Supersymmetric dark matter in the harsh light of the Large Hadron Collider

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I review the status of the model of dark matter as the neutralino of supersymmetry in the light of constraints on supersymmetry given by the 7- to 8-TeV data from the Large Hadron Collider (LHC).

Large Hadron Collider | supersymmetry | dark matter

Models for the dark matter particle span a huge range of masses, from 1 millionth of an electronvolt and lower to masses larger than that of the sun. The particles in these models vary in interaction strength from that of gravitational particle interactions to the gravitational force of a macroscopic black hole. And yet, most of the literature on the particle nature of dark matter is concentrated in one small region of this parameter space.

The particles that have received most of the attention belong to the generic class called weakly interacting massive particles (WIMPs). These are neutral, stable particles whose number density was determined by the constraint that they were in thermal equilibrium at some time in the early universe. Even within this class, a particular hypothesis has received special attention, that the dark matter particle is the "neutralino," the lightest supersymmetric partner of the photon, the Z boson, and the Higgs bosons.

There are good reasons to favor this neutralino hypothesis for dark matter. However, they are entirely theoretical. The neutralino fits easily into our current picture of particle physics. Supersymmetry is the unique extension of the Poincaré space–time symmetry. New physical interactions are required at the teraelectronvolt mass scale to allow us to compute the symmetry-breaking potential of the Higgs boson. The extension of space–time symmetry to supersymmetry naturally achieves this. When the Higgs potential is computed, the symmetry-breaking shape of the potential is related to the large value of the top quark Yukawa coupling. The addition of new particles related to the familiar elementary particles by supersymmetry changes the predictions for the very short distance values of the strong, weak, and electromagnetic couplings. The changes are such that these couplings become approximately equal at about 10^{16} GeV, supporting the idea of a grand unification of couplings at this mass scale. These features of supersymmetry are all discussed in more detail in pedagogical reviews such as refs. 1–4.

The final piece of the puzzle would be the explanation of dark matter. In fact, under rather weak hypotheses, supersymmetry requires a new discrete symmetry that makes its lightest new particle absolutely stable. There are several possibilities that make the lightest supersymmetric particle neutral. It may, for example, be a sneutrino or a gravitino. Here, I concentrate on the case in which the lightest supersymmetric particle is a neutralino, notated $\tilde{\chi}^0$. If the $\tilde{\chi}^0$ is stable, this particle satisfies all of the basic hypotheses of the WIMP model.

To finish the picture, we need the mass scale of supersymmetric particles. From particle physics arguments, this should be of the order of the mass scale of the Higgs boson, 100–200 GeV. The WIMP hypothesis also points to a specific mass scale. The final density of WIMPs in the universe depends inversely on the WIMP pair annihilation cross section. To obtain the density of dark matter actually observed today starting from thermal equilibrium in the early universe, a WIMP should have an annihilation cross section σ of just about 1 picobarn (5).

Astronomers may recognize this value as the canonical dark matter annihilation cross section, $\sigma c = 3 \times 10^{-26}$ cm^2/s. Remarkably, this is the natural size of an electroweak cross section involving the exchange of a particle of about 200 GeV. The coincidence of this scale with the electroweak scale is often hyped as "the WIMP miracle," but certainly it makes the story I have just told more compelling.

However, a theoretically compelling story often has an awkward collision with reality. The ATLAS and CMS experiments at the CERN Large Hadron Collider have considered the discovery of supersymmetric particles one of their major goals. The search for supersymmetry by these experiments has been described by Ian Hinchliffe* and Maria Spiropulu† in their presentations to this colloquium. Enormous effort has been put into this search, and unexpected levels of sensitivity have been achieved—but no new particles have been discovered. Is it time to give up on supersymmetric dark matter?

My viewpoint is that supersymmetric dark matter is still very much alive but is constrained by the exclusions from the Large Hadron Collider (LHC). We have needed to change our attitude about the qualitative form of the particle spectrum in supersymmetry. This shift of viewpoint has many consequences, which I trace out in this lecture.

"Natural" Supersymmetry Spectra

The symmetry of supersymmetry relates particles with the same strong, weak, and electromagnetic quantum numbers and with spins differing by 1/2 unit. For example, supersymmetry relates the electron to a spin 0 particle with electric charge −1. We do not see pairs of particles in nature whose quantum numbers align in this way. Thus, most models of supersymmetry introduce a new particle for each known particle in the standard model of particle physics. As partners of the quarks and leptons, we introduce new spin 0 squarks and sleptons; as partners of the vector bosons, we introduce spin 1/2 gauginos. The known particles are light; their partners, which are not yet discovered, must be heavy. Thus, if supersymmetry is a symmetry of nature, it must be spontaneously broken.

