90. Supersymmetry, Part II (Experiment)

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90.1 Introduction

Supersymmetry (SUSY), a transformation relating fermions to bosons and vice versa [1–9] is one of the most compelling possible extensions of the Standard Model of particle physics (SM).

On theoretical grounds SUSY is motivated as a generalization of space-time symmetries. A low-energy realization of SUSY, *i.e.*, SUSY at the TeV scale, is, however, not a necessary consequence. Instead, low-energy SUSY is motivated by the possible cancellation of quadratic divergences in radiative corrections to the Higgs boson mass [10–15]. Furthermore, it is intriguing that a weakly interacting, (meta)stable supersymmetric particle might make up some or all of the dark matter in the universe [16–18]. In addition, SUSY predicts that gauge couplings, as measured experimentally at the electroweak scale, unify at an energy scale $\mathcal{O}(10^{16})$ GeV ("GUT scale") near the Planck scale [19–24].

In the minimal supersymmetric extension to the Standard Model, the so called MSSM [11,25,26], a supersymmetry transformation relates every chiral fermion and gauge boson in the SM to a supersymmetric partner with half a unit of spin difference, but otherwise with the same properties (such as mass) and quantum numbers. These are the "sfermions": squarks ($\tilde{q}$) and sleptons ($\tilde{\ell}$, $\tilde{\nu}$), and the "gauginos". The MSSM Higgs sector contains two doublets, for up-type quarks and for down-type quarks and charged leptons respectively. After electroweak symmetry breaking, five Higgs bosons arise, of which two are charged. The supersymmetric partners of the Higgs doublets are known as "higgsinos." The weak gauginos and higgsinos mix, giving rise to charged mass eigenstates called "charginos" ($\tilde{\chi}^{\pm}$), and neutral mass eigenstates called "neutralinos" ($\tilde{\chi}^{0}$). The SUSY partners of the gluons are known as "gluinos" ($\tilde{g}$). The fact that such particles are not yet observed leads to the conclusion that, if supersymmetry is realized, it is a broken symmetry. A description of SUSY in the form of an effective Lagrangian with only "soft" SUSY breaking terms and SUSY masses at the TeV scale maintains the cancellation of quadratic divergences of soft SUSY breaking scalar mass squared parameters.

The phenomenology of SUSY is to a large extent determined by the SUSY breaking mechanism and the SUSY breaking scale. This determines the SUSY particle masses, the mass hierarchy, the field contents of physical particles, and their decay modes. In addition, phenomenology crucially depends on whether the multiplicative quantum number of R-parity [26], $R = (-1)^{3(B-L)+2S}$, where B and L are baryon and lepton numbers and S is the spin, is conserved or violated. If R-parity is conserved, SUSY particles (sparticles), which have odd R-parity, are produced in pairs and the decays of each SUSY particle must involve an odd number of lighter SUSY particles. The lightest SUSY particle (LSP) is then stable and often assumed to be a weakly interacting massive particle (WIMP). If R-parity is violated, new terms λ_{ijk}, λ'_{ijk} and λ''_{ijk} appear in the superpotential, where ijk are generation indices; λ-type couplings appear between lepton superfields only, λ''-type are between quark superfields only, and λ'-type couplings connect the two. R-parity violation implies lepton and/or baryon number violation. More details of the theoretical framework of SUSY are discussed elsewhere in this volume [27].

Today, low-energy data from flavor physics experiments, high-precision electroweak observables as well as astrophysical data impose strong constraints on the allowed SUSY parameter space. Recent examples of such data include measurements of the rare B-meson decay $B_s \to \mu^+\mu^-$ [28,29], measurements of the anomalous magnetic moment of the muon [30], and accurate determinations of the cosmological dark matter relic density constraint [31,32].

These indirect constraints are often more sensitive to higher SUSY mass scales than experiments searching for direct sparticle production at colliders, but the interpretation of these results is often strongly model dependent. In contrast, direct searches for sparticle production at collider experiments are less subject to interpretation ambiguities and therefore they play a crucial role in the search for SUSY.

The discovery of a Higgs boson with a mass around 125 GeV imposes constraints on SUSY models, which are discussed elsewhere [27,33].

In this review we limit ourselves to direct searches, covering data analyses at LEP, HERA, the Tevatron and the LHC, with emphasis on the latter. For more details on LEP and Tevatron constraints, see earlier PDG reviews [34].

90.2 Experimental search program

The electron-positron collider LEP was operational at CERN between 1989 and 2000. In the initial phase, center-of-mass energies around the Z-peak were probed, but after 1995 the LEP experiments collected a significant amount of luminosity at higher center-of-mass energies, some 235 pb^{-1} per experiment at $\sqrt{s} \geq 204$ GeV, with a maximum $\sqrt{s}$ of 209 GeV.

Searches for new physics at e^+e^- colliders benefit from the clean experimental environment and the fact that momentum balance can be measured not only in the plane transverse to the beam, but also in the direction along the beam (up to the beam pipe holes), defined as the longitudinal direction. Searches at LEP are dominated by the data samples taken at the highest center-of-mass energies.

Constraints on SUSY have been set by the CDF and D0 experiments at the Tevatron, a proton-antiproton collider at a center-of-mass energy of up to 1.96 TeV. CDF and D0 collected integrated luminosities between 10 and 11 fb^{-1} each up to the end of collider operations in 2011.

The electron-proton collider HERA provided collisions to the H1 and ZEUS experiments between 1992 and 2007, at a center-of-mass energy up to 318 GeV. A total integrated luminosity of approximately 0.5 fb^{-1} was collected by each experiment. Since at HERA baryons collide with leptons, SUSY searches at HERA typically look for R-parity violating production of single SUSY particles.

The Large Hadron Collider (LHC) at CERN started proton-proton operation at a center-of-mass energy of 7 TeV in 2010. By the end of 2011 the experiments ATLAS and CMS had collected about 5 fb^{-1} of integrated luminosity each, and the LHCb experiment had collected approximately 1 fb^{-1}. In 2012, the LHC operated at a center-of-mass energy of 8 TeV, and ATLAS and CMS collected approximately 20 fb^{-1} each, whereas LHCb collected 2 fb^{-1}. In 2015, the LHC started Run 2, with a center-of-mass energy of 13 TeV. At the end of Run 2 in November 2018, ATLAS and CMS had both collected approximately 140 fb^{-1}, and LHCb had collected almost 6 fb^{-1}.

Proton-(anti)proton colliders produce interactions at higher center-of-mass energies than those available at LEP, and cross sections of QCD-mediated processes are larger, which is reflected in the higher sensitivity for SUSY particles carrying color charge: squarks and gluinos. Large background contributions from Standard Model processes, however, pose challenges to the trigger and analysis. Such backgrounds are dominated by multijet production processes, including, particularly at the LHC, those of top quark production, as well as jet production in association with vector bosons. The proton momentum is shared between its parton constituents, and in each collision only a fraction of the total center-of-mass energy is available in the hard parton-parton scattering. Since the parton momenta in the longitudinal direction are not known on an event-by-event basis, use of momentum conservation constraints in an analysis is restricted to the transverse plane, leading to the definition of transverse variables, such as the missing transverse momentum, and the transverse mass. Proton-proton collisions at the LHC differ from proton-antiproton collisions at the Tevatron in the sense that there are no valence anti-quarks in the proton, and that gluon-initiated processes play a more dominant role. The increased center-of-mass energy of the LHC compared to the Tevatron, as well as the increase at the LHC between Run 1 and Run 2, significantly extends the kinematic reach for SUSY searches. This is reflected foremost in the sensitivity for squarks and gluinos, but also for other SUSY particles.

The main production mechanisms of massive colored sparticles at hadron colliders are squark-squark, squark-gluino and gluino-gluino production; when "squark" is used "antisquark" is also implied. Assuming R-parity conservation, the typical SUSY search signature at hadron colliders contains high-p_{T} jets, which are produced in the decay chains of heavy squarks and gluinos, and significant missing momentum originating from the two LSPs produced at the end of the decay chain, which escape experimental detection. Standard Model backgrounds with missing transverse momentum include leptonic W/Z-boson decays, heavy-flavor decays to neutrinos, and multijet events that may be affected by instrumental effects such as jet mismeasurement.

Selection variables designed to separate the SUSY signal from the Standard Model backgrounds include H_{T}, $E_{\mathrm{T}}^{\mathrm{miss}}$, and m_{eff}. The quantities H_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$ refer to the measured transverse energy and the missing transverse momentum in the event, respectively. They are usually defined as the scalar sum of the transverse jet momenta or calorimeter clusters transverse energies measured in the event (H_{T}), or the magnitude ($E_{\mathrm{T}}^{\mathrm{miss}}$) of the negative vector sum of transverse momenta of reconstructed objects like jets and leptons in the event ($\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$). The quantity m_{eff} is referred to as the effective mass of the event and is defined as $m_{\mathrm{eff}} = H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$. The peak of the m_{eff} distribution for SUSY signal events correlates with the SUSY mass scale, in particular with the mass difference between the primary produced SUSY particle and the LSP [35], whereas the Standard Model backgrounds dominate at low m_{eff}. Additional reduction of multijet backgrounds can be achieved by demanding isolated leptons or photons in the final states; in such events the lepton or photon transverse momentum may be added to H_{T} or m_{eff} for further signal-background separation.

At the LHC, alternative approaches have been developed to increase the sensitivity to pair production of heavy sparticles with TeV-scale masses focusing on the kinematics of their decays, and to further suppress the background from multijet production. Prominent examples of these new approaches are searches using the α_{T} [36–40], *razor* [41], *stransverse mass* (m_{T2}) [42], and *contransverse mass* (m_{CT}) [43] variables. Recently, the topological event reconstruction methods have expanded with the *super-razor* [44] and *recursive jigsaw reconstruction* [45] techniques. Furthermore, frequently the searches for massive SUSY particles attempt to identify their decay into top quarks or vector bosons, which are themselves unstable. If these are produced with a significant boost, jets from their decay will typically overlap, and such topologies are searched for with *jet-substructure* [46] techniques.

90.3 Interpretation of results

Since the mechanism by which SUSY is broken is unknown, a general approach to SUSY via the most general soft SUSY breaking Lagrangian adds a significant number of new free parameters. For the minimal supersymmetric standard model, MSSM, *i.e.*, the model with the minimal particle content, these comprise 105 new real degrees of freedom. A phenomenological analysis of SUSY searches leaving all these parameters free is not feasible. For the practical interpretation of SUSY searches at colliders several approaches are taken to reduce the number of free parameters.

One approach is to assume a SUSY breaking mechanism and lower the number of free parameters through the assumption of additional constraints. Before the start of the LHC, interpretations of experimental results were predominately performed in constrained models of gravity mediated [50, 51], gauge-mediated [52–54], and anomaly mediated [55, 56] SUSY breaking. The most popular model was the constrained MSSM (CMSSM) [50, 57, 58], which in the literature is also referred to as minimal supergravity, or MSUGRA.

