PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 55, Nos 1 & 2
July & August 2000
pp. 307–313

# Beyond the Standard Model: Working group report

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**Abstract.** This report summarises the work done in the 'Beyond the Standard Model' working group of the Sixth Workshop on High Energy Physics Phenomenology (WHEPP-6) held at the Institute of Mathematical Sciences, Chennai, Jan 3–15, 2000. The participants in this working group were: R Adhikari, B Ananthanarayan, K P S Balaji, Gour Bhattacharya, Gautam Bhattacharyya, Chao-Hsi Chang (Zhang), D Choudhury, Amitava Datta, Anindya Datta, Asesh K Datta, A Dighe, N Gaur, D Ghosh, A Goyal, K Kar, S F King, Anirban Kundu, U Mahanta, R N Mohapatra, B Mukhopadhyaya, S Pakvasa, P N Pandita, M K Parida, P Poulose, G Raffelt, G Rajasekaran, S Rakshit, Asim K Ray, A Raychaudhuri, S Raychaudhuri, D P Roy, P Roy, S Roy, K Sridhar and S Vempati.

**Keywords.** Neutrino; supersymmetry; CP violation; supernova.

**PACS Nos 11.30.Pb; 12.60.-i; 14.60.Pq**

## 1. Introduction

During the first few days of the Workshop several problems were identified for investigation within the 'Beyond the Standard Model' working group of WHEPP-6. These problems addressed various extensions of the Standard Model (SM) currently under consideration in the particle physics phenomenology community. Smaller subgroups were formed to focus on each of these problems. The progress *till the end of the workshop is summarised in this report*.

## 2. The neutral scalar sector in *R*-parity-violating SUSY models

Gautam Bhattacharyya, Chao-Hsi Chang (Zhang), Amitava Datta and Anindya Datta

Consider that $R$-parity is broken [1] only through the bilinear terms, given by $\mu_i L_i H_u$ in the superpotential, where $L_i$ is the lepton doublet superfield of the $i$th generation and $H_u$ is the Higgs superfield that gives mass to the up-type quarks. For simplicity, assume that $\mu_1 = \mu_2 = 0$, but $\mu_3 \neq 0$. In such a scenario, the $\tau$-sneutrino will receive a vacuum expectation value (vev), denoted by $v_3$. Also, corresponding to $\mu_3$, there is a soft parameter

$B_3$, which appears as $B_3\mu_3 L_3 H_u^* + \mathrm{h.c.}$ in the scalar potential. Similar to $\mu$, $B$ and $v_d$ $(v_u)$ in the minimal supersymmetric standard model (MSSM), in the $R$-parity breaking sector, we now have three additional mass-dimensional parameters: $\mu_3$, $B_3$ and $v_3$. They will be constrained by the following considerations:

- Mixing of neutrinos with the neutralinos produces neutrino mass. In this way only one neutrino becomes massive and the mass is proportional to $(\mu_3 v_d - \mu v_3)^2/M$, where $M$ is a typical neutralino mass (say, order 100 GeV). The neutrino mass so obtained should be less than order 1 eV or so in order to be consistent with the recent data.
- Charged lepton–chargino mixing will put constraints in the parameter space from the requirement that the lightest eigenvalue should be 1.777 GeV, the experimentally observed $\tau$-lepton mass. One should also check that the $\tau$ branching ratios in different modes should be consistent with the very precise experimental data that exist.

Keeping in mind the above constraints, one can analyse the consequence of sneutrino-Higgs mixing in phenomenology, mainly from the following two angles:

- A possible change in the scalar mass spectrum relative to the prediction in the MSSM with conserved $R$-parity; in particular, checking whether the maximum mass of the 'lightest Higgs' (in the mass basis, of course, one will not have a pure Higgs state, but here by 'lightest Higgs' we mean the one which is dominantly Higgs and not sneutrino) after radiative correction could in principle be more than what MSSM predicts.
- Examining the change in the branching ratios of the 'lightest Higgs' in different modes and their implications on collider searches.

## 3. Models of neutrino mass

S F King, Asim K Ray and A Raychaudhuri

The present data from the atmospheric and solar neutrino experiments are indicative of neutrino oscillations driven by a non-zero neutrino mass splitting and mixing among the flavour eigenstates. The atmospheric neutrino results can be explained in terms of a maximal mixing of the $\nu_\mu$ and another neutrino with a mass squared splitting around $\Delta m^2 \sim 10^{-2}$ eV$^2 = \Delta_a$. The solar neutrino data admit several alternative possibilities with the $\nu_e$ oscillating to another neutrino – the vacuum solution (near maximal mixing, $\Delta m^2 \sim 10^{-10}$ eV$^2$), MSW large angle (near maximal mixing, $\Delta m^2 \sim 10^{-5}$ eV$^2$), and MSW small angle ($\sin^2 2\theta \sim 10^{-3}$, $\Delta m^2 \sim 10^{-5}$ eV$^2$). Let us indicate the solar splitting by $\Delta_s$ ($\ll \Delta_a$).