Supersymmetry breaking gives mass to the postulated new particles. In models of supersymmetry at the teraelectronvolt energy scale, these mass terms and related terms from supersymmetry breaking provide the driving force for new physical
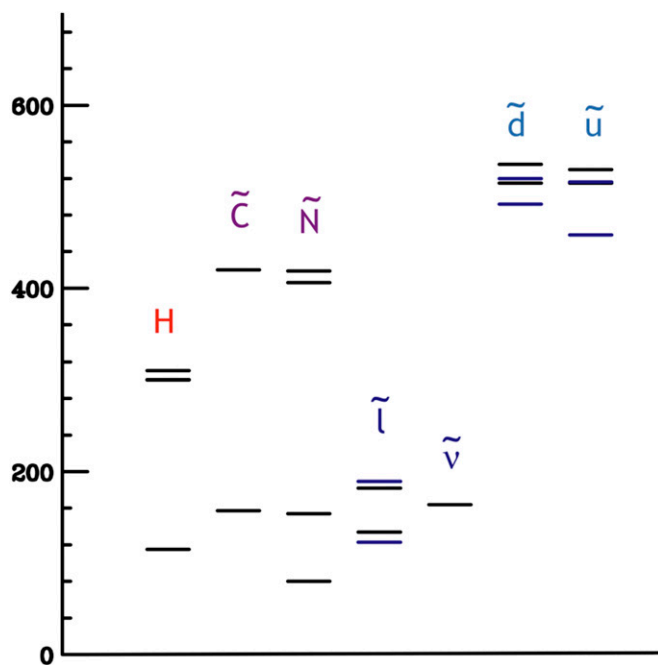
Fig. 1. A typical supersymmetry spectrum from an MSUGRA model. Masses are in gigaelectronvolts.

phenomena. Most importantly, these terms create the potential energy of the Higgs boson and give this potential energy function the form that leads to the nonzero Higgs field vacuum expectation value. The masses of all quarks, leptons, and vector bosons are proportional to the Higgs field expectation value and also to the coupling of those particles to the Higgs field. Thus, the masses of all familiar particles arise as a secondary consequence of supersymmetry breaking.

There is no definite prediction for the mechanism of supersymmetry breaking. Models that have been proposed contain many possibilities. A consequence is that we do not know the pattern of masses of the new particles predicted by supersymmetry. Most likely, this pattern is completely different from the pattern of masses of the quarks, leptons, and gauge bosons. Unfortunately, all predictions of supersymmetry, including the predictions for searches and for the properties of dark matter, depend on detailed properties of this unknown mass spectrum.

Expectations for the LHC. Before the LHC experiments, most particle physicists expected the mass spectrum of supersymmetric particles to look something like the spectrum shown in Fig. 1. This expectation was based on a scheme for supersymmetry breaking called MSUGRA or cMSSM. This is the hypothesis that the terms in the Lagrangian arising from supersymmetry breaking have the minimal number of parameters and are unified at the grand unification scale. In MSUGRA, all of the superpartners receive mass of roughly the same magnitude. The lightest particles have masses comparable to the Higgs boson mass and Higgs field vacuum expectation value,

$$m_h \sim 125 \text{ GeV}, \quad v = 246 \text{ GeV}. \quad [1]$$

Although the Higgs boson mass was not known before the LHC experiments, it is difficult to build a model of supersymmetry in which this mass is much higher than about $0.6v$. The lightest neutralino could in principle be any linear combination of the superpartner of the $U(1)$ gauge boson ("bino"), the superpartner of the neutral $SU(2)$ gauge boson ("wino"), and the superpartners of the neutral Higgs bosons ("Higgsinos"). In MSUGRA, it

is typical that that the lightest mass eigenstate is mainly composed of the bino. The MSUGRA hypotheses give the masses of the bino, wino, and gluino (the partner of the gluon) in an ~1:2:7 ratio. The squarks, the partners of the quarks, have masses that are almost identical. The degeneracy of the squarks follows from unification hypotheses and also from the fact that corrections from the strong interactions give the same boost to all of the squark masses.

A spectrum of supersymmetric particles of this form is set up to be discovered at the LHC. The overall constraint on the mass spectrum puts the masses of the superpartners of the quarks and gluons below 1 TeV, well within the range that can be accessed by the LHC even at the center of mass energy of 7 TeV. The squarks and gluinos couple to the strong interactions and have relatively large pair-production cross sections in gluon–gluon and gluon–quark collisions. The squarks have spin 0, which leads to lower cross sections, but there are 12 of them, one for each left-handed and one for each right-handed quark species. These particles decay to the wino or even directly to the bino, emitting energetic quarks. The momentum of the emitted quarks appears unbalanced, because much or all of the balancing momentum is carried away by dark matter particles. (Particle physicists call such unbalanced momentum "missing energy," and I follow this usage below.) So it is not surprising that there were high expectations for supersymmetry to be discovered in the early stages of the LHC experiments.

By now it is well known that those expectations were not fulfilled. Fig. 2 shows two attempts to constrain the parameters m_0 and $m_{1/2}$ of MUSUGRA, which give the unification-scale masses, assumed universal, for scalars and gauginos. Fig. 2, *Top* shows a 2008 prediction from ref. 6, the blue region being that
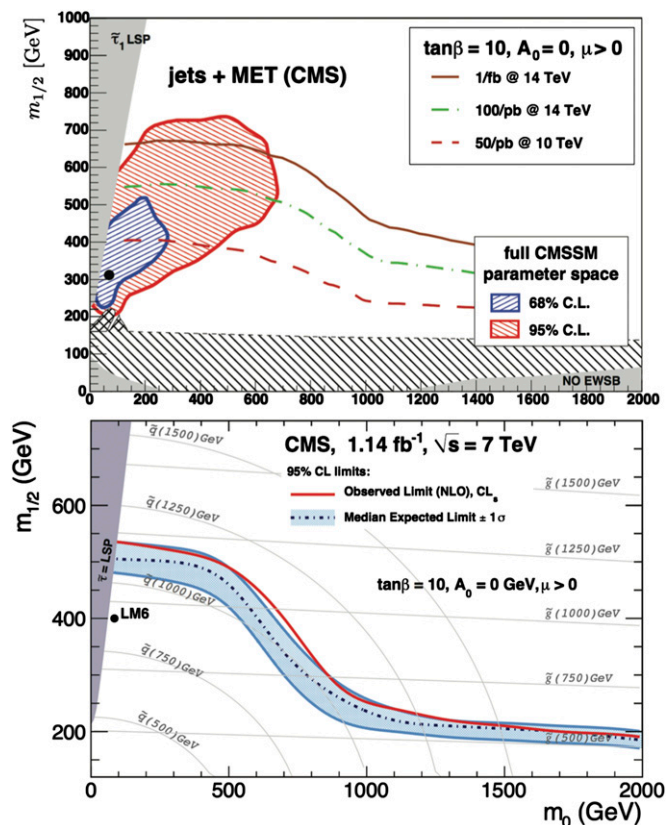

