Forward dihadron correlations in the Gaussian approximation of JIMWLK

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Abstract

We compute forward dihadron azimuthal correlations in deuteron-gold collisions using a Gaussian approximation for the quadrupole operator. The double parton scattering contribution is found to be part of our dihadron calculation. We obtain a good description of the PHENIX data for the azimuthal-angle dependent away side peak and a relatively good estimate for the pedestal contribution.

Keywords: Dihadron correlations, JIMWLK, BK

1. Introduction

At high energy or, equivalently, small $x$, the interactions of hadrons are expected to be dominated by nonlinear strong color fields. A convenient effective theory approach to studying these color fields is provided by the Color Glass Condensate (for a review see e.g. [1]).

Measurements of correlations between two forward hadrons in dAu collisions at RHIC [2,3] seem to show indications of “initial state” or “cold nuclear matter” effects that are significantly stronger than in pp collisions or at central rapidities. The upcoming LHC proton-lead collisions will provide more opportunities to study these phenomena in a wider kinematical range.

These observations have provided an impetus for renewed interest in the gluonic correlations included in the JIMWLK evolution, see e.g. [4]. In particular it was argued that the result of a full JIMWLK evolution, at finite $N_c$, can quite accurately be captured by the so called Gaussian approximation, relating higher point Wilson line correlators to the two-point function. These recent theoretical developments were not fully reflected in the pioneering calculations of dihadron correlations in [5,6] where a factorized approximation is derived in a certain kinematical limit. The main purpose of this work (see Ref. [7]) is to implement the Gaussian approximation, which so far has only been tested for particular coordinate space configurations, in a full calculation of the dihadron correlation.

2. Single inclusive baseline

We shall here use the dipole operator obtained from solving numerically the BK evolution equation using the Balitsky running coupling prescription [8]. The BK equation requires an initial condition, for which we take the
\[ p + p \to \pi^0/h^- + X, \sqrt{s} = 200 \text{ GeV} \]

\[ d + Au / p + p \to \pi^0 + X, \sqrt{s} = 200 \text{ GeV} \]

Figure 1: \( \pi^0 \) production in forward \( p+p \) collisions compared with BRAHMS \[\text{[12]}\] \( h^- \) and STAR \[\text{[13]}\] \( \pi^0 \) data.

Figure 2: Nuclear suppression factor \( R_{dAu} \) compared with PHENIX \[\text{[3]}\] and STAR \[\text{[13]}\] \( \pi^0 \) data. Note that the STAR data is at a slightly different rapidity.

McLerran-Venugopalan model \[\text{[9]}\]

\[ S(r)_{x=m} = \exp \left\{ -\frac{r^2 Q_s^2}{4} \ln \left( 1 + \frac{1}{r^2 A_{QCD}} \right) \right\}, \]

with \( Q_s^2 = 0.2 \text{ GeV}^2 \) for the proton at \( x_0 = 0.007 \) similarly as in Ref. \[\text{[10]}\]. Following Ref. \[\text{[11]}\] we can then calculate single inclusive hadron production in forward rapidities. The comparison with STAR \( \pi^0 \) and BRAHMS charged hadron data is shown in Fig. \[\text{[1]}\]. This parametrization overestimates the pion yield by a factor \( \sim 3 \), but describes the charged hadron yield correctly. We prefer to use the same parameters as Ref. \[\text{[10]}\] to see clearly the effects of including the Gaussian quadrupole. We expect most of the overall normalization error to cancel in the per trigger correlation and not affect the systematics of the away side peak.

For a nuclear target we use larger initial saturation scale, and we set \( Q_{s0}^2 = 0.72 \text{ GeV}^2 \) at same \( x_0 = 0.007 \) which fits the most central PHENIX \( R_{dAu} \) data shown in Fig. \[\text{[2]}\]. However it seems quite impossible to simultaneously describe STAR minimum bias data. We consider the normalization issue of the single inclusive baseline as the largest uncertainty in our calculation.

