Dark matter and the LHC

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An abundance of astrophysical evidence indicates that the bulk of matter in the universe is made up of massive, electrically neutral particles that form the dark matter (DM). While the density of DM has been precisely measured, the identity of the DM particle (or particles) is a complete mystery. In fact, within the laws of physics as we know them (the Standard Model, or SM), none of the particles have the right properties to make up DM. Remarkably, many new physics extensions of the SM – designed to address theoretical issues with the electroweak symmetry breaking sector – require the introduction of new particles, some of which are excellent DM candidates. As the LHC era begins, there are high hopes that DM particles, along with their associated new matter states, will be produced in $pp$ collisions. We discuss how LHC experiments, along with other DM searches, may serve to determine the identity of DM particles and elucidate the associated physics. Most of our discussion centers around theories with weak-scale supersymmetry, and allows for several different DM candidate particles.

1. Introduction

The LHC program has been described as the greatest experiment ever to be mounted in physics. Certainly this seems to be true on many different levels: the largest, costliest, most massive detectors; the most collaborators per experiment; the highest energy reach of any accelerator experiment. The intellectual stakes of the LHC program are enormous: on the theory side, the extreme sensitivity of the scalar sector of the Standard Model (SM) to very high scale physics beckons for new physics at the weak scale ($\sim 100 - 1000$ GeV), possibly ushering in a new paradigm for the laws of physics.

We discuss how LHC experiments may serve to validate the extended Copernican principle. In previous times, we have learned that the earth is not the center of the solar system, that our galaxy is not the entire universe, and that we do not live in any special place or time. Now, due to an impressive accumulation of astrophysical data, we learn that our star, our planet, and ourselves are not even made up of the dominant form of matter in the universe. It now appears that most of the matter in the universe – the so-called dark matter (DM) – must consist of massive, electrically and (likely) color neutral particles that were produced with non-relativistic velocities (cold DM or CDM) in the early universe. None of the particles of the SM have the right properties to make up CDM. Thus, CDM constitutes decisive evidence for physics beyond the Standard Model\cite{1}.

Compelling arguments suggest the CDM particle is linked to the weak nuclear interactions, and further, that it has a mass of order the weak scale: $\sim 100 - 1000$ GeV. This is often referred to as the WIMP miracle, and the dark matter particles referred to as WIMPS (weakly interacting mass particles). Many attractive theoretical scenarios designed to ameliorate the extreme sensitivity of the scalar sector of the SM to radiative corrections, naturally include candidates for CDM particles with weak scale masses that interact with ordinary matter with cross sections comparable to those for weak nuclear interactions. Regardless of its origin, if CDM is composed of WIMPs, then it may be possible to produce and study the DM particle(s) directly at the LHC. In fact, the LHC may well turn out to be a DM factory, where the nature of DM particles and their properties might be studied in a controlled environment. In any collider experiment, WIMPS would be like neutrinos in that they would escape the detector without depositing any energy in the experimental apparatus, resulting in an apparent imbalance of energy and momentum in collider events. While WIMPs would manifest themselves only as missing (transverse) energy at collider experiments, it should nevertheless be possible to study the visible particles produced in WIMP-related production and decay processes to study the new physics associated with the WIMP-sector.

Indeed, there exists a real possibility that much of the mystery surrounding DM and its properties can be cleared up in the next decade by a variety of experiments already operating or soon-to-be deployed. In this effort, experiments at the LHC will play a crucial role. There are – in tandem with LHC – a variety of other dark matter search experiments already in oper-
ation, or in a deployment or planning phase. Direct Detection (DD) experiments seek to directly measure relic DM particles left over from early stages of the Big Bang. These DD experiments range from terrestrial microwave cavities that search for axions via their conversion to photons, to crystalline or noble liquid targets located deep underground that search for WIMP-nucleon collisions.

DM can also be searched for in indirect detection (ID) experiments. In ID experiments, one searches for WIMP-WIMP annihilation into various SM particles including neutrinos, gamma rays and anti-matter. Clearly, this technique applies only if the DM is self-conjugate, or if DM particles and anti-particles are roughly equally abundant. One ID search method involves the use of neutrino telescopes mounted deep under water or in polar ice. The idea is that if relic WIMPs are the DM in our galactic halo, the sun (or earth) will sweep them up as they traverse their galactic orbits, and gravitationally trap these in the central core where they can accumulate, essentially at rest, to densities much higher than in the Milky Way halo. These accumulated WIMPs can then annihilate one with another into SM particles with energies \( E \lesssim m_{\text{WIMP}} \) and most SM particles would be immediately absorbed by the solar material. However, neutrinos can easily escape the sun. Thus, WIMP annihilation in the sun results in an isotropic flux of high energy neutrinos from the solar core – these energies are impossible to produce via conventional nuclear reactions in the sun – some of which would make it to earth. These neutrinos occasionally interact with nuclei in ocean water or ice and convert to a high energy muon, which could then be detected via Cerenkov radiation by photomultiplier tubes that are parts of neutrino telescopes located within the medium.

Another possibility for ID is to search for the by-products of WIMP annihilation in various regions of our galactic halo. Even though the halo number density of WIMPs would be quite low, the volume of the galaxy is large. Occasionally one expects relic WIMP-WIMP annihilation to SM particles. The trick is then to look for rare anti-matter production or high energy gamma ray production from these WIMP halo annihilations. A variety of land-based, high altitude and space-based anti-matter and gamma ray detectors have been or are being deployed. The space-based Pamela experiment is searching for positrons and anti-protons. The land-based HESS telescope will soon be joined by the GLAST satellite in the search for high energy gamma rays. While high energy anti-particles would provide a striking signal, these lose energy upon deflection when traversing the complicated galactic magnetic field, and so can only be detected over limited distances. Gamma rays, on the other hand, are undeflected by magnetic fields, and so have an enormous range. Moreover, these would point back to their point of origin. Thus, the galactic center, where dark matter is expected to accumulate at a high density, might be a good source of GeV-scale gamma rays resulting from WIMP-WIMP annihilation to vector boson \( (V = W, Z) \) pairs or to quark jets, followed by \( (V \rightarrow )q 
\rightarrow \pi^0 \rightarrow \gamma \gamma \) after hadronization and decay.

If WIMPs and their associated particles are discovered at the LHC and/or at DD or ID search experiments, it will be a revolutionary discovery. But it will only be the beginning of the story as it will usher in a new era of dark matter astronomy! The next logical step would be the construction of an \( e^+e^- \) collider of sufficient energy so that WIMP (and related particles) can be produced and studied with high precision in a clean, well-controlled experimental environment. The precise determination of particle physics quantities associated with WIMP physics will allow us to deduce the relic density of these WIMPs within the standard Big Bang cosmology. If this turns out to be in agreement with the measured relic density, we would have direct evidence that DM consists of a single component. If the predicted relic density is too small, we could make the case for multiple components in the DM sector. If the predicted density is too large, we would be forced to abandon the simplest picture and seek more complicated (non-thermal) mechanisms to account for the measurement, or deduce that this detected WIMP itself is unstable. The determination of the properties of the DM sector will also serve as a tool for a detailed measurement of astrophysical quantities such as the galactic and local WIMP density and local velocity profiles, which could shed light on the formation of galaxies and on the evolution of the universe.

2. Evidence for dark matter

Dark matter in the universe was first proposed in the 1930s by astronomer Fritz Zwicky\[^2\]. In the 1970s and on, evidence for DM accrued at an accelerating pace. Here we discuss the major classes of evidence for DM in the universe.

- **Galactic clusters:** In the 1930s, Zwicky studied nearby clusters of galaxies, bound to each other by gravity in spite of the expansion of the universe. Using arguments based on the virial theorem from classical mechanics, Zwicky concluded there was not enough visible mass within the
galactic clusters to successfully bind them; he thus concluded that there must be large amounts of non-luminous, or dark matter, existing within the clusters.

- **Rotation curves**: In the 1970s, V.C. Rubin and W.K. Ford\[3\] began an intensive study of the rotation curves of galaxies. They were able to measure stellar velocity as a function of distance from the galactic center. With most of the visible matter concentrated in or around the galactic center, one expects the stellar rotational velocities to fall off with distance from the galactic center in accord with Newtonian gravitation. Instead, the stellar velocities tended to flatness out to the furthest distances which could be probed. This is in accord with a diffuse halo of dark particles surrounding the galaxy out to the furthest distances.

- **Lensing**: In General Relativity, the path of light through space-time is bent, or “lensed” as it passes by a large mass distribution. Lensing effects are observed when light from distant galaxies or clusters passes by large mass distributions. Numerous studies of both strong and weak (statistical) lensing show the presence of large quantities of DM in the universe.

- **Hot gas in clusters**: Hot gas bound to clusters of galaxies can be mapped out by the emitted x-rays. The visible mass in these galaxies would not have enough gravity to bind the hot gas, which requires additional binding from putative DM.

- **Cosmic microwave background (CMB)**: Detailed studies of anisotropies in the cosmic microwave background has resulted a very precisely measured CMB power spectrum. The peaks and valleys in this spectrum are extremely sensitive to the composition of the universe, and independently show that the universe is comprised of about 70% dark energy (DE), 25% DM and 4% baryons, along with tiny fractions of neutrinos and photons. Thus the “known stuff” makes up just about 5% of the content of our Universe.

- **Large scale structure**: Measurements of large scale structure, when compared to simulations of the evolution of structure in the universe, match very well with a universe composed of both cold dark matter (possibly with some warm DM) and DE.

- **Big Bang nucleosynthesis**: One of the triumphs of Big Bang cosmology is that given an initially hot, dense universe, one can calculate the abundances of the light elements produced via nucleosynthesis during the first few hundred seconds. The measured abundances agree with observation if the baryon-to-photon ratio $\eta_B \equiv n_B/n_\gamma \sim 6 \times 10^{-10}$. The photon number density is known from thermodynamics, so this implies a baryonic mass density of the universe of about $\sim 4\%$, consistent with the value independently obtained from CMB data discussed above.

- **Distant supernovae probes**: Probes of distant supernovae\[4\] have allowed an extension of the Hubble diagram out to redshifts of $z \sim 1$. A best fit match to the Hubble diagram indicates the presence of both dark energy and dark matter in the universe.

- **Colliding galactic clusters**: Observation of colliding clusters of galaxies – a recent example comes from the so-called bullet cluster – shows an actual separation of dark matter (deduced from lensing) from the gaseous halo made of baryonic matter. This is exactly what is expected if a vast halo of non-interacting dark matter accompanies the luminous matter and gas in galactic clusters.

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**Figure 1.** Measurements from CMB, large scale structure and supernovae plotted in the $\Omega_\Lambda$ vs. $\Omega_{\text{matter}}$ plane. Adapted from [http://www.astro.washington.edu/astro323/WebLectures/](http://www.astro.washington.edu/astro323/WebLectures/)

The $\Lambda$CDM universe: Collating all the data together, especially that from CMB, red shifts of high-$z$ supernovae, and large scale structure, allows one to fit to the composition of the universe. We see from Fig. 1 that these very diverse data find consistency
amongst themselves, leading to the so-called “concordance” model for the universe, the $\Lambda$CDM model. (Here, $\Lambda$ stands for Einstein’s cosmological constant, which may be the source of the DE). In the $\Lambda$CDM model, the universe is composed of about 70% DE, 25% DM, 4% baryons with a tiny fraction of neutrinos and radiation. The measured abundance of CDM in our universe[3],

$$\Omega_{CDM} h^2 = 0.111^{+0.011}_{-0.015} \ (2\sigma),$$

where $\Omega_{CDM} = \rho_{CDM}/\rho_c$, with $\rho_{CDM}$ the CDM mass density, $\rho_c$ the critical closure density and $h$ is the scaled Hubble parameter, serves as a severe constraint on all particle physics theories that include a dark matter candidate. Since DM may well consist of more than one component, strictly speaking the relic density serves as an upper bound $\Omega_X h^2 \leq 0.122$ on the density of any single component $X$. We now turn to a discussion of some of the particle physics candidates for the DM particle $X$.

