

- Sneutrinos: From LEP we have an indirect limit of $m_{\tilde{\nu}} > 94$ GeV (DELPHI 2003) in neutralino & slepton searches. This assumes $m_{\tilde{e}_R} - m_{\tilde{\chi}_1^0} > 10$ GeV. From the Z-width we can obtain the model independent limit $m_{\tilde{\nu}} > 44.7$ GeV.
- Neutralino: The limit $m_{\tilde{\chi}_1^0} > 46$ GeV (DELPHI 2003) has been derived from the direct searches for $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \tilde{\chi}_2^0$. This assumes gauge coupling unification and a common gaugino mass $m_{1/2}$ at GUT scale. Even in the Z-decays, the contribution to the width depends on the higgsino component of the lightest neutralino, so $m_{\tilde{\chi}_1^0} \simeq 0$ GeV is still in principle allowed [20].
- Here we have $m_{\tilde{\chi}_1^\pm} \geq 94$ GeV (DELPHI 2003), assuming GUT scale universality of m_0 and $m_{1/2}$ and using multiple direct search channels from production of charginos, neutralinos and sleptons. It also assumes either no third generation sfermion mixing or $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} > 6$ GeV. From the Z-width we can extract a strict limit of $m_{\tilde{\chi}_1^\pm} \geq 45$ GeV.

7.3 Supersymmetry at hadron colliders

Since the particles collided at hadron colliders (protons and other nuclei) are heavier they are not as susceptible to losing energy through bremsstrahlung as the light leptons. Thus they can more readily be accelerated in a circular collider with periodic acceleration. However, this mass both means that linear colliders are inappropriate since the acceleration is smaller for the same applied fields, and that it is more difficult to steer the hadrons in a circular orbit. Thus the energy available at a hadron collider is limited by the strength of the bending magnets.

Up to 2009 the highest energy hadron collider was the Tevatron based at Fermilab outside of Chicago, that collided protons and anti-protons at $\sqrt{s} = 1.96$ TeV. The current record is held by the Large Hadron Collider (LHC) at CERN, colliding protons at a top energy of $\sqrt{s} = 13$ TeV.⁵

Since a proton-proton collider mostly collides partons, the quarks and gluons inside the protons, and since the strong coupling is large, this means that we can get large cross sections and potentially many events for QCD charged sparticles, *i.e.* squarks and gluinos, provided their masses are low enough. Cross sections for particles that have only electroweak charges (sleptons, electroweakinos, Higgs bosons) are expected to be considerably smaller, however, these sparticles are also expected to be lighter. The balance between these factors means that both types of sparticles are searched for.

As discussed earlier, with R-parity conservation sparticles are produced in pairs and both decay to the LSP. In Fig. 7.8 we show the sparticle mass spectrum for a particular mSUGRA benchmark point called SPS1a that has $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $A_0 = -100$ GeV, $\tan \beta = 10$ and $\text{sgn } \mu = +$ [21].⁶ By producing the squarks or gluinos near the top of the mass spectrum in a collision we see that we can get many different quite long decay chains, called cascades. We illustrate such an event in Fig. 7.9.

In hadron collisions the momenta of the incoming partons is unknown, so no complete momentum balance can be made. However, the sum of the momenta in the direction transverse

⁵The LHC was designed to operate at $\sqrt{s} = 14$ TeV, but has had problems fully reaching that energy. In the next round of the LHC to start in 2022, called Run III, the plan is to go to $\sqrt{s} = 13.5$ TeV.

⁶This benchmark point is now quite old and clearly excluded by searches, but it still serves as a nice illustration of the kind of sparticle spectrum expected in mSUGRA models.

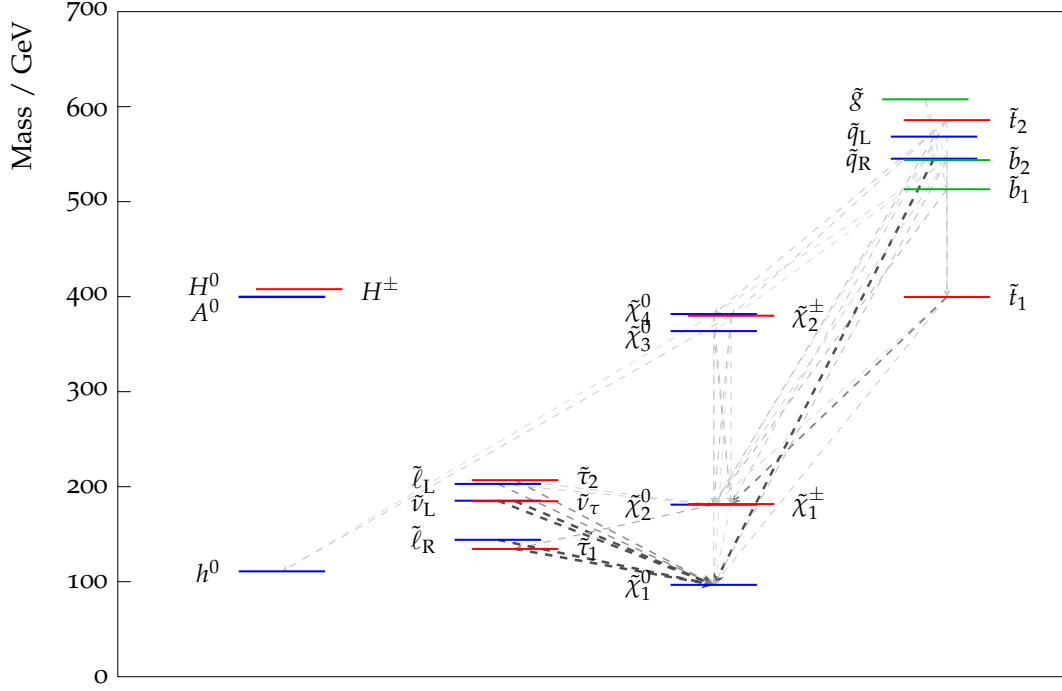


Figure 7.8: Supersymmetric particle mass spectrum (coloured solid lines) and possible decay channels (dashed lines) for the SPS1a benchmark point. Only decays with branching ratios above 5% are shown. The line opacity indicates relative branching ratios. This plot was generated using PySLHA 3.0.1 [22].

