

# Light Gauginos – a Solution to More than the EDMs?

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In this talk I want to present questions that remained unclear to me in the last years. These questions concern the Electric Dipole Moments of electron and neutron and the way people exclude regions of parameter space.

## 1. Introduction and Outline

As this talk was primarily aimed at raising questions that could be discussed in private after the talk or during the workshop, it is not suited to be reproduced just as it was given. I will try to incorporate the discussion and also results from the discussion into this small article.

In the next section I will discuss light gauginos. I will present my opinion about the electric dipole moments and their measurements in the third section. My conclusions will follow in section four.

## 2. Light gauginos

When supersymmetry (SUSY) was found and the minimal supersymmetric standard model (MSSM) was introduced [1], people also looked at possibilities to restrict the large number of parameters by symmetry arguments. There are two different symmetry arguments. One argument is based on symmetries and simple boundary conditions of the renormalization group equations [2]. The second and more straight forward argument is based on symmetries in the low energy theory like lepton number conservation, baryon number conservation,  $R$ -parity, or a continuous  $R$ -symmetry [3].

The continuous  $R$ -symmetry restricts the soft breaking parameters quite severely: it puts the trilinear terms and the gaugino mass terms to zero. This scenario has been discussed a lot: [4,5]. Of course, with no independent phases left, all

SUSY induced CP violation has to vanish. [6] tried to quantify this vanishing assuming that the continuous  $R$ -symmetry is only an approximate symmetry. But with no continuous  $R$ -symmetry, what is the motivation for "light" gaugino mass parameters?

### 2.1. What does "light" mean?

Performing computations "light" means, that expansions in a ratio of the light mass versus some other mass converges quite quickly. So "light gauginos" means actually small gaugino mass parameters. This does not imply that all the particles are at the same mass as the parameters. And of course, the gluinos  $\tilde{g}$  and the lightest neutralino  $\tilde{\chi}_1^0$  will be of the same order as the corresponding gaugino mass parameter.

#### 2.1.1. Charginos

Let's look for instance at the simple chargino mass matrix:

$$\mathcal{M}^{\tilde{\chi}^+} = \begin{pmatrix} m_{SU(2)} & \sqrt{2}m_W \sin \beta \\ \sqrt{2}m_W \cos \beta & \mu \end{pmatrix} \quad (1)$$

The term with the  $W$ -mass sets the scale for the lighter chargino  $\tilde{\chi}_1^+$ . Even when  $m_{SU(2)} \rightarrow 0$ ,  $\tilde{\chi}_1^+$  will be heavier than 45 GeV, provided  $\tan \beta$  will not become too large, and can nearly become as heavy as the  $W$  boson, especially for small  $|\mu|$ , see Figure 1.

#### 2.1.2. Gluinos

Although there are 8 gluinos, they do not acquire different masses like charginos or neutralinos. Their mass matrix is just the  $SU(3)$  gaugino mass parameter. So they become massless in the limit of the continuous  $R$ -symmetry.

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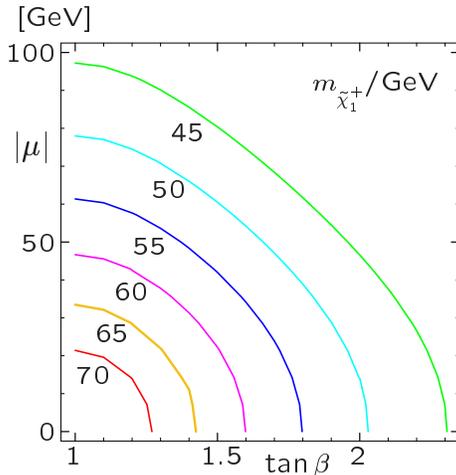


Figure 1.  $\tilde{\chi}_1^+$  mass contours in the  $|\mu|$ - $\tan\beta$  plane for  $m_{SU(2)} = 0$ .

### 2.1.3. Neutralinos

For the neutralinos the situation is more complicated. When both gaugino mass parameters that enter the neutralino mass matrix are exactly zero, an exact photino state  $\tilde{\gamma}$  with mass zero decouples from the other neutralinos. The situation remains similar, if both mass parameters are equal, even if they are not zero. Then one neutralino will be an exact  $\tilde{\gamma}$ . This  $\tilde{\gamma}$  does not couple to the  $Z$  boson at all. So all limits that are derived from LEP experiments with the analysis of the  $Z$  peak do not apply. But the second lightest neutralino  $\tilde{\chi}_2^0$  becomes then the particle, that the LEP collaborations were looking for — aside from the fact, that it can decay. One can apply now the limits from LEP to this  $\tilde{\chi}_2^0$ . Again  $\tan\beta$  is quite important.  $|\mu|$  works in the opposite direction as with the  $\tilde{\chi}_1^+$ : now the bigger  $|\mu|$ , the heavier  $\tilde{\chi}_2^0$ , see Figure 2. For a thorough discussion about the neutralino mass matrix see [7].

