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Why continue looking for supersymmetry? Over and above the aesthetic and theoretical motivations from string theory, there are several longstanding phenomenological motivations for TeV-scale supersymmetry such as the electroweak scale, and the lightest supersymmetric particle (LSP) as cold dark matter. Run 1 of the LHC has actually provided three extra motivations, namely the stabilization of the electroweak vacuum, and successful predictions for the Higgs mass and couplings. How to look for it? There are several examples of emergent supersymmetry, the most recent being on the surfaces of topological insulators, and some sort of effective supersymmetry could be useful for boosting the power of laser arrays. At the LHC, attention is moving towards signatures that had previously been neglected, such as long-lived charged particles - which might be an opportunity for the MoEDAL experiment.

1. Introduction

In addition to its intrinsic elegance and role in string theory, there have been many phenomenological arguments suggesting that supersymmetry might appear at an accessible energy scale, including its ability to make the electroweak mass scale appear more natural [1], its provision of an interesting dark matter candidate [2], and its ability to facilitate the grand unification of particle interactions [3].

However, in the absence (so far) of supersymmetry at the LHC, some physicists are questioning the primacy of this paradigm for particle physics beyond the Standard Model (SM). Actually, I would argue the opposite, namely that the discovery of the Higgs boson in Run 1 of the LHC has provided three new motivations for supersymmetry at a potentially accessible energy scale. One new motivation is vacuum stability. Feeding the Higgs mass measured at the LHC and the top quark mass measured there and at Fermilab into renormalization-group calculations of the effective potential in the SM suggest that our present electroweak vacuum is unstable [4], and raise the question how the universe even arrived in this state [5]. These issues would be avoided in a supersymmetric extension of the SM. Moreover, supersymmetry also predicted correctly the mass of the Higgs boson [6] and that its couplings should resemble those in the SM [7].

However, before addressing the main subject of this paper, namely the search for supersymmetry at the level of fundamental particles, I also mention the appearance of supersymmetry in monopole physics and a couple of avatars of supersymmetry at less fundamental levels. One is an example of emergent supersymmetry in superconductivity, and the other is an example of induced supersymmetry, which may have an application in laser technology.

2. Supersymmetric Avatars

There are many instances where supersymmetry emerges at an effective level, with examples including nuclear and atomic physics [8]. Supersymmetry also emerges in some theories with topological avatars. One such example is provided by magnetic monopoles [9]: there is a lower bound (BPS) on the monopole mass:

$$E \geq \left\| \int_{S^2} \text{Tr}[\phi \mathbf{B} \cdot d\mathbf{S}] \right\|, \quad (2.1)$$

which is saturated if the Higgs mass and potential vanish, as happens in $N = 2$ supersymmetric theories. BPS monopole solutions are generically supersymmetric, so maybe the MoEDAL experiment will discover (at least approximate) supersymmetry at the same time as a monopole?

Another interesting recent example is provided by calculations [10] and experiments [11] that suggest the emergence of supersymmetry on the surfaces of topological insulators, at the boundary in parameter space between normal and topological superconductors, as illustrated in Fig. 1.

This is all very well, but what use is supersymmetry? Another recent paper has introduced the concept of “supersymmetric engineering” with application to arrays of semiconductor lasers [12]. The issue here is how to concentrate the energy emission in a single mode. Inspired by supersymmetric quantum mechanics, the proposed solution is to construct an array with identical spectra at the levels of the $n > 1$, but with the lowest $n = 1$ mode unpaired, as illustrated in Fig. 2. In theory, all the energy should be emitted in this lowest mode, and experiment indeed seems to show an enhancement in such a “supersymmetric” array [12]. Maybe supersymmetry will turn out to be a useful idea, even before its discovery at a fundamental level?

3. Searches for Fundamental Supersymmetry

What about the searches for supersymmetry at the level of fundamental particle physics? As is well known, there have been many experimental searches for supersymmetry at the LHC and

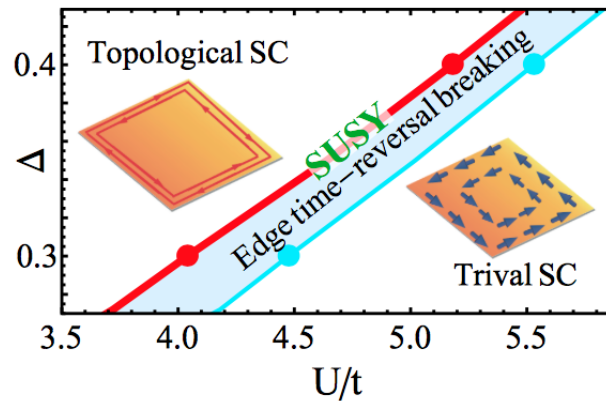


Figure 1. Emergent supersymmetry in the quantum phase diagram of interacting topological superconductors. $N = 1$ space-time supersymmetry emerges at the boundary between the topological and trivial superconducting phases. Figure taken from [10].

