PROBIR ROY

Highlights of Research

The main thrust of my research in recent years has been in the quest for new physics beyond the Standard Model of particle interactions. Despite its impressive phenomenological successes, the latter scheme suffers from serious theoretical inadequacies suggesting the occurrence of new physics beyond it at energy scales to be probed shortly by forthcoming experiments. Our major effort has of late been directed to the study of neutrino mass and mixing patterns as well as to supersymmetry phenomenology. These are aspects of high energy interactions where effects of the earlier-mentioned new physics are most likely to emerge.

Neutrino masses are much tinier than those of other elementary particles, while their asymmetric mixing pattern of one near-maximal, one large and one rather small mixing angle pose a mysterious puzzle. We have worked on constraining schemes with four light neutrinos (three active, one sterile) from neutrino oscillation data. We have also proposed new experimental ways of sharpening our knowledge of the neutrino mass and mixing parameters through long baseline laboratory experiments. In case neutrino masses arise from the effects of higher (compactified) dimensions, these dimensions **must discriminate** between neutrino flavours, as we have shown by analyzing the current neutrino oscillation data.

Naturalness arguments, in relation to the spontaneous symmetry breakdown mechanism in the electroweak theory, suggest that the onset of new physics (such as supersymmetry) should occur at or around the TeV energy scale. Though the Large hadron Collider, under construction, is a suitable machine for discovering superparticles, careful determination of their properties in relation to theoretical predictions will be possible only at the proposed International Linear Collider. To that end, we have made pioneering studies of different supersymmetry effects in such a collider: signals of anomaly mediated supersymmetry breaking and supersymmetric flavour violation. Some highlights are given below.

• *Linear collider studies of supersymmetric effects*

We have analyzed [1,3] diagnostic signals for anomaly mediated supersymmetry breaking [1] in chargino pair production from e^+e^- collision at TeV energies. The existence of a neutral winolike stable Lightest Supersymmetric Particle, closely degenerate in mass with a charged wino, makes the latter quasistable – leading to characteristic multilepton events containing displaced vertices and/or soft pions. In addition, the possible occurrence of significant mixing between muon sneutrino and tau sneutrino states has been studied by carefully analyzing a final state configuration with $\mu\tau +$ jets $+ \not{E}_T$. Realistic rate estimates suggest the observability of both phenomena in a TeV linear collider.

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• Long baseline neutrino studies

Remarkable experimental discoveries have recently been made [1] in the sneutrino sector from the study of solar atmospheric and reactor neutrinos. We know now that at least two of the neutrinos are massive and their masses are bounded from below by ~ 0.05 eV and ~ 0.008 eV. Furthermore, the mixing angles among the three neutrinos are given by $\theta_{12} \sim 32^\circ$, $\theta_{23} \sim 45^\circ$ and $|\theta_{12}| \gtrsim 12^\circ$. Still unanswered are questions like the nature of the neutrino mass hierarchy (normal or inverted), the role of CP-violation, the precise values of the mixing angles, the absolute scale of neutrino masses etc. A major step in finding answers to these will be taken by the initiation of long baseline experiments [2] with neutrino beams from accelerators. A crucial aspect of this studies will be the unraveling of the matter effect. We have studied [3,4] this effect in lowest order perturbation through both for variable and constant earth density profiles. We have derived useful expressions for neutrino survival and transition probabilities and discussed their numerical consequences A particularly startling result [4] is that the difference between muon neutrino and antineuttrino survival probabilities is a measure of the deviation from maximal flavour mixing for the muon neutrino.

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• *Neutrino oscillations and light neutrino flavours*

Neutrino oscillations generally suggest tiny, nonvanishing neutrino masses which might originate through the seesaw mechanism [1] linking the electroweak and very heavy lepton nonconserving scales. There is evidence of neutrino oscillations in data obtained from three different sources: solar, atmospheric and the laboratory, the latter pertaining to the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos. The central values of neutrino mass-squared differences given by these measurements cannot be fit [2] by the hypothesis of three light neutrinos; one is obliged to postulate a fourth light neutrino which must be a singlet under the electroweak gauge group. There has been considerable study of the implications of such a light sterile neutrino, as reviewed in Ref. [3].

We proposed [4] such a model of four light neutrinos (three electroweak active: ν_e, ν_μ, ν_τ and one sterile ν_s) by use of the discrete symmetry Z_5 implemented on the seesaw mechanism.

