Relativistic Heavy Ion Collisions: Jet Modification in Dense Matter

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Abstract

This paper reviews the theoretical developments in the study of modified fragmentation function to investigate the properties of jet modification in dense matter for Au+Au and Pb+Pb collisions. We discuss the measurements involved in modifying the fragmentation function that gives an overview on how jets are reconstructed due to multiple scattering in the medium. We continue to study the location where the jets form and the energy it loses to demonstrate the physical picture of jets which leads to energy loss calculations for propagating partons and the modified fragmentation function. Furthermore, we theoretically test power corrections to energy loss calculations for jets collisions and compare the theoretical predictions with the experimental results.

1 Introduction

In heavy ion collisions, Quark-Gluon Plasma (QGP) is created which represents the state at extremely high temperature or pressure. Heavy ion runs at the Large Hadron Collider (LHC) at $\sqrt{s} = 2760\text{GeV}$ per nucleon pair, and at the Relativistic Heavy Ion Collider (RHIC) at $\sqrt{s} = 200\text{GeV}$ per nucleon pair provides a better understanding of jets modification in QGP at these energy scales. At CERN, LHC detectors observe what happens when two Pb nuclei collides, whereas, RHIC detectors observe what happens when two Au collides. When the two nuclei collide, it gives "quasi" free quarks and gluons which then forms a hadronic gas. Several observations has been made regarding the behavior of jets without considering what happens in the background when the jets are formed. [1]

Jets are collimated spray of hadrons that result from the scattered hard quarks or gluons produced by hadronization in high energy collisions. Jets are necessary to examine the internal structure of QGP and multiple scattering in the medium that changes the whole jet structure. However, partons within the jets cannot be effectively measured, so we detect final hadrons. Those are extracted from the background and in order to do so, we need to systematically study the phase space of various jets observables which is reconstructing jets via jet mass, area and energy. The new methodology of studying jets isolates particles within a jet from the background [2]. Since the radiated partons scatters out of jets in a dense medium, we need to re-construct an entire jet around the leading parton in order to look at the leading hadron.

In this paper, we examine how jets are modified when we include additional partons from the background in the fragmentation function. This is then followed by energy loss calculations where jets travel through the medium theoretically. The results obtained theoretically are compared with the experimental data collected at RHIC and LHC to test the energy loss power corrections. We then understand how the jet function differs from the fragmentation function.

2 Modified Quark Fragmentation Function

In a medium, partons induce thermal gluons that leads to energy dependence of the parton's energy loss. During hadronization, partons from jets can combine with the particles coming out from medium that forms final hadrons and are confirmed by studying the jet fragmentation function (FF). FF describes the probability for distributing hadrons with a momentum fraction y that is produced in the hadronization of the outgoing hard parton due to multiple scattering in the medium. The differentiation of the evolution equation for the medium modified fragmentation function via HT-M scheme is, [3,6]

$$\frac{\partial D_q^h(z,\mu^2,p^-)|_{\zeta_i}^{\zeta_f}}{\partial log(\mu^2)} = \frac{\alpha_s(\mu)}{2\pi}\int_z^1 \frac{dy}{y}P(y)d\zeta K_{p^-,\mu^2}(y,\zeta)D_q^h(\frac{z}{y},\mu^2,p^-y)|_{\zeta}^{\zeta_f} \tag{1}$$

In the equation above, $D_q^h(z,\mu^2,p^-)$ is FF that represents the number of hadrons that the quark jet produces, y is the momentum fraction that remains in the parent parton after it radiates a gluon, μ^2 is virtuality of the jet, ζ_i is where the location of jet forms, and ζ_f is where the jet exits, ζ is the location of scattering and p^- is the light-cone momentum of the jet along its axis.

Jets tend to lose energy when they transverse through a dense medium which softens transverse momentum (p_T) and the nuclear modification factor (R_{aa}) provides the ratio of the binary scaled differential yield to produce a high p_T hadron in heavy-ion collision yield to that in p-p collision yield. The p_T and R_{aa} represents the parameters that quantifies the yield of a hard leading particle in a jet. The nuclear modification factor R_{aa} is [1],

$$R_{aa}(b_{min},b_{max}) = \frac{\frac{d^2N_{AA}(b_{min},b_{max})}{d^2p_Tdy}|_{y=0}}{<N_{bin}(b_{min},b_{max})> \frac{d^2N_{pp}}{d^2p_Tdy}} \tag{2}$$

In the equation above, $\frac{d^2N_{AA}(b_{min},b_{max})}{d^2p_Tdy}$ gives the yield of particles in a nucleus-nucleus collision for p_T and rapidity y for different centralities and $\frac{d^2N_{pp}}{d^2p_Tdy}$ yields in proton-proton collisions in the same p_T and y bins, N_{bin} is the number of binary nucleon-nucleon collisions in the same impact parameter. R_{aa} provides measurement for particle production difference in pp and AA collisions as it accounts for the geometry of collision.

