TIFR Annual Report 2008-09
THEORETICAL PHYSICS

High Energy Physics

HIGHLIGHTS

The formalism for analyzing the collective neutrino oscillations for nonspherical sources, like coalescing neutron stars, was developed.

The nature of the apparent singularity in the renormalization group evolution of neutrino Dirac phase at $\theta_{13} = 0$ was clarified.

Renormalization group evolution of neutrino masses and mixing was calculated in the Type-III seesaw mechanism, including threshold effects.

The viability of texture zeroes and flavour symmetries of neutrino mass matrices was analytically and quantitatively explored in a bottom-up approach.

Charge-parity asymmetry in the decays $B \to K\mu^+\mu^-$ was calculated in the framework of the standard model extended by a fourth generation.

The decays $B \to K\mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ were analyzed for possible signatures of new physics operators that can help identify their Lorentz structure.

It was found that the present upper bound on the branching ratio of $B_s \to \mu^+\mu^-$ puts strong constraint on the minimal supergravity parameter space. The minimum value of the branching ratio can go well below the present LHCb sensitivity.

The production and detection of the Kaluza Klein excitation of the gluon in a model of warped compactification has been studied.

Using the method proposed earlier by us (TIFR theorists), the location of the critical end point of QCD was determined to the highest accuracy ever. A scan of colliding energies at the RHIC accelerator at BNL, New York can potentially test this prediction.

Incorporation of baryonic chemical potential in the domain wall quarks was shown to be free of divergences proportional to μ^2 for a large class of fermion actions although the chiral symmetry was shown to be broken for any nonzero chemical potential at any lattice spacing.

TEXT

Research in High Energy Physics was carried out in the broad areas of Beyond Standard Model Physics, Lattice Gauge Theory and Quantum Chromodynamics.

Collective neutrino oscillations in non-spherical geometry

The formalism for analyzing the collective neutrino oscillations for non-spherical sources, like coalescing neutron stars, was developed. It was shown that as long as the neutrino ensemble displays self-maintained coherence, the problem becomes effectively one-dimensional along the streamlines of the overall neutrino flux. This approach for the first time provided a formal definition of the "single-angle approximation" frequently used for analyses of supernova neutrino oscillations. [Basudeb Dasgupta and Amol Dighe, with Alessandro Mirizzi and Georg Raffelt (Max Planck Institute for Physics, Munich)]

Renormalization group evolution of neutrino mixing parameters near $\theta_{13} = 0$

In the most general scenario with non-vanishing CP violating Dirac and Majorana phases, the renormalization group evolution of neutrino mixing parameters was explored in the vicinity of $\theta_{13} = 0$, in terms of its structure in the complex $\mathcal{U}_{e3}$ plane. The apparent singularity in the evolution of the Dirac CP phase δ at $\theta_{13} = 0$ was clarified, and a parameterization was formulated that naturally avoids this singularity. For the class of neutrino mass models with $\theta_{13} = 0$ at the high scale, the maximum value of θ_{13} generated by the RG evolution was bounded, when the low energy effective theory is the standard model or its minimal supersymmetric extension.

[Amol Dighe and Shamayita Ray, with Srubabati Goswami (PRL, Ahmedabad)]

Renormalization group evolution of neutrino masses and mixing in the Type-III seesaw mechanism

The standard model extended by heavy right handed $SU(2)_L$ triplet fermions, which generate neutrino masses through the Type-III seesaw mechanism, was analyzed. The renormalization group evolution of the effective neutrino mass matrix was calculated, with particular emphasis on the threshold effects and the role of Majorana phases.

[Amol Dighe and Shamayita Ray, with Joydeep Chakrabortty (HRI, Allahabad) and Srubabati Goswami (PRL, Ahmedabad)]

Texture zeroes and discrete flavor symmetries in neutrino mass matrices

Texture zeroes in neutrino mass matrix may give us hints about the symmetries involved in neutrino mass generation. An analytic framework was developed for examining the viability of these texture zeroes in a model independent, bottom-up approach. The deviation from flavour symmetries was quantified and its dependence on the absolute neutrino mass scale, the neutrino mass ordering, and the mixing angle θ_{13} was studied.

