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SUSY

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INTRODUCTION

In modern elementary particle physics, the notion of gauge symmetries is a key concept and underlies all physical theories, since gauge symmetries can be used to create Lagrangians and, consequently, equations of motion. The unification of electromagnetism and weak interaction is realized by means of U(1) $\times$ SU(2) symmetry, and the QCD is described by SU(3) symmetry. To create unified physical theories, i.e., to include Einstein's general theory of relativity in the Standard Model, it is necessary to consider new types of symmetries [1]. Currently, one of the proposed methods of unification is the use of the so-called supersymmetry, the first formulations of which appeared in the late 60's and led to the creation of local supersymmetry (or supergravity) in the late 70's [2]. Supersymmetry (SUSY) is a proposed fundamental theory linking bosons and fermions. Any physical, classical or quantum theory can include supersymmetry. Currently, supersymmetry is used in string theory and quantum field theory to harmonize the Standard Model with Einstein's theory of relativity, and experimentally, collider experiments are searching for the Lightest Supersymmetric Particle (LSP) and other supersymmetric particles. Supersymmetry is one of the most promising theories for extending the Standard Model and may be the key to solving many problems in particle physics and cosmology.

1 STANDARD MODELS PROBLEMS

The discovery of a new scalar particle by the ATLAS and CMS collaborations at the LHC was one of the most important events in particle physics in the last few years. The results obtained are very close to the theoretical predictions for the Higgs boson within the Standard Model (SM). This fact emphasizes the triumph of the SM. However, despite its ability to explain the vast majority of experimental results in particle physics, the SM has a number of serious problems. These include the following experimentally established facts. First, in the SM neutrinos, unlike other fermions, are represented only by left-handed components, and it is impossible to write out a gauge invariant renormalizable mass summand for them. As a result, the lepton number is conserved in the SM and oscillations, i.e., transitions of neutrinos of one flavor to neutrinos of another flavor, are forbidden. Therefore, the observation of neutrino oscillations clearly indicates that the mass of neutrinos is different from zero, which is contrary to the SM predictions. Secondly, the data of precision cosmology indicate the presence in the Universe, in addition to visible baryonic matter, of non baryonic dark matter, which contibutes dominantly in dynamical rules at large-scale. The main reason of presence of the non baryonic dark matter basis on the fact that the density of non relativistic matter provided by cosmic microwave background (CMB) is several times bigger than that for baryonic matter. Another reasons base on the analyzing data on the rotation curves of galaxies and observations of gravitational lensing effects. Thirdly, it is a very curious fact that our world is composed of matter only, and not of matter and antimatter equally, as might be expected. This is confirmed, for example, by the fact that if there were some distant regions in the Universe composed of antimatter, then there would be characteristic radiation from the boundaries of these regions due to annihilation of matter and antimatter, which is not observed in reality. There is no mechanism of generation of the Baryonic Asymmetry of the Universe in the SM. In view of these observations, we are forced to believe that the SM is a part of another, more fundamental theory, which somehow solves the problems described above. At present, a great number of models describing phenomena beyond the SM have been proposed. These include models with extra dimensions, Lorentz symmetry breaking, and many others. One of the most attractive and promising ideas of SM extension are supersymmetric models [3].

2 SUSY

Supersymmetry is a symmetry between bosons and fermions, which arose as a result of the desire to generalize the Poincaré algebra to representations with different spin by introducing so-called graded Lie algebras, i.e., by adding anti-commutators to the usual commutators of the Lorentz algebra. Let Q be the generator of a supersymmetry algebra. Acting on a bosonic state it transforms it into a fermionic state, and vice versa:

$$\overline{Q}|boson >= |fermion > and\ Q|fermion >= |boson >$$

Since bosons commute with each other and fermions anticommute, it follows immediately that supersymmetric generators must also anticommute, i.e., they must be fermionic and change spin by a half-integer and change statistics [4]. To make the Standard Model supersymmetric, it is necessary to introduce a new fermionic partner for each boson and a new bosonic partner for each fermion. Each SM particle and its supersymmetric partner have the same quantum numbers, except for spin. In SUSY, processes with violation of the conservation of lepton and baryon numbers become possible, which leads to the possibility of proton decay. To avoid this, a new type of symmetry (R- parity) is introduced to suppress such processes. R-parity is defined as $R = (-1)^{3(B-L)+2S}$, where S is the spin of the particle and B and L are the baryon and lepton charges. For SM particles R-parity is equal to $+1$, and for supersymmetric particles it is -1 [5].

2.1 MSSM

The Minimum Supersymmetric Standard Model (MSSM) is a supersymmetric extension of the Standard Model with the smallest possible number of new fields. In MSSM every known fundamental particle is a component of a chiral or vector supermultiplet and must have a superpartner with spin $1/2$ different from its own. Only chiral supermultiplets can hold fermions whose left and right components are transformed differently by the gauge group. The scalar superpartners of quarks and leptons are called squarks and sleptons, respectively. The Higgs doublet in the SM is also extended to a chiral supermultiplet by the addition of a Higgsino with spin 1/2. But after breaking the electroweak symmetry it can only give mass to up-type quarks. To give mass to the lower-type quarks and charged leptons, one more Higgs supermultiplet must be introduced. The SM gauge fields extended by fermionic fields with spin 1/2 are called gauginos and form vector supermultiplets, as shown in Figure 1 right [5]. The

Names	spin 0	spin 1/2	Names	spin 1/2	spin 1
squarks, quarks	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	gluino, gluon	$\tilde{g}$	g
(3 x families)	$\tilde{u}_R^*$	$\bar{u}_R$	winos, W bosons	$\tilde{W}^{\pm}\ \tilde{W}^0$	$W^{\pm}\ W^0$
	$\tilde{d}_R^*$	$\bar{d}_R$	bino, B boson	$\tilde{B}^0$	B^0
sleptons, leptons	$(\tilde{\nu}_L, \tilde{e}_L)$	(ν_L, e_L)			
(3 x families)	$\tilde{e}_R^*$	$\bar{e}_R$			
Higgs, Higgsinos	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$			
	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$			

