Implications of low and high energy measurements on SUSY models

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Abstract

New Physics searches at the LHC have increased significantly lower bounds on unknown particle masses. This increases quite dramatically the tension in the interpretation of the data: low energy precision data which are predicted accurately by the SM (LEP observables like M_W or loop induced rare processes like $B \to X_s \gamma$ or $B_s \to \mu^+ \mu^-$) and quantities exhibiting an observed discrepancy between SM theory and experiment, most significantly found for the muon $g - 2$ seem to be in conflict now. $(g - 2)_\mu$ appears to be the most precisely understood observable which at the same time reveals a 3-4 σ deviation between theory and experiment and thus requires a significant new physics contribution. The hints for a Higgs of mass about 125 GeV [1, 2], which is precisely what SUSY extensions of the SM predict, seem to provide a strong indication for SUSY. At the same time it brings into serious trouble the interpretation of the $(g - 2)_\mu$ deviation as a SUSY contribution.

1   Minimal Super Symmetric extensions of SM

The Standard Model (SM), although doing surprisingly well in describing most of the precision data at the quantum level, is incomplete as it does not incorporate dark matter (DM) for example and it has fine tuning problems most notably it predicts a vacuum energy contribution induced by the Higgs condensate which is 50 orders of magnitude too large[2] and also the Higgs mass is not protected from being much heavier than other SM particles. As we know all SM states are protected either by chiral or by gauge symmetries, except from the Higgs. Supersymmetry (SUSY) imposing an invariance under the exchange of bosons/fermions with fermions/bosons in a field theory in principle is able to cure these problems. Exact SUSY would not only predict a vanishing cosmological constant, as

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[2]With the Higgs vacuum expectation value $v = 246.22$ GeV and a Higgs mass of about 125 GeV the contribution from the Higgs mechanism to the vacuum density is $\rho_H^{\mathrm{vac}} = \frac{1}{8} m_H^2 v^2 \simeq 1.1841 \cdot 10^8$ GeV^4 [3]. With $\kappa = 8\pi G_N/c^2$ the contribution to the cosmological constant is given by $\Lambda_H = \kappa \rho_H^{\mathrm{vac}} \simeq 5.1095 \cdot 10^{-2}$ cm^{-2}. This compares to the observed value $\Lambda_{\mathrm{obs}} = \kappa \rho_{\mathrm{crit}} \Omega_\Lambda \simeq 1.6517 \cdot 10^{-56}$ cm^{-2} .

$\langle H \rangle = 0$ for a supersymmetric Hamiltonian [4], but also vanishing anomalous magnetic moments like $a_{\mu\,\text{exactSUSY}} = 0$, or $(\bar{B} \rightarrow X_s\gamma)_{\text{exact SUSY}} = 0$ [5]. Since the SM predicts positive values for these observables the SUSY complement of the supersymmetric extension of the SM should yield negatively interfering contributions of the same size.

If supersymmetry is imposed, scalars have fermionic partners protected by chiral symmetry and therefore also scalars are required to be massless in the symmetric phase[3]. Not only the SM gauge symmetry is broken. As we know from observation, any SUSY extensions of the SM must be broken in such a way that all sparticles are heavier than all SM particles. Still, for the Higgs a minimal SUSY extensions of the SM predicts a light Higgs $m_h < M_Z$ + radiative corrections ≤ 140 GeV and finding a Higgs in this range is a strong argument in favor of SUSY (see the blue-band plot Fig. 3 in [6]).

In broken SUSY scenarios, patterns present at the exact symmetry level often are completely spoiled and radiative correction effects of either sign and much enhanced relative to the SM are possible. Order of magnitude enhancements of radiatively suppressed SM results, possible in $B_s \rightarrow \mu^+\mu^-$ decay, for example, are the most interesting possibilities. However, precision data largely constrain the size of SUSY contributions as long as the SM predictions match the data. A particular role here plays the muon $g - 2$ because a 3 to 4 σ contribution is substantial. One also could understand the supersymmetrized SM as the particular extension of the SM which is able to hide the rich structure it predicts from producing substantial observable effect below the 1 TeV scale.