2.1 Energy Loss Model of a Jet

Hard jets lose energy when it propagates through QGP medium. The total energy loss from the jet cone is the sum of energy loss by leading parton and the radiated gluons along with the scattered gluons out of jet cone. The interacting hard jets and the dense nuclear medium usually leads to jet energy loss. So, the estimation of fractional energy loss for Pb and Au collisions is given as [5],

$$\frac{\Delta E}{E} = \frac{\Delta q^-}{q^-} = \int_{\frac{\mu_o^2}{Q^2}}^{1-\frac{\mu_o^2}{Q^2}} \frac{dy}{y}\int_{\mu_o^2}^{Q^2}\frac{d\mu^2}{\mu^2}\frac{P(y)}{y(1-y)}\int_0^L K_{q^-,\mu^2}d\zeta \tag{3}$$

where, E is the jet energy, Q^2 is the momentum scale, μ_o is the fixed value of virtuality, ζ is the location of scattering, q^- is the light cone energy of hard jet, K is the single emission kernel that contributes to multiple scattering, and P(y) is a splitting function that defines the probability of splitting with a momentum fraction y, [2]

$$P_q(y) = [\frac{1+(1-y)^2}{y}]C_F\frac{\alpha_s(\mu^2)}{2\pi} \tag{4}$$

$$P_g(y) = [\frac{y}{1-y} + \frac{1-y}{y} + y(1-y)]C_A\frac{\alpha_s(\mu^2)}{2\pi} \tag{5}$$

where, $P_q(y)$ is the splitting function for a quark, $P_g(y)$ is a splitting function for a gluon, constants C_F and C_A are $\frac{4}{3}$ and 3, respectively, and the strong coupling constant, α_s,

$$\alpha_s = \frac{4\pi}{(\frac{11N_c}{3} - \frac{2N_f}{3})log(\frac{Q^2}{\Lambda^2_{QCD}})} \tag{6}$$

where, $Q >$ 1 GeV, N_f is the number of flavors which is 3, N_c is the number of colors which is 3, $\Lambda =$ 0.2 GeV which is a cut-off parameter that represents the scale of soft processes in the collision.

2.2 Single Emission Kernel due to Multiple Scattering

In order to understand energy loss of jets, the single quark emission kernel due to multiple scattering needs to be computed first. To do so, the multiple scattering emissions needs to be iterated which is related to the approximations made to the quark emission kernel calculations and follows the HT approach. Initial approach for single emission kernel, K contribution to multiple scattering gives,

$$K_{q^-,\mu^2}d\zeta = \frac{2\hat{q}}{\mu^2}[2 - 2cos(\frac{\mu^2\zeta}{2q^-})] \tag{7}$$

However, the above equation doesn't involve the additional terms that represents the partons coming from the medium. So, the single emission kernel, K due to multiple scattering yields after the power correction yields,

$$K_{q^-,\mu^2}d\zeta = \frac{2\hat{q}}{\mu^2}[2 - 2cos(\frac{\mu^2\zeta}{2q^-}) - \frac{\mu^2\zeta}{2q^-}sin(\frac{\mu^2\zeta}{2q^-}) + (\frac{\mu^2\zeta}{2q^-})^2cos(\frac{\mu^2\zeta}{2q^-})] \tag{8}$$

In the equation above, $\hat{q}$ represents an unevaluated parameter which is the jet transport coefficient which represents the soft matrix elements that isn't included in the energy loss calculation, and instead is a considered to be a constant.

We examine the fractional energy loss for partons shown in Equation 2 and determine the difference in inserting different K_{q^-,μ^2} equation as shown in Equation 6 and Equation 7.

