The Light Neutralinos from GmSUGRA

Shabbar Raza

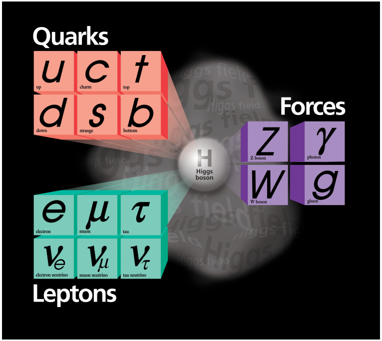
Department Physics and Astronomy
Federal Urdu University of Arts, Science and Technology, Karachi, Pakistan

in collaboration with Tianjun Li and Waqas Ahmed

Outline

- The Standard Model
- Grand Unification
- Low Energy Supersymmetry
- General minimal Supergravity Model(GmSUGRA
- Axion:A brief review
- Axinos: The SUSY Partner of Axion
- Preliminary Scan Results for Light Bino from GmSUGRA
- Summary

The Standard Model (SM)



- The SM is a highly successful theory and has been tested rigorously.
- The SM is based on the gauge symmetry groups of strong nuclear force, weak nuclear force and electromagnetic force i.e $SU(3)_c \times SU(2)_L \times U(1)_Y$
- $SU(3)_c \longrightarrow$ QCD part
- $SU(2)_L \times U(1)_Y \longrightarrow$ Electroweak part

Shortcomings of the SM

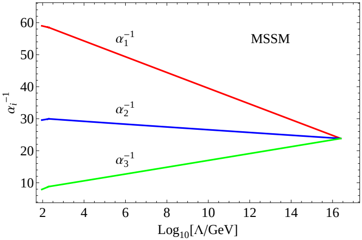
- In the SM neutrinos are massless
- No dark matter (non-baryonic) candidate
- Gauge hierarchy problem ($\delta m_h^2 \propto \Lambda^2$)
- Electric charge is not fully quantized
- Non-unification of gauge couplings

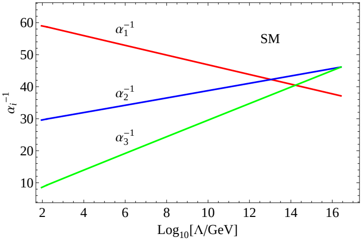
Grand Unification (GUTs)

- Unification of SM gauge couplings ($M_{GUT} \sim 10^{16}\,\mathrm{GeV}$);
- Unification of matter/quark-lepton multiplets;
- Electric charge quantization ;
- Seesaw physics / neutrino oscillations;
- Quark-Lepton mass relations;

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

- Arguably the most compelling extension of the Standard Model;
- Relates fermions to bosons and vice versa;
- Resolves the gauge hierarchy problem ;
- Provides cold dark matter candidate (LSP);
- Predicts new particles accessible at the LHC, and thereby enables unification of the SM gauge couplings;





The Minimal Supersymmetric Standard Model (MSSM)

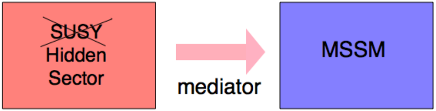
	Chiral Superfields	spin 0	spin $\frac{1}{2}$	$(SU(3), SU(2), U_Y(1))$
squarks and quarks	Q	$(\tilde{u}_L \, \tilde{d}_L)$	$(u_L \, d_L)$	$(3, 2, \frac{1}{6})$
	U^c	$\tilde{u}^c$	u^c	$(\bar{3}, 1, -\frac{2}{3})$
	D^c	$\tilde{d}^c$	d^c	$(\bar{3}, 1, \frac{1}{3})$
sleptons and leptons	L	$(\tilde{\nu} \, \tilde{e}_L)$	$(\nu \, e_L)$	$(1, 2, -\frac{1}{2})$
	E^c	$\tilde{e}^c$	e^c	$(1, 1, 1)$
Higgs and higgsinos	H_u	$(H_u^+ \, H_u^0)$	$(\tilde{H}_u^+ \, \tilde{H}_u^0)$	$(1, 2, \frac{1}{2})$
	H_d	$(H_d^0 \, H_d^-)$	$(\tilde{H}_d^0 \, \tilde{H}_d^-)$	$(1, 2, -\frac{1}{2})$

