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High energy heavy ion collisions: Lessons from relativistic heavy ion collider

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Abstract. In this talk, I review the recent results from RHIC and discuss their significance.

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1. Introduction

Quantum chromodynamics (QCD) is successful to a large extent in describing the observables related to strong interaction. It is therefore regarded as the theory of strong interaction. Attempts are being made over the last two decades to understand the strong interaction in extreme conditions, i.e. at high temperature and high density.

Theoretically QCD at extreme conditions has been studied using lattice calculations. Most interesting result from these calculations is the expected phase transition from confined hadronic matter to deconfined quark gluon plasma (QGP) phase. There are several predictions of different observables as signatures of this phase transition. The prediction on the order of phase transition also varies depending on the use of quark mass in lattice calculations. While for zero dynamical quark mass, first-order phase transition is predicted, for non-zero quark mass, the prediction varies from second order to continuous phase transition [1]. The prediction from lattice calculations on energy density for phase transition is 3 GeV/fm^3. Early universe is expected to have gone through this kind of energy density and so has undergone the phase-transition from QGP phase to hadronic phase.

Experimentally, in high energy heavy-ion collisions, energy density suitable for phase transition is expected to be reached. First series of experiments at AGS at BNL and at SPS at CERN gave enough hints that in these collisions some interesting phenomena occurred.

At SPS energy, using Bjorken's formula an energy density $\approx$3GeV/fm^3 has been achieved. Some observables predicted earlier as signatures of phase transitions have been observed. Some prominent examples are J/Ψ suppression, strangeness enhancement etc. Some other observables predicted to give more direct signature of phase transition, e.g. fluctuations, were not so prominent.

At very high energy, elementary collisions are explained using perturbative QCD as the production of particles via scattering of elementary partons and subsequent hadronization forming jets of hadrons. This phenomenon of jet production is studied in detail using e^+e^-, pp, α–α collisions. Even though energy at SPS is low ($\sqrt{s} \approx 20$ GeV), efforts were made to look at the production of jets using the spectra of leading π^0 in pp collisions. Observation of spectra up to 4 GeV/c and near power law behaviour showed us that we are close to have the regime where jets are produced in heavy-ion collisions [2]. It was therefore needed theoretically to bring the language of jet-physics in the study of heavy-ion collisions.

Observations of J/Ψ suppression can be mentioned as the most interesting result from SPS. J/Ψ production was expected to be suppressed at deconfined phase where color-screening is expected to reduce the production cross-section of cc-bar pair. This observation however could be explained using some other (e.g. absorption by co-moving hadrons) pictures which explains the data equally well.

With this wealth of existing information from SPS and AGS, about 10-fold increase in $\sqrt{s}$ at RHIC brings us to a new regime of high energy heavy-ion collisions, where we expect to encounter the phenomena, where SPS energy probably provided threshold scenario, for example we expect to have jets copiously produced at RHIC energy.

We give short description of RHIC machine and four experiments participating in last four years of data taking. We will then discuss in somewhat detail the phenomena related to the hard scattering e.g. hard probe via leading hadrons and production of heavy flavors.

Relativistic heavy ion collider

Relativistic heavy ion collider (RHIC) operational at Brookhaven National Laboratory (BNL), USA is a dedicated collider for heavy-ion research. Parameters of RHIC are given below:

RHIC energy = 100 GeV/beam.
Collision systems used = AuAu, dAu, pp.
Luminosity = 10^{30} cm^{-2}s^{-1} for pp, 10^{26} cm^{-2} s^{-1} for heavy ions.
Ions per beam = 1×10^9.
Maximum number of bunches per cycle = 60.
Bunch width = 30 ns.

Accelerator complex is shown in figure 1. Tandem-Van-de-Graf and AGS are used for pre-acceleration of the beam. It should be mentioned that RHIC is the only collider for polarised protons in the world. RHIC became operational in the year 2000 by colliding Au ions at $\sqrt{s} = 130$ GeV. Subsequently, data were collected for AuAu, pp and dAu systems for $\sqrt{s} = 200$ GeV. Another advantage of RHIC is that pp data taken at RHIC can be used as reference for heavy-ion data, thereby cancelling the systematics to large extent. Four intersection regions in the collider are equipped with four experiments, two large ones, e.g. PHENIX and STAR and two smaller ones, e.g. BRAHMS and PHOBOS [3].