A viable Minimal Supersymmetric extensions of the SM (MSSM) is possible only if we supplement the SM with an additional Higgs doublet (2HDM). One reason is supersymmetry itself, the other is anomaly cancellation of the SUSY partners of the Higgses. We thus have the SM with two scalars, a lighter h and a heavier H, a pseudoscalar A and the charged Higgses $H^{\pm}$ the spectrum of which is doubled by the SUSY completion, the sparticles. The vacuum expectation values of the two scalars $v_i = \langle H_i \rangle$ $(i = 1, 2)$ define the new parameter $\tan\beta = v_1/v_2$. In the minimal SUSY models the masses of the extra Higgses at tree level are severely constrained by mass- and coupling-relations. Only two independent parameters are left, which we may choose to be $\tan\beta$ and m_A. Very important is the fact that the SM gauge structure is not touched when going to the MSSM and gauge and Yukawa couplings of the sparticles are completely fixed by the gauge couplings of the SM.

In general 2HDMs do not exhibit the phenomenologically well established "minimal flavor violation" (MFV) constraint, which demands FCNC and CP patterns to be close to what we have in the SM [7]. The trick which saves the peculiar SM features is R-parity, a Z_2 symmetry between the two Higgs doublet fields $H_1 \leftrightarrow H_2$. As a byproduct SUSY+R-parity implies a stable lightest SUSY particle (LSP) which is a good candidate for the astrophysically established dark matter. The LSP usually is the lightest neutralino $\tilde{\chi}_1^0$, but also a gravitino can be a viable DM candidate. At the LHC

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[3]In supersymmetric quantum field theories if not all then at least the leading ultraviolet singularities cancel. This stabilizes the relation between bare and renormalized quantities. In particular the only quadratic divergences exhibited in the SM, the Higgs mass renormalization, is then absent in the symmetry limit. Note that conformal symmetry also could provide a solution to the Higgs hierarchy problem. The argumentation refers to a scenario where the renormalized theory is the long distance tail of an underlying theory at short distances which is exhibiting a physical cut-off.

the existence of a LSP would be signaled by events with missing transversal energy.

Even with the constraints mentioned, SUSY extensions of the SM allow for a large number ~ 100 of free symmetry breaking parameters. Free parameters typically are masses and mixings of the neutralinos, the higgsino mass μ ($+\mu H_1 H_2$ term of the 2HDM Higgs potential) and $\tan\beta$.

This changes if one marries SUSY with GUT ideas, in fact SUSY-GUTs (e.g. as based on SU(5)) are the only theories which allow for grand unification broken at a low scale (~ 1 TeV). This provides strong constraints on the SUSY breaking mechanism, specifically we distinguish the constrained CMSSM a SUSY-GUT with soft breaking masses universal at the GUT scale. The NUHM is as CMSSM with non-universal Higgs masses. Minimal super gravity (mSUGRA) exhibits super gravity induced SUSY breaking with $m_{3/2} = m_0$ at the bare level. These models assume many degeneracies of masses and couplings in order to restrict the number of parameters. Typically, SM parameters are supplemented by $m_{1/2}$ (scalar-matter mass, like $m_{\tilde{q}}$, $m_{\tilde{\ell}}$), m_0 (the $U(1)_Y \otimes SU(2)_L$ gaugino masses, $m_{\tilde{\gamma}}$, $m_{\tilde{Z}}$, $m_{\tilde{W}}$ and gluino mass $m_{\tilde{g}}$), sign(μ), $\tan\beta$, A (trilinear soft breaking term), and more for less constraint models.