Figure 1: (Left) Chiral multiplets in the MSSM. The particle indices L and R denote the chirality of the SM partner. (Right) Vector multiplets in the MSSM

superpartners of gluons are called gluino, and the superpartners of W- and B-bosons are wino and bino, respectively. It is known from experimental observations that SUSY cannot be an exact symmetry: no "selectron"with mass equals to the electron mass has been found. Therefore, supersymmetry must be spontaneously broken at a higher level, the consequence of which is the presence of mass terms for supersymmetric particles at the electroweak level. Without assumptions about the mechanism of supersymmetry breaking, these mass terms can be treated as independent parameters. Spontaneous breaking of SU(2)L × U(1)Y symmetry leads to significant mixing of third-generation squarks and sleptones because of their large Yukawa couplings. Also binos, vinos and Higgsinos mix to form two charged states, called charginos $\widetilde{\chi}_i^{\pm}$, and four neutral mass-ordered states, called neutralinos $\widetilde{\chi}_j^0$. The Higgs sector of the MSSM consists of one CP-odd (A), two CP-even (h, H) neutral Higgs bosons, and two charged Higgs bosons ($H^{\pm}$). Despite the fact that the sector contains five states, two parameters are sufficient to describe its properties. Although the mass parameters are unknown and can take any value, Higgsinos with masses of $\sim$ 100 GeV, and stop and gluinos on the scale of $\sim$ 1 TeV are predicted [5]. The main reason for the attractiveness of the MSSM model is that it solves the hierarchy problem as discussed in Section 2.4. Another important advantage is the availability of candidate particles for the dark matter role as mentioned in Section 3.1. Usually, the lightest neutralino is chosen as the dark matter particle in MSSM, it is the LSP. Currently, MSSM is one of the main targets of research for experiments at the LHC.

2.2 GRAVITY COUPLING

Unification with gravitation is one of the main arguments in favor of supersymmetry. The general idea is to unify all forces of nature, including quantum gravity. However, the graviton has spin 2, while all other gauge bosons (photon, gluons, W- and Z-bosons) have spin 1. Hence, they belong to different representations of the Poincaré group. In order to unify them, one can use supersymmetry transformations. Starting from the graviton with spin 2 and acting by supersymmetry generators, we obtain the following chain of states [4]:

$$2 \to \frac{3}{2} \to 1 \to \frac{1}{2} \to 0$$

Thus, partial unification of fermions with bosons arises naturally in an attempt to unify gravitation with other interactions. Also in case of a choice of supersymmetry in a local form, the general theory of relativity (theory of gravitation) or supergravity is naturally obtained.

2.3 RUNNING COUPLING CONSTANTS

According to the Grand Unification Theory (GUT), all known interactions are different branches of a unified interaction. The unification of interactions occurs at high energy. The energy dependence of the running coupling constants is described by the renorm-group equations. In SM the running constants of strong and weak interactions decrease with increasing energy, while the electromagnetic running coupling constant increases. Therefore, it is possible that at certain energy they become equal. After processing the data obtained at the LEP [6] and Tevatron [7] accelerators it became possible to check the theory of unification of running constants numerically. The following constants are compared:

$$\alpha_1 = \frac{5\,g'^2}{3\,4\pi} = 5\alpha/(3\cos^2\theta_w) = 0,017$$

$$\alpha_2 = \frac{g^2}{4\pi} = \alpha/(\sin^2\theta_w) = 0,034$$

$$\alpha_3 = \frac{g_s^2}{4\pi} = 0,018,$$

where g' , g, and g_s are the usual coupling constants for the groups U(1), SU(2), and SU(3), respectively, and α is the fine-structure constant. Figure 2 shows

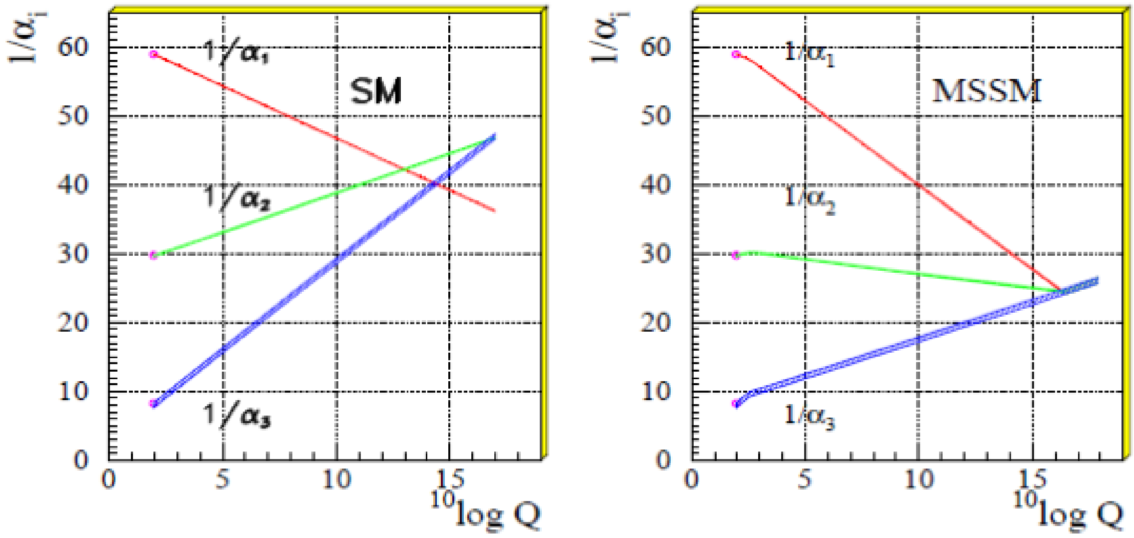


Figure 2: Evolution of the inverse coupling constants in the case of SM (left) and in the case of its supersymmetric extension (MSSM) (right)

the evolution of the inverse coupling constants as functions of the logarithm of the energy where it is clearly seen that in SM unification at a single point is impossible. This is eliminated at the 8σ level. In the case of SUSY the slopes of the curves are modified due to the contribution of supersymmetric particles to the evolution of the coupling constants and the possibility of their unification appears. From the curve fitting we find the supersymmetry breaking point MSUSY and the unification point MGUT:

$$M_{SUSY} = 103,4 \pm 0,9 \pm 0,4$$

$$M_{GUT} = 1015,8 \pm 0,3 \pm 0,1,$$

where the first error follows from the uncertainty in the measurement of the coupling constants and the second from the uncertainty in the mass splitting of supersymmetric particles. This observation was regarded as the first prerequisite for SUSY.

