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Beyond the standard model: Working group report

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Abstract. This report summarises the activities of the working group on 'Physics beyond the Standard Model'. The results of investigations in incorporating R-parity in grand unification, the possibility of a light charged Higgs boson in extension of MSSM and radiative generation of neutral vector boson self-couplings within the MSSM are described. Also given is an account of activities in neutrino physics, namely a proposal for a study of the atmospheric muon anomaly in deep underground mines, a field theoretic study of neutrino oscillations and a mechanism to generate appropriate masses of three active plus one sterile neutrino species.

Keywords. Supersymmetry; R-parity; unification; gauge-boson self-couplings; neutrino masses and mixings; atmospheric muon anomaly.

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1. Introduction

As its name suggests, this working group focussed on phenomenological implications of various scenarios going beyond the standard model. The scope of the investigations included radiative corrections to various observables, 'low energy' constraints including those obtained at LEP, as well as consequences at neutrino experiments. However, investigations into possible signatures at the Tevatron, the forthcoming B-factories as well as at planned hadron and lepton colliders, were considered to constitute a separate working group.

While many different scenarios going beyond the standard model were discussed, most of the activity concentrated on (i) supersymmetric models and (ii) models/signatures for neutrino oscillations. Consequently, this report deals exclusively with activities on these two fronts. Due to reasons of logistics, we, unfortunately, have to forego an account of the discussions on models of dynamical symmetry breaking as well as those on non-supersymmetric grand unification.

A few special seminars were also organized as part of the group activities. They served to initiate discussions on new and interesting developments and, hopefully, will lead to research projects. A few of these seminars are described at the end of the report.

2. Supersymmetry

One of the motivations of invoking supersymmetry, and a reason for its continuing popularity despite lack of any evidence, is that it provides us with a natural framework for discussing physics at a high energy scale, including grand unification. This, however, throws up problems of its own. Could the additional states be light or have nontrivial effects on mass relations and thereby affect experimental constraints? Could grand unification induce R-parity violating interactions? These were some of the questions addressed during the workshop.

Possibly large radiative corrections due to the extra states in the MSSM have long been a subject of much interest. In the event of direct collider signatures being suppressed on account of peculiar dynamical/kinematical reasons, large radiative corrections may serve as indirect evidence. Even in the optimistic case of direct collider evidence, the form of radiative corrections may prove to be useful in distinguishing between scenarios. Various such effects were discussed during the workshop and one particular example, namely the corrections to the triple gauge boson vertices was worked out.

2.1 *Grand unification and R-parity violation*

Supersymmetry and gauge invariance, together with the field content of the minimal supersymmetric standard model (MSSM), allow a family of terms in the superpotential that violate baryon (B) and lepton number (L) [1], and can lead to catastrophic proton decay. In the MSSM, these terms are forbidden in an *ad hoc* manner by imposing a global Z_2 discrete symmetry [2] under which the quark and lepton superfields change by a sign, while the Higgs superfields remain invariant. This symmetry is often referred to as matter parity (R-parity at the level of component fields). At the level of the MSSM, such a discrete symmetry is not required for the internal consistency of the theory, and is imposed only for phenomenological reasons.

The MSSM itself is expected to be only a low-energy effective theory of a more complete and, perhaps, a simpler theory. One attractive candidate is supersymmetric grand unification. Gauge coupling constant unification [3] suggests that this theory would be manifest above a scale $\sim 10^{16}$ GeV, and the standard model (SM) gauge group would be embedded in a larger (simple?) group G. Candidates for G include $SU(5)$, the Pati–Salam group $SU(4)\times SU(2)\times SU(2)$, $SO(10)$, and E_6 [4]. While $SU(5)$ unification [5] offers great simplifications in the structure of the observed representation structure of matter and Higgs fields of the SM, it is not entirely satisfactory for a variety of reasons including the fact that one needs more than a single irreducible representation for a single SM family, with anomaly cancellation appearing in a miraculous manner. $SO(10)$ unification [6], on the other hand, offers an elegant extension of $SU(5)$ (as well as Pati–Salam) unification. While retaining all their useful features, it offers a further simplification in the form of a 16-dimensional representation that includes all the 15 fermions of a given generation as well as a candidate for a right handed neutrino. Unlike $SU(5)$, it also ensures anomaly cancellation in a natural way. Single step breaking of $SO(10)$ also retains the features of coupling constant unification, and is found to provide accurate predictions for the mass of the top-quark now confirmed by Tevatron experiments [7]. Furthermore, the $(B-L)$ generator of $SO(10)$ can be broken in a manner that would produce an unbroken Z_2 matter parity [8], which is what is required to make the MSSM a viable low energy extension of the standard model (SM).