The usually chosen hierarchy of three neutrino mass eigenstates is $m_3 \gg m_2 > m_1$ with $\Delta_{32}^2 \simeq \Delta_{31}^2 \sim \Delta_a$ and $\Delta_{12}^2 \sim \Delta_s$. Most work on neutrino mass models focusses on this mass spectrum.

In this subgroup a study of models generating an *inverted* hierarchy with *bimaximal* mixing was undertaken. In this scenario $m_3 > m_2 \gg m_1$ with $\Delta_{32}^2 \sim \Delta_s$ and $\Delta_{31}^2 \simeq \Delta_{21}^2 \sim \Delta_a$. Neutrino mass models were obtained which reproduce the bimaximal nature of the mixing and which generate the large $\nu_1 - \nu_2$ and $\nu_1 - \nu_3$ splittings. However, these models left the $\nu_2$ and $\nu_3$ states degenerate. Different mechanisms for generating the small $\Delta_s$ splitting between these states were considered and it was concluded that effects of renormalization group (RG) evolution from a high mass scale may be a convenient method to achieve this goal.

## 4. Renormalization group constraints on models of neutrino masses and mixings

K P S Balaji, Asesh K Datta, A Dighe, R N Mohapatra, M K Parida, G Rajasekaran and Asim K Ray

Suppose that the neutrino masses are all equal at some high scale ($\Lambda$), i.e. $m_{\nu_1} = m_{\nu_2} = m_{\nu_3} = m_0$ at $\Lambda$. An interesting exercise would be to examine what happens to the mass ordering, splittings, and their mixing angles at low energy due to RG running with the above initial condition. Choice of $\Lambda$ is one important aspect in this exercise. There is one scenario [2] in which one chooses $\Lambda = 10^{13}$ GeV. This choice was motivated by the 'see-saw argument' that if one wants to obtain a neutrino mass of order 1 eV from the relation $m_\nu = m_t^2/\Lambda$, then $\Lambda$ turns out to be order $10^{13}$ GeV. They concluded that the low energy predictions of masses and mixing angles were incompatible with data. In another scenario [3], one assumes the degeneracy of the neutrinos at the Planck scale and considers a two-step running – first, to the intermediate scale $10^{13}$ GeV, and then down to low energy. The $\beta$-functions controlling the evolution are different in the two steps. In this way it was possible to fit the atmospheric neutrino anomaly and the large angle MSW solar neutrino data within both the SM and the MSSM but the vacuum oscillation could not be explained.

Broadly with this type of set-up in mind, different subgroups took the following lines of action:

- Consider the possibility that these neutrinos are of Majorana nature, i.e. $m = \eta_{\rm CP}|m|$, where $\eta_{\rm CP} = \pm 1$. Then the initial condition of degeneracy stated above would change in the sense that even though the magnitudes of these masses are the same, the signs may be different. This would affect the RG running and consequently the low energy predictions would be different.
- It may be possible to generate large neutrino flavour mixings.
- Instead of a degenerate structure, one can assume a quasi-degenerate mass spectrum at the high scale and investigate the consequences at low energy.

## 5. CP violation in SUSY

Amitava Datta, N Gaur, S F King, A Kundu and B Mukhopadhyaya

It has long been realised that flavour changing neutral current (FCNC) constraints tightly restrict mass splittings of SUSY particles. Constraints from $K^0$–$\bar{K}^0$ mixing and CP violation in the $K$-sector have been well studied in the literature and the implications for the $B$-meson system worked out.

Recently it has been realised that in some regions of parameter space more severe constraints on SUSY mass splittings may actually emerge from the requirement that charge and colour breaking minima must be absent in all stages of the RG evolution of the SUSY parameters from a high scale. In this subgroup the focus was on these situations. How the resulting constraints mesh with the data from the mixing in the $K$ and $B$ systems was examined. The impact on CP violation – in particular, on the recent measurements of $\epsilon'/\epsilon$ – were examined. CP asymmetries in the $B$-system were considered with an eye on the $B$ factories.

