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Working group report: Beyond the standard model

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The working group on *Beyond the Standard Model* concentrated on identifying interesting physics issues in models of 'new physics' which go beyond the standard model. There were two aspects to this activity. One was to familiarise participants with the areas, for which the expertise available among the participants was very useful. The other aspect involved is the identification and formulation of research problems out of these issues, with the ultimate aim of building fruitful collaborations.

In view of the range of current interest in the high energy physics community, this working group was organised according to the following focal themes:

- *Superstring-inspired phenomenology*: This included
  - models of low-scale quantum gravity with one or more extra dimensions,
  - noncommutative geometry and gauge theories,
  - string-inspired grand unification.
- *Models of supersymmetry-breaking*: This included
  - Supersymmetry-breaking in minimal supergravity (mSUGRA) models,
  - gauge-mediated SUSY-breaking (GMSB),
  - anomaly-mediated SUSY-breaking (AMSB) and variants.
- *Properties (masses and mixing) of ordinary and exotic fermions*: This included
  - vector-like fermions and their properties,
  - the Brookhaven muon anomaly and its possible explanations,
  - CP-violating effects,
  - models of neutrino masses and oscillations.

The working group activity was divided into two parts: (a) reviews and presentation of materials for the dissemination of expertise and (b) preliminary investigation of research problems. In category (a), some special sessions were held jointly with the B- and collider physics working group, with a view to introduce interested participants to some of the computational tools currently relevant for particle phenomenology. Thus in this group, in addition to several seminars and reports on recently completed works covering various aspects of the focal themes, discussions took place on the packages HERWIG (S Moretti), SoftSUSY (B Allanach) and SUSPECT (A Djouadi), all of these being computational packages useful in obtaining rates for various standard model and supersymmetric processes, and deriving the mass spectra under different SUSY breaking schemes.

Research problems identified and studied in category (b) during the workshop are described below.

1. Variants of the Randall–Sundrum model

P Das, U Mahanta and S Raychaudhuri

The purpose of this activity was to study models of extra dimensions and low-scale quantum gravity which go beyond the minimal Randall–Sundrum (RS) model and identify problems of phenomenological interest. After an extensive literature survey, some recently suggested models of interest were identified [1,2], which possess the good features of the RS construction while removing some of its undesirable features, such as the use of a S^1/Z_2 geometry. Both the models cited above are multi-brane models with strong gravity localised on a brane-intersection. The meaning of localisation is that the graviton wavefunction falls off exponentially outside the intersection. The standard model fields 'live' on a nearby brane, whose distance from the intersection sets the scale for the weakness of Newtonian gravity. These models may be thought of as interpolating between the ADD and RS scenarios, with a possibility of enhanced collider signatures and many interesting astrophysical consequences. The gravity-in-a-box model of Lykken *et al* is worked out more explicitly, and it is shown that in this model ADD cross-sections scale as

$$\sigma_{\text{Box}} = (2\mathscr{K} z_0 + 1)\ \sigma_{\text{ADD}}$$

where $\mathscr{K}$ is the curvature of extra dimensions and z_0 is the separation of the SM-brane from the intersection where gravity 'lives'. Clearly there can be significant collider effects and stringent bounds on the curvature of the extra dimensions may be obtained from a study of collider and astrophysical signals.

Phenomenological studies of these models were initiated at the workshop. The methodology decided was as follows:

- To work out the model of Arkani–Hamed *et al* in detail to obtain Feynman rules. These would involve basically simple scalings of the Feynman rules in the ADD model.
- To identify major phenomenological signatures for these models and obtain constraints on them from current data.
- To make predictions for future colliders, such as the large hadron collider (LHC) and NLC, and determine if the models have characteristic signals which may enable them to be identified among several new physics candidates.

2. Neutrino-mixing in brane-world models

B Brahmachari, A Giri, S Raychaudhuri, A K Ray, P Roy and N Singh

This study was aimed at probing further implications of theoretical models [3] containing one singlet fermion in the bulk and three active neutrinos in the brane. The zero mode of the bulk fermion is the sterile neutrino in the limit where radius of compactification is very small. The bulk excitations of singlet fermion gives corrections to 'given' active neutrino masses and mixing when extra dimensions are large. Interesting mixing patterns between ordinary and sterile neutrinos can also be generated. With

$$\sqrt{2}m \to \sqrt{2}m\,(1,1,1,1,\ldots)$$

and

$$\delta_5 \to \begin{pmatrix} 1/R & 0 & \ldots \\ 0 & 2/R & \ldots \\ \ldots & 0 & 3/R \\ \ldots & \ldots & \ldots \end{pmatrix}$$

it is possible to finally obtain a neutrino mass matrix

$$\left(\begin{array}{ccc|c} \delta & m & \sqrt{2}m & 0 \\ m & 0 & 0 & 0 \\ \sqrt{2}m & 0 & 0 & \delta_5 \\ 0 & 0 & \delta_5 & 0 \end{array}\right)$$

whose implications in view of the current neutrino data and rare leptonic decays are to be taken up for investigation.

