The Minimal Supersymmetric Standard Model

Part II: Phenomenology

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This report summarizes my contribution to a talk presented at the Supersymmetry Seminar organized by Prof. Jörg Jäckel at the Institute for Theoretical Physics in Heidelberg during the winter term 2020/2021 in collaboration with Jonah Cedric Strauß.
We study the theoretical foundations and phenomenological implications of the minimal supersymmetric extension of the well-known Standard Model of Particle Physics.
The starting point for the second part of the talk is the MSSM-124. We want to understand how we can constrain its huge parameter space to reduce the number of relevant degrees of freedom to a reasonable amount which may allow us to verify phenomenological predictions in current or future experiments. We will focus on the "phenomenological" MSSM, the "minimal supergravity" framework and highlight the role of supersymmetry in the context of grand unified theories. To conclude the discussion we present some ideas on extensions beyond the MSSM that may tackle several open problems such as the explanation of the value of the Higgs-higgsino mass parameter μ.

1 Introduction

The study of Supersymmetry provides a fruitful playground for physicists to test various aspects of physics beyond the Standard Model (BSM) ranging from Early Universe Cosmology and Dark Matter to modern theoretical frameworks such as String Theory or the AdS/CFT-correspondence.
At the end of the first part of our talk we concluded the discussion of the theoretical foundations of the MSSM with a parameter count that left us with the unsatisfying observation that one would need to determine 124 independent parameters in total to fully characterize the model. Such a large amount of relevant parameters makes the MSSM not phenomenologically viable [1].
The phenomenology of the MSSM is to a large extend determined by the SUSY breaking mechanism and the associated SUSY breaking scale [2]. We will motivate phenomenological constraints we want to put on the MSSM and see how they are implemented technically. Additionally we want to highlight the (possible) importance of gravity at high energies. This will help us to reduce the number of relevant parameters and may provide a starting point for actual experimental tests. For a schematic overview of the main concepts we want to discuss, have a look at Figure 1 at the beginning of the next page.

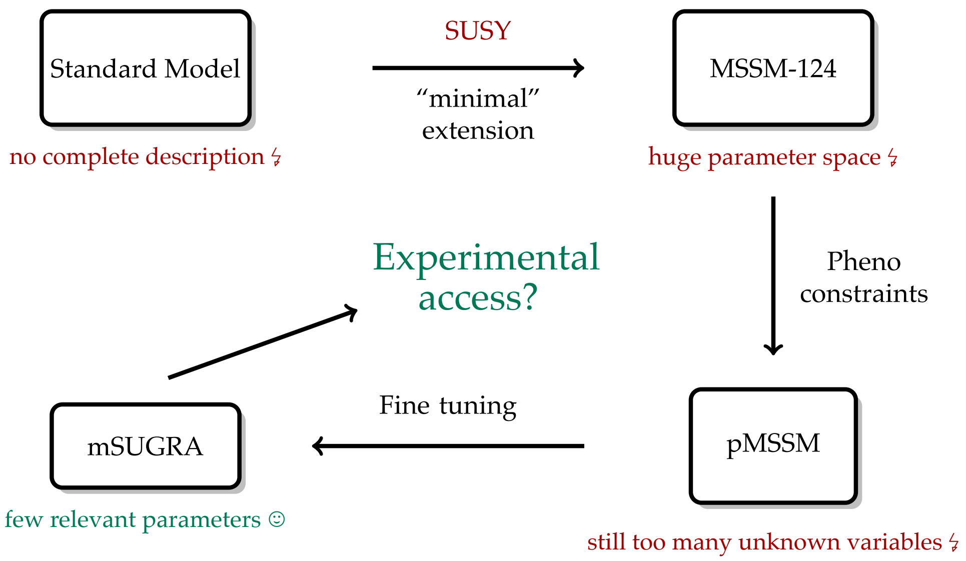


Figure 1: Schematic overview of the "roadmap" of our talk.