Fig. 2. Comparison of the preferred region of supersymmetry parameter space, in the MSUGRA variables $m_0, m_{1/2}$ (6), to the 2011 exclusion limit for SUSY given by the CMS experiment (7).
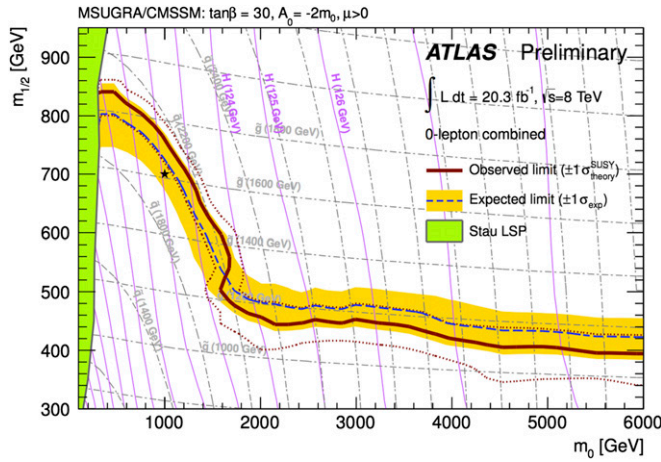
Fig. 3. Excluded region of the MSUGRA parameter space reported by ATLAS, using the full 2012 data set, from ref. 8.

preferred at 68% confidence. Fig. 2, *Bottom* shows the constraint on supersymmetry, in this same parameter space, reported by the CMS experiment at the 2011 Lepton–Photon Conference (7). The region below the red line, which includes the blue region on the left and most of the 95% confidence region, is ruled out. Fig. 3 shows the most recent constraint of this type of supersymmetric model by the ATLAS experiment (8). All points below the red curve are excluded at 95% confidence. The new limits correspond to exclusion of a gluino mass of 1,150 GeV for much larger squark masses or of a squark mass of 2,000 GeV for much larger gluino masses.

Constraint of "Naturalness." What do these exclusions tell us? It is tempting to jump to the conclusion that supersymmetry is incorrect. However, a more conservative conclusion is that it is the general picture of the supersymmetry spectrum shown in Fig. 1 that is incorrect. Maybe that is not so surprising, because this type of spectrum represents only the simplest possibility.

In searching for a principle that might be used to shape the supersymmetry spectrum, a number of authors have called attention

to the formula that relates the Higgs field vacuum expectation value v to the supersymmetry breaking mass parameters. This formula is conveniently written in terms of the Z boson mass, $m_Z = (g^2 + g'^2)^{1/2} v/4$. Supersymmetry requires two Higgs doublet fields, called H_u and H_d. The ratio of vacuum expectation values is parameterized as $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$. With this notation, the relation is

$$m_Z^2 = 2\frac{M_{H_d}^2 - \tan^2\beta\, M_{H_u}^2}{\tan^2\beta - 1} - 2\mu^2, \qquad [2]$$

where M_{H_u} and M_{H_d} are the supersymmetry breaking masses of the two Higgs fields, and μ is the Higgsino mass. Technically, μ is supersymmetry preserving, but often it is generated as a result of supersymmetry breaking, for example, by the Giudice–Masiero mechanism (9). The parameter μ receives no large renormalizations. The parameters $M_{H_u}^2$ and $M_{H_d}^2$ receive large logarithmic corrections proportional to the top and bottom quark couplings to the Higgs bosons. The corrections to $M_{H_u}^2$ are sensitively dependent on the top squark masses. More indirectly, they involve the gluino mass, because this corrects the top squark masses in the next higher order.

Using this formula, we can apply the following logic: Ultimately, we will want to explain the value of the Higgs field vacuum expectation value from a higher theory. Unless there is a complex interplay of the short distance values of the parameters μ, M_{H_u}, and M_{H_d} and the various renormalizations of the latter two parameters, this will be possible only if there are no large cancellations among the three terms of Eq. **2**. This implies restrictions on the masses of the various superpartners that enter this formula. In particular,

$$\mu \lesssim 200 \text{ GeV}. \qquad [3]$$

Masses of other superpartners are restricted to the extent that they enter radiative corrections to the key parameters. For example, for the top squarks and the gluino,

$$m(\tilde{t}) \lesssim 1 \text{ TeV}, \quad m(\tilde{g}) \lesssim 3 \text{ TeV}. \qquad [4]$$

Further superpartners are much more weakly constrained. This argument is a weak form of a "naturalness" argument.

