Search for color charge dependence of energy loss at RHIC

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Abstract. The non-Abelian feature of quantum chromodynamics (QCD) results in the gluons losing more energy than quarks in the medium formed in high energy heavy-ion collisions. Experimental results in p+p collisions when compared to NLO pQCD calculations show that at high transverse momentum ($p_T$) the produced protons-anti-protons are dominantly from gluon jets and charged pions have substantial contribution from quark jets. If such a scenario is applied to heavy-ion collisions at RHIC, one would expect the difference in quark and gluon energy loss to have an effect on measured observables, such as high $p_T$ $\bar{p}(p)/\pi$ ratios and the nuclear modification factor for various particles species. We discuss the experimental results and some possible future measurements.

Keywords: Heavy-ion collisions, quantum chromodynamics, color factor, parton energy loss, particle ratio and nuclear modification factor
PACS: 25.75.-q,25.75.Nq,12.38.Mh

1. Introduction

Results from central heavy-ion collisions at the Relativistic Heavy-Ion Collider (RHIC) show that at large transverse momentum ($p_T > 6$ GeV/c) hadron production is suppressed relative to their production in nucleon-nucleon collisions [1]. This is due 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 the average energy loss of partons in a static medium is given as, $\langle \Delta E \rangle \propto \alpha_s C_X \langle \hat{q} \rangle L^2$ [2], where $\alpha_s$ is the strong coupling constant, $C_X$ is the color factor ($4/3$ for quarks and $3$ for gluons), $\langle \hat{q} \rangle$ is the medium transport co-efficient which depends on gluon density and parton momenta and $L$ is the path length a parton traverses in the medium. In a Bjorken-expanding medium the path length dependence is reduced to linear, $\Delta E \sim \alpha_s^2 C_X dN^g/dy L/A_{\perp}$ [3], where there are experimental handles on the parton rapidity density $dN^g/dy$ and the transverse area of the collision $A_{\perp}$. A simple estimate of ratio of energy loss of gluons and quarks for similar conditions in heavy-ion collisions then is only determined by the
color factors of gluon and quark, $\Delta E_g/\Delta E_q \sim 9/4$. This indicates gluons will lose more energy in the medium compared to quarks because of their stronger coupling. The aim of this paper is to investigate if such a difference in energy loss between gluons and quarks can be observed at RHIC.

Before proceeding to present the experimental results we briefly discuss the color factors in QCD. The color factors are related to the underlying gauge group of QCD and can be estimated from the dimension of the group. For a SU group of dimension $N_c$, the color factors are given as $C_A = N_c$, $C_F = \frac{N_c^2 - 1}{2N_c}$, and $T_F = 1/2$. Where $A$ and $F$ are the adjoint and fundamental representation of the group. For QCD, $N_c = 3$, therefore $C_A = 3$ and $C_F = 4/3$. In this theory the quarks are represented by Dirac fields in the fundamental representation and the gluons lie in the adjoint representation of SU(3). The color factors are technically the eigenvalues of the Casimir operators of the gauge group and physically they are related to the fundamental couplings of the theory. The coupling strength of a gluon to a quark is proportional to $C_F$, $C_A$ is related to the strength of gluon self coupling (a fundamental property of QCD arising due to the non-Abelian nature of the gauge theory) and the strength of splitting of a gluon into a quark pair is proportional to $T_F$. The values of the color factors have been experimentally measured at LEP (e.g ALEPH experiment measures them as $C_A = 2.93 \pm 0.14 \pm 0.58$ and $C_F = 1.35 \pm 0.07 \pm 0.26$ at $\alpha_s = 0.119 \pm 0.006 \pm 0.026$ ) \cite{4}. The measurements exploited the jet angular distribution in events with four jet production in $e^+ + e^-$ collisions. Such events have all three basic vertices which are sensitive to the color factors. The measurements experimentally established SU(3) as the underlying gauge group for QCD. Given their fundamental role in QCD theory and as they appear directly in the energy loss calculations which relates to the observed high $p_T$ hadron suppression in heavy-ion collisions relative to $p+p$ collisions, it may be interesting to look for signatures of effects of color factors on various observables. In high-energy collisions, depending on the kinematics, produced hadrons may arise from different parton source. In 200 GeV collisions, for example, at mid-rapidity (anti-)protons are mainly from gluons while pion production have substantial contribution from quarks. Therefore these final state hadrons provide us a powerful tool to test the above mentioned fundamental QCD properties. Next we will discuss the experimental results.