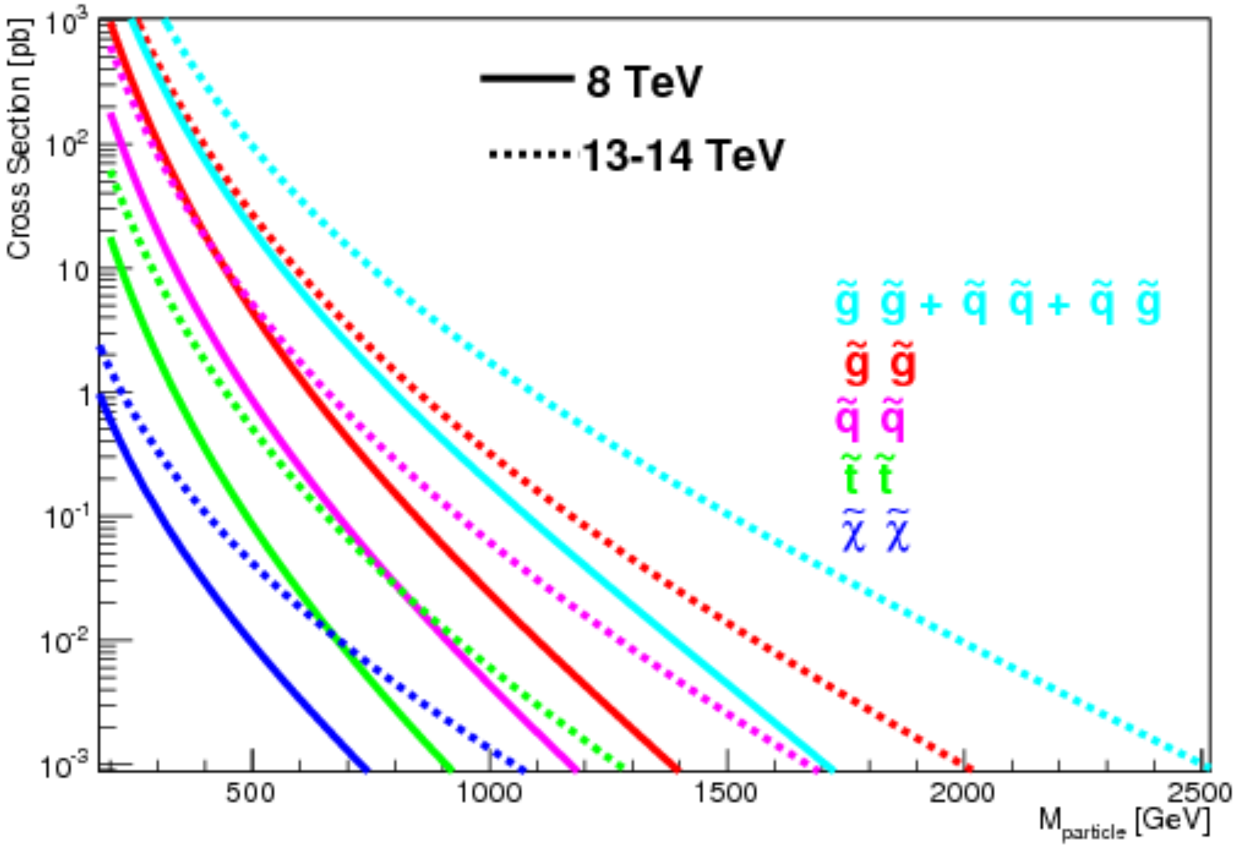

Figure 90.1: Cross sections for pair production of different sparticles as a function of their mass at the LHC for a center-of-mass energy of 8 TeV (solid curves) and 13-14 TeV (dotted curves), taken from Ref. [47]. Typically the production cross section of colored squarks and gluinos, calculated with NLL-FAST [48] at $\sqrt{s}$ =8 and 13 TeV, is several orders of magnitude larger than the one for electroweak gauginos, calculated with Prospino [49] at $\sqrt{s}$ =8 and 14 TeV for higgsino-like neutralinos. Except for the explicitly shown pair production of stops, production cross sections for squarks assumes mass degeneracy of left- and right-handed u, d, s, c and b squarks.

These constrained SUSY models are theoretically well motivated and provide a rich spectrum of experimental signatures. However, with universality relations imposed on the soft SUSY breaking parameters, they do not cover all possible kinematic signatures and mass relations of SUSY. In such scenarios the squarks are often nearly degenerate in mass, in particular for the first and second generation. The exclusion of parameter space in the CMSSM and in CMSSM-inspired models is mainly driven by first and second generation squark production together with gluino production. As shown in Fig. 90.1 [47–49] these processes possess the largest production cross sections in proton-proton collisions, and thus the LHC searches typically provide the tightest mass limits on these colored sparticles. This, however, implies that the allowed parameter space of constrained SUSY models today has been restrained significantly by searches from ATLAS and CMS. Furthermore, confronting the remaining allowed parameter space with other collider and non-collider measurements, which are directly or indirectly sensitive to contributions from SUSY, the overall compatibility of these models with all data is significantly worse than in the pre-LHC era (see section II.8 for further discussion), indicating that very constrained models like the CMSSM are no longer good benchmark scenarios to solely characterize the results of SUSY searches at the

LHC.

For these reasons, an effort has been made to complement the traditional constrained models with more flexible approaches.

One approach to study a broader and more comprehensive subset of the MSSM is via the phenomenological-MSSM, or pMSSM [59–61]. It is derived from the MSSM, using experimental data to eliminate parameters that are free in principle but have already been highly constrained by measurements of *e.g.*, flavor mixing and CP-violation. This effective approach reduces the number of free parameters in the MSSM to typically 19 or even less, making it a practical compromise between the full MSSM and highly constrained models such as the CMSSM.

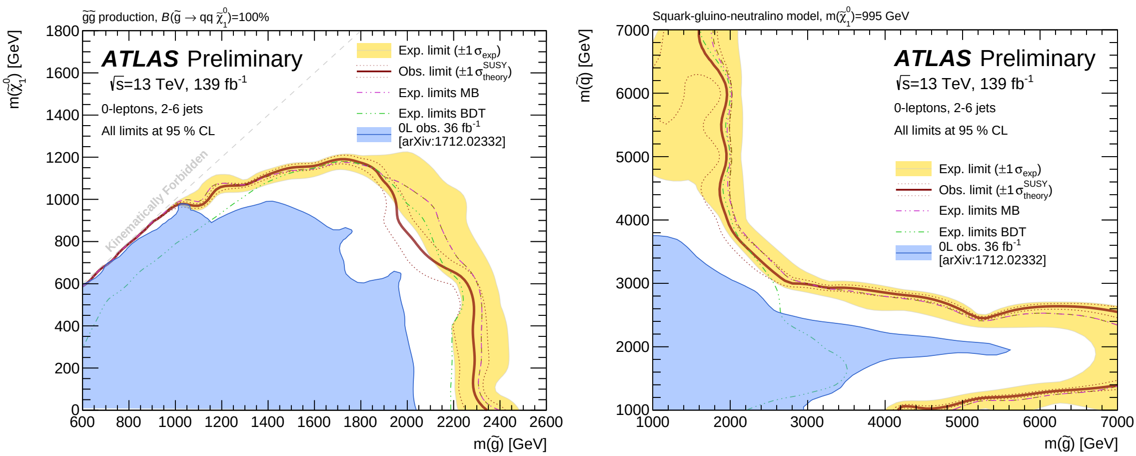

Figure 90.2: Left: lower mass limits, at 95% C.L., on gluino pair production and decay in a simplified model with $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$. Right: 95% C.L. mass limits on gluinos and squarks assuming gluino and squark production, and $m_{\tilde{\chi}_1^0} = 995$ GeV. Results of the ATLAS collaboration.

Even less dependent on fundamental assumptions are interpretations in terms of so-called simplified models [62–65]. Such models assume a limited set of SUSY particle production and decay modes and leave open the possibility to vary masses and other parameters freely. Therefore, simplified models enable comprehensive studies of individual SUSY topologies, and are useful for optimization of the experimental searches over a wide parameter space without limitations on fundamental kinematic properties such as masses, production cross sections, and decay modes.

As a consequence, ATLAS and CMS have adopted simplified models as the primary framework to provide interpretations of their searches. In addition to using simplified models that describe prompt decays of SUSY particles, the experiments are now also focusing more on the use of simplified models that allow for decays of long-lived SUSY particles as they can arise in different SUSY scenarios (see Section 90.7 for further discussion). Today, almost every individual search provides interpretations of their results in one or even several simplified models that are characteristic of SUSY topologies probed by the analysis.

However, while these models are very convenient for the interpretation of individual SUSY production and decay topologies, care must be taken when applying these limits to more complex SUSY spectra. Therefore, in practice, simplified model limits are often used as an approximation of the constraints that can be placed on sparticle masses in more complex SUSY spectra. Yet, depending on the assumed SUSY spectrum, the sparticle of interest, and the considered simplified model limit, this approximation can lead to a significant mistake, typically an overestimation, in the assumed constraint on the sparticle mass (see for example [66]). Only on a case-by-case basis can it be determined whether the limit of a given simplified model represents a good approximation of the true underlying constraint that can be applied on a sparticle mass in a complex SUSY spectrum. In the following, we will point out explicitly the assumptions that have entered the limits when quoting interpretations from simplified models.

This review covers results up to September 2019 and since none of the searches performed so far have shown significant excess above the SM background prediction, the interpretation of the presented results are exclusion limits on SUSY parameter space. Unless stated differently, all quoted exclusion limits are at 95% confidence level.

90.4 Exclusion limits on gluino and squark masses

Gluinos and squarks are the SUSY partners of gluons and quarks, and thus carry color charge. Limits on squark masses of the order 100 GeV have been set by the LEP experiments [67], in the decay to quark plus neutralino, and for a mass difference between squark and quark plus neutralino of typically at least a few GeV. However, due to the colored production of these particles at hadron colliders (see e.g. Fig. 90.1), hadron collider experiments are able to set much tighter mass limits.

Pair production of these massive colored sparticles at hadron colliders usually involve both the s-channel and t-channel parton-parton interactions. Since there is a negligible amount of bottom and top quark content in the proton, top- and bottom squark production proceeds through s-channel diagrams only. In the past, experimental analyses of squark and/or gluino production typically assumed the first and second generation squarks to be approximately degenerate in mass. However, in order to have even less model dependent interpretations of the searches, the experiments have started to also provide simplified model limits on individual first or second generation squarks.

Assuming R-parity conservation and assuming gluinos to be heavier than squarks, squarks will predominantly decay to a quark and a neutralino or chargino, if kinematically allowed. The decay may involve the lightest neutralino (typically the LSP) or chargino, but, depending on the masses and couplings of the gauginos, may involve heavier neutralinos or charginos. For pair production of first and second generation squarks, the simplest decay modes involve two jets and missing momentum, with potential extra jets stemming from initial state or final state radiation (ISR/FSR) or from decay modes with longer decay chains (cascades). Similarly, gluino pair production leads to four jets and missing momentum, and possibly additional jets from ISR/FSR or cascades. Associated production of a gluino and a (anti-)squark is also possible, in particular if squarks and gluinos have similar masses, typically leading to three or more jets in the final state. In cascades, isolated photons or leptons may appear from the decays of sparticles such as neutralinos or charginos. Final states are thus characterized by significant missing transverse momentum, and at least two, and possibly many more high p_{T} jets, which can be accompanied by one or more isolated objects like photons or leptons, including τ leptons, in the final state. Table 90.1 shows a schematic overview of characteristic final state signatures of gluino and squark production for different mass hierarchy hypotheses and assuming decays involving the lightest neutralino.

Table 90.1: Typical search signatures at hadron colliders for direct gluino and first- and second-generation squark production assuming different mass hierarchies.

Mass Hierarchy	Main Production	Dominant Decay	Typical Signature
$m_{\tilde{q}} \ll m_{\tilde{g}}$	$\tilde{q}\tilde{q}, \tilde{q}\bar{\tilde{q}}$	$\tilde{q} \to q\tilde{\chi}_1^0$	≥ 2 jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ + X
$m_{\tilde{q}} \approx m_{\tilde{g}}$	$\tilde{q}\tilde{g}, \bar{\tilde{q}}\tilde{g}$	$\tilde{q} \to q\tilde{\chi}_1^0$	≥ 3 jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ + X
		$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	
$m_{\tilde{q}} \gg m_{\tilde{g}}$	$\tilde{g}\tilde{g}$	$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	≥ 4 jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ + X

90.4.1 *Exclusion limits on the gluino mass*

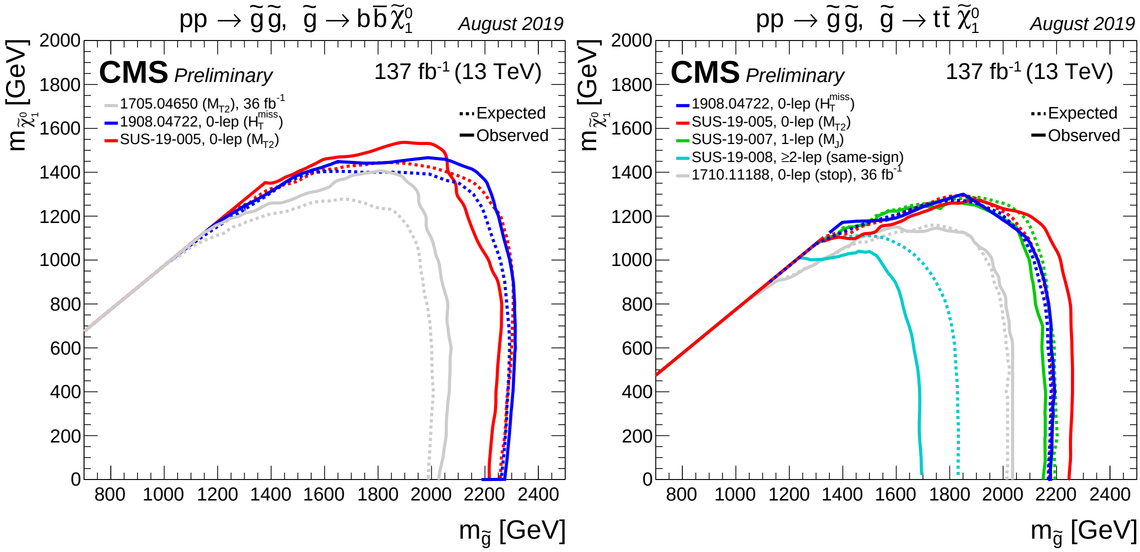

Figure 90.3: Lower mass limits, at 95% C.L., on gluino pair production for various decay chains in the framework of simplified models. Left: $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$. Right: $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$. Results of the CMS collaboration.