to the beam direction is zero. Thus with escaping LSPs we can observe **missing transverse energy**, $\cancel{E}_T$ or E_T^{miss} , *i.e.* an imbalance in the directional sum of all energy deposits transverse to the beam direction. The rest of the signal depends on which particles are searched for. In broad terms this means that if searching for gluino or squark production then at some point the cascade decay must shed colour charge to arrive at the LSP, resulting in Standard Model quarks or gluons that hadronise and produce jets in the detector (hadronic showers). If instead searching for electroweakly produced particles or Higgs bosons, one usually assumes an absence of significant jet activity, and instead looks for leptons from the decays of the sleptons or electroweakinos, possibly through vector bosons.

At the LHC the Standard Model backgrounds are much more significant and problematic. For example, at design luminosity the LHC produces about 10 pairs of top quarks per second. Due to the top quark decay $t \rightarrow bW^+$, resulting in charged leptons and potential missing energy from neutrinos in W decays, as well as jets produced in hadronic W decays and from the b -quarks, this alone is a significant background to many supersymmetry searches. Figure 7.10 shows the expected backgrounds and signals produced in different channels at the $\sqrt{s} = 14$ TeV LHC for different assumed particle masses. One can see that even the largest supersymmetric cross sections that we get for squark and gluino production are orders of magnitude below the Standard Model backgrounds for masses beyond 500 GeV.

To cope with this challenge, the searches define kinematical variables that are designed to separate supersymmetry events from Standard Model events. For example, searching for the production of squarks and/or gluinos decaying to the LSP, one expects jets and missing

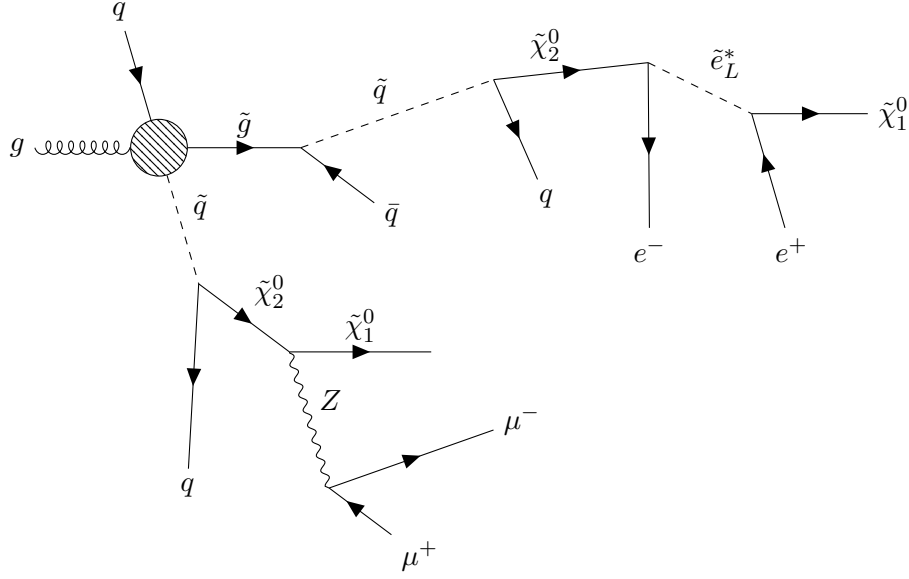


Figure 7.9: Cascade decays starting with the production of a gluino and squark pair from a gluon–quark interaction.

energy from two LSPs. One can then define the **effective mass**

$$M_{\text{eff}} = \sum p_T^{\text{jet}} + \cancel{E}_T, \quad (7.12)$$

from the sum of the transverse momentum of the jets in the event, p_T , and the missing energy. The expectation is then that this is more significant in squark and gluino production events than in Standard Model events, so that a high requirement on M_{eff} reduces the number of background events without significantly removing events with sparticles. This helps for example to combat $t\bar{t}$ production because the jet p_T s in those events are limited by the energy in the top quark mass, while the more massive squarks and gluinos will have higher jet p_T s.

However, there are also models where this kind of approach is ineffective. Imagine a scenario where only the lightest stop $\tilde{t}_1$ is light enough to be copiously produced. If $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} < m_W$ then the stop will dominantly decay as $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ or $\tilde{t}_1 \rightarrow b\nu\tilde{\chi}_1^0$, where all final state particles have rather low energy (p_T), so-called **soft particles**. As for the degenerate neutralino scenario discussed above, this is very difficult to discover with standard techniques.

