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Working group report: Quark gluon plasma

Coordinators: PRADIP ROY[1] and BEDANGADAS MOHANTY[2,*]

Contributors: A P Balchandran[3], A Bhattacharyya[4], A K Chaudhuri[2], S Datta[5], S Digal[6], F Flueret[7], S Gupta[5], P Jaikumar[6], S H Lee[8], N Mathur[5], A Mishra[9], A P Mishra[10], H Mishra[11], B Mohanty[2], P Roy[1], P S Somia[10] and A M Srivastava[10]
[1]Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata 700 064, India
[2]Variable Energy Cyclotron centre,1/AF Bidhan Nagar, Kolkata 700 064, India
[3]Department of Physics, Syracuse University, Syracuse, NY 13244-1130, USA
[4]Calcutta University, 92 Acharya Prafulla Chandra Road, Kolkata 700 009, India
[5]Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India
[6]The Institute of Mathematical Sciences, C.I.T. Campus, Taramani, Chennai 600 113, India
[7]LLR - Ecole Polytechnique, Route de Saclay,91128 Palaiseau France
[8]Yonsei University, 262 Seongsanno, Seodaemun-GU Seoul 120-749, Korea
[9]Indian Institute of Technology, Hauz Khas, Delhi 110 016, India
[10]Institute of Physics, Sachivalaya Marg, Bhubaneswar 751 005, India
[11]Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India
*Corresponding author
E-mail: pradipk.roy@saha.ac.in; bedanga@rcf.rhic.bnl.gov

Abstract. The 10th Workshop on High Energy Physics Phenomenology (WHEPP-10) was held at the Institute of Mathematical Sciences, Chennai during January 2–13, 2008. One of our working grops (WG) is QCD and QGP. The discussions of QGP WG include matter at high density, lattice QCD, charmonium states in QGP, viscous hydrodynamics and jet quenching, colour factor in heavy ion collisions and RHIC results on photons, dileptons and heavy quark. There were two plenary talks and several working group talks with intense discussions regarding the future activities that are going to be persued.

Keywords. Quantum chromodynamics; colour superconductivity; heavy quarks; hydrodynamics.

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1. Acoustic peaks in CMBR and relativistic heavy ion collisions

A M Srivastava

QGP phase in heavy-ion collisions lasts for 10^{-22} s. Finally, only hadrons are detected carrying information of the system at freeze-out stage. This is quite like

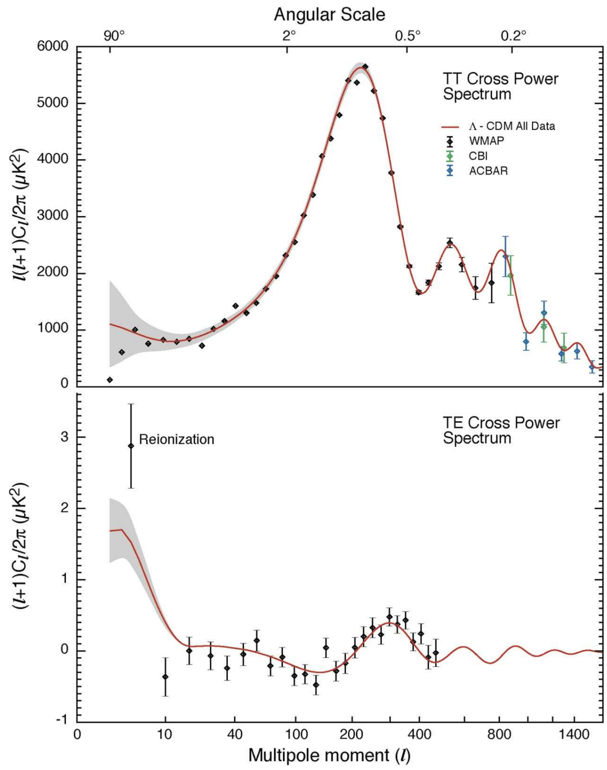

Figure 1. Acoustic peaks in CMBR anisotropy power spectrum.

CMBR which carries the information at the surface of last scattering in the universe. Just like for CMBR (see figure 1), one has to deduce information about the earlier stages from the properties of hadrons coming from the freeze-out surface.

This apparent correspondence with CMBR is much deeper. There are strong similarities in the nature of density fluctuations in the two cases (with the obvious difference of the absence of gravity effects for relativistic heavy-ion collision experiments).