### 2.1.4. 1-loop mass corrections

It is well known, that the mass corrections to the higgs boson are quite sizeable. As similar graphs are participating, one can expect similar corrections for the gauginos. But there is one big difference to the higgs corrections, where one calculates a  $\delta m_h^2$  that is proportional to  $m_t^4$ , whereas

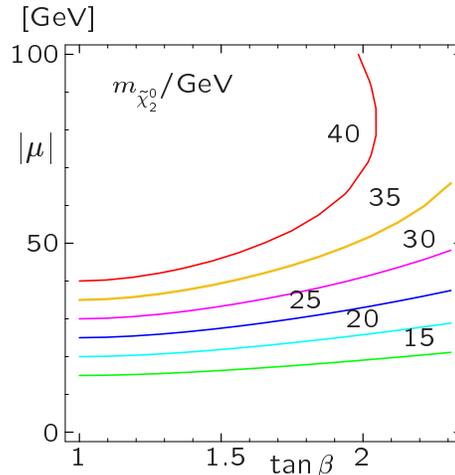


Figure 2.  $\tilde{\chi}_2^0$  mass contours in the  $|\mu|$ - $\tan\beta$  plane for  $m_{U(1)} = m_{SU(2)} = 0$ .

$\delta m_\lambda$  is only proportional to  $m_t^3$ , so that the corrections are not up to 50 GeV, but only up to 1 or 2 GeV.

One can also expect that the corrections to the  $\tilde{g}$  are bigger than to the  $\tilde{\gamma}$  because of the strong coupling. This is the reason, why one expects the  $\tilde{\gamma}$  to be the lightest supersymmetric particle (LSP) in this scenario.

## 2.2. Why are they not seen yet?

This question is more tough, but there are answers and arguments, that can be brought up. The first point is, that these light gauginos really escape detection — just like the neutrinos escaped detection for a long time. I will be more specific for each of the gauginos later. The second point is, that they can also be misinterpreted as other particles. This argument is used by many people for various other effects, too [8,9]. And there are measurements, that would favor the existence of light gauginos [5,8,10–12], see especially the discussion in [11].

### 2.2.1. Charginos

As  $\tilde{\chi}_1^+$  is lighter than the  $W$ -boson, it must have been produced by LEP. Looking at the cross section  $e^+e^- \rightarrow X$ , one expects to see a threshold when  $\tilde{\chi}_1^+\tilde{\chi}_1^+$  is pair produced. But since there is

no fine spaced energy scan done by LEP above the  $Z$ -peak, one can easily miss the threshold. Of course, there has to be a higher cross section for  $e^+e^- \rightarrow X$  above the  $\tilde{\chi}_1^+ \tilde{\chi}_1^+$  threshold. But how do the LEP experiments calibrate their detectors, if not by that cross section, which is assumed to be the standard model one? The comparison to the Monte Carlo Data is done by the same procedure, too. My conclusion: it is possible, that the pair production of  $\tilde{\chi}_1^+ \tilde{\chi}_1^+$  is not clearly visible just by looking at the production cross section.

Ok, so lets look into the decays! At least they should be seen in LEP, right? If I take the scenario of tiny gaugino mass parameters for real, I will have to look at the signature of  $\tilde{\chi}_1^+$  decay, because it can be dramatically different from the normal decay. [13] proposes the hadronic decay  $\tilde{\chi}_1^+ \rightarrow u\bar{d}\tilde{g}$  to be dominant. That decay would then just increase the hadronic cross section. To see this increase in the hadronic cross section, one would have to make either a fine spaced energy scan, to see the threshold or to know exactly the expected standard model background. Of course, the standard model background is quite well known.

But what is the procedure, with which the hadronic cross section is compared to the theoretical prediction? It is the Monte Carlo studies for the detectors; and they compare to the measured cross section, making the assumption, that it is the standard model cross section. In some sense this seems to me like a vicious circle. But I also think these complicated procedures are necessary, to extract reliable data from the complicated detectors. And the experimentalists are doing a marvellous job!