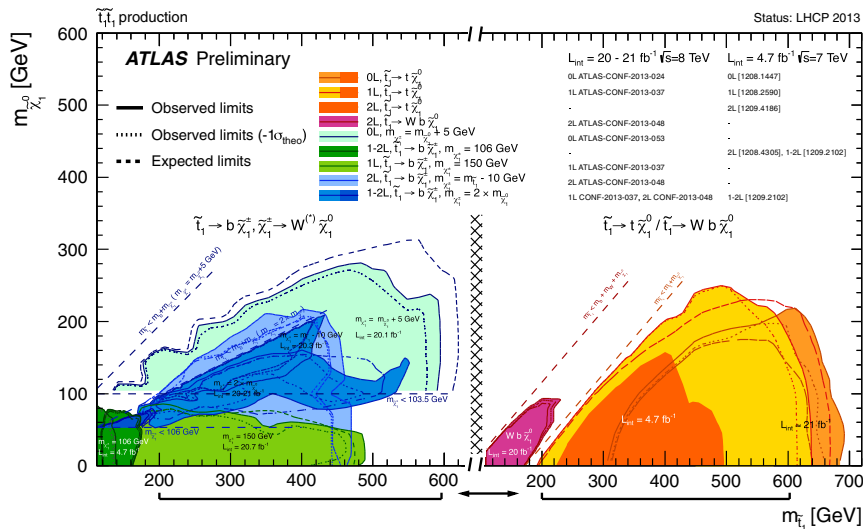**Fig. 4.** Compilation of limits from the ATLAS experiment from searches for direct production of top squark pairs (21), shown in the plane of top squark mass vs. the mass of the lightest neutralino. Each limit has an individual reference, shown in the figure. The figure should be interpreted with some care, because each individual search assumes a 100% branching ratio to the final state most appropriate for its signal.
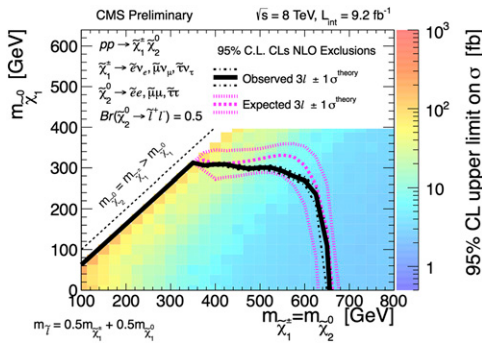
Fig. 5. Exclusion of charginos and neutralinos by the CMS experiment, assuming a model in which the chargino decays to a slepton which then decays further to a lepton plus the lightest neutralino. Reprinted with permission from ref. 23.

Stronger forms have been used and debated in the literature (10–13).

This logic makes it possible that the supersymmetry spectrum has a form in which only a small number of superpartners have masses below the 1-TeV scale. Those particles relevant to creating the Higgs potential must be light, but the others can be much heavier. This idea has been discussed for some time, for example, in the models of refs. 14 and 15. Recently, Papucci et al. formalized this idea under the name "natural supersymmetry" (16), and many other authors followed up the idea as an explanation of why supersymmetry is not seen at the LHC. One must of course explain why a few superpartners have masses much smaller than the others. Some interesting physical mechanics that give a spectrum of this form, with relatively light third-generation squarks and very heavy first- and second-generation squarks, have been proposed in refs. 17–19.

If the top and bottom squarks are the only relatively light quark superpartners, this takes a great deal of pressure off the LHC constraints on supersymmetry. It is not only that the number of accessible squark species is reduced from 12 to 4 or even to 1. In large regions of the parameter space, the squark production reactions with the largest cross sections are the excitation processes such as

$$q+q \to \tilde{q}+\tilde{q}, \quad q+g \to \tilde{q}+\tilde{g}. \quad \text{[5]}$$

These acquire their large cross sections only if very energetic valence quarks appear in the initial state, requiring squarks with the same quantum numbers in the final state. However, there are no valence b or t quarks in the proton. These two changes in the production dynamics decrease the expected cross section for squark production by a factor of 50 (20). The ATLAS and CMS experiments have been very creative in increasing their search reach for top and bottom squarks, but, still, this is a large deficit to overcome. The current constraints on top squarks from ATLAS are shown in Fig. 4 (21).

Searches for Charginos and Neutralinos. Even if supersymmetry is difficult to discover through strong interaction production of squark and gluino pairs, it might be discovered at the LHC through the direct production of electroweak superpartners. The ATLAS and CMS experiments have also put great effort into the pursuit of this strategy. The cross sections for the pair production of electroweak states are typically suppressed relative to the cross sections for pair production of squarks and gluinos of comparable mass by a factor of several hundred (22). However, the electroweak partners can decay directly to multiple isolated leptons with unbalanced visible momentum, an easily recognized signature.

In the best cases, this can lead to constraints on supersymmetry for masses above the electroweak scale. Fig. 5 shows limits on the wino and bino masses in a particular scenario that yields events with two energetic leptons and missing momentum (23).

However, the naturalness principle of the previous section brings in a new difficulty here. The electroweak superpartners include the superpartners of the $SU(2) \times U(1)$ gauge bosons and the Higgs bosons. These particles mix, and so we use the terms "neutralino" and "chargino" to denote a generic mass eigenstate. However, the spectrum is very different, depending on whether the lightest mass eigenstate is mainly composed of a gauge boson partner or a Higgs boson partner. In MSUGRA, the lightest neutralino is mainly the $U(1)$ gauge partner, the bino. This, along with the other assumptions of the MSUGRA model, leads to a spectrum of the form shown in Fig. 6, *Left*. The masses of the wino and bino are tied together and required to be near the Higgs boson mass scale. Pair production of winos followed by decay to the wino to the bino can often produce a multilepton signature.

