How light can sleptons be?

Even S. Håland

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Abstract

Several searches for production of sleptons has been performed in collider experiments such as the currently running LHC, and its predecessor LEP. In this article we investigate the limits on the slepton mass(es) set by these experiments, with special emphasis on how light sleptons are allowed to be with the current limits. We also take a look at the models used in these searches, how these compare to the MSSM, and how the limits from these searches can be related to the sleptons in the MSSM.

1 Introduction

The Minimal Supersymmetric Standard Model (MSSM) is the smallest possible supersymmetric of the Standard Model (SM). Roughly explained the MSSM introduces one superpartner for each SM particle (with some complications in the Higgs sector), and the SM particles and their superpartners (often called sparticles) differ by $\frac{1}{2}$ in spin. The sparticles we will focus on here are the superpartners of the SM leptons, which are scalar (i.e. spin-0) particles called *sleptons*, and we will focus mainly on the first two generations of charged sleptons, i.e. selectrons ($\tilde{e}$) and smuons ($\tilde{\mu}$).

In particle collider experiments, such as the Large Electron-Positron Collider (LEP) and the currently running Large Hadron Collider (LHC), several searches for production of sleptons have been done, but so far without any sign of their existence. The consequence of such "negative" searches is usually that new limits are put on the masses of the relevant sparticles (or other parameters).

In this article we will try to summarize the current status of the limits on the selectron and smuon masses. However, since the MSSM is a quite complicated model with 105 free parameters, one has to make assumptions and simplifications when setting limits, and these are (of course!) somewhat different from analysis to analysis. We will therefore also take a look at which assumptions are made in the different analyses. But before all this, let us look at how sleptons are described in the MSSM.

2 Sleptons in the MSSM

As mentioned in the introduction the sleptons are the scalar superpartners of the SM leptons. In the SM there is an important difference between left- and right-handed chiral states, in that the left-handed leptons are organized in weak isospin doublets, while the right-handed ones are singlets (i.e. they do not transform under $SU(2)_L$). This mean that, when constructing a supersymmetric theory, we need to introduce separate superpartners for the left- and right-handed leptons. For this reason we talk about left- and right-handed sleptons ($\tilde{\ell}_L$ and $\tilde{\ell}_R$) even though they are scalar particles.

This has some consequences when we are breaking SUSY. As we know, SUSY must be a broken symmetry, since otherwise particles and sparticles would have equal masses, meaning that SUSY would have been discovered a long time ago. For the first two generations of (charged) sleptons (neglecting the Yukawa coupling) the mass is given as

$$m_{\tilde{\ell}}^2 = m_\ell^2 + (T_3 - Q\sin^2\theta_W)\cos 2\beta m_Z^2, \tag{1}$$

where m_ℓ is the mass of the corresponding SM lepton, T_3 is weak isospin, Q is electric charge, θ_W is the Weinberg angle, β is given by the ration between the vacuum expectation values of the two Higgs doublets of the MSSM, and m_Z is the mass of the Z-boson. Interesting to notice is that $m_{\tilde{\ell}}$ depends on weak isospin, which is different for $\tilde{\ell}_L$ ($T_3 = -1/2$) and $\tilde{\ell}_R$ ($T_3 = 0$), meaning that their masses are different. The mass difference is given by

$$m_{\tilde{\ell}_L}^2 - m_{\tilde{\ell}_R}^2 = -\frac{1}{2}\cos 2\beta m_Z^2. \tag{2}$$

By convention we have $0 < \beta < \frac{\pi}{2}$, and it is (apparently, check this!) in the MSSM a common assumption that $\tan\beta > 1$, meaning that $\cos 2\beta < 0$, so

$$m_{\tilde{\ell}_L}^2 > m_{\tilde{\ell}_R}^2.$$

This mass splitting is however usually assumed to be small, and in experiments $\tilde{\ell}_R$ and $\tilde{\ell}_L$ are often (but not always) assumed to be mass degenerate.

3 Constrained models

As mentioned in the introduction the MSSM has 105 free parameters (plus the 19 free parameters of the SM), which makes it somewhat difficult to use for phenomenological predictions and interpretation of experimental data. For this reason we need to consider constrained models, where the number of free parameters is drastically reduced. We will not go into much details here, but simply mention a few of the most popular once, which are also the most relevant for the analyses discussed later. This review is mainly based on ref. [1].

The first model we should mention is a very popular one known as minimal supergravity (mSUGRA) or constrained MSSM (CMSSM). This model provides a mechanism for explaining SUSY breaking through gravitational interactions at Planck scale, and at GUT scale the model only depends on five free parameters,

$$m_{1/2},\ m_0,\ A_0,\ \tan\beta \text{ and } \mathrm{sgn}(\mu),$$

where $m_{1/2}$ is a common gaugino mass, m_0 is a common scalar mass, A_0 is a universal tri-linear Yukawa coupling, $\tan\beta$ is the ratio between the vacuum expectation values for the two Higgs doublets of the MSSM and $\mathrm{sgn}(\mu)$ is the sign of the Higgs mass parameter. The MSSM parameters at electroweak scale are obtained by the renormalization group equation.