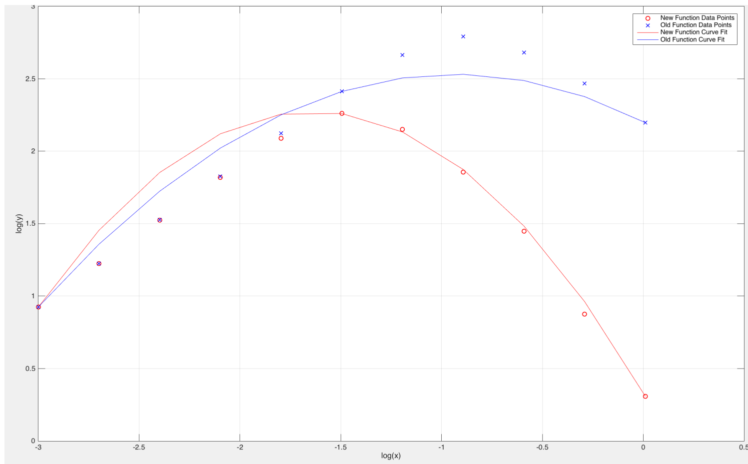


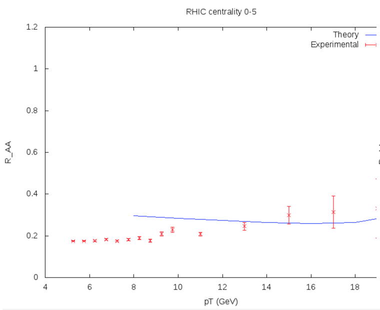
Figure 1: The fractional energy loss in jets as presented in Equation 3 is represented with emission kernel Equation 6 (shown in blue) and emission kernel Equation 7 (shown in red). It can be seen that the difference due to the emission kernel is by some $\hat{q}$ factor.

3 Results/Discussions

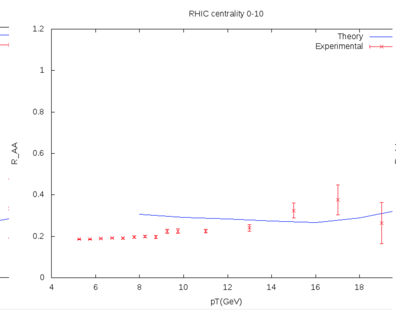
3.1 Testing Power Corrections to Energy Loss Calculations

In order to test power corrections, we use Equation 3 to find the energy loss, ΔE for some jet energy E by finding the first maximum energy loss at some length factor, L. L is the distance traveled by a jet where the emission first occurs. We then compute the mean escape length of the hard jet. By plotting E against L_{max}, we extrapolate a function which is used to determine the L_{max} values for jet energies. This is then used to compute R_{aa} values at various centrality for Pb+Pb and Au+Au collisions. The following results provided for RHIC and LHC shows the plot for R_{aa} against p_T for various centralities.

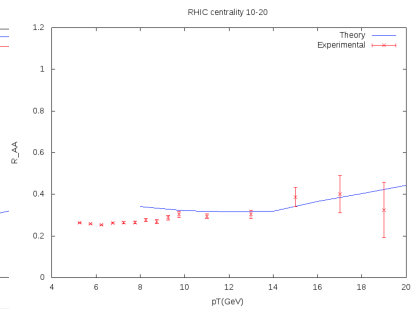
The theoretical predictions made with the power corrections to energy loss calculations concurs with the



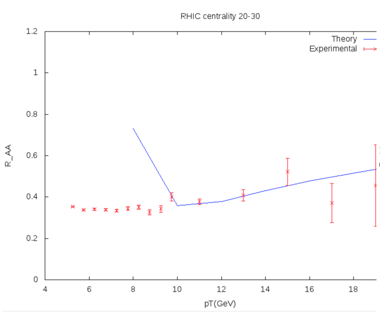
(a) RHIC Centrality 0-5



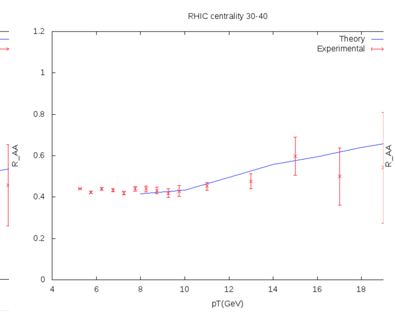
(b) RHIC Centrality 0-10



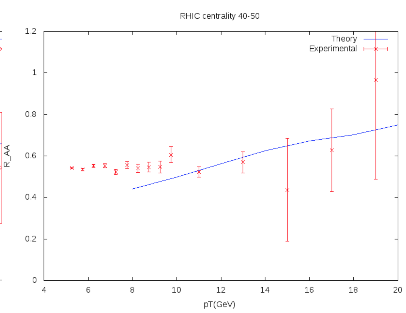
(c) RHIC Centrality 10-20



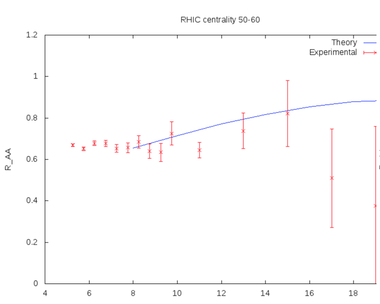
(d) RHIC Centrality 20-30



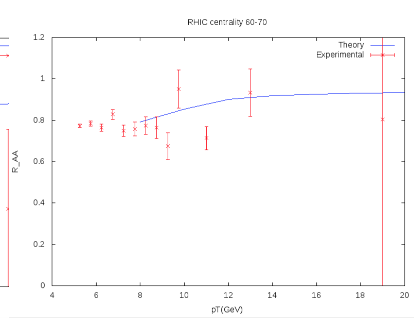
(e) RHIC Centrality 30-40



(f) RHIC Centrality 40-50



(g) RHIC Centrality 50-60



(h) RHIC Centrality 60-70

Figure 2: Representation of the preliminary theoretical prediction (with $\mathrm{Q}^2 of 100 GeV^2) of \mathrm{R}_{AA}$ against p_T for Au+Au Collisions (RHIC) along with the errors from the experimental results obtained at various centralities.