Atmospheric oscillations occur between ν_μ and ν_τ (with maximal mixing) as psueduo-Dirac partners. Solar ones take place between ν_e and ν_s and possible $\nu_e - \nu_\mu$ oscillations account for the LSND data. A radiative model [5], also realizing this scenarios has been constructed later. Constraints on the four neutrino schemes from the nonmaximality of the solar neutrino mixing angle [6] and the nonobservation of neutrinoless double data decay [7] have also been worked out.

We have further discussed [10] an alternative approach to the neutrino-oscillation data. Suppose one wants to retain the three light neutrino hypothesis of the Standard Model? How much of the observed atmospheric neutrino anomaly can be accommodated by this if solar and LSND neutrino oscillations are assumed to explain the corresponding data? Standard Model interactions, considered exclusively, are known [8] to allow a universal survival probability s equal to the ratio of ratios $R \equiv (\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e)_{\rm expt}/(\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e)_{MC}$ (MC standing for Monte Carlo expectation) consistent with both the sub-GeV and the multi-GeV data; but these do not allow [9] any variation of R with the zenith angle. We have postulated [10] large anomalous diagonal ν_τ-quark contact interactions (something allowed by all experimental constraints at present) and shown that these can lead to significant variations of R with the zenith angle. Reports from the super-Kamiokande experiment imply that such variations have been observed [11].

One of the intriguing ideas to explain the smallness of the neutrino masses involves the proposition that the right chiral neutrino propagates in the bulk comprising extra dimensions, while the left chiral neutrinos, along with other Standard Model fields, live on a 3-brane. These are models in this genre in which there are three or four light Majorana neutrinos (with assumed tiny masses) on the brane and their mixing is induced by the sterile Kaluza-Klein tower of states from the compactification of the right chiral neutrino. We have examined these models phenomenologically. Using the currently available neutrino mass squared differences and mixing angles from the solar, atmospheric and reactor experiments as well as the cosmological upper bound on the sum of the stable neutrino masses, we are able to [12] exclude these models.

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- *Oblique Parameters (papers no. 91, 92, 93, 96, 98 and 106 in publist)*

Radiative corrections to electroweak processes have become extremely important in view of the high precision (at the $\lesssim 10^{-3}$ level) with which corresponding observables have been measured — especially at LEP. In this context, the approximation [1] of retaining only the vector boson self-energy terms among all 1-loop corrections is quite accurate (except in the $Zb\bar{b}$ vertex which needs to be handled separately) and simplifies the formalism enormously. This motivated Peskin and Takeuchi [2] as well as Altarelli and Barbieri [3] to define the oblique parameters $S,\ T,\ U$ (or equivalently $\epsilon_1, \epsilon_2, \epsilon_3$) which are directly related to experimental observables. Not only are these gauge-invariant and scheme-invariant, the new physics contributions add linearly to those of the standard model (SM) within the above approximation. Thus one can define $(\tilde{S},\ \tilde{T},\ \tilde{U}) \equiv (S,\ T,\ U) - (S,\ T,\ U)^{SM}$ as the new physics contributions. These contributions are especially sensitive to non-decoupled new physics such as technicolor which tends to generate large, positive values for $\tilde{S}$ and $\tilde{T}$, while present data suggest tiny (with small errors) for these quantities are compatible with zero. In defining S, T and U, Peskin and Takeuchi had used the linear momentum approximation. We have given more general definitions [4] of these parameters that are *independent of any momentum approximation*. On very general grounds, we have demonstrated [4] that there are six oblique parameters S, T, U, V, W, X, but that data already shows that the last three, if nonzero, are really quite small.

Initially, efforts were made [5] to determine $\tilde{S},\ \tilde{T},\ \tilde{U}$ by making "global" fits of experimental observables treated as constant parameters. In collaboration with G. Bhattacharya and S. Banerjee [6], we showed how high statistics LEP measurements in the Z lineshape region enabled one to make a highly accurate "local" fit to the data as a function of the CM energy $\sqrt{s}$ in terms of $\tilde{S}$, $\tilde{T}$ and $\tilde{U}$ (utilizing the W-mass value for $\tilde{U}$). Later, LEP experimentalists have used this approach at any exhaustive level. It may be noted that the data disfavour many non-decoupled new physics models which prefer large positive $\tilde{S},\ \tilde{T}$. On the other hand, decoupled new physics models tend to have numerically small values of $\tilde{S},\ \tilde{T}, U$ not incompatible with experimental results. Our work has been widely cited, e.g. in the longer paper of Ref. [2] as well as by Ellis [7] and Altarelli [8]. It has now become a standard reference in papers being written on oblique corrections or oblique parameters [e.g. 9].

