SUPERSYMMETRY AT PRESENT AND FUTURE COLLIDERS

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ABSTRACT

The theoretical expectations for the supersymmetric particle spectrum is reviewed and a brief overview on present constraints on supersymmetric models from collider experiments is presented. Finally, we discuss the discovery potential of future colliders experiments.

1. Introduction

The standard model of elementary particle physics (SM) is in excellent agreement with present experimental results. Nonetheless, the theory suffers from a variety of theoretical shortcomings and is generally believed to be the low energy effective theory describing the physics at and below the scale of spontaneous electro-weak symmetry breaking given by the mass of the $Z$ boson, $m_z = 91.187$ GeV. In particular, finding an explanation for the hierarchy between $m_z$ and the Planck scale, $M_P = 10^{19}$ GeV is considered a severe problem and most theorists expect that the mechanism to solve this problem should manifest itself already at energies below 1 TeV. Presently, the most popular and the most promising candidate for this new physics is supersymmetry (SUSY).

In supersymmetric theories the quadratically divergent higher order contributions to scalar mass terms from bosons (fermions) are automatically canceled by the contributions of the fermionic (bosonic) superpartner.

This implies immediately that the number of fields has to be doubled with respect to the SM. In addition, two Higgs doublets are required in order to give masses to down-type and up-type fermions and to cancel the Higgsino (= fermionic superpartner of the Higgs bosons) contributions to the triangle anomalies. The particle content of the minimal supersymmetric extension of the SM (MSSM) together with their quantum numbers is presented in table 1.

Furthermore, all the couplings of the superpartners are determined by SUSY and in particular one finds that they have to be mass degenerate with their SM counterpart. This later requirement is in clear contradiction with the measurement of the $Z$
Table 1. The MSSM particle content.

| Superfields | SM fields | Superpartner | SU(3)$_c$ | SU(2)$_L$ | U(1)$_Y$ |
|-------------|-----------|--------------|-----------|-----------|-----------|
| Gauge Multiplets | | | | | |
| $G$ | $g$ | $g$ | 8 | 1 | 0 |
| $\tilde{W}$ | $W$ | $\tilde{W}$ | 1 | 3 | 0 |
| $\tilde{B}$ | $B$ | $\tilde{B}$ | 1 | 1 | 0 |
| Matter Multiplets | | | | | |
| $\hat{Q}$ | $(u, d)_L$ | $\tilde{Q} = (\tilde{u}, \tilde{d})_L$ | 3 | 2 | 1/3 |
| $\hat{U}^c$ | $\tilde{u}_L$ | $\tilde{U}^c = \tilde{u}^*_R$ | 3 | 1 | −4/3 |
| $\hat{D}^c$ | $\tilde{d}_L$ | $\tilde{D}^c = \tilde{d}^*_R$ | 3 | 1 | 2/3 |
| lepton | $\tilde{L}$ | $(\nu, e)_L$ | 1 | 2 | −1 |
| $\hat{E}^c$ | $\tilde{e}_L$ | $\tilde{E}^c = \tilde{e}^*_R$ | 1 | 1 | 2 |
| Higgs | $\hat{H}_1$ | $H_1$ | $\{\tilde{H}^0_1, \tilde{H}^-_1\}$ | 1 | 2 | −1 |
| $\hat{H}_2$ | $H_2$ | $\{\tilde{H}^0_2, \tilde{H}^2_2\}$ | 1 | 2 | 1 |

line-shape at LEP which tells us that there are no new particles with masses below about $m_Z/2$ except maybe for electro-weak singlets such as the fermionic partners of the photon and of the gluon.

In general it is very difficult to construct realistic low energy models where SUSY is broken spontaneously. Instead it became standard to break SUSY explicitly via soft SUSY breaking terms. These terms are thought to arise from spontaneous SUSY breaking via dilaton or moduli fields (Superstring Theories) or via gravitational coupling to a "hidden sector", where the spontaneous SUSY breaking takes place without posing any experimental constraints on our visible world.

With these soft SUSY breaking terms we can give masses to all the superpartners and thus evade all experimental constraints. In particular, we can give a negative squared mass to the Higgs bosons needed for the spontaneous electro-weak symmetry breaking (EWSSB).