2   Low energy monitor: the muon anomaly

Formally a_μ is one of the simplest observables one can imagine, just the electromagnetic vertex $(-ie)\,\bar{u}(p')\left[\gamma^\mu F_1(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m_\mu}F_2(q^2)\right]u(p)$ in the static limit where $F_1(0) = 1$, $F_2(0) = a_\mu$. And it has a simple experimental consequence, it is responsible for the Larmor precession of a muon circulating in a homogeneous magnetic field and which can be measured very precisely. Presently we have [8, 9, 10, 11, 12]

$$a_\mu^{\text{Exp.}} = 1.16592080(63) \times 10^{-3} \qquad a_\mu^{\text{The.}} = 1.16591797(60) \times 10^{-3} \tag{1}$$

$$\delta a_\mu = a_\mu^{\text{Exp.}} - a_\mu^{\text{The.}} = (283 \pm 87) \cdot 10^{-11}, \tag{2}$$

which is a $3.3\,\sigma$ deviation. If we take quoted errors and uncertainties to be estimated correctly and if we assume it is not a statistical fluctuation[4] we have to conclude that we see physics beyond the SM: $\delta a_\mu = \Delta a_\mu^{\text{NP}}$.

Nevertheless, the status of the theory must be examined. In particular the estimates of hadronic effects is by no means always 100 % certain. Recently, it has been shown that taking into account properly $\rho - \gamma$ mixing, which is absent in τ-decay, actually accounts for the τ versus e^+e^- discrepancy [10]. It means that τ data have to be corrected according to $v_0(s) = r_{\rho\gamma}(s)\,R_{\text{IB}}(s)\,v_-(s)$ with a mixing correction $r_{\rho\gamma}(s)$ which had not been taken into account in previous analyses [11]. These findings have been obtained/confirmed in a different approach based on the Hidden Local Symmetry model [13]. For a concise review of the muon $g - 2$ status and future see Graziano Venanzoni's contribution to these Proceedings [14].

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[4]The statistical error of $a_\mu^{\text{Exp.}}$ is $54 \cdot 10^{-11}$, other errors are systematic.
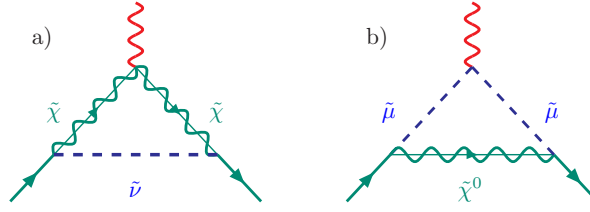
Figure 1: Leading SUSY contributions to $g-2$ in supersymmetric extension of the SM. For subleading corrections see [15].

The muon is particularly interesting because possible contributions from unknown heavier states yield contributions

$$a_\mu^{NP} = C\, m_\mu^2/M_{NP}^2 \tag{3}$$

where naturally $C = O(\alpha/\pi)$ ($\sim$ lowest order a_μ^{SM}). Typical New Physics scales required to satisfy $\Delta a_\mu^{NP} = \delta a_\mu$ are $M_{NP} = 2.0^{+0.4}_{-0.3}$ TeV, 100^{+21}_{-13} GeV and 5^{+1}_{-1} GeV for $C = 1$, α/π and $(\alpha/\pi)^2$, respectively.

Different extensions of the SM yield very different effects in a_μ such that a_μ is a very good monitor to look for physics beyond the SM. It is not so easy to get substantial effects with obvious new physics possibilities: in view that the τ yields $a_\mu(\tau) \simeq 42 \cdot 10^{-11}$ only, and bounds like $m_L > 100$ GeV for a heavy lepton or $m_{b'} \gtrsim 200$ GeV for a heavy quark show that sequential fermions (4th family) would not be able to give a substantial effect. Similarly, possible Z', W' or leptoquarks, which have to satisfy bounds like $M_{Z',W'} > 600 - 800$ GeV, depending on the GUT scenario, yield tiny effects only. They can be estimated by rescaling the weak SM contribution with $(M_W/M_{W'})^2 \sim 0.01$, which gives 1% of $19.5 \cdot 10^{-10}$, too small to be of relevance. More examples have been reviewed in [9].

Before the recent results from the LHC, constraints on the mass spectrum from LEP and the Tevatron already excluded sufficiently light new states which could produce a 3-4 σ effect, unless the coupling is unusually strong, with the risk that perturbative arguments fail to be reliable.

