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Dijet production at EIC and interplay of Sudakov and saturation effects in Weizsäcker-Williams TMD gluon distribution

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Abstract

We study production of dijets at the EIC using the small-x Improved Transverse Momentum Dependent factorization (ITMD), which is a framework based on the Color Glass Condensate theory. Dijet production in DIS is the simplest process directly coupled to the Weizsäcker-Williams TMD gluon distribution, which is the only small-x gluon distribution possessing the gluon number density interpretation. We study various observables sensitive to the interplay of the Sudakov effects and the nonlinear effects, in particular the azimuthal correlations between the jet system and the scattered electron.

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1 Introduction

One of the goals of the new Electron Ion Collider (EIC) [1] is to provide a conclusive evidence for the gluon-saturated hadronic state of matter. At sufficiently large energy, the colliding hadrons are dominated by gluons with small longitudinal momentum fractions x that start to spatially overlap and eventually recombine leading to the saturation phenomenon [2]. The Color Glass Condensate (CGC) theory [3] is an effective theory of QCD that incorporates the saturation and provides a description of particle collisions occurring at very high energies. In practice, CGC calculations are rather complicated for processes involving more then one hadronic final state. However, if the final state jets possess transverse momenta significantly larger then the saturation scale ($\sim$ 1-2 GeV) a simplification occurs and the CGC description can be reformulated in terms of the so-called small-x improved Transverse Momentum Dependent (TMD) factorization (ITMD) [4]. Here, the improvement means that the factorization formula involves not only the leading power contribution, but also all the kinematic twist corrections [5] that are sensitive to azimuthal correlations. The genuine twist corrections correspond to the hard multi-gluon exchange and are suppressed by the powers of the hard scale.

In general, ITMD involves multiple small-x TMD gluon distributions that differ by gauge links required by the gauge invariance [6, 7]. Two particularly interesting gluon distributions are the dipole distribution appearing in the inclusive DIS and the so-called Weizsacker-Williams (WW) distribution. Unlike the first one, the WW distribution has a gluon number density interpretation, which makes it the most basic TMD gluon distribution. Yet, it does not appear in the simplest inclusive processes. The most clean probe of the WW distribution is dijet production in photon-hadron collisions [8].

In the present work [9] we study dijet production for the EIC kinematics within the ITMD framework, focusing on the azimuthal correlations between the scattered electron and the dijet system, although the correlations between the jets itself are also analyzed. A proper theoretical description requires the WW TMD gluon distribution incorporating both the saturation effects (i.e. the nonlinear evolution in energy) and the Sudakov effects that are important for azimuthal correlations for sufficiently hard jets. Since, at present, direct fits of the WW distribution are not available, we calculated it within the mean field approximation from the dipole TMD gluon distribution fitted to HERA data [10] and evolving according to the nonlinear version of the Kwieciński-Martin-Stasto equation [11]. Next, we incorporated a proper perturbative Sudakov factor [12]. For other calculations of related observables both in CGC and ITMD see [13–15].

2 Framework

The contribution of unpolarized gluons to the ITMD factorization formula (called the ITMD* formalism) for dijet production in electron-hadron collision reads

$$d\sigma_{eh\to e'+2j+X} = \int \frac{dx}{x}\frac{d^2k_T}{\pi}\,\mathcal{F}_{gg}^{(3)}(x,k_T,\mu)\,\frac{1}{4xP_e\cdot P_h}\,d\Phi(P_e,k;p_e,p_1,p_2)\,|\overline{M}_{eg^*\to e'+2j}|^2, \quad (1)$$

where P_h, P_e are momenta of the incoming hadron and electron, respectively. Further, $k = xP_h + k_T$ is the momentum of the initial-state space-like gluon entering the hard collision and p_e,$p_{1,2}$ are the momenta of the final-state electron and the final-state partons. $d\Phi$ denotes the full phase space involving the scattered electron. The scattering amplitude $\overline{M}_{eg^*\to e'+2j}$ is calculated with incoming gluon being off-mass shell in a gauge invariant way. It includes all helicity configurations of involved partons, as we well as the summation over color and flavor degrees of freedom. $\mathcal{F}_{gg}^{(3)}(x,k_T,\mu)$ is the hard-scale-dependent unpolarized WW gluon density, counting the number of gluons at resolution scale μ. The hard scale dependence comes from the Sudakov form factor calculated in [12] at leading logarithmic approximation. For exact definitions see [9].