Another model we should mention is the phenomenological MSSM (pMSSM), which is a way of limiting the MSSM parameter space by including three assumptions; *i)* No new sources of CP-violation, *ii)* no flavour changing neutral currents, *iii)* first and second generation universality. The last assumption implies that the masses of first and second generation sfermions are equal. With these assumptions the number of free parameters is reduced to 19.

Finally we should mention that in

4 Slepton production in particle colliders

The MSSM is usually defined as conserving R-parity, given as

$$R = (-1)^{2s+3B+L},$$

where s is spin, B is baryon number and L is lepton number. This has the interesting consequences that sparticles will always be produced in pairs in particle colliders, the lightest sparticle (LSP) will be stable, and all other sparticles will (possibly via multiple steps) decay to the LSP. Conservation of R-parity (and some other quantum numbers) means that slepton searches target production of $\tilde{\ell}^+\tilde{\ell}^-$, and it is a very common assumption that the LSP is the lightest neutralino, $\tilde{\chi}_1^0$, which is an excellent candidate particle for dark matter. Often sleptons are assumed to decay directly to $\tilde{\chi}_1^0$, plus the corresponding SM lepton. The mass difference,

$$\Delta m = m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}, \tag{3}$$

is in this case quite important, since it basically determines the momentum of the lepton, which is what you observe in the detector. Scenarios with small Δm is in some experiments hard to study.

In hadron colliders, such as the LHC, the cross section for slepton production is expected to be quite small, since the production of coloured (s)particles should be dominant, since hadrons (protons) are strongly interacting particles. However, if coloured sparticles are sufficiently heavy, production of sleptons (and other electroweak sparticles) could be the leading SUSY production channel. At leading order a pair of sleptons can be produced through $q\bar{q}$ annihilation to a virtual Z/γ, which splits into $\tilde{\ell}^+\tilde{\ell}^-$ (s-channel). In lepton colliders there is a similar s-channel, only with e^+e^- annihilation, but in addition there is also a t-channel with neutralino exchange available at leading order.

5 Slepton mass limits

Now that we have introduced some theory and phenomenology concerning sleptons it is time to move into the more experimental details. We will mainly focus on searches done at LEP and the LHC, as the best current limits stems from these experiments. We will take a look at what the actual limits are, and which assumptions that are made in the various searches.

5.1 LEP

The Large Electron-Positron collider (LEP) was a 27 km e^+e^- collider at CERN running between 1989 and 2000, and is still the most powerful lepton collider ever built, with a peak energy of 209 GeV. Although this is much less than the energy at which the LHC collides protons, and the total delivered luminosity is much smaller than in the LHC, it is interesting to notice that the LEP experiments still has the most general limits on the masses of both selectrons and smuons.

An absolute lower limit on the selectron masses, $m_{\tilde{e}_L}$ and $m_{\tilde{e}_R}$, within the MSSM is set by the ALEPH experiment in ref. [2] to be

$$m_{\tilde{e}_R} > 73 \text{ GeV},$$
$$m_{\tilde{e}_L} > 107 \text{ GeV},$$

assuming R-parity conservation, and that $\tilde{\chi}_1^0$ is the LSP. It is also assumed that scalar masses and gaugino masses are unified to m_0 and $m_{1/2}$ respectively at

GUT scale, and that $\tan\beta > 1$, as mentioned previously. Finally, mixing between $\tilde{e}_L$ and $\tilde{e}_R$ is neglected. It is however noteworthy that these limits are for *any* Δm (see eq. 3).

A limit on the smuon mass, $m_{\tilde{\mu}}$, was also set at LEP by the DELPHI experiment [3]. In this analysis it was assumed that only right-handed smuons would be light enough to be produced in LEP, so the limit only applies to $\tilde{\mu}_R$'s, and is given as

$$m_{\tilde{\mu}_R} > 94 \text{ GeV},$$

interpreted in the CMSSM, for $1 < \tan\beta < 40$, $-1000 \text{ GeV} \leq \mu \leq 1000 \text{ GeV}$, and assuming no mass splitting in the third generation of sfermions. (The last assumption is done because this gives the most conservative limit.) The limit applies to scenarios with $\Delta m > 10$ GeV. Notice that, although the limit is for to right-handed smuons, since $m_{\tilde{\mu}_L} > m_{\tilde{\mu}_R}$, it also serves as a conservative limit on $m_{\tilde{\mu}_L}$. The same analysis (ref. [3]) also presents a mass limit on $\tilde{e}_R$ at 94 GeV, which is higher than the one discussed previously by ALEPH. However, the DELPHI-analysis requires $\Delta m > 10$ GeV, so the ALEPH limit is still the most general one on $m_{\tilde{e}_R}$.

5.2 LHC

The Large Hadron Collider (LHC) at CERN is the most powerful particle collider ever built. It spends most of its operational time accelerating and colliding protons, first in Run I (2010-2012) at 7-8 TeV, and now in Run II (since 2015) at 13 TeV. With such a powerful accelerator a lot of people expected that the discovery of SUSY was just around the corner, but despite great efforts and plenty of searches no significant deviations from the Standard Model has been seen.