The most promising New Physics scenarios are provided by SUSY extensions of the SM because in these models the muon Yukawa coupling is enhanced by $\tan\beta = v_1/v_2$ which naturally may be expected to be as large as the top to bottom quark mass ratio (assuming $y_t = y_b$) $\tan\beta = v_1/v_2 = m_t/m_b \sim 40$. Such enhanced supersymmetric contributions to a_μ stem from sneutrino–chargino and smuon–neutralino loops as shown in Fig. 1. The renormalization group improved 1-loop MSSM result is given by

$$a_\mu^{SUSY} \simeq \frac{\text{sign}(\mu M_2)\, \alpha(M_Z)}{8\pi \sin^2\Theta_W} \frac{\left(5 + \tan^2\Theta_W\right)}{6} \frac{m_\mu^2}{M_{SUSY}^2} \tan\beta \left(1 - \frac{4\alpha}{\pi} \ln \frac{M_{SUSY}}{m_\mu}\right) \tag{4}$$

with M_{SUSY} a typical SUSY loop mass and the sign is determined by the Higgsino mass term μ. Obviously, the 3-4 σ deviation in muon $g - 2$ (if real) requires sign(μ) positive and $\tan\beta$ preferably large. These are clear cut constraints which cannot be obtained easily based on LHC data alone. In GUT constrained models where neutralino masses are constrained by limits on the colored sector from the LHC, typically now $M_{SUSY} > 500$ GeV. If we assume $\delta a_\mu = \Delta a_\mu^{SUSY}$ we find

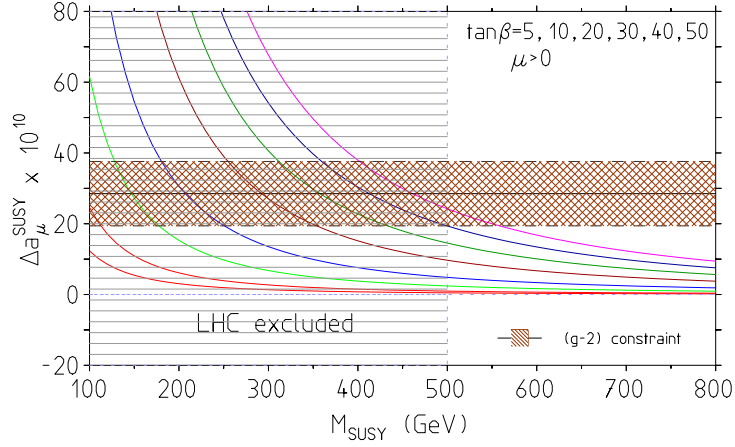Figure 2: Constraint on large $\tan\beta$ SUSY contributions as a function of M_{SUSY}. The horizontal band shows $\Delta a_{\mu}^{\mathrm{NP}} = \delta a_{\mu}$. The region left of $M_{\mathrm{SUSY}} \sim 500$ GeV is excluded by LHC searches. If $m_h \sim 125 \pm 1.5$ GeV actually $M_{\mathrm{SUSY}} > 800$ GeV depending on details of the stop sector ($\{\tilde{t}_1, \tilde{t}_2\}$ mixing and mass splitting) and weakly on $\tan\beta$.

$\tan\beta \simeq M_{\mathrm{SUSY}}^2/(65.5 \text{ GeV})^2$, which for $M_{\mathrm{SUSY}} \simeq 500$ GeV requires $\tan\beta \simeq 58$ (see Fig. 2), which is in conflict with a Higgs near 125 GeV as we will see below.

3   High energy precision physics: LEP, B-physics

Here we are looking at SM precision observables like G_F (muon lifetime), Z observables M_Z, Γ_Z, g_V, g_A, $\sin^2 \Theta_{\mathrm{eff}}$ (LEP1/SLD) W and *top* observables M_W, Γ_W, m_t and Γ_t (LEP2/Tevatron). An important observable is the W mass given by