Another example of the use of kinematics is the distribution of invariant masses. In Fig. 7.11 we show an example of two sequential two-body decays. Even if particle A here is invisible, for example the LSP, we can use two visible decay products a and b to form the invariant mass m_{ab} . One can show that the distribution for m_{ab} has a triangular shape with a sharp endpoint at the maximum

$$(m_{ab}^{\text{max}})^2 = \frac{(m_C^2 - m_B^2)(m_B^2 - m_A^2)}{m_B^2}, \quad (7.13)$$

where we have assumed that a and b are massless.⁷ This can be used both to select events that potentially have supersymmetric particles in them depending on the value of the invariant

⁷A more complicated expression covers the massive case.

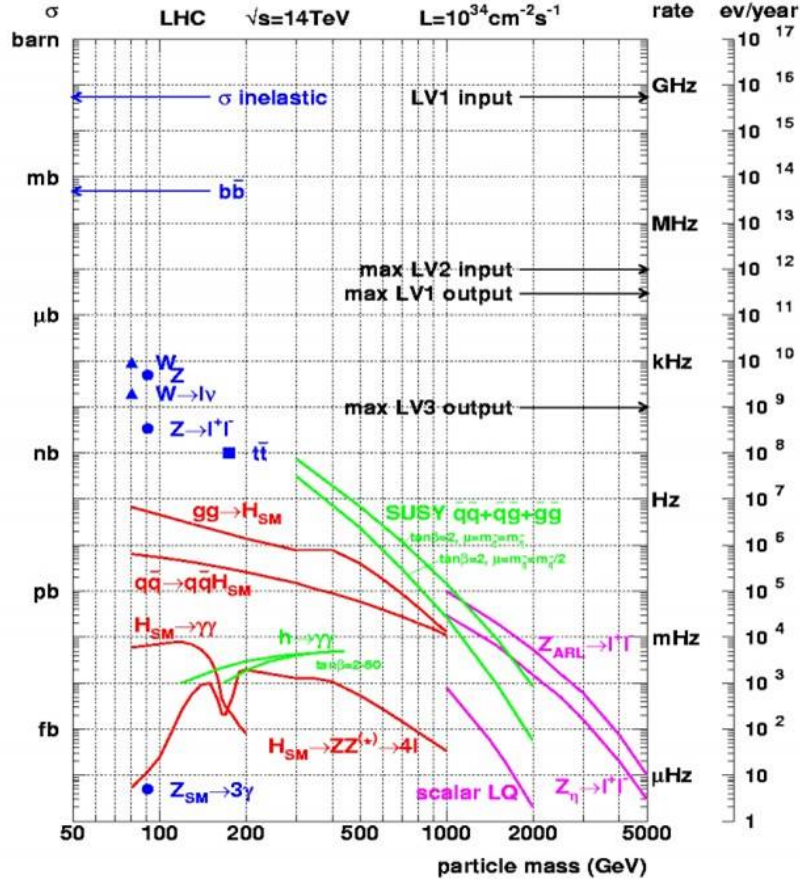


Figure 7.10: Plot of the expected cross sections and rates for various processes at the $\sqrt{s} = 14$ TeV LHC plotted against the mass of the particles, assuming the design final luminosity of the LHC (rate of data taking). The current Run II of the LHC has collected around 140 fb^{-1} of data, so the lowest point on the cross section axis indicates that $\mathcal{O}(1)$ events are expected to have been produced by now.

mass, and to determine relationships between the particle masses. In Fig. 7.12 we show a simulation of the invariant mass distribution of two opposite-sign same-flavour (OSSF) leptons $m_{\ell\ell}$ from the production of $\tilde{\chi}_2^0$ and its decay chain $\tilde{\chi}_2^0 \rightarrow \ell^\pm \tilde{\ell}_R^\mp \rightarrow \ell^\pm \ell^\mp \tilde{\chi}_1^0$.

As alternatives to these standard searches for pair produced particles with missing energy there are ongoing searches for decaying LSPs when R-parity is violated, or the production of single particles.⁸ There is also the possibility of **massive metastable charged particles** (MMCPs), typically in scenarios with a gravitino LSP, where the next-to-lightest supersymmetric particle (NLSP) is charged and long-lived because the decay to the gravitino is via a very weak gravitational coupling. The latter also includes so-called **R-hadrons** if the NLSP has colour charge, which means that it will hadronise after production and be a short-lived but very massive meson or baryon. We should also mention the searches for the extra Higgs

⁸Single particle production at the LHC requires rather large R-parity violating couplings for the $LQ\bar{D}$ or $\bar{U}\bar{D}\bar{D}$ operators, of the order of $\lambda > 10^{-2}$.

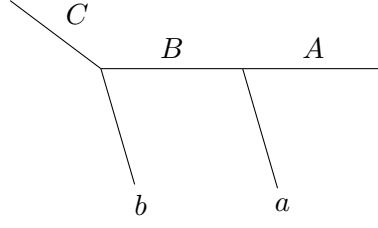


Figure 7.11: A generic illustration of two successive two-body decays $C \rightarrow bB$ and $B \rightarrow aA$.