	Vector Superfields	spin $\frac{1}{2}$	spin 1	$(SU(3), SU(2), U_Y(1))$
gluinos and gluons	G	$\tilde{g}$	g	$(8, 1, 0)$
winos and W-bosons	W	$\widetilde{W}^\pm, \widetilde{W}^0$	$W^\pm, W^0$	$(1, 3, 0)$
bino and B-boson	B	$\widetilde{B}$	B	$(1, 1, 0)$

- $h, H, A, H^\pm$
- $R = (-1)^{3(B-L)+2S}$, R=1 (particles), R=-1 (sparticles)
- $\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_u^0 + N_{14}\tilde{H}_d^0$, Neutralino LSP. This is prime DM candidate.

SUSY Phenomenology

- SUSY is a broken symmetry ($m_e \neq m_{\tilde{e}}$)



- We have to break SUSY by introducing soft supersymmtery breaking terms (SSB)
- MSSM+SSB more than 100 parameters
- We have to relate these parameters (CMSSM,NUHM2 ..).

The EWSSUY from Genral minimal Supergravity (GmSUGRA) Model

$$\frac{1}{\alpha_2} - \frac{1}{\alpha_3} = k \left(\frac{1}{\alpha_1} - \frac{1}{\alpha_3} \right) ,$$

$$\frac{M_2}{\alpha_2} - \frac{M_3}{\alpha_3} = k \left(\frac{M_1}{\alpha_1} - \frac{M_3}{\alpha_3} \right) ,$$

With $k = 5/3$ and assuming gaue coupling unification at the GUT scale $(\alpha_1 = \alpha_2 = \alpha_3)$,

$$M_3 = \frac{5}{2} M_1 - \frac{3}{2} M_2 .$$

The EWSSUY from Genral minimal Supergravity (GmSUGRA) Model

$$m^2_{\tilde{Q}_i} = \frac{5}{6}(m_0^U)^2 + \frac{1}{6} m^2_{\tilde{E}_i^c} ,$$
$$m^2_{\tilde{U}_i^c} = \frac{5}{3}(m_0^U)^2 - \frac{2}{3} m^2_{\tilde{E}_i^c} ,$$
$$m^2_{\tilde{D}_i^c} = \frac{5}{3}(m_0^U)^2 - \frac{2}{3} m^2_{\tilde{L}_i} .$$

In addition, the Higgs soft masses m_{H_u} and m_{H_d}, and the trilinear soft terms A_U, A_D and A_E can all be free parameters

Axions: Solution to Strong CP problem of QCD

- The most compelling way of resolving the strong CP problem of QCD seems to be provided by invoking the Peccei and Quinn (PQ) mechanism
- The CP-violating θ-term in the QCD Lagrangian, which is experimentally required to be excessively tiny
- One can replace the θ-term by a term involving a new fundamental pseudo-scalar field, the axion.
- This is achieved by introducing a global, chiral U(1) symmetry group, which is spontaneously broken at some high energy scale $f_a \sim 10^{11}$ GeV.

Axions: Solution to Strong CP problem of QCD, Continues

- The QCD anomaly breaks this chiral U(1) symmetry at the one-loop level, and hence the axion becomes not a true Goldstone boson but a pseudo-Goldstone boson with a tiny mass of order Λ^2_{QCD}/f_a
- As the lightest pseudo-scalar consistent with the known particle phenomenology, the axion can be very important in cosmology and astrophysical processes
- Axion physics and cosmology are very rich fields which have been thoroughly explored in the literature.