Limits set by the Tevatron experiments on the gluino mass assume the framework of the CMSSM, with $\tan\beta = 5$ (CDF) or $\tan\beta = 3$ (D0), where $\tan\beta$ is the ratio of vacuum expectation values of the Higgs fields for up-type and down-type fermions. Furthermore, $A_0 = 0$ and $\mu < 0$ is assumed, and the resulting lower mass limits are about 310 GeV for all squark masses, or 390 GeV for the case $m_{\tilde{q}} = m_{\tilde{g}}$ [68, 69]. These limits have been superseded by those provided by ATLAS and CMS, and the tightest constraints have been set with up to approximately 140 fb^{-1} of data recorded at the LHC at a center-of-mass energy of 13 TeV.

Limits on the gluino mass have been established in the framework of simplified models. Assuming only gluino pair production, in particular three primary decay chains of the gluino have been considered by the LHC experiments for interpretations of their search results. The first decay chain $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ assumes gluino mediated production of first and second generation squarks (on-shell or off-shell) which leads to four light flavor quarks in the final state. Therefore, inclusive all-hadronic analyses searching for multijet plus $E_T^{\rm miss}$ final states are utilized to put limits on this simplified model. These limits are derived as a function of the gluino and neutralino (LSP) mass. As shown in Fig. 90.2 (left), using the cross section from next-to-leading order QCD corrections and the resummation of soft gluon emission at next-to-leading-logarithmic accuracy as reference [48], the ATLAS collaboration [70] excludes in this simplified model gluino masses below approximately 2.3 TeV, for a massless neutralino. In scenarios where neutralinos are not very light, the efficiency of the analyses is reduced by the fact that jets are less energetic, and there is less missing transverse momentum in the event. This leads to weaker limits when the mass difference $\Delta m = m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ is reduced. For example, for neutralino masses above about 1.2 TeV no limit on the gluino mass can be set for this decay chain. Therefore, limits on gluino masses are strongly affected by the assumption of the neutralino mass. Similar results for this simplified model have been obtained by CMS [71].

The second important decay chain of the gluino considered for interpretation in a simplified model is $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$. Here the decay is mediated via bottom squarks and thus leads to four jets from

b quarks and $E_{\mathrm{T}}^{\mathrm{miss}}$ in the final state. Also for this topology inclusive all-hadronic searches provide the highest sensitivity. However, with four b quarks in the final state, the use of secondary vertex reconstruction for the identification of jets originating from b quarks provides a powerful handle on the SM background. Therefore, in addition to a multijet plus $E_{\mathrm{T}}^{\mathrm{miss}}$ signature these searches also require several jets to be tagged as b-jets. As shown in Fig. 90.3 (left), for this simplified model CMS [71] excludes gluino masses below ≈ 2.3 TeV for a massless neutralino, while for neutralino masses above ≈ 1.5 TeV no limit on the gluino mass can be set. Comparable limits for this simplified model are provided by searches from ATLAS [72].

Gluino decays are not limited to first and second generation squarks or bottom squarks; if kinematically allowed, decays to top squarks via $\tilde{g} \to \tilde{t}t$ are also possible. This leads to a "four tops" final state $tttt\tilde{\chi}_1^0\tilde{\chi}_1^0$ and defines the third important simplified model, $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$, characterizing gluino pair production. The topology of this decay is very rich in different experimental signatures: as many as four isolated leptons, four b-jets, several light flavor quark jets, and significant missing momentum from the neutrinos in the W decay and from the two neutralinos. As shown in Fig. 90.3 (right), the CMS search based on the m_{T2} variable [73] rules out gluinos with masses below ≈ 2.25 TeV for massless neutralinos in this model. For neutralino masses above ≈ 1.3 TeV, no limit can be placed on the gluino mass. The ATLAS multiple b-jets search [72] obtains similar limits.

The ATLAS collaboration also provides limits in a pMSSM-inspired model with only gluinos and first and second generation squarks, and a bino-like $\tilde{\chi}_1^0$ [70]. As shown in Fig. 90.2 (right), assuming $m_{\tilde{\chi}_1^0} = 995$ GeV, gluinos with masses below ≈ 1.6 TeV are excluded for any squark mass. For $m_{\tilde{q}} \approx m_{\tilde{g}}$, the mass exclusion is about 3.0 TeV. The dependence of these limits on $m_{\tilde{\chi}_1^0}$ is illustrated in Ref. [70]. For massless $\tilde{\chi}_1^0$, gluino masses below 2.2 TeV are excluded for all squark masses.

R-parity violating gluino decays are searched for in a number of final states. Searches in multi-lepton final states set lower mass limits of 1 to 1.4 TeV, depending on neutralino mass and lepton flavor, on decays mediated by λ and λ' couplings [74–78], assuming prompt decays. Searches for displaced vertices are sensitive to non-prompt decays [79–82]. Multijet final states have been used to search for fully hadronic gluino decays involving λ'', by CDF [83], ATLAS [79, 84–86] and CMS [87–89]. Lower gluino mass limits range between 600 and 2000 GeV depending on neutralino mass and flavor content of the final state.

90.4.2 *Exclusion limits on squark masses*

Limits on first and second generation squark masses set by the Tevatron experiments assume the CMSSM, and amount to lower limits of about 380 GeV for all gluino masses, or 390 GeV for the case $m_{\tilde{q}} = m_{\tilde{g}}$ [68, 69].

At the LHC, limits on squark masses have been set using up to approximately 140 fb^{-1} of data at 13 TeV. Interpretations in simplified models typically characterize squark pair production with only one decay chain of $\tilde{q} \to q\tilde{\chi}_1^0$. Here it is assumed that the left and right-handed $\tilde{u}$, $\tilde{d}$, $\tilde{s}$ and $\tilde{c}$ squarks are degenerate in mass. Furthermore, it is assumed that the mass of the gluino is very high and thus contributions of the corresponding t-channel diagrams to squark pair production are negligible. Therefore, the total production cross section for this simplified model is eight times the production cross section of an individual squark (e.g. $\tilde{u}_L$). Under these assumptions, ATLAS obtains a lower squark mass limit of ≈ 1.9 TeV for light neutralinos [70], as shown in Fig. 90.4 (left). The effects of heavy neutralinos on squark limits are similar to those discussed in the gluino case (see Section 90.4.1), and only for neutralino masses below ≈ 800 GeV can any squark masses be excluded.

For the same analysis ATLAS also provides an interpretation of their search result in the aforementioned pMSSM-inspired model with only gluinos and first and second generation squarks,

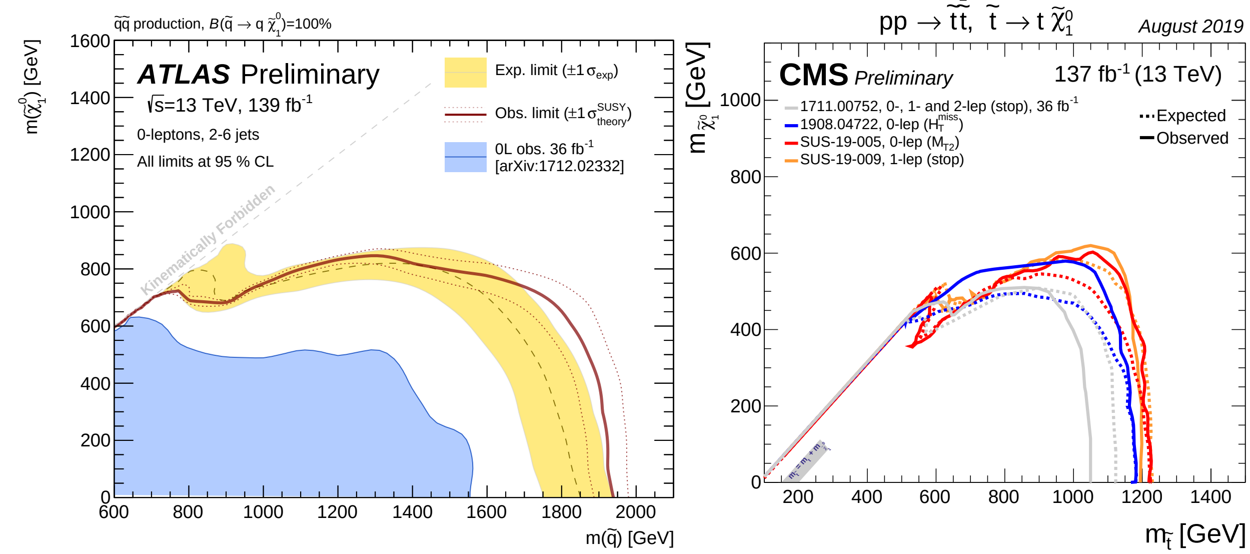

Figure 90.4: Left: 95% C.L. exclusion contours in the squark-neutralino mass plane defined in the framework of simplified models assuming a single decay chain of $\tilde{q} \rightarrow q\tilde{\chi}_1^0$, obtained by ATLAS. Right: the 95% C.L. exclusion contours in the stop-neutralino mass plane defined in the framework of a simplified model assuming a single decay chain of $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ as obtained by CMS.

and a bino-like $\tilde{\chi}_1^0$ [70], as shown in Fig. 90.2 (right). In this model, squark production can take place with non-decoupled gluinos, enhancing the squark production cross section through gluino exchange diagrams.

If the assumption of mass degenerate first and second generation squarks is dropped and only the production of a single light squark is assumed, the limits weaken significantly. For example, the CMS limit on degenerate squarks of 1750 GeV for light neutralinos drops to ≈ 1300 GeV for pair production of a single light squark, and for neutralinos heavier than ≈ 600 GeV no squark mass limit can be placed [73]. It should be noted that this limit is not a result of a simple scaling of the above mentioned mass limits assuming eightfold mass degeneracy but it also takes into account that for an eight times lower production cross section the analyses must probe kinematic regions of phase space that are closer to the ones of SM background production. Since signal acceptance and the ratio of expected signal to SM background events of the analyses are typically worse in this region of phase space not only the 1/8 reduction in production cross section but also a worse analysis sensitivity are responsible for the much weaker limit on single squark pair production.

For single light squarks ATLAS also reports results of a dedicated search for pair production of scalar partners of charm quarks [90]. Assuming that the scalar-charm state exclusively decays into a charm quark and a neutralino, scalar-charm masses up to 800 GeV are excluded for neutralino masses below 260 GeV.

Besides placing stringent limits on first and second generation squark masses, the LHC experiments also search for the production of third generation squarks. SUSY at the TeV-scale is often motivated by naturalness arguments, most notably as a solution to cancel quadratic divergences in radiative corrections to the Higgs boson mass. In this context, the most relevant terms for SUSY phenomenology arise from the interplay between the masses of the third generation squarks and the Yukawa coupling of the top quark to the Higgs boson. This motivates a potential constraint on the masses of the top squarks and the left-handed bottom squark. Due to the large top quark mass, significant mixing between $\tilde{t}_L$ and $\tilde{t}_R$ is expected, leading to a lighter mass state $\tilde{t}_1$ and a

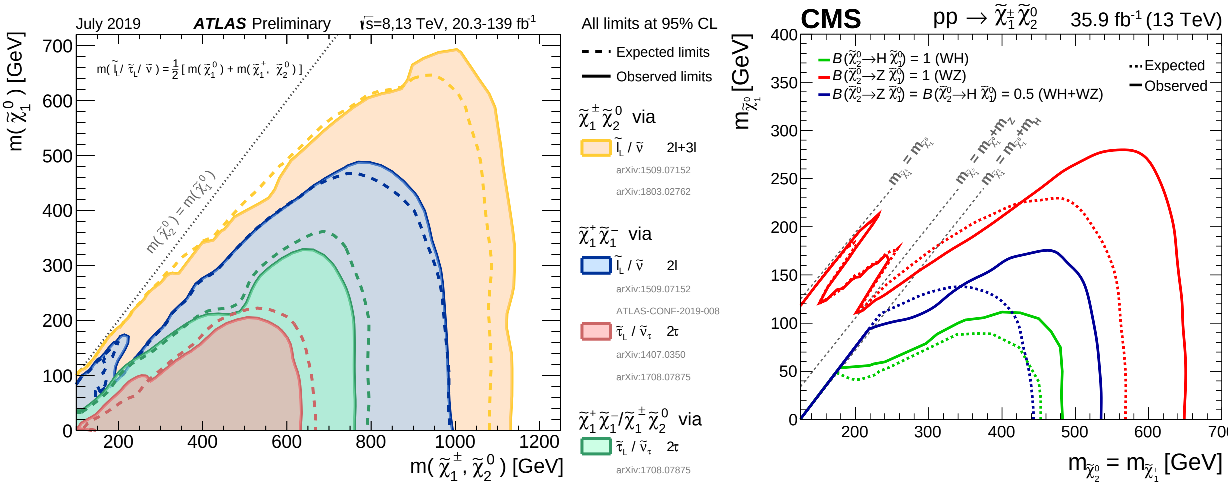

Figure 90.5: LHC exclusion limits on chargino and neutralino masses in a number of simplified models. Left: limits on chargino and neutralino masses for pair production of charginos, pair production of heavier neutralinos, or pair production of chargino and neutralino, under the assumption of light sleptons mediating the decays. Right: limits on chargino and neutralino masses for pair production of chargino and neutralino, under the assumption of decoupled sleptons, and chargino/neutralino decay through W^*, Z^* or H.

heavier mass state $\tilde{t}_2$. In the MSSM, the lightest top squark ($\tilde{t}_1$) can be the lightest squark.