However, if the only light states of the supersymmetry spectrum are those required to be light by naturalness, the lightest neutralinos should be mostly Higgsino. The Higgsino masses are naturally degenerate, clustering near the value $|\mu|$ with small mass splittings of the order of $m_Z^2/m(\tilde{b})$, typically 10 GeV or smaller. Then any leptons or jets emitted in the decays of heavier to lighter Higgsinos are essentially invisible to the LHC experiments. Fig. 7, from the ATLAS report (24), shows how the search efficiency cuts off as the mass difference between the heavier and lighter electroweak partners becomes small. In the electroweak sector also, a natural spectrum of superpartners is also one that is very difficult to discover at the LHC.

Future Supersymmetry Searches at the LHC. Natural supersymmetry spectra are more difficult to discover at the LHC, but they cannot hide forever. The next run of the LHC will reach an energy of 13–14 TeV and is expected to accumulate a data sample 10 times larger than the current one. The combination of these factors increases the range of the LHC in searching for superpartners by about a factor of 3 in the masses of the particles that can be discovered.

A particularly important target for this next round of searches is the gluino. As I have noted above, the gluino mass is limited by
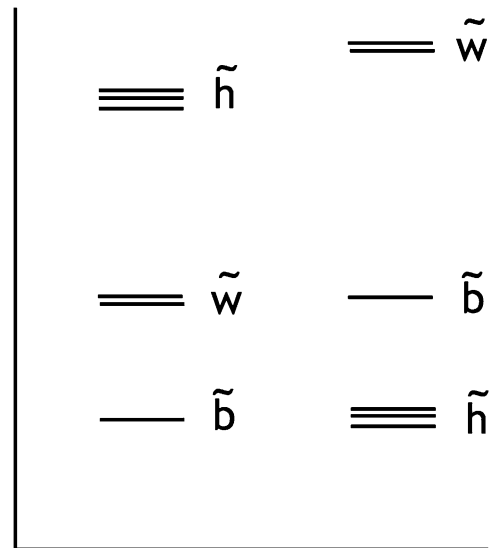

Fig. 6. Typical mass spectra of neutralinos and charginos in supersymmetry models. (*Left*) MSUGRA-type spectrum with a bino-like lightest neutralino. (*Right*) Spectrum with a Higgsino-like lightest neutralino.
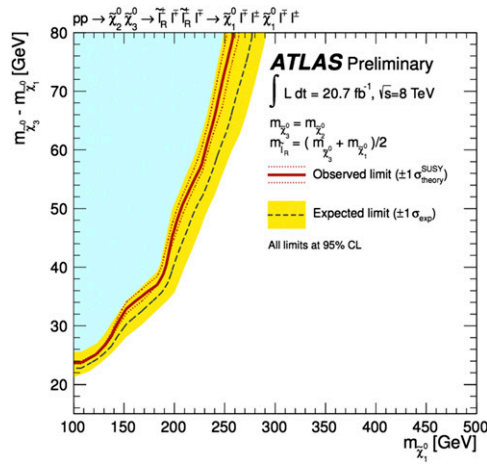
Fig. 7. Exclusion limits for production of heavy neutralino pairs decaying to lighter neutralinos plus leptons, plotted against the mass difference of the neutralinos on the vertical axis, from an ATLAS 4-lepton plus missing momentum search. Reprinted with permission from ref. 24.

naturalness constraints. When the LHC acquires enough energy to produce pairs of gluinos, these particles will decay to lighter superpartners with large energy release and large missing energy.

In supersymmetry spectra in which the lightest squarks are the top and bottom squarks, the dominant decays of the gluino will be to third-generation quark pairs plus missing energy. The ATLAS and CMS experiments have been able to search very effectively for gluino pair production with decays of this type. For example, the CMS limits on a gluino that decays dominantly to $t\bar{t}\tilde{\chi}^0$ are shown in Fig. 8 (25). The current limits on the gluino mass in this scenario are

$$m(\tilde{g}) \gtrsim 1.3 \text{ TeV}, \qquad [6]$$

stronger than the more generic gluino mass limits shown in Fig. 3. This makes it very likely that, if the gluino mass satisfies the weak naturalness limit given in Eq. 4, this supersymmetric particle will be discovered at the LHC with 13–14 TeV and 300 fb^{-1} of data. We will see it before the end of the decade.

Another important target is the search for direct pair production of neutralinos. A reaction

$$q + \bar{q} \rightarrow \tilde{N}\tilde{N}, \qquad [7]$$

even one in which the final state is completely invisible, can be detected if the initial quarks emit gluons or photons. This always happens to some degree, with the characteristic transverse momenta of the initial state radiation being distributed logarithmically up to the mass of the produced particlers. Searches for initial state radiation associated with the production of invisible particles are reported in refs. 26 and 27. In the coming decade, these searches will become sensitive to electroweak pair production for particles in the 100-GeV mass range.

We can summarize the conclusions of this section in the following way: The significant exclusions by the ATLAS and CMS experiments have without doubt elminated many plausible models of supersymmetry. However, the parameter space of supersymmetry is large and contains mass spectra of many different types. The constraint that supersymmetry breaking naturally generates the symmetry-breaking potential of the Higgs boson puts definite constraints on these spectra, but these constraints are relatively weak. The models that satisfy these constraints in the minimal way are quite difficult to discover at the LHC. However, difficult is not impossible; there are definite

targets, and the ATLAS and CMS experiments should reach them before the end of the decade.

