PROCEEDINGS OF SCIENCE

SUSY at the LHC

Bhaskar Dutta[*†]
Texas A&M University
E-mail: dutta@pysics.tamu.edu

In this talk I discuss the status of supersymmetry(SUSY) models in the light of the current experimental data from the Large Hadron Collider (LHC). I discuss the surviving SUSY scenarios and their possible origins. I also discuss the search strategies to investigate these models at the ongoing LHC.

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*Speaker.

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1. Introduction

Minimal SUSY extension of the SM (MSSM) seems to possess many important virtues. For example, the hierarchy problem is solved, grand unification of the gauge couplings is achieved, the electroweak symmetry can be broken radiatively, a dark matter (DM) candidate can be obtained in the R parity conserving scenarios which can explain the precisely measured 27% of the universe etc. The MSSM also explains the observed discrepancy in the measurement of anomalous magnetic moment of muon. Further, the MSSM predicts the Higgs Boson mass to be $\leq$ 135 GeV and the observed Higgs boson mass is 125 GeV.

However, no SUSY particle has been observed yet. The most important question we try to answer in this talk is whether low energy SUSY models built around the electroweak scale in order to resolve all the puzzles of the SM should no longer to be considered as a valid extension of the SM. I will evaluate the LHC constraints to answer this question.

2. LHC results

The most sought after channel to find SUSY at the LHC is the squark, gluino pair prodcution processes which subsequently decay into variouss final states, e.g., 4 jets + $\not{E}_T$, Jets + leptons + $\not{E}_T$ etc. Nothing has been observed in these final states and the current bounds on $\tilde{q}$, $\tilde{g}$ are at around 1.6 - 2 TeV [1, 2]. The models where the colorless and colored sectors are tied with a mSUGRA(minimal supergravity)/CMSSM(constrained MSSM) like bounday conditions with the masses for both types being same are almost ruled out when one tries to explain the anomalous magnetic moment of muon.

How about the constraint on stop mass? One interesting aspect of the MSSM is that it provides the correct Higgs mass which contains a large one loop correction involving stop masses. Now let us look at the stop mass constraint from the LHC in Figure 1 [3, 4]. We find that the mass constraint is ∼1.1 TeV, however, *if the lightest neutralino $\tilde{\chi}_1^0$ is $\geq$ 400 GeV, there is no constraint on the stop mass.* The Higgs mass is satisfied even when the stop mass is multi-TeV which means that *we have enough parameter space left to be searched at the LHC.*

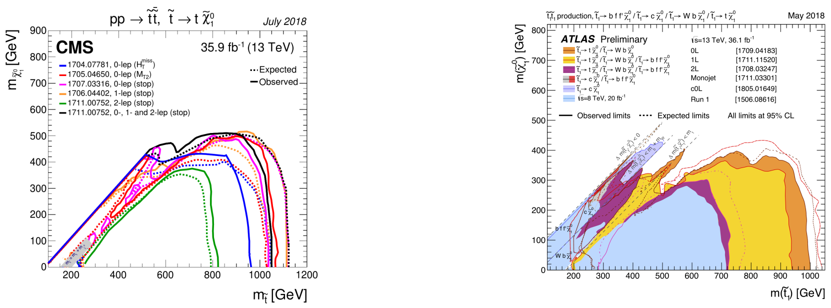

Figure 1: Stop pair peruction at the LHC: CMS (left) [3] and ATLAS (right) [4].

Let us now now turn our attention to the colorless sector, $\tilde{e}, \mu$, $\tilde{\chi}^0_{1,2,3,4}$, $\tilde{\chi}^{\pm}_{1,2}$ [3, 4]. These particles are very important to understand the muon g-2 discrepancy and DM abundance calculations. From Figure 2, we find that the the bounds cease to exist if the $\tilde{\chi}_1^0 \geq 250(700)$ GeV for