3. Radino phenomenology

D Choudhury, P Das, A Datta, K Huitu, B Mukhopadhyaya and S Raychaudhuri

The investigation begins with a close scrutiny of a recent work [4] describing a supersymmetrised Randall–Sundrum model. The salient features of this model are:

- The radion field, or dilaton field, in the minimal RS model is replaced by a radion superfield, which is a scalar superfield with components

  $$\hat{T} = (T, \widetilde{T}, F_T)$$

  where T is the radion, $\widetilde{T}$ is the radino, the spin-1/2 superpartner of the radion and F_T is an auxiliary field.
- Unlike mSUGRA, the Kähler potential of this model is not completely fixed. Different ansätze exist, with different phenomenological consequences. In particular, this can give rise to new quartic couplings in the scalar sector of the model.

Important phenomenological consequences follow, of which only a few have been studied so far. Two sectors of the theory change drastically compared to the minimum supersymmetric standard model (MSSM):

(a) *Higgs sector*: The scalar radion mixes with the fields in the two Higgs doublets thus

$$\begin{pmatrix} H_1^0 \\ H_2^0 \\ \frac{1}{2}(T+T^*) \end{pmatrix} \qquad \begin{pmatrix} G^0 \\ A^0 \\ \frac{1}{2}(T-T^*) \end{pmatrix},$$

so that the scalar field content of the theory is

– 3 neutral physical scalars;
– 2 neutral physical pseudoscalars;
– 2 charged scalars $H^{\pm}$ (this sector is unaffected by the radion superfield).

In such a scenario, it is still possible to have $\tan\beta \simeq 1$ as the mass of the lightest Higgs boson can be pushed up as high as $\sim$700 GeV, unlike the case in the MSSM, where $\tan\beta \simeq 1$ is ruled out by LEP data and the mass of the lightest Higgs boson cannot be much above 130 GeV.

It was decided to work out the masses and mixing angles of these scalars and determine the couplings as in the famous work of Gunion and Haber, and use these to determine LEP and Tevatron bounds on the radino scenario.

(b) *Neutralino sector*: Just as there are mixings in the scalar sector, there are mixings of the radino field with the neutral gauginos and the Higgsinos. We get a 5×5 mass matrix

$$\left(\begin{array}{cccc|c} M_1 & 0 & -v_d & v_u & 0 \\ 0 & M_2 & v_d & -v_u & 0 \\ -v_d & v_d & 0 & -\mu & \mu_1 v/\Lambda \\ v_u & -v_u & -\mu & 0 & \mu_2 v/\Lambda \\ 0 & 0 & \mu_1 v/\Lambda & \mu_2 v/\Lambda & 2\widetilde{m}_{3/2} \end{array}\right)$$

where Λ is the radion vev and $\widetilde{m}_{3/2}$ is the gravitino mass. There are also extra soft SUSY-breaking parameters μ_1 and μ_2 which are the coefficients of trilinear terms in the superpotential involving the radion superfield.

The result of these extra mixings can be expected to cause major changes in the neutralino sector, especially with regard to the structure of the LSP. This in turn will have repercussions on typical SUSY search strategies.

It was decided to work out the neutralino sector in detail especially to evaluate the modified Feynman rules. It would then be interesting to look at phenomenology at colliders and also at the dark matter problem.

4. *SO*(10) GUT multiplets and neutrino mass matrices

K Agashe, B Brahmachari and A Raychaudhuri

$SO(10)$ models with minimal set of Higgs fields ($10, \overline{16}+16$ and 45) have been considered in this project. We know that minimal quark–lepton unification forces us to have similar mixing patterns in the quark and lepton sectors. Here the problem is a tangible explanation of small V_{cb} along with maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing. Following a recent suggestion by Pati [5] given here, we get the structure

$$M_D = \begin{pmatrix} 0 & \varepsilon+\eta \\ -\varepsilon+\eta & 1 \end{pmatrix}, \quad M_L = \begin{pmatrix} 0 & -3\varepsilon+\eta \\ 3\varepsilon+\eta & 1 \end{pmatrix}.$$

The difference in coefficients of ε in the two cases is due to the vacuum expectation values of 45 along the B–L direction. Large mixing in the 2–3 sector of neutrinos can arise due to large mixing in the charged lepton sector. To do this, we need opposite signs in η and ε whereby a small V_{cb} is also a natural consequence. A similar texture, given by Albright *et al* [6] has been studied by this subgroup side by side.

The goal of this project is to explain Pati's ansatz for the right-handed Majorana mass matrix with suitable choices of $SO(10)$ multiplets and family symmetries. An explanation, for example, can be envisaged in terms of additional global $U(1)$ symmetries.

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