Relic Density and Exceptional Spectra

Up to this point, I have considered only the constraints on the supersymmetry spectrum that come from particle physics considerations. If we are to associate the lightest neutralino with the dark matter, there is an additional set of issues that need to be addressed.

No Miracle in Supersymmetry. In the Introduction to this article, I reviewed the prediction of the WIMP model that, to produce the correct current abundance of dark matter, the WIMP annihilation cross section should be about 1 pb. I stated that this is the cross section that would be expected if the annihilation is mediated by the exchange of a particle of mass 200 GeV with electroweak couplings. This is just the situation of models of supersymmetry. However, when we look at supersymmetric models in detail, there are further difficulties in obtaining the correct value for this cross section.

Although generically, supersymmetry predicts a cross section for neutralino pair annihilation of the order of 1 pb, the numerical coefficient that appears in front of this cross section can be large or small, depending on the additional elements of the physics. The value of this coefficient depends on whether the lightest neutralino is mostly bino, wino, or Higgsino.

Higgsino-like neutralinos can annihilate into pairs of W and Z bosons. The annihilation involves a full-strength $SU(2)$ gauge interaction and is further enhanced by the presence of spin 1 particles in the final state. For Higgsino dark matter particles of mass about 200 GeV, this cross section is about a factor of 10 too large. Wino-like neutralinos have an even larger annihilation cross section.

Bino-like neutralinos decay mainly into quark and lepton pairs. However, because neutralinos are Majorana particles, S-wave annihilation must produce a final state with total spin 0. The rate for producing such a "helicity suppressed" two-fermion state is suppressed by a factors of $m_f^2/m^2(\tilde{b})$, where m_f is the final-state fermion mass (28). This gives an annihilation cross section about a factor of 10 too small.

The overall picture of supersymmetry predictions for the dark matter relic density is illustrated in Fig. 9, from ref. 29. The most
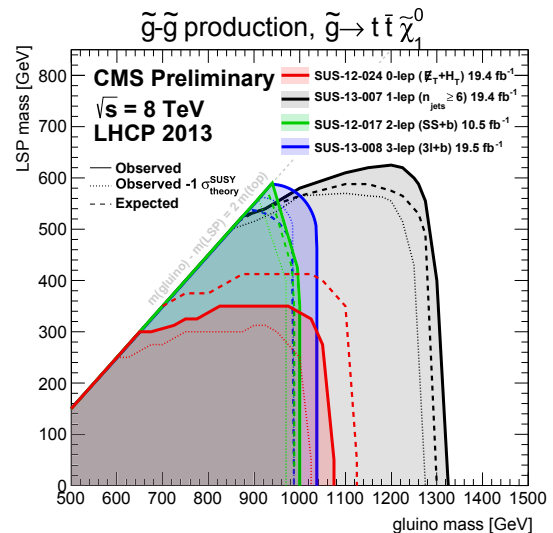

Fig. 8. Compilation of limits from the CMS experiment from searches for production of gluino pairs that decay to $t\bar{t}\tilde{\chi}^0$ (25). Each limit has an individual reference, shown in the figure.
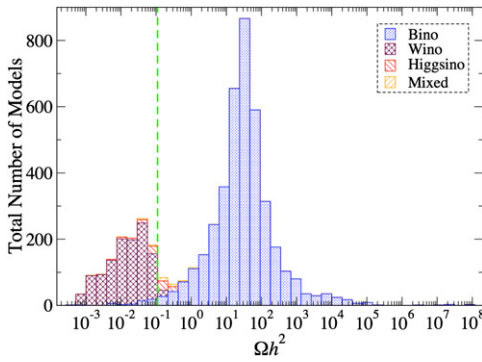
Fig. 9. Predictions for the dark matter relic density from supersymmetry models explored in the parameter space scan of ref. 29. The vertical dashed line marks the measured value. The shading shows that bino-like neutralinos typically give predictions to the right of this line, and that wino- and Higgsino-like neutralinos typically give predictions to the left of this line. Reprinted with permission from ref. 29.

easily obtained values of the dark matter density are an order of magnitude either higher or lower than the observed value. The models that give the correct dark matter relic density have supersymmetric mass spectra that are exceptional in some way. Still, if the lightest neutralino is the dark matter, our universe is based on one of these exceptional cases. Then we must understand the physical implications of that choice. In this section, I discuss some strategies for generating the exceptional spectra that give the correct relic density and their implications for supersymmetry and dark matter discovery.

Coannihilation Scenarios. If the lightest neutralino is mostly bino, direct neutralino pair annihilation has too small a cross section. To solve the problem, we must get rid of the excess supersymmetric particles in some way. To do this, we can make use of other cross sections for converting supersymmetric to normal matter that do not have helicity suppression and so can take the required value of about 1 pb.

One possibility is resonant annihilation through a Higgs boson of mass approximately $2\, m(\tilde{b})$. Because supersymmetric models contain an extended Higgs sector, this particle can be different from the known Higgs boson at 125 GeV. Searches for the required bosons are reported in refs. 30 and 31. The possibility of such a dark matter annihilation resonance is still open.

Here, however, I concentrate on an alternative scenario, called "coannihilation." By assumption, a WIMP was in thermal equilibrium in the high-temperature plasma of the very early universe. As the universe cools, the density of WIMPs decreases. At a point called the "freeze-out temperature," the density of WIMPs becomes small enough that WIMPs cannot find partners with which to annihilate. Below this temperature, the population of WIMPs in the universe is frozen. For a WIMP of mass about 200 GeV with electroweak interactions, the freeze-out temperature is about 10 GeV. This means that any particles whose masses are within 10 GeV of the WIMP mass and carry the same conserved quantum number as the WIMP can contribute to the annihilation rate of this quantum number (32).