Bottom squarks are expected to decay predominantly to $b\tilde{\chi}^0$ giving rise to the characteristic multi b-jet and $E_{\rm T}^{\rm miss}$ signature. Direct production of bottom squark pairs has been searched for at the Tevatron and at the LHC. Limits from the Tevatron are $m_{\tilde{b}} > 247$ GeV for a massless neutralino [91] [92]. The LHC experiments have surpassed these limits, and the latest results are based on up to 140 fb^{-1} of data collected at $\sqrt{s} = 13$ TeV. CMS has set a lower limit of $m_{\tilde{b}} >\approx 1250$ GeV for massless neutralinos in this model [73]. For $m_{\tilde{\chi}_1^0} \approx 700$ GeV or higher no limit can be placed on direct bottom squark pair production in this simplified model. Limits from ATLAS are comparable [93]. Further bottom squark decay modes have also been searched for by ATLAS [94, 95] and CMS [71, 76, 96].

The top squark decay modes depend on the SUSY mass spectrum, and on the $\tilde{t}_{\rm L}$-$\tilde{t}_{\rm R}$ mixture of the top squark mass eigenstate. If kinematically allowed, the two-body decays $\tilde{t} \to t\tilde{\chi}^0$ (which requires $m_{\tilde{t}} - m_{\tilde{\chi}^0} > m_t$) and $\tilde{t} \to b\tilde{\chi}^{\pm}$ (which requires $m_{\tilde{t}} - m_{\tilde{\chi}^{\pm}} > m_b$) are expected to dominate. If not, the top squark decay may proceed either via the two-body decay $\tilde{t} \to c\tilde{\chi}^0$ or through $\tilde{t} \to bf\bar{f}'\tilde{\chi}^0$ (where f and $\bar{f}'$ denote a fermion-antifermion pair with appropriate quantum numbers). For $m_{\tilde{t}} - m_{\tilde{\chi}^0} > m_b$ the latter decay chain represents a four-body decay with a W boson, charged Higgs H, slepton $\tilde{\ell}$, or light flavor squark $\tilde{q}$, exchange. If the exchanged W boson and/or sleptons are kinematically allowed to be on-shell ($(m_{\tilde{t}} - m_{\tilde{\chi}^{\pm}}) > (m_b + m_W)$ and/or $(m_{\tilde{t}} - m_{\tilde{\ell}}) > m_b$), the three-body decays $\tilde{t} \to Wb\tilde{\chi}^0$ and/or $\tilde{t} \to bl\tilde{\ell}$ will become dominant. For further discussion on top squark decays see for example Ref. [97].

Limits from LEP on the $\tilde{t}_1$ mass are $m_{\tilde{t}} > 96$ GeV in the charm plus neutralino final state, and > 93 GeV in the lepton, b-quark and sneutrino final state [67].

The Tevatron experiments have performed a number of searches for top squarks, often assuming direct pair production. In the $b\ell\tilde{\nu}$ decay channel, and assuming a 100% branching fraction, limits are set as $m_{\tilde{t}} > 210$ GeV for $m_{\tilde{\nu}} < 110$ GeV and $m_{\tilde{t}} - m_{\tilde{\nu}} > 30$ GeV, or $m_{\tilde{t}} > 235$ GeV for

$m_{\tilde{\nu}} < 50$ GeV [98] [99]. In the $\tilde{t} \to c\tilde{\chi}_1^0$ decay mode, a top squark with a mass below 180 GeV is excluded for a neutralino lighter than 95 GeV [100] [101]. In both analyses, no limits on the top squark can be set for heavy sneutrinos or neutralinos. In the $\tilde{t} \to b\tilde{\chi}_1^\pm$ decay channel, searches for a relatively light top squark have been performed in the dilepton final state [102] [103]. The CDF experiment sets limits in the $\tilde{t}-\tilde{\chi}_1^0$ mass plane for various branching fractions of the chargino decay to leptons and for two value of $m_{\tilde{\chi}_1^\pm}$. For $m_{\tilde{\chi}_1^\pm} = 105.8$ GeV and $m_{\tilde{\chi}_1^0} = 47.6$ GeV, top squarks between 128 and 135 GeV are excluded for W-like leptonic branching fractions of the chargino.

The LHC experiments have improved these limits substantially. As shown in the right plot of Fig. 90.4, limits on the top squark mass assuming a simplified model with a single decay chain of $\tilde{t} \to t\tilde{\chi}_1^0$ now surpass 1 TeV. The most important searches for this top squark decay topology are dedicated searches requiring zero or one isolated lepton, modest $E_{\mathrm{T}}^{\mathrm{miss}}$, and four or more jets out of which at least one jet must be reconstructed as a b-jet [71, 73, 104–106]. For example, CMS excludes top squarks with masses below about 1200 GeV in this model for massless neutralinos, while for $m_{\tilde{\chi}_1^0} >$ 600 GeV no limits can be provided.

Assuming that the top squark decay exclusively proceeds via the chargino mediated decay chain $\tilde{t} \to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to W^{\pm(*)}\tilde{\chi}_1^0$ yields stop mass exclusion limits that vary strongly with the assumptions made on the $\tilde{t}-\ \tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ mass hierarchy. For example, for $m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} + m_{\tilde{\chi}_1^0})/2$, a stop mass below ≈ 1150 GeV for a light $\tilde{\chi}_1^0$ is excluded, while no limit can be placed for $m_{\tilde{\chi}_1^0} > 550$ GeV [104]. These limits, however, can weaken significantly when other assumptions about the mass hierarchy or the decay of the charginos are imposed [104, 106–108].

If the decays $\tilde{t} \to t\tilde{\chi}_1^0$ and $\tilde{t} \to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to W^{\pm(*)}\tilde{\chi}_1^0$ are kinematically forbidden, the decay chains $\tilde{t} \to Wb\tilde{\chi}^0$ and $\tilde{t} \to c\tilde{\chi}^0$ can become important. The one-lepton ATLAS search provides for the kinematic region $m_{\tilde{t}} - m_{\tilde{\chi}^\pm} > m_b + m_W$ lower limits on the top squark mass of ≈ 700 GeV for a neutralino lighter than ≈ 570 GeV [109]. Other analyses with zero, one or two leptons also target this kinematic region [105, 106, 110–114].

For the kinematic region in which even the production of real W bosons is not allowed, ATLAS and CMS improve the Tevatron limit on $\tilde{t} \to c\tilde{\chi}^0$ substantially. Based on a monojet analysis [115] ATLAS excludes top squark masses below $m_{\tilde{\chi}_1^0} \approx 450$ GeV along the kinematic boundary for the $\tilde{t} \to c\tilde{\chi}^0$ decay. A dedicated analysis for $\tilde{t} \to c\tilde{\chi}^0$ excludes stop masses below 500 GeV for $m_{\tilde{\chi}_1^0}$ below 420 GeV [90]. The CMS collaboration uses the hadronic searches [111, 113] to place constraints on this particular stop decay and excludes $m_{\tilde{t}} \approx 550$ GeV for $m_{\tilde{\chi}_1^0}$ below 450 GeV. The exclusion at $m_{\tilde{t}} \approx m_{\tilde{\chi}_1^0}$ is also about 550 GeV.

The other decay chain relevant in this phase region is $\tilde{t} \to bf\bar{f}'\tilde{\chi}^0$. Here the ATLAS one-lepton [106] and two-lepton [110] searches exclude up to $m_{\tilde{t}} \approx 440$ GeV for $m_{\tilde{\chi}_1^0}$ below 340 GeV, while the monojet analysis [115] excludes at the kinematic boundary top squarks below 400 GeV. As for the $\tilde{t} \to c\tilde{\chi}^0$ decay, CMS uses the zero-lepton searches [111, 113] to also place constraints on $\tilde{t} \to bf\bar{f}'\tilde{\chi}^0$. Also in this case CMS excludes $m_{\tilde{t}} \approx 550$ GeV for $m_{\tilde{\chi}_1^0}$ below 450 GeV.

In general, the variety of top squark decay chains in the phase space region where $\tilde{t} \to t\tilde{\chi}_1^0$ is kinematically forbidden represents a challenge for the experimental search program and more data and refined analyses will be required to further improve the sensitivity in this difficult but important region of SUSY parameter space.

R-parity violating production of single squarks via a λ'-type coupling has been studied at HERA. In such models, a lower limit on the squark mass of the order of 275 GeV has been set for electromagnetic-strength-like couplings $\lambda' = 0.3$ [116]. At the LHC, both prompt [75, 78, 117] and non-prompt [80, 118] R-parity violating squark decays have been searched for, but no signal was found. Squark mass limits are very model-dependent.

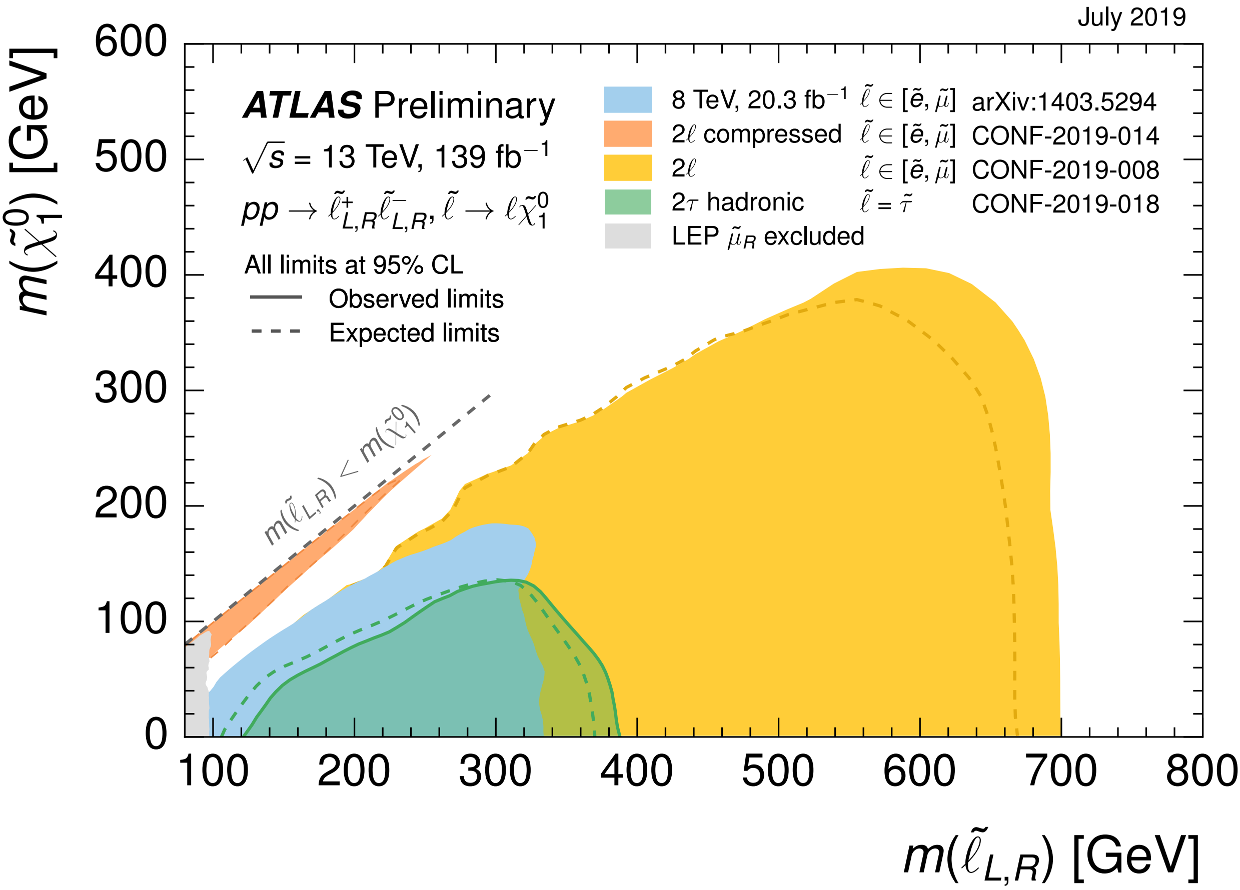

Figure 90.6: LHC exclusion limits on slepton (selectron and smuon) masses, assuming equal masses of selectrons and smuons, degeneracy of $\tilde{\ell}_{\mathrm{L}}$ and $\tilde{\ell}_{\mathrm{R}}$, and a 100% branching fraction for $\tilde{\ell} \to \ell\tilde{\chi}^0_1$.