[Amol Dighe, with Narendra Sahu (Lancaster University)]

Resolving the neutrino mass hierarchy with atmospheric neutrinos using a Liquid Argon detector

Large-mass Liquid Argon detectors were explored for their potential of determining the neutrino mass hierarchy through interactions of atmospheric neutrinos. Results were given for a 100 kT sized magnetized detector which provides separate sensitivity to both muon and electron neutrinos and antineutrinos. The sensitivity for the unmagnetized version of such a detector was also discussed. After including the effect of smearing in neutrino energy and direction and incorporating the relevant statistical, theoretical and systematic errors, a binned analysis of the simulated data was performed. The sensitivity was marginalized over the presently allowed ranges of neutrino parameters and determined as a function of θ_{13}. It was found that such a detector offers superior capabilities for hierarchy resolution, allowing a 4σ determination for a 100 kT detector over a 10 year running period for values of $\sin^2 2\theta_{13} \geq 0.05$. For an unmagnetized detector, a 2.5σ hierarchy sensitivity is possible for $\sin^2 2\theta_{13} = 0.04$. [Pomita Ghoshal with Raj Gandhi (HRI, Allahabad), Srubabati Goswami (PRL, Ahmedabad) and S Uma Sankar (IIT Bombay)]

Mass hierarchy determination, atmospheric neutrinos and $\theta_{13} = 0$

The possibility of determining the neutrino mass hierarchy in the limit $\theta_{13} = 0$ using atmospheric neutrinos as the source was examined. In this limit, in which θ_{13} driven matter effects are absent, independent measurements of Δ_{31} and Δ_{32} can, in principle, lead to hierarchy determination. Since the difference between these two is Δ_{21}, one needs an experimental arrangement where $\Delta_{21}L/E \geq 1$ can be achieved. This condition can be satisfied by atmospheric neutrinos since they have a large range of energies and baselines. In spite of this, it was found that hierarchy determination in the $\theta_{13} = 0$ limit with atmospheric neutrinos is not a realistic possibility, even in conjunction with an apparently synergistic beam experiment like T2K or NOνA. The reasons for this were discussed, and also in the process the conditions that must be satisfied in general for hierarchy determination if $\theta_{13} = 0$ were clarified. [Pomita Ghoshal with Raj Gandhi (HRI, Allahabad), Srubabati Goswami (PRL, Ahmedabad) and S Uma Sankar (IIT Bombay)]

The Fourth family: A Natural explanation for the observed pattern of anomalies in B-CP asymmetries

It was shown that a fourth family of quarks with t' mass in the range of (400 - 600) GeV provides a rather natural explanation for the several indications of new physics that have been observed involving CP asymmetries of the b-quark. The built-in hierarchy of the 4×4 mixing matrix is such that the t' readily provides a needed perturbation to $\sin 2\beta$ as measured in $B \to \psi K_s$ and simultaneously is the dominant source of CP asymmetry in $B_s \to \psi\phi$. The difficulty in understanding the large observed difference in direct CP asymmetries in $B \to K^-\pi^+$ versus $B^- \to K^-\pi$ also tends to get amiliorated. Such heavy masses point to the tantalizing possibility that the 4th family plays an important role in the electroweak symmetry breaking. [Ashutosh Kumar Alok with Amarjit Soni (BNL, Upton, New York), Anjan Giri (Punjab U.), Rukmani Mohanta (Hyderabad U.), and Soumitra Nandi (HRI, Allahabad)]

Large forward-backward asymmetry in $B \to K\mu^+\mu^-$ from new physics tensor operators

The constraints on new physics contribution to the forward-backward asymmetry of muons, $A_{FB}(q^2)$, were studied for $B \to K\mu^+\mu^-$. It was found that new physics, in the form of vector/axial-vector operators, does not contribute to $A_{FB}(q^2)$ whereas scalar/pseudoscalar operators can enhance it only by a few per cent. However new physics the form of tensor operators can take the peak value of $A_{FB}(q^2)$ to as high as 40% near the high q^2 end point. In addition, if both scalar/pseudoscalar and tensor operators are present, then $A_{FB}(q^2)$ can be more than 15% for the entire high q^2 region $q^2 > 15 GeV^2$. The observation of significant A_{FB} would imply the presence of new physics tensor operators, whereas its q^2 dependence could further indicate the presence of new scalar/pseudoscalar physics. [Ashutosh Kumar Alok and Amol Dighe, with S. Uma Sankar (IIT Bombay)]