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• *Constraints on R-parity violating couplings*

The conservation of R-parity, $R_p = (-1)^{3B+L+2s}$ is a major assumption in the Minimal Supersymmetric Standard model (MSSM), but as yet there is no credible theoretical basis for it. Hence R_p-violating models have been constructed [1] in the literature since a spontaneous violation of R-parity requires an additional singlet superfield to be added to the spectrum of MSSM, making it nonminimal, the trend has been in considering cases with explicit violations of R_p. Experimentally, the lack of observation of proton decay suggests [2] that perhaps baryon and lepton conservation cannot be both violated together but explicit either one can be.

We have first considered the most general R-parity breaking interactions with lepton conservation but breaking the baryon number symmetry. The 1-loop evolution of Yukawa coupling strength in this theory has been considered and the imposition of perturbative unitarity (or a fixed point behaviour of the cou;ing) at all top coupling scales has been shown to yield [3] strong constraints on the new couplings. Our work inspired Goity and Sher [4], who gave a more general derivation. We have also used [5] information from rare nonleptonic decays of heavy-quark mesons to put new bounds on the magnitudes of some such couplings. The main technical advance was the use of the computational method of Carlson and Milana [6] to sort out the complications due to exclusive strongly interacting final states from the ratio of the partial widths of a B^+ meson into two-body final states, say $K^+\bar{K}^0$ and K^+J/ψ.

Turning to the opposite scenario, with assumed baryon conservation but violating lepton number, we have derived [7] strong upper bounds on certain product combinations of R_p-breaking Yukawa couplings. The input has been information from rare leptonic decays of the long-lived neutral kaon, the muon and the tau as well as from the mixings of neutral K- and B-mesons. One of these bounds is comparable and another superior to corresponding ones obtained [8] contemporaneously from neutrinoless double-beta decay.

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• *τ-number Violating Signals of R-parity Breaking*

While the electron number L_e and the muon number L_μ are experimentally known to be accurately conserved, such is not the case for the τ-number L_τ. There has recently been theoretical motivation, in the context of R-parity breaking supersymmetric scenarios [1], to explore signals of τ-number violation; superstring models hint at [2] the violation of lepton number $L = L_e + L_\mu + L_\tau$ and hence that of R-parity $(-1)^{3B+L+2s}$. In collaboration with Ma [3], we did demonstrate from existing τ-phenomenology that observable τ-number violations were possible via the production and L_τ-violating decays of two on-shell unstable LSP neutralinos. A characteristic signature would be a like sign ditau signal as generated in collider processes such as $p\bar{p} \to \tau\tau(\text{jet})\ (\text{jet}) + (\not{E},\ \not{p}_T)$ and $ep \to \bar{\tau}\bar{\tau}(\text{jet})\ (\text{jet}) + (\not{E},\ \not{p}_T)$ for which reasonable cross sections were estimated. This work has had a significant impact on the growing literature on R-parity breaking models, as is clear from the citation in Masiero's two talks [4,5].

Afterwards, together with Godbole and Tata, we have made [6] a thorough phenomenological investigation of the pair-production and τ-number nonconserving decays of two unstable LSP neutralinos at LEP 200 (and also, in principle in the next linear collider). Consequent signals are spectacular: spherical events with m leptons (containing at least one τ) and n jets ($m, n \leq 4$), the most characteristic of which are like sign $\tau\tau$ events. Recent experimental progress, made in the identification of τ's via low-multiplicity narrow hadronic jets, has made our signals viable for detection. We have enumerated these signals for each LSP candidate and have provided quantitative estimates for the favoured case when the LSP is a neutralino. We have also outlined measures to distinguish these signatures from other similar new physics signals. Our proposal has already elicited interest from experimentalists at OPAL and L3 who are searching for the signals proposed by us at LEP 200. This paper has had a significant impact on the literature considering that its citation level, as seen in the SPIRES index, is nearly seventy.