### 2.2.2. Gluinos

The  $\tilde{g}$  is expected to be very light. As such a light colored state it will affect the running of  $\alpha_s$ . This change of running is actually in quite good agreement with the measurements performed with  $q\bar{q}$  bound states [12,14], but it is off for the measurement done at the  $\tau$  [15]. Nevertheless, assuming a 10% relativistic correction for the  $\tau$ -measurement brings this measurement in the correct range for the light gluino prediction. But it needs a 100% correction to bring

the  $q\bar{q}$  bound state measurements into the correct range of the standard model prediction. Of course, both predictions assume the measurement at the  $Z$ -peak to be correct.

The Aleph collaboration at LEP did an additional study for the running of  $\alpha_s$  and the number of light flavors [16]. It ruled out a light  $\tilde{g}$ , but this study was criticized by [17]. Although I don't understand [16] fully, especially since they rely heavily on the Monte Carlo studies and sophisticated statistical techniques, I think they did a good work. But one question remains for me: why did the other LEP collaborations neither confirm nor contradict this analysis?

### 2.2.3. Neutralinos

Here we have to look at two of them: the  $\tilde{\gamma}$ , which is assumed to be the LSP, and the  $\tilde{\chi}_2^0$ .

I thought I could ignore the question about the  $\tilde{\gamma}$  because it will not couple to the  $Z$  boson. Actually it will couple exactly the same like an ordinary photon, with the only difference, that one of the other particles has to be a SUSY particle. Since SUSY particles are quite heavy, i.e. much heavier than the normal quarks and leptons, I assumed, that the effects would be too small to be seen anyway. But during the workshop I was made aware that there exist dedicated searches for a light  $\tilde{\gamma}$  in the low energy  $e^+e^-$  cross section [18]. But these experimental results do not exclude a light  $\tilde{\gamma}$ , they just give limits on the mass of the scalar electrons. Other restrictions for a  $\tilde{\gamma}$  can be found from cosmological arguments [19] and other inclusive detector measurements [20].

For the  $\tilde{\chi}_2^0$  the situation is quite complicated. One has to worry not only about the production of  $\tilde{\chi}_2^0 \tilde{\chi}_2^0$  at the  $Z$  peak, one has also to think about possible decays. Again [13] proposes decay modes into  $\tilde{g}$  and hadrons. These decay modes look similar to the decays of the  $\tilde{\chi}_1^0$  in  $R$ -Parity violating models [21,22]. Keep in mind, that LEP did extensive studies for  $R$ -Parity violation! But on the other hand the situation is not the same: there is no simple way to translate limits obtained for  $R$ -Parity violating models into limits for this hadronic  $\tilde{\chi}_2^0$  decay, since one of the main features of the  $R$ -Parity violating models can be the enhancement in the lepton multiplicity [22]. But

the hadronic decay of  $\tilde{\chi}_2^0$  will reduce the lepton multiplicity.

#### 2.2.4. My opinion on light gauginos

Whenever I asked experimentalists about excluding the light gaugino scenario by experimental data, I got the answer, "We would have to make a dedicated study". Only G. Dissertori gave a definite answer. So I — for myself — cannot rule out that light gaugino scenario. And in addition, there are some problems, where light gauginos offer a solution.

#### 2.3. Motivation for light gauginos

When one looks at the unconstrained MSSM that has all soft breaking parameters with arbitrary phases, one will immediately have problems with existing measurements on  $CP$  violating variables and on flavor changing processes. The usual way to handle this kind of situation is to apply constraints on the parameters, either by using renormalization group equations with restrictive boundary conditions or applying low energy symmetry arguments like "alignment" [23,24].

On the other hand, light gauginos are another way of suppressing many of the problematic diagrams that give too big results for  $CP$  violating observables. [6] has quantified this argument for the electric dipole moments (EDMs) of electron and neutron. In [24] one can see the vanishing of the SUSY effects in  $K^0-\bar{K}^0$  mixing with vanishing gaugino masses. [25] has demonstrated this vanishing also for a top quark mass of 175 GeV.

One motivation for me to look for light gauginos is, that almost everybody seems inclined to consider the relevant parameter space to be already ruled out, but no one could really convince me about that.

### 3. Electric dipole moments

The second big question I wanted to present in the workshop was about EDM measurements. It can be brought to the point, that I have doubts about the prerogatives that are assumed when a macroscopic measurement is compared to calculations that involve questions of low energy QCD. My feeling was — and is to some extent even now — that the accuracy of the QCD related topics

is not the same as the claimed accuracy of the experiments that measure the EDMs: do we really know atomic or nuclear physics to the precision of  $10^{-12}$ , which is the inherent precision of the EDMs. A discussion about that point with Maxim Pospelov during the workshop was very helpful for me.

