1 TIFR Annual Report (2011-12) - Department of Theoretical Physics

2 Highlights

High Energy Physics

The QCD cross-over temperature (175 MeV, ie, about 2 trillion Kelvin) was determined by comparison of theoretical predictions and experimental data.

A lattice calculation of the quark and glue momenta and angular momenta in the proton was carried out, yielding the following distribution of proton spin – quark orbital angular momentum: 0.50 (2), quark spin: 0.25 (12), gluon angular momentum: 0.25 (8).

An analytic model was proposed to understand event-by-event fluctuations of the initial geometry in ultra-relativistic heavy ion collisions.

The momentum diffusion coefficient for heavy quarks was estimated non-perturbatively and was found to be in the right ballpark to explain the heavy quark flow seen in the PHENIX experiment at RHIC, but very different from the leading-order perturbation theory. A lattice action was proposed, which preserves the chiral invariance on the lattice exactly for the overlap Dirac quarks with non-zero chemical potential.

The bulk-viscosity of a rapidly expanding pure glue plasma was calculated.

Transport properties were estimated for an anisotropically-expanding (2+1)-flavour hot QCD plasma within a quasi-particle description and quark-gluon plasma at the RHIC and LHC.

A study was made of charmonium production at the Large Hadron Collider.

Optimization of the baseline and the parent muon energy for a low energy neutrino factory was carried out, for determining mass ordering and CP phase of neutrinos.

Conditions for the seeding of neutrino oscillation instabilities inside a supernova were analytically identified.

It was shown that the constraints on the Higgs mass at the LHC imply large mass splittings between the fourth generation quarks or leptons.

A unique class of new physics models that would explain the anomalies observed in B meson decays was pointed out.

A detailed study of a supersymmetric model with two large R-parity-violating couplings showed that such a model can simultaneously lead to large flavour-violating effects at low energies as well as distinctive signals at the LHC.

TEXT

High Energy Physics

Scale for the Phase Diagram of Quantum Chromodynamics:

Matter described by Quantum Chromodynamics (QCD), the theory of strong interactions, may undergo phase transitions when its temperature and the chemical potentials are varied. QCD at finite temperature is studied in the laboratory by colliding heavy-ions at varying beam energies. A test was presented of QCD in the non-perturbative domain through a comparison of thermodynamic fluctuations predicted in lattice computations with the experimental data of baryon number distributions in high-energy heavy-ion collisions. This study provided evidence for thermalisation in these collisions, and allowed computation of the crossover temperature between normal nuclear matter and a deconfined phase called the quark gluon plasma. This value allowed setting a scale for the phase diagram of QCD. [Sourendu Gupta with X. Luo (USTC, Hefei, China), B. Mohanty (VECC, Kolkata), H.G. Ritter (LBNL, USA) and N. Xu (LBNL, USA & CCNU, China]

Lattice calculation of the quark and glue momenta and angular momenta in the proton:

A quenched QCD calculation of the quark and glue momenta and angular momenta in the proton is reported. These include the quark contributions from both the connected and disconnected insertions. The calculation was carried out on a $16^3 \times 24$ quenched lattice with Wilson fermions. The glue operator is comprised of gauge-field tensors constructed from the overlap operator. The u and d quark momentum/angular momentum fraction is 0.66(5)/0.72(5), the strange momentum/angular momentum fraction is 0.024(6)/0.023(7), and that of the glue is 0.31(6)/0.25(8). The orbital angular momenta of the quarks are obtained from subtracting the angular momentum component from its corresponding spin. As a result, the quark orbital angular momentum constitutes 0.50(2) of the proton spin, with almost all it coming from the disconnected insertion. The quark spin carries a fraction 0.25(12) and glue carries a fraction 0.25(8) of the total proton spin. [Nilmani Mathur with K.F. Liu (U. of Kentucky) *et al* (ChiQCD collaboration)].