R-parity violating production of single top squarks has been searched for at LEP, HERA, and the Tevatron. For example, an analysis from the ZEUS collaboration [119] makes an interpretation of its search result assuming top squarks to be produced via a λ' coupling and decay either to $b\tilde{\chi}^\pm_1$ or R-parity-violating to a lepton and a jet. Limits are set on λ'_{131} as a function of the top squark mass in an MSSM framework with gaugino mass unification at the GUT scale.

The search for top squark pair production in the context of R-parity violating supersymmetry has now also become a focus point for searches at the LHC. CMS and ATLAS have performed searches for top squarks using a variety of multilepton final states [75, 120]. The λ'-mediated top squark decay $\tilde{t} \to b\ell$ has been studied by ATLAS for prompt decays [121], and by ATLAS and CMS for non-prompt decays [122–124], setting limits up to $1.4 - 1.6$ TeV in simplified models for this mode. CMS also searched for the λ'-mediated decay $\tilde{t} \to b\ell qq$, setting lower stop mass limits of 890 GeV (e) or 1000 GeV (μ) [125]. The fully hadronic R-parity violating top squark decays $\tilde{t} \to bs$, $\tilde{t} \to ds$, and $\tilde{t} \to bd$, involving λ'', have been searched for by ATLAS [75, 79, 94, 126], and CMS [127, 128], and lower top squark mass limits up to 610 GeV were set.

It should be noted that limits discussed in this section belong to different top and bottom squark decay channels, different sparticle mass hierarchies, and different simplified decay scenarios. Therefore, care must be taken when interpreting these limits in the context of more complete SUSY models.

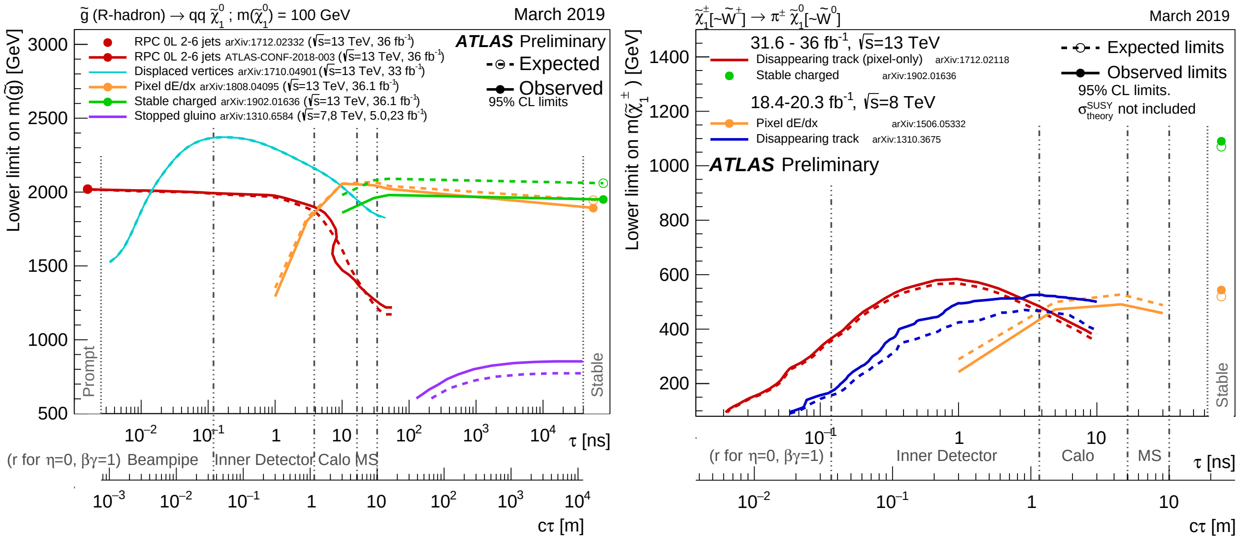

Figure 90.7: Limits at 95% C.L. on the gluino mass in R-hadron models (left), and on the chargino mass in a model where the wino-like chargino is almost degenerate with the LSP (right), as a function of gluino or chargino lifetime, as obtained by ATLAS.

90.4.3 *Summary of exclusion limits on squarks and gluinos assuming R-Parity conservation*

A summary of the most important squark and gluino mass limits for different interpretation approaches assuming R-parity conservation is shown in Table 90.2.

For gluino masses rather similar limits of about 2.3 TeV are obtained from different model assumptions, indicating that the LHC is indeed probing direct gluino production at the TeV scale and beyond. However, for neutralino masses above approximately 1 to 1.4 TeV, in the best case scenarios, ATLAS and CMS searches do not place any limits on the gluino mass.

Limits on direct squark production, on the other hand, depend strongly on the chosen model. Especially for direct production of top squarks there are still large regions in parameter space where masses below 1 TeV cannot be excluded. This is also true for first and second generation squarks when only one single squark is considered. Furthermore, for neutralino masses above ≈ 500 GeV no limits on any direct squark production scenario are placed by the LHC.

90.5 Exclusion limits on the masses of charginos and neutralinos

Charginos and neutralinos result from mixing of the charged wino and higgsino states, and the neutral bino, wino and higgsino states, respectively. The mixing is determined by a limited number of parameters. For charginos these are the wino mass parameter M_2, the higgsino mass parameter μ, and $\tan\beta$, and for neutralinos these are the same parameters plus the bino mass parameter M_1. If any of the parameters M_1, M_2 or μ happened to be substantially smaller than the others, the chargino/neutralino composition would be dominated by specific states, which are referred to as bino-like ($M_1 \ll M_2, \mu$), wino-like ($M_2 \ll M_1, \mu$), or higgsino-like ($\mu \ll M_1, M_2$). If gaugino mass unification at the GUT scale is assumed, a relation between M_1 and M_2 at the electroweak scale follows: $M_1 = 5/3 \tan^2\theta_W M_2 \approx 0.5 M_2$, with θ_W the weak mixing angle. Charginos and neutralinos carry no color charge.

90.5.1 *Exclusion limits on chargino masses*

If kinematically allowed, two body decay modes such as $\tilde{\chi}^\pm \to \tilde{f}\bar{f}'$ (including $\ell\tilde{\nu}$ and $\tilde{\ell}\nu$) are dominant. If not, three body decays $\tilde{\chi}^\pm \to f\bar{f}'\tilde{\chi}^0$, mediated through virtual W bosons or sfermions,

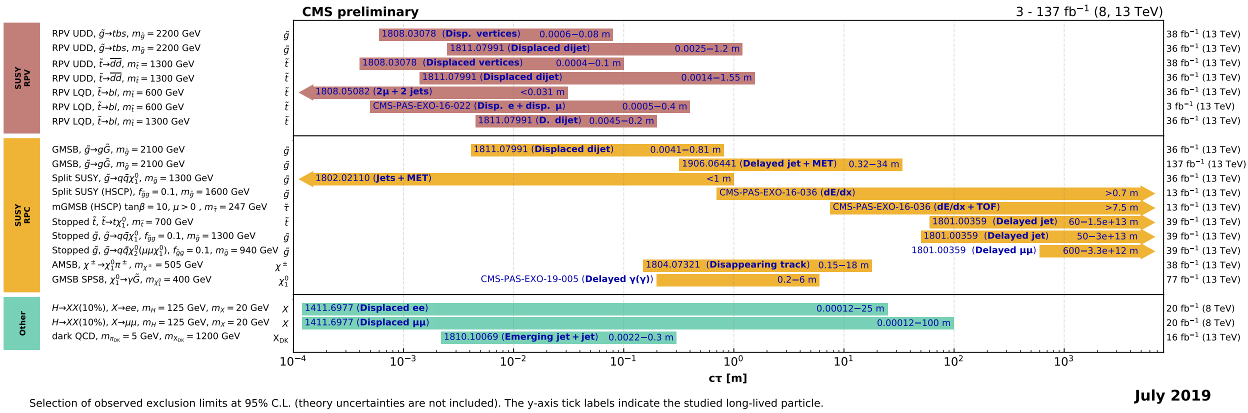

Figure 90.8: Excluded regions, at 95% C.L., in the lifetimes of long-lived particles in several models, as obtained by CMS.

become dominant. If sfermions are heavy, the W mediation dominates, and $f\bar{f}'$ are distributed with branching fractions similar to W decay products (barring phase space effects for small mass gaps between $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^0$). If, on the other hand, sleptons are light enough to play a significant role in the decay, leptonic final states will be enhanced.

At LEP, charginos have been searched for in fully-hadronic, semi-leptonic and fully leptonic decay modes [129] [130]. A general lower limit on the lightest chargino mass of 103.5 GeV is derived, except in corners of phase space with low electron sneutrino mass, where destructive interference in chargino production, or two-body decay modes, play a role. The limit is also affected if the mass difference between $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_1$ is small; dedicated searches for such scenarios set a lower limit of 92 GeV.

At the Tevatron, charginos have been searched for via associated production of $\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ [131] [132]. Decay modes involving multilepton final states provide the best discrimination against the large multijet background. Analyses have looked for at least three charged isolated leptons, for two leptons with missing transverse momentum, or for two leptons with the same charge. Depending on the $(\tilde{\chi}^{\pm}_1 - \tilde{\chi}^0_1)$ and/or $(\tilde{\chi}^0_2 - \tilde{\chi}^0_1)$ mass differences, leptons may be soft.

At the LHC, the search strategy is similar to that at the Tevatron. As shown in Fig. 90.1, the cross section of pair production of electroweak gauginos at the LHC, for masses of several hundreds of GeV, is at least two orders of magnitude smaller than for colored SUSY particles (e.g. top squark pair production). For this reason a large data sample is required to improve the sensitivity of LEP and Tevatron searches for direct chargino/neutralino production. With the full LHC Run 1 and Run 2 data sets, ATLAS and CMS have surpassed the limits from LEP and Tevatron in regions of SUSY parameter space.

Chargino pair production is searched for in the dilepton plus missing momentum final state. In a simplified model interpretation of the results, assuming mediation of the chargino decay by light sleptons ($\tilde{e}$ and $\tilde{\mu}$), ATLAS [133] and CMS [134] set limits on the chargino mass up to 1 TeV for massless LSPs, but no limits on the chargino mass can be set for $\tilde{\chi}^0_1$ heavier than 480 GeV. Limits are fairly robust against variation of the slepton mass, unless the mass gap between chargino and slepton becomes small. For decays mediated through $\tilde{\tau}$ or $\tilde{\nu}_\tau$, limits of 630 GeV are set by ATLAS [135] for LSPs not heavier than 200 GeV. The CMS experiment provides similar limits [136]. ATLAS also sets limits on charginos decaying via a W boson [133]: chargino masses below 420 GeV are excluded for massless LSPs, but no limits are set for LSPs heavier than 120 GeV.

The trilepton plus missing momentum final state is used to set limits on $\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ production,

Table 90.2: Summary of squark mass and gluino mass limits using different interpretation approaches assuming R-parity conservation. Masses in this table are provided in GeV. Further details about the assumptions and analyses from which these limits are obtained are discussed in the corresponding sections of the text.

Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
Simplified model	$m_{\tilde{\chi}_1^0}$= 0, $m_{\tilde{q}} \approx m_{\tilde{g}}$	$\approx$ 3000	$\approx$ 3000
$\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0}$= 0, all $m_{\tilde{q}}$	-	$\approx$ 2200
	$m_{\tilde{\chi}_1^0}$= 0, all $m_{\tilde{g}}$	$\approx$ 2600	-
Simplified models $\tilde{g}\tilde{g}$			
$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0}$ =0	-	$\approx$ 2300
	$m_{\tilde{\chi}_1^0}$ >$\approx$ 1200	-	no limit
$\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0}$ =0	-	$\approx$ 2300
	$m_{\tilde{\chi}_1^0}$ >$\approx$ 1500	-	no limit
$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0}$ =0	-	$\approx$ 2250
	$m_{\tilde{\chi}_1^0}$ >$\approx$ 1300	-	no limit
Simplified models $\tilde{q}\tilde{q}$			
$\tilde{q} \to q\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0}$ =0	$\approx$ 1900	-
	$m_{\tilde{\chi}_1^0}$ >$\approx$ 800	no limit	-
$\tilde{u}_L \to q\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0}$ =0	$\approx$ 1300	-
	$m_{\tilde{\chi}_1^0}$ >$\approx$ 600	no limit	-
$\tilde{b} \to b\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0}$ =0	$\approx$ 1250	-
	$m_{\tilde{\chi}_1^0}$ >$\approx$ 700	no limit	-
$\tilde{t} \to t\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0}$ =0	$\approx$ 1200	-
	$m_{\tilde{\chi}_1^0}$ >$\approx$ 600	no limit	-
$\tilde{t} \to b\tilde{\chi}_1^\pm$	$m_{\tilde{\chi}_1^0}$ =0	$\approx$ 1150	-
$(m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} - m_{\tilde{\chi}_1^0})/2)$	$m_{\tilde{\chi}_1^0}$ >$\approx$ 550	no limit	-
$\tilde{t} \to Wb\tilde{\chi}_1^0$ $(m_W < m_{\tilde{t}} - m_{\tilde{\chi}^0} < m_t)$	$m_{\tilde{\chi}_1^0}$ <$\approx$ 570	$\approx$ 700	-
$\tilde{t} \to c\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0}$ <$\approx$ 450	$\approx$ 550	-
	$m_{\tilde{t}} \approx m_{\tilde{\chi}_1^0}$	$\approx$ 550	-
$\tilde{t} \to bff'\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0}$ <$\approx$ 450	$\approx$ 550	-
	$m_{\tilde{t}} \approx m_{\tilde{\chi}_1^0}$	$\approx$ 550	-
$(m_{\tilde{t}} - m_{\tilde{\chi}^0} < m_W)$			

assuming wino-like $\tilde{\chi}^\pm$ and $\tilde{\chi}_2^0$, bino-like $\tilde{\chi}_1^0$, and $m_{\tilde{\chi}^\pm} = m_{\tilde{\chi}_2^0}$, leaving $m_{\tilde{\chi}^\pm}$ and $m_{\tilde{\chi}_1^0}$ free. Again, the branching fraction of leptonic final states is determined by the slepton masses. If the decay is predominantly mediated by a light $\tilde{\ell}_\mathrm{L}$, i.e. $\tilde{\ell}_\mathrm{R}$ is assumed to be heavy, the three charged-lepton flavors will be produced in equal amounts. It is assumed that $\tilde{\ell}_\mathrm{L}$ and sneutrino masses are equal, and diagrams with sneutrinos are included. In this scenario, ATLAS [137] and CMS [138] exclude chargino masses below 1140 GeV for massless LSPs; no limits are set for LSP masses above 700 GeV. If the decay is dominated by a light $\tilde{\ell}_\mathrm{R}$, the chargino cannot be a pure wino but needs to have a large higgsino component, preferring the decays to tau leptons. Limits are set in various scenarios. If, like for $\tilde{\ell}_L$, a flavor-democratic scenario is assumed, CMS sets limits of 1060 GeV on the chargino mass for massless LSPs, but under the assumption that both $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^0_2$ decay leads to tau leptons in the final state, the chargino mass limit deteriorates to 620 GeV for massless LSPs [138]. ATLAS assumes a simplified model in which staus are significantly lighter than the other sleptons in order to search for a similar multi-tau final state, and sets a lower limit on the chargino mass of 760 GeV in this model [135]. The CMS experiment provides similar limits [136].

If sleptons are heavy, the chargino is assumed to decay to a W boson plus LSP, and the $\tilde{\chi}^0_2$ into Z plus LSP or H plus LSP. In the WZ channel, ATLAS [137, 139] and CMS [140] limits on the chargino mass reach 650 GeV for massless LSPs, but no limits are set for LSPs heavier than 300 GeV. In the WH channel, for $m_H = 125$ GeV and using various Higgs decay modes, ATLAS [141–143] and CMS [140] set lower limits on the chargino mass up to 740 GeV for massless LSPs, but vanish for LSP masses above 240 GeV.

The results on electroweak gaugino searches interpreted in simplified models are summarized in Fig. 90.5 for the two cases of light or decoupled sleptons. For both cases, ATLAS and CMS have comparable limits.

In both the wino region (a characteristic of anomaly-mediated SUSY breaking models) and the higgsino region of the MSSM, the mass splitting between $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_1$ is small. The chargino decay products are very soft and may escape detection. These compressed spectra are hard to detect, and have triggered dedicated search strategies. ATLAS has performed a search for charginos and neutralinos in a compressed mass spectrum using initial state radiation [144]. For wino-like charginos, assuming degenerate $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_2$, exclusion contours in the chargino-mass versus $\Delta m(\tilde{\chi}^{\pm}_1 - \tilde{\chi}^0_1)$ plane are derived. As an example, such charginos are excluded below 200 GeV for $\Delta m(\tilde{\chi}^{\pm}_1 - \tilde{\chi}^0_1) = 10$ GeV. CMS has searched for chargino-pair production through vector-boson-fusion [145], also targetting compressed mass spectra. Assuming degenerate $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_2$, charginos with a mass below 112 GeV are excluded for $\Delta m(\tilde{\chi}^{\pm}_1 - \tilde{\chi}^0_1) = 1$ GeV. CMS has published further searches for such compressed spectra with soft leptons [146] or a soft tau lepton [147].

90.5.2 *Exclusion limits on neutralino masses*

In a considerable part of the MSSM parameter space, and in particular when demanding that the LSP carries no electric or color charge, the lightest neutralino $\tilde{\chi}^0_1$ is the LSP. If R-parity is conserved, such a $\tilde{\chi}^0_1$ is stable. Since it is weakly interacting, it will typically escape detectors unseen. Limits on the invisible width of the Z boson apply to neutralinos with a mass below 45.5 GeV, but depend on the Z-neutralino coupling. Such a coupling could be small or even absent; in such a scenario there is no general lower limit on the mass of the lightest neutralino [148]. In models with gaugino mass unification and sfermion mass unification at the GUT scale, a lower limit on the neutralino mass is derived from limits from direct searches, notably for charginos and sleptons, and amounts to 47 GeV [149]. Assuming a constrained model like the CMSSM, this limit increases to 50 GeV at LEP; however the strong constraints now set by the LHC increase such CMSSM-derived $\tilde{\chi}^0_1$ mass limits to well above 200 GeV [150–152].

In gauge-mediated SUSY breaking models (GMSB), the LSP is typically a gravitino, and the phenomenology is determined by the nature of the next-to-lightest supersymmetric particle (NLSP). A NLSP neutralino will decay to a gravitino and a SM particle whose nature is determined by the neutralino composition. Final states with two high p_T photons and missing momentum are searched for, and interpreted in gauge mediation models with bino-like neutralinos [153–158].

Assuming the production of at least two neutralinos per event, neutralinos with large non-bino components can also be searched for by their decay in final states with missing momentum plus

Table 90.3: Summary of weak gaugino mass limits in simplified models, assuming R-parity conservation. Masses in the table are provided in GeV. Further details about assumptions and analyses from which these limits are obtained are discussed in the text.

Assumption	m_χ
$\tilde{\chi}_1^\pm$, all $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$	> 92
$\tilde{\chi}_1^\pm$ $\Delta m > 5$, $m_{\tilde{\nu}} > 300$	> 103.5
$\tilde{\chi}_1^\pm$, $m_{(\tilde{\ell},\tilde{\nu})} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})/2$	
$m_{\tilde{\chi}_1^0} \approx 0$	> 1000
$\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^0} > 480$	no LHC limit
$\tilde{\chi}_1^\pm$, $m_{\tilde{\ell}} > m_{\tilde{\chi}_1^\pm}$	
$m_{\tilde{\chi}_1^0} \approx 0$	> 420
$\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^0} > 120$	no LHC limit
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$, $m_{\tilde{\ell}_\mathrm{L}} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})/2$	
$m_{\tilde{\chi}_1^0} \approx 0$	> 1140
$m_{\tilde{\chi}_1^0} > 700$	no LHC limit
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$, $m_{\tilde{\ell}_\mathrm{R}} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})/2$	flavor-democratic
$m_{\tilde{\chi}_1^0} \approx 0$	> 1060
$m_{\tilde{\chi}_1^0} > 600$	no LHC limit
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$, $m_{\tilde{\tau}} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})/2$	$\tilde{\tau}$-dominated
$m_{\tilde{\chi}_1^0} \approx 0$	> 620
$m_{\tilde{\chi}_1^0} > 260$	no LHC limit
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$, $m_{\tilde{\ell}} > m_{\tilde{\chi}_1^\pm}$, $\mathrm{BF}(WZ) = 1$	
$m_{\tilde{\chi}_1^0} \approx 0$	> 650
$m_{\tilde{\chi}_1^0} > 300$	no LHC limit
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$, $m_{\tilde{\ell}} > m_{\tilde{\chi}_1^\pm}$, $\mathrm{BF}(WH) = 1$	
$m_{\tilde{\chi}_1^0} \approx 0$	> 740
$m_{\tilde{\chi}_1^0} > 240$	no LHC limit

any two bosons out of the collection γ, Z, H. A number of searches at the LHC have tried to cover the rich phenomenology of the various Z and H decay modes [74,96,138,140,142,156,159–165].

Heavier neutralinos, in particular $\tilde{\chi}_2^0$, have been searched for in their decays to the lightest neutralino plus a γ, a Z boson or a Higgs boson. Limits on electroweak production of $\tilde{\chi}_2^0$ plus $\tilde{\chi}_1^\pm$ from trilepton analyses have been discussed in the section on charginos; the assumption of equal mass of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ make the limits on chargino masses apply to $\tilde{\chi}_2^0$ as well. Multilepton analyses have also been used to set limits on $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production; assuming equal mass and decay through light sleptons, limits are set up to 680 GeV for massless LSPs [166]. Again, compressed spectra with small mass differences between the heavier neutralinos and the LSP form the most challenging region.

In $\tilde{\chi}_2^0$ decays to $\tilde{\chi}_1^0$ and a lepton pair, the lepton pair invariant mass distribution may show a structure that can be used to measure the $\tilde{\chi}_2^0 - \tilde{\chi}_1^0$ mass difference in case of a signal [35]. This structure, however, can also be used in the search strategy itself, as demonstrated by ATLAS

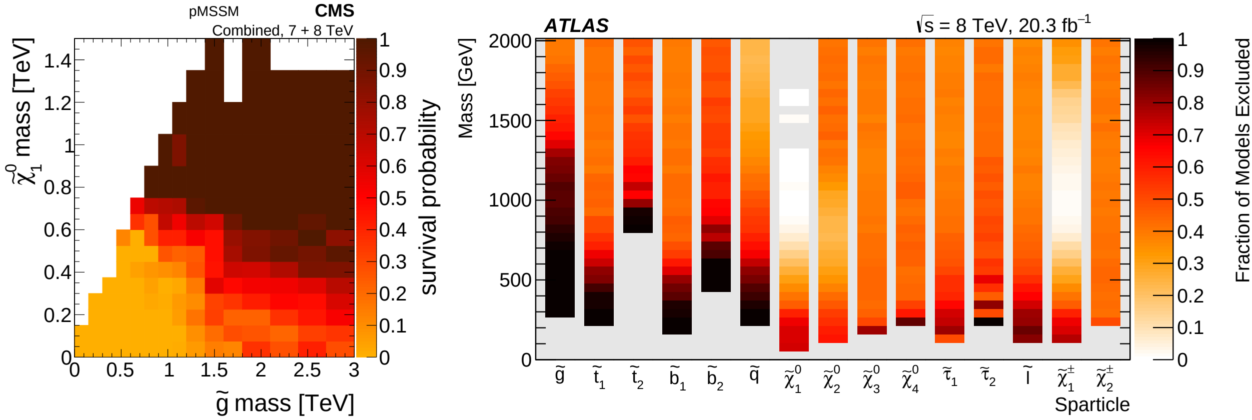

Figure 90.9: The plot on the left shows the survival probability of a pMSSM parameter space model in the gluino-neutralino mass plane after the application of the relevant CMS search results. The plot on the right shows a graphical representation of the ATLAS exclusion power in a pMSSM model. Each vertical bar is a one-dimensional projection of the fraction of models points excluded for each sparticle by ATLAS analyses. The experimental results are obtained from data taken at $\sqrt{s} = 7$ and 8 TeV.