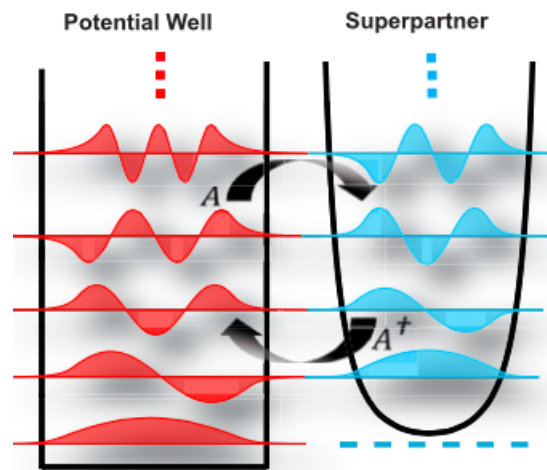


Figure 2. Supersymmetric engineering: a semiconductor laser array is designed with coupled “supersymmetric” pairs of higher-energy modes, lying above an unpaired fundamental mode. Figure adapted from [12].

elsewhere, which have been unsuccessful so far [13,14]. There have also been many searches for other possible extensions of the SM, which have been equally fruitless. The supersymmetry searches have focused mainly on the missing-energy signature that would be favoured if the lightest supersymmetric particle (LSP) provides the astrophysical dark matter [2].

This raises the questions whether it would be more productive to continue such missing-energy searches, possibly looking more closely at some under-explored nooks of parameter space, or whether one should focus on novel signatures? One of the issues here is that there are many possible phenomenological manifestations of supersymmetry, and there are no clear theoretical indications which to use as guidelines for experimental searches. “There are no signposts in superspace.”

The approach we have taken in the MasterCode Collaboration [15] is to compile all the available experimental, phenomenological, experimental, astrophysical and cosmological constraints that bear upon the possible masses of supersymmetric particles, and explore their

implications in frequentist statistical analyses of a range of different supersymmetric models. The relevant measurements include include electroweak data, flavour observables, dark matter measurements including the overall cosmological density of cold dark matter and upper limits on direct and indirect dark matter searches, and the (so far) null results of LHC searches¹.

Among all the laboratory measurements, there are none that provide unimpeachable evidence for new physics beyond the SM. However, there are a couple of instances that merit closer attention. One is the longstanding discrepancy between the experimental measurement [18] and the SM calculation [19] of the anomalous magnetic moment of the muon, $g_\mu - 2$, illustrated in Fig. 3, and another is the appearance of several anomalies in flavour physics. We look forward to experimental verification of the $g_\mu - 2$ discrepancy, which may soon be provided by an experiment at Fermilab [20]. This discrepancy could be explained if there are some electroweakly-interacting supersymmetric particles (sparticles) with low masses, but for the time being we treat it as an optional constraint on supersymmetric models. In parallel, we await clarification by the LHCb and Belle-2 experiments of the flavour anomalies, which would be difficult to explain in simple supersymmetric models.

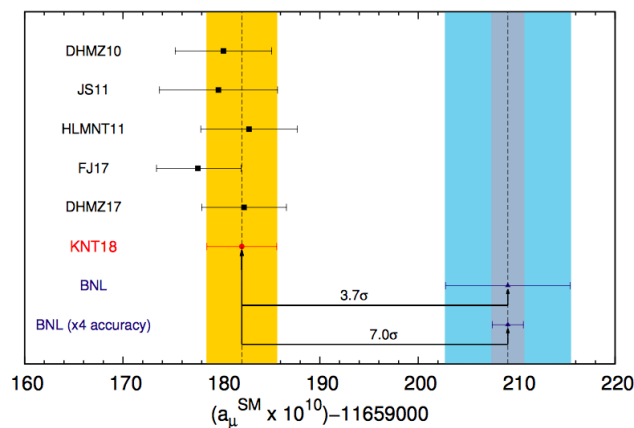


Figure 3. Theoretical calculations of the anomalous magnetic moment of the muon, $g_\mu - 2 = 2a_\mu$ in the Standard Model (yellow band on the left) [19] disagree with the experiment measurement (blue band on the right) [18].