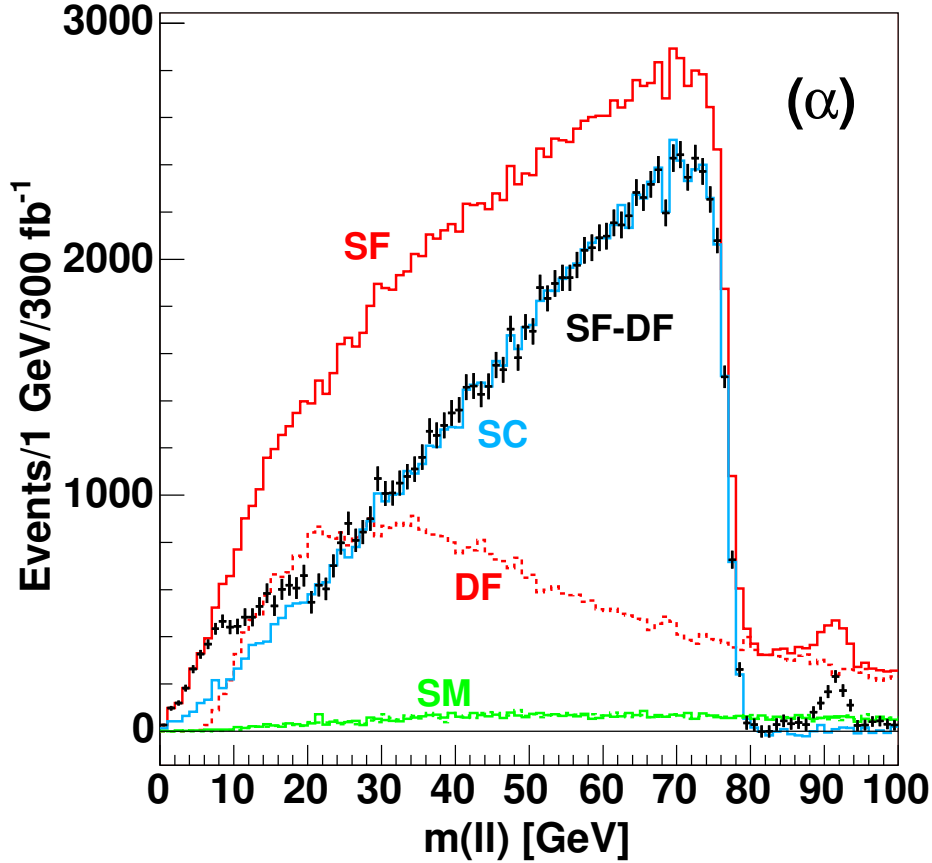


Figure 7.12: Invariant mass distribution of opposite sign same flavour (OSSF) dileptons for the mSUGRA benchmark model point SPS1a [23].

states predicted in the MSSM.⁹

7.4 Current bounds on sparticle masses

The LHC has finished its Run II and collected a total of around 140 fb⁻¹ of data per experiment at $\sqrt{s} = 13$ TeV of energy. It is currently preparing for Run III to start in 2022. Direct bounds from the LHC experiments ATLAS and CMS now supersede bounds from other colliders (Tevatron and LEP) in almost all channels, with some exceptions for models

⁹But we don't really have time.

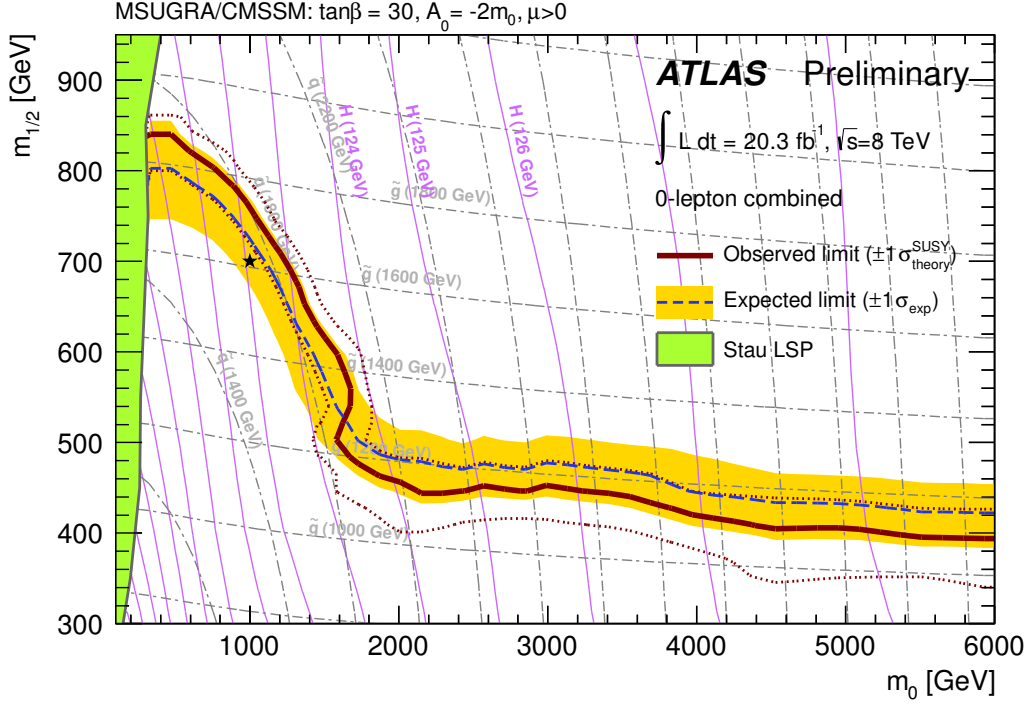


Figure 7.13: Plot of the excluded area in the $m_{1/2}$ - m_0 plane of the mSUGRA parameter space for $\tan\beta = 30$, $A_0 = -2m_0$ and $\mu > 0$ for searches using missing energy and jets. The limit is the red line. The green area is theoretically forbidden because it has a charged LSP (the stau) [24].

with degenerate masses. The below limits are mostly limits with the full Run II dataset and represent the current state-of-art in sparticle searches. We mostly use examples from ATLAS, the corresponding plots from CMS are very similar.