2.4 HIERARCHY PROBLEM

The hierarchy problem is the difference (10^{16}) between scale of masses determining the weak interaction and Planck mass determining the strength of the gravitational interaction. The large value of the Planck mass relative to the weak mass corresponds to the relative weakness of the gravitational interaction, the strength of which is inversely proportional to the Planck mass. If this mass is so large, the gravitational force must be extremely weak. Why is the gravitational force so much weaker than the other fundamental forces we know? According to quantum field theory, which combines quantum mechanics and special relativity, there should be no difference. In fact, quantum field theory states that the mass of the weak interaction and Planck mass constant should be roughly equal. In quantum field theory the Planck mass is important not only because it determines the scale on which gravitation is strong. Among other things, it is the mass at which both gravitation and quantum mechanics are significant and at which physical rules must be violated. In SM radiative corrections must be added to the mass of the light Higgs boson. These corrections destroy the hierarchy unless they are reduced to the nearest 10^{-14}. Such a reduction requires a fine-tuning of the coupling constants. Supersymmetry has a way to obtain a cancelation of quadratic terms (also known as a cancelation of quadratic divergences). Moreover, supersymmetry automatically cancels all quadratic corrections in all directions of perturbation theory. This happens due to the contributions of superpartners of SM particles. There are two types of contributions: the contributions of the heavy Higgs boson and its superpartner, and the contributions of the heavy gauge boson and the heavy calibrino. In both cases there is a reduction of quadratic terms. This is true up to the supersymmetry breaking scale, M_{SUSY} , which should not be too large ($\leq$ 1 TeV) for the fine-tuning to be natural. By requiring for self-consistency of perturbation theory that the radiative corrections to the mass do not exceed the mass itself, one obtains:

$$\delta M_h^2 \sim g^2 M_{SUSY} \sim M_h^2 \tag{2.1}$$

So if $M_h \sim 10^2$ GeV and $g \sim 10^{-1}$, then $M_{SUSY} \sim 10^3$ GeV in order for the relation to be valid. Hence, one can obtain the same estimate of the supersymmetry breaking scale $M_{SUSY} \sim 1$ TeV as from the coupling constants unification condition [4]. Therefore, it is usually said that supersymmetry solves the problem of hierarchies provided that the scale of supesymmetry breaking is within the reach of LHC.

3 SUSY IN COSMOLOGY

3.1 DARK MATTER

The problem of dark matter in the Universe remains one of the most important unsolved problems in astrophysics and cosmology. Based on the Lambda-CDM cosmological model, non-relativistic matter makes up ≈30% of the total density of matter in the Universe, out of which only 5% is baryonic matter, while the rest is a non-luminous form of matter not described by the Standard Model. Evidences of the presence of dark matter are: the study of galaxy rotation curves (the dependence of the rotation rate of galactic objects on the distance to the galaxy center), CMB anisotropy, the problem of the formation of the large-scale structure of the Universe at the observed level of CMB anisotropy, gravitational lensing, and others. The widely discussed candidate for the role of dark matter particles are WIMPs (from WIMP Weakly Interacting Massive Particle). This term is used to refer to a class of particles characterized, first of all, by such values of mass and annihilation cross section that allow frozen-out amount to explain all the obsereved dark matter density. Supersymmetric theories can offer candidates for the role of WIMPs. In the case of conserved R-parity, the LSPs should be stable and hence could have persisted in the Universe since the Big Bang. As candidates for the role of dark matter particles in SUSY can be: neutralino, gravitino, sneutrino.

3.1.1 DIRECT SEARCHES

Several experiments have currently reached the sensitivity to start probing the WIMP paradigm using different target materials and detection principles, including the detection of an annual modulation signal associated with the time variation of the expected DM scattering rate in the detector due to the motion of the Earth relative to the Sun. Three collaborations, namely CRESST [8], CoGeNT [9] and CDMS [10] have also published results compatible with the detection of a small number of candidate signal events, which were not possible to ascribe to any of the considered background sources. There is not a general consensus regarding the interpretation of these results and the picture is further complicated by the detection of a modulation signal made by the DAMA/LIBRA experiment [11]. This finding has been not confirmed by other experiments and its interpretation in terms of dark mass and scattering cross section is in very strong tension with the results of other experiments, in particular of XENON100 [12], which is currently excluding the regions of the plane DM mass versus spin-independent scattering cross section favored by DAMA as well as the low WIMP mass regions favored by CRESST, CoGeNT, and CDMS. A neutralino with a mass close to 10 GeV, as required by these experiments, might be generated by relaxing the assumption of gaugino mass unification [13] while DM isospin violating interactions seem the only possibility to reconcile DAMA with XENON100. In Figure 3 presented the regions in