2 Phenomenology of the MSSM

As the first step towards phenomenological access to the relevant parameters of the MSSM, we want to have a look at three hypothetically allowed phenomena in the MSSM, that are relatively well controlled by various experimental constraints. For specific regions of the parameter space we encounter that:

- The respective lepton numbers L_e, L_μ and L_τ are not conserved.
- Flavor-changing neutral currents (FCNCs) are not suppressed.
- New sources of CP-violation are present.

In the MSSM, the non-diagonal terms in the sfermion mass matrices and in the trilinear coupling matrices can induce FCNCs. In Figure 2 at the beginning of the next page, an hypothetical example process describing such a FCNC is presented. These kind of phenomena are already present in the Standard Model at higher loop orders, but they are highly suppressed which can be explained for example by the GIM-mechanism [3], which relates those processes to the unitarity or the presence of complex phases in the CKM matrix.
The understanding of CP-violation and its sources in the SM and beyond is very important. In weak interactions CP-violation has extensive implications for the V-A structure of the couplings and the non-trivial quark mixing (CKM matrix). Another source of possible CP-violation in the SM is given by the topological θ-term. The famous Sakharov conditions tell us that we need CP-violation in order to describe baryogenesis in the Early Universe. Experimental tests of CP-violation are usually performed in the context of electric

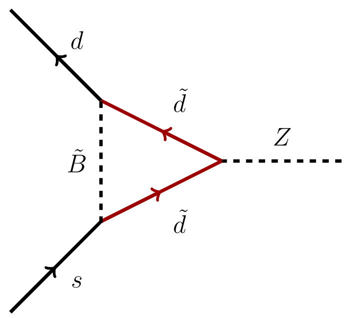


Figure 2: An example diagram for a hypothetical FCNC process ($s \to d$) in the MSSM involving a Bino and sdown quarks. Such processes can occur if the MSSM squark masses are flavor-violating.

dipole moments of electrons and neutrons as well as studies of the Kaon-system. Those measurements put severe constraints on the beforehand presented sources. To give some explicit values we refer for example to [4], where they found out that for TeV-ish sfermion and gaugino masses the absolute values of the complex phases of the gaugino mass parameters, the trilinear couplings and $|\mu|$ have to be $\leq 10^{-2} - 10^{-3}$.
In the MSSM the amount of new CP-violating phases has increased drastically. This now gives room for two different explanations: One possibility could be that those phases all are approximately zero (which is usually assumed) or there could be non-trivial cancellations amongst the new phases that might lead to tiny measurable effects. In the end this would be a horrible fine tuning task.
With these general observations at hand we define the "phenomenological" MSSM (pMSSM) by three basic assumptions [1]:

1. We do not allow any additional sources of CP-violation. This is implemented by setting all phases in the soft SUSY breaking potential to zero.

2. We also do not allow processes inducing FCNCs. This results in a simple, diagonal structure of the sfermion and trilinear coupling matrices.

3. We assume first and second generation universality, this means we assume that the scalar masses are the same for the first two generations. This is motivated by results on Kaon mixing which put severe constraints on the splitting of the masses. The same we do for the trilinear couplings A^u, A^d and A^ℓ, usually they are even set to zero since they are not important for phenomenology[1].

This already facilitates the general structure of the MSSM a lot!

1. Since they are proportional to the sfermion masses, only the third generation trilinear couplings have phenomenological impact.

We summarize the remaining parameters in the pMSSM in the following:

- $\tan\beta = v_u/v_d$, the ratio of the VEVs from the two-Higgs doublets.
- $m_A^2 = 2m_{12}^2/\sin 2\beta$, the mass of the pseudoscalar Higgs boson.
- M_1, M_2 and M_3, the bino, wino and gluino masses.
- μ, the Higgs-higgsino mass parameter.
- $m_{\tilde{q}}$, $m_{\tilde{u}_R}$, $m_{\tilde{d}_R}$, $m_{\tilde{\ell}}$ and $m_{\tilde{e}_R}$, the first/second generation sfermion masses.
- $m_{\tilde{Q}}$, $m_{\tilde{t}_R}$, $m_{\tilde{b}_R}$, $m_{\tilde{L}}$ and $m_{\tilde{\tau}_R}$, the third generation sfermion masses.
- A^t, A^b and A^τ, the third generation trilinear couplings.