3. DM candidates

While the evidence for the existence of DM in the universe is now very convincing, and while the density of dark matter in the universe is becoming precisely known, the identity of the dark matter particle(s) is a complete mystery. None of the particles in the Standard Model have the right properties to make up CDM. Many candidates, however, have been proposed in the theoretical literature. To appreciate the variety of candidate particles proposed, we list a number of possibilities. The range of masses and interaction strengths of many of these candidates is shown in Fig. 2.

- **Planck mass black hole remnants**: It is possible many tiny black holes (BHs) were produced in the early universe. Ordinarily, these BHs would decay via Hawking radiation. However, it has been suggested that once they reach the Planck mass, quantum gravity effects forbid further radiation, making them stable, and hence good CDM candidates[9].

- **Q-balls**: These objects are topological solitons that occur in quantum field theory[10, 11].

- **Wimpzillas**: These very massive beasts were proposed to show that viable DM candidates could have masses far beyond the weak scale[12].

- **Axions**: The symmetries of the QCD Lagrangian allow the term $-\mathcal{L} \supset \tfrac{g_{QCD}}{2M_P^2} F^{\mu\nu} F_{\mu\nu}$ which gives rise to CP violation in the strong interactions. However, measurements of the neutron electric dipole moment (EDM) require $\theta_{QCD} \lesssim 10^{-10}$. Why this parameter is so much smaller than its natural value of $\sim 1$ is referred to as the strong CP problem. The most compelling solution to the strong CP problem – the Peccei-Quinn-Weinberg-Wilczek solution[13] – effectively replaces the parameter $\theta_{QCD}$ by a quantum field, and the potential energy allows the field to relax to near zero strength. However, a remnant of this procedure is that a physical pseudoscalar boson – the axion $a$ – remains in the spectrum. The axion is an excellent candidate for CDM in the universe[14]. Its favored mass range is $m_a \sim 10^{-5} - 10^{-3}$ eV, where the lower bound gives too high a relic density, and the upper bound comes...
from limits on stellar cooling. Axions have a very weak but possibly observable coupling to two photons. They are at present being searched for in terrestrial microwave cavity experiments such as ADMX\cite{15}. Since they have little direct impact on LHC physics, we will not dwell on them in as much detail as some other possible candidates.

- **WIMPs and the WIMP miracle:** Weakly interacting neutral, massive particles occur in many particle physics models where the SM is extended to address the physics associated with electroweak symmetry breaking (EWSB). If the associated new particles sector has a conserved “parity-like” quantum number that distinguishes it from the SM sector, the lightest particle in this new sector is stable and (if electrically and color neutral) frequently makes an excellent DM candidate. Examples of WIMP particles come from 1. lightest neutralino state in SUSY theories with conserved $R$-parity\cite{16}, 2. lightest Kaluza-Klein excitations from extra-dimensional theories with conserved $KK$-parity\cite{17, 18} and 3. lightest $T$-odd particles in Little Higgs theories with conserved $T$-parity\cite{19, 20, 21, 22, 23}.

It is possible to calculate the *thermal* WIMP abundance from the Big Bang using very general principles. The initial condition is that at early universe temperatures $T > m_{WIMP}$, the WIMPs would have been in thermal equilibrium with the cosmic soup. In this case, their abundance follows straightforwardly from equilibrium statistical mechanics. As the universe expands and cools, ultimately the WIMPs fall out of thermal equilibrium at a temperature where the expansion rate of the universe equals the WIMP annihilation rate, because then the WIMPs are unable to find one another to annihilate fast enough: this is known as the freeze-out temperature $T_F$. As a result, the WIMP density does not drop exponentially as the Universe continues to cool, but reduces only as $R^{-3}$ due to the expansion of the Universe. The WIMP abundance after freeze-out can be found by solving the Boltzmann equation in a Friedman-Robertson-Walker universe for the WIMP number density. The WIMP mass density today, $\rho(T_0)$, is then given by

$$\rho(T_0) = \left(\frac{T_0}{T_\gamma}\right)^3 T_\gamma^{-3} \frac{4\pi^3 q_\gamma G_N}{45} \left[ \int_0^{x_F} \langle \sigma v_{\text{ani}} \rangle dx \right]^{-1}$$

where $T_\gamma = 2.72$ K is the current temperature of the CMB, $T_0$ is the corresponding neutralino temperature, $g_* \sim 100$ is the number of relativistic degrees of freedom at WIMP freeze-out, $\langle \sigma v \rangle$ is the thermally averaged WIMP annihilation cross section times relative velocity, and $x_F = T_F/m_{WIMP} \approx 1/20$ is the scaled freeze-out temperature. But for the fact that photons are reheated as various species decouple, the temperatures of the WIMPs and photons would have been the same. Since the reheating process is assumed to be isentropic, the ratio $\left(\frac{T_0}{T_\gamma}\right)^3$ is simply given by the ratio of the number of effective degrees of freedom at freeze-out to that today, and is about 20. Dividing by the closure density $\rho_\gamma = 8.1 \times 10^{-57} h^2$ GeV$^4$ then gives us $\Omega_{WIMP} h^2$, where $h$ is the Hubble parameter in units of 100 km/s/Mpc. For $s$-wave annihilation, $\langle \sigma v \rangle$ is independent of $x$; then, for $\Omega h^2 \sim 0.1$, we find it is about 10 pb – about the size of an electroweak cross section for annihilation of non-relativistic particles with a mass of about 50 GeV, not far from the weak scale! This provides independent astrophysical evidence that new physics – the dark matter particle – may well be lurking at the weak scale! The co-incidence of the scale of dark matter with the scale of EWSB is sometimes referred to as the WIMP miracle, and suggests that the new physics that governs EWSB may coincide with the DM sector, and inspires many to believe that WIMPs are the prime candidate to constitute the cold dark matter of the universe\cite{24}.

- **SuperWIMPs:** SuperWIMPs are electrically and color neutral stable DM candidates that interact with much smaller strength (perhaps only gravitationally) than WIMPS. Such particles often occur in particle physics theories that include WIMPs. Examples include 1. the lightest $n = 1$ level $KK$ graviton $G^1_{\mu\nu}$ in extra-dimensional theories, 2. the gravitino $\tilde{G}$ (the superpartner of the graviton) in SUSY theories and 3. the axino $\tilde{a}$ (the fermionic member of the axion supermultiplet). Since superWIMP interactions with

\footnote{We point out that it has recently been argued\cite{23} that $T$-parity is generically not conserved because of anomalies in the quantum theory. It has, however, been pointed out that whether $T$-parity is or is not conserved can only be definitively addressed only in the context of a UV-completion of the model\cite{24}.}

\footnote{See, however, Ref. \cite{25}.}
ordinary matter have strengths far below conventional weak interaction strengths, they are not expected to yield observable signals in DD or ID search experiments. However, they can lead to intriguing new phenomena at collider experiments such as LHC and ILC. If every WIMP decays to a superWIMP, then superWIMPs inherit the thermally produced number density of WIMPs, and their contribution to $\Omega_{CDM}h^2$ is reduced from the corresponding would-be WIMP contribution by the ratio of the superWIMP to WIMP masses. The superWIMPs produced from WIMP decay may be either warm or cold dark matter depending on the WIMP lifetime and WIMP-superWIMP mass gap [26]. SuperWIMPs may also be produced during the re-heating of the Universe after inflation; this component of their relic abundance is cold, and its magnitude depends on the reheating temperature $T_R$.

Of the possibilities mentioned above, supersymmetry stands out for several reasons. Weak scale supersymmetry provides an elegant mechanism to stabilize the weak scale against runaway quantum corrections to the Higgs scalar mass that arise when the SM is embedded into a larger theory that includes particles with masses hierarchically larger than the weak scale, e.g. grand unified theories (GUTs). Unless the Higgs boson mass parameter is tuned with uncanny precision, these corrections drive the weak scale as well as the physical Higgs boson mass to the GUT scale. The supersymmetric extension of the SM, with weak scale superpartners requires no such a fine tuning, and (unlike many examples discussed above) provides a framework that is perturbatively valid all the way up to the GUT or Planck scale.

SUSY theories thus naturally meld with GUTs, preserving many of their successes, and providing successful predictions where non-SUSY GUTS appear to fail. The latter include the celebrated unification of gauge couplings and the value of the ratio $m_b/m_t$. In many SUSY models with unified values of scalar mass parameters renormalized at an ultra-high energy scale, radiative corrections drive the weak scale squared Higgs boson mass parameter to negative values triggering EWSB if the top quark mass is in the range 150-200 GeV. This radiative EWSB mechanism was discovered in the mid-1980s, well before the top mass was determined to be $\sim 172$ GeV by experiments at the Fermilab Tevatron. In addition, fits to precision electroweak measurements – plotted on the $m_t$ vs. $M_W$ plane – now indicate a slight preference for SUSY (with light sparticles) over the SM [27].

Although weak scale SUSY theories have the very attractive features noted above, the presence of many new scalar fields also gives rise to potential new problems not present in the SM. If supersymmetry is broken in an ad hoc manner, flavour-changing processes (that do not also change electric charge) occur at unacceptably large rates, as do some CP-violating processes. This is probably a clue about the (presently unknown) mechanism by which the superpartners acquire SUSY-breaking masses. But the most severe problem caused by the appearance of scalars is that we can write renormalizable interactions that violate baryon and/or lepton number conservation. These interactions would cause the proton to decay within a fraction of a second, in sharp contrast to a lower limit on its life-time in excess of $10^{30}$ years (independent of the mode of decay)!

To forbid these potentially disastrous interactions, we need to posit an additional conservation law, which is often taken to be the conservation of a parity-like quantum number (referred to as $R$-parity) taken to be $+1$ for ordinary particles and $-1$ for their SUSY partners. As a result, the lightest SUSY particle must be stable (since all lighter particles have $R=+1$).

Unlike the SM, SUSY theories with a conserved $R$-parity naturally include several candidates for DM. All that is needed is that the lightest superpartner be electrically and color neutral. These include, but are not limited to: 1. the lightest neutralino $\tilde{Z}_1$, a true WIMP candidate, 2. the gravitino $\tilde{G}$, a gravitationally interacting spin-$\frac{1}{2}$ superWIMP candidate, 3. the spin-$\frac{1}{2}$ axino $\tilde{\alpha}$, which is the superpartner of the axion, and 4. the superpartner of a sterile neutrino. The super-partner of ordinary neutrinos is excluded as galactic DM because it would already have been detected by direct searches for DM. The axino interaction strength is between that of a true WIMP and a gravitino superWIMP.

Finally, we remark here that the SM does not include a viable mechanism for baryogenesis in the early universe, primarily because the $CP$ violation is too small. In SUSY theories, with their added richness, several mechanisms appear to be possible: electroweak baryogenesis, leptogenesis (which is connected to GUT theories and neutrino mass), so-called Affleck-Dine baryogenesis involving decay of flat directions of the SUSY scalar potential and finally, the possibility of inflaton decay to heavy neutrino states.