Charge-parity (CP) asymmetry in $B \to (X_s, X_d)\mu^+\mu^-$ with four generations

The Wolfenstein parameterization of the quark mixing (Cabibbo-Kobayashi-Maskawa) was extended to four generations. In this framework, the CP asymmetry $A_{CP}(q^2)$ in the decays $B \to X_s\mu^+\mu^-$ and $B \to X_d\mu^+\mu^-$ was calculated. It was shown that in the high q^2 region, the CP asymmetry may be enhanced up to 25 times the standard model expectation. [Ashutosh Kumar Alok, Amol Dighe and Shamayita Ray]

$B_s \to \mu^+\mu^-$ decay in the R-parity violating minimal supergravity

The process $B_s \to \mu^+\mu^-$ was studied in the context of the R-parity violating minimal supergravity in the high tan β regime. It was found that the present upper bound on $\mathrm{Br}(B_s \to \mu^+\mu^-)$ puts strong constraint on the minimal supergravity parameter space. The constraints become more severe if the upper bound is close to its standard model prediction. The minimum value of the branching ratio can go well below the present LHCb sensitivity. [Ashutosh Kumar Alok with Sudhir Kumar Gupta (Iowa State University)]

Probing extended Higgs sector through rare $b \to s\mu^+\mu^-$ transitions

The constraints on the scalar/pseudoscalar new physics contribution to the average forward backward asymmetry $< A_{FB} >$ of muons in $B \to K\mu^+\mu^-$ and the longitudinal polarization asymmetry A_{LP} of muons in $B_s \to \mu^+\mu^-$ was studied. It was found that the maximum possible value of $< A_{FB} >$ allowed by the present upper bound on $\mathrm{Br}(B_s \to \mu^+\mu^-)$ is about 1% at 95% C.L. and hence will be very difficult to measure. On the other hand, the present bound on $\mathrm{Br}(B_s \to \mu^+\mu^-)$ fails to put any constraints on A_{LP}, which can be as high as 100%. The measurement of A_{LP} will be a direct evidence for an extended Higgs sector, and combined with the branching ratio $\mathrm{Br}(B_s \to \mu^+\mu^-)$ it can even separate the new physics scalar and pseudoscalar contributions. [Ashutosh Kumar Alok and Amol Dighe, with S. Uma Sankar (IIT Bombay)]

The "inverse problem" in collider physics

As a major initiative in the area of collider physics, the study of the so-called "inverse problem" has been taken up. This addresses the question: if some deviation from the Standard Model is observed at one of the present or upcoming colliders, how can we tell what is the underlying new physics which could have caused it? As a first exercise in this, a study of ILC signals for a model with a universal extra dimension was made and ways of distinguishing them from other kinds of new physics, such as supersymmetry, were devised. [Sreerup Raychaudhuri with B. Bhattacharjee, A. Kundu (University of Calcutta) and S.K. Rai (Helsinki University)]

Collider signatures of warped compactification models

In a model of warped compactification, with all SM fields except the Higgs, in the bulk the most important signatures come from the production of Kaluza-Klein excitations of gauge bosons. In particular, the excitation of the gluon with its huge branching into tops is expected to be the best candidate. The production of this from excitation from gluon-initiated states at the LHC has been the focus of our studies. In this context, associated production and the production of the excited gluon at the next-to-leading order in QCD has been studied. [K. Sridhar with M. Guchait (TIFR) and F. Mahmoudi(Uppsala University)]

Quarkonia in LHC

Non-Relativistic QCD (NRQCD) has enjoyed success in predicting cross-sections of the various quarkonium states at the Tevatron. However, the effective theory has only been tested in predictions of the differential distributions but not the absolute values of the cross-sections. Moreover, the polarisation of J/ψ at large p_T measured by the Tevatron experiments are clearly at variance with NRQCD predictions. These latter predictions come from the heavy-quark symmetry of NRQCD. This symmetry can also be used to predict the cross-section for h_c at the LHC. The study of this state at LHC will be important in understanding quarkonium dynamics and also the, as yet poorly-determined, properties of h_c. [K. Sridhar]