One of the models we have studied is a phenomenological version of the minimal supersymmetric extension of the SM with 11 parameters, the pMSSM11 [21]. We have analyzed its parameter space with and without the $g_\mu - 2$ constraint, using a sample of 2×10^9 parameter sets. Best-fit spectra in these two scenarios are shown in Fig. 4 [21]. Dropping $g_\mu - 2$, we found that several squarks could well have masses around 1 TeV, opening promising prospects for future LHC searches, as well charginos and neutralinos. If $g_\mu - 2$ is included in the fit, sleptons, charginos and neutralinos could well have masses around 400 GeV, and these and some squarks might be accessible to the LHC, whereas others might be out of its reach. Our fits with and without $g_\mu - 2$ also offer some prospects for producing sparticles at the 3-TeV e^+e^- centre-of-mass energy proposed for CLIC, and the ILC operating at 1 TeV also has some prospects in the fit with $g_\mu - 2$. However, the prospects for discovering supersymmetry at lower-energy e^+e^- colliders are not promising in either of our pMSSM11 analyses.

There has been a lot of interest in the prospects for discovering the stop squark: arguments based on the naturalness of the electroweak mass scale suggest that it might be relatively light,

¹It has been suggested that weakly-interacting cold dark matter of the type suggested by supersymmetry has issues with the absence of cusps and of satellite galaxies. However, it has also been argued that there is in fact no cusp-core problem (see, e.g., [16]), nor any missing-satellite problem (see, e.g., [17]). In the absence of consensus on these issues, here we stick with the supersymmetric cold dark matter paradigm.

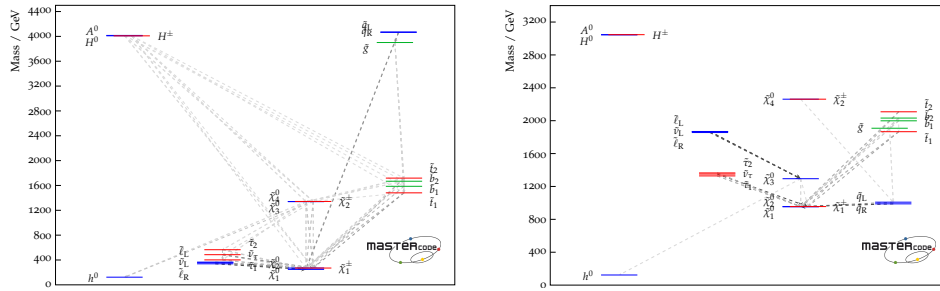


Figure 4. Best-fit spectra in the pMSSM11 obtained in global fits including (dropping) the $g_\mu - 2$ constraint in the left (right) panel [21].

whereas some have argued for a heavier stop squark on the basis on the Higgs mass measurement. We find that a stop squark weighing ~ 1 TeV is quite compatible with m_H and other constraints at the $\Delta\chi^2 = 1$ (68% confidence) level, and that a range of masses around 500 GeV is allowed at the $\Delta\chi^2 = 4$ (95% confidence) level. We have also studied the likely ranges of Higgs decay branching ratios in our fits. As illustrated in Fig. 5, in general we find best-fit values that are very close to those in the SM, but 20% deviations appear quite possible at the $\Delta\chi^2 = 4$ (95% confidence) level. These might be accessible to the upcoming higher-precision Higgs measurements at HL-LHC.

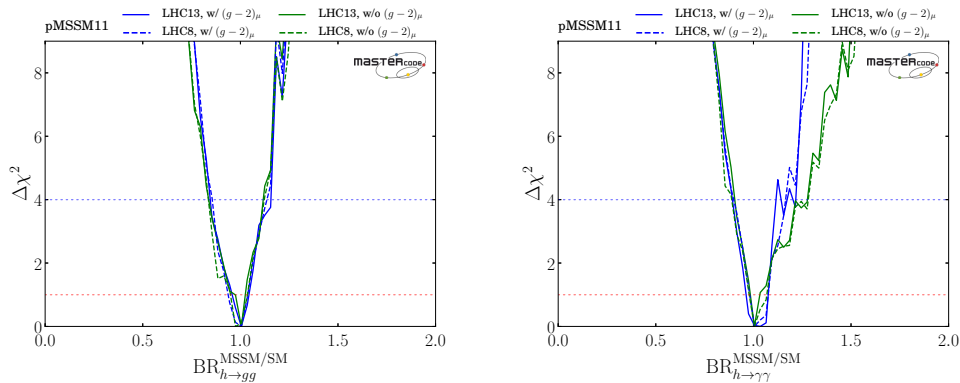


Figure 5. One-dimensional χ^2 likelihood functions for the branching ratios of the Higgs boson decays to gg (left panel) and $\gamma\gamma$ (right panel) in global fits with/without the $g_\mu - 2$ constraint (blue/green) and including/dropping LHC Run 2 measurements (solid/dashed) [21].