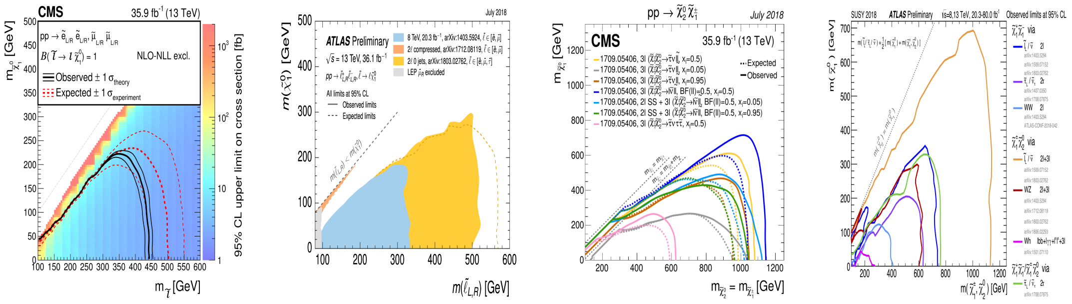

Figure 2: slepton pair peruction at the LHC: CMS (frist plot from the left) [3] and ATLAS (second plot) [4]. Chargino-neutralino pair peruction at the LHC: CMS (3rd plot) [3] and ATLAS (4th plot) [4].

slepton(chargino/heavy neutralino) productions and the constraints go away when ΔM (mass difference between these particles and $m_{\tilde{\chi}_1^0}$) ≤ 60 for the entire parameter space for sleptons and for most of the parameter space for charginos and heavy neutralinos.

Can we still explain the $\sim$3 σ muon g-2 anomaly [5, 6] in the context of the MSSM [7]? At present, Fermilab is making measurement to confirm the Brookhaven result. In order to understand the explanation, we divide our parameter space into the following three regions *based on the possible decomposition of the lightest neutralino* (Table 1) which is useful to understand the nature of the DM candidate: Using this group of decomposition, we show the allowed parameter space by the

Region		$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$
I	$M_1 \gg \mu$	higgsino	higgsino
	$M_1 \ll \mu$	bino	higgsino
	$M_1 \sim \mu$	bino-higgsino	bino-higgsino
II	$M_1 \gg M_2$	wino	bino ($M_1 \ll \mu$)
			higgsino ($M_1 \gg \mu$)
			bino-higgsino ($M_1 \sim \mu$)
	$M_1 \ll M_2$	bino	wino
	$M_1 \sim M_2$	bino-wino	bino-wino
III	$M_2 \sim \mu \ll M_1$	wino-higgsino	wino-higgsino
	$M_2 \sim \mu \gg M_1$	bino	wino-higgsino
	$M_2 \sim \mu \sim M_1$	mixed	mixed

Table 1: Composition of $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ in different regions based on the ratios M_1/M_2 and M_1/μ [7].

existing data in Table 2. We find that $m_{\tilde{\mu},\tilde{\chi}_i^{0,\pm}}$ can be as large as 1 TeV and a lot of parameter space exists with ΔM between the these particles and $m_{\tilde{\chi}_1^0}$ being not so large ≤ 60 where the experimental bounds do not apply.

The DM abundance in SUSY model gets important contributions from the coannhillation regions, i.e., where the mass gaps between the lightest neutralino and selectrons, smuons, staus, charginos, heavier netralinos is $5-15$ GeV [8], especially the stau scenario [9, 10] can be responsible for the entire DM abundance in a thermal DM scenario. The stau neutralino coannihilation

	Region-I	Region-II	Region-III
$m_{\tilde{\mu}_1}$	911.78 (992.38)	715.16 (904.52)	957.74 (996.20)
$m_{\tilde{\mu}_2}$	1000.88 (1000.88)	1000.92 (1000.92)	1000.86 (1000.93)
$m_{\tilde{\chi}_1^0}$	390.05 (478.42)	197.71 (197.71)	482.08 (637.11)
$m_{\tilde{\chi}_2^0}$	477.76 (491.96)	963.56 (963.56)	947.02 (966.17)
$m_{\tilde{\chi}_1^\pm}$	477.19 (487.97)	197.95 (197.95)	910.37 (939.92)
$m_{\tilde{\chi}_2^\pm}$	1007.69 (1007.89)	1006.65 (1006.65)	1033.37 (1055.87)

Table 2: Maximum values of the masses (in GeV) of smuons, neutralinos and charginos for $\tan\beta = 50$, resulted from a MSSM parameter scan. The values shown in each column correspond to $(g-2)_\mu$ within 1σ and those in the brackets correspond to $(g-2)_\mu$ within 2σ [7].

regions are found to be very effective since the lightest stau can naturally be close to the lightest neutralino [9].