3. Dihadron correlations

Consider a large \( x \) quark with momentum \( p^+ \) from the probe deuteron or proton, propagating eikonally through the target nucleus or proton. It can radiate a gluon with momentum \( k^+ = zp^+ \) and is left with longitudinal momentum \( q^+ = (1-z)p^+ \). In the high energy limit the scattering of both the quark and the gluon can be described by the eikonal approximation, where they pick up a phase given by a Wilson line in the color field of the target. The detailed derivation of the double inclusive cross section is performed in Ref. \[\text{[5]}\] and results in the following expression for the \( qA \to qgX \) cross section:

\[ \frac{\text{d}^2 \sigma^{qA \to qgX}}{\text{d}k^+ \text{d}k_T \text{d}q^+ \text{d}^2 q_T} = C_T \delta(p^+ - k^+ - q^+) \int \frac{d^2 x_T}{(2\pi)^2} \frac{d^2 b_T}{(2\pi)^2} \frac{d^2 b_T'}{(2\pi)^2} \frac{d^3 b_T}{(2\pi)^2} \frac{d^3 b_T'}{(2\pi)^2} \exp\left[ i q_T \cdot (x_T - b_T) - i q_T \cdot (x_T - b_T') \right] \]

\[ \times \sum_{gT,\bar{g}T} \delta^{(4)}(x_T' - b_T') \delta^{(4)}(x_T - b_T) \left[ S^{(4)}(b_T, x_T, b_T', x_T') - S^{(3)}(b_T, x_T, z_T') - S^{(3)}(z_T, x_T', b_T') + S^{(2)}(z_T, z_T') \right], \]

with \( z_T = z x_T + (1-z)b_T \) and likewise, \( z_T' = z x_T' + (1-z)b_T' \). The momenta of the produced gluon and quark are \( k_T \) and \( q_T \) respectively. Likewise, \( x_T, x_T' \) should be interpreted as the transverse position of the gluon and \( b_T, b_T' \) of
have, using the fact that the expectation values must be color singlets, in the kinematical regime the “DPS” limit. In this limit the Wilson lines of the quark and the gluon are uncorrelated and we

dipole at the location of the gluon and a fundamental representation one at the location of the quark. We call this

process has been considered to be completely separated from the correlated dihadron production. However, when

4. Double parton scattering

The Δφ independent pedestal in the experimentally measured coincidence probability is mostly due to the double
darton scattering contribution where two hadrons are produced independently of each other. In previous works [6,15] this

process has been considered to be completely separated from the correlated dihadron production. However, when

one uses the Gaussian approximation for the quadrupole function one can show that Eq. (2) actually contains part of

this DPS (Double Parton Scattering) contribution.

The DPS contribution is obtained when gluon is emitted far away from the quark: |b_T − b'_T| ≈ |x_T − x'_T| ≈ 1/Q_s, \( w_T \equiv \|b_T - x_T\| \gg 1/Q_s \). In this limit the only surviving correlation in \( S^{(4)} \) is the product of an adjoint representation dipole at the location of the gluon and a fundamental representation one at the location of the quark. We call this

kinematical regime the “DPS” limit. In this limit the Wilson lines of the quark and the gluon are uncorrelated and we

have, using the fact that the expectation values must be color singlets,

\[
S^{(4)}(b_T, x_T, b'_T, x'_T) \approx S^{(4)}_{DPS}(b_T, x_T, b'_T, x'_T) = \frac{N_c^2}{N_c^2 - 1} \left\langle \tilde{D}(b_T, b'_T) \right\rangle \left\langle \tilde{D}^2(x_T, x'_T) - \frac{1}{N_c^2} \right\rangle,
\] (3)

Figure 3: The quark-gluon parton level correlations near forward RHIC kinematics Shown are the “naive large-\( N_c \)” approximation (labeled as “elastic” in the plot) used in [6] and our Gaussian approximation for the quadrupole and its large-\( N_c \) limit. Note that fixed Δφ-independent pedestal of 0.0002 GeV\(^{-4}\) is added to the “elastic” approximation for the purposes of visualization.

Figure 4: The \( \pi^0 \) azimuthal angle correlation compared to the PHENIX [3] dAu result. The Δφ independent pedestal is adjusted to fit the experimental data. The initial saturation scale is \( Q_0^2 = 0.72 \text{ GeV}^2 \) at \( x_0 = 0.007 \) and the large-\( N_c \) limit of the Gaussian approximation is used.
where $\hat{D}$ is a correlator of two Wilson lines (two point function) in the fundamental representation, and the expectation value of $D^2 \sim 1/N_c^2$ can be identified as the two point function in the adjoint representation.

