TIFR Annual Report 2009-10
THEORETICAL PHYSICS

High Energy Physics

HIGHLIGHTS

A set of discriminating variables was devised to solve the 'LHC inverse problem' in trilepton and four-lepton signals with accompanying jets and missing transverse energy, taking four popular models of new physics beyond the Standard Model.

A novel phenomenon of "multiple splits" in the spectra of neutrinos from a supernova was discovered and analytically investigated.

The chiral anomaly relation was shown non-perturbatively to remain the same at finite density. A new simpler lattice Dirac operator for nonzero density was proposed and shown to have desirable properties. Smooth behaviour was predicted for certain observables at current RHIC and future LHC energies, any deviations from which signal the presence of a nearby critical point. A better method define a renormalized Polyakov loop, the order parameter for the deconfinement transition, was given. A state of massive "constituent" quarks was argued to exist as an intermediate phase between confined nuclear matter and the plasma of deconfined massless quarks and gluons.

Charmonium suppression in strongly coupled quark-gluon plasma was demonstrated.

Using QCD simulation light tetraquark states have been investigated with a goal to find out whether lightest scalar mesons sigma and kappa have a large tetraquark component.

Bottom-hadron spectra and particularly their mass splittings have been investigated. The findings on the mass of the Ω_b is consistent with the recent CDF measurement and furthermore the mass for the as-yet-unobserved Ξ'_b is predicted to be 5955(27) MeV.

TEXT

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

Inverse problem at the LHC

The LHC Inverse Problem refers to the question of determining the naure of the new physics beyond the standard model from LHC observables. At the LHC, one of the cleanest signals for new physics searches is multileptons in the final states associated with missing transverse energy. The most interesting models of new physics which induce such signals are known to be supersymmetry with R-parity conservation, a universal extra dimension with conservation of KK-parity, little Higgs models with conserved T-parity and the standard model with a fourth sequential generation of heavy fermions. It was found that a judiciously chosen set of observables, critically involving the number of identifiable jets and leptons, can collectively provide distinct footprints for each of these models. Simple pairwise correlation of such observables can enable unambiguous identification of the underlying model, even with a relatively small data sample.
[B. Bhattacherjee and S. Raychaudhuri with A. Kundu (Calcutta) and S.K. Rai (Helsinki)]

Challenging the Higgs sector of the minimal UED model

In recent times, the Universal Extra Dimensions (UED) model has emerged as a viable option for physics beyond the Standard Model (SM). The Higgs sector of the Universal Extra Dimensions has a rather involved set-up. The phenomenology of such a Higgs sector of the UED was explored in detail with the Large Hadron Collider (LHC) in focus, including relevant decay branching fractions involving the KK-Higgs excitations and possible production modes of the KK-Higgs bosons. It was pointed out that collider searches of such Higgs bosons face generic difficulties due to soft end products which result from severe degeneracies in the masses of the involved excitations in the minimal version of the UED.

[B. Bhattacherjee with P. Bandyopadhyay (HRI, Allahabad) and A.K. Datta (HRI, Allahabad)]

Multiple splits of supernova neutrinos

In regions of high neutrino density inside a core collapse supernova, nonlinear neutrino oscillations take place. These collective effects swap the electron neutrino and antineutrino spectra with those of another flavor in certain energy intervals bounded by sharp spectral splits. It was pointed out that this phenomenon is far more general than previously appreciated: typically one finds one or more swaps and accompanying splits in the neutrino and antineutrino channels for both inverted and normal neutrino mass hierarchies. Depending on an instability condition, swaps develop around spectral crossings (energies where the electron neutrino or antineutrino fluxes are equal to that of another flavor) and the widths of swaps are determined by the spectra and fluxes. An analytical explanation of this novel phenomenon was presented.
[B. Dasgupta and A. Dighe, with G. Raffelt (MPI, Munich) and A. Smirnov (ICTP, Trieste)]

New-physics contributions to the forward-backward asymmetry in $\mathbf{B \to K^* \mu^+ \mu^-}$

The forward-backward asymmetry (AFB) and the differential branching ratio (DBR) in $B \to K^* \mu^+ \mu^-$ was studied in the presence of new physics (NP) with different Lorentz structures. The effects of NP contributions from vector-axial vector (VA), scalar-pseudoscalar (SP), and tensor (T) operators, as well as their combinations, were calculated, and their features were explained through analytic approximations. Two mechanisms were found that can give a significant deviation from the standard-model predictions, in the direction indicated by the recent measurement of AFB by the Belle experiment. They involve the addition of the following NP operators: (i) VA, or (ii) a combination of SP and T. These two mechanisms can be distinguished through measurements of DBR in $B \to K^* \mu^+ \mu^-$ and AFB in $B \to K^* \mu^+ \mu^-$.
[A. Alok, A. Dighe and D. Ghosh, with D. London (Montreal), M. Nagashima (Montreal), A. Szynkman (Montreal) and J. Matias (IFAE, Barcelona)]