The Peccei-Quinn Mechanisim in a Nutshell

- The Peccei-Quinn symmetry is an anomalous global $U(1)$ symmetry, broken at a high scale $f_a \sim 10^{11}$ GeV.
- After the breaking, the only surviving field in a non-supersymmetric model is the pseudo-goldstone boson of the symmetry, the axion
- Due to the anomalous nature of the symmetry, the axion couples with the gluon field as

$$L_{PQ} = \frac{\alpha_s}{8\pi f_a} a F^a_\mu \tilde{F}^\mu_a$$

- This coupling has the same form as the QCD θ term and therefore a non-vanishing θ can be reabsorbed into a and becomes a dynamical field.
- At the chiral QCD phase transition the axion acquires a mass and a potential via instanton effects and relaxes to the minimum with zero effective θ solving the strong CP problem

Axinos: The SUSY Partner of Axion

- The supermultiplet Φ consists of pseudo-scalar axion a, its fermionic partner, the axino $\tilde{a}$, and the scalar partner saxion s

$$\Phi = \frac{1}{\sqrt{2}}(s + ia) + \sqrt{2}\tilde{a}\theta + F_\Phi \theta\theta.$$

where F_Φ is the auxiliary field

- One can write the superpotential as

$$W_{PQ} = \frac{\alpha_s}{4\sqrt{2}\pi f_a} \Phi W^\alpha W_\alpha.$$

W^α is the vector multiplet containing the gluino λ^α and the gluon.

Axinos Models

- There are different axion models, depending on the PQ charges of the SM fields
- The KVSZ models assume the existence of heavy colored states charged under the PQ symmetry
- The DFSZ models mix the axion with the Higgs fields and give PQ charge also to SM fields
- If $\tilde{\chi}_1^0$ is not the LSP, but the Lightest Ordinary SUSY particle (LOSP), then $\tilde{\chi}_1^0 \to \tilde{a}\gamma$
- In such scenario we have axion/axino ($a\tilde{a}$) dark matter
- The neutralino abundance is converted into axino abundance with $\Omega_{\tilde{a}} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{\chi}_1^0}} \Omega_{\tilde{\chi}_1^0} h^2$

Neutralino Decays to Axino and Gamma

- The decay width of neutralino (bino) LOSP is give as:

$$\Gamma(\chi \to \tilde{a}\gamma) = \frac{\alpha_{em}^2 C_{a\chi\gamma}^2}{128\pi^3} \frac{m_{\tilde{\chi}_1^0}^3}{(f_a/N)^2} \left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{\chi}_1^0}^2}\right)^3$$ [1]

where $C_{a\chi\gamma} = (C_{aYY}/\cos\theta_W)Z_{11}$, with Z_{11} standing for the bino part of the lightest neutralino

- In DFSZ model, $N = 8$ and $C_{aYY} = 8/3$
- In KSVZ model, $N = 1$ and $C_{aYY} = 0, 2/3, 8/3$ for $e_Q = 0, -1/3, 2/3$ respectively

[1] arXiv:hep-ph/0101009

Neutralino Lifetime for $\tilde{\chi}_1^0 \to \tilde{a}\gamma$

- The neutralino lifetime for the process $\tilde{\chi}_1^0 \to \tilde{a}\gamma$

$$\tau(\tilde{\chi}_1^0 \to \tilde{a}\gamma) = 0.33\mathrm{sec}\frac{1}{C_{aYY}^2 Z_{11}^2}\left(\frac{\alpha_{em}^2}{1/128}\right)^{-2}\left(\frac{f_a/N}{10^{11}\mathrm{GeV}}\right)^2 \times\left(\frac{100\mathrm{GeV}}{m_{\tilde{\chi}_1^0}}\right)^{-3}\left(1-\frac{m_{\tilde{a}}^2}{m_{\tilde{\chi}_1^0}^2}\right)^3$$

Neutralino Decays to Axino and Gamma

- For large enough neutralino masses we also have $\tilde{\chi}_1^0 \to \tilde{a} Z$