The Higgs boson is the last missing building block of the SM and its discovery is not a priori an indication for SUSY. However, there are fundamental differences between the SM and the MSSM Higgs sector that might allow us to disentangle the two models. As stated above, the Higgs sector of the MSSM consists of two Higgs doublets which after EWSSB reduces to two CP-even Higgs bosons, $h^0$ and $H^0$, one CP-odd Higgs boson, $A^0$, and a pair of charged Higgs bosons, $H^{\pm}$. Because of SUSY the Higgs potential contains only two independent parameters typically chosen to be $m_{A^0}$ and the ratio of the Higgs vacuum expectation values, $\tan \beta \equiv \langle H_2 \rangle / \langle H_1 \rangle$. It

\textsuperscript{a}However, the discovery of a fundamental scalar would severely limit any alternative solution to the hierarchy problem such as compositeness models or techi-color models.
also predicts a well defined upper limit for the lightest MSSM Higgs boson:

\[ m_{h_0} \lesssim m_z + \text{radiative corrections} \simeq 130 \text{ GeV}, \]  

(1)

such that non-discovery of a Higgs boson below about 130 GeV would rule out the MSSM. This bound can be evaded by coupling the Higgs fields to an additional gauge singlet. In this extended model the Higgs mass becomes a free parameter depending on this coupling. However, an upper limit analogous to the triviality bound in the SM remains if one requires this coupling to remain perturbative up to some high scale (say, \( M_P \)).

The soft SUSY breaking terms can be written as follows:

\[ V_{soft} = V_0 + V_{1/2} + V_A + V_B, \]  

(2)

where \( V_0 = \sum \phi \phi^\dagger \phi \phi \) gives a mass to all the spin 0 particles (the sum is over all Higgs bosons, squarks and sleptons), \( V_{1/2} = \sum m_i \psi_i \psi_i + \text{h.c.} \) gives a mass to all the spin 1/2 partners of the gauge bosons (\( \psi_i = B, \tilde{W}, \tilde{g} \)), \( V_A \) describes the trilinear Higgs-squark-squark interactions, and \( V_B \) describes the Higgs mixing term which is usually replaced in favor of \( \tan \beta \). With these additional terms we can construct a model that satisfies all experimental constraints.

Unfortunately, the predictability of these models is very limited due to the large number of free parameters. The situation can be improved by making assumptions about the origin of these parameters. In minimal supergravity models one usually assumes that the soft mass terms generated via gravity are universal at \( M_P \) for all fields with the same spin and that the squark-squark-Higgs interactions are proportional to the corresponding quark-quark-Higgs Yukawa interactions. That means that the SUSY particle spectrum is determined in terms of only four parameters \( m_0^2, m_{1/2}, A, \) corresponding to the four terms in eq.\(^b\). This universality of the soft SUSY breaking terms is broken via renormalization group evolution from \( M_P \) to \( m_Z \) and one again obtains a non-degenerate particle spectrum. However, this evolution is predictable if we assume that the MSSM is the full theory all the way to \( M_P \) without any intermediate scales\(^c\). We obtain

\[ m_{\tilde{F}}^2 = C_0^F m_0^2 + C_{1/2}^F m_{1/2}^2 + C_D^F D, \]  

(3)

where we have neglected the \( A \) parameter which is mainly important for the left/right mixing of the top squarks. Here, we have defined \( D = m_w^2 \cos 2\beta \) and \( C_D^F = T_3 - \tan^2 \theta_w Y_F / 2 \) (\( Y_F \) denotes the \( U(1)_Y \) hypercharges shown in table \( \| \) and \( \theta_w \) is the Weinberg angle). In the case of small Yukawa couplings these coefficients are given\(^b\) the Higgs mass parameter of the superpotential, \( \mu \), is determined by fixing \( m_a \).\(^c\) Clearly this is not the case in grand unified theories (GUTs) but the hope was that the numerical results will not be much affected by the RG integration between \( M_P \) and \( M_{\text{GUT}} = 2 \times 10^{16} \) GeV. This assumption may be an oversimplification as was pointed out recently in refs.\(^\| \).
by $C^F_0 \simeq 1$ and $C^F_{1/2} \simeq 6.5, 6, 6, 0.5, 0.15$, for $F = Q, U, D, L, E$. The coefficients for the third generation $F = Q_3, U_3$ (and possibly $F = D_3$ in the limit of large $\tan \beta$) can be reduced by up to about 50% through the effects of a large top Yukawa coupling. It is this effect of the top Yukawa coupling that renders the coefficients $C^H_2$ and $C^H_{1/2}$ negative and, hence, destabilizes the symmetric minimum. As a result, $H_2$ (and via mixing also $H_1$) acquire a non-vanishing VEV that break the electro-weak symmetry spontaneously. The fact, that over a large region of the parameter space only the Higgs fields and none of the scalar superpartners acquire a VEV is one of the reasons for the popularity of this scenario.