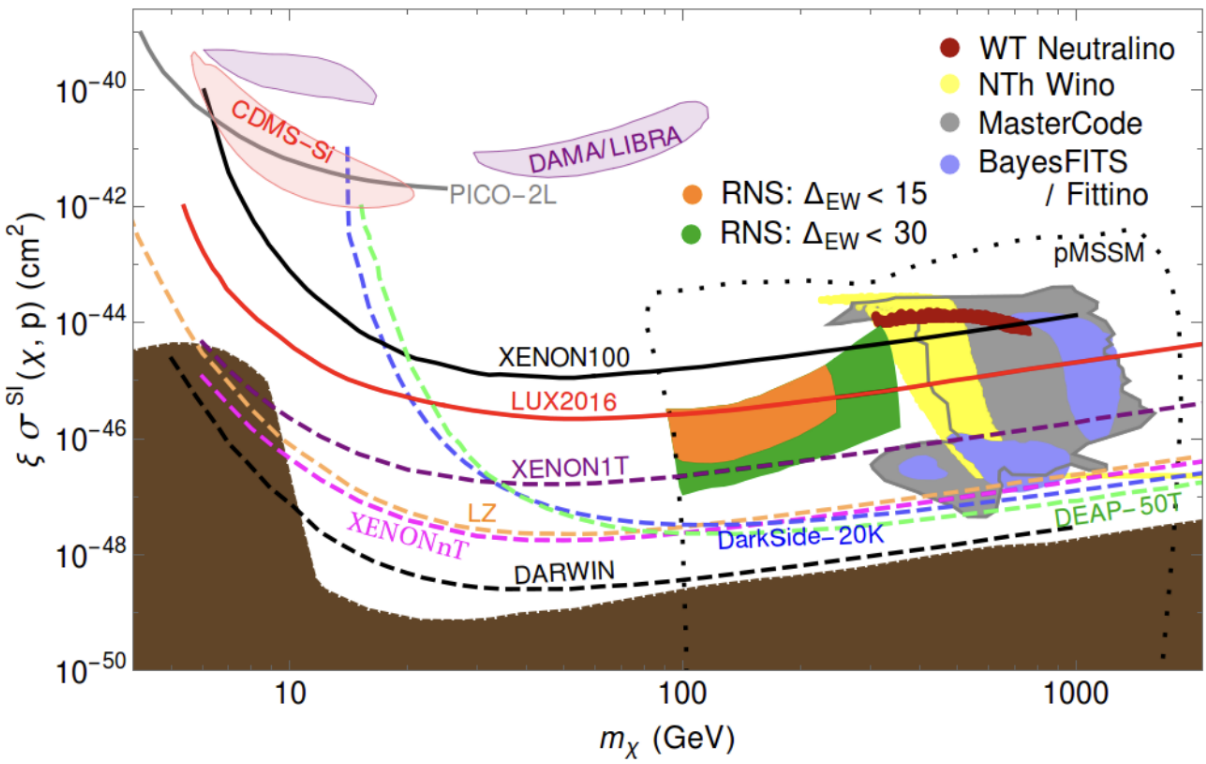


Figure 3: Plot of rescaled spin-independent WIMP detection rate $\xi\sigma^{SI}(\chi,p)$ versus m_χ from several published results versus current and future reach (dashed) of direct WIMP detection experiments

the plane DM mass m_χ versus spin-independent DM-nucleon scattering cross section $\xi\sigma^{SI}(\chi,p)$ favored by several independent analyses. The factor ξ in the y-axis leaved to account for a possible depleted local abundance of WIMPs. For the experimental projections and for all models except RNS and pMSSM, it is assumed that $\xi = 1$ (i.e. it is assumed that WIMPs comprise the totality of DM). The lower brown-shaded region denotes the solar neutrino floor: within this region, WIMP signals would have to contend with a formidable νp scattering background [14]. Several supersymmetric configurations appear already excluded by current direct detection searches. Moreover, the next generation of ton-scale experiments will be able to probe the vast majority of the presently allowed configurations. However, DM candidates with a mass in the 10 GeV (100 GeV) range and spin-independent cross sections smaller than roughly 10^{45} cm^2 (10^{49} cm^2) will be very difficult (if not impossible) to discover even with the next generation of direct detection experiments, since an experiment sensitive to such a low scattering cross sections would also measure the large flux of solar and atmospheric neutrinos which would therefore constitute a copious and irreducible background source [15]. In addition, several experiments are also probing the spin-dependent DM interactions using nuclei with unpaired protons as target materials [16]. The spin-dependent WIMP-nucleon scattering cross section $\xi\sigma^{SD}(\chi,p)$ versus m_χ is shown in Figure 4. These scattering reactions take place via Z and squark exchange. While a variety of underground experiments have developed bounds on σ^{SD}, the best recent bounds come from the IceCube experiment which monitors WIMP annihilation into high energy neutrinos in the solar core. In most cases, the solar annihilation rate reaches equilibration with the solar WIMP capture rate and the latter depends mainly on σ^{SD}. This is because the proton carries spin and there are plenty of protons within the sun to serve as targets for WIMP scattering and capture. The rate is relatively insensitive to σ^{SI} since that rate requires enhancement by the number of nucleons in the nuclei [14].

3.1.2 INDIRECT SEARCHES

Alternatively, DM could be revealed through the observation of SM particles produced in space by DM annihilations or decays. This detection strategy is known as the DM indirect detection technique. WIMPs are expected to

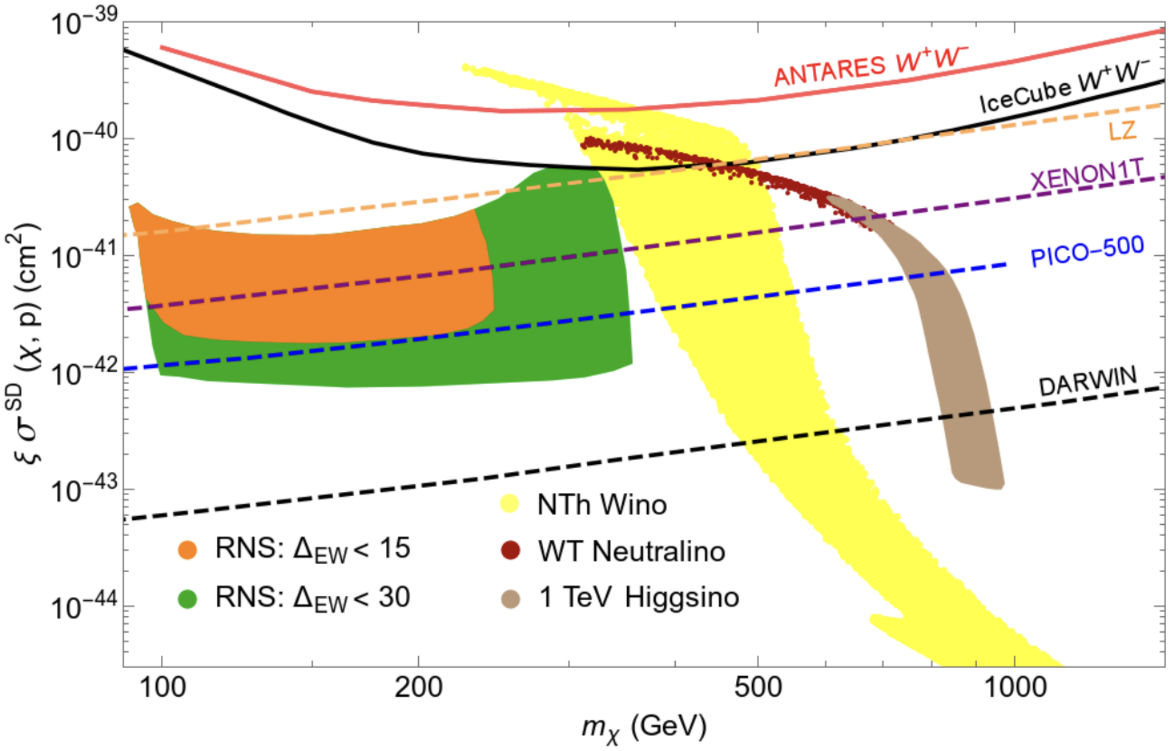


Figure 4: Plot of rescaled spin-dependent WIMP detection rate $\xi\sigma^{SD}(\chi, p)$ versus m_χ from several published results versus current ANTARES and IceCube reach and projected (dashed) LZ, XENON1T, PICO-500 and DARWIN reaches