2. Experimental results

To study the color 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 two 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 and (b) at a given $p_T$, varying the beam energy would effectively mean probing the quark dominated jet production at lower beam energy and changing to a gluon dominated jet production at higher
energy. For example at $p_T = 10 \text{ GeV/c}$, $x_T(200) \sim 0.1$, where $x_T = 2p_T/\sqrt{s_{NN}}$, thereby probing regions of different partonic sources. NLO pQCD calculations which describe the $p+p$ collisions can be used to get an idea about which hadron species are dominantly produced from quark and gluon jets at RHIC. Figure 1 shows that at RHIC the high $p_T$ $\pi^+ + \pi^−$ and $p+\bar{p}$ production is reasonably well described by NLO pQCD calculations using the AKK fragmentation functions (FF) [5]. These NLO pQCD calculations do not provide charge separated results. Figure 1 (right panel) also shows the gluon jet contribution factor to various produced hadrons as a function of $p_T$ from these NLO pQCD calculations [6]. The gluon-jet contribution factor is the ratio of contribution to produced hadron spectra from gluon jets to the total yields from both gluon and quark jets. All results are presented for the factorization scale of $\mu = p_T$. At high $p_T$ the baryons seems to be dominantly produced from gluon jets ($> 90\%$), whereas mesons have significant contribution from quark jets ($\sim 20-50\%$). This information drives the choice of various observables discussed below which can be sensitive to the difference in quark and gluon energy loss.

### 2.1. Particle ratios

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 [5]. 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 denser medium formed in central $Au+Au$ collisions will lead to a lower $\bar{p}/p$ ratio relative to $p+p$ or $d+Au$ collisions at high $p_T$. Similar arguments can be made in favour of high $p_T$ $\bar{p}(p)/\pi$ ratio. A dense partonic medium in central $Au+Au$ collisions where gluons lose more energy than quarks would results in a lower $\bar{p}(p)/\pi$.
Fig. 2. Left panel: $\bar{p}/p$ ratio vs. $p_T$ in central Au+Au and minimum bias $d+Au$ collisions at 200 GeV [5, 7]. The lines are model calculations with and without energy loss [8]. Right panel: $\bar{p}/\pi^-$ ratio vs. $p_T$ for central, peripheral Au+Au, minimum bias $d+Au$ and $p+p$ collisions at 200 GeV [5, 7]. Also shown is the calculation from a model based on coalescence and jet quenching [9] for central Au+Au collisions.

ratio at high $p_T$ compared to the corresponding ratios from peripheral Au+Au, $d+Au$ or $p+p$ collisions. Figure 2 shows the $\bar{p}/p$ ratio for central Au+Au collisions at 200 GeV at high $p_T$ (>$6$ GeV/$c$) is comparable or slightly higher to $d+Au$ results [5, 7]. This is in contrast to the expectations from color charge dependence of energy loss. Comparison to model calculations [8] without energy loss is in reasonable agreement with the $d+Au$ results, whereas calculations including color charge dependence of energy loss give a much lower value of the $\bar{p}/p$ ratio compared to data for most of the measured $p_T$ range. Right panel of figure 2 also shows that at high $p_T$ (>$6$ GeV/$c$) the $\bar{p}/\pi^-$ ratios for central, peripheral Au+Au and minimum bias $d+Au$ and $p+p$ collisions at 200 GeV [5, 7] are comparable indicating absence of color charge dependence of parton energy loss. Model calculations based on coalescence and jet quenching [9] (dashed lines) for central Au+Au collisions predict a much lower value for the ratio at high $p_T$.

2.2. Species dependence of nuclear modification factor

The high $p_T$ $p+\bar{p}$ production is gluon dominated while $\pi^+ + \pi^-$ has significant contribution from quark jets (Fig. 1). The stronger coupling of the gluons with the medium formed in Au+Au collisions will then lead to a lower value of the nuclear modification factor (NMF) ($R_{CP}(p_T) = \frac{(N_{\text{cent}}^\text{per})/d^2N_{\text{cent}}/dydp_T}{(N_{\text{min}}^\text{per})/d^2N_{\text{per}}/dydp_T}$) for $p+\bar{p}$ compared to $\pi^+ + \pi^-$ at high $p_T$. Figure 3 shows the $R_{CP}$ for $p+\bar{p}$ is comparable to $R_{CP}$ of $\pi^+ + \pi^-$ at high $p_T$ (>$6$ GeV/$c$) for central Au+Au collisions at 200 GeV [7]. This is in contrast to the naive expectation of difference in energy loss due to color factors $C_A$ and $C_F$ being reflected in $R_{CP}$. 
2.3. Energy dependence of nuclear modification factor