The strongest current limits in terms of mass are on the gluino and squarks simply because of the large production cross sections. Significant bounds on electroweakinos and sleptons exist, but these are either model dependent (depend on squark/gluino mass assumptions and cascade decays), or weaker if they rely only on electroweak production.

7.4.1 Squarks and gluinos

In Fig. 7.13 we show the limits from the ATLAS experiment on the mSUGRA model using searches for jets plus missing energy with all the data collected at 8 TeV. The mSUGRA parameters $\tan\beta$ and A_0 have been chosen in order to give relatively large Higgs masses for small values of $m_{1/2}$ and m_0 . The figure also shows the corresponding first and second generation squark masses, the gluino mass (both dot-dashed lines), and the Higgs mass (purple) for these parameter values. We then have the following approximate bounds in mSUGRA: $m_{\tilde{q}} > 1600$ GeV and $m_{\tilde{g}} > 1100$ GeV. Bounds on the mSUGRA space directly have not been updated since this plot.

Notice that in the figure the squark mass bound is more or less equivalent to the mass required for a sufficiently heavy Higgs, thus the direct search does not constrain the squarks

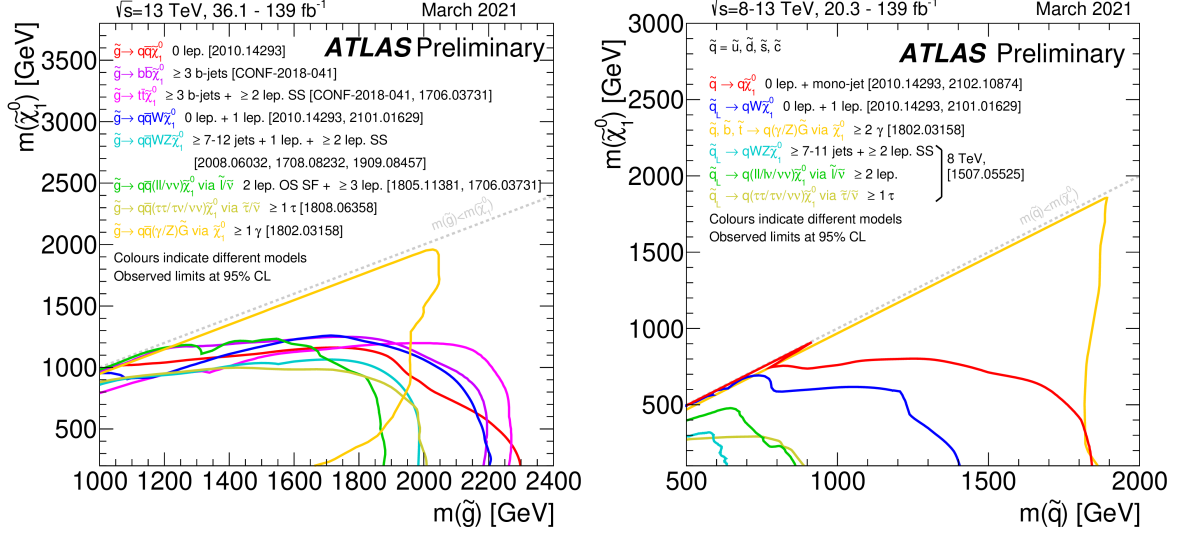


Figure 7.14: Excluded regions in the $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ (left) and $(m_{\tilde{q}}, m_{\tilde{\chi}_1^0})$ (right) mass planes under different assumptions on the decays of the gluino and squarks [25]. References for the individual analysis given in the figure.

masses significantly more here than the indirect constraint from the Higgs mass.

An important question is how these bounds change as we move away from the mSUGRA assumptions. In mSUGRA the resulting gluino and squark decays are very much constrained by the model. For more general models the limits depend on what decay chains are dominant. In Fig. 7.14 we show current limits in the gluino–lightest neutralino and squark–lightest neutralino mass planes under various assumptions on the decay chain shown in different colours.

For the gluino the most minimal assumption we can make is that the gluino sheds its adjoint colour charge in the decay to two quarks of the first or second generation and a neutralino, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$, either by a direct three-body decay or via an intermediary squark (red line). We then get limits up to $m_{\tilde{g}} > 2300$ GeV under the assumption of a very light neutralino. This limit gradually weakens as the neutralino mass increases, and disappears beyond $m_{\tilde{\chi}_1^0} > 1000$ GeV for $m_{\tilde{g}} > 1000$ GeV. For $m_{\tilde{g}} < 1000$ GeV (not visible on the plot) most of the parameter space is excluded, with the exception that a small sliver remains when $m_{\tilde{g}} \simeq m_{\tilde{\chi}_1^0}$ in the degenerate scenario.

For the first two generations of squarks the most minimal decay is $\tilde{q} \rightarrow q\tilde{\chi}_1^0$. Here the bound (red) reaches to around $m_{\tilde{q}} > 1800$ GeV for a light neutralino, while for heavier neutralinos the bound disappears beyond $m_{\tilde{\chi}_1^0} > 700 - 800$ GeV for $m_{\tilde{q}} > 800$ GeV. Below a squark mass of around 800 GeV most of the parameter space is excluded, but we again lose sensitivity when there is degeneracy between the squark and the neutralino. Here a search for mono-jets has some impact in closing the gap, which shows as a spike in the excluded region between 800 and 900 GeV, however, despite poor visibility in the plot, a very degenerate squark–neutralino pair is still allowed below 800 GeV.