[167, 168] and CMS [96, 169].

In models with R-parity violation, the lightest neutralino can decay even if it is the lightest supersymmetric particle. If the decay involves a non-zero λ coupling, the final state will be a multi-lepton one. Searches for events with four or more isolated charged leptons by ATLAS [74] and CMS [78] are interpreted in such models. With very small coupling values, the neutralino would be long-lived, leading to lepton pairs with a displaced vertex, which have also been searched for [118, 124, 170].

Various searches, including searches for multi-lepton and lepton plus jets events, and searches for events with a displaced hadronic vertex, with or without a matched lepton, are interpreted in a model with R-parity violating neutralino decays involving a non-zero λ' coupling [75, 80, 86, 171]. Neutralino decays involving non-zero λ'' lead to fully hadronic final states, and searches for multi-jet events and jet-pair resonances are used to set limits, typically on the production of colored particles like top squarks or gluinos, which are assumed to be the primary produced sparticles in these interpretations, as discussed earlier [79, 84, 86].

The limits on weak gauginos in simplified models are summarized in Table 90.3. Interpretations of the search results outside simplified models, such as in the phenomenological MSSM [172–176], show that the simplified model limits must be interpreted with care. Electroweak gauginos in models that are compatible with the relic density of dark matter in the universe, for example, have particularly tuned mixing parameters and mass spectra, which are not always captured by the simplified models used.

90.6 Exclusion limits on slepton masses

In models with slepton and gaugino mass unification at the GUT scale, the right-handed slepton, $\tilde{\ell}_{\mathrm{R}}$, is expected to be lighter than the left-handed slepton, $\tilde{\ell}_{\mathrm{L}}$. For tau sleptons there may be considerable mixing between the L and R states, leading to a significant mass difference between the lighter $\tilde{\tau}_1$ and the heavier $\tilde{\tau}_2$.

90.6.1 *Exclusion limits on the masses of charged sleptons*

The most model-independent searches for selectrons, smuons and staus originate from the LEP experiments [177]. Smuon production only takes place via s-channel γ^*/Z exchange. Search results are often quoted for $\tilde{\mu}_\mathrm{R}$, since it is typically lighter than $\tilde{\mu}_\mathrm{L}$ and has a weaker coupling to the Z boson; limits are therefore conservative. Decays are expected to be dominated by $\tilde{\mu}_\mathrm{R} \to \mu\tilde{\chi}^0_1$, leading to two non-back-to-back muons and missing momentum. Slepton mass limits are calculated in the MSSM under the assumption of gaugino mass unification at the GUT scale, and depend on the mass difference between the smuon and $\tilde{\chi}^0_1$. A $\tilde{\mu}_\mathrm{R}$ with a mass below 94 GeV is excluded for $m_{\tilde{\mu}_\mathrm{R}} - m_{\tilde{\chi}^0_1} > 10$ GeV. The selectron case is similar to the smuon case, except that an additional production mechanism is provided by t-channel neutralino exchange. The $\tilde{e}_\mathrm{R}$ lower mass limit is 100 GeV for $m_{\tilde{\chi}^0_1} < 85$ GeV. Due to the t-channel neutralino exchange, $\tilde{e}_\mathrm{R}\tilde{e}_\mathrm{L}$ pair production was possible at LEP, and a lower limit of 73 GeV was set on the selectron mass regardless of the neutralino mass by scanning over MSSM parameter space [178]. The potentially large mixing between $\tilde{\tau}_\mathrm{L}$ and $\tilde{\tau}_\mathrm{R}$ not only makes the $\tilde{\tau}_1$ light, but can also make its coupling to the Z boson small. LEP lower limits on the $\tilde{\tau}$ mass range between 87 and 93 GeV depending on the $\tilde{\chi}^0_1$ mass, for $m_{\tilde{\tau}} - m_{\tilde{\chi}^0_1} > 7$ GeV [177].

At the LHC, pair production of sleptons is not only heavily suppressed with respect to pair production of colored SUSY particles but the cross section is also almost two orders of magnitude smaller than the one of pair production of charginos and neutralinos. With the full data sets of Run 1 and Run 2, however, ATLAS and CMS have surpassed the sensitivity of the LEP analyses under certain assumptions.

Table 90.4: Summary of slepton mass limits from LEP and LHC, assuming R-parity conservation and 100% branching fraction for $\tilde{\ell} \to \ell\tilde{\chi}^0_1$. Masses in this table are provided in GeV.

Assumption	$m_{\tilde{\ell}}$
$\tilde{\mu}_\mathrm{R}$, $\Delta m(\tilde{\mu}_\mathrm{R}, \tilde{\chi}^0_1) > 10$	> 94
$\tilde{e}_\mathrm{R}$, $\Delta m(\tilde{e}_\mathrm{R}, \tilde{\chi}^0_1) > 10$	> 94
$\tilde{e}_\mathrm{R}$, any Δm	> 73
$\tilde{\tau}_\mathrm{R}$, $\Delta m(\tilde{\tau}_\mathrm{R}, \tilde{\chi}^0_1) > 7$	> 87
$\tilde{\nu}_e$, $\Delta m(\tilde{e}_\mathrm{R}, \tilde{\chi}^0_1) > 10$	> 94
$m_{\tilde{e}_\mathrm{L,R}} = m_{\tilde{\mu}_\mathrm{L,R}}$, $m_{\tilde{\chi}^0_1} \approx 0$	> 700
$m_{\tilde{\chi}^0_1} >\approx 400$	no LHC limit
$m_{\tilde{\tau}_\mathrm{L}} = m_{\tilde{\tau}_\mathrm{R}}$, $m_{\tilde{\chi}^0_1} \approx 0$	> 390
$m_{\tilde{\chi}^0_1} >\approx 130$	no LHC limit

ATLAS and CMS have searched for direct production of selectron pairs and smuon pairs at the LHC, with each slepton decaying to its corresponding SM partner lepton and the $\tilde{\chi}^0_1$ LSP. In simplified models, ATLAS [133] and CMS [179] set lower mass limits on sleptons of 700 GeV for degenerate $\tilde{\ell}_\mathrm{L}$ and $\tilde{\ell}_\mathrm{R}$, for a massless $\tilde{\chi}^0_1$ and assuming equal selectron and smuon masses, as shown in Fig. 90.6. The limits deteriorate with increasing $\tilde{\chi}^0_1$ mass due to decreasing missing momentum and lepton momentum. As a consequence, no limits are set for $\tilde{\chi}^0_1$ masses above 400 GeV. Limits are also derived without the assumption of slepton mass degeneracy [133, 179]. A dedicated search for sleptons with small mass difference between $\tilde{\ell}$ and $\tilde{\chi}^0_1$ is performed by ATLAS [144] demanding the presence of ISR jets.

ATLAS and CMS have also searched for $\tilde{\tau}$-pair production. In simplified models, ATLAS excludes $\tilde{\tau}$ masses between 120 and 390 GeV assuming light $\tilde{\chi}_1^0$, combining the production of degenerate left- and right-handed $\tilde{\tau}$s [180]. The CMS analysis [181] covers lower masses and closes the mass gap with LEP. No limits are set for $\tilde{\chi}_1^0$ masses above 130 GeV.

In gauge-mediated SUSY breaking models, sleptons can be (co-)NLSPs, *i.e.*, the next-to-lightest SUSY particles and almost degenerate in mass, decaying to a lepton and a gravitino. This decay can either be prompt, or the slepton can have a non-zero lifetime. Combining several analyses, lower mass limits on $\tilde{\mu}_{\rm R}$ of 96.3 GeV and on $\tilde{e}_{\rm R}$ of 66 GeV are set for all slepton lifetimes at LEP [182]. In a considerable part of parameter space in these models, the $\tilde{\tau}$ is the NLSP. The LEP experiments have set lower limits on the mass of such a $\tilde{\tau}$ between 87 and 97 GeV, depending on the $\tilde{\tau}$ lifetime. ATLAS and CMS have searched for final states with τs, jets and missing transverse momentum, and has interpreted the results in GMSB models setting limits on the model parameters [183, 184]. CMS has interpreted a multilepton analysis in terms of limits on gauge mediation models with slepton NLSP [185]. CDF has put limits on gauge mediation models at high $\tan\beta$ and slepton NLSP using an analysis searching for like-charge light leptons and taus [186].

Limits also exist on sleptons in R-parity violating models, both from LEP and the Tevatron experiments. From LEP, lower limits on $\tilde{\mu}_{\rm R}$ and $\tilde{e}_{\rm R}$ masses in such models are 97 GeV, and the limits on the stau mass are very close: 96 GeV [187]. CMS has searched for resonant smuon production in a modified CMSSM scenario [188], putting limits on λ'_{211} as a function of $m_0, m_{1/2}$.

90.6.2 *Exclusion limits on sneutrino masses*

The invisible width of the Z boson puts a lower limit on the sneutrino mass of about 45 GeV. Tighter limits are derived from other searches, notably for gauginos and sleptons, under the assumption of gaugino and sfermion mass universality at the GUT scale, and amount to approximately 94 GeV in the MSSM [189]. It is possible that the lightest sneutrino is the LSP; however, a left-handed sneutrino LSP is ruled out as a cold dark matter candidate [190, 191].

Production of pairs of sneutrinos in R-parity violating models has been searched for at LEP [187]. Assuming fully leptonic decays via λ-type couplings, lower mass limits between 85 and 100 GeV are set. At the Tevatron [192, 193] and at the LHC [188, 194–196], searches have focused on scenarios with resonant production of a sneutrino, decaying to $e\mu$, $\mu\tau$ and $e\tau$ final states. No signal has been seen, and limits have been set on sneutrino masses as a function of the value of relevant RPV couplings. As an example, the LHC experiments exclude a resonant tau sneutrino with a mass below 2.3 TeV for $\lambda_{312} = \lambda_{321} > 0.07$ and $\lambda'_{311} > 0.11$.

The limits on sleptons in simplified models are summarized in Table 90.4.

90.7 Exclusion limits on long-lived sparticles

Long-lived sparticles arise in many different SUSY models. In particular in co-annihilation scenarios, where the NLSP and LSP are nearly mass-degenerate, this is rather common in order to obtain the correct Dark Matter relic density. Prominent examples are scenarios featuring stau co-annihilation, or models of SUSY breaking, e.g. minimal anomaly-mediated SUSY breaking (AMSB), in which the appropriate Dark Matter density is obtained by co-annihilation of the LSP with an almost degenerate long-lived wino. However, in general, also other sparticles can be long-lived and it is desirable to establish a comprehensive search program for these special long-lived cases, which lead to distinct experimental search signatures, including displaced vertices or disappearing tracks, etc.

Past experiments have performed dedicated searches for long-lived SUSY signatures, but given the absence of any experimental evidence for SUSY so far, more effort and focus has gone into such searches at the LHC recently. As for the interpretation of more standard searches for e.g. R-parity conserving SUSY, simplified models are also a convenient tool to benchmark long-lived scenarios (see e.g. [197, 198]).

If the decay of gluinos is suppressed, for example if squark masses are high, gluinos may live longer than typical hadronization times. It is expected that such gluinos will hadronize to long-living strongly interacting particles known as R-hadrons. In particular, if the suppression of the gluino decay is strong, as in the case that the squark masses are much higher than the TeV scale, these R-hadrons can be (semi-)stable in collider timescales. Searches for such R-hadrons exploit the typical signature of stable charged massive particles in the detector. R-hadrons decaying in the detector are searched for using dE/dx measurements and searches for displaced vertices. As shown in the left plot of Fig. 90.7, the ATLAS experiment excludes semi-stable gluino R-hadrons with masses below $1.9-2.3$ TeV for all lifetimes in a simplified model where such gluinos always form R-hadrons, and decay into jets and a light neutralino, by combining a number of analyses [79,199–201]. A combination of CMS searches for long-lived particles, as shown in Fig. 90.8, reaches similar limits [82, 202–204].