Another reason is the fact that the gauge couplings meet within the experimental errors at a single scale, $M_{\text{GUT}} \simeq 2 \times 10^{16}$ GeV which allows to embed the SM gauge-groups into a single unified gauge group such as $SU(5)$. In SUSY-GUT models, the universality of the gaugino masses in $V_{1/2}$ is not only a (model-depending) assumption but an inevitable consequence of gauge invariance. A violation of the resulting low energy prediction

$$\frac{M_{\tilde{g}}}{m_{1/2}} : \frac{M}{m_{1/2}} : \frac{M'}{m_{1/2}} = \frac{\alpha_s}{\alpha_{\text{GUT}}} : \frac{\alpha_{\text{em}}}{\sin^2 \theta_w \alpha_{\text{GUT}}} : \frac{5\alpha_{\text{em}}}{3 \cos^2 \theta_w \alpha_{\text{GUT}}} \simeq 2.5 : 0.8 : 0.4, \quad (4)$$

would be a indication against minimal SUSY-GUT. Note that the gauginos of a broken gauge symmetry are no mass eigenstates but they obtain a SUSY invariant mass via mixing with the Higgsinos. The resulting neutral (charged) mass eigenstates are the neutralinos (charginos). In the SUSY limit (ie: $M' = M = \mu = 0$ and $\tan \beta = 1$) one linear combination of $\tilde{B}$ and $\tilde{W}_3^3$ combines with one linear combination of $\tilde{H}_1^0$ and $\tilde{H}_2^0$ to form a Dirac fermion with mass $m_\chi$ while the other fields remain massless. On the other hand, in the limit of a large SUSY breaking scale $M_{\text{SUSY}} \gg m_\chi$ the the mass eigenstates are the gauginos with majorana masses $M'$, $M$ and the Higgsinos with a Dirac mass $\mu$. The chargino sector is analogous with $m_\chi$ replaced by $m_\tilde{\chi}$, etc.

An important property of the MSSM is its minimality not only with respect to its particle content but also with respect to the allowed particle interactions. In general, any model constrained solely by gauge invariance will contain new interactions that violate lepton number and baryon number. These interactions have to be suppressed below the present limits by imposing an additional symmetry. The most popular candidate for such a symmetry, $R$-parity, is defined such that all superpartners change sign while the SM particles remain invariant. $R$ parity conservation implies that the lightest supersymmetric partner (LSP) is stable and, hence, will contribute to the dark matter (DM) of the universe.

The existence of a stable LSP is not only important for DM search but also for the SUSY search at colliders. Most experimental analysis assumes that the superpartner decay (possibly via cascade decays) into the LSP which escapes from the detector undetected. The evidence for such an event would be the missing transverse energy that had been carried away by the LSP.
Table 2. Present and Future Colliders.

| name                  | Type   | $\sqrt{s}$ | $\int \mathcal{L} dt$ | date       |
|-----------------------|--------|------------|------------------------|------------|
| $e^+e^-$ Colliders:   |        |            |                        |            |
| LEP-I circular        | circular | $m_z$      | 0.1 fb$^{-1}$          | now        |
| LEP-II circular       | circular | 180 GeV    | 0.5 fb$^{-1}$          | 1996/7     |
| NLC linear            | linear  | 0.5 ~ 2 TeV | 50 ~ 200 fb$^{-1}$    | 2005/10    |
| Hadron Colliders:     |        |            |                        |            |
| Tevatron (CDF and D0) | $p\bar{p}$ | 1.8 TeV    | 0.1 fb$^{-1}$          | now        |
| Tevatron (main injector) | $p\bar{p}$ | 2 TeV     | 1 fb$^{-1}$           | 1999       |
| TeV*                  | $p\bar{p}$ | 2 TeV     | 10 fb$^{-1}$          | 2000/1     |
| Di-Tevatron           | $p\bar{p}$ | 4 TeV     | 20 fb$^{-1}$          | 2000/1     |
| LHC                   | $pp$    | 14 TeV     | 10 ~ 100 fb$^{-1}$    | 2004/8     |