An additional assumption made in this plot is that all the eight squarks of the first two-generations are degenerate in mass and adding to the cross section. Should one squark

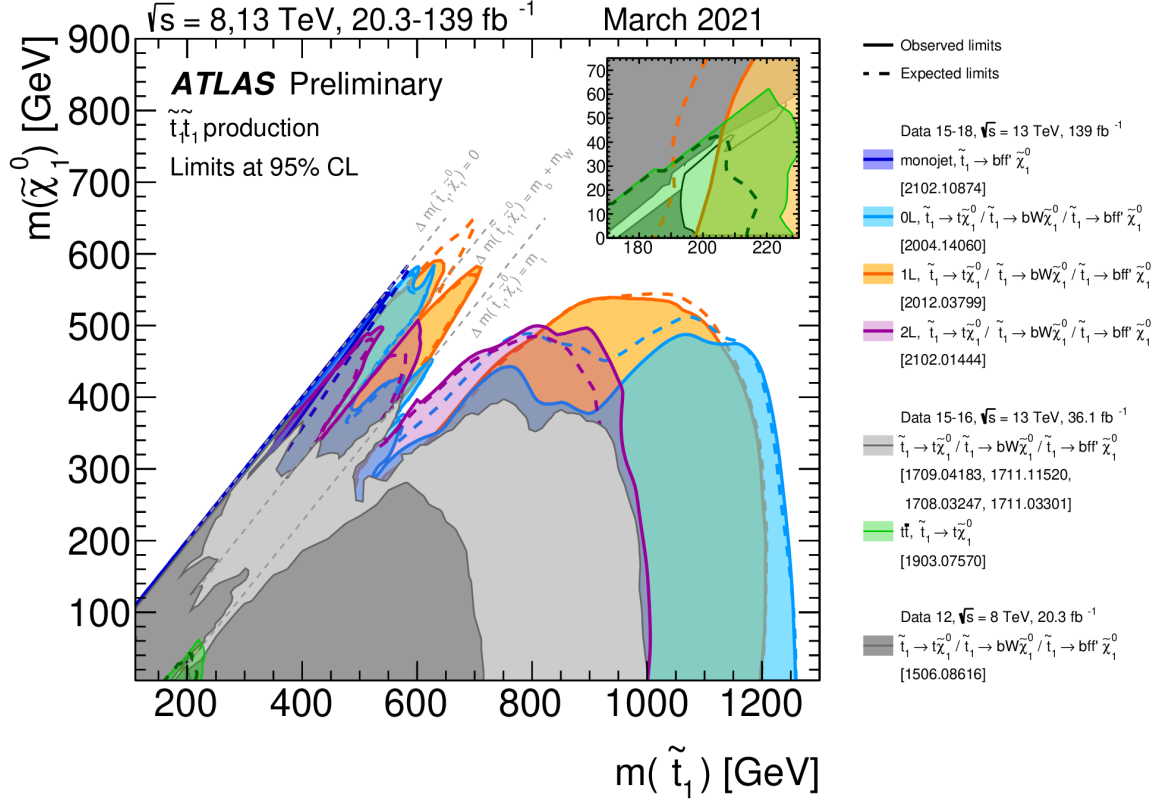


Figure 7.15: Plot of the excluded area in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ mass plane [25]. References for the individual analysis given in the figure.

generation or flavour be significantly lighter than the others this means a further reduction in the production cross section and thus a weaker bound. It is also fairly clear that removing R-parity, meaning that the LSP decays, also weakens the above conclusions due to the possible absence of significant missing energy.

7.4.2 Stop

For the stop there are many possible competing decay channels, meaning that limits set are rather model dependent. The two main decay categories for the lightest stop are decays via the chargino, $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$, a supersymmetrised version of the Standard Model $t \rightarrow bW^+$, and decays directly to the neutralino $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / bW\tilde{\chi}_1^0 / b\tilde{f}'\tilde{\chi}_1^0$, where $f\tilde{f}'$ represents the fermions in a W decay, and where the dominant decay mode depends on the stop–neutralino mass difference. Since the chargino decay is also typically $\tilde{\chi}_1^+ \rightarrow f\tilde{f}'\tilde{\chi}_1^0$, the experimental signature of stop production is $b\tilde{f}'\tilde{\chi}_1^0$, a mixture of missing energy, fermions that may either be leptons or result in jets, and a b -quark that forms a jet with distinct properties, called a b -jet.

A summary of (the many) ATLAS searches for the stop is found in Fig. 7.15 showing limits in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ mass plane. The dashed grey lines show the regions where the different stop decays are kinematically possible. We observe that for light neutralinos the limit goes all the