Despite the lack of direct evidence for SUSY, its many attractive features lead many theorists to expect weak scale supersymmetry to manifest itself as the next paradigm for the laws of physics. While SUSY could have fortuitously revealed itself in experiments at LEP
4. Supersymmetric theories

The representations of the SM make a clear distinction between the “matter” and “force” sectors of the theory. The spin-half matter particles have different gauge quantum numbers from the spin-one gauge bosons (which necessarily must be in the adjoint representation of the gauge group) that mediate the strong and electroweak interactions. Spin-zero fields, which are essential for spontaneous EWSB (and which mediate a non-gauge force between particles), belong to yet another representation. In supersymmetric theories, where bosons and fermions belong to the same supermultiplet, bosons and fermions transform the same way, providing a level of synthesis never previously attained.

The superfield formalism, where bosonic and fermionic fields are combined into a single superfield, provides a convenient way for constructing supersymmetric models of particle physics. This is analogous to the familiar isospin formalism where particles of different charge are combined to form an isomultiplet. Chiral scalar superfields include one chiral-component of a spin-half fermion, together with a complex scalar field, the superpartner of this chiral fermion. A massive Dirac fermion necessarily has two chiral components, and so needs two chiral superfields to describe it. For example, the Dirac electron therefore has two complex scalar superpartners (denoted by \( \tilde{e}_L \) and \( \tilde{e}_R \)), one corresponding to each chirality of the electron/positron. Notice that the number of polarization states for fermions (four, because there are two polarizations each for the electron and positron) is exactly the same as the number of bosonic polarization states (each complex spin zero field corresponds to two polarization states, one for the spin-zero particle, and one for the spin-zero antiparticle). This equality of bosonic and fermionic degrees of freedom is a general feature of SUSY models. Moreover, the gauge quantum numbers for the spin-zero partners of the chiral fermion fields must be the same as for the corresponding fermions, so that the usual minimal coupling prescription completely fixes the gauge interactions of these particles.

Gauge superfields include spin-1 gauge bosons along with spin-\( \frac{1}{2} \) self-conjugate (or Majorana) gauginos, both tranforming under the adjoint representation. Finally, there are gravitational supermultiplets containing massless spin-2 graviton fields and spin-\( \frac{3}{2} \) gravitinos. These are all representations of \( N = 1 \) supersymmetry, where there is just one super-charge. We will focus here only on \( N = 1 \) SUSY since it leads most directly to phenomenologically viable models with chiral fermions.

The superfield formalism\[28, 29, 30\] facilitates the construction of a supersymmetric version of the Standard Model, known as the Minimal Supersymmetric Standard Model, or MSSM. As explained above, for each quark and lepton of the SM, the MSSM necessarily includes spin-0 superpartners \( \tilde{q}_L \) and \( \tilde{q}_R \) along with \( \tilde{e}_L \) and \( \tilde{e}_R \), whose gauge quantum numbers are fixed to be the known gauge quantum numbers of the corresponding fermions. Thus, for example, the right-handed up quark scalar (usually denoted by \( \tilde{u}_R \)) is a color-triplet, weak isosinglet with the same weak hypercharge \( 4/3 \) as the right-handed up-quark. The MSSM thus includes a plethora of new scalar states: \( \tilde{e}_L, \tilde{e}_R, \tilde{\nu}_L, \tilde{\nu}_R, \tilde{d}_L, \tilde{d}_R \) in the first generation, together with analogous states for the other two generations. Spin-zero squark partners of quarks with large Yukawa couplings undergo left-right mixing: thus, the \( \tilde{t}_L \) and \( \tilde{t}_R \) states mix to form mass eigenstates — \( \tilde{t}_1 \) and \( \tilde{t}_2 \) — ordered from lowest to highest mass.

The spin-0 Higgs bosons are embedded in Higgs superfields, so that the MSSM also includes spin-\( \frac{1}{2} \) higgsinos. Unlike in the SM, the same Higgs doublet cannot give a mass to both up- and down- type fermions without catastrophically breaking the underlying supersymmetry. Thus the MSSM includes two Higgs doublets instead of one as in the SM. This gives rise to a richer spectrum of physical Higgs particles, including neutral light \( h \) and heavy \( H \) scalars, a pseudoscalar \( A \) and a pair of charged Higgs bosons \( H^\pm \).

The gauge sector of the MSSM contains gauge bosons along with spin-half gauginos in the adjoint representation of the gauge group: thus, along with eight colored gluons, the MSSM contains eight colored spin-\( \frac{1}{2} \) gluinos. Upon electroweak symmetry breaking, the four gauginos of \( SU(2)_L \times U(1)_Y \) mix (just as the \( SU(2)_L \) and \( U(1)_Y \) gauge bosons mix) amongst themselves and the higgsinos, to form charginos – \( \tilde{W}_L^\pm \) and \( \tilde{W}_R^\pm \) – and neutralinos – \( \tilde{Z}_1, \tilde{Z}_2, \tilde{Z}_3 \) and \( \tilde{Z}_4 \). The \( \tilde{Z}_1 \) state, the lightest neutralino, is often the lightest supersymmetric particle (LSP), and turns out to be an excellent WIMP candidate for CDM in the universe.

If nature is perfectly supersymmetric, then the spin-0 superpartners would have exactly the same mass as
the corresponding fermions. Charged spin-0 partners of the electron with a mass of 0.51 MeV could not have evaded experimental detection. Their non-observation leads us to conclude that SUSY must be a broken symmetry. In the MSSM, SUSY is broken explicitly by including so-called soft SUSY breaking (SSB) terms in the Lagrangian. The SSB terms preserve the desirable features of SUSY, such as the stabilization of the scalar sector in the presence of radiative corrections, while lifting the superpartner masses in accord with what is necessary from experiment. It is important to note that the equality of dimensionless couplings between particles and their superpartners is still preserved (modulo small effects of radiative corrections): in particular, phenomenologically important gauge interactions of superpartners and the corresponding interactions of gauginos remain (largely) unaffected by the SSB terms.

The addition of the SSB Lagrangian terms may seem ad-hoc and ugly. It would be elegant if instead supersymmetry could be spontaneously broken. But it was recognized in the early to mid-1980’s that models where global SUSY is spontaneously broken at the weak scale ran into serious difficulties. The situation is very different if we elevate SUSY from a global symmetry to a local one. In local SUSY, we are forced to include the graviton/gravitino super-multiplet into the theory, in much the same way that we have to include spin-1 gauge fields to maintain local gauge invariance of Yang-Mills theories. Theories with local SUSY are known as supergravity (SUGRA) theories because they are supersymmetric and necessarily include gravity. Moreover, the gravitational sector of the theory reduces to general relativity in the classical limit. Within the framework of SUGRA it is possible to add an additional sector whose dynamics spontaneously breaks SUSY but which interacts with SM particles and their superpartners only via gravity (the so-called hidden sector). The spontaneous breakdown of supersymmetry results in a mass for the gravitino in the same way that in local gauge theories gauge bosons acquire mass by the Higgs mechanism. This is, therefore, referred to as the super-Higgs mechanism. The remarkable thing is that because of the gravitational coupling between the hidden and the MSSM sectors, the effects of spontaneous supersymmetry breaking in the hidden sector are conveyed to the MSSM sector, and (provided the SUSY-breaking scale in the hidden sector is appropriately chosen) weak scale SSB terms that lift the undesirable degeneracies between the masses of SM particles and their superpartners are automatically induced. Indeed, in the limit where $M_{\text{Pl}} \rightarrow \infty$ (keeping the gravitino mass fixed), we recover a global SUSY theory along with the desired SSB terms! The gravitino typically has a weak scale mass and decouples from particle physics experiments because of its tiny gravitational couplings. For reasons that we cannot discuss here, these locally supersymmetric models are free of the above-mentioned difficulties that plague globally supersymmetric models.

Motivated by the successful unification of gauge couplings at a scale $M_{\text{GUT}} \sim 2 \times 10^{16}$ GeV in the MSSM, we are led to construct a GUT based on local supersymmetry. In this case, the theory renormalized at $Q = M_{\text{GUT}}$ contains just one gaugino mass parameter $m_{1/2}$. Renormalization effects then split the physical gaugino masses in the same way the measured values of the gauge couplings arise from a single unified GUT scale gauge coupling. In general, supergravity models give rise to complicated mass matrices for the scalar superpartners of quarks and leptons, with concomitant flavor violation beyond acceptable levels. However, in models with universal soft SUSY breaking terms, a super-GIM mechanism suppresses flavor violating processes. In what has come to be known as the minimal supergravity (mSUGRA) model, a universal scalar mass $m_0$ and also a universal SSB scalar coupling $A_0$ are assumed to exist at a high scale $Q = M_{\text{GUT}} - M_{\text{Pl}}$. The physical masses of squarks and sleptons are split after renormalization, and can be calculated using renormalization group techniques. Typically, in the mSUGRA model, we have $m_{\tilde{q}} \sim m_{\tilde{t}_L} \sim m_{\tilde{b}_L}$. Although the Higgs scalar mass parameters also start off at the common value $m_0$ at the high scale, the large value of the top quark Yukawa coupling drives the corresponding squared mass parameter to negative values and EWSB is radiatively broken as we have already discussed. Within this framework, the masses and couplings required for phenomenology are fixed by just a handful of parameters which are usually taken to be,

$$m_0, ~ m_{1/2}, ~ A_0, ~ \tan \beta, ~ \text{and} ~ \text{sign}(\mu).$$

Here $\tan \beta$ is the ratio of the vacuum expectation values of the Higgs fields that give masses to up and down type fermions, and $\mu$ is the supersymmetric higgsino mass parameter whose magnitude is fixed to reproduce the measured value of $M_Z$. If all parameters are real, then potentially large $CP$-violating effects are suppressed as well. Computers codes such as Isajet, SuSpect, SoftSUSY and Spheno that calculate the full spectrum of sparticle and Higgs boson masses are publicly available.

The mSUGRA model (sometimes referred to as the constrained MSSM or CMSSM) serves as a paradigm for many SUSY phenomenological analyses. However,
it is important to remember that it is based on many assumptions that can be tested in future collider experiments but which may prove to be incorrect. For instance, in many GUT theories, it is common to get non-universal SSB parameters. In addition, there are other messenger mechanisms besides gravity. In gauge-mediated SUSY breaking models (GMSB)[33], a special messenger sector is included, so gravitinos may be much lighter than all other sparticles, with implications for both collider physics and cosmology. In anomaly-mediated SUSY breaking (AMSB) models[34], gravitational anomalies induce SSB terms, and the gravitino can be much heavier than the weak scale. There are yet other models[35] where SSB parameters get comparable contributions from gravity-mediated as well as from anomaly-mediated sources, and very recently, also from gauge-mediation[36]. The pattern of superpartner masses is sensitive to the mediation-mechanism, so that we can expect collider experiments to reveal which of the various mechanisms that have been proposed are actually realized in nature. We also mention that in both the GMSB and AMSB models, it is somewhat less natural (but still possible!) to obtain the required amount of SUSY dark matter in the Universe. Although these are all viable scenarios, they have not been as well scrutinized as the mSUGRA model.

