Final Technical Report
Physics of Nuclear Collisions at High Energy
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Principle Investigator: Rudolph C. Hwa
Institute of Theoretical Science
University of Oregon, Eugene, Oregon, OR 97403
Phone: 541-346-5202
Email: hwa@uoregon.edu

Summary of Research in the overall Grant Period 1996-2014

A large number of problems have been studied in a variety of fields, ranging from elementary particles to biological systems. The majority of problems are in heavy-ion collisions that belong to a central component of the nuclear physics program. Our emphasis is to find alternative approaches that depart from the standard models so as to fill in the gaps left by conventional calculations. From such gaps we broaden our scope finding defects in the orthodoxy and suggest a new paradigm that may be more valid, especially at higher energy such as at LHC.

The problems are divided into eight sections in the following. The numbers given after the title of each section are references in the publication list that follows the summary.

A. Multiplicity Fluctuations and Phase Transition

[1, 3, 5-8, 11, 15, 17, 19, 21, 26, 30-32, 34, 36-39, 42, 49, 52, 64, 70, 71, 94, 108]

The scaling behavior of hadronic observables in quark-hadron phase transition (PT) has been studied at Oregon for many years. Critical behavior has been one of the most interesting and vibrant subjects in condensed-matter and statistical physics and should also be of fundamental importance to understand in the case of quark-hadron PT after quark-gluon plasma is formed in heavy-ion collisions. The beam scan experiments are designed to study the onset of deconfinement. We believe that the end of deconfinement and the beginning of hadronization is a more interesting and ultimately rewarding region to study PT because the system is at equilibrium just before confinement sets in. That is where a large body of statistical physics can be applied. Based on the common knowledge that fluctuations of all scales occur at and near the critical point, our research has been centered around the fluctuations of hadronic multiplicities in bins of varying sizes. For analytical calculations we have used the Ginzburg-Landau (GL) theory of PT, while for numerical calculations we have used the Ising model to simulate the condition of PT. Those were studies made in the 90s. The collision energy in those days and even in the 2000s at RHIC were not high enough to allow unambiguous determination of intermittency, which is the scaling behavior of the factorial moments. Theoretically, we went further to propose erraticity as the next step after intermittency. It is the study of the fluctuation of spatial patterns from event to event. Those investigations have laid dormant until now when higher collision energies at LHC became possible.

In central Pb-Pb collisions at LHC the multiplicity of particles produced is so high that it becomes feasible to examine the nature of transition from the deconfined quark-gluon state to the confined hadron state by methods that rely on the availability of high multiplicity events. That transition may or may not be recognizable as a critical phenomenon, since hadronization takes place on the surface over a period of time while the system expands. The accumulation of hadrons emitted over that period can smear out any signal of interest even in the best circumstance for critical transition. We have proposed a method to find signatures of PT by studying the spatial patterns of every event in small p_T windows to avoid the overlapping problem. That is where LHC data on event structure become valuable because even after narrow cuts in p_T there are still enough particles produced to allow the study of scaling properties in small (η, ϕ) bins. Fluctuations of bin multiplicities in each event are quantified by factorial moments, and then the event-by-event fluctuations of spatial patterns are analyzed in terms of erraticity. Definitive numerical results are obtained for the intermittency and erraticity indices in each of the four classes of systems generated.

Currently, the PI is in close contact with investigators in India who are in the ALICE collaboration and are actively pursuing the analysis that we have proposed. In fact, there are preliminary signs of interesting results suggesting that the system created at LHC is in the proximity of criticality, far more so than the system generated by AMPT, which is a MC code that does not contain dynamics capable of giving rise to collective behavior.

B. J/ψ Suppression and $D^{\pm}$ Asymmetry

[4, 14, 16, 18, 24, 28, 29, 35, 40]

The conventional explanation of J/ψ suppression in heavy-ion collisions is in terms of absorption of the $c\bar{c}$ states by hadronic comovers and quark-gluon plasma. Without negating such an explanation, we have examined the possibility that the supply of gluons that create the $c\bar{c}$ state may be depleted due to gluon interaction before the hard subprocess. The best signal for gluon depletion would be the observation of reduced rate of production of $D\bar{D}$ pairs. The acollinearity of back-to-back $D\bar{D}$ pair is also of interest. An increase of acollinearity should be accompanied by an enhancement of the J/ψ suppression because of the medium effect that is associated with the depletion of gluons. Since D^+ is $c\bar{d}$, while D^- is $d\bar{c}$, the baryon-rich region in heavy-ion collisions should have a higher probability of producing D^- than D^+. That is based on the recombination model, which has given the correct asymmetry of $D^{\pm}$ production in $\pi^{\pm} - p$ interaction. In studying that asymmetry one considers a mixture of hard and soft components of the mechanism for charm production. The associated gluon density is therefore relevant to the question of whether gluon depletion can contribute to the suppression of J/ψ production.