SU(N) Gauge Theory at Large N

A detailed study of thermodynamics of SU(N) gauge theories at large N, by studying the theory numerically for N=3-6 and trying to understand the large N limit, was completed. An accurate estimate of the latent heat was obtained for the theory with different number of colors, which is of help in understanding the nature of transition for the theory with three colors, the theory for strong interactions. The bulk thermodynamic quantities for the theory with different number of colors was also studied. It was found that the bulk thermodynamic quantities have very nice scaling with the number of colors, with the magnitude of the subleading correction small. The scaling with the 'tHooft coupling, the usual basis for understanding scaling with number of colors, is much worse. Moreover, no evidence was found of the presence of a strongly coupled, nearly conformal phase in the deconfined gluon plasma. [S. Datta and S. Gupta]

Anomalies at finite density and chiral fermions

A chiral anomaly arises in Quantum Chromodynamics (QCD) in the massless quark limit. The famous Adler-Bell-Jackiw work established it perturbatively while Fujikawa provided a new non-perturbative insight into it. The chiral anomaly relates non-trivial topological sectors of the gauge fields to the exact zero modes of the Dirac operator and is thought to explain the heaviness of the η'. For the physically interesting case of QCD with two light flavours, the order of the chiral phase transition depends on the size of the anomaly term, which in turn decides the existence of the QCD critical point.

It was shown perturbatively from the computation of the triangle diagram at zero temperature that the anomaly equation does not have any finite density correction terms. Using the Fujikawa method, it was established non-perturbatively that the anomaly relation is unaffected in the presence of a finite chemical potential. This has an important implication for the lattice field theory in designing the lattice Dirac operator for nonzero μ – it should lead to a μ-independent anomaly relation on the lattice. A physically better motivated method of introducing the chemical potential in the Overlap Dirac operator was proposed. This proposal would save much of the computational effort required for obtaining higher order susceptibilities needed to locate the QCD critical point reliably. [R.V. Gavai and S. Sharma]

Charmonium suppression in strongly coupled quark-gluon plasma

Charmonium suppression due to the presence of screening of static color fields was proposed as a signature of QGP formation long ago. The fate of charmonium suppression in a strongly coupled QGP medium was studied in the presence of shear viscosity. A medium modified form of Cornell potential was employed. It was found that both direct and sequential suppression of charmonium states are very sensitive to the shear viscosity to entropy density ratio. The flavor dependence of charmomium survival probability was also studied. The results showed excellent agreement with the recent experimental results from RHIC.
[V.C. Joshi with B.K. Patra (IIT, Roorkee) and V. Agotiya (IIT, Roorkee)]

Lattice QCD predictions for shapes of event distributions along the freeze-out curve in heavy-ion collisions

QCD phase diagram in the temperature (T)- baryonic chemical potential (μ_B) plane may have a critical point for the realistic up, down and strange quark masses. The TIFR group has presented substantial evidence in the recent past for such a critical point from their own lattice QCD computations, which other groups in the world are also converging to. Our results suggest that heavy-ion collision experiments at moderate colliding energies, achievable at RHIC (USA), FAIR (Germany) and NICA (Russia) could find it. In these collisions of heavy-ions, a fireball is created which evolves chemically and thermally before freezing out.

The question of how close the freeze-out gets to the critical point by constructing certain ratios of nonlinear quark number susceptibilities was addressed. On the lattice they are related to the radius of convergence of the series for the pressure in terms of μ_B. Experimentally, they are governed by the variance, skew and kurtosis of the event distribution of baryon number. Smooth behaviour was predicted for three ratios of these quantities at current RHIC and future LHC energies, any deviations from which signal the presence of a nearby critical point. Clear peaks were shown to be present at the location corresponding to our estimate of the QCD critical point.

The computations were performed on the Cray X1 of the Indian Lattice

Gauge Theory Initiative (ILGTI) at TIFR. [R.V. Gavai and S. Gupta]

Renormalized Polyakov loop in the Fixed Scale Approach

The Polyakov loop, L, defined as the product of the time-like gauge links at a given site, is the order parameter for the deconfinement transition. Of course, an order parameter should be physical, i.e., independent of the lattice spacing, a, in the continuum limit. The Polyakov loop needs to be renormalized for this to be true : the bare Polyakov loop vanishes in the continuum limit. Previous attempts to reormalize it depended on perturbation theory or other technical assumptions. In this work, the so-called fixed scale approach of simulations was employed, in which temperature is varied by changing the temporal lattice size, and it was shown how to define a renormalized Polyakov loop which is valid for both the phases below and above T_c. The definition itself does not depend on any lattice artifacts or the lattice size in the deconfined phase. Moreover, it displays the expected behaviour for the free energy of a static quark in the confined phase as the physical volume is increased. [R.V. Gavai]