copiously annihilate in galactic and extragalactic regions where the DM density is large compared to the present mean cosmic density. There are a large assortment of final states that can be searches for including, $\overline{p}$, e^+, $\overline{d}$, γ-line spectra and γ-continuum spectra. Annihilation products of particular interest are γ-rays which provide direct information on the region where the associated annihilations have occurred. In addition, the expected signal rates are highly dependent on the assumed dark matter density distribution. The portrait of theory versus experiment is usually presented in the thermally averaged cross section times velocity (in the limit as $\upsilon \to 0$) $\langle\sigma\upsilon\rangle$ versus m_χ plane. There were selected $\chi_1\chi_1 \to W^+W^- \to \gamma$ continuum limits since most of the SUSY models in consideration have this dominant annihilation channel. The plane plot is shown in Figure 5 [14]. There ploted the recent combined Fermi-LAT+MAGIC limits found from examining continuum gamma ray spectra from the dwarf spheroidal galaxy Segue I [17]. In addition, there are ploted the updated 10 years/254 hours of HESS search for continuum gamma rays [18] and also shown a projected

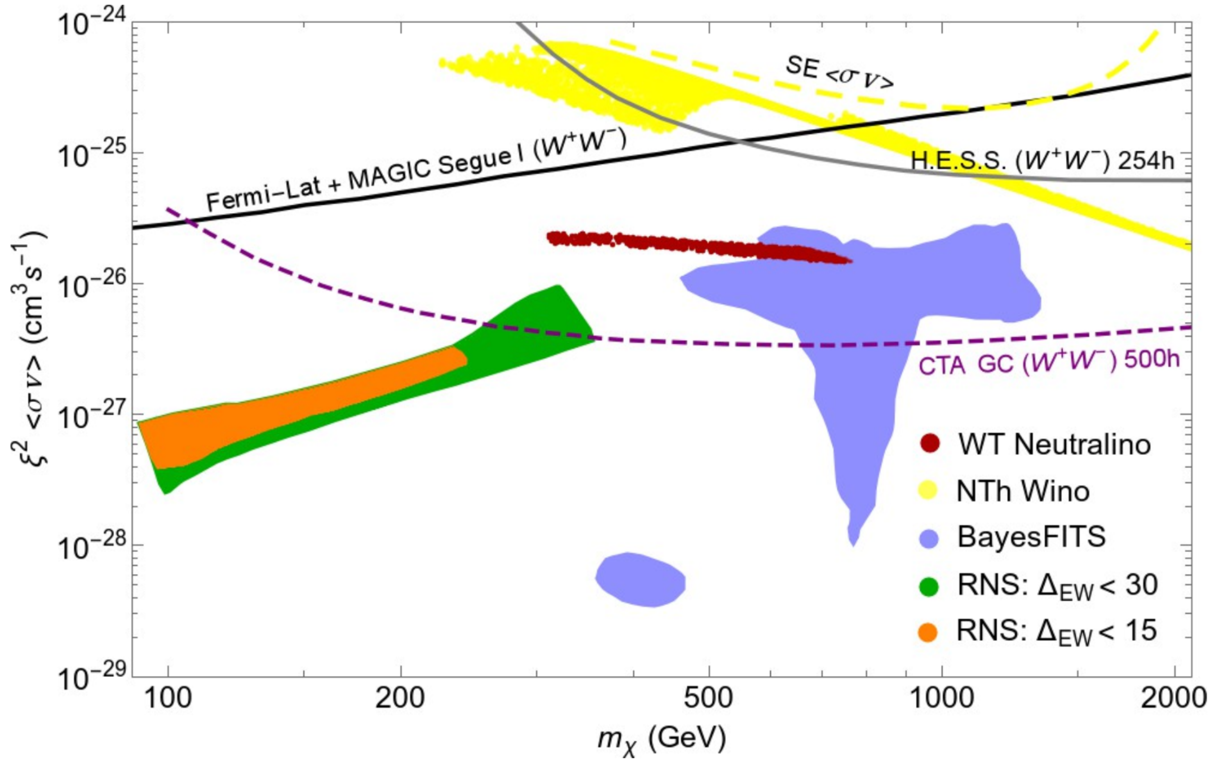


Figure 5: Plot of rescaled thermally-averaged WIMP annihilation cross section times velocity $\xi^2\langle\sigma v\rangle$ versus m_χ from several published results along with current Fermi-LAT/MAGIC combined reach via W^+W^- channel and projected (dashed) CTA reach

gamma ray reach of the CTA collaboration assuming 500 hours of observation.

3.2 BARYOSYNTHESIS

It is well known that baryonic asymmetry is observed in the Universe, the basis of which is the absence of antimatter on macroscales up to the scale of galaxy clusters. The problem generation of baryonic charge was first considered by A.D. Sakharov [19], who suggested that in the early Universe baryonic excess could arise as a result of $p\overline{p}$ - annihilation, baryosynthesis. The necessary conditions for the emergence of baryonic asymmetry from initially charge-symmetric matter in the hot Universe are then as follows: 1) non-conservation of the baryonic charge; 2) violation of C- and CP-invariance; 3) deviation from thermal equilibrium, and also, the value of B - L must be conserved [20]. SUSY provides possibilities of electrically weak phase transition of the first kind, which ensures fulfillment of condition (3), and also includes numerous new sources of

CP - violations.

During primordial inflation [21], all scalar fields with a shallow potential can acquire non-zero vacuum expectation values (VEVs). Supersymmetric extensions of the SM include plenty of such scalar fields, called flat directions, along which the scalar potential identically vanishes in the limit of exact SUSY. An important example is flat directions of the MSSM, which comprise the scalar partners: squark, slepton and Higgs fields.

Affleck and Dine proposed a novel scenario for generating baryon asymmetry of the universe that utilizes supersymmetric flat directions [22]. According to this scenario, a condensate forms along the flat direction during the inflationary epoch. The non-zero VEV of the condensate spontaneously breaks C and CP. As a result, during the post-inflationary evolution, baryon number violating operators (which are induced by new physics at a high scale) result in a rotating trajectory for the VEV. If the flat direction has a non-zero baryon number B, the rotating condensate carries a baryon asymmetry. This asymmetry is transferred to ordinary particles when the condensate decays to fermions [23].