#### 3.1. EDM of the neutron

The basic question about the calculation of the EDM of the neutron  $d_N$  is, how one can combine the result of the various contributions of the particles, that make up the neutron. The first estimates were based on the non-relativistic SU(6) quark model with

$$d_N = (4/3)d^d - (1/3)d^u . \quad (2)$$

And the other QCD contributions to  $d_N$  were estimated by a Naive Dimensional Analysis [26]. Different estimates were made in [27] and a few months ago I found even another proposal [28]. This multitude of possible models, that give opposite results for  $d_N$  — as has been shown in [29] — shows that the theoretical part of the measurements is not really under control. So any restriction derived from the non measurement of  $d_N$  can just be applied if one makes additional assumptions that are not part of the MSSM.

In the workshop I was made aware of more accurate calculations for the composition of the neutron [30], see the discussion in [31]. A new estimate of the chromoelectric contribution has been obtained in [32]. So some part of my criticism of the neutron EDM has lost its basis. But the possibility of cancellations is still present. And the points in parameter space where these cancellations take place depend on the specific assumptions about the neutron.

#### 3.2. EDM of the electron

In contrast to  $d_N$  the EDM of the electron  $d_e$  is easy to calculate and theoretically fully under control. The problematic point comes with the measurement, because a direct measurement with free electrons seems to be impossible. One argument for the impossibility is the charge of the electron.

The usual way is to measure atomic quantities and to relate them to  $d_e$ . The most accurate mea-

measurements today are done with  $d_a(^{205}\text{Tl}; 6^2P_{1/2})$  [33]. The relevant calculations were done in [34], pointing out, that  $d_{\text{Tl}}$  has four sources and only one of them is the intrinsic  $d_e$ . The other three are (1) an intrinsic nucleon EDM, (2)  $P, T$ -odd nucleon-nucleon interaction, (3)  $P, T$ -odd electron-nucleon interaction. Non measurement of  $d_{\text{Tl}}$  requires the sum of all four sources to be smaller than the experimental limit.

To derive a limit on  $d_e$  from the  $d_{\text{Tl}}$  measurement one has to assume, that all other three contributions are much smaller than the first. Of course, the probability that two of these four contributions cancel each other is very small. But on the other hand: more contributions mean more possibilities for cancellations.

### 3.3. EDM of $^{199}\text{Hg}$

I was made aware of this type of measurement, that restricts the parameters of the MSSM, by Toby Falk during SUSY99 and then later again by Maxim Pospelov at this workshop, see their article [31].

As it uses again atomic and nuclear physics to relate the measurement to the EDMs of the constituents of the atom, my uneasy feeling about the accuracy remains. But it is another argument, that has to be taken into account. Any model should describe all phenomena that are encountered in nature, so it should explain the non-measurement of  $d_{\text{Hg}}$ , too.

## 4. My conclusions

*"...the supersymmetry algebra is the only graded Lie algebra of symmetries of the S-matrix consistent with relativistic quantum field theory"* [35]. This citation reflects the major motivation for SUSY. Since we live in a world where masses are nonzero, it is necessary that SUSY is broken. But this breaking of SUSY introduces a lot of new parameters in the low energy Lagrangian, that are constrained by stability requirements and their effect on measurements.

Stability requirements just restrict the parameters in a way, that the vacuum of the model is compatible with what we see in everyday life: we don't see any electric or colored net charge in the

vacuum. And we see that particles are massive, but not superheavy (of order of the Planck mass). And we see, that the electro-weak symmetry is broken to the electric charge. So the vacuum of SUSY has to fulfill these constraints, which it does easily enough with the mechanism of spontaneous symmetry breaking in the electro-weak sector.

But there are a lot of other effects, that wait for an explanation: we see a large baryon asymmetry in the universe (BAU), but the vacuum of the Lagrangian of the MSSM looks symmetric between baryons and antibaryons. And the proton is quite stable, too. And we also find, that  $CP$  violation is quite small. Actually, the only visible effect up to now is observed in the neutral kaon sector [36].

For the explanation of BAU one needs quite a large  $CP$  violating phase [37], but other measurements, like the EDMs, can be interpreted as restricting these possible phases — or at least specific combinations of them. Another usual interpretation is, that the masses of the SUSY particles are so heavy, that their effect in the EDMs are suppressed. But having very heavy SUSY particles makes the explanation of the observed vacuum more difficult.

Another interpretation for the non-observation of EDMs can be light gauginos [6]. It also allows the other SUSY particles to stay "light" and helps therefore in the explanation of the electro-weak symmetry breaking. The "cost" for this interpretation is, that one is away from the mainstream of model building. And one has to investigate carefully, if other measurements will not rule out this scenario.

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