THEORETICAL ASPECTS OF SUPERSYMMETRY*

Jan Kalinowski

Institute of Theoretical Physics, Warsaw University
Hoża 69, 00-681 Warsaw, Poland

(Received September 16, 2002)

Some theoretical aspects of the minimal supersymmetric standard model and problems in unravelling its underlying structure are briefly discussed.

PACS numbers: 12.60.Jv

The Standard Model (SM) of electroweak interactions has successfully been tested at a per-mille accuracy at LEP [1]. With recent luminosity upgrades of the Tevatron and HERA colliders [2] further tests will be possible, or hopefully first signals of new physics may emerge. There are many arguments why the SM cannot be the ultimate theory, most of them linked to the problem of mass generation and energy scales. In the SM mass generation is achieved by introducing an SU(2) doublet of scalar Higgs fields with a non-vanishing vacuum expectation value $v = 246$ GeV of the neutral component. The v is however unstable against radiative corrections leading to the famous hierarchy problem: the presence of two vastly different scales — the electroweak scale set by the v and the scale of grand unification, or Planck scale $M_{\rm P} \sim 10^{19}$ GeV.

A number of theoretical ideas have been proposed to deal with the hierarchy problem, which can broadly be classified into three categories:

- supersymmetry, which provides a mechanism to stabilize the energy gap between the v and $M_{\rm P}$ against radiative corrections,
- compositeness, which fills the gap by postulating many intermediate energy scales in between,
- large extra dimensions, by closing the gap assuming that the $M_{\rm P}$ is an apparent scale related to the fundamental one of the same order as v.

---

* Presented at the X International Workshop on Deep Inelastic Scattering (DIS2002) Cracow, Poland, 30 April–4 May, 2002.

For compositeness, no working model satisfying all precision electroweak measurements exists. The extra-dimension ideas often resort to supersymmetry for stabilizing various scales that appear there, and at the same time they provide new mechanisms of supersymmetry breaking [3].

Supersymmetry still is the only theoretical concept that provides a highly predictive extension of the SM and which allows for precision calculations of measurable quantities. The supersymmetric SM however is not yet a complete theory in the sense that the physics of all of its parameters related to the mechanism of supersymmetry breaking is not understood. Nevertheless it is a complete effective theory because the structure of the full effective Lagrangian is known.

Supersymmetry, being almost as old as the SM itself, was not invented or designed to solve some of the SM problems. It turned out however, that it can beautifully accommodate or explain (at least in the technical sense) some of the outstanding problems of the Standard Model, like the hierarchy problem, the gauge coupling unification, the radiative electroweak symmetry breaking. It predicts the heavy top quark, provides a candidate for dark matter, offers new ideas on matter asymmetry of the universe *etc.*

One of the most important implications of the fits to precision measurements, the strong indication for a light Higgs boson $m_H = 85^{+54}_{-34}$ GeV with the 95% CL upper limit 196 GeV [1], is in perfect agreement with the most robust prediction of supersymmetric extensions of the SM, *i.e.* the existence of a light Higgs boson. This result fuels strong hopes for a discovery of the Higgs boson in near future and, hopefully, supersymmetric particles. At present, the direct searches for supersymmetry are searches in the dark because present accelerators are not powerful enough to explore most of the parameter space. Since several talks at this meeting dealt with the current experimental limits and prospects for future supersymmetry searches [4] (within MSSM and beyond), I will concentrate on some theoretical aspects of low-energy supersymmetry and address the question of unravelling the underlying structure of the theory.

Since supersymmetry must be broken at low energy, and the mechanism of its breaking is still unknown, even the minimal supersymmetric model (MSSM) introduces more than 100 new parameters (see below). The MSSM is understood as an effective low energy model defined by three assumptions: (a) minimal particle content, (b) R-parity conservation, (c) most general soft supersymmetry breaking terms. The number of parameters can be further enlarged by relaxing (a) or (b), or reduced by constraining (c) with additional assumptions on SUSY breaking mechanism.

(a) *Minimal particle content:* the MSSM consists of the SM particles and their superpartners — quarks and squarks, leptons and sleptons, gauge bosons and gauginos. In addition, the MSSM contains two hypercharge