5. Supersymmetric dark matter

5.1. Neutralino relic density

Once a SUSY model is specified, then given a set of input parameters, it is possible to all compute superpartner masses and couplings necessary for phenomenology. We can then use these to calculate scattering cross sections and particle decay patterns to evaluate SUSY signals (and corresponding SM backgrounds) in collider experiments. We can also check whether the model is allowed or excluded by experimental constraints, either from direct SUSY searches, e.g. at LEP2 which requires that $m_{\tilde{W}_1} > 103.5$ GeV, $m_{\tilde{e}} > 100$ GeV, and $m_{\tilde{h}} > 114.4$ GeV (for a SM-like light SUSY Higgs boson $h$), or from indirect searches through loop effects from SUSY particles in low energy measurements such as $B(b \to s\gamma)$ or $(g-2)_\mu$. We can also calculate the expected thermal LSP relic density. To begin our discussion, we will first assume that the lightest neutralino $\tilde{Z}_1$ is the candidate DM particle.

As mentioned above, the relic density calculation involves solving the Boltzmann equation, where the neutralino density changes due to both the expansion of the Universe and because of neutralino annihilation into SM particles, determined by the thermally averaged $\tilde{Z}_1\tilde{Z}_1$ annihilation cross section. An added complication occurs if neutralino co-annihilation is possible. Co-annihilation occurs if there is another SUSY particle close in mass to the $\tilde{Z}_1$, whose thermal relic density (usually suppressed by the Boltzmann factor $\exp(-N/\Lambda)$ is also significant. In the mSUGRA model, co-annihilation may occur from a stau, $\tilde{\tau}_1$, a stop $\tilde{t}_1$ or the lighter chargino $\tilde{W}_1$. For instance, in some mSUGRA parameter-space regions the $\tilde{t}_1$ and $\tilde{Z}_1$ are almost degenerate, so that they both have a significant density in the early universe, and reactions such as $\tilde{Z}_1\tilde{\tau}_1 \to \gamma\gamma$ occur. Since the electrically charged $\tilde{t}_1$ can also annihilate efficiently via electromagnetic interactions, this process also alters the equilibrium density of neutralinos. All in all, there are well over a thousand neutralino annihilation and co-annihilation reactions that need to be computed, involving of order 7000 Feynman diagrams. There exist several publicly available computer codes that compute the neutralino relic density: these include DarkSUSY[37], MicroMegas[38] and IsaRed[39] (a part of the Isatools package of Isajet[40]).

As an example, we show in Fig. 3 the $m_{0} v.s. m_{1/2}$ plane from the mSUGRA model, where we take $A_0 = 0$, $\mu > 0$, $m_t = 171.4$ GeV and $\tan\beta = 10$. The red-shaded regions are not allowed because either the $\tilde{t}_1$ becomes the lightest SUSY particle, in contradiction to negative searches for long lived, charged relics (left edge), or EWSB is not correctly obtained (lower-right region). The blue-shaded region is excluded by LEP2 searches for chargino pair production ($m_{\tilde{W}_1} < 103.5$ GeV). We show contours of squark (solid) and gluino (dashed) mass (which are nearly invariant under change of $A_0$ and $\tan\beta$). Below the magenta contour near $m_{1/2} \sim 200$ GeV, $m_h < 110$ GeV, which is roughly the LEP2 lower limit on $m_h$ in the model. The thin green regions at the edge of the unshaded white region has $\Omega_{\tilde{Z}_1} h^2 : 0.094 - 0.129$ where the neutralino saturates the observed relic density. In the adjoining yellow regions, $\Omega_{\tilde{Z}_1} h^2 < 0.094$, so these regions require multiple DM components. The white regions all have $\Omega_{\tilde{Z}_1} h^2 > 0.129$ and so give too much thermal DM: they are excluded in the standard Big Bang cosmology. The DM-allowed regions are classified as follows:

- At very low $m_0$ and low $m_{1/2}$ values is the so-called bulk annihilation region[41]. Here, sleptons are quite light, so $\tilde{Z}_1\tilde{Z}_1 \to \tilde{\ell}\tilde{\ell}$ via $t$-channel slepton exchange. In years past (when $\Omega_{\text{CDM}} h^2 \sim 0.3$ was quite consistent with data), this was regarded as the favored region. But today LEP2 sparticle search limits have increased the LEP2-forbidden
region from below, while the stringent bound $\Omega_{CDM} h^2 \leq 0.13$ has pushed the DM-allowed region down. Now hardly any bulk region survives in the mSUGRA model.

- At low $m_0$ and moderate $m_{1/2}$, there is a thin strip of (barely discernable) allowed region adjacent to the stau-LSP region where the neutralino and the lighter stau were in thermal equilibrium in the early universe. Here co-annihilation with the light stau serves to bring the neutralino relic density down to its observed value[42].

- At large $m_0$, adjacent to the EWSB excluded region on the right, is the hyperbolic branch/focus point (HB/FP) region where the superpotential $\mu$ parameter becomes small and the higgsino content of $\tilde{Z}_1$ increases significantly. Then $\tilde{Z}_1$ can annihilate efficiently via gauge coupling to its higgsino component and becomes mixed higgsino-bino DM. If $m_{\tilde{Z}_1} > M_W$, $M_Z$, then $\tilde{Z}_1 \tilde{Z}_1 \to WW$, $ZZ$, $Zh$ is enhanced, and one finds the correct measured relic density[43].

We show the corresponding situation for tan $\beta = 52$ in Fig. 4. While the stau co-annihilation and the HB/FP regions are clearly visible, we see that now a large DM consistent region now appears.

- In this region, the value of $m_A$ is small enough so that $\tilde{Z}_1\tilde{Z}_1$ can annihilate into $bb$ pairs through s-channel $A$ (and also $H$) resonance. This region has been dubbed the $A$-funnel[44]. It can be quite broad at large tan $\beta$ because the width $\Gamma_A$ can be quite wide due to the very large $b$- and $\tau$- Yukawa couplings. If tan $\beta$ is increased further, then $\tilde{Z}_1\tilde{Z}_1$ annihilation through the (virtual) $A^*$ is large all over parameter space, and most of the theoretically-allowed parameter space becomes DM-consistent. For even higher tan $\beta$ values, the parameter space collapses due to a lack of appropriate EWSB.

Figure 3. DM-allowed regions in the $m_0 - m_{1/2}$ plane of the mSUGRA model for tan $\beta = 10$ with $A_0 = 0$ and $\mu > 0$.

Figure 4. DM-allowed regions in the $m_0 - m_{1/2}$ plane of the mSUGRA model for tan $\beta = 52$ with $A_0 = 0$ and $\mu > 0$. The various colors of shading is as in Fig. 3.

It is also possible at low $m_{1/2}$ values that a light Higgs $h$ resonance annihilation region can occur just above the LEP2 excluded region[45]. Finally, if $A_0$ is large and negative, then the $t_1$ can become light, and $m_{\tilde{t}_1} \sim m_{\tilde{Z}_1}$, so that stop-neutralino co-annihilation[46] can occur.

Up to now, we have confined our discussion to the mSUGRA framework in which compatibility with [41] is obtained only over selected portions of the $m_0 - m_{1/2}$ plane. The reader may well wonder what happens if we relax the untested universality assumptions that underlie mSUGRA. Without going into details, we only
5.2. Neutralino direct detection

Fits to galactic rotation curves imply a local relic density of \( \rho_{CDM} \sim 0.3 \text{ GeV/cm}^3 \). For a 100 GeV WIMP, this translates to about one WIMP per coffee mug volume at our location in the galaxy. The goal of DD experiments is to detect the very rare WIMP-nucleus collisions that should be occurring as the earth, together with the WIMP detector, moves through the DM halo.

DD experiments are usually located deep underground to shield the experimental apparatus from background due to cosmic rays and ambient radiation from the environment or from radioactivity induced by cosmic ray exposure. One technique is to use cryogenic crystals cooled to near absolute zero, and look for phonon and ionization signals from nuclei recoiling from a WIMP collision. In the case of the CDMS experiment[49] at the Soudan iron mine, target materials include germanium and silicon. Another technique uses noble gases cooled to a liquid state as the target. Here, the signal is scintillation light picked up by photomultiplier tubes and ionization. Target materials include xenon[50], argon and perhaps neon. These noble liquid detectors can be scaled up to large volumes at relatively low cost. They have the advantage of fiducialization, wherein the outer layers of the detector act as an active veto against cosmic rays or neutrons coming from phototubes or detector walls: only single scatters from the inner fiducial volume qualify as signal events. A third technique, typified by the COUPP experiment[51], involves use of superheated liquids such as \( CF_3I \) located in a transparent vessel. The nuclear recoil from a WIMP-nucleon collision then serves as a nucleation site, so that a bubble forms. The vessel is monitored visually by cameras. Background events are typically located close to the vessel wall, while neutron interactions are likely to cause several bubbles to form, instead of just one, as in a WIMP collision. This technique allows for the use of various target liquids, including those containing elements such as fluorine, which is sensitive to spin-dependent interactions.

The cross section for WIMP-nucleon collisions can be calculated, and in the low velocity limit separates into a coherent spin-independent component (from scattering mediated by scalar quarks and scalar Higgs bosons) which scales as nuclear mass squared, and a spin-dependent component from scattering mediated by the \( Z \) boson or by squarks, which depends on the WIMP and nuclear spins[29]. The scattering cross section per nucleon versus \( m_{\text{WIMP}} \) serves as a figure of merit and facilitates the comparison of the sensitivity of various experiments using different target materials.

\[ \sigma_{\text{SI}} \propto \frac{1}{m_{\text{WIMP}}} \]

In Fig. 5, we show the spin-independent neutralino-proton scattering cross-section vs \( m_{\tilde{Z}_1} \) in a variety of SUSY models, compatible with collider constraints where thermally produced Big Bang neutralinos saturate the observed dark matter density.

![Spin-independent Direct Detection](image-url)
present purpose. The key thing to note is that while the various models have a branch where $\sigma_{SI}(p\tilde{Z}_1)$ falls off with $m_{\tilde{Z}_1}$, there is another branch where this cross-section asymptotes to just under $10^{-8}$ pb\cite{47,48,52}. Points in this branch (which includes the HB/FP region of mSUGRA), are consistent with \cite{1} because $\tilde{Z}_1$ has a significant higgsino component. Neutralinos with an enhanced higgsino content can annihilate efficiently in the early universe via gauge interactions. Moreover, since the spin-independent DD amplitude is mostly determined by the Higgs boson-higgsino-gaugino coupling, it is large in models with MHDM which has both gaugino and higgsino components. Thus the enhanced higgsino component of MHDM increases both the gaugino and higgsino components. Thus the enhancing higgsino content can annihilate efficiently in the early universe as well as the spin-independent DD rate. The exciting thing is that the experiments currently being deployed– such as Xenon-100, LUX and WARP– will have the sensitivity to probe this class of models. To go further will require ton-size or greater target material.

We note here that if $m_{\text{WIMP}} \lesssim 150$ GeV, then it may be possible to extract the WIMP mass by measuring the energy spectrum of the recoiling nuclear targets\cite{64}. Typically, of order 100 or more events are needed for such a determination to 10-20%. For higher WIMP masses, the recoil energy spectrum varies little, and WIMP mass extraction is much more difficult. Since the energy transfer from the WIMP to a nucleus is maximized when the two have the same mass, DD experiments with several target nuclei ranging over a wide range of masses would facilitate the distinction between somewhat light and relatively heavy WIMPs, and so, potentially serve to establish the existence of multiple WIMP components in our halo.

5.3. Indirect detection of neutralinos

As explained in Sec. \cite{1} there are also a number of indirect WIMP search techniques that attempt to detect the decay products from WIMP annihilation at either the center of the sun, at the galactic center, or within the galactic halo.

