Searching the Color Glass Condensate Through $p_T$ Suppression

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In this work the rapidity and transverse momentum dependence of the nuclear modification ratio is evaluated for the dilepton production at RHIC and LHC, using the Color Glass Condensate (CGC) framework. The ratio is compared for two distinct dilepton mass values, concerning the transverse momentum distribution, and a suppression of the Cronin peak is verified even for large mass. The nuclear modification ratio suppression in the dilepton rapidity spectra, as obtained for hadrons at RHIC, is verified for LHC energies at large transverse momentum, although not present at RHIC energies. These results consolidate the dilepton as a most suitable observable for QCD high density approaches.

1 Introduction

The RHIC data on high energy collisions regarding the transverse momentum spectra of the hadrons, present some interesting results\textsuperscript{[1,2]}. The comparison between multiplicity of hadrons per unit of space in $d - Au$ and $p - p$, and in central and peripheral collisions has being the main object of investigation. These comparisons are performed introducing the nuclear modification ratio, for example

$$R_{dAu} = \frac{dN_{dAu \rightarrow hX}/dydp_T}{N_{col} dN_{pp \rightarrow hX}/dydp_T},$$

where the normalization factor $N_{col}$ is the number of binary collisions, $y$ and $p_T$ are the rapidity and transverse momentum of the hadron. For the case of $d - Au$ collisions the ratio becomes larger than 1 at mid rapidity $y \approx 0$ and saturates at large $p_T$. This implies a peak at intermediate $p_T$ (2-5 GeV), which is called Cronin effect or Cronin peak. As one goes to large rapidities, the suppression of the ratio $R_{dAu}$ (smaller than 1) was observed and a flat behavior at large $p_T$ is found. Such effects are measured concerning the transverse momentum hadron spectra. In order to avoid systematic errors, the ratio of a given centrality class to the peripheral one should take $R_{CP}$ instead of the ratio $R_{dAu}$. The peripheral nuclear collision behaves as a $pp$ collision and the ratio is obtained through the same run process and same particle species. In both defined ratios, the conclusions are the same, a significant reduction of the yield of charged hadrons measured in $dAu$ collisions when compared with the $pp$ collisions at forward rapidities is found\textsuperscript{[2]}. Such suppression effect is consistent with the expected saturation of the gluon distribution,
as proposed by the Color Glass Condensate approach when quantum evolution is considered and by the quantum evolution of the BK equation.

The main interest related to the Cronin effect is regarding the hadron $p_T$ spectra, however, in a recent work we have demonstrated that the dilepton production should also be considered as an observable to study this effect. The dileptons analyzed in the context of the Color Glass Condensate (e.g. 5,6,7,8) present the same features of the Cronin effect in such approach and do not present final states interactions, carrying not disturbed information about the Color Glass Condensate. In this work, the ratio between $p - Au$ and $p - p$ differential cross section is evaluated, analyzing the transverse momentum and the rapidity distributions of the dileptons. Comparing with the previous results, where the dilepton mass $M = 3$ GeV was employed, we calculate for larger values of mass and present the results as a function of rapidity and transverse momentum $p_T$ of the dileptons. We discuss the results and the kinematical limits of the rapidity for this observable.

## 2 Dilepton production in the CGC approach

The dilepton production at high energies is dominated by the bremsstrahlung of a virtual photon by a quark from a hadron interacting with a dense background gluonic field of the nucleus, and afterwards decaying into a lepton pair.

The Color Glass Condensate is a QCD classical effective theory to deal with the high dense partonic system. In this theory the small $x$ gluons are described by a color source density $\rho_a$ and radiated from fast moving color sources with internal dynamics frozen by Lorentz time dilatation, thus forming a color glass. The observables are obtained by means of an average over all configurations of the color sources, performed through a weight functional $W_{\Lambda^+}[\rho]$, which depends upon the dynamics of the fast modes, and upon the intermediate scale $\Lambda^+$, which defines fast ($p^+ > \Lambda^+$) and soft ($p^+ < \Lambda^+$) modes. The modifications to the effective classical theory are governed by a functional, nonlinear, evolution equation JIMWLK for the statistical weight functional $W_{\Lambda^+}[\rho]$ associated with the random variable $\rho(x)$.