Many of the features of $SO(10)$ unification were examined during this workshop. It was found that the constraints from non-observation of proton decay imply that the Z_2 symmetry, embedded in $SO(10)$ as a discrete subgroup of $B-L$, is essentially unique. Choice of Higgs representations that break $SO(10)$ down to the SM which also break this Z_2 symmetry invariably induce *all* the terms in the superpotential which this symmetry was supposed to eliminate. Thus, $SO(10)$ unification does not allow the possibility of generalized lepton or baryon parities [9] alone. Also considered were Z_3 matter parities that are discrete anomaly free. It was found that it is not possible to reconcile any of these Z_3 matter parities with unification.

2.2 *Light charged Higgs bosons* [10]

Experimental searches at LEP already impose significant indirect lower bounds on the mass of the charged Higgs boson in the MSSM. These bounds are particularly severe for low $\tan\beta$. This region is of special interest since here the $H^+\bar{t}b$ coupling is large, while the partial widths of H^+ into light SM fermions is small, allowing other interesting decay modes of the charged Higgs boson to have sizeable branching ratios.

However, these indirect lower bounds on m_{H^+} can be relaxed considerably in relatively modest extensions of the MSSM. Specifically, an extension based on $E(6)$ models with an extra $U(1)$ factor, which only adds one new parameter to the description of the low-energy Higgs sector, is sufficient to re-introduce the possibility of a substantial branching fraction for $t\to H^+b$ decays, although in these models the smallest allowed value of m_{H^+} still lies beyond the region that can be covered by searches for H^+H^- production at LEP. An even more dramatic reduction of the indirect lower bound on m_{H^+} becomes possible in the NMSSM, where one adds one $SU(2) \times U(1)_Y$ singlet Higgs superfield to the MSSM. In this model, the charged Higgs boson could still be light enough to be discovered at LEP, if $\tan\beta$ lies between 1.7 and 4, or even lower if one allows for intermediate scales. In this range of $\tan\beta$, the charged Higgs boson might dominantly decay into an on-shell W boson and a light neutral Higgs boson, which would complicate the search for $t \to H^+b$ decays at hadron colliders. On the other hand, the indirect lower bound on m_{H^+} was found to be less model-dependent for intermediate and large $\tan\beta$. For $\tan\beta > 4$, the bound in the $E(6)$ model or the NMSSM lies within 10 to 15 GeV of the MSSM value, which is itself quite modest.

If LEP experiments fail to observe a signal for neutral Higgs boson production after accumulating several hundred pb^{-1} of data at $\sqrt{s} = 200\,\mathrm{GeV}$, even in the $E(6)$ models $t \to H^+b$ decays would become impossible for $\tan\beta \leq 2$, unless there is substantial mixing in the stop sector. However, even in this pessimistic scenario, light Higgs bosons at small $\tan\beta$ could still be accommodated in the NMSSM, independent of stop mixing. Thus, we may conclude that there remains plenty of parameter space for light charged Higgs bosons at small and moderate values of $\tan\beta$.

2.3 *Neutral vector boson self-couplings within the MSSM*

With the present and the forthcoming colliders it has become possible to probe sectors of the standard model, that were hardly explored before. One such example is that of the vector-boson self interactions. Since the SM one loop corrections to these have been found to be small, any substantial departure in their values from that predicted within the SM is likely to indicate the presence of new physics effects at a nearby scale.

The MSSM corrections to the CP-even $WW\gamma$ and WWZ form factors have been studied in the literature. It was found that for certain regions of the parameter space, these effects could be large enough to be explored at the next linear collider, and in the most optimistic case, even at LEP2! Motivated by this, it was decided to examine the triple neutral gauge boson (viz. $ZZ\gamma$, $\gamma\gamma Z$ and ZZZ) vertex form factors within the MSSM.

As the first step, the most general vertex forms, consistent with Bose symmetry and gauge invariance, where applicable, were derived. The analysis also encompassed the cases where more than one of the gauge bosons could be off-shell.

It can be established very easily that, the CP-even form factors can receive contributions only from triangle graphs mediated by (i) the SM fermions and (ii) the charginos. In the ZZZ case, neutralino diagrams also contribute. These diagrams were calculated in terms of the Passarino–Veltman loop functions.

A preliminary scan of the MSSM parameter space, consistent with all present constraints, shows that the above form factors can be significantly larger than those predicted within the SM! A more careful study of the problem is thus called for, and this is being pursued currently. We must warn though that it is unlikely that form factors of such magnitudes would be observable at the first-generation NLC. To unambiguously infer the existence of unseen supersymmetric partners, we might have to wait until the second generation NLC or a muon collider.

3. Neutrino physics

One of the most interesting recent experimental results is that concerning the atmospheric muon anomaly. As experimental evidence mounts, it is but natural that a lot of activity would center on this subject. During this workshop, this issue was examined on two fronts: (i) devising new experimental methods that would cross-check and complement super-Kamiokande; and (ii) examining the minimal extensions of the SM that could lead to the favoured spectrum in a natural way.