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F} \ (1 + \Delta r) \tag{5}$$

where $\Delta r = f(\alpha, G_F, M_Z, m_t, \cdots)$ represents the radiative correction to the tree level mass-coupling relation, which depends on the independent parameters of the theory. They differ from the SM by additional contributions in extensions of the SM and thus allow to constrain the parameter space of the extended model. In SUSY models M_W is sensitive to the top/stop sector parameters and actually M_W is essentially the only observable which slightly improves in MSSM fits (see Fig. 25 of [16]) while

$$\sin^2 \Theta_{\mathrm{eff}} = \frac{1}{4} \left(1 - \mathrm{Re}\, \frac{v_{\mathrm{eff}}}{a_{\mathrm{eff}}}\right) \tag{6}$$

remains unaffected [6] (see Figs. 14 and 15 of [17] and Fig. 1 of [18] and Fig. 4 of [6]). The global fit of LEP data [19] does not improve when going from the SM to the MSSM, i.e. SUSY
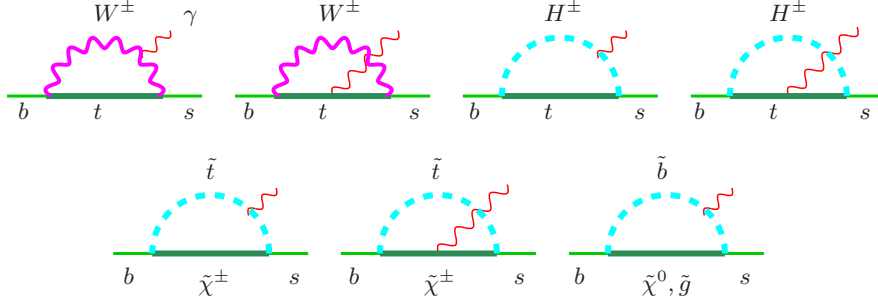
Figure 3: Leading graphs in $b \to s\gamma$. SM, 2HDM and SUSY specific contributions.
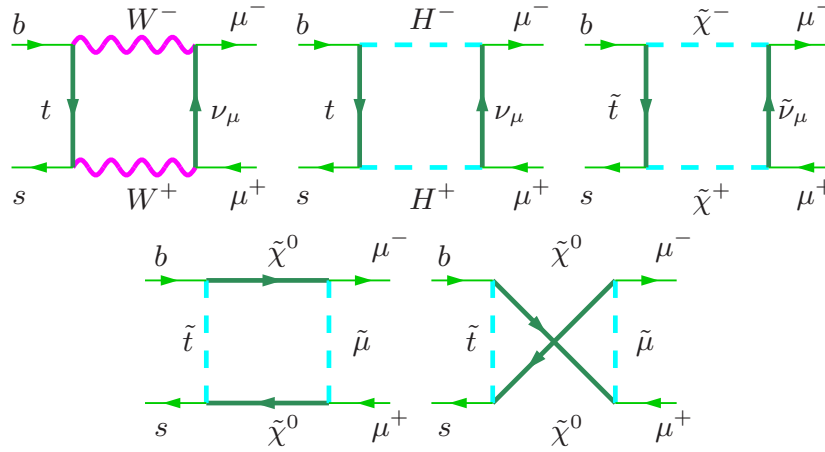
Figure 4: Leading graphs in $B_s \to \mu^+\mu^-$. SM, 2HDM and SUSY specific contributions.

effects are strongly constrained here. MSSM results merge into SM results for larger SUSY masses, as decoupling is at work.

Data on the penguin loop induced $B \to X_s\gamma$ transition (see Fig. 3) yields another strong constraint on deviations from the SM [20]. Indeed, the SM prediction [21] $\mathcal{B}(b \to s\gamma)_{\mathrm{NNLL}} = (3.15 \pm 0.23) \cdot 10^{-4}$ is consistent within 1.2 σ with the experimental result [22] $\mathcal{B}(b \to s\gamma) = (3.55 \pm 0.24 \pm 0.09) \cdot 10^{-4}$. It implies that SUSY requires heavier $m_{1/2}$ and/or m_0 in order not to spoil the good agreement.

The very rare box loop induced decay $B_s \to \mu^+\mu^-$ (see Fig. 4) is very interesting because SUSY contributions (box contributions with W's replaced by charged Higgses $H^\pm$) are able to enhance the SM value

$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) = (3.1 \pm 1.4) \times 10^{-9} \tag{7}$$

by two orders of magnitude, especially in scenarios with non-universal Higgs masses (NUHM). The best bound obtained recently by LHCb [24] is

$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) < 1.4 \times 10^{-8} , \tag{8}$$

and gets closer to the SM value again constraining too large effects from beyond the SM.