This still leaves 19 open parameters, which makes comprehensive studies of the pMSSM computationally very expensive. In actual experiments we need to construct even more simplified models with only two or three parameters to be able to test any predictions. One possible way to construct such a "simpler" model, may be to study possible connections to gravity at high energy scales which might render the underlying structure of the theory relatively simple in the high energy regime. This idea is known as mSUGRA und we will present the general concept behind it in the next section.
To conclude this section we need to discuss SUSY-breaking. A key problem of the MSSM is, that it fails to give a natural explanation of the fundamental origin of the SUSY breaking parameters. In the last talks we learned about gauge- and gravity mediated SUSY breaking which might provide a way around this problem. We won't go into details here, but for a visualization of the general idea of these concepts, have a look at Figure 3.

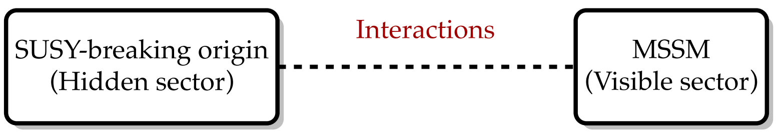


Figure 3: Visualization of the idea of gravity-mediated SUSY breaking.

The general idea is that the SUSY-breaking occurs in the hidden sector and is mediated at some messenger scale M_{mess} via fundamental interactions to the MSSM. The understanding of how SUSY breaking is "naturally" encoded in this framework might also help to facilitate phenomenological access to the MSSM.

3 The Minimal Supergravity Framework

We want to include Gravity, or more precisely local Supergravity, in our setting. The relevant physical scale in this context is the Planck scale $M_{\text{Planck}} \sim 10^{19}$ GeV, since it is

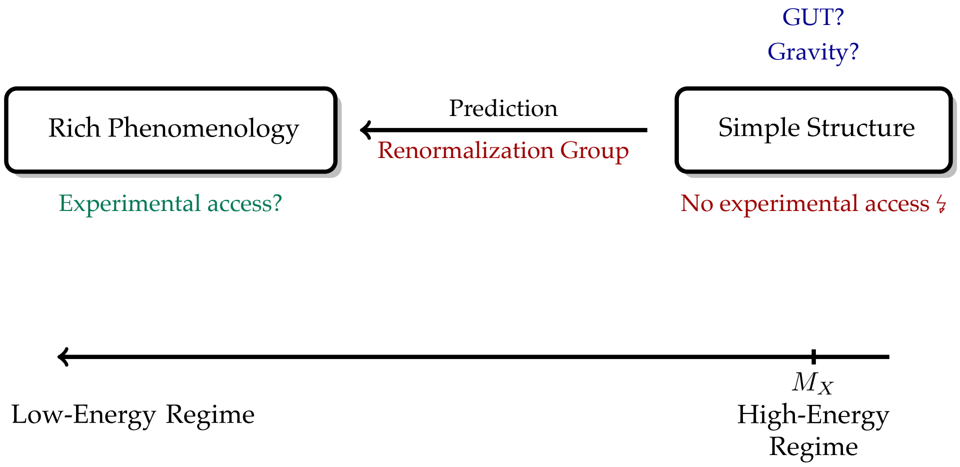


Figure 4: An overview of the idea of the mSUGRA framework. Assuming a simple high-energy structure of the theory, we can derive low-energy predictions using standard renormalization group techniques.

the scale where the strength of the gravitational interaction is assumed to be of $\mathcal{O}(1)$. All of the phenomenological problems discussed before are solved at once if one assumes that the MSSM parameters obey a set of boundary conditions at some high-energy scale M_X. We will in the following refer to this scale as the "unification scale", for reasons that will become clear in the following. These boundary conditions can be implemented quite naturally, when assuming gravity-mediated SUSY breaking in the hidden sector with $m_{\text{soft}} \sim \frac{\langle F \rangle}{M_{\text{Planck}}}$ as discussed at the end of the previous section. The idea is then to access the low-energy MSSM phenomenology via standard renormalization group techniques using these boundary conditions as input parameters. This idea is visualized at the beginning of this page in Figure 4.
The implementation of the boundary conditions is realized by assuming a "minimal" normalization of the kinetic terms in the SUGRA Lagrangian:

$$\mathcal{L}_{\text{SUGRA}} \supset -\frac{1}{M_{\text{Planck}}} F \left(\frac{1}{2}\alpha\lambda\lambda + \frac{1}{6}\beta\phi\phi\phi + \frac{1}{2}\gamma\phi\phi \right) + \text{h.c.} - \frac{1}{M_{\text{Planck}}^2} F F^* \delta\phi\phi^*. \quad (1)$$