2. SUSY in Present and Future Collider Experiments

Now after we have introduced the theoretical framework we will present limits on the supersymmetric parameter space from collider experiments. The main constraints on the SUSY particle masses come from high energy $e^+e^-$ or hadron collider experiments. In addition, there are various other experiments whose primary importance for SUSY is to constrain individual (e.g. $R$ parity violating) interactions rather than particle masses. In Table 2 we have listed all relevant high energy collider projects that are presently running (LEP-I, Tevatron), approved (LEP-II, main injector, LHC), considered (TeV*, Di-Tevatron) and under discussion (NLC with the option for $e^-\gamma$, $e^-e^-$, and $\gamma\gamma$ collision).

2.1. SUSY at $e^+e^-$ Colliders

The clearest constraints come from LEP experiments at CERN that has collected $O(10^7)$ on-shell Z’s. The high statistics not only to rules out any squarks and charged sleptons with a mass below $m_z/2$ but allows also to establish similar lower limits on the sneutralino masses from the Z line-shape and some parameter dependent lower limit on the lightest neutralino mass.

LEP-II is expected to start operating by the end of 1996 and the members of the various working groups are asked to make discovery and exclusion plots for a center-of-mass energies of $\sqrt{s} = 175$, 192, and 205 GeV. Any $e^+e^-$ collider with $\sqrt{s} \gtrsim 200$ GeV would have to be linear due to excessive power-loss of a circular collider via synchrotron radiation. The discovery potential of the next linear $e^+e^-$
collider (NLC) with an initial energy of $\sqrt{s} \gtrsim 500$ GeV and an option for an upgrade to $1.5 \sim 2$ TeV is under continuing study.

The discovery potential of any of these $e^+e^-$ machines for a charged particle is roughly given by $\sqrt{s}/2$ minus a few % due to phase-space suppression near threshold.

The discovery of the lightest Higgs boson is possible for masses $m_{h^0} \lesssim \sqrt{s} - 100$ GeV. This means that non-discovery of a Higgs boson at LEP-II would constrain the MSSM parameter space but one would have to wait for the NLC to rule out the MSSM.

The disadvantage is that squarks can only be produced via the s-channel which is suppressed for high energies and that gluinos can only be produced in squark decay if $M_{\tilde{g}} < m_{\tilde{q}}$.

2.2. SUSY at Hadron Colliders

The best constraint on the gluino mass, $M_{\tilde{g}} > 144$ GeV (or $M_{\tilde{g}} > 212$ if $M_{\tilde{g}} = m_{\tilde{q}}$), come from the D0 experiment at TEVATRON.

The SUSY discovery potential of was studied by the SUSY working group for the LHC workshop and more recently in ref. The disadvantage is that a Higgs boson with a mass $m_{h^0} \lesssim 2m_w$ decays predominantly into $b\bar{b}$ pairs and discovery at a hadron collider in this case is difficult. In particular, there is a hole in the $\tan\beta-m_{A^0}$ plane for $4 \lesssim \tan\beta \lesssim 15$ and 100 GeV $\lesssim m_{A^0} \lesssim 200$ GeV where no MSSM Higgs boson can be detected.

3. Summary

$e^+e^-$ colliders provide the ideal environment for the discovery of Higgs bosons and for a spectroscopy of the electro-weak superpartners (= sleptons, charginos and neutralinos). The lightest chargino might well be within the range of LEP-II. At the NLC with $\sqrt{s} = 500$ GeV one will for sure discover at least one Higgs boson or rule out the MSSM and any other SUSY-GUT model that requires perturbativity of the couplings up to $M_{GUT}$. Many if not all electro-weak superpartners are expected to lie within the reach of the NLC upgrade with $\sqrt{s} = 1.5 \sim 2$ TeV.

On the other hand, the search for colored superpartners is more promising in hadron colliders because (a) squarks and gluinos are expected to be heavier (see, eq. (3)) (b) the production rate at high energies is dominated by t-channel exchange of gluinos (squark production) or of squarks (gluino production) absent in $e^+e^-$ colliders. Thus, we conclude that $e^+e^-$ and hadron colliders are very much complimentary in the search for SUSY.
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