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• *Project on Very Heavy Neutrino Detection*

A very heavy neutrino lying hidden in the mass range $10^2 - 10^3$ GeV is suggested in several "beyond the Standard Model" scenarios [1,2] (4th generation, left-right symmetry, E_6 GUT ...). Such a neutrino, if unstable, can be detected in forthcoming pp supercolliders. Pair-produced dominantly by the gluon fusion mechanism, they will decay within the detector yielding a distinct final state of charged dileptons and jets without missing p_T.

We had first investigated [3] with Dicus the production amplitude mediated by a virtual Z. For that mechanism one needs an extra generation of quarks (contributing to the quark loop) to generate rates high enough to be measurable at the SSC and LHC. We also showed how dilepton charge signs or angular correlations can discriminate between Dirac or Majorana neutrinos that are very heavy. The former allows only unlike sign decay dileptons while the later leads to both like and unlike sign ones. Also, the angular pair correlation, in the gg CM system, is peaked for zero angular difference in the Dirac case but is flat for the Majorana one.

Our work inspired Datta and Pilaftsis [4] to investigate the corresponding Higgs-mediated amplitude for the specific case of a heavy Majorana neutrino of the kind that occurs in left-right symmetric models. They found larger rates than in the Z-mediated case. Recently, in collaboration with D. Choudhury and R. Godbole, we have investigated [5] Higgs-mediated pair-production of heavy neutrinos (both Dirac and Majorana) via gluon fusion. We compute substantial production cross sections for pp supercolliders even *without* any extra generation of quarks. This result had escaped the authors of Ref. [4]. The angular correlation in the gg CM system is once again flat for Majorana neutrinos, but in the Dirac case it peaks for the angular difference being zero when the Higgs is a scalar and π when it is a pseudoscalar.

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• *Lepton-hadron-photon processes*

The work here spanned electroweak theories as well as partons, scale invariance, two photon processes etc.

In 1969 it was not clear that the relation $M_W M_Z^{-1} = \cos\theta_W$ in electroweak theories followed from a general consideration of weak isospin invariance rather than just from Higgs doublets. In collaboration with J. Pestieau (while going on a different tack concerning the Lee-Wick mechanism of negative metric scalars), we introduced [1] the mass-mixing scheme of Sakurai into Glashow's 1961 model and showed how it naturally led to the relation between the charged and neutral weak boson masses. The line of reasoning was later taken on by others [2]. Our contribution has been acknowledged by many authors including Veltman [2]. We also emphasized first the neutral-current induced forward-backward asymmetry in $e\bar{e} \to \nu\bar{\nu}$. Furthermore, an analysis of weak interaction loops was done [4] employing Wilson's short-distance scale invariance and a new structure was discovered in radiative nonleptonic weak decay. The importance of this work has recently been underlined by Gaillard [4].

Deep inelastic scaling for one particle inclusive annihilation $e^+e^- \to H + X$ was proposed [5] in collaboration with J. Pestieau. This stimulated Gribov and Lipatov to write reciprocity relations between this reaction and deep inelastic electron scattering. Together with J. Pestiean and H. Terazawa, we evaluated [6] the laboratory range of virtual photons for the latter process. The impact of this work has been discussed by Yennie [6].

A major contribution was made [7] on two-photon processes. This is a sum-rule, to lowest order in α_{EM}, on the difference $\Delta\sigma$ of total hadronic crosssections of two real polarized photons colliding with a CM energy $\sqrt{s}$ and net helicity 2 and 0; to wit: $\int_0^\infty ds s^{-1}\, \Delta\sigma(s) = 0$. It is called [8] the *Roy Sum Rule* in the literature. Because of its sound theoretical footing, it has become a benchmark in the study of resonances coupling to the 2γ channel — as evident from the use [8] of the sum-rule one decade after its invention.

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- *Two dimensional field theory and gauge theory*

With G. Bhattacharya, an explicit operator solution was given [2] to the $U(n)$-symmetric Thirring Model by inventing the spinor-inversion technique. Moreover, with P. Mitra, a nonperturbative solution was constructed [2] for QCD in 2D with diagonal colour and the solution was interpreted as representing a phase with the dynamical symmetry reduction $SU(n) \rightarrow [U(1)]^{n-1}$.