Strangeness form factors and parton distribution function

Using N_f=2+1 clover fermion configurations the strangeness electromagnetic form factors of the nucleon were calculated. In the evaluation of the disconnected insertion, the Z(4) stochastic method, along with unbiased subtractions from the hopping parameter expansion were used. The magnetic form factor at the lowest $Q^2 = 0.39 GeV^2$ on the lattice was found to be negative with 3 σ signal for the lowest quark mass. Upon Q^2 and chiral extrapolations, $G^s_M(Q^2 = 0) = -0.017(25)(07)$ was obtained, where the first error is statistical, and the second reflects the uncertainties in Q^2 and chiral extrapolations. This result is consistent with experimental values, and moreover errors are an order of magnitude smaller.

A lattice QCD study of lowest moments, $< x >$ and $< x^2 >$, of the parton distribution function of the nucleon to include those of the sea quarks was performed. This calculation yielded 5σ signals for $< x >$ for the u, d, and s quarks, but $< x^2 >$ is consistent with zero within errors. The perturbatively renormalised $< x >$ for the strange quark at $\mu = 2$ GeV was $< x >_{s+\bar{s}} = 0.027 \pm 0.006$ which is consistent with the experimental result. The ratio of $< x >$ for s vs. u/d in the disconnected insertion with quark loops was found to be 0.88 ± 0.07. This is about twice as large as the phenomenologically fitted $\frac{< x >_{s+\bar{s}}}{< x >_{\bar{u}} + < x >_{\bar{d}}}$ from experiments where $\bar{u}$ and $\bar{d}$ include both the connected and disconnected insertion parts. [N. Mathur with K.-F. Liu, T. Doi, M. Deka and T. Draper (University of Kentucky)].

Baryon resonances from lattice QCD

Highly excited states for isospin 1/2 baryons were calculated for the first time using lattice QCD with two flavours of dynamical quarks by using an anisotropic Wilson lattice. The lowest four energies were reported in each of the six irreducible representations of the octahedral group at two pion masses as low as about 400 MeV. Clear evidence was found for a $5/2^-$ state in the pattern of negative-parity excited states which was in agreement with the pattern of physical states, and spin 5/2 has been realized for the first time on the lattice.

A comprehensive study of the cascade baryon spectrum using lattice QCD affords the prospect of predicting the masses of states not yet discovered experimentally, and determining the spin and parity of those states for which the quantum numbers are not yet known. Using $N_f = 0$, 2, and 2+1 flavour fermions a comprehensive project has been undertaken to study cascade baryons and preliminary results were very encouraging. Preliminary results indicated clear signal for spin 5/2 states along with excited states for other spin representations. [N. Mathur in collaboration with International Hadron Spectrum Collaboration].

Thermal Phase Transition for QCD with Realistic Quark Masses

Several features of the thermal, chiral symmetry restoring, deconfining crossover was studied for QCD with small (almost real) quark masses. Static quantities, like screening masses, provide important theoretical understanding of the thermal phase. The spatial Wilson loop is one interesting observable, which shows an area law even in the deconfined phase and can be understood in terms of the confining nature of SU(3) gauge theory in three dimensions. Excellent agreement was found with perturbative matchings of the spatial string tension with that of the 3-dimensional theory, indicating that dimensional reduction gives a good description of this observable at temperatures twice the transition temperature, or lower. [Saumen Datta with RBRC-Bielefeld Collaboration]

QCD at finite chemical potential with six time slices

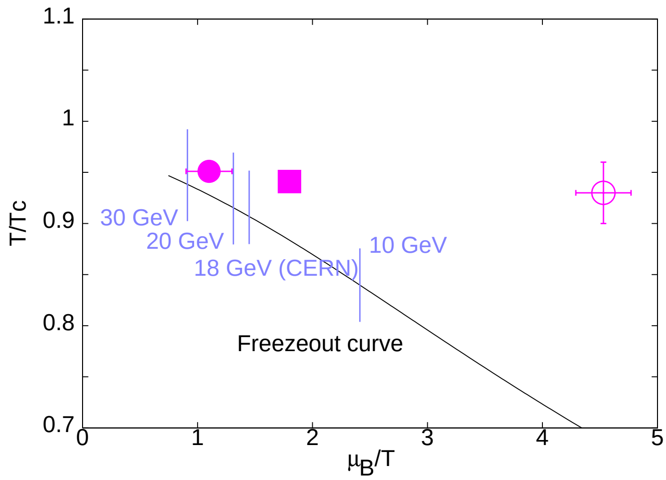

Figure 1: TIFR (Gavai-Gupta) results for the QCD critical point. Recent finer lattice result denoted by square, coarse lattice results by circles (filled : Gavai-Gupta 2005; Open : Fodor-Katz 2003).