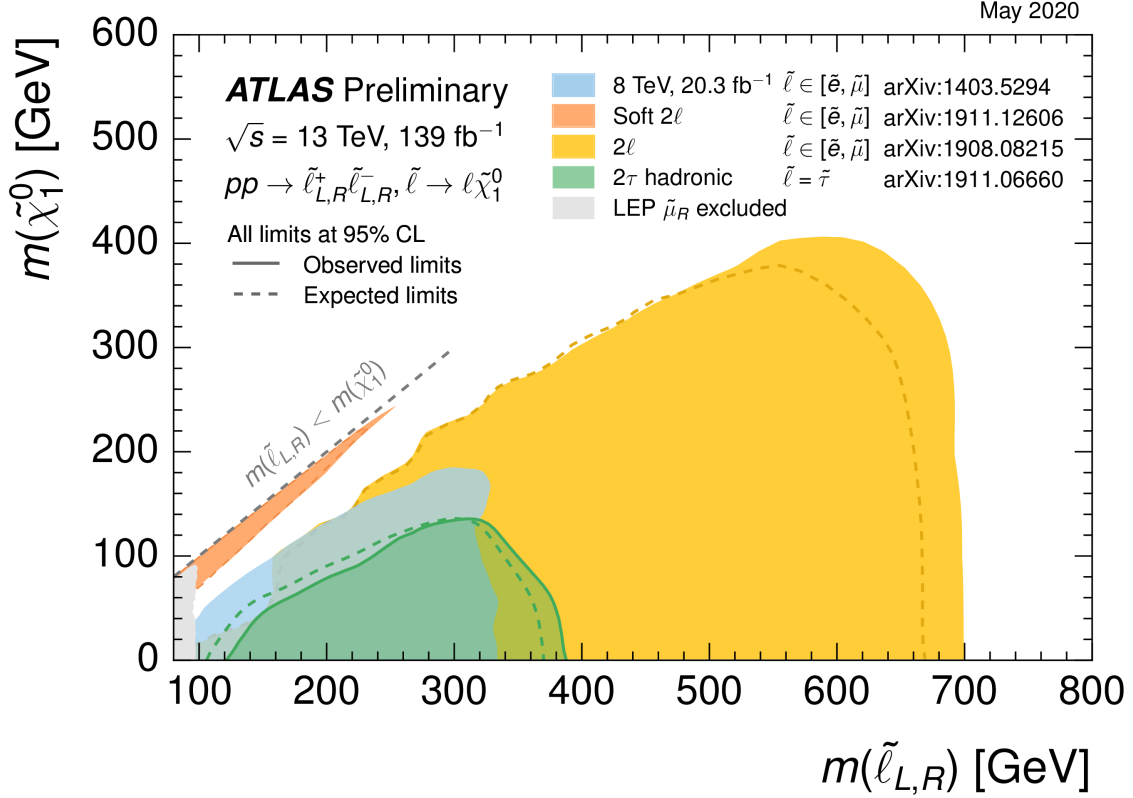


Figure 7.16: Plot of the excluded area in the $(m_{\tilde{\ell}_{L,R}}, m_{\tilde{\chi}_1^0})$ plane for mass degenerate right- and left-handed sleptons of different flavours [25].

way up to $m_{\tilde{t}_1} > 1250 \text{ GeV}$, while there are essentially no limits for $m_{\tilde{\chi}_1^0} > 580 \text{ GeV}$. Again degenerate scenarios have weaker bounds. When the stop approaches the neutralino plus top mass stop masses down to 600 GeV are allowed. And, again not very visible, for a degenerate stop-neutralino the limit is virtually non-existent. As an additional complication, if the stop-neutralino mass difference is below the bottom quark mass, the standard stop decays no longer work and the flavour changing neutral current decay $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ becomes dominant. This decay has multiple still open theoretical questions, both about the potentially long lifetime of the stop in this scenario, and exactly where in parameter space this transition occurs.

7.4.3 Sleptons

The mass bounds on sleptons will be very dependent on the assumed production mechanism. If the sleptons are produced indirectly in cascade decays from heavier squarks or gluinos they could have large cross sections, however, the most model independent bounds come from assuming only direct electroweak pair production through a virtual photon or Z .

The result for degenerate right- and left-handed charged sleptons from electroweak production, assuming decays with 100% branching ratio to the lightest neutralino, are shown in Fig. 7.16. These limits separate between selectron and smuon production, and stau production. The former are assumed degenerate, and have stricter bounds than the stau, which is harder to reconstruct due to the many different possible tau decays involving extra neutrinos.

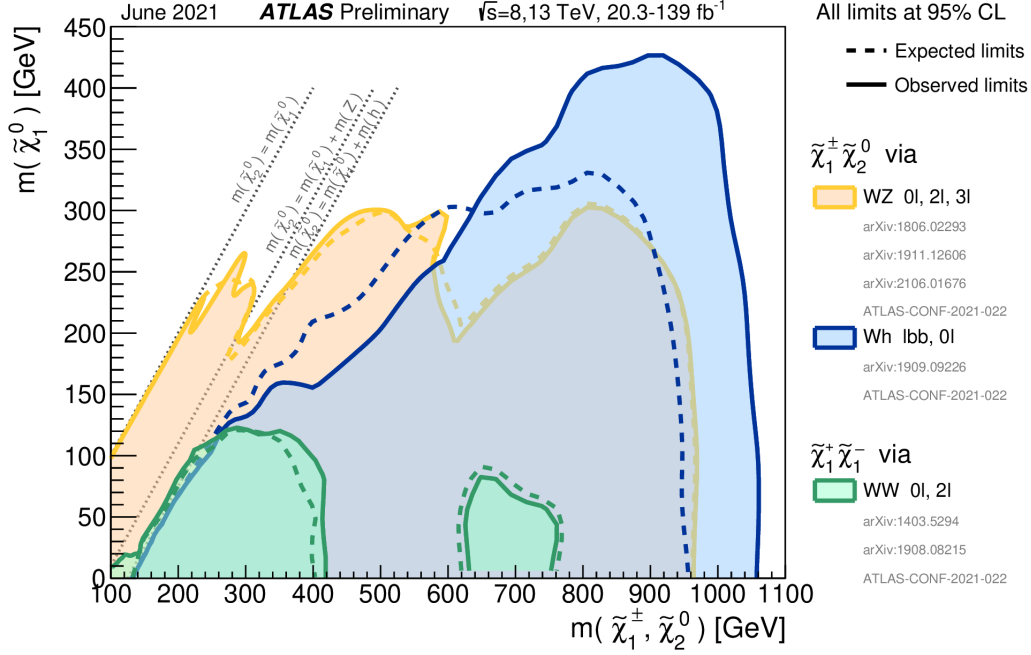


Figure 7.17: Plot of the excluded area in the $(m_{\tilde{\chi}_1^\pm, \tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0})$ mass plane for different search signatures [25]. This plot assumes a degenerate wino-like $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ and a 100% branching ratio to the given decay channels.