5.3.1. Neutrino telescopes

Neutrino telescopes such as ANTARES or IceCube can search for high energy neutrinos produced from WIMP-WIMP annihilation into SM particles in the core of the sun (or possibly the earth). The technique involves detection of multi-tens of GeV muons produced by $\nu_\mu$ interactions with polar ice (IceCube) or ocean water (ANTARES). The muons travel at a speeds greater than the speed of light in the medium, thus leaving a tell-tale signal of Cerenkov light which is picked up by arrays of phototubes. The IceCube experiment, currently being deployed at the south pole, will monitor a cubic kilometer of ice in search of $\nu_\mu \rightarrow \mu$ conversions. It should be fully deployed by 2011. The experiment is mainly sensitive to muons with $E_\mu > 50$ GeV.

In the case of neutralinos of SUSY, mixed higgsino dark matter (MHDM) has a large (spin-dependent) cross-section to scatter from hydrogen nuclei via $Z$-exchange and so is readily captured. Thus, in the HB/FP region of mSUGRA, or in other SUSY models with MHDM, we expect observable levels of signal exceeding 40 events/km$^2$/yr with $E_\mu > 50$ GeV. For the mSUGRA model, the IceCube signal region is shown beneath the magenta contour labelled $\mu$ in Fig. \ref{fig:icecube_signal_region}. These results were obtained using the Isajet-DarkSUSY interface\cite{37}. Notice that DD signals are also observable in much the same region (below the contour labelled DD) where the neutralino is MHDM.
5.3.2. Anti-matter from WIMP halo annihilations

WIMP annihilation in the galactic halo offers a different possibility for indirect DM searches. Halo WIMPs annihilate equally to matter and anti-matter, so the rare presence of high energy anti-matter in cosmic ray events – positrons $e^+$, anti-protons $\bar{p}$, or even anti-deuterons $\bar{D}$ – offer possible signatures. Positrons produced in WIMP annihilations must originate relatively close by, or else they will find cosmic electrons to annihilate against, or lose energy via bremsstrahlung. Anti-protons and anti-deuterons could originate further from us because, being heavier, they are deflected less and so lose much less energy. The expected signal rate depends on the WIMP annihilation rate into anti-matter, the model for the propagation of the anti-matter from its point of origin to the earth, and finally on the assumed profile of the dark matter in the galactic halo. Several possible halo density profiles are shown in Fig. 7. We see that while the local WIMP density is inferred to a factor of $\sim 2$-3 (we are at about 8 kpc from the Galactic center), the DM density at the galactic center is highly model-dependent close to the core. Since the ID signal should scale as the square of the WIMP density at the source, positron signals will be uncertain by a factor of a few with somewhat larger uncertainty for $\bar{p}$ and $\bar{\pi}$ signals that originate further away. Anti-particle propagation through the not so well known magnetic field leads to an additional uncertainty in the predictions. The recently launched Pamela space-based anti-matter telescope can look for $e^+$ or $\bar{p}$ events while the balloon-borne GAPS experiment will be designed to search for anti-deuterons. Anti-matter signals tend to be largest in the case of SUSY models with MHDM or when neutralinos annihilate through the $A$-resonance [59].

5.3.3. Gamma rays from WIMP halo annihilations

As mentioned in the Introduction, high energy gamma rays from WIMP annihilation offer some advantages over the signal from charged antiparticles. Gamma rays would point to the source, and would degrade much less in energy during their journey to us. This offers the possibility of the line signal from $Z_1^0\bar{Z}_1^0 \rightarrow \gamma\gamma$ processes that occur via box an triangle diagrams. While this reaction is loop-suppressed, it yields monoenergetic photons with $E_{\gamma} \sim m_{\text{WIMP}}$, and so can provide a measure of the WIMP mass. Another possibility is to look for continuum gamma rays from WIMP annihilation to hadrons where, for instance, the gamma is the the result of $\pi^0$ decays. Since the halo WIMPS are essentially at rest, we expect a diffuse spectrum of gamma rays, but with $E_{\gamma} < m_{\text{WIMP}}$. Because gamma rays can traverse large distances, a good place to look at is the galactic center, where the WIMP density (see Fig. 7) is expected to be very high. Unfortunately, the density at the core is also very uncertain, making predictions for the gamma ray flux uncertain by as much as four orders of magnitude. Indeed, detection of WIMP halo signals may serve to provide information about the DM distribution in our galaxy.

Anomalies have been reported in the cosmic gamma ray spectrum. In one example, the Egret experiment [57] sees an excess of gamma rays with $E_{\gamma} > 1$ GeV. Explanations for the Egret GeV anomaly range from $Z_1\bar{Z}_1 \rightarrow b\bar{b} \rightarrow \gamma$ with $m_{\text{Z}_1} \sim 60$ GeV [58], to miscalibration of the Egret calorimeter [59]. The GLAST gamma ray observatory is scheduled for lift-off in 2008 and should help resolve this issue, as will the upcoming LHC searches [60].

5.4. Gravitino dark matter

In gravity-mediated SUSY breaking models, gravitinos typically have weak scale masses and, because they only have tiny gravitational couplings, are usually assumed to be irrelevant for particle physics phenomenology. Cosmological considerations, however, lead to the gravitino problem, wherein overproduction of gravitinos, followed by their late decays into SM particles, can disrupt the successful predictions of Big Bang nucleosynthesis. The gravitino problem can be overcome by choosing an appropriate range for $m_{\tilde{G}}$ and a low enough re-heat temperature for the universe after in-
flation\cite{61} as illustrated in Fig. 8 or by hypothesizing that the $\tilde{G}$ is in fact the stable LSP, and thus constitutes the DM\cite{62}.

Gravitinos can also be produced by decay of the next-to-lightest SUSY particle, the NLSP. In the case of a long-lived neutralino NLSP, the neutralinos will be produced as usual with a thermal relic abundance in the early universe. Later, they will each decay as $\tilde{Z}_1 \rightarrow \gamma \tilde{G}$, $Z \tilde{G}$ or $h \tilde{G}$. The total relic abundance is then

$$\Omega_{\tilde{G}} h^2 = \Omega_{\tilde{G}}^{TP} h^2 + \frac{m_{\tilde{G}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1} h^2.$$  

(4)

The $\tilde{G}$ from NLSP decay may constitute warm/hot dark matter depending in the $\tilde{Z}_1 - \tilde{G}$ mass gap, while the thermally produced $\tilde{G}$ will be CDM\cite{26}.

The lifetime for neutralino decay to the photon and a gravitino is given by \cite{64},

$$\tau(\tilde{Z}_1 \rightarrow \gamma \tilde{G}) \simeq \frac{48\pi m_{\tilde{G}}^2}{m_{\tilde{Z}_1}^2} A^2 \left(1 - r^2 \right) \frac{r^2}{(1 + 3r^2)}$$

$$\sim 5.8 \times 10^8 \text{s} \left(\frac{100 \text{ GeV}}{m_{\tilde{Z}_1}}\right)^3 \frac{1}{A^2} \left(1 - r^2 \right)^2 \frac{r^2}{(1 + 3r^2)},$$

(5)

where $A = (v_4^{(1)} \cos \theta_W + v_3^{(1)} \sin \theta_W)^{-1}$, with $v_4^{(1)}$ being the wino and bino components of the $\tilde{Z}_1$\cite{28}. $M_P$ is the reduced Planck mass, and $r = m_{\tilde{G}}/m_{\tilde{Z}_1}$. Similar formulae (with different mixing angle and $r$-dependence) hold for decays to the gravitino plus a $Z$ or $h$ boson. We see that – except when the gravitino is very much lighter than the neutralino as may be the case in GMSB models with a low SUSY breaking scale – the NLSP decays well after Big Bang nucleosynthesis. Such decays would inject high energy gammas and/or hadrons into the cosmic soup post-nucleosynthesis, which could break up the nuclei, thus conflicting with the successful BBN predictions of Big Bang cosmology. For this reason, gravitino NLSP scenarios usually favor a stau NLSP, since the BBN constraints in this case are much weaker.

Finally, we remark here upon the interesting interplay of baryogenesis via leptogenesis with the nature of the LSP and NLSP. For successful thermal leptogenesis to take place, it is found that the reheat temperature of the universe must exceed $\sim 10^{10}$ GeV\cite{65}. If this is so, then gravitinos would be produced thermally with a huge abundance, and then decay late, destroying BBN predictions. For this reason, some adherents of leptogenesis tend to favor scenarios with a gravitino LSP, but with a stau NLSP\cite{66}.

5.5. Axino dark matter

If we adopt the MSSM as the effective theory below $M_{\text{GUT}}$, and then seek to solve the strong CP problem via the Peccei-Quinn solution \cite{13}, we must introduce not only an axion but also a spin-$\frac{1}{2}$ axino $\tilde{a}$ into the theory. The axino mass is found to be in the range

Figure 8. An illustration of constraints from Big Bang nucleosynthesis which require $T_R$ to be below the various curves, for the HB/FP region of the mSUGRA model with $m_0 = 2397$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$ and $\tan \beta = 30$, from Kohri et al.\cite{67} to which we refer the reader for more details.

Here, we consider the consequences of a gravitino LSP in SUGRA models. If gravitinos are produced in the pre-inflation epoch, then their number density will be diluted away during inflation. After the universe inflates, it enters a re-heating period wherein all particles can be thermally produced. However, the couplings of the gravitino are so weak that though gravitinos can be produced by the particles that do partake of thermal equilibrium, gravitinos themselves never attain thermal equilibrium: indeed their density is so low that gravitino annihilation processes can be neglected in the calculation of their relic density. The thermal production (TP) of gravitinos in the early universe has been calculated, and including EW contributions, is given by the approximate expression \cite{63}:

$$\Omega_{\tilde{G}}^{TP} h^2 \simeq 0.32 \left(\frac{10 \text{ GeV}}{m_{\tilde{G}}}\right) \left(\frac{m_{1/2}}{1 \text{ TeV}}\right)^2 \left(\frac{T_R}{10^8 \text{ GeV}}\right)^3$$

(3)

where $T_R$ is the re-heating temperature.
of keV-GeV\cite{67}, but its coupling is suppressed by the Peccei-Quinn breaking scale $f_a$, which is usually taken to be of order $10^9 - 10^{12}$ GeV; thus, the axino interacts more weakly than a WIMP, but not as weakly as a gravitino. The axino can be an compelling choice for DM in the universe\cite{68}.

Like the gravitino, the axino will likely not be in thermal equilibrium in the early universe, but can still be produced thermally via particle scattering. The thermal production abundance is given by\cite{68,69}

$$\Omega_{\tilde{a}}^{TP} h^2 \simeq 5.5 g_*^6 \log \left( \frac{1.108}{g_s} \frac{10^{11} \text{GeV}}{f_a/N} \right)^2 \times \left( \frac{m_{\tilde{a}}}{100 \text{ MeV}} \right) \left( \frac{T_R}{10^4 \text{ GeV}} \right), \quad (6)$$

where $f_a$ is the PQ scale, $N$ is a model-dependent color anomaly factor that enters only as $f_a/N$, and $g_s$ is the strong coupling at the reheating scale.