Recently, the asymmetry of the production of Λ_c^+ and Λ_c^- at LHC has been measured in pp collsions. Heavy-quark recombination has been applied to study that asymmetry. It will not be long before such problems will be investigated in nuclear collisions at LHC.

C. Fluctuation Analysis in Human Brain Activities

[43, 46, 53, 54, 58, 64, 71, 85]

This is an area of study that seems to be totally out of line from nuclear physics. What does a physicist know about human electroencephalogram (EEG)? The brain may be far more complicated than the physics of particle production, but the observables are not more complicated, only different. After some fluctuation analysis, the EEG signals can be reduced to a set of numbers in just the same way that an event of multiparticle production is described by a set of numbers specifying the momenta of the detected particles. EEG that records the brain electrical activities shows a high degree of fluctuations both spatially on the scalp and temporally over various time scales. Since the human brain dynamics is that of a highly nonlinear system, we have examined the nature of the fluctuations in the EEG time series in the framework of nonlinear analysis. By using detrended fluctuation analysis we find scaling behaviors that provide very useful information about the characteristics of the brain function. The scaling parameters for stroke and normal subjects turn out to lie in different areas of a parameter space so that it is possible to distinguish the two types of subjects by our method.

The method of analysis is significant for practical use, since the usual method involves MRI which is expensive and not easily accessible. Our method can lead to devices that can be used in an ambulance on its way to the emergency room so that a medic can tell whether a stroke-like symptom is indeed due to a stroke or to some other reason such as overdose. To do more on the problem, extensive data are needed beyond the 28 subjects we had at hand. That requires a large amount of funding so as to collect more data in the emergency room. We applied to NIH, but failed. The practice of NIH is that there should be sufficient preliminary result to be deemed worthy of consideration for funding, but to get more results requires more funding. It is a catch-22 problem that outsiders without existing institutional support cannot overcome.

D. Phase Transition and Chaos in Nonlinear Systems

[2, 9, 10, 12, 13, 19, 22, 25, 33, 44, 63, 70]

Interest in chaotic behavior of nonlinear systems has grown so much that it includes nearly all natural sciences and some social and economic sciences. However, the notion of classical trajectories in usual description of chaos is ineffective and inappropriate for studies of systems in which the number of constituents can increase, such as in branching processes characteristic of particle production. With focus on only the observables, namely, the momenta of detected particles, each event is characterized by a spatial pattern in momentum space. The issue is how to learn from the spatial pattern that a system is chaotic. We found that the measure of erraticity that we have initiated is close to the Lyapunov exponent. What is needed is the addition of the notion of entropy defined appropriately for a system with many events. We introduced an entropy index μ that can be used to characterize chaotic behavior: the larger μ is, the more chaotic is the system. Not only does it work for for the study of quark and gluon jets, it can reproduce what the Lyapunov exponent can do for classical chaos. Publication of our paper [13] in Phys. Rev. E attests to the acceptance of our approach by the community of nonlinear dynamics as a viable alternative to the conventional method.

The versatility of our method is demonstrated by our application of it to ECG (heartbeat) time series. Since the abnormal heartbeats during fibrillation are irregular and have erratic shapes, we have used wavelets in the definition of entropy index due to their capability to zoom and shift. The entropy index can be used in clinical diagnostics as a measure of cardiac health in much the same way that body temperature is used as a gauge of general health. The technical detail that a medic has to learn may be a serious deterrent.

Another area outside physics where the study of fluctuation of patterns is useful is phase transition in evolutionary biology. The problem can be made precise by focusing on an evolutionary game as a model for the evolution of cooperative behavior, analogous to the

Ising model. Depending on the payoff parameter, there can be a rich variety of spatial patterns. We found that the scaling index ν is very close to the one we obtained earlier for the GL description of PT. It suggests the possibility that biological evolution modeled by the game can be a PT as understood by physicists.