nos. For all slepton flavours we see that there is a gap in the mass plane down to very low masses where no sleptons are excluded, all the way down to masses below 100 GeV where the LEP bound applies. This is yet another example of the problems with degeneracy. If the slepton–neutralino mass difference is around 50 GeV and lower, it becomes difficult to reliably reconstruct the soft leptons from the slepton decay and to separate them from the ordinary Standard Model pair production of lepton pairs.

7.4.4 Charginos and neutralinos

As for the sleptons, bounds are dependent on the production process assumed. The search for direct electroweak pair production of the lightest neutralino, $\tilde{\chi}_1^0 \tilde{\chi}_1^0$, has the same problem as at LEP, the coupling is vanishingly small for a non-higgsino $\tilde{\chi}_1^0$. This means that it is the heavier neutralinos and charginos that are typically searched for. Here some considerations on the possible masses hierarchies come into play. If the lightest neutralino is dominantly bino and the next-to-lightest dominantly wino ($M_1 < M_2 < |\mu|$) then the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ states are degenerate in mass and the most important searches will be for $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production.¹⁰ These then decay as $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$ or $\tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0$, and $\tilde{\chi}_1^\pm \rightarrow W \tilde{\chi}_1^0$, where the bosons may be off-shell if the mass difference is small. This is the scenario usually considered by the experiments, in part because winos give the largest electroweak production cross sections.

¹⁰Again because of the coupling in Eq. (7.11) the production of a pair of wino-like $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ is suppressed and the cross section is small.

We show the current limits assuming degenerate wino-like states $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ in Fig. 7.17. We can see that limits up to 1050 GeV can be set for $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ when the lightest neutralino is below around 200 GeV. When the bosons in the decay go off-shell we see that the sensitivity of the searches go down significantly. If we move away from the wino-production scenario the production cross sections drop, and so does the reach of the experiments in the mass plane.

An additional important complication appears if the lightest neutralino is wino ($M_2 < M_1, |\mu|$) or higgsino ($|\mu| < M_1, M_2$). Then the lightest neutralino and chargino, $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ (for higgsinos also $\tilde{\chi}_2^0$), are degenerate, and the crucial question becomes how degenerate they are. If the mass difference is small but above around 300 MeV, then the particles are very difficult to discover at all, despite potentially having very large cross sections if they are light. The decays of the produced $\tilde{\chi}_1^\pm$ (and for higgsinos $\tilde{\chi}_2^0$) into $\tilde{\chi}_1^0$ lead to very soft decay products, either leptons in $\tilde{\chi}_1^\pm \rightarrow \ell^\pm \nu_\ell \tilde{\chi}_1^0$ (and $\tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$), or decays to pions (the lightest hadronic states) $\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$ (and $\tilde{\chi}_2^0 \rightarrow \pi^0 \tilde{\chi}_1^0$), that are unobservable above the backgrounds of a hadron collider.

If instead the mass difference becomes of the order of or less than the pion mass the width of the chargino can become so small that the state is sufficiently long lived to decay somewhere inside the detector, and not, effectively, at the interaction point. This would lead to charged tracks from the charginos that disappear somewhere inside the detector. Such disappearing track signatures are readily observable, and in fact the limits on very degenerate neutralinos and charginos are stronger than the limits on only somewhat degenerate ones.

The consequences of this complication is that it is very difficult to exclude near massless wino- or higgsino-like charginos and neutralinos at the LHC. However, since the chargino mass is constrained by the Z -width measured at LEP, there is an absolute lower limit of 45 GeV for both in this scenario. To improve significantly on this limit one may have to wait for a new lepton collider.

7.5 Precision observables

A different way to exclude supersymmetric models is their indirect effect on very accurately measured SM processes, so-called precision observables, through loop diagrams with sparticles. We will here discuss four of the most sensitive probes: electroweak precision observables, the value of the anomalous magnetic moment of the muon $(g-2)_\mu$, the flavour changing neutral current (FCNC) process $b \rightarrow s\gamma$ and the very rare (and FCNC) process $B_s \rightarrow \mu\mu$.

7.5.1 Electroweak precision observables

When we talk about electroweak precision observables, we study parameters such as M_W (or M_Z), Γ_W , Γ_Z , m_t and $\sin\theta_W$, as well as the Higgs mass m_h and the properties of the Higgs such as its couplings to all the other particles (gauge and Yukawa couplings) and its self-coupling.

Up to last year we studied all of these as *functions* of the unknown Higgs mass, looking for deviations that could be a sign of supersymmetry. We show a fit to all available electroweak data and direct exclusion bounds in Fig. 7.18 by the **Gfitter** collaboration just before the LHC started taking data, a fit pretty much indicating that the most probable SM Higgs mass was 125 GeV.

Figure 7.19 shows a similar plot for mSUGRA. At that time the absolute minimum of the fit, even taking into account the different number of parameters, gave a better fit