3. Exploring SUSY Models

From the LHC results it appears that we would need the colored particles being heavier than the the non-colored sector. There are many SUSY mass scenarios where this can be achieved. In this talk, I will mention one scenario which is based on type IIB de Sitter string vacua. In this scenario all moduli are stabilized and the MSSM is sequestered and consequently the spectrum of soft-terms is hierarchically smaller than the gravitino mass $m_{3/2}$ [11]. This interesting feature makes these models compatible with gauge coupling unification and TeV scale SUSY with no cosmological moduli problem. Depending on the moduli dependence of the Kahler metric for matter fields and on the mechanism responsible to obtain a de Sitter vacuum, two interesting scenarios for phenomenology have been found [12]: (i) a typical MSSM scenario where all soft-terms: $m_{1/2} \sim m_0 \sim m_{3/2}\varepsilon \ll m_{3/2}$ and (ii) a split-SUSY scenario where gaugino masses are suppressed with respect to scalar masses: $m_{1/2} \sim m_{3/2}\varepsilon \ll m_0 \sim m_{3/2}\sqrt{\varepsilon} \ll m_{3/2}$ $\varepsilon m_{3/2}/M_{Planck} \ll 1$.

In scenario (i), squarks and gluions are considered to be heavy. If we make the sleptons and the gauginos to be heavy as well, we can still be left with a few hundred GeV μ which means that the lightest SUSY particle is Higgsino. This scenario has been investigated in the context of both non-thermal DM [13] and thermal DM [14] for allowed parameter space. In the non-thermal scenario, the DM abundance is given by the following expression [13]

$$\left(\frac{n_\chi}{s}\right) = \min\left\{\left(\frac{\mathrm{n}_\chi}{\mathrm{s}}\right)^{\mathrm{obs}} \frac{\langle\sigma \mathrm{v}\rangle^{\mathrm{th}}}{\langle\sigma \mathrm{v}\rangle} \sqrt{\frac{\mathrm{g}_*(\mathrm{T_f})}{\mathrm{g}_*(\mathrm{T_{rh}})}} \frac{\mathrm{T_f}}{\mathrm{T_{rh}}}, \quad \mathrm{Y}_\phi \mathrm{Br}_\chi\right\}, \tag{3.1}$$

where $\left(\frac{n_\chi}{s}\right)^{\mathrm{obs}} \simeq \Omega^{\mathrm{obs}} \left(\frac{\rho_{\mathrm{crit}}}{m_\chi s h^2}\right)$ (where n_χ, s, m_χ and ρ_{crit} are the number density of DM particles, entropy density, DM mass and critical density of today's universe respectively). $Y_\phi \simeq \frac{3T_{\mathrm{rh}}}{4m_\phi}$ is the yield of particle abundance from modulus decay (m_ϕ is the modulus mass, T_{rh} T_f are the reheat and freeze-out temperatures respectively and g^* is the number of relativistic degrees of freedom at a temperature T), and Br_ϕ is the branching ratio of the modulus decay into R-parity odd particles. The first entry in the bracket refers to the *Annihilation Scenario*, while the second entry refers to the *Branching Scenario*. Since in the non-thermal scenario the ratio $T_\mathrm{f}/T_\mathrm{rh}$ is forced to be greater than one, it means that the ratio $\langle\sigma v\rangle^{\mathrm{th}}/\langle\sigma v\rangle$ has to be smaller than one in order not to overproduce DM in the Annihilation Scenario. In Figure 3 we superimpose the impact of direct and indirect detection constraints in this model and show the allowed parameter space from these experiments.

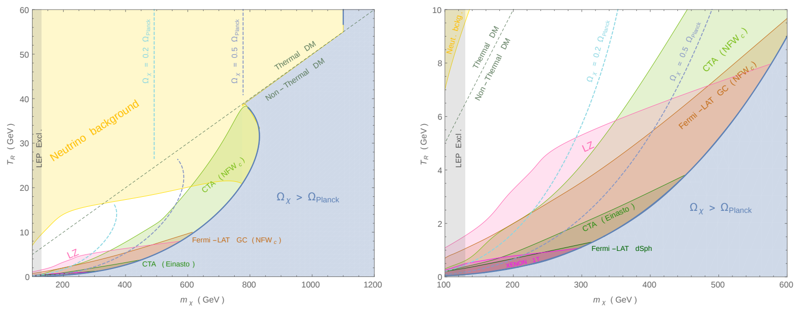

Figure 3: Combined indirect and direct detection bounds. The plot on the right is simply a zoom on the region for $T_R = 10$ GeV [13].