The hadronic cross section of the dilepton production is obtained employing the collinear factorization and considering the forward rapidity region, and read as:

$$
\frac{d\sigma^{pA\rightarrow q\bar{q}^*X}}{dp_T^2 dM \ dx_F} = \frac{4\pi^2}{M} R_A^2 \frac{\alpha_s^2}{3\pi} \frac{1}{x_1 + x_2} \times \int \frac{dl_T}{(2\pi)^3} W(p_T, l_T, x_1) C(l_T, x_2, A),
$$

where $x_F$ being the longitudinal momentum fraction given by $x_F = x_1 - x_2$ (related to the rapidity $y$), $M$ is the lepton pair mass, $x_1$ and $x_2$ are the momentum fractions carried by the quark from the proton and by the gluonic field from the nucleus, respectively, defined in the formal way. The squared center of mass energy is denoted by $s$ and $l_T = q_T + p_T$ is the total transverse momentum transfer between the nucleus and the quark. The expression is restricted to the forward region only, which means positive rapidities ($y$ or $x_F$). The function $W(p_T, l_T, x_1)$ can be written as:

$$
W(p_T, l_T, x_1) = \int_{x_1}^{1} dz \frac{z}{z} F_2(x_1/z, M^2) \\
\times \left\{ \frac{(1 + (1 - z)^2)z^2 l_T^2}{p_T^2 + M^2(1 - z)((p_T - zl_T)^2 + M^2(1 - z))} + \frac{1}{p_T^2 + M^2(1 - z)((p_T - zl_T)^2 + M^2(1 - z))} \right\}.
$$

Here $R_A$ is the nuclear radius, $z \equiv p^-/k^-$ (light-cone variables) is the energy fraction of the proton carried by the virtual photon. The function $C(l_T)$ is the field correlator function and
defined by \[ C(l_T) \equiv \int d^2x_\perp e^{il_T \cdot x_\perp} \langle U(0)U^\dagger(x_\perp) \rangle_\rho, \] (4)

with the averaged factor representing the average over all configurations of the color fields sources in the nucleus, \( U(x_\perp) \) is a matrix in the \( SU(N) \) fundamental representation which represents the interactions of the quark with the classical color field of the nucleus. All the information about the nature of the medium crossed by the quark is included in the function \( C(l_T) \). In particular, it determines the dependence on the saturation scale \( Q_s \) (and on energy), implying that all saturation effects are encoded in this function.

\[ F_2(x, Q^2) \] is the partonic structure function, which takes into account the quark distribution of the proton projectile. In our calculations the CTEQ6L parametrization \[ ^{16} \] was used for the structure function, and the lepton pair mass gives the scale for the projectile quark distribution.

The energy dependence introduced in the Eq. (2) in the correlator function \( C(l_T, x, A) \) is performed by means of the saturation scale \( Q_{s,A}(x) \) and provides the investigation of the effect of the quantum evolution in the dilepton production. We are based in the GBW parametrization \[ ^{17} \] to obtain the \( x \) dependence of the saturation scale \( (Q_s^2 = (x_0/x)^A) \), and the parameters have been taken from the dipole cross section extracted from the fit procedure by CGCfit \[ ^{18} \] parametrization. The nuclear radius, which appears in the Eq. (2), is taken from the Woods-Saxon parametrization, which has the form, \( R_A = 1.2A^{1/3} \text{ fm} \), while the proton radius (for \( pp \) calculations) is taken from the fits.

In this work we have evaluated the cross sections using the function \( C(l_T, x, A) \) based in the McLerran-Venugopalan (MV) theory, introducing an \( x \) dependence through the nuclear saturation scale, which is parametrized in the form \( Q_s^2(x, A) = A^{1/3}Q_s^2 \).

The correlator function employed here is a non-local Gaussian distribution of color sources, predicted in Ref. \[ ^{19} \] as a mean-field asymptotic solution for the JIMWLK equation written in the following form \[ ^{9,20} \]

\[ C(l_T, x, A) \equiv \int d^2x_\perp e^{il_T \cdot x_\perp} e^{-\chi(x, x_\perp, A)}, \] (5)

with

\[ \chi(x, x_\perp, A) \equiv \frac{2}{\gamma c} \int \frac{dp}{p} (1 - J_0(x_\perp p)) \times \ln \left( 1 + \left( \frac{Q_s^2(x, A)}{p^2} \right)^\gamma \right), \]

where, \( \gamma \) is the anomalous dimension (\( \gamma \approx 0.64 \) for BFKL) and \( c \approx 4.84 \) \[ ^{9,20} \].

One has specified the cross section to evaluate the dilepton differential cross section, and in the next section, the nuclear modification ratio for the dilepton production is investigated and related to the measured Cronin effect.

## 3 Cronin effect and the dilepton production

As discussed in the introduction of this work, the Cronin effect is related to the measurement of the hadron transverse momentum spectra. Here, the appearance of the same effects in the dilepton \( p_T \) and rapidity spectra are investigated for a lepton pair mass \( M = 6 \text{ GeV} \). In a previous work \[ ^{5} \] the investigation was performed for the \( p_T \) distribution of dileptons with mass \( M = 3 \text{ GeV} \). Now, one evaluates the \( p_T \) and rapidity spectra for the dilepton at RHIC and LHC energies, \( \sqrt{s} = 200 \text{ GeV} \) and \( \sqrt{s} = 8800 \text{ GeV} \), respectively.
We have defined the nuclear modification ratio for the dilepton production in the following form,

\[
R_{pA} = \frac{\frac{d\sigma(pA)}{A^{1/3} dM dx_F dp_T^2}}{\frac{\sigma(pp)}{\pi R_A^2 dM dx_F dp_T^2}}.
\] (6)

The comparison between the results for the ratio \( R_{pA} \) considering two distinct lepton pair masses can be verified in the Fig. 1 for LHC energies, where the expected result is found; the effect of the suppression of the ratio is reduced if the dilepton mass is increased at a fixed rapidity.