In Eq. (1) we do not include the WW distribution of linearly polarized gluons in unpolarized target [16]. In general, it does contribute for $Q^2 > 0$, but it is suppressed by the power of the jet transverse momentum. As discussed in the following Section, we select our cuts in such a way that the linearly polarized part can be neglected. Thus, our calculation is directly sensitive to the solely unpolarized gluon number density.

3 Results

In Fig. 1 we show the WW gluon distribution for the proton (left) and for the lead (right) as a function of $\ln k_T$ for $x = 10^{-3}$ and couple of choices of the hard scale μ, calculated following the procedure outlined in in Section 1. Note first, that the scale-independent distribution has no maximum, unlike the dipole TMD gluon distribution. It is consistent with early calculations

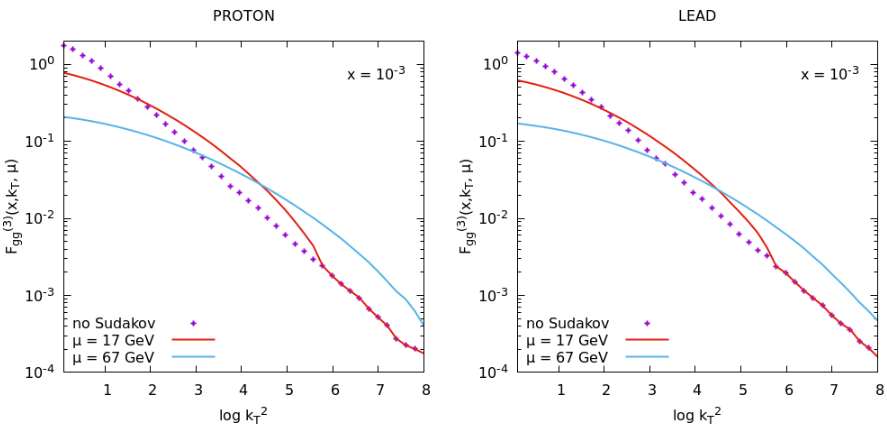

Figure 1: The WW gluon density in the proton (left) and lead (right), with and without Sudakov resummation, as a function of the transverse momentum for a few values of the hard scale μ.

of that distribution in the McLerran-Venugopalan model. The Sudakov form factor gives a suppression at $k_T < \mu$ and slight enhancement for $k_T > \mu$ compared to the distribution without the Sudakov resummation.

We generated dijet events for electron-proton and electron-lead collisions at $\sqrt{S} = 90\,\text{GeV}$ per nucleon using the KaTie [17] Monte Carlo. We have applied the following cuts

$$\begin{gathered} Q^2 > 1\,\text{GeV}^2, \qquad 0.1 < \nu < 0.85 \\ \Delta R^{\text{Breit}} < 1, \qquad p_{T1}^{\text{Breit}} > p_{T2}^{\text{Breit}} > 3\,\text{GeV}, \\ -4 < y_1^{\text{lab}}, y_2^{\text{lab}} < -1\,, \end{gathered} \tag{2}$$

where Q^2 is the photon virtuality, ν is inelasticity, ΔR is the jet radius in the rapidity-azimuthal angle plane and p_{T1}, p_{T2}, y_1, y_2 are transverse momenta and rapidities of the jets. The selection of the cuts follows our assumptions and goals. First, we want the transvere momenta to be higher then the saturation scale to justify the use of the ITMD formalism rather then the full CGC approach. Second, we want to utilize solely the WW distribution of unpolarized gluons, which is assured thanks to the condition $Q^2/p_T^2 \ll 1$ that holds for most of the events. Further, it turns out that in order to achieve a good focusing on the reasonably small gluon x probed in the WW distribution, as required by the formalism, one should use the forward rapidity cuts. This is illustrated in Fig. 2.