## 6. Non-universal SUSY

Amitava Datta, S F King, M K Parida and D P Roy

Unlike supergravity which predicts the universality of gaugino masses (i.e. $M_1 = M_2 = M_3$) at the SUSY breaking scale, some GUT models do predict $M_1 \neq M_2 \neq M_3$ [4]. It is worthwhile to study how 'natural' these models are, i.e. how much 'fine-tuning' is necessary in these models. Fine-tuning, *a la* Barbieri and Giudice [5], is quantitatively defined as $\Delta_a = |(\delta m_Z^2/m_Z^2)/(\delta a/a)|$, where $a$ is a GUT scale parameter. Low values of $\Delta$ indicate the theory is more natural, or in other words, less fine-tuning is necessary. The requirement of not too much fine-tuning puts an upper limit on the supersymmetry breaking scale. In supergravity models assuming a 10% fine-tuning puts an upper limit of about 1 TeV on the superparticle masses [5], while in gauge-mediated models because of its in-built non-universal boundary conditions one requires more fine-tuning, or, in other words, naturalness constraints are stronger than in the supergravity scenario [6]. This group plans to probe which parts of parameter space in non-universal models yield smaller values of $\Delta$ and then explore the possibilities of their detection at LHC. They also plan to study the impact of non-universal gaugino masses on gauge coupling unification.

## 7. (M+1)SSM

B Ananthanarayan, S F King, U Mahanta, P N Pandita, D P Roy and S Vempati

In the non-minimal supersymmetric Standard Model ((M+1)SSM), the bilinear term in the superpotential is written as $\lambda N H_d H_u$, where $N$ is a gauge singlet and $\lambda$ is a dimensionless parameter. This term is analogous to $\mu H_d H_u$ in the MSSM. Thus in the non-minimal model $\lambda\langle N\rangle$ plays the role of the $\mu$ parameter. This group plans to (a) study 'fine-tuning' in this model, and (b) examine its implications in electroweak baryogenesis. The electroweak baryogenesis window is very tightly constrained in the MSSM but the window opens up in the (M+1)SSM.

## 8. Anomaly mediated SUSY breaking models

D Choudhury, D Ghosh, S F King, A Kundu, B Mukhopadhyaya, S Raychaudhuri, P Roy, S Roy and K Sridhar

In the anomaly mediated SUSY breaking (AMSB) models, where the information of SUSY breaking is communicated from the hidden sector to the observable sector via the super Weyl anomaly contribution, the gaugino masses at the SUSY breaking scale are controlled by their respective $\beta$-functions, given by $M_i \propto \beta_i$, i.e. $M_3 : M_2 : M_1 = 8.8 : 1 : 3.3$. This should be contrasted against the boundary conditions in supergravity models where the gaugino masses are all equal at the GUT scale ($M_3 = M_2 = M_1$) and in gauge mediated models where $M_3 : M_2 : M_1 = \alpha_3 : \alpha_2 : \alpha_1$. It follows that in the AMSB models

- (Neutralino) LSP is Wino dominated.
- Lighter chargino is nearly degenerate with LSP.

One disturbing feature of AMSB models is that the slepton squared-masses are negative. To avoid phenomenological problems with these tachyonic sleptons one dumps an *ad hoc* positive contribution to the mass squared values at the high scale.

The usual chargino search strategy relies on the decay $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0$ (LSP) + lepton + missing energy. If the mass difference between the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ is very small, as is the case in AMSB, then the emitted lepton is too 'soft' to be tagged. In this case, of course, the chargino has a longer lifetime and one expects to observe short tracks inside the detector.

This group plans to look at the following mode: In an $e^+e^-$ machine consider the pair production $e^+e^- \to \tilde{e}_L^+\tilde{e}_L^-$ (via $t$-channel $\tilde{W}_3$ exchange). Then $\tilde{e}_L^+ \to \tilde{\chi}_1^0$ (LSP) $e^+$ and $\tilde{e}_L^- \to \tilde{\chi}_1^-\nu$. The chargino thus produced can decay only as $\tilde{\chi}_1^- \to \pi^-\tilde{\chi}_1^0$ due to lack of phase space. Thus the final state consists of $e^{\pm}\pi^{\mp}$ plus missing energy, which would be considered as signal events for AMSB models.

## 9. Supernova constraints on ADD models

A Goyal, K Kar and S Raychaudhuri

Following the work of Arkani–Hamed, Dimopoulos and Dvali (ADD) [7], there has been much interest in recent times in higher-dimensional theories where the extra dimensions (beyond $(3+1)$ dimensional spacetime) are compactified but have sizes large compared to the Planck length. A class of such theories defined in $(4+d)$ dimensions have the extra dimensions compactified on a $d$-torus of radius $R$. The effective Newton's gravitational constant, $\hat{G}_N^d$, in these theories is related to one of the usual 4-dimensional situation, $G_N$ by $\hat{G}_N^d = 4\pi V_d G_N / S_d$, where $S_d$ is the surface area of the compactified surface in $d$-dimensions and $V_d$ its volume.