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{a} Z) = \frac{\alpha_{em}^2 C_{a\chi\gamma}^2}{128\pi^3} \tan^2\theta_W \frac{m_{\tilde{\chi}_1^0}^3}{(f_a/N)^2} \times PS\left(\frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2}, \frac{m_{\tilde{a}}^2}{m_{\tilde{\chi}_1^0}^2}\right)$$

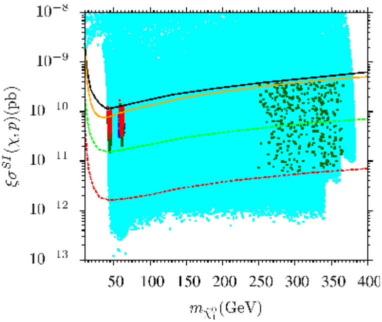
where $C_{a\chi\gamma} = (C_{aYY}/\cos\theta_W) Z_{11}$, with Z_{11} standing for the bino part of the lightest neutralino

$$\mathrm{PS}(x,y) = \sqrt{1-2(x+y)+(x-y)^2}\left[(1-y)^2 - \frac{x}{2}(1-6\sqrt{y}+y) - \frac{x^2}{2}\right].$$

Even at $m_{\tilde{\chi}_1^0} \gg m_Z, m_{\tilde{a}}$, $\tau(\tilde{\chi}_1^0 \to \tilde{a} Z) \simeq 3.35 \tau(\tilde{\chi}_1^0 \to \tilde{a}\gamma)$

Light Neutralino Searches at CEPC

- We have two typed of Light neutralinos solutions that is solutions with correct relic density (Z-resonamce and h-resonance)[2] and neutralino with large density [3]
- At CEPC we can probe it via
  $e^+e^- \to e^+e^- + \gamma \to \tilde{\chi}_1^0(bino) + \tilde{\chi}_1^0(bino) + \gamma$

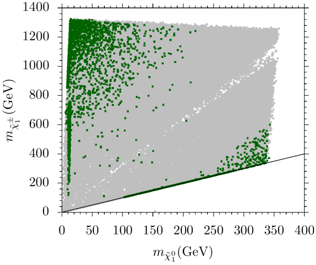


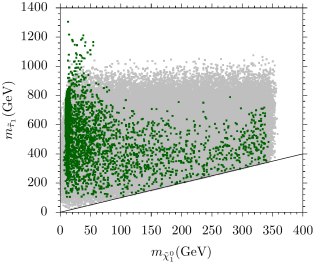
[2] arXiv:1709.06371
[3] arXiv:1409.3930

Light Neutralino Searches at CEPC

- The light neutralinos with large relic density may also be probed at the CEPC
- At the CEPC, the bino can be pair-produced via $t-$ channel selecton and then bino decays into axino and photon ($\tilde{\chi}_1^0 \to \tilde{a}\gamma$) as follows
- $e^+e^- \to \tilde{\chi}_1^0(bino) + \tilde{\chi}_1^0(bino) \to 2\tilde{a} + 2\gamma$

Light Neutralino from GmSUGRA (preliminary results)





Gray points satisfy REWSB and neutralino as LSP conditions. Dark green points satisfy additional spartcile mass and B-physics bounds including $m_h = 125 \pm 3\,\mathrm{GeV}$ bounds.

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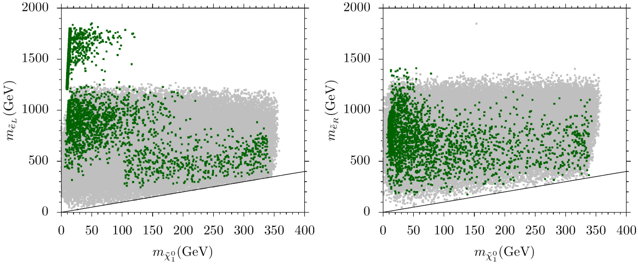