Also like the gravitino, the axino can be produced non-thermally by NLSP decays, where the NLSP abundance is given by the standard relic density calculation. Thus,

$$\Omega_{\tilde{a}} h^2 = \Omega_{\tilde{a}}^{TP} h^2 + \frac{m_{\tilde{a}}}{m_{\text{NLSP}}} \Omega_{\text{NLSP}} h^2. \quad (7)$$

In this case, the thermally produced axinos will be CDMS only for $m_{\tilde{a}} \gtrsim 0.1$ MeV\cite{68}, while the axinos produced in NLSMP decay will constitute hot/warm DM\cite{20}. Since the PQ scale is considerably lower than the Planck scale, the lifetime for decays such as $\tilde{Z}_1 \rightarrow \gamma \tilde{a}$ are of order $\sim 0.03$ sec well before BBN. Thus, the axino DM scenario is much less constrained than gravitino DM.

Note also that if axinos are the CDM of the universe, then models with very large $\Omega_{\tilde{Z}_1} h^2 \sim 100 - 1000$ can be readily accommodated, since there is a huge reduction in relic density upon $\tilde{Z}_1$ decay to the axino. This possibility occurs in models with multi-TeV scalars (and hence a multi-TeV gravitino) and a bino-like $\tilde{Z}_1$. In this case with very large $m_{\tilde{G}}$ there is no gravitino problem as long as the re-heat temperature $T_R \sim 10^6 - 10^8$ GeV. This range of $T_R$ is also what is needed to obtain successful non-thermal leptogenesis (involving heavy neutrino $N$ production via inflaton decay)\cite{70} along with the correct abundance of axino dark matter\cite{71}. A scenario along these lines has been proposed\cite{72} to reconcile Yukawa-unified SUSY models, which usually predict a vast over-abundance of neutralino DM, with the measured relic density.

6. SUSY DM at the LHC

6.1. Sparticle production at the LHC

Direct production of neutralino dark matter at the LHC ($pp \rightarrow \tilde{Z}_1 \tilde{Z}_1 X$, where $X$ stands for assorted hadronic debris) is of little interest since the high $p_T$ final state particles all escape the detector, and there is little if anything to trigger an event record. Detectable events come from the production of the heavier superpartners, which in turn decay via a multi-step cascade which ends in the stable LSP.

In many models, the strongly interacting squarks and/or gluinos are among the heaviest states. Unless these are extremely heavy, these will have large production cross sections at the LHC. Strong interaction production mechanisms for their production include, 1. gluino pair production $\tilde{g}\tilde{g}$, 2. squark pair production $\tilde{q}\tilde{q}$ and 3. squark-gluino associated production $\tilde{q}\tilde{g}$. Note here that the reactions involving squarks include a huge number of subprocess reactions to cover the many flavors, types (left- and right-), and also the anti-squarks. The various possibilities each have different angular dependence in the production cross sections\cite{73}, and the different flavors/types of squarks each have different decay modes\cite{74}. These all have to be kept track of in order to obtain a reliable picture of the implications of SUSY in the LHC detector environment. Squarks and gluinos can also be produced in association with charginos and neutralinos\cite{75}. Associated gluino production occurs via squark exchange in the t or u channels and is suppressed if squarks are very heavy.

If colored sparticles are very heavy, then electroweak production of charginos and neutralinos may be the dominant sparticle production mechanism at the LHC. The most important processes are pair production of charginos, $\tilde{W}^+_i \tilde{W}^-_j$ where $i,j = 1,2$, and chargino-neutralino production, $\tilde{W}^+_i \tilde{Z}_j$, with $i = 1, 2$ and $j = 1 - 4$. In models with unified GUT-scale gaugino masses and large $|\mu|$, $Z \tilde{W}_1 \tilde{W}_1$ and $Z \tilde{Z}_2 \tilde{W}_1$ couplings are large enough that $\tilde{W}_1 \tilde{W}_1$ and $\tilde{W}_1 \tilde{Z}_2$ production occurs at significant rates. The latter process can lead to the gold-plated trilepton signature at the LHC\cite{76}. Neutralino pair production ($pp \rightarrow \tilde{Z}_1 \tilde{Z}_1 X$ where $i,j = 1 - 4$) is also possible. This reaction occurs at low rates at the LHC unless $|\mu| \simeq M_{1,2}$ (as in the case of MHDM). Finally, we mention slepton pair production: $\tilde{l}^+ \tilde{l}^-$, $\tilde{\nu}_l \tilde{l}$ and $\tilde{\nu}_{\ell} \tilde{l}$, which can give detectable dilepton signals if $m_{\tilde{l}^\pm} \lesssim 300 \text{ GeV}$\cite{77}.

In Fig. 9 we show various sparticle production cross sections at the LHC as a function of $m_{\tilde{g}}$. Strong interaction production mechanisms dominate at low mass,
while electroweak processes dominate at high mass. The associated production mechanisms are never dominant. The expected LHC integrated luminosity in the first year of running is expected to be around 0.1 fb\(^{-1}\), while several tens of fb\(^{-1}\) of data is expected to be recorded in the first several years of operation. The ultimate goal is to accumulate around 500-1000 fb\(^{-1}\), corresponding to \(10^5\)–\(10^6\) SUSY events for \(m_{\tilde{g}} \sim 1\) TeV.

The gluinos can only decay via \(\tilde{g} \rightarrow q\bar{q}\), while gravitational interactions are negligible, three-body decays to the wino-like chargino and neutralino usually have larger branching fractions on account of the larger gauge coupling. If \(|\mu| < M_2\), gluinos and squarks may thus decay most of the time to the heavier charginos and neutralinos, resulting in lengthy cascade decay chains at the LHC.

Squarks decay always to two-body modes: \(\tilde{g} \rightarrow g\tilde{g}\) if it is kinematically allowed, or \(\tilde{q}_L \rightarrow q'\tilde{W}_i\), while \(\tilde{q}_R \rightarrow q\tilde{Z}_j\) only, since right-squarks do not couple to charginos. Slepions do not have strong interactions so cannot decay to gluinos. Their electroweak decays are similar to corresponding decays of squarks \(\ell_L \rightarrow \ell'\tilde{W}_i\), \(\ell_R \rightarrow \ell\tilde{Z}_j\) only.

Charginos may decay via two-body modes: \(\tilde{W}_i \rightarrow W\tilde{Z}_j\), \(\tilde{W}_j \rightarrow WZ\), \(\tilde{Z}_i \rightarrow W\tilde{Z}_j\), or even to \(\phi W_j\) or \(H^-\tilde{Z}_j\), where \(\phi = h, H, A\). If two-body modes are inaccessable, then three-body decays dominate: \(\tilde{W}_i \rightarrow Z_j f f'\), \(f = Z, W\) and \(f' = Z, W\) are SM fermions which couple to the \(W\). Frequently, the decay amplitude is dominated by the virtual \(W\) so that the three-body decays of \(\tilde{W}_i\) have the same branching fractions as those of the \(W\). Neutralinos decay via \(Z_i \rightarrow \tilde{W}_j + f f'\), where \(f, f' = Z, W\) if two body neutralino decays are closed, then \(Z_i \rightarrow \tilde{Z}_j f f', \tilde{Z}_j \rightarrow Z_i f f', \tilde{Z}_j \rightarrow Z_i f f'\), where \(f, f' = Z, W\). In models with the branching fraction for radiative decays \(\tilde{Z}_i \rightarrow \tilde{Z}_j + \gamma\) (that only occurs at the one-loop level) may be significant[78]. The cascade decay modes of neutralinos depend sensitively on model parameters[79].

If \(\tan \beta\) is large, then \(b\) and \(\tau\) Yukawa coupling effects become important, enhancing three body decays of \(\tilde{g}\), \(\tilde{W}_i\) and \(\tilde{Z}_j\) to third generation fermions[80]. For very large values of \(\tan \beta\) these decays can even dominate, resulting in large rates for \(b\)-jet and \(\tau\)-jet production in SUSY events[81].

Finally, the various Higgs bosons can be produced both directly and via sparticle cascades at the LHC[82]. Indeed, it may be possible that \(h\) is first discovered in SUSY events because in a sample of events enriched for SUSY, it is possible to identify \(h\) via its dominant \(h \rightarrow bb\) decays rather than via its sub-dominant decay modes, as required for conventional searches[82]. The heavier Higgs bosons decay to a variety of SM modes, but also to SUSY particles if these latter decays are kinematically allowed, leading to novel signatures such as \(H, A \rightarrow \tilde{Z}_2\tilde{Z}_2 \rightarrow 4\ell + E_{T}^{\text{miss}}\) [83].

The cascade decays terminate in the LSP. In the case of a \(\tilde{Z}_1\) LSP, the \(\tilde{Z}_1\) is a DM candidate, and leaves its imprint via \(E_{T}^{\text{miss}}\). In the case of a weak scale \(\tilde{G}\) or \(\tilde{G}\) LSP, then \(\tilde{Z}_1\) will decay as discussed above. In these

Figure 9. Cross sections for production of various sparticles at the LHC. Gaugino mass unification is assumed.

6.2. Sparticle cascade decays

In \(R\)-parity conserving models, sparticles decay to lighter sparticles until the decay terminates in the LSP[74]. Frequently, the direct decay to the LSP is either forbidden or occurs with only a small branching fraction. Since gravitational interactions are negligible, gluinos can only decay via \(\tilde{g} \rightarrow q\bar{q}\), where the \(q\) and \(\tilde{g}\) can be of any flavor or type. If two body decay modes are closed, the squark will be virtual, and the gluino will decay via three body modes \(\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1\), \(q\bar{q}\tilde{W}_j\). If squarks are degenerate, and Yukawa coupling effects negligible, three-body decays to the wino-like chargino and neutralino usually have larger branching fractions on account of the larger gauge coupling. If \(|\mu| < M_2\), gluinos and squarks may thus decay most of the time to the heavier charginos and neutralinos, resulting in lengthy cascade decay chains at the LHC.
cases, the $\tilde{Z}_1$ lifetime is long enough that it decays outside the detector, so one still expects large $E_T^{\text{miss}}$ in the collider events. An exception arises for the case of super-light gravitinos (with masses in the eV to keV range) that are possible in GMSB models: see \textsuperscript{[6]}. Then, the decay may take place inside inside the detector, possibly with a large vertex separation. It is also possible that the NLSP is charged and quasi-stable, in which case collider events may include highly ionizing tracks instead of, or in addition to, $E_T^{\text{miss}}$.

The decay branching fractions depend on the entire spectrum of SUSY particle masses and their mixings. They are pre-programmed in several codes: Isajet\textsuperscript{[40]}, SDECAY\textsuperscript{[84]} and Spheno\textsuperscript{[85]}.

6.3. Event generation for LHC

Once sparticle production cross sections and decay branching fractions have been computed, it is useful to embed these into event generator programs to simulate what SUSY collider events will look like at LHC. There are several steps involved:

- Calculate all sparticle pair production cross sections. Once all initial and final states are accounted for, this involves over a thousand individual subprocess reactions. In event generation, a particular reaction is selected on a probabilistic basis, with a weight proportional to its differential cross-section.

- Sparticle decays are selected probabilistically into all the allowed modes in proportion to the corresponding branching fractions.

- Initial and final state quark and gluon radiation are usually dealt with using the parton shower (PS) algorithm, which allows for probabilistic parton emission based on approximate collinear QCD emission matrix elements, but exact kinematics. The PS is also applied at each step of the cascade decays, which may lead to additional jet production in SUSY collider events.

- A hadronization algorithm provides a model for turning various quarks and gluons into mesons and baryons. Unstable hadrons must be further decayed.

- The beam remnants – proton constituents not taking part in the hard scattering – must be showered and hadronized, usually with an independent algorithm, so that energy deposition in the forward detector region may be reliably calculated.

At this stage, the output of an event generator program is a listing of particle types and their associated four-vectors. The resulting event can then be interfaced with detector simulation programs to model what the actual events containing DM will look like in the environment of a collider detector.