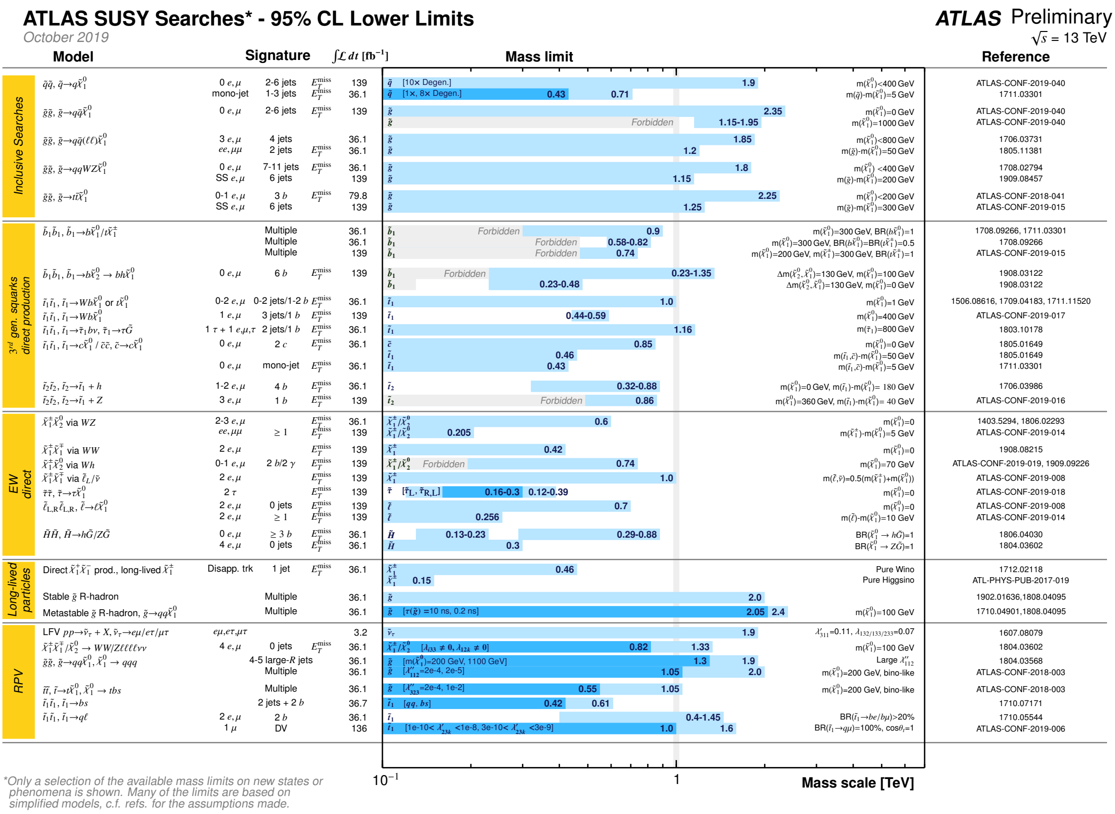

Figure 90.10: Overview of the current landscape of SUSY searches at the LHC. The plot shows exclusion mass limits of ATLAS for different searches and interpretation assumptions. The corresponding results of the CMS experiment are similar.

Alternatively, since such R-hadrons are strongly interacting, they may be stopped in the calorimeter or in other material, and decay later into energetic jets. These decays are searched for by identifying the jets [205–207] or muons [207] outside the time window associated with bunch-bunch collisions. As shown in Fig. 90.8, the CMS collaboration sets limits on such stopped R-hadrons over 13 orders of magnitude in gluino lifetime, up to masses of 1390 GeV [207].

Top squarks can also be long-lived and hadronize to a R-hadron, for example in the scenario where the top squark is the next-to-lightest SUSY particle (NLSP), with a small mass difference to the LSP. Searches for massive stable charged particles are sensitive to such top squarks. Tevatron limits are approximately $m_{\tilde{t}} > 300$ GeV [208,209]. ATLAS sets a limit of 1340 GeV on such top squarks [200], the CMS limits are comparable [204].

In addition to colored sparticles, also sparticles like charginos may be long-lived, especially in scenarios with compressed mass spectra. Charginos decaying in the detectors away from the primary vertex could lead to signatures such as kinked-tracks, or apparently disappearing tracks, since, for example, the pion in $\tilde{\chi}_1^{\pm} \to \pi^{\pm}\tilde{\chi}_1^0$ might be too soft to be reconstructed. At the LHC, searches have been performed for such disappearing tracks, and interpreted within anomaly-mediated SUSY breaking models [210–212]. The right plot of Fig. 90.7 shows constraints for different ATLAS searches on the chargino mass-vs-lifetime plane for an AMSB model ($\tan\beta = 5$, $\mu > 0$) in which a wino-like $\tilde{\chi}^{\pm}$ decays to a soft pion and an almost mass-degenerated wino-like $\tilde{\chi}_1^0$ [200,201,211,212]. For a similar model, CMS excludes $c\tau$ values between 0.15 and 18 m for a chargino mass of 505 GeV [210], see Fig. 90.8. Charginos with a lifetime longer than the time needed to pass through the detector appear as charged stable massive particles. Limits have been derived by the LEP experiments [213], by D0 at the Tevatron [209], and by the LHC experiments [200,214], and such charginos with mass below 1090 GeV are excluded.

In gauge mediation models, NLSP neutralino decays need not be prompt, and experiments have searched for late decays with photons in the final state. CDF have searched for delayed $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ decays using the timing of photon signals in the calorimeter [215]. CMS has used the same technique at the LHC [216]. Results are given as exclusion contours in the neutralino mass versus lifetime plane, and for example in a GMSB model with a neutralino mass of 300 GeV, $c\tau$ values between 10 and 2000 cm are excluded [216]. D0 has looked at the direction of showers in the electromagnetic calorimeter with a similar goal [217], and ATLAS has searched for photon candidates that do not point back to the primary vertex, as well as for delayed photons [218].

Charged slepton decays may be kinematically suppressed, for example in the scenario of a NLSP slepton with a very small mass difference to the LSP. Such a slepton may appear to be a stable charged massive particle. Interpretation of searches at LEP for such signatures within GMSB models with stau NLSP or slepton co-NLSP exclude masses up to 99 GeV [213]. Searches of stable charged particles at the Tevatron [208,209] and at the LHC [200,204] are also interpreted in terms of limits on stable charged sleptons. The limits obtained at the LHC exclude stable staus with masses below 430 GeV when produced directly in pairs, and below 660 GeV when staus are produced both directly and indirectly in the decay of other particles in a GMSB model.

90.8 Global interpretations

Apart from the interpretation of direct searches for sparticle production at colliders in terms of limits on masses of individual SUSY particles, model-dependent interpretations of allowed SUSY parameter space are derived from global SUSY fits. Typically these fits combine the results from collider experiments with indirect constraints on SUSY as obtained from low-energy experiments, flavor physics, high-precision electroweak results, and astrophysical data.

In the pre-LHC era these fits were mainly dominated by indirect constraints. Even for very constrained models like the CMSSM, the allowed parameter space, in terms of squark and gluino masses, ranged from several hundreds of GeV to a few TeV. Furthermore, these global fits indicated that squarks and gluino masses in the range of 500 to 1000 GeV were the preferred region of parameter space, although values as high as few TeV were allowed with lower probabilities [219–226].

With ATLAS and CMS now probing mass scales around 1 TeV and beyond, the importance of the direct searches for global analyses of allowed SUSY parameter space has increased. For example, imposing the new experimental limits on constrained supergravity models pushes the most likely values of first generation squark and gluino masses significantly beyond 2 TeV, typically resulting in overall values of fit quality much worse than those in the pre-LHC era [150–152,174,227–234].

Also the measured value of m_h pushes the sparticle masses upwards. Although these constrained models are not yet ruled out, the extended experimental limits impose very tight constraints on the allowed parameter space.

For this reason, the emphasis of global SUSY fits has shifted towards less-constrained SUSY models. Especially interpretations in the pMSSM [172–176, 214, 227] but also in simplified models have been useful to generalize SUSY searches, for example to redesign experimental analyses in order to increase their sensitivity for compressed spectra, where the mass of the LSP is much closer to squark and gluino masses than predicted, for example, by the CMSSM. As shown in Table 90.2, for neutralino masses above $0.5-1$ TeV the current set of ATLAS and CMS searches, interpreted in simplified models, cannot exclude the existence of squarks or gluinos with masses only marginally above the neutralino mass. However, as these exclusion limits are defined in the context of simplified models, they are only valid for the assumptions in which these models are defined.

As an alternative approach, both ATLAS [172] and CMS [173] have performed an analysis of the impact of their searches on the parameter space of the pMSSM. Fig. 90.9 shows graphically the LHC exclusion power in the pMSSM based on searches performed at $\sqrt{s} = 7$ and 8 TeV. The plot on the left shows the survival probability in the gluino-neutralino mass plane, which is a measure of the parameter space that remains after inclusion of the relevant CMS search results. As can be seen, gluino masses below about 1.2 TeV are almost fully excluded. This result agrees well with the typical exclusion obtained at 8 TeV in simplified models for gluino production. However, as shown in the right plot of Fig. 90.9, when a similar analysis for other sparticles is performed it becomes apparent that exclusions on the pMSSM parameter can be significantly less stringent than simplified model limits might suggest. This is especially apparent for the electroweak sector, where even at rather low masses several of the pMSSM test points still survive the constraint of ATLAS searches at $\sqrt{s} = 7$ and 8 TeV. This again indicates that care must be taken when interpreting results from the LHC searches and there are still several scenarios where sparticles below the 1 TeV scale are not excluded, even when considering the most recent results at $\sqrt{s} = 13$ TeV.

Furthermore, the discovery of a Higgs boson with a mass around 125 GeV has triggered many studies regarding the compatibility of SUSY parameter space with this new particle. Much of it is still work in progress and it will be interesting to see how the interplay between the results from direct SUSY searches and more precise measurements of the properties of the Higgs boson will unfold in the future.

90.9 Summary and Outlook

The absence of any observation of new phenomena at the first run of the LHC at $\sqrt{s} = 7/8$ TeV, and after the second run at $\sqrt{s} = 13$ TeV, place significant constraints on SUSY parameter space. Today, inclusive searches probe production of gluinos at about 2.3 TeV, first and second generation squarks in the range of about 1 to 1.9 TeV, third generation squarks at scales around 600 GeV to 1.2 TeV, electroweak gauginos at scales around $400 - 1100$ GeV, and sleptons around 700 GeV. However, depending on the assumptions made on the underlying SUSY spectrum these limits can also weaken considerably.

With the LHC having reached almost its maximum energy of about $\sqrt{s} = 14$ TeV, future sensitivity improvement will have to originate from more data, the improvement of experimental analysis techniques and the focus of special signatures like the one arising in long-lived sparticle decays. Therefore, it is expected that the current landscape of SUSY searches and corresponding exclusion limits at the LHC, as, for example, shown in Fig. 90.10 from the ATLAS experiment [235] (CMS results are similar [236]), will not change as rapidly anymore as it did in the past, when the LHC underwent several successive increases of collision energy.

The interpretation of results at the LHC has moved away from constrained models like the

CMSSM towards a large set of simplified models, or the pMSSM. On the one hand this move is because the LHC limits have put constrained models like the CMSSM under severe pressure, while on the other hand simplified models leave more freedom to vary parameters and form a better representation of the underlying sensitivity of analyses. However, these interpretations in simplified models do not come without a price: the decomposition of a potentially complicated reality in a limited set of individual decay chains can be significantly incomplete. Therefore, quoted limits in simplified models are only valid under the explicit assumptions made in these models. The recent addition of more comprehensive interpretations in the pMSSM will complement those derived from simplified models and, thus, will enable an even more refined understanding of the probed SUSY parameter space.

In this context, the limit range of $1.5-2.3$ TeV on generic colored SUSY particles only holds for light neutralinos, in the R-parity conserving MSSM. Limits on third generation squarks and electroweak gauginos also only hold for light neutralinos, and under specific assumptions for decay modes and slepton masses.

The next LHC runs at $\sqrt{s}=13$ or 14 TeV with significantly larger integrated luminosities (notably the High-Luminosity LHC), will provide a large data sample for future SUSY searches. As mentioned above, the improvement in sensitivity will largely have to come from a larger data set, and evolution of trigger and analysis techniques, since there will be no significant energy increase at the LHC anymore. Although the sensitivity for colored sparticles will increase somewhat as well, the expanded data set will be particularly beneficial for electroweak gaugino searches, and for the more difficult final states presented by compressed particle spectra, stealth SUSY, long-lived sparticles, or R-parity violating scenarios.

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