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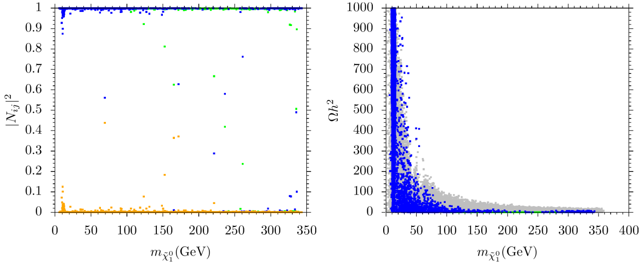

Gray points satisfy REWSB and neutralino as LSP conditions. (Left) Blue, green and orange points satisfy spartcile mass and B-physics bounds including $m_h = 125 \pm 3\,\mathrm{GeV}$ bounds respresent bino-componet, wino-component and higgsino-components respectively.(Right) Blue points show bino-type neutralino solutions and green points represent wino-dominant solutions.

	Point 1	Point 2	Point 3	Point 4
m_0	1387	1439	1449	1537
$m_{\tilde{Q}}$	1280.8	1316	1358.3	1404.1
$m_{\tilde{U}^c}$	1748.5	1851.1	1765.8	1981.3
$m_{\tilde{D}^c}$	1790.6	1857.7	1715.7	1945.9
$m_{\tilde{L}}$	19.8	140	912.9	475.7
$m_{\tilde{E}^c}$	472.6	192.6	756.2	132.2
M_1	0.1588	1.822	96.81	132.6
M_2	790.9	1015	812.9	1023
M_3	-1186	-1517.9	-977.33	-1203
$A_t = A_b$	3944	3693	3632	4981
A_τ	241	-536.3	-403.1	-238.2
$\tan\beta$	28.3	34.7	17.6	21.3
m_{H_u}	673.5	836.3	2631	3284
m_{H_d}	1193	647.3	2618	3284
m_h	123	122	123	125
$m_{H,A}$	1582,1572	1394, 1385	2515,2499	3060,3040
$m_{H^\pm}$	1585	1397	2516	3061
$m_{\tilde{g}}$	2638	3297	2220	2676
$m_{\tilde{\chi}^0_{1,2}}$	5.84,682	8.8, 878	45.9,326	62,355
$m_{\tilde{\chi}^0_{3,4}}$	2152, 2152	2461,2461	337, 712	363, 882
$m_{\tilde{\chi}^\pm_{1,2}}$	684, 881	2155, 2462	333,704	362,876
$m_{\tilde{u}_{L,R}}$	2625,2832	3165,3342	2374,2542	2752,2975
$m_{\tilde{t}_{1,2}}$	1838, 2056	2394,2607	1173, 1731	1069 ,1811
$m_{\tilde{d}_{L,R}}$	2627, 2880	3166, 3388	2375,2561	2753, 3016
$m_{\tilde{b}_{1,2}}$	1957, 2500	2447,2813	1717 ,2433	1812,2777
$m_{\tilde{\nu}_{(1,2),3}}$	437, 434	549,522	978, 935	670, 532
$m_{\tilde{e}_{L,R}}$	447, 574	550, 546	984 ,909	683,
$m_{\tilde{\tau}_{1,2}}$	356,618	265,627	816, 941	264 ,549
$\sigma_{SI}(\mathrm{pb})$	3.151×10^{-13}	3.98×10^{-13}	8.05×10^{-11}	7.33×10^{-11}
$\Omega_{CDM}h^2$	574	86	0.11	0.103

Summary

- The prelinemary scan results for the light bino from GmSUGRA are presented
- The light binos with large relic density can decay via $\tilde{\chi}_1^0 \to \tilde{a}\gamma$
- Such binos can be probed at the CEPC via $e^+e^- \to \tilde{\chi}_1^0(bino) + \tilde{\chi}_1^0(bino) \to 2\tilde{a} + 2\gamma$
- The light binos with correct relic density may also be probed at the CEPC via $e^+e^- \to e^+e^- + \gamma \to \tilde{\chi}_1^0(bino) + \tilde{\chi}_1^0(bino) + \gamma$