Several programs are available, including Isajet\textsuperscript{[40]}, Pythia\textsuperscript{[86]} and Herwig\textsuperscript{[87]}. Other programs such as Madevent\textsuperscript{[88]}, CompHEP/CalcHEP\textsuperscript{[89]} and Whizard\textsuperscript{[90]} can generate various $2 \rightarrow n$ processes including SUSY particles. The output of these programs may then be used as input to Pythia or Herwig for showering and hadronization. Likewise, parton level Isajet SUSY production followed by cascade decays can be input to Pythia and Herwig via the Les Houches Event format\textsuperscript{[91]}.

6.4. Signatures for sparticle production

Unless colored sparticles are very heavy, the SUSY events at the LHC mainly result in gluino and squark production, followed by their possibly lengthy cascade decays. These events, therefore, typically contain very hard jets (from the primary decay of the squark and/or gluino) together with other jets and isolated electrons, muons and taus (identified as narrow one- and three-prong jets), and sometimes also photons, from the decays of secondary charginos and neutralinos, along with $E_T^{\text{miss}}$ that arises from the escaping dark matter particles (as well as from neutrinos). In models with a super-light gravitino, there may also be additional isolated photons, leptons or jets from the decay of the NLSP. The relative rates for various $n$-jet + $m$-lepton + $k$-photon + $E_T^{\text{miss}}$ event topologies is sensitive to the model as well as to the parameter values, and so provide a useful handle for phenomenological analyses.

Within the SM, the physics background to the classic $\text{jets} + E_T^{\text{miss}}$ signal comes from neutrinos escaping the detector. Thus, the dominant SM backgrounds come from $W + \text{jets}$ and $Z + \text{jets}$ production, $t\bar{t}$ production, QCD multijet production (including $b\bar{b}$ and $c\bar{c}$ production), $WW$, $WZ$, $ZZ$ production plus a variety of $2 \rightarrow n$ processes which are not usually included in event generators. These latter would include processes such as $ttt$, $t\bar{t}b$, $ttW$, $WWW$, $WWZ$ production, etc. Decays of electroweak gauge bosons and the $t$-quark are the main source of isolated leptons in the SM. Various additional effects– uninstrumented regions, energy mis-measurement, cosmic rays, beam-gas events– can also lead to $E_T^{\text{miss}}$ events.

In contrast to the SM, SUSY events naturally tend to have large jet multiplicities and frequently an observable rate for high multiplicity lepton events with large
Thus, if one plots signal and background versus multiplicity of any of these quantities, as one steps out to large multiplicity, the expected SUSY events should increase in importance, and even dominate the high multiplicity channels in some cases. This is especially true of isolated multi-lepton signatures, and in fact it is convenient to classify SUSY signal according to lepton multiplicity\cite{92}:

- zero lepton + jets + $E_T^{miss}$ events,
- one lepton + jets + $E_T^{miss}$ events,
- two opposite sign leptons + jets + $E_T^{miss}$ events (OS),
  - same-flavor (OSSF),
  - different flavor (OSDF),
- two same sign leptons + jets + $E_T^{miss}$ events (SS),
- three leptons + jets + $E_T^{miss}$ events (3l),
- four (or more) leptons + jets + $E_T^{miss}$ events (4l).

6.5. LHC reach for SUSY

Event generators, together with detector simulation programs can be used to project the SUSY discovery reach of the LHC. Given a specific model, one may first generate a grid of points that samples the parameter (sub)space where signals rates are expected to vary significantly. A large number of SUSY collider events can then be generated at every point on the grid along with the various SM backgrounds to the SUSY signal mentioned above. Next, these signal and background events are passed through a detector simulation program and a jet-finding algorithm is implemented to determine the number of jets per event above some $E_T(jet)$ threshold (usually taken to be $E_T(jet) > 50 - 100$ GeV for LHC). Finally, analysis cuts are imposed which are designed to reject mainly SM BG while retaining the signal. These cuts may include both topological and kinematic selection criteria. For observability with an assumed integrated luminosity, we require that the signal exceed the chance 5 standard deviation upward fluctuation of the background, together with a minimum value of ($\sim 25\%$) the signal to background ratio, to allow for the fact that the background is not perfectly known. For lower sparticle masses, softer kinematic cuts are used, but for high sparticle masses, the lower cross sections but higher energy release demand hard cuts to optimize signal over background.

In Fig. 10 we illustrate the SUSY reach of the LHC within the mSUGRA model assuming an integrated luminosity of 100 fb$^{-1}$. We show the result in the $m_0 - m_{1/2}$ plane, taking $A_0 = 0$, $\tan \beta = 10$ and $\mu > 0$. The signal is observable over background in the corresponding SUSY channel below the corresponding curve. We note the following.

1. Unless sparticles are very heavy, there is an observable signal in several different event topologies. This will help add confidence that one is actually seeing new physics, and may help to sort out the production and decay mechanisms.

2. The reach at low $m_0$ extends to $m_{1/2} \sim 1400$ GeV. This corresponds to a reach for $m_{\tilde{g}} \sim 3.1$ TeV.

3. At large $m_0$, squarks and sleptons are in the 4 – 5 TeV range, and are too heavy to be produced at significant rates at LHC. Here, the reach comes mainly from just gluino pair production. In this range, the LHC reach is up to $m_{1/2} \sim 700$ GeV, corresponding to a reach in $m_{\tilde{g}}$ of about 1.8 TeV, and may be extended by $\sim 15-20\%$ by b-jet tagging\cite{93}.

In Fig. 10 we can see a comparison of the LHC reach (notice that it is insensitive to $\tan \beta$ and sign($\mu$)) with that of the Tevatron (for clean 3l events with 10 fb$^{-1}$),
and the proposed $e^+e^-$ International Linear Collider (ILC), with $\sqrt{s} = 0.5$ or 1 TeV along with various dark matter DD and ID search experiments. We remark that:

- While LHC can cover most of the relic density allowed region, the HB/FP region emerges far beyond the LHC reach.
- As already noted, the DD and ID experiments have the greatest sensitivity in the HB/FP region where the neutralino is MHDM. In this sense, DD and ID experiments complement LHC searches for SUSY.
- The ILC reach is everywhere lower than LHC, except in the HB/FP region. In this region, while gluinos and squarks can be extremely heavy, the $\mu$ parameter is small, leading to a relatively light spectrum of charginos and neutralinos. These are not detectable at the LHC because the visible decay products are too soft. However, since chargino pair production is detectable at ILC even if the energy release in chargino decays is small, the ILC reach extends beyond LHC in this region [91].

Finally, we note here that while the results presented above are for the LHC reach in the mSUGRA model, the LHC reach (measured in terms of $m_{\tilde{g}}$ and $m_{\tilde{q}}$) tends to be relatively insensitive to the details of the model chosen, as long as gluino and squark production followed by cascade decays to the DM particle occur.

### 6.6. Early discovery of SUSY at LHC without $E_T^{\text{miss}}$

Recently, it has been pointed out that a SUSY search using the traditional $jets + E_T^{\text{miss}}$ signature may not be possible for a while after start-up due to various detector calibration issues. In this case, it is possible to abandon using the $E_T^{\text{miss}}$ cut, and instead require a high multiplicity of isolated leptons: SS, OSSF, OSDF, $3\ell$. The high lepton multiplicity requirement severely reduces SM background while maintaining large enough signal rates. In Ref. [95], it is claimed an LHC reach of $m_{\tilde{g}} \sim 750$ GeV is possible with just 0.1 fb$^{-1}$ of integrated luminosity, without using an $E_T^{\text{miss}}$ cut.

### 6.7. Determination of sparticle properties

Once a putative signal for new physics emerges at LHC, the next step is to establish its origin. This will entail detailed measurements of cross sections and distributions in various event topologies to gain insight into the identity of the new particles being produced, their masses, decay patterns, spins, couplings (gauge quantum numbers) and ultimately mixing angles. These measurements are not straightforward in the LHC environment because of numerous possible SUSY production reactions occurring simultaneously, a plethora of sparticle cascade decay possibilities, hadronic debris from initial state radiation and lack of invariant mass reconstruction due to the presence of $E_T^{\text{miss}}$. All these lead to ambiguities and combinatoric problems in reconstructing exactly what sort of signal reactions are taking place. In contrast, at the ILC, the initial state is simple, the beam energy is tunable and beam polarization can be used to select out specific processes.

While it seems clear that the ILC is better suited for a systematic program of precision sparticle measurements, studies have shown (albeit in special cases) that interesting measurements are also possible at the LHC. We go into just a subset of all details here in order to give the reader an idea of some of the possibilities suggested in the literature.

One suggested starting point is the distribution of effective mass $M_{\text{eff}} = E_T^{\text{miss}} + E_T(j1) + E_T(j2) + E_T(j3) + E_T(j4)$ in the inclusive SUSY sample, which sets the approximate mass scale $M_{\text{SUSY}} \equiv \min(m_{\tilde{g}}, m_{\tilde{q}})$ for the strongly interacting sparticles being produced [96], and provides a measure of $M_{\text{SUSY}}$ to 10-15%.

More detailed information on sparticle masses may be accessed by studying specific event topologies. For instance, the mass of dileptons from $\tilde{Z}_2 \rightarrow \ell^+\ell^- Z_1$ decays is bounded by $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ (this bound is even more restrictive if $\tilde{Z}_2$ decays via an on-shell slepton) [97]. We therefore expect an OSSF invariant mass distribution to exhibit an edge at $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ (or below) in any sample of SUSY events so long as the “spoiler” decay modes $\tilde{Z}_2 \rightarrow \tilde{Z}_1 Z$ or $\tilde{Z}_1 h$ are closed. Contamination from chargino production can be statistically removed by subtracting out the distribution of OSDF dileptons. In MHDM models, there may be more than one visible mass edge because the $\tilde{Z}_3$ may also be accessible in cascade decays.

In the happy circumstance where production of gluinos or a single type of squark is dominant, followed by a string of two-body decays, then further invariant mass edges are possible. One example comes from $\tilde{g} \rightarrow b\tilde{b}_1 \rightarrow b\bar{b}\tilde{Z}_2 \rightarrow b\bar{b}\ell\ell\tilde{Z}_1$; then one can try to combine a $b$-jet with the dilepton pair to reconstruct the squark-neutralino mass edge: $m(b\ell\ell) < m_{\tilde{b}_1} - m_{\tilde{Z}_1}$. Next, combining with another $b$-jet can yield a gluino-neutralino edge: $m(b\bar{b}\ell\ell) < m_{\tilde{g}} - m_{\tilde{Z}_1}$. The reconstruction of such a decay chain may be possible as shown in Ref. [98], where other sequences of two-body decays...
are also examined. In practice, such fortuitous circumstances may not exist, and there are many combinatoric issues to overcome as well. A different study\cite{98} shows that end-point measurements at the LHC will make it possible to access the mass difference between the LSP and the stau in a mSUGRA scenario where the stau co-annihilation mechanism is operative.

These end-point measurements generally give mass differences, not masses. However, by an analysis of the decay chain $\tilde{q}_L \rightarrow q \tilde{Z}_2 \rightarrow q \ell^\pm \ell^\mp$ and the introduction of the so-called $m_{T2}$ variable. We will refer the reader to the literature for details\cite{100}.