![Figure 1: Ratio \( R_{pA} \) for LHC energies, for \( y = 5 \) and \( y = 6 \), comparing results for \( M = 3 \) GeV and \( M = 6 \) GeV.](image1)

The performed analysis is only for forward rapidities. However, the maximum value of rapidity depends on the value of the mass and the transverse momentum. In the Fig. 2 one presents the limit values for the rapidity as a function of the dilepton transverse momentum and mass for RHIC and LHC energies. The region of large mass and large \( p_T \) implies small values for the rapidity limit values. In the RHIC kinematical regime, the mass region between 2 and 10 GeV implies forward maximum values of rapidity from 2.97 to 2.65 respectively at \( p_T \approx 10 \) GeV and range between 4.26 to 2.97 respectively at \( p_T \approx 2 \) GeV for an energy \( \sqrt{s} = 200 \) GeV.

![Figure 2: Maximal value of dilepton rapidity as a function of the mass \( M \) and transverse momentum \( p_T \) for RHIC and LHC energies.](image2)

For LHC energies the same behavior is verified, however, the range of the maximum rapidity...
is dramatically modified. For the mass region between 2 and 10 GeV, the maximum rapidity range goes from 6.76 to 6.43 respectively at $p_T \approx 10$ GeV and goes from 8.04 to 6.76 respectively at $p_T \approx 2$ GeV for an energy $\sqrt{s} = 8800$ GeV. The nuclear modification ration, is investigated up to the maximal value of the forward rapidity for mass $M = 6$ GeV at RHIC and LHC energies.

![Figure 3: Ratio $R_{pA}$ as a function of rapidity and $p_T$ for dileptons at RHIC energies.](image)

In the Fig. the nuclear modification ratio for RHIC energies is shown for dilepton mass $M = 6$ GeV. The weak dependence of the ratio $R_{pA}$ with the rapidity range for the RHIC energies is verified, since independent of the $p_T$ value, the ratio does not vary significantly with rapidity. This occurs due to the fact that one evaluates the ratio $R_{pA}$ only at forward rapidities. The suppression of the ratio with the increase of the rapidity is verified concerning the hadron spectra from mid rapidity ($y = 0$) to forward rapidity ($y = 3.2$). In the case of the dileptons, the same suppression is verified, however as we are restricted to the forward rapidities, such suppression is small in the rapidity range investigated here. For completeness, in such range of rapidity ($1.5 < y < 3$) and for $M = 6$ GeV, the nuclear dense system is being proved with the momentum fraction from $x = 10^{-2}$ down to $x = 10^{-3}$ at $p_T \approx 10$ GeV, being not too small $x$ region. The suppression of the ratio (absence of a Cronin type peak) in the $p_T$ distribution is verified, although the suppression is practically the same as one goes up in rapidity.

The comparison with the previous ratio results evaluated for mass $M = 3$ GeV was done in the Fig. for LHC energies. In the Fig. the nuclear modification ratio for LHC energies is shown for dilepton mass $M = 6$ GeV. Due to the large range of forward rapidities at LHC energies, one verifies the large suppression of the nuclear modification ratio with the increase of the rapidity. This suppression is intensified at large $p_T$. The suppression of the same ratio with the transverse momentum is also verified and is intensified at large rapidities.

At LHC, the large range of rapidity provides the $x$ range in the large $p_T$ region ($p_T \approx 10$ GeV) stays between $10^{-4}$ and $10^{-6}$. In this kinematical region, there are large effects of saturation predicted by the Color Glass Condensate: the large suppression of the nuclear modification ratio comparing with the expected Cronin peak shows the existence of the saturation effects, in both, rapidity and transverse momentum distributions.

In this work the ratio $R_{pA}$ was investigated for dilepton mass $M = 6$ GeV and shown as a function of rapidity and $p_T$. One has discussed the region of maximum value of rapidity as a function of the dilepton mass and transverse momentum. The results presented here, show that the dilepton should be considered as a good observable to provide a tool to investigate the properties of the Cronin effect, since it presents the effect of suppression of the ratio $R_{pA}$ in both
distributions, rapidity and transverse momentum, and does not present final state interactions. One expects that such saturation effects are from the similar mechanisms observed in the hadrons transverse momentum and rapidity spectra, and considers the dilepton production should clarify the status of final and initial state effects in the Cronin effect being a cleanest probe to the Color Glass Condensate dynamics.

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