$Y = \pm 1$ Higgs doublets and their superpartners, higgsinos, which is the minimal content of an anomaly-free supersymmetric model. The supersymmetric structure of the model also requires (at least) two Higgs doublets to generate mass for up- and down-type quarks (and charged leptons). All renormalizable supersymmetric interactions of matter superfields, consistent with the baryon and lepton number conservation, follow from the superpotential:

$$W = \varepsilon_{\alpha\beta}\left[Y^L_{ij}H^\alpha_1 L^\beta_i E_j + Y^D_{ij}H^\alpha_1 Q^\beta_i D_j - Y^U_{ij}H^\alpha_2 Q^\beta_i U_j - \mu H^\alpha_1 H^\beta_2\right], \quad (1)$$

where H, L, Q denote SU(2) doublets, E, U are SU(2) singlets of Higgs, lepton and quark superfields, respectively, $\varepsilon_{\alpha\beta}$ ($\varepsilon_{12} = 1$) contracts SU(2) doublet fields, Y^L, Y^D, Y^U are the 3×3 Yukawa coupling matrices and μ is the Higgs superfield mass parameter. The matter superfields couple to gauge superfields according to the SU(3)×SU(2)×U(1) gauge symmetry. After the gauge symmetry breaking, the fields with the same SU(3)×U(1)$_{\mathrm{EM}}$ quantum numbers can mix. For example, the charged mass eigenstates, charginos, are linear combinations of charged winos and higgsinos, while the neutralinos are mixtures of bino and neutral wino and higgsinos.

(b) *R-parity:* since all quantum numbers of L and H_1 superfields are identical, additional terms with H_1 replaced by L can appear in Eq. (1)

$$\begin{aligned} W_{\not R} \;=\; & \varepsilon_{\alpha\beta}[\lambda_{ijk}L^\alpha_i L^\beta_j E_k + \lambda'_{ijk}L^\alpha_i Q^\beta_j D_k + \eta_i L^\alpha_i H^\beta_2] \\ & +\lambda''_{ijk}U_i D_j D_k\,, \end{aligned} \quad (2)$$

where the last term is also allowed by the supersymmetry and gauge structure. The terms in the first line violate lepton number ($\not L$), while the last term violates baryon number ($\not B$). If all couplings are present, one can build an effective four-fermion operator QUDL mediating proton decay which is suppressed only by the squark mass. With all couplings of order 1 and squark masses of order 1 TeV it would be a disaster — proton would decay after 10^{-10} seconds. The simplest solution to stabilize the proton is to impose a discrete symmetry defined as R-parity

$$R_p = (-1)^{3(B-L)+2S} \quad (3)$$

which forbids all terms in Eq. (2). With R_p conserved, proton is stable ($\tau_p > 10^{32}$ y), supersymmetric particles are produced in pairs, the Lightest Supersymmetric Particle (LSP, in most cases the lightest neutralino) is stable and is a candidate for dark matter. However, to stabilize the proton it is enough to forbid either $\not L$ or $\not B$ terms. In light of non-zero neutrino mass and oscillations, an interesting possibility is to allow $\not L$ and forbid only $\not B$

terms. This can be achieved by imposing a Z_3 symmetry, called "baryon parity" [5], under which fields (Q, U, D, L, E) have Z_3 charges $(0, 2, 1, 2, 2)$, respectively. It turns out that baryon parity is the only discrete anomaly free with the minimal particle content of the supersymmetric model which allows for lepton number violation and therefore neutrino masses, prevents dimension 4 *and* 5 proton decay operators, but also allows the LSP decay. Whether any discrete symmetry is a real symmetry is essentially an experimental question, the answer to which will teach us about the structure of the MSSM at high scale, and the fate of the universe.

(c) *Most general soft supersymmetry breaking terms:* the minimal extension of the SM with unbroken supersymmetry has actually fewer free parameters than the SM in spite of large number of new fields. However, supersymmetry must be broken. Since the fundamental origin of supersymmetry breaking is unknown, our ignorance can be parameterized by adding the most general soft-supersymmetry breaking terms in the scalar potential [6] consistent with gauge invariance and R-parity conservation

$$\begin{aligned}
V_{\rm soft} \; = \; & m_1^2|H_1|^2 + m_2^2|H_2|^2 - m_3^2 \left(\varepsilon_{\alpha\beta} H_1^\alpha H_2^\beta + \text{ h.c.} \right) \\
& + \sum_{\tilde f} (M^2_{\tilde f})_{ij} \tilde f_i^* \tilde f_j + \tfrac{1}{2} \left(\sum_{\tilde g} M_{\tilde g} \tilde g \tilde g + \text{ h.c.} \right) \\
& + \varepsilon_{\alpha\beta} \left(A_{ij}^L H_1^\alpha \tilde L_i^\beta \tilde E_j + A_{ij}^D H_1^\alpha \tilde Q_i^\beta \tilde D_j + A_{ij}^U H_2^\alpha \tilde Q_i^\beta \tilde U_j + \text{ h.c.} \right) ,
\end{aligned} \tag{4}$$

where summing runs over all sfermions ($\tilde f = \tilde Q$, $\tilde U$, $\tilde D$, $\tilde L$, $\tilde E$) and gauginos ($\tilde g$=bino, wino, gluino). The $V_{\rm soft}$ includes three Higgs mass parameters m_i^2, five Hermitian 3×3 scalar squared-mass matrices $M^2_{\tilde f}$, three complex 3×3 trilinear scalar couplings A and three complex Majorana gaugino masses $M_{\tilde g}$. Exploiting global symmetries of the model, one finds [7] 105 new parameters in addition to 19 SM ones bringing total number of independent parameters to 124. Among the new ones are 36 real mixing angles and 40 CP-violating phases in the sfermion sector, and 3 CP-violating phases in the higgsino/gaugino sector. With so many parameters it is hard to accept the MSSM as a fundamental theory. Moreover, the model exhibits phenomenologically bad features, like unsuppressed FCNC and CP-violating phenomena. As a result, most of the 124-parameter space is already excluded. The MSSM is viable only at very special regions of the full parameter space.