In SUSY+R-parity scenarios the dark matter relict density [25] $\Omega_{\mathrm{CDM}}h^2 = 0.1126 \pm 0.0081$ represents a tough constraint for the relic density of neutralinos produced in the early universe. A DM neutralino is a WIMP DM candidate. The density predicted is [26]

$$\Omega h^2 \sim \frac{0.1\,\mathrm{pb}}{\langle \sigma v \rangle} \sim 0.1 \left(\frac{M_{\mathrm{WIMP}}}{100\mathrm{GeV}} \right)^2 \,, \tag{9}$$

where $\langle \sigma v \rangle$ is the relativistic thermally averaged annihilation cross-section. In most scenarios the dominating neutralino annihilation process is $\chi + \chi \rightarrow A \rightarrow b\bar{b}$ and the observed relict density requires the cross section to be tuned to $\langle \sigma v \rangle \sim 2 \cdot 10^{-26}$ cm^3/s [5]. Note that except from Ω_{CDM} all observables prefer heavier SUSY masses such that effects are small by decoupling. The muon $g - 2$ in contrast requires moderately light SUSY masses and in the pre-LHC era fitted rather well with expectations from SUSY (see e.g. Fig. 2 of [28] and [29]).

4   Implications of LHC data

Direct LHC search limits have been taken into account above in some cases. LHC events most directly test the colored sector of the MSSM. In models like the CMSSM and NUHM, constrained by coupling unification at the GUT scale, the colored sector parameters get closely related to the uncolored sector. Consequently, one obtains model dependent constraints on physics controlled via standard precision tests. Typically, in constrained models LHC data have a strong influence on a large part of SUSY parameter space [30]. The impact is very well illustrated e.g. in Figs. 1 of [31, 32].

A particular role is played by the mass of the light Higgs. At tree level in the MSSM $m_h \leq M_Z$. This bound receives large radiative corrections from the $t/\tilde{t}$ sector, which changes the upper bound to [33]

$$m_h^2 \sim M_Z^2 \cos^2 2\beta + \frac{3\sqrt{2}G_\mu m_t^4}{2\pi^2 \sin^2\beta} \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right) + \cdots \tag{10}$$

which in any case is well below 200 GeV. A given value of m_h fixes the value of $m_{1/2}$ represented by $\{m_{\tilde{t}_1}, m_{\tilde{t}_2}\}$. Global frequentist fits to the CMSSM and NUHM1 scenarios predict $m_h \sim 119$ GeV in fits incorporating the $(g-2)_\mu$ constraint and ~ 126 GeV without it. If $m_h \simeq 125$ GeV as suggested by

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[5]The cross section is of the form

$$\langle \sigma v \rangle \propto \tan^2\beta \, \frac{m_b^2}{M_Z^2} \frac{M_\chi^4}{(4M_\chi^2 - M_A^2)^2 + M_A^2\Gamma_A^2}$$

and has to be adjusted to $M_\chi \approx 1.8\,M_A$ to 2.2 M_A. On resonance the cross section would be too big, too far off resonance too small [27].

most recent LHC Higgs searches [1, 2] $m_{1/2}$ would be fixed around 800 to 950 GeV. Together with the narrow bound from the cosmic relict density in the CMSSM one would also fix m_0 at a relatively low value depending sensitively on $\tan\beta$, however.

As we see, the present LHC data have a quite dramatic impact on SUSY scenarios. The main outcome is that in constrained models like CMSSM, NUHM1, mSUGRA or NUHM2 all allowed parameter points with $m_h \sim 125$ GeV are inconsistent with the observed $(g-2)_\mu$ [34, 32] ! However, in unconstrained SUSY extensions of the SM, only direct searches for sneutrino, chargino, smuon and neutralino states (or corresponding mass bounds) can lead to definite conclusions.