In Fig. 3 we show azimuthal correlations between the total transverse momentum of jets and the scattered electron calculated in two different frames: the LAB frame and the Breit frame. We observe rather mild saturation effects with our kinematic cuts. The Sudakov suppression is on the other hand very significant for the observable studied.

4 Conclusion

In order to study the Weizsäcker-Williams TMD gluon distribution for unpolarized gluons we apply the ITMD formalism to dijet production at the EIC. We investigated various selections of cuts to choose the proper ones, that allow to observe both the saturation effects and Sudakov suppression. We find that the azimuthal correlations between the dijet system and scattered electron provides a more sensitive probe of those effects then the dijet azimuthal correlations

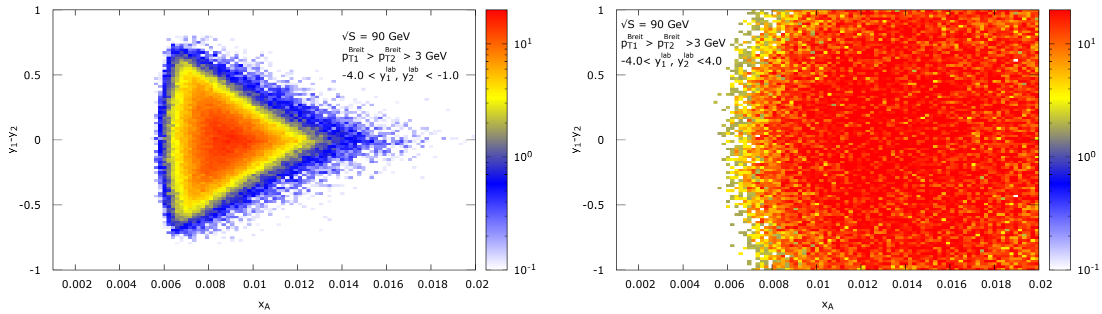

Figure 2: Density plots representing contribution of events for a given gluon x and jet rapidity difference for the asymmetric rapidity cuts (left) and the symmetric rapidity cuts (right). The asymmetric rapidity cuts provide a much better focusing of the cross section around smaller values of x required by the formalism.

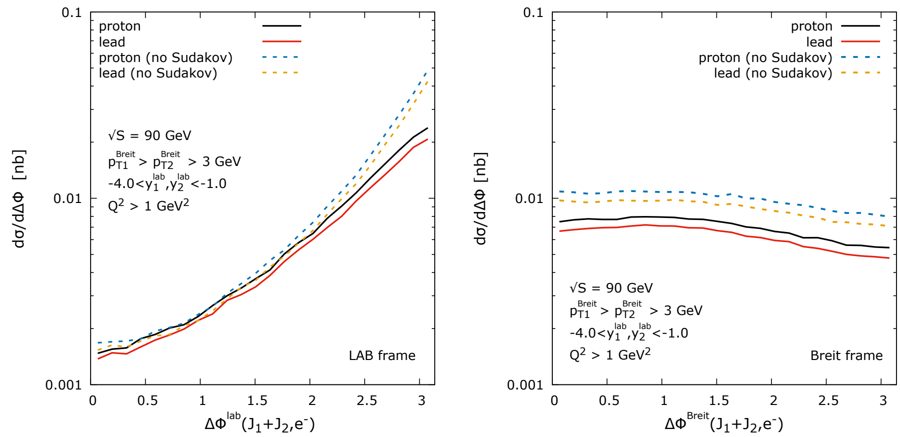

Figure 3: Azimuthal correlations between the total transverse momentum of the di-jets and the transverse momentum of the scattered electron in two frames: the LAB frame (left), the Breit frame (right).

alone. For more details see [9].

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