The gauge coupling unification, however, suggests that physics might be simpler at or near the unification scale, and the Renormalization-Group Equations (RGE) can provide the link between low- and high-scale theories. There are two general approaches along these lines.

The *top-down* approach imposes a particular structure on the soft SUSY breaking terms at a common high energy scale (such as the GUT or Planck scale) and the RGE are used to derive the low-energy MSSM parameters. This approach is usually characterized by the scenario in which supersymmetry breaking is mediated to the visible sector. Several theoretical scenarios have been examined in some detail: for example gravity-, gauge-, anomaly- and gaugino-mediated supersymmetry breaking. Each one is characterized by a handful of independent parameters which makes the phenomenological analyses of low-energy theory much simpler and more predictive.

However the top-down approach may be too restrictive: the phenomenologically viable region of 124-parameter space is larger than any RGE-derived region of the above scenarios. Moreover, our imagination of devising high-scale supersymmetry-breaking scenarios is certainly limited.

The *bottom-up* approach uses the RGE as a telescope to explore the high-energy physics by exploiting the low-energy experimental input to the maximum extent possible. At present only the experimental limits on the parameter space can be used to gain some insight on high-energy theory. However, in future, once supersymmetry is discovered, we will have many experimental measurements. Recent collider studies [8] have shown how the low-energy supersymmetry Lagrangian parameters can be reconstructed from precision measurements at future linear accelerators. It is important to perform the above reconstruction independently of any theoretical assumptions [9] (in practice, loop-corrections will induce some model-dependence). This is a necessary requirement for verifying experimentally any relations among them when extrapolated to high scales. Although such extrapolations extend over 13 orders of magnitude, they can be carried out in a stable way in supersymmetric theories [10].

We are still far from understanding all possible facets of the MSSM, not to mention non-minimal supersymmetric models. Nevertheless, low-energy supersymmetry remains the most elegant solution to the hierarchy problem and provides a possible link to high scales where particle physics meets gravity.

Work supported by the Polish State Committee for Scientific Research (KBN) Grant 5 P03B 119 20.

REFERENCES

[1] T. Saeki, *Acta Phys. Pol.* **B33**, 3831 (2002) these proceedings and references therein.

[2] M. Petteni, *Acta Phys. Pol.* **B33**, 3855 (2002) these proceedings; K. Śliwa, *Acta Phys. Pol.* **B33**, 3861 (2002) these proceedings; M. Wolter, *Acta Phys. Pol.* **B33**, 2915 (2002) these proceedings; A. Mehta, *Acta Phys. Pol.* **B33**, 3937 (2002) these proceedings.

[3] Z. Lalak, presented at this conference but not submitted to the proceedings.
[4] N. De Filippis, *Acta Phys. Pol.* **B33**, 3881 (2002) these proceedings; J. Haller, *Acta Phys. Pol.* **B33**, 3875 (2002) these proceedings; R. Ströhmer, *Acta Phys. Pol.* **B33**, 3887 (2002) these proceedings; G. Wrochna, *Acta Phys. Pol.* **B33**, 3929 (2002) these proceedings.
[5] L.E. Ibáñez, G.G. Ross, *Nucl. Phys.* **B368**, 3 (1991).
[6] L. Girardello, M. Grisaru, *Nucl. Phys.* **B194**, 65 (1982).
[7] S. Dimopoulos, D. Sutter, *Nucl. Phys.* **B452**, 496 (1995).
[8] S.Y. Choi *et al.*, *Eur. Phys. J.* **C14**, 535 (2000); *Eur. Phys. J.* **C22**, 563 (2001); *Eur. Phys. J.* **C23**, 769 (2002); A. Bartl *et al.*, *Z. Phys.* **C76**, 549 (1997); *Eur. Phys. J.* **C6**, 1 (2000); *Eur. Phys. J.* **C18**, 379 (2000).
[9] M. Brhlik, G.L. Kane, *Phys. Lett.* **B437**, 331 (1998); J. Kalinowski, *Acta Phys. Pol.* **B30**, 1921 (1999).
[10] G.A. Blair, W. Porod, P.M. Zerwas, *Phys. Rev.* **D63**, 017703 (2001).