3.3 INFLATION

Inflation is one of the most motivated scenarios for the early Universe, which is consistent with the recent observations of the CMB anisotropies [24]. Although inflation was originally introduced to solve the horizon, flatness, monopole problems, and so on, it can also give an explanation to the origin of primordial density fluctuations, which are responsible for the large scale structure of the present Universe. The main idea of the Universe inflation model is that in the early Universe there was a form of matter that created "anti-gravity"forcing the Universe to expand with acceleration > 0. This model assumes the existence of a scalar field, the inflaton, wich potential energy responsible for the expansion of the Universe. Such a potential must be relatively flat in order to guarantee long duration of inflation and small deviation of scale invariance of primordial density fluctuations. However, many of the surviving models suffer from being sensitive to possible Ultra-Violet (UV) physics. If not protected by symmetry, generic corrections to the potential can provide an $O(1)$ contribution to the slow-roll parameter η spoiling the predictions required for a successful inflation. This is known as the η-problem [25], and is a theoretical challenge facing any inflationary model. SUSY may be naturally combined with inflation since it govern the dynamics of the early Universe, when high energy physics was important [26]. In particular, according to the Lyth bound [27], low values of the tensor-to-scalar ratio r imply that the scale of inflation should be less than the Planck scale, and SUSY provides a mechanism for maintaining a hierarchy of scales without fine-tuning. The first implementations of supersymmetric models of inflation considered only global SUSY. But since the dynamics of inflation occur at early stages of the history of the Universe and is sensitive to UV scales, it is necessary to also consider local SUSY or supergravity (SUGRA). In SUGRA the so-called F-term scalar potential is sensitive to the shape of the Kähler potential, and this can lead to the reemergence of the η-problem in the presence of quadratic contributions to the Kähler potential. One solution to this problem is no-scale SUGRA [28], where the Kähler potential takes a logarithmic form and circumvents the above problem. No-scale SUGRA models are so-called because the scale at which SUSY is broken is undetermined in the first approximation, and the scale of the effective potential responsible for inflation can be naturally much smaller than the Planck scale, as required. Alternatives to no-scale SUGRA have also been proposed, for example using a non-compact Heisenberg symmetry [29] or a shift symmetry [30]. Different SUSY models propose different candidates for inflaton such as sneutrinos and combinations of Higgs bosons.

4 EXPERIMENTAL SEARCH FOR SUSY

In most SUSY models, R-parity is assumed to be conserved. This has two essential consequences. If R-parity is conserved, then supersymmetric particles are born only in pairs. Example of cross sections as a function of the particle

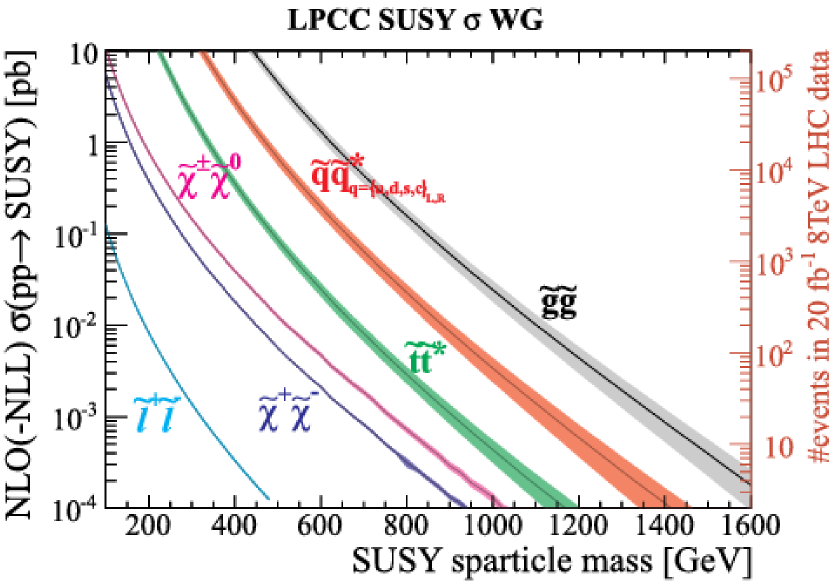


Figure 6: Cross sections of selected supersymmetric processes at the LHC

mass is shown in Figure 6 [31]. For a given mass scale, the dominant process is the birth of gluino pairs, followed by the birth of squarks, sneutrons, and sneutrinos. In addition to the exclusion of the baryon number violation another important consequence of R-parity conservation is the stability of the LSP. This, in turn, means that for every supersymmetric particle born in a collision there will be one LSP at the end of the chain of decays. Weakly interacting LSPs behave like neutrinos and lead to a momentum imbalance called "missing transverse momentum". Over the past decades significant p_T^{mis} has been considered as the most sensitive observable parameter for detecting the birth and decay of supersymmetric particles at colliders. The SUSY phenomenology and hence the expected signatures in the detector are determined by the nature of the LSP, which, in turn, depends on the underlying SUSY violation mechanism. For example, in minimal supergravity models, the LSP is the lightest neutralino $\widetilde{\chi}_1^0$, and in the GMSB (Gauge-Mediated Supersymmetry Breaking) model the LSP is a nearly massless gravitino. Although the various existing SUSY models are an important guide for constructing searches with high discovery potential, they are known to cover a relatively small region of the SUSY parameter space. Therefore, the ATLAS and CMS collaborations have extended the investigated phenomenologies including scenarios predicted by the "simplified models"MSSM or pMSSM. Study of supersymmetric models at accelerators implies first of all detection of superpartner particles and observation and study of various phenomena that are explained in particular by supersymmetric SM expansions. However, many SM processes lead to final states similar to those predicted by SUSY and thus represent a background that needs to be carefully isolated. Figure 7 below shows diagrams of the gluino decays selected for the search [5].