Another important way to search for supersymmetry is to look directly for the scattering of LSP dark matter particles on matter in a deep underground laboratory. The preferred mass range for the LSP in our analysis is ~ 300 GeV if the $g_\mu - 2$ constraint is included, or ~ 1 TeV if is dropped. Either way, the cross section for spin-independent dark matter scattering could be very close to the present experimental upper limits [21], as seen in Fig. 6. On the other hand, it might also be much smaller, below the ‘floor’ [22] where astrophysical neutrino backgrounds become important.

How heavy could the LSP be? The cosmological density of dark matter is an important constraint, which can be respected by a heavy LSP only if its rate of annihilation in the early universe is enhanced in some way. This can happen if the LSP is nearly degenerate with the next-to-lightest supersymmetric particle, the NLSP, and the two species coannihilate. In such a case, the mass difference might be so small that the NLSP has a long lifetime for decay into the LSP.

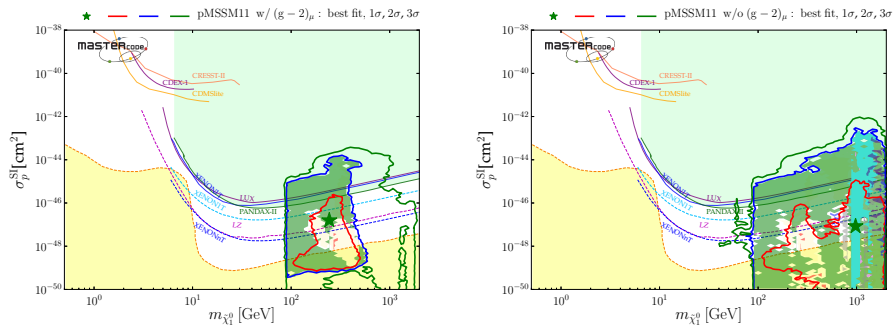


Figure 6. Predictions for spin-independent dark matter scattering in global fits with (without) the $g_\mu - 2$ constraint in the left (right) panel, showing direct constraints (solid lines), the prospective sensitivities of future experiments (dashed lines) and the neutrino ‘floor’ [22]. The 68% (95%) CL regions are outlined in red (blue), and the colours inside these regions correspond to the dominant mechanisms controlling the cosmological LSP density. See [21] for details.

There are other scenarios in which the NLSP might be long-lived, e.g., if the LSP is the gravitino in which case the NLSP decay would be suppressed by a gravitation-strength coupling, or in split supersymmetric scenarios in which the sparticle mediating NLSP decay is very heavy. Alternatively, the LSP would itself be unstable and long-lived if there is a small coupling violating R parity. With all these motivations, there has recently been increased interest in searches for long-lived unstable sparticles at the LHC.

4. Anomalous Sparticle Signatures in the MoEDAL Experiment

Whilst MoEDAL has been designed to optimize its ability to detect magnetic monopoles, it also has capabilities to detect other heavily-ionizing particles [23]. In particular, MoEDAL’s nuclear track detectors (NTDs) are sensitive to the relatively high ionization from slow-moving singly-charged particles with velocities $\beta < 0.2$. The stau slepton, $\tilde{\tau}$, is a prime candidate to be the NLSP. Unfortunately most directly-produced $\tilde{\tau}$ s would be produced with larger values of β , as seen in the left panel of Fig. 7 [24]. Therefore, MoEDAL has relatively low efficiency ϵ and hence sensitivity to direct $\tilde{\tau}$ production:

$$\epsilon \cdot \sigma \sim (< 10^{-3}) \cdot (< 100) / \text{fb} \quad (4.1)$$

for $m_{\tilde{\tau}} > 100$ GeV. However, the picture improves for $\tilde{\tau}$ s that are produced indirectly via the cascade decays of heavier sparticles, as illustrated in the left panel of Fig. 7 [24] - which is actually expected to be the dominant production mechanism. As a result, at the end of Run 3 of the LHC, when ATLAS and CMS hope to have gathered $\sim 300 / \text{fb}$, MoEDAL may have comparable sensitivity to some supersymmetric scenarios with long-lived $\tilde{\tau}$ s, as seen in the right panel of Fig. 7 [24].