The phase diagram of QCD with two light quarks in the baryon chemical potential-temperature (μ_B-T) plane has earlier been investigated by us on lattices with a cut-off $a = 1/4T$. As a step towards continuum limit, and in order to estimate the cut-off effects, the investigations were continued to lattices at a finer lattice cutoff $a = 1/6T$. The QCD cross over coupling at $\mu_B = 0$, T_c, was determined for a quark mass corresponding to $m_\pi/m_\rho = 0.3$, as in our earlier result on $a = 1/4T$. The cross over at vanishing chemical potential was identified through the Polyakov loop susceptibility, χ_L, and was cross checked with two measures related to the quark number susceptibilities, χ_{nm}. These measures are consistent with each other within the accuracy of our computations. The Taylor expansion of the baryon number susceptibility, in a series in the baryon chemical potential (μ_B) was investigated. The radius of convergence of the series was studied at various temperatures. The critical point occurs when the radius of convergence identifies a singularity on the real axis, through the fact that the series coefficients are all positive. The region of the location of the QCD critical point was found to be $T^E/T_c \approx 0.94$ and $\mu_B^E/T < 1.8$. The extrapolation of various susceptibilities and linkages to finite chemical potential was also investigated.

The computations were performed on the Cray X1 of the Indian Lattice Gauge Theory Initiative (ILGTI) at TIFR. [R.V. Gavai and Sourendu Gupta]

Dissipative Hydrodynamics at Non-vanishing Net Baryon Number Density

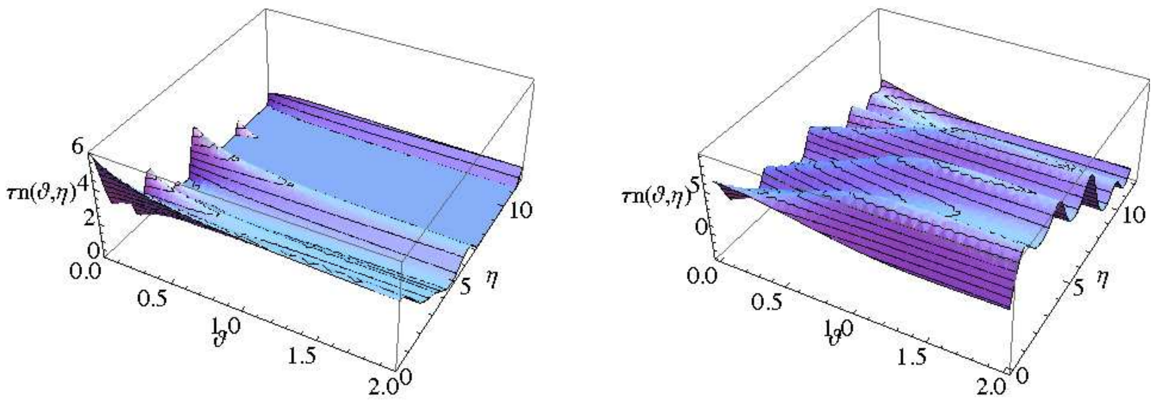

Figure 2: Evolution of conserved number density using Fick's (Left) and Kelly's (right) diffusion equation.

Diffusion of conserved number densities was studied in relativistic heavy-ion collisions where the fireball evolves under longitudinal Bjorken flow. The difference between the usual (Fick) diffusion equation and a relativistic causal version (Kelly's equation) was examined. It was found that in the Fick theory the memory of the initial state is wiped out very quickly, whereas in the Kelly theory there are long-lived transients (see the Figure). If freezeout occurs at an epoch of a few times the relaxation time, then these transients give observational consequences. [R.S. Bhalerao and Sourendu Gupta]

Domain wall and overlap quarks at nonzero temperature and baryon density

Domain wall fermions are defined by extending the space-time by one extra dimension. The mass of the 5-dimensional fermions, M, and the length of the extra (fifth) dimension, L_5, can be shown to control the chiral symmetries in the original theory. The zero modes of the fermion, attached to the boundary (walls) of the fifth dimension, become the massless quarks in the limit of $L_5 \to \infty$, when the domain wall fermions reduce to the overlap fermions. However, the finiteness of L_5 provides a knob to control the chiral symmetries and still manage the complexity of the computer simulations.

