chi}_1^+ \to u\bar{d}, c\bar{s}$
- NLSP mass is close to the LSP mass and the NLSP coannihilation $\tilde{\chi}_2^0\tilde{\chi}_1^+ \to u\bar{d}, c\bar{s}$ also contributes to the relic density
- In model 11 ($-1/5$: 3 : 1) the LSP is a higgsino with mass 1015 GeV and the relic density is via the same chargino coannihilation processes as in model 9 including the NLSP coannihilation contribution
- In model 20 ($5/2$: $-3/2$: 1) the LSP is a higgsino of mass 1507 GeV and the contributions to the relic density are due to the chargino coannihilation $\tilde{\chi}_1^0\tilde{\chi}_1^+ \to t\bar{b}$; $\tilde{\chi}_1^-\tilde{\chi}_1^+ \to t\bar{t},\ b\bar{b}$ in addition to the main annihilation channel $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b},\ t\bar{t}$
- NLSP mass is close to the LSP mass and the NLSP coannihilation $\tilde{\chi}_2^0\tilde{\chi}_1^+ \to t\bar{b}$ also contributes to the relic density; gives the correct relic density for $A_0 \sim -1$ TeV

Results : Direct detection

- Spin-independent cross section of DM-nucleon scattering by Higgs exchange
- Higgs coupling to the lightest neutralino depends upon the product of the higgsino and the gaugino fraction of the neutralino
- Pure bino DM therefore easily evade the direct detection limits from XENON100
- Model 19 ($-5 : 3 : 1$) with a 159 GeV LSP is predominantly bino with a higgsino mixture ($N_{11} = 0.826, N_{13} = 0.449, N_{14} = 0.338$) having a SI cross section $\sim 1.01 \times 10^{-8}$ pb which is incompatible with the XENON100 exclusion limits
- Model 20 ($5/2 : -3/2 : 1$) with 1.5 TeV higgsino DM easily evades the XENON100 bound as the gaugino fraction is small and similarily does model 11($-1/5 : 3 : 1$)
- Wino dark matter models 2 ($-3 : 1 : 1$), 3 ($-13/5 : 1 : 1$) and 5 ($41/15 : 1 : 1$) with a small mixing of higgsino have larger SI cross sections that may be within the reach of XENON1T and Super-CDMS

Results : Muon $g-2$

- Discrepancy between experiment and SM prediction for muon anomalous magnetic moment can be explained through a SUSY contribution to a_μ
- This requires a light mass spectrum of the gauginos and the sleptons which puts a severe restriction on the SUSY models
  Martin and Wells, Phys. Rev. D (2003); Stockinger, J. Phys. G (2007)
- SUSY contribution to muon $(g-2)$ for light binos is through the bino-smuon loop so the largest $a_\mu^{SUSY} = 2.65 \times 10^{-10}$ comes from model 24 which has the lightest LSP (177 GeV bino) and slepton spectrum
- Tension between relic density constraint satisfied through stau-coannihilation and muon $(g-2)$ explained by light smuon and neutralino
- Gaugino masses arising from more than one scalar representation like 1+24, 1+75 and 1+200 of $SU(5)$ it is possible to explain muon $(g-2)$ from SUSY contributions along with the Planck-WMAP relic density
  Mohanty et al., JHEP (2013)
- If one were to have non-universal scalar masses it may be possible to adjust the stau mass to control the relic relic density and the smuon mass to fit muon $(g-2)$ using a single scalar representation for getting non-universal gaugino masses
  Miller and Morais, JHEP (2013); Badziak et al., JHEP (2013)

Conclusions

- We have analysed all possible non-universal gaugino mass models that arise from $SU(5), SO(10), E(6)$ SUSY GUT models
- Assuming full gauge symmetry group is broken to the SM symmetry group at the GUT scale (no intermediate scales)
- Comparative study performed among these models using collider constraints, lightest Higgs mass and the relic density
- Model $24(-1/2 : -3/2 : 1)$ found to be the best candidate to explain muon $(g-2)$ among all the models studied
- Model 19 $(-5 : 3 : 1)$ ruled out by XENON100 while three models $2(-3 : 1 : 1)$, $3(-13/5 : 1 : 1)$ and $5(41/5 : 1 : 1)$ with a TeV scale wino DM can be probed in upcoming direct detection experiments like XENON1T and Super-CDMS
- Non-universality in scalar sector useful in explaining muon $g-2$ while being consistent with relic density and other constraints
- Effect of intermediate scale in a two step symmetry breaking can give rise to different gaugino mass ratios than the ones studied here