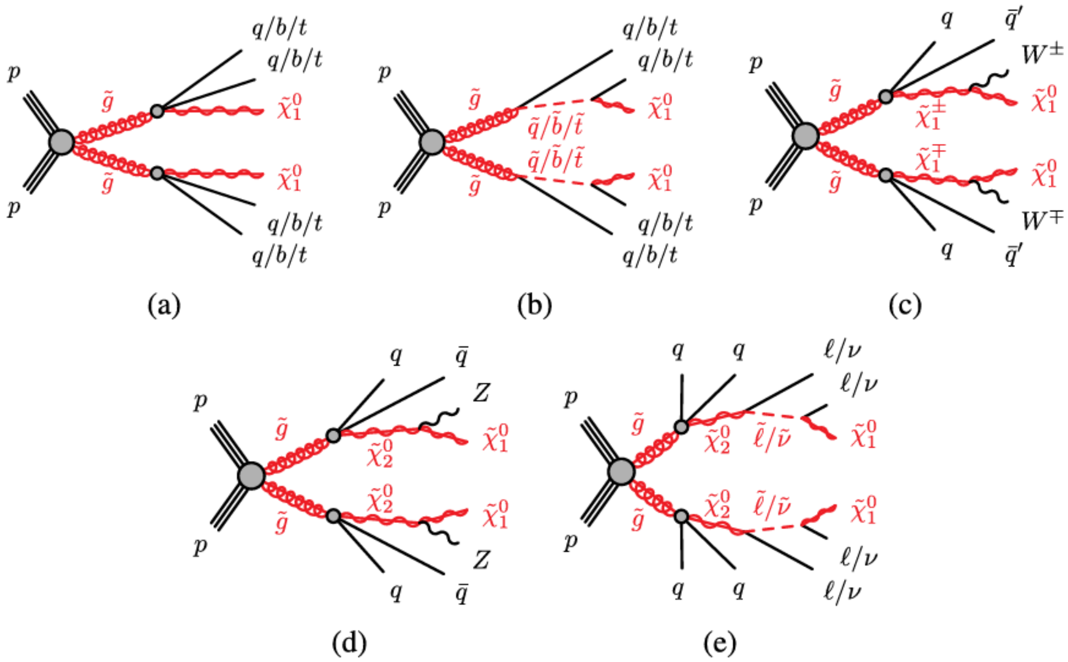


Figure 7: Selected decays of gluino, conserving R-parity, under different assumptions about the SUSY spectrum: (a) gluino mass is smaller than quark mass, which leads to decay via virtual quarks (if quark mass is a few hundred GeV larger than gluino mass, this mode is reduced); (b) gluino is heavier than squarks; (c, d, e) electroweakinos and slaptones are lighter than gluino

Optimal sensitivity to the different SUSY spectra is achieved by further classifying candidate events according to the number of b-strings, W-/Z-/H-bosons, top quarks, and the number, charge, and flavor of leptons. No significant deviations from the SM were observed in the data collected by the ATLAS and CMS detectors. The results of the searches were interpreted within simplified models of the different production and decay modes and are summarized in Figure 8. Figure 8 on the left offers a summary of all combined gluino searches

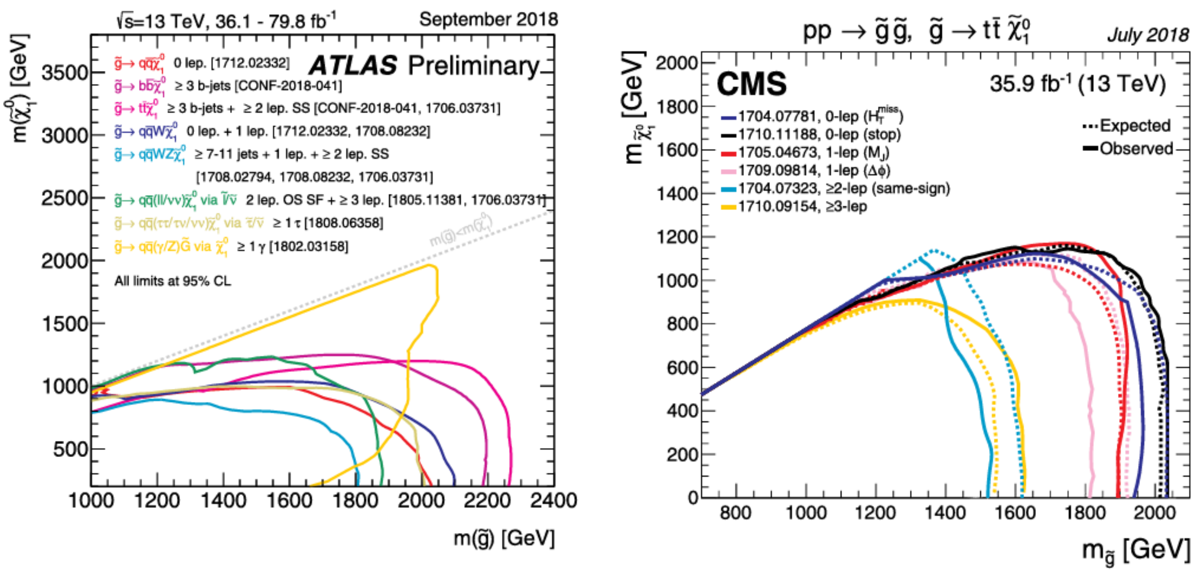


Figure 8: (a) mass limits established in the ATLAS experiment studies for different simplified models. (b) mass limits established in the CMS experiment studies

performed at ATLAS, Figure 8 on the right compares the sensitivities of the different CMS analyses targeting gluino decay via scalar top quarks. In all cases, gluino with mass less than $\sim$ 2 TeV for $\widetilde{\chi}_1^0$ masses less than $\sim$ 1 TeV are excluded with a 95% credible probability. In SUSY violation scenarios where the LSP is a nearly massless gravitino (e.g., GMSB), $\widetilde{g}$-pair production can lead to final states with two high-energy photons together with jets and a large missing transverse momentum p_T^{mis}. However, in the processes involving gravitino there is a challenge for the colliders searches for SUSY: particles next order to the LSP appear to be long-living and hence at the conditions of accelerator experiments they look like stable. Another direction in the search for supersymmetric particles is the search for stops. It is assumed that the lightest stop may have a mass of the same order of magnitude as the mass of the top quark. This search faces a number of experimental problems: for a given stop mass the cross section of stop-pair production is much smaller than that of gluino production; because of the expected small stop masses the SM particles resulting from decay introduce a significant background into the measurements. Birth of stop-pairs are usually characterized by a large missing transverse momentum p_T^{mis} from two LSPs and the presence of two b-jets. These two criteria are common and basic in searches for various supersymmetric particles. Figure 9 shows the decay channels selected for the stop search. The