Note that we suppressed all the indices for simplicity. A careful comparison with the the initial terms in $\mathcal{L}_{\text{soft}}$ then allows us to find relatively simple relations for the input parameters, i. e.

$$\begin{aligned} m_{1/2} &= \alpha \frac{\langle F \rangle}{M_{\text{Planck}}}, & m_0^2 &= \delta \frac{|\langle F \rangle|^2}{M_{\text{Planck}}^2} \\ A_0 &= \beta \frac{\langle F \rangle}{M_{\text{Planck}}}, & B_0 &= A_0 - m_0 = \gamma \frac{\langle F \rangle}{M_{\text{Planck}}}. \end{aligned} \quad (2)$$

This relatively simple structure allows to simplify the structure of the relevant couplings at the initial scale as follows:

- The scalar squared-masses are flavor-diagonal and universal:

$$\begin{aligned} m^2_{\tilde{q}}(M_X) &= m^2_{\tilde{u}}(M_X) = m^2_{\tilde{d}}(M_X) = m_0^2 \mathbb{1} \\ m^2_{\tilde{\ell}}(M_X) &= m^2_{\tilde{e}}(M_X) = m_0^2 \mathbb{1} \\ m^2_1(M_X) &= m^2_2(M_X) = m_0^2. \end{aligned} \tag{3}$$

- The same is true for the A-parameters:

$$A^U(M_X) = A^D(M_X) = A^E(M_X) = A_0^2 \mathbb{1}. \tag{4}$$

- Additionally we assume unification of the (tree level) gaugino masses:

$$M_1(M_X) = M_2(M_X) = M_3(M_X) = m_{1/2}. \tag{5}$$

These relations provide our starting point for the subsequent renormalization group evolution towards the low-energy regime. Just as a reminder, we define the beta function as $\beta(g) = \frac{\partial g}{\partial \ln M}$, the rate of change of the renormalized coupling at the scale M, where the bare coupling is fixed [5]. As an example, the RG evolution of the gaugino mass parameters yields the following, well known relation:

$$M_i = \frac{\alpha_i\left(M_Z\right)}{\alpha_{\mathrm{GUT}}} m_{1/2} \longrightarrow M_3\left(M_Z\right) = \frac{\alpha_3\left(M_Z\right)}{\alpha_2\left(M_Z\right)} M_2\left(M_Z\right) = \frac{\alpha_3\left(M_Z\right)}{\alpha_1\left(M_Z\right)} M_1\left(M_Z\right). \tag{6}$$

This tells us that

$$M_1 = \frac{5}{3} \tan^2\theta_W M_2 \sim \frac{1}{2} M_2, \tag{7}$$

where the factor $\frac{5}{3}$ comes from the unification scheme in our SU(5) model, i. e.

$$g \cdot Y_{\mathrm{GUT}} = g_Y \cdot Y \implies \frac{g}{g_Y} = \sqrt{\frac{5}{3}} \tag{8}$$

and θ_{W} is the Weinberg angle measured to be $\sin^2\theta_{\mathrm{W}} \approx 0.23$.
To visualize the general idea on how to get a rich phenomenological low-energy MSSM spectrum from only a few input parameters according to the scheme described beforehand, have a look at Figure 5 at the beginning of the next page.