One can argue that sub-horizon fluctuations in the azimuthal distribution of particle momenta in the experiments at the Relativistic Heavy Ion Collider (RHIC) may display oscillatory behaviour, as well as some level of coherence just as for CMBR in the case of inflationary density fluctuations in the universe.

Also, flow anisotropies for superhorizon fluctuations in RHIC should be suppressed by a factor $H^{\rm S}_{\rm fr}/\lambda/2$, where $H^{\rm S}_{\rm fr}$ is the sound horizon at the freeze-out time $t_{\rm fr}$ (~ 10 fm/c for RHIC) and λ is the wavelength of the fluctuation. We incorporate these factors and plot r.m.s values of the Fourier components of spatial anisotropies estimated from HIJING [1]. The result is shown in figure 2.

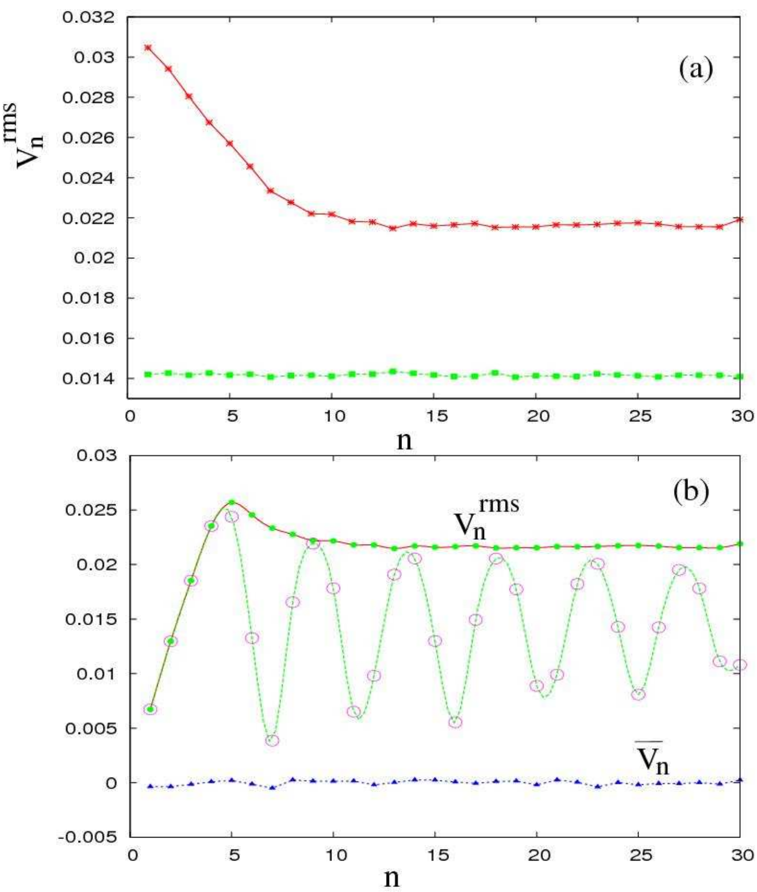

Figure 2. These plots represent V_n^{rms} calculated from the Fourier coefficients F_ns of the spatial anisotropy. In (**a**), the solid curve is obtained using parton positions from HIJING while the dotted curve is for uniformly distributed partons. (**b**) shows plots obtained from the solid plot in (a) by including factors of acoustic horizon and coherence etc.

2. Skyrmions in CFL matter

P Jaikumar, A P Balchandran, H Mishra, A M Srivastava, V Tiwari and S Datta

At high density, attractive interaction between quarks leads to Cooper pairing, characterized by the formation of a $\langle qq\rangle$ condensate. The condensate breaks several symmetries of the QCD Lagrangian spontaneously. The symmetry breaking pattern is

$$G : SU(3)_{[\mathrm{c}]} \times SU(3)_{\mathrm{L}} \times SU(3)_{\mathrm{R}} \to SU(3)_{\mathrm{c+L+R}} : H, \tag{1}$$

so that colour and flavour symmetries are broken to a diagonal subgroup. The spontaneous symmetry breaking leads to the formation of Goldstone modes corresponding to axial phase fluctuations in left- and right-handed flavour. An effective theory for the Goldstone modes can be written down. This is described by the Lagrangian,

$$\mathcal{L}_{\rm eff} = \frac{f_\pi^2}{4}{\rm Tr}[\partial_m u U \partial^\mu U], \tag{2}$$