The broken color gauge theory of Pati and Salam with Han-Nambu quarks was considered [3] in collaboration with G. Rajasekaran and deep inelastic processes were studied in this theory. A theorem was proved on the deep inelastic suppression of quark colour and the manifestation of gluon colour. This work paved the way for later experimental tests which have gone against such a theory.

Together with T. Walsh, we made [4] a proposal to detect a glueball as the leading fragment of a gluon jet in collinear hadronic decay products of a high mass $q\bar{q}$ system. This would be a clear glueball signature if sought for instance on a toponium peak. Depending on whether or not the iota or the theta is copiously produced in this way, the present controversy regarding their glueball interpretations can be clearly resolved.

In collaboration with A. Mukherjee, we have discovered [5] the occurrence of "anomalous" angular momentum for meron pairs in a nonabelian gauge theory. This is the third example of such a phenomenon after the two original examples connected with monopoles found by 1) Saha and 2) 't Hooft, Hasenfrantz, Jackiw and Rebby. We have also demonstrated [13] the corresponding spin-isospin mixing phenomenon.

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• *Supersymmetry applications*

In collaboration with O. Shanker, we put [1] forward the first natural theory of ultralight Dirac neutrinos from supersymmetric grand unification. This was done through the novel introduction of doubly degenerate Majorana states in supersymmetric grand unification. Not only is a new 4×4 mass-matrix proposed, yielding an ultralight Dirac neutrino, but the lightness of the latter relative to its charged family members is explained by the ratio of the supersymmetry-breaking and grand-unifying scales $M_{\rm SUSY}/M_{\rm GUT} \sim 10^{-6}$. The significance of this work has been emphasized by Wolfenstein [2] and by Ross [2].

A very important goal in connection with Higgs particles is getting some idea about their masses. In the Minimal Supersymmetric Standard Model (MSSM) supersymmetry is broken explicitly by soft operators and the Higgs scalar masses obey various bounds. If the MSSM is the low energy residue of an underlying $N = 1$ supergravity theory, severe constraints ensue on those operators. They result is a tightening of those Higgs mass bounds in a way that sensitively depends on the mass of the top quark. This was demonstrated by us in collaboration with P. Majumdar [3] including a spectacular improvement on specialization of no-scale theories. Many discussions [4] of this work can be found in the literature.

A nonzero mass $m_{3/2}$ is acquired by the gravitino $\tilde{G}$ in spontaneously broken $N = 1$ supergravity theories. Though a value of $m_{3/2}$ in the range 10^2 GeV to 10^2 TeV is natural in Polonyi-type theories, there exist other models predicting $m_{3/2}$ to be in the region of 10^{-6} eV as well those preferring it to be near the Planck mass. Is it possible to theoretically limit the enormous range available for the gravitino mass? Our answer to this poser is yes. Though there is still no completely acceptable quantum extension of general relativity, tree-level unitarity works for scattering amplitudes including gravitational interactions at energies below the Planck scale $M_{P\ell}$. Neither supersymmetrization nor its spontaneous breakdown should alter this classical nature of gravity at length scales greater than 10^{-33} cm. Yet this is what will happen if $m_{3/2}$ is too small. Together with T. Bhattacharya, we have considered [5] the pair-production of two longitudinally polarized gravitinos in the collision of two gauge bosons in their CM frame, and find that tree unitarity breaks down at an energy scale $E_{cr} = 12\sqrt{2\pi}\ M_{PL} M^{-1} m_{3/2}$ where M is the mass of the corresponding gaugino. Requiring E_{cr} to be at least M_{PL}, we obtain $M m_{3/2}^{-1} \leq 12\ \sqrt{2\pi}$ where, from the standpoint of the gauge hierarchy problem M is expected to be ≤ 0 (TeV).

The above work has been followed up by an exhaustive analysis [6] of relevant single- and double-gravitino tree amplitudes in spontaneously broken $N = 1$ supergravity theories clarifying the cancellations of non-Planckian energy growths through supercurrent conservation and the super-Higgs mechanism and also illuminating the constraint on Planckian energy growth from perturbative unitarity. The importance of our work has been recognized by Drees, Ellis, Jetzer and Sciama [7]. **An interesting consequence of our work** is that, if the gravitino were the main source of dark matter in the universe, it would have to be cold dark matter.

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