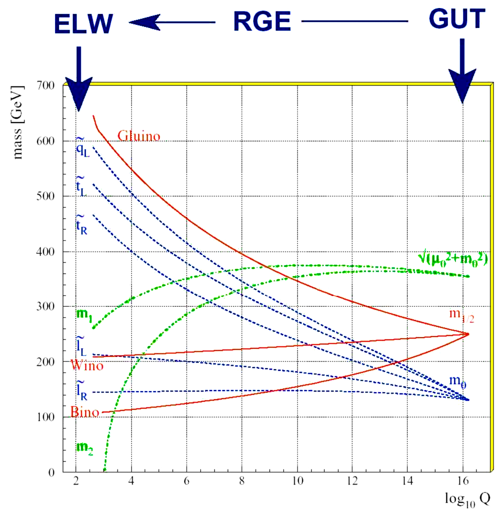


Figure 5: Running of the relevant parameters in the mSUGRA approach[2].

A final parameter count yields that the mSUGRA model only needs four additional continuous and one additional discrete parameter to be entirely characterized:

- $\tan\beta$, the ratio of the VEVs in the two-Higgs doublet model.
- $m_{1/2}$, the universal gaugino mass.
- m_0, the universal scalar (sfermion/Higgs) mass.
- A_0, the universal trilinear coupling.
- $\mathrm{sign}(\mu)$, the sign of the Higgs-higgsino mass parameter.

The relations for $\tan\beta$ and $|\mu|$ come from the two minimum conditions for the Higgs potential[3]:

$$m_Z^2 = \frac{m_{H_d}^2 + \mu^2 - (m_{H_u}^2 + \mu^2)\tan^2\beta}{\tan^2\beta - 1} \tag{9}$$

$$\sin^2 2\beta = \frac{B_0\mu}{m_{H_u}^2 + m_{H_d}^2 + \mu^2} \tag{10}$$

Additional constraints such as the unification of the top, bottom and tau Yukawa couplings at the GUT scale can further restrict the possible values of $\tan\beta$ and A_0.
In total we can conclude that the mSUGRA framework provides a promising candidate for a phenomenologically accessible SUSY model that may be tested in current or future experiment.
Since the concept of unification may play a central role in the discussion of SUSY phenomenology, but is often not part of the standard curriculum of Particle Physics or Quantum Field Theory lectures we want to discuss it in more detail in the next section.

2. Figure taken from: https://www.physi.uni-heidelberg.de/~uwer/lectures/ParticlePhysics/Vorlesung/Lect-10b.pdf (10.02.21)
3. At this point we have to assume that electroweak symmetry breaking occurs which directly lead us to these conditions.

4 Grand Unification and Supersymmetry

As we have seen before, the concept of unification plays a central role in the construction of appropriate phenomenological models of the MSSM. Here, we want to discuss the importance of SUSY in the context of the unification of the Standard Model gauge couplings, which was one of the first proposed examples of phenomenological implications in the early days of SUSY research [6].

We define the Standard Model as the most general renormalizable field theory with gauge group

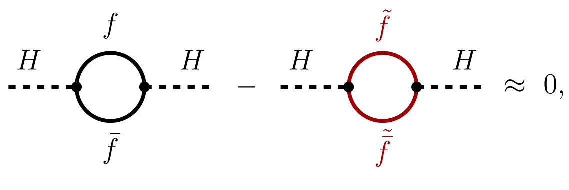
$$\mathcal{G}_{\text{SM}} = \text{SU}(3) \times \text{SU}(2) \times \text{U}(1), \tag{11}$$

with associated gauge couplings α_3, α_2 and α_1, three generations of fermions and a scalar doublet [7]. We know that the respective couplings are larger for the larger component of the gauge group, i. e.

$$\alpha_3\,(m_Z) > \alpha_2\,(m_Z) > \alpha_1\,(m_Z)\,. \tag{12}$$

An interesting observation is, that the values of the running couplings come relatively close together at some high energy scale $\Lambda_{\text{GUT}} \sim 10^{16}$ GeV (cf. left plot in Figure 6). To understand how this picture might look like in the MSSM[4], we first have a look at the value of the Higgs-higgsino mass parameter μ.