Searches for slepton production has been done by both ATLAS and CMS, which are the two multi-purpose experiments at the LHC. We will however stick to discussing results from the ATLAS experiment, because only ATLAS has set limits on the slepton mass using 13 TeV data, while the limits from 8 TeV analyses are quite similar for the two experiments.

Two ATLAS analyses searching for slepton production is found in refs. [4] (8 TeV) and [5] (13 TeV). The limits in the latter are (much) stronger, but somewhat different models are used in the searches, which is why we should mention both of them.

In the 8 TeV analysis results are interpreted in a pMSSM framework. It is (as usual) assumed that the lightest neutralino is the LSP, and also that the slepton is the next-to-lightest sparticle (NLSP) (i.e. it always decays as $\tilde{\ell} \to \tilde{\chi}_1^0 \ell$). The resulting exclusion limits for mass degenerate left- and right-handed sleptons is shown in Figure 1, with $m_{\tilde{\ell}}$ on the x-axis and $m_{\tilde{\chi}_1^0}$ on the y-axis. (Ref. [4] also contains separate limits

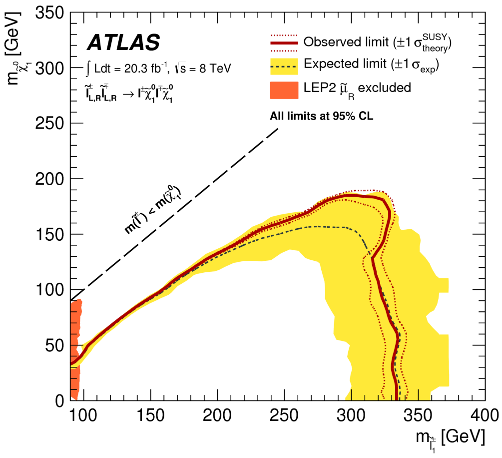

Figure 1: Exclusion limits on mass degenerate left- and right-handed sleptons from ATLAS at 8 TeV [4].

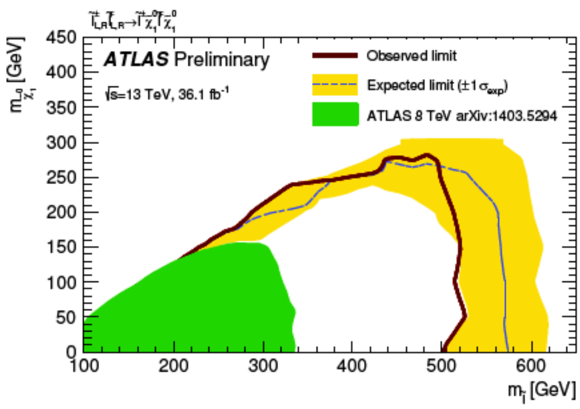

Figure 2: Exclusion limits on mass degenerate left- and right-handed sleptons from ATLAS at 13 TeV [5].

for $\tilde{\ell}_L$ and $\tilde{\ell}_R$.) The red line marks the area excluded in this search, while the orange area is the limit from LEP on the $\tilde{\mu}_R$ mass. We see that excluded are has been quite significantly extended, but (as mentioned) the ATLAS search do not reach the smaller Δm's.

Much of the same can also be said about the limits at 13 TeV, shown in Figure 2, which were presented at the LHCP conference in May 2017. The green area is the previous limit at 8 TeV, while the red on is the new observed limit. For this search a so-called simplified model is used, where the only free parameters are $m_{\tilde{\ell}}$ and $m_{\tilde{\chi}_1^0}$. It is noteworthy that, although the limits are extended by quite a bit, the limits in the compressed region (meaning small Δm) aren't improved at all compared to the 8 TeV search.

One might wonder why LEP, after all these years, still has better limits than the LHC experiments in the compressed region, and there is a very specific reason for this. ATLAS (and CMS) are primarily designed to search for new (heavy) particles. Such particles should, when decaying, lead to final state particles with high transverse momentum (p_T). The ATLAS detector is therefore designed to only keep events where such particles are present, and the trigger system [6] in ATLAS is really efficient only for leptons with $p_T \gtrsim 20$ GeV. Scenarios with low Δm will typically lead to final states with so-called *soft* leptons (i.e. low p_T), which are hard to study with ATLAS, hence sensitivities to such scenarios are low.

However, a study done in ref. [7] shows that the LHC at 14 TeV with 100 fb^{-1} of data could be sensitive to Δm's as low as 3 GeV up to $m_{\tilde{\ell}_L} \approx 150$ GeV. This study does however not make use of the traditional technique of studying final states with $\ell^+\ell^-$ and MET, but makes use of events with energetic jets from initial state radiation (ISR). The idea is that the produced sleptons will recoil against these jets, leading to leptons with high p_T also in low Δm scenarios.

6 Summary and conclusions

References

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