Lastly, we mention the application of our analysis to cryogenic turbulence. The irregular reversals of wind direction in such turbulence are found to have fluctuating intervals that can be related to critical behavior. Detrended fluctuation analysis of the wind reversal time series results in a scaling behavior that has a large scaling exponent. The properties found suggest that the wind reversal phenomenon exhibits signs of self-organized criticality.

E. Color Mutation Model

[20, 23, 25, 31]

Since perturbative QCD is not applicable to soft interaction, and non-perturbative QCD is too difficult to implement, the physics of soft interaction in hadronic collisions is ordinarily described by some model. Usually such models do not reproduce the intermittency data of NA22. It is in that background that we have undertaken the task of building a model that incorporates all the conventional features of soft interaction and fit the essential data on multiparticle production including intermittency. Our model, called ECOMB for eikonal color mutation branching, has the important feature that the partons in color space undergo an evolution process, implemented by near-neighbor interaction that involves emission or absorption of gluons, the choice being determined by an energy principle that favors the lowering of the energy of the global configuration. The process is called color mutation. At every stage of the mutation process the link length in pseudo-rapidity between partons may expand or contract as a result of the stochastic color forces of the many-parton system. The evolution process continues until a configuration is reached where the whole system contains two color neutral subsystems. A branching then takes place so that the two clusters undergo color mutation separately and independently. Parameters in the model are tuned to fit $dN/dy, P_n$ and F_q for varying bin size. The branching gives rise to the possibility of self-similarity, the crucial characteristics responsible for intermittency.

F. Quark Recombination Model

[45, 47, 48, 50, 51, 55-57, 59-62, 66-68, 72, 73, 80-84, 86, 87, 89-91, 95-97, 99, 105]

The recombination model (RM) has been a major area of research in Oregon on heavy-ion collisions. The original work on recombination started in 1977 for particle production in the fragmentation region in pp collisions. It was treated in more detail in 1980 using the valon model to describe the hadron structure as well as the recombination function. The subject laid dormant for many years until RHIC data called for a way to explain the large p/π ratio at intermediate p_T, which the nuclear community had regarded as proton anomaly. It is not a good practice for a community to declare that a phenomenon is anomalous when the conventional approach cannot explain it. The Oregon version of the RM (besides Duke and TAM versions) considers the recombination of thermal ($\mathcal{T}$) and shower ($\mathcal{S}$) partons in the late stage of the evolution of the system. It does not have a MC code to describe the space-time evolution. The thermal partons are assumed to have an exponential form in transverse momentum in order to fit the low p_T data. That aspect of the problem has been under some criticism. It is a price we paid for not pursuing the problem of earlier time, yet succeed in getting many features that reproduce the data, in particular, the difference in low p_T distribution for p and π despite using the same $\mathcal{T}$, and of course the correct p/π ratio at intermediate p_T by virtue of $\mathcal{TS}$ recombination.

We have successfully treated not only p_T distributions of all identified particles for wide ranges of p_T, but also centrality dependence and azimuthal anisotropy in the RM without hydrodynamics. It is conventional in the nuclear community to regard the second harmonic moment of azimuthal asymmetry, v_2, as due to elliptic flow, so much so that the two have become synonymous. Since hard and semihard partons take ~ 6 fm/c to travel from the center to the surface of the medium in the transverse plane, rapid thermalization is not a realistic assumption if jet production is to be taken into account. In our approach the shower partons are produced in the vacuum after the jet emerges from the medium, and the thermal partons include the bulk soft partons and the enhanced partons due to excitation by the energy loss from the jets. Since recombination occurs at late time after the medium has cooled down from the deconfinement phase, the local thermal partons in the immediate vicinity of a shower patron do not carry information about the global system nor the history of how hot it has been in the initial phase. That is like water vapor condensing at 100°C independent of how hot the vapor has previously been heated to. For that reason our thermal parton distribution is universal in the same sense as universal hadrosynthesis. Taking careful account of the initial geometry of the elliptical system in noncentral collisions, we find that where the enhanced partons go relative to the jet direction depends on the azimuthal angle of the hard patron relative to the event plane. Such dependence results in ϕ-anisotropy in the produced hadrons at low p_T. Attention to such details leads to v_2 that reproduces the observed data. Furthermore, the recombination of thermal and shower partons can account for the higher moments v_n. This is important because it breaks the shackles of v_n phenomenology to hydrodynamics. Elliptic flow becomes only a possible, but not a necessary cause for v_2.

At LHC many more jets and minijets are produced than at RHIC. Thus the neglect of shower partons as is conventionally done in hydro studies cannot be justified. We show that even at low transverse momenta the shower partons dominate over the thermal partons at the time of hadronization. That dominance drastically changes the hadronization problem. TS recombination becomes important even at p_T as low as 1 GeV/c. Two-jet recombination turns out still to be not as important as SS recombination in one jet. The p_T distributions of all identified particles are well reproduced in our calculation, not only for pions and protons, but also for $K, \Lambda, \Xi, \Omega, \phi$ wherever data exist. It follows from our study that any theoretical treatment of hadrons produced at low p_T at LHC would be incomplete without taking the effects of minijets into account. In particular, the parameters in the hydrodynamical formalism cannot be determined by phenomenology in the soft sector without including also the soft partons from minijets.

G. Correlations

[69, 75-79, 88, 92, 93, 102]

Since hadronization by recombination has been found to be so successful in explaining the p_T distributions, it is natural to extend the study to correlations among hadrons in jets produced at heavy-ion collisions. There are various ways of studying correlation. One is to use a trigger and study the associated particle distributions in various variables. On the same side we have investigated the pedestal and peak structure in jet correlation in the framework of a correlated emission model. Away-side azimuthal distribution is obtained in a Markovian parton scattering model that can explain the double-bump structure observed. One can also consider autocorrelation, which is to treat two hadrons on equal footing without designating one of them as trigger. We have successfully done that in the RM.

There is observed in d+Au collisions a forward-backward asymmetry that is of interest. If the transverse broadening of the initial partons is important as is the usual explanation for the Cronin effect, then there is more broadening in the forward (F) direction than in the backward (B) direction. Thus B/F should be < 1. But the data show $B/F > 1$ for $1 < p_T < 5$ GeV/c. Since there are more thermal partons in the B direction than in the F direction, thermal-shower recombination leads naturally to $B/F > 1$. In fact, the data on R_{CP} for $\eta = 0$ to 3.2 can be well reproduced in the recombination model. That is significant because no new physics has been inserted in going from the backward to the forward direction, in contrast to the approach based on saturation physics.

There is a difference in the associated particle distributions in central AA and pp collisions on the same side as the trigger. Even with medium-modified fragmentation function it seems hard to accommodate a factor of 3 difference at $p_T \sim 1$ GeV/c. That is readily obtained in the recombination model due to the abundance of thermal partons at low p_T in AA collisions.

There is a puzzle which we have called the Omega puzzle. Data on particles associated with Ω trigger suggest that such events have jet structure. However, the exponential p_T distribution of Ω suggests that no jets are involved. We resolve this puzzle by suggesting that the Ω is produced by the recombination of the enhanced thermal partons in the ridge that can have other hadrons in association with the trigger, all having exponential p_T distributions.

H. Minijets and Ridges

[98, 100, 101, 103, 104, 106, 107, 109-113]

As mentioned in Sec. F, minijets are important, especially at LHC. But even at RHIC it is because of minijets that we can account for the ridge phenomenon. As hard and semihard partons lose energy to the medium, the thermal partons that are enhanced recombine and form the ridge, which is therefore correlated to the jet that provides the trigger. This mechanism has been applied to different collision systems.

For pp collisions at LHC we interpret the ridge phenomenon in terms of soft partons excited by observed or unobserved jets without longitudinal correlation. The idea is analogous to the adage that a rising tide raises all boats, even though there are no intrinsic horizontal correlation among the boats. That is, soft partons that are separated in rapidity can both be excited by the same hard or semihard parton. Our mechanism succeeds in explaining that the ridge yield is very small for $p_T < 1$ and >3 GeV/c, but jumps up by nearly an order of magnitude in the $1 < p_T < 2$ GeV/c bin due to the enhancement of soft partons in the p_T region. A basic issue opened up by our study is whether a system of high density soft partons can be created in pp collisions. The system may be too small for the applicability of hydrodynamics, but azimuthal anisotropy can nevertheless exist for small systems in non-central collisions, as the ridge structure on the near side demonstrates.

At RHIC it was found by PHOBOS that there exists ridge structure that seems to have a long range in η. We have shown on empirical grounds that the ridge data can be fitted by use of the inclusive distribution of charged particles measured by PHOBOS without inserting extra long-range correlation. We then advance a model to implement the relationship between single-particle distribution and the ridge on the basis of parton model without hydro or CGC. The formation of ridge is due to the same mechanism as describe above, namely: transverse correlation stimulated by semihard partons. It is related to the azimuthal anisotropy generated by minijets.

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