5   Comments and Outlook

SUSY is the natural mechanism to tame the cosmological constant problem as well as the Higgs hierarchy problem of the SM. However, to make a SUSY extension of the SM not to spoil phenomenologically established minimal flavor patterns of the SM one has to supplement it by assuming R-parity as an extra symmetry. Most of the popular MSSM scenarios assume in addition GUT to be at work which heavily constrains the parameter ambiguities in the possible soft SUSY breakings. One should be aware of the fact that SUSY and GUT are uncorrelated symmetry concepts, GUT assumptions almost always made in SUSY extensions of the SM may not be realistic. Unlike chiral symmetry, gauge symmetry and super symmetry gauge unification is not imposed to protect light states since the GUT scale is only two or three orders of magnitude below M_{Planck}.

Another comment concerns the nature of dark matter. DM is quite commonly assumed to consist of one or several species of elementary particle. In the SUSY+R-parity framework the LSP is an elementary particle. Here we should keep in mind that normal matter in the universe is dominated by nucleons, i.e., the normal matter density is 99% frozen energy and the light fermion masses generated in electroweak symmetry breaking represent a minor correction only. What if dark matter is not the result of the existence of a stable heavy elementary particle, but again mostly a form of frozen energy? One could think of unflavored SU(4) confined states. Such dark matter would be bosonic with no new fermionic matter which would form DM stars. Stability of such matter would be natural similar to B conservation for normal baryonic matter. In this context direct DM searches [35] are extremely important and progress in this field will bring more light into the DM puzzle.

Before the LHC was in operation one was expecting that SUSY improves agreement with experiment for observables like a_μ and marginally for M_W. After the first LHC results the expectations have changed. The situation looks somewhat disturbing. If a Higgs of mass near 125 GeV was confirmed one would have a strong point for SUSY at work[6]. But the $(g-2)_\mu$ deviation requires unexpectedly

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[6]There is in fact a very different scenario which predicts a Higgs of mass in this region: Schlereth's model [36] of composite weak bosons, exhibiting the weak gauge bosons as vector mesons and the Higgs as a weak version of the η' predicts a Higgs boson of mass somewhat above the ones of the gauge bosons [37]

large $\tan\beta$ now. Trivially, $\tan\beta > m_t/m_b$ requires that the top-bottom Yukawa couplings must exhibit an inverse hierarchy $y_b > y_t$ relative to the masses, which to me looks quite unnatural.

I start to worry about the muon anomaly result in the sense that it is not 100% clear to me whether experiments measure what theoreticians calculate, namely $a_\mu = F_2(0)$? The fact that perfect charged one-particle states do not exist, due to the infrared problem of QED, could affect the measurement at the level of precision we are dealing with. To my knowledge, in deriving the equations of motion of the muon in the external field the radiation field is neglected. The possible problem has been investigated at leading order in [38] some time ago, but no higher order results have been worked out so far. At the given level of precision this is an issue which should be investigated more carefully.

Within the next 5 years a new muon $g-2$ experiment will go into operation at Fermilab (E989) [39]. It will be an upgraded Brookhaven experiment (E821) working with ultra-relativistic magic energy muons. An alternative project is being designed at J-PARC which will work with ultra-cold muons [40]. The experiment will have very different systematics and therefore will provide a very important crosscheck of the storage ring experiments. The accuracy attempted is $\delta a_\mu = 16 \cdot 10^{-11}$. Provided the deviation (2) is real and the central value would not move the 3σ would turn into a 9σ deviation, provided theory is able to reduce theoretical uncertainties accordingly. If SUSY or 2HDM would be at work this experiment would provide invaluable information about the sign of the parameter μ and pin down $\tan\beta$ like no other experiment [41].

One has to be aware that much of the tension in the interpretation of the data we are confronted with may be a result of too special model assumptions used in analyzing the data. First LHC data primarily constrain the colored sector. In those SUSY models which do not assume a strong correlation between the colored and the uncolored sector a future ILC(1000) would play a prominent role in disentangling the true structure beyond the SM. For much more detailed discussions I refer to [42] beside the articles quoted earlier.

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