In order to reproduce the correct values of the W and Z boson masses, in the Georgi-Glashow model [6] we need values of $\mu^2 \sim (100\ \text{GeV})^2$ [5]. The large discrepancy in the orders of magnitude of the relevant physical scales is often referred to as the gauge hierarchy problem. At this point SUSY may provide a way around: If SUSY breaking in the MSSM works such that the mass differences of the superpartners are large enough, one can reproduce the correct Higgs mass. These additional superpartners in the particle spectrum lead to interesting cancellations in the computation of the running of the gauge couplings via diagrams such as



where the sfermions are denoted by a tilde (and highlighted in red). For an example calculation of the MSSM effects in the running couplings we refer for example to the respective exercise in [7].

4. For our talk we restrict ourselves to a unification scheme with gauge group $\mathcal{G}_{\text{MSSM}} = \text{SU}(5) \supset \text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$ as described in [6].

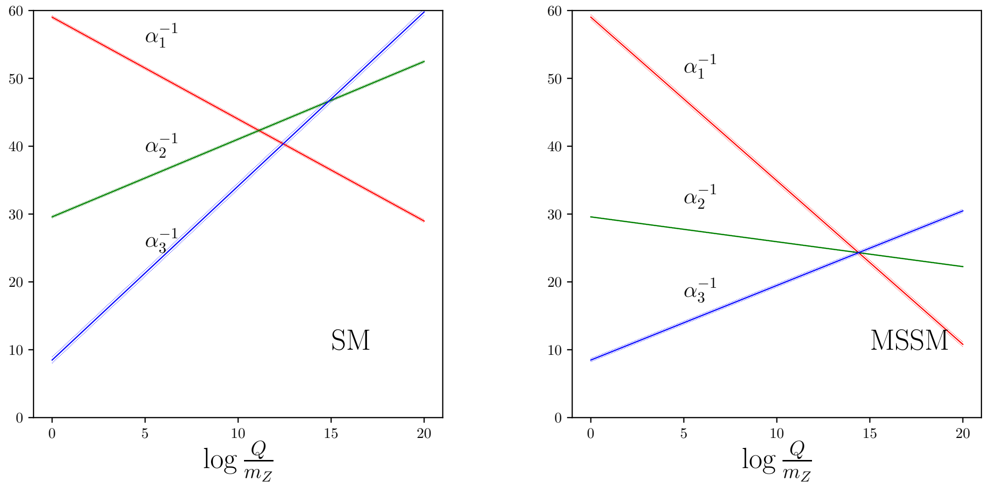


Figure 6: Running of the (inverse) gauge couplings in the SM and the MSSM, plots inspired by [8].

The explicit formulas for the beta functions are given by

$$\beta_{g_i} = \frac{\mathrm{d}}{\mathrm{d}t} g_i = \frac{b_i}{16\pi^2} g_i^3 \quad \text{with} \quad (b_1, b_2, b_3) = \begin{cases} (\frac{41}{10}, -\frac{19}{6}, 7) & \text{in the SM} \\ (\frac{33}{5}, 1, -3) & \text{in the MSSM} \end{cases} \tag{13}$$

where $t = \log \frac{Q}{m_Z}$. For $\alpha_i = g_i^2/4\pi$ this yields

$$\frac{\mathrm{d}}{\mathrm{d}t} \alpha_i^{-1} = -\frac{b_i}{2\pi}. \tag{14}$$

As we see in the right plot in Figure 6 the unification of the gauge couplings at some high energy scale may be realized in the MSSM. In the end it remains a complicated fine tuning task[5].

At this point we want to remark that even if this result might look very interesting, and was often referred to as one of the most promising advertisements for the realization of SUSY in nature, it is of course only an approximate result and the picture will already look a lot different at the next loop order.

5 Going Beyond the MSSM

As the name already suggests, the "minimal" supersymmetric extension of the Standard Model may not be enough to solve all our remaining problems. Many extensions of the MSSM have been proposed to deal with various open questions such as the missing ex-

5. There has been a lot of work considering the qualitative assessment of fine-tuning in theoretical models. Probably the most commonly used measure of fine tuning is the Barbieri-Giudice measure characterized by $\Delta_i \equiv \left| \frac{\partial \ln m_Z^2}{\partial \ln p_i} \right|$, where the p_i are the MSSM parameters at the scale M_X which are set by the fundamental SUSY breaking dynamics. The larger the value of $\Delta \equiv \max \Delta_i$ the more fine tuning is needed [2, 7].

planation of the fundamental origin of SUSY breaking, the "total" particle content, the explicit structure of $\mathcal{G}_{\mathrm{MSSM}}$[6] and many more.