Understanding anisotropy generated by fluctuations in heavy-ion collisions:

Event-by-event fluctuations are central to the current understanding of ultra-relativistic heavy ion collisions. In particular, fluctuations in the geometry of the early-time collision system are responsible for new phenomena such as triangular flow, which have solved important puzzles in existing data. A simple model was proposed where initial fluctuations stem from independent flux tubes randomly distributed in the transverse plane. The moments of the initial anisotropies (dipole asymmetry, eccentricity, triangularity), which are the sources of anisotropic flow, and their mutual correlations were calculated analytically. Analytic results were in good agreement with calculations from commonly-used Monte-Carlo codes, providing a simple understanding of the fluctuations contained in these models. Any deviation from these results in future experimental data would thus indicate the presence of non-trivial correlations between the initial flux tubes and/or extra sources of fluctuations that are not present in current models. [R.S. Bhalerao with M. Luzum and J.-Y. Ollitrault (Saclay)]

Heavy quark momentum diffusion coefficient from Lattice QCD:

Since both the charm and the bottom quarks are much heavier than the temperatures attained in current heavy ion collisions, one expects them to be produced largely in the early, pre-equilibrated state of the collision, and thus provide a window to examine the early stages of the fireball. It is expected that the thermalisation time of the heavy quarks is much larger than that of the light quarks. Experimentalists can test this expectation by measuring the so-called elliptic flow velocity v_2 of the thermalised quarks which is expected to be a lot lesser for these heavier quarks. PHENIX results at the RHIC, on the other hand, showed that the open charm mesons show a large elliptic flow, v_2^D. It had been shown that such large values of v_2^D arise due to very small diffusion coefficients for the heavy quarks in a Langevin description of the motion of the heavy quark, much smaller than the values indicated by perturbation theory.

A nonperturbative estimate of the diffusion coefficient in QCD is, therefore, essential to understand the heavy quark flow results. Lattice QCD, together with numerical Monte Carlo techniques, provides the only way of doing first principle nonperturbative calculations in the quark-gluon plasma. Unfortunately, such calculations need to be done in Euclidean space, and extracting the diffusion coefficient requires an analytic continuation, which is extremely nontrivial. The momentum diffusion coefficient for heavy quarks was determined numerically in a deconfined gluon plasma in the static approximation. The correlation function of the color electric field was studied using Monte Carlo techniques. The diffusion coefficient for temperatures in the range T_c to $2T_c$ was extracted from the long distance behavior of such a correlator. This nonperturbative estimate of the diffusion coefficient was found to be in the right ballpark to explain the heavy quark flow seen in the PHENIX experiment at RHIC, and is very different from the leading order perturbation theory. [Debasish Banerjee, Rajiv V. Gavai, and Saumen Datta with Pushan Majumdar(IACS, Kolkata)]

Bulk-viscosity of a rapidly expanding pure glue plasma:

In this work, bulk viscosity, ζ and its ratio with the shear viscosity, ζ/η were investigated for an anisotropically expanding pure glue plasma in the presence of turbulent color fields. It was shown that the anisotropy in the momentum distribution function of gluons, which was determined from a linearised transport equation eventually led to the bulk viscosity. For the isotropic (equilibrium) state, a recently proposed quasi-particle model of pure SU(3) lattice QCD equation of state was employed where the interactions were encoded in the effective fugacity. It was argued that the interactions present in the equation of state, significantly contribute to the bulk viscosity. Its ratio with the shear viscosity is significant even at $1.5T_c$. Thus, one needs to take in account the effects of the bulk viscosity while studying the hydrodynamic expansion of QGP in RHIC and LHC. [Vinod Chandra (Joshi) with V. Ravishankar (IIT Kanpur)]

Transport properties of an anisotropically expanding (2+1)-flavor hot QCD plasma within a quasi-particle description and quark-gluon plasma at RHIC and LHC:

In this project, bulk and shear viscosities,η and ζ were estimated for quark-gluon-plasma produced in relativistic heavy ion collisions within semi-classical transport theory in a recently proposed quasi-particle model of (2+1)-flavor lattice QCD equation of state. These transport parameters were found to be highly sensitive to the interactions present in hot

QCD. Contributions to the transport coefficients from both the gluonic sector and the matter sector were investigated. The matter sector was found to be significantly dominating over the gluonic sector, and that was true for both the shear and bulk viscosities. The temperature dependences of the quantities, $\zeta/\mathcal{S}$, and ζ/η suggested a sharply rising trend for the ζ closer to QCD transition temperature. Both η and ζ were shown to be equally significant for the temperatures that are accessible in the relativistic heavy ion collision experiments, and hence play crucial role while investigating the properties of the quark-gluon plasma. [Vinod Chandra (Joshi) with V. Ravishankar (IIT Kanpur)]

A Study of Charmonium Production at the LHC:

Non-Relativistic QCD (NRQCD) has been tested in predictions of the differential distributions of various quarkonium states at the Tevatron 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. Moreover, predictions for J/ψ polarisation that result from the heavy-quark symmetry of NRQCD are completely at variance with data. Heavy-quark symmetry can also be used to predict the cross-section for $\eta_c$and a study of the production of this resonance at the Large Hadron Collider has been completed. [K.Sridhar with S.S. Biswal (Orissa A&T U., Bhubaneswar)]

New Flow Observables in Ultra-relativistic Heavy Ion Collisions:

In ultra-relativistic heavy ion collisions, event-by-event fluctuations of the initial transverse density profile result in a collective flow pattern which also fluctuates event by event. A number of new correlation observables were proposed to characterize these fluctuations. How they should be analysed experimentally was described and it was argued that most of these quantities can be measured at RHIC and LHC. [R.S. Bhalerao with M. Luzum and J.-Y. Ollitrault (Saclay)]

Chiral extrapolation beyond the power-counting regime:

Chiral effective field theory can provide valuable insight into the chiral physics of hadrons when used in conjunction with non-perturbative schemes such as lattice QCD. We used chiral effective field theory for extrapolating the mass of the rho meson to the physical pion mass, outside the chiral power-counting regime, in quenched QCD (QQCD). The method involves an analysis of the renormalisation flow curves of the low energy coefficients in a finite-range regularized effective field theory. The analysis identifies an optimal regulator, which is embedded in the lattice QCD data themselves. This optimal regulator is the regulator value at which the renormalisation of the low energy coefficients is approximately independent of the range of quark masses considered. By using recent precision, quenched lattice results, the extrapolation was tested directly by truncating the analysis to a set of points above 380 MeV, while being blinded of the results probing deeply into the chiral regime. The result is a successful extrapolation to the chiral regime. [Nilmani Mathur with J.M.M. Hall (U. of Adelaide), F.X. Lee (Geroge Washington U., D.B. Leinweber (U. of Adelaide), K.F. Liu (U. of Kentucky), R.D. Young (U. of Adelaide) and J.B. Zhang (Zhejiang U.)]

A faster method of computation of lattice quark number susceptibilities:

Quantum Chromo Dynamics (QCD), the theory of strong interactions, may have a critical point in the temperature (T)-baryon number density (or the baryonic chemical potential μ_B). The search for this critical point is one of the major experimental goals of many heavy ion collider experiments world wide. It, therefore, appears natural to have a first principles theoretical exploration of the QCD critical point. The "fermion sign problem" poses itself as a big obstacle in this. One of the techniques to circumvent the sign problem at finite density is to compute the baryon number susceptibility as a Taylor series expansion in chemical potential near zero, as advocated by the TIFR group earlier. For the precise estimation of the radius of convergence, one needs to compute ratios of as many higher orders of baryon number susceptibilities as possible.

By adding the chemical potential as a Lagrange multiplier for the point-split number density term, the quark number susceptibilities were computed in two flavor QCD for staggered fermions in a novel proposal. Since lesser number of quark propagators are required at any order, this method leads to faster computations. A subtraction procedure was proposed to remove the inherent undesired lattice terms. It was demonstrated to work well by comparing the results with the existing ones where the elimination of these terms is analytically guaranteed. It was further shown that the ratios of susceptibilities are robust, opening a door for better estimates of location of the QCD critical point through the computation of the tenth and twelfth order baryon number susceptibilities without significant additional computational overload. [Rajiv V. Gavai and S. Sharma (U. of Bielefeld, Germany)]

Exact chiral invariance at finite density on the lattice:

The existence of a QCD critical point has been argued on the basis of its symmetries, called the chiral symmetries. Most theoretical computations looking for it use the staggered quarks.

These i) break the flavour and spin symmetry on the lattice and ii) have no flavour singlet axial symmetry, whereas QCD critical point is expected to exist only if there are two light and one moderately heavy quark in such computations with a mild temperature dependence of the singlet axial anomaly. The overlap Dirac fermions offer a possibility to improve upon this situation, as they have continuum-like symmetries. Unfortunately, adding the chemical potential turns out to be nontrivial for them. All the existing proposals break the crucial chiral symmetry on the lattice for nonzero chemical potential or needed external sources to be present.