The thermodynamics of ideal gas of domain wall quarks for finite L_5 was investigated, both analytically and numerically, for both zero and nonzero baryon chemical potential. The μ_B^2-dependent divergence was shown analytically to be absent for a class of actions with nonzero chemical potential, although the chiral symmetry was demonstrated to be broken for any nonzero μ_B at any finite lattice spacing for all of them. The contribution of the heavy modes of mass M of was shown to be irrelevant in the continuum limit. The ranges of M and L_5 for which the continuum limit can be reached on relatively coarser lattices were determined numerically. Modifications of the domain wall operator, as well as the overlap operator, were proposed that reduce substantially the finite cut-off effects in thermodynamic quantities for the currently used N_T =6-8 lattices. [R.V. Gavai and Sayantan Sharma]

Thermodynamics of Ideal Overlap Quarks on the lattice

The Overlap operator is a discretization scheme of the fermion kinetic operator that preserves exact chiral symmetry on the lattice. It is, however, highly non-local. Implementing overlap fermions numerically, requires a lot of computational effort. The thermodynamics of an ideal gas of overlap quarks was investigated for zero and non-zero quark chemical potential. A systematic numerical study for the optimum choice of the parameters to best approximate the continuum limit on relatively coarse lattices was done. Limitations of the existing method of the introduction of the chemical potential was shown. It was also shown that in the presence of finite chemical potential, the chiral symmetry is explicitly broken on the lattice. [Debasish Banerjee, Rajiv Gavai and Sayantan Sharma]

Thermodynamics of SU(N) Gauge Theories

The thermodynamics of SU(N) gauge theories at large N was investigated, by studying the theory numerically for N=3-6. Such a study is useful both for understanding various properties of the finite temperature transition of SU(3) gauge theory, the gauge group for strong interactions, and as an intermediate step in understanding the connections of results of heavy ion collison experiments with those of the supersymmetric SU(∞) theories obtained via AdS-CFT correspondence. Both the deconfinement temperature, $T_d/\Lambda_{\overline{MS}}$, as well as equation of state for the deconfined phase of the large N theory, was studied . It was found that the approach to conformality in the deconfined phase of SU(N) theory is similar to what is predicted from weak coupling theory. [Saumen Datta and Sourendu Gupta]

Thermodynamics and Finite-Size Scaling in Scalar Field Theory

The thermodynamics of the 1-component real scalar field theory was investigated numerically in the symmetric phase. The couplings were evaluated in 1-loop lattice perturbation theory near the critical line, while the operators were calculated non-perturbatively on the lattice. Finite size scaling of the thermodynamic quantities were studied. It was found that for

$mL > 4.5$ and $LT \geq 4$ (where m is the mass, L and T are the lattice extents in the spatial and temporal directions respectively), the thermodynamic limit can be attained. [Debasish Banerjee, Saumen Datta, Sourendu Gupta]

Mesonic Observables in QGP: Study in QCD Motivated Model

While bulk thermodynamic quantities of strongly interacting matter at finite temperatures, T, can be calculated from first principles using lattice QCD, real time observables which are of direct interest for signatures of the deconfined phase, are extremely difficult to obtain from first principles in a non-perturbative regime. It becomes even more difficult in the presence of a finite baryon number chemical potential, μ_B. Real-time observables of experimental interest were studied using a QCD-inspired model, which incorporates the dynamics of the important degrees of freedom near the QCD phase transition. The parameter region in (T, μ_B) where this model may suitably describe the properties of the deconfined phase were carefully examined. Meson-like probes of the plasma were studied in this regime. [Saumen Datta with P. Deb, A. Bhattacharyya (University of Calcutta) and S. Ghosh (Bose Inst., Kolkata)]