To conclude this discussion we want to present some conceptual ideas on the explanation of the value of the Higgs-higgsino mass parameter μ to get a feeling on how model building in the context of the MSSM works and how those different ideas lead to further complexity in the resulting parameter spaces.

The general problem with μ is that it is actually a SUSY preserving parameter but from phenomenological constraints we know that it must be of the order of the SUSY breaking scale. A natural way of dealing with this discrepancy would be a symmetry enforcing $\mu = 0$, and a small SUSY breaking parameter generating a value of μ that is not parametrically larger than the breaking scale.

In proposed extensions of the MSSM a first idea would be to replace μ by the vacuum expectation value of a new $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$ scalar singlet. This is often referred to as the next-to-minimal SSM (NMSSM). Another possibility would be the addition of a new broken $\mathrm{U}(1)$ gauge symmetry to the NMSSM, which is then called the $\mathrm{U}(1)$-extended SSM or USSM for short [10]. New mass terms analogous to the μ term in the MSSM could be introduced by allowing all renormalizable terms in the superpotential ("generalized" NMSSM) [11].

Interesting connections to modern research on Axion physics may provide a solution to the strong-CP problem and solve the μ problem at the same time. Such models include additional gauge singlets which are charged under the so called Peccei-Quinn symmetry. The breaking of the PQ symmetry may then be connected to SUSY breaking and would yield values of μ of the order of the electroweak scale [12].

For work on higher dimensional Higgs multiplets we refer for example to [13]. Here, the concept of custodial symmetry which is used to test the electroweak sector of the SM with high precision plays a central role. Such models may provide interesting phenomenological implications for future experimental studies.

Even if most of these publications we referred to have already been published a few years ago, these (short) considerations already show that beyond the MSSM studies go into various interesting directions and even if large areas of the possible MSSM parameter space are already ruled out by experiment, there might be a chance that SUSY is realized in Nature and provides a beautiful explanation of many fascinating phenomena.

6. In the context of GUTs there has been a lot of research on the embedding of the Standard Model gauge group into larger groups such as $\mathrm{SO}(10)$ which facilitates the inclusion of neutrinos or even more complicated groups such as E_6 or $E_8 \times E_8$ motivated by the study of String Theory [9].

6 Conclusion and Outlook

Getting access to the rich phenomenology of the MSSM has turned out to be a very challenging task due to the complexity of the underlying parameter space with its 124 relevant parameters in the simplest version of the MSSM.
Using very general phenomenological constraints on flavor-changing neutral currents and CP-violation which are tested with high precision by various experiments, we were able to reduce the number of relevant parameters in the MSSM already by a large amount.
The fact that the MSSM does not provide an explanation for the origin of SUSY breaking can be seen as a huge problem at first but it also allowed us to develop the mSUGRA framework in the second part of our talk assuming gravity-mediated SUSY breaking at some high energy scale and a minimal structure of the kinetic terms of the SUGRA Lagrangian. From this we were able to construct a model for low-energy MSSM phenomenology resulting from a renormalization group approach starting with a relatively simple structure of the theory at high energies.
We then discussed the concept of gauge coupling unification in more detail in the context of the Standard Model. We presented the explicit formulas for the running of the (inverse) couplings and how the superpartners in the MSSM change this result.
To conclude our talk we presented some ideas on beyond the MSSM models that try to explain some of the remaining open questions such as the value of the μ parameter.
Of course, there have been extensive studies and experimental tests of SUSY phenomenology in the last couple of years. Unfortunately it has turned out, that up to now no promising signatures of SUSY have been detected by experiments and we therefore have to put even more severe constraints on new models. Maybe these new constraints will help us in the end to finally detect SUSY signatures in future experiments or to ultimately rule out the possibility of a realization of SUSY in Nature.

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