A lattice action was proposed for the overlap Dirac quarks with nonzero chemical potential. It was shown to preserve the chiral invariance on the lattice exactly, in contrast, to all earlier proposals. This permits one to define an order parameter whose density dependence can signal the chiral transition even on the lattice. It was further demonstrated that this action arises from the Domain wall formalism by letting the chemical potential count only the physically relevant wall modes, thus providing a neat physical interpretation as to why it is better. This work opens up an avenue for computations of QCD critical point with these better and more realistic quarks, thereby increasing the reliability of the corresponding predictions. [Rajiv V. Gavai and S. Sharma(U. of Bielefeld, Germany)]

Diffusion of heavy quarks in plasma:

The energy loss and flow of heavy quarks in the medium created in the relativistic heavy ion collisions has been a subject of great interest. A large flow of the heavy-light mesons has been observed in the highest energy runs in RHIC, BNL. The p_T dependence of the flow can be understood by a Langevin model, but the momentum diffusion coefficient, κ, required to explain the data is much larger than the perturbative estimate of the same.

A nonperturbative study was carried out of the momentum diffusion coefficient for heavy quarks in a deconfined gluon plasma in the static approximation. In this approximation, the momentum diffusion can be extracted from the correlation function of the color electric fields. For temperatures $T_c < T \leq 2T_c$, our nonperturbative estimate of the diffusion coefficient was found to be in the right ballpark to explain the heavy quark flow seen by the PHENIX experiment at RHIC. [Debasish Banerjee, Saumen Datta and Rajiv V. Gavai, with P. Majumdar (IACS, Kolkata]

Quasi-static probes of the QCD plasma:

Screening correlators and masses were studied at finite temperature in QCD with two flavours of dynamical staggered quarks on a lattice. The spectrum of screening masses show a hierarchical approach to chiral symmetry restoration. Control of explicit chiral symmetry breaking through the quark mass was shown to be an important step to understanding this phenomenon. No sign of decays was found in the finite temperature scalar meson-like correlators in the confined phase. [Debasish Banerjee, Rajiv Gavai and Sourendu Gupta]

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

Lattice QCD results were presented along the freezeout curve of heavy-ion collisions for the ongoing RHIC energy scan as well as the LHC heavy-ion runs planned for this year. The skew and kurtosis of the event distribution of baryon number were positive at all energies studied. Three ratios were predicted of non-linear susceptibilities along the freezeout curve as functions of the colliding energy, $\sqrt{S_{NN}}$. They have smooth behaviour except in the vicinity of a critical point; this can have multiple benefits. [Rajiv Gavai and Sourendu Gupta]

Optimization of a low energy neutrino factory:

A low energy neutrino factory has the potential to discover the mass ordering and the CP phase of neutrinos. Optimization of the parent muon energy and the source-to-detector baseline distance was carried out in order to achieve this. It was found that the sensitivity of a given setup typically increases with parent muon energy, reaching saturation for higher energies. In the light of recent measurement of large theta13 mixing angle, the baseline of 2500 km and 1500 km were shown to be optimal for the determination of mass ordering and CP phase,respectively. [Amol Dighe, with S. Goswami (PRL, Ahmedabad) and S. Ray (Cornell U.)]

Conditions for the seeding of neutrino oscillation instabilities inside a supernova:

Neutrino-neutrino interactions in dense neutrino streams, like those emitted by a core-collapse supernova, can lead to self-induced neutrino flavour conversions. While this is a non-linear phenomenon, it was shown that the onset of these conversions can be examined through a standard stability analysis of the linearised equations of motion. It was shown that the potentials due to neutrinos and ordinary matter should be comparable for the instability to form. [Arka Banerjee and Amol Dighe, with G. Raffelt (MPI, Munich)]

Large mass splittings for fourth generation fermions allowed by LHC Higgs exclusion:

with a fourth generation, the allowed mass spectra in the fourth generation quark and lepton sectors were explored as functions of the Higgs mass. Using the constraints from unitarity and oblique parameters, it was shown that a heavy Higgs allows large mass splittings in these sectors, opening up new decay channels involving W emission. The possibility of the W-emission channel could substantially change the search strategies of fourth generation fermions at the LHC and impact the currently reported mass limits.[Amol Dighe and Diptimoy Ghosh, with R.M.Godbole and A. Prasath (IISc, Bengaluru)]

Explaining anomalous data observed in B_s meson decays:

Recently observed anomalies in the decays of B_s mesons to $[J/\psi phi]$, and the like-sign dimuon asymmetry, hint at possible new physics in the $Bs^0\bar{B}_s^0$ mixing. With a model-independent parametrization, it was shown that such new physics should contribute significantly to the absorptive part of the $Bs^0\bar{B}_s^0$ mixing amplitude. It was pointed out that this would imply a large enhancement of the rate of B_s decaying to two tau leptons. [Amol Dighe and Diptimoy Ghosh, with A. Kundu and S. Patra (U. of Calcutta)]

Correlated study of low-energy processes and LHC signals in a supersymmetric model without R parity:

Observation of a particular set of low-energy flavour-changing processes which are naturally suppressed in the Standard Model may require the existence of supersymmetry with two relatively large R-parity-violating couplings of the LQD-type, together with reasonably light superparticles. At the LHC, such interactions would be expected to give rise to clear signals with convenient leptonic triggers, including some multileptons of the same sign. A detailed investigation of these signals, taking care to correlate with low-energy requirements and taking proper account of the Standard Model backgrounds as well as those arising from the R-parity -conserving sector of the supersymmetric model, leads to clear indications that R-parity violation as envisaged in this scenario can be detected at the LHC - even, perhaps, in the current run. [Biplob Bhattacharya and Sreerup Raychaudhuri, with G. Bhattacharyya (SINP, Kolkata)]

Explanation of the anomalous forward-backward anomaly in $t\bar{t}$ production at the Tevatron in a model with R-parity violating supersymmetry:

The CDF and D0 experiments at the Tevatron report an anomalously large forward-backward asymmetry in top pair production. An attempt to understand this anomaly in a R-parity violating supersymmetric model, which allows for t-channel exchanges of bottom squarks has been made. The model also predicts a small but verifiable effect at the Large Hadron Collider. [K. Sridhar]

Kaluza-Klein gluon production in association with a $t\bar{t}$ pair at the LHC:

The Kaluza-Klein excitation of the gluon is the most important signature of the Bulk Randall-Sundrum Model. Because of the strong coupling of the Kaluza-Klein gluon to top quarks its production in association with a tt(bar) pair is significant. A detailed simulation of this associated production process is under way. [K. Sridhar with B.C. Allanaach (Cambridge U., DAMTP)]

Higgs signal in Chargino-Neutralino production at the LHC:

An analysis was carried out of the prospect of detecting a Higgs signal in a mSUGRA/cMSSM based Supersymmetric(SUSY) model via chargino-neutralino($\chi_1^\pm \chi_2^0$) production at 8 TeV LHC energy. The signal was studied in the $\ell + b\bar{b}+$ MET channel following the decays, $\chi_1^\pm \to W^\pm \chi_1^0$, $\chi_2^0 \to \chi_1^0 h$ and $h \to b\bar{b}$. In this analysis reconstruction of the Higgs mass out of two b-jets played a very crucial role in determining the signal to background ratio. Two techniques were followed to reconstruct the Higgs mass: (A) adding momenta of two identified b-jets, and (B) jet substructure technique. In addition, by imposing a certain set of selection cuts the significance was observed to be better for the method (B). A viable signal can be obtained for the Higgs mass $\sim$ 125 GeV with an integrated luminosity 100 fb^{-1}. [Diptimoy Ghosh with M. Guchait and D. Sengupta (TIFR/DHEP]

Magic Messengers in Gauge Mediation and signal for 125 GeV boosted Higgs boson.

The most general renormalisable messenger sector was considered, with magic messenger fields instead of usual SU(5) complete multiplets. The soft supersymmetry breaking terms were derived, showing that the gaugino sector can be parametrised by only two parameters. These parameters can be chosen appropriately to obtain various patterns of gaugino masses and different ratios among them. The sfermion sector can also be characterized by two independent parameters which can be adjusted to change the relative masses of squarks and sleptons. A judicious choice of parameters also allows us to achieve the lightest Higgs boson mass about 125 GeV. This work focussed on a scenario where a comparatively large hierarchy exists between the U(1) and SU(2) gaugino mass parameters. In such a case, the lightest Higgs boson originating from the decay of the next-to-lightest neutralino, following the direct production of chargino neutralino pair, can be considerably boosted. It was shown that a boosted Supersymmetric Higgs signal with a decent signal to background ratio can be obtained using the jet substructure technique at LHC with 8 TeV center of mass energy and an integrated luminosity of about 30 fb^{-1}. [Diptimoy Ghosh with P. Byakti (SINP, Kolkata)]