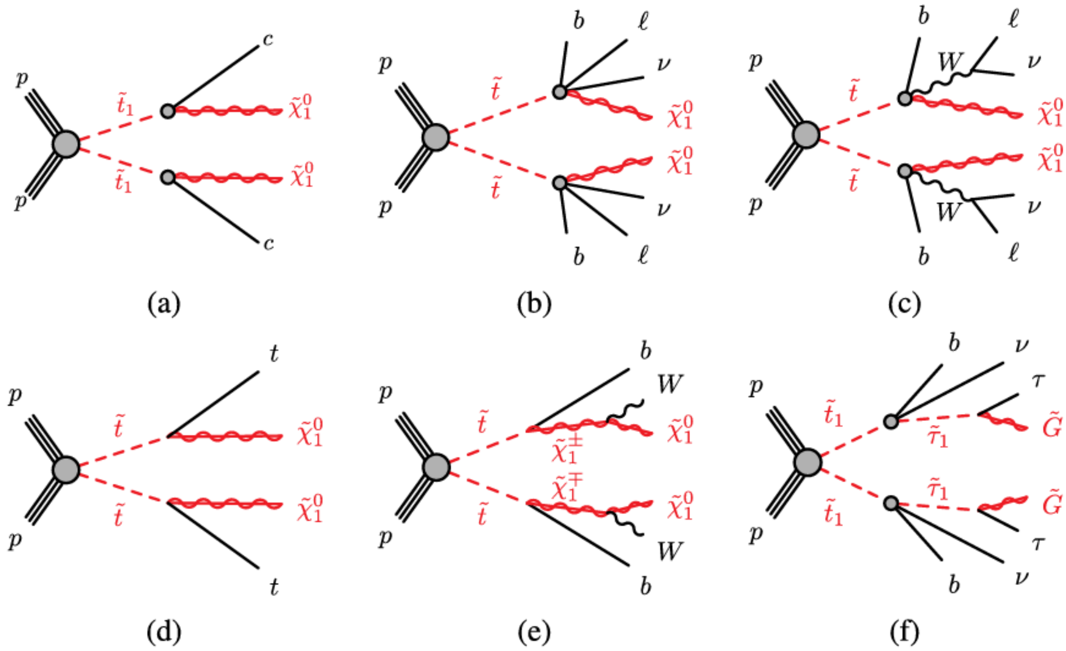
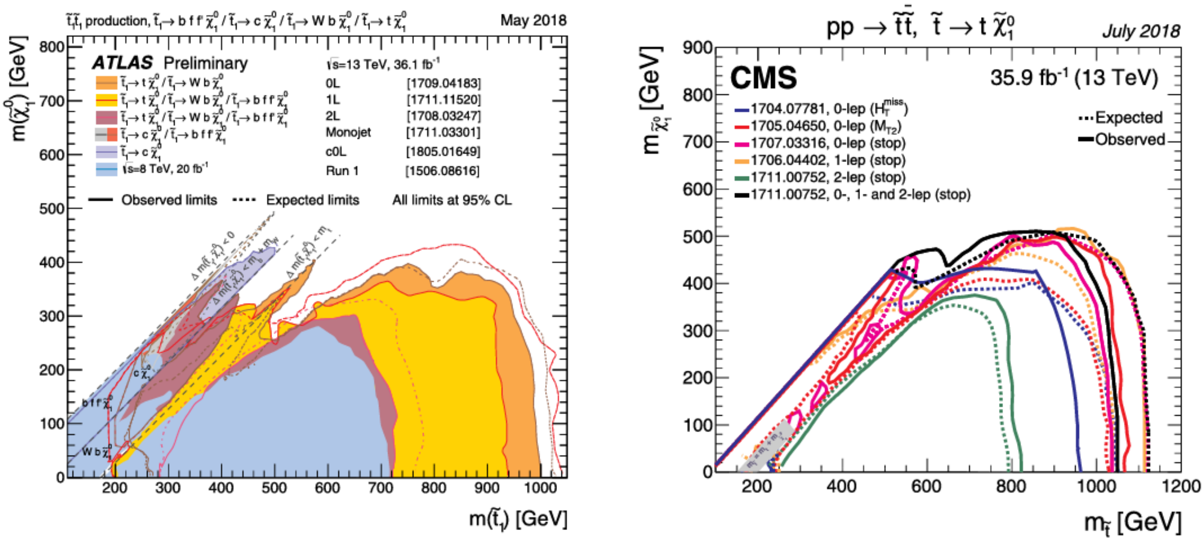


Figure 9: Selected decay modes for $\widetilde{t}$ under the assumption of $\widetilde{\chi}_1^0$ and $\widetilde{G}$ as a LSP.

mass limits established by the ATLAS and CMS searches are presented in Figure 10.



(a) (b)

Figure 10: (a) mass limits set in the $\widetilde{t}$ studies of the ATLAS experiment for different simplified models. (b) mass limits established in the $\widetilde{t}$ studies of the CMS experiment

These results show that the LHC experiments exclude the existence of stops lighter than 1 TeV in the decay of $\widetilde{t}$ to top quark and $\widetilde{\chi}_1^0$ with masses smaller than 400 GeV at the LHC. The LHC is also used to search for long-lived supersymmetric particles [5]. At present supersymmetric particles have not been discovered, nevertheless for many of them strict mass constraints are obtained.

CONCLUSION

Supersymmetry is one of the most promising theories for extending the Standard Model due to its natural explanation of many key questions, such as the hierarchy problem, inflation, and baryosynthesis due to the the Affleck-Dine mechanism. SUSY also proposes several candidates for the role of dark matter: neutralino, gravitino, and sneutrino. Thanks to proton-proton collisions at 13 TeV, the LHC allows the ATLAS and CMS experiments to explore the energy frontier. Supersymmetry has been considered the most promising theory for the past 60 years, combining cosmological and physical arguments and prompting searches in the data collected to date. Hundreds of searches have been conducted, expanding our understanding of nature. The results of direct searches for supersymmetric particles show that the LHC has eliminated the existence of gluinos below 2 TeV, and stops and gauginos up to 1 TeV. These constraints demonstrate the great potential of the collider experiments. However, they are generally obtained in optimistic scenarios where supersymmetric particles decay into the final state. In fact, SUSY may be hiding at lower mass scales as a result of complex mass spectra and mixed modes of decays. Thus, the question of the possible existence of supersymmetry remains open, and the search for supersymmetric partners is still one of the most important tasks of modern experimental physics.

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