Scenario 2 is is characterized by long lifetime of gluinos with displaced vertex, disappearing tracks and stable massive particles. This scenario appears in models [15, 16] and the LHC signatures are discussed in [17, 18].

4. Noncolored sector at the LHC

A few challanges at the LHC: (i) how can we probe the colorless SUSY sector (especially, if the first two generations are heavy)? (ii) how can we search for a sparticle spectrum with not so large ΔM (i.e., containing smaller Missing energy)?and (iii) how to find particles with longer life time?

There have been attempts to answer the questions raised in the first two items using vector boson fusion process to search for charginos, neutralinos, selectrons, smuons (e.g., [19, 20, 21]) and monojet plus leptons and taus (e.g., [22, 23, 24]).

Using monojet plus leptons, it is found that selectron and smuon can be probed at the ongoing LHC upto 200 GeV for 3000 fb^{-1} fb luminosity for $\Delta M \leq 60$ GeV [22]. In Table 3, the reach is shown for various mass differences [22]. Similarly, for Higgsino type neutralinos [23] (the scenario discussed in the previous section), the projected reach is 200 GeV for 1 ab^{-1} and the current reacah is about 160 GeV [25, 26]. For staus the reach for a stau-neutralino gap ≤ 25 GeV (important for coannihilation) is shown in Figure 4 [24].

5. Conclusion

SUSY extension of the SM is highly motivated since it provides solutions to many SM puzzles, e.g., origin of DM, origin of electroweak scale, hierarchy problem, grand unification etc. However

Table 3: Heavier model benchmarks for the small ($\Delta m = 10, 20$ GeV), intermediate ($\Delta m = 30, 40$ GeV), and large ($\Delta m = 50, 60$ GeV), mass gap event selection tunes.

Benchmark	S_{10}^{160}	S_{20}^{160}	S_{30}^{160}	S_{40}^{160}	S_{50}^{160}	S_{60}^{160}
Events at $\mathscr{L} = 300$ fb^{-1}	43.4	39.8	24.5	27.5	29.5	28.3
$S \div (1+B)$	0.24	0.22	0.11	0.12	0.12	0.12
$S \div \sqrt{1+B}$	3.3	3.0	1.7	1.8	1.9	1.8
Benchmark	S_{10}^{200}	S_{20}^{200}	S_{30}^{200}	S_{40}^{200}	S_{50}^{200}	S_{60}^{200}
Events at $\mathscr{L} = 1000$ fb^{-1}	72.1	67.3	41.8	45.8	52.9	63.6
$S \div (1+B)$	0.12	0.11	0.06	0.06	0.07	0.08
$S \div \sqrt{1+B}$	3.0	2.8	1.5	1.7	1.9	2.3
Benchmark	S_{10}^{300}	S_{20}^{300}	S_{30}^{300}	S_{40}^{300}	S_{50}^{300}	S_{60}^{300}
Events at $\mathscr{L} = 3000$ fb^{-1}	48.7	55.4	31.7	33.8	46.8	60.7
$S \div (1+B)$	0.03	0.03	0.01	0.02	0.02	0.03
$S \div \sqrt{1+B}$	1.2	1.3	0.7	0.7	1.0	1.2

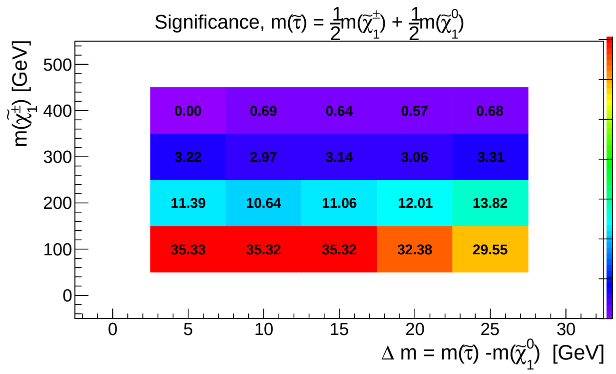

Figure 4: Signal significance as a function of $\tilde{\chi}_1^{\pm}$ mass and $m(\tilde{\tau}) - m(\tilde{\chi}_1^0)$ [24].

no SUSY particle has been observed yet and the LHC constraint for the squarks, gluino is around 2 TeV. However the reaches for non-colored sparticles are not good especially for the sparticles with not so large mass gaps and these particle are important to understand the to explain the DM abundance and the observed muon g-2 anomaly.

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