The beam energy dependence of NMF vs. $p_T$ provides a chance to probe the quark dominated jet production and gluon dominated jet production at a given $p_T$. Hence in principle it is sensitive to the color charge effect of parton energy loss. Figure 3 shows the $R_{AA}$ for charged pions for central Au+Au collisions at 200 and 62.4 GeV [7]. The charged pion $p+p$ reference for 200 and 62.4 GeV are from Refs. [5, 10] respectively. A difference in shape of the high $p_T$ dependence of $R_{AA}$ is observed, but it cannot be attributed to color charge effect without understanding the role of initial jet spectra and the energy dependence of parton energy loss. Therefore one has to rely on model comparison. One such model calculation [11] shown in the figure seems to have a reasonable agreement with the measurements at high $p_T$. The energy dependence of high $p_T$ NMF with neutral pions can found in Ref. [12]. To get a clear signature of color charge effect using this observable, experimental measurements with better precision are need and going to higher beam energies will be advantageous.

3. Discussion on absence of strong color charge effect on energy loss at RHIC

Results from most of experimental observables presented do not indicate any color charge dependence of parton energy loss in the medium formed in heavy ion collisions at RHIC. We discuss below some of the possible physics reasons for not observing the color charge effect. (a) Can different mechanisms of energy loss (radiative and collisional) smear the possibility of observing the difference in energy loss of quarks and gluons through hadronic observables? (b) Is it because we have gluon dominated matter at RHIC? (c) Is there a possibility of quark and gluon jet conversion in the medium which leads to an effectively similar quark and gluon energy loss? (d) Is the energy of the jet not large enough at RHIC to see the differ-
ence in fractional energy loss of quarks and gluons? (e) Is it possible that there is a two component picture of heavy ion collisions with a core where partons lose all their energy and a corona from where the bulk of observed hadrons are emitted? The high $p_T$ $R_{AA} < 1$ can be then due to absorption of a given fraction of partons in the medium (a downward shift in the normalization of the spectra) rather than energy loss of every parton (sideward shift in the spectra) \cite{13}. (f) At RHIC $\alpha_s$ is fairly large, compared to LEP where the measurements of color factors were made. Will a high $\alpha_s$ or a stronger coupling lead to non-observation of the color effect in energy loss of partons? (g) Experimental sensitivity: One set of energy loss calculations with FF which describe RHIC data and using a hydrodynamical description of the soft matter evolution, shows a difference between pion and $p + \bar{p}$ $R_{AA}$ due to color charge effect. However the difference cannot be resolved given the present uncertainties in the measurements \cite{13}.

Different energy loss mechanism at RHIC: At RHIC we observe a similar suppression pattern at high $p_T$ in Au+Au relative to $p+p$ collisions for particles consisting of light flavour quarks ($\pi$, $\eta$ and $p + \bar{p}$) and heavy quarks (non-photonic electrons from semi-leptonic decay of heavy quark mesons) \cite{14}. This led to the possibility of significant contribution to energy loss of partons through collisional process in addition to radiative energy loss. We discussed that the radiative energy loss is directly proportional to the color factor. Recent calculations \cite{15} have found similar dependence for the collisional energy loss. The parton nuclear modification factor with both radiative and collisional energy loss included shows a significantly larger difference between gluon and quark energy loss. This rules out the possibility of different energy loss mechanisms being responsible for the absence of the color charge effect in the experimental observables presented.

Gluon dominated matter at RHIC: At RHIC we observe a splitting along baryon and meson lines in the produced hadron $m_T$ spectra at high $m_T$ (Figure 4) \cite{16}. Pythia simulations show this is a characteristic feature of gluon jet events. For quark jet events, simulations show a splitting based on mass of the hadron. Preliminary
Color charge dependence of energy loss at RHIC

analysis of STAR experiment $d+Au$ collision data (Figure 4) shows a generalized $m_T$ scaling for various particles at low $p_T$. Such a scaling is predicted from a color glass condensate scenario in the initial state [16]. Furthermore, the $(p + \bar{p})/(\pi^+ + \pi^-)$ ratio from quark jets in $e^+e^-$ collisions are lower compared to those from Au+Au collisions [7]. All these observations taken together indicate that for the $p_T$ range studied, there may be significantly large contributions from gluon jets to all particle production at RHIC. So there is a need to carry out measurements at still higher $p_T$ to see a clear effect of color charge on various observables.