The QCD Phase Structure at High Baryon Density

Dense nuclear matter has been a subject of great interest for a long time. Various ideas such as nuclear matter, quark matter, colour superconducting quark matter and more recently quarkyonic matter have been discussed vigourously. Confinement and spontaneous chiral symmetry breaking are two major characteristics of the phase at low temperatures and densities. The former binds coloured quarks interacting through coloured gluons to colour-neutral hadrons. The latter brings in pions as Goldstone bosons and gives the essentially massless quarks in the QCD Lagrangian a dynamically generated effective 'constitutent' mass. As the temperature/density of our hadronic phase is increased, both these features may end, leading to newer phases.

It was argued that chiral symmetry restoration can occur either by an evaporation of the gluonic quark dressing in a hot environment, or by quark percolation in a cold environment, leading to cluster fusion of the gluon clouds making up the effective quark mass. It was suggested that

the coincidence of color deconfinement and chiral symmetry restoration at high temperatures and vanishing baryon density arises through the first of these two mechanisms. Arguing that for low temperature and large baryon densities an evaporation of the gluon dressing is not likely, a three-phase structure of matter was obtained in QCD (apart from a possible color superconductor): i) hadronic matter, ii) a plasma of massless quarks and gluons, with no intrinsic scale, full color deconfinement and chiral symmetry restoration and iii) a plasma of deconfined massive quarks, with their mass as intrinsic scale. The phase of massive quarks is limited in temperature by evaporation, i.e., by the first of the above alternatives, and in baryon density by the second, i.e., by quark percolation. In addition to basic massive quarks, the quark plasma can also contain diquarks as local quark-quark bound states in the colored background.
[R.V. Gavai with P. Castorina (Catania U. & INFN, Catania) and H. Satz (Bielefeld U.]

Spectroscopy of light tetraquark states

Using QCD simulation, an investigation is being carried out whether there are any light tetraquark states as predicted by various model calculations. This will allow us to search for hadronic states beyond usual two and three quark states. The main goal is to find out the lightest scalar mesons sigma and kappa have a large tetraquark component, as is strongly supported by many phenomenological studies. A two-flavor dynamical simulation was performed with Chirally Improved quarks and the quenched simulation with overlap quarks, finding qualitative agreement between both results. The spectrum was determined using the generalized eigenvalue method with a number of tetraquark interpolators at the source and the sink. In all the channels, one unavoidably finds lowest scattering states $\pi(k)\pi(-k)$ or $K(k)\pi(-k)$ with back-to-back momentum $k = 0, 2\pi/L, \ldots$. However, an additional light state wsa found in the $I = 0$ and $I = 1/2$ channels, which may be interpreted as the observed resonances sigma and kappa with a sizable tetraquark component. In the exotic repulsive channels $I = 2$ and $I = 3/2$, where no resonance is observed, no light state was found in addition to the scattering states.
[N. Mathur with S. Prelovsek (Ljubljana), T. Draper (Kentucky), C. Lang (Graz), K-F. Liu (Kentucky) and D. Mohler (TRIUMF)]

Bottom hadrons from lattice QCD

Bottom-hadron mass splittings were calculated with respect to B_d and Λ_b using full QCD with 2+1 flavors of dynamical Kogut-Susskind sea quarks and domain-wall valence quarks along with a static heavy quark. The calculation was performed on lattices having spatial volume of $(2.5\ \text{fm})^3$ with lattice spacing about 0.124 fm and a range of pion masses as low as 291 MeV. The results are in agreement with experimental observations and other lattice calculations within our statistical and systematic errors. In particular, the mass of the Ω_b wsa found to be consistent with the recent CDF measurement. A prediction was also made for the as-yet-unobserved Ξ_b' to have a mass of 5955(27) MeV.
[N. Mathur with H-W. Lin (Jefferson Lab), K. Orginos (Jefferson Lab and William-Mary Coll.)]

Next-to-leading order QCD corrections to boson pair production at the LHC in extra dimension models

Models of extra dimensions contain Kaluza Klein gravitons which arise from compactifying the dimensions extra to the usual four dimensions, and these modify the predictions of the standard model. The di-boson production channel is one of the important channels at the LHC to probe such effects of new physics. Leading order studies of observables at the LHC are very sensitive to the renormalization and factorization scales and to have a precise prediction a next-to-leading order (NLO) QCD calculation is required. With this as aim, computation of NLO QCD corrections to ZZ and WW production at the LHC in extra dimension models were carried out. Large K-factors were obtained and significant reduction in sensitivity to factorization scale was obtained.
[A. Tripathi with N. Agarwal (Allahabad), V. Ravindran (HRI, Allahabad) and V.K. Tiwari (Allahabad)]