where $U = U_{\rm L}^{\rm dagger} U_{\rm R}$ is a phase for a composite 4-quark state composed of two left-handed and two right-handed quarks. In addition, there are massive flavoured bosons B_μ in this theory which are colour singlets. Their contribution to the action is given by

$$\mathcal{L}_{\rm eff} = -\frac{1}{4}4g^2[\,F^2(B^2)] - m_V^2 B^2, \tag{3}$$

where $F^{\mu\nu}(B^2)$ is the non-Abelian field strength. The low-energy theory of the CFL phase therefore, has a pseudoscalar octet (pions, kaons, etc.) as well as colour neutral vector mesons that mediate flavour-changing weak interactions. Note that weak interactions are not required for this. The flavour changes take place since the condensates carry flavour as well as colour which are locked together by the form of the condensate. We intend to explore the effect of these flavour changing interactions on the neutrino emission rate by studying the decay and scattering of the CFL Goldstone bosons. That is important for the neutrino cooling of neutron stars that can contain such exotic phases of quark matter at high density.

Aside from this interesting possibility, we realized that it is possible to have skyrmions in the CFL phase. This is because the effective theory of the CFL phase has a formal resemblance to the vacuum chiral Lagrangian of QCD which admits baryons as topological solitons (skyrmions). However, our skyrmions are realized at finite chemical potential, and would have different properties. An interesting consequence of this is the fate of the axial anomaly at high density, which mediates $\pi^0 \to \gamma\gamma$. This would determine how brightly the CFL phase, if present in neutron stars, can shine.

3. Neutrino emission in magnetized CFL matter

P Jaikumar and H Mishra

The colour superconducting phases of QCD are expected to be realized in the interior of neutron stars. Such compact stars typically have magnetic fields in the range of 10^9–10^{14} G at the surface. The interior fields are expected to be even stronger by few orders of magnitude. The effect of such strong magnetic fields in colour superconducting phases is only the beginning to be explored.

Due to strong magnetic field, the quark motion perpendicular to the magnetic field is restricted by the gyro-radius. The superconducting gap displays de-Haas–van Alphen oscillations as a function of the magnetic field. This is because the Landau level quantization depends on the strength of the magnetic field. These modifications due to the magnetic field are expected to change the cooling behaviour of the neutron star since the quarks now have a non-linear dispersion relation.

The neutrino emission from a magnetized neutron star can be studied within an effective theory of the CFL phase (we restrict our study to the CFL phase although a generic study may be possible). In a magnetic field, rotational symmetry is broken and additional terms are possible in the CFL effective Lagrangian. We may write

$$\mathcal{L}_{\rm eff} = \frac{f_\pi^2}{4}{\rm Tr}[\partial_m u U \partial_\mu \Theta^{\mu\nu} U], \tag{4}$$

where $\Theta^{\mu\nu}$ involves the invariant tensors $u^\mu u^\nu, g^{\mu\nu}$ and $F^{\mu\rho}F^{\rho\nu}$ with u being the fluid four-velocity and F being the field strength for electromagnetism. Each of the coefficient for these terms must be determined by a matching calculation at the level of the microscopic theory of quarks and gluons. At high density, this is feasible because QCD is amenable to perturbation theory at high density. The analysis can be carried out by the well-known high-dense loop limit.

Once the coefficients are known, the effective Lagrangian for the magnetized CFL phase is known. The U field can now be gauged by electroweak fields and electroweak decays of the CFL octet of pions (described by U) can be computed. They comprise the leading contribution to the neutrino emissions rate and hence the cooling of the neutron star. The rates can then be confronted by temperature data on cooling of neutron stars to determine if exotic phases of QCD can exist inside compact stars.

4. CFL phase and collapse of black holes

A M Srivastava

Stars collapsing to black hole will go through stages with densities exceeding the neutron star density. Hence densities required for exotic phases such as the CFL phase may be achieved for time durations of the order of miliseconds, e.g., for $M \sim 10M_\odot$, $\rho \sim 10^3\rho_{\rm NS}$ while collapsing to black holes. Neutrino emission during such stages may be very distinctive from what is coming from a collapse to normal neutron star.

The main point is to remember that massive stars collapsing to black hole provide new laboratory for achieving densities far above neutron star densities. Preliminary calculations suggest that heating during collapse does not raise the temperature of the core above about 30 MeV. Hence CFL phase should be possible.

