Lecture Notes in Physics Monographs 68

Supersymmetry: Structure and Phenomena

Extensions of the Standard Model

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Foreword

Supersymmetry is one of the most discussed themes in modern particle physics, although there is no convincing evidence yet for its existence in nature. Intrigued by the uniqueness and theoretical beauty of this symmetry, researchers in the field are confident that interest will continue in the coming years and even decades. In fact, many of the most exciting recent developments in mathematical physics, quantum field theory and string theory were obtained using the concepts of supersymmetry.

Still the most fascinating aspect of supersymmetry resides in the possibility that it might extend the celebrated standard model of elementary particle physics into an energy range accessible to present and planned experiments: its experimental discovery might thus be "around the corner". This so-called "low-energy" supersymmetry, the supersymmetric generalization of the standard model of strong, weak and electromagnetic interactions, is the central subject of the present book.

Nir Polonsky is well suited as an author of such a book as he is an expert in the field and, throughout his career, has made important contributions to its development. In the present monograph he provides a "guided tour" through this vast field of "low-energy" supersymmetry. In a convincing way he selects the essential topics and provides a consistent account of the field, avoiding the discussion of unnecessary details. His clear and patient explanations make this book useful both for the experienced researcher in the field and the student who wants to take the first steps towards learning supersymmetry. All physicists interested in this subject will want to have this book on their shelves.

Bonn, Germany,
July 2001

Hans Peter Nilles

Preface

Moor: point
my horse
where birds sing.

Basho (Translation by Lucien Stryk)

These notes provide an introductory yet comprehensive discussion of the phenomenology associated with supersymmetric extensions of the Standard Model of electroweak and strong interactions. The choice of topics and of their presentation is meant to draw readers with various backgrounds and research interests, and to provide a pedagogical tour of supersymmetry, structure and phenomena. The intensive and ongoing efforts to understand and discover such phenomena, or to alternatively falsify the paradigm predicting it, and the central role of supersymmetry in particle physics studies, mean that such a journey is a well-motivated endeavor, if not a necessity. This is particularly true as we look forward to moving into a new era of discoveries with the forthcoming commissioning of CERN's Large Hadron Collider (LHC), which is scheduled to operate by the year 2005.

Even though our focus is on (weak-scale) supersymmetry, it would still be impossible to cover within these notes all that it entails. In the following, we choose to stress the more elementary details over the technicalities, the physical picture over its formal derivation. While some issues are covered in depth, many others are only sketched or referred to, leaving the details to either optional exercises or further reading. Our mission is to gain acquaintance with the fundamental picture (regardless of the reader's background), and we will attempt to do so in an intuitive fashion while providing a broad and honest review of the related issues. Many reviews, lecture notes, and text books (most notably, Weinberg's book [1]) are available and references will be given to some of those, as well as to some early and recent research papers on the subjects discussed. Some areas are particularly well covered by

reviews, e.g., the algebra on the one hand and experimental searches on the other hand, and hence will not be explored extensively here.

Before discussing supersymmetry and the "TeV World", it is useful to recall and establish our starting point: the Standard Model of electroweak and strong interactions as characterized and tested at currently available energies $\sqrt{s} \lesssim 200 - 300$ GeV (per parton). We therefore begin with a brief summary of the main ingredients of the SM. Hints for an additional structure within experimental reach will be emphasized, and the known theoretical possibilities for such a structure, particularly supersymmetry, will be introduced. This will be done in the first part of the notes. The second part provides a phenomenological "bottom-up" construction of supersymmetry, followed by a brief discussion of the formalism – providing intuitive understanding as well as the necessary terminology. We then supersymmetrize the Standard Model, paying attention to some of the details while only touching upon others.

In the third part of the notes we turn to an exploration of a small number of issues which relate ultraviolet and infrared structures. These include renormalization and radiative symmetry breaking, unification, and the lightness of the Higgs boson, issues which underlie the realization of the weak scale. This particular choice of topics does not only lay the foundation for supersymmetry phenomenology but also represents some of the successful predictions of weak-scale supersymmetry. Subsequently, we discuss in the fourth part some of the difficulties in extending the standard model, the most important of which is the flavor problem. Its possible resolutions are used as an organizing principle for the model space, which is then characterized and described.

Throughout these notes we attempt to leave the reader with a clear view of current research directions and avenues which stem from the above topics. Some more technical and specialized issues are explored further in the fifth and last part of the notes. These include the possible origins of neutrino mass and mixing and the implications of the different scenarios: vacuum stability and the respective constraints; classifications of supersymmetry-breaking operators; and an introductory discussion of extended supersymmetry. These serve as a (subjective) sample of contemporary and potential avenues of research. The reader is encouraged to explore the literature given throughout the notes for technical discussions of other topics of interest.

As physicists, our interest is in confronting theory with experiment. Here, we will argue for and motivate supersymmetry as a reasonable and likely perturbative extension of the standard model. Whether supersymmetry is realized in nature, and if so in what form, can and must be determined by experiment. Experimental efforts in this direction are ongoing and will hopefully result in an answer or a clear indication within the next decade. Discovery will only signal the start of a new era dedicated to deciphering the ultraviolet theory from the data: supersymmetry, by its nature (and as we will demonstrate), relates the infrared and the ultraviolet regimes. By doing so it provides us with extraordinary opportunities for a glimpse at scales we cannot

reach, and to answer fundamental questions regarding unification, gravity, and much more. The more one is familiar with the ultraviolet possibilities and their infrared implications, the more one can direct experiments towards a possible discovery.

Clearly, a lot of work is yet to be done and there is always room for new ideas to be put forward. It is my hope that these notes convince and enable one to follow (if not participate in) the story of weak-scale supersymmetry, and new physics in general, as it unveils. It is not our aim to equip the reader with calculation tools or to review in these notes each and every aspect or possibility. Rather, we will attempt to enable the interested reader to form an educated opinion and identify areas of interest for further study and exploration. Many of the issues discussed will be presented from an angle which differs from other presentations in the literature, for the potential benefit of both the novice and expert readers. Our bibliography is comprehensive, however it is far from exhaustive or complete. Most research articles on the subject (which were written in the last decade) can be found in the Los Alamos National Laboratory electronic archive http://xxx.lanl.gov/archive/hep-ph, and the Stanford Linear Accelerator Center's Spires electronic database http://www.slac.stanford.edu/spires/hep lists relevant articles and reviews.

The core of the manuscript is based on the lecture series "Essential Supersymmetry" which appeared in the proceedings of the TASI-98 school [2]. However, the material was revised, updated and significantly extended. I thank Francesca Borzumati for her help with the figures, and Howard Haber and Chris Kolda for providing me with Fig. 8.1 and Fig. 7.2, respectively. I also thank Francesca Borzumati, Lee Hyun Min, Yasanury Nomura, and Myck Schwetz for their careful reading of earlier versions of the manuscript and for their comments. I benefited from work done in collaboration with Jonathan Bagger, Francesca Borzumati, Hsin-Chia Cheng, Jens Erler, Glennys Farrar, Jonathan Feng, Hong-Jian He, Jean-Loic Kneur, Chris Kolda, Paul Langacker, Hans-Peter Nilles, Stefan Pokorski, Alex Pomarol, Shufang Su, Scott Thomas, Jing Wang, and Ren-Jie Zhang. This manuscript was completed during my tenure as a Research Scientist at the Massachusetts Institute of Technology, and I thank Bob Jaffe for his encouragement. Finally, I thank Peter Nilles for his support.

Cambridge, May 2001 *Nir Polonsky*