3.1 *Study of the atmospheric neutrino anomaly using upward and downward-going high energy neutrinos*

The muon flux in underground experiments originating from atmospheric neutrinos with high energy (multi GeV range) can be used to study the parameter space relevant for the neutrino-oscillation explanation for the atmospheric muon anomaly. As a particular example, one may compare the data on the muon flux in KGF using muon events in the zenith angle range from 60 to 120 degrees with data for upward-going muons in the Kamiokande experiment. The rate of muon production in the rock surrounding the detector can be calculated using the atmospheric neutrino flux from the literature. A detailed Monte Carlo study is in progress.

3.2 *Field-theoretical study of neutrino oscillations with $\bar{\nu}_\mu$s from μ^+ at rest*

The aim is to achieve a rigorous field-theoretic calculation of the coherence length for neutrino oscillations in this context without taking refuge to wave packet treatments. An essential ingredient is a proper handling of finite width effects. The expression for the total amplitude including neutrino production and detection by the Wigner–Weisskopf approximation was worked out during the workshop. The boundary conditions were modelled after the LSND experiment. A critical examination of the ensuing cross section expression is in progress (in association with Stockinger).

3.3 *Radiative neutrino mass matrix for three active plus one sterile species* [11]

The totality of the neutrino-oscillation data – emerging from solar, atmospheric and LSND experiments – requires a fourth sterile neutrino ν_s to be added to the three already-known electroweak-active species $\nu_{e,\mu,\tau}$. A specific model for a 4×4 neutrino mass-matrix was proposed [12] some time ago. The form of this matrix agrees with subsequent phenomenological analyses of all neutrino-oscillation data. During this workshop, a model was constructed wherein this form of the neutrino mass-matrix arises as a purely radiative correction. The construction involves an extension of the Zee model to include an extra $U(1)$ gauge symmetry [13]. The scenario includes three extra $SU(2)_L$-singlet Higgs scalars (two charged, one neutral) in addition to the usual two doublets and all neutrino mass-matrix elements are generated at the one-loop level. The breaking scale of the extra $U(1)$ gauge symmetry is controlled by the VEV of one of the former Higgses. The resulting mass eigenvalues lead to the approximate relationship

$$(\Delta m^2)_{\rm atm} \simeq 2\sqrt{(\Delta m^2)_{\rm solar}(\Delta m^2)_{\rm LSND}},$$

which is well-satisfied by the data.

4. Special seminars

4.1 *Neutral current interactions and atmospheric neutrinos* [14] (by Francesco Vissani)

For neutral currents (NC) interactions to discriminate between scenarios of atmospheric neutrinos oscillation, measuremements should reach the 20–30% precision level. In fact, while in the $\nu_\mu \leftrightarrow \nu_\tau$ hypothesis the NC interactions rate is unaffected, in the $\nu_\mu \leftrightarrow \nu_s$ case 40% of the original ν_μ fluxes (due to $R_{\mu/e} \approx 0.6$) becomes sterile under weak interactions, and therefore the NC gets reduced of a factor $40\% \times \nu_\mu^0/(\nu_e^0 + \nu_\mu^0) \approx 27\%$. Higher precision is required in real experimental situations, due to the presence of misidentification effects. Among the events mostly induced by NC, the π^0-events are of interest at present, due to the possibility to detect this signal at the super-Kamiokande. An analysis of the existing data suggests that the channel of oscillation $\nu_\mu \leftrightarrow \nu_\tau$ is slightly favoured, but large uncertainties in the neutrino-induced π-production rate and nuclear effects do not permit us to exclude different oscillation scenarios. Future data and experimental studies of the neutrino interactions in the GeV region should allow us to reduce the errors in the measurements, and perform sensible NC tests on the atmospheric neutrinos.

4.2 *CP violation in the lepton sector and long-baseline neutrino experiments* [15] (by Walter Grimus)

Can CP (and T) violating effects in the lepton sector be observed in neutrino oscillation experiments? We consider such effects in two schemes with four massive neutrinos that can accommodate the results of all neutrino oscillation experiments. Using the constraints on the mixing parameters that follow from the results of short-baseline neutrino oscillation experiments, it is possible to derive rather strong upper bounds on the effects of CP violation in $\nu_\mu \leftrightarrow \nu_e$ transitions in long-baseline neutrino oscillation experiments. It can be shown that the effects of CP violation in $\nu_\mu \leftrightarrow \nu_\tau$ transitions in long-baseline oscillation experiments can be as large as that allowed by the requirement of unitarity of the mixing matrix. While matter effects do complicate the extraction of information, certain T-odd asymmetries can be used to reveal T and CP violation in the lepton sector.

4.3 *On baryogenesis via leptogenesis* [16, 17] (by Francesco Vissani)

The see-saw model permits not only ordinary neutrinos to acquire mass, but provides also a theoretical framework to account for the baryon asymmetry of the Universe in terms of a lepton asymmetry ΔL generated by out-of-equilibrium decay of heavy-neutrinos N_i [16]. The asymmetry generated per decay has been evaluated using different formalisms, and the existence of new contributions, in addition to those considered in the original proposal, has been shown [17].

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