Mass measurements allow us to check consistency of specific SUSY models with a handful of parameters, and together with other measurements can readily exclude such models. But these are not the only interesting measurements at the LHC. It has been shown that if the NLSP of GMSB models decays into a superlight gravitino, it may be possible to determine its lifetime, and hence the gravitino mass at the LHC\cite{101}. This will then allow one to infer the underlying SUSY breaking scale, a scale at least as important as the weak scale! A recent study\cite{102} suggests that this is possible even when the the decay length of the NLSP is too short to be measured. While linear collider experiments will ultimately allow the precision measurements that will directly determine the new physics to be softly broken supersymmetry\cite{113}, it will be exciting to analyze real LHC data that will soon be available to unravel many of the specific details about how (or if) SUSY is actually implemented in nature.

6.8. Measuring DM properties at LHC and ILC

SUSY discovery will undoubtedly be followed by a program (as outlined in Sec. 6.7) to reconstruct sparticle properties. What will we be able to say about dark matter in light of these measurements? Such a study was made by Baltz et al.\cite{104} where four mSUGRA case study points (one each in the bulk region, the HB/FP region, the stau coannihilation region and the A-funnel region) were examined for the precision with which measurements of sparticle properties that could be made at LHC, and also at a $\sqrt{s} = 0.5$ and 1 TeV $e^+e^-$ collider. They then adopted a 24-parameter version of the MSSM and fit its parameters to these projected measurements. The model was then used to predict several quantities relevant to astrophysics and cosmology: the dark matter relic density $\Omega_{\tilde{Z}_1}h^2$, the spin-independent neutralino-nucleon scattering cross section $\sigma_{SI}(\tilde{Z}_1p)$, and the neutralino annihilation cross section times relative velocity, in the limit that $v \rightarrow 0$: $\langle \sigma v \rangle_{s\rightarrow0}$. The last quantity is the crucial particle physics input for estimating signal strength from neutralino annihilation to anti-matter or gammas in the galactic halo. What this yields then is a collider measurement of these key dark matter quantities.

As an illustration, we show in Fig. \ref{fig:neutralino_relic} (taken from Ref. \cite{104}) the precision with which the neutralino relic density is constrained by collider measurements for the LCC2 point which is in the HB/FP region of the mSUGRA model. Measurements at the LHC cannot fix the LSP composition, and so unable to resolve the degeneracy between a wino-LSP solution (which gives a tiny relic density) and the true solution with MHDM. Determinations of chargino production cross sections at the ILC can easily resolve the difference. It is nonetheless striking that up to this degeneracy ambiguity, experiments at the LHC can pin down the relic density to within $\sim 50\%$ (a remarkable result, given that there are sensible models where the predicted relic density may differ by orders of magnitude!). This improves to 10-20% if we can combine LHC and ILC measurements.

![Figure 11. Determination of neutralino relic abundance via measurements at the LHC and ILC, taken from Ref. [104].](image-url)
This collider determination of the relic density is very important. If it agrees with the cosmological measurement it would establish that the DM is dominantly thermal neutralinos from the Big Bang. If the neutralino relic density from colliders falls significantly below $\Omega_\chi h^2$, it would provide direct evidence for multi-component DM—perhaps neutralinos plus axions or other exotica. Alternatively, if the collider determination gives a much larger value of $\Omega_\chi h^2$, it could point to a long-lived but unstable neutralino and/or non-thermal DM.

The collider determination of model parameters would also pin down the neutralino-nucleon scattering cross section. Then if a WIMP signal is actually observed in DD experiments, one might be able to determine the local DM density of neutralinos and aspects of their velocity distribution based on the DD signal rate. This density should agree with that obtained from astrophysics if the DM in our Galaxy is comprised only of neutralinos.

Finally, a collider determination of $\langle \sigma v \rangle_{v=0}$ would eliminate uncertainty on the particle physics side of projections for any ID signal from annihilation of neutralinos in the galactic halo. Thus, the observation of a gamma ray and/or anti-matter signal from neutralino halo annihilations would facilitate the determination of the galactic halo dark matter density distribution.

7. Some non-SUSY WIMPs at the LHC

7.1 $B_\mu^1$ state from universal extra dimensions

Models with Universal Extra Dimensions, or UED, are interesting constructs which provide a foil for SUSY search analyses[18]. In the 5-D UED theory, one posits that the fields of the SM actually live in a 5-D brane world. The extra dimension is “universal” since all the SM particles propagate in the 5-D bulk. The single extra dimension is assumed to be compactified on a $S_1/Z_2$ orbifold (line segment). After compactification, the 4-D effective theory includes the usual SM particles, together with an infinite tower of Kaluza-Klein (KK) excitations. The masses of the excitations depend on the radius of the compactified dimension, and the first ($n=1$) KK excitations can be taken to be of order the weak scale. In these theories, KK-parity $(-1)^n$ can be a conserved quantum number. If this so-called KK-parity is exact, then the lightest odd KK parity state will be stable and can be a DM candidate. At tree-level, all the KK excitations in a given level are essentially degenerate. Radiative corrections break the degeneracy, leaving colored excitations as the heaviest excited states and the $n=1$ KK excitation of the SM $U(1)_Y$ gauge boson $B_\mu^1$ as the lightest[105] KK odd state: in the UED case, therefore, the DM particle has spin-1. The splitting caused by the radiative corrections is also essential to assess how the KK excitations decay, and hence are crucial for collider phenomenology[106].

The relic density of $B_\mu^1$ particles has been computed, and found to be compatible with observation for certain mass ranges of $B_\mu^1[107]$. Also, in UED, the colored excitations can be produced with large cross sections at the LHC, and decay via a cascade to the $B_\mu^1$ final state. Thus, the collider signatures are somewhat reminiscent of SUSY, and it is interesting to ask whether it is possible to distinguish a jets + leptons + $E_T^{miss}$ signal in UED from that in SUSY. Several studies[108] answer affirmatively, and in fact provide strong motivation for the measurement of the spins of the produced new particles[109]. UED DM generally leads to a large rate in IceCube, and may also give an observable signal in anti-protons and possibly also in photons and positrons[108][110]. DD is also possible but the SI cross section is typically smaller than $10^{-9}$ pb.

7.2. Little Higgs models

Little Higgs models[19][22] provide an alternative method compared to SUSY to evade the quadratic sensitivity of the scalar Higgs sector to ultra-violet (UV) physics. In this framework, the Higgs boson is a pseudo-Goldstone boson of a spontaneously broken global symmetry that is not completely broken by any one coupling, but is broken when all couplings are included. This then implies that there is quadratic sensitivity to UV physics, but only at the multi-loop level. Specific models where the quadratic sensitivity enters at the two-loop level should, therefore, be regarded as low energy effective theories valid up to a scale $\Lambda \sim 10$ TeV, at which a currently unknown, and perhaps strongly-coupled UV completion of the theory is assumed to exist. Models that realize this idea require new TeV-scale degrees of freedom that can be searched for at the LHC: new gauge bosons, a heavy top-like quark, and new spin-zero particles, all with couplings to the SM. These models, however, run into phenomenological difficulties with precision EW constraints, unless a discrete symmetry—dubbed $T$-parity[20]—is included. SM particles are then $T$-even, while the new particles are $T$-odd.

We will set aside the issue (mentioned earlier) of whether $T$-parity conservation is violated by anomalies[23], and assume that a conserved $T$-parity can be introduced[24]. In this case, the lightest $T$-odd particle $A_H$ — the Little Higgs partner of the hypercharge gauge boson with a small admixture of the neutral $W_{3H}$ boson
- is stable and yields the observed amount of DM for a reasonable range of model parameters\[110\]. In this case, the DM particle has spin-1, though other cases with either a spin-\(\frac{3}{2}\) or spin-0 heavy particle may also be possible. \(A_H\) can either annihilate with itself into vector boson pairs or \(tt\) pairs via s-channel Higgs exchange, or into top pairs via exchange of the heavy T-odd quark in the t-channel. Co-annihilation may also be possible if the heavy quark and \(A_H\) are sufficiently close in mass. Signals at the LHC[111] mainly come from pair production of heavy quarks, and from single production of the heavy quark in association with \(A_H\). These lead to low jet multiplicity events plus \(E_T^{\text{miss}}\).

The \(E_T^{\text{miss}}\) comes from the escaping \(A_H\) particle, which must be the endpoint of all T-odd particle decays\[112\]. If \(A_H\) is the dominant component of galactic DM, we will generally expect small DD and ID rates for much the same reasons that the signals from the bino LSP tend to be small\[111\]: see, however, Ref.[112] for a different model with large direct detection rate.

8. Outlook

The union of particle physics, astrophysics and cosmology has reached an unprecedented stage. Today we are certain that the bulk of the matter in the universe is non-luminous, not made of any of the known particles, but instead made of one or more new physics particles that do not appear in the SM. And though we know just how much of this unknown dark matter there is, we have no idea what it is. Today, many theoretical speculations which seek to answer one of the most pressing particle physics puzzles, “What is the origin of EWSB and how can we embed this into a unified theory of particle interactions?” automatically also point to a resolution of this 75 year old puzzle as to what the dominant matter component of our universe might be. Particle physicists have made many provocative suggestions for the origin of DM, including supersymmetry and extra spatial dimensions, ideas that will completely change the scientific paradigm if they prove to be right.

The exciting thing is that many of these speculations will be directly tested by a variety of particle physics experiments along with astrophysical and cosmological searches. The Large Hadron Collider, scheduled to commence operation in 2008, will directly study particle interactions at a scale of 1 TeV where new matter states are anticipated to exist for sound theoretical reasons. These new states may well be connected the DM sector, and so in this way the LHC can make crucial contributions to not only particle physics, but also to cosmology.

Any discovery at LHC of new particles at the TeV scale will make a compelling case for the construction of a lepton collider to study the properties of these particles in detail and to elucidate the underlying physics. Complementary to the LHC, there are a variety of searches for signals from relic dark matter particles either locally or dispersed throughout the galactic halo. The truly unprecedented thing about this program is that if our ideas connecting DM and the question of EWSB are correct, measurements of the properties of new particles produced at the LHC (possibly complemented by measurements at an electron-positron linear collider) may allow us to independently infer just how much DM there is in the universe, and quantitatively predict what other searches for DM should find\[113\].

Particle physics, cosmology and astrophysics are rapidly obliterating their boundaries and merging into a single discipline. The ΛCDM model that has emerged posits that 70% of the energy budget of the Universe is contained in so-called dark energy, weird stuff with negative pressure that is completely different from anything that we have ever encountered! Thus, not only are the particles we are made of a small fraction of the total matter content of the Universe, most of the energy of the universe appears to be in non-material dark energy, extending even further the Copernican principle\[114\]. This ΛCDM framework is being incisively probed by observation, and may possibly need modification.

The nature of dark energy is a completely open question. Experiments over the next decade or two will, we expect, reveal the identity of dark matter and, we hope, will provide clues as to the origin of dark energy. This unprecedented synthesis of the physics of both the largest and smallest scales observable in nature should make the next twenty years very exciting!

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\[3\]We note here that it is also possible to construct so-called twin-Higgs models\[113\] where the Higgs sector is stabilized via new particles that couple to the SM Higgs doublet, but are singlets under the SM gauge group. In this case, there would be no obvious new physics signals at the LHC.

\[4\]These studies have only just begun, and have only been carried out in the context of supersymmetry, which unlike extra-dimensional or Little Higgs models, is a complete theory, valid up to very high energy.

\[5\]Our colleagues who subscribe to the multiverse view carry this yet further, suggesting that our Universe is just one of many. Unlike for the ideas discussed here, we are not aware of possible tests for this view.
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