5. Pulsar signals and baryon inhomogeneity in quark–hadron phase transition

A M Srivastava

Quark–hadron phase transition may produce baryon inhomogeneity for a short time duration (expected with a first-order transition, but one can check this possibility more generally). This will affect the angular momentum of a rapidly rotating star. Some of these effects will remain even after the neutron star core again becomes homogeneous (by pressure balance, diffusion etc.). This can be verified by looking for perturbation in pulsar signals.

6. Two-step conversion of neutron star to strange star

A Bhattacharya

Two-step conversion of a neutron star to a strange star is studied. In the first step the neutron star is converted to a two-flavoured quark matter. The velocity of the front varies along the radius of the star and conversion time is about 1 ms. The main observation of this study is the following: As the first conversion leaves behind a two-flavour quark matter, the second conversion starts. The time taken for the second conversion is about 100 s. Consideration of rotation changes the results qualitatively. The velocity along the pole is more than that along the equator. As a result, the front breaks up.

Future studies include motion of a shock front/phase boundary using the Polyakov loop model. Particular emphasis will be given to the possibility of a bounce.

7. Kaons (anti) in asymmetric nuclear matter (ANM)

A Mishra

The optical potentials for the kaon doublet in ANM are computed in chiral $SU(3)$ model. At high density these depend sensitively on asymmetry parameter. Kaons and anti-kaon dispersion relations are different in ANM implying different flow (kaon/antikaon ratio) pattern expected at CBM @ FAIR. Such a study is relevant for bulk matter of neutron star, exotic nuclei, like deeply bound kaonic atom. The inclusion of hyperons is worth investigating.

8. Colour superconductor (SC) at moderate density

A Mishra and H Mishra

We need to understand matter at high density or very high temperature because extreme conditions exist in the universe such as in compact astrophysical objects. Quarks are fermions – come in three colours (red, green and blue) and in different flavours (up, down, strange...). One gluon exchange interaction is attractive in colour antisymmetric channel. Any attractive interaction (however weak it might be) makes the Fermi surface unstable to form Cooper pairs (Bardeen–Cooper–Schreiffer) and lead to superconductivity. Hence dense quark matter will form Cooper pairs.

Colour superconductivity at asymptotically large densities allows to use pQCD. However, at intermediate densities (5–$10\rho_0$) one should resort to effective models (e.g. NJL model). It is also important to note that at realistic densities strong coupling dynamics is not controlled. As μ decreases g increases. Cooper pairs become more localized. The ratio of coherence length ($\sim 1/D$) to inter-quark distance ($\sim 1/\mu$) decreases. So the question to be answered is: 'Is there a BEC di-quark molecule in the QCD phase diagram?'

9. Transport coefficient in causal hydrodynamics

S Gupta and A Mishra

Transport coefficients beyond Navier–Stokes causal relativistic fluid dynamics contains terms beyond the Navier–Stokes limit. Each new term in the fluid equations comes with new transport coefficients. As usual, these transport coefficients parametrize properties of the fluid and cannot be computed in fluid dynamics. However, a microscopic computation is possible. The matching of the short distance theory to the fluid dynamics (in the Navier–Stokes limit) give the Green–Kubo formula. This can be systematically extended to the new transport coefficients. A computation in a model (the Nambu–Jona–Lasinio model) has been initiated. The possible signals of the critical end point of QCD was initiated.

10. Search for the effects of the QCD colour factor in high-energy collisions at RHIC

Bedangadas Mohanty

In central heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) it is observed that at large transverse momentum ($p_T > 6$ GeV/c) hadron production is suppressed relative to their production in nucleon–nucleon collisions [2]. This has been attributed to the medium-induced energy loss of the parton propagating through the dense medium formed in heavy-ion collisions. Theoretical models incorporating such a mechanism find that the average energy loss of partons is proportional to the colour factor of the parton (4/3 for quarks and 3 for gluons) [3]. A simple estimate of the ratio of energy loss of gluons (ΔE_g) and quarks (ΔE_q) for similar conditions in heavy-ion collisions is found to be determined by the ratio of their colour factors, $\Delta E_g/\Delta E_q \sim 9/4$. This indicates that gluons will lose more energy in the medium compared to quarks because of their stronger coupling.