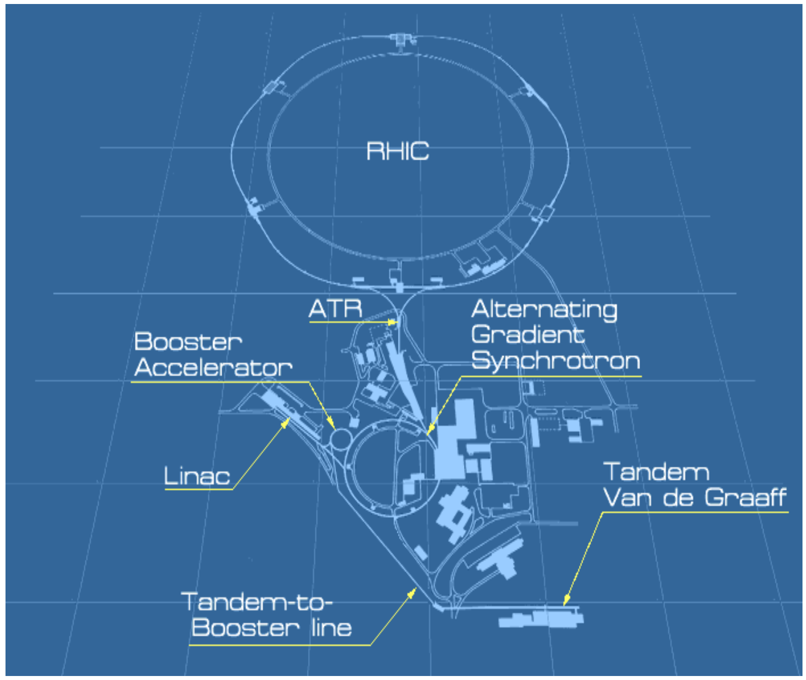

Figure 1. RHIC accelerator complex four experiments (STAR, PHENIX, BRAHMS and PHOBOS) take data at four intersection points.

2. Centrality selection

Considering the picture of two Lorentz contracted nuclei colliding each other it is needed to know the extent of overlap of colliding nuclei. It might go from peripheral (large impact parameter) to central (b0) collisions. Determination of centrality is important for many reasons, e.g. QGP is expected to be formed for collisions where overlap is more, i.e. for central collisions. Experiments at RHIC are equipped with specialized detectors which can select events with specific centrality while taking data. Refined selection can be made later while analysing data. These detectors select events which respond to the observables correlated to the centrality of the collisions. The observables are from (i) multiplicity in particular phase-space region, which should be high for central collision and will go down while going towards peripheral collisions, (ii) forward energy (E_{F}) from spectator neutrons, which will have anti-correlation with centrality, i.e. for central collisions E_{F} will be small as most of the neutrons will participate in reaction and will increase for peripheral collisions.

Figure 2 shows typical multiplicity (negative hadron) distribution for minimum bias data. For centrality selection some fraction of these events are chosen, e.g. 0–5% correspond to events constituing top 5% in this distribution.

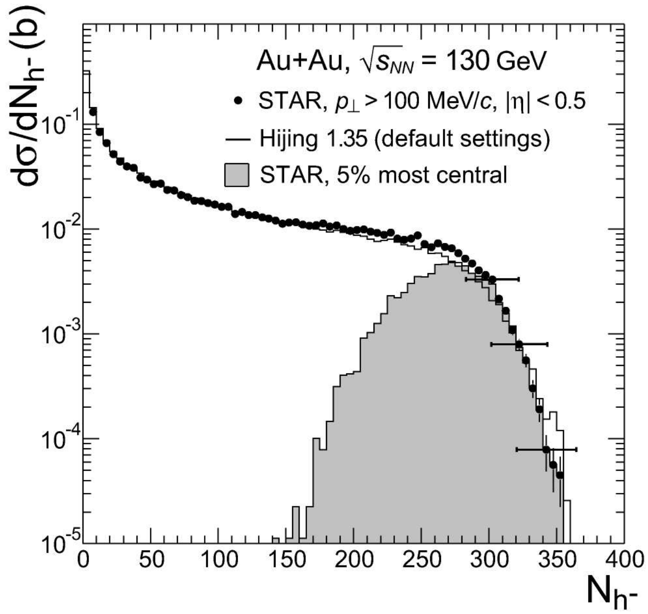

Figure 2. Minimum bias distribution for negatively charged hadrons. This can be used to select centrality class of the events. Shaded region showed events with selected centrality.

3. Results

3.1 *Global observables*

Observables in the heavy-ion reaction giving global information about the reaction include, multiplicity of produced particles, total transverse energy, total energy in the forward region etc. Any model describing the reaction mechanism in heavy-ion collisions should be able to explain these global observables before going into detailed localised variables. In heavy-ion collisions, colliding nuclei are thought to undergo two types of processes for particle production. In one scenario, participant pairs collide and produce particles in softer region of p_{T} spectra. Number of participants (N_{part}) varies as A of the colliding nuclei. N_{part} for various centralities can be determined taking proper geometry of the collision. Experiments adopt Monte–Carlo approach or analytic approach for determining N_{part} [4]. The uncertainty in the determination of N_{part} contributes maximum in the total error on these observables. Another scenario comes from the picture of particle production via scattering of elementary constituents of nuclei contributing to the hard region of the spectra. In AA collisions, spectra in hard region are thought to be the result of independent binary collisions. Number of binary collisions varies as A^{α}, where α could be of the order of 2.

One of the first observations made at RHIC was the particle production by measuring $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta/0.5{*}N_{\mathrm{part}}$. $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ is the rapidity density of the produced charged particles around mid-rapidity. This variable has been studied with the variation of number of participant (figure 3) and with $\sqrt{s}$ (figure 4). Number of participants represent the increase in centrality of the collision.

It is seen that $n_{\mathrm{ch}}/0.5N_{\mathrm{part}}$ increases with N_{part} thereby suggesting the presence of another mechanism in particle production. While looking at $\sqrt{s}$ dependence of this quantity, it is found that in heavy-ion collisions, it deviates from observations from *pp* and similar $\sqrt{s}$. Comparing data from 200 GeV and 130 GeV measured

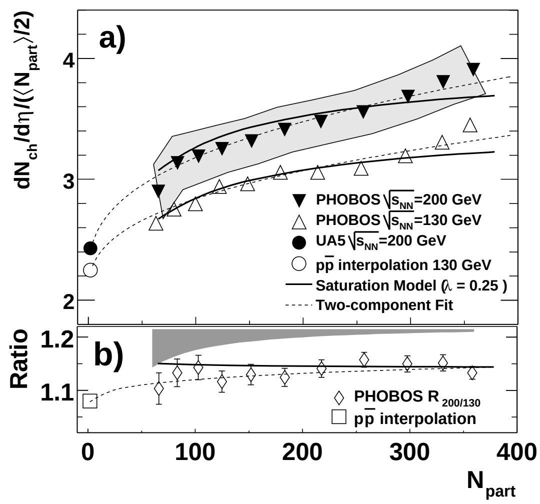

Figure 3. $\mathrm{dN_{ch}}/\mathrm{d}\eta/(0.5\langle N_{\mathrm{part}}\rangle$ with N_{part}. This represents the particle production per participant pair, and it is seen to increase with increasing centrality.

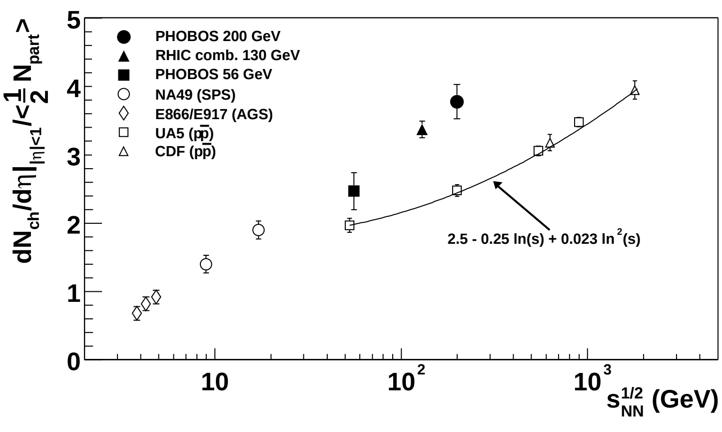

Figure 4. $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta/(0.5\langle N_{\mathrm{part}}\rangle)$ with $\sqrt{s}$. For heavy-ion collisions, particle production increases faster with $\sqrt{s}$ compared to *pp* collisions.

by the same experiment showed an increase by about 1.14 times in 200 GeV compared to 130 GeV and is independent of centrality. Similar observations have been made by PHENIX and STAR by measuring transverse energy E_{T} in the collisions [5].

Pseudorapidity (η) distributions of the produced charged particles are studied in detail over the entire range of η by PHOBOS Collaboration as shown in figure 5.

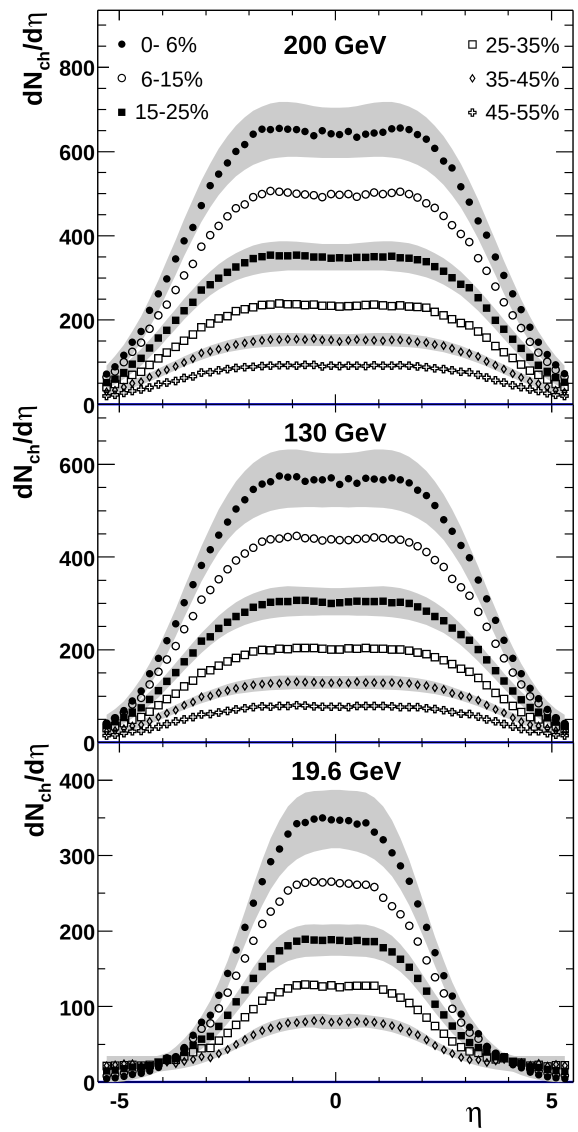

Figure 5. Pseudorapidity distribution of charged particle production. Entire range of η has been shown for three different energy ranges.

It is found that in central collisions, pseudorapidity density at mid-rapidity increases from ≈ 350 to ≈ 700 for RHIC maximum energy. Using Bjorken's estimate for energy density achieved in the collision, it implies about 2 fold increase in energy density. The shape of the η-distribution shows a larger region where $\mathrm{d}N/\mathrm{d}\eta$ tends to remain constant, thereby suggesting the approach of Bjorken's boost-invariant scenario [7].

4. Collective phenomena

For information about phase transition or the property of the phase, it is important to study the collective behaviour of the system, where concepts of thermodynamics can be applied. Azimuthal distributions of produced particles can be analysed to obtain information regarding the collective behaviour of the produced system. Various terms in the Fourier expansion of azimuthal distribution of produced particles describe various flow components, e.g., radial flow component, directed flow, elliptic flow etc [8]. Detailed collective behaviour of the system can be studied using various models. We discuss here elliptic flow, as there are wealth of information available from RHIC.

Elliptic flow has been one of the first measurements at RHIC, which can be obtained by v_2 (second harmonic component of Fourier expansion) and it has been predicted to carry the information from initial state of the collisions. Several types of measurements have been made for v_2. v_2 has been studied with centrality and with p_{T}. Use of hydrodynamical models with various equation of states for results on identified particle v_2 has concluded that local thermal equilibrium has been established [9].

However the pseudorapidity dependence of v_2 as shown in figure 6 is not yet explained. This looks similar to pseudorapidity dependence of multiplicity and thereby speculating that they are of similar origin.

Recent results are obtained from STAR where v_2, v_4, v_6 have been measured with p_{T}. v_4 and v_6 have been said to be more sensitive to the initial conditions [10].

v_2 has been obtained for various identified baryons and identified mesons. Considering them to be produced as a result of quark coalescence, results are put together for v_2/n, where $n = 2$ for mesons and $n = 3$ for baryons considering meson consisting of two quarks and baryons with three quarks. Observed scaling in figure 7 supports quark coalescence model.

5. Hard probe

It is expected that at RHIC a large fraction of particles will be produced via hard processes. Apart from the details of production of jets in heavy-ion collisions, another interesting prediction was the expected energy loss of partons while passing through the media resulting in softened fragmentation function [11]. This energy loss is predicted to be dependent on gluon density. Following variables have been studied for AA collisions to investigate the effect.

(i) Spectra of leading particles.

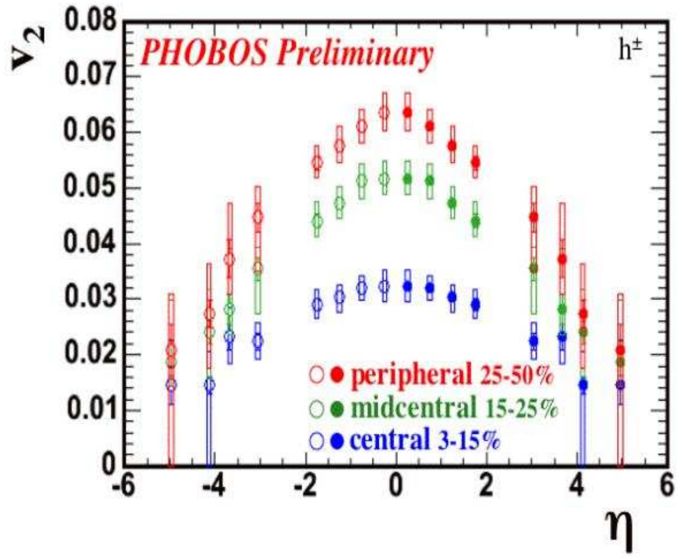

Figure 6. η dependence of v_2 for various centralities. The distribution looks similar to η distribution of multiplicity.

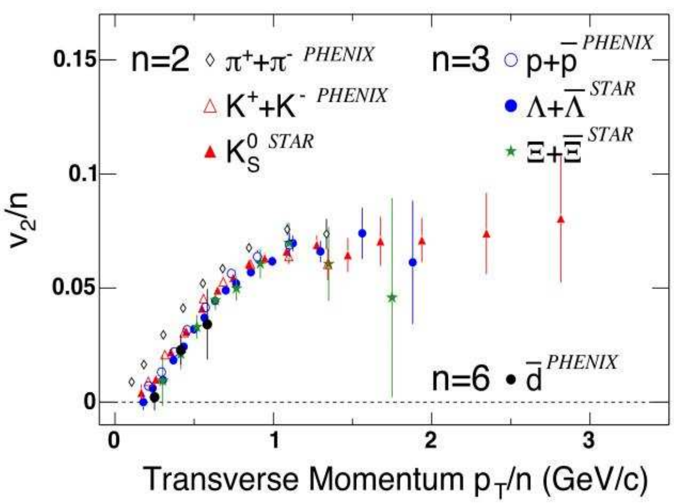

Figure 7. Variation of v_2, v_4, v_6 with p_T. v_2 has been scaled down to show all of them in the figure.

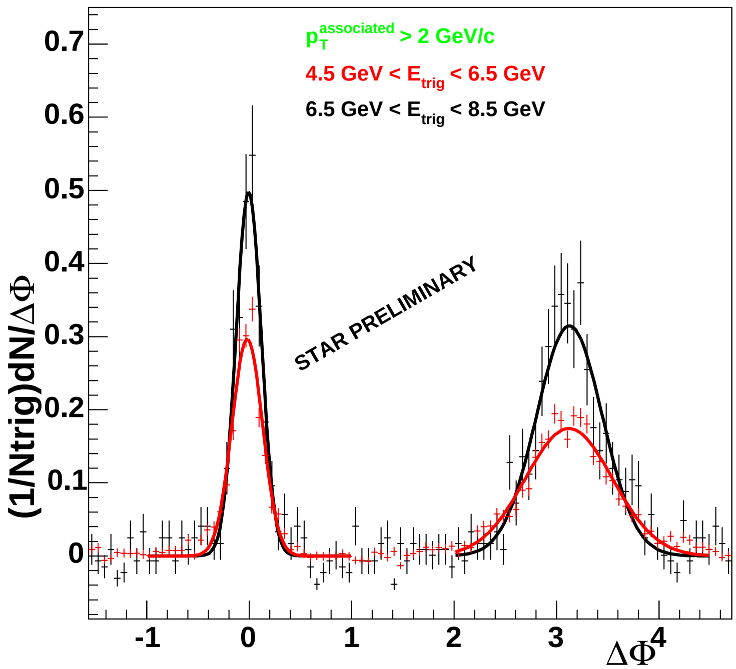

Figure 8. Azimuthal correlation using photons of various energies as trigger and charged tracks with different p_{T} as associated particles. Here correlation function is shown for two different E_{trig} and $p_{\mathrm{T}}^{\mathrm{associated}} > 2$ GeV/c.

(ii) Azimuthal correlation of large p_{T} particles.
(iii) v_2 at large p_{T}.

RHIC has the advantage of taking data with *pp* and dAu. It is therefore possible to study the formation of jets in detail in *pp* and its modification in dAu which is expected to give information on nuclear modification factors in the initial state of the system. Detailed studies have been made via construction of jets in *pp* and by studying the correlations between high p_{T} particles in *pp* and dAu for obtaining the parameters of jets. STAR has studied the correlation between trigger photons, which come mostly from π^0 and associated charged particles. Photons with various energy ranges (4.5–6.5 GeV, 6.5–8.5 GeV, 8.5–10.5 GeV) are associated with charged tracks having p_{T} above 2 GeV/c. Figure 8 shows the correlation function for dAu collisions for $E_{\mathrm{trig}} = 4.5$–6.5 GeV/c and $p_{\mathrm{T}}^{\mathrm{associated}} > 2$ GeV/c. Two clear peaks are seen for near angle and back angle correlations. Widths and strengths of the peaks are studied for varying E_{trig}. Peaks are seen to get narrower with increasing $p_{\mathrm{T}}^{\mathrm{associated}}$ and peak heights increase with increasing E_{trig} [12].

In addition to photon correlation, STAR and PHENIX have used the correlation between charged particle as trigger and associated charged particles with p_{T} lower than p_{T} of trigger particle [13].

Jet transverse momenta $\langle j_{\mathrm{T}} \rangle$ have been calculated from the widths of the correlation functions. PHENIX obtained a value of 585 ± 25 MeV/c, while STAR obtained 450 ± 150 MeV/c.

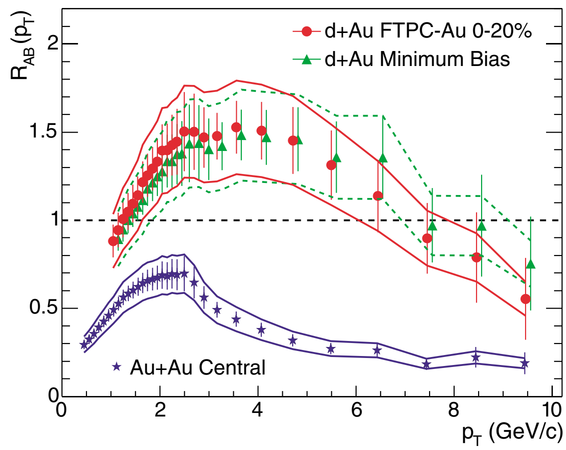

Figure 9. Spectra suppression factor for dAu and AA system with p_T.

Spectra of leading particles have been measured for pp, dAu and AuAu collisions. While going from pp to pA system, several nuclear effects are known to be seen. One important one is the Cronin effect, which enhances the spectra for $p_T > 2$ GeV/c. This effect is explained to be due to multiple scattering of partons in the nuclear media. To study the effect on spectra, ratio between spectra from pA or AA with spectra from pp are taken. Spectra from pp are scaled for nuclear thickness factor which are obtained by taking nuclear geometry. This factor can be obtained analytically or by using Monte Carlo technique [14]. Figure 9 shows the ratio (R_{AB}) for dAu and AuAu collisions. For dAu system, Cronin effect is observed via increasing R_{AB} with p_T. It is found that for central AuAu system spectra are softened considerably at higher p_T. This effect is thought to be due to energy loss of partons in nuclear medium. This energy loss was predicted to be the signature of formation of extreme dense medium. In such a large density, matter is expected to exist in deconfined phase. This energy loss is therefore an indirect proof of the formation of QGP.

Theoretically, formation of initial dense gluon system (colour gluon condensate), in AA collisions can also soften the spectra [15]. But CGC is expected to soften the spectra for dAu system as well due to the formation of similar initial system in dAu collisions. Lack of softening of the spectra in dAu therefore establishes the fact that this energy loss is due to dense system produced in the final state of the system. These observations are also supported by the vanishing of far angle correlations in AuAu central events as compared to correlation in pp, as shown in figure 10. It was however not established yet whether the effect is due to gluonic system or partonic system, which will possibly be checked using γ-tagged jets.

It should be mentioned that even though R_{dAu} has been found to show no suppression at midrapidity, but for larger rapidity, it has been shown by BRAHMS that the spectra are suppressed considerably (figure 11). There have been several explanations on this issue, one of them is the shadowing inside Au nucleus, thereby reducing the production of hard components.

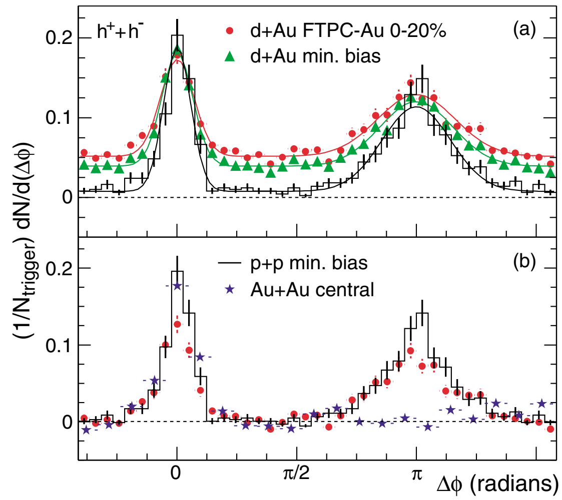

Figure 10. Azimuthal correlation for pp, dAu and AA-central systems. Correlation functions are constructed using high p_T charged tracks as trigger and charged tracks with $p_T < p_T^{\rm trigger}$ as associated tracks.

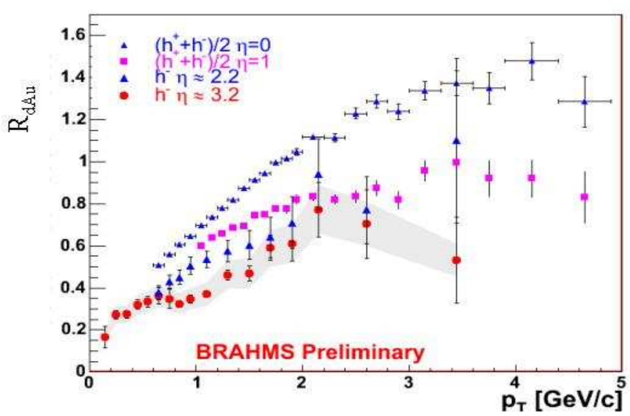

Figure 11. Spectra suppression factor for different η regions.

This explanation has been supported by PHENIX that in dAu collisions, suppression is observed in the rapidity direction of incoming Au, but in the direction of incoming deuteron, no such suppression is observed.

Observations have also been made by looking at the composition of jets. This has been measured by measuring the spectra and correlations for identified particles. It has been found that $R_{\rm CP}$, giving the ratio of identified particle spectra for central to peripheral collisions, has two distinct groups, one for mesons and other for baryons as shown in figure 12. This grouping has been said to be due to the formation of quark coalescence as discussed earlier.

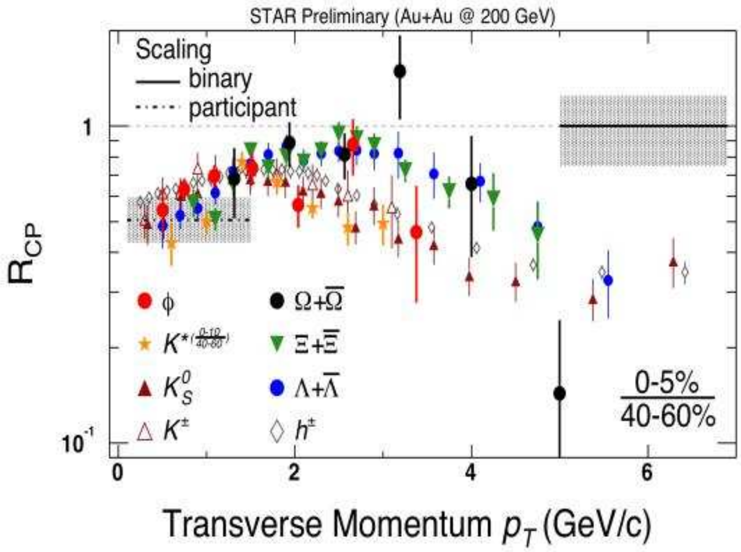

Figure 12. Spectra suppression factor for identified baryons and mesons.

v_2 has been measured for high p_{T} region as well. It was expected that at high p_{T} where jets dominate, there will be no azimuthal anisotropy, but the observations show finite v_2 even at $p_{\mathrm{T}} = 6$–7 GeV/c. One of the explanations is the path length dependent energy loss of the partons, which has been supported by the difference in spectra suppression factor for correlations found in in-plane and out-of-plane directions [16].

6. Heavy flavor

Production of J/Ψ in AA collisions is found to be one of the most important observables. J/Ψ is the bound state of cc and its production is expected to be suppressed in deconfined state of matter due to Debye screening. At SPS energy, production of J/Ψ is found to be suppressed in comparison to the yield in pp collisions with increasing centrality. Detailed studies are then made at SPS using different collisions systems. Comparisons are made using pA and AB collisions and in the case of AB system absorption cross-section (21.6 $\pm$ 2.5 mb) is found to be significantly higher compared to pA system (7.4 $\pm$ 1.4 mb) [17].

At RHIC there is extensive programme for charmonia studies. PHENIX is equipped to study the production using both e^+e^- and $\mu^+\mu^-$ channels. STAR has the capability of looking into e^+e^- channels. PHENIX has taken data in pp, dAu and AuAu collisions which will help to make comparative studies of production and modifications in J/Ψ yield. In dAu collisions it is possible to study the system from the point of view of initial state effect which will help to disentangle final state effect in AA collisions. PHENIX has reported rapidity distributions of J/Ψ for pp, dAu system. Detailed comparison by looking into ratio of yield in central to

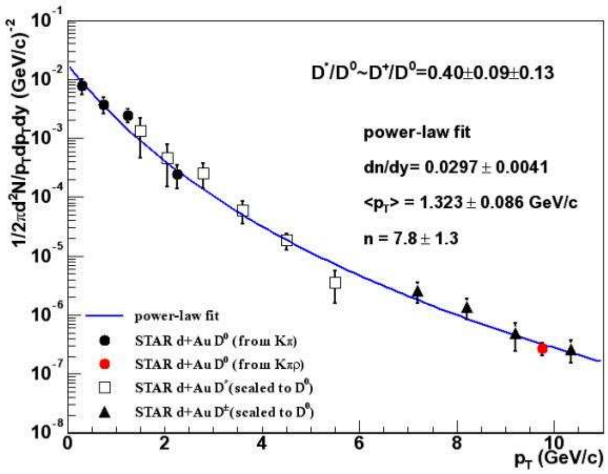

Figure 13. Spectra for reconstructed D mesons.

peripheral collisions indicates presence of weak shadowing and more statistics are needed to disentangle nuclear effects clearly.

Apart from the study of cc bound state, another observable is the detection of open charm which can be used as control measurement for J/Ψ measurement. This can be studied using direct reconstruction of D meson into which charm decays with subsequent decays to $K^{\pm}$ or $e^{\pm}$. In STAR $(D^0 + D^0)/2$ have been reconstructed in dAu collisions (figure 13). Semileptonic decay channels have been used by detecting electrons by STAR and PHENIX for pp, dAu and AA systems. From single particle yield we can estimate charm cross-section [18].

In PHENIX calorimeters have been used to detect electrons, in STAR in addition to calorimetric measurement, time of flight has been used for the identification of electrons. Figure 14 shows the compilation of electron spectra from pp from various measurements. STAR yield is systematically higher compared to PHENIX, but the error estimates need to be taken seriously before drawing any conclusion. PHENIX has measured non-photonic electron spectra for AA collisions and found to be consistent with pp with binary collision scaling for dAu. pp, dAu and AA spectra are combined [19]. It is therefore interesting to find that while leading particles at high p_{T} in central AA collisions showed considerable suppression in yield compared to pp, heavy flavors follow binary scaling suggesting the possible energy loss to be different for heavy flavors.

7. Direct photons

Photons are produced at various stages of the evolution of the system. Apart from the decay products of light hadrons which dominate low or intermediate p_{T}, thermal photons as blackbody radiation can be produced from partonic/hadronic media. They also populate low or intermediate p_{T} region. Another interesting

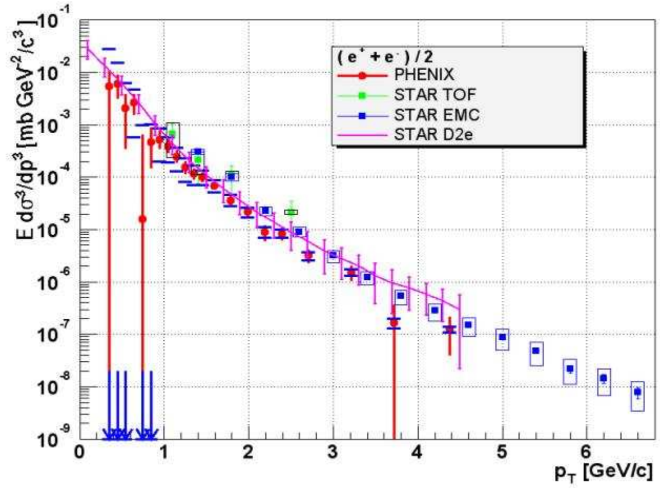

Figure 14. Spectra of single electrons and positrons supposed to be produced by charm decay.

thing is the production of direct photons from the initial state of the system. These 'direct' photons do not fragment or interact in transition, and can therefore be used to probe the initial state of the system very well. The production rate of these photons can be calculated using perturbative QCD.

At SPS, detailed measurement of single photons has been done in WA98 experiment, which shows significant production of single photons in addition to the yield from known sources. At RHIC, PHENIX has measurement of direct photons for *pp* and *AA* collisions using Pb-glass and Pb-Scintillator arrays. Figure 15 shows the double ratio for photon production at various p_{T}. It has been compared with binary scaled pp results and NLO pQCD calculations (figure 15). Centrality dependence has been studied and it is found that there is no suppression in the production of direct photon and it follows estimates from pQCD calculations [20].

8. Discussion

In the last four years of operations of RHIC quite impressive amount of data have been collected. It is therefore necessary to have a perspective view of the information collected so far.

A whole new chapter is opened at RHIC with huge amount of data collected at high p_{T} region. It is almost unambiguous that these high p_{T} particles are products of jets. Suppression of leading particle spectra gives rise to the explanation of energy loss of partons. Suppression of back angle correlation length supports the picture and even talk about surface emission of high p_{T} particles. Existence of v_2 at high p_{T} supports the picture of path length dependent energy loss. Competing scenario of energy loss at initial stage in color glass condensate (CGC) seems to be not the case as suggested by dAu results. For observation of suppression even in case of dAu at

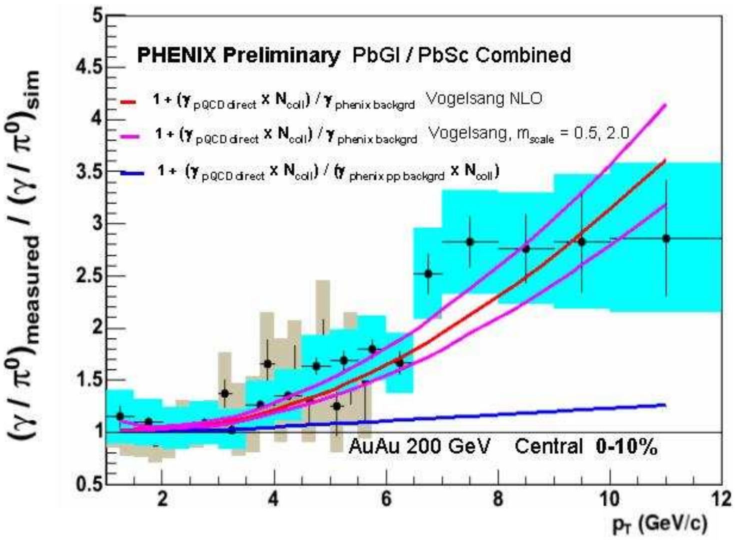

Figure 15. Double-ratio of measured γ/π^0 for single photons and similar ratio from simulation with p_{T}. Calculations from various binary collision scalings are shown. Data seems to follow binary collision scaling.

higher rapidity seems to be explicable using shadowing picture, even though details of CGC in such a picture should be looked into. Looking at no energy loss from heavy flavor products in same context needs explanation. Dead cone effect which prohibits them to loose energy in the cone seems to be an explanation. Overall observations, therefore coming out of these exclusive observables at RHIC directs us towards the formation of dense system.

But more than 99% of the particles are produced at soft region and are supposed to come out from the dense matter. It is therefore essential that soft sector should support the above scenario. Observations from various flow components in detail seem to suggest local thermodynamic equilibrium. But some details of v_2 (e.g η dependence) and v_2 at high p_{T} need more attention. Another puzzle in soft sector is the apparent discrepancy between momentum space observables (flow) and co-ordinate space observables (via HBT). Many other observables (most prominently strangeness) in soft sector seems to suggest the existence of dense locally equilibrated hot system, which will most likely be in deconfined phase. But there is no 'smoking gun' like observation for phase transition or of deconfined phase. Many exotic observables needing large statistics (e.g. J/Ψ, direct photon, photon tagged jets) will hopefully resolve these questions for our final conclusion.

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