For massless quarks the four-point function $S^{(4)}$ causes the integral (2) to diverge logarithmically in the DPS limit. Physically this means that the quark emits a very small transverse momentum gluon. The quark and gluon subsequently scatter independently off the target. The DPS limit corresponds to a splitting happening a long time before the interaction with the target. This logarithmically divergent contribution must be regulated by confinement scale physics in the wavefunction of the projectile. It is in fact exactly the kind of contribution that is represented by double parton scattering, discussed in this context e.g. in Ref. [16].

We add to the dihadron production cross section the DPS contribution. In order to avoid double counting the logarithmically divergent DPS part is subtracted from Eq. (2). This forces us to introduce an arbitrary (soft) cutoff scale $\Lambda_{QCD}$. The DPS contribution is then divided into two separate parts. The first one corresponds to taking two partons from the same nucleon in the deuterium, described by a single-nucleon double parton distribution function, which we model by implementing a kinematical constraint $x_i + x_j < 1$ following Ref. [16]. The second contribution involves taking one parton from the neutron and the other one from the proton, which is not bound by the same kinematical constraint. Once we have obtained the corresponding parton distribution functions, the DPS yield is essentially the single inclusive yield squared.

As a result we obtain an order-of-magnitude estimate for the $\Delta \phi$ independent pedestal. When comparing with PHENIX data, we obtain for the trigger transverse momentum range $1.1 \ldots 1.6$ GeV a pedestal $0.11$ GeV$^{-1}$, whereas the experimental value is $0.176$ GeV$^{-1}$. Similarly for the trigger transverse momentum $1.6 \ldots 2$ GeV we obtain $0.08$ GeV$^{-1}$, and the experimental value reads $0.163$ GeV$^{-1}$ [3].

5. Conclusions

We have shown that the previously used “naive large-$N_c$” approximation for the quadrupole is not accurate, and the width and especially the height of the back-to-back peak is modified when more accurate Gaussian approximation is used. In addition, the naive approximation misses an important logarithmically divergent DPS contribution, which is included consistently in our work.

We obtain a relatively good estimate for the $\Delta \phi$ independent pedestal background, and a good description of the $\Delta \phi$ dependent part of the PHENIX data. We also point out that the “naive large-$N_c$” approximation clearly underestimates the height of the away side peak.

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References

[1] T. Lappi, Int.J.Mod.Phys. E20, 1 (2011) [arXiv:1003.1852 [hep-ph]].
[2] E. Braidot, arXiv:1102.0931 [nucl-ex].
[3] PHENIX, A. Adare et al., Phys.Rev.Lett. 107, 172301 (2011) [arXiv:1105.5112 [nucl-ex]].
[4] A. Dumitru, J. Jalilian-Marian, T. Lappi, B. Schenke and R. Venugopalan, Phys.Lett. B706, 219 (2011) [arXiv:1108.4764 [hep-ph]].
[5] C. Marquet, Nucl. Phys. A796, 41 (2007) [arXiv:0708.0231 [hep-ph]].
[6] A. Dumitru, J. Jalilian-Marian, T. Lappi, B. Schenke and R. Venugopalan, Phys.Lett. B706, 219 (2011) [arXiv:1108.4764 [hep-ph]].
[7] C. Marquet, Nucl. Phys. A796, 41 (2007) [arXiv:0708.0231 [hep-ph]].
[8] J. L. Albacete and C. Marquet, Phys.Rev.Lett. 105, 162301 (2010) [arXiv:1005.4065 [hep-ph]].
[9] T. Lappi and H. Mäntysaari, arXiv:1209.2853 [hep-ph].
[10] I. Balitsky, Phys. Rev. D75, 014001 (2007) [arXiv:hep-ph/0609105].
[11] L. D. McLerran and R. Venugopalan, Phys. Rev. D49, 2233 (1994) [arXiv:hep-ph/9309289].
[12] J. L. Albacete and C. Marquet, Phys.Lett. B687, 174 (2010) [arXiv:1001.1378 [hep-ph]].
[13] A. Dumitru, A. Hayashigaki and J. Jalilian-Marian, Nucl. Phys. A765, 464 (2006) [arXiv:hep-ph/0506308].
[14] B. Schenke, J. Adams et al., Phys. Rev. C84, 034905 (2011) [arXiv:1105.4065 [hep-ph]].
[15] M. Strikman and W. Vogelsang, Phys.Rev. D83, 034029 (2011) [arXiv:1009.6523 [hep-ph]].