In this paper we investigate if such a difference in energy loss between gluons and quarks can be observed at RHIC. In high-energy collisions, depending on the kinematics, produced hadrons may arise from different partonic sources. In 200 GeV collisions, for example, at mid-rapidity (anti-)protons are mainly from gluons while pion production has substantial contribution from quarks [4,5]. Therefore, these final state hadrons provide us a powerful tool to test the QCD colour factor effects on experimental observables. To study the colour charge effect on parton energy loss in heavy-ion collisions we need to focus on the high p_T (>6 GeV/c) region and identify observables sensitive to quark and gluon jets in heavy-ion collisions. There are three ways of investigating this effect: (a) at a given beam energy, finding out which of the produced hadrons are dominantly coming from quark jets and gluon jets, (b) at a given p_T, varying the beam energy would effectively mean probing the quark-dominated jet production at lower beam energy to a gluon-dominated jet production at higher energy [6] and (c) looking at anti-particle to particle ratio as a function of p_T because in quark fragmentation, the leading hadron is more likely to be a particle rather than an anti-particle, and there is no such preference from a gluon jet [4].

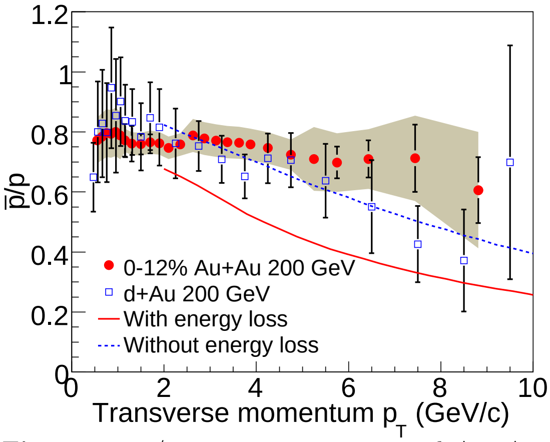

Figure 3. $\bar{p}/p$ ratio vs. p_T in central Au+Au and minimum bias d+Au collisions at 200 GeV [4,7]. The lines are model calculations with and without energy loss [6].

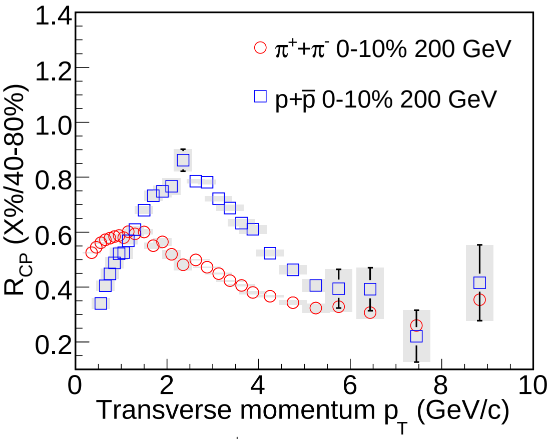

Figure 4. R_{CP} of $\pi^+ + \pi^-$ and $p + \bar{p}$ vs. p_T in central Au+Au collisions at 200 GeV [7]

10.1 *Experimental results*

Some of the experimental observables currently accessible at RHIC and sensitive to the colour factor effect on parton energy loss are the following: (i) If anti-protons are dominantly produced from fragmentation of gluon and protons have relatively larger contribution from quark jets, then it is expected that for the same beam energy, the parton energy loss in central Au+Au collisions will lead to a lower $\bar{p}/p$ ratio relative to p+p or d+Au collisions at high p_T [7]. (ii) The high p_T p+$\bar{p}$ production is gluon-dominated while $\pi^+ + \pi^-$ has significant contribution from quark jets [5]. The higher energy loss for the gluons in the medium formed in Au+Au collisions will then lead to a lower value of the nuclear modification factor

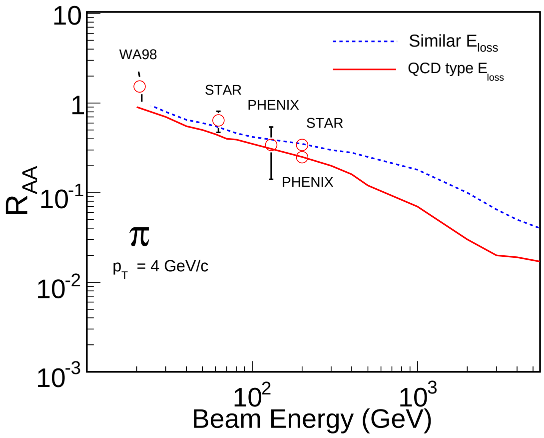

Figure 5. R_{AA} of π ($p_{\rm T}$ = 4 GeV/c) vs. $\sqrt{s_{NN}}$ in central heavy-ion collisions [7,8]. The data are compared to model calculations with parton energy loss without colour factor effect (dashed line) and with colour factor effect (solid line) [6].