MoEDAL is also installing a complementary detector for penetrating particles, MoEDAL Apparatus for Penetrating Particles (MAPP) [25]. This will search for long-lived neutral particles, particles with electric charges $\ll e$, and other anomalously-penetrating particles. A demonstration detector was installed in December 2017, and the full detector will be ready for Run 3 of the LHC. This is one of a number of approved [26] and proposed [27] experiments at the LHC to look for long-lived, weakly-interacting particles [28], which can probe supersymmetric scenarios in which the NLSP is almost degenerate with the LSP, is neutral and has no strong interactions

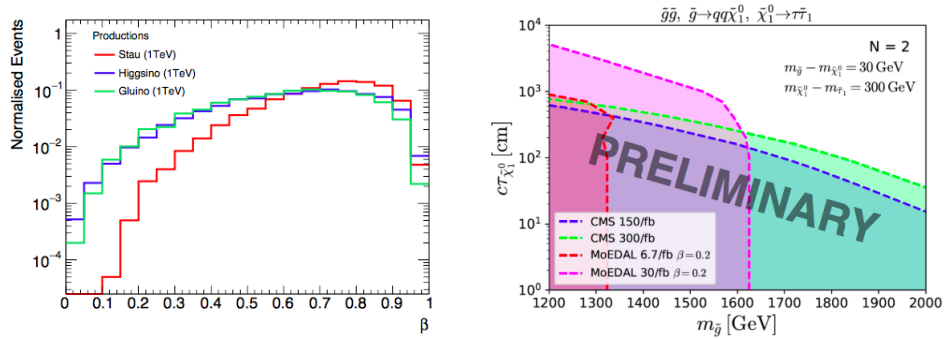


Figure 7. Left panel: Calculations of the velocity distributions of sparticles at the LHC. Right panel: Comparison between the sensitivities of MoEDAL and CMS to the production of sparticles at the LHC. Figures taken from [24].

5. Longer-Term Prospects for Supersymmetry

The LHC will continue to run into the mid-2030s, aiming to accumulate in ATLAS and CMS $\gtrsim 20$ times more than the $\sim 140/\text{fb}$ that they have accumulated so far, not all of which has been analyzed for many supersymmetric signatures. Theoretically, it is certainly possible that sparticles may be lying beyond the current reaches of ATLAS and CMS, but within reach of future LHC runs. This could happen, for example, if the NLSP is a stop squark that is almost degenerate with the LSP. MoEDAL will continue its parallel searches for particles with anomalous ionization signatures.

There are many ongoing discussions about possible high-energy colliders beyond the LHC. One possibility being discussed actively at CERN is a large circular tunnel able to accommodate a collider for electrons and positrons at relatively low energies but very high luminosities (FCC-ee) [29], and/or a collider for protons at 100 TeV in the centre of mass (FCC-hh) [30,31], also with a very high luminosity. These will enable the search for supersymmetry to be carried into the range above 10 TeV, via both direct searches [30,31] (see Fig. 8) and indirect probes [29].

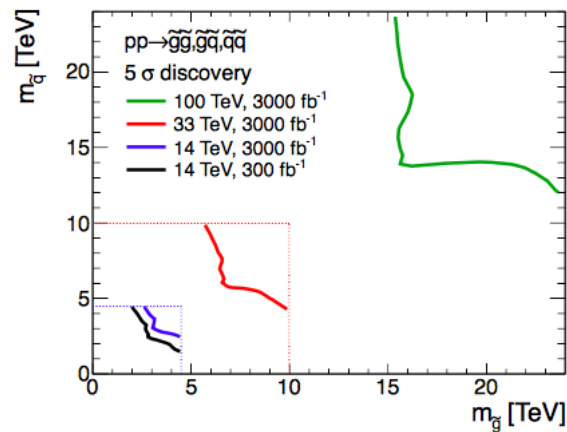


Figure 8. Estimated 5- σ discovery reaches for squarks and gluinos at the LHC (14 TeV), HE-LHC (33 TeV) and FCC-hh (100 TeV) [30].

Acknowledgements

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