We can use this idea to solve the problem that the bino pair annihilation cross section is too small. We need only bring another supersymmetric particle down in mass to near degeneracy with the bino and allow reactions involving this particle to be the dominant ones that annihilate supersymmetry. For example, if the tau slepton is close in mass to the bino, the reactions

$$\tilde{b}+\tilde{\tau} \to \gamma + \tau, \quad \tilde{\tau}+\tilde{\tau} \to \tau+\tau \qquad [8]$$

have no helicity suppression and thus generate annihilation cross sections of the required size. Models with wino and top squark coannihilation have also been proposed. A recent survey of randomly chosen supersymmetric models includes an even wider variety of coannihilation scenarios (33).

Fig. 10 shows the stau coannihilation region in a model proposed in ref. 34 that introduces a light stau to boost the rate for $h \to \gamma\gamma$. At the moment, only the Higgs properties constrain this model, and the constraints are avoided by pushing the bino and stau only slightly higher in mass.

Coannihilation requires that the masses of the lightest supersymmetric particles are nearly degenerate, in the important sense that particles emitted in the decay of the heavier particle to the lighter one are too soft to be observed by the LHC detectors. Then the same exceptional requirements on the spectrum that make it possible for a supersymmetric model to yield the correct dark matter density also make that model more difficult to discover.

"Well-Tempered" Scenarios. The Higgsino has too large an annihilation cross section to give the correct dark matter density. To solve this problem, we can put another neutral supersymmetric particle below the Higgsino and mix it with the Higgsino with a small mixing angle. The annihilation cross section is decreased
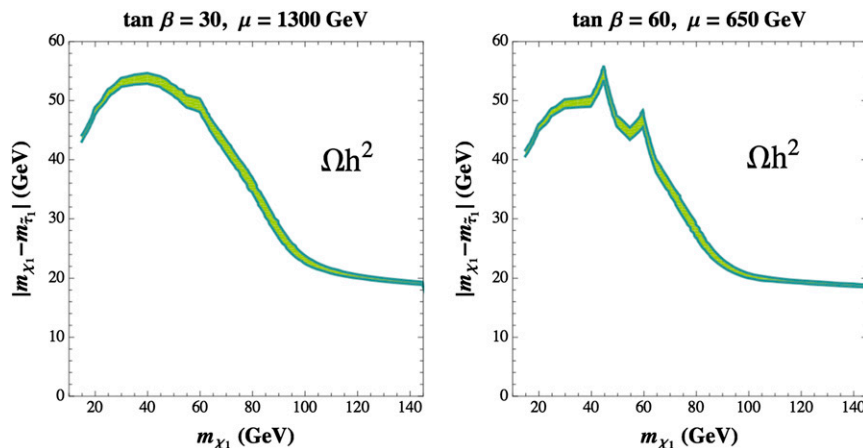

Fig. 10. Region of the model space of the supersymmetry model with light tau sleptons, predicting a result consistent with the observed dark matter relic density, using the mechanism of stau coannihilation. Reprinted with permission from ref. 34.

proportionate to the fourth power of the mixing angle. If the lighter particle is the bino, this scenario is called the "well-tempered neutralino" (35). The scenario was seen originally in "focus point" MSUGRA models (36). Another solution is to introduce an $SU(2) \times U(1)$ singlet field, which might play a role in boosting the Higgs boson mass to 125 GeV. Its supersymmetric partner, the singlino, could be the WIMP if it acquired a substantial annihilation cross section by mixing with the Higgsino.

The natural supersymmetry spectra discussed in the previous section place the Higgsinos at a mass around 200 GeV. A bino or singlino that mixes with the Higgsino would be also be in this mass range. It is plausible that all other superpartners are much heavier. This leads to a very definite picture of dark matter detection. Dark matter in the galaxy annihilates dominantly to the final states WW and ZZ with a cross section close to the canonical value $\sigma c = 3 \times 10^{-26}$ cm^2/s. The direct detection cross section is dominated by exchange of the 125-GeV Higgs boson and has a value close to 1 zeptobarn. Neither value is currently excluded, but both values will be challenged by next-generation experiments.

Is the Dream Alive?

If dark matter is a WIMP, then studies of dark matter in astrophysical settings tie into studies of possible new physics at the 100-GeV to -TeV energy scale. There is a converse to this statement. If dark matter is a WIMP, it potentially can not only be discovered but also studied in detail in high-energy collider experiments. Then, potentially, we can use the properties of the WIMP to predict the dark matter density and the direct detection cross section, allowing a confrontation of microscopic predictions with the results of astrophysical observations. This is the dream of those of us concerned with the particle physics origin of dark matter, that the tight connection we hope for between new physics at the largest and smallest length scales would be directly confirmed.