Quark and Gluon jet conversions: Recently a theoretical [17] attempt has been made to understand why the observed $p(\bar{p})/\pi$ at high $p_T$ in Au+Au and $d+Au$ collisions do not reflect the color charge effect of the energy loss. One way by which the effect of color charge gets reduced is by allowing for conversions between quark and gluon jets through both inelastic ($q\bar{q} \leftrightarrow gg$) and elastic ($gq(\bar{q}) \rightarrow q(\bar{q})g$) scatterings with thermal partons in a quark gluon plasma (QGP). The conversion rate depends on the collisional width and is found to be larger for quark jets than gluon jets for a chemically equilibrated QGP. This increases the final abundance of gluon jets and hence compensating for their larger energy loss in QGP. In such a scenario it is observed that if the net quark to gluon jet conversion rate in heavy-ion collisions is much larger (collisional width enhanced by $\sim 6$ times) than that given by the lowest order in QCD, the results are in reasonable agreement with experimental high $p_T p/\pi$ ratio [17].

Jet energy and energy loss fluctuations: Recent theoretical calculations [11] based on the Guylassy-Levai-Vitev (GLV) approach to the medium-induced non-Abelian energy loss with realistic probability distribution of energy loss and multi-gluon fluctuations indicate that only in the limit $E_{jet} \rightarrow \infty$ and $\Delta E/E \rightarrow 0$ does the energy loss for quarks and gluons approach the naive ratio $\Delta E_g/\Delta E_q = C_A/C_F = 9/4$. For large fractional energy losses this ratio is determined by the $\Delta E < E$ constraint, thereby indicating we need to move to higher momentum region to see the color charge effect.

$\alpha_s$ value at RHIC and accurate determination of color factor: Experimental analysis for measuring the color charge factors using $O(\alpha_s^2)$ QCD predictions instead of $O(\alpha_s^3)$ results in an introduction of a relative factor of about $1 + 2\alpha_s$ in the ratio of the color factors $T_F/C_F$ [18]. This together with the observation of the charged particle multiplicity ratio of gluon to quark jets (which should be equal to $C_A/C_F$ [19]) approaching the $C_A/C_F$ value asymptotically with increasing $Q^2$ [20] indicates the possibility of color charge being increasingly screened at low $Q^2$ or larger $\alpha_s$ values (RHIC: $\alpha_s$ values considered is around 0.2 - 0.4). So one possible question can be, within the typical $Q^2$ values encountered within the medium formed in heavy ion collisions at RHIC, is it possible to have detectable color charge differences? In other words is it possible to resolve the different color charge carriers at relatively small $Q^2$ or large $\alpha_s$ values? These possibilities indicate having measurements at higher momentum than currently available may be neccessary to see the color charge effect.
4. Possible future measurements

In view of no clear evidence of color charge effect on energy loss observed at RHIC, it may be worthwhile to discuss of more promising future measurements in addition to extending the current measurements to higher $p_T$ and higher beam energy. The ratio of NMF of high $p_T$ heavy-flavored mesons to light-flavored mesons ($R_{D/h}$) in heavy ion collisions can be sensitive to color charge dependences of medium-induced parton energy loss [21]. This ratio is affected by (a) mass dependence of parton energy loss, (b) difference in partonic $p_T$ spectrum for light and heavy quarks, (c) difference in light and heavy quark fragmentation function and (c) color charge dependence of parton energy loss, where charm mesons and beauty mesons exclusively probe the quark energy loss in the medium. However for $p_T > 14$ GeV/c the ratio $R_{D/h}$ being $> 1$ is solely due to color charge effect on parton energy loss. This can be a very clean signature for observing the color charge effect. On similar lines, the ratio of NMF of high $p_T$ $\phi$ meson to light-flavored mesons in heavy ion collisions can also be sensitive to color charge effect of parton energy loss, as the $\phi$ meson is dominantly formed by coalescence of $s$-quarks [22]. 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 can also be considered as a signature of color charge effect on parton energy loss.

5. Summary

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 $p_T$ believed to be sensitive to color charge effect on medium induced partonic energy loss like, $\bar{p}/p$, $\bar{p}/p^-$, $R_{CP}$ of $\pi^+ + \pi^-$ and $p + \bar{p}$ do not show the naively expected results due to difference in quark and gluon energy loss. We have discussed some of the possibilities that can lead to an absence of this effect. In addition to extending the measurements to high $p_T$ and higher beam energy, measurements of the ratio of nuclear modification factor of high $p_T$ heavy-flavored mesons to light-flavored mesons and $\phi$ meson to light-flavored mesons in heavy ion collisions or studying the species dependence of suppression pattern in away side ($\Delta \phi \sim \pi$) of identified particle di-hadron correlation may be considered as an alternative way of investigating the color charge effect on medium induced parton energy loss at RHIC.

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