The characteristic scale of this problem is the 'string scale', $M_s$, given by, $M_s \sim (\hat{G}_N^d)^{-1/2}$, while the radius of compactification ($R$) – which can be regarded as the *size* of the extra dimensions – is given by, $R \sim (1\ \mathrm{TeV}/M_s)^{(\frac{2}{d}+1)}$. The size of $R$ can be estimated from the above and is presented for different values of $d$ in the table 1 below.

In the ADD-type models, only gravitation is assumed to exist in the bulk while the matter and gauge fields live in a 3-brane. The gravitational field in higher dimensions under the usual Kaluza–Klein (KK) reduction yields 4-dimensional gravity and additional fields which transform as vectors and scalars of the 4-dimensional Lorentz group. For each of these, there is a tower of KK excitations. Of these, the graviton and the dilaton towers couple to the matter fields.

Strong bounds have been derived on the 'string scale' $M_s$ from the cooling of supernovae. The *Gravistrahlung* of the graviton and dilaton and their KK excitations cool the supernova which leads to a reduction of the emitted neutrino flux. In order that this does not contradict the data on neutrinos observed from the SN 1987A supernova, one obtains a lower bound of 50 TeV (4 TeV) on $M_s$ for $d = 2$ (3) [8]. This subgroup investigated the effect on these bounds of:

- competing processes like $\gamma e \to e G_{\vec{n}}$, where $G_{\vec{n}}$ represents the states in the graviton tower, etc.
- core constitution, variation in core density, etc.

The conclusion was that the bounds are robust.

## 10. Right-handed neutrino production in hot dense plasmas and constraints on the ADD scenario

N Gaur, A Goyal, G Raffelt and S Raychaudhuri

It has been shown [9] that if sterile (i.e. singlet) neutrinos are assumed to exist in the bulk in ADD-type models, then it leads to an effective magnetic moment for the $\nu_e$ given by

$$\mu_{\mathrm{eff}} \sim 10^{-11}\mu_B \left(\frac{E}{10\,\mathrm{MeV}}\right)^{(d/2)} \left(\frac{1\ \mathrm{TeV}}{M_s}\right)^{(d/2)} .$$

The existing bounds on $\mu_{\mathrm{eff}}$ from $\nu_e - e$ scattering, supernova neutrino fluxes, etc., imply a corresponding lower bound on $M_s$.

The subgroup investigating this area examined the constraints on $M_s$ from

- $\nu_L \leftrightarrow \nu_R$ conversion in background electromagnetic plasmas of high density as found in stellar interiors.
- $\nu_R$ production in the early universe.

**Table 1.** The compactification radius, $R$, for different number of extra dimensions, $d$, which are compactified.

| $d$ | 1 | 2 | 3 | . | . | 6 |
|---|---|---|---|---|---|---|
| $R$ (cm) | $10^{13}$ | $10^{-1}$ | $10^{-7}$ | . | . | $10^{-13}$ |

### 11. $Z$ partial widths in ADD models

Gour Bhattacharya, U Mahanta, P Poulose, S Rakshit and S Raychaudhuri

This group plans to compute the one loop corrections to the $Zf\bar{f}$ vertex with Kaluza–Klein gravitons and dilatons inside the loop. On account of the per milli level precision to which these vertices have been measured at LEP, any new physics contribution to them is expected to be severely constrained.

## Acknowledgements

We thank all the participants of this Working Group for their all-round cooperation. The work of AR has been supported by grants from the Department of Science and Technology and the Council of Scientific and Industrial Research, India.

## References

[1] G Bhattacharyya, hep-ph/9709395; *Nucl. Phys. Proc. Suppl.* **52A**, 83 (1997)
H Dreiner, hep-ph/9707435
R Barbier *et al*, hep-ph/9810232
[2] J Ellis and S Lola, hep-ph/9904279
[3] J A Casas, J R Espinosa, A Ibarra and I Navarro, hep-ph/9905381
[4] See, for example, S F King, *Pramana – J. Phys.* **55**, 161 (2000)
[5] R Barbieri and G Giudice, *Nucl. Phys.* **B306**, 63 (1988)
[6] G Bhattacharyya and A Romanino, *Phys. Rev.* **D55**, 7015 (1997)
[7] N Arkani-Hamed, S Dimopoulos and G Dvali, *Phys. Lett.* **B429**, 263 (1999)
For an introductory discussion, see, for example, S Raychaudhuri, *Pramana – J. Phys.* **55**, 171 (2000)
[8] S Cullen and M Perelstein, *Phys. Rev. Lett.* **83**, 268 (1999)
[9] G C McLaughlin and J N Ng, *Phys. Lett.* **B470**, 157 (1999)