Some years ago, Baltz, Battaglia, Wizansky, and I studied the feasibility of reconstructing dark matter properties from collider measurements in the context of the models of supersymmetry (37). The program turns out to be more complex than one might anticipate. It is necessary, of course, to discover the WIMP and the particles that it exchanges in its annihilation reaction. For bino dark matter, for example, it is necessary to discover and to measure the mass and quantum numbers both for the WIMP itself and for the lightest slepton or chargino. In a coannihilation scenario, it is necessary to measure the small mass difference between the bino and the next heaviest superpartner to 5% accuracy. In a Higgsino mixing scenario, it is necessary to measure the mixing angle to about 10°. In addition, it is necessary to exclude other scenarios that might lead to very different values of the dark matter parameters. For example, the role played by resonant annihilation through the Higgs boson A^0 must be clarified, either by discovering this particle or by setting limits on it that bound its contribution. It is also necessary to pin down any auxiliary parameters that affect the rates of supersymmetry reactions, most importantly, the ratio of Higgs vacuum values $\tan\beta$.

This is a very challenging set of requirements for a hadron collider experiment. It calls for a type of particle physics experiment that is capable of making comprehensive particles searches in a given mass range and capable of precision measurements on new particles that are discovered in these searches.

An ideal choice would be an e^+e^- collider capable of pair producing the lightest few states of the supersymmetry spectrum. For WIMPs of mass 200 GeV, in the mass range of natural supersymmetry spectra, the International Linear Collider (ILC), planned for an energy of 500 GeV and allowing energy upgrades to 1 TeV, would provide just the capabilities that are needed.
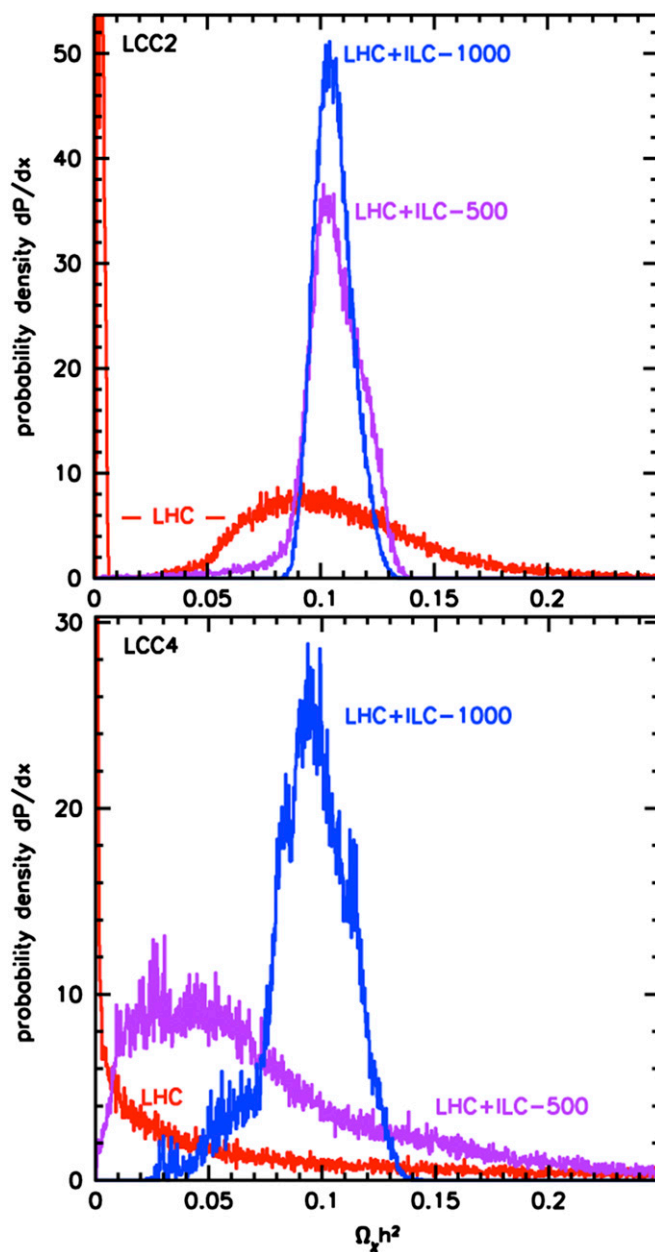

Fig. 11. Prediction of the dark matter relic density in two models with neutralino dark matter from measured supersymmetry masses and production cross sections, based on observables and measurement accuracies available at the LHC, the ILC at 500 GeV, and the ILC at 1 TeV. Reprinted with permission from ref. 37.

Some projections for predictions of the dark matter cosmic density, from ref. 37, are shown in Fig. 11. To make these plots, we started from two particular supersymmetry models that gave values for the dark matter relic density close to the currently measured value. Fig. 11 shows the expected form for the posterior-likelihood function for the dark matter density $\Omega_\chi h^2$ as measurements with the expected precision from the LHC and from successive stages of the ILC included. A check of the microscopic theory of supersymmetry against the measured value of the dark matter density at the 10–20% level would be available at the end of this program. Similar convergence is seen for the dark matter direct detection cross section. If these predictions match the observations, that would be a remarkable confirmation of the

story presented in the Introduction to this article. Whatever the result, we will learn much about dark matter and its microscopic origin by carrying out this program.

Conclusion

The idea that the neutralino of supersymmetry comprises the cosmic dark matter is strongly challenged today by the LHC experiments. Still, the parameter space of supersymmetry is large. The detailed mass spectrum of supersymmetry can take many forms, including well-motivated scenarios that evade the present constraints from the LHC.

The LHC results will become stronger from the increases in energy and luminosity expected before the end of this decade. The natural spectra discussed above predict signals of supersymmetric dark matter at the next stages of the LHC and dark matter detection experiments. Exclusion of these signals might bring an end to the theory of neutralino dark matter. However, equally well, these experiments could bring long-awaited proof that this theory is correct.

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