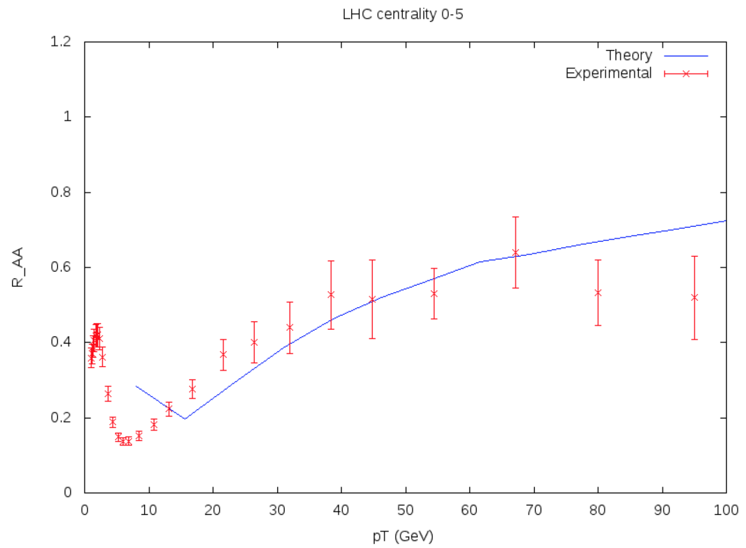


Figure 3: Sample representation of the preliminary theoretical prediction (with $\mathrm{Q}^2 of 100 GeV^2) of \mathrm{R}_{AA}$ against p_T for Pb+Pb Collisions (LHC) along with the errors from the experimental results obtained for Centrality 0-5.

experimental data when $\hat{q}$ value for the theoretical prediction is huge compared to the experimental data. This leads to the conclusion that it is difficult to test corrections to the medium modified fragmentation function. So, we need to find a better approach in adding the corrections to the medium modified fragmentation function.

4 Future Work

4.1 Jet Function

In comparison to the fragmentation function that evaluates only a parton, a jet function evaluates the probability of an entire jet giving hadrons. A new jet function which is a semi-inclusive jet function $J_i(y, \omega_J, \mu)$, provides information about a jet with energy ω_J and radius R, that carries a fraction y of the light-cone momentum component of some parton i to initiate a jet. [4]

The jet function for a quark is expressed as,

$$J_q(y,\omega_J,\mu) = \delta(1-y)+\frac{\alpha_s}{2\pi}L[P_q(y)+P_g(y)]-\frac{\alpha_s}{2\pi}\{C_F[2(1+y^2)(\frac{ln(1-y)}{1-y})+(1-y)]-\delta(1-y)d_J^{q,alg}+P_g(y)2ln(1-y)+C_F y\} \tag{9}$$

The jet function for a gluon is expressed as,

$$J_q(y,\omega_J,\mu) = \delta(1-y)+\frac{\alpha_s}{2\pi}L[P_g(y)+2N_f P_q(y)]-\frac{\alpha_s}{2\pi}[\frac{C_A(1-y_y^2)^2}{y}(\frac{ln(1-y)}{1-y})-\delta(1-y)d_J^{g,alg}+4N_f(P_q(y)ln(1-y)+T_F y(1-y))] \tag{10}$$

In the above equation, $L = ln\frac{\mu^2}{\omega_J^2 tan^2\frac{R}{2}}$, $\omega_J = (\frac{\mu_J}{tan^2\frac{R}{2}})^2$, $\mu_J = \mu R$, $d_J^{q,alg} = C_F(\frac{13}{2} - \frac{3\pi^2}{4}) + C_A\frac{\pi^2}{12}$, and other variables have been defined in the earlier section. Using this expression, we can evaluate p_T and R_{aa} values theoretically and examine the results of jet function and compare those to that of fragmentation function.

5 Conclusion

We begin by evaluating the different emission kernel equations. Then proceed to test the power correction to the energy loss calculations. Our theory prediction was in good agreement with the experimental results obtained from RHIC and LHC given that we use high $\hat{q}$ value. This can be concluded by stating that it is too difficult to add more corrections to the medium modified fragmentation function.

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