(NMF) ($R_{\rm CP}(p_{\rm T}) = \frac{\langle N_{\rm bin}^{\rm peri}\rangle {\rm d}^2 N_{\rm cent}/{\rm d}y{\rm d}p_{\rm T}}{\langle N_{\rm bin}^{\rm cent}\rangle {\rm d}^2 N_{\rm peri}/{\rm d}y{\rm d}p_{\rm T}}$) for p+$\bar{p}$ compared to $\pi^+ + \pi^-$ at high $p_{\rm T}$. (iii) The beam energy dependence of NMF, as discussed above.

Figure 3 shows that the $\bar{p}/p$ ratio for central Au+Au collisions at 200 GeV at high $p_{\rm T}$ (>6 GeV/c) is comparable or slightly higher than d+Au results [4,7]. This is in contrast to the expectations from colour charge dependence of energy loss. A comparison to model calculations [6] without energy loss is in reasonable agreement with the d+Au results, whereas calculations including colour charge dependence of energy loss give a much lower value of the $\bar{p}/p$ ratio compared to the data for most of the measured $p_{\rm T}$ range.

Figure 4 shows that $R_{\rm CP}$ for p+$\bar{p}$ is comparable to $R_{\rm CP}$ of $\pi^+ + \pi^-$ at high $p_{\rm T}$ (>6 GeV/c) for central Au+Au collisions at 200 GeV [7]. This is in contrast to the naive expectation of the difference in energy loss due to colour factors of quarks and gluons being reflected in $R_{\rm CP}$.

Figure 5 shows R_{AA} for pions with $p_{\rm T}$ = 4 GeV/c for central heavy-ion collisions at $\sqrt{s_{NN}}$ from 17.3 GeV to 200 GeV [7,8]. The results are compared to model calculations with quark and gluons having similar colour factors (dashed line) and calculations with quarks and gluons having different colour factors as given by QCD (solid line). Current measurements are not able to differentiate the two scenarios. The difference in two scenarios is expected to be much larger at LHC energies.

10.2 *Conclusion*

The non-Abelian features of QCD suggest that gluons, which have a stronger coupling than quarks with the medium formed in heavy-ion collisions, lose more energy. Observation of this effect will link the experimental observations in high energy heavy-ion collisions to one of the basic ingredients of QCD, the gauge group. So far all the measurements at high $p_{\rm T}$ believed to be sensitive to colour charge effect on medium-induced partonic energy loss like, $\bar{p}/p$, $\bar{p}/\pi^-$ [5], $R_{\rm CP}$ of $\pi^+ + \pi^-$ and $p+\bar{p}$ do not show the naively expected results due to difference in quark and gluon energy loss. A more clear picture can emerge if we understand the following: (a) The role of different mechanisms of energy loss (radiative and collisional) [9]. (b) Role of gluon-dominated matter at initial stages in RHIC. (c) The possibility of quark and gluon jet conversion in the medium [10]. (d) The energy of the jet may not be large enough at RHIC to see the difference [11]. (e) The possibility that there is a two-component picture in heavy-ion collisions with a core where partons lose all their energy and a corona from where the bulk of observed hadrons are emitted. (f) The role of the value of α_s at RHIC. It is fairly large, compared to LEP where the measurements of colour factors were made. (g) Experimental sensitivity [12].

10.3 *Outlook*

As there is clear evidence of colour charge effect on energy loss observed at RHIC, it may be worthwhile to discuss about the more promising future measurements in addition to extending the current measurements to higher $p_{\rm T}$ and higher beam energy. The ratio of NMF of high $p_{\rm T}$ heavy-flavoured mesons to light-flavoured mesons ($R_{D/h}$) in heavy-ion collisions can be sensitive to colour charge dependences of medium-induced parton energy loss [13]. On similar lines, the ratio of NMF of high $p_{\rm T}$ ϕ-meson to light-flavoured mesons in heavy-ion collisions can also be sensitive to colour charge effect of parton energy loss, as the ϕ-meson is dominantly formed by coalescence of s-quarks. Looking for difference in the species dependence (pions and anti-protons) of suppression pattern in away side ($\Delta\phi \sim \pi$) identified particle di-hadron correlation and γ-jet correlations can also be